Climate change

Current and future impacts on historic vessels and the UK maritime heritage sector

Volume One: Overview

Image: Ian Kippax

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EXECUTIVE SUMMARY

- **INTRODUCTION**

It is now unequivocally recognised that 'human influence has warmed the atmosphere' at an unprecedented scale with many changes being 'irreversible for centuries to millenia', especially in relation to the ocean, ice sheets and global sea level.[1] These changes will impact every region of the world and it is vital that collective action is taken to keep human induced global warming to a specific level to reach at least net zero CO^2 emissions if the effects are to be held within viable limits.

This paper looks at the impact of climate change on maritime heritage, setting it first in a wider context and examining likely scenarios for the UK under the current scientific predictions. It highlights the fact that historic vessels are made of perishable materials and will therefore suffer particularly from changes to weather. However, it also identifies the key role which our sector can play in the fight against climate change. Historic vessels have an opportunity to be part of the solution by maintaining and sharing the unique skills and knowledge which have been handed down over generations, such as: the use of sustainable materials and traditional techniques; specialist understanding of the sea and the weather; and the ability to sail engine-less craft with zero carbon emissions.

The report has been split into two volumes, the first of which provides an overview of climate change, its implications and likely impacts. The second focusses on areas in which the historic vessel sector can take action, both to mitigate against and adapt to the changes that are coming. It is an essential read for any historic vessel custodian preparing and planning for the future, also giving an understanding of ways in which to reduce emissions without impairing the significance of the craft and contribute to national targets. The detailed bibliography offers avenues for further research and lists examples drawn from across the heritage sector.

- **BACKGROUND**

National Historic Ships UK (NHS-UK) is an independent advisory body, set up in July 2006 and funded by the Department for Digital, Culture, Media & Sport to provide objective advice on all matters relating to historic vessels. It has a wide remit, looking not only at the immediate issues concerning historic vessels in the UK, but also addressing questions relating to their supporting infrastructure and potential to contribute in the wider economic, social and community context. It maintains the National Historic Ship Registers, which comprise: the National Register of Historic Vessels; the National Historic Fleet; the Overseas Watch List; the National Archive of Historic Vessels; and the UK Replica List.[2]

[1] AR6 WGI Summary for Policymakers Headline Statements (ipcc.ch)
[2] www.nationalhistoricships.org.uk

This report was researched and written by a research intern from the University of Oxford during an extended placement with NHS-UK. As the representative body for historic vessels, NHS-UK was concerned to develop specialist guidance about the likely impacts of the changing climate on maritime heritage to help the sector prepare for what lies ahead. The evidence in this paper can also be drawn on by heritage organisations when developing sustainable projects or writing funding bids and will be used by NHS-UK in its role as an advisor to Government, local authorities, funding bodies and other key stakeholders.

- **SUMMARY**

In summary, this Report looks at both the direct and indirect impacts of climate change on maritime heritage, plus the likely consequences that these will bring. It covers: temperature rises and the subsequent strain on historic materials; thermal expansion and contraction; increased fire risks; greater likelihood of pest and plant infestations, including marine borers; plus ocean acidification. Sea level rise is a concern for many historic vessels operating on the coast, with higher potential for storm surges, flooding and further coastal erosion. Flash flooding inland will also increase and case studies identify areas where this has already affected historic vessels and put them at risk, such as in the Lake District, the wider inland waterways and the River Severn. By contrast, summer droughts may occur more frequently bringing issues of water availability and changes in humidity. Weather unpredictability may change the working seasons, both from a tourism perspective and for those seeking to maintain or conserve their craft.

Environmental pollution and degradation is addressed as an influencer of climate change. One of the most significant risks to the global marine environment today is from 8,500 shipwrecks worldwide which continue to emit pollution even from the seabed. The burning of fossil fuels is recognised as a key driver of the atmospheric changes and those historic vessels which also use these fuels make a small contribution to our global emissions. Every year an estimated 14 million pieces of plastic enter canals and rivers in the UK[3] harming marine life, creating a hazard for mariners, blocking waterways and costing huge sums to clear. Over-fishing has brought further degradation of the ocean, with some species now facing extinction and the livelihoods of many people threatened.

Indirect impacts are those which result from the actions of humans trying to mitigate or adapt to the direct impacts. Further research is required into these, but there is some evidence to suggest that renewable energy sources can cause damage to other sites, or deterioration and corrosion to other materials in the sea, including metal. There is a need to ensure that the aesthetic appeal of heritage assets is not negatively impacted by structures built to protect against climate change, such as coastal flooding defences.

[3] https://canalrivertrust.org.uk/news-and-views/features/plastic-and-litter-in-our-canals?utm_source=facebook&utm_medium=social&utm_campaign=plasticschallenge_2020

Equally, it is important to be careful that our search for sustainable resources does not restrict our ability to replace historic material with 'like for like' substitutes.

Having identified the scale of the problem in *Volume One*, this Report then seeks to mitigate it in *Volume Two*, stressing the need to think about long-term sustainability and begin making changes now. It offers some practical ways to adapt, such as implementing sustainable travel to your site, introducing a hybrid work policy for staff, reducing waste during events, changing to 'Vegware' products at catering outlets and installing water fountains, or using an eco-friendly search engine. A number of historic vessels are already adopting practical approaches to the plastic pollution problem the ocean is facing by undertaking beach cleans, litter picks and waste-related projects. The land management approach of re-wilding can also be applied to those vessels which have a supporting shore base.

The Report calls for each organisation to calculate its own carbon footprint and begin working towards becoming carbon neutral. For those vessels which presently rely on fossil fuels to operate, it is recognised that carbon neutrality is not always possible to achieve, particularly where the fuel-burning element is an integral part of why that craft is significant. However, the paper looks at the use of alternatives in the form of electric engines, bio-fuels, horse-drawn and sail transport, as well as covering adaptations that some vessels have already been required to make to comply with regulations associated with the use of new fuels. The potential for off-setting carbon is considered, plus the significant contribution that the historic sail cargo fleet can make in raising awareness of climate friendly transportation.

An environmental policy should be developed and built into the vessel statement of significance or conservation management plan. This will then drive all future activity, with green principles built into every project. Vessel custodians are encouraged to begin forward planning and 'future-proofing', including drafting an emergency or disaster plan for any climate change events which may occur, such as flooding or fires. There is a need to capture baseline data and continue to monitor changes to the vessel, so as to inform future mitigations or decisions you might take in response to new conditions. As well as holding data about the environment in which the vessel is kept or operates, there is also a role for vessel owning organisations to capture data on climate which can contribute to the overall UK picture on global warming. The findings provide an ideal way to educate the public about climate change through ocean literacy voyages which use historic vessels to build an awareness of what can be done to protect our planet.

Traditional shipbuilding and maritime craft skills typical to the UK can help in our efforts to apply more sustainable techniques, as well as the re-use of materials for building and conservation work. Training initiatives such as the Shipshape Heritage Training Partnership project run by NHS-UK, which saw 26 young people undertake a 12-month placement in the skills of conserving, maintaining and operating historic vessels, are an ideal way to keep these techniques alive. Re-using materials to create a local circular economy is also something which fits well with the ethos of historic vessels, often bringing conservation benefits by sourcing products more appropriate to the craft than a new replacement would be. Organisations are urged to consider generating or using renewable energy and a range of case studies give examples of the different ways this might be applied, from heat pumps to solar panels or wind turbines, thermal power and tide energy.

- **CONCLUSION**

The Report concludes that we must make changes now if we are to protect our historic vessels, their associated infrastructure and environment for the future. It recognises that some of the issues are complex and need to be tackled at a national level, while demonstrating the many ways in which historic vessel owners can play their part. NHS-UK undertakes to maintain a watching brief as new guidance and research emerges and to disseminate this to the sector, as well as continuing its advocacy work to develop best practice in our approach to dealing with climate-related issues. It is clear that although climate change represents the greatest single threat we are facing, it also offers an opportunity – a way for maritime heritage to engage with the wider heritage community to make a difference and help safeguard the things we are passionate about for future generations to enjoy.

VOLUME ONE: OVERVIEW AND IMPACTS

INTRODUCTION

Climate change is both the single biggest threat and opportunity for UK maritime heritage today. Climate change itself is not new – our climate has always been in flux. However, the scale and speed of the climate change currently occurring *is* new and this unprecedented change is anthropogenic. Climate change has never before been driven primarily by human activity.[4]

The consequences and scale of climate change are daunting and it is very difficult to fully comprehend the threat. It is impacting the whole of the UK and will continue to do so: it is not an issue confined to one region, meaning that vessels around the UK coast and inland waterways will likely have diverse experiences of climate change. It is highly variable. Some craft will be affected more than others and in different, complex ways.

Every single historic asset in the UK will be impacted by climate change to some degree: "heritage anchors a sense of place – and every place has a climate story".[5] Climate change is an all-encompassing and wide-ranging problem, with serious potential and actual impacts, some of which are already clear to see in the sector. Extreme weather events like floods, storms, and heatwaves, are currently relatively infrequent, although their incidence is increasing. Some threats to heritage posed by climate change are as yet unknown or are

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[4] Trow, 2008, 6.
[5] http://climateheritage.org

only now becoming apparent, because climate change is a risk multiplier, meaning it exacerbates less significant threats and creates new and unforeseen ones.[6] Some environmental risks, such as insect infestations and fluctuating temperatures, can appear less dangerous but, over time, will have a huge cumulative effect on heritage and only continue to increase in severity and frequency.

Fundamentally, climate change will shape *how* and *why* maritime heritage is at risk. [7] Climate change will not only affect the historic vessels and infrastructure themselves, but also the modern facilities used to support heritage and the people working with or benefiting from it, including volunteers, staff, and visitors.

PROTECTING HISTORIC VESSELS

Britain is an island nation and it is therefore important to protect its maritime heritage in order to tell the story of its past. Ships, particularly historic vessels, are emotive even to those who have never sailed or been onboard them. They bring Britain's history to life on both a global and local scale, from the coast and estuaries to inland rivers and waterways, through Victorian battleships like HMS *Warrior* to canal boats in the landlocked Black Country of the West Midlands.

Ninety per cent of the variations between the best and worst scenarios for climate change laid out by the Intergovernmental Panel for Climate Change (IPCC) are due to differences in future management, not differences in the scale of climate change.[8] Internationally and nationally, the importance of tackling climate change has now been recognised. It is no longer simply a moral issue, but a legal issue, too, in which every part of society has a role to play in reducing greenhouse gas emissions and improving sustainability. The heritage sector is no different. Working with and adapting to climate change so as to protect assets and inspire others to action will become an integral future activity. Heritage's ability to tackle climate issues head-on has been recognised nationally and internationally, in both the Paris Agreement of 2016 which committed to keeping global temperature rise below 2^{o}C, reflecting a global consensus on the need to mitigate greenhouse-gas emissions and achieve a net zero carbon future, and in the United Nation's Sustainable Development Goals (SDGs).

SDG 11.4 in particular, stresses the need to "strengthen efforts to protect and safeguard the world's cultural and natural heritage."[9] The SDGs also identify the important role of conservation and preservation of natural and cultural heritage to encourage sustainable development, "enhancing adaptivity and reducing the vulnerability of communities, from building social cohesion to guiding resilience planning… Heritage [is] a vector for climate

[6] https://historicengland.org.uk/research/current/threats/heritage-climate-change-environment/reponses/

[7] Fluck & Historic England, 2016, 11.

[8] Parry in Whimster, 2008, 21.

[9] There are 17 integrated SDGs. The fourth specific target of SDG11 (Target 11.4) is "Strengthen efforts to protect and safeguard the world's cultural and natural heritage". https://www.un.org/sustainabledevelopment/cities/

communication, science and research."[10] The Paris Agreement recognises the potential of cultural heritage in helping communities move forwards on climate action, affirming the significance of traditional knowledge. It also highlights the role of non-governmental stakeholders in addressing climate change, with clear opportunities for heritage in this area.

It is imperative that we protect our heritage now, while simultaneously taking action against climate change. It is strategically necessary to understand and respond to the risks and hazards posed by climate change and take a long-term view, rather than simply prioritising short-term conservation measures. We not only need to increase our sustainability in all areas in order to mitigate future climate change, we also need to begin to adapt to the changes which have already occurred, as has been recognised by large heritage organisations across the UK.[11] Mitigation refers to actions taken or to be taken to reduce the consumption of energy and water and the production of waste in order to ease future climate change, whereas adaptation means extending the useable life of materials and assemblies in order to adjust to present climate change.[12] Conservation has now necessarily shifted from trying to prevent change to managing it appropriately and proportionately.[13] Furthermore, in many cases, conservation will not automatically translate to preservation: the National Trust, for example, has come to recognise that conservation is about the understanding and management of change.[14]

Heritage organisations in the UK and worldwide have, in the past two decades, begun to research the effects of climate change and to advise their members of action they can and should take to both mitigate and adapt.[15] These organisations are generally concerned with buildings, land use, and archaeology, although this includes maritime archaeology, primarily shipwrecks and submerged structures. Nonetheless, many of their principles, such as in reducing and conserving the energy that historic buildings use or being aware of the impacts of intense pluvial episodes on historic buildings, can be applied to the historic vessels in our care. Historic vessels, however, have many unique needs and are affected by climate change in ways that have not previously been discussed in the broader UK heritage sector, leaving a significant gap in research studies to date.

Chiefly, historic vessels are made of far more perishable materials, such as timber as opposed to brick and tile, and are subjected to different environmental conditions. Historic vessels may still have a working or operational life and thus have a different purpose to static infrastructure in the UK heritage landscape. Many remain in private ownership and are managed differently to heritage assets in national care. Change can be daunting for private owners and small charitable organisations, especially where short-term economic cost interventions are necessary. This document has therefore been produced to inform the

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[10] http://climateheritage.org/about/
[11] Fluck & Historic England, 2016, 10.
[12] Cassar, 2008c, 5.
[13] Whimster, 2008, 22.
[14] Watson, 2008, 13.
[15] Historic England, Historic Environment Scotland, Heritage Fund, English Heritage, The National Trust, UNESCO.

sector and alert the wider heritage community of the risks posed by climate change. It will be used to drive innovation in adapting historic vessels and their associated infrastructure to the severe and unprecedented threat they are facing.

TACKLING CLIMATE CHANGE IN RELATION TO HISTORIC VESSELS

Because of its composition, the historic vessel sector is uniquely well-placed to tackle climate change issues and consequently there are many opportunities in this area. We can learn much from our maritime past:

- Some of the historic vessels in our care date from a time before human action and energy consumption grew to such a scale that it began to damage the natural world and climate, when energy resources were scarce and expensive. Materials were often more sustainable, sourced locally and used efficiently – lessons can be learnt from traditional ship-building techniques. We can also be inspired by materials and objects used on board, as often these ships date from a period before the widespread use of 'disposables', such as single-use plastics.
- Some historic vessels still rely on pre-Industrial Revolution sources of energy, being engineless and not dependent on fossil fuels, such as sailing barges like the *Cambria* or horse-drawn narrow boats like *Saturn*. Others, which had engines installed during their working life, retain sail or oars as their primary propulsion method, or have had electric engines fitted instead, as owners choose to return to a quieter, more sustainable means of travel.
- Working and living by the sea and waterways has long taught sailors to be sensitive to the weather, to be in tune with the natural world and respectful of it. Consequently, some of the biggest advocates of climate change policy are sailors or those connected with the sea. For example:
    - Ellen MacArthur, who founded the Ellen MacArthur Foundation to promote circular economies "based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems",[16] developed the idea while sailing solo around the world, when she realised that her boat, with its finite resources, was a microcosm of the planet.[17]
    - Boats have been used in climate change protests as forms of imagery and symbolism around the world. In July 2019, Extinction Rebellion used boats in London, Bristol, Cardiff, Glasgow, and Leeds[18] and in February 2020, Direct Action for Divestment (DAD) [from fossil fuels] protestors occupied the front quad of St John's College, Oxford for five days,[19] alongside a 4-metre model

[16] https://www.ellenmacarthurfoundation.org/circular-economy/what-is-the-circular-economy
[17] Wardrobe Crisis Podcast, Episode 57, September 2018.
[18] https://www.independent.co.uk/news/uk/home-news/extinction-rebellion-protests-london-bristol-cardiff-leeds-glasgow-climate-change-a9005531.html
[19] https://cherwell.org/2020/02/01/breaking-climate-protesters-end-occupation-of-st-johns/

of the RSS *Sir David Attenborough* atop a banner reading 'Change Course on Climate.'[20]

There are opportunities for cultural institutions to draw attention to the insights and stories of those with intimate skill and knowledge of the weather.

- With high numbers of historic vessels remaining in operational use, they are uniquely placed to contribute to climate communication, science, research and sail cargo trade, by taking part in plastic and scientific surveys, beach and waterways cleans, carrying out sustainable fishing, or joining the new eco-friendly cargo traders**.**

Britain's history can inform the future; "the past may not have always been a comfortable place, but in their struggle to buffer the surrounding environment its inhabitants learnt some practical lessons that we would be foolish to ignore in our own battle against climate change."[21] Heritage is well placed "to speak of the issue of loss and destruction from climate impacts, including assessing and managing risk to community and cultural heritage values and aiding in planned relocation and climate mobility."[22]

PURPOSE OF THIS REPORT

This Report will:

- Give an overview of climate change.
- Detail its long term predicated direct and indirect impacts, building a better picture of how climate change is already affecting and will affect maritime heritage in the UK in terms of timing, scale, and nature, accompanied by multiple case studies.
- Detail the opportunities presented by climate change, which include political, economic, social, and technological openings, alongside the provision of sector-specific advice and recommendations for multiple stakeholders on how to manage, adapt to, and mitigate climate change impact, while preserving the cultural significance and character of their assets.
- Give thought to vessels that will lose significance if blanket policies are initiated; for example, those craft which rely on coal-burning as part of a historic re-enactment.
- Recognise that there is no single solution. Any action taken to adapt to and mitigate climate change and its effects will vary by location, vessel type, vessel purpose, vessel past and current working life – everything that makes each vessel and its assets significant and unique.
- Take a long-term, holistic approach to any projects or changes, being aware that some changes could be, at best, unnecessary, or at worst, actively harmful. Problems and solutions need to be thoroughly researched and examined from every angle.

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[20] https://www.commondreams.org/newswire/2020/01/29/oxford-students-occupy-college-climate-change-protest

[21] Whimster, 2008, 21.

[22] http://climateheritage.org/about/

- Provide a series of recommendations accompanied by examples from the sector, showing ways in which historic vessels have already begun to tackle climate change issues head-on or are being used as evidence in an environmental context.

OVERVIEW OF CLIMATE CHANGE

'Climate' refers to the long-term manifestations of weather and other atmospheric conditions, both globally and in the UK. The 'climate' of a region is usually represented by a statistical summary of its weather conditions long-term:[23] our weather is the visible effect of climate change. 'Climate change', therefore, refers to a large-scale, continuing shift in those weather patterns and in average temperatures across the world.[24] Although British weather can seem extreme or unpredictable, it is usually not. Climate change makes incidences of extreme weather more frequent. Although some extreme events may have occurred by chance in a climate unmodified by man, it is possible to state that human activities have increased the risk of the occurrence of such events; the magnitude, likelihood, and frequency of normal climate processes; and the incidence of previously unknown effects.[25] Because climate change affects the weather, it ultimately effects the environment – the whole of the natural world or ecosystem, locally, regionally, and globally[26] – often in unforeseen and irrevocable ways.

Climate change at this scale is unprecedented and man-made (anthropogenic). Fundamentally, anthropogenic substances and processes that alter the earth's energy budget change the global climate system:[27] greenhouse gases, aerosol emissions, and land use are drivers of climate change. Greenhouse gas (GHG) emissions, which include carbon dioxide, methane, and nitrous oxide, originated with the Industrial Revolution, when the burning of fossil fuels began to take place on a mass scale. These issues in turn cause atmospheric, oceanic, and cryospheric (ice-covered parts of the earth) warming. Warming of the climate system is unequivocal,[28] with global average temperatures rising by nearly 0.8^{o}C since the late nineteenth century and around 0.2^{o}C per decade over the past 25 years.[29] Warming then drives further negative atmospheric conditions, many of which directly bear on historic vessels, such as sea level rise, flooding of coastal regions, variations in seasonality, more extreme weather[30] and ocean acidification.[31] Climate pollution can also refer to smaller actions, such as contributions to noise or plastic pollution, which is ultimately detrimental to the environment, including human life and livelihoods.

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[23] https://wikidiff.com/climate/environment
[24] https://www.metoffice.gov.uk/weather/climate-change/what-is-climate-change
[25] Stott, P. A., Stone, D. A. & Allen, 2004, Abstract.
[26] https://wikidiff.com/climate/environment
[27] IPCC, *Summary for Policymakers*, 2013, 13.
[28] IPCC, *Summary for Policymakers,* 2013.
[29] UKCP09, *The climate of the UK and recent trends*, 2009, 4..
[30] https://www.metoffice.gov.uk/weather/climate-change/what-is-climate-change
[31] IPCC, *Summary for Policymakers*, 2013, 12.

The changes in our climate and associated impacts are projected to continue and worsen, as is shown in the climate change scenarios provided by the UK Climate Impacts Programme[32] and the Intergovernmental Panel on Climate Change[33] These models, alongside case studies on what is already happening to some historic vessels, can be used to help identify how historic vessels may be affected by climate change in the future, although it is hard to know exactly what may happen and when. There are many uncertainties and consequently both UKCIP and the IPCC present multiple scenarios with varying degrees of confidence. It is important, therefore, to understand the level of certainty associated with specific changes and to ensure that any action taken reflects this.

It's worth being aware that some of the IPCC models appear to have been *under* predicted, which serves as a warning to take the climate change threat seriously. Their accuracy can be examined by comparing recent climate observations with the projections, as is summarised in an IPCC assessment report, where "comparison of the coincident periods 1990 to 2006 suggests that atmospheric carbon dioxide observations are remarkably consistent with the projections; global mean surface temperature observations are following a trend at the *upper* part of the range projected by the IPCC; and observed sea level has been rising *faster* (3.3mm+ 0.4 mm/year since 1993) than the rise projected by the models (best-estimate rise of 2 mm/year). Although the period of sixteen years is relatively short, these results suggest that the IPCC projections have not exaggerated but may in some respects be an underestimate of the projected change."[34] The Sixth Assessment Report of the IPCC, published in August 2021, states that 'global surface temperature will continue to increase until at least the mid-century under all emissions scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in carbon dioxide (CO2) and other greenhouse gas emissions occur in the coming decades.'[35] This report shows a greater degree of certainty than any of the earlier IPCC publications and makes it clear that the need for adaptation and mitigation is urgent.

Scientific organisations, both in the UK and globally, such as the IPCC and the UK Met Office, are constantly researching the causes and impacts of climate change. Due to its devolved government, there are differences in policies, laws, and advice across the UK. Notably, the Scottish and Welsh parliaments declared a climate emergency in April 2019,[36] whereas the English parliament did not do so until a week later, in May 2019.[37] Local councils across the UK have declared their own climate emergencies, and, as there is no single definition of a climate emergency, many of these local areas have individual

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[32] UKCIP, www.ukcip.org.uk

[33] https://www.ipcc.ch

[34] Street, 2008, 5.

[35] AR6 WGI Summary for Policymakers Headline Statements (ipcc.ch)

[36] 'Climate emergency' declared by Welsh Government,' April 2019, *BBC.com*: https://www.bbc.co.uk/news/uk-wales-politics-48093720 'Nicola Sturgeon declares 'climate emergency' at SNP conference,' April 2019, *BBC.com*: https://www.bbc.co.uk/news/uk-scotland-scotland-politics-48077802

[37] 'UK Parliament declares climate change emergency', May 2019, *BBC.com*: https://www.bbc.co.uk/news/uk-politics-48126677

targets, often more stringent or ambitious than those at national level.[38] Historic vessel custodians should be aware of these differences and take steps to identify both the national and local area climate measures.

Climate Change in the UK

For the UK, the impacts of climate change could at first seem modest and perhaps even welcome, such as warmer winters with fewer frosts or cold spells, sunnier summers with more frequent heatwaves,[39] as well as longer growing seasons. This is a superficially comforting picture as there are harsher realities of climate change: increasingly frequent extreme weather events, flooding due to rising sea levels and storm surges, and above all huge indirect social and economic tolls.[40]

Historically, it has been difficult for the average person to view climate change from an individual perspective and in some ways, this is still the case. However, the increasing pace of climate change means that many aspects, such as the UK's changing weather pattern, are no longer imperceptible to the individual but are instead increasingly discernible. Since the 1950s, many of the observed changes are unprecedented over decades to millennia.[41] For example, the vulnerability of European citizens was made evident during the summer heatwave of 2003, when more than 70,000 people died as a direct result.[42] The summer of 2003 is believed to be the hottest in Europe since at least 1500.[43] A 2015 publication subsequently reported that similar events, which would typically only occur twice a century in the early 2000s, are now expected to happen twice a decade. For extreme events like that of 2003, the return time will reduce from thousands of years in the late twentieth century to around a hundred years in a decade's time.[44] By the 2040s, heatwaves like that of 2003 may be expected to happen every other year and by the 2080s, they will be considered cold for summer.[45] This was swiftly backed up by the British Isles' summer heatwave of 2018, which was the joint hottest British summer since records began in 1910, tied with those of 1976, 2003 and 2006, and was the hottest yet in England.[46] July 2021 saw the UK experience yet another mini heatwave, with temperatures exceeding 30°C.

Many media headlines relating to climate change and the heritage industry focus on positives, for example, expounding a longer tourism season as weather warms in the UK, praising "a shift in weather in the last few years" which has led to tourism hotspots "enjoying warmer autumns".[47] This hides the fact that, as the tourism season extends at

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[38] 'UK Parliament declares climate change emergency', May 2019, *BBC.com*: https://www.bbc.co.uk/news/uk-politics-48126677
[39] UKCIP in White, 2008, 14.
[40] Whimster, 2008, 21.
[41] IPCC, *Summary for Policymakers*, 2013.
[42] Robine et al., 2003, 171.
[43] Stott, Stone, & Allen, 2004.
[44] Christidis, Jones, and Stott, 2015, 46-50.
[45] Christidis, Jones, and Stott, 2015, 46-50.
[46] 'Heatwave: 2018 was the joint hottest summer for UK', *BBC.com*: https://www.bbc.co.uk/news/uk-45399134
[47] 'The tourist season in Newquay is longer than ever but there is work to do to make it a bustling year-round resort,' *Cornwall Live*: https://www.cornwalllive.com/news/cornwall-news/tourist-season-newquay-longer-ever-788253

both ends, the middle – the hottest months of the year – may become too hot for tourists to tolerate, thus negatively impacting tourism of all kinds, including heritage tourism. The 2018 heatwave visibly impacted the heritage sector, most notably in the way that land scorched by the heatwave revealed new monuments through crop marks, as was reported in national and local media.[48] What is not often discussed in news articles of this kind is the long-term potential for these heatwaves to devastate the heritage sector, particularly historic vessels, which are made of vulnerable materials and where much of the tourism activity and public engagement takes place outdoors.

LONG-TERM PREDICTED DIRECT AND INDIRECT IMPACTS ON UK MARITIME HERITAGE

The likely consequences and scale of climate change on the heritage sector are daunting[49] making it the most serious single threat to long-term conservation.[50] It will not only be the fabric of historic vessels which will be adversely impacted, but also their associated infrastructure on land, such as dry-docks, slipways, museums, harbours, piers, and ports. The impact of climate change can be split into two categories: direct and indirect.

Direct impacts relate to physical, biological, and chemical processes caused by greenhouse gas emissions, although some of these effects are removed by one or two steps, for example, where melting of the cryosphere has led to changes in the hydrological cycle and sea level, or where ocean acidification has arisen, which in turn has caused changes to the flora and fauna of the ocean. This is summarised in *Appendix 1: Direct Impacts*.[51]

Indirect impacts are the result of human actions undertaken to adapt to or mitigate the threat which, influenced by people's attitudes and values, also have an effect on the fabric and/or setting of heritage assets,[52] such as the enhancement of flood resistance measures and building of flood defences, or the management of coastal retreat.

All impacts will have physical, social, and economic consequences, and when assessing this the complex interaction between natural, cultural, and social aspects of heritage should be taken into account.[53] Impacts, both direct and indirect, will therefore take the form of 'heritage risks', affecting the historic environment, and 'business risks', affecting operations, personnel, facilities, and income.[54]

The direct and indirect impacts listed here will all be presented with various case studies from the maritime heritage sector, showing trends that are already occurring, and how

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[48] An example in national media: 'Heatwave crop marks reveal 200 ancient sites in Wales,' *BBC.com*: https://www.bbc.co.uk/news/uk-wales-46542523
An example in local media: 'Crop marks unveil 'unusual' ancient remains dating back thousands of years', *Derby Telegraph*: https://www.derbytelegraph.co.uk/burton/scropton-heat-crop-marks-revealed-1895608
[49] Historic England, https://historicengland.org.uk/research/current/threats/heritage-climate-change-environment/what-effects/
[50] UNESCO, https://whc.unesco.org/en/series/22/
[51] Largely adapted from Cassar, 2005e, Table 1.
[52] Historic England: https://historicengland.org.uk/research/current/threats/heritage-climate-change-environment/impacts-climate-change/
[53] Cassar, 2008c, 8.
[54] As outlined by Fluck & Historic England, 2016, 17.

vessels and their associated infrastructure are adapting to and mitigating these. 'Adaptation' refers to changing how we conserve and manage heritage assets: "adaptation is about being flexible in order to be resilient… planning for what is ahead without being constrained by future uncertainty. By its nature, it is an interactive and reflexive process."[55] The most effective way to adapt to climate change "is to embed consideration of current and future climate-related impacts into all strategic plans, processes, and everyday practice,"[56] which is also the method preferred by most businesses in an Environment Agency-commissioned report.[57] Mitigation, on the other hand, refers to actively trying to prevent further climate change.

Not all mitigation and adaptation measures will apply to every vessel and its custodians equally, but still provide good examples to learn from. Some of these could have been done differently in order to be more effective. This is by no means a criticism but is instead simply part of the fundamental process of continually adapting to climate change as the science becomes updated and more effects become known or more evident, as has been recognised by various UK historic bodies.[58]

DIRECT IMPACTS

The direct impacts of climate change are physical, biological, and chemical processes. How these will relate to maritime heritage has been summarised in Table 1: Direct Impacts (see Appendices) which shows how different climate change impacts are caused and interact to multiply. These impacts will bring a wide variety of issues for maritime heritage and historic vessels, as well as causing normal environmental processes, such as corrosion, to accelerate at an unprecedented pace.

TEMPERATURE RISE

Warming of the climate system is unequivocal and includes atmospheric, cryospheric, and oceanic temperature increases, as well as a rise in inland waters, all of which will impact maritime heritage. Each of the last three decades has seen the Earth's surface become warmer than any preceding decade since 1850.[59] Central England temperature has risen by about 1^{o}C since the 1970s and temperatures in Scotland and Northern Ireland have risen by about 0.8^{o}C since about 1980,[60] compared to a global mean of 0.85 [0.65 to 1.06] °C over the period 1880 to 2012.[61] It is predicted that by the end of the 21st century, global surface temperature will have exceeded at least 1.5°C relative to 1850 to 1900. The five warmest years in measured UK air temperature (since records began in 1910) have occurred post-

[55] Fluck & Historic England, 2016, 19.
[56] Fluck & Historic England, 2016, 19.
[57] Environment Agency. *Acclimatise*, *2015*. *Business Opportunities in a Changing Climate. Managing Impacts and Market Opportunities*. 2015.
[58] Fluck & Historic England, 2016, 19.
[59] IPCC, Summary for Policymakers, 2013, 5.
[60] UKCP09, *The climate of the UK and recent trends*, 2009, 4.
[61] IPCC, *Summary for Policymakers*, 2013, 5.

2000.[62] Furthermore, as of 2020, the Cumbrian lakes revealed a warming trend. The UK Centre for Ecology & Hydrology (UKCEH) has been monitoring the biological, chemical, and physical properties of four Cumbrian Lakes since 1945 and is the world's largest long-term lake monitoring programme. Across all four lakes, despite their differing size and location, UKCEH have seen a clear long-term temperature rise.[63] Warming will continue and will exhibit inter-annual-to-decadal variability and a lack of regional uniformity.[64]

The increasing profile of the reality of temperature rise and the hazards it brings has been highlighted by historic vessels. The reality of the melting Arctic has been famously and poignantly exemplified by the discovery of Sir John Franklin's HMS *Erebus*, lost in the Northwest Passage in 1848, when *Erebus* was unable to penetrate through ice sheets which no longer exist.[65] Similarly, the logbooks from USS *Jeanette*, which sank in June 1881, show her becoming trapped in Arctic ice in areas where that ice no longer extends.[66] Logs from other historic ships been able to clearly and definitively illustrate warming trends and weather changes, as they provide historical data. Nearly 75% of the planet is covered by water and so most weather events occur over water.[67] Having information about weather events in the past can help scientists to create models to predict how weather conditions are likely to change as global temperature continues to rise. Thousands of historic logbooks exist, providing a rich source of such information.

An increase in both atmospheric and oceanic temperature brings multiple risks to historic vessels and their associated infrastructure, including the increased risk of fire, animal infestations, and strain on materials due to greater seasonal temperature contrasts. Temperature changes will result in changes in the global water cycle: the contrast in precipitation between wet and dry regions and seasons will increase (although there may be regional exceptions);[68] there will be increased seasonal contrasts and variability of water availability, in addition to increasing temperature contrasts, further resulting in strain on materials. The increasing salinity of water upstream is also linked to global warming and changes in air circulation over Europe.[69] Temperature increase in the sea will affect the conditions that have helped preserve Britain's rich maritime heritage. These temperature-induced changes to salinity, acidity, and flora and fauna will harm maritime archaeological remains.[70] While maritime archaeology is not the primary focus of this report, what survives on the seabed can impact the significance of other historic vessels, as well as informing our knowledge about types of craft. It is therefore relevant and important to note that climate change will affect wrecks and archaeology as well as vessels which are still extant.

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[62] https://www.metoffice.gov.uk/weather/climate-change/what-is-climate-change

[63] https://www.ceh.ac.uk/news-and-media/blogs/lakes-hot-water-warming-trend-revealed-eight-decades-cumbrian-lake-temperature

[64] IPCC, *Summary for Policymakers*, 2013, 20.

[65] Palin, 2018, Chapter 13.

[66] https://graphics.reuters.com/CLIMATE-CHANGE-ICE-SHIPLOGS/0100B4QE2FC/index.html

[67] https://www.reuters.com/investigates/special-report/climate-change-ice-shiplogs/

[68] IPCC, Summary for Policymakers, 2013, 20.

[69] Paalvast, Peter; van Der Velde, Gerard, 2011, 1822

[70] Fluck & Historic England, 2016, 15

- **THE IMPACT OF TEMPERATURE RISE ON CONTROLLED ENVIRONMENTS**

Temperature rise will also affect heritage which needs to be kept in a controlled environment. Extremes of external temperature will put pressure on the equipment that maintains stable conditions, for example in archive repositories. Some instances of air conditioning failure have already occurred during particularly hot weather, as has been recorded by Historic England.[71] Many historic vessels have their own associated archives or have deposited documents and artefacts in a local or county repository for safekeeping. The SS Great Britain Trust and the University of Bristol manages the Brunel Institute, which houses a significant maritime collection, including an archive vault.[72] The vault is a carefully controlled environment, with every element monitored, from the ambient temperature to lighting that only operates when someone enters the archive.[73]

In some cases, the vessels themselves are kept in climate-controlled environments to preserve original fabric. For instance, this applies to the hull of ss *Great Britain* which sits in a temperature-controlled dry dock below a glass plate at the waterline known as the 'Glass Sea'. The Glass Sea serves to keep the air in the dry dock as dry as possible as the SS *Great Britain's* iron hull is extremely vulnerable to corrosion, caused by moisture. The air is kept dry by a huge de-humidification plant which ensures the atmosphere around the hull is maintained at a relative humidity of 20%, which is as arid as the Arizona Desert.[74]

The National Historic Fleet vessel *Peggy* is a small clinker-built boat, built in 1789 and located in Douglas, Isle of Man.[75] *Peggy* was found stored in a boat cellar, where she had lain undiscovered for more than 150 years. The humid environment and intermittent flood conditions had damaged her and, after conservation, she could only be returned to the same cellar if the internal environment could be controlled and tidal inundations prevented. While the boathouse is in an inter-tidal zone experiencing increased frequency of flooding, this would be technically possible at considerable financial cost. However, while it would protect the vessel's fabric, it would result in irreversible damage to and/or removal of large sections of the historic fabric of the boat cellar, the Cabin Room above and the well-preserved private dock outside. It was therefore decided that *Peggy* should be situated in the courtyard of the Nautical Museum, Castletown, with a structure enclosing the entire space, to control the external environment.[76]

As with ss *Great Britain*, *Peggy* illustrates that historic vessels often have strict conservation needs requiring large, enclosed areas with environmental controls, precisely because of their age, fabric, lives, and significance. As the climate emergency progresses, such

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[71] Fluck & Historic England, 2016, 12
[72] https://www.ssgreatbritain.org/brunel-institute
[73] https://www.ssgreatbritain.org/brunel-institute/archive-vault
[74] http://www.ssgreatbritain.org/your-visit/things-to-see/dry-dock
[75] Blackford, 2018, 38
[76] Blackford, 2018, 39

environmental controls may become difficult to maintain and thought will have to be given to back-up technology in the event of a primary system failure.

Many historic maritime artefacts are also kept in controlled museum environments, such as the Union Jack flown on HMS *Minotaur* at the Battle of Trafalgar, the only British flag from the Battle of Trafalgar still in the UK.[77] It is now held by the National Maritime Museum in Greenwich where it is on display in the Nelson, Navy, Nation Gallery in a purpose-built display case constructed from approved conservation materials. Some materials, such as textiles and paper, are more sensitive to change in environmental conditions than others. It is often wide, sudden fluctuations in environment that can be more harmful than environmental conditions at particular levels, as these can cause damage on a molecular level to textiles and paper from the fibres constantly swelling and shrinking. Extremes are also potentially harmful; for example, if humidity is too high this can encourage mould and insect attack, while being too dry can cause embrittlement and splitting of fibres.

- **STRAIN ON MATERIALS DUE TO INCREASED TEMPERATURE CONTRASTS, MOISTURE, AND HUMIDITY; FREEZE-THAW**

The most extreme indication of the speed and occurrence of changes in temperatures will be an increase in freeze-thaw. Freeze-thaw is a process of erosion which occurs where water penetrates material, becomes ice and expands as the temperature drops, thus pushing the crack apart and making it larger. When the temperature rises again, the ice melts, the water evaporates, and new water fills the now larger crack, repeating the process.[78] Freeze-thaw events occur most often when seasonal climate is near 0^{o}C.[79] The most commonly affected materials are rock, steel, wood, concrete, and asphalt.[80] Even trees can be damaged by frost events.[81]

Freeze-thaw processes will change with only a few degrees variation in temperature or small percentage changes in precipitation and water volume[82] and are therefore a crucial way of showing the major impact that even a small alteration in temperature will have on heritage. The extent to which freeze-thaw events may occur in Europe is yet unknown. They may reduce as temperatures rise,[83] or dramatically increase due to changes in daily moisture levels.

Even without the addition of freezing temperatures and water, changes in daily temperatures and moisture levels will result in higher risks associated with thermal expansion. Thermal expansion is the process through which a material grows due to a rise in

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77 https://www.independent.co.uk/news/uk/home-news/trafalgar-union-jack-britains-only-flag-from-admiral-nelsons-famous-victory-acquired-by-national-a6702026.html
78 http://www.ssc.education.ed.ac.uk/BSL/geography/freezethawd.html
79 Grossi et al, 2007, 278.
80 http://www.valent-roofing.co.uk/2019/03/27/how-the-freeze-thaw-cycle-can-affect-a-roof/
81 Grossi et al, 2007, 275.
82 Grossi et al, 2007, Abstract.
83 Grossi et al, 2007, 273.

temperature, usually evident as a fractional change in length or volume.[84] This will then be followed by thermal contraction as temperatures and the material cool. Repetition of this process, and an increase in the extremes of the process as seasonal and daily contrasts in temperatures increase, will likely cause adverse impacts on the materials of historic vessels. This is a normal process and one which many traditionally-built ships will have accounted for. However, in future, historic vessels may struggle to adjust to the speed and frequency of these changes.

Ships which are not currently in climate-controlled environments, such as HMS *Unicorn*, may experience detrimental effects as temperatures increase and the climate and weather becomes more unpredictable and changeable. HMS *Unicorn* is a sailing frigate of the Leda class, built in 1824 and now a museum ship in Dundee. *Unicorn* is one of only five frigates surviving in the world and the most original wooden ship dating from the nineteenth Century. She was built in peacetime shortly after the sea campaign against Napoleon, as part of a programme of re-equipping the Royal Navy, and as such was not required for immediate service. Consequently, she was not rigged, but instead her hull was roofed over and she was put into 'ordinary' (reserve). She remained in this state for her entire life which ensured her long-term preservation. However, when HMS *Unicorn* was docked in 1972 it was noted that her hull had suffered considerably from hogging after 150 years afloat. This has continued to worsen and a plan is being drawn up to move her to a dry dock for permanent display to avoid further exposure to her present conditions.[85]

- **INCREASED FIRE RISKS**

Fires are a real and continued risk to historic vessels, as was famously demonstrated by the fire on board *Cutty Sark* in May 2007[86] which was caused by an industrial hoover being left on. In that instance, it was fortunate that her masts and a large number of planks had been removed and were in storage at the time due to a major conservation project being under way. Historic vessels are likely to burn more easily than modern vessels – *Cutty Sark*'s middle deck was made of pitch pine,[87] which is highly flammable and would have helped the fire to spread.

In January 2016, fire broke out in Medina Village at David Heritage Racing Yachts and destroyed over thirty boats. The fire was believed to have been accidental and started in a car workshop attached to the end of an industrial unit where the boats were stored, quickly spreading. Three irreplaceable historic vessels over 100 years old were lost: the 1902 36ft cutter *Witch*; the 1897 35ft steam launch *Kariat*; and the 1905 admiral's steam pinnace *Vere*, which had made several trips to Dunkirk in the World War Two evacuation. A slightly

[84] https://www.britannica.com/science/thermal-expansion
[85] http://www.frigateunicorn.org/history
[86] https://www.dailymail.co.uk/travel/article-595792/Cutty-Sark-destroyed-fire.html
[87] https://www.telegraph.co.uk/news/uknews/1552295/Police-launch-Cutty-Sark-arson-investigation.html

younger vessel, the 58ft 6" Alfred Mylne ketch, built in 1927, *Fedoa of Bute*, was also destroyed, along with numerous smaller yachts.[88]

Both these events – the 2007 *Cutty Sark* fire and the 2016 Medina Village fire – were unrelated to climate change. However, they serve to illustrate the huge and devastating risk that fires pose to historic vessels. It is likely that, as the climate continues to change, the risk of fires occurring will increase, as well as their potential severity. Alterations in climate patterns and perturbations of the geophysical equilibrium will result in changes in precipitation patterns and increases in drought, leading to greater likelihood of fires quickly spreading through dry material, like timber.[89] The chance of wildfires will also increase, again due to prolonged periods of hot, dry weather and this will pose a risk to historic vessels in the vicinity.[90]

- **DISRUPTION TO STAFF, VOLUNTEERS, AND VISITORS, INCLUDING CHANGES TO TOURISM SEASONS**

Increasing temperatures can bring uncomfortable working conditions and disruption to the tourism season, affecting volunteers, staff, and visitors at historic vessels and maritime heritage sites. Extreme events like heatwaves will disrupt the ability of staff and volunteers to travel to work, whether that be at a museum or in an office environment managing the conservation of historic vessels and their related objects, or as an individual working on board a static or operational craft. Tube, bus, and train delays already occur during heatwaves, often because of speed restrictions put in place to protect infrastructure, particularly rail tracks, which can be up to 20^{o}C hotter than the air temperature and can buckle in the heat, endangering life.[91]

Extreme temperatures will impact the ability of staff to work effectively *in* offices and *on* vessels, as well as visitors in both instances. For example, HMS *Victory* has poor internal airflow, resulting in a stagnation of the environment and high Relative Humidity (RH) of an average of 72% in 2016.[92] As atmospheric temperatures increase and heatwaves become more common, the ship will become even hotter and closer, creating an environment at best uncomfortable and at worse impossible to work in or visit. This will dramatically affect the conservation which can be carried out and will also discourage tourists and those holding events onboard her, which can offer a vital source of funding.[93]

Those working in historic or listed buildings like the staff at National Historic Ships UK, who are based in offices at the Old Royal Naval College leased via Royal Museums Greenwich,

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[88] https://www.yachtingworld.com/news/the-irreplaceable-boats-lost-in-the-2016-cowes-fire-the-greatest-single-loss-of-classic-yachts-70708

[89] Colette; UNESCO, 2007, 16-17.

[90] Fluck & Historic England, 2016, 42.

[91] 'Heatwave causes train delays and cancellations across UK - here's why', July 2019, *The Mirror*: https://www.mirror.co.uk/science/heatwave-causes-train-delays-cancellations-18773866

[92] McCormack, 2016, 106.

[93] McCormack, 2016, 107.

will find the workspace unsuited to a rapidly warming climate and lacking in modern environmental controls. Already in summer, these offices get very hot, creating an environment which is uncomfortable to work in. Long-term, this could affect the storage of archives on site and a huge investment would be required to make such places environmentally suitable as workplaces.[94]

It is likely, therefore, that home working will become common, and this trend has been strengthened and proved viable by the 2020 Covid-19 pandemic. However, this places increased pressure upon the communications and IT systems that support homeworking, leading on some occasions to those systems failing.[95] This could be exacerbated by heatwaves, with equipment vulnerable to heat exhaustion. Additionally, temperature and humidity can affect Wi-Fi signals, as electrical equipment is made to perform in a specific temperature range, meaning that if the temperature is too high or too low, poor Wi-Fi speed will likely be experienced,[96] thus impacting on public ability to successfully work from home. Humidity can also decrease Wi-Fi signal strength and can make the home as uncomfortable a workspace as some offices.[97]

Heatwaves will affect the tourism season itself, extending it at both ends, which at first may be a welcome opportunity, but quickly decreasing the middle of the season, in the hottest months of the year, when it will simply be too hot for travel and visiting attractions. Extended tourism seasons and increases in the numbers of tourists as the weather becomes warmer and more favourable will also bring new risks to historic vessels which are part of the tourism industry, such as increased footfall and visitor numbers at certain times, creating greater erosion and risk of pests being brought on board. HMS *Victory*, for example, operates 364 days a year and, as of 2016, had an average of 400,000 visitors per year, who were already bringing risks to the ship, such as moisture on wet days and through breathing, and acting as carriers of fungal spores and insects.[98] Such effects will require monitoring in light to changing tourism patterns, particularly if these lengthen or intensify.

- **MARINE BORERS, OTHER ANIMAL AND PLANT INFESTATIONS**

Many types of marine borers (commonly known as shipworms) are warm water species; therefore, their activity will likely increase and be found further northwards in the future due to a warmer climate and milder, wetter winters.[99,100] Such species, including *Lyrodus pedicellatus*, may prove to be both more abundant and more destructive than *Teredo navalis*, the species of marine wood borer which has previously posed the highest borer hazard in northern Europe.

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[94] Fluck & Historic England, 2016, 12.
[95] Fluck & Historic England, 2016, 12.
[96] https://the-weather-station.com/does-weather-affect-your-wifi/
[97] https://the-weather-station.com/does-weather-affect-your-wifi/
[98] McCormack, 2016, 107.
[99] Watson, 2008, 12-13.
[100] Borges, 2014, 97.

In a survey running from 2001 to 2011[101] across 15 European locations, the wood borers *L. pedicellatus* and *Limnoria quadripunctata* were found to be present in the first year of exposure of wood in Portsmouth. In subsequent years, *T. navalis* was also present but *L. pedicellatus* was shown as more virulent than either *T. navalis* or *L. quadripunctata.*[102] All three of these species are established in European waters, but must be considered cryptogenic, as there is no definite evidence of their native or introduced status.[103] Furthermore, two additional species were found to definitively be alien to European waters and should be monitored as they may expand their distribution range further in Europe as the climate continues to change (in terms of temperature and salinity), becoming invasive.[104]

Shipworm damage *upstream* in temperate rivers will also likely grow across North West Europe, as increased temperatures cause dry and warm summers and changes in air circulation, decreasing river discharges and ultimately extending the salinity gradient upstream in the summer and autumn, as concluded by an experiment in the Rhine-Meuse estuary in the Netherlands.[105] A one-degree temperature increase by 2050 compared to 1990 alongside a weak change in the air circulation over Europe could lead to an increased chance of shipworm damage upstream from once in 36 years to once in 27 years and a two degree increase to once in 22 years, respectively. Under a strong change in air circulation alongside a one- or two-degree temperature increase, the chance of shipworm damage will likely increase to once in 6 or 3 years, respectively.[106] The Rotterdam port area can be used as a typical illustration of the estuaries of all large temperate rivers in North West Europe, including the Thames.[107] Shipworm damage will therefore not solely be a problem for ocean and coastal vessels, but will extend further inland.[108]

There have been examples in the UK of increased shipworm activity in localised warmed water. In the Solent at Fawley (at the mouth of Southampton Water) and at Shoreham-by-Sea to the east of Portsmouth, coal-fired power stations drew in water for cooling and then discharged the heated water into the local waterways. This locally heated water resulted in an increase in shipworm population and an increase in the types of shipworms present, which suggested that global oceanic warming will have similar effects on shipworms and consequently the danger they pose to historic vessels.

Teredo navalis and *pedicellatus*-like *Lyrodus* species should therefore be monitored due to their destructive capability.[109] If shipworms encounter optimal conditions, they are able to

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[101] Borges et al, 2014b.
[102] Borges, 2014a, 99.
[103] Borges et al, 2014b
[104] Borges et al, 2014b
[105] Paalvast, 2011
[106] Paalvast, Peter; van der Velde Gerardvan, 2011, 1822.
[107] Paalvast, Peter; van der Velde Gerardvan, 201, 1828.
[108] Paalvast, Peter; van der Velde Gerardvan, 2011, 1822.
[109] Borges et al, 2014b.

destroy fir piles 15 cm in diameter in six weeks,[110] and 10 m-long, 25 cm thick oak pilings can be turned into sawdust in 7 months.[111] Within 10 years they can completely destroy large maritime wooden structures and some studies have calculated that with a growth rate of 0.5–1 mm per day in temperate waters like around Scandinavia, a 20 cm-long piece of wood can be completely consumed by *T. navalis* within a year.[112] Temperature and salinity increases will expand the amount of time optimal for shipworm growth and reproduction, and may even see an upsurge in the number of breeding seasons they have in a given year.[113] The time taken to destroy wood is incredibly short, particularly in relation to the age of the ships in our care and their length of service. Shipworms are highly damaging and their destructivity will escalate.

Already, particularly aggressive *L. pedicellatus* have been recorded in the historic Langstone Harbour,[114] although their presence is dispersed due to the limited amounts of wood available for larval settlement. The amount of natural wood flowing into the harbour means that shipworm populations struggle to establish and survive. Nonetheless, this demonstrates that shipworms will continue to affect historic quays, harbours, and ships. At the nearby Portsmouth Harbour, there is a much larger presence of wood, used in the Naval Dockyard and in Gosport Marina, providing a much more favourable environment for shipworms now and in the future. Additionally, the *Mary Rose* wreck site offers a striking insight into ship worm activity. Although the bulk of the ship was salvaged in 1982,[115] parts remained on the seabed and were brought up considerably later. Live shipworms were present in these historic timbers and, although the damage done by them was not extensive, they showed that these timbers must have become recently exposed after being buried in the mud. Mud is an anoxic environment, meaning that shipworms and other animals generally cannot survive there. Becoming exposed, therefore, threatens maritime archaeology and this exposure through removal of seabed sediment can also be linked to climate change (see *III.I.ii.a Coastal Inundation, Coastal / Submarine Erosion, Tidal Changes, and Coastal Storminess*).

Other species of wood borers have been recorded in the UK, including the crustaceans *Limnoria* and *Chelura*. *Limnoria* is very active in the timbers at the seaward end of South Parade Pier in Portsmouth. There are three species of *Limnoria* in UK waters, all reported in the Solent area. Seawater warming would favour *L. tripunctata*, which is not currently the main species but would therefore become problematic. *L. tripunctata* is particularly resistant to creosote, meaning that it is a particular problem for wharves constructed of creosoted timber. Warming will affect marine borer populations in a way that will be

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[110] Snow, 1917 in Paalvast, Peter; van der Velde Gerardvan, 2011, pp. 1822-1829.
[111] Cobbs, 2002 in Paalvast, Peter; van der Velde Gerardvan, 2011, pp. 1822-1829.
[112] Kingsley, 2016, 187.
[113] Paalvast, Peter; van der Velde Gerardvan, 2011, 1823.
[114] Murphy, Pater, and Dunkley, 2008, 19
[115] https://maryrose.org/about-the-mary-rose/

detrimental to historic vessels and maritime infrastructure in the UK, by increasing their aggression or through the introduction of new species.

It will become important to research how to improve the durability of wooden materials in the marine environment while taking into account the potential environmental damages of the use of harsh chemicals. The historic maritime environment will be crucial in this research: for example, it is known that the Royal Navy historically stayed at sea for long periods due to its practice of copper sheathing the hulls of ships, giving protection against marine borers and fouling. While much can be learned from historic ship building practices, certain established and proven chemicals traditionally used to treat wood for marine use have now been banned as being harmful to the environment. Creosote has also been made illegal in many other countries because of its toxic and carcinogenic properties[116] and the EU directive in 2003 further limited the use of creosote and copper-chrome-arsenic (CCA) in wood destined to be used in marine construction.[117]

Various types of tropical hardwood were tested over a period of thirty years in the marine waters of the Netherlands, with the results showing that the hardness of the timber and the presence of silica particles and poisonous alkaloids in wood affords considerable protection against shipworm attacks, although, after thirty years of exposure, even the most resistant hardwoods showed some damage to shipworms.[118] This illustrates another problem for historic vessels: there is a need to balance using local materials with wood foreign to Britain in conservation projects, with potentially more timber needing replacement due to shipworm damage. National Historic Ships UK's guidance on ship conservation advises the replacement of timber using like-for-like materials wherever possible to maintain the authenticity of the vessel.

Beyond shipworms, other infestation problems worsened by climate change are becoming apparent. In the eighteenth-century Sheerness dockyard wall there is a population of yellowtail North African scorpions. The Sheerness yellowtail scorpions most likely arrived in cargoes of Italian masonry during the Georgian era and settled into the port's dockyard walls, continuing to survive due to the warm Kent weather.[119] However, in the past two decades, due to global warming, they have vastly grown in numbers. As of 2002, there were an estimated 10,000 – 15,000 yellowtail scorpions living in crevices in the dockyard wall.[120] The scorpions are not aggressive and for most of their lives remain in stasis, only moving

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[116] Snow, 1917; Hoppe, 2002 in Paalvast, Peter; van der Velde Gerardvan, 2011, pp. 1822-1829.

[117] European Commission, 2003. Directive 2003/2/EC of 6 January 2003 relating to restrictions on the marketing and use of arsenic (10th adaptation to technical progress to Council directive 76/769/EEC. Official J. Eur. Comm. L4/9eL4/11, 9.1.2003 referenced in Borges, 2014, 98.

[118] Paalvast, Peter; van der Velde Gerardvan, 2011, 1828.

[119] https://www.theguardian.com/uk/2002/may/12/robinmckie.theobserver

[120] https://www.theguardian.com/uk/2002/may/12/robinmckie.theobserver

when prey passes the crevices they live in, although they cause problems during maintenance of the site.[121]

HMS *Victory* offers a good example of the difficulties arising from pest infestations on historic ships, with her long-lasting problem with Death Watch beetles in particular. Death Watch beetle has been known to be present on *Victory* since at least 1932, soon after she was dry-docked.[122] They can cause serious deterioration as their larvae feeds on timber – and their larval life cycle can be up to fifteen years in length, meaning that a significant amount of damage can be done. Furthermore, they only emerge as adults, often resulting in the damage being done long before their presence is discovered.[123] Such infestations are traditionally a normal fact of life on historic ships; however, it is possible that the numbers of Death Watch beetles and other pests onboard ships like *Victory* will increase with climate change if not checked, as changes to the hydrological cycle accompanying temperature rise cause increased humidity, which in turn provides a more favourable environment for Death Watch beetle.

As well as affecting ships, temperature change may also lead to new pests and diseases attacking archive materials,[124] resulting in the need to rethink the storage and care of archival documents. Finally, traditional natural repair materials may become increasingly difficult to source after being attacked[125] and after rising temperatures and other climatic changes have resulted in a dearth of native British flora.

Global temperature warming could also contribute to a rise in plant infestations in waterways as the environment becomes more favourable to extreme growth. In turn, this could result in decreasing water depth, particularly on canals, or could create dangers for visitors; for example, overgrowths of algae on canals which could disguise the water's edge.

- **OCEAN ACIDIFICATION**

As sea temperatures rise, the acidity of sea water will increase. Ocean acidification is quantified by decreases in pH, a measure of acidity using a logarithmic scale, where a pH decrease of 1 unit corresponds to a 10-fold increase in hydrogen ion concentration, or acidity. The increase in atmosphere concentrations of carbon dioxide, methane, and nitrous oxide have reached levels unknown in the last 800,000 years, with carbon dioxide concentrations specifically increasing by 40% since pre-Industrial times. This has been primarily caused by fossil fuel emissions and secondarily from emissions from land use change. The ocean has absorbed around 30% of the emitted anthropogenic carbon dioxide, which has caused the ocean to acidify. Since the beginning of the industrial era, the pH of ocean surface water has decreased by 0.1, corresponding to a 26% increase in hydrogen ion

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[121] Murphy, Pater, and Dunkley, 2008, 19.
[122] McCormack, 2016, 105.
[123] Pinniger, 2015 in McCormack, 2016, 105.
[124] Fluck & Historic England, 2016, 16.
[125] Fluck & Historic England, 2016, 16.

concentration.[126] Acidification is a very serious environmental problem, affecting both structures in water, through ocean acidification, and structures on land, through acid rain. Corrosion by sulphurous acid rain amongst heritage assets on land is particularly well-known, most obviously on sandstone or limestone monument.[127] Corrosion of metals in water is an electrochemical process in which the metal disintegrates.[128] Water composition is also of importance for the formation of protective layers of the metal surface; these metal layers are often important in determining the corrosion rate, with the water composition usually determining whether certain types of local corrosion can occur at all.[129]

Importantly, ocean acidification affects the flora and fauna that survive and thrive in the seas, which, in addition to being environmentally detrimental in itself, in turn results in problems for historic ships, as marine pests increase in numbers as detailed above and heritage boats taking part in fishing are impacted.

Like many other climate and environmental processes, corrosion in water is a chemical process which occurs naturally. However, as climate change increases and more emitted pollutants are absorbed by the ocean, the pH of the ocean will decrease to unprecedented rates at unprecedented speed, resulting in a sharp increase in corrosion to historic vessels, particularly those parts of them which have the most contact with water, namely, the hull below the waterline.

Ocean acidification is a particularly interesting climate change phenomenon to consider in relation to maritime, because not only does it directly affect ships today, but those vessels have, in the past, contributed to ocean acidification, and many still do, through their use of fossil fuels. The EU Science Hub has reported a study which found that along major shipping lanes, sulphur dioxide (SO_2) emissions from ships could further ocean acidification at a rate that is twofold with respect to that caused by carbon dioxide (CO_2) emissions. This is because some ships use exhaust gas cleaning systems, or "scrubbers", to wash their exhaust gases to meet the current EU regulations on air quality which restrict the release of SO_2emissions. The resulting acid wash water, which contains SO_2, is then released into the sea, leading to the acidification of the water.[130] As shipping is an international industry, environmental, security and safety standards are developed by the International Maritime Organization (IMO), a United Nation specialised agency. In the EU, the sulphur limits established by the IMO are transposed by Directive 2012/33/EU as regards the sulphur content of marine fuels. As of 1 January 2015, EU Member States must ensure that ships in the Baltic, the North Sea and the English Channel are using fuels with a sulphur content of

126 IPCC, *Summary for Policymakers*, 2013.
127 Kucera, 1988, 167.
128 Kucera, 1988, 183.
129 Kucera, 1988, 183
130 https://ec.europa.eu/jrc/en/news/ocean-acidification-exacerbated-emissions-ships-major-shipping-routes

no more than 0.10%. Higher sulphur contents are still possible, but only if the appropriate exhaust cleaning systems are in place.[131]

Smaller ships and craft which are not part of industrial shipping, including historic vessels, can still contribute to ocean acidification today, and have done in the past, if they use fossil fuels. This can be mitigated by carbon off-setting or conversion to partial or full-use of renewable fuels.

SEA LEVEL RISE, INCLUDING COASTAL INUNDATION AND FLOODING AND COASTAL EROSION

Sea levels do rise and fall naturally over time. However, global sea-level rise has accelerated between the mid-nineteenth and mid-twentieth century at an unprecedented level of change.[132] Sea level rise is occurring because of anthropogenic global warming, resulting, firstly, in thermal expansion of sea water as water heats up and occupies more space.[133] It is estimated that around 50% of sea-level rise in the past 25 years is attributable to warmer oceans simply occupying more space.[134] Secondly, global warming is causing melting of the cryosphere, including both ice sheets and glaciers. Glaciers naturally partly melt in the warmer summer months, but recently greater than average summer melting has occurred, resulting in higher run off, ultimately causing sea levels to rise.[135] Alongside melting glaciers, the Greenland and Antarctic ice sheets, which also sit on land, are melting more quickly, again resulting in runoff into the ocean. Additionally, scientists believe that melt water from above and sea water from below is seeping beneath Greenland's ice sheets, lubricating them, and resulting in them moving more quickly into the sea. In addition to these two main changes, land uplift or post-glacial rebound is the process of land rising somewhat after the removal of the weight of ice sheets, which reduces the relative rise of sea levels.[136] Nonetheless, sea levels are likely to still rise at unprecedented rates.

It can be said with high confidence that maximum global mean sea level during the last interglacial period (129,000 to 116,000 years ago) was, for several thousand years, at least 5 m higher than present and did not exceed 10 m above present.[137] As of 2009, global sea level rise was at about 3 mm per year, with human activities likely to have contributed between a quarter and half of the rise in the last half of the twentieth century.[138] Between the period 1901 to 2010, global mean sea level rose by 0.19 [0.17 to 0.21] m[139] and is expected to continue to rise during the twenty first century. Around the UK specifically, sea level rose by about 1mm/year in the twentieth century, corrected for land movement. The rate for the 1990s and 2000s has been higher than this.[140] Under all scenarios, the rate of

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[131] https://ec.europa.eu/jrc/en/news/ocean-acidification-exacerbated-emissions-ships-major-shipping-routes
[132] IPCC, Summary for Policymakers, 2013.
[133] https://www.nationalgeographic.com/environment/global-warming/sea-level-rise/
[134] https://climate.nasa.gov/news/2680/new-study-finds-sea-level-rise-accelerating/
[135] https://www.nationalgeographic.com/environment/global-warming/sea-level-rise/
[136] Milne & Shennan, 2013, 452-459.
[137] IPCC, Summary for Policymakers, 2013.
[138] UKCP09, *The climate of the UK and recent tren*ds, 2009, 4.
[139] IPCC, Summary for Policymakers, 2013.
[140] UKCP09, *The climate of the UK and recent tren*ds, 2009, 4.

sea level rise will very likely exceed that observed during 1971 to 2010 due to increased ocean warming and increased loss of mass from glaciers and ice sheets.[141]

This initially may not sound like a very large amount of change, but for an island country like the UK, many coastal livelihoods and heritage projects will be in jeopardy by even an incremental sea level rise, and, furthermore, the rate of sea level rise is rapidly increasing. Sea level rise projections developed by the Met Office Hadley Centre and published in 2019 have demonstrated that UK sea levels will continue to rise well beyond 2100 under all future emissions scenarios, although the severity of that rise will depend upon greenhouse gas mitigation measures. Under a low emissions scenario, the approximate projected ranges at 2300 are 0.5 – 2.2 m for London and Cardiff, and 0.0 – 1.7 m for Edinburgh and Belfast. Under a high emissions scenario, this increases to 1.4 –- 4.3 m for London and Cardiff, and 0.7 – 3.6 m for Edinburgh and Belfast.[142]

Sea level rise will inevitably result in changing coastlines. Britain's coastlines have always changed continually, but the rate of this change and where its greatest impacts will be are affected in unprecedented ways by sea-level rise, changes to coastal currents, storm patterns and other climate change related factors.[143]

In terms of maritime heritage, this will most obviously result in the loss of coastal heritage assets and archaeology, alongside livelihoods and communities, by both inundation (flooding) and erosion. Furthermore, increased sea levels will lead to higher wave energy and, alongside increases in storminess due to warming affecting the global hydrological cycle, this will result in intensification in the incidence and severity of storm surges, which will be highly destructive to both coastal heritage and heritage in and alongside rivers, such as places in the Thames Estuary. Assets on the coastal fringe will become increasingly at risk from inundation, damage, or loss from erosion.[144]

- **COASTAL INUNDATION, COASTAL / SUBMARINE EROSION, TIDAL CHANGES, AND COASTAL STORMINESS**

Coastal and submarine erosion is already taking place at an accelerated pace. Coastal erosion refers to erosion on the coastline, whereas submarine erosion refers to erosion occurring offshore below sea level. Erosional and depositional processes are a normal process of coastal and marine environments; however, climate change will increase their occurrence, speed, and intensity.

Increased sea level rise, coupled with changes to the global hydrological cycle, will encourage storminess and incidences of extreme coastal floods, causing various problems:

- Sudden destruction events

[141] IPCC, Summary for Policymakers, 2013.
[142] https://www.metoffice.gov.uk/research/news/2019/uk-sea-level-projections-to-2300
[143] Fluck & Historic England, 2016, 15.
[144] https://historicengland.org.uk/research/current/threats/heritage-climate-change-environment/what-effects/

- Immoveable heritage assets will also be lost over time as the sea level rises and British coastlines alter. Some historic vessels are likely to need relocation and new ports and docks will have to be built further inland.
- Flooding may damage buildings and materials not designed to withstand prolonged immersion.[145]
- Rapidly flowing water may also erode structures.[146]
- Organic materials, such as, timbers may swell and distort when wet.[147]
- Damage can also occur when inherent salt and water (frost) crystals carried through the substrate are released through inappropriate drying or very cold conditions. [148]
- After the water has drained away, various moulds, fungi, and insects will find a home in the damp, salty environment left behind. [149] When saturated (defined as when moisture content is above 25%) timber is vulnerable to rot because of fungal and insect attack.[150] This is especially true if the structures are left damp for too long. If dried too quickly and at temperatures that are too high, organic materials can shrink, split, or twist.[151]
- Water will become trapped in internal spaces, such as behind panelling, including in areas on ships where it was not designed to be. If not allowed to dry out, this will lead to rot and further problems[152]
- Floorboards, too, can be damaged by inundation, buckling if they become saturated because of prolonged immersion in water. [153]
- On the other hand, inorganic porous materials do not generally suffer directly from biological attack[154] and aluminium, bronze, copper, and brass objects, components, and fixtures will therefore not be damaged by water immersion if they are allowed to dry out quickly. [155]
- Iron and steel will oxidise and rust and expand when exposed to water, though they should not be harmed by a single immersion event if they are dried quickly.[156]
- Rusting of supporting buildings, particularly in maritime environments, can lead to serious structural problems. [157]
- Increased coastal flooding will not only pose a threat to the fabric of buildings and historic vessels, but also to equipment and archives, such as those located coastally or on the banks of tidal rivers, as at the National Maritime Museum in Greenwich

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[145] Colette; UNESCO, 2007, 23.
[146] Colette; UNESCO, 2007, 23.
[147] Pickles & Historic England, 2016, 32.
[148] Pickles & Historic England, 2010, 32.
[149] Colette; UNESCO, 2007, 23.
[150] Pickles & Historic England, 2010, 33.
[151] Pickles & Historic England, 2010, 32.
[152] Pickles & Historic England, 2010, 33.
[153] Pickles & Historic England, 2010, 33.
[154] Pickles & Historic England, 2010, 32.
[155] Pickles & Historic England, 2010, 34.
[156] Pickles & Historic England, 2010, 34.
[157] Pickles & Historic England, 2010, 34

and at the National Museum of the Royal Navy in Portsmouth. Consequently, the storage of archives, in some cases, may need to be rethought and any specialist equipment needed to move it should be considered and sourced in advance.[158]

- The depositional environment of submarine and intertidal cultural heritage will alter, resulting in increased risk of corrosion of metal vessels and infrastructure,[159] applying to any ships or structures in harbours and docklands. Some ships, for example, may experience increased electrolytic corrosion to their hulls due to various changing factors around their moorings.

Increased coastal erosion, alongside inundation, will result in the loss of buildings and structures. Coastal erosion will not only take the form of wearing away beaches, but will also result, in some places, in sudden landslides and coastline collapse.[160] Historic ports, harbours, piers, and lighthouses will be particularly vulnerable. Furthermore, increased storminess will likely also lead to an upsurge in the severity of wind-driven salt, which can also be corrosive to structures, both buildings and ships. Increased storminess will therefore damage both historic buildings and offices supporting the sector in multiple ways.

The Tall Ship *Glenlee*, moored at the Riverside Museum in Glasgow, has anchor chains for moorings, with the weight of the chain acting as dampers, which has long been a successful system for securing her safely. However, around 2015 her moorings were supplemented by adding Octoplait 3" diameter springs because the team had noticed that winter storms seemed to be gaining in strength and frequency. Storm surges were also more frequent and prominent with surges regularly over 1-1.5metres above predicted tides.

- **STORM SURGES**

Tidal flooding and storm surges are a natural process, occurring when storms coincide with high tides, such as the storm surge of December 2013 and the winter of 2013/14 in the south and west of the UK, including at Porthleven on the Cornish coast, Dawlish in Devon, sections of the River Thames, and the Somerset levels. However, climate change may increase the frequency and intensity of storm surges as sea levels rise. The storm surge of December 2013 took place during one of the UK's most prolonged periods of exceptional weather for more than a century,[161] which was no coincidence. There were several gales with winds peaking at 80 mph, and it was the wettest January since 1766, when records began.[162]

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158 Fluck & Historic England, 2016, 8.

159 Fluck & Historic England, 2016, 43.

160 For example: https://www.mirror.co.uk/news/uk-news/huge-chunk-uk-coastline-collapses-21637588

161 https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2014/winter-storms-january-to-february-2014---met-office.pdf

162 http://www.metoffice.gov.uk/climate/uk/interesting/2014-janwind

Projections of the height of extreme storm surges in a future climate are subject to uncertainty as they are difficult to calculate and may change depending upon the level of future emissions from human activities, which in turn depend on various socio-economic factors and degrees of mitigation.[163]

Extreme water levels will increase as average sea-levels continue to rise, and changes in the number, path, and strength of atmospheric cyclonic storms may alter the formation and evolution of storm surges around the UK.[164] The number of low-pressure storm systems crossing the UK during winter is predicted to increase from approximately five per winter in the present day to eight per winter during the 2080s, in one of the IPCC's climate simulations, 'A2'. This will likely be accompanied by a strengthening of the winter winds by as much as 6% over some south of England locations and average winter storm tracks will move south across the UK.[165]

The predicted increasing intensity and frequency of storm surges due to anthropogenic climate change is of particular concern for historic vessels located on inland flood plains. Storm surges will not only affect coastal areas but will cause high levels of flooding and damage inland.[166] The levels of damage caused inland are also associated with the calculation of risk. Risk is calculated by *likelihood x consequences*. Those with historic vessels situated on inland flood plains may be inclined to think that increased storm surges in the future will not affect them because of the relatively low likelihood of such an event, even as its likelihood does increase. In turn, this makes the consequences of such a flooding event higher, as there is likely to be a lack of preparedness for such an event and a lack of consideration of the value of assets situated on such flood plains.

CASE STUDY: ROYAL MUSEUMS GREENWICH AND THE THAMES FLOOD BARRIER

Maritime Greenwich, a UNESCO World Heritage site, is situated in the Thames Estuary on the Thames Flood Plain (the tidal Thames and its natural floodplain extends from Teddington in west London to Sheerness/Shoeburyness in the outer estuary).[167] It is home to the National Maritime Museum, Royal Observatory, the Queen's House, the clipper ship *Cutty Sark*, and the offices of National Historic Ships UK.[168] The National Maritime Museum houses thousands of historic maritime artefacts, including a number of historic vessels such as *Prince Frederick's Barge* and *Miss Britain III*.

The most significant threat to Greenwich and wider London arises from a combination of high tides and storm surges caused by low pressure systems travelling over the North Sea, and the funnelling of water from the southern North Sea into the Thames Estuary.[169]

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[163] Lowe and Gregory, 2003, 1322.
[164] Lowe, J. and Gregory, J. M. 2003, 1314.
[165] Lowe, J. and Gregory, J. M. 2003, 1318.
[166] Lowe, J. and Gregory, J. M. 2003, 1313.
[167] *London's Warming: The Impacts of Climate Change on London. Technical Report*. 2002, 217.
[168] https://www.rmg.co.uk
[169] *London Climate Change Partnership, 2002, Climate Change Impacts in a London Evaluation Study, Final Report, 311pp., in* Collette; UNESCO, 2007, 67.

However, London is protected by the Thames Barrier, designed and built in the 1970s in response to the catastrophic floods of 1953 and now one of the best tidal defence systems in the world.[170] The Barrier was designed to provide a high standard of protection to beyond 2030.[171] Historical trends of extreme water levels were used in its design, but the effects of climate change have now increased the incidence of such events. As a result, the Thames Barrier was designed to be used two to three times per year, but, as of 2007, was being used 6/7 times per year.[172] In 2014, the Barrier was raised a record 50 times. By comparison, it had been raised 124 times in its entire history, from 1982 to 2013.[173] The 2014 closures therefore accounted for 40.3% of its entire life closures.

Climate change is resulting in higher sea levels and changes in storm patterns, increasing storminess and the incidence of flooding by storm surges, which poses a significant long-term threat to the Royal Museums Greenwich and its displays. Observations in the Thames Estuary show that the mean and extreme water levels have been rising over the last two centuries. A long-term rising trend of 0.4 mm per year during the nineteenth century and 2.2 mm per year in the twentieth century has been observed at Sheerness (in the direction of the Thames Estuary). In a scenario of unmitigated future emissions, North Sea storm surges *will* increase. The United Kingdom Climate Impacts Programme (UKCIP) has suggested that the sea-level in the Thames Estuary will rise between 0.26 and 0.86 m by the 2080s compared to its average level between 1961 and 1990.[174] River levels in the Thames Estuary have risen more rapidly than the average sea level rise, due to the reclamation of inter-tidal areas and the deepening of channels.[175] In addition, global warming could result in a reduction in the total number of mid-latitude cyclones, but an increase in the number of intense events.[176] Coupled with rising sea levels, the strengthening of the winter winds over some of southern England, and the movement of average winter storm tracks south across the UK,[177] this favours the flooding of Western European tidal areas like the River Thames.

The Thames Barrier could be broken by one such extreme storm surge, in which case, along with the indirect £30bn cost of damages to the flood plain, the *Cutty Sark* and collections at the Royal Museums Greenwich would be lost or catastrophically damaged. Although there is still a low likelihood of the Thames Barrier breaching, that likelihood is constantly increasing. Were such an event ever to occur, the economic and cultural consequences are extraordinarily high. After the initial impact on historical artefacts, tourism would be slow to start back up again due to problems with fixing damage to buildings, transport, and physical

[170] Collette; UNESCO, 2007, 68.
[171] Collette; UNESCO, 2007, 68.
[172] Colette; UNESCO, 2007, 23.
[173] https://www.gov.uk/guidance/the-thames-barrier#thames-barrier-closures
[174] UKCIP in Colette; UNESCO, 2007, 23.
[175] Colette; UNESCO, 2007, 68.
[176] Lowe, J. and Gregory, J. M. 2003, 1314.
[177] Lowe, J. and Gregory, J. M. 2003, 1318.

spaces, resulting in further loss of income and a consequent effect on the ability to undertake conservation projects.

The Thames Barrier provides protection from a 1-in-2,000-year event, declining to 1-in-1,000 by 2030. The Thames Barrier can holdfast up until 2025 before the 1,000-year return flood event is exceeded.[178] By the 2050s, a 34 cm rise in sea level at Sheerness would change the 1-in-1,000-year flood level to a 1-in-200-year flood event, and by 2100, it is estimated that the Thames Barrier will need to be closed about 200 times per year to protect London from flooding.[179] The Environment Agency has stated that the Thames Barrier is expected to continue to protect London to its current standard up until 2070.[180]

Work to protect the flood plain and the heritage situated on it is beyond the scope of any individual organisation. The Thames Estuary 2100 Project (TE2100), conducted by the British Environment Agency, of which Phase 1 runs from 2012 until 2035,[181] aims to determine tidal flood risk and the appropriate level of flood protection needed for London and the Thames Estuary over the next 100 years. The project also maintains and improves the Thames Estuary's flood protections, including walls, gates, embankments, and pumps.[182] The project assesses the thresholds for responding to different amounts of sea level rise, creating flexible 'adaptation pathways'.[183] During 2019-2020, the TE2100 Project is undergoing a review, setting out how the Environment Agency and partners will continue to manage tidal flood risk until the end of the century.[184]

OTHER FORMS OF INLAND FLOODING AND FLASH FLOODING

A flood is "the overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas that are not normally submerged. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods [as covered above], and glacial lake outburst floods."[185]

Increased inland flooding will not only be caused in estuaries by storm surges. Although flooding is a natural part of annual and seasonal river processes, it is also connected to climate change: increased and more devastating inland flooding, particularly flash flooding, can be seen as a climate change impact, as floods are affected by various characteristics of precipitation, such as intensity, duration, time of year, and phase (rain or snow), and are

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178 Colette; UNESCO, 2007, 69.
179 London Climate Change Partnership, *London's Warming: The Impacts of Climate Change on London,* 2002, 204.
180 Policy paper: Thames Estuary TE2100 Plan, Updated 29th May 2020: https://www.gov.uk/government/publications/thames-estuary-2100-te2100/thames-estuary-2100-te2100
181 Policy paper: Thames Estuary TE2100 Plan, Updated 29th May 2020: https://www.gov.uk/government/publications/thames-estuary-2100-te2100/thames-estuary-2100-te2100
182 Policy paper: Thames Estuary TE2100 Plan, Updated 29th May 2020: https://www.gov.uk/government/publications/thames-estuary-2100-te2100/thames-estuary-2100-te2100
183 Climate Change Risk Assessment for London, January 2012: http://climatelondon.org/publications/climate-change-risk-assessment-for-london/
184 Thames Estuary 2100 – 2020 Review, September 2019: https://www.london.gov.uk/moderngov/documents/s79843/04a.3%20TE2100%20-%202020%20Review%20-%20Intro%20to%20the%20project%20Sept%202019.pdf
185 Seneviratne et al., 2012,175

also affected by drainage basin conditions, such as water levels in rivers, the presence of snow and ice, and soil character and status,[186] all of which are now changing due to climate change. Flash flooding occurs when precipitation falls so quickly and intensely that the underlying ground cannot drain it away fast enough, leading to large volumes of destructive water running through areas and riverbanks being broken by the sudden increase in volume.[187] Climate change causes variations in the global hydrological cycle through changes to atmospheric temperature, wind patterns, and atmospheric pressure, all of which result in increased evaporation of water from land and sea, in turn leading to increased frequency and intensity of precipitation, cloudiness, and humidity.[188] The IPCC has noted that climate change may therefore have increased the risk of rainfall-dominated flood occurrence in some UK river basins.[189] As surface run-off depends strongly on the rainfall intensity and frequency, changes in intense precipitation events, rather than mean precipitation, due to climate change will impact more strongly on floods.[190]

In the UK, the winter of 2020 (December 2019 – February 2020) was the wettest winter on record (since 1862) for the UK, as well as the 5th mildest.[191] Total annual average precipitation over England and Wales has not changed significantly since rainfall records began in 1766, but the seasonal variations appear to show that rain is now less likely in summer and more likely in winter. UKCIP predicts that by 2070, under a high emission scenario, average winter precipitation will increase, while average summer rainfall will decrease.[192] Furthermore, UKCIP anticipates that between 1990 and 2070, extreme hourly rainfall intensity associated with an event that typically occurs once every two years will increase by 25%.[193]

Even if the number of storms affecting the UK does not increase, the intensity of rainfall will, resulting in increased severity of storms, as rising temperatures lead to faster evaporation of water from land and sea and as the air temperature grows it holds more water vapour – there is an increase of around 7% of water vapour held by the air for every 1^{o}C increase in temperature.

Warmer, wetter winters will lead to more saturated ground, meaning that any rainfall will result in a greater chance of flooding as the ground's ability to absorb it is decreased. At other times, climate change will bring drought due to more water being absorbed from land and sea when temperatures rise – meaning that when rain does then fall on these areas, it isn't absorbed by the dried-out soil but instead immediately runs off directly into rivers and the sea,[194] which can result in flash flooding. Flash flooding is also impacted by other

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186 Seneviratne et al., 2012,175
187 https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/rain/flash-floods
188 https://climaterealityproject.org/blog/climate-crisis-and-flooding-what-you-need-know
189 https://www.ipcc.ch/site/assets/uploads/2018/03/SREX-Chap3_FINAL-1.pdf, page 177
190 Maraun et al, 2008, 833.
191 https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2020/2020-winter-february-stats
192 https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/ukcp-infographic-headline-findings.pdf
193 https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/ukcp-infographic-headline-findings.pdf
194 https://climaterealityproject.org/blog/climate-crisis-and-flooding-what-you-need-know

anthropogenic actions, such as urbanisation, where surfaces are covered in impermeable materials like concrete; cities are provided with limited or under-capacity drainage networks; deforestation occurs, where tree coverage is significantly reduced for farming or urbanisation; and the existence of dykes, dams, and reservoirs in the river basin[195] decrease the opportunity for precipitation to be intercepted on its way to the ground.

It may not be immediately obvious that inland flooding will affect historic vessels, particularly since craft are made to be on water and to cope with changing water levels. However, riverbanks are now being breached more regularly as major flooding events become more common and this is affecting inland historic vessels in several ways. Firstly, structures associated with historic vessels on riversides or lakesides are now much more likely to become inundated in the event of unusually high-water levels and flash flooding. As well as being inundated, these structures are also more likely to be damaged by unusually strong water and objects swept into the water. Similarly, any moored or anchored boats are also at risk of being swept away by strong waters and colliding with other structures within the water or on top of it, such as bridges, or being submerged or damaged within flooded boathouses, all of which can cause significant damage to them.

CASE STUDY: STEAM LAUNCH *SHAMROCK*, LAKE WINDERMERE, LAKE DISTRICT

The Lake District is no stranger to flooding – in an area of so many hills, mountains, rivers, and large bodies of water, flooding is a normal part of seasonal and annual cycles. However, in recent years flooding in the Lake District has been unprecedented with extreme flooding occurring more and more often.[196] This has caused tragic losses of life, homes, and livelihoods. It has also impacted historic vessels. In 2009, torrential rain resulted in water levels on Windermere, England's largest lake, rising to a record high, measuring 2.9 m above the weir at Newby Bridge.[197] Some areas of the Lake District received more than 400 mm of rainfall in a 72-hour period, and Seathwaite, Cumbria, recorded 316 mm of rainfall within 24 hours:[198] the rainfall was exceptionally prolonged and heavy.[199] Many rivers in the Lake District exceeded their previous maximum flows by a wide margin.[200] Inside a boathouse on Windermere was the National Historic Fleet steam launch *Shamrock*.

Shamrock was built in 1906 by Nathaniel Shepherd, boat and yacht builder at Bowness-on-Windermere for Mr W M Birtwistle, a cotton millionaire from Blackburn. She was privately owned for many years, then passing into the hands of a charitable trust established to care

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195 Seneviratne et al., 2012,175.
196 https://www.friendsofthelakedistrict.org.uk/FAQs/flooding-in-cumbria
197 https://www.shamrocktrustuk.org/friends/
198 https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2009/heavy-rainfall_flooding-in-the-lake-district-cumbria---november-2009---met-office.pdf
199 https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2009/heavy-rainfall_flooding-in-the-lake-district-cumbria---november-2009---met-office.pdf
200 https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2009/heavy-rainfall_flooding-in-the-lake-district-cumbria---november-2009---met-office.pdf

for her.[201] Today, she remains operational and is regularly steamed on the lake for the purpose for which she was designed and built.[202]

Shamrock had been safely berthed inside the same boathouse on Windermere for thirty years and had survived a number of floods, equipped with 7' (2.13 m) of headroom above her cabin. However, the extraordinary rise in Windermere's levels was above this 7' mark, resulting in her cabin roof being squashed against the steel beams attached to the three main timber support beams in the boathouse, severely damaging her, although she did not sink.

Extensive repair work was undertaken and *Shamrock* has now been rebuilt as near as possible to her pre-disaster state.[203] The Shamrock Trust reflected that the flooding served to "demonstrate the vulnerability of our historic launches" and "alerted many people to the risk of losing such boats permanently".[204]

In 2015, the Lake District again experienced unprecedented flooding when Storm Desmond swept across the North of England. The Met Office confirmed a record rainfall in Cumbria with 341.4mm of rain in just 24 hours.[205] It seems likely that such extreme flooding incidences will increase and continue to endanger historic vessels in the area.

CASE STUDY: WINDERMERE JETTY, LAKE DISTRICT

The Windermere Jetty Museum of Boats, Steam and Stories[206] is a collection of new buildings designed by Carmody Groarke Architects. The buildings allow for the exhibition and conservation of a collection of steamboats and other inland vessels of significant size and weight. A wet dock allows the display of boats on water within the museum and offers boating excursions on the lake, and a Conservation Workshop is linked to a boat yard and slipway. Windermere Jetty is a part of Lakeland Arts, one of the most significant arts and heritage organisations in the North of England.

The buildings were designed specifically to provide robustness against the climate, paying particular attention to flood defences due to their lakeside position. A crucial part of this was raising the building levels to withstand a 100-year flood scenario, accompanied by a sheet pile wall at the lake edge. The Conservation Workshop sits in the flood plain, due to its relationship with the slipway, and so materials and detailing within the conservation building were picked for their durability and ease to source replacements. Services are placed at high levels throughout. Large, cantilevered overhangs protect window and door

[201] https://www.shamrocktrustuk.org
[202] https://www.shamrocktrustuk.org/history/
[203] https://www.shamrocktrustuk.org/friends/
[204] https://www.shamrocktrustuk.org/friends/
[205] https://www.independent.co.uk/news/uk/home-news/cumbria-deluge-breaks-historic-rainfall-record-1824353.html
[206] https://windermerejetty.org

openings from Cumbrian weather and hidden gutters are sized for the annual rainfall in the lakes.

In addition to being built to be climate change resilient, the building has also been designed to minimise energy consumption during its operation, actively aiming to mitigate climate change causes. The museum is comprised of six sheds, each building having a different function, allowing each structure to be isolated, finished, and environmentally tempered to different needs, ranging from working conservation in the boat shed to museum-conditioned gallery space.[207] To further reduce the chances of flooding of the museum, outside hard-surfaced groundworks were kept to a minimum and concrete slipways and Tarmac for vehicle access were interspersed with permeable areas of Westmorland slate waste, accompanied by a reed bed receiving rainwater run-off, providing attenuation and filtration, returning water back to the lake.[208] This also reduced the carbon footprint of the build.[209]

The sustainability of the building long-term has been improved using natural ventilation; by an intelligent control system which monitors the internal air quality and temperature, optimising internal performance and comfort; and, by low water use appliances being specified throughout. Additionally, the environmental systems in the gallery have been designed in direct response to the collection and not to conventional standards.

Windermere Jetty is an excellent example of how an organisation can respond to the risk of adverse weather, in this case the potential for extreme and unprecedented flood events, by creating a structure specifically designed to protect its collection from and mitigate the impact of climate change. The latter is achieved by improving sustainability across all areas, from reducing the carbon footprint of the build itself to lowering the energy consumption and materials use of the museum long-term. Finally, reed beds adjacent to the building provide natural treatment and attenuation of surface water run-off prior to discharging it to the lake.

CASE STUDY: IRONBRIDGE CORACLE SHED

Coracles are small, keelless boats. They were an early form of water transportation, typically used for fishing, although their main use today in Europe tends to be recreational. In Wales, however, a number of licences still exist to permit their use as a fishing vessel.[210] Coracle design (shape and size) differs around the world and across the United Kingdom. This is due to various factors, including the materials available locally to construct the vessel from, its intended use, the conditions of the water where it will be based and even personal preferences of the builder. Coracles are therefore defined into 'types'. In the UK alone,

[207] https://www.architectsjournal.co.uk/buildings/all-aboard-carmody-groarkes-windermere-jetty-museum/10041181.article
[208] https://www.architectsjournal.co.uk/buildings/all-aboard-carmody-groarkes-windermere-jetty-museum/10041181.article
[209] https://www.architectsjournal.co.uk/buildings/all-aboard-carmody-groarkes-windermere-jetty-museum/10041181.article
[210] https://www.nationalhistoricships.org.uk/page/coracle-society

there are more than twenty different coracle types – usually named after rivers or, in some places the locale.[211]

The Ironbridge Coracle Shed is in the Ironbridge Gorge, a UNESCO World Heritage site on the banks of the River Severn. Ironbridge Coracle Trust is a small voluntary charity which is working to preserve the story of coracles in the Gorge. Its current Lottery funded project is to restore the shed and conserve the collection of objects stored within it. Each November and January/February the River Severn floods with water from Wales[212] as part of a natural annual and seasonal cycle. In addition, every 20 years or so, the River Severn floods to 6-8m above its normal level in the narrow gorge.[213] The archive of historic photos of major floods in the Gorge support this, documenting major floods in 1908, 1928, 1947/8… 2000, and 2020, and, of course, not forgetting the Great Flood of 1794. Despite this, there are no permanent flood barriers in the Gorge.

The 2020 flooding was much worse than usual, caused by a combination of saturated ground and intense rainfall which meant that there was nowhere for the water to drain away to. Ironbridge was flooded three times in two weeks.[214] The coracle shed was built in the 1920s on wooden stilts on the riverbank. Installation of new timber supports and braces took place in 2019 just before the flooding struck, otherwise this historic structure would not have survived.[215] This highlights the precarity of many of the structures associated with the historic vessel sector: "We are only temporary custodians of our past and we owe it to the next generation to protect their legacy."[216] By their very nature, historic structures are more likely to have structural issues as a consequence of their long lifetimes and so constant maintenance is crucial, as is looking ahead to extreme or uncertain weather events, just as at the Ironbridge Coracle Shed. The project manager commented that "our luck has lasted, but we need to be prepared for next time."[217]

As well as taking individual action to protect heritage buildings and vessels, it is also vital that national intervention is considered. The project manager at Ironbridge Coracle Shed highlighted that "building permanent flood barriers in historic landscapes of Outstanding Universal Value is a difficult and expensive process and there is no central government funding for UK World Heritage Sites. Historic buildings affected by flooding require sensitive

[211] https://www.nationalhistoricships.org.uk/page/coracle-society

[212] https://www.coraclesociety.org.uk/news/11-05-2020/ironbridge-flooding-–-impact-rogers-family-coracle-shed

[213] Blockley, Marion; Heritage Fund. 'Living and working in a threatened landscape', 2020: https://www.heritagefund.org.uk/blogs/living-and-working-threatened-landscape

[214] Blockley, Marion; Heritage Fund. 'Living and working in a threatened landscape', 2020: https://www.heritagefund.org.uk/blogs/living-and-working-threatened-landscape

[215] Blockley, Marion; Heritage Fund. 'Living and working in a threatened landscape', 2020: https://www.heritagefund.org.uk/blogs/living-and-working-threatened-landscape

[216] Blockley, Marion; Heritage Fund. 'Living and working in a threatened landscape', 2020: https://www.heritagefund.org.uk/blogs/living-and-working-threatened-landscape

[217] Blockley, Marion; Heritage Fund. 'Living and working in a threatened landscape', 2020: https://www.heritagefund.org.uk/blogs/living-and-working-threatened-landscape

and careful treatment to recover from the impact of flood damage." [218] Additionally, building floodplains in one area can negatively impact others downstream. Government action is necessary, particularly in considering development on floodplains, coordination with insurance bodies, and preparing and planning for such emergencies. All of this is part of vital sustainable development and response to the climate emergency.

It is unclear whether the unprecedented severity of this year's flood is attributable to climate change – there is simply not enough data. Furthermore, severe flooding every twenty years has been part of life in the Ironbridge Gorge for at least the past century. However, it is evident that climate change and other anthropogenic developments contribute to the intensity and severity of flooding and that this year's flood was more severe than any in the past have been. In addition to the unprecedented levels of high water this year, in other parts of the gorge, particularly at the bottom of Coalbrooke, Dale End, flash flooding has visibly got worse in the past thirty years.

CASE STUDY: CANAL & RIVER TRUST

Inland flooding can also affect canals and guidance has been released by the Canal and River Trust on preparing for such an eventuality.[219] The advice includes checking ropes on vessels in order to build in some slack to allow for rising water levels. [220] Additionally, some mooring locations are dangerous, particularly those with changing water levels, a steep fall or shallow bank. [221] Canal boat owners should also ensure that drain holes are regularly cleaned out in order to stop them becoming corroded and blocked with debris; bilge pumps are working and have an automatic float switch; and the battery has a good level of charge. [222]

WATER AVAILABILITY: WINTER PRECIPITATION, SUMMER DROUGHTS AND CHANGES IN HUMIDITY

Increased incidences of extreme precipitation events are likely to increase, with a change in precipitation patterns, a projected increase in winter precipitation of around 33% [223] and increased intensity of individual episodes throughout the year. [224] It is well understood that higher temperatures affect the hydrological cycle, leading, at the global scale, to higher atmospheric moisture content and increased evapotranspiration. [225]

As well as extreme precipitation leading to fluvial (river) flooding, as has been covered above, extreme precipitation can also lead to pluvial flooding in areas not near any waterways and to rainwater penetration of structures. Intense pluvial events and

[218] Blockley, Marion; Heritage Fund. 'Living and working in a threatened landscape', 2020: https://www.heritagefund.org.uk/blogs/living-and-working-threatened-landscape
[219] https://canalrivertrust.org.uk/enjoy-the-waterways/boating/a-guide-to-boating/preparing-for-a-flood
[220] https://canalrivertrust.org.uk/enjoy-the-waterways/boating/a-guide-to-boating/preparing-for-a-flood
[221] https://canalrivertrust.org.uk/enjoy-the-waterways/boating/a-guide-to-boating/preparing-for-a-flood
[222] https://canalrivertrust.org.uk/enjoy-the-waterways/boating/a-guide-to-boating/preparing-for-a-flood
[223] Fluck & Historic England, 2016, 15.
[224] Fluck & Historic England, 2016, 39.
[225] Maraun et al, 2008, 833.

persistent periods of rainfall on saturated or impermeable ground can damage buildings, penetrate historic hulls, flood heritage areas, exacerbate erosion[226] and contribute to soil instability. As extreme precipitation increases, these impacts will only continue to be felt more strongly.

A key impact of increased precipitation on historic vessels will be water ingress. The current structures in place on the vessels to cope with precipitation and leaks may not be sufficient. Adaptations to manage increased precipitation may be difficult without affecting the structure or physical appearance of the vessel.[227]

Extreme precipitation events could take the form of increased hail, both in frequency and size, resulting in damage to ship's hulls. Seemingly paradoxically, higher incidences of droughts (more intense and frequent) will also be experienced alongside these pluvial events.[228] This is because climate change will increase the extremes of weather we experience.

Droughts could also result in the drying out of certain geologies, such as clay, leading to an increase in subsidence, the lowering or collapse of the ground,[229] affecting heritage structures.[230] In contrast, when the ground becomes waterlogged it can swell. Clay-rich soils are particularly susceptible to this shrink-swell action, which causes a change in volume of the ground. Swelling pressures can cause heaving, or lifting, of structures while shrinkage can result in differential settlement. The British Geological Survey described shrink-swell behaviour as "the most damaging geohazard in Britain today," which has cost the British economy an estimated £3 billion over the past 10 years.[231]

At its worst, drought could lower inland water levels. Droughts can be characterised into three classes: 'meteorological drought', a period of time with lower-than-average rainfall; 'agricultural drought', a period of time where agricultural output is reduced as a result of insufficient water; and 'hydrological drought', a period of time where stream flows fall below an expected rate.[232]

Changing water availability will also impact humidity levels. As temperatures increase, evaporation will increase, resulting in humidity increases, which will pose problems to the conservation of historic vessels.

CASE STUDY: CANAL & RIVER TRUST

In June 2020, a pound of the Grand Union Canal between North Lock, at Frog Island, and Tile Kiln Lock, near Abbey Park in Leicester was left with almost no water, which,

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226 Fluck & Historic England, 2016, 15

227 Fluck & Historic England, 2016, 39.

228 Fluck & Historic England, 2016, 15

229 http://www.bgs.ac.uk/research/engineeringGeology/shallowGeohazardsAndRisks/whatisShrinkSwell.html

230 Fluck & Historic England, 2016, 16

231 http://www.bgs.ac.uk/research/engineeringGeology/shallowGeohazardsAndRisks/whatisShrinkSwell.html

232 Canal & River Trust, 'Water Resources Strategy 2015-2020', 2015, 9.

according to the Canal and River Trust, was caused by lack of rainfall. The water was around 18" lower than would normally be expected for the time of year. The Canal and River Trust responded by feeding water manually to increase the canal level. Visitors to the canal reported seeing fish left 'gasping for air' alongside stranded boats.[233]

This shows that although canal water levels are typically much less variable than rivers, they can still change considerably over short periods. Most canal water levels are managed around a normal operating zone (NOZ) which is typically +/- 200 mm, but water levels outside of the NOZ may be experienced at times. Canal levels are not only affected by the weather, but also by several anthropogenic and structural factors, such as length of pound, proximity to controlled and uncontrolled inflows, amount that upstream and downstream locks are being used, navigable depth in relation to pound datum, and canal freeboard.[234] The Canal & River Trust, however, has clearly stated that climate change is a key pressure on their water resources, in addition to changes in funding, environmental legislation (a likely reduction in abstraction volumes), and increased network uses.[235]

Climate change is causing extreme weather events, such as the sudden heatwave which brought drought to the Leicester Grand Union Canal – these are impacting water levels in canals and will continue to do so. Climate change will result in altered inland water levels throughout the year, including both floods and droughts. This will affect the use and mooring of heritage craft. At the extreme, canal pounds could periodically completely, or nearly fully, drain, resulting in damage to the underside of boats.

Even if this does not happen, the patterns of usage of canal boats will be dramatically altered. During and after exceptionally dry weather conditions in 2018 and 2019, the Canal and Rivers Trust imposed restrictions on various sections of canals across the country.[236] Navigational drought, a period of time where a shortage of water resources in a hydrological unit (waterways supplied by the same source) leading to restrictions or navigation closure, has been recognised in the Canals and Rivers Trust's *Water Resources Strategy* 2015-2020.[237] The Trust currently considers there to be a 5% probability of drought closure every year.[238] However, this may rise in the future, especially as the Trust believes that one of the greatest pressures on their water resources comes from climate change.[239] As of 2019, the Canal & River Trust technical and operational teams were working together to monitor developing drought conditions, reviewing the demands of each canal, and liaising with boating organisations. They have produced drought plans, providing advice and details of actions to be undertaken when pre-defined

233 https://www.leicestermercury.co.uk/news/leicester-news/section-grand-union-canal-through-4185805

234 https://canalrivertrust.org.uk/business-and-trade/inland-marina-development-guide/design/water-levels-flood-risk-discharges-and-water-quality

235 Canal & River Trust, 'Putting the water into waterways. Annual Report 2019', 2019, 4.

236 Canal & River Trust, 'Putting the water into waterways. Annual Report 2019', 2019, 2

237 Canal & River Trust, 'Water Resources Strategy 2015-2020', 2015, 3.

238 Canal & River Trust, 'Water Resources Strategy 2015-2020', 2015, 3.

239 Canal & River Trust, 'Water Resources Strategy 2015-2020', 2015, 3.

water resource risk triggers have been reached, ranging from early warning signs (aiming to preserve water supplies to reduce water shortages), during the drought itself and into drought recovery and normal operation.

CASE STUDY: HMS *VICTORY*

HMS *Victory* is known to have a humid environment, as its timber structure holds onto a lot of moisture, and it has poor internal airflow. This leads to stagnation, which is more pronounced on the lower decks, and a corresponding rise in average humidity. It has an average relative humidity (RH) in the region of 72%. This results in ever-present mould and fungus spores, which thrive in conditions above 60% RH, causing a threat to the structural survival of the ship as some of the fungal species degrade lignin and cellulose. There is also evidence that fungal decay allows attacks by Death Watch beetle on oak heartwood that would otherwise not be possible. Reports from the HMS *Victory* quarterly reviews in the 1970s show beetle counts were high at this time and there was also a notable spread of fungal attack around the ship, suggesting a symbiotic relationship, "where the beetles act as carriers for the fungal species which also promote the decay that allow them to feed, grow, and reproduce".[240]

A robust environmental system has been in place onboard *Victory* since 2016, including a dehumidification unit in the aft end of the orlop deck, which has produced a c. 10% reduction in the RH in this area - sufficient to hold the average RH in this area below the 65% at which mould and fungus becomes most prolific. This is also currently one of the only areas within the ship that shows no active Death Watch beetle population, which is an "encouraging sign that artificial environmental control will help [*Victory*] to suppress biological attack."[241] If humidity increases because of climate change, it will become harder to maintain controls such as this.

WEATHER UNPREDICTABILITY AND CHANGES IN WEATHER PATTERNS

Unpredictable weather and changes in weather patterns will result in changes to traditional working seasons,[242] such as the typical fitting-out and maintenance season for operational craft. This will not just be in terms of volunteer and staff well-being – such as rising temperatures increasing the likelihood of heat stroke and exhaustion – but also in practical terms: there may simply not be a time of year when the weather can be predicted with enough reliability to ensure that conservation or maintenance work can take place without endangering staff and volunteers or the vessel itself.

This may also impact the annual work plan for a historic vessel. Ten years ago, the driest part of the summer would have been July, August and September, but staff at the tall ship *Glenlee*, in Glasgow, have noticed that now May, June, and July are the driest months, meaning that the annual work plan has had to change, with the team at *Glenlee*

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240 McCormack, 2016, 106.
241 McCormack, 2016, 108.
242 Fluck & Historic England, 2016, 13

trying to get aloft as early in the year as possible. Weather unpredictability has also begun to affect fieldwork in maritime heritage. Historic England has reported that, as of 2016, fieldwork on the *Royal Anne* Galley wreck, off Old Lizard Point, Cornwall, had to be postponed for several successive years due to inclement weather, especially as it is a particularly exposed dive site.[243] *Royal Anne*, launched in 1709, was an eighteenth-century Royal Navy galley frigate, a type of small, fast warship[244] which sank in 1721 in a storm off Lizard Point, killing all of the some 300 crew and passengers bar three, two sailors and a boy.

From a museum perspective, the Dover Museum and Bronze Age Boat Gallery have found that changing weather patterns have made it difficult to maintain a stable relative humidity in the Bronze Age Boat case during the summer months. They tend to rely on building management or heating, ventilation, and air conditioning (HVAC) systems to help regulate temperature and humidity all year round, but this is very expensive both financially and in terms of energy consumption. Finding ways to do this in a more sustainable way is something they are conscious of.

Severe windstorms around the UK have become more frequent in the past few decades, though not above that seen in the 1920s.[245] Wind-driven rain – rain given horizontal velocity by wind[246] – is also a major problem, as it is one of the most important moisture sources affecting facades,[247] especially in coastal areas. It can saturate building fabric, leading to staining and structural damages in the long term.[248] Wind-driven rain can penetrate surfaces which otherwise seem impenetrable.[249] As climate change affects wind speed and the frequency of storms, damage caused by wind-driven range will likely begin to increase and become more apparent. Wind-driven rain is currently a problem in areas which suffer from hurricanes, such as Florida, USA.[250]

ENVIRONMENTAL POLLUTION AND DEGRADATION

Although modern ships are much more likely to unwittingly pollute oceans, such as in incidents of severe oil spills, like the *Exxon Valdez* oil spill of 1989, where 37,000 metric tonnes of crude oil were spilt,[251] historic vessels are not immune to this.

Shipwrecks can physically foul water and fauna, increasing toxicity, and can hinder UV and oxygen entering the water column, through the release of oil. 75% of oil-polluting shipwrecks globally belong in the remit of historic vessels, as they date back to the Second World War. The global risk of marine pollution from 8,500 wrecks worldwide is today

[243] Fluck & Historic England, 2016, 13
[244] Camidge, Johns and Rees, 2006, 13
[245] UKCP09, *The climate of the UK and recent trends*, 2009, 4
[246] http://www.urbanphysics.net/Winddrivenrainbuilding.htm
[247] http://www.urbanphysics.net/Winddrivenrainbuilding.htm
[248] https://www.coreconservation.co.uk/wind-driven-rain/
[249] https://www.faia.com/resources-%281%29/agency-catastrophe-guide/post-storm-information/wind-drive-rain-coverage
[250] https://www.faia.com/resources-%281%29/agency-catastrophe-guide/post-storm-information/wind-drive-rain-coverage
[251] https://evostc.state.ak.us/oil-spill-facts/q-and-a/

considered one of the most significant risks to the global marine environment[252] and the threat of environmental pollution from post-1940 wrecks has become an emerging concern, after the Second World War witnessed history's single largest loss of shipping and was the deadliest conflict the world has ever seen, with an estimated 60 million deaths.[253] An evolving Atlantic, Mediterranean, and Indian Ocean (AMIO) Second World War shipwreck database has catalogued the location and ownership of over 3,950 vessels exceeding 1,000 tons, around 51% of which lie off Britain.[254]

Due to the age of the oil-polluting historic wrecks, naturally occurring corrosion has accelerated the chances of oil discharge, as the majority have been underwater for 75-85 years.[255] In addition to this, ocean acidification due to climate change will further accelerate corrosion, increasing the likelihood and severity of oil pollution from historic wrecks.

The environmental risk from wrecks will increase as the wrecks corrode, which may be increased by ocean acidification, and by collapse, which could surge in the event of severe weather spells and sea temperature rise.

- **FUEL USAGE**

One of the main ways in which humans currently cause climate change is through the burning of fossil fuels. When fossil fuels are burned, they release greenhouse gases into the atmosphere.[256] These gases not only add to global warming, but also to the creation of smog, acid rain, and every other climate issue outlined in this report. Major sources of emissions include cars and trucks, coal-fired power plants, large industrial operations, and ships and planes.[257] Historic vessels which also use fossil fuels contribute to the impact. Fossil fuels provide the fuel for most forms of energy consumption, including heating and electricity.

- **PLASTIC POLLUTION**

Plastic pollution is a form of environmental degradation closely related to climate change. Plastic, just over a century old,[258] is derived from fossil fuels and is not biodegradable, meaning it does not decompose: it simply breaks down into tinier and tinier pieces, known as microplastics.[259] This also means that the first pieces of plastic ever manufactured still exist today, unless they have been burned.[260] This means that plastic waste can quickly accumulate. Furthermore, 40% of the plastic produced annually

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252 Monfils, 2005: 3, 4 in Kingsley, 2016, 186.

253 https://www.nationalww2museum.org/students-teachers/student-resources/research-starters/research-starters-worldwide-deaths-world-war

254 Kingsley, 2016. 184-191

255 Kingsley, 2016. 184-191

256 https://www.epa.gov/nutrientpollution/sources-and-solutions-fossil-fuels

257 https://www.epa.gov/nutrientpollution/sources-and-solutions-fossil-fuels

258 https://www.nationalgeographic.com/environment/habitats/plastic-pollution/

259 https://www.nationalgeographic.org/encyclopedia/great-pacific-garbage-patch/

260 Thompson et al, 2005 in Thompson, 2017, 7

is single-use,[261] meaning that it was designed to be used once, usually for a very brief time, such as a few minutes, and then thrown away, and over 75% of the plastic ever produced is already waste.[262] Because plastic is composed of major toxic pollutants, it also has the potential to cause significant harm to the environment in terms of air, water, and land pollution,[263] as well as to the human body if it enters the food chain. Although research in this area is increasing, there is still little known about the exact impacts on human health, although it is known that many of our food containers, made of foamed plastic, contain styrene and benzene, which are toxic and carcinogenic, and if entering our body as microplastics could adversely impact our respiratory, nervous, and reproductive systems.[264]

Plastic pollution is a particular problem in oceans and waterways, as much of the disposed plastic ultimately ends up in waterways and thus in the ocean, whether by accidentally going overboard when carried by container ships, or from lack of or inadequate recycling structures, as suggested by a recent study by Plastic Patrol, where the majority of litter collected (on land) was actually highly recyclable.[265] Over 80% of the annual input of marine plastic comes from land-based sources, with the remainder coming from plastics at sea, the majority as a result of fishing activities, such as lost and discarded fishing gear.[266] A study modelling mismanaged plastic waste discharged from the land estimated annual inputs to the ocean of 4.8–12.7 million tonnes of plastics globally, 10,000–27,000 tonnes of which was in the UK.[267] Around 70% of all the litter in the oceans is made of plastic.[268] Furthermore, every year an estimated 14 million pieces of plastic enter canals and rivers in the UK.[269] Plastic is present on shorelines, in the water column, in sediments, and in organisms.[270] Most visibly, this can accumulate in enormous patches: for example, the Great Pacific Garbage Patch, also known as the Pacific trash vortex, which is two distinct collections of debris bounded by the massive North Pacific Subtropical Gyre. The patch sits near the surface of the ocean, at a depth of a few centimetres to a few metres, making the vortex's area nearly impossible to measure, although it is located from roughly from 135°W to 155°W and 35°N to 42°N[271] and it is estimated that in the North Pacific Gyre there is a concentration of 18 kg of plastic per km^2.[272] On the ocean floor there is an average estimated 70kg of plastic per km^2 and on beaches globally the concertation is much higher, at 2,000kg/km^2, some of which is

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[261] https://www.nationalgeographic.com/environment/habitats/plastic-pollution/

[262] https://www.wwf.org.au/news/news/2019/wwf-releases-report-on-global-plastic-pollution-crisis

[263] https://www.conserve-energy-future.com/causes-effects-solutions-of-plastic-pollution.php

[264] UNEP, 2013, 14-15.

[265] https://www.circularonline.co.uk/news/single-use-litter-study-a-crucial-wake-up-call-to-us-all/

[266] https://www.eunomia.co.uk/reports-tools/plastics-in-the-marine-environment/

[267] Thompson, 2017, 8.

[268] Thompson, 2017, 4.

[269] https://canalrivertrust.org.uk/news-and-views/features/plastic-and-litter-in-our-canals?utm_source=facebook&utm_medium=social&utm_campaign=plasticschallenge_2020

[270] Barnes et al. 2009; Law & Thompson 2014; GESAMP 2016 in Thompson, 2017, 7.

[271] https://en.wikipedia.org/wiki/Great_Pacific_garbage_patch

[272] https://www.eunomia.co.uk/reports-tools/plastics-in-the-marine-environment/

dropped directly and some of which is washed up.[273] Although it is difficult to accurately make long-term future predications, assuming current habits endure, Jambeck et al. (2015) have predicted a three-fold increase in the amount of plastics in the ocean between 2015 and 2025,[274] while a World Wildlife Fund report has warned that in a business-as-usual scenario, an additional 104 million metric tons of plastic pollution could enter our ecosystems by 2030.[275]

As well as harming marine life by disrupting the food chain and trapping and killing animals and affecting human life through its toxicity, plastic pollution can also be detrimental to ships and smaller vessels. Most obviously, some of the wildlife that is harmed – either by being killed or sub-lethally harmed, such as through comprising their ability to feed or migrate – is commercially important to vessels engaging in fishing. Forty-nine commercially important species, including sardines, herring, hake, whiting, and red mullet have been known to ingest microplastics.[276] For example, in the Firth of Clyde over 80% of the commercially important *Nephrops norvegicus* (Norway lobster, Dublin Bay prawn or sometimes scampi) contained microplastics.[277] Even small quantities of plastic could be commercially damaging, either by damaging stocks or by being perceived negatively by customers.

Plastic litter can also become caught in fishing gear, with an average cost of £1,600 to each Scottish trawler interviewed in a survey.[278] Plastic pollution reduces the amenity value of coastlines, necessitating costly ongoing clean-up operations, all while negatively impacting tourism, with an EU-wide survey demonstrating that 70% of visitors noticed litter on either most or every visit to the coast[279] and that this influenced the locations they chose to visit.[280] It is a hazard for mariners, by impacting navigation or, in more extreme instances, by wrapping around propellers or entering engines, as shown in *A Plastic Voyage*, a Sky documentary about eXXpedition, a group of female scientists who sailed around the UK collecting plastic pollution data and plastic to analyse. A large piece of plastic caused their engine to cut out while leaving port and the sailors commented that they had never seen anything like it before. There are numerous lifeboat call-outs related to entangled propellers. The seriousness of this was highlighted by the sinking of the Ferry M/V *Soe-Hae* in 1993 which was, in part, caused by rope around the propellers, and resulted in 292 deaths.[281]

These hazards will worsen as plastic pollution increases. Marine infrastructure, too, is affected: over 71% of harbours and marinas surveyed in the UK reported that their users

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[273] https://www.eunomia.co.uk/reports-tools/plastics-in-the-marine-environment/
[274] Jambeck et al., 2015 in Thomspon, 2007, 13
[275] Wijnand de Wit, Adam Hamilton, Rafaella Scheer, Thomas Stakes, and Simon Allan for WWF, 2019, 9.
[276] Kuhn et al. 2015; GESAMP 2016 in Thompson, 2017, 19
[277] Murray & Cowie 2011 in Thompson, 2017, 19
[278] Mouat et al., 2010 in Thompson, 2017, 19
[279] Hartley et al. 2013 in Thompson, 2017, 21
[280] Brouwer et al. 2015 in Thompson, 2017, 21
[281] Cho 2005 in Thompson, 2017, 19

had experienced "entangled propellers, entangled anchors, entangled rudders and blocked intake pipes and valves" and the total annual cost of removing litter from 34 UK harbours was estimated at approximately £236,000.[282] Based on this, it has been estimated that marine litter costs the ports and harbour industry in the UK approximately £2.1 million each year.[283] In Europe, cleaning plastic waste from coasts and beaches costs about €630 million per year and studies suggest that the total economic damage to the world's marine ecosystem caused by plastic amounts to at least $13 billion every year.[284] The future costs of removing all single-use plastics accumulating in the environment is estimated by the UN to be higher than the cost of preventing littering today.[285] The economic damage caused by plastic waste is vast.

Plastic waste can have knock-on effects, for example if plastic bags block waterways this can exacerbate natural disasters like flooding. The only way to eliminate plastic is to burn it, and this results in carbon dioxide emissions. By 2030, carbon dioxide emissions from incineration of plastics may triple.[286] Such emissions are damaging to the natural world, contributing to global warming and environmental degradation, and are also detrimental to human health, as incineration not only releases carbon dioxide, but also toxic gases, halogens, and nitrous and sulphur oxides, all of which affect air quality.[287] Poorly regulated incineration or open burning have been shown to heighten respiratory ailments, increase the risk of heart disease, and damage the human nervous system.[288]

- **OVERFISHING**

Catching fish has always been part of human history. However, when vessels catch fish faster than stocks can replenish, in a process known as 'overfishing', fishing becomes damaging to the environment. According to the Food and Agriculture Organization of the United Nations, the number of overfished stocks globally has tripled in half a century and today fully one-third of the world's assessed fisheries are currently pushed beyond their biological limits.[289] Overfishing will result in extreme marine degradation, ultimately resulting in extinction of certain species and harming the billions of people globally who rely on fish for food and who have fishing as their principal livelihood.

INDIRECT IMPACTS

Indirect impacts are the human actions undertaken to adapt to or mitigate the direct impacts, which ultimately also influence the fabric and/or setting of heritage assets. They can be a consequence of decisions taken now by managers anticipating future change or

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282 Thompson, 2017, 21.
283 Mouat et al. 2010 in Thompson, 2017, 21.
284 European Commission, 2015 in UNEP, 2018, vii.
285 UNEP, 2018, 16.
286 WWF, 2019, 9.
287 WWF, 2019, 15.
288 WWF, 2019, 15.
289 https://www.worldwildlife.org/threats/overfishing

can be impacts related to attempts at climate change mitigation, such as the expansion of the renewable energy sector.[290] The decisions and changes made are impacted by commitment and predominantly by economic factors.

These include:[291]

- The addition of renewable energy sources and generation of sustainable energy
    - For example, it has been suggested that increased wave action and energy will increase the ability of sea water to corrode iron and steel. This could be caused by the presence of wind farms and their high voltage transmission power cables. These cables are not only present near wind farms but could also run undersea from the mainland to islands, or could be running besides rivers and canal banks, or crossing over them, supported by pylons.
    - Similarly, there is some evidence to suggest that the presence of high voltage transmission power cables and their electromagnetic fields could alter sea water composition, resulting in increased oxygen levels or microbe growth leading to metal corrosion.
    - Historic England states that it "supports measures to reduce fuel consumption, increase energy efficiency and exploit renewable energy source" and is seeking to reduce the environmental impact of its own activities. However, it also "recognises that some renewable energy technologies have the potential to cause serious damage to irreplaceable historic sites, which are themselves an integral part of the wider environmental and sustainability agenda."[292] Therefore, it is important that renewable energy balances the benefits it delivers with the environmental costs in carries. Historic England believes that this can be achieved by:[293]
        - Considering the cumulative effects of projects.
        - Considering their specific impacts.
        - Ensuring that the implications of renewable energy developments are adequately reflected in national, regional, and local planning policy and at all stages of the environmental impact assessment process.
        - Achieving a sound understanding of the character and importance of the historic asset involved, whether at the scale of individual buildings and sites or more extensive historic areas and landscapes, to achieve high-quality designed projects.
    - Historic England also suggests that "given the rapidity with which renewable energy technologies are evolving, renewable energy projects and their associated infrastructure should aim to be reversible where possible."[294]

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[290] Murphy, Pater, and Dunkley, 2008, 18.
[291] https://historicengland.org.uk/research/current/threats/heritage-climate-change-environment/impacts-climate-change/
[292] https://historicengland.org.uk/advice/planning/infrastructure/renewable-energy/
[293] https://historicengland.org.uk/advice/planning/infrastructure/renewable-energy/
[294] https://historicengland.org.uk/advice/planning/infrastructure/renewable-energy/

- The enhancement of flood resistance measures and building of flood and coastal defences.
    - For example, steel sheet pilings, which are increasingly being used to prevent coastal and riverbank erosion, possibly emit stray electric currents, causing corrosion to steel and other metals nearby.
    - In areas where coastal defences are to be strengthened or enhanced, there can also be both an aesthetic and a physical impact upon historic features.[295]
    - Where defences are not properly maintained, the loss of historic structures may be inevitable[296] - installing flood defences is not the end point.
    - For example, the breakwater barriers built in Agropoli in the Italian province of Salerno led to the proliferation of the *Posidonia oceanica* algae, which has negative consequences on the marine biodiversity of the area.[297]
- The management of coastal retreat.
- Pro-active changes in land management and environmental stewardship.
    - Many of the exotic hardwood timbers traditionally used in UK boatmaking have been heavily logged, resulting in severe ecological decline and climate change through deforestation, causing strict controls on logging. For example, Cuban Mahogany was so heavily logged that trade in it almost completely halted and shifted to Honduran Mahogany. Both are now CITES Appendix II and IUCN Red List, so trade is now very rare and strictly controlled. This is a positive environmental initiative but restrictions such as this can make 'like for like' fabric replacements in historic vessel conservation projects very difficult to achieve.
    - It is important to consider the carbon footprint of timber used in UK boatbuilding, maintenance, and conservation. UK timber stocks are small, particularly for old growth timber and what is now produced here is grown faster than it used to and therefore is often not of good enough quality. This leads to less exotic or previously unused species being frequently imported from Europe, Scandinavia or further afield, with associated climate impacts.
    - Reforestation projects in the UK cannot grow fast enough for the need, solving problems not now but in 100 years' time.
- Changes to buildings to improve comfort, safety and/or running costs.
- Improving the energy efficiency of buildings and vessels.[298]

CONCLUSION

This volume has provided an explanation of what climate change is, how it has evolved and the likely predictions for the UK. It has given an overview of the science and made clear the

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[295] Fluck & Historic England, 2016, 37.
[296] Fluck & Historic England, 2016, 37.
[297] Sesana et al., 2019, 163
[298] https://historicengland.org.uk/research/current/threats/heritage-climate-change-environment/reponses/

effects that are already taking place, which will likely worsen as the century progresses. It has recognised the scale of the challenge we are collectively facing and has sought to break down those aspects of climate change most relevant to the historic vessel sector so as to demonstrate the impacts likely to affect the craft in our care. The case studies within the Direct Impacts section leave no doubt of the extent to which any one of these changes could affect our surviving historic vessels, with catastrophic results.

Volume Two of this Report looks at how best to use this information to safeguard significant heritage assets. It offers ways in which we can mitigate the effects of climate change and adapt to aspects which we can't alter. It shows that historic vessels can be part of the solution to the problem we are facing, leading the way to educate the wider population, raise awareness, reduce plastic pollution and marine degradation, re-using materials and maintaining traditional skills, as well as gathering data on the pace of climate change. It offers guidance on how to handle carbon emissions, forward plan and adopt green principles in all future projects.

Both volumes mark an important step forward in the climate change journey for maritime heritage in the UK, offering the first specialised paper addressing the likely impacts on the historic vessel sector and identifying positive actions that can be taken to counter and manage these as we move ahead.