Severn Estuary Commission

Climate Baseline, Future Projections and Recommendations

Technical Note

WSP UK Limited – October 2024

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Introduction

Background

Estuaries and their surrounding wetlands are bodies of water usually found where rivers meet the sea.[1] Being home to unique plant and animal species that have adapted to brackish water, estuaries are delicate ecosystems. Estuary communities are especially vulnerable to future changes in climate variables such as rising sea-levels, increases in storm surge heights, changing precipitation and temperature patterns and others.

The environment of the Severn Estuary is one of the most dynamic in the UK, with changes in sea level, waves and storms all playing their part in shaping this coastline. Historical records show that severe storms have caused coastal erosion and flooding, however, extreme weather events are becoming more and more frequent. One of the biggest threats to the Estuary is from rising sea levels which, coupled with significant storm events, exacerbate the effects of coastal erosion and flooding.[2]

Purpose of the study

This study intends to assess the future changes in climate variables such as precipitation, temperature, sea level rise, storms and storm surges, that could have a material impact on the environmental conditions within the Severn Estuary. This will include:

- A current baseline study of the relevant climate variables over the past few decades corresponding to the geographical location of the estuary. This will include historic extreme weather events that have affected the area.
- A study of future changes in climate variables for the time periods of 2030s (2021-2050), 2050s (2041-2070) and 2080s (2071-2100) for the estuary's location.
- A list of conclusions and recommendations paving way for further research on impacts of climate change on the estuary.

Key sources

This study derives its data from the Met Office UK climate averages[3], IPCC WGI Interactive Atlas[4] , Climate Risk Indicators (CRI)[5] and other data sources. Where climate projection data was not available and to support the identification of climate impacts, a literature review was undertaken. Other open access, publicly available sources have been used for gathering information on extreme weather events that have affected the estuary, particularly over the last few decades.

[1] NOAA. (n.d). What is an estuary? [Online] Available at: https://oceanservice.noaa.gov/facts/estuary.html

[2] Severn Estuary Partnership. (n.d.) Climate Change [Online] Available at: https://severnestuarypartnership.org.uk/the-estuary/environmental-quality/climate-change/#:~:text=One%20of%20the%20biggest%20threats,%2C%20engineers%2C%20and%20local%20communities.

[3] Met Office. (2022). UK Climate Averages [Online] Available at: https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-averages

[4] IPCC. (2021). IPCC WGI Interactive Atlas. [Online] Available at: https://interactive-atlas.ipcc.ch/

[5] Nigel Arnell. (2021). The Climate Risk Indicators. Available at: https://uk-cri.org/

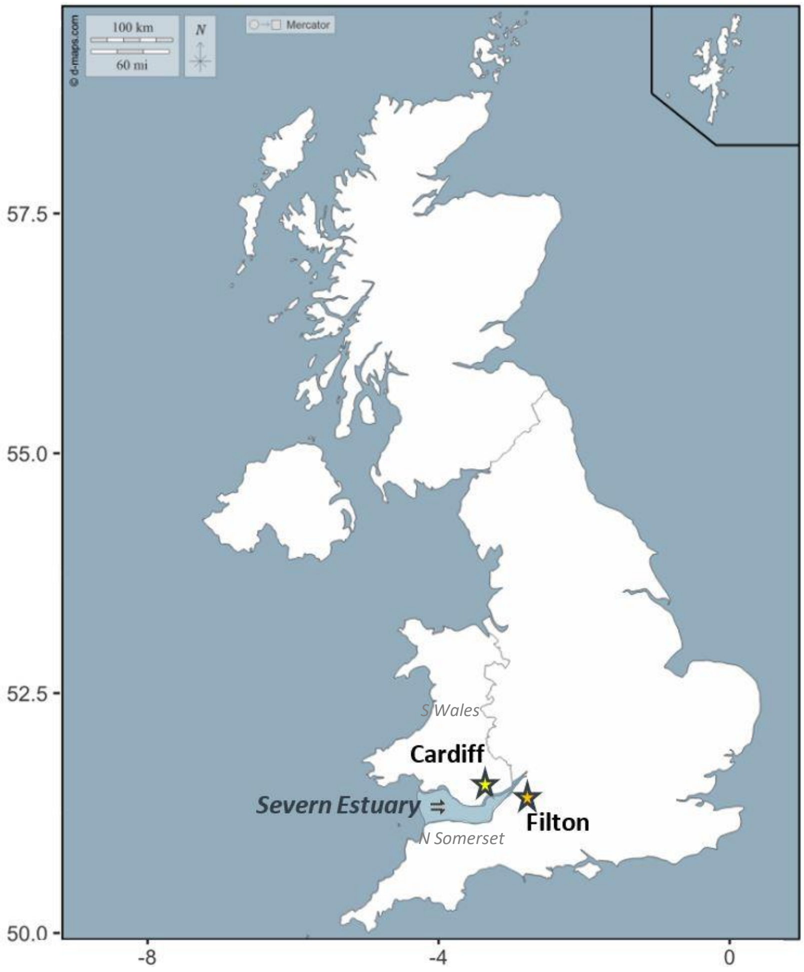
Current Climate Baseline

The marine environment of the Severn Estuary is one of the most dynamic in Europe. Severe storms have caused coastal erosion and flooding of the area over the years. The local weather around the Severn Estuary is influenced by the wider coastal environment it experiences. The ocean brings cool winds in summer and mild winds in winter, keeping the estuary at a relatively mild temperature year-round.

The climate within the Severn Estuary, along with much of the UK, is classified as an 'Oceanic' climate within the Köppen-Geiger Climate classification system. This system defines different climate zones across the globe, for example, tropical, arid, polar and continental. Characteristics of the Oceanic zone (Cfb) include cool winters and warm summers, with year-round rainfall.[6]

The nearest weather stations to the estuary are Cardiff and Filton, as shown in **Figure 1**. The current climate baseline data in this section has been presented primarily based on data from these two weather stations over the period of 1991-2020.

Figure 1 - Location of Cardiff and Filton weather stations in the UK



[6] Severn Estuary Partnership. (n.d.) Weather and Climate [Online] Available at: https://severnestuarypartnership.org.uk/the-estuary/environmental-quality/weather-and-climate-change/

Climate variables

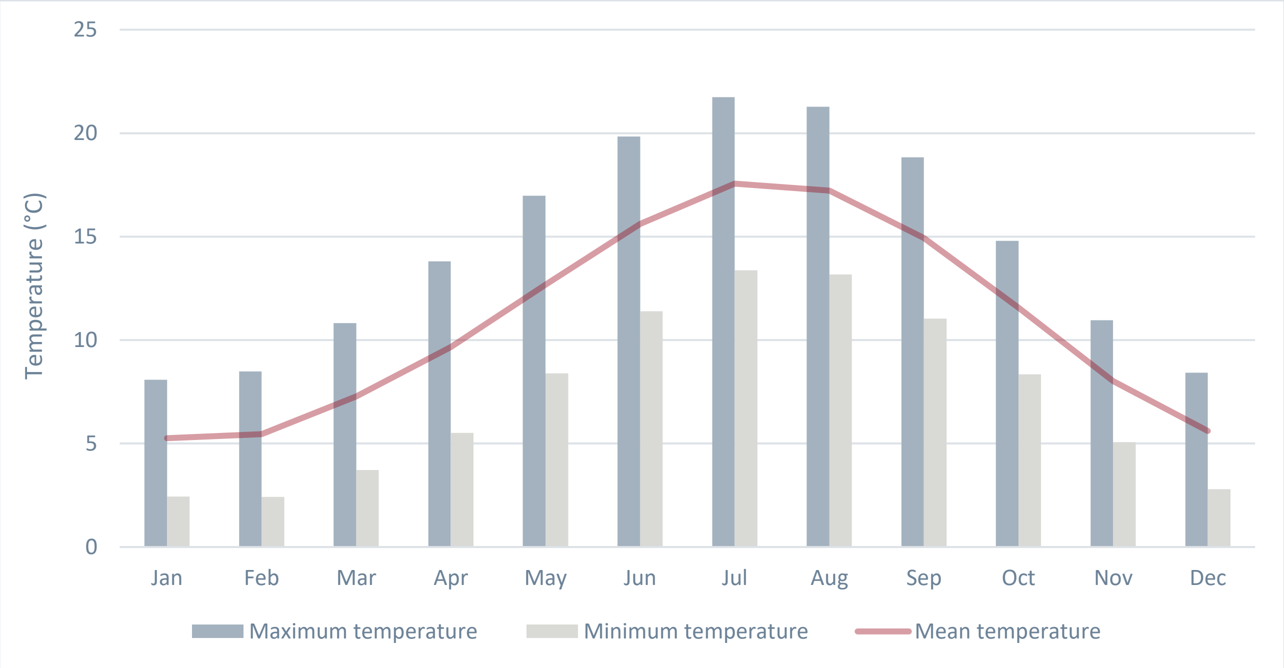
Temperature

Land temperature

With climate change, average UK land air temperature has risen in recent years. 2023 was the second warmest year on record for the UK in the series from 1884, with only 2022 warmer.[7] The coastline of the Severn Estuary has experienced this increase in temperature as well. Winter temperatures in the Severn Estuary have increased between 1.4 and 2.2°C. Summer temperatures have increased between 1 and 1.8°C.[8] The annual temperature range of the estuary is relatively mild, with warm summers and cool winters.

At the Filton weather station (South Gloucestershire), the average maximum temperature is around 14.5°C, compared to 14.9°C at the Cardiff weather station. The minimum temperature for Filton and Cardiff is 7.3°C and 7.2°C on average. Maximum temperatures across the Severn Estuary region tend to peak around June to August which can be seen in **Figure 2** and **Figure 3**.

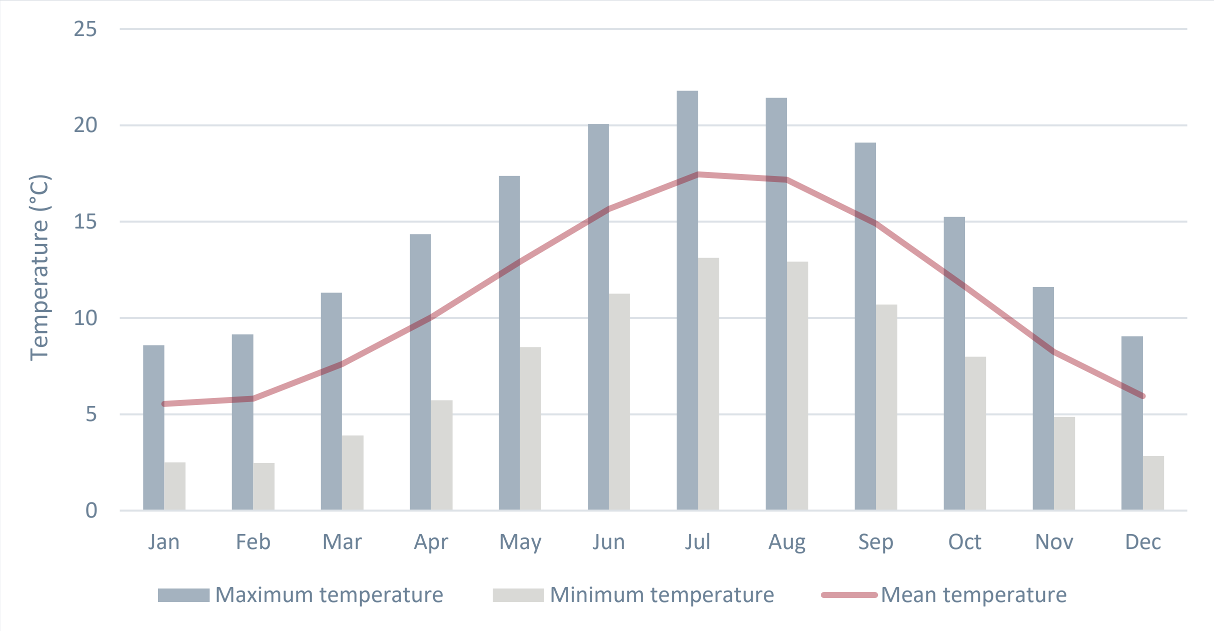
Figure 2- Long-term average monthly maximum, minimum and mean temperatures for Filton weather station over the baseline period (1991-2020)



[7] Met Office. (2024). State of the UK Climate 2023 [Online] Available at: https://www.metoffice.gov.uk/research/climate/maps-and-data/about/state-of-climate

[8] Severn Estuary Partnership (2015) Climate Change Report Card 1 [Online] Available at: https://severnestuarypartnership.org.uk/wp-content/uploads/sites/2/2015/10/ClimateChangeReportCard1.pdf

Figure 3 - Long-term average monthly maximum, minimum and mean temperatures for Cardiff weather station over the baseline period (1991-2020)



Sea surface temperature

The sea surface is the boundary between the ocean and atmosphere. The UK coastal sea surface temperature has increased by about 0.7°C over the past three decades.[9] As per IPCC's WGI Interactive Atlas, the long-term average sea surface temperature for the region corresponding to Severn estuary is 7.7°C over the baseline period of 1995 to 2014.[10] These temperatures are higher upstream than they are downstream (e.g. ranging between 11-13.5°C in 2006).[11]

Sunshine hours

The west of Britain is a relatively sunnier place than most of the UK. Sunshine hours across South-west England and South Wales tend to peak from May to July. The average annual sunshine hours for Filton and Cardiff weather stations have been recorded as 1,658 and 1,572, respectively, over the baseline period.

Precipitation

Rainfall

All regions of the UK, including the Severn Estuary, have experienced an increase in heavy winter precipitation events in the past few decades. However, extreme summer precipitation events have decreased.

[9] Robins P. et al. (2016) Impact of climate change on UK estuaries: A review of past trends and potential projections. Estuarine, Coastal and Shelf Science [Online] Available at: [Impact of climate change on UK estuaries: A review of past trends and potential projections - ScienceDirect]

[10] IPCC (2021) IPCC WGI Interactive Atlas: Regional Information (Advanced) [Online] Available at: https://interactive-atlas.ipcc.ch/

[11] NEODASS (2006), in MCCIP (2008) Marine Climate Change Impacts Annual Report Card 2007-2008, Summary Report, MCCIP, Lowestoft.

The UK's west coast experiences more rainfall than the east coast, because of the prevailing south westerly winds driving from across the Atlantic – the Severn Estuary is no exception, with South Wales and North Somerset being the rainiest places within the estuary. Further eastwards, Bristol and Gloucestershire are drier.[12] The months of October to January see the most rainfall, whereas April to June are the driest months. **Table 1** presents the long-term average seasonal and annual rainfall for Filton and Cardiff weather stations over the baseline period.

Table 1 - Long-term average seasonal and annual rainfall (mm) for Filton and Cardiff weather stations over the baseline period (1991-2020)

Season	Filton weather station	Cardiff weather station
Winter	230.1 mm	359.5 mm
Summer	190.1 mm	261.9 mm
Annual	819.0 mm	1203.3 mm

Snow and ice

Precipitation falls as snow when the air temperature is below 2°C and there is moisture in the atmosphere.[13] The average number of days with snow lying on ground for both Cardiff and Filton weather stations range between 5 to 10 days per year over the baseline period of 1991-2020.

Frost

Ground frost refers to the formation of ice on the ground, objects or trees, whose surface have a temperature below the freezing point of water. Over the baseline period of 1991-2020, for both Cardiff and Filton weather stations, the average number of days of ground frost range between 60 to 80 annually. An air frost occurs when the air temperature falls to or below the freezing point of water.[14] The annual average number of air frost days for both these stations is 32.9.

Sea level

Sea level rise

The landmass of the UK has been naturally shifting over the past 4,000 years.[15] The northwest of Scotland is rising relative to sea level while the southeast of England is sinking. This process is termed as isostatic adjustment. Locally, the southwest of the UK, which includes the Bristol Channel and Severn Estuary, has been sinking at a rate of 0.6 to 0.9 mm per year.[16]

UK relative sea level rose by about 1mm per year during the 20th century, but this rate increased during the 1990s and 2000s.[17] The tide gauge data for the Bristol Channel and Severn Estuary over a 15-year time period (1993 to 2007) indicated that there had been a rise in mean sea levels.

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[12] Severn Estuary Partnership. (n.d.) Weather and Climate [Online] Available at: https://severnestuarypartnership.org.uk/the-estuary/environmental-quality/weather-and-climate-change/

[13] Met Office. (n.d.) How does snow form? [Online] Available at: https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/snow/how-does-snow-form

[14] Met Office. (n.d.) What is frost [Online] Available at: https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/frost-and-ice/frost#:~:text=Frost%20occurs%20when%20the%20temperature,air%20frost'%2C%20respectively).

[15] Shennan I and Horton B (2002) Holocene land- and sea-level changes in Great Britain, Journal of Quaternary Science, Wiley and Sons Ltd

[16] MCCIP (2010) Marine Climate Change Impacts Partnership Annual Report Card 2010-11, Summary Report, MCCIP, Lowestoft

[17] Severn Estuary Partnership (2015) Climate Change Report Card 1 [Online] Available at: https://severnestuarypartnership.org.uk/wp-content/uploads/sites/2/2015/10/ClimateChangeReportCard1.pdf

The mean sea level pressure in Southern England, including the Severn Estuary area, is between 1014-1016 hPa over the baseline period.

Waves

Waves themselves, or (more often) in combination with strong winds, high tides or storm surges, can cause coastal erosion and damage to infrastructure. Breaches of defences can lead to major flooding incidents.[18]

It has been reported that wave heights in the North Atlantic have increased post 1960s.[19,20] Increases in monthly mean and maximum wave height in the north-eastern Atlantic occurred between 1960 and 1990; however, this rise in wave height may be part of long-term natural variability. This is because natural variability in wave climate is large, and the role of human influence is still very unclear.[21] There has been no clear pattern of change in wave height since 1990.

Wind

Storms

Severe windstorm trends around the UK are difficult to identify for reasons such as low numbers of such storms, their decadal variability, unreliability and lack of direct wind speed observations. Some research has shown that although man-made factors have influenced sea level pressure distributions (and hence atmospheric circulation patterns) over the second half of the 20th century, there continues to be a high degree of uncertainty associated with research on the recent increase in storminess over the UK.[22]

Over the baseline period, the long-term average seasonal and annual wind speed values (at 10 m) for Filton weather station are presented in **Table *2***. Corresponding data is unavailable for Cardiff.

Table 2 - Long-term average seasonal and annual wind speed (knots) for Filton weather stations over the baseline period (1991-2020)

Season	Mean wind speed (at 10 m)
Winter	9.0 knots
Summer	7.9 knots
Annual	8.4 knots

Storm surges

Significant damage to coastlines can be caused by storm surges (or tidal surges) which are flows of higher than normal sea level that can flood coastlines.[19] They are usually caused when low atmospheric pressure occurs together with driving winds and high tides. These events, whilst rare

[18] Severn Estuary Partnership (2015) Climate Change Report Card 2 [Online] Available at: https://severnestuarypartnership.org.uk/wp-content/uploads/sites/2/2015/10/ClimateChangeReportCard2.pdf

[19] Lowe, J.A. et al., (2009) UK Climate Projections science report: Marine & Coastal Projections, Met Office Hadley Centre, Exeter, UK © Crown copyright

[20] Wolf J and Woolf D K (2006) Waves and climate change in the North-east Atlantic, Geophysical Research Letters, 33, in MCCIP Annual Report Card 2007-2008 Scientific Review – Storms and Waves

[21] Osborn T J (2004). Simulating the winter North Atlantic Oscillation: the roles of internal variability and greenhouse gas forcing. Climate Dynamics, 22, 605-623 in Woolf D and Wolf J (2010) Storms and Waves in MCCIP Annual Report Card 2010-11, MCCIP Science Review

[22] Gillett N P and Thompson D W J (2003) Simulation of recent southern hemisphere climate change, Science, October 2003 Vol. 302 No. 5643

on the estuary in their extreme form, can overtop or breach sea defences and cause flooding and erosion depending on the weather conditions at the time.[18]

Extreme weather events

Examples of extreme weather events that have affected the Severn Estuary and its surrounding area have been listed below:

- In February 2022, Storm Eunice hit parts of the UK bringing gusts up to 90 mph in Southwest England and South Wales. Ten severe flood warnings were issued for the Severn Estuary as strong winds could combine with high spring tides and lead to coastal flooding.[23]
- In April 2019, Storm Hannah brought some very strong winds with locations along the coast of South Wales recording gusts of over 60 Kt. The storm centred in the Irish sea before tracking eastwards across England, bringing very strong winds to exposed western coastal areas.[24]
- In June 2011, a mild tsunami hit the Cornish coast shifting water levels in a short span of time. Landslide at sea was the likely cause of this surging wave along the south coast.[25]
- In March 2008, severe storms were experienced along the South Wales coast causing disruption to transport and power supplies. Because of these, damage to property was caused along the Somerset coast as well. The combination of strong winds, low pressure and a high tide, resulted in coastal flooding at several locations on the south coast.[26]
- During the years 1981, 1984 and 1990 there were significant storm surges which caused substantial damage and flooding along the coast of Somerset and some coastal flooding over low lying areas of Southeast Wales. Notable storms also occurred in 1996, 2008 and 2010, all of which caused damage along exposed coastlines of Somerset and some limited coastal damage and flooding in South Wales.[27]

Wider UK Context

According to the latest State of the UK Climate Report 2023[28], the UK's climate is changing, with recent decades warmer, wetter, and sunnier than the 20th century on a national and local scale. This report highlights that the UK land temperatures have warmed by 1.25°C compared to 1961-1990, which is at a broadly consistent, though slightly higher, rate than the observed change in global mean land temperatures (1.15°C). The key findings from the report are:

- Six of the 10 years in the most recent decade (2014–2023) have been in the top-ten warmest for the UK.
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[23] BBC. (2022). Storm Eunice heads for UK and prompts danger to life warning [Online] Available at: https://www.bbc.com/news/uk-60417263

[24] Met Office. (2019). Storm Hannah 26 to 27 April 2019 [Online] Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2019/2019_005_storm_hannah.pdf

[25] National Oceanography Centre. (2016). Coastal Flooding, 1607 Floods, recent Storm Surges and Weather Events in the Severn Estuary [Online] Available at: https://www.slideshare.net/slideshow/2011-04-coastal-flooding-1607-floods-recent-storm-surges-and-weather-events-in-the-severn-estuary-kevin-horsburgh/57567181#24

[26] Met Office. (2012). Strong winds 10-12 March 2008 [Online] Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2008/strong-winds-10-12-march-2008---met-office.pdf

[27] Severn Estuary Partnership (2015) Climate Change Report Card 5 [Online] Available at: https://severnestuarypartnership.org.uk/wp-content/uploads/sites/2/2015/10/ClimateChangeReportCard5.pdf

[28] Kendon, M. et al. (2024). State of the UK Climate 2023. *International Journal of Climatology 44(S1) pp/1-117.* DOI 10.1002/joc.8553. https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.8553

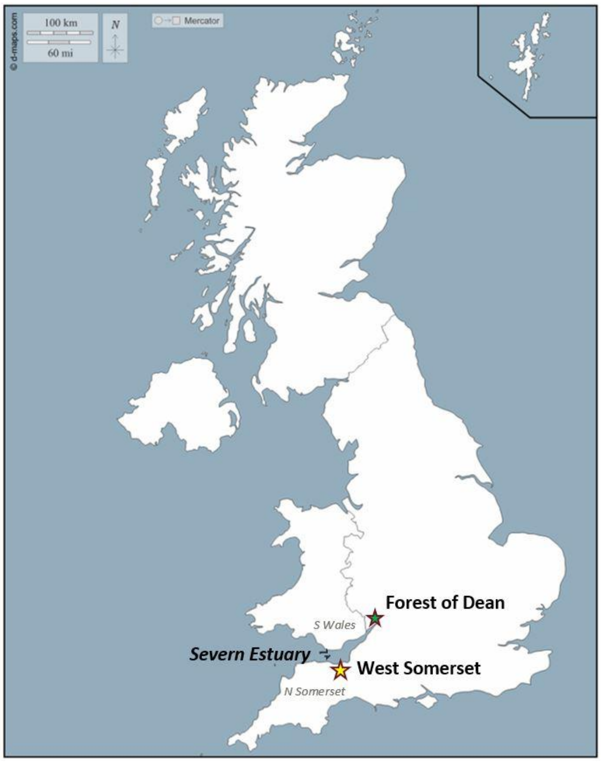
- 2023 was the second warmest year on record; the mean temperature for 2023 was 9.97°C, which is 0.83°C above the 1991–2020 long-term average.
- In terms of the highest maximum temperatures, the most recent decade (2014–2023) was 35.6°C, 2.1°C higher than 1991–2020 and 4.3°C higher than 1961–1990, showing greater increases in extremes than when comparing the changes in annual means.
- The UK's average lowest minimum temperature for the most recent decade 2014–2023 was −14.6°C, 0.9°C higher than 1991–2020 and 4.4°C higher than 1961–1990.
- The number of 'warm days' (daily maximum temperatures above 25°C) have increased by 63% for the most recent decade (2014 – 2023) compared to 1961-1990 and 'very hot days' (daily maximum above 30°C) have trebled, again showing greater increases in the trends for extreme events.
- The most recent decade (2014-2023) has had 6 fewer days of air frosts and 11 fewer days of ground frosts when compared with 1991-2020 and 17/28 fewer air/ground frost days when compared to 1961-1990.
- Increasing temperatures has resulted in annual Growing Degree Days to be 6% higher than 1991–2020 and 21% higher than 1961–1990. This is also observable through the downward trend in Heating Degree Days and upward trend in Cooling Degree Days.
- Increasing temperatures are also observed within the data for the annual mean sea-surface temperature (SST) for 2023 near-coast waters around the UK, demonstrating a 1.3°C increase above the 1961–1990 long term average making this the UK's warmest year for near-coast SST in a series from 1870 for the second successive year.
- The UK's annual precipitation shows large annual variability inherent to the UK climate, with some decadal variability. Two years in the most recent decade (2014–2023) have been in the top-ten wettest, and there has been a marked increase in winter rainfall in the last few decades coupled with a slight increase in autumn rainfall.
- The number of days of rain greater than or equal to 10 mm ('very wet days') for the UK during 2023 was 41 days. This was 6 days more than the 1991–2020 long term average. This suggests an increase in the number of days of widespread heavy rain in the last few decades, however caution is needed in this interpretation due to the large annual and decadal variability in UK rainfall.
- Summer rainfall has increased, coupled with a slight increase in spring rainfall. There is no obvious reducing trend in the occurrence of top-ten driest months, seasons or years in the last three decades.
- Three years in the most recent decade 2014–2023 have been in the top-ten sunniest in the UK series; and this is the sunniest 10-year period.
- Despite the warming climate, impactful snow events are still to be expected but their number and severity have declined since the 1960s.
- There is a marginal downward trend of annual mean wind speeds, falling from ~18.5km/h in 1970 to ~17km/h in 2023.
- A measure of 'storminess' can record large-scale systems affecting the UK; with the most recent decades recording fewer occurrences of maximum gust speeds as a factor of 'storminess', however it is difficult to infer trends due to considerable annual and decadal variations.
- Since the beginning of the 20th century, sea levels in the UK have risen by about 1.5mm/year, but observational evidence suggests the rate is increasing which is consistent with estimate of global sea level rise.

- There were 16 extreme storm-surge events in 2023, however it is difficult to discern trends due to the number of factors that affect extreme sea level in the UK namely a combination of storm surges, waves, tides and the mean sea level.

Future Climate Projections

Changes to the local climate of the Severn Estuary will have impacts on its social, economic and natural environment, and it is important to understand these changes for effective climate risk management. The UKCP18[29] probabilistic projections have been used to infer future changes in a range of climate variables that may affect the Severn Estuary. The Climate Risk Indicators (CRI),[30] developed as part of the UK Climate Resilience Programme have been used in this assessment.[31] The CRI utilises the UKCP18 projections and allows for a range of climate related indicators (including but not limited to, Met Office Heatwaves and heat stress). Data has been extracted from the CRI Explorer for two representative local authority areas of 'Forest of Dean' and 'West Somerset' (**Figure 4**) corresponding to the time periods of 2030s (2021-2050), 2050s (2041-2070) and 2080s (2071-2100) for RCP4.5 and RCP8.5.[32] Additionally, a summary of relevant UKCP09 climate projections has been included in this report. However, it should be noted that much of this data was not incorporated into the most recent climate projections (UKCP18).

Figure 4 - Location of Forest of Dean and West Somerset Local Authority Areas



[29] Met Office. (2018). UKCP Data. Available at: https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/data/index

[30] Nigel Arnell. (2021). The Climate Risk Indicators. Available at: https://uk-cri.org/

[31] There are inherited limitations and uncertainties within the data. Further information on the methodology used to produce this data can be found in Arnell, et al., (2021) Changing climate risk in the UK: a multi-sectoral analysis using policy-relevant indicators. Climate Risk Management 31, 100265 10.1016/j.crm.2020.100265

[32] Representative Concentration Pathways (RCP) are climate change scenarios to project future greenhouse gas concentrations. RCP4.5 is described by the IPCC as an intermediate scenario. RCP 4.5 IS likely to result in global temperature rise between 2°C and 3°C. RCP8.5 is generally taken as the basis for worst-case climate change scenarios with global Severn Estuary Partnership (2015) Climate Change Report Card 1 [Online] Available at: https://severnestuarypartnership.org.uk/wp-content/uploads/sites/2/2015/10/ClimateChangeReportCard1.pdf temperatures likely to rise by over 4°C.

Change in climate variables - Land

UKCP18 projections

The climatic conditions for Severn Estuary have and will continue to change over the century. Climate change is projected to lead to warmer wetter winters and hotter drier summers, with an increase in the intensity and frequency of extreme events such as heatwaves, drought, extreme rainfall leading to flash flooding, storms and wind events.

The average rainfall in winter months alongside the number of wettest months of year will witness a significant rise. The rainfall in the summer months, are predicted to decline under both scenarios. When viewed in conjunction with the projected increase in average summer temperature, the summers may be expected to be hotter and drier. The winters may get wetter with a significant rise in average rainfall predicted across the two scenarios.

Both the climate change scenarios predict a steady rise in the occurrence of heatwaves considering a threshold of 25^{o}C. This is also reinforced by the predictions for increasing heat stress, more significantly in the RCP8.5 scenario, predicting a stark increase from the 2050s to the 2080s.

Based on the current climate baseline and the future climate projections, the climate trends for the site are summarised in **Table 3.** The level of confidence in the climate science and projection data is provided for each time period.

Table 3 - Climate trends and land-based hazards for the Severn Estuary

Climate Parameter	Climate Trend	Data Confidence			Hazards
		Conf 2030s	Conf 2050s	Conf 2080s	
Sea Level Rise	Increased mean sea level and high tides	High	High	High	Coastal and inland flooding
		High	High	High	Coastal erosion
		High	High	High	Higher water table
		High	High	High	Saline intrusion and/or salt spray exposure
Precipitation	Increased number of dry days and decreased precipitation (summer)	Moderate	Moderate	High	Dry soil hardening, cracking and destabilisation
		High	High	High	Heatwaves
		High	High	High	Wildfire
		Moderate	Moderate	High	Reduced water availability
	Increased frequency, volume and duration of extreme precipitation events (winter)	Moderate	Moderate	High	Heavy Rainfall
		Moderate	Moderate	High	Soil destabilisation, landslips, landslides or subsidence
		Moderate	Moderate	High	Surface water flooding (and standing water)
Wind	Increased intensity of wind and storm activity	Low	Low	Low	High winds
		Low	Low	Low	Lightning and lightning strikes

Climate Parameter	Climate Trend	Data Confidence			Hazards
		Conf 2030s	Conf 2050s	Conf 2080s	
Temperature	Increased frequency and intensity of hot spells (summer)	High	High	High	Hot days (and nights)
	Decreased frequency, volume and duration of cold days/snow/ice events (winter)	High	High	High	Low temperature days (with snow/ice)

Table 4 and **Table 5** provide climate projections based on CRI data for relevant climate variables for the local authority areas of Forest of Dean and West Somerset, respectively. The projections are provided against the model reference period of 1981-2010 and the baseline period of 1991-2020. The tables shows the 50th percentile (10th percentile to 90th percentile) values. The information presented below illustrates how the climate may evolve across the Severn Estuary by the end of the century. The data for Model Reference time period (1981-2010) was not available for select climate variables.

Table 4 - Climate Baseline and 50th percentile Projections (Anomalies) for Forest of Dean local authority area for the 2030s, 2050s and 2080s for RCP4.5 and RCP8.5. Numbers in brackets represent the 10th and 90th percentile range of the inter-model spread.

Climate variable	Model Reference*	Baseline*	CMIP5 projections (Changes from the baseline) for RCP4.5			CMIP5 projections (Changes from the baseline) for RCP8.5		
	1981-2010	1991-2020	2030s	2050s	2080s	2030s	2050s	2080s
Mean Annual Temperature (Change ºC)	10.8	11.1	0.8 (0.4; 1.4)	1.3 (0.6; 2.1)	2.3 (1.2; 3.4)	1.1 (0.5; 1.7)	2.0 (1.1; 2.9)	3.8 (2.2; 5.4)
Maximum Summer Temperature (Change ºC)	21.0	21.1	1.2 (0.3; 2.2)	2.0 (0.6; 3.5)	3.6 (1.3; 5.8)	1.6 (0.5; 2.7)	3.0 (1.1; 4.8)	5.8 (2.6; 9.2)
Minimum Winter Temperature (Change ºC)	2.4	2.6	0.7 (0.02; 1.5)	1.2 (0.2; 2.2)	1.8 (0.5; 3.3)	0.9 (0.2; 1.7)	1.6 (0.5; 2.9)	3.0 (1.2; 5.1)
Cold weather alert (events/year)	2.8	2.7	1.8 (1.3; 2.2)	1.5 (1.0; 2.0)	1.2 (0.6; 1.8)	2.1 (1.6; 2.6)	1.6 (1.0; 2.3)	1.0 (0.5; 1.8)
Frost days (days/year)	42.5	40.8	33.6 (26.9; 40.5)	28.8 (20.7; 37.6)	22.4 (13.2; 33.2)	31.6 (24.4; 39.0)	24.2 (15.8; 34.5)	14.8 (6.8; 27.3)
Met Office Fire Danger- exceptional (days/year)	0.03	0.04	0.09 (0.02; 0.3)	0.1 (0.02; 0.5)	0.4 (0.05; 2.4)	0.1 (0.02; 0.4)	0.2 (0.03; 1.2)	1.5 (0.1; 10.3)
Met Office Fire Danger- very high (days/year)	20.9	22.5	30.1 (18.8; 44.7)	38.8 (21.3; 61.4)	55.9 (28.1; 84.7)	33.0 (20.1; 50.9)	47.8 (24.2; 75.8)	77.6 (36.5; 112.7)
Average winter rainfall (anomalies) (% Change)	332.0	359.5	5.1 (-4.5; 15.4)	8.0 (-4.4; 21.7)	15.2 (-1.2; 32.5)	6.5 (-3.4; 50.9)	11.8 (-2.3; 28.8)	24.9 (2.1; 51.8)
Average summer rainfall (anomalies) (% Change)	238.4	261.9	-6.8 (-22.6; 7.1)	-14.3 (-32.5; 2.6)	-24.1 (-44.7; -5.6)	-9.1 (-25.8; 6.6)	-19.7 (-40.3; -0.2)	-35.8 (-60.5; -9.8)
SPEI Drought Index	0.06	0.07	0.1 (0.05; 0.2)	0.2 (0.07; 0.3)	0.2 (0.1; 0.4)	0.1 (0.06; 0.2)	0.2 (0.08; 0.3)	0.3 (0.1; 0.4)

* *Values corresponding to Cardiff weather station have been used wherever local authority area data is not available.*

Table 5 - Climate Baseline and 50th percentile Projections (Anomalies) for West Somerset local authority area for the 2030s, 2050s and 2080s for RCP4.5 and RCP8.5. Numbers in brackets represent the 10th and 90th percentile range of the inter-model spread.

Climate variable	Model Reference*	Baseline*	CMIP5 projections (Changes from the baseline) for RCP4.5			CMIP5 projections (Changes from the baseline) for RCP8.5		
	1981-2010	1991-2020	2030s	2050s	2080s	2030s	2050s	2080s
Mean Annual Temperature (Change ºC)	10.8	11.1	0.8 (0.3; 1.4)	1.3 (0.6; 2.1)	2.2 (1.2; 3.4)	1.1 (0.5; 1.6)	1.9 (1.0; 2.8)	3.7 (2.1; 5.3)
Maximum Summer Temperature (Change ºC)	21.0	21.1	1.2 (0.2; 2.1)	1.9 (0.6; 3.4)	3.5 (1.3; 5.6)	1.5 (0.4; 2.6)	2.8 (1.1; 4.6)	5.6 (2.5; 8.8)
Minimum Winter Temperature (Change ºC)	2.4	2.6	0.7 (0.03; 1.5)	1.2 (0.2; 2.2)	1.8 (0.5; 3.3)	0.9 (0.2; 1.8)	1.7 (0.5; 2.9)	3.0 (1.2; 5.1)
Cold weather alert (events/year)	2.3	2.2	2.2 (1.7; 2.7)	1.9 (1.4; 2.5)	1.5 (0.9; 2.2)	1.6 (1.2; 2.0)	1.2 (0.8; 1.8)	0.7 (0.3; 1.5)
Frost days (days/year)	38.7	36.9	29.8 (23.3; 36.5)	25.1 (17.3; 33.8)	19.0 (10.5; 29.7)	27.7 (21.0; 35.1)	20.8 (12.9; 30.9)	12.1 (5.0; 24.0)
Met Office Fire Danger-exceptional (days/year)	0	0	0 (0; 0.02)	0.01 (0; 0.06)	0.04 (0; 0.4)	0 (0; 0.03)	0.02 (0; 0.2)	0.3 (0.01; 3.4)
Met Office Fire Danger-very high (days/year)	6.1	6.8	9.8 (5.4;16.6)	13.0 (6.2; 26.1)	22.9 (8.8; 48.2)	11.2 (6.0; 20.1)	17.9 (7.4; 38.8)	41.9 (12.9; 79.4)
Average winter rainfall (anomalies) (% Change)	20.9	22.5	3.9 (-4.2; 12.9)	5.9 (-4.5; 17.3)	11.2 (-2.3; 26.2)	5.2 (-3.7; 14.9)	9.3 (-2.9; 23.9)	19.5 (0.6; 42.6)
Average summer rainfall (anomalies) (% Change)	332.0	359.5	-8.4 (-25.2; 6.0)	-14.9 (-34.0; 2.5)	-23.7 (-45.4; -4.3)	-11.1 (-28.1; 5.3)	-20.8 (-42.0; -0.1)	-36.0 (-61.7; -8.9)
SPEI Drought Index	0.06	0.07	0.1 (0.06; 0.2)	0.1 (0.07; 0.3)	0.2 (0.1; 0.3)	0.1 (0.06; 0.2)	0.2 (0.08; 0.3)	0.3 (0.1; 0.4)

* *Values corresponding to Cardiff weather station have been used wherever local authority area data is not available.*

Climate variables – Marine

UKCP09 projections

The UKCP09 climate projections indicate an increase in both winter and summer mean air temperature across the Severn Estuary area. Marine air temperature for the Severn Estuary is projected to rise in line with land air temperature.[33] It is estimated that by 2080 sea levels will be 30-40cm higher than they are at present based on a medium greenhouse gas emissions scenario. Projections of storm behaviour used by the UKCP09 wave model show storm tracks moving south, resulting in lower wave heights to the north of the UK and slightly larger wave heights in some southerly regions, especially the southwest. Models suggest that coastal squeeze, habitat loss, coastal erosion and steepening of beach profiles will all increase in the future because of further sea level rise and possible changes to wave conditions.

Around the UK the size of storm surge expected to occur on average about once in 50 years is projected to increase by less than 0.9 mm/year over the 21st century. For the Severn Estuary, an increase in the 50-year skew surge[34] return level of around 0.8 mm/year is anticipated. Storm surge events are difficult to predict beyond a few days ahead as they are controlled by various interlinked weather and marine factors, and this is why much uncertainty remains in future projections.[35]

IPCC Atlas

Table 6 provides climate projections from the IPCC WGI Interactive Atlas for marine climate variables for the region highlighted in **Figure 5** wherein Severn Estuary falls. These projections are provided against the baseline period of 1995-2014.

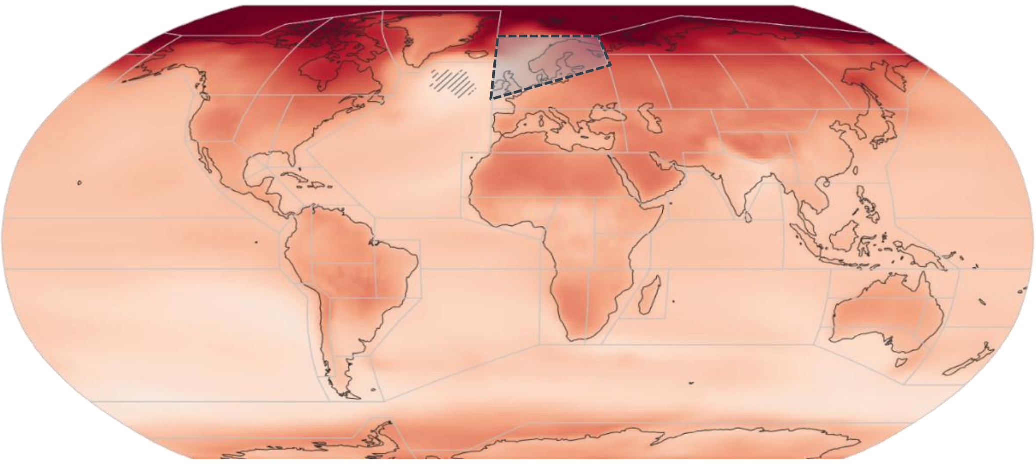


Figure 5 - Location of the region for which climate data has been extracted for Severn Estuary from IPCC WGI Interactive Atlas

[33] Severn Estuary Partnership (2015) Climate Change Report Card 1 [Online] Available at: https://severnestuarypartnership.org.uk/wp-content/uploads/sites/2/2015/10/ClimateChangeReportCard1.pdf

[34] According to UKCP09, a skew storm surge is a way of calculating the height of a storm surge and is the height difference between a predicted astronomical high tide and the nearest (in time) observed or modelled high tide.

[35] Lowe, J.A. et al., (2009) UK Climate Projections science report: Marine & Coastal Projections, Met Office Hadley Centre, Exeter, UK © Crown copyright

Table 6 - Climate Baseline and 50th percentile Projections (Anomalies) for the region corresponding to Severn Estuary for the 2030s, 2050s and 2080s for RCP4.5 and RCP8.5. Numbers in brackets represent the 10th and 90th percentile range of the inter-model spread.

Climate variable	Baseline	CMIP5 projections (Changes from the baseline) for RCP4.5			CMIP5 projections (Changes from the baseline) for RCP8.5		
	1995-2014	2030s	2050s	2080s	2030s	2050s	2080s
Sea surface temperature (change °C)	7.7	0.6 (-0.1; 1.2)	1.0 (0.3; 1.8)	1.8 (0.7; 3.1)	0.7 (0.1; 1.4)	1.4 (0.4; 2.4)	3.3 (1.7; 4.8)
Sea ice concentration (change %)	3.0	-0.4 (-2.0; 1.1)	-0.9 (-3.4; 0.3)	-1.8 (-4.6; -0.3)	-0.6 (-2.4; 1.0)	-1.5 (-3.8; -0.1)	-2.6 (-6.5; -0.5)
Sea level rise (m)	N/A	0.1 (0; 0.2)	0.2 (0.1; 0.3)	0.4 (0.1; 0.7)	0.1 (0; 0.2)	0.2 (0.1; 0.4)	0.5 (0.2; 0.8)
pH at surface (pH)	8.1	-0.1 (-0.1; -0.1)	-0.1 (-0.1; -0.1)	-0.2 (-0.2; -0.2)	-0.1 (-0.1; -0.1)	-0.2 (-0.2; -0.2)	-0.4 (-0.5; -0.4)
Surface wind (absolute m/s)	6.0	-0.5 (-1.6; 0.7)	-0.8 (-2.7; 0.7)	-1.9 (-3.9; 1.2)	-0.4 (-1.9; 0.5)	-1.2 (-3.2; 0.8)	-2.8 (-5.4; -0.4)

Data Gaps

Based on data and literature review, there are numerous gaps in marine climate projection data for the Severen Estuary. These include any quantifiable projection data on (not exhaustive):

- Water temperature
- Turbidity
- Salinity
- pH level
- Storm Surge
- Storminess
- Wind

There are also wider gaps in the climate data to support robust analysis of:

- Compound events
- Interdependencies
- Extreme events
- Return periods
- Flood hazards

Assumptions and limitations

The following assumptions and limitations have been identified for the assessment:

- The UKCP18 projections have been used to infer future changes in a range of climate variables. At the time of writing, these represent the most up-to-date representation of future climate in the UK.
- There are inherent uncertainties associated with climate projections, given they are not predictions of the future. It is possible that future climate will differ from the future baseline climate against which the resilience of the scheme has been assessed, depending on global emissions over the next century. The 'moderate' (RCP4.5) and 'high' emissions scenario (RCP 8.5) using the 2080s time slice (2070 – 2099 - the longest temporal scale available through UKCP18) has been used to develop the future baseline. This is consistent with the precautionary principle.
- There are inherited limitations and uncertainties within the CRI data. Further information on the methodology used to produce this data can be found in Changing climate risk in the UK: a multi-sectoral analysis using policy-relevant indicators.[36]
- Any further research, analysis or decision-making should take account of the accuracies and uncertainties associated with climate projections. It is also important to note that the projections are based on selected observational data, the results of climate model ensembles and a selected range of existing climate change research and literature available at the time of assessment. Any future decision-making based on this assessment should consider the range of literature, evidence and research available at that time and any changes to this.

[36] Climate Risk Management. (2021). Changing climate risk in the UK: A multi-sectoral analysis using policy-relevant indicators [Online] Available at: https://www.sciencedirect.com/science/article/pii/S2212096320300553

Impacts of Climate Change

Given the data available and the literature review[37,38,39,40,41,42], qualitative generalisations can be made about climate changes and impacts in the Severn Estuary that will affect the wider human and natural environment. These are summarised in this section.

Possible Climate Changes Drivers and Impacts in the Severn Estuary

Rising Temperatures

The Severn Estuary is likely warming due to increased air and ocean/river temperatures. This warming can affect the growth and reproduction of plants and animals, as well as the overall health of the ecosystem. There is also likely to be northern migration of species. Some native species are likely to be lost while Mediterranean/Lusitanian species are and will be increasingly prevalent. However, overall, there is likely to be a decrease in species diversity and food webs. There is also likely to be an increase prevalence and susceptibility to non-native invasive species.

Altered Salinity

Changes in precipitation patterns and sea level rise could alter the salinity of the estuary. Increased rainfall can lead to more freshwater inflow, reducing salinity, while droughts can increase salinity by reducing freshwater input. As such, increased seasonal differences in water salinity are more likely due to the changes in wetter winters and drier summers.

Increased salinisation of land and freshwater is also more likely with climate change due to sea level rise, storminess and coastal flooding. This salination can increase the loss of coastal wetlands and marshes which filter nutrients, microbial agents and chemicals, and help protect the coast from storm surges.

[37] Harrison, L.M., Coulthard, T.J., Robins, P.E. *et al.* (2022) Sensitivity of Estuaries to Compound Flooding. *Estuaries and Coasts* 45, 1250–1269. https://doi.org/10.1007/s12237-021-00996-1

[38] Leal Filho, W., Nagy, GJ., Martinho, F., *et al*. (2022) Influences of Climate Change and Variability on Estuarine Ecosystems: An Impact Study in Selected European, South American and Asian Countries. Int J Environ Res Public Health. Jan 5;19(1):585. doi: 10.3390/ijerph19010585. PMID: 35010857; PMCID: PMC8744635.

[39] Lonsdale, J., Leach, C., Parsons, D., *et al.* (2022) Managing estuaries under a changing climate: A case study of the Humber Estuary, UK, Environmental Science & Policy, Volume 134, , Pages 75-84, ISSN 1462-9011, https://doi.org/10.1016/j.envsci.2022.04.001.

[40] Robins, P., Skov, M., Lewis, M., *et al.* (2021) A review of climate change impacts on UK estuaries. Centre for Applied Marine Sciences, School of Ocean Sciences, Bangor University, LL59 5AB

[41] Robins, P., Lewis, M., Elnahrawi, M., *et al.* (2021) Compound Flooding: Dependence at Sub-daily Scales Between Extreme Storm Surge and Fluvial Flow. *Front. Built Environ.* 7:727294. doi: 10.3389/fbuil.2021.727294

[42] Robins, P., Skov, M., Lewis, M., *et al.* (2019) Impact of climate change on UK estuaries: A review of past trends and potential projections, Estuarine, Coastal and Shelf Science, Volume 169, 2016, Pages 119-135, ISSN 0272-7714,https://doi.org/10.1016/j.ecss.2015.12.016.

Acidification

Higher levels of carbon dioxide in the atmosphere lead to more CO^2 being absorbed by the ocean, causing ocean acidification. Acidification can affect the availability of minerals needed by marine organisms to build shells and skeletons. Changes in water chemistry can also increase rates of deterioration of maritime archaeological sites.

Increased Precipitation and Storm Intensity

More frequent and intense storms can lead to greater stormwater runoff, erosion, and sedimentation leading to increased turbidity, water cloudiness and contamination. This can negatively affect the wider estuarine ecosystems. For example, reduced light penetration can negatively affect the growth and health of aquatic plants and the animals that depend on them.

Sea-Level Rise

Rising sea levels can alter the dynamics of estuaries, potentially increasing the resuspension of sediments. This can lead to higher turbidity levels as sediments are more easily stirred up by tidal and wave action. Rising sea levels is likely to be the main driver of increased rates of erosion and coastal flooding and thus, a decrease of intertidal, marsh, wetland, wider-coastal environments. However, sea level rise can also result in increased accretion and reduced transportation of sediment overall.

Sea level rise can also lead to increased salinisation of land and freshwater. Coastal squeeze and the loss of coastal wetlands and marshes which filter nutrients, microbial agents and chemicals, and help protect the coast from storm surges is also an issue.

Sea level rise can result can also result in the loss of amenity, agricultural, industrial and residential land.

Increased Storm Surge and Coastal Flooding

Climate change could impact surge heights that will drive increase coastal flooding depths and extent. Both land and marine-based changes will limit the capacity for the estuary to respond to flooding.

Changes in River Flows

Flows across the catchment are likely to increase in the winter and decrease in the summer. This could have an effect on the temporal length and scale of mixing which is critical for water quality and environmental. In addition, changes in flows (seasonally and due to drought/high rainfall events) are likely affect levels of nutrients in the estuary and lead to more frequent and severe eutrophication, hypoxia and harmful algal blooms.

Warmer and Wetter Conditions

Higher temperatures and increased rainfall can result in increased transmission of water-borne and food-borne diseases caused by microbial pathogens in estuarine zones. It can also lead to increased frequency of contamination from discharge of sewage and agriculture run-off.

Wider Changes in the Environment

Climate change can alter a range of environmental cues (tide/salinity/temperature/photoperiod) that affect the synchronisation of reproductive cycle of marine and terrestrial species. Climate change also may influence the concentrations of toxic metals, organic chemicals, algal toxins derived from harmful algal blooms (HABs) and human pathogen contaminants in seafood.

Conclusions and Recommendations for Future Studies

Summary

Evidence and understanding of how climate change will affect estuaries is growing, but there are still many complexities and uncertainties. While there is robust data and consensus around general trends, particularly land-based climate variables, the specific impacts on estuarine systems can vary widely depending on local conditions and the interplay of various environmental and human factors. Ongoing research and monitoring are essential to continue to build and further refine analysis of climate change risks to estuaries.

At the time of writing, there is a lack of available localised data on the projected climatic changes and their impact on the Severn Estuary. As such, it is challenging to draw robust conclusions as to how the hydrological, ecological, geomorphological and human systems in the Severen Estuary will respond and function in the future.

However, based on current data and literature review, climate change is, and will continue, driving change in the Severn Estuary, with rising temperatures being a key trend. Increased air and water temperatures are impacting the growth and reproduction of local flora and fauna, leading to shifts in species distribution. In the future, native species may decline while Mediterranean and Lusitanian species become more common, potentially reducing overall biodiversity and disrupting food webs. Additionally, the estuary is becoming more susceptible to non-native invasive species, further threatening the ecosystem's balance.

Changes in precipitation patterns and sea level rise could alter the estuary's salinity. Increased rainfall can reduce salinity by adding more freshwater, while droughts can increase it by limiting freshwater input. These shifts are likely to cause more pronounced seasonal differences in salinity, with wetter winters and drier summers. The rising sea levels and increased storminess could also contribute to salinisation of land and freshwater, leading to the loss of coastal wetlands and marshes, which play crucial roles in nutrient filtration and coastal protection.

Other potential climate change impacts include ocean acidification affecting marine organisms' ability to build shells/skeletons and the deterioration of archaeological sites; increased storminess leading to greater stormwater runoff, erosion, and sedimentation affecting water quality and chemistry; sea-level rise affecting turbidity and increasing erosion; changes in river flows affecting nutrient levels and leading to more frequent eutrophication and harmful algal blooms; warmer and wetter conditions increasing the transmission of water-borne and food-borne diseases; and greater precipitation resulting in contamination from sewage and agricultural runoff.

Gaps and Recommendations

To better understand climate change in estuaries, there are several key areas of study which are essential: current climate baselines, future climate projections, and estuarine systems.

To effectively monitor and understand the potential impacts of climate change, several key types of baseline data for the Severn Estuary are important. These local data include water temperature at depth, salinity, dissolved oxygen, pH levels, turbidity, nutrient levels, sea surface temperature, weather data (e.g., temperature, humidity, atmospheric pressure, rainfall, and wind speed/direction). Critically, this data should cover the whole of the estuary and have a fine (greater than 25km^2) spatial resolution. Some of this data exists for the Severn Estuary, but not all, and not all is available covering the whole of the estuary nor to a fine resolution. It is recommended that field studies and monitoring are undertaken to gather this data to effectively baseline current conditions and includes:

- Maintaining measurements at existing locations, while also incorporating new site locations to undertake measurements;
- Data gathering on water temperature at depth, salinity, dissolved oxygen, pH levels and sea surface temperatures across the estuary; and
- Undertake new studies to determine current patterns in turbidity, sedimentation and nutrient levels and what potential land use and management practices may influence them.

To increase understand the climatic changes that could cause the most significant impact to the Severn Estuary in the future, more climate projection data is required. The key data gaps include quantifiable climate projection data for the estuary on (not exhaustive): water temperature, turbidity, salinity, pH level, storm surge, storminess, and wind. These data should cover the whole of the estuary and be at a resolution of $50km^2$ or finer. In order to obtain these projections, further climate modelling will be necessary; however, it is noted that current climate science and modelling might not have the capacities yet to do this level of analysis. There are also wider gaps in the data on: compound events, cascading impacts, interdependencies, extreme events and return periods. To fill these gaps, it is recommended that:

- Further climate modelling and analysis is undertaken
- Dynamic models are used and advanced to better predict estuarine change, coupled with climatic changes to simulating environmental stress to support future modelling
- Make comparisons with similarly positioned habitat conditions globally and those representative of future climatic conditions in the estuary.

Finally, to effectively understand climate change impacts on the systems of the Severn Estuary, several technical deep dives are recommended. These, where possible, should be underpinned by quantifiable climate projection data. However, where climate data is not available, qualitative assessments, for instance using a climate story-line approach, could help further explore the complexities and uncertainties of the impacts of climate change. Ideally, these studies will be specifically for the Severn Estuary; however, it is also noted that it might not be possible in all cases where studies from other estuaries could be used as a proxy. The topics of the technical deep dives include:

- Nutrient Cycling and Water Quality: Investigating how climate change influences nutrient loading (e.g., nitrogen and phosphorus) from surface runoff and its effects on water quality. This should include research into the links between climate change and harmful algal blooms and eutrophication.
- Hydrodynamics and Salinity: Research on how changes in precipitation and freshwater flow regimes affect estuarine hydrodynamics and salinity levels.
- Sediment Dynamics: Assessment of sediment transport and deposition processes under changing climatic conditions with a focus on projecting changes in estuarine morphology and habitat availability.
- Ecosystem Resilience and Adaptation: Studies on the resilience of estuarine ecosystems to climate-induced stressors, such as increased salinity and temperature, and the effectiveness of habitat restoration efforts.
- Biodiversity and Species Distribution: Research on how climate change affects the distribution and abundance of estuarine species, including birds, fish and invertebrates.

- Maritime Archaeological impacts: Researching how climate change can affect preservation and rates of deterioration of underwater and coastal archaeological sites.
- Socioeconomic Impacts: Assessing the socioeconomic dimensions of climate change on estuarine communities, including the impacts on fisheries, tourism, and coastal livelihoods

These studies will collectively help build a comprehensive understanding of how climate change impacts estuarine environments and more specifically, gain a picture of the future of the Severn Estuary.

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