Submission ID: S381C7B96

I submitted scientific data a while ago. I am just an ordinary man on a Clapham Omnibus as a LCJ stated many years ago. It is now 3 years old namely 2022 and there have been changes. At now [redacted] years old I would have hoped one of your young researchers might have updated all the International Scientific data from the Experts for the Inspector to see before making his decision. I can see that the changes are for the worse especially as Pacific Islands and coastal areas are being submerged around the world. That is the reason why Sea Level Minster Marshes are the last place to construct such an important National Generating Centre, electricity and water do not mix

Climate change

Global warming and climate change refer to an increase in average global temperatures and its effects on the local weather and climate.[1] Fig.1 shows the historical trend of global and north hemisphere surface temperature variations. Natural events and human activities are believed to be contributing to an increase in average global temperatures.[2] According to IPCC (AR4,WGI), "most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gases concentrations". Greenhouse gases such as Carbon Dioxide (CO_2), methane and nitrous oxide, act like a blanket surrounding the earth, keeping the heat supposed to escape into the outer space in and then warming the earth. It is observed that the concentration of man-made "greenhouse" gases have increased markedly as a result of human activity since 1750 and now far exceed pre-industrial values.[3] John Cook, writing the popular Skeptical Science blog summarizes the key indicators of a human finger print on climate change.

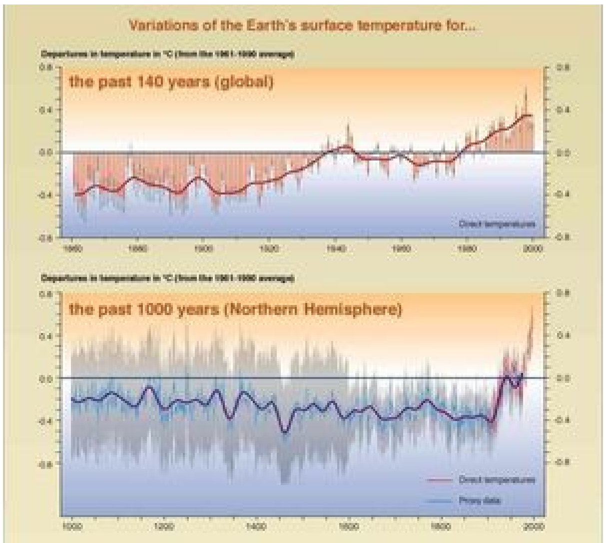

Fig.1 Variations of the global and Northern hemisphere temperature (<http://www.ipcc.ch/present/graphics.htm>)

The effects of climate change may be physical, ecological, social or economic. Due to the global warming and climate change, the hydrological cycle of precipitation and evapo-transpiration will change. The frequency of extreme weather, like drought, heavy rainfall, floods and tropical cyclones will increase in some areas. The decreased volume of mountain and oceanic glaciers and snow cap has contributed to the observed sea level rise,[2] IPCC (AR4,WGI) reported that since 1961, global average sea level had risen at an average rate of 1.8 [1.3 to 2.3] mm/yr. The socio-economic impact of climate change is mainly embodied in the effect on food production and on human health.[4] Generally, low-latitude areas are at most risk of having decreased crop yields. Food supply, heat stress, poor air & water quality and flooding will all have their impact on public health.

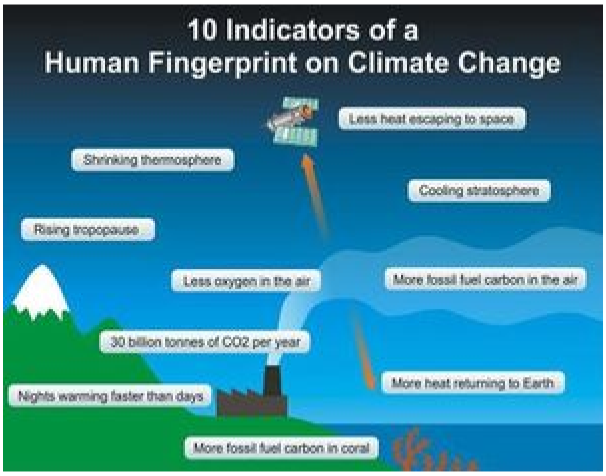

Fig. 2: John Cook, 10 indicators of a human fingerprint on climate change, Skeptical Science, July 30, 2010

In terms of water management, climate change not only leads to the need of strengthening flood protection, but also to making urban, agricultural and environmental systems more drought and heat resilient.

Projects at Water Resources Management that involve climate change include:

Effect of Climate Change on Urban Water Management Design Criteria

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[1] http://www.ipcc.ch/publications_and_data/ar4/wg1/en/spm.html

[2] Intergovernmental Panel on Climate Change (IPCC). "Summary for Policymakers". in Solomon 2007.

[3] http://www.skepticalscience.com/10-Indicators-of-a-Human-Fingerprint-on-Climate-Change.html

http://www.youtube.com/watch?v=S9ob9WdbXx0&feature=player_embedded#,
the truth of climate change

[4] Schneider, S.H., *et al*. "Assessing key vulnerabilities and the risk from climate change". in Parry 2007, p. 781. http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch19.html.

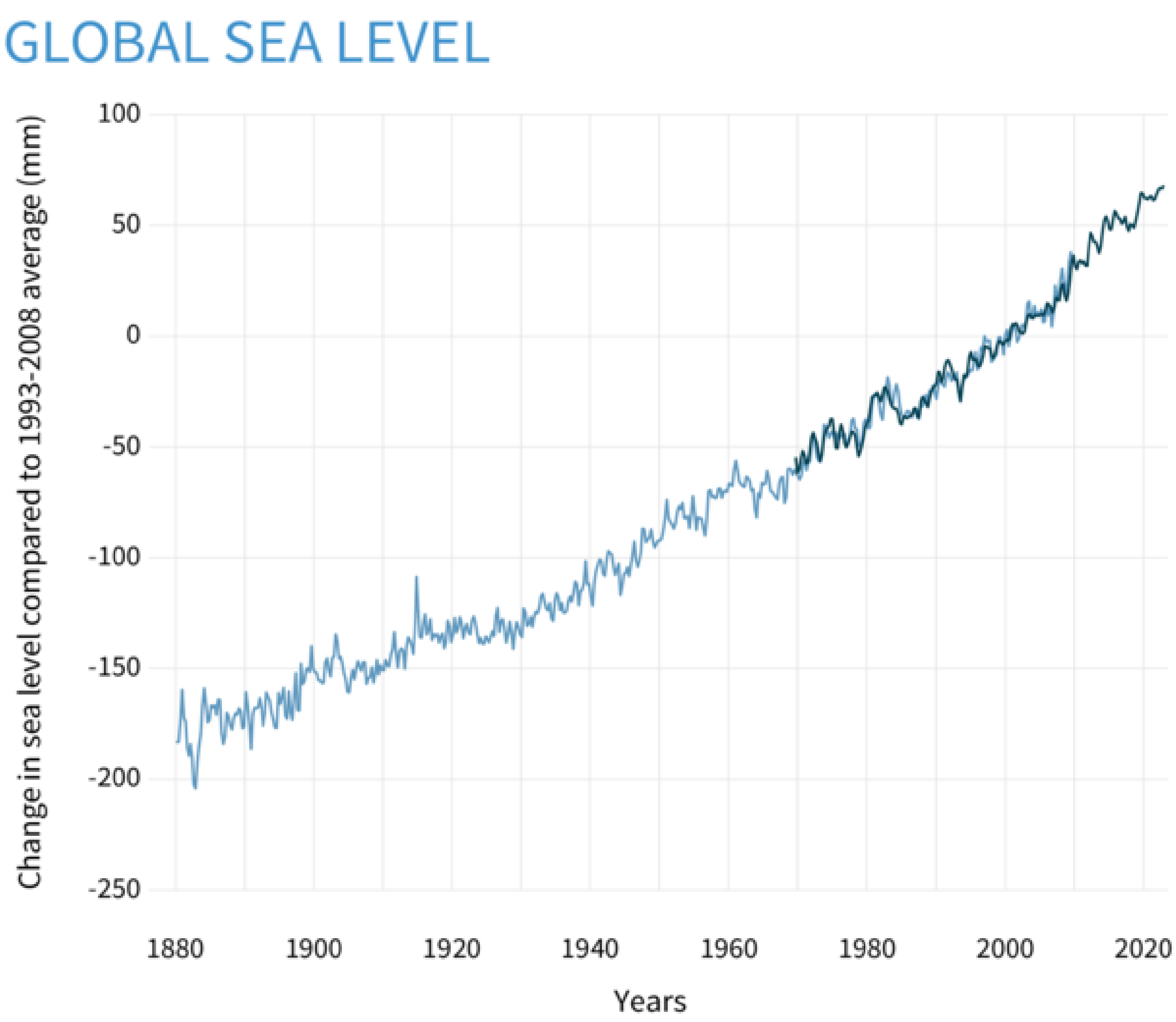
[5] http://en.wikipedia.org/wiki/Effects_of_global_warming

Climate Change: Global Sea Level

BY REBECCA LINDSEY | REVIEWED BY RICK LUMPKIN, GREG JOHNSON, PHILLIP THOMPSON, AND WILLIAM SWEET
PUBLISHED APRIL 19, 2022

HIGHLIGHTS

- Global average sea level has risen 8–9 inches (21–24 centimeters) since 1880.
- In 2022, global average sea level set a new record high—101.2 mm (4 inches) above 1993 levels.
- The rate of global sea level rise is accelerating: it has more than doubled from 0.06 inches (1.4 millimeters) per year throughout most of the twentieth century to 0.14 inches (3.6 millimeters) per year from 2006–2015.
- In many locations along the U.S. coastline, the rate of local sea level rise is greater than the global average due to land processes like erosion, oil and groundwater pumping, and subsidence.
  - High-tide flooding is now 300% to more than 900% more frequent than it was 50 years ago.
- If we are able to significantly reduce greenhouse gas emissions, U.S. sea level in 2100 is projected to be around 0.6 meters (2 feet) higher on average than it was in 2000.
- On a pathway with high greenhouse gas emissions and rapid ice sheet collapse, models project that average sea level rise for the contiguous United States could be 2.2 meters (7.2 feet) by 2100 and 3.9 meters (13 feet) by 2150.



(http://www.climate.gov/media/15200)

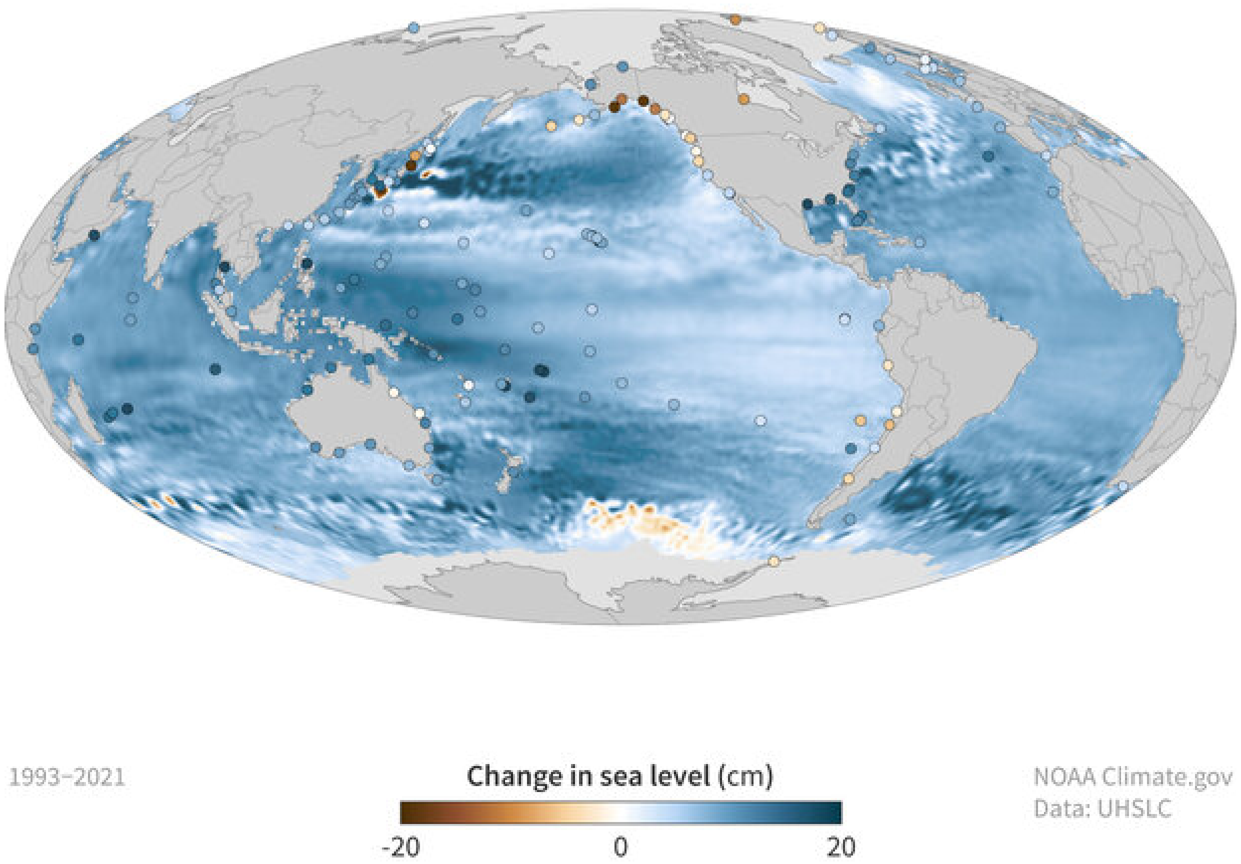
Seasonal (3-month) sea level estimates from Church and White (2011) (http://www.cmar.csiro.au/sealevel/GMSL_SG_2011.html) (light blue line) and University of Hawaii Fast Delivery (http://uhslc.soest.hawaii.edu/data/?fd) sea level data (dark blue). The values are shown as change in sea level in millimeters compared to the 1993-2008 average. NOAA Climate.gov image based on analysis and data from Philip Thompson, University of Hawaii Sea Level Center (https://uhslc.soest.hawaii.edu/).

Global mean sea level has risen about 8–9 inches (21–24 centimeters) since 1880. The rising water level is mostly due to a combination of melt water from glaciers and ice sheets and thermal expansion of seawater as it warms. In 2022, global mean sea level was 101.2 millimeters (4 inches) above 1993 levels, making it the highest annual average in the satellite record (1993-present).

The global mean water level in the ocean rose by 0.14 inches (3.6 millimeters) per year from 2006–2015, which was 2.5 times the average rate of 0.06 inches (1.4 millimeters) per year throughout most of the twentieth century. By the end of the century, global mean sea level is likely to rise at least one foot (0.3 meters) above 2000 levels, even if greenhouse gas emissions follow a relatively low pathway in coming decades.

In some ocean basins, sea level has risen as much as 6-8 inches (15-20 centimeters) since the start of the satellite record. Regional differences exist because of natural variability in the strength of winds and ocean currents, which influence how much and where the deeper layers of the ocean store heat.

SEA LEVEL CHANGE (1993-2021)



(http://www.climate.gov/media/14660)

Between 1993 and 2021 mean sea level has risen across most of the world ocean (blue colors). In some ocean basins, sea level has risen 6-8 inches (15-20 centimeters). Rates of *local* sea level (dots) on the coast can be larger than the global average due to geological processes like ground settling or smaller than the global average due to processes like the centuries-long rebound of land masses from the loss of ice-age glaciers. Map by NOAA Climate.gov based on data provided by Philip Thompson, University of Hawaii (https://uhslc.soest.hawaii.edu/).

Past and future sea level rise at specific locations (http://tidesandcurrents.noaa.gov/sltrends/sltrends.html) on land may be more or less than the global average due to local factors: ground settling, upstream flood control, erosion, regional ocean currents, and whether the land is still rebounding from the compressive weight of Ice Age glaciers. In the United States, the fastest rates of sea level rise are occurring in the Gulf of Mexico from the mouth of the Mississippi westward, followed by the mid-Atlantic. Only in Alaska and a few places in the Pacific Northwest are sea levels falling, though that trend will reverse under high greenhouse gas emission pathways.

Why sea level matters

In the United States, almost 30 percent (https://www.census.gov/library/stories/2019/07/millions-of-americans-live-coastline-regions.html) of the population lives in relatively high population-density coastal areas, where sea level plays a role in flooding, shoreline erosion, and hazards from storms. Globally, 8 of the world's 10 largest cities are near a coast, according to the U.N. Atlas of the Oceans.

(http://www.climate.gov/media/14145)

South Beach, Miami on May 3, 2007. Photo by Flickr user James Williamor (https://www.flickr.com/photos/bz3rk), via a Creative Commons license.

In urban settings along coastlines around the world, rising seas threaten infrastructure necessary for local jobs and regional industries. Roads, bridges, subways, water supplies, oil and gas wells, power plants, sewage treatment plants, landfills—the list is practically endless—are all at risk from sea level rise.

Higher background water levels mean that deadly and destructive storm surges, such as those associated with Hurricane Katrina, "Superstorm" Sandy, and Hurricane Michael—push farther inland than they once did. Higher sea level also means more frequent high-tide flooding, sometimes called "nuisance flooding (https://www.climate.gov/news-features/understanding-climate/understanding-climate-billy-sweet-and-john-marra-explain)" because it isn't generally deadly or dangerous, but it can be disruptive and expensive. (Explore past and future frequency of high-tide flooding at U.S. locations with the Climate Explorer (https://crt-climate-explorer.nemac.org/high_tide_flooding/?lat=38.98&lon=-76.49&city=Annapolis%2C+MD&county=Anne+Arundel+County&area-id=24003&fips=24003&zoom=7&mode=high_tide_flooding&tidal-station=8575512&tidal-station-name=Annapolis%2C+MD&tidal-station-mhhw=0.52), part of the U.S. Climate Resilience Toolkit. (https://toolkit.climate.gov/))

(http://www.climate.gov/media/6429)

Nuisance flooding in Annapolis in 2012. Around the U.S., nuisance flooding has increased dramatically in the past 50 years. Photo by Amy McGovern.

In the natural world, rising sea level creates stress (https://www.climate.gov/news-features/features/future-marylands-blackwater-marsh) on coastal ecosystems that provide recreation, protection from storms, and habitat for fish and wildlife, including commercially valuable fisheries. As seas rise, saltwater is also contaminating freshwater aquifers (https://www.usgs.gov/mission-areas/water-resources/science/saltwater-intrusion?qt-science_center_objects=0#qt-science_center_objects), many of which sustain municipal and agricultural water supplies and natural ecosystems.

What’s causing sea level to rise?

Global warming is causing global mean sea level to rise in two ways. First, glaciers and ice sheets worldwide are melting (https://www.climate.gov/news-features/featured-images/2017-state-climate-mountain-glaciers) and adding water to the ocean. Second, the volume of the ocean is expanding as the water warms. A third, much smaller contributor to sea level rise is a decline in the amount of liquid water on land—aquifers, lakes and reservoirs, rivers, soil moisture. This shift of liquid water from land to ocean is largely due to people depleting ground water.

(http://www.climate.gov/media/3965)

Pedersen Glacier, at Aialik Bay in Alaska’s Kenai Mountains, in 1917 (left) and 2005 (right). In the early 20th century, the glacier met the water and calved icebergs into a marginal lake near the bay. By 2005, the glacier had retreated, leaving behind sediment allowed the lake to be transformed into a small grassland. Photos courtesy of Louis H. Pedersen (1917) and Bruce F. Molina (2005), obtained from the Glacier Photograph Collection, Boulder, Colorado USA: National Snow and Ice Data Center/World Data Center for Glaciology. **Large images:** 1917 (/sites/default/files/pedersen1920_HR.jpg) | 2005 (/sites/default/files/pedersen2005_HR.jpg)

From the 1970s up through the last decade or so, melting and heat expansion were contributing roughly equally to observed sea level rise. But the melting of mountain glaciers (https://www.climate.gov/news-features/understanding-climate/climate-change-glacier-mass-balance) and ice sheets has accelerated:

- The decadal average loss from glaciers in the World Glacier Monitoring Service’s reference network quintupled over the past few decades, from the equivalent of 6.7 inches (171 millimeters) of liquid water in the 1980s, to 18 inches (460 millimeters) in the 1990s, to 20 inches (-500 millimeters) in the 2000s, to 33 inches (850 millimeters) for 2010-2018.
- Ice loss from the Greenland Ice Sheet increased seven-fold from 34 billion tons per year between 1992-2001 to 247 billion tons per year between 2012 and 2016.
- Antarctic ice loss nearly quadrupled from 51 billion tons per year between 1992 and 2001 to 199 billion tons per year from 2012-2016.

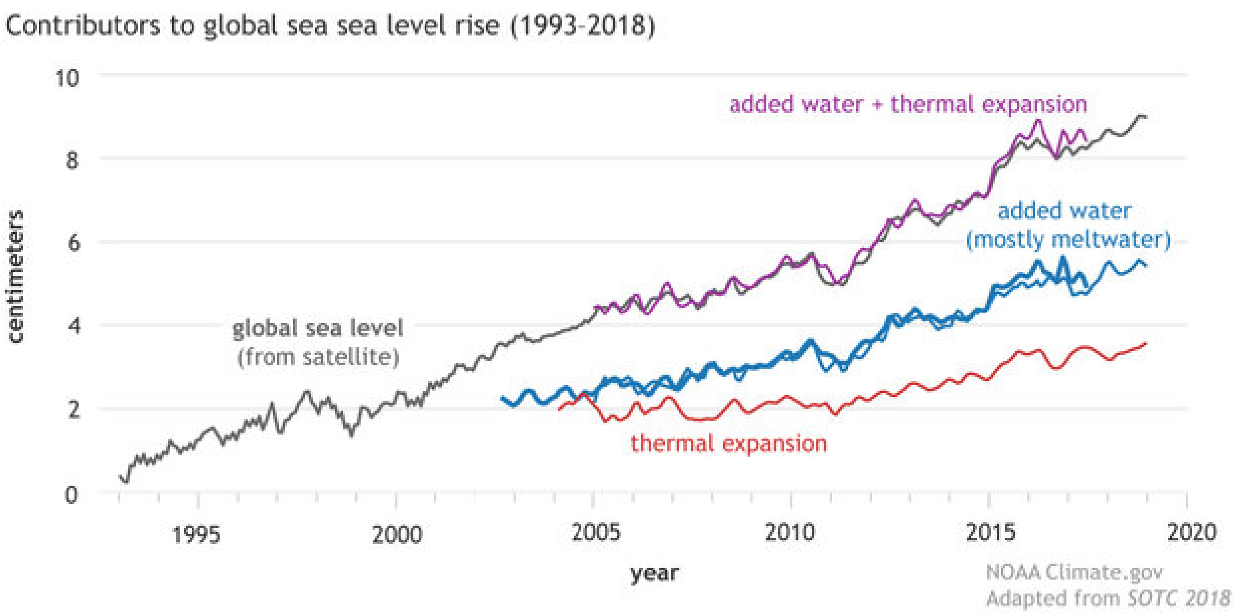
As a result, the amount of sea level rise due to melting (with a small addition from groundwater transfer and other water storage shifts) from 2005–2013 was nearly twice the amount of sea level rise due to thermal expansion.

(http://www.climate.gov/media/14169)

Melt streams on the Greenland Ice Sheet on July 19, 2015. Ice loss from the Greenland and Antarctic Ice Sheets as well as alpine glaciers has accelerated in recent decades. NASA photo (http://earthobservatory.nasa.gov/IOTD/view.php?id=86508) by Maria-José Viñas.

Measuring sea level

Sea level is measured by two main methods: tide gauges (https://www.climate.gov/news-features/climate-tech/reading-between-tides-200-years-measuring-global-sea-level)and satellite altimeters (https://www.nesdis.noaa.gov/jason-3/mission.html). Tide gauge stations from around the world have measured the daily high and low tides for more than a century, using a variety of manual and automatic sensors. Using data from scores of stations around the world, scientists can calculate a global average and adjust it for seasonal differences. Since the early 1990s, sea level has been measured from space using radar altimeters, which determine the height of the sea surface by measuring the return speed and intensity of a radar pulse directed at the ocean. The higher the sea level, the faster and stronger the return signal is.



(http://www.climate.gov/media/12868)

Observed sea level since the start of the satellite altimeter record in 1993 (black line), plus independent estimates of the different contributions to sea level rise: thermal expansion (red) and added water, mostly due to glacier melt (blue). Added together (purple line), these separate estimates match the observed sea level very well. NOAA Climate.gov graphic, adapted from Figure 3.15a in *State of the Climate in 2018* (https://www.ametsoc.org/ams/index.cfm/publications/bulletin-of-the-american-meteorological-society-bams/state-of-the-climate/).

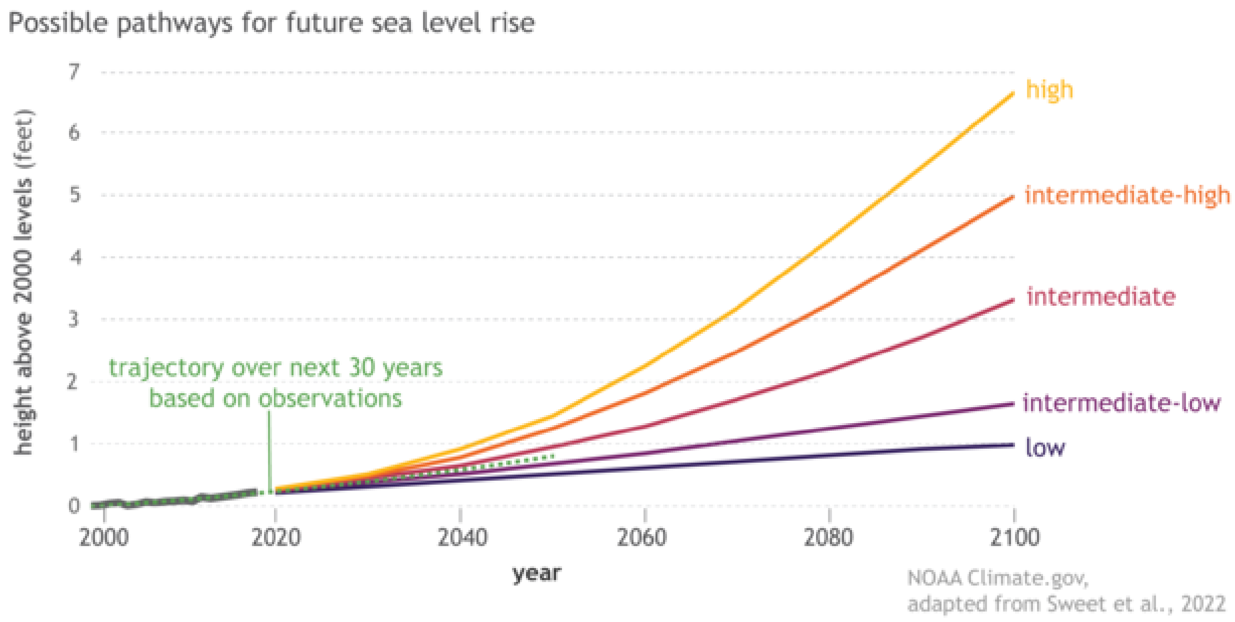
To estimate how much of the observed sea level rise is due to thermal expansion, scientists measure sea surface temperature using moored and drifting buoys (https://www.climate.gov/news-features/climate-tech/doing-their-part-drifter-buoys-provide-ground-truth-climate-data), satellites, and water samples collected by ships. Temperatures in the upper half of the ocean are measured by a global fleet of aquatic robots (https://www.climate.gov/news-features/features/argo-revolution). Deeper temperatures are measured by instruments lowered from oceanographic research ships.

To estimate how much of the increase in sea level is due to actual mass transfer—the movement of water from land to ocean—scientists rely on a combination of direct measurements of melt rate and glacier elevation made during field surveys, and satellite-based measurements (http://earthobservatory.nasa.gov/Features/GRACE/page2.php) of tiny shifts in Earth's gravity field. When water shifts from land to ocean, the increase in mass increases the strength of gravity over oceans by a small amount. From these gravity shifts, scientists estimate the amount of added water.

Future sea level rise

As global temperatures continue to warm, additional sea level rise is inevitable. How much and by when depends mostly on the future rate of greenhouse gas emissions. But another source of uncertainty is whether big ice sheets in Antarctica and Greenland will melt in a steady, predictable way as the Earth gets warmer, or whether they will reach a tipping point and rapidly collapse.

Every four or five years, NOAA leads an interagency task force that reviews the latest research on sea level rise and issues a report on likely— and 'unlikely but plausible'—amounts future sea level rise for different greenhouse gas and global warming pathways. In the 2022 report, the task force concluded that even on the pathway with the lowest possible greenhouse gas emissions and warming (1.5 degrees C), global mean sea level would rise at least 0.3 meters (1 foot) above 2000 levels by 2100. On a pathway with very high rates of emissions that trigger rapid ice sheet collapse, sea level could be as much as 2 meters (6.6 feet) higher in 2100 than it was in 2000.



(http://www.climate.gov/media/14136)

Observed sea level from 2000-2018, with future sea level through 2100 for six future pathways (colored lines) The pathways differ based on future rates of greenhouse gas emissions and global warming and differences in the plausible rates of glacier and ice sheet loss. NOAA Climate.gov graph, adapted from Sweet et al., 2022.

One piece of good news: the task force concluded that an extreme possibility (8.2 feet above 2000 levels by 2100) that they couldn't rule out at the time of their 2017 report appears to be less likely based on the latest science. This doesn't mean global sea level rise of that much won't *ever* happen, only that it is extremely unlikely to happen by 2100. Still, on a pathway with high greenhouse gas emissions, if processes triggering rapid ice sheet collapse kick in, global sea level could rise upwards of 3.7 meters (12 feet) higher in 2150 than it was in 2000.

Now the bad news: the report reaffirmed that many parts of the United States can expect their local rate and overall amount of sea level rise to exceed the global average. Extrapolating from observed rates, sea levels on average along the contiguous U.S. are expected to rise as much over the next 30 years (10-12 inches over 2020-2050) as they have over the last 100 years (1920-2020). In some regions, the increases will be even larger. In the western Gulf of Mexico, for example, sea level rise is likely to be about 16-18 inches higher than 2020 levels by 2050—almost a ½ foot higher than the national average.

Projections for U.S. sea level rise for the end of the century and beyond depend on which greenhouse gas pathway we follow and how the major ice sheets respond to this ocean and atmospheric warming. If we are able to significantly reduce greenhouse gas emissions, U.S. sea level in 2100 is projected to be around 0.6 meters (2 feet) higher on average than it was in 2000. But on a pathway with high greenhouse gas emissions and rapid ice sheet collapse, models project that average sea level rise for the contiguous United States could be 2.2 meters (7.2 feet) by 2100 and 3.9 meters (13 feet) by 2150.

About the data used in the time series graph

These data (https://www.climate.gov/sites/default/files/Climate_dot_gov_dashboard_SeaLevel_Jan2021update.txt) are for education and communication purposes only. The early part of the time series shown in the graph above comes from the sea level group (http://www.cmar.csiro.au/sealevel/index.html) of CSIRO (Commonwealth Scientific and Industrial Research Organisation), Australia's national science agency. They are documented in Church and White (2011). The more recent part of the time series is from the University of Hawaii Sea Level Center (UHSLC (http://uhslc.soest.hawaii.edu/data/?fd)). It is based on a weighted average of 373 global tide gauge records collected by the U.S. National Ocean Service, UHSLC, and partner agencies worldwide. The weights for each gauge in the global mean are determined by a cluster analysis that groups gauges from locations where sea level tends to vary in the same way. This prevents over-emphasizing regions where there are many tide gauges located in close proximity. The most recent year of data should be considered preliminary. Scientific users should acquire research-quality data directly from UHSLC and/or the NOAA Tides and Currents (https://tidesandcurrents.noaa.gov/sltrends/) webpage.

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More sea level data and information from NOAA and partners

Global Ocean Heat and Salt Content (https://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/) page at NCEI

Tides and Currents Sea Level Trends (http://tidesandcurrents.noaa.gov/sltrends/sltrends.html) page at the National Ocean Service

Digital Coast Sea Level Rise Viewer (http://coast.noaa.gov/digitalcoast/tools/slr) at the Coastal Services Center

Coastal Flood Risk (https://toolkit.climate.gov/topics/coastal-flood-risk) page at the U.S. Climate Resilience Toolkit

CoastalDEM v2.1: A high-accuracy and high-resolution global coastal elevation model trained on ICESat-2 satellite lidar

Scott A. Kulp[1]*, Benjamin H. Strauss[1]

In Brief
In 2018, Climate Central released CoastalDEM v1.1, a near-global coastal digital elevation model (DEM) that used an artificial neural network to reduce errors present in a DEM derived from NASA's Shuttle Radar Topography Mission (SRTM). CoastalDEM v1.1 was tested against lidar-derived elevation data in the US and Australia, and showed greatly reduced vertical bias and root mean square error (RMSE) compared to SRTM in both forests and cities.

Here we present CoastalDEM v2.1, the newest version of Climate Central's digital elevation model. We have made a number of substantial improvements to our neural network architecture, input datasets, and training data, resulting in a DEM that outperforms not only SRTM and CoastalDEM v1.1, but all leading, publicly-available, global-scale models tested. This is especially true in low-lying and densely populated areas, which are most important for assessing coastal vulnerability, but also where most DEMs struggle due to the presence of tall buildings.

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1. Introduction

Accurate elevation data is essential to accurately assess the vulnerability of coastal communities to threats from sea level rise (SLR) and coastal flooding. While a few developed countries, such as the US, Australia, the UK, and others in Europe, have released high-quality elevation data derived from airborne lidar, most of the rest of the world, particularly in developing countries, relies on lower-accuracy global digital elevation models (DEMs) derived from satellite radar. These DEMs suffer from large vertical errors with a positive bias [1, 2]—especially in densely populated areas, where accurate vulnerability statistics are most important, but where satellite radar sensors see building tops as hills and mountains [3, 4, 5].

In recent years, efforts have been made to improve global elevation models by predicting and reducing their errors, though most attempts have either covered a very small area [6, 7] or only sought to reduce bias in vegetated areas, rather than cities [8, 9, 10, 11]. CoastalDEM v1.1 [2] was the first global-scale DEM that used an artificial neural network to correct errors present in NASA's SRTM. We tested this model against lidar-derived elevation data in the US and Australia, and found it greatly improved vertical bias and RMSE compared to SRTM in both forests and cities. However, as version 1.1 was trained on ground truth data in the US alone, and despite its high performance in Australia, there must be less confidence in its accuracy in areas with dissimilar vegetation, architecture, and population density.

Ideally, an error-correcting model would instead use high-quality globally-available ground truth data to train the model. However, at the time CoastalDEM v1.1 was generated, the best available candidate global dataset was ICESat, which was a 2003-2010 NASA satellite mission that, among other objectives, collected elevation profile measurements at points along straight lines across Earth's surface using a single laser altimeter beam (satellite lidar). These points had a large footprint (70 m) and were about 170 m apart along the linear tracks [12]. These data were also noisy, suffering from a multi-meter positive bias in certain terrain types, including forests [13]. While useful to help validate global elevation models, the data from the first ICESat mission were not suitable for use in training a neural network.

In late 2018, NASA launched the ICESat-2 mission, which promised much more dense and accurate land elevation measurements compared to its predecessor. Specifically, ICESat-2 features 6 beams (in 3 pairs, spaced 3 km apart) and gives elevation values every 100 m along track (each value is based on an algorithmic assessment of multiple photon measurements within each 100 m segment). [14]. Additionally, ICESat-2 computes vegetation height at every point, largely reducing this source of error, though no such correction is performed for urban structures. Early validation results [15, 16] suggest ICESat-2 terrain measurements contain vertical bias of less than 10 cm, and

RMSE less than 1 m, though these studies do not investigate performance in urban areas.

2. Technological Advances in CoastalDEM v2.1

- **Trained on high-quality global elevation data.** CoastalDEM v1.1 was trained using airborne lidar-derived elevation models in the US alone, which risked overfitting the model. CoastalDEM v2.1 is trained using data from NASA's recent ICESat-2 mission [14], which covers land across the entire world. This choice was aimed at further improving performance in other countries where architecture and population density can be very different than what exists in the US.
- **More accurate base elevation.** CoastalDEM v1.1 was based off of NASA's SRTM v3.0, whose errors were particularly severe with a >2 m positive bias and >4 m RMSE. CoastalDEM v2.1 instead uses NASA's recently-released NASADEM dataset, a more accurate reprocessing of SRTM's source data [17]. This gives CoastalDEM v2.1 a better "starting point" from which improvements are made.
- **Wider input elevation range.** CoastalDEM v1.1 only considered pixels whose SRTM elevation lies between 1-20 m. CoastalDEM v2.1 instead predicts corrections for all pixels on land between -10 m and 120 m. This choice was aimed at improving results both in low, flat regions with areas of negative vertical error due to random noise, as well as locations with tall skyscrapers that cause errors exceeding 20 m.
- **Larger and more sophisticated convolutional neural network (CNN) architecture.** CoastalDEM v1.1 used a small and multilayer perceptron neural network with 40 hidden units to predict errors present in SRTM. CoastalDEM v2.1 employs a far larger CNN with many thousands of hidden units, which is better suited to learn the highly nonlinear relationships between each of the input variables and the actual elevation.
- **New and updated input variables.** CoastalDEM v1.1 used a total of 23 input variables, including SRTM elevation, population density, and vegetation density. Since then, we have acquired more accurate versions of many of these datasets (such as NASADEM and WorldPop [18]), as well as added new ones. In addition, the convolutional neural network architecture allows us to utilize large input windows about each target, effectively resulting in over a thousand input variables for each pixel. These give the neural network much more context for each location to better improve predictions and reduce errors.

3. Results

3.1 Validation against ICESat-2

Here we use land elevation measurements from NASA's ICESat-2 as ground truth to assess the global accuracy of global DEMs. We include the six most-recently released products – CoastalDEM v2.1, CoastalDEM v1.1 [2], NASADEM [17], TanDEM-X [19], MERIT [8], and AW3D30 [20]. We assess each of the DEMs at their native horizontal resolutions, including CoastalDEM v1.1 at 1 arc-second. We disregard all ICESat-2 points flagged as being covered by clouds or snow. Additionally, all error values exceeding 50 m are treated as outliers and removed from the assessment (fewer than 0.005% of points have a discrepancy this large).

We have empirically found that DEM performance varies by elevation. Since CoastalDEM's intended purpose is for coastal flood modeling on land presently above sea level especially in populated areas, we primarily focus on land between 0-5 m relative to the EGM96 geoid (spanning the range of most storm and projected sea-level rise scenarios through the year 2100 [21, 22]), and where population density exceeds 1,000 people per square kilometer. More specifically, when assessing vertical accuracy of a DEM, we consider only grid cells where the "true" (ICESat-2) *or* the "estimated" (DEM) elevations are greater than zero and lower than the given maximum elevation (most often, 5 m). For brevity, for the rest of this report we only list the upper elevation bounds assessed (<5 m, <10 m, or <20 m), with the lower bound of 0 m left implied. All available data points present in ICESat-2 that meet the above requirements and given filters are used in the following assessments.

In the whole of the <5 m elevation band (including all areas, regardless of population density), the 30 m version of CoastalDEM v2.1 virtually eliminates global median bias to less than 0.01 m, contains an RMSE of 2.63 m, and LE90 (90th percentile linear error) of 2.99 m (Table 1), and outperforms the other global DEMs by a considerable margin. CoastalDEM v1.1 is found to contain errors with a slight negative bias. The updated CoastalDEM corrects that observed bias, while also reducing RMSE/LE90 by 20-50% compared to its competitors. CoastalDEM v2.1 thus shows the highest global accuracy when evaluated with these criteria.

In coastal areas with at least moderate development (greater than 1,000 people per square kilometer, where roughly half of the world's total population lives [18]) and in the elevation range at greatest risk from tides, storms and sea level rise (<5 m), mean vertical bias improves by more than 80%, from -0.5 m with CoastalDEM v1.1 to -0.1 m with CoastalDEM v2.1. These results reflect bias reductions from 91-95% compared to the other comparable DEMs, while maintaining RMSE/LE90 improvements of 20-40%. In segments of coastline with very high population density (greater than 10,000 people per square km, where errors caused by tall buildings are most severe) and the same elevation range (<5 m), CoastalDEM v2.1 contains a slightly positive bias, though still outperforms CoastalDEM v1.1 by 20%, and other DEMs by 80%.

At higher elevations (<20 m), CoastalDEM v2.1 contains slightly elevated errors, with a negative bias at about -0.2 m across all population densities. However, even here, CoastalDEM v2.1's median bias, RMSE, and LE90 outperform each of the other global DEMs. Across the board, performance at <10 m falls between the <5 m and <20 m results.

DEMs can contain spatially-autocorrelated errors even when they exhibit strong global performance, so it is important to also assess bias and RMSE at smaller spatial scales. Here we employ the GADM 2.0 dataset [23], a collection of global administrative units, to assess error distributions across regions. These distributions are computed at the smallest-available units by binning error values between -50 m to +50 m at 0.01 m intervals, which are added and aggregated to estimate error distributions at wider spatial scales, including across countries. We then use these binned distributions to estimate all relevant error metrics, including the median and LE90. Detailed error statistics by nation are presented in Supplementary Dataset S1.

Importantly for more local applications, CoastalDEM's performance is strong across most nations. In Figures 1 and 2, we present choropleth maps of nations' median biases and RMSE's under CoastalDEM v2.1, as well as TanDEM-X and MERIT. These maps only consider areas with at least moderate population density (more than 1,000 people per square kilometer) and below 5 m elevation. Only countries with at least 1,000 pixels meeting these requirements ($n \geq 1000$) are shaded. Under these metrics, CoastalDEM v2.1 consistently outperforms other global DEMs, with median bias lower in 90% of countries, and RMSE lower in at least 78% of countries. This is particularly notable in Asia and South America, which contain large populations near the coastline, and in many cases do not have lidar-derived elevation models available. National-level error statistics are available in Supplementary Dataset 1.

Figure 3 provides further evidence of consistent performance across small spatial scales. Here we assess error across smaller ('level 1") administrative units, roughly equivalent to US counties. We applied the same domain filtering as the preceding figures (>1,000 people per square kilometer, <5 m elevation). This figure presents median bias and RMSE density plots based on all (roughly 1,000 in count) of these small regions. Results for each of the global DEMs are represented by the colored curves, with steeper curves closer to 0 m corresponding to more consistent and accurate results. Again we find CoastalDEM v2.1 outperforms each of the competing DEMs, especially in terms of median bias.

Elevation profiles in select cities comparing ICESat-2, CoastalDEM v2.1, TanDEM-X, and MERIT are presented in Figures 4 and 5. We can see more clearly here that ICESat-2 is an imperfect truth set, especially in such densely populated areas - there are substantial noise and "spikes" in these measurements that can exceed tens of meters. That said, CoastalDEM v2.1's profiles generally do a better job than the other DEMs in following ICESat-2's curves. In fact, CoastalDEM appears to generate an even smoother elevation profile than ICESat-2. CoastalDEM v2.1's increasingly negative computed bias at higher population densities may not reflect true bias, but rather may be explained at least in part by the possibility that ICESat-2 has increasingly positive bias with density.

Table 1. Global error statistics across each DEM, three elevation thresholds (5 m, 10 m, and 20 m), and three population density bands (any density (Any), more than 1,000 people per km^2 (>1K), and more than 10,000 people per km^2 (>10K)). ICESat-2 is used as ground truth. For each row, only pixels are included whose elevation falls below the elevation threshold (according to ground truth or the DEM), and whose population density falls within the given band. Rows presenting CoastalDEM v2.1 statistics are in bold. All units are in meters except for population density, which is people per km^2.

DEM	Max Elev	Pop Density	Mean Bias	Median Bias	RMSE	LE90
CoastalDEM v2.1	**5**	**Any**	**-0.03**	**0.00**	**2.63**	**2.99**
CoastalDEM v1.1	5	Any	-0.06	-0.45	4.02	4.24
NASADEM	5	Any	1.59	0.66	4.65	6.40
TanDEM-X	5	Any	1.81	0.31	4.67	6.43
MERIT	5	Any	1.46	1.26	3.39	4.00
AW3D30	5	Any	2.41	1.43	5.54	7.97
CoastalDEM v2.1	**10**	**Any**	**-0.24**	**-0.12**	**2.89**	**3.39**
CoastalDEM v1.1	10	Any	-0.14	-0.62	4.42	4.75
NASADEM	10	Any	1.55	0.65	4.67	6.40
TanDEM-X	10	Any	1.74	0.29	4.63	6.43
MERIT	10	Any	1.43	1.26	3.46	4.11
AW3D30	10	Any	2.26	1.38	5.45	7.70
CoastalDEM v2.1	**20**	**Any**	**-0.33**	**-0.15**	**3.23**	**3.75**
CoastalDEM v1.1	20	Any	0.31	-0.45	4.83	5.73
NASADEM	20	Any	1.49	0.63	4.72	6.41
TanDEM-X	20	Any	1.72	0.30	4.78	6.65
MERIT	20	Any	1.41	1.27	3.71	4.36
AW3D30	20	Any	2.14	1.33	5.45	7.54
CoastalDEM v2.1	**5**	**>1K**	**-0.11**	**0.08**	**2.53**	**3.01**
CoastalDEM v1.1	5	>1K	-0.47	-0.29	3.01	3.81
NASADEM	5	>1K	1.21	1.01	3.56	5.29
TanDEM-X	5	>1K	1.81	1.35	3.21	4.89
MERIT	5	>1K	1.95	1.79	3.40	4.86
AW3D30	5	>1K	2.60	2.19	4.39	6.70
CoastalDEM v2.1	**10**	**>1K**	**-0.40**	**-0.14**	**2.79**	**3.33**
CoastalDEM v1.1	10	>1K	-0.70	-0.55	3.26	4.25
NASADEM	10	>1K	1.23	1.03	3.62	5.35
TanDEM-X	10	>1K	1.75	1.31	3.34	5.05
MERIT	10	>1K	1.89	1.76	3.51	4.90
AW3D30	10	>1K	2.58	2.19	4.41	6.71
CoastalDEM v2.1	**20**	**>1K**	**-0.47**	**-0.18**	**2.97**	**3.63**
CoastalDEM v1.1	20	>1K	-0.32	-0.45	3.59	4.92
NASADEM	20	>1K	1.27	1.07	3.69	5.44
TanDEM-X	20	>1K	1.74	1.31	3.44	5.11
MERIT	20	>1K	1.90	1.76	3.67	5.05
AW3D30	20	>1K	2.54	2.18	4.43	6.63
CoastalDEM v2.1	**5**	**>10K**	**-0.20**	**0.42**	**3.73**	**3.71**
CoastalDEM v1.1	5	>10K	-1.15	-0.52	4.83	5.57
NASADEM	5	>10K	2.05	2.01	4.74	6.76
TanDEM-X	5	>10K	2.85	2.59	4.21	5.93
MERIT	5	>10K	2.85	2.88	4.75	6.42
AW3D30	5	>10K	4.25	3.70	6.57	9.69
CoastalDEM v2.1	**10**	**>10K**	**-0.85**	**-0.07**	**4.40**	**4.78**
CoastalDEM v1.1	10	>10K	-1.19	-0.67	5.15	6.53
NASADEM	10	>10K	2.06	2.05	5.04	7.33
TanDEM-X	10	>10K	2.72	2.58	4.73	6.73
MERIT	10	>10K	2.66	2.83	5.11	6.96
AW3D30	10	>10K	4.40	3.80	6.88	10.37
CoastalDEM v2.1	**20**	**>10K**	**-1.09**	**-0.24**	**4.77**	**5.62**
CoastalDEM v1.1	20	>10K	-0.50	-0.38	5.48	7.84
NASADEM	20	>10K	1.99	2.04	5.34	7.76
TanDEM-X	20	>10K	2.60	2.54	5.08	7.25
MERIT	20	>10K	2.65	2.84	5.50	7.72
AW3D30	20	>10K	4.36	3.73	7.12	10.72

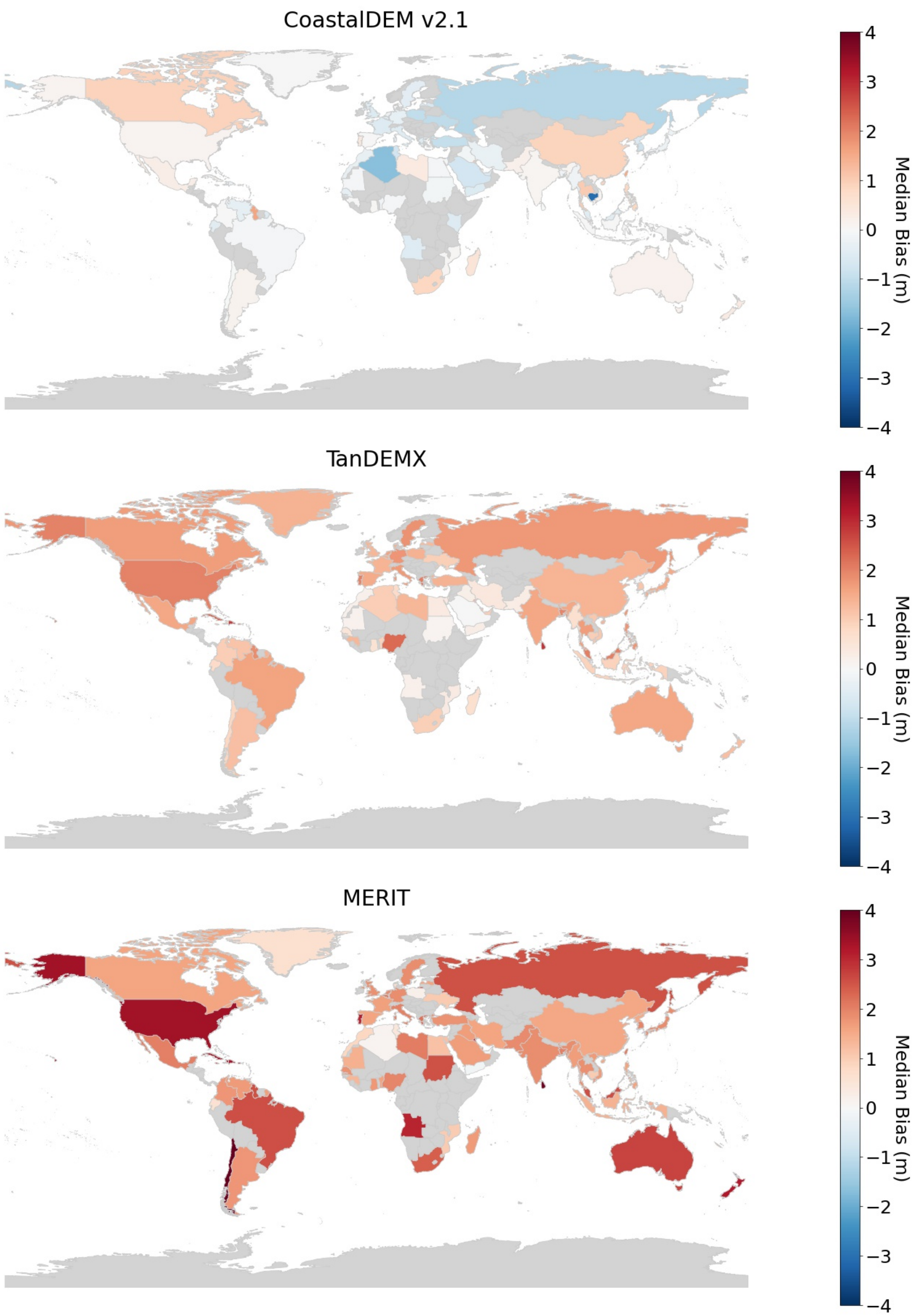

Figure 1. Choropleths presenting median bias under CoastalDEM v2.1, TanDEM-X, and MERIT in low-elevation regions across coastal nations, using ICESat-2 as ground truth. Only grid cells with elevation <5 m and population density >1000 people per km^2 are considered, and only nations with $n \geq 1000$ of these grid cells are evaluated.

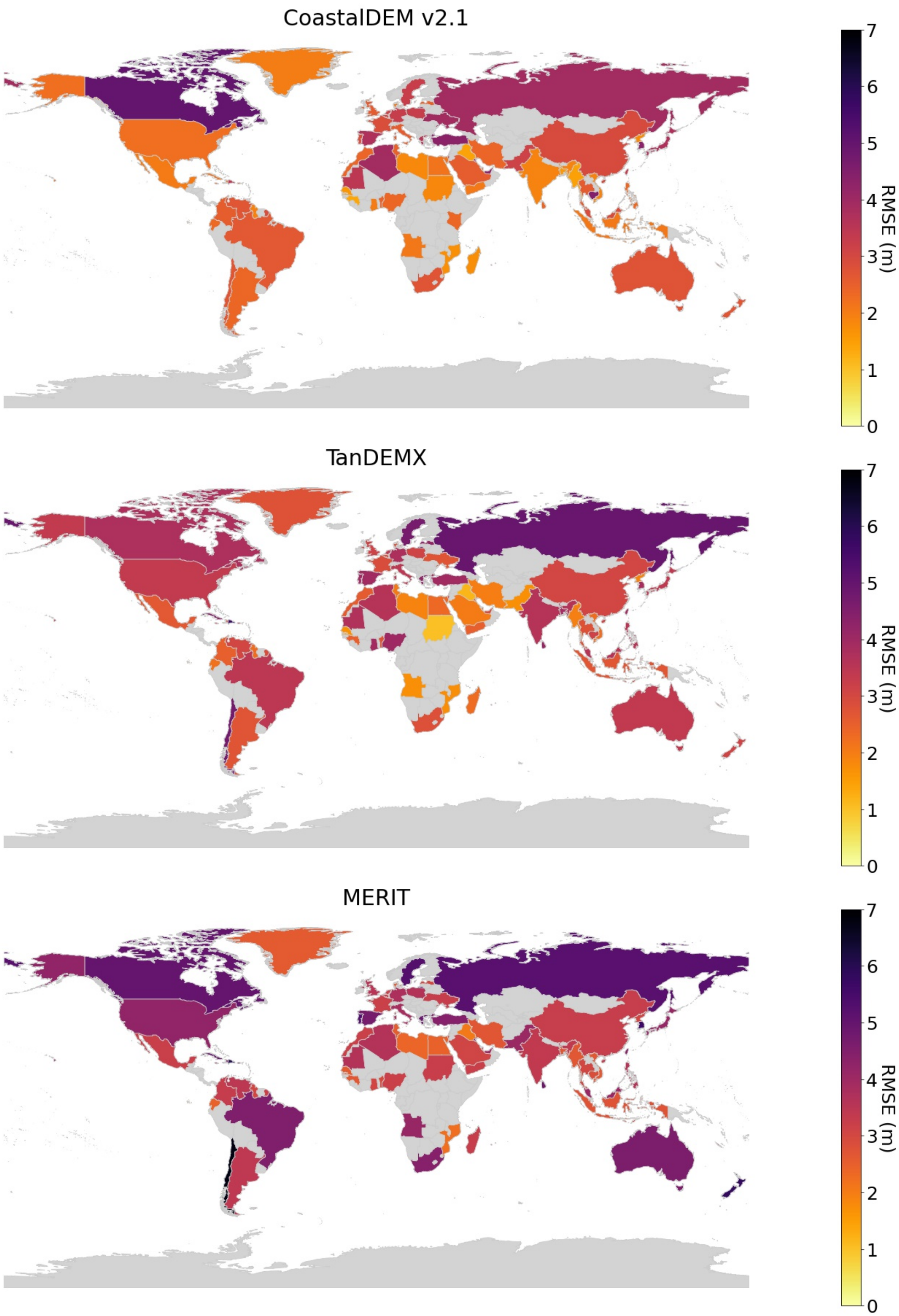

Figure 2. Choropleths presenting RMSE under CoastalDEM v2.1, TanDEM-X, and MERIT in low-elevation regions across coastal nations, using ICESat-2 as ground truth. Only grid cells with elevation <5 m and population density >1000 people per km^2 are considered, and only nations with $n \geq 1000$ of these grid cells are evaluated.

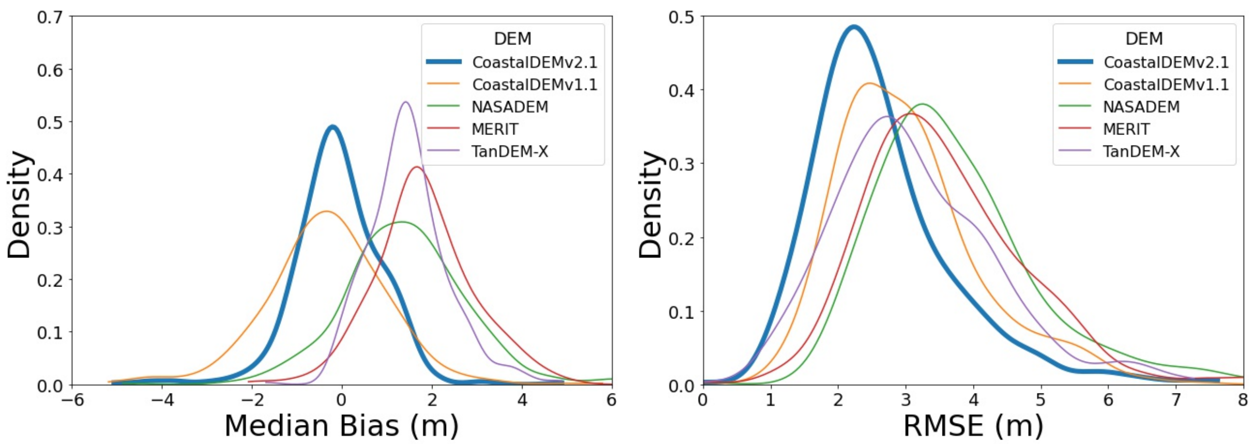

Figure 3. Density plots of median bias (left) and RMSE (right) for each of the global DEMs across level-1 administrative units (GADM 2.0), using ICESat-2 as ground truth. CoastalDEM v2.1 is highlighted in blue. Only grid cells whose elevations are lower than 5 m and contain >1000 people per square km are considered.

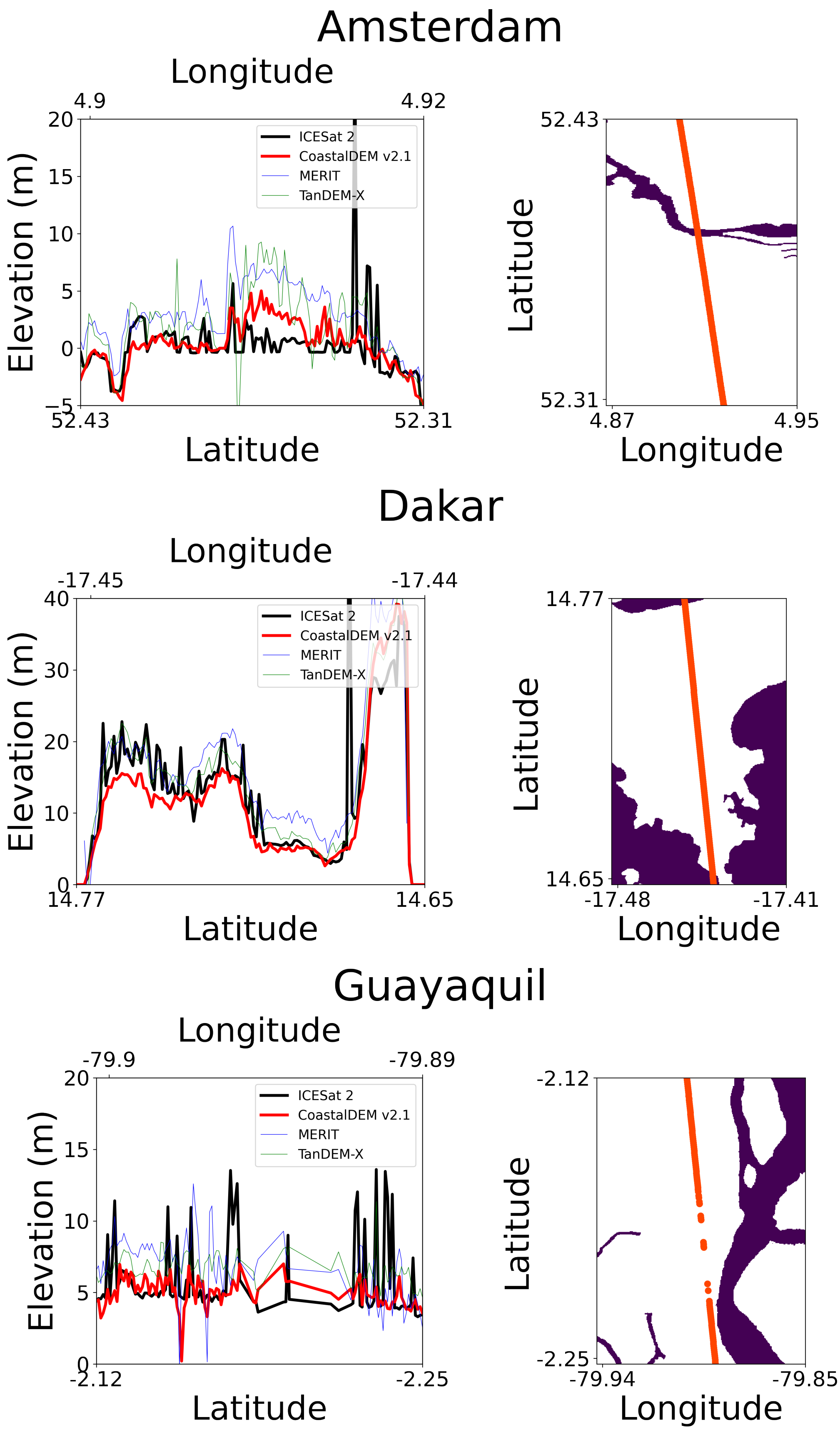

Figure 4. Elevation profiles under CoastalDEM v2.1, TanDEM-X, MERIT, and ICESat-2 in Amsterdam, Dakar, and Guayaquil along an ICESat-2 beam path. For each city, the left panel presents estimated elevation along the path according to each dataset, with ICESat-2 and CoastalDEM v2.1 highlighted in black and red, respectively. The right panel shows a map view where the path lies on the city in red, with water bodies highlighted in purple.

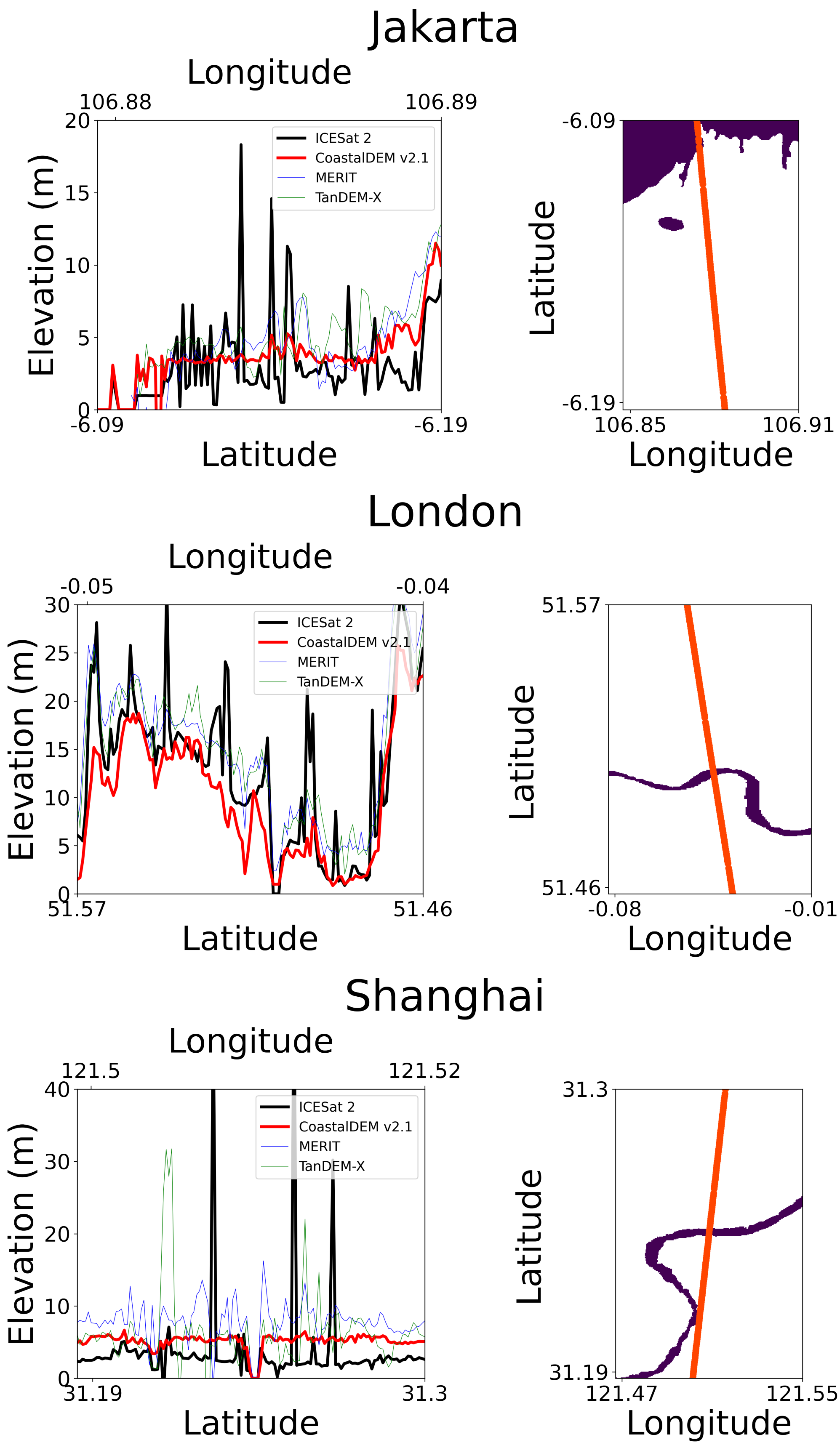

Figure 5. Elevation profiles under CoastalDEM v2.1, TanDEM-X, MERIT, and ICESat-2 in Jakarta, London, and Shanghai along an ICESat-2 beam path. For each city, the left panel presents estimated elevation along the path according to each dataset, with ICESat-2 and CoastalDEM v2.1 highlighted in black and red, respectively. The right panel shows a map view where the path lies on the city in red, with water bodies highlighted in purple.

3.2 Validation against airborne lidar-derived DEMs

While ICESat-2 is the best global elevation data source presently available, the fact that we train the CNN using it as ground truth means we risk misstating accuracy if ICESat-2 is our only validation. For instance, systematic errors present in ICESat-2 measurements could potentially have been learned by the neural network and propagated across the output dataset. Further, while we use all available and applicable ICESat 2 measurements to assess the DEMs, a small fraction (under 20%) of them was also used to train the CNN model, potentially skewing the results. Finally, since our results above (Figures 4 and 5) suggest that ICESat-2 itself contains significant error in densely-populated areas, we seek further validation to better understand CoastalDEM v2.1's performance in such regions. To resolve these concerns, we use two high-accuracy elevation DEMs derived from airborne lidar as ground truth in the error assessments.

In the United States, NOAA makes publicly available high-quality DEMs across the entire US coastline, which are classified to bare earth elevation, with vertical errors <20 cm RMSE [24]. These data are released at about 5 m horizontal resolution, which we downsample to 1 arc-second (about 30 m) using median filtering. Meanwhile, in Australia, Geospace Australia [25] collected and publicly released bare-earth lidar-derived elevation data along much of their coastlines. These data offer <16 cm vertical RMSE [26] at roughly 25 m horizontal resolution, which we also downsample to 1-arcsecond to match CoastalDEM v2.1.

National results for both the US and Australia are presented in Table 2. We focus on grid cells with population densities exceeding 1,000 per square kilometer. We can again see that CoastalDEM v2.1 exhibits median bias substantially closer to zero than each competing global DEM, and lower RMSE/LE90 values in the elevation band <5 m. CoastalDEM v2.1 even outperforms CoastalDEM v1.1 in the US, which is particularly notable, as the latter was specifically trained using NOAA's lidar-based US coastal DEMs as ground truth.

Figure 6 presents error maps in select cities in the US and Australia. Colors represent the difference between elevation according to the designed global DEM and the corresponding lidar-derived DEM. We can see how CoastalDEM v2.1 performs strongly relative to the other DEMs overall. Of special note is the region around Miami, FL – possibly due to dense development and vegetation, multi-meter biases are present in all past global DEM's across most of south Florida. CoastalDEM v2.1 is the first to have brought down and flattened errors here, without appearing to compromise accuracy in other areas of the US.

Finally, US state-level choropleths of median bias and RMSE for each global DEM can be found in Figures 7 and 8. Again considering points below 5 m and with >1,000 people per square kilometer, we find that CoastalDEM v2.1 median bias outperforms the competing global DEMs in all but three states (Maine, Rhode Island, and Pennsylvania).

These error statistics derived from DEMs based on airborne lidar are overall similar to the global results using data based on ICESat-2 satellite lidar. The airborne lidar ground-truth values were not used in computing CoastalDEM v2.1. The consistency in error assessment across testing approaches mitigates concerns about potential overfitting of our neural network model.

Table 2. Error statistics in the USA and Australia across each DEM and three elevation thresholds (5 m, 10 m, and 20 m). Airborne lidar-derived elevation data are used as ground truth. For each row, only pixels are included whose elevation falls below the elevation threshold (according to ground truth or the DEM), and whose population density exceeds 1K per square kilometer. Rows presenting CoastalDEM v2.1 statistics are in bold. All units are in meters

Nation	DEM	Max Elev	Mean	Median	RMSE	LE90
USA	**CoastalDEM v2.1**	**5**	**-0.12**	**-0.06**	**1.95**	**2.83**
USA	CoastalDEM v1.1	5	0.47	0.59	2.42	3.30
USA	NASADEM	5	1.89	1.66	3.60	5.49
USA	TanDEM-X	5	2.38	1.91	3.36	4.79
USA	MERIT	5	3.19	3.11	3.97	5.72
USA	AW3D30	5	3.65	3.54	5.06	6.94
USA	**CoastalDEM v2.1**	**10**	**-0.27**	**-0.20**	**2.11**	**3.09**
USA	CoastalDEM v1.1	10	0.16	0.23	2.58	3.50
USA	NASADEM	10	1.99	1.72	3.63	5.59
USA	TanDEM-X	10	2.49	1.98	3.49	5.02
USA	MERIT	10	2.90	2.82	3.71	5.35
USA	AW3D30	10	3.45	3.23	4.85	6.69
USA	**CoastalDEM v2.1**	**20**	**-0.36**	**-0.24**	**2.36**	**3.43**
USA	CoastalDEM v1.1	20	0.72	0.38	3.37	4.95
USA	NASADEM	20	2.02	1.72	3.71	5.68
USA	TanDEM-X	20	2.66	2.09	3.75	5.40
USA	MERIT	20	2.74	2.65	3.67	5.26
USA	AW3D30	20	3.36	3.14	4.87	6.70
Australia	**CoastalDEM v2.1**	**5**	**-0.23**	**0.10**	**2.49**	**3.63**
Australia	CoastalDEM v1.1	5	-0.24	-0.19	2.33	3.33
Australia	NASADEM	5	1.53	1.23	3.54	5.41
Australia	TanDEM-X	5	2.01	1.50	2.99	4.26
Australia	MERIT	5	2.51	2.43	3.98	5.54
Australia	AW3D30	5	2.97	2.67	4.06	5.43
Australia	**CoastalDEM v2.1**	**10**	**-0.75**	**-0.34**	**3.00**	**4.53**
Australia	CoastalDEM v1.1	10	-0.29	-0.35	2.71	3.71
Australia	NASADEM	10	1.80	1.51	3.67	5.54
Australia	TanDEM-X	10	1.98	1.46	2.99	4.25
Australia	MERIT	10	2.57	2.45	4.11	5.74
Australia	AW3D30	10	3.10	2.79	4.15	5.41
Australia	**CoastalDEM v2.1**	**20**	**-0.97**	**-0.51**	**3.55**	**5.29**
Australia	CoastalDEM v1.1	20	0.66	0.17	3.43	5.13
Australia	NASADEM	20	1.94	1.63	3.73	5.69
Australia	TanDEM-X	20	2.01	1.50	3.06	4.41
Australia	MERIT	20	2.62	2.50	4.31	6.15
Australia	AW3D30	20	3.24	2.97	4.22	5.51

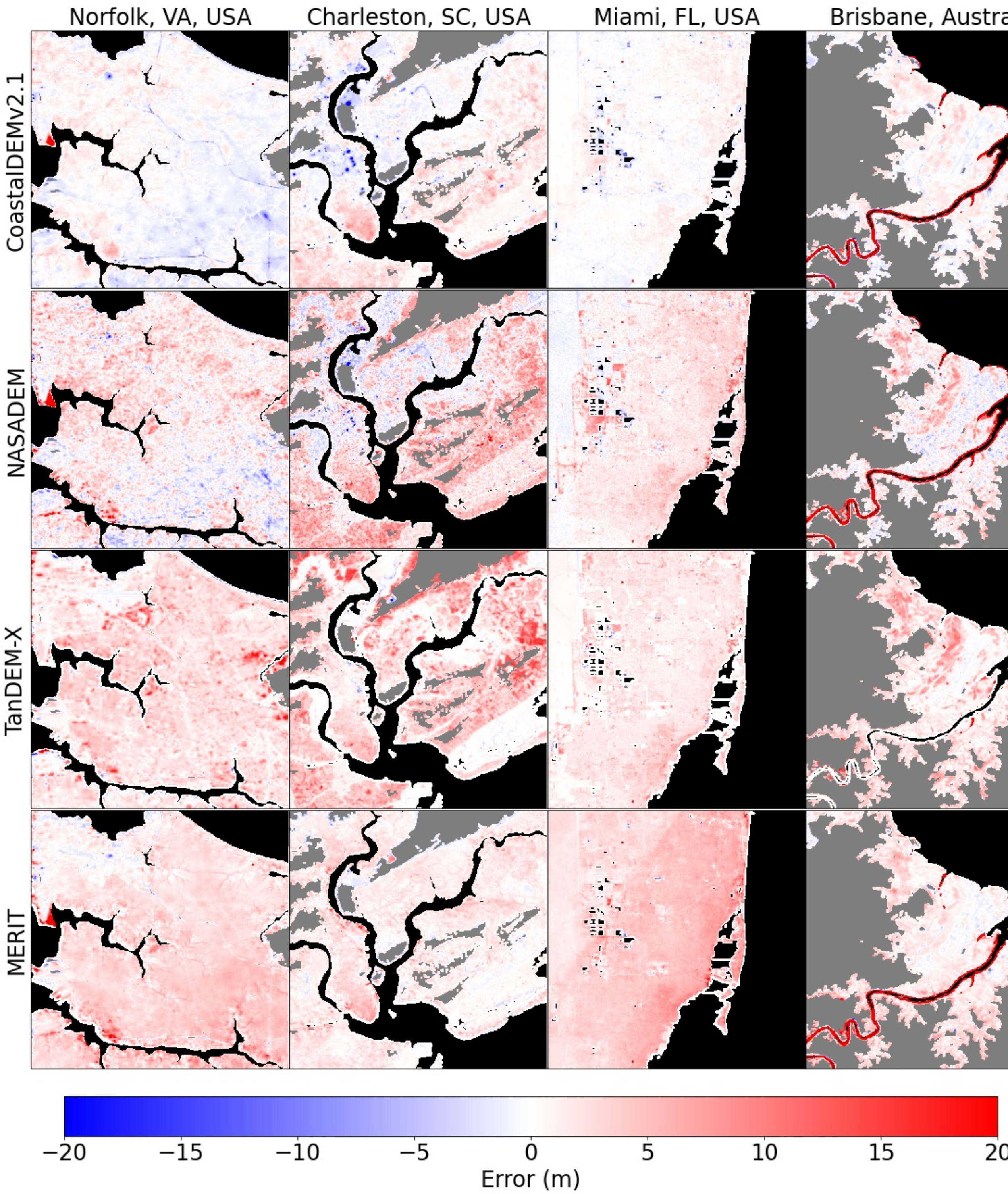

Figure 6. Maps of select US and Australian cities presenting the difference between global DEMs (CoastalDEM v2.1, NASADEM, TanDEM-X, and MERIT) and a lidar-derived DEM. Black areas represent existing water bodies, and gray areas represent pixels whose elevation exceeds 20m.

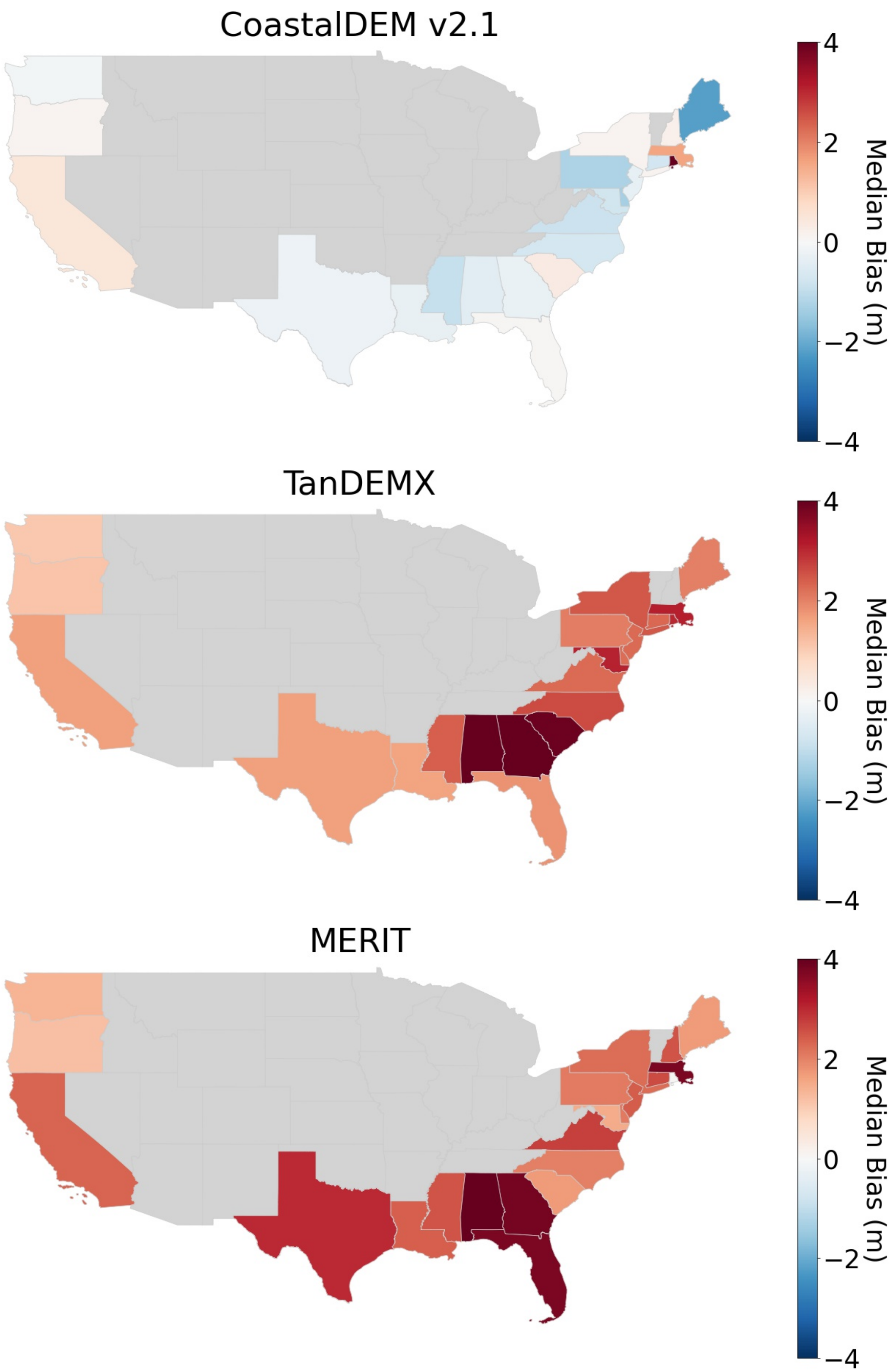

Figure 7. Choropleths presenting median bias under CoastalDEM v2.1, NASADEM, TanDEM-X, and MERIT in low-elevation regions across US states, using elevation data from NOAA's coastal lidar as ground truth. Only pixels whose elevations are lower than 5 m are considered. Only areas with population densities above 1,000 people per square kilometer are included.

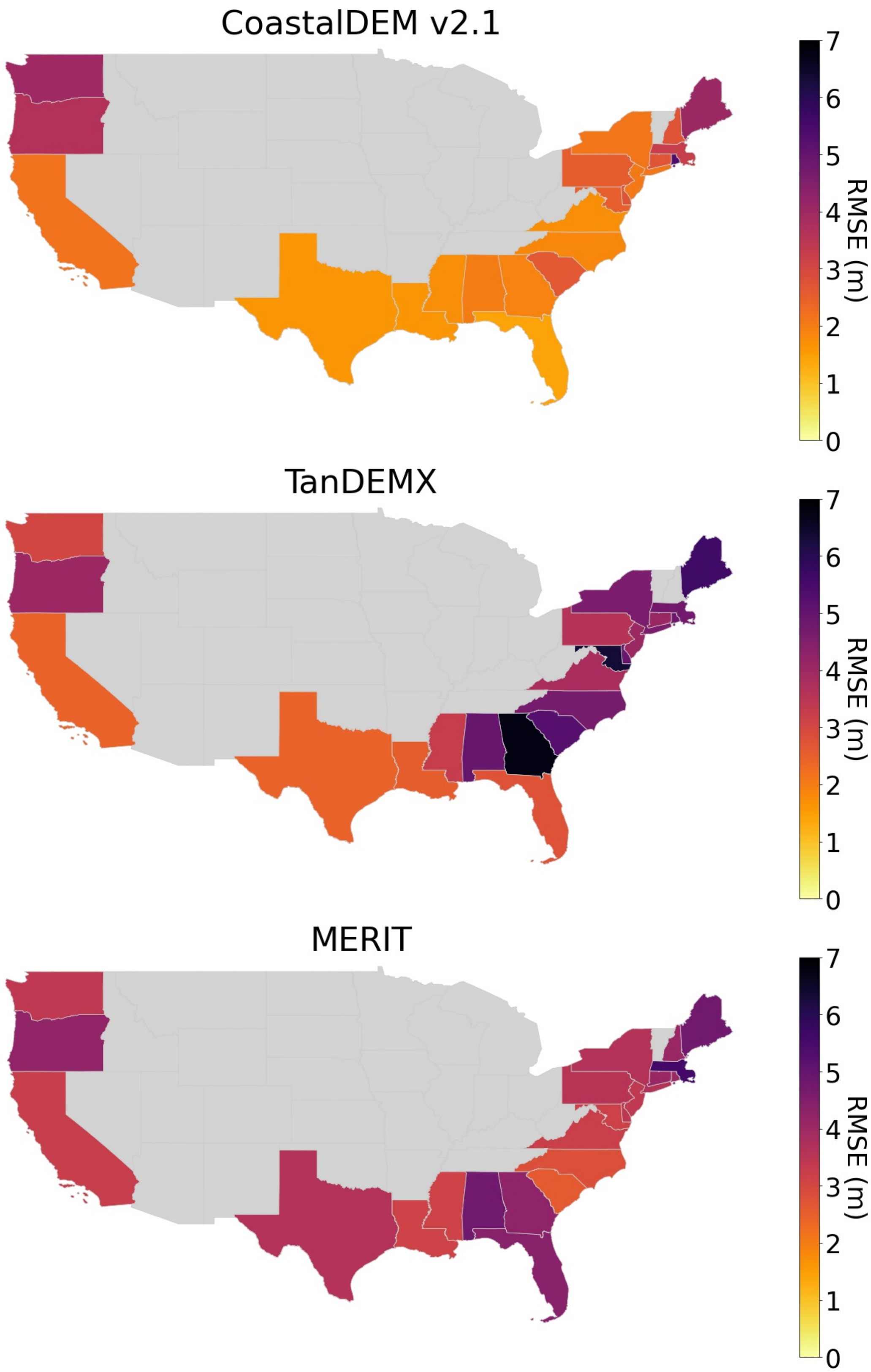

Figure 8. Choropleths presenting median RMSE under CoastalDEM v2.1, NASADEM, TanDEM-X, and MERIT in low-elevation regions across US states, using elevation data from NOAA's coastal lidar as ground truth. Only pixels whose elevations are lower than 5 m are considered. Only areas with population densities above 1,000 people per square kilometer are included.

4. Discussion

Climate Central has invested and will continue to invest significant resources and energy into improving CoastalDEM. As more and improved additional data sets become available, we intend to add them in improving the neural network.

As proud of CoastalDEM performance as we are, we acknowledge that neither CoastalDEM nor any global product is likely to ever outperform high-quality airborne lidar elevation data. While acknowledging the high current cost of comprehensive airborne lidar data collection, we strongly encourage coastal countries and allied entities to develop and freely release quality airborne lidar data for use in evaluating coastal flood risk – and in so doing, retire the need for higher-error global datasets like CoastalDEM.

We also acknowledge that the original SRTM data from which NASADEM and CoastalDEM were derived was collected in year 2000. The surface of the earth is changing with time, especially in areas prone to subsidence due to high rates of groundwater or fossil fuel extraction, or river-delta-sediment compaction. In addition, artificial earth works have the potential to alter the coastal risk profiles represented by SRTM, NASADEM, and CoastalDEM. This temporal quality calls for more up-to-date and regular refreshes of coastal DEMs with airborne lidar and new remote sensing capabilities that may become available.

5. Conclusion

CoastalDEM was developed to provide an improved, widely available, near-global digital elevation model for the primary purpose of evaluating coastal flood risk considering storms and sea level rise. With this use case in mind, elevations below 5 m are of particular interest as they span the range of most tides, storms, and projected sea-level-rise scenarios through the year 2100.

In addition, coastal areas with high population density are both areas where accurate vulnerability assessments are especially important and areas where the urbanized, built environment has challenged remote sensing technologies intended to measure ground elevations, resulting in material vertical bias that negatively impacts coastal flood risk assessments. Reducing vertical bias was the primary objective of creating CoastalDEM v1.1 and the objective of investing in the improvements with CoastalDEM v2.1. Reducing error scatter, measured by RMSE and LE90, was the secondary objective.

Performance data indicate vertical bias and error scatter are consistently and substantially reduced with CoastalDEM v2.1. With version 2.1, CoastalDEM further improves its reduced-bias performance lead over comparable global DEMs. CoastalDEM v2.1 is particularly strong in the elevation range below 5 m where coastal flood risk is acute and in densely populated regions where buildings and the built environment adversely affect other global DEMs. Near-zero bias means smaller elevation errors propagating into coastal flood analysis so critical to understanding the threat posed by sea level rise.

6. Availability

CoastalDEM v2.1 is available at 30 m and 90-m horizontal resolution by license from Climate Central via `https://go.climatecentral.org/coastaldem/`. No-cost, non-commercial licenses at 90 m horizontal resolution are available to qualified academic and research organizations (see Supplementary Dataset 2 for 90 m error statistics). With no-cost licenses available and vertical bias demonstrably near zero, CoastalDEM v2.1 is a superior global DEM for sea level rise and coastal flood risk assessments.

7. Methods

7.1 ICESat-2

NASA distributes ICESat-2 measurements as a large collection of HDF5 files. Here, we download the entirety of the L3A Land and Vegetation Height Version 3 (ATL08) dataset [27], which contains a number of elevation metrics at points 12 m apart along six beam tracks. For each point, we extract the fields *h_te_mean*, *latitude*, *longitude*, and *layer_flag*. The variable *h_te_mean* refers to the mean height returned by photons within the point's footprint, and *layer_flag* is a binary variable that is 1 if the point is likely covered by snow or clouds (points flagged as such are removed). Elevations are referenced to WGS84, which we convert to EGM96 using NOAA's VDatum tool [28]. All points in the entire ICESat-2 dataset meeting the given requirements and filters described in this report were used in the assessments.

7.2 CoastalDEM v2.1

Like CoastalDEM v1.1, CoastalDEM v2.1 uses an artificial neural network to predict errors present in another global DEM (here, NASADEM), using a number of global datasets as inputs. These inputs include elevation, population density, and vegetation density and height metrics. In total, CoastalDEM v2.1 ingests 7 independent input datasets to feed the model.

Instead of using a multilayer perceptron network as with CoastalDEM v1.1, CoastalDEM v2.1 employs a larger and more sophisticated convolutional neural network architecture [29]. CNNs are specifically designed for and are widely used in tasks involving imagery, making them a good fit for the raster datasets used here.

Where CoastalDEM v1.1 was trained using airborne lidar-derived elevation data as ground truth, in the US only, CoastalDEM v2.1 was instead trained using global ICESat-2 elevation measurements. While these data are not as accurate as airborne lidar, using such a global dataset reduces the risk of overfitting the model on US-centric data. Further, while CoastalDEM v1.1 was trained and defined only where SRTM elevations were between 1 and 20 m, CoastalDEM v2.1 is generated where NASADEM elevations are between -10 and 120 m, capturing a much larger domain.

Acknowledgments

The authors gratefully acknowledge Don Bain and Kelly Van Baalen for their thoughtful insights and comments on the manuscript. This research was supported by Climate Central and grants from the National Science Foundation (ICER-1663807) and the National Aeronautics and Space Administration (80NSSC17K0698).

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CoastalDEM® v2.1

A New, High-Accuracy and High-Resolution Global Coastal Elevation Model Trained on ICESat-2 Satellite Lidar

Climate Central has released CoastalDEM® v2.1[1], a near-global digital elevation model for ocean coastal areas. CoastalDEM v2.1 substantially reduces bias and error scatter, improving on its predecessor, CoastalDEM v1.1, making it the best-performing of all leading, publicly-available, global digital elevation models (DEMs) tested.

CoastalDEM was developed to provide a widely available, near-global digital elevation model for the primary purpose of evaluating coastal flood risk considering storms and sea level rise. With no-cost licenses available and vertical bias demonstrably near zero, CoastalDEM v2.1 is a superior global DEM for sea level rise and coastal flood risk assessments.

CoastalDEM v2.1 is the result of substantial new investment, new neural network architecture, and additional and improved input datasets. It is also informed by feedback from and interaction with many coastal flood risk practitioners and licensees of CoastalDEM from around the world.

Improved Coastal Elevations

In order to assess worldwide accuracy of global DEMs, Climate Central compared land elevation measurements from NASA's ICESat-2 as ground truth to CoastalDEM v2.1, and 5 other recently released, widely-available global DEMs: CoastalDEM v1.1, NASADEM, TanDEM-X, MERIT, and AW3D30. All DEMs were evaluated at their native horizontal resolutions, including both versions of CoastalDEM at 1 arc-second (≈ 30 m or about 98 feet).

CoastalDEM v2.1 virtually eliminates global median bias to less than 0.01 m (0.5 inch). CoastalDEM v2.1 outperforms the other global DEMs by a significant margin in the whole of the most important 0 - 5m elevation band, including all areas regardless of population density. For example, CoastalDEM v2.1 shows a mean vertical bias of -0.03 m (1.2 inches), CoastalDEM v1.1 has a mean bias of -0.06 m (2.4 inches), while the other DEMs show mean biases that range from 1.46 m (4.8 feet) to 2.41 m (7.9 feet) (Figure 1). A little more than an inch compared to almost 8 feet is huge when attempting to evaluate coastal flood risk due to sea level rise.

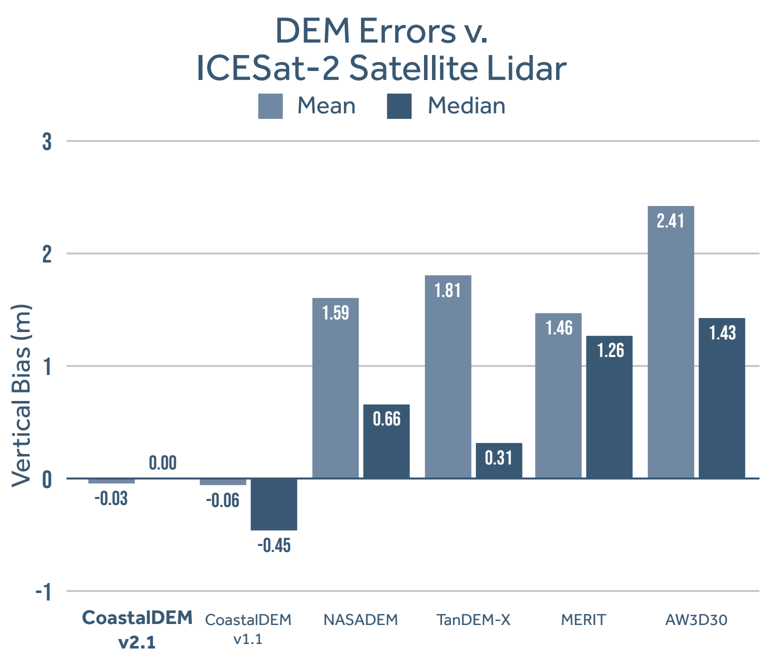

Figure 1: Global mean and median bias error statistics across each global DEM in the less than 5 m elevation band, and all population density bands. ICESat-2 is used as ground truth.

Performance Across Nations

Having a global satellite lidar elevation dataset from ICESat-2 affords the opportunity to evaluate CoastalDEM v2.1's performance across nations. Figure 2 uses Choropleth maps to show CoastalDEM v2.1's low vertical bias as compared to the other DEMs. These views give DEM users an indication of the relative confidence, in terms of bias when compared to satellite lidar ground truth from ICESat-2, they may have in CoastalDEM 2.1 versus the comparable global DEM's accuracy by region and country.

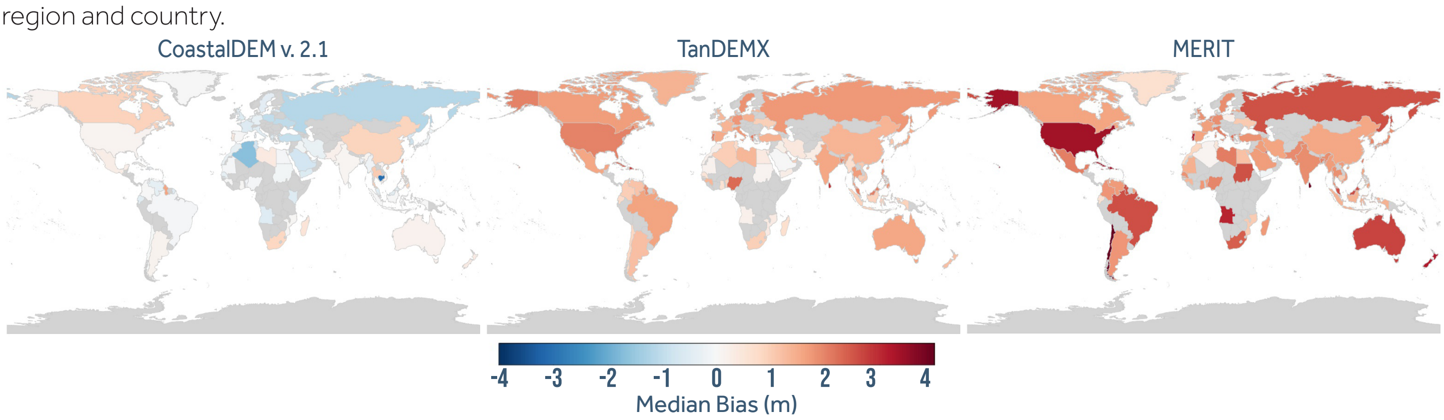

Figure 2: Choropleth maps presenting median bias under CoastalDEM v2.1, TanDEM-X, and MERIT in low-elevation regions across coastal nations, using ICESat-2 as ground truth. Only pixels with elevation < 5 m and population density >1000 people per square km are considered, and only nations with n ≥ 1000 of these pixels are evaluated.

AVAILABILITY

CoastalDEM v2.1 is available at 30 m and 90 m horizontal resolution by license from Climate Central via

https://go.climatecentral.org/coastaldem/

No-cost, non-commercial licenses at 90 m horizontal resolution are available to qualified academic and research organizations.

[1] S. Kulp and B. H. Strauss, "CoastalDEM v2.1: A High-accuracy and -resolution Global Coastal Elevation Model Trained on ICESat-2 Lidar"

ADVANCING EARTH AND SPACE SCIENCE

Earth's Future

RESEARCH ARTICLE
10.1029/2022EF002880

New LiDAR-Based Elevation Model Shows Greatest Increase in Global Coastal Exposure to Flooding to Be Caused by Early-Stage Sea-Level Rise

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Key Points:

- Calculations using radar-based global elevation models available to date have generally underestimated the extent of lowest coastal areas that are most exposed to sea-level rise (SLR)
- A recent lowland elevation model (global LiDAR lowland DTM (GLL_DTM_v2)) derived from only satellite LiDAR data is currently most accurate, we recommend such LiDAR data to be used in SLR impact assessments
- Applying this model we find that the greatest increase in coastal area below mean sea level will occur in the early stages of SLR, contrary to earlier assessments

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract The latest projections indicate that sea-level rise (SLR) is certain to exceed 2 m in coming centuries, and a rise by 4 m is considered possible. Radar-based land elevation models applied to date suggest that the increase of area below mean sea level, that is potentially exposed to permanent flooding, will accelerate as SLR proceeds, being relatively limited initially. However, applying new and more accurate satellite LiDAR elevation data we find the opposite pattern, with the fastest increase in the area of exposed land occurring in the early stages of SLR. In one-third of countries most of this increase will be caused by the first meter of SLR and in nearly all within the first 2 m. We conclude that in many regions the time available to prepare for increased exposure to flooding may be considerably less than assumed to date, and that better elevation data will support timely preparations. The global LiDAR lowland DTM (GLL_DTM_v2) elevation data set developed for this assessment is available in the public domain.

Plain Language Summary The latest sea-level rise (SLR) projections indicate that future sea levels are certain to exceed 2 m and a rise by 4 m is considered possible. Land elevation models applied to date suggest that the increase of land area below sea level will be limited at first but will go faster when SLR continues. When we apply a new and more accurate elevation model we find the opposite pattern, with the fastest increase during the early stages of SLR. In one-third of countries most of this increase will be during the first meter of SLR, and in almost all within the first 2 m. We conclude that in many regions the time available to prepare for increased exposure to flooding may be considerably less than assumed to date, and that better elevation data will support timely preparations. The global LiDAR lowland DTM (GLL_DTM_v2) elevation data set developed for this assessment is available in the public domain.

1. Introduction

The latest (6th) Assessment Report of the International panel for Climate Change (IPCC, 2021) provides sea-level rise (SLR) projections not only for 2100 but also for the centuries beyond. While SLR in the low carbon emission scenario (SSP1-2.6) is unlikely to exceed 0.62 m by 2100, this could increase to over 3 m by 2300. In the high emission scenario (SSP5-8.5) SLR could approach 2 m by 2150 (0.98–1.88 m) and 7 m by 2300. In addition, rates of land subsidence caused by drainage and groundwater abstraction are of the same order as SLR in many coastal regions and in some urban areas even much higher (Herrera-García et al., 2021; Hooijer & Vernimmen, 2021; Nicholls et al., 2021; Syvitski et al., 2009). It therefore is likely that relative SLR (hereafter: SLR), which includes land subsidence, will in most densely populated coastal areas reach 1 m well before 2150, and 4 m in centuries to come.

For climate change adaptation, the relevance of SLR lies mostly in increased coastal exposure to flooding, which may translate either in actual flooding or in increased cost of adaptation measures. The timing of mean sea level (MSL) exceeding land elevation as SLR proceeds may be the most meaningful parameter to exposure projections especially in parts of the world with limited coastal protection, as this implies the possibility of permanently losing land to the sea. Determining this timing requires application of a global digital elevation model (GDEM). However, existing GDEMs have been found to be too inaccurate for SLR related assessments, amongst others because they are created using radar data that is unable to penetrate dense vegetation and also measures elevations of non-ground features in built-up areas (Gesch, 2018; Hooijer & Vernimmen, 2021).

With the recent (2018) launch of Earth observation satellites carrying LiDAR sensors that are known to have much higher vertical accuracy than earlier radar data sources, a new generation of global elevation models is evolving.

The first version of such a model (Global LiDAR Lowland DTM; GLL_DTM_v1) at 0.05-degree (~5 km near the equator) horizontal resolution was published in 2020 (Vernimmen et al., 2020) and applied to estimate global coastal land area distribution below 2 m + MSL (Hooijer & Vernimmen, 2021). The ICESat-2 LiDAR data is used because it is the most accurate of the new satellite LiDAR datasets at present (Liu et al., 2021). As these data continued to come in, a higher horizontal resolution elevation model (GLL_DTM_v2) at 0.01-degree (~1 km near the equator) is developed and presented here that is suitable for refined analyses.

The radar-based SRTM was the first GDEM and is still most commonly used in global coastal SLR impact assessments to date (e.g., Brown et al., 2021; Jevrejeva et al., 2018; Nicholls et al., 2021; Schuerch et al., 2018; Syvitski et al., 2009) despite having low vertical accuracy by any measure (Vernimmen et al., 2020). The MERIT GDEM is also often used in global and regional assessments (Haasnoot et al., 2021; Kirezci et al., 2020) but while having somewhat improved accuracies compared to its source SRTM it still cannot be used with high confidence in SLR assessments (Gesch, 2018; Hooijer & Vernimmen, 2021). A more recent development is the use of ICESat-2 LiDAR data to improve vertical accuracy of NASADEM (CoastalDEM v2.1; Kulp & Strauss, 2021) and Copernicus DEM (FABDEM; Hawker et al., 2022).

As existing GDEMs all generally overestimate surface elevation, especially in forested and built-up areas (Gesch, 2018; Hawker et al., 2022), they have in common that the rate of increase of land below MSL would in most regions be expected to accelerate as SLR progresses, with the increase in flood exposure being underestimated initially. We have applied the new GLL_DTM_v2 to investigate whether this relatively limited initial impact followed by an acceleration is a valid expectation or an artefact of GDEM inaccuracy.

Our assessment considers only the position of the land surface relative to MSL, that is, we quantify potential exposure to flooding rather than vulnerability. Whether and how the land will increasingly flood due to SLR depends on factors such as the presence and effectiveness of flood defenses as well as trends in extreme storm surges, rainfall and extreme river levels.

The manuscript is organized as follows. We first present the GLL_DTM_v2 GDEM with an accuracy assessment including a comparative validation of other GDEMs commonly applied in flood risk assessments. We then apply GLL_DTM_v2 to analyze the global distribution and timeline patterns of land exposure to SLR between 1 and 4 m and compare the results with those using the other GDEMs.

2. Materials and Methods

2.1. Generating GLL_DTM_v2

Land elevation is determined from the second version of the GLL_DTM_v2 at 0.01-degree horizontal resolution (i.e., ~1 km near the equator). This version is a refinement of the GLL_DTM_v1 described by Vernimmen et al. (2020) at 0.05-degree horizontal resolution. We now apply more data filtering steps to remove outliers in the ICESat-2 data that can have a greater impact at this higher resolution as fewer data segments are available in each grid cell. The land mask is improved to include the mangrove distribution data set of Global Mangrove Watch (Bunting et al., 2018) for the year 2016 and excludes cells which consist of water for more than 50% according to the ASTER water body data set (Abrams et al., 2020).

The model is created from version 5 of the ICESat-2 ATL08 geophysical data product provided by the National Snow and Ice Data Center (Neuenschwander et al., 2021). The data collection period of 14 October 2018–8 June 2022 used here exceeds the planned 3-year operational lifespan of ICESat-2 (Neuenschwander & Pitts, 2019) and ensures near-optimal data coverage from this source. We resampled the terrain height ("h_te_median" variable) from 58.6 million 100 m data segments along all 203,351 currently available ICESat-2 near-polar ground tracks to a 0.01-degree land grid by calculating the median elevation of 100 m data segments within each 0.01-degree grid cell. Before resampling, all data segments with a median terrain height below −7 m + MSL are removed because they are considered unrealistic in coastal lowland, noting that −7 m + MSL is the lowest land elevation value found in pumped polders in the Netherlands. To limit the effect of remaining outliers on median elevation values only grid cells with 5 or more 100 m data segments are retained. Of all GLL_DTM_v2 grid cells, 21.6% are without data segments and 6.8% have 1 to 4 data segments. From the 71.6% of grid cells with data segments (on average 24 segments per grid cell), outliers are identified and removed if the respective cell has at least four neighbors with data, is not bordered by water cells and the elevation deviates more than 2 m from the median elevation of the immediate 8 (both in cardinal and ordinal directions) neighbor grid cells (2.4% of data cells, 1.7% of all grid

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cells). If the respective cell has less than 4 neighbors and is not bordered by water cells, elevation values below 0 m + MSL are also considered outliers and are removed (0.2% of data cells, 0.1% of all grid cells). Values for the resulting set of "no data" grid cells (30.3% of the cell total after outlier removal) are interpolated between data cell values through inverse distance weighted (IDW) interpolation. The implemented IDW method only takes into account the nearest raster cells that have a value in all directions up to a distance of 10 km (99.9% of grid cell center points with data are within 10 km of at least one neighbor, 85.2%, 98.8%, and 99.6% of grid cell center points are within 1, 3 and 5 km, respectively). We apply a power of 2 to determine the weight from distance.

The ICESat-2 data are referenced to the WGS84 ellipsoid. The ICESat-2 data are transformed to the EGM96 geoid using the 5-min version available from https://sourceforge.net/projects/geographiclib/files/geoids-distrib/. To convert the vertical datum from the EGM96 geoid to MSL, we use the mean dynamic ocean topography (MDT), which is the difference between the mean sea surface and the geoid. Following Muis et al. (2017), we use an estimate by Rio et al. (2014), who calculated the MDT by combining geodetic data (i.e., altimetric mean sea surface over the period 1993–2012 and an accurate geoid) with in situ data, at 0.25-degree resolution (http://www.aviso.altimetry.fr/). For referencing to MDT on land, the closest value at sea is used.

2.2. Global Digital Elevation Models (GDEMs)

Nine near-global DEMs that are available in the public domain with some of them previously being applied in global and local assessments of flood risk (Brown et al., 2018, 2021; Haasnoot et al., 2021; Jevrejeva et al., 2018; Kirezci et al., 2020; Koks et al., 2019; Neumann et al., 2015; Nicholls et al., 2021; Schuerch et al., 2018; Zhang et al., 2019), are compared with the GLL_DTM_v2. These are SRTM v4.1 (Jarvis et al., 2008), MERIT-DEM (Yamazaki et al., 2017), CoastalDEM v2.1 (Kulp & Strauss, 2021), TanDEM-X (Rizzoli et al., 2017), Copernicus DEM GLO-30 v2020-02 (Airbus, 2020), FABDEM (Hawker et al., 2022), NASADEM v1 (Crippen et al., 2016), ASTER GDEM v3 (Abrams et al., 2020), and ALOS AW3D30 v3.2 (Tadono et al., 2016). The first seven are radar-based or apply a machine-learning combination of radar and ICESat-2 LiDAR data (CoastalDEM v2.1, FABDEM), while the latter two are optical-based. The first four have a horizontal resolution of 3-arc- seconds (~90 m at the equator) while the latter five have a horizontal resolution of 1-arc-second (~30 m at the equator). They cover areas varying from 60°N to 56°S (SRTM, NASADEM and CoastalDEM v2.1), 90°N–60°S (MERIT), 80°N–60°S (FABDEM), 82°N–82°S (AW3D30), 83°N–83°S (ASTER), 84°N–84°S (TanDEM-X) to 84°N–90°S (Copernicus DEM).

All GDEM elevations except TanDEM-X, Copernicus DEM and FABDEM are orthometric heights referenced to the EGM96 geoid. TanDEM-X is referenced to the WGS84 ellipsoid and transformed to the EGM96 geoid. Both Copernicus DEM and FABDEM are referenced to the WGS84 ellipsoid and have orthometric heights referenced to the EGM2008 geoid. All GDEMs are converted from the EGM96 geoid to MSL using the MDT (Rio et al., 2014) and from EGM2008 geoid to MSL using the CNES-CLS18 MDT (Mulet et al., 2021). After transformation, the GDEMs are resampled to the same 0.01-degree grid as GLL_DTM_v2, by calculating the median of elevation values at native resolution within each 0.01-degree grid cell.

2.3. GDEM Vertical Accuracy Assessment by Comparison With Local DTMs

The vertical accuracy of the GLL_DTM_v2 and other GDEMs is determined through validation against existing well-described and accurate local DTMs for major lowland regions across three continents are used: (a) The Everglades in the USA, (b) The Netherlands lowlands, and (c) the Mekong Delta in Vietnam; the first two of these are based on airborne LiDAR, whereas the Mekong Delta data set is generated from a topographic map based on field surveys. The latter DTM is reported to have a mean deviation of 0.2 m and mean absolute deviation of 0.6 m against local benchmarks (Minderhoud et al., 2019), whereas for the two LiDAR-derived DTMs vertical accuracies are not provided in scientific publications. However, the LiDAR data used in the creation of the DTMs are within 0.245 m (FEMA, 2022) and 0.15 m (AHN3, 2022) at 95% confidence levels for The Everglades and The Netherlands, respectively. The validation datasets are further described in Vernimmen et al. (2020).

In addition to validation at the GLL_DTM_v2 horizontal resolution of ~1 km, validation for the most accurate GDEMs (Table 1) is also carried out at native horizontal resolution of ~90 m (CoastalDEM v2.1) and ~30 m (FABDEM) for which GLL_DTM_v2 and the local DTMs are resampled to the same native horizontal resolution as the respective GDEMs. For comparison, GLL_DTM_v2 is downscaled to ~90 m (12×12 cells within original

Table 1
Vertical Accuracy of GLL_DTM_v2 and Existing GDEMs for Areas Below 10 m + MSL (as Compared to Local DTMs), at 0.01-Degree Horizontal Resolution

	ICESat-2 LiDAR-based	Radar-based (ICESat-2 LiDAR corrected)		Radar-based					Optical-based	
Statistical measure	GLL_DTM_v2	CoastalDEM 2.1	FABDEM	SRTM	MERIT	NASADEM	TanDEM-X	CopernicusDEM	ASTER	AW3D30
Everglades NOAA sea-level rise DEM (14,121 km²)										
Within 0.5 m [%]	86.6	34.7	50.2	1.1	7.6	22.7	23.7	36.3	0.5	1.3
Within 1 m [%]	95.9	63.4	73.6	2.7	19.6	43.2	39.9	58.3	1.1	3.9
ME [m]	0.05	−0.03	0.66	4.44	2.05	0.83	1.80	1.34	7.98	4.12
MAE [m]	0.27	0.86	0.86	4.45	2.15	1.57	1.82	1.45	7.99	4.12
RMSE [m]	0.44	1.06	1.36	4.96	2.59	2.16	2.67	2.40	8.69	4.75
Netherlands AHN3 (19,047 km²)										
Within 0.5 m [%]	78.8	48.6	77.6	19.0	17.2	44.7	71.9	63.3	2.3	27.6
Within 1 m [%]	92.2	80.5	95.8	43.5	45.8	73.2	81.8	88.1	4.6	52.5
ME [m]	−0.09	−0.38	−0.21	−0.69	0.96	0.39	0.52	0.10	8.44	−0.14
MAE [m]	0.37	0.66	0.39	1.27	1.20	0.91	0.67	0.67	8.51	1.22
RMSE [m]	0.65	0.93	0.61	1.63	1.46	1.52	1.56	1.37	9.42	1.76
Mekong Delta TOPODEM (38,510 km²)										
Within 0.5 m [%]	74.5	49.8	68.2	32.2	12.8	33.3	47.9	66.3	0.1	30.2
Within 1 m [%]	96.2	78.9	86.9	61.2	33.5	61.3	74.1	81.2	0.2	56.1
ME [m]	0.16	0.03	0.23	−0.11	1.31	−0.33	0.88	0.36	6.55	0.21
MAE [m]	0.37	0.64	0.52	1.01	1.42	0.97	0.93	0.70	6.55	1.11
RMSE [m]	0.48	1.00	1.19	1.53	1.78	1.53	1.69	1.59	7.21	1.69
Mean of 3 areas (71,678 km²)										
Within 0.5 m [%]	80.0	44.4	65.3	17.4	12.5	33.6	47.9	55.3	1.0	19.7
Within 1 m [%]	94.8	74.3	85.4	35.8	32.9	59.2	65.3	75.9	2.0	37.5
ME [m]	0.04	−0.13	0.23	1.21	1.44	0.30	1.07	0.60	7.65	1.40
MAE [m]	0.34	0.72	0.59	2.24	1.59	1.15	1.14	0.94	7.68	2.15
RMSE [m]	0.53	0.99	1.06	2.70	1.94	1.74	1.97	1.79	8.44	2.74

Note. Presented are mean elevation differences (ME = mean error, MAE = mean absolute error) between the local DTM, GLL_DTM_v2, and existing GDEMs, as well as RMSE and the area percentage differences within ranges −1 to +1 m and −0.5 to +0.5 m. Based on this analysis, CoastalDEM 2.1 and FABDEM are the most accurate after GLL_DTM_v2, for coastal land below 10 m + MSL.

0.01-degree grid) and ∼30 m (36 × 36 cells) resolution. The local DTMs are resampled by calculating the median of elevation values at native resolution within each ∼90 and ∼30 m grid cell.

We also determine vertical accuracy separately for built-up and forested areas at different horizontal resolutions. A grid cell is considered built-up if more than 50% is classified as built-up according to the World Settlement Footprint 2015 data set at 10 m horizontal resolution (Marconcini et al., 2020). A cell is considered forested if more than 50% is classified as having a canopy height of more than 3 m according to the Global Forest Canopy Height 2019 data set derived from GEDI satellite LiDAR data at 30 m horizontal resolution (Potapov et al., 2021). Since the extent of GEDI (51.6°N–51.6°S) does not fully cover The Netherlands, forest validation is only carried out over The Everglades and the Mekong delta.

2.4. Current Coastal Lowland Population Distribution

Global population distribution in 2020 is determined from the UN adjusted Gridded Population of the World database (Centre for International Earth Science Information Network (CIESIN) & Columbia University, 2018).

2.5. Calculation of Elevation Below 2 m + MSL Within Major Deltas of the World

Using SRTM, Syvitski et al. (2009) identified 33 deltas which have large areas below 2 m. Considering the low vertical accuracy of the SRTM data used in that study we calculated for the same deltas the areas below 2 m + MSL using GLL_DTM_v2, to demonstrate the effect of applying improved elevation data. The spatial extent of these deltas is obtained from https://www.globaldeltarisk.net/data.html referring to Tessler et al. (2015).

2.6. Coverage of Analysis and Area Calculations

All analyses are within the SRTM extent (60°N–56°S) to allow comparison amongst GDEMs. All areas presented are calculated applying the equal area projection (Brodzik et al., 2014). Area calculations under projected SLR level apply the "bathtub" approach (Gesch, 2018), that is, coastal water levels are projected inland across the floodplain, not considering flood defenses or other barriers.

3. Results and Discussion

3.1. Accuracy of GLL_DTM_v2 Compared to Other GDEMs

Validated at 0.01-degree (∼1 km) horizontal resolution against local elevation models covering 71,678 km^2 (2.3% of global coastal land below 10 m + MSL) for The Everglades (USA), The Netherlands, and Mekong Delta (Vietnam), GLL_DTM_v2 has a Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) of 0.34 and 0.53 m (Table 1, Figure S1 in Supporting Information S1), respectively, compared to 0.59–7.68 m/0.99–8.44 m for other published GDEMs (Table 1). Furthermore, we find that GLL_DTM_v2 is accurate within 0.5 and 1 m over 80.0/94.8% which is higher than the 44.4/74.3% and 65.3/85.4% achieved by CoastalDEM v2.1 and FABDEM over the combined validation areas (Table 1).

On average, MAE improves from 0.33 to 0.32 m and RMSE from 0.54 to 0.50 m after outlier removal (Table S1 in Supporting Information S1). Interpolation of "no data" grid cells has limited impact on overall accuracy (MAE from 0.32 to 0.34 m and RMSE from 0.50 to 0.53 m; Table S1, Figure S2 in Supporting Information S1), supporting the use of the applied IDW interpolation method in lowland areas that tend to be flat.

3.2. Accuracy of Other GDEMs, and Implications to SLR Impact Assessments

The most commonly applied GDEM, SRTM, has an MAE of 2.24 m and RMSE of 2.70 m when resampled to 0.01-degree resolution for coastal land below 10 m + MSL (Table 1). Despite major improvements compared to SRTM and other earlier products, considerable inaccuracies remain in CoastalDEM v2.1 and FABDEM with MAE/RMSE of 0.72/0.99 m and 0.59/1.06 m at the 0.01-degree resolution and 0.86/1.18 m and 0.75/1.29 m at native resolution of ∼30–90 m (Table S2 in Supporting Information S1). It should be noted that vertical GDEM accuracy needs to be at least half the SLR increment to assess exposed land areas at the 68% confidence level

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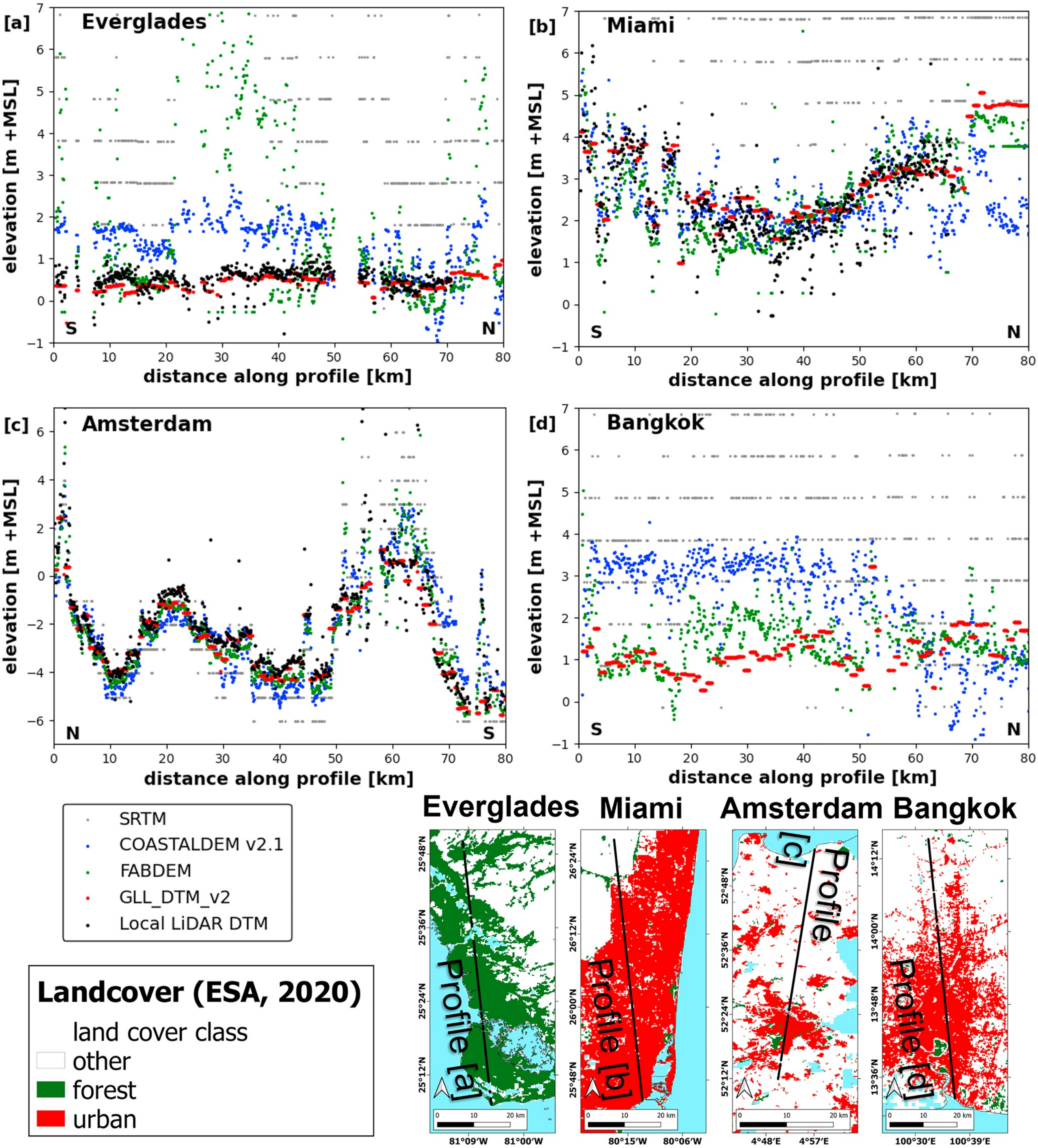

Figure 1. (a, c) Elevation cross sections along ICESat-2 flight lines covering (a) mangrove forest and coast in the Everglades (USA) (b) Miami (USA), (c) Amsterdam (Netherlands) and (d) Bangkok (Thailand). Location of the cross sections is shown with in the background European Space Agency Climate Change Initiative Land Cover for 2020, reclassified to forest and urban cover (ESA, 2020). Shown are GLL_DTM_v2 and selected GDEMs at native resolution (SRTM and CoastalDEM v2.1 at ~90 m and FABDEM at ~30 m) as well as local airborne LiDAR data for Everglades and Miami (NOAA Sea Level Rise DEM, 2020) and Amsterdam (AHN3, 2019). Note that NOAA LiDAR data are not available beyond ~70 km along the profile.

(Gesch, 2018). With RMSEs above 1 m, these GDEMs therefore allow confident quantification of exposed area for SLR exceeding 2 m whereas GLL_DTM_v2 allows this for SLR around 1 m.

3.3. Effect of Horizontal Resolution and Land Cover on Vertical Accuracy

While the 0.01-degree (~1 km) horizontal resolution of GLL_DTM_v2 is lower than the horizontal resolution of other GDEMs we demonstrate that the impact of horizontal resolution on vertical accuracy is limited in coastal lowlands, as these tend to be flat. At resampled horizontal resolutions of ~1 km, ~90, and ~30 m, we find MAE values for GLL_DTM_v2 of 0.34/0.43/0.45 m, and RMSE of 0.53/0.68/0.71 m, respectively (Table S2, Figure S3 in Supporting Information S1), which indicates higher accuracy than the other GDEMs at any resolution (Table S2 in Supporting Information S1). This is especially true for forested areas and dense urban areas where GLL_DTM_v2 outperforms all GDEMs by at least a factor 2 (Table S3, Figure S4 in Supporting Information S1). This is also illustrated in Figure 1 where elevation profiles over four areas demonstrate that GLL_DTM_v2 closely resembles the topography as derived from local airborne LiDAR DTMs where available, while CoastalDEM v2.1 has major outliers both upwards and downwards especially over urban areas, and major vegetation signals remain visible over forest (Everglades) in both CoastalDEM v2.1 and FABDEM. Moreover, vertical accuracy of GLL_DTM_v2 is relatively consistent across land cover types with MAE values of 0.34, 0.30, and 0.56 m, and RMSE of 0.53 m, 0.46 and 0.80 m for all land, forested and built-up areas, respectively (Tables S2–S4 in Supporting Information S1). This consistency amongst land cover types is lower for the other GDEMs, with a range in MAE from 0.13 to 0.98 m and RMSE from 0.53 to 1.83 m for CoastalDEM v2.1 and FABDEM, respectively (Tables S2–S4 in Supporting Information S1).

3.4. Estimates of Exposed Area Applying GLL_DTM_v2 and Other GDEMs

Application of GLL_DTM_v2 results (within SRTM extent) in global areas below MSL of 123 thousand km^2 by 2020 (SLR = 0 m) and 482/937/1,586 thousand km^2 after 1, 2, and 4 m SLR, respectively (Figures 2 and 3, Table S5 in Supporting Information S1), compared to 7–179, 7–376, 9–790, and 42–1,554 thousand km^2 for existing published GDEMs for these same amounts of SLR (Figure 2, Tables S6–S10 in Supporting Information S1). Within the full global extent, pole to pole, the area below 4 m + MSL is 1,749 thousand km^2, indicating that 9.3% of global coastal lowland is not covered by SRTM-based GDEMs.

The increase in coastal land area below MSL according to GLL_DTM_v2 (within SRTM extent) is 359 thousand km^2 over the first meter of SLR (from 123 to 482 thousand km^2) and 455 thousand km^2 over the second meter of SLR (from 482 to 937 thousand km^2). Combined, the total area below MSL after 2 m of SLR is 1.2–2.4 times higher when compared to seven GDEMs that are fully or partly radar-based (Figure 2, Table S5–S9 in Supporting Information S1). After 2 m of SLR the increase in coastal land area below MSL gradually decreases until a total area of 1,586 thousand km^2 at 4 m of SLR, 1.9 times higher when compared to SRTM. Acceleration of land area below MSL as SLR progresses is found using SRTM, MERIT, NASADEM and the optical-based GDEMs,

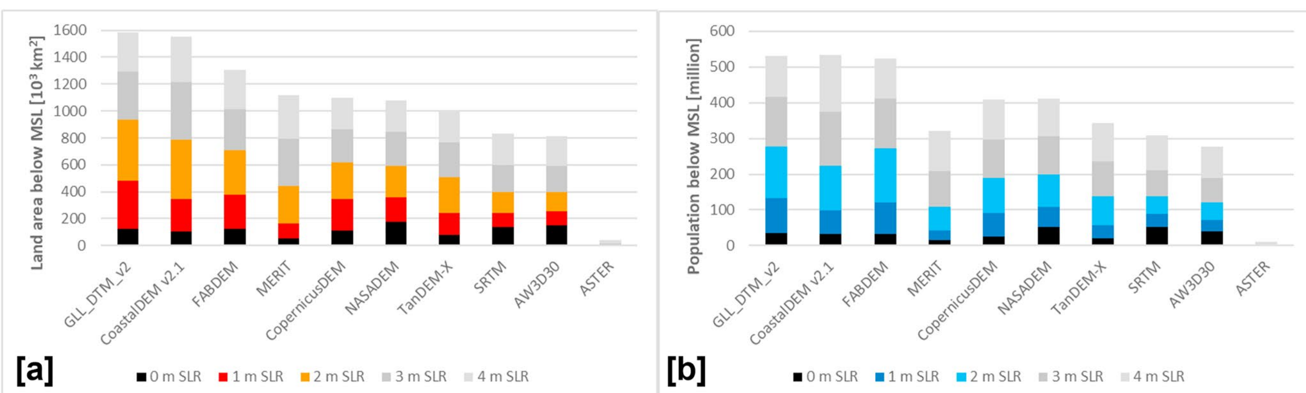

Figure 2. (a) Land area and (b) population below MSL after 0 (2020), 1, 2, 3, and 4 m of sea-level rise (SLR) for GLL_DTM_v2 as compared with GDEMs (all within SRTM extent). Population data from (Centre for International Earth Science Information Network (CIESIN) & Columbia University, 2018). In Tables S5–S10 in Supporting Information S1 details for 26 countries with over 2.0 million people currently (2020) living on land below 4 m + MSL. Sources are ranked by total land below MSL at 4 m SLR.

whereas the other four radar-based GDEMs also show a gradual deceleration in land area below MSL after 2 m of SLR but not to the same degree as GLL_DTM_v2. This demonstrates that the least accurate GDEMs yield the least realistic assessments of coastal land exposed to SLR.

Of the 26 countries with the greatest populations on land below 4 m + MSL (Table S2 in Supporting Information S1), GLL_DTM_v2 demonstrates that 5 (19%) and 24 (92%) will have over 50% of such land below MSL after 1 and 2 m SLR respectively, whereas application of SRTM would yield 4 (15%) and 12 (46%) countries (Figure 3). For some individual countries the differences are even more striking. Nigeria for example, will see a 16,242 km^2 increase of land below MSL over the first meter of SLR and 2,198 km^2 over the fourth according to GLL_DTM_v2 (Figure 4, Table S5 in Supporting Information S1), whereas SRTM suggests this would be 58 and 1,998 km^2 respectively, that is, a sharp acceleration from a far lower base (Figure 4, Table S6 in Supporting Information S1). Similar major differences are seen for Bangladesh, Brazil, Cameroon, Indonesia, Malaysia, Mozambique, Philippines, Sri Lanka and Thailand, with SRTM and most derived GDEMs yielding areas below MSL that are unrealistically low overall, but especially in the first meter of SLR (Tables S6–S10 in Supporting Information S1). The recent GDEMs that used ICESat-2 LiDAR data to correct NASADEM (CoastalDEM v2.1) and Copernicus DEM (FABDEM) yield similar patterns as GLL_DTM_v2 for many countries, but

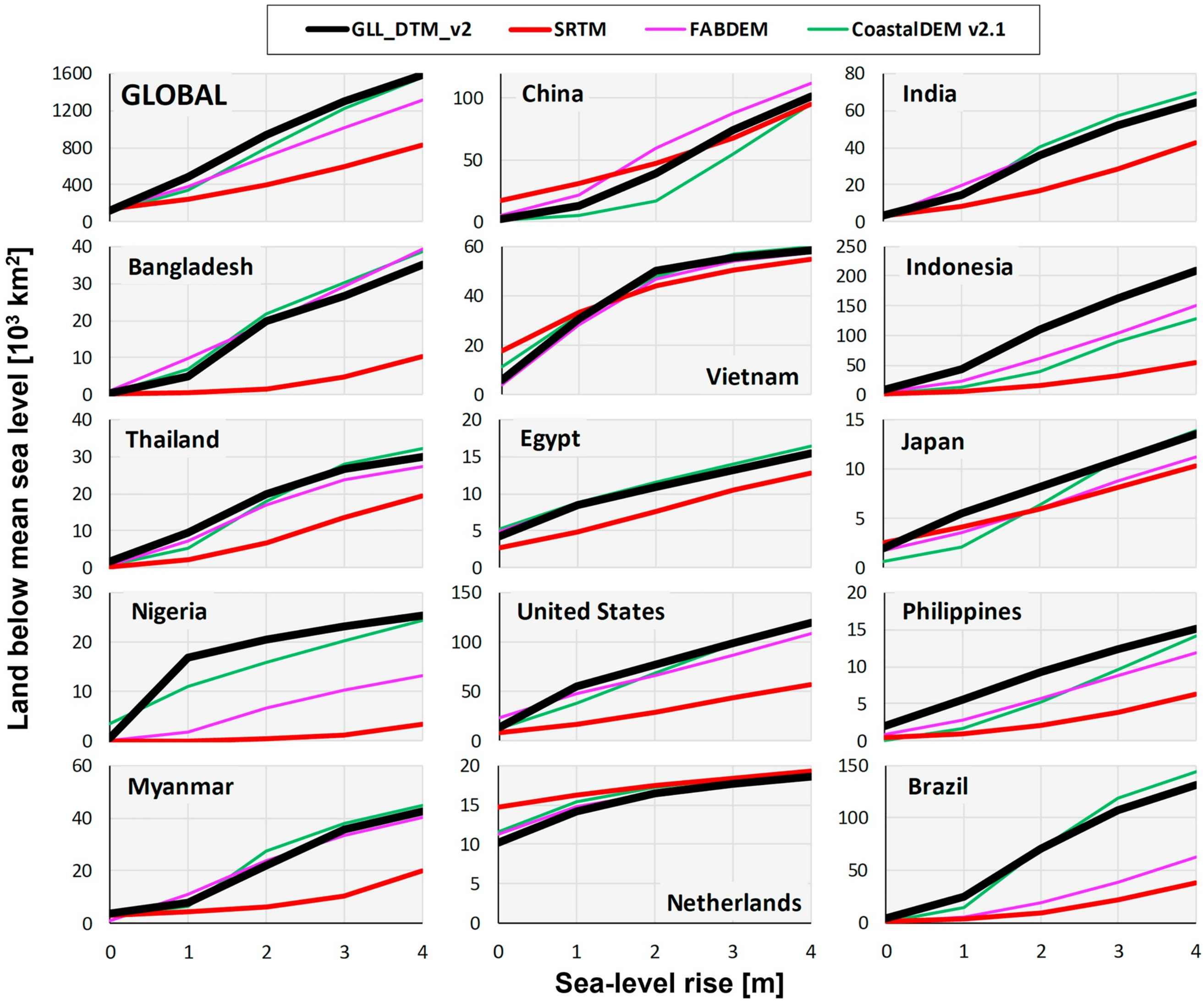

Figure 3. Land area below MSL as SLR progresses. Shown are selected countries with highest lowland population (Table S5 in Supporting Information S1), for the ICESat-2 LiDAR-based GLL_DTM_v2, the most commonly used SRTM and the most recently published CoastalDEM v2.1 and FABDEM that we find to be the most accurate GDEMs after GLL_DTM_v2 (Table 1).

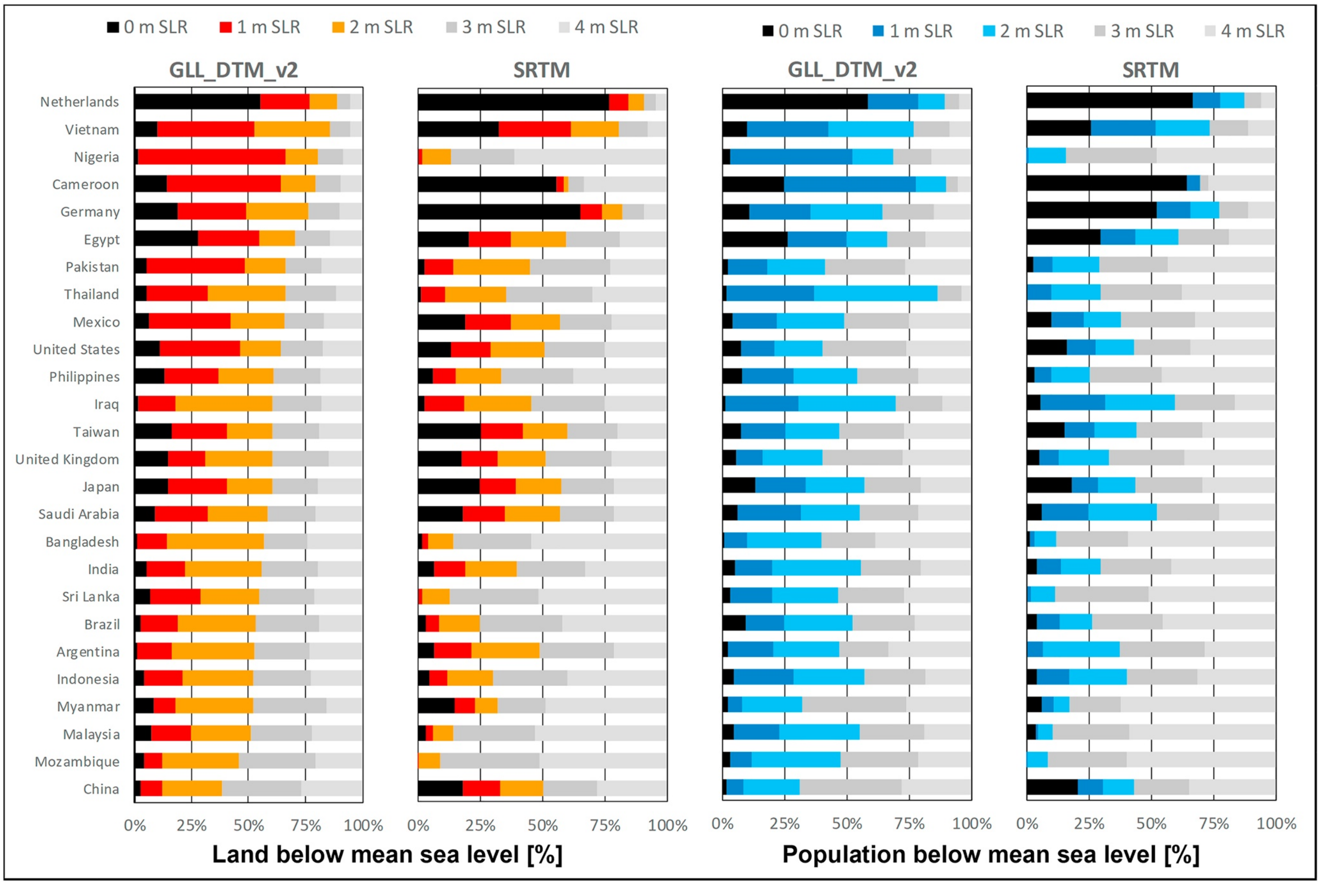

Figure 4. Land and population below mean sea level after different increments of sea-level rise (SLR). Countries shown have at least 2.0 million people currently (2020) living on land that is below 4 m above MSL (GLL_DTM_v2; Table S5 in Supporting Information S1), for GLL_DTM_v2 and SRTM (Table S6 in Supporting Information S1). Countries are ranked by percentage of land below MSL at 2 m SLR according to GLL_DTM_v2. The "0 m SLR" scenario presents the 2020 situation as determined by both elevation datasets.

differences exist here too, most notably in countries with relatively extensive areas of lowland forest (including mangrove) such as Brazil, Nigeria, Philippines and Indonesia, but in the case of CoastalDEM v2.1 also in China and Japan (Figure 3, Figure S5 in Supporting Information S1). Apart from forested areas, we also find differences in urban areas as illustrated for Bangkok where CoastalDEM v2.1 is higher compared to both GLL_DTM_v2 and FABDEM (Figure 1, Figures S5–S6 in Supporting Information S1). Overall, GLL_DTM_v2 is lower than CoastalDEM v2.1 and FABDEM, for 51.0% and 58.3% of the coverage area, respectively. While CoastalDEM v2.1 and FABDEM are generally somewhat higher than GLL_DTM_v2, there are also areas where they are lower (Figure S6 in Supporting Information S1).

The examples of SRTM and other (partly) radar-based GDEMs yielding the greatest underestimation of area below MSL after SLR are mostly of developing countries that rely largely on publicly available global data for risk assessments. Governments of such countries could wrongly conclude that SLR is not of immediate concern to them if they use these GDEMs for flood risk projections. It is worth noting that these GDEMs also sometimes yield unrealistically high areas to be currently below MSL, for instance in The Netherlands and Vietnam (Figures 3 and 4), that are not supported by local more accurate DTMs (Table 1), however this is less likely to negatively affect flood risk assessments as these countries tend to use the local DTMs.

Patterns in population below MSL largely reflect patterns in area below MSL, but are enhanced in some countries. Thailand for example, will see 66% of the land area and as much as 87% of population that is currently below 4 m + MSL becoming below MSL at 2 m SLR, including most of the greater Bangkok area. The corresponding figures for China show the opposite difference with 38% of land and as little as 31% of population (Figure 4, Table S5 in Supporting Information S1).

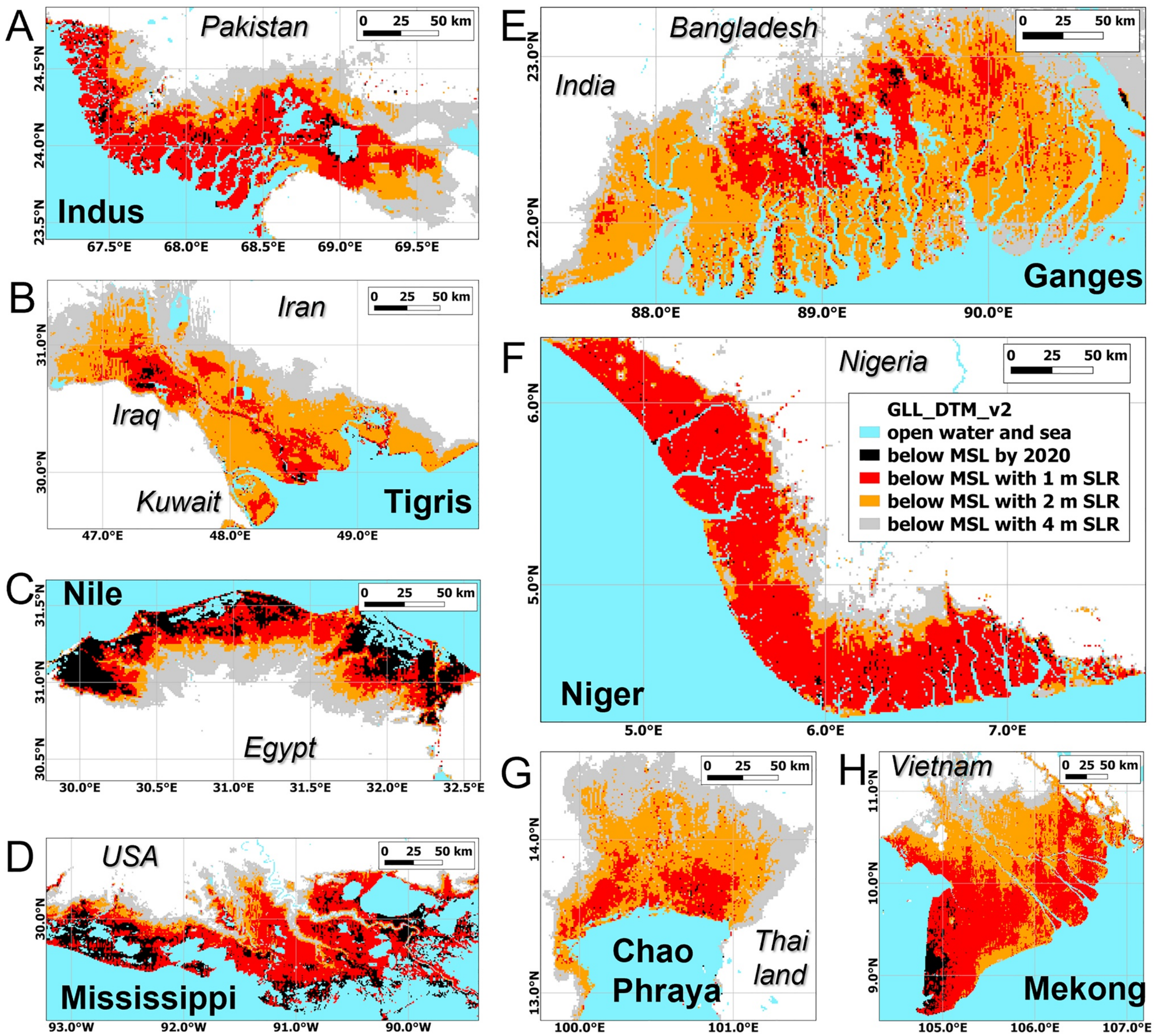

Figure 5. Examples of eight deltas that could potentially be largely flooded with 1 m of SLR, and almost entirely at 2 m SLR. Indicated is the area below mean sea level (MSL) currently (SLR = 0 m) and with 1, 2, or 4 m of SLR. (a) Indus, (b) Tigris, (c) Nile, (d) Mississippi, (e) Ganges, (f) Niger, (g) Chao Phraya, and (h) Mekong.

3.5. Preparation Time for SLR May Be Less Than Expected in Many Countries

The effect on SLR impact projections of using GLL_DTM_v2 instead of earlier GDEMs can be illustrated by comparing the results for 33 deltas highlighted by Syvitski et al. (2009) for having large areas below 2 m + MSL considered to be at high flood risk. Applying GLL_DTM_v2 the overall area below 2 m + MSL across these deltas is 219,621 km^2 whereas it is 91,660 km^2, or 2.4 times less, according to SRTM (Figure 5; Table S1 in Supporting Information S11). In some individual deltas, such as Niger, Irrawaddy and Chao Phraya, the area below MSL yielded by GLL_DTM_v2 is over 5 times the SRTM result. This implies that for these deltas the urgency of flood exposure by SLR and land subsidence is also considerably greater than could be known before satellite LiDAR data became available, demonstrating the importance of using accurate LiDAR-based DEMs when preparing for SLR.

4. Conclusions

The implication of the coastal elevation patterns revealed using a satellite LiDAR-based GDEM is that the world as a whole will see considerably more coastal land below sea level sooner than was indicated by earlier radar-based GDEMs, and consequently will have less time to prepare for the impacts. However, the large regional differences revealed by the same data, suggest that countries will see very different timeline patterns in exposure to flooding. Countries or regions where land will be below MSL sooner than expected, may be encouraged to start preparing for SLR faster. This also highlights the need for high-accuracy local DEMs to plan better. Detailed adaptation and mitigation planning should not rely solely on coarser resolution global elevation data.

This study confirms that assessing areas most vulnerable to SLR will require application of elevation models that are much more accurate than those available until recently (Gesch, 2018; Hooijer & Vernimmen, 2021). Such data are now becoming available globally from satellites carrying LiDAR instruments. Further refinement to horizontal resolutions higher than the ∼1 km offered by GLL_DTM_v2 are possible by merging sparse satellite LiDAR information with the Copernicus DEM radar data that are found to be least inaccurate amongst uncorrected radar-based GDEMs (Table 1), as was done by FABDEM (Hawker et al., 2022). However, while the CoastalDEM v2.1 and FABDEM products demonstrate that combining radar and satellite LiDAR data does achieve improved vertical accuracy compared to earlier products, overall vertical error remains almost twice as high as in GLL_DTM_v2. Particularly in extensive areas of lowland forest and other dense vegetation, and in some urban areas, terrain elevation presented by these products often remains too high (Figure 1, Figures S5 and S6 in Supporting Information S1). In coastal lowlands, that are usually very flat with limited vertical elevation variation over short distances, a lower resolution can therefore result in improved vertical accuracy. For some applications, certainly at the global and regional scale, we propose that achieving optimum vertical accuracy may have higher priority than aspiring to the highest possible horizontal resolution at the cost of vertical accuracy. Although we have demonstrated the overall higher accuracy of GLL_DTM_v2, also compared to higher resolution products, the lower resolution of the product means that there will be limitations in using it for coastal lowlands that are less than a kilometer wide, as well as for some urban areas that have man-made smaller-scale surface topography. The greatest advantage of using GLL_DTM_v2 will therefore be achieved in large deltaic plains and in densely vegetated areas.

The GLL_DTM_v2 elevation data set at ∼1 km horizontal resolution will suffice for such applications and is available in the public domain. It is created in a transparent and replicable way that allows others to build on this work and further refine the model in future as more satellite LiDAR data become available.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The data used in this study are available on Zenodo under https://doi.org/10.5281/zenodo.6534526.

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Erratum

In the originally published article, the columns in Table 1 were incorrectly formatted. In the Data Availability Statement, the link to the Zenodo site was incorrectly listed as https://doi.org/10.5281/zenodo.7228643. The columns in Table 1 have been correctly formatted, and the link in the Data Availability Statement has been corrected to https://doi.org/10.5281/zenodo.6534526. This may be considered the authoritative version of record.

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Exploratory sea level projections for the UK to 2300

SC150009

Flood and Coastal Erosion Risk Management Research and Development Programme

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Professor Doug Wilson
Director, Research, Analysis and Evaluation

Executive summary

Background

This project has developed new projections of mean and extreme sea levels to the year 2300. This information is critical for long-term planning and the UK's adaptation response to increasing sea levels. Flood and coastal erosion risk management authorities, developers and infrastructure operators all need information about the likely impacts of climate change on sea levels so they can incorporate appropriate levels of protection into their designs. Some assets and developments have expected life spans that go beyond the end of the 21st century. These schemes need information about how extreme sea levels and waves may change over longer timescales.

In 2016 the Environment Agency, Scottish Environmental Protection Agency, Natural Resources Wales, the Welsh Government and the Department for Food, Environment and Rural Affairs commissioned the Met Office to develop new projections of sea level rise for the UK out to the year 2300. The work complements the updated projections of mean and extreme sea level rise to 2100 developed under the UK Climate Projections 2018 (UKCP18) project.[1] The data associated with this work are available through the UKCP18 data portal and the results are incorporated in associated UKCP18 project publications. The project also carried out a literature review of past and future expected impacts of climate change on waves.

Approach

The Met Office extended the sea level rise projections to 2300 by constructing a simpler version of the model used in the UKCP18 projections. The model was based on phase 5 of the coupled model inter-comparison project (CMIP5) projections to ensure consistency between the 2100 and exploratory 2300 marine projections. Future extreme sea levels for 46 UK tidal gauges were produced, derived from time series of mean sea level rise to 2300 and current best estimates of the return periods for observed sea levels. The research assessed low, medium–low and high emissions of greenhouse gas concentration trajectories or 'representative concentration pathways' (RCPs) as adopted by the Intergovernmental Panel on Climate Change for its fifth Assessment Report.

Key findings

- Sea level will continue to rise to 2300 under all climate change projections. The global average sea level ranges at 2300, relative to a 1981-2000 baseline period, are:

  - 0.6–2.2m (low emissions scenario, RCP 2.5)
  - 0.9–2.6m (medium–low emissions scenario, RCP 4.5)
  - 1.7–4.5m (high emissions scenario, RCP 8.5)

  The UK land surface is tilting, with Scotland rising and southern England sinking, such that greater rates of sea level rise will be experienced in the south of England.

- By 2300, sea water levels with a current probability of only 0.01% of occurring in any one year, could be experienced every year.

[1] www.metoffice.gov.uk/research/collaboration/ukcp

- There is limited consensus on how waves will be affected by climate change. The research indicates there may be a reduction in average offshore wave height, but extreme offshore wave heights may increase. The sea level rise element of climate change is expected to be a greater threat to coastal defences than changes in offshore waves.
- Higher sea levels will cause waves to carry greater energy to the shore, which will have an impact on sea defences. Nearshore waves will be higher and break later, increasing flood water volumes in areas already affected by coastal flooding. This will have implications for the expected lifetime and continued performance of coastal defences, likely requiring greater investment in flood and coastal erosion risk management to maintain current defence lines and standards of protection.
- There is a large degree of unquantified uncertainty with these projections, which must be recognised by anyone using the research's findings. The uncertainty is associated mostly with the potential for accelerated ice loss from the West Antarctic ice sheet.

How will the research be used?

This research will be useful for infrastructure operators and those managing the risks of our changing climate. A detailed assessment of the results is presented both in this project and in the UKCP18 Marine Report published by the Met Office in 2018. The underlying dataset is publically available from the UKCP18 data portal (www.metoffice.gov.uk/research/collaboration/ukcp/download-data).

Contents

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1 Introduction

1.1 Background

In 2016, the Met Office was commissioned by the Environment Agency, Scottish Environmental Protection Agency, Natural Resources Wales, the Welsh Government and the Department for Food, Environment and Rural Affairs (Defra) to develop new projections of sea level rise for the UK out to the year 2300. The work described in this report complements the updated projections of mean and extreme sea level rise to 2100 developed under the UK Climate Projections 2018 (UKCP18) project. The data associated with this work are available through the UKCP18 data portal[2] and the results incorporated in associated UKCP18 project publications. The project also carried out a literature review of past and future expected impacts of climate change on waves.

Information on projections of mean and extreme sea levels to the year 2300 is critical for long-term planning and the UK's adaptation response to increasing sea levels. Flood and coastal erosion risk management authorities, developers and infrastructure operators all need information about the likely impacts of climate change on sea levels so they can incorporate appropriate levels of protection into their designs. Some assets and developments have expected life spans that go beyond the end of the 21st century. These schemes need information about how extreme sea levels and waves may change over longer timescales.

1.2 Drivers of sea level change

This section presents background information on the various drivers of sea level change and how these can interact with each other. Much of the information is taken from the UKCP18 Marine Report (Palmer et al. 2018b), which includes additional discussion. Changes in sea level occur due to a broad range of geophysical processes that operate on different spatial scales and time scales. A schematic of the different sea level components that can contribute to sea level change, including sea level extremes, and how these fit together, is presented in Figure 1.1.

[2] www.metoffice.gov.uk/research/collaboration/ukcp/download-data

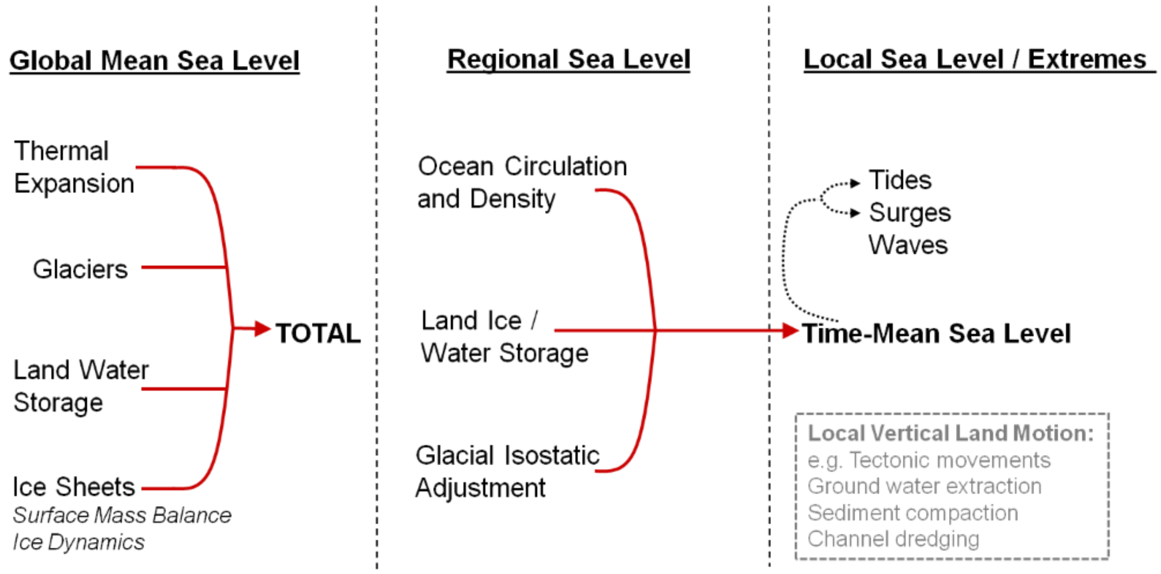

Figure 1.1 Summary of the major contributors to changes in: global mean sea level, regional sea level, and local sea level and extremes

Notes: The black dashed lines indicate the potential interaction between local time-mean sea level and tide and surge characteristics.
The grey text highlights some of the non-climatic processes that can give rise to sea level change through vertical land motion.
Source: Palmer et al. (2018b, Figure 2.1.1).

1.2.1 Drivers of changes in global mean sea level

Changes in global mean sea level (Figure 1.1, left column) arise due to either a change in the average ocean density (for example, if the ocean becomes less dense, the volume increases and the global mean sea level rises) or a change in global ocean mass through the input or removal of water.

For global mean sea level, changes in density are overwhelmingly dominated by thermal expansion (that is, the tendency for seawater to become less dense as temperature increases). Under anthropogenic climate change, freshwater input to the ocean arises from the loss of land-based ice from mountain glaciers and the Greenland and Antarctic ice sheets.

Following the methods described in Chapter 13 of the Fifth Assessment Report (AR5) by the Intergovernmental Panel on Climate Change (IPCC) AR5 (Church et al. 2013), the sea level projections presented here include both surface mass balance (that is, the balance between accumulated snowfall and ice melt) and ice dynamics (that is, changes in rate of discharge in active ice flows) for each of the ice sheets.

Finally, changes in land water storage – through processes such as groundwater extraction and reservoir impoundment – make a substantial contribution to the change in global mean sea level. The full list of mass (or freshwater) inputs to the ocean considered in the projections presented here is:

- glaciers
- Greenland ice sheet surface mass balance
- Greenland ice sheet ice dynamics
- Antarctic ice sheet surface mass balance

- Antarctic ice sheet ice dynamics
- changes in land water storage

1.2.2 Drivers of changes in regional sea levels

On regional scales, a number of additional processes come into play (Figure 1.1, middle column).

Firstly, changes in local seawater density and/or ocean circulation leave their imprint in the shape of the sea surface. While temperature effects dominate density changes for global mean sea level, locally both changes in temperature and salinity are important factors. Due to the differing responses among climate models the spatial pattern of change associated with this term in climate change projections is highly uncertain (which is accounted for in our sea level projections).

Secondly, changes in land-based ice and land water storage are also associated with spatial patterns of regional sea level change. These spatial patterns depend on the geographic distribution of the mass changes and arise from:

(i) the solid Earth response to changes in local mass loading

(ii) the effect of the mass redistribution on the Earth's gravity field

(iii) the combined effect of (i) and (ii) on the Earth's rotation (see, for example, Tamisiea and Mitrovica 2011)

This report refers to the combined effect of these 3 processes as 'mass fingerprints'.

Thirdly, the ongoing response of the Earth system to the last deglaciation (which terminated approximately 10,000 years ago) – referred to as glacial isostatic adjustment (GIA) – gives rise to a spatial pattern of relative sea level change across the UK with peak magnitudes of approximately ±1mm per year. This pattern is characterised by a relative sea level fall that is centred on western Scotland and a relative sea level rise to the south of the mainland UK, with maximum values in the south-east and south-west. While vertical land movement is the dominant contribution to this pattern, gravitational and rotational effects also make a substantial contribution. Due to the long adjustment timescales associated with GIA, the rates of change are time-invariant for the sea level projections presented in this report.

The superposition of these 3 different spatial elements determines the relative sea level change for a given location in the time-mean sea level projections presented in Section 3.1).

Changes in sea level extremes (Figure 1.1, right column) are discussed in Section 3.2.

1.3 Approach used in this project

The method for exploratory extended sea level projections is described in Palmer et al. (2018a) and the UKCP18 Marine Report (Palmer et al. 2018b). An important aspect of these extended projections is that they can be used seamlessly with the UKCP18 21st century sea level projections. However, the extended projections are exploratory and there is a greater degree of unquantified uncertainty than there is with the UKCP18 21st century projections. In particular, there is deep uncertainty associated with potential changes in the dynamic ice input to the ocean from the West Antarctic ice sheet on these extended time horizons (see, for example, DeConto and Pollard 2016), which could lead to substantially larger sea level rise.

The extended projections presented in this report therefore provide illustrative example projections against which vulnerabilities can be assessed. Note that work to develop updated ‘high end/H++’ scenarios for sea level rise over the coming centuries is being explored at the Met Office in collaboration with the wider research community.

The assessment of potential changes in extreme coastal water levels makes use of the updated coastal flood boundary conditions for UK mainland and islands (Environment Agency 2019). The coastal flood boundary conditions represent our best understanding of current coastal water level extremes and the updated dataset includes the severe winter storms of 2013 to 2014. This project combined the return level curves from 46 tide gauge locations with the extended sea level projections to illustrate how coastal extreme water levels may change under future sea level rise over the coming centuries. The report focuses on a few example locations that span a range of behaviour around the UK and the plan is to release a full dataset for users as part of the UKCP18 data portal.

The final element of this report is a review of the literature on projected wave changes for the North Atlantic and North Sea with results pertinent to the UK coastline. This work includes a synthesis of the recent wave modelling results presented in Bricheno and Wolf (2018) and the related work presented in the UKCP18 Marine Report (Palmer et al. 2018b).

1.4 Structure of the report

Section 2 presents an overview of the extended sea level projections to 2300.

Section 3 illustrates and discusses future return levels of extreme water for example sites around the UK.

Section 4 summarises results of past and projected 21st century wave climate in the North Atlantic and North Sea.

2 Data and methods

One of the main limitations to exploring climate change projections beyond 2100 is the availability of climate model simulations from phase 5 of the Coordinated Modelling Intercomparison Project (CMIP5) beyond this time horizon. Although climate change scenarios based on representative concentration pathways (RCP) were specified out to 2300 (see Section 2.1), few modelling centres carried out these extended simulations due to the computational expense. The method presented here makes use of a simple two-layer climate model (Section 2.2) to extend individual CMIP5 model simulations of global surface temperature and global thermal expansion to 2300. These projections of global surface temperature and thermal expansion are then combined with additional assumptions to provide global and regional sea level projections to 2300 that are traceable to the CMIP5 model ensemble. This report presents a brief overview of the data and methods used. Full details of the two-layer model simulations are available in Palmer et al (2018a). The methods used to translate these simulations into global and regional sea level projections are described in the UKCP18 Marine Report (Palmer et al. 2018b).

2.1 Extended RCP scenarios

The extended sea level projections are based on 3 of the 4 extended RCP climate change scenarios described by Meinshausen et al. (2011). These extended scenarios were devised by making simple assumptions based on either smoothly stabilising concentrations or constant emissions for the period post 2100. The 3 scenarios are the same as used in the UKCP18 21st century sea level projections and can be thought of as:

- a ‘low’ emissions scenario (RCP2.6)
- a ‘medium–low’ emissions scenario (RCP4.5)
- a ‘high’ emissions scenario (RCP8.5)

Figure 2.1 presents time series of the atmospheric greenhouse gas concentrations and global surface temperature response (based on the two-layer model simulations).

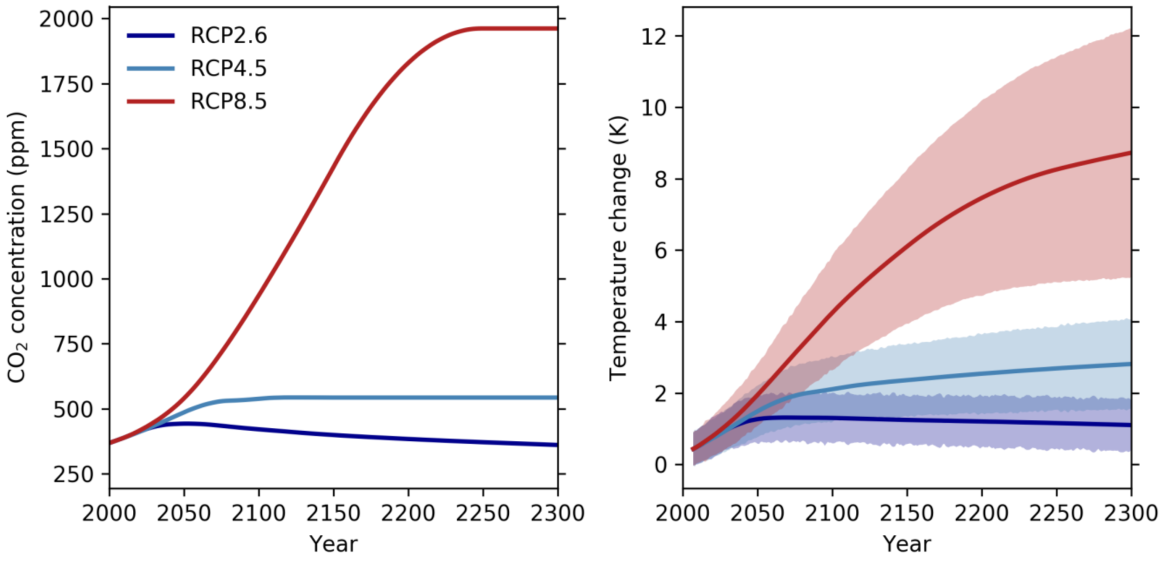

Figure 2.1 Left: Carbon dioxide concentrations for the coming centuries under 3 extended RCPs. Right: Associated global mean surface temperature change for the two-layer model ensemble used in the extended sea level projections

Notes: Temperature change is shown relative to the 1981 to 2000 average.
The shaded regions represent the 5th to 95th percentile range, assuming a normal distribution.
Source: UKCP18 Marine Report (Palmer et al. 2018b, Figure 4.1).

2.2 Two-layer model

The time-mean sea level projections presented in this report make use of a simple two-layer energy balance model (Figure 2.2) to emulate the response of the more complex CMIP5 climate models. Essentially, this means using a much simpler and computationally efficient model to estimate what each CMIP5 model would have done if it had run on to 2300.

The two-layer model is a well-established modelling framework and has been used in numerous previous studies as an aid to understanding the climate change response in complex global climate models (for example, CMIP5). The two-layer model projections make use of parameter settings developed for individual CMIP5 models by Geoffroy et al (2013a, 2013b). These are used to produce an ensemble of two-layer model simulations, factoring in the limitations in the two-layer model performance using a subset of CMIP5 model simulations that were run to 2300 (see Palmer et al. 2018a for details).

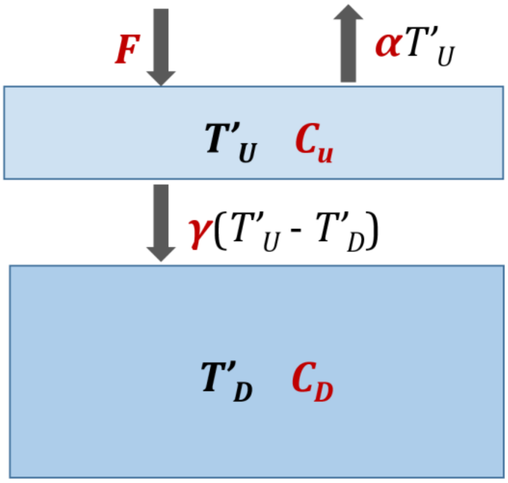

Figure 2.2 Schematic representation of the two-layer energy balance model

Notes: The model consists of an upper ocean layer, which represents surface temperature and the atmosphere and a deep ocean layer.
F is the radiative forcing at top-of-atmosphere, *α* is the climate feedback parameter, *γ* is the heat exchange coefficient.
T'_U and T'_D represent temperature perturbations from a pre-industrial equilibrium state.
Prognostic variables are indicated in black and tuneable parameters are indicated in red.
Source: Palmer et al (2018b, Figure A1.2.1)

Global surface temperature is a prognostic variable in the two-layer model and is therefore directly output from the model. Time series of global ocean heat content change (informed by the layer temperatures and heat capacities) are converted to the sea level rise due to global thermal expansion using the CMIP5 model-specific coefficients documented by Lorbacher et al. (2015).

Overall, the two-layer model ensemble projections of global surface temperature and thermal expansion compare favourably with CMIP5 climate model ensemble projections over the 21st century and also individual CMIP5 model simulations that are available to 2300 (Figures 2.3 and 2.4).

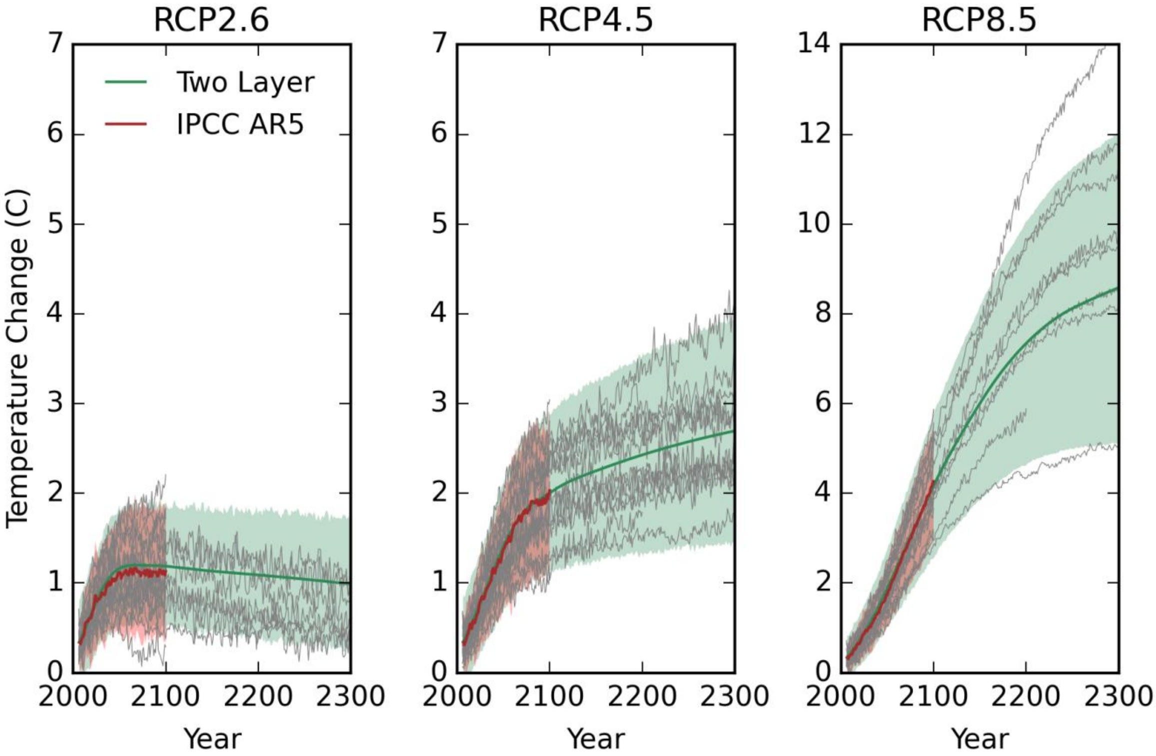

Figure 2.3 Ensemble projections of global mean surface temperature change relative to a baseline period of 1986 to 2005

Notes: Time series include:

- the 21 member IPCC AR5 ensemble (red, shaded regions indicate 5th to 95th percentile range)
- the 14 member two-layer model ensemble (green, shaded regions indicate 5th to 95th percentile range)
- individual CMIP5 model projections (grey lines)

Source: Palmer et al (2018b, Figure A1.2.2)

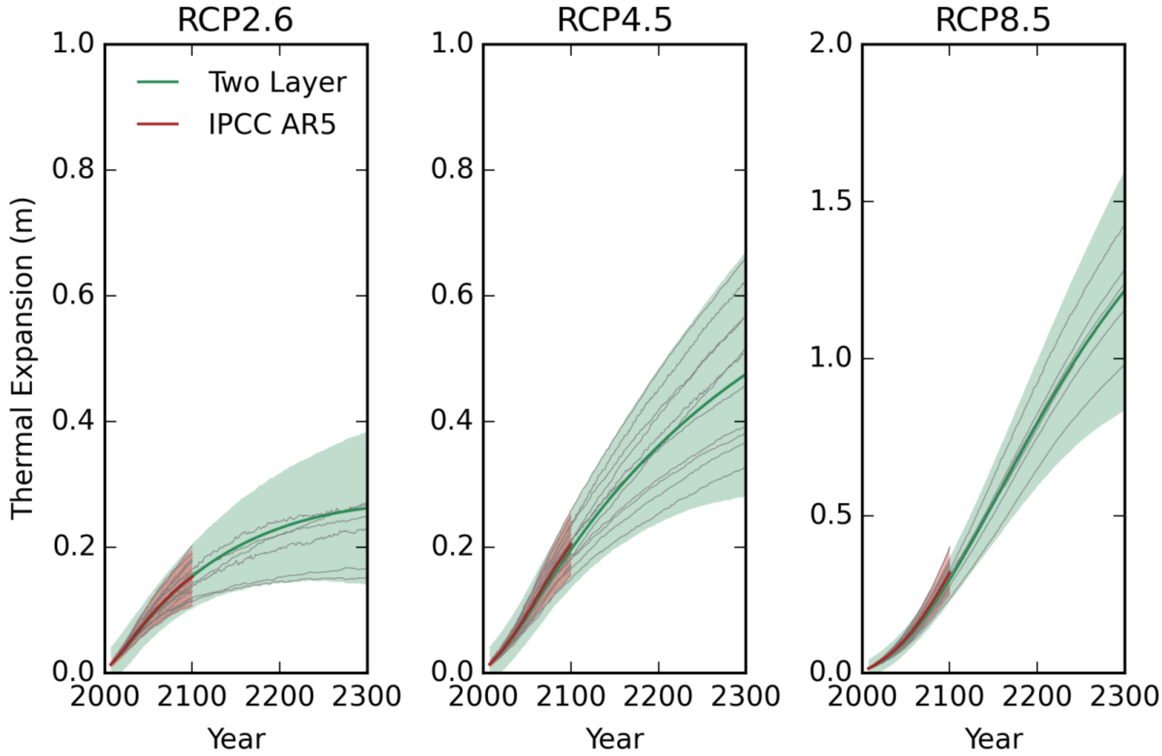

Figure 2.4 Ensemble projections of the global mean sea level change associated with global thermal expansion relative to a baseline period of 1986 to 2005

Notes: Time series include:

- the 21 member IPCC AR5 ensemble (red, shaded regions indicate 5th to 95th percentile range)
- the 14 member two-layer model ensemble (green, shaded regions indicate 5th to 95th percentile range)
- individual CMIP5 model projections (grey lines)

Source: Palmer et al (2018b, Figure A1.2.3)

2.3 Global mean sea level projections to 2300

The two-layer model ensemble projections of global mean surface temperature (Figure 2.3) and thermal expansion (Figure 2.4) are combined with additional assumptions to generate projections of global mean sea level that extend to 2300.

- The rise in global mean sea level due to thermal expansion is taken directly from the two-layer model ensemble.
- The projections of global surface temperature are used as the basis for determining future changes in glacier ice melt and changes in surface mass balance for the Greenland and Antarctic ice sheets using the same relationships as described in IPCC AR5 (Church et al. 2013).
- A statistical fit to the scenario-dependent projections of Levermann et al. (2014) is used to provide an estimate of contribution from Antarctic ice dynamics using the same approach as for the UKCP18 21st century sea level projections.
- The rates of ice dynamic loss for Greenland and changes in land water are assumed to remain constant after 2100.

The methods are summarised in Table 2.1 with further details available in the UKCP18 Marine Report (Palmer et al. 2018b).

Table 2.1 A summary of methods used for each mass component time series

Mass component	Method
Antarctica: surface mass balance	The same relationship with global surface temperature used in the IPCC AR5 21st century projections is applied out to 2300 (Church et al. 2013).
Antarctica: ice dynamics	A statistical fit to the Levermann et al. (2014) results is used up to 2100, with rates held constant between 2100 and 2300.
Greenland: surface mass balance	The same relationship with global surface temperature used in the IPCC AR5 (Church et al. 2013) is used up to 2100, with rates held constant between 2100 and 2300.
Greenland: ice dynamics	The mass loss rates at 2100 from the IPCC AR5 21st century projections are held constant between 2100 and 2300 (Church et al. 2013).
Glaciers	The same relationship with global surface temperature used in the IPCC AR5 21st century projections is applied out to 2300 (Church et al. 2013), with a cap on the total sea level equivalent of 0.32m to reflect current estimates of global glacier volume (Grinsted 2013).
Land water storage	The rates at 2100 from the IPCC AR5 21st century projections are held constant between 2100 and 2300 (Church et al. 2013).

Source: UKCP18 Marine Report (Palmer et al. 2018b, Table A.1.2.1)

The resulting global mean sea level projections show that sea level will continue to rise throughout the 22nd and 23rd centuries under all scenarios (Figure 2.5). This behaviour is in contrast to global surface temperature, which post-2100 shows a marked reduction in the rate of rise under RCP4.5 and a decrease under RCP2.6. The 5th to 95th percentile ranges for global mean sea level rise at 2300 are much larger that the corresponding ranges at 2100 (Table 2.2). In particular, the large range for RCP8.5 is dominated by uncertainty in the dynamic ice input from Antarctica. These illustrative projections suggest that the total glacier mass could be exhausted (from glacial melt) by the middle of the 22nd century under RCP8.5 (or the 23rd century under RCP4.5).

The extended sea level projections presented in this report show a high degree of consistency with the 21st century projections presented in UKCP18, promoting their seamless use across timescales (Table 2.2). At 2100, the extended projections (based on the two-layer model ensemble) are typically in agreement with the UKCP18 21st century projections (based on the CMIP5 model ensemble used in IPCC AR5) to within a centimetre or so.

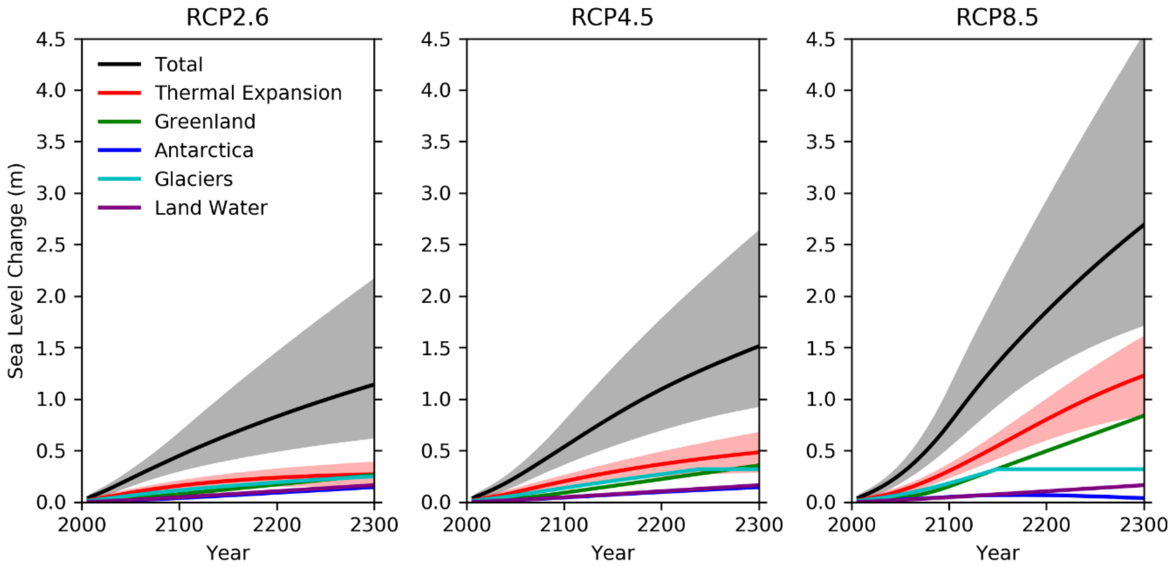

Figure 2.5 Time series of global time-mean sea level change to 2300 with a baseline period of 1981 to 2000

Notes: Individual components are indicated by the coloured lines.
The 5th to 95th percentile range from the model ensemble is indicated by the shaded regions for total and thermal expansion.
Note that the surface mass balance and ice dynamics terms for Greenland and Antarctica have been combined.
Source: UKCP18 Marine Report (Palmer et al. 2018b)

Table 2.2 Comparison of the UKCP18 21st century global time-mean sea level projections and the extended projections presented in this section

	Year	RCP2.6	RCP4.5	RCP8.5
UKCP18 21st century projections	2100	0.44 (0.29–0.67)	0.54 (0.38–0.79)	0.78 (0.56–1.12)
Extended projections (this report)	2100	0.45 (0.30–0.68)	0.54 (0.36–0.79)	0.76 (0.53–1.12)
	2200	0.8 (0.5–1.5)	1.1 (0.7–1.8)	1.8 (1.3–2.9)
	2300	1.1 (0.6–2.2)	1.5 (0.9–2.6)	2.7 (1.7–4.5)

Notes: The numbers given are the central estimates for the year indicated, with the 5th to 95th percentile range given in brackets.
Numbers beyond 2100 are quoted to the nearest 0.1m, given the lower confidence associated with projections on these extended time horizons.
Source: UKCP18 Marine Report (Palmer et al. 2018b, Table 4.2.1)

2.4 From global to regional projections

A number of additional processes need to be accounted for to provide regional projections for the UK.

Each of the global mean sea level components (Figure 2.5) is associated with a non-uniform spatial pattern of change (see Section 1.1). Essentially, each of the mass and freshwater input time series is combined with a corresponding ‘mass fingerprint’ to determine the local effect of each individual component.

Potential changes in local ocean circulation and density are accounted for by establishing regression relationships between global thermal expansion and the local ‘oceanographic’ sea level. These regression relationships vary by climate model and hence additional regional uncertainty is introduced for this term.

Finally, an estimate of the ongoing effects of GIA is included in the regional sea level projections.

The various mass fingerprints and example regression relationships are presented in the UKCP18 Marine Report (Palmer et al. 2018b).

The combined uncertainty in regional sea level projections is computed using a 100,000 member Monte Carlo simulation. For each member of the Monte Carlo, a set of global mean sea level time series is drawn at random from the underlying distributions. Uncertainties in the mass fingerprints, the oceanographic sea level regressions and GIA are factored in by also making random draws from several estimates of each.

Statistics for the full Monte Carlo set are then used to compute the overall uncertainty, following the approach presented in IPCC AR5 (Church et al. 2013). That is, the 5th and 95th percentiles of the 100,000 members provide the basis for the uncertainties in total regional sea level change.

However, there may be a greater than 10% chance that the real world response lies outside these ranges. This likelihood cannot be accurately quantified. In particular, it is not possible to rule out substantial additional sea level rise associated primarily with dynamic ice discharge from the West Antarctic ice sheet (see Section 3.2.1 of Palmer et al. 2018b for further discussion).

2.5 Environment Agency coastal flood boundary conditions

In 2008, the Environment Agency set up the R&D project, ‘Coastal Flood Boundary Conditions for UK Mainland and Islands’ (SC060064) to provide a consistent set of still water return level curves around the coasts of England, Wales and Scotland (Environment Agency 2011).

In 2017, the project was reviewed and the return level curves were updated in 2018 with additional data and improved science methods (Environment Agency 2019). Since the original study was commissioned in 2008, nearly 10 years of additional observational data have been recorded at Class A gauge sites. The review also identified additional secondary channel data available at Class A gauge sites. Many of the statistical methods applied during the 2018 update were the same as detailed in the 2011 report. However, a number of significant improvements were made including (Environment Agency 2019):

- improved tidal analysis and determination of skew surges with explicit calculation of the 18.6 year nodal cycle
- improved determination and removal of the long-term mean sea level trend at each tide gauge

- improved statistical treatment of the shape parameter in the skew surge distribution
- more complete determination of uncertainty (confidence intervals) in the statistical method including the choice of threshold
- a physically based approach to the determination of the extremal index parameter, used to generate the final probabilities of extremes

For most tide gauge locations, the changes in 200-year return level associated with the update are less than 0.1m. At a small number of locations the changes exceed 0.1m; for example, there is an increase of around 0.19m at the Mumbles in south Wales and a decrease of around 0.16m at Felixstowe on the east coast of England.

The update also increased the geographical extent of the analysis. The original report considered all open coastline around England, Scotland and Wales (Environment Agency 2011). The 2018 update also analysed data from the following island tide gauges:

- St Mary's (Scilly Isles)
- Holyhead (Anglesey)
- Port Erin (Isle of Man)
- Stornoway (Hebrides)
- Lerwick (Shetland)
- Belfast (Northern Ireland)
- Portrush (Northern Ireland)
- Jersey

Data on these tide gauges from Environment Agency (2019) are tabulated for ease of reference in Appendix D.

2.6 Note on percentiles

In simplified terms, a percentile refers to the percentage of different projections falling below that level. For example, when we say that the 5th percentile of the RCP8.5 projections of mean sea level change for 2300 is 1.7m, the implication is that 5% of model projections fall below 1.7m and the other 95% are above 1.7m. Where the number of model projections is insufficient to clearly identify this level, a normal probability distribution is fitted to the model projections and the 5th percentile of the fitted distribution is used. The 'central estimate' usually refers to the 50th percentile projection (that is, the median value).

2.7 Definition of return period

Two conflicting definitions of return period are in common use. This report calls them the correct definition and the intuitive definition.

- **Correct definition.** The return period is defined as the expected average amount of time between exceedances. In other words, it is the reciprocal of the average rate of exceedance.

- **Intuitive definition**. The return period is defined as the reciprocal of the exceedance probability.

For long return periods (for example, 200 years), these definitions are very similar. To see the difference between them, it is necessary to look at short return periods.

Consider the one-year return level. Using the correct definition, the one-year return level is the level that is expected to be exceeded once per year on average. Even in an unchanging climate, such exceedances would not be distributed uniformly in time. There would be some years with no exceedances of the one-year return level, some with just one and some with more than one. In the long run, however, an average of one exceedance of the one-year return level per year would be expected.

Using the intuitive definition produces an absurdity. If the return period is the reciprocal of the exceedance probability, then the probability of exceeding the one-year return level must be one; it would be the level that can be guaranteed to be exceeded every year without fail. This is not meaningful in the context of the probabilistic model used here, which allows for random variations in the surge component of sea level.

This report therefore uses the correct definition. The correct definition is also used in Environment Agency (2019).

Under the correct definition, the relationship between the return period and annual exceedance probability is not a simple reciprocal. Instead it is:

$$1 - AEP = \exp\left(\frac{-1}{RP}\right) \tag{2.1}$$

where RP is return period and AEP is annual exceedance probability.

Users who wish to work in terms of annual exceedance probability can use this relationship to convert from return period to annual exceedance probability. This is an expression of the Poisson relationship, which is more familiar as:

$$\text{Prob(no events)} = \exp(-\gamma) \tag{2.2}$$

where γ is the average rate of occurrence.

This relationship is well-approximated for large return periods by:

$$AEP \approx \frac{1}{RP}\ , (RP \gg 1) \tag{2.3}$$

For ease of reference, the best estimates of present day return levels from Environment Agency (2019) are reproduced in Appendix D.

3 Projections of coastal extreme water levels

Century-timescale changes in coastal sea level extremes are expected to be overwhelmingly dominated by the steady increase in coastal water level associated with anthropogenic sea level rise (see Section 1.1). UKCP18 reports a 'best estimate' projection of no change for the future characteristics of storm surges around the UK (Palmer et al. 2018b). In addition, UKCP18 analysis of historical case studies showed essentially no interaction between potential future time-mean sea level change and the characteristics of surge events. However, stakeholders should be aware of the potential for substantial changes in tidal characteristics (including tidal amplitude) under a sea level rise of the order of 1m and higher (see, for example, Pickering et al. 2012, Palmer et al 2018b).

Projections of time-mean sea level change for the UK coastline are presented in Section 3.1. These projections are then combined with the current best estimate of present day return levels in Section 3.2.

3.1 Projections of time-mean sea level change out to 2300

As part of the UKCP18 data delivery, the regional projections presented here are made available on a ~12.5km grid around the UK coastline (Figure 3.1). The time series shown are based on the average of 49 UK ports and are illustrative of the time evolution of sea level rise for the UK as a whole and the dependence on RCP climate change scenario (Figure 3.1, left panel).

As with the UKCP18 21st century projections, the UK is broadly characterised by the largest sea level rise in the south of the UK (and also Shetland) and the smallest sea level rise in southern Scotland and Northern Ireland (Figure 3.1, right panel). These spatial variations are primarily the result of the spatial pattern of GIA and the mass fingerprint associated with the Greenland ice sheet.

This spatial pattern of sea level rise is also illustrated by the projections presented for the UK's capital cities, which illustrate the geographical representations around the UK (Figure 3.2).

Larger rises are seen for London and Cardiff, with central estimates that exceed 2m and 95th percentiles that exceed 4m for the RCP8.5 scenario. For London and Cardiff, the projection ranges at 2300 are approximately 0.5m to 2.2m, 0.8m to 2.6m and 1.4m to 4.3m for low (RCP2.6), medium–low (RCP4.5) and high (RCP8.5) emissions respectively.

Edinburgh and Belfast show smaller values, with central estimates less than 2m and 95th percentiles of approximately 3.5m for RCP8.5. The values for Edinburgh and Belfast are substantially lower than those for London and Cardiff, with corresponding ranges at 2300 of approximately 0.0m to 1.7m, 0.2m to 2.1m and 0.7m to 3.6m. Edinburgh and Cardiff also show the potential for a decrease in local sea level over the coming centuries under the RCP2.6 and RCP4.5 scenarios. This decrease arises primarily from the vertical land uplift associated with GIA in these locations; this is because the regional projections are projections of relative sea level (that is, sea level relative to the local land level).

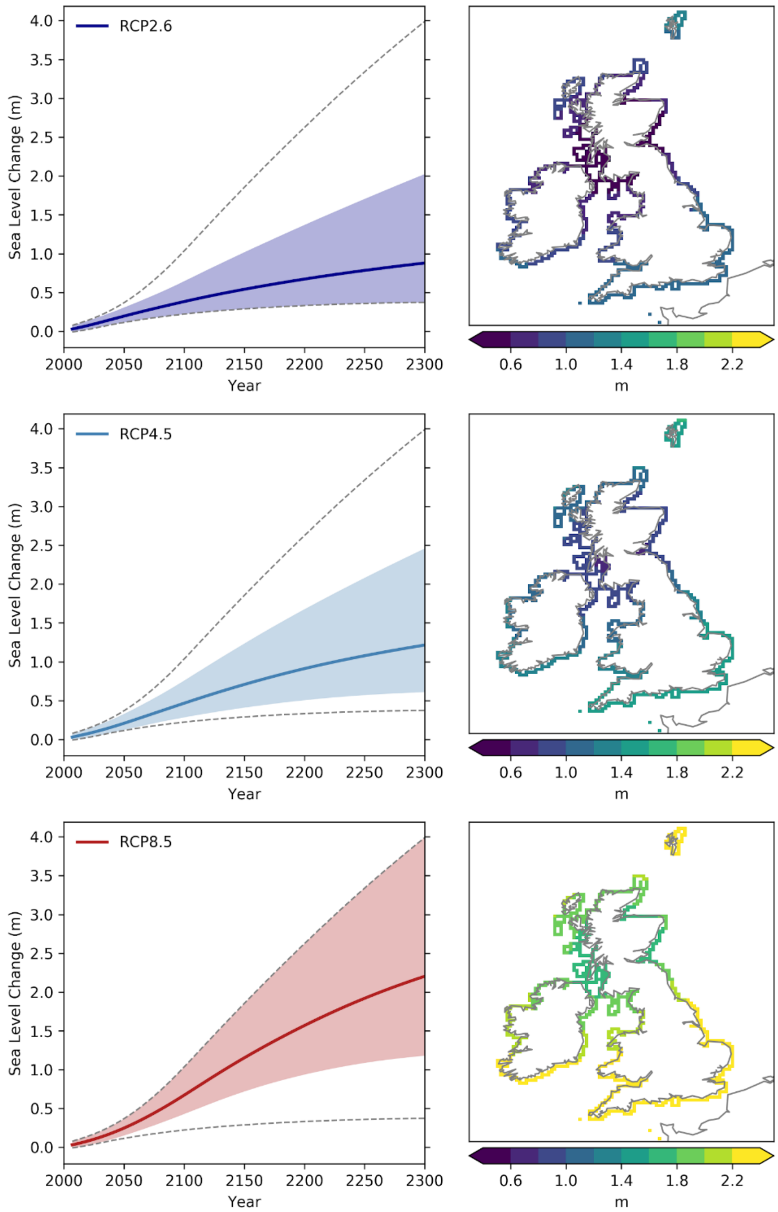

Figure 3.1 Left panel: Time series of time-mean sea level change based on the average of 49 UK ports. Right panel: The spatial pattern of change at 2300 associated with the central estimate of each RCP scenario

Notes: In the left panel, the solid line and shaded regions represent the central estimate and 5th to 95th percentile confidence range for each RCP scenario as indicated in the legend. The dashed lines indicate the overall range across RCP scenarios. All projections are presented relative to a baseline period of 1981 to 2000. Source: UKCP18 Marine Report (Palmer et al. 2018b, Figure 3.1.3).

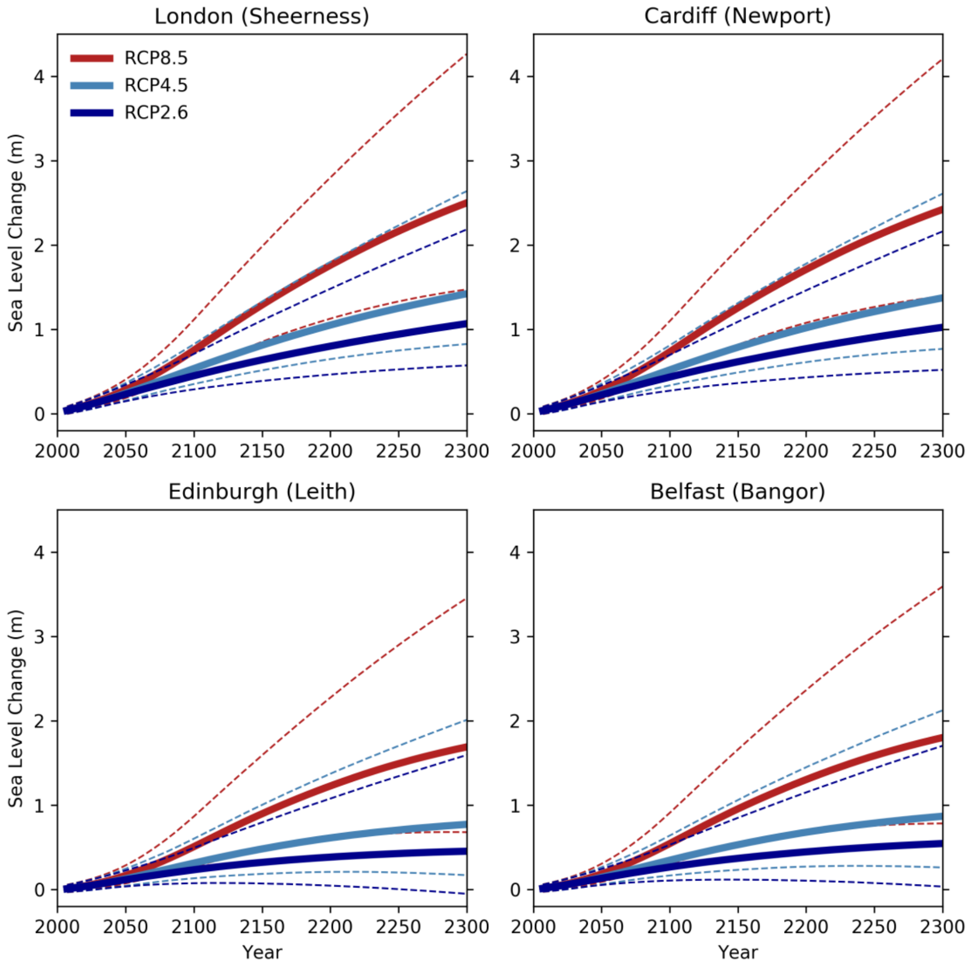

Figure 3.2 Time series of the time-mean relative sea level change for UK capital cities based on the nearest Class A tide gauge location (indicated in brackets)

Notes: Solid lines indicate the central estimate and dashed lines indicate the 5th to 95th percentile range for each RCP scenario as indicated in the legend (top left panel). All projections are presented relative to a baseline period of 1981 to 2000.
Source: UKCP18 Marine Report (Palmer et al. 2018b, Figure 3.1.4)

3.2 Changes in future return levels

The 2018 update of coastal flood boundary conditions for UK mainland and islands (Environment Agency 2019) documents the current best estimate of present day extreme still water levels (tide plus surge, but not including waves). In this report, future extreme water levels at UK tide gauges are projected by adding the 5th, 50th and 95th percentiles of projected regional relative time-mean sea level change to the present day extreme still water levels.

Figure 3.3 illustrates the projection of future return levels at 4 example tide gauge sites; tabulated data for all the 46 studied sites are provided in Appendix A. All of the data produced by this project will be made available through the UKCP18 user interface.

The uncertainty within the projection for each RCP is treated as follows in Figure 3.3. The shaded red band shows the 5th to 95th percentile range of the RCP8.5 projection. For any given panel, this band has the same vertical extent at every return period, because it shows uncertainty in the mean sea level projection only. Uncertainty in the present day return levels (which varies by return period) is not included. Combining uncertainty in present day return levels and projections of future change in a meaningful way is not straightforward and it is expected that this combination will form the basis of further work.

To avoid cluttering the plot, the uncertainty in the RCP2.6 projection is shown as a single vertical line at the 1,000-year return period, instead of a band of shading. Similarly, the uncertainty in the RCP4.5 projection is shown as a single vertical line at the 10-year return period.

Full details of the locations of the tide gauges can be found on the UK National Tide Gauge Network website (www.ntslf.org/data/uk-network-real-time) and/or the Permanent Service for Mean Sea Level website (www.psmsl.org). Nominal tide gauge locations are also given in the tables in Appendices A and D.

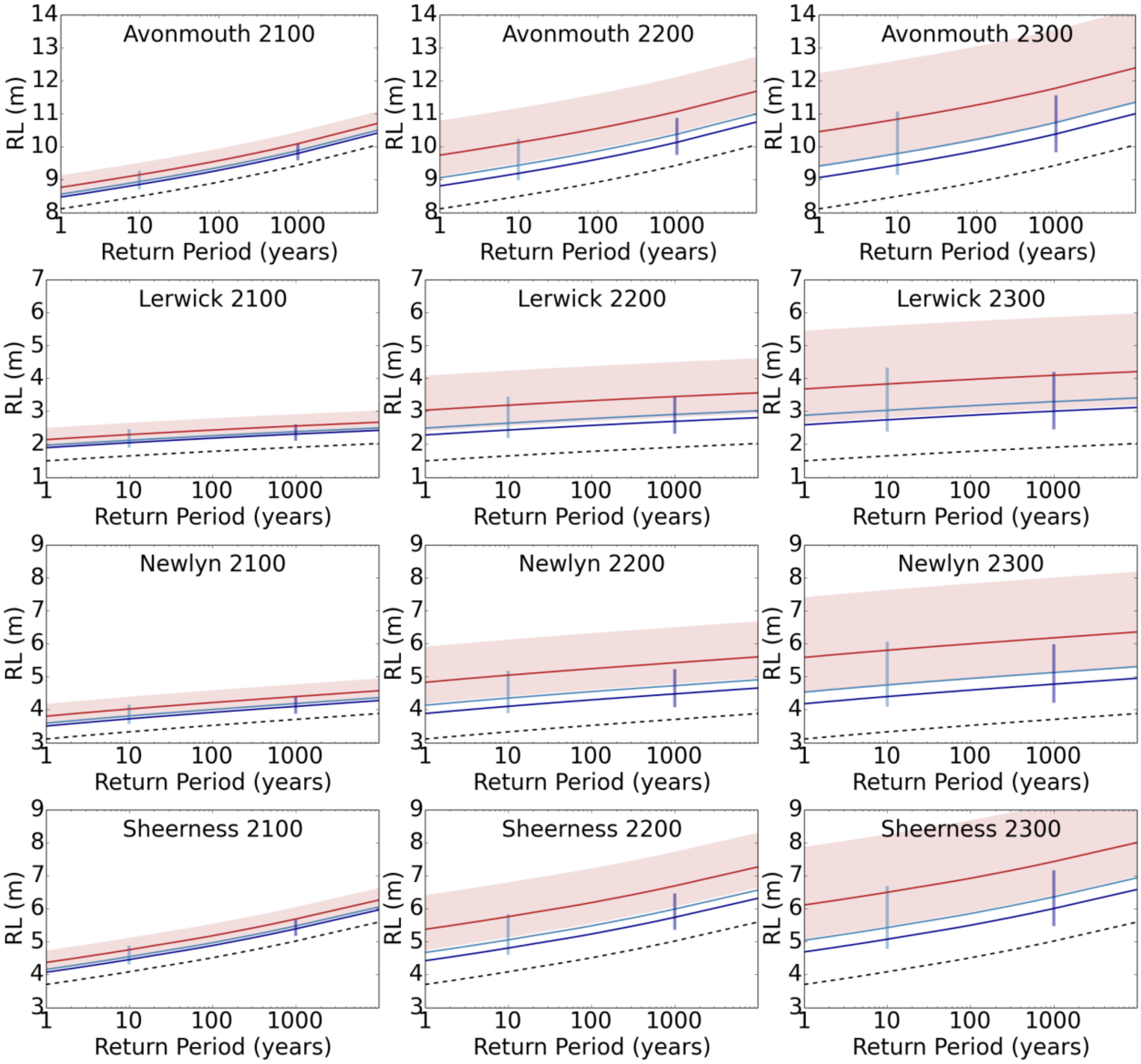

Figure 3.3 Projected future return level curves for 4 example sites.

Notes: The present day return level curve is shown by the dashed line.
The lowest (dark blue) continuous line shows the central estimate of the RCP2.6 projection.
The next (light blue) continuous line shows the central estimate of the RCP4.5 projection.
The upper (red) continuous line shows the central estimate of the RCP8.5 projection.
For details of the representation of uncertainty see the main text.

3.2.1 Discussion

The projected future extreme still water levels are not, strictly speaking, above Ordnance Datum Newlyn (ODN) because the projections include relative mean sea level change whereas ODN is an absolute datum. For full details see Appendix C.

At those coastal sites that currently experience low variability in sea level extremes (that is, they have a shallow return level curve), projected future still water[3] return levels for 2100 may be outside the envelope of present day return levels (Figure 3.3). For example, the 2100 projected one-year return level for Lerwick under RCP8.5 (high emissions) is a level that would not be expected to occur there under sustained present day mean sea levels even once in 10,000 years.

Similarly, at coastal sites that currently experience high variability in sea level extremes (that is, they have a steep return level curve), projected future still water return levels for 2100 may be inside the envelope of present day return levels. For example, the 2100 projected one-year return level for Avonmouth under RCP8.5 is a level that would be expected to occur there about every 40 years under sustained present day mean sea levels.

The return level curve at Avonmouth is steeper than the other return level curves (Figure 3.3). This is associated with the large variability in sea level at Avonmouth. One reason for this large variability at Avonmouth is that the Bristol Channel is close to resonance with the dominant mode of tidal variability, the M2 lunar mode with time period of 12 hours 25 minutes. This brings a caveat to the projections: they do not include possible changes in tidal characteristics with increased water depth.

The UKCP18 Marine Report (Palmer et al. 2018b) presents the results of a simple model experiment to investigate this effect. Comparison of their Figure 4.3.2 with Figure 4 in Pickering et al. (2012) depicting a sea level rise of 2m shows a strikingly similar spatial pattern of increase and decrease except for the region which spreads out from the Bristol Channel, where signs of change disagree between the 2 models. Flather and Williams (2000) also reported an increase in tidal range in this region with a 0.5m mean sea level rise. Flather and Williams (2000) used the same model as Palmer et al. (2018b), whereas Pickering et al. (2012, 2017) identified a decrease using 2 quite different independent global and regional models. Pelling et al. (2013) again using a different model also reported a decrease in the Bristol Channel with a 2m sea level rise and a fixed coastline. Idier et al. (2017) used a substantially higher resolution model (~2km rather than ~12.5km) and found spatially variable increases and decreases in the Bristol Channel.

Therefore, there is disagreement between models about the sign of the change in and around the Bristol Channel. More generally, Pickering et al. (2017) noted that the tidal response is strongly influenced by the treatment of the coastline: a more realistic treatment of coastal recession assuming no hard coastal engineering (in contrast to the use of simple vertical walls) is capable even of reversing the sign of the tidal response at some sites.

Although projections of change in the tidal range, particularly for the Bristol Channel, appear to be model-dependent, changes in tidal range at the coast of up to 10% (under a mean sea level increase of 3m) are seen at some locations. This is of scientific interest, but it is stressed that it is a secondary effect, with the change in time-mean sea level being the dominant effect.

[3] Still water level refers to water level averaged over a period (say ~15 minutes) much longer than the period of a surface wave. It accounts for tide and surge but not intermittent overtopping by waves.

Another caveat is that this report does not consider changes in extreme sea level arising as a result of changes in atmospheric storminess. Palmer et al. (2018b) in the UKCP18 Marine Report considered such changes and concluded that a central estimate of no change during the 21st century was representative of the 5 different simulations they considered. The central estimate in this report is consistent with UKCP18. It is reasonable to neglect this inflation because it is a small uncertainty compared with the much larger uncertainties in time-mean sea level change.

4 Past and future wave climate in the North Atlantic including the UK

This section presents an overview of the past (20th century) and future wave climate (21st century), with a focus on the eastern North Atlantic and surrounding UK seas (for example, the North Sea).

4.1 Overview of waves and wave generation

Waves are generated by winds acting on the sea surface. When local wind within an area of interest blows across the sea surface, it creates ‘wind waves’. Over time, waves formed in remote regions may travel long distances until they reach a location. These waves are self-sustaining and are not formed by the local winds. These are known as ‘swell waves’ or simply ‘swell’.

The parameters of wave climate[4] that are often considered for various applications are:

- the significant wave heights (SWHs)
- wave direction
- wave period

SWH is traditionally defined as the mean wave height (trough to crest) of the highest third of the waves (Holthuijsen 2007, p. 70). The wave direction is defined as the direction from where the waves are coming (for example, a westerly wave direction is one where waves are coming from the west and travelling east). The wave direction is measured in degrees from true North (which is 0 degrees). The wave period is known as the duration of one cycle to the next from the crest of one wave to the crest of another. It is measured in seconds.

The wave heights depend not only on the speed of the predominant winds but also on the wind direction and its variation (Wolf and Woolf 2006, Debernard and Røed 2008). These determine the length of the fetch[5] and the duration for which waves are forced (grown) by the wind. The frequency, intensity and passage of strong tropical or extra-tropical storms contribute to wave generation or changes in wave characteristics, and swell is especially dependent on the frequency of occurrence and the intensity of such storms in remote areas (Young et al. 2011).

For the UK therefore, the wave climate in coastal areas that are more exposed to the North Atlantic (that is, the western areas) is likely to be affected by swell, whereas the wave climate in more enclosed coastal areas (that is, along the North Sea) is likely be dominated by local wave characteristics (Bricheno and Wolf 2018).

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[4] Wave climate is the distribution of wave characteristics averaged over a period of time for a particular location.

[5] Fetch is the area of ocean over which the wind blows in a constant direction.

4.2 Review of 20th century wave climate in the North Atlantic

This section describes the results of wave climate studies of changes in wave characteristics during the 20th century in the North Atlantic. For the purposes of this study, the North Atlantic is subdivided here further into 2 separate geographical areas:

- the north-east Atlantic (Section 4.2.1)
- the North Sea (Section 4.2.2)

4.2.1 North-east Atlantic

The majority of the existing research agrees on the direction of change in wave heights in the past several decades in the north-east Atlantic.

During the second half of the 20th century, SWHs increased in the north-east Atlantic; this finding is valid for almost all metrics (mean or extreme wave heights) used in the various analyses performed on annual, seasonal or a monthly scale. For example, Draper (1986), Sterl et al. (1998) and Cox and Swail (2001) found increases in the winter season wave heights, which is often reflected in the increases in annual mean and extreme SWH over the north-east Atlantic. Such increases in annual mean and extremes were also established by Wang et al. (2012). Some authors found that the increases were larger for the extremes compared with the mean SWHs (Cox and Swail 2001, Young et al. 2011).

Although these studies found a robust change in wave heights, the large wave climate variability in the wider North Atlantic, which is in part driven by large-scale climate modes such as the North Atlantic Oscillation (NAO) (see Section 4.3), sometimes results in very weak wave climate changes being identified in this larger region. For instance, Woolf et al. (2002) did not find any significant trends in either annual mean or winter mean SWH when considering the North Atlantic as a whole. However, they did focus on a very large area and a relatively short time period (1991 to 2000). A short time period of this kind reduces the likelihood of obtaining a robust change signal when superimposed on high wave climate variability.

4.2.2 North Sea

During the 20th century, the direction of change was also positive for both mean and extreme SWHs in the North Sea. This finding applies to the northern North Sea (see, for example, Vikebo et al. 2003), the central North Sea (Rye 1976, Pfizenmayer and von Storch 2001) and the southern North Sea (Caires et al. 2008).

As with the north-east Atlantic, the wave climate exhibits large interannual variability in the North Sea, with some authors correspondingly obtaining no significant trends in wave heights or highlighting the large interannual variability by identifying years with increases or decreases in wave activity (see, for example, Bacon 1989, Bacon and Carter 1991, Weisse and Günther 2007). For example, Weisse and Günther (2007) pointed out that severe wave conditions decreased off the UK North Sea coast between 1958 and 2002.

4.3 Review of possible causes of 20th century changes in wave climate

The relationship between wind, storminess and wave climate is complex as shown in the following studies.

- Neu (1984) commented that the low and medium sea states resulted from the influence of the prevailing westerlies, while the high and extreme sea states were generated mostly by cyclonic disturbances and mid-Atlantic storms.
- Harrison and Wallace (2005) performed a sensitivity study on the changes in wave heights and wave period in relation to changes in wind speed. They concluded that the wave heights depended on the increases in wind speed rather than being directly proportional to the wind speed itself. In contrast, the wave period depended directly on the wind speed values.
- Wolf and Woolf (2006) found that, for a location west of the Hebrides, the strength of the westerly winds contributed the most to the increase in the mean and maximum monthly wave heights, and the frequency, intensity, track and speed of storms did not significantly affect the mean wave heights. The maximum wave heights, however, were influenced greatly by the intensity, track location and speed of movement of the storms.

Many authors found a significant increase in wind speeds over the North Atlantic and especially over the north-east Atlantic since the 1950s after analysing various sources of data and using analysis periods of different lengths (Rodewald 1972, Neu 1984, Cox and Swail 2001, Bertin et al. 2013). This is consistent with the earlier noted increase in SWHs in the North-east Atlantic.

Many studies identified an overall link between wave climate and the NAO[6] in the North Atlantic, or specifically in the north-east Atlantic and the European shelf seas (see, for example, Kushnir et al.1997, The WASA Group 1998, Günther et al. 1997, Wang and Swail 2001, Bauer 2001, Woolf et al. 2002, Wang and Swail 2002, Gulev and Grigorieva 2004, Sterl and Caires 2005, Dupuis et al. 2006, Dodet et al. 2010, Mackay et al. 2010, Le Cozannet et al. 2011, Bertin et al. 2013, Bromirski and Cayan 2015, Martinez-Asensio et al. 2015).

When the NAO index is in its positive phase, the mid-latitude westerly winds are stronger than normal. A decrease in westerly wind strength occurs during a negative NAO index phase. Consequently during episodes of stronger westerly winds (during a positive NAO phase), it would be expected that the SWHs would increase as well (Jevrejeva et al. 2014). Correlations between wave heights and the NAO were positive in the north-east Atlantic (Shimura et al. 2013), while the correlations were negative in the south-west of the North Atlantic (Bertin et al. 2013) and in the subtropics south of 40°N (Kushnir et al. 1997, Wang and Swail 2001, Shimura et al. 2013). For the North Sea, Bauer (2001) established that the wave variability (the dominant modes of

[6] The NAO is a hemispheric meridional oscillation in atmospheric mass between a centre of action near Iceland and another over the subtropical North Atlantic (Visbeck et al. 2001). It mainly dominates the northern hemisphere winter (December, January, February) season. There are 2 phases. During a positive NAO phase, the strength of the mid-latitude westerlies increases, leading to warmer than normal and wetter than normal conditions in north-western Europe. A negative phase of the NAO results in a weaker pressure gradient between the Icelandic Low and Azores High, weakening the westerly winds and resulting in colder than normal and drier than normal conditions in north-western Europe.

synoptic scale wave variability were estimated using wavelet spectrum analysis) of the North Sea was lower when the NAO index was higher and vice versa.

Finally, studies have also focused on changes in cyclonic activity over the second half of the 20th century. Research to date indicates that storm frequency increased in the north-east Atlantic and the shelf seas (The WASA Group 1998, Gulev and Grigorieva 2004). Weisse et al. (2005) identified that the number of storms increased between 1958 and 1990, but decreased between 1990 and 1995 in the north-east Atlantic and southern North Sea; Paciorek et al. (2002) found an increase in the number of intense cyclones in the North Atlantic. As stated in Jevrejeva et al. (2014), during episodes of increased storminess, it would be expected that SWHs would increase.

4.4 Review of 21st century wave projections for the North Atlantic

There is a considerable interest in potential future changes in the wind and wave climate in light of the increased vulnerability of coastal areas. This interest is due to more people settling there and to the expanding exploration and economic development of oil and gas fields in the ocean.

The IPCC AR5 concluded that:

> '… in general, there is *low confidence* in wave model projections because of uncertainties regarding future wind states, particularly storm geography, the limited number of model simulations used in the ensemble averages, and the different methodologies used to downscale climate model results to regional scales' (Church et al. 2013, Chapter 13, p. 1204).

The most important message from the section in the UKCP18 Marine Report (Palmer et al. 2018b) on waves is that, around the UK coastline:

- the annual mean SWHs are projected to decrease by 10–20% at the end of the 21st century (2070 to 2099) compared with the historic wave climate under the highest emissions scenario (RCP8.5)
- changes in extreme waves are also of the order 10–20%, but there is no agreement in the sign of change among the model projections

For further details of each study included in the summary text below, such as the atmospheric models used to derive relevant wave climate variables and the magnitude of change and particular metric associated with a given study and emissions scenario used, see Tables B.1 to B.5 in Appendix B.

4.4.1 North-east Atlantic

At the end of the 21st century, several studies (Wang et al. 2004, Wang and Swail 2006, Leake et al. 2008, Lowe et al. 2009, Fan et al. 2013, Fan et al. 2014) projected an increase in mean SWHs during the winter season or across all seasons. The magnitude of this change is generally of the order of 5cm to 35cm. However, one study (Fan et al. 2013) projected an increase of over 50 cm within the north-east Atlantic during the winter months under the A1B emissions scenario (see Table B.3 in Appendix B).

In terms of more extreme metrics (that is, the 90th or 99th percentile of SWHs, seasonal or annual maxima or period mean of seasonal or annual maxima), many studies have again projected increases in these wave metrics. For the 90th or 99th percentile of SWHs, Wang et al. (2004) and Wang and Swail (2006) reported an up to

50cm increase in the winter or summer extremes in the north-east Atlantic (or 11% and 9% respectively compared with the relevant baseline climate values). Even greater increases in the period mean winter maximum SWHs have been projected (up to 130cm under the A2 scenario) for the period 2070 to 2100 by Leake et al. (2008), while Bricheno and Wolf (2018) indicated that the period mean annual maximum along west-facing coasts will increase by about 10–20% under RCP4.5 and 8.5 (see Table B.3 in Appendix B).

In contrast to these studies listed above, 2 studies that focused on the north-east Atlantic or the North Atlantic as a whole indicated decreases (Hemer et al. 2013b, Bricheno and Wolf 2018). The former found reductions in the monthly or seasonal mean (for example, winter monthly means will decrease by about 1m, while seasonal summer mean will decrease by about 0.2m) and 99th percentile of SWHs in the North Atlantic as a whole. The latter found that compared to historic (top panel, Figure 4.1), annual mean SWHs will decrease by about 0–5% (middle panel in Figure 4.1). Bricheno and Wolf also looked at changes in annual maximum SWH (see bottom panel, Figure 4.1)

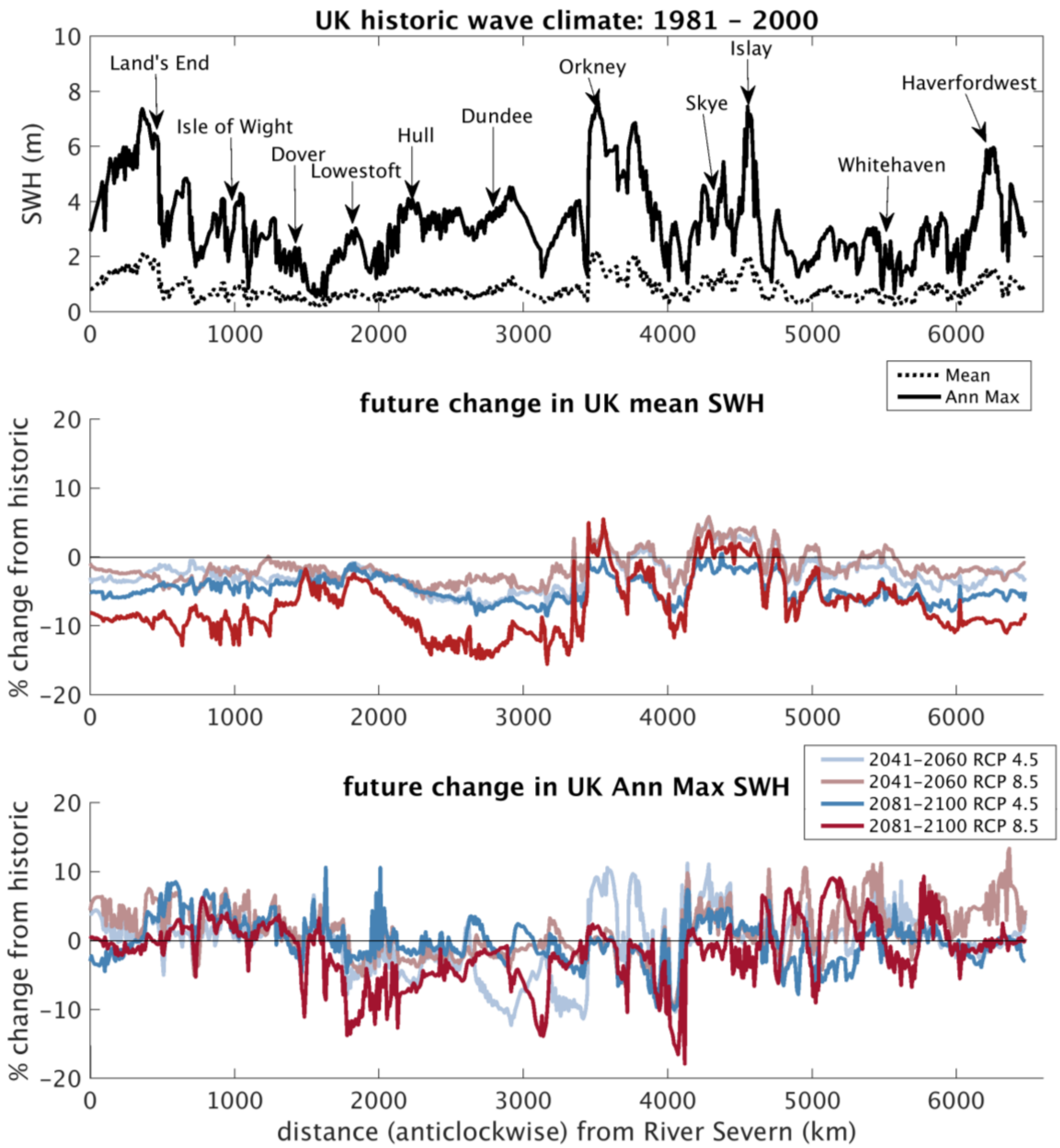

Figure 4.1 Coastal strip plots of historical wave climate and projected future changes for UK mainland

Notes: The modelled coastline of the British mainland is 'unwrapped' anticlockwise, starting and ending in the Bristol Channel.
The top panel shows the mean SWH (dotted line) and mean annual maximum wave height (AnnMax) (solid line) from the historical simulation.
The middle and bottom panels show percentage changes in mean SWH and AnnMax respectively relative to a 1981 to 2000 baseline period.
The 4 coloured lines represent 'mid-21st century' (2041 to 2060) and 'end-21st century' (2081 to 2100) change signals for RCP4.5 and RCP8.5.
Source: UKCP18 Marine Report (Palmer et al. 2018b, Figure 3.3.3)

Quite a few studies can be grouped together according to the geographical regions they established results for. Below the results are summarised for:

- areas to the north and north-west of the UK
- areas to the west of the British Isles
- areas to the south-west of the British Isles
- areas around the UK and Ireland
- the Liverpool Bay area

The studies that produced numerical results are summarised in more detail below. The detailed list of study results is given in Appendix B (Section B.1 and Tables B.3 and B.4.)

Areas to the north and north-west of the UK

The studies do not agree on the direction of change in wave climate. While Kaas et al. (2001) reported an increase in winter, spring and autumn mean SWHs in these areas, Mitchell et al. (2016) indicated a statistically significant decrease in the ensemble mean of the annual mean SWHs near the Bernera site (north-west of the UK) by the mid-century. Lowe et al. (2009) and Wolf et al. (2015) provided mixed results.

In contrast to Kaas et al. (2001), the study by Lowe et al. (2009) indicated that the winter (changes by up to -0.4m) and spring mean, and the annual extreme (changes by -0.3cm per year) SWHs would decrease north of the UK. However, they indicated that the summer and autumn SWHs would increase around the UK and north-west of Scotland respectively.

The study by Wolf et al. (2015) established an increase for the annual mean SWHs by mid-century contrary to that of Mitchell et al. (2016), but a decrease in this parameter by the end of the century to the north-west of Scotland contrary to Kaas et al. (2001). At the same time, Wolf et al. (2015) found that the 30-year period mean annual maxima would increase by between 10 and 20% in the north-west approaches, which is at odds with the results found by Lowe et al. (2009).

Areas to the west of the British Isles

Three of the studies agree that, in these areas, the wave climate will experience decreases.

Reductions were identified in the spring, summer and autumn mean and 99th percentile of SWHs in the West European shelf seas (Zacharioudaki et al. 2011); Gallagher et al. (2016a, 2016b) cited a decrease as large as -10% for the winter mean, and up to -5% for the spring and autumn mean SWHs off the west coast of Ireland for RCP8.5. They also found a decrease in the annual mean SWHs of about 5–10% off the Atlantic coast of Ireland for both scenarios.

Both Gallagher et al. (2016a, 2016b) and Aarnes et al. (2017) identified decreases in the 95th or 99th percentile of the SWHs. In the winter, the extremes would decrease by about 5%, while in summer the reductions would be largest at more than 10% (Gallagher et al. 2016a, 2016b). The annual 99th percentile and maximum would decrease by about 2–6% to the west of UK and Ireland (Aarnes et al. 2017).

Only one study indicated increases in these areas: Debernard and Røed (2008) found an increase in the winter 99th percentile of SWHs by 2–4% west of the British Isles and up to a 6% increase in the 99th percentile of the annual SWH west of the British Isles.

Areas to the south-west of the British Isles

Several studies agreed that the annual mean SWHs would decrease (Zacharioudaki et al. 2011, Reeve et al. 2011, Wolf et al. 2015, Perez et al. 2015).

Zacharioudaki et al. (2011) estimated a 3-5% reduction, while Reeve et al. (2011) indicated a decrease in annual mean wave power of -2.27% under the B1 scenario at the Wave Hub test site off the north coast of Cornwall; however, they found an increase of similar magnitude under the A1B scenario. Perez et al. (2015) established a decrease varying between 0.04m and 0.08m, depending on the emissions scenario. A decrease in the summer seasonal mean (up to 15%) and 95th percentile of SWHs was also indicated by Gallagher et al. (2016a, 2016b) off the south coast of Ireland.

In contrast and further enhancing the picture of the changes to the south-west of the UK and Ireland, several studies established an increase in seasonal means, and seasonal and annual extremes in these areas (Leake et al. 2008, Lowe et al. 2009, Zacharioudaki et al. 2011, Wolf et al. 2015). Numerical results include:

- an increase in winter mean around 0.1m in the English Channel (Lowe et al 2009)
- >0.14m south-west of the UK (Leake et al. 2008)
- 4–8% (Zacharioudaki et al. 2011)
- changes in the extremes varying around >0.4m for the winter maximum (Leake et al. 2008)
- 10–20% by the end of the century for the period mean of annual maximum SWHs. (Wolf et al. 2015)

Figure 4.2 shows the change in SWH between the present day and future projections as established by Wolf et al. (2015) in a report for the RISES-AM EU FP7 Collaborative Research Project (Responses to coastal climate change: Innovative Strategies for high End Scenarios – Adaptation and Mitigation).

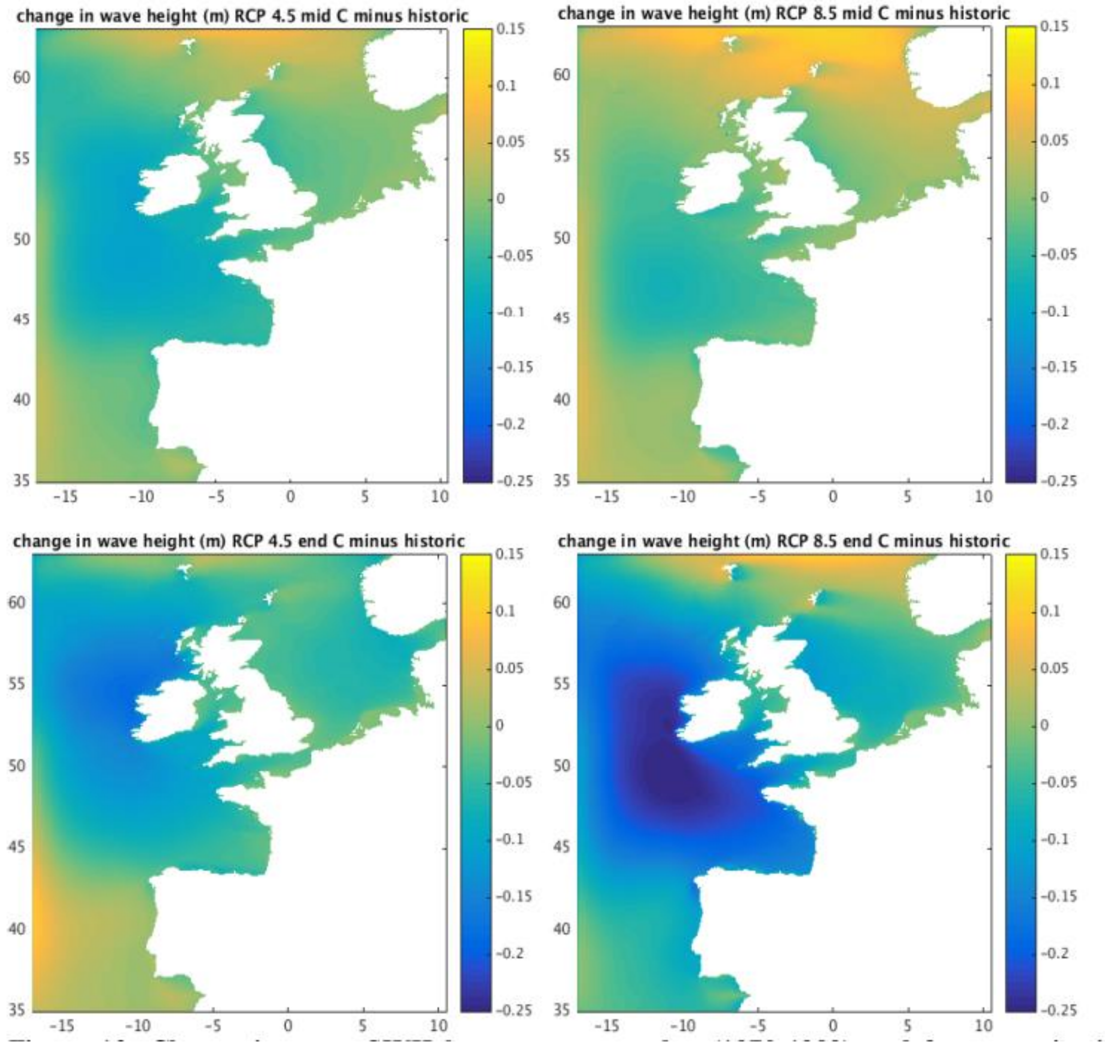

Figure 4.2 Change in mean SWH between present day (1970 to 1999) and future projections: RCP4.5 (left column) and RCP8.5 (right column). Top row: mid-century (2030 to 2059). Bottom row: end-century (2070 to 2099)

Source: Wolf et al. (2015, Figure 13)

Areas around Ireland or UK as a whole

Three studies agreed that the annual mean SWHs would decrease:

- Perez et al. (2015) (see above)
- Aarnes et al. (2017): reductions of 2–6% and up to 8% around Great Britain and Ireland
- Bricheno and Wolf (2018): decreases of 0–5% around the UK coast

However, 2 studies provide conflicting results about the annual maximum SWHs

- Wolf et al. (2015) found increases varying between 10% and 30% around Ireland, except for the areas to the east of Ireland in the 30-year period mean of annual maximum SWHs.
- Aarnes et al. (2017) indicated a decrease in the annual 90th percentile of 2–4% around the UK and 4–6% around Ireland.

Liverpool Bay area:

Brown et al. (2012) found differing patterns of change depending on the month or season of the year in the Liverpool Bay area including:

- increases in mean monthly SWHs in December, November and June (largest, about 16% in June)
- increases in large and extreme wave events[7] varying between 0.31% and 9.5% during the winter months
- decreases in the rest of the months (largest in September, -20%)
- decreases in seasonal mean SWHs (for example, about -8.8% for spring and -5.5% for summer)

4.4.2 North Sea

Two studies that consider the North Sea as a whole agreed that seasonal mean SWHs and/or annual extreme waves will increase in the future (Kaas et al. 2001, Caires et al. 2008).

The rest of this section follows a similar structure to that in the previous section. The projected changes are presented in order according to the geographical focus of the reviewed studies and projected results; the southern and eastern North Sea, and the western North Sea are presented separately.

The studies that established numerical results are summarised in more detail here. The detailed list of study results is given in Appendix B (Section B.2 and Table B.5).

Southern and eastern sections of the North Sea

The majority of the research agrees that annual median or extremes – or winter mean and extremes – will increase in the future (Debernard and Røed 2008, Grabemann and Weisse 2008, Lowe et al. 2009, Groll et al. 2014, Wang et al. 2014, Grabemann et al. 2015, Wolf et al. 2015). Wolf et al. (2015) found increases for the eastern North Sea only; they found decreases for the southern North Sea.

The identified increases in the seasonal or annual extremes vary between 5% and 8% (Debernard and Røed 2008, Wolf et al. 2015) or from 5% to 8% up to 18% for the annual 99th percentile (or 0.25–0.35m, Grabemann and Weisse 2008). Wang et al. (2014) also established that the 1 in 10 years SWH event would double or triple in frequency along the Danish coast under RCP8.5.

For the southern North Sea, however, Leake et al. (2008) obtained somewhat conflicting results depending on the emissions scenario. They identified increases near East Anglia in the winter mean and winter maximum SWH of 0.1m and 0.2m respectively, and an increase in the annual maximum SWH of 0.2m under the A2 scenario. Under the B2 emissions scenario, they identified decreases of -0.04m (-0.19m) in the winter mean (extremes) and a -0.56m reduction in the annual maximum.

Western and north-western sections of the North Sea

Existing research agrees on the projected decreases in the annual mean/median and extreme SWHs (Debernard and Røed 2008, Grabemann and Weisse 2008, De Winter

[7] See Section B.1.5 in Appendix B for definitions of the 'large' and 'extreme' wave events.

et al. 2012, Groll et al. 2014, Grabemann et al. 2015, Wolf et al. 2015, Aarnes et al. 2017). For example the annual mean SWH is projected to decrease by 2–4% (Debernard and Røed 2008) and up to 6% (Aarnes et al. 2017) by the end of the century. Aarnes et al. (2017) identified the same percentage reductions for the annual maximum, 90th and 99th percentile SWHs. Grabemann and Weisse (2008), Groll et al. (2014) and Grabemann et al. (2015) also all pointed to decreases;, Grabemann and Weisse (2008), Groll et al. (2014) established decreases of between 0.02m and 0.05m in the median SWH in the western and north-western parts of the North Sea, while Grabemann et al. (2015) projected reduction of between 0.25m and 0.75m in the annual median off the northern British coast.

Finally, some authors did not identify significant changes either when considering the North Sea as a whole or when studying a small area close to the UK or Dutch coasts: De Winter et al. (2012) indicated that the annual mean wave climate would not differ in the future in a small area in front of the Dutch coast or a small decrease would be seen in the annual maximum. Wolf et al. (2015) found that the future wave climate off the north Norfolk coast will not change compared with the current wave climate.

4.5 Uncertainty sources and considerations

Projections of 21st century wave climate are inherently uncertain. This has to some degree already been noted through the differing sign and/or magnitude of the wave heights projections in the literature. Some key sources of uncertainty are discussed below.

4.5.1 Climate model uncertainty

Uncertainty in the climate model is important to consider. The number of climate models and which specific models are being used varies (see Tables B.1 and B.2 in Appendix B). Each individual study has its own set of atmospheric climate models that are used to drive a (set of) wave model(s). This gives rise to ‘structural’ uncertainty because the ways in which the mathematical equations are solved within each model and the used parameterisations differ.

4.5.2 Emissions scenario uncertainty

Different emissions scenarios will give rise to different wave climate projections, particularly at the end of the 21st century. For instance, RCP8.5, being the highest concentration pathway, will give rise to the largest changes in wave heights in general. This would mainly be attributed to the large climate change effects on atmospheric circulation, which would then have an impact on the wave climate. On the other hand, RCP2.5, which would include strong greenhouse gas mitigation measures, would result in the least change in wave climate relative to the present since there would be less external climate forcing that could change the atmospheric circulation and hence ultimately the wave climate.

4.5.3 Experimental method

Another source of uncertainty is the experimental method used to produce the wave climate projections.

Some studies (for example, Wang and Swail 2006) used statistical methods where a statistical relationship between a large-scale driving variable such as mean sea level pressure from a global climate model (GCM) and the parameter of interest (waves in this case) is first established. The statistical relationship is formed from observed wave data compared with the historical mean sea level pressure fields from re-analysis data. The projections of changes in mean sea level pressure fields are then inputted into the statistical model to give projections of wave climate for the period of interest.

Some studies use wave models to obtain the wave climate simulations, with GCMs providing boundary input information. To obtain local-scale results, these studies use a technique called dynamical downscaling where the output of GCMs is used as input to regional climate models, which then provide higher resolution boundary information for a regional wave model representing the area of interest. These methodological differences will lead to different projections of the local wave climate.

4.5.4 Natural climate variability

The variability in the natural climate should also be considered when talking about the uncertainty in the wave climate projections. As mentioned previously, inherently large wave variability has been observed in the 20th century and hence some authors have commented that the changes by the end of this century may be partly related to internal variability rather than to external forcing (Grabemann et al. 2015). Mitchell et al. (2016) also indicated that the changes in wave climate by 2050 were smaller than the interannual variability of the wave climate in the Bernera and Wave Hub sites, as well as being smaller than the uncertainty in the climate projections. Hence the characterisation of the interannual variability of the wave climate would remain important for the years up to the middle of this century.

4.5.5 Locally driven waves versus swell waves

Those areas that are less exposed around the UK, such as the Irish Sea and the east coast of the UK may be dominated by high internal wave variability well into the 21st century. This is because these regions are far less influenced by swell waves that originate from remote locations than they are from locally generated waves from storm systems. Extracting a robust climate change signal in these regions as a result of the high variability associated with the generation of wind waves from storm systems (especially from a single model) can be difficult.

Studies have found that, when only one GCM was used under a few emissions scenarios, the results depended on the emissions scenario (Wang et al. 2004, Reeve et al. 2011). However, when a larger GCM ensemble was used in addition to the various emissions scenarios, all the studies agreed that the modelling uncertainty was greater than the emissions scenario uncertainty (Wang and Swail 2006, Debernard and Røed 2008, Grabemann and Weisse 2008, Charles et al. 2012, Wang et al. 2015).

4.5.6 Additional sources of uncertainty

Two studies explored additional sources:

- natural variability (Grabemann et al. 2015)
- wave climate generation methodology (Hemer et al. 2013a)

Grabemann et al. (2015) concluded that emissions scenarios had the least importance as a source of uncertainty. Hemer et al. (2013a) who studied the ensemble of opportunity in the COWCLIP project,[8] concluded that the uncertainty due to study methodology was greater than the modelling or emissions scenario uncertainty.

Finally, the geographical scope of the study and the time periods used are also important. Some authors have focused on larger areas in the North Atlantic and others on smaller regions. In terms of the time period, this consideration includes both the baseline period and the future time period in the 21st century against which the historic or baseline values are compared. For example, some authors have used a 1961 to 1990 baseline, whereas others have employed a 1971 to 2000 reference period. Similar time offsets are evident at the end of the 21st century.

4.6 Review of possible causes of 21st century changes in wave climate

Many authors have indicated that the changes in the projected wave climate are significantly related to the expected changes in wind characteristics (Kaas et al. 2001, Debernard and Røed 2008, Grabemann and Weisse 2008, Mori et al. 2010, Brown et al. 2012, Charles et al. 2012, De Winter et al. 2012, Hemer et al. 2013a, Gallagher et al. 2016a, Gallagher et al. 2016b).

Some authors have found that, in a warming climate, the intensity of the westerlies will increase in winter, leading to enhanced wind speeds and ultimately higher winter seasonal mean SWHs in the North-east Atlantic (Wang et al. 2004, Fan et al. 2013, Fan et al. 2014). These authors suggested that this would be due to an increased frequency of the positive phase of the NAO.

Research has also linked changes in wave climate to changes in the cyclonic activity in the future (Wang and Swail 2006). Lowe et al. (2009) indicated that, in winter and autumn, the changes in total SWH were closely linked to the changing storms in the North Atlantic. More frequent occurrence of strong cyclones expected in a warmer climate (Wang et al. 2004) was projected to affect wave development and lead to increases in wave heights in the north-east Atlantic.

4.7 Gaps in understanding

An important caveat to have in mind for all of the discussed studies is the realism of the storminess characteristics in the GCM simulations. Since the swell waves are generated remotely, the hypothesis is that the climate projections may be more robust – in that they may be less sensitive to the precise details of how weather systems change in the future. But if extreme wave climate conditions are of interest, the representation of storms and the atmospheric resolution of the model will still be important, because very strong winds or very large storms create long period swell (Andrew Saulter, personal communication).

Another specific gap in the existing research is the consideration of the retreat of Arctic sea ice and how it can affect the wave climate on northward facing coasts (especially in the north north-east parts of the North Atlantic) through the potential for a larger fetch for northerly winds and a systematic increase of the wave maxima. It is also worth considering whether and how the changes in ice coverage may affect the storm track (Andrew Saulter, personal communication).

[8] Coordinated Ocean–Wave Climate Projections project

Finally, although some of the models do include wave generation processes in shallow waters, wave climate changes closer to coasts are not directly inferable from the existing research and merit focused investigation.

4.8 Conclusions from the waves literature review

During the second half of the 20th century, SWHs have increased in the north-east Atlantic, consistent with the identified increases in wind speed and storm frequency, and in the number of intense cyclones passing through the area. In the North Sea, the mean and extreme SWHs have increased as well. The wave climate in both regions was characterised by high interannual and decadal variability.

The UKCP18 21st century projections of offshore average wave height suggest changes of the order of 10–20% and a general tendency towards lower wave heights (Palmer et al. 2018b). Changes in extreme offshore waves are also of the order of 10–20%, but there is no agreement on the sign of the change among the model projections. High resolution wave simulations suggest that the changes in wave climate over the 21st century on exposed coasts will be determined by the global response to climate change. However, more sheltered coastal regions are likely to remain dominated by local weather variability over the 21st century.

In terms of the established changes in the offshore wave climate in the north-east Atlantic and various smaller areas around the UK, the rest of the studies indicate the following.

- For the north-east Atlantic, existing research agrees on the projected increases in seasonal mean SWHs, or seasonal and annual extremes of SWHs. The changes vary between 5cm and 35cm or up to 50cm for the seasonal means, around 50cm for seasonal extremes, and up to 130cm or by about 10–20% for the period mean of the annual maxima for west-facing coasts.

- For the areas north or north-west of the UK, the existing studies do not agree on the sign of the change in annual and seasonal mean and extreme SWHs.

- For the areas to the west of the British Isles, most studies indicate a decrease in the seasonal mean and extreme SWHs (the changes vary between -5 and -10%). In agreement with the UKCP18 findings, the annual mean of the SWHs is also projected to decrease (by 5–10% off the west coast of Ireland). The annual maxima or 99th percentile are found to decrease by about 2–6% west of the UK and Ireland. Only one study indicated increases in the annual extremes west of the British Isles by 2–6% (Debernard and Røed 2008).

- For the areas to the south-west of the British Isles, in accordance with the UKCP18 results the annual mean SWHs were projected to decrease by several studies (the changes were between 3% and 5% or 0.04–0.08m). The annual extremes were projected to increase by 10–20% for the period mean of the annual maxima. The results on the changes in the summer mean SWHs are conflicting; several studies projected increases in seasonal means and extremes especially for winter (increases of winter means are between 4% and 8%, or around 0.1m, while the extremes would rise by about 0.4m).

- For the areas around Ireland and the UK, in general, the studies indicated that the annual mean SWHs would decrease (by between 2 and 8%) in agreement with the UKCP18 results and the above mentioned results about the areas to the west of UK; The results regarding the changes in the annual extreme SWHs are conflicting.

- For the Liverpool Bay area, the research has indicated decreases in seasonal and most monthly means (up to -20% in September and up to -8.8% in spring), but increases in extreme wave events of between 0.31% and 9.5%. The findings on the changes in the average SWHs are in parallel with the UKCP18 results.

For the North Sea, the results from the reviewed studies indicate an increase in the projected seasonal means or extremes of the wave climate, and of the annual extremes in the basin as a whole. Considering regional changes in the wave climate, the research indicates an increase in annual median or extremes, or winter mean and extreme SWHs within the southern and eastern North Sea. The projected changes vary between 5% and 8%, or up to 18% for seasonal and annual extremes, or also between 0.25 and 0.35m for the annual 99th percentile. The studies agree that the western and north-western sections of the North Sea will be characterised by reductions in the annual mean and extreme SWHs varying around 2–6%, or between 0.02–0.05m and 0.25–0.75m.

Despite the uncertainties in the wider literature, for decision-making purposes, it is recommended that the headlines within the UKCP18 wave study that translate to pertinent wave climate projections at coastal locations around the UK are followed.

Finally, in coastal flood risk assessment any change in offshore wave climate due to climate change does not have as great an impact as the increased water depths due to sea level rise, which allow a bigger wave to reach the flood defences. Waves are depth limited in the UK shallow water coastline (controlling features are water depth, wavelength and seabed slope) and any changes to offshore wave height without a commensurate increase in water depth are not transformed to the defence. Wave height and period are critical features for consideration in coastal defence and 2 important points are highlighted with wave height (assuming no changes predicted to wave period).

- With increasing wave height, breaking later, flood water volumes will increase in the flood zones.
- With increasing wave height, breaking later, the energy of the waves increases by the square (that is, a wave that is twice as high will have 4 times the energy). This has huge implications for the infrastructure vulnerability on the coast in the UK.

In summary, the sea level rise element of climate change is expected to have a greater impact on coastal defences than changes in offshore wave magnitudes due to changes in weather patterns (Tim Hunt, personal communication).

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List of abbreviations

AnnMax	mean annual maximum wave height
AR5	Fifth Assessment Report
CMIP5	Coordinated Modelling Intercomparison Project Phase 5
GCM	global climate model
GIA	glacial isostatic adjustment
IPPC	Intergovernmental Panel on Climate Change
NAO	North Atlantic Oscillation
ODN	Ordnance Datum Newlyn
RCP	representative concentration pathway
RCM	regional climate model
SWH	significant weave height
UKCIP18	UK Climate Projections 2018

Glossary

Fingerprint	The characteristic pattern of global mean sea level change associated with a specific land-based mass source.
Glacial isostatic adjustment (GIA)	The ongoing movement of the lithosphere in response to the removal of ice mass at the end of the last Ice Age.
Representative concentration pathway (RCP)	These replace the emissions scenarios (of climate change). See the glossary entry in IPPC AR5 (Church et al. 2013, Glossary, p. 1461).
Return level	The level that is expected to be exceeded on average once per return period.
Return period	See definition and discussion in Section 2.7.
Still water level	Still water level refers to the water level averaged over a period (say ~15 minutes) much longer than the period of a surface wave. It accounts for tide and surge but not intermittent overtopping by waves.
Time-mean sea level	Sea level at a given location averaged over a period long enough to remove the influence of the tides and short-term climatic variability. Typically an averaging period of at least one year is used.

Appendix A: Projections of future extreme coastal still water levels at UK tide gauges

Projections of future extreme still water levels at selected UK tide gauge locations and different RCPs are shown in Tables A.1 to A.4. This information is also available via the UKCP18 user interface (https://ukclimateprojections-ui.metoffice.gov.uk/). Please note the following.

- Nominal latitude (Nom. Lat.) and nominal longitude (Nom. Long.) may be slightly different to the exact latitude and longitude of the gauge because the location of the nearest Continental Shelf 3 (CS3) coastal shelf model grid box is used.
- 'Chain' is the coastal chainage defined in Environment Agency (2011).
- The results are given under the lower, central and upper estimates of mean relative sea level change for each RCP.
- Even though the uncertainty in the Environment Agency (2019) estimates of present day return levels is not included, the range (upper minus lower) is not zero at 2017. This is because the projections of mean sea level change are provided relative to a baseline period of 1981 to 2000 and therefore there is some uncertainty in the projected sea level rise prior to 2017.
- Full details of the locations of the tide gauges can be found on the UK National Tide Gauge Network website (www.ntslf.org/data/uk-network-real-time) and/or the Permanent Service for Mean Sea Level website (www.psmsl.org).

Table A.1 RCP2.6: Projected future extreme water levels (1, 200 and 10,000 year return levels) for 6 sites and 3 future times (2100, 2200, 2300)

rcp26 (lower) **central** (upper)

Site	Chain (km)	Nom.Lat.	Nom. Long.	1 year return level (m)				200 year return level (m)				10,000 year return level (m)			
				2017	**2100**	**2200**	**2300**	**2017**	**2100**	**2200**	**2300**	**2017**	**2100**	**2200**	**2300**
Newlyn	0.0	50.06	-5.42	(3.06) **3.11** (3.17)	(3.34) **3.5** (3.77)	(3.53) **3.88** (4.59)	(3.66) **4.18** (5.35)	(3.53) **3.58** (3.64)	(3.81) **3.97** (4.24)	(4.0) **4.35** (5.06)	(4.13) **4.65** (5.82)	(3.83) **3.88** (3.94)	(4.11) **4.28** (4.54)	(4.31) **4.66** (5.37)	(4.43) **4.95** (6.12)
Avonmouth	380.0	51.5	-2.75	(8.06) **8.11** (8.17)	(8.31) **8.47** (8.73)	(8.46) **8.8** (9.49)	(8.55) **9.06** (10.19)	(9.02) **9.07** (9.12)	(9.26) **9.43** (9.69)	(9.42) **9.76** (10.45)	(9.51) **10.02** (11.15)	(10.0) **10.05** (10.11)	(10.25) **10.41** (10.67)	(10.4) **10.74** (11.43)	(10.49) **11.0** (12.13)
Tobermory	2320.0	56.61	-6.25	(2.94) **2.98** (3.04)	(3.06) **3.22** (3.48)	(3.07) **3.41** (4.12)	(3.02) **3.53** (4.69)	(3.76) **3.8** (3.86)	(3.88) **4.04** (4.3)	(3.89) **4.23** (4.94)	(3.84) **4.35** (5.51)	(4.39) **4.43** (4.49)	(4.51) **4.67** (4.94)	(4.53) **4.87** (5.57)	(4.47) **4.98** (6.14)
Lerwick	nan	60.17	-1.08	(1.45) **1.5** (1.55)	(1.74) **1.9** (2.16)	(1.95) **2.28** (2.98)	(2.09) **2.59** (3.74)	(1.78) **1.83** (1.88)	(2.07) **2.23** (2.48)	(2.28) **2.61** (3.31)	(2.42) **2.92** (4.07)	(1.98) **2.02** (2.08)	(2.27) **2.42** (2.68)	(2.48) **2.81** (3.51)	(2.62) **3.12** (4.27)
Sheerness	4314.0	51.5	0.75	(3.65) **3.7** (3.75)	(3.91) **4.07** (4.33)	(4.08) **4.42** (5.1)	(4.19) **4.69** (5.8)	(4.61) **4.65** (4.71)	(4.86) **5.02** (5.28)	(5.04) **5.37** (6.05)	(5.15) **5.64** (6.76)	(5.54) **5.59** (5.65)	(5.8) **5.96** (6.22)	(5.98) **6.31** (6.99)	(6.09) **6.58** (7.7)
Dover	4410.0	51.17	1.42	(3.75) **3.8** (3.86)	(4.01) **4.17** (4.43)	(4.18) **4.52** (5.19)	(4.29) **4.78** (5.89)	(4.63) **4.68** (4.74)	(4.89) **5.05** (5.31)	(5.06) **5.4** (6.07)	(5.17) **5.66** (6.77)	(5.34) **5.39** (5.45)	(5.6) **5.76** (6.02)	(5.77) **6.11** (6.79)	(5.88) **6.38** (7.49)

Notes: Each cell shows return levels under the (lower) central (upper) estimates of mean relative sea level change for the RCP2.6 scenario.
The central estimate for 2017 is the central estimate given by Environment Agency (2019) and is included primarily as a check.
Uncertainty in the present day return levels is not included.

Table A.2 RCP4.5: Projected future extreme water levels (1, 200 and 10,000 year return levels) for 6 sites and 3 future times (2100, 2200, 2300)

rcp45 (lower) **central** (upper)

Site	Chain (km)	Nom. Lat.	Nom. Long.	1 year return level (m)				200 year return level (m)				10,000 year return level (m)			
				2017	2100	2200	2300	2017	2100	2200	2300	2017	2100	2200	2300
Newlyn	0.0	50.06	-5.42	(3.06) **3.11** (3.17)	(3.4) **3.59** (3.89)	(3.72) **4.13** (4.91)	(3.91) **4.53** (5.8)	(3.53) **3.58** (3.64)	(3.87) **4.06** (4.36)	(4.19) **4.6** (5.38)	(4.38) **5.0** (6.27)	(3.83) **3.88** (3.94)	(4.18) **4.36** (4.66)	(4.49) **4.91** (5.69)	(4.69) **5.31** (6.57)
Avonmouth	380.0	51.5	-2.75	(8.06) **8.11** (8.17)	(8.37) **8.55** (8.84)	(8.65) **9.05** (9.81)	(8.8) **9.41** (10.64)	(9.02) **9.07** (9.13)	(9.33) **9.51** (9.8)	(9.6) **10.01** (10.77)	(9.76) **10.37** (11.6)	(10.0) **10.05** (10.11)	(10.31) **10.49** (10.78)	(10.58) **10.99** (11.75)	(10.74) **11.35** (12.58)
Tobermory	2320.0	56.61	-6.25	(2.94) **2.98** (3.04)	(3.12) **3.3** (3.59)	(3.23) **3.64** (4.41)	(3.22) **3.83** (5.09)	(3.75) **3.8** (3.86)	(3.94) **4.12** (4.41)	(4.05) **4.45** (5.23)	(4.04) **4.65** (5.91)	(4.39) **4.43** (4.49)	(4.57) **4.75** (5.04)	(4.68) **5.09** (5.86)	(4.68) **5.28** (6.54)
Lerwick	nan	60.17	-1.08	(1.45) **1.5** (1.55)	(1.79) **1.97** (2.26)	(2.09) **2.49** (3.25)	(2.28) **2.88** (4.13)	(1.78) **1.83** (1.88)	(2.12) **2.3** (2.59)	(2.42) **2.82** (3.58)	(2.6) **3.21** (4.46)	(1.98) **2.02** (2.08)	(2.32) **2.5** (2.78)	(2.62) **3.02** (3.78)	(2.8) **3.41** (4.66)
Sheerness	4314.0	51.5	0.75	(3.65) **3.7** (3.76)	(3.97) **4.15** (4.44)	(4.26) **4.67** (5.42)	(4.44) **5.04** (6.25)	(4.6) **4.65** (4.71)	(4.93) **5.11** (5.4)	(5.22) **5.62** (6.37)	(5.4) **6.0** (7.21)	(5.54) **5.59** (5.65)	(5.87) **6.05** (6.34)	(6.16) **6.56** (7.31)	(6.34) **6.93** (8.15)
Dover	4410.0	51.17	1.42	(3.75) **3.8** (3.86)	(4.07) **4.25** (4.54)	(4.36) **4.77** (5.51)	(4.54) **5.14** (6.35)	(4.63) **4.68** (4.74)	(4.95) **5.13** (5.42)	(5.24) **5.65** (6.39)	(5.42) **6.02** (7.23)	(5.34) **5.39** (5.45)	(5.66) **5.85** (6.14)	(5.96) **6.36** (7.11)	(6.14) **6.73** (7.95)

Notes: Each cell shows return levels under the (lower) central (upper) estimates of mean relative sea level change for the RCP4.5 scenario.
The central estimate for 2017 is the central estimate given by Environment Agency (2019) and is included primarily as a check.
Uncertainty in the present day return levels is not included.

Table A.3 RCP8.5: Projected future extreme water levels (1, 200 and 10,000 year return levels) for 6 sites and 3 future times (2100, 2200, 2300)

rcp85 (lower) **central** (upper)															
Site	**Chain (km)**	**Nom. Lat.**	**Nom. Long.**	**1 year return level (m)**				**200 year return level (m)**				**10,000 year return level (m)**			
				2017	**2100**	**2200**	**2300**	**2017**	**2100**	**2200**	**2300**	**2017**	**2100**	**2200**	**2300**
Newlyn	0.0	50.06	-5.42	(3.05) **3.11** (3.17)	(3.55) **3.8** (4.17)	(4.19) **4.83** (5.91)	(4.55) **5.59** (7.42)	(3.52) **3.58** (3.64)	(4.02) **4.27** (4.64)	(4.66) **5.3** (6.38)	(5.02) **6.06** (7.89)	(3.83) **3.88** (3.94)	(4.33) **4.58** (4.95)	(4.96) **5.6** (6.68)	(5.32) **6.36** (8.19)
Avonmouth	380.0	51.5	-2.75	(8.05) **8.11** (8.17)	(8.52) **8.76** (9.13)	(9.11) **9.74** (10.79)	(9.43) **10.45** (12.23)	(9.01) **9.07** (9.12)	(9.48) **9.72** (10.08)	(10.07) **10.7** (11.75)	(10.39) **11.41** (13.19)	(9.99) **10.05** (10.11)	(10.46) **10.7** (11.06)	(11.05) **11.68** (12.73)	(11.37) **12.39** (14.17)
Tobermory	2320.0	56.61	-6.25	(2.93) **2.98** (3.04)	(3.25) **3.48** (3.84)	(3.58) **4.21** (5.28)	(3.67) **4.69** (6.48)	(3.75) **3.8** (3.86)	(4.07) **4.3** (4.66)	(4.4) **5.03** (6.1)	(4.49) **5.51** (7.3)	(4.38) **4.43** (4.49)	(4.7) **4.93** (5.29)	(5.03) **5.67** (6.73)	(5.12) **6.14** (7.94)
Lerwick	nan	60.17	-1.08	(1.45) **1.5** (1.55)	(1.91) **2.14** (2.5)	(2.4) **3.04** (4.08)	(2.65) **3.68** (5.45)	(1.77) **1.83** (1.88)	(2.24) **2.47** (2.83)	(2.73) **3.37** (4.41)	(2.98) **4.01** (5.78)	(1.97) **2.02** (2.08)	(2.44) **2.67** (3.03)	(2.93) **3.56** (4.61)	(3.18) **4.21** (5.98)
Sheerness	4314.0	51.5	0.75	(3.64) **3.7** (3.76)	(4.12) **4.37** (4.73)	(4.74) **5.37** (6.41)	(5.09) **6.11** (7.88)	(4.6) **4.65** (4.71)	(5.08) **5.32** (5.68)	(5.7) **6.33** (7.37)	(6.04) **7.07** (8.83)	(5.54) **5.59** (5.65)	(6.02) **6.26** (6.62)	(6.63) **7.27** (8.31)	(6.98) **8.01** (9.77)
Dover	4410.0	51.17	1.42	(3.74) **3.8** (3.86)	(4.22) **4.47** (4.83)	(4.84) **5.48** (6.52)	(5.2) **6.22** (7.99)	(4.62) **4.68** (4.74)	(5.1) **5.35** (5.71)	(5.72) **6.36** (7.4)	(6.08) **7.1** (8.87)	(5.34) **5.39** (5.45)	(5.82) **6.06** (6.42)	(6.44) **7.07** (8.11)	(6.79) **7.82** (9.58)

Notes: Each cell shows return levels under the (lower) central (upper) estimates of mean relative sea level change for the RCP8.5 scenario.
The central estimate for 2017 is the central estimate given by Environment Agency (2019) and is included primarily as a check.
Uncertainty in the present day return levels is not included.

Table A.4 RCP8.5: Projected future extreme water levels (1, 200 and 10,000 year return levels) for all sites (central estimate only) and 3 future times (2100, 2200, 2300)

rcp85 50th percentile															
Site	Chain (km)	Nom.Lat.	Nom. Long.	1-year return level (m)				200-year return level (m)				10,000-year return level (m)			
				2017	2100	2200	2300	2017	2100	2200	2300	2017	2100	2200	2300
Newlyn	0.0	50.06	-5.42	3.11	3.8	4.83	5.59	3.58	4.27	5.3	6.06	3.88	4.58	5.6	6.36
St Mary’s	nan	49.94	-6.25	3.41	4.11	5.14	5.9	3.84	4.54	5.57	6.33	4.11	4.81	5.84	6.6
Padstow	128.0	50.61	-4.92	4.56	5.24	6.25	6.98	5.05	5.72	6.73	7.47	5.42	6.1	7.1	7.84
Ilfracombe	250.0	51.28	-4.08	5.43	6.09	7.07	7.78	5.99	6.65	7.62	8.34	6.45	7.11	8.09	8.8
Hinkley	326.0	51.28	-3.08	7.05	7.7	8.69	9.41	7.78	8.44	9.42	10.14	8.54	9.19	10.18	10.89
Avonmouth	380.0	51.5	-2.75	8.11	8.76	9.74	10.45	9.07	9.72	10.7	11.41	10.05	10.7	11.68	12.39
Newport	398.0	51.5	-2.92	7.45	8.1	9.08	9.79	8.33	8.98	9.96	10.67	9.25	9.9	10.88	11.59
Mumbles	492.0	51.61	-3.92	5.51	6.16	7.12	7.82	6.34	6.99	7.95	8.65	6.99	7.63	8.6	9.29
Milford Haven	622.0	51.61	-5.08	4.2	4.84	5.8	6.48	4.84	5.48	6.44	7.12	5.33	5.97	6.92	7.61
Fishguard	712.0	52.06	-4.92	3.1	3.72	4.65	5.31	3.62	4.24	5.17	5.83	3.99	4.61	5.54	6.2
Barmouth	832.0	52.72	-4.08	3.46	4.06	4.96	5.59	4.38	4.98	5.88	6.52	5.09	5.69	6.59	7.22
Holyhead	1012.0	53.28	-4.75	3.37	3.93	4.79	5.37	3.94	4.51	5.36	5.95	4.35	4.92	5.77	6.36
Llandudno	1110.0	53.39	-3.75	4.7	5.27	6.14	6.74	5.33	5.91	6.77	7.37	5.81	6.39	7.25	7.85
Hilbre Island	1154.0	53.39	-3.25	5.24	5.83	6.7	7.32	5.96	6.54	7.42	8.03	6.5	7.08	7.96	8.57
Port Erin	nan	54.17	-4.75	3.27	3.79	4.59	5.12	3.95	4.48	5.27	5.81	4.44	4.97	5.76	6.3
Heysham	1254.0	54.06	-2.92	5.86	6.42	7.27	7.85	6.86	7.42	8.26	8.84	7.63	8.19	9.03	9.62
Workington	1390.0	54.61	-3.58	5.09	5.61	6.4	6.93	5.95	6.47	7.26	7.79	6.62	7.14	7.93	8.46
Portpatrick	1648.0	54.83	-5.25	2.82	3.32	4.07	4.57	3.56	4.06	4.81	5.3	4.09	4.59	5.34	5.84
Millport	1782.0	55.72	-4.92	2.67	3.14	3.86	4.31	3.65	4.12	4.84	5.3	4.44	4.91	5.63	6.08
Port Ellen	nan	55.61	-6.08	1.45	1.94	2.67	3.15	2.24	2.73	3.47	3.94	2.81	3.3	4.03	4.51
Tobermory	2320.0	56.61	-6.25	2.98	3.48	4.21	4.69	3.8	4.3	5.03	5.51	4.43	4.93	5.67	6.14
Ullapool	2564.0	57.94	-5.25	3.22	3.74	4.48	4.97	3.9	4.42	5.16	5.65	4.34	4.85	5.6	6.09
Stornoway	nan	58.17	-6.25	2.89	3.44	4.22	4.75	3.44	3.99	4.77	5.3	3.78	4.33	5.11	5.64
Kinlochbervie	2670.0	58.5	-5.08	3.17	3.72	4.49	5.01	3.94	4.48	5.25	5.78	4.46	5.01	5.78	6.3
Lerwick	nan	60.17	-1.08	1.5	2.14	3.04	3.68	1.83	2.47	3.37	4.01	2.02	2.67	3.56	4.21
Wick	2870.0	58.39	-3.08	2.4	2.93	3.69	4.2	2.91	3.44	4.2	4.71	3.21	3.74	4.5	5.01
Moray Firth	3012.0	57.61	-4.08	2.85	3.33	4.05	4.52	3.35	3.84	4.56	5.02	3.71	4.2	4.92	5.38

rcp85 50th percentile															
Site	**Chain (km)**	**Nom.Lat.**	**Nom. Long.**	**1-year return level (m)**				**200-year return level (m)**				**10,000-year return level (m)**			
				2017	**2100**	**2200**	**2300**	**2017**	**2100**	**2200**	**2300**	**2017**	**2100**	**2200**	**2300**
Aberdeen	3226.0	57.17	-2.08	2.69	3.19	3.93	4.42	3.22	3.72	4.46	4.94	3.58	4.07	4.82	5.3
Leith	3420.0	56.06	-3.25	3.37	3.85	4.57	5.03	3.96	4.43	5.15	5.62	4.41	4.89	5.61	6.07
North Shields	3630.0	55.06	-1.42	3.21	3.77	4.61	5.19	3.85	4.42	5.26	5.84	4.42	4.98	5.82	6.4
Whitby	3720.0	54.5	-0.58	3.36	3.98	4.88	5.53	4.11	4.72	5.63	6.28	4.81	5.42	6.32	6.97
Immingham	3888.0	53.61	-0.25	4.17	4.81	5.77	6.46	5.06	5.7	6.66	7.35	5.92	6.57	7.52	8.21
Cromer	4096.0	52.94	1.25	3.07	3.75	4.75	5.49	4.08	4.76	5.76	6.5	5.03	5.7	6.71	7.45
Lowestoft	4162.0	52.5	1.75	2.02	2.7	3.71	4.46	3.27	3.95	4.96	5.71	4.31	4.99	6.01	6.76
Felixstowe Pier	4232.0	51.94	1.42	2.68	3.36	4.37	5.11	3.74	4.41	5.42	6.16	4.77	5.45	6.46	7.2
Sheerness	4314.0	51.5	0.75	3.7	4.37	5.37	6.11	4.65	5.32	6.33	7.07	5.59	6.26	7.27	8.01
Dover	4410.0	51.17	1.42	3.8	4.47	5.48	6.22	4.68	5.35	6.36	7.1	5.39	6.06	7.07	7.82
Newhaven	4526.0	50.72	0.08	3.87	4.54	5.55	6.29	4.46	5.13	6.14	6.88	4.96	5.63	6.64	7.38
Portsmouth	4616.0	50.83	-1.08	2.55	3.22	4.23	4.97	3.1	3.77	4.77	5.51	3.49	4.15	5.16	5.9
Bournemouth	4682.0	50.61	-1.92	1.4	2.08	3.08	3.83	1.9	2.58	3.59	4.33	2.28	2.95	3.96	4.7
Weymouth	4736.0	50.61	-2.42	1.82	2.49	3.5	4.24	2.35	3.02	4.03	4.77	2.76	3.43	4.44	5.18
Exmouth	4836.0	50.61	-3.42	2.76	3.43	4.44	5.18	3.34	4.01	5.02	5.75	3.66	4.34	5.34	6.08
Devonport	4950.0	50.28	-4.08	2.95	3.63	4.65	5.4	3.47	4.15	5.17	5.92	3.84	4.53	5.54	6.29
Portrush	nan	55.28	-6.58	1.61	2.12	2.87	3.36	2.29	2.8	3.55	4.04	2.78	3.29	4.04	4.53
Belfast	nan	54.72	-5.75	2.16	2.67	3.43	3.92	2.96	3.46	4.22	4.72	3.69	4.2	4.96	5.45
Jersey	nan	49.17	-2.08	6.21	6.89	7.92	8.67	6.75	7.43	8.46	9.21	7.2	7.88	8.9	9.66

Appendix B: Wave literature review summary tables and results by focus area

B.1 North-east Atlantic

The majority of the studies indicate an **increase** in the mean and extreme SWHs in the north-east Atlantic.

- Wang et al. 2004:
  - increase in winter and autumn means of 5–35cm and 5–20cm respectively
  - increase in winter 90th percentile of up to 50cm (11% of baseline)
- Wang and Swail 2006:
  - increase in winter, spring and summer mean SWHs (for winter the increase is up to 12cm, about 6%, for A2 emissions scenario)
  - increase in winter, spring, summer and autumn extreme SWHs under A2 scenario (for summer the increase is largest up to 50cm or 9%)
- Leake et al 2008:
  - increase of >14cm of the winter mean SWHs for A2 and B2
  - increase of up to 130cm for A2 and up to 100cm for B2 in period mean of winter maximum for 2070 to 2100
- Lowe et al. 2009:
  - increase in winter, spring and summer mean SWHs
- Fan et al. 2013:
  - increase of 7–8% and up to 15% or >0.5m increase in winter mean SWHs
- Fan et al. 2014:
  - winter mean wind waves energy increases in the future
- Bricheno and Wolf 2018:
- increase up to about 10–20% in the period mean annual maximum along west-facing coasts under RCP4.5/8.5

However, 2 studies indicated a **decrease** in SWHs in the North-east Atlantic or the North Atlantic as a whole.

- Hemer et al. 2013b focused on the North Atlantic as whole. They indicated that:
  - reductions in monthly mean and 99th percentile of SWHs were projected for the future

- the monthly means in winter would decrease by about 1m and the seasonal summer mean would decrease by about 0.2m

- Bricheno and Wolf 2018:

- a decrease in the annual mean SWHs varying between 0% and 5% (see middle panel of Figure 4.1)

B.1.1 Areas to the north and north-west of the UK

One study indicates an **increase** in mean or extreme SWHs: Kaas et al. (2001) projected an increase in winter, spring and autumn mean SHWs;

Two studies indicated **mixed results**:

- Lowe et al. (2009) projected a decrease in winter and spring mean SWHs (up to -0.4m for winter) to the north of UK, but an increase in the summer mean SWHs around the UK and in the autumn mean SWHs north-west of Scotland. They also found a statistically significant trend in annual extremes of -0.3cm per year north of Scotland.

- Wolf et al. (2015) showed that, while an increase in annual mean SWHs can be expected mid-century north of the British Isles (see Figure 4.2), by the end of the century this parameter will decrease north-west of Scotland (Figure 4.2). They also indicated that the 30-year period means of annual maxima would increase in the north-west approaches (Western Isles of Scotland) by between 10% and 20%.

Mitchell et al. (2016) found a statistically significant **decrease** in the ensemble mean of the annual mean SWH near the Bernera site by the mid-century.

B.1.2 Changes to the west of the British Isles

Three studies indicate that **decreases** are to be expected in these areas:

- Zacharioudaki et al. (2011) indicated a decrease in spring, summer and autumn mean and 99th percentile SWHs in the West European shelf seas.

- Gallagher et al. (2016a, 2016b) found decreases in the winter (summer) seasonal mean of up to -10% (up to -15%) off the west (south) coast of Ireland for RCP8.5. For spring (autumn), they found a small decrease in the seasonal mean SWHs of less than 5% for both scenarios. The annual mean SWHs were projected to decrease by 5–10% off the Atlantic coast of Ireland in both scenarios. They also found robust decreases in the 95th percentile of SWHs varying by about -5% for the winter and summer seasons and for the annual extremes off the west and southern coasts. The largest changes were seen for RCP8.5 in summer when reductions in the 95th percentile were projected to be > 10%.

- Aarnes et al. (2017) established that the annual 99th percentile (annual maximum) would decrease by 2–4% and up to 6% (no change or up to 2–4% under RCP4.5 or up to 4–% under RCP8.5) to the north and west of the UK and Ireland.

One study indicated an **increase**: Debernard and Røed (2008) found an increase in the winter 99the percentile of SWHs of 2–4% west of the British Isles, and an increase of up to 6% in the 99the percentile of the annual SWH west of British Isles.

B.1.3 Changes to the south-west of the British Isles

Several studies agree that the annual mean SWHs will **decrease**:

- Zacharioudaki et al. 2011:
  - decrease of -3% to -5% in annual mean SWHs (their Figure 5) south-west of the UK
- Wolf et al. 2015:
  - decrease in annual mean wave heights south-west of the UK in mid-century (see Figure 4.2)
- Perez et al. 2015:
  - period mean SWHs decreasing in all RCPs, varying between 0.04m for RCP2.6 and up to about 0.08m for RCP8.5 in mid- and late century periods to the south-west of the UK
- Reeve et al 2011 obtained conflicting results at the Wave Hub under the 2 emissions scenarios they used:
  - an increase in annual mean wave power by 2.95% under A1B
  - a decrease by 2.27% under the B1 scenario
- Gallagher et al. 2016a and 2016b:
  - a decrease in the summer mean and 95th percentile SWHs
  - a decrease in seasonal mean of up to 15% off the south coast of Ireland for RCP8.5
  - robust decrease in the 95th percentile off the south coast

Several studies are in accord that some seasonal means, extremes or the annual extremes will **increase**:

- Leake et al. 2008:
  - an increase in winter mean of >0.14m for A2 and B2 scenarios south-west of the UK (their Figure 7)
  - >0.4m increase in winter maximum SWH for January, February and March (their Figure 8)
- Lowe et al. 2009:
  - increase in winter mean SWHs in the south-west approaches and an increase of around 0.1m in the English Channel
  - increase in the spring mean SWHs in the south-west approaches to the UK
  - increase in the summer mean SWHs in the waters around the UK
  - increase in the maximum annual wave heights in the English Channel
- Zacharioudaki et al. 2011:
  - agreed with the findings of Lowe et al. (2009) and Leake et al. (2008) and also indicated that the winter mean SWHs would increase by 4–8% south-west of the UK

    - in accordance with Leake et al. (2008) they found that the winter 99th percentile would also increase to the south-west of the UK

- Wolf et al. 2015:
    - agreed with Lowe et al. (2008) and indicated that the 30-year period means of annual maxima would increase in the south-west (English Channel) between 10% and 20% by the end of the century

B.1.4 Around Ireland or UK

Three studies agreed that **decreases** in the annual mean SWHs would be evident around the UK or Ireland.

- Perez et al. 2015:
    - period mean annual SWHs would decrease around Great Britain and Ireland in all RCPs
- Aarnes et al. 2017:
    - decreases around the UK and Ireland varying between 2–4% and 6–8% respectively for 2071 to 2100
    - decreases in annual 9th percentile around the UK and Ireland varying between 2–4% and 4–6% respectively for 2071 to 2100
- Bricheno and Wolf 2018:
    - decreases in annual mean in sites around the UK coast varying between 0% and 5% for the future (see middle panel of Figure 4.1)

One study does not agree with these findings: Wolf et al. (2015) found **increases** in 30-year period mean of annual maximum SWHs varying between 10% and 30% around Ireland by the end of the century except for the eastern coast.

B.1.5 About the Liverpool Bay area

Brown et al. (2012) found differences in the SWH change patterns depending on the month or season of the year.

- They found **increases** in mean monthly SWHs in December and November (between 2.5 and 3%), and also in June of about 16%. Positive trends in large wave events (waves >3m) and extreme (waves >5m) varying between 0.31% and 9.5% respectively were found during the winter months, with a largest increases in January.
- **Decreases** were found for the rest of the months (lowest reductions in May about 2%, largest decreases for September -20%). All seasonal means were decreasing (more specifically by 8.8% in spring and 5.5% in summer).

B.2 North Sea changes

Two studies that considered the North Sea as a whole agreed that seasonal mean SHWs and annual extreme waves would **increase** in the future.

- Kaas et al. 2001:

- winter, spring and autumn mean SWHs will increase, with the increase being largest in autumn
- there is a tendency for an increase of the annual 99.9th percentile for waves

- Caires et al. 2008:
  - the annual exceedances above a threshold will increase by 0.001m per year in the future

B.2.1 Southern and eastern sections

The majority of the research agreed that annual median or extremes, or winter mean and extremes will **increase** in the future:

- Debernard and Røed 2008 – 6-8% increase is expected for the winter, summer and annual extremes along the North Sea east coast.
- Grabemann and Weisse 2008 – increase in the annual median SWHs in the Eastern North Sea, as well as an Increase by 0.25-0.35m (5-8%, up to 18%) of 99p in eastern and southern North Sea.
- Lowe et al. 2009 – an increase in winter means in southern North Sea, and in summer means in southern and eastern North Sea; they also found an increase in winter and the annual maximum in the southern North Sea.
- Groll et al. 2014 – Also found an increase in the annual median of the SWHs in eastern North Sea by the end of the century, and rise in the 99p of SWHs in the southern and eastern North Sea by the end of the century.
- Wang et al. 2014 showed that the 1 in 10 years SWHs will double or triple in frequency along Danish coast under RCP8.5.
- Grabemann et al. 2015 – also found an increase in the annual median SWHs in the south and eastern North Sea, as well as a rise in the annual maximum and 99p extreme waves in the same areas.
- Wolf et al. 2015 – Increase of annual mean SWHs in the eastern North Sea by the mid-century for RCP8.5, and an increase of 5% along the eastern North Sea for the period mean of annual maximum SWHs.

Finally, Leake et al. had somewhat conflicting results depending on the emissions scenario: An increase in winter mean (extremes) of 0.1m (0.2m) near East Anglia, and an increase in annual maximum of SWHs of 0.2m in southern North Sea was projected under the A2 scenario, while a decrease of -0.04m (-0.19m) in the winter mean (extremes), and of -0.56m for the annual maximum was identified for southern North Sea under the B2 emissions scenario.

B.2.2 Western sections

Existing research agreed on projected **decreases** in the annual mean and extreme SWHs in the western sections of the North Sea:

- Debernard and Røed 2008: a decrease of 2–4% in annual mean SWHs and a reduction in the 99th percentile of annual SWHs along the UK east coast

- Aarnes et al 2017: similar changes of 2–4% and up to a 6% decrease in annual mean SWHs, together with a 2–4% reduction in the annual 90th percentile, 99th percentile and maximum in the western North Sea

The rest of the studies indicated the changes in metres and not as a relative change.

- Grabemann and Weisse (2008) found a decrease in annual median SWHs by ranging between 0.02m and 0.05m off the UK coast.
- De Winter et al. (2012) indicated a projected decrease in the annual maximum in western North Sea.
- Groll et al. (2014) indicated a decrease of 0.04m in the annual median in the north-west North Sea extending towards south and central North Sea.
- Grabemann et al. (2015) found a reduction of -0.25m to -0.75m off the northern British coast in the annual median wave heights. They also indicated a decrease in the annual maximum and the 99th percentile in the west and north-western North Sea.
- Wolf et al. (2015) found a slight decrease in the annual mean SWHs, especially in the southern and western North Sea, in both periods for RCP4.5 and in late period for RCP8.5. They also identified a decrease in southern North Sea of the period mean of the annual maximum.

No projected changes or very small changes were established by 2 studies that either considered the North Sea as a whole or focused on relatively small areas close to the UK or Dutch coasts.

- De Winter et al. 2012 focused on a small area in front of the Dutch coast. They found that the annual mean wave climate is not projected to differ, but projected a small decrease in the annual maximum.
- Wolf et al. (2015) found that the future wave climate off the north Norfolk coast would not change compared with today.

Table B.1 Summary table of the GCMs used in the simulations for studies focused on north-east Atlantic and around the British Isles

(A)

Study\ model	CGCM2	ECHAM4	MRI-CGCM2	HadCM3	HadAM3H	GFDL CM2.1	CSIRO Mk3.5	ECHAM 5	BCCR BCM	Complete CMIP3 18 model ensemble	8 GCMs from COWCLIP	GFDL HiRAM	EC-Earth ESM	Set of CMIP5 models
	CMIP2 models		CMIP3 models								See Hemer et al. 2013a	CMIP5 models		
Kaas et al. 2001		X												
Wang et al. 2004	X													
Wang and Swail 2006	X	X		X										
Leake et al. 2008				X	X HadRM3H									
Debernard and Røed 2008		X			X				X					
Lowe et al. 2009				X HadRM3 PPE										
Zacharioudaki et al. 2011								X						

Study\ model	CGCM2	ECHAM4	MRI-CGCM2	HadCM3	HadAM3H	GFDL CM2.1	CSIRO Mk3.5	ECHAM 5	BCCR BCM	Complete CMIP3 18 model ensemble	8 GCMs from COWCLIP	GFDL HiRAM	EC-Earth ESM	Set of CMIP5 models
								CLM RCM						
Reeve et al. 2011[1]														
Brown et al 2012				X HadRM3 PPE										
Hemer et al. 2013b							X Cubic Conformal atm RCM	X Cubic Conformal atm RCM						

Notes: [1] Used MPI GCM and RCM without explicitly specifying the names of the models.
RCM = regional climate model

(B)

Study\ model	CGCM2	ECHAM4	MRI-CGCM2	HadCM3	HadAM3H	GFDL CM2.1	CSIRO Mk3.5	ECHAM5	BCCR BCM	CMIP3 18 model ensemble mean	8 GCMS from COWCLIP	GFDL HiRAM	EC-Earth ESM	Set of CMIP5 models
	CMIP2 models		CMIP3 models								See Hemer et al. 2013a	CMIP5 models		
Hemer et al. 2013a COWCLIP	X Wang and Swail 2006	X Wang and Swail 2006	X Atm only model at 20km resolution Mori et al. 2010	X Wang and Swail 2006			X Hemer et al. 2013b	X Hemer et al. 2013b X Semedo et al. 2013				X Fan et al. 2013		
Fan et al. 2013												X		
Fan et al. 2014				Boundary conditions used for atm only simulations X		Boundary conditions used for atm only simulations X		Boundary conditions used for atm only simulations X		Boundary conditions used for atm only simulations X				
Perez et al. 2015														X[2] 17 models
Wolf et al. 2015													X	

Study\ model	CGCM2	ECHAM4	MRI-CGCM2	HadCM3	HadAM3H	GFDL CM2.1	CSIRO Mk3.5	ECHAM5	BCCR BCM	CMIP3 18 model ensemble mean	8 GCMS from COWCLIP	GFDL HiRAM	EC-Earth ESM	Set of CMIP5 models
	CMIP2 models		CMIP3 models								See Hemer et al. 2013a	CMIP5 models		
													RCA4 RCM	
Mitchell et al. 2016				X HadRM3 PPE										
Gallagher et al. 2016a, 2016b													X	
Aarnes et al. 2017													X	X[3] Plus 5 more models
Bricheno and Wolf 2018											X		X RCA4 RCM	

Notes: [2] Used the following 17 CMIP5 models: CMCC-CMS, MPI-ESM-LR, ACCESS1.3, EC-EARTH, CMCC-CM, MPI-ESM-MR, HadGEM2-CC, ACCESS1.0, CNRM-CM5, HadGEM2-ES, GISS-E2-R, BNU-ESM, HadCM3, CanESM2, MIROC4h, GFDL-ESM2G, CanCM4

[3] Additional 5 CMIP5 models: HadGEM2-ES, IPSL-CM5A-MR, GFDL-CM3, MIROC5, MRI-CGCM3

Table B.2 Summary table of the GCMs used in the simulations for North Sea studies

Study\ model	ECHAM4	HadCM3	HadAM3H	ECHAM5	BCCR BCM	EC-Earth ESM	HadGEM2 ESM	Set of CMIP5 models
	CMIP2 model	CMIP3 models				CMIP5 models		
Kaas et al. 2001	X							
Leake et al. 2008		X	X HadRM3H					
Caires et al. 2008				X 17 runs ESSENCE project				
Debernard and Røed 2008	X		X		X			
Grabemann and Weisse 2008	X RCAO RCM		X RCAO RCM					
Lowe et al. 2009		X HadRM3 PPE						
De Winter et al. 2012				X 17 runs ESSENCE project				
Groll et al. 2014				X COSMO CLM RCM				

Study\ model	**ECHAM4**	**HadCM3**	**HadAM3H**	**ECHAM5**	**BCCR BCM**	**EC-Earth ESM**	**HadGEM2 ESM**	**Set of CMIP5 models**
	CMIP2 model	CMIP3 models				CMIP5 models		
Wang et al. 2014						X	X	X[1] Plus 18 more models
Grabemann et al. 2015	X RCAO RCM		X RCAO RCM	X COSMO CLM, REMO, HIRHAM RCMs				
Wolf et al. 2015		X HadRM3 PPE						
Wolf et al. 2015						X RCA4 RCM		
Aarnes et al. 2017						X		X[2] Plus 5 more models

Notes: [1] Additional 18 CMIP models: ACCESS1.0, BCC-CSM1-1, BCC-CSM1-1(m), CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3-6-0, FGOALS-s2, GFDL-ESM2M, INMCM4, IPSL-CM5A-MR, MIROC5, MIROC-ESM, MIROC-ESM-CHEM, MPI-ESM-LR, MPI-ESM-MR, MRI-CGCM3, NorESM1-M

[2] Additional 5 CMIP5 models: HadGEM2-ES, IPSL-CM5A-MR, GFDL-CM3, MIROC5, MRI-CGCM3

Table B.3 North-east Atlantic and areas around the British Isles: positive changes

(A) NORTH-EAST ATLANTIC

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Wang et al. 2004 – statistical relationship between cold season sea level pressure and SWH, 2070 to 2099	CGCM2	IS92a, A2, B2	Increase of 5–35cm			Increase of 5–20cm		Increase of up to 55cm in 90th percentile over 1990 to 2080 (11% of baseline value)				
Wang and Swail 2006 – statistical relationship between seasonal sea level pressure and SWH, 2080 to 2099	CGCM2, HadCM3 and ECHAM4	IS92a, A2, B2	Increase of up to 12cm for 1990 to 2080 (about 6% of the climate value for 1990) A2 scenario	Increase	Increase			Increase under A2	Increase under A2	Increase of up to 50cm or 9% (Jul, Aug, Sep)	Increase under A2	
Leake et al. 2008 – wave modelling, 2070 to 2100	HadCM3, HadAM3H, HadRM3H	A2 and B2	>14cm for A2 and B2 scenarios in north-east Atlantic					Increase of up to 130cm for A2 and up to 100cm for B2 in period mean of				

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
								winter maximum for 2070 to 2100 for north-east Atlantic				
Lowe et al. 2009 –wave modelling, 2080 to 2089	HadCM3 GCM/HadRM3 RCM PPE	A1B	Increase in north-east Atlantic	Increase in north-east Atlantic	Increase in north-east Atlantic							
Fan et al. 2013 – wave modelling; 2081 to 2100	GFDL HiRAM	A1B	7–8% and up to 15% or >0.5m									
Fan et al. 2014 – wave modelling, 2081 to 2100	HadCM3, GFDL CM2.1, ECHAM5, CMIP3 18 model ensemble mean	A1B	Wind waves energy increase in north-east Atlantic									
Bricheno and Wolf 2018 – wave modelling; 1970 to 1999, 2030 to 2059, 2070 to 2099	EC-Earth ESM/RCA4 RCM; 8 GCMs from COWCLIP	RCP4.5 and RCP8.5										Increase up to ~10–20% in period mean annual maximum

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
												along west-facing coasts under RCP4.5/ 8.5

(B) NORTH, NORTH-WEST OF THE UK

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Kaas et al. 2001 – wave modelling, 2060 to 2089	ECHAM4	IS92a	Increase	Increase		Increase						
Lowe et al. 2009 – wave modelling, 2080 to 2089	HadCM3 GCM/HadRM3 RCM PPE	A1B			Increase in waters around UK	Increases to the north-west of Scotland						
Wolf et al. 2015 – wave modelling; 2030 to 2059, 2070 to 2099	EC-EARTH ESM, RCA4 RCM	RCP4.5, RCP8.5					Increase in mid-century (see Figure 4.2, their					30 year period means of annual maxima increase

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
							Figure 13), north of the British Isles					in north-west approach es (western isles of Scotland) varying between 10% and 20%

(C) WEST OF THE BRITISH ISLES

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Debernard and Røed 2008 – wave and surge modelling, 1961 to 1990, 2071 to 2100	HadAM3H, ECHAM4, BCCR BCM	A2, B2, A1B						2–4% in 99th percentile west of British Isles				Up to 6% increase in 99th percentile of annual SWH west of British Isles

(D) SOUTH-WEST OF THE BRITISH ISLES

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Leake et al. 2008 – wave modelling, 2070-2100	HadCM3, HadAM3H, HadRM3H	A2 and B2	>0.14m for A2 and B2 scenarios south-west of UK (their Figure 7)					>0.4m increase in maximum SWH for Jan, Feb, Mar (their Figure 8)				
Lowe et al. 2009 – wave modelling, 2080 to 2089	HadCM3 GCM/HadRM3 RCM PPE	A1B	Increase in south-west approaches Increase ~0.1m in English Channel	Increase in south-west approaches to UK	Increase in waters around UK							Maximum increase in wave heights in English Channel
Reeve et al. 2011 – wave modelling, 2061 to 2100; Wave Hub site	MPI GCM and RCM	A1B and B1					Mean wave power will increase by 2.95% under A1B and will decrease by 2.27% under B1 scenario					
Zacharioudaki et al. 2011 –	ECHAM5 GCM and CLM RCM	B1, A1B and A2	4–8% increase to south-					Increase in 99th percentile south-				

Authors and method	**GCMs (and RCMs)**	**Emissions scenarios**	**Changes in mean (median)**					**Changes in extremes**				
			Winter	**Spring**	**Summer**	**Autumn**	**Annual**	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
wave modelling, 2061 to 2100			west of UK					west of UK				
Wolf et al. 2015 – wave modelling; 2030 to 2059, 2070 to 2099	EC-EARTH ESM, RCA4 RCM	RCP4.5, RCP8.5										30 year period means of annual maxima increase in south-west (English Channel) varying between 10% and 20% by the end of the century

(E) IN THE LIVERPOOL BAY AREA OR AROUND IRELAND

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Brown et al. 2012 – wave modelling 2050 to -2060, 2060-2070, 2070-2080 (focus on Liverpool Bay area)	1 member of the HadCM3/ HadRM3 PPE	A1B	For Dec, increase of 2.5–3% in mean monthly SWH		For June, increase of ~ 16% of mean monthly SWH	For Nov, increase of 2.5–3% in mean monthly SWH		Positive trends in large[1] and extreme[2] wave events varying between 0.31% and 9.5% respectively – largest increase in Jan				
Wolf et al. 2015 – wave modelling, 2030 to 2059, 2070 to 2099 (notes about areas around Ireland)	EC-EARTH ESM, RCA4 RCM	RCP4.5, RCP8.5										Increases in 30 year period mean of annual maximum of 10–30% around Ireland except for eastern coast by the end of the century

Notes: [1] Large wave events are >3m.

[2] Extreme wave events are >5m.

Table B.4 North-east Atlantic and areas around the British Isles: negative changes

(A) NORTH-EAST ATLANTIC

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Hemer et al. 2013b – wave modelling, 2070 to 2099 (focus on North Atlantic as a whole)	ECHAM5 and CSIRO Mk3.5 GCMs and Cubic Conformal atm RCM	A2	Monthly mean decrease of ~1m	Monthly mean decrease	Monthly mean decrease of ~0.2m	Monthly mean decrease		Decrease in monthly 99th percentile				
Bricheno and Wolf 2018 – wave modelling, 2030 to 2059, 2070 to 2099	EC-Earth ESM/RCA4 RCM; 8 GCMs from COWCLIP	RCP4.5 and RCP8.5					Decrease in north-east North Atlantic varying between 0% and 5% (see middle panel in Figure 4.1)					

(B) NORTH AND NORTHWEST OF UK

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Lowe et al. 2009 – wave modelling, 2080 to 2099	HadCM3 GCM/HadRM3 RCM PPE	A1B	Decrease of up to -0.4m to the north of UK	Decrease to the north of UK								Statistically significant trend of -0.3cm per year north of Scotland
Wolf et al. 2015 – wave modelling, 2030 to 2059, 2070 to 2099	EC-EARTH ESM, RCA4 RCM	RCP4.5, RCP8.5					Decrease in annual mean wave heights north-west of Scotland by the end of century (see Figure 4.2)					
Mitchell et al. 2016 – wave modelling, 2040 to 2069 (focus on Wave Hub and Bernera locations to the south-west and north-west of the UK respectively)	5 members of the HadCM3/ HadRM3 PPE	A1B					Statistically significant decrease in ensemble mean near the Bernera site (north-west of UK) by mid-century					

(C) WEST OF UK AND IRELAND

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Zacharioudaki et al. 2011 – wave modelling, 2061 to 2100	ECHAM5 GCM and CLM RCM	B1, A1B and A2		Decrease in West European shelf seas					Decrease in 99th percentile SWH in West European shelf seas			
Gallagher et al. 2016a, 2016b – wave modelling, 2070 to 2099 (focus on areas around Ireland)	EC-Earth ESM	RCP4.5, RCP8.5	Decrease in seasonal mean of up to 10% off the west coast of Ireland for RCP8.5	Small decreases of <5% for both scenarios	Decrease off the west coast	Small decreases of <5% for both scenarios	Decrease in ensemble mean of 5–10% off the Atlantic coast of Ireland in both scenarios	Robust decrease in 95th percentile off the west coast under RCP8.5; decrease > 5% in 90th percentile off the west coast in RCP4.5		Robust decrease in 95th percentile off the west coast Largest changes in 95th percentile for RCP8.5 >10% reduction		Robust decrease in 95th percentile off the west coast of less than 5% under RCP8.5 Decrease of over 5% in 90th percentile off the west coast in RCP4.5
Aarnes et al. 2017 – wave modelling, 2070 to 2099	6 CMIP5 GCMs (see Table B.1)	RCP4.5, RCP8.5										Annual 99th percentile (annual maximum) decreases

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summe r	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
												of 2–4% and up to 6% (no change or up to 2–4% under RCP4.5 or up to 4–6% under RCP8.5) to north and west of UK and Ireland

(D) TO THE SOUTHWEST OF UK, IN ENGLISH CHANNEL, AND SOUTH OF IRELAND

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Zacharioudaki et al. 2011 – wave modelling, 2061 to 2100	ECHAM5 GCM and CLM RCM	B1, A1B and A2					Decrease -3% to -5% in annual mean SWH (their Figure 5) south-west of UK					

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Wolf et al. 2015 – wave modelling, 2030 to 2059, 2070 to 2099	EC-EARTH ESM, RCA4 RCM	RCP4.5, RCP8.5					Decrease in annual mean wave heights south-west of UK in mid-century, (see Figure 4.2)					
Perez et al. 2015 – statistical relationship between sea level pressure and waves; several periods – 2010 to 2039, 2040 to 2069 and 2070 to 2099 – compared with 1975 to 2004	Set of CMIP5 GCMs (see Appendix B Table 1A)	RCP2.6, RCP4.5, RCP8.5					Period mean SWH decreasing in all RCPs, varying between 0.04m for RCP2.6 and up to ~0.08m for RCP8.5 in mid- and late century periods to the south-west of UK					
Gallagher et al. 2016a, 2016b – wave modelling, 2070 to 2099 (focus on areas around Ireland)	EC-Earth ESM	RCP4.5, RCP8.5			Decrease in seasonal mean of up to 15% off the south coast of					Robust decrease in 95th percentile off the south coast		

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
					Ireland for RCP8.5							

(E) AROUND UK AND IRELAND

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Perez et al. 2015 – statistical relationship between sea level pressure and waves; several periods – 2010 to 2039, 2040 to 2069 and 2070 to 2099 – compared with 1975 to 2004	Set of CMIP5 GCMs (see Appendix B Table 1A)	RCP2.6, RCP4.5, RCP8.5					Period mean SWH decreasing around Great Britain and Ireland in all RCPs					
Aarnes et al. 2017 – wave modelling, 2070 to 2099	6 CMIP5 GCMs (see Appendix B Table 1A)	RCP4.5, RCP8.5					Decreases around UK and Ireland varying between 2–4% and 6–8%					Decreases in annual 90th percentile around UK and Ireland varying between 2–4% and 4–6%

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
							respectively for 2071 to 2100					respectively for 2071 to 2100
Bricheno and Wolf 2018 – wave modelling, 1970 to 1999, 2030 to 2059, 2070 to 2099	EC-Earth ESM/RCA4 RCM; 8 GCMs from COWCLIP	RCP4.5 and RCP8.5					Decrease in sites around UK coast varying between 0% and 5% (see middle panel in Figure 4.1)					

(F) LIVERPOOL BAY AREA

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Brown et al. 2012 – wave modelling, 2050 to 2060, 2060 to 2070, 2070 to 2080 (focus on Liverpool Bay area)	1 member of HadCM3/HadRM3 PPE	A1B	Decrease for Jan and Feb monthly means Seasonal mean decreasing	Decrease for spring season monthly means lowest in May (~2%) Seasonal mean decreasing by 8.8% in spring	Decrease for the summer season monthly means Seasonal mean decreasing by 5.5% in summer	Decrease for the autumn season monthly means – largest in Sep (-20%) Seasonal mean decreasing						

Table B.5 North Sea: positive and negative changes

(A) NORTH SEA AS A WHOLE

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Kaas et al. 2001 – wave modelling, 2060 to 2089	ECHAM4	IS92a	Increase	Increase		Largest increase						Tendency of increasing 99.9th percentile
Caires et al. 2008 – wave and extreme value analysis modelling, 1950 to 2100	ESSENCE 17 member ensemble	A1B										0.001m per year Annual extremes (exceedances above a threshold)

(B) SOUTHERN AND EASTERN SECTIONS OF NORTH SEA

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Leake et al. 2008 – wave modelling, 2070 to 2100	HadCM3, HadAM3H, HadRM3H	A2 and B2	0.1m, near East Anglia, A2 But -0.04m for B2 in southern North Sea					0.2m, winter maximum near East Anglia, A2) But -0.19m for B2 in southern North Sea				0.2m in annual maximum, southern N Sea, A2 But -0.56m for B2 for southern North Sea
Debernard and Røed 2008 – wave and surge modelling, 2071 to 2100	HadAM3, ECHAM4, BCCR BCM	A2, B2, A1B						6–8%, 99th percentile, North Sea east coast		6–8%, 99th percentile on North Sea east coast		6–8% in 99th percentile, North Sea east coast
Grabemann and Weisse 2008 – wave modelling, 2071 to 2100	HadAM3H and ECHAM4/ OPYC GCMs and RCAO RCM	A2 and B2					Increase in 50th percentile in eastern North Sea					Increase by 0.25–0.35m (5–8%, up to 18%) of 99th percentile in eastern and southern North Sea

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Lowe et al. 2009 – wave modelling, 2070 to 2100	HadCM3 GCM/ HadRM3 RCM PPE	A1B	Increase in winter mean in southern North Sea		Summer means increasing in southern and eastern North Sea			Increase in winter maximum in southern North Sea				Increase in annual maximum in southern North Sea
Groll et al. 2014 – wave modelling, 2011 to 2040, 2041 to 2070, 2071 to 2100	ECHAM5/ MPI-OM GCM, COSMO CLM RCM	A1B and B1					Increase in 50th percentile in eastern North Sea by the end of century					Increase in 99th percentile in southern and eastern North Sea by end of century
Wang et al. 2014 – statistical relationships between sea level pressure and wave characteristics, 2070 to 2099	20 CMIP5 GCMs (see Table B.2)	RCP4.5 and RCP8.5										1 in 10 years SWHs will double or triple in frequency along Danish coast under RCP8.5
Grabemann et al. 2015 – wave	ECHAM4, ECHAM5, HadAM3H GCMs and	A2, B2, A1B and B1					Increase in median in south and					Increase in annual maximum and 99th percentile

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
modelling, 2071 to 2100	REMO, HIRHAM, RCAO and COSMO CLM RCMs						east North Sea					in south and east North Sea
Wolf et al. 2015 – wave modelling, 2030 to 2059, 2070 to 2099	EC-EARTH ESM, RCA4 RCM	RCP4.5, RCP8.5					Increase, in eastern North Sea by mid-century for RCP8.5, But a slight decrease, especially in southern North Sea, in both periods RCP4.5 and in late period RCP8.5 (see below)					5% along the eastern North Sea in period mean of annual maximum But a decrease in southern North Sea

(C) WESTERN SECTIONS OF NORTH SEA

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Debernard and Røed 2008 – wave and surge modelling, 1961 to 1990, 2071 to 2100	HadAM3, ECHAM4, BCCR BCM	A2, B2, A1B					-2 to -4% reduction					Decreasing, 99th percentile, along UK east coast
Grabemann and Weisse, 2008 – wave modelling, 2071 to 2100	HadAM3H and ECHAM4/ OPYC GCMs and RCAO RCM	A2 and B2					-0.02 to -0.05m off UK coast of median of wave heights					
De Winter et al. 2012 – wave modelling, 2071 to 2100	ESSENCE project 17 member ensemble	A1B										Decrease of annual maximum
Groll et al. 2014 – wave modelling, 2011 to 2040, 2041 to 2070, 2071 to 2100	ECHAM5/ MPI-OM GCM, COSMO CLM RCM	A1B and B1					-0.04m in median in north-west North Sea, extending					

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
							towards south and central North Sea					
Grabemann et al. 2015 – wave modelling, 2071 to 2100	ECHAM4, ECHAM5, HadAM3H GCMs and REMO, HIRHAM, RCAO and COSMO CLM RCMs	A2, B2, A1B and B1					-0.25m to -0.75m off north British coast in median annual wave heights					Decrease, annual maximum, 99th percentile in west and north-west North Sea
Wolf et al. 2015 – wave modelling, 2030 to 2059, 2070 to 2099 (annual mean notes based on their Figure 13)	EC-EARTH ESM, RCA4 RCM	RCP4.5, RCP8.5					Slight decrease, especially in southern and western North Sea, in both periods RCP4.5 and in late period RCP8.5					

Authors and method	GCMs (and RCMs)	Emissions scenarios	Changes in mean (median)					Changes in extremes				
			Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
Aarnes et al. 2017 – wave modelling, 2070 to 2099	6 CMIP5 GCMs	RCP4.5, RCP8.5					-2 to -4% and up to -6% in western North Sea					-2 to -4%, in western North Sea in annual 90th percentile, 99th percentile and maximum

(D) NO PROJECTED CHANGES OR SMALL CHANGES

Authors and method	GCMs (and RCMs)	Emissions scenarios	Comments
De Winter et al. 2012 – wave modelling, 2071 to 2100	ESSENCE project 17 member ensemble	A1B	Annual mean wave climate is not projected to differ in a small area in front of the Dutch coast. A small decrease in annual maximum in that area.
Wolf et al. 2015 – wave modelling; 2070 to 2100	Members of the HadCM3 GCM/ HadRM3 RCM PPE	A1B	Future wave climate off the north Norfolk coast will not change compared with today.

Appendix C: Datum and interpretation of the extreme sea level projections, or ‘Why don’t you call the results ‘ODN’?’

Ordnance Datum Newlyn (ODN) is an absolute datum. In simplified terms, this means that the zero of ODN is a fixed distance above the unmoving centre of the Earth. The present day extreme sea levels given in Environment Agency (2019) use ODN as their datum.

Coastal planners need to know about sea level relative to coastal assets. The results presented here therefore combine present day extreme sea levels with projections of local relative sea level change (that is, change relative to the local land, which undergoes vertical land movement and so is not fixed relative to ODN). So while the extreme sea levels quoted in tables such as those in Appendix A are the levels that coastal planners need to know, they are not, strictly speaking, in ODN.

This is illustrated with an example.

The central estimate of the 20-year return level of still water at Tobermory in the Inner Hebrides at the present day is 3.45m above ODN (Environment Agency 2019). The projected Tobermory 20-year return level for 2100 under RCP8.5 determined by this project is 3.95m. A simple conceptual interpretation of this projection for Tobermory (sidestepping practical issues[9]) is as follows.

Make a mark in 2017 on the harbour wall at Tobermory at zero ODN. The projected Tobermory 20-year return level for 2100 (3.95m) will be 3.95m above where that Tobermory mark will be in 2100. But due to vertical land movement at Tobermory over the period (2017 to 2100), this is **not** exactly 3.95m above the zero of ODN. This is why the projected future results in this report are not reported as ‘ODN’. This is illustrated in Figure C.1.

[9] As an example of a practical issue, access to that level of the harbour wall might be extremely inconvenient. But we can *imagine* making the mark.

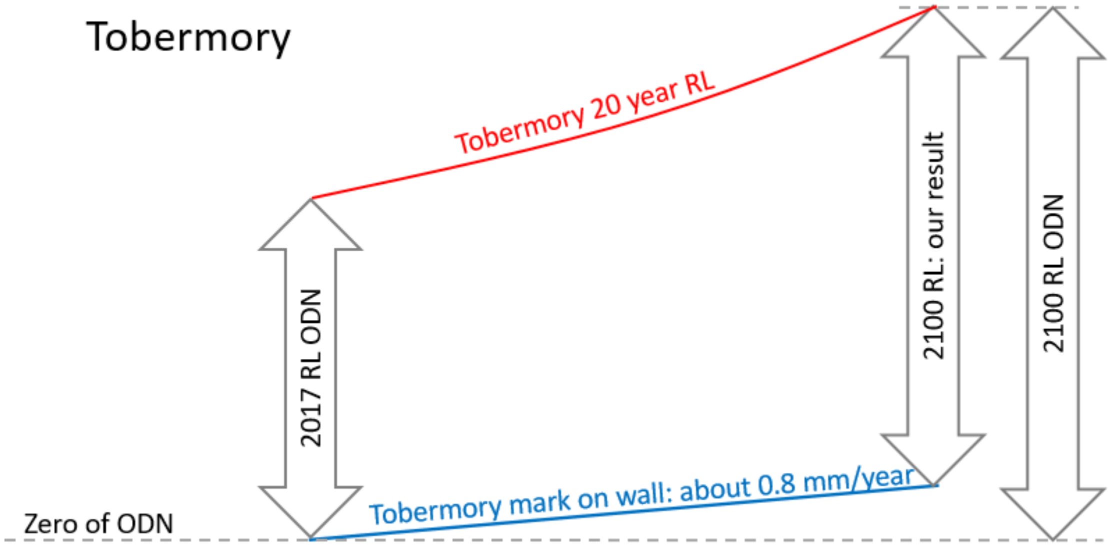

Figure C.1 Schematic diagram showing the interpretation of results: specifically why the results are not, strictly speaking, 'ODN'

Notes: Figures in this diagram are approximate and are for illustration only. For details see text.
For actual Tobermory data, see Appendix A.
RL = return level

Appendix D: Coastal flood boundary data

For ease of reference, the present day still water level return periods from the 2018 update of ‘Coastal flood boundary conditions for UK mainland and islands’ (Environment Agency 2019) are given in Table D.1.

‘Chain’ is the chainage as given by Environment Agency (2011).

‘Nom. Lat.’ and ‘Nom. Long.’ are the nominal latitude and longitude of the site. These may not be identical to the latitude and longitude of the physical tidal gauge. Rather, they are the centre of the active grid box in the surge tide model nearest to the physical tide gauge. The return levels are given in metres ODN.

Table D.1 Return levels (in mODN)

Site	Chain (km)	Nom. Lat.	Nom. Long.	Return period (years)															
				1	2	5	10	20	25	50	75	100	150	200	250	300	500	1,000	10,000
Newlyn	0.0	50.06	-5.42	3.11	3.18	3.26	3.33	3.39	3.41	3.47	3.5	3.52	3.56	3.58	3.6	3.61	3.65	3.7	3.88
St Mary's*	nan	49.94	-6.25	3.41	3.48	3.56	3.61	3.67	3.69	3.74	3.77	3.79	3.82	3.84	3.86	3.87	3.9	3.96	4.11
Padstow	128.0	50.61	-4.92	4.56	4.63	4.73	4.79	4.85	4.87	4.93	4.96	4.99	5.02	5.05	5.07	5.08	5.13	5.19	5.42
Ilfracombe	250.0	51.28	-4.08	5.43	5.51	5.61	5.68	5.75	5.77	5.85	5.89	5.92	5.96	5.99	6.01	6.03	6.09	6.17	6.45
Hinkley	326.0	51.28	-3.08	7.05	7.14	7.25	7.34	7.44	7.47	7.57	7.63	7.67	7.73	7.78	7.82	7.85	7.93	8.06	8.54
Avonmouth	380.0	51.5	-2.75	8.11	8.22	8.37	8.49	8.61	8.65	8.79	8.86	8.92	9.01	9.07	9.12	9.16	9.27	9.43	10.05
Newport	398.0	51.5	-2.92	7.45	7.56	7.7	7.81	7.92	7.96	8.07	8.14	8.2	8.27	8.33	8.37	8.41	8.52	8.67	9.25
Mumbles	492.0	51.61	-3.92	5.51	5.62	5.77	5.88	5.98	6.02	6.13	6.19	6.23	6.3	6.34	6.38	6.4	6.48	6.59	6.99
Milford Haven	622.0	51.61	-5.08	4.2	4.29	4.4	4.49	4.57	4.6	4.68	4.73	4.76	4.81	4.84	4.87	4.89	4.95	5.04	5.33
Fishguard	712.0	52.06	-4.92	3.1	3.17	3.26	3.33	3.4	3.42	3.49	3.52	3.55	3.59	3.62	3.64	3.65	3.7	3.77	3.99
Barmouth	832.0	52.72	-4.08	3.46	3.59	3.75	3.87	3.99	4.03	4.14	4.21	4.26	4.33	4.38	4.42	4.45	4.54	4.67	5.09
Holyhead	1012.0	53.28	-4.75	3.37	3.44	3.55	3.62	3.7	3.72	3.79	3.84	3.87	3.91	3.94	3.96	3.98	4.03	4.1	4.35
Llandudno	1110.0	53.39	-3.75	4.7	4.78	4.9	4.98	5.06	5.09	5.17	5.22	5.25	5.3	5.33	5.36	5.38	5.44	5.53	5.81
Hilbre Island	1154.0	53.39	-3.25	5.24	5.34	5.47	5.57	5.66	5.69	5.78	5.84	5.87	5.92	5.96	5.99	6.01	6.08	6.17	6.5
Port Erin*	nan	54.17	-4.75	3.27	3.36	3.48	3.57	3.66	3.69	3.78	3.83	3.87	3.92	3.95	3.98	4.0	4.07	4.15	4.44
Heysham	1254.0	54.06	-2.92	5.86	5.99	6.16	6.29	6.42	6.46	6.59	6.67	6.72	6.8	6.86	6.9	6.93	7.03	7.17	7.63
Workington	1390.0	54.61	-3.58	5.09	5.21	5.35	5.47	5.58	5.61	5.73	5.79	5.84	5.91	5.95	5.99	6.02	6.11	6.22	6.62

Site	Chain (km)	Nom. Lat.	Nom. Long.	Return period (years)															
				1	2	5	10	20	25	50	75	100	150	200	250	300	500	1,000	10,000
Port Patrick	1648.0	54.83	-5.25	2.82	2.92	3.06	3.15	3.25	3.28	3.37	3.43	3.47	3.52	3.56	3.59	3.61	3.68	3.78	4.09
Millport	1782.0	55.72	-4.92	2.67	2.79	2.96	3.09	3.22	3.26	3.39	3.47	3.52	3.6	3.65	3.69	3.73	3.83	3.97	4.44
Port Ellen	nan	55.61	-6.08	1.45	1.56	1.7	1.81	1.91	1.94	2.04	2.1	2.14	2.2	2.24	2.27	2.3	2.37	2.47	2.81
Tobermory	2320.0	56.61	-6.25	2.98	3.09	3.23	3.34	3.45	3.48	3.59	3.65	3.69	3.76	3.8	3.84	3.87	3.95	4.06	4.43
Ullapool	2564.0	57.94	-5.25	3.22	3.32	3.44	3.53	3.62	3.65	3.74	3.78	3.82	3.87	3.9	3.92	3.94	4.0	4.08	4.34
Stornoway *	nan	58.17	-6.25	2.89	2.97	3.07	3.14	3.22	3.24	3.31	3.35	3.37	3.41	3.44	3.46	3.47	3.52	3.58	3.78
Kinlochbervie	2670.0	58.5	-5.08	3.17	3.28	3.42	3.52	3.62	3.65	3.74	3.8	3.84	3.9	3.94	3.97	3.99	4.06	4.16	4.46
Lerwick*	nan	60.17	-1.08	1.5	1.54	1.6	1.65	1.69	1.71	1.75	1.77	1.79	1.81	1.83	1.84	1.85	1.88	1.91	2.02
Wick	2870.0	58.39	-3.08	2.4	2.48	2.57	2.64	2.71	2.73	2.79	2.83	2.85	2.88	2.91	2.93	2.94	2.98	3.04	3.21
Moray Firth	3012.0	57.61	-4.08	2.85	2.92	3.01	3.08	3.14	3.16	3.22	3.26	3.29	3.32	3.35	3.37	3.39	3.43	3.5	3.71
Aberdeen	3226.0	57.17	-2.08	2.69	2.77	2.86	2.93	3.0	3.02	3.09	3.13	3.15	3.19	3.22	3.24	3.25	3.3	3.36	3.58
Leith	3420.0	56.06	-3.25	3.37	3.45	3.56	3.63	3.71	3.73	3.81	3.85	3.88	3.93	3.96	3.98	4.0	4.06	4.14	4.41
North Shields	3630.0	55.06	-1.42	3.21	3.29	3.4	3.48	3.56	3.59	3.68	3.73	3.77	3.82	3.85	3.89	3.91	3.99	4.08	4.42
Whitby	3720.0	54.5	-0.58	3.36	3.45	3.57	3.67	3.77	3.8	3.9	3.96	4.0	4.07	4.11	4.15	4.18	4.26	4.37	4.81
Immingham	3888.0	53.61	-0.25	4.17	4.27	4.42	4.53	4.65	4.68	4.8	4.88	4.93	5.0	5.06	5.1	5.14	5.24	5.38	5.92
Cromer	4096.0	52.94	1.25	3.07	3.19	3.35	3.48	3.61	3.65	3.79	3.88	3.93	4.02	4.08	4.13	4.17	4.29	4.45	5.03
Lowestoft	4162.0	52.5	1.75	2.02	2.17	2.38	2.55	2.72	2.77	2.93	3.03	3.1	3.2	3.27	3.32	3.37	3.5	3.69	4.31
Felixstowe Pier	4232.0	51.94	1.42	2.68	2.81	2.97	3.11	3.24	3.29	3.43	3.52	3.58	3.68	3.74	3.79	3.82	3.95	4.12	4.77

Site	Chain (km)	Nom. Lat.	Nom. Long.	Return period (years)															
				1	**2**	**5**	**10**	**20**	**25**	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**500**	**1,000**	**10,000**
Sheerness	4314.0	51.5	0.75	3.7	3.81	3.96	4.08	4.21	4.25	4.37	4.45	4.51	4.59	4.65	4.7	4.74	4.85	5.01	5.59
Dover	4410.0	51.17	1.42	3.8	3.91	4.06	4.17	4.29	4.33	4.44	4.51	4.56	4.63	4.68	4.72	4.75	4.84	4.97	5.39
Newhaven	4526.0	50.72	0.08	3.87	3.94	4.04	4.12	4.2	4.22	4.3	4.35	4.38	4.43	4.46	4.49	4.51	4.57	4.66	4.96
Portsmouth	4616.0	50.83	-1.08	2.55	2.63	2.73	2.8	2.87	2.89	2.96	3.0	3.03	3.07	3.1	3.12	3.14	3.19	3.25	3.49
Bournemouth	4682.0	50.61	-1.92	1.4	1.47	1.56	1.63	1.69	1.71	1.78	1.81	1.84	1.88	1.9	1.93	1.94	1.99	2.06	2.28
Weymouth	4736.0	50.61	-2.42	1.82	1.89	1.99	2.05	2.12	2.15	2.22	2.26	2.28	2.32	2.35	2.37	2.39	2.44	2.51	2.76
Exmouth	4836.0	50.61	-3.42	2.76	2.84	2.95	3.03	3.1	3.13	3.2	3.24	3.27	3.31	3.34	3.36	3.37	3.42	3.48	3.66
Devonport	4950.0	50.28	-4.08	2.95	3.02	3.11	3.18	3.25	3.27	3.34	3.38	3.4	3.44	3.47	3.49	3.51	3.55	3.62	3.84
Portrush	nan	55.28	-6.58	1.61	1.71	1.83	1.92	2.0	2.03	2.12	2.17	2.21	2.26	2.29	2.32	2.35	2.41	2.5	2.78
Belfast	nan	54.72	-5.75	2.16	2.26	2.39	2.49	2.6	2.64	2.74	2.8	2.85	2.91	2.96	2.99	3.02	3.11	3.23	3.69
St Helier (Jersey)*	nan	49.17	-2.08	6.21	6.29	6.38	6.45	6.52	6.54	6.61	6.65	6.68	6.72	6.75	6.78	6.8	6.85	6.93	7.2

Notes: Levels are given in mODN unless otherwise stated and are correct to base year 2017.
Sites marked with * are referenced to a local datum.

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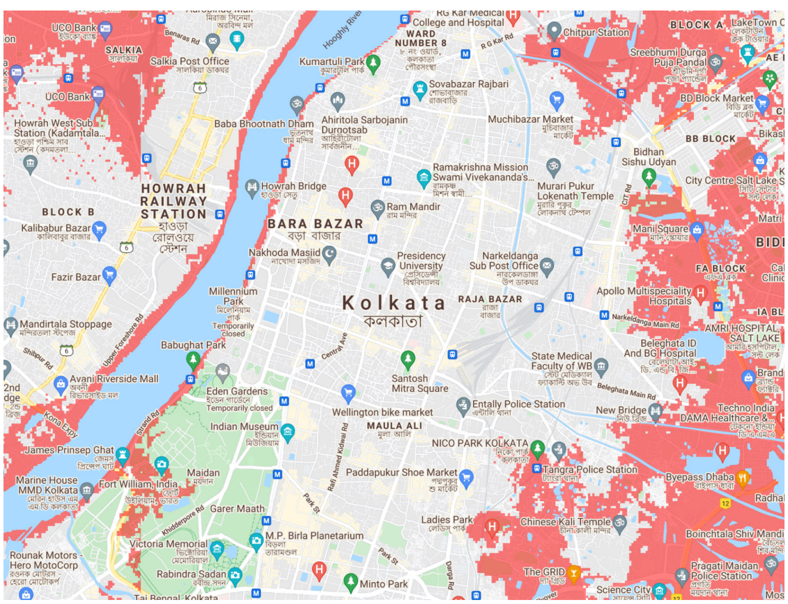

Kolkata: Land projected to be below annual flood level in 2050

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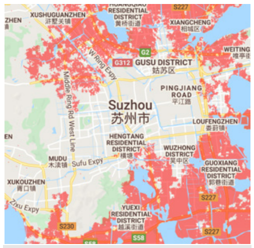
Explore Coastal Flood Risk by Year

These images show the same location under 3 different settings, side by side.

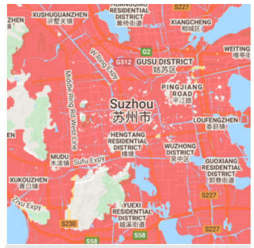
Suzhou, China: Land projected to be below tideline in 2030

- Year: 2030
- Projection Type: Sea Level Rise Only
- Pollution Scenario: Moderate Cuts
- Luck: Medium (50th Percentile)
- Sea Level Rise Model: Kopp et al. 2014
- Tool link



Suzhou, China: Land projected to be below tideline in 2100

- Year: 2100
- Projection Type: Sea Level Rise Only
- Pollution Scenario: Unchecked Pollution
- Luck: Medium (50th Percentile)
- Sea Level Rise Model: Kopp et al. 2014
- Tool link



Suzhou, China: Land projected to be below annual flood level in 2030

- Year: 2030
- Projection Type: Sea Level Rise + Annual Flood
- Pollution Scenario: Unchecked Pollution
- Luck: Medium (50th Percentile)
- Sea Level Rise Model: Kopp et al. 2014
- Tool link

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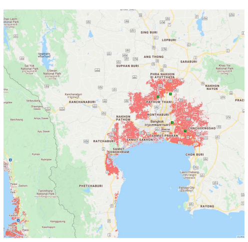
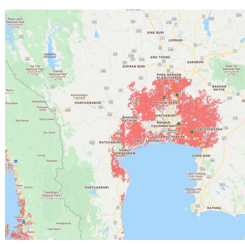
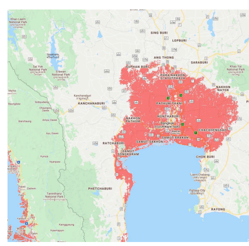


Bangkok: Land below 3 feet of water (tool link)



Bangkok: Land below 4.5 feet of water (tool link)



Bangkok: Land below 7 feet of water (tool link)

Are you underestimating your coastal flood risk?

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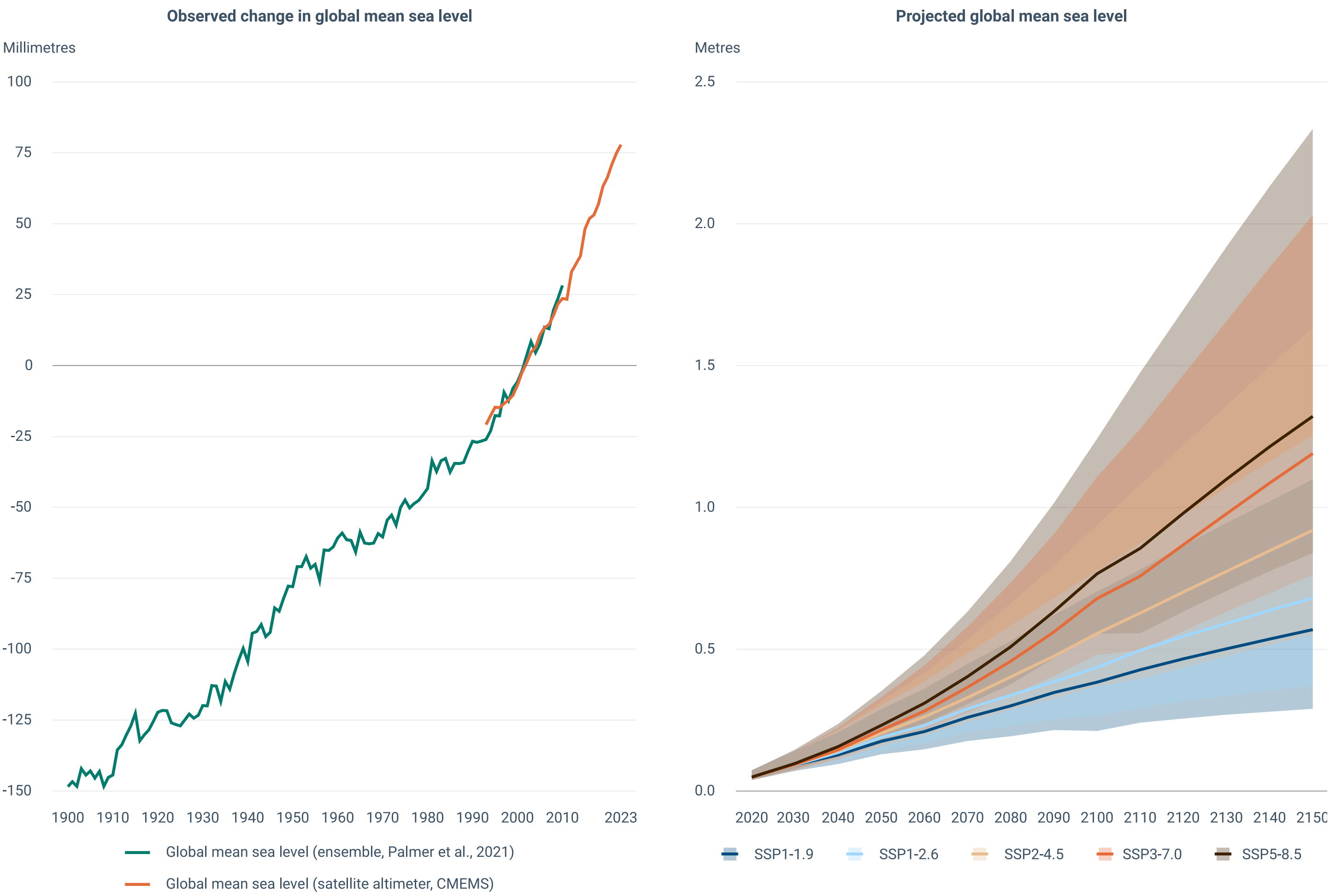
European Environment Agency

Global and European sea level rise

Published 14 Jan 2025

Global mean sea level (GMSL) has risen about 21cm since 1900, at an accelerating rate. GMSL reached its highest value ever in 2023. GMSL will likely rise by 0.28-0.55m under a very low emissions scenario (SSP1-1.9) and 0.63-1.02m under a very high emissions scenario (SSP5-8.5) by 2100, relative to the 1995-2014 average. GMSL simulations that include the possibility of fast disintegration of the polar ice sheets project a rise of up to 5m by 2150. Most coastal regions in Europe have experienced an increase in sea level relative to land, except for the northern Baltic Sea coast.

Figure 1. Observed and projected change in global mean sea level



The global mean sea level (GMSL) in 2023 was the highest ever measured by the satellite-based monitoring system. **GMSL reconstructions** based on tide gauge observations show a rise of 21cm from 1900 to 2020 at an average rate of 1.7mm/year[1][2]. The rate of GMSL rise accelerated to 3.3mm/year over the period 1993-2018 and 3.7mm/year over the period 2006-2018, more than twice as fast as during the 20th century[3][1].

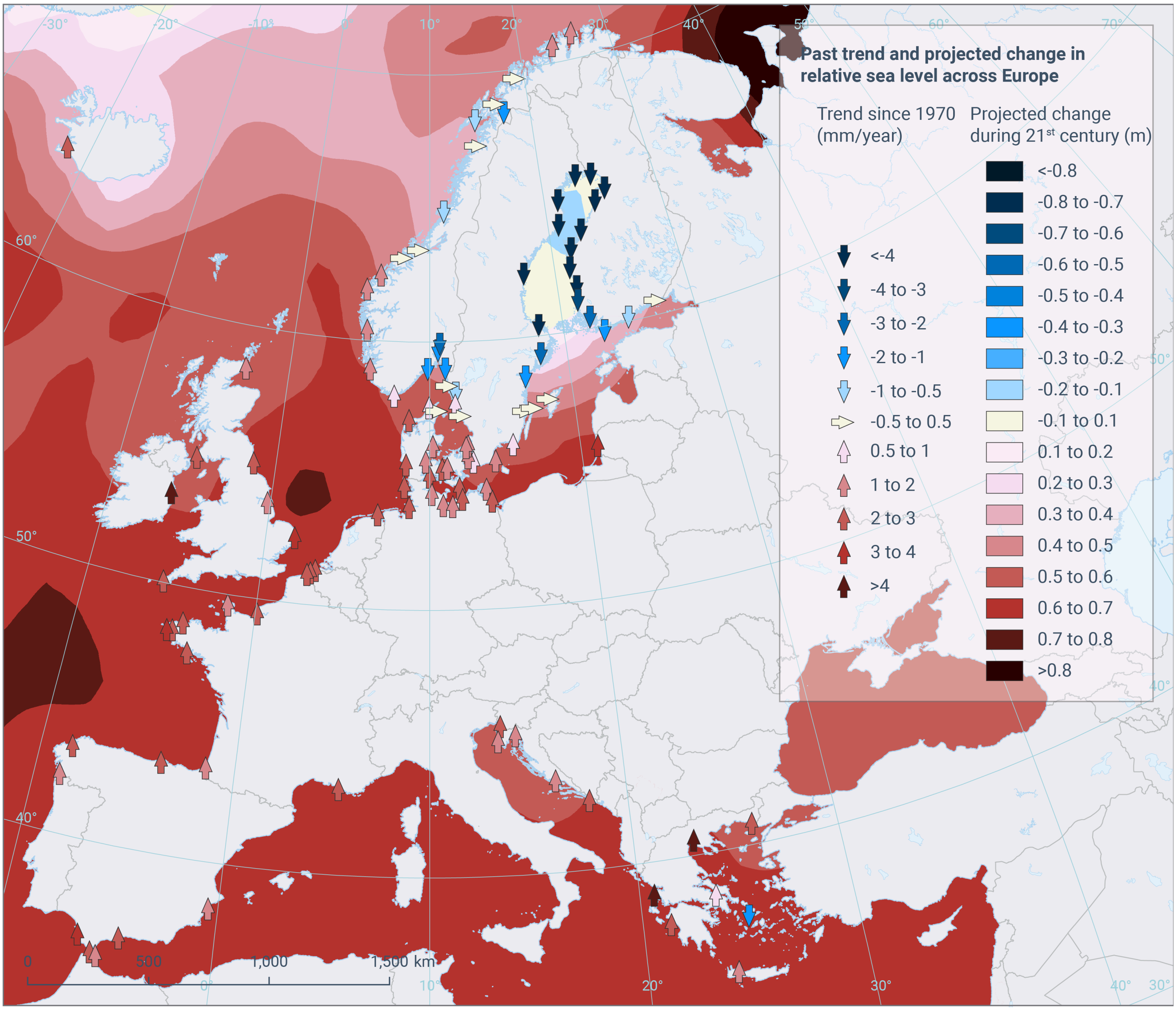
Since 1970, anthropogenic forcing has been the **predominant cause** of this accelerating sea level rise both globally and in European regional seas. Thermal expansion of ocean water was initially the main driver, however melting of glaciers and of the Antarctic and Greenland ice sheets have exceeded the effects of thermal expansion since about 2000[4][5][1].

Global climate models **project** that the rise in GMSL during the 21st century (i.e. by 2100, relative to the period 1995-2014), with 66% confidence, will likely be in the range of 0.28-0.55m for a very low emissions scenario (SSP1-1.9). For an intermediate emissions scenario, 0.44-0.76m (SSP2-4.5) and 0.63-1.02m for a very high emissions scenario (SSP5-8.5). Model simulations that include the possibility of fast disintegration of the polar ice sheets, which is assessed to have a low likelihood, project a GMSL rise of up to about 5m by 2150 under a very high emissions scenario (SSP5-8.5)[1].

The future behaviour of the Greenland and Antarctic ice sheets is still rather uncertain, particularly under higher emissions scenarios. Studies considering processes that can lead to a **faster disintegration** of the Antarctic ice sheet, including a potential collapse of marine-based sectors, have estimated a GMSL rise of up to 2.3m by 2100 and up to 5.4m by 2150[6][7][8][1]. The consideration of such high-end scenarios is important for long-term coastal risk management, in particular in densely populated coastal zones. Each five year delay in the peaking of global greenhouse gas emissions increases the median sea-level rise projections for 2300 by 0.2m and extreme sea-level rise projections (95th percentile) by up to 1m[9].

The NASA Sea Level Projection Tool allows users to visualise and download the sea level projection data from the Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report (AR6).

Figure 2. Past trend and projected change in relative sea level across Europe



Reference data: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO

Most European coastal regions experience increases in both absolute sea level (as measured by satellites) and relative sea level (as measured by tide gauges), the latter being more relevant for **coastal protection**. There are sizeable differences in the rates of sea level change across Europe. Notably, sea levels relative to land along the northern Baltic Sea coast and — to a lesser degree — the northern Norwegian coast are sinking. This is due to rising land levels caused by post-glacial rebound since the last ice age.

In future, relative sea level change along most of the European coastline is projected to be reasonably similar to the global average. Main exceptions are the northern Baltic Sea and the northern Norwegian coasts, which are experiencing considerable land rise as a consequence of post-glacial rebound and changes in the gravity field of the Greenland ice sheet. As a result, sea level relative to land in these regions will continue to rise more slowly than elsewhere or **may even decrease**[10][1]. Further information on past and projected changes sea level rise in Europe is available on the European Climate Data Explorer. A dedicated EU policy sector page on coastal areas is available on Climate-ADAPT.

Supporting information

Definition

This indicator comprises several metrics to describe past and future sea level rise globally and along European coastlines:

- observed change in global mean sea level, based on reconstructions from tide gauge measurements (since 1900) and on satellite altimeter data (since 1993);
- projected change in global sea level for five different forcing scenarios and spatial trends in relative sea level along the European coastline, based on tide gauge stations with long time series (since 1970).

Methodology

Methodology for indicator calculation

Sea level changes can be measured using tide gauges and remotely from space using satellite altimeters. Many tide gauge measurements have long multi-decadal time series, with some exceeding 100 years. However, the data can be distorted by various regional and local effects, such as vertical land motion processes. Furthermore, there are significant gaps in the spatial coverage of tide gauges with long time series, including in Europe.

Satellite altimeters enable absolute sea level to be measured from space and provide much better spatial coverage (except at high latitudes); however, their record is limited to about 30 years. The global and European sea level trends are calculated from a combination of nine partly overlapping satellite missions. The data are corrected for seasonal variations, the inverse barometer effects and post-glacial rebound.

Sea level projections are based on process-based models, which are rooted in state-of-the-art climate model simulations. Projections for relative mean sea level in Europe consider the gravitational and solid Earth response and land movement due to glacial isostatic adjustment, but not land subsidence as a result of human activities.

Model-based projections for changes in regional sea level rise included only grid cells that are covered at least half by sea. Data for other grid cells partly covered by land and by sea were extrapolated using the nearest-neighbour method.

Policy/environmental relevance

Justification for indicator selection

No rationale for indicator selection have been specified.

Context description

Sea level is an important indicator of climate change because it can have significant impacts on settlements, infrastructure, people and natural systems. The potential impacts include flooding, coastal erosion and the submergence of flat regions along continental coastlines and on islands. Rising sea levels can also cause saltwater intrusion into low-lying aquifers, thus threatening water supplies and endangering coastal ecosystems and wetlands.

Changes in global mean sea level result from a combination of several physical processes. Thermal expansion of the oceans occurs as a result of warming ocean water. Additional water is added to the ocean from a net melting of glaciers and small ice caps, and from the disintegration of the large Greenland and Antarctic ice sheets.

The locally experienced changes in sea level differ from global average changes for various reasons, including changes in large-scale ocean circulation, changes in the gravity field, and vertical land movement due to the ongoing effects of post-glacial rebound, local groundwater extraction or other processes.

Accuracy and uncertainties

No uncertainties have been specified.

Data sources and providers

- Tide Gauge Data (1970 - 2022), Permanent Service for Sea Level (PSMSL)
- IPCC AR6 Sea Level Projections, Intergovernmental Panel for Climate Change (IPCC AR6 WG1)
- An ensemble approach to quantify global mean sea-level rise over the 20th century from tide gauge reconstructions (data provided in Supplementary data with the publication), Palmer et al., 2021
- Global Ocean Mean Sea Level time series and trend from Observations Reprocessing (OMI_CLIMATE_SL_GLOBAL_area_averaged_anomalies), Copernicus Marine Service (CMS)
- IPCC AR6 Sea-Level Rise Projections, IPCC AR6 Sea-Level Rise Projections

Metadata

DPSIR

Impact

Topics

Water # Climate change adaptation # Seas and coasts

Tags

Climate change # Coasts # Sea level # CLIM012

Temporal coverage

1900-2150

Geographic coverage

Belgium
Croatia
Denmark
Earth
Finland
France
Germany
Greece
Iceland
Ireland
Italy
Lithuania
Netherlands
Norway
Spain
Sweden
United Kingdom

Typology

Efficiency indicator (Type C - Are we improving?)

UN SDGs

SDG13: Climate action

Unit of measure

FIG1: mm (observed changes) and m (projected changes)

FIG2: mm/year (trends) and m (projected change)

Frequency of dissemination

Once a year

References and footnotes

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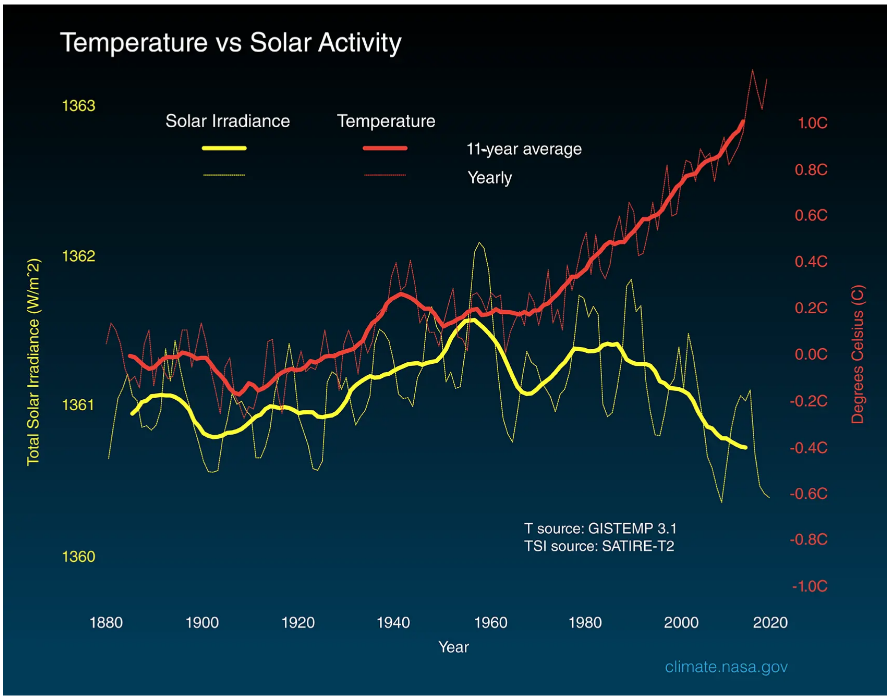
Is the Sun causing global warming?



The above graph compares global surface temperature changes (red line) and the Sun's energy received by Earth (yellow line) in watts (units of energy) per square meter since 1880. The lighter/thinner lines show the yearly levels while the heavier/thicker lines show the 11-year average trends. Eleven-year averages are used to reduce the year-to-year natural noise in the data, making the underlying trends more obvious.

The amount of solar energy Earth receives has followed the Sun's natural 11-year cycle of small ups and downs with no net increase since the 1950s. Over the same period, global temperature has risen markedly. It is therefore extremely unlikely that the Sun has caused the observed global temperature warming trend over the past half-century.

No. The Sun can influence Earth's climate, but it isn't responsible for the warming trend we've seen over recent decades. The Sun is a giver of life; it helps keep the planet warm enough for us to survive. We know subtle changes in Earth's orbit around the Sun are responsible for the comings and goings of the ice ages. But the warming we've seen in recent decades is too rapid to be linked to changes in Earth's orbit and too large to be caused by solar activity.

One of the "smoking guns" that tells us the Sun is not causing global warming comes from looking at the amount of solar energy that hits the top of the atmosphere. Since 1978,

The Sun, Volcanoes, and More

What do volcanoes have to do with climate change?

What happens if the next solar cycle becomes less active? Will we enter into a new ice age?

Do small particles in the air (aerosols) have a warming or cooling effect on the climate?

scientists have been tracking this using sensors on satellites, which tell us that there has been no upward trend in the amount of solar energy reaching our planet.

A second smoking gun is that if the Sun were responsible for global warming, we would expect to see warming throughout all layers of the atmosphere, from the surface to the upper atmosphere (stratosphere). But what we actually see is warming at the surface and cooling in the stratosphere. This is consistent with the warming being caused by a buildup of heat-trapping gases near Earth's surface, and not by the Sun getting "hotter."

READ MORE

- The Causes of Climate Change
- What Is the Sun's Role in Climate Change?
- There Is No Impending 'Mini Ice Age'
- Climate Change: Incoming Sunlight (NOAA)
- Earth's Energy Budget Remained Out of Balance Despite Unusually Low Solar Activity

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Science Editor: **Susan Callery**

Site last updated: November 30, 2023

Environment Agency

Rationalising the Main River Network (RMRN): Stour Marshes De-maining Project - Consultation Response Document

We are the Environment Agency. We protect and improve the environment.

We help people and wildlife adapt to climate change and reduce its impacts, including flooding, drought, sea level rise and coastal erosion.

We improve the quality of our water, land and air by tackling pollution. We work with businesses to help them comply with environmental regulations. A healthy and diverse environment enhances people's lives and contributes to economic growth.

We can't do this alone. We work as part of the Defra group (Department for Environment, Food & Rural Affairs), with the rest of government, local councils, businesses, civil society groups and local communities to create a better place for people and wildlife.

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Foreword

We are committed to working with local organisations, landowners and communities to ensure the right organisations are managing the right watercourses.

The 3 de-maining pilots that we consulted on in January/February 2018 are an important step in making this happen. We are a national organisation and our focus is on managing watercourses where the flood risk is greatest to people and property, therefore in some locations we are not best placed to lead and manage flood risk.

Working with local partners such as internal drainage boards (IDBs) and local authorities (LAs) we want to ensure the right organisations are managing the right watercourses, supporting local decisions and actions.

We consulted on proposals to de-main 18 watercourses along a length of approximately 76 kms in Suffolk, the South Forty Foot Catchment in Lincolnshire and River Stour Marshes in East Kent. We received 16 responses to the consultation.

The views and opinions expressed were varied and covered a range of topics such as future management and regulation of the watercourses, the environment and how maintenance works would be funded.

The feedback will inform our decision on how we plan to proceed in transferring watercourses and assets in these locations and also the approach we take across England in the future.

I would like to thank everyone who has taken part in the consultation and the preceding public drop-ins and meetings. Thanks is also given to our IDB and LA partners who are willing to take on the flood and water level management of these watercourses and provided their time and information to support the consultation.

Executive summary

The Environment Agency want to empower local communities, Internal Drainage Boards (IDBs) and Local Authorities (LAs) to take responsibility for their local flood risk where they want to, and where appropriate.

We have carried out a consultation on proposals to transfer the management of flood risk for the following sections of the following rivers from the Environment Agency to other risk management authorities (RMAs).

- Suffolk Rivers, Suffolk - to East Suffolk Internal Drainage Board and Suffolk County Council (LLFA) (some flood risk management activities will transfer to Suffolk Coastal District Council and Waveney District Council)
- South Forty Foot Catchment, South Lincolnshire - to Black Sluice Internal Drainage Board
- Stour Marshes, East Kent - to the River Stour (Kent) Internal Drainage Board

This means re-designating these sections of river from main river to ordinary watercourse – a process we refer to as de-maining. These sections of watercourse would then be regulated, and where deemed necessary, maintained by the IDBs and LAs listed against each watercourse above. We believe that this action would empower these IDBs and LAs, giving them the ability to manage these sections of watercourse and carry out works for the benefit of local people, where they see fit.

The consultation took place from 15 January until 12 February 2018 to get feedback from all of those individuals, groups and organisations who are affected by, or interested in, our proposals. The consultation set out all of the information on our proposals. It explained how the proposed sections of watercourse are currently managed and funded and provided details on future management and funding, if de-maining does or doesn't take place.

We have now analysed the responses from the consultation.

This document provides a summary of the responses received and describes the next steps in the process.

Contents

1. Introduction

1.1. Purpose of this document

The Environment Agency is reviewing all of the comments received during the consultation. Thank you to everyone who responded.

The purpose of this document is to:

- provide an overview of how we ran the consultation
- share a summary of the feedback received for each consultation question
- present summary information on:
    - the number of responses submitted
    - the types of organisations that responded
- explain what will happen next.

1.2. What changes we are proposing and why

The Environment Agency proposes to transfer responsibility for the following sections of rivers and assets from the Environment Agency to the River Stour (Kent) Internal Drainage Board (IDB):

- The Lampen Stream - 1.2km
- The Minster Stream - 9.7km, including the following assets: West Monkton Stop, Minster Siphon, Scout Hut Stop, Ebbsfleet Stop, Saltwater Trash Screen
- The Richborough Stream - 9.2km, including the following assets: Ash Level Stop, Richborough Siphon, Goldstone Siphon
- The uppermost reach of the Great Stour - 5.6km
- The Gosshall Stream - 2.8km, including the following assets: Gosshall Siphon, Fleet Stop
- The Shelvingford Arm - 0.8km
- The General Valley Feed - 0.4km, including the following asset: General Valley Stop
- The North and South Stream and Broad Dyke - 5km
- Sparrow Bridge - 0.5km
- The Hogwell Sewer -1.3km, including the following asset: Hogwell Siphon

This will result in these stretches of the rivers being deleted from the statutory main river map. They will be re-designated as ordinary watercourses, a term we refer to as de-maining, and will then be managed, regulated and maintained by the River Stour (Kent) IDB.

We prioritise maintenance activities based on flood risk to people and property, and focus management at locations with high flood risk. This means that some main river watercourses, deemed at low risk of flooding, can suffer from intermittent funding. Where flood risk to people and property is low and we have willing partners, we can explore opportunities to transfer responsibility to manage, regulate and maintain a watercourse to other RMAs such as an IDB, LLFA, or district council, where it is appropriate to do so.

These sections of watercourse have low levels of flood risk to people and property and are not associated with major rivers or major population centres. Therefore, we are proposing to transfer management, regulation and the power to undertake maintenance of these sections of watercourse to the River Stour (Kent) IDB. These sections of river fall within the IDB's Internal Drainage District. This IDB is willing to take on responsibility for these sections of river and they have the appropriate skills and governance arrangements in place to do so. This is in line with the requirements set out in the Statutory Main River Guidance (please refer to the Appendices).

De-maining these watercourses would allow for local decision-making in how these sections of watercourse are managed to allow works to be carried out for the benefit of local people, where it is deemed necessary to supplement riparian owner maintenance responsibilities. Our permissive powers to undertake maintenance would no longer apply to the sections of river and we would no longer regulate flood risk activities.

The table below details the responsible party for specific roles on the watercourses, both currently and if the proposed de-mainment goes ahead (see column headed 'Future responsibility').

Table 1: Current and future roles and responsibilities

Role	Current responsibility	Future responsibility
Overall responsibility for the flood risk management of the watercourse	Environment Agency	The River Stour (Kent) IDB
Regulation – issuing permits for works on or near to the watercourse	To undertake any flood risk activities on any of the watercourses listed above, you must apply to the Environment Agency for a Flood Risk Activity Permit under the Environmental Permitting Regulations. The Environment Agency currently charges £170 for a single activity under a Flood Risk Activity Permit, with an additional £40 charge applied for each additional activity on the same application	To undertake any works or activities on or close to any of the watercourses listed above, you would need to apply for Land Drainage Consent from The River Stour (Kent) IDB. The cost of applications made under the Land Drainage Act 1991 (any in-channel works) incur a £50 fee. Applications made under the IDBs byelaws (works within 8m of a watercourse) do not have a fee charged.
Permissive power to maintain the watercourse	The Environment Agency has permissive powers to maintain the watercourse	The River Stour (Kent) IDB has the same permissive powers to maintain ordinary watercourses within its drainage district. If de-mained the watercourse would become an ordinary watercourse and be included in the IDB maintenance programme. The EA would no longer have these powers.

2. How we ran the consultation

2.1 What we did and when

In September and October 2017 we met and consulted with Kent County Council, Canterbury City Council, Ashford Borough Council, Dover District Council, Thanet District Council, the Parish Council Forum, the East Kent Catchment Improvement Partnership, the Ashford Water Group and Natural England. All these organisations expressed interest and gave their support to the aims of the project.

To engage with a wider audience and the general public we exhibited a project stand at the East Kent Ploughing Match on 27 September 2017 and then held pre-consultation public drop-in sessions on 4 October 2017 at Minster Village Hall, 19 October 2017 at Little Chart Village Hall and 25 October 2017 at Great Mongeham Village Hall. These were all hosted in partnership with the River Stour (Kent) Internal Drainage Board whose board members were on-hand to talk to the event attendees. See photos on page 10.

We used the feedback from the public drop-in sessions and meetings to help us finalise our consultation proposals. A formal consultation on the proposals was then published online using our online engagement tool Citizen Space between 15 January and 12 February 2018. Information on the questions asked and a summary of responses to these questions can be found in section 3 below.

2.2 Additional advertising

A Proposal of Designation Change notice was placed in the Legal Notices section of four newspapers in the Kent Messenger Media Group; the KM Extra, the Thanet KM Extra, the East Kent Mercury and the Kentish Gazette & Kentish Express. Examples of the notice can be seen on page 11.

As listed in the last paragraph of the Legal Notice, an A4 folder containing a complete set of river maps and associated documents was available for public viewing in the reception area of the Canterbury City Council main offices at Military Road, CT1 1YW and also in the Environment Agency Canterbury office at Rivers House, CT2 0AA.

An Email containing a newsletter and two pdf advertising posters was sent to the following Parish Councils: Ash, Wye & Hinxhill, Wickhambreaux, Hoath, Monkton, Northbourne, Egerton, Pluckly, Little Chart, Herne & Broomfield, Shoulden, Mongeham and Minster. They were asked to help advertise and promote the consultation by uploading information onto their web pages and display the posters on their parish notice boards.

An Email containing a newsletter and two pdf advertising posters was sent to the following Kent County Council libraries: Deal, Ash, Minster, Herne Bay and Sandwich. They were asked to help advertise and promote the consultation by uploading information onto their web pages and display the posters on their public information notice boards.

An Email containing a newsletter and two pdf advertising poster was sent to over 150 recipients on the mailing lists of a variety of East Kent organisations including local councils, non-government organisations, local utility and infrastructure companies, estate agents, environmental charities, defra partner organisations and members of the East Kent

Catchment Improvement Group. They were asked to help advertise and promote the consultation by uploading information onto their web pages and display the posters on their notice boards.

Every rate payer and member of the River Stour (Kent) Internal Drainage Board (totalling over 350 individuals) was sent a newsletter through the mail advertising the consultation and requesting that they log onto the Citizen Space web page and give their opinions on the proposals.

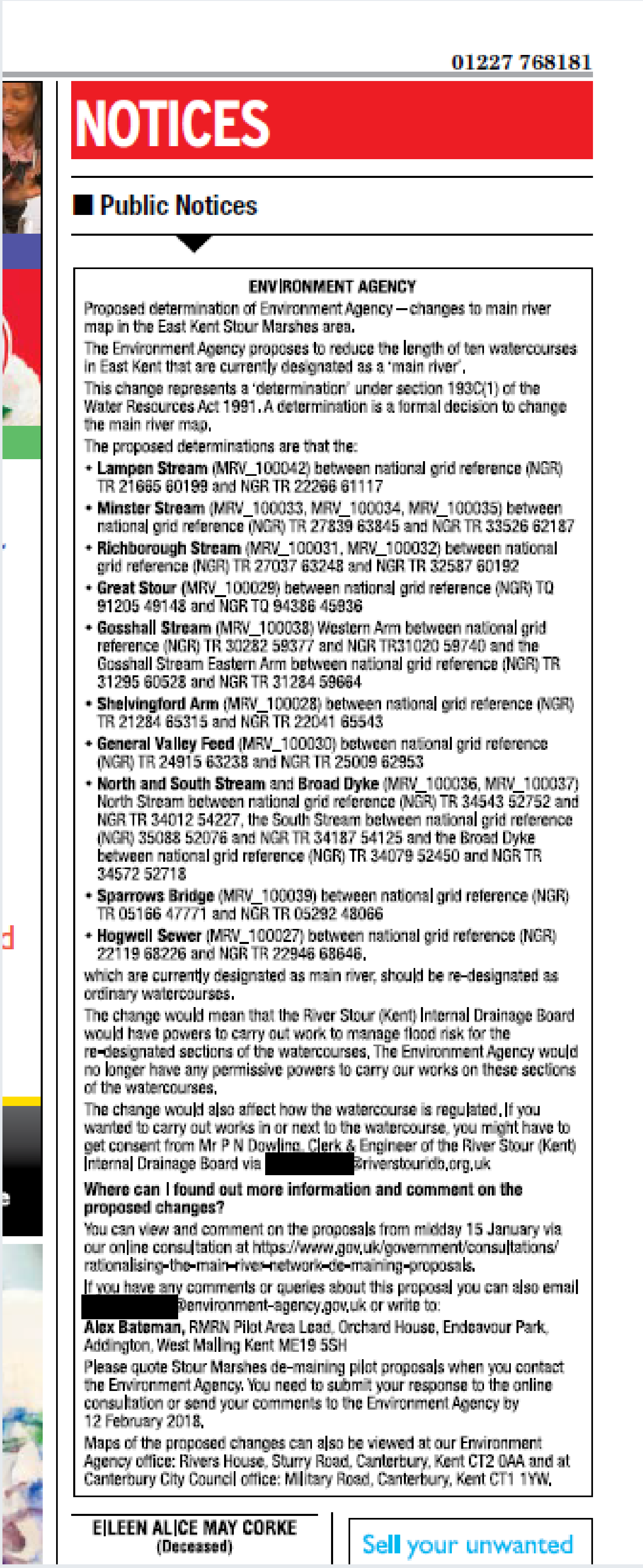
Through our area communication team, Julie Foley (Area Manager for Kent, South London and East Sussex) sent personal Emails to the following members of parliament who have de-maining watercourses in their constituencies: the Rt Hon Damian Green MP, Rosie Duffield MP, Charlie Elphicke MP and Craig Mackinlay MP.

Minster Village Hall drop-in session

Little Chart Village Hall drop-in session.

Example of the Proposal for Designation Change Notice.

This one was advertised in the Kent Messenger Extra which covers the Canterbury and Whitstable areas of the north Kent coast.



01227 768181

NOTICES

Public Notices

ENVIRONMENT AGENCY

Proposed determination of Environment Agency – changes to main river map in the East Kent Stour Marshes area.

The Environment Agency proposes to reduce the length of ten watercourses in East Kent that are currently designated as a 'main river'.

This change represents a 'determination' under section 193C(1) of the Water Resources Act 1991. A determination is a formal decision to change the main river map.

The proposed determinations are that the:

- **Lampen Stream** (MRV_100042) between national grid reference (NGR) TR 21665 60199 and NGR TR 22266 61117
- **Minster Stream** (MRV_100033, MRV_100034, MRV_100035) between national grid reference (NGR) TR 27839 63845 and NGR TR 33526 62187
- **Richborough Stream** (MRV_100031, MRV_100032) between national grid reference (NGR) TR 27037 63248 and NGR TR 32587 60192
- **Great Stour** (MRV_100029) between national grid reference (NGR) TQ 91205 49148 and NGR TQ 94386 45936
- **Gosshall Stream** (MRV_100038) Western Arm between national grid reference (NGR) TR 30282 59377 and NGR TR31020 59740 and the Gosshall Stream Eastern Arm between national grid reference (NGR) TR 31295 60528 and NGR TR 31284 59664
- **Shelvingford Arm** (MRV_100028) between national grid reference (NGR) TR 21284 65315 and NGR TR 22041 65543
- **General Valley Feed** (MRV_100030) between national grid reference (NGR) TR 24915 63238 and NGR TR 25009 62953
- **North and South Stream** and **Broad Dyke** (MRV_100036, MRV_100037) North Stream between national grid reference (NGR) TR 34543 52752 and NGR TR 34012 54227, the South Stream between national grid reference (NGR) 35088 52076 and NGR TR 34187 54125 and the Broad Dyke between national grid reference (NGR) TR 34079 52450 and NGR TR 34572 52718
- **Sparrows Bridge** (MRV_100039) between national grid reference (NGR) TR 05166 47771 and NGR TR 05292 48066
- **Hogwell Sewer** (MRV_100027) between national grid reference (NGR) 22119 68226 and NGR TR 22946 68646.

which are currently designated as main river, should be re-designated as ordinary watercourses.

The change would mean that the River Stour (Kent) Internal Drainage Board would have powers to carry out work to manage flood risk for the re-designated sections of the watercourses. The Environment Agency would no longer have any permissive powers to carry our works on these sections of the watercourses.

The change would also affect how the watercourse is regulated. If you wanted to carry out works in or next to the watercourse, you might have to get consent from Mr P N Dowling, Clerk & Engineer of the River Stour (Kent) Internal Drainage Board via [redacted]@riverstouridb.org.uk

Where can I found out more information and comment on the proposed changes?

You can view and comment on the proposals from midday 15 January via our online consultation at https://www.gov.uk/government/consultations/rationalising-the-main-river-network-de-maining-proposals.

If you have any comments or queries about this proposal you can also email [redacted]@environment-agency.gov.uk or write to:

Alex Bateman, RMRN Pilot Area Lead, Orchard House, Endeavour Park, Addington, West Malling Kent ME19 5SH

Please quote Stour Marshes de-maining pilot proposals when you contact the Environment Agency. You need to submit your response to the online consultation or send your comments to the Environment Agency by 12 February 2018.

Maps of the proposed changes can also be viewed at our Environment Agency office: Rivers House, Sturry Road, Canterbury, Kent CT2 0AA and at Canterbury City Council office: Military Road, Canterbury, Kent CT1 1YW.

EILEEN ALICE MAY CORKE
(Deceased)

Sell your unwanted

3. Summary of consultation feedback

A total of three responses were received.

Two were submitted online through the Citizen Space portal and answered the formal consultation questions. These can be viewed in full at https://consult.environment-agency.gov.uk.

A third was received as a word.doc attachment to an Email sent to Alex Bateman, the Stour Marshes Pilot Area Lead. This contained more general observations and while not in the approved format, provided valuable feedback on the de-maining proposals specific to the North and South Streams near Sandwich.

The word diagram below illustrates some of the key themes that were raised during the consultation.

A breakdown of responses by respondent type is shown below.

Table 2: Breakdown of consultation responses by type of respondent

Respondent type	Number of responses	%
Member of the public	1	33.3
Internal drainage boards		
Drainage associations		
Local authorities		
District Councils	1	33.3
Parish Councils		
Elected representatives, including MPs		
Landowners and tenants		
Farming associations		

Environmental bodies	1	33.3
Regional flood and coastal committees		
Water companies		
Recreational and commercial river users		
Community groups		
Flood action groups		
Other		

The following pages summarise the responses received for each consultation question and the general themes emerging from the consultation.

The first comment in each of the 'You Said' boxes is from a member of the pubic who was responding on behalf of an organisation or group.

The second comment is from a representative of Dover District Council and these can be taken as the views of the District Council.

The third response was received from a member of the public as an Email attachment and so was not submitted through the Citizen Space format. Where relevant subject matter can be taken from this submission to fit a Citizen Space question, the comments refer not just to the North and South Streams and Broad Dyke stretches of watercourse proposed for de-maining, but to the entire Delf Stream. This is an off-line moderated response and published in a separate document.

3.1 Question: Overall, do you support the de-maining proposals?

Responses to this question supported the notion of de-maining the watercourses to strengthen local decision making and to defer their management and control to the IDB.

"Local people are more likely to have the sort of detailed understanding of the hydrological, riparian and environmental issues"

There were no responders who said that they didn't support the proposals. However, the essence of the third responders' comments (there is no quote below directly applicable to this question) highlights a number of management and financial concerns and the overall theme of this submissions, while not an absolute 'no', is sceptical of success.

You said…	Our response…
I believe that local people are more likely to have the sort of detailed understanding of the hydrological, riparian and environmental issues that is necessary for proper stream management than the EA.	We agree. The Environment Agency may not be the best organisation to undertake management and maintenance in the way that is asked for by local communities. The River Stour (Kent) IDB have extensive experience in watercourse and riparian management and if de-maining proceeds, will continue to maintain the river in a sensitive way in order to meet their environmental responsibilities.
Dover District Council are aware that the Internal Drainage Board are looking to manage the EA de-mained rivers in the Dover District. DDC recognise that the IDB will need to do this without increasing budgets, but will have the opportunity to utilise the EA precept costs.	This is correct; the IDB intends to adopt these rivers in order to continue maintenance and work within existing annual budgets (no increase to rates and levies as a result of these transfers).

3.2 Question: If de-maining goes ahead the Environment Agency will no longer be responsible for these watercourses. This responsibility will pass to the risk management authorities as set out in this consultation. How satisfied would you be about this?

Two responses to this question showed support for the idea that the responsibility for these watercourses can pass from the Environment Agency to a different risk management authority.

"Local IDB people...would be better equipped to plan and carry out the necessary work"

Dover District Council demonstrated an understanding that if the River Stour (Kent) IDB do adopt them, they will have to review their own maintenance programme.

"It's understood the IDB can manage if the EA de-main the mentioned rivers"

The third response objected on the grounds that fragmenting the river system would inevitably lead to dividing the management responsibilities. It suggested that "the whole system should be transferred to the IDB", and that as the decision to de-main seems to be financially driven, future funding restrictions may impact on management activities and success.

You said…	Our response…
Local IDB people, if appropriately-funded, have a better understanding of the multi-facetted issues arising from river management in their areas and would be better equipped to plan and carry out the necessary work	We agree, and this project is designed to pass them the responsibility for future watercourse management.
It's understood the IDB can manage if the EA de-main the mentioned rivers. However, the IDB will need to follow a similar process and cut back on their own maintenance to other lower priority water courses.	This is correct; the IDB considers the rivers proposed for transfer to be of local importance (even though they are considered to be low-risk in terms of national criteria) and it will need to adjust its wider maintenance programme (reducing some lower priority watercourses to bi-annual maintenance).
The current proposals to transfer only the North and South Stream above the inverted siphon (Moles Hole) and Broad Dyke to the IDB will be to fragment responsibilities even further. The whole system should be transferred to the IDB. It is fully recognised that there are financial issues involved, both for the EA and IDB and the IDB only want to take over a limited stretches in steps. However, financial problems are not going to improve in future years. Surely	The rivers proposed for de-maining and transfer, referred to in this comment, are the small uppermost reaches of the North and South Streams. The Environment Agency and the IDB already manage and maintain a number of rivers on this system and will continue to liaise and coordinate their activities to ensure joined up management.

it is better for the EA, who want to be relieved of the responsibility, and the IDB to address the issues once and for all rather than have them continuing to occur over a protracted period of time.	

3.3 Question: If de-maining goes ahead the Environment Agency will no longer be responsible for regulating flood risk for these watercourses. This responsibility will pass to the risk management authorities as set out in this consultation. How satisfied would you be about this?

Responses to this question were generally in favour of the responsibility for regulating flood risk on these watercourses passing to the River Stour (Kent) IDB.

"Satisfied with the overall approach of encouraging local responsibility for the river management"

However, the suggestion was made that by having two risk management authorities each responsible for different sections of the same watercourse, an opportunity for whole catchment management has been lost.

Dover District Council are fully aware that these are watercourses of low consequence with low population densities living nearby.

"The rivers in the district hold very little flood risk"

There were no responders who said that they didn't support the proposal.

You said…	Our response…
Satisfied with the overall approach of encouraging local responsibility for the river management. However, I strongly believe in the importance of a 'whole catchment' approach to river management - this is the only logical approach to what is a wholly integrated system. To split off the upper reaches of the North and South Streams and allow them to be managed by the EA seems irrational and unworkable and a lost opportunity to set up a whole-river approach.	Whole catchment management does not always represent the most efficient use of funds and resources. The Environment Agency prioritises maintenance based on flood risk to people and property, watercourse management must be focussed at locations with high flood risk or where the consequences of flooding are most significant. The upper reaches of the North and South Streams have a low flood risk and are in the operational area of the River Stour (Kent) IDB, an established partner organisation willing to assume management responsibility for these watercourses.
It's been explained that the rivers in the District hold very little flood risk - providing the IDB can carry some maintenance on a bi-annual basis.	The Environment Agency will no longer undertake responsive patrolling on these watercourses or manage the watercourse to reduce flood risk to people and property. The River Stour (Kent) IDB will take on the powers to manage the watercourses to reduce flood risk and maintenance operations will be carried out based on evidence from assessment.

3.4 Question: If de-maining goes ahead how satisfied are you with the proposed maintenance works?

There was insufficient detail given by the first two responders to draw anything other than very general assumptions of support about this question.

The third responder cites a history of inappropriate or insufficient maintenance as resulting in the current poor state of the watercourse.

"The watercourse has been poorly maintained, particularly since the Environment Agency took over responsibility"

While this is not a clear objection to a change of management authority, it can be seen as evident dissatisfaction with the current maintenance works. The suggestion is made that the entire Delf stream would be better managed by just one organisation.

You said…	Our response…
Local knowledge of environmental issues, special species that need protection etc.	Both the EA and IDB are committed to protecting and enhancing the natural environment and will continue to work together and with others to achieve this aim.
As per my previous comments.	See response comments given to questions 3.3
The watercourses have been poorly maintained, particularly since the Environment Agency took over responsibility **Over the past 750 years since its inception, many of the problems of the Delf, namely the condition of the banks, restricted flow, weed growth, siltation, eutrophication and algal problems have been due not to physical issues but to issues related to who was responsible for its management and maintenance (eg dispute between the EA and Sandwich Council as to who is responsible for the Delf in Sandwich). The De-maining process is a once in a lifetime opportunity to address and resolve these issues.**	We acknowledge your comments and concerns about the management of the Delf Stream. Past maintenance works carried out have included targeted in-channel vegetation cutting, bankside scrub and tree cutting, removal of urban debris and a five year de-silting programme along the entire stretch of watercourse. Future management decisions will be based on the results of evidence from watercourse surveys and assessments.

3.5 Question: If de-maining goes ahead how satisfied are you with how money will be raised to pay for maintenance?

The first response to this question raised concerns as to whether the River Stour (Kent) IDB would have sufficient financial resilience to take on the new watercourses and continue their existing maintenance programme without there being a detrimental effect somewhere else in their business plan.

"Just not sure how the proposal will work…presumably there will be detrimental effects somewhere?"

Dover District Council also mentioned finance constraints. Despite this, neither responder raised serious doubts.

You said…	Our response…
Just not sure how the proposal will work, if no new money is available. If it is just a case of transferring money from one part of the existing IDB budget to another, then presumably there will be detrimental effects somewhere?	The River Stour (Kent) IDB is funded by Special Levies on District Council, based on the amount of non-agricultural land in its district, and Drainage Rates on agricultural landowners. The on-going maintenance of these watercourses will be achieved by savings from reduced maintenance on other local, lower priority IDB maintained watercourses and will therefore not result in an increase to rates and levies. The IDB does not however intend to completely decommission these lower priority watercourses, just reduce their frequency of maintenance.
It would seem the finance restraints are being passed onto the IDB. However the IDB will be able to claim some EA precept cost back to help future maintenance.	The EA and IDB consider this process to be a review of the local river network, to ensure that rivers are managed by those most appropriate. As some of the rivers to be de-commissioned are already supported by EA Precept (paid by the IDB) some adjustments have been agreed to the on-going maintenance.

3.6 Question: If de-maining doesn't go ahead how satisfied are you with what is proposed in relation to future maintenance?

Responses to this question were evenly split in support of, and objection to, the proposal.

The first responder, aware that the watercourse of concern (the North and South Streams) has a low flood risk does not see an issue arising from reduced future maintenance.

"I don't see the reduction of maintenance is likely to be an issue in this particular case"

The second raised concern that a reduction in maintenance could increase the flood risk in connecting watercourses which should be taken as some level of objection.

The third response is an observation about the role of Sandwich Town Council in ascertaining current watercourse condition and therefore maintenance requirements; although the sections of watercourse proposed for de-maining ends well short of the Sandwich town area referred to in the comment.

You said…	Our response…
Because the section of the North and South Streams under discussion are of such apparently low flood risk, and are very unlikely to impinge on any housing areas. I don't see the reduction of maintenance is likely to be an issue in this particular case.	The sections of North and South Stream and Broad Dyke proposed for de-maining are watercourses of 'low consequence'. However, the River Stour (Kent) IDB will continue to conduct periodic maintenance operations based on evidence from watercourse inspections, to ensure flood risk is maintained at an acceptable level.
The rivers could suffer as a consequence and have a knock on effect to connecting watercourses and increase flood risk.	The Environment Agency has a strategic overview role for all riparian flood risk. The Environment Agency and River Stour (Kent) IDB will continue to work in partnership to implement a programme of planned watercourse maintenance for flood risk management across the Stour Marshes area.
Sandwich Town Council (STC) are currently undertaking a photographic survey of the underground system of the Delf through Sandwich to review the degree of siltation. I believe this is a step towards the STC accepting responsibility for the Delf through Sandwich, something which both the EA and IDB are reluctant to do.	These comments refer to a section of watercourse that is outside the geographic area and scope of this project.

3.7 Question: If de-maining goes ahead how satisfied are you with changes to who undertakes maintenance work on assets?

There are twelve assets in the Stour Marshes area proposed for handover to the River Stour (Kent) IDB.

The first response is incorrect in saying there are no assets involved. The second responder hopes that the IDB will continue to maintain them, and the third proposes that the Hacklinge Pumping Station should remain in EA ownership but be operated by the IDB.

You said…	Our response…
No assets involved, apparently.	There are twelve assets on the watercourses proposed for de-maining, all of which will require routine inspection and maintenance work to ensure they are operational and fit for purpose.
I can't really comment other than I hope they're maintained when taken over by the IDB.	The responsibility for asset maintenance will pass to the River Stour (Kent) IDB, which is willing to take on these assets to ensure that water levels can continue to be managed appropriately. The IDB will ensure its own standard maintenance operations and with appropriate risk assessment.
Hacklinge Pumping Station, which is not planned to be handed over to the IDB, could continue in EA ownership with its operation, as happens now, being managed by the IDB.	There is no provision within the scope of the current project to divide the ownership and management of assets. It is not a planned project outcome.

3.8 Question: If de-maining goes ahead how satisfied are you with changes to who is responsible for managing and considering the environment in the areas affected by the de-maining proposals?

Whilst not making a definite statement about the suitability of the IDB to assume environmental management responsibilities, the first responder comments that local knowledge and environmental expertise are important trait of the new organisation.

You said…	Our response…
Local knowledge of, and expertise in, environmental issues are of real importance.	The River Stour (Kent) IDB will continue to maintain the river in a sensitive way in order to meet their environmental responsibilities. They will be responsible to ensure that there is no deterioration to current environmental status. Natural England will remain the statutory authority for the management of any designated sites of environmental importance.
Dover District Council acknowledges that its powers may increase as a consequence and may have to provide support where necessary.	The proposed transfer of responsibilities from the EA to the IDB should not directly affect the powers of Dover District Council.

3.9 Question: Having read the information in this consultation, have you changed your views on the de-maining proposals?

There was just one response to this question and the text is a reaffirmation of the respondents answer to question 3.1 concerning support for localism in management decision making.

Despite the absence of a definitive 'yes' or 'no', I think the answer to this question can be taken as no change of view.

Dover District Council did not leave a comment.

You said…	Our response…
Still convinced of the importance of local knowledge and expertise, subject to funding being available to take on work previously conducted by the EA.	See response to question 3.1
No comment.	No response.

3.10 Question: Overall, do you support the de-maining proposals?

Both responders to this question supported the de-maining proposals, the second giving a definite 'yes'.

You said…	Our response…
As described above several times.	Thank you for supporting this project.
Yes, otherwise the rivers won't be maintained enough having adverse effects on other IDB maintained watercourses.	Thank you for supporting this project.

3.11 Question: Please tell us if you have any further comments or information that you would like to share with us regarding the Stour Marshes de-maining proposals.

Neither respondent left a comment in response to this question

You said…	Our response…
No comment	No response.
No comment	No response.

4. Next steps

We will take into account all of the consultation responses received and consider these alongside the criteria set out in the Statutory Main River Guidance to the Environment Agency (please refer to appendix 5.3) before deciding whether to proceed with the proposal.

If we decide to proceed with de-maining we will publish a “proposal for designation change” notice on GOV.UK and in local newspapers. We will also notify people who have responded to the consultation and provided us with an email address. Anyone can challenge the decision to de-main by email or in writing to Department for Environment, Food and Rural Affairs (Defra) within 6 weeks of the publication of the Notice.

5. Appendices

5.1 List of consultation participants

Dover District Council
The River Stour (Kent) Internal Drainage Board

5.2 Statutory Main River Guidance

This guidance sets out the basis on which the Environment Agency should decide whether or not a river or watercourse is treated as a 'main river'. The guidance has been issued under section 193E of the Water Resources Act 1991.

Main rivers are usually larger rivers and streams. They are designated as such, and shown on the Main River Map. The Environment Agency carries out maintenance, improvement or construction work on main rivers to manage flood risk. Other rivers are called 'ordinary watercourses'. Lead local flood authorities, district councils and internal drainage boards carry out flood risk management work on ordinary watercourses.

The Environment Agency is responsible for maintaining a map of the main river (the Main River Map) and making any changes to it, and determining whether or not a watercourse, or part of a watercourse, is to be treated as a main river or part of a main river. This guidance has been issued by the Secretary of State for Environment, Food and Rural Affairs and the Environment Agency is required to have regard to it.

A. Criteria for determining whether or not a watercourse or part of a watercourse is suitable to become or to remain a main river or a part of a main river

References to a watercourse include both a whole watercourse and parts of a watercourse.

The criteria below are primarily directed at the management of flood risk. Any determination will need to be made in the context of the Environment Agency's other relevant functions (and this may include environmental considerations, where relevant).

1. Principal criteria

Flood consequence

1.1 A watercourse should be a main river if significant numbers of people and/or properties are liable to flood. This also includes areas where there are vulnerable groups and areas where flooding can occur with limited time for warnings.

Managing flooding across the catchment

1.2 A watercourse should be a main river where it could contribute to extensive flooding across a catchment.

1.3 A watercourse should be a main river if it is required to reduce flood risk elsewhere or provide capacity for water flowing from, for example, a reservoir, sewage treatment works or another river.

2. Secondary considerations if changing the status of a watercourse

An efficient network

2.1 When considering changing the status of a watercourse, the Environment Agency should avoid short stretches of watercourses of alternating main river and ordinary watercourse status to provide clarity and to minimise inefficiency through multiple authorities acting on the same watercourse.

Competence, capability and resources

2.2 When considering changing the status of a watercourse, the Environment Agency should consider if those taking on responsibility have sufficient competence, capability and/or resources for flood risk management, including whether their governance enables sufficient competence, capability and/or resources, and local accountability. In carrying out this assessment, the Environment Agency should seek Defra's views.

Other relevant criteria

2.3 The Environment Agency may have regard to other relevant factors that it considers appropriate when exercising its discretion to determine whether to change the status of a watercourse or part of a watercourse. The Environment Agency should consider relevant benefits or costs for the local community and representations from the local community and others in response to consultation.

B. Guidance in respect of consultation and publication under section 193C(2) and (5) Water Resources Act 1991

How proposed amendments are publicised

There are two types of change the Environment Agency may make to the main river map:

factual changes (updating the map so the location of watercourses is more accurate)

designation changes (changing an ordinary watercourse so that it is a main river, or a main river so that it is an ordinary watercourse)

Under section 193C(2) of the Water Resources Act 1991 the Environment Agency must publicise any proposed changes to the main river map and consider representations made.

Factual changes

1.1 The Environment Agency must publish notices of proposed factual changes on GOV.UK.

1.2 The Environment Agency should also consider contacting the landowners when the map is being amended to show the correct course of a culvert (a structure that lets the watercourse go under a road, for example).

Designation changes

2.1 The Environment Agency must publicise proposed designation changes in the following ways:

by writing to any person who owns land next to the watercourse, and other key stakeholders (for example, Internal Drainage Boards or Local Authorities);

by placing public notices in local newspapers;

by publishing notices on GOV.UK;

by placing notices in local buildings (for example, in libraries or council offices).

2.2 The Environment Agency should carry out proportionate and meaningful consultation on designation changes by:

giving stakeholders an opportunity to shape, comment on and influence the outcome. Stakeholders include directly affected landowners, relevant public bodies, relevant interest groups and other persons, including the local community, affected by or interested in a proposed determination to change the designation of a watercourse;

providing sufficient information and allowing enough time to enable stakeholders to understand how the proposal affects them and engage with the issues. This should include providing relevant information on the flood risk, environmental aspects, the costs and benefits for local communities and coordinating with those taking on the responsibility for the watercourse to help the public have access to information on proposed future management of the watercourse; and

taking into account the views of all those who respond to the consultation when reaching its decision.

2.3 Anyone aggrieved by the designation change has the right to appeal to the Secretary of State.

6. Acknowledgements

We would like to thank all the local authorities who agreed to meet with us in the pre-consultation phase, everyone who attended the village hall drop-in sessions and those people who logged their opinions on Citizen Space. Their contributions and support were central in developing our consultation proposals.

We would also like to thank the Kent Messenger Media Group and Minster Parish Council for helping us to advertise and promote this consultation.

We would also like to thank all consultees who took the time to attend meetings, public drop-in sessions and respond to the consultation. Your feedback has been extremely valuable and will help inform our decision on whether or not to proceed with the Stour Marshes de-maining pilot proposals.

7. Glossary

Word/phrase	Definition/explanation
Asset	A flood risk management asset can be a flood defence such as a wall, embankment or a structure such as a pumping station, weir, sluice gate or a watercourse channel. As a result of its failure or removal or alteration, the likelihood of flooding from main river to people, property, designated environmental sites or infrastructure would increase.
Asset decommissioning	Planned shut-down or removal of an asset from operation or usage.
Asset maintenance work	Works to maintain the performance and reliability of an asset.
Byelaws	Byelaws are local laws made by a local council under an enabling power contained in a public general act or a local act requiring something to be done – or not done – in a specified area. They are accompanied by some sanction or penalty for their non-observance.
Competent authority	An authority or authorities identified under a relevant piece of legislation who has the legally delegated power to perform the designated function.
De-maining	Re-designation of a watercourse from main river to ordinary watercourse.
Designated sites	Sites which have been identified under law for having specific environmental protection. Depending on the designation, undertaking works on these sites often require permission or assent from the competent authority. All of the sites except LNRs (see below) are of national or international importance. The main sites covered by this category are: Special Protection Areas and Special Areas of Conservation: these are often referred to as Habitats Directive sites, N2K sites or Protected Areas. Ramsar sites: these are wetlands of international importance designated under the Ramsar convention and are treated in the UK as Protected Areas. Sites of Special Scientific Interest (SSSI): these are nationally important habitat and geological sites designated by Natural England. Scheduled Ancient Monuments (SAMs): Scheduled monuments are of national importance and scheduled under the Ancient Monuments and Archaeological Areas Act 1979 Local Nature Reserves (LNRs): these may have ecological importance on local scale and are

	designated under National Parks and Access to the Countryside Act 1949.
District Councils	Local authorities who perform the flood risk management activities of district and borough and city councils, as well as the second tier responsibilities of unitary authorities.
Environmental Non-Governmental Organisations (ENGOs)	A non-governmental organization (NGO) in the field of environmentalism. Examples of ENGOs include the Wildlife Trusts, RSPB, WWT and Blueprint for Water.
Environmental Permitting Regulations	The Environmental Permitting Regulations (England and Wales) 2010 require the Environment Agency to control certain activities which could harm the environment or human health. Flood Risk Activity Permits are issued under these regulations.
FCERM grant in aid	Government grants from the Department for Environment, Food and Rural Affairs (Defra) for flood and coastal erosion risk management.
Flood risk	Flood risk is expressed by combining information on probability (sometimes referred to as likelihood) and consequence (sometimes referred to as impact).
Flood Risk Activity Permit	Permission to ensure that any activities planned in, over, under or next to a watercourse do not cause a risk of flooding or make existing flood risk worse. A permit is also necessary to ensure work will not interfere with flood risk management assets or adversely affect the local environment, fisheries or wildlife
Flood and Water Management Act 2010	The legislation by which risk management authorities operate when exercising their powers.
Flood risk management activities	Works and activities to manage and reduce the risks of flooding from rivers and the sea to people, property and the natural environment. This includes flood defence projects, flood warning, informing planning decisions, regulation and the maintenance of asset and watercourses.
Governance	The way that organisations or countries are managed at the highest level, and the systems for doing this.
General drainage charge	Statutory levy payable by the occupiers of agricultural land and buildings and woodland outside an Internal Drainage District (currently used in Anglian Region only) to pay for flood risk management activities
Hydromorphological harm	Describes the hydrological and geomorphological processes and attributes of surface water bodies. For example for rivers, hydromorphology describes the form and function of the channel as well as its connectivity (up and downstream and with groundwater) and flow regime, which defines its ability to allow migration of aquatic organisms and maintain natural continuity of sediment transport through the fluvial system. The Water Framework Directive requires surface waters to be managed in such a way as to safeguard their hydrology and geomorphology so that ecology is protected.

Internal Drainage Boards	An internal drainage board (IDB) is a local public body that manages water levels within their local area, known as an 'internal drainage district.' Working with key partners such as the Environment Agency and lead local flood authorities, IDBs are a fundamental part of managing flood risk and land drainage within England.
IDB precept	Payments from IDBs to the Environment Agency to reflect water moving from internal drainage districts into main rivers.
Internal Drainage District	Internal drainage boards (IDB) are public bodies which manage water levels in some areas where there is a special need for drainage. These areas are known as internal drainage districts.
Land Drainage Act	The legislation by which land drainage activities are undertaken. Land drainage in the UK has a specific and particular meaning as a result of a number of Acts of Parliament such as the Land Drainage Act 1991. In this context, land drainage refers to the responsibilities and activities of "internal drainage districts" and "internal drainage boards", both of which are specifically defined by relevant legislation.
Lead Local Flood Authority	The unitary authorities or county councils responsible for local sources of flooding. LLFAs also develop, maintain and apply a strategy for local flood risk management in their areas and maintain a register of flood risk assets. LLFAs are also responsible for regulatory activities on ordinary watercourses outside of an internal drainage district.
Local authorities	This term has been used in this consultation to reflect : County councils and unitary authorities District, borough or city councils
Local levy	Funding raised by county councils and unitary authorities via council tax and other council funding mechanisms. May be raised either from within existing budgets or by raising council tax.
Maintenance programme	An annual programme of maintenance activities which is developed and where appropriate published by risk management authorities. The Environment Agency maintenance programme is available on GOV.UK.
Main river	Main river means all watercourses shown as such on the statutory main river maps held by the Environment Agency and published on GOV.UK.
Ordinary watercourse	A watercourse that does not form part of a main river.
Ordinary watercourse consents	Ordinary watercourse regulation ensures that activities that might affect ordinary watercourses do not increase the risk of flooding on a particular site or further upstream or downstream and do not adversely affect the environment. Regulation consists of issuing consents for acceptable work and undertaking enforcement action to deal with unacceptable activities.
Permissive powers	Powers which confer on an organisation the right to do things but not the duty to do them.

Regional flood and coastal committees	RFCCs are committees established by the Environment Agency under the Flood and Water Management Act 2010 that brings together members appointed by lead local flood authorities (LLFAs) and independent members with relevant experience for 3 purposes: to ensure there are coherent plans for identifying, communicating and managing flood and coastal erosion risks across catchments and shorelines to promote efficient, targeted and risk-based investment in flood and coastal erosion risk management that optimises value for money and benefits for local communities to provide a link between the Environment Agency, LLFAs, other risk management authorities, and other relevant bodies to engender mutual understanding of flood and coastal erosion risks in its area.
Riparian landowners	Owner of property (i.e. land) alongside a natural watercourse. Under common law they possess rights and responsibilities relating to the stretch of the watercourse which falls within the boundaries of their property.
Risk Management Authority	Risk management authorities (RMAs) are the Environment Agency, internal drainage boards, lead local flood authorities, district and borough councils, coastal protection authorities, water and sewerage companies and highways authorities. The Flood and Water Management Act 2010 requires these Risk Management Authorities to co-operate with each other, act in a manner that is consistent with the National Flood and Coastal Erosion Risk Management Strategy for England and the local flood risk management strategies developed by Lead Local Flood Authorities and exchange information. They have flexibility to form partnerships and to act on behalf of one another.
Statutory main river map	A map that shows watercourses designated by the Environment Agency as main rivers. The Statutory Main River Guidance that can be found on GOV.UK sets out the basis on which the Environment Agency should decide whether or not a **river** or watercourse is treated as a '**main river**'.
Statutory duties	The duties and functions that an organisation must undertake by law.
Watercourse	Includes all streams, rivers, ditches, drains, cuts, dykes, sluices, sewers (other than public sewers) and passages through which water flows.
Water Framework Directive	This Directive is European Union legislation that covers all inland and coastal waters. The Directive sets a framework which should provide substantial environmental benefits for managing water over the long term. River Basin Management Plans are developed and published in accordance with this legislation.

WFD objectives	Water body objectives consist of two pieces of information: the status (such as ‘good’) and the date by which that status is planned to be achieved (for example, ‘by 2021’). The status part of an objective is based on a prediction of the future status that would be achieved if technically feasible measures are implemented and, when implemented, would give rise to more benefits than they cost. The objective also takes into account the requirement to prevent deterioration and, as far as practicable, the requirements of protected areas.

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Sea Level

Understanding the past – Improving projections for the future

The Oceans are changing. Many observations show that the ocean has been changing over the last several decades. About 93% of the excess heat produced by greenhouse gases has been absorbed by the oceans. This results in an increase of ocean volume through thermal expansion. There has also been addition of water from glaciers and ice sheets, and changes in storage of water on or in the land (e.g. retention of water in man-made dams and extraction of water from aquifers). Together these result in changes in sea level.

Sea-level rise is a response to increasing concentrations of greenhouse gases in the atmosphere and the consequent changes in the global climate. Sea-level rise contributes to coastal erosion and inundation of low-lying coastal regions, particularly during extreme sea level events. It also leads to saltwater intrusion into aquifers, deltas and estuaries. These changes impact on coastal ecosystems, water resources, and human settlements and activities. Regions at most risk include heavily populated deltaic regions, small islands (especially coral atolls), and sandy coasts backed by major coastal developments.

This area contains

- Why does sea level change
- Past sea level change
- Future sea level change
- Measurements and data

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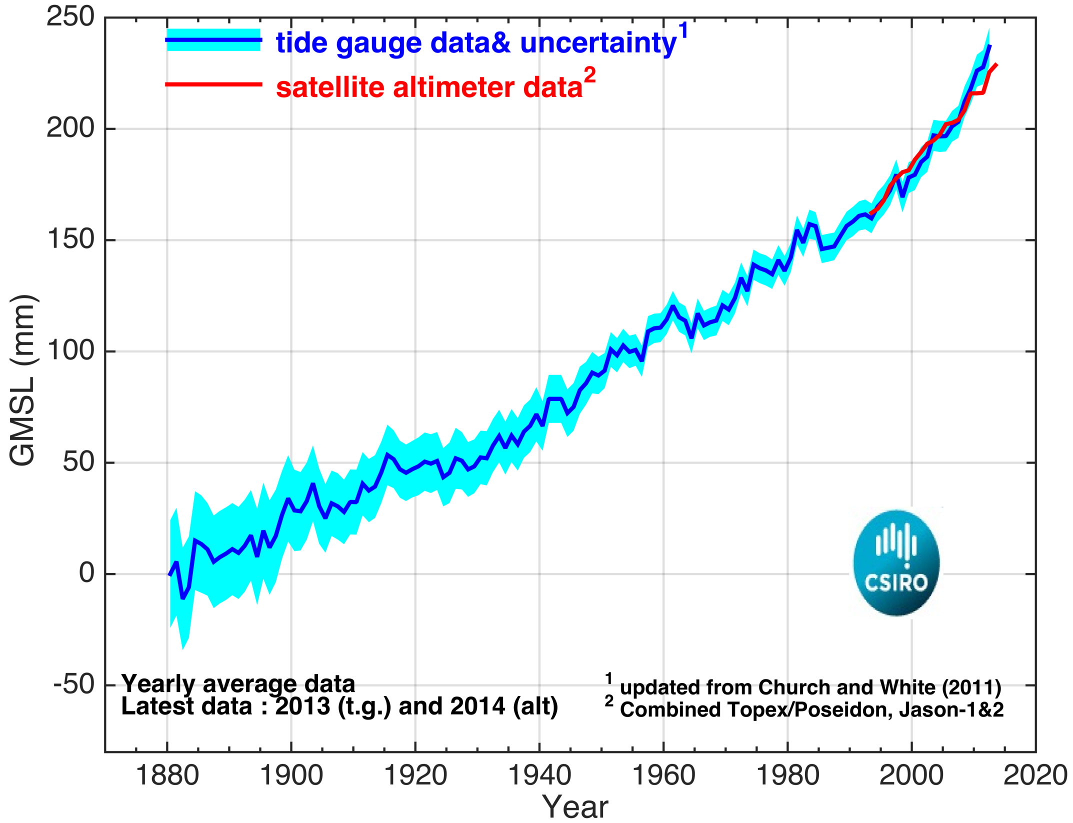
end of 2014



Our most recent estimate of changes in global averaged sea level since 1993 are estimated from satellite altimeter data (red) and, since 1880, by combining in-situ sea level data from coastal tide gauges and the spatial patterns of variability determined from satellite altimeter data (blue).

Note that error bars have not been shown for the altimeter data (red curve) for clarity, but are about ±5 mm.

Note that the number of gauges going in to the estimate drops off for the last couple of years because of delays getting the most recent data into the PSMSL archive, which is where we get this data from. This is simply due to the the time it takes the various national archives to compile and submit the data.

click here to download a print-quality pdf of this figure.

Benoit Legresy, last modified 22/09/2014.

CSIRO acknowledges the Traditional Owners of the land, sea and waters, of the area that we live and work on across Australia. We acknowledge their continuing connection to their culture and pay our respects to their Elders past and present. View our vision towards reconciliation.

Sea Level

LATEST MEASUREMENT: June 2023

101 (± 4.0) mm

SATELLITE DATA: 1993-PRESENT

Data source: Satellite sea level observations.
Credit: NASA's Goddard Space Flight Center

RISE SINCE 1993

100.5

millimeters

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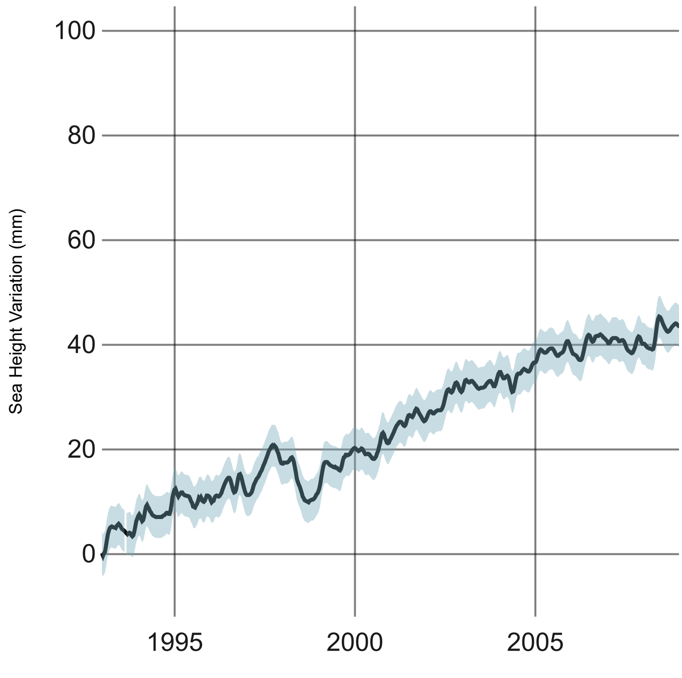
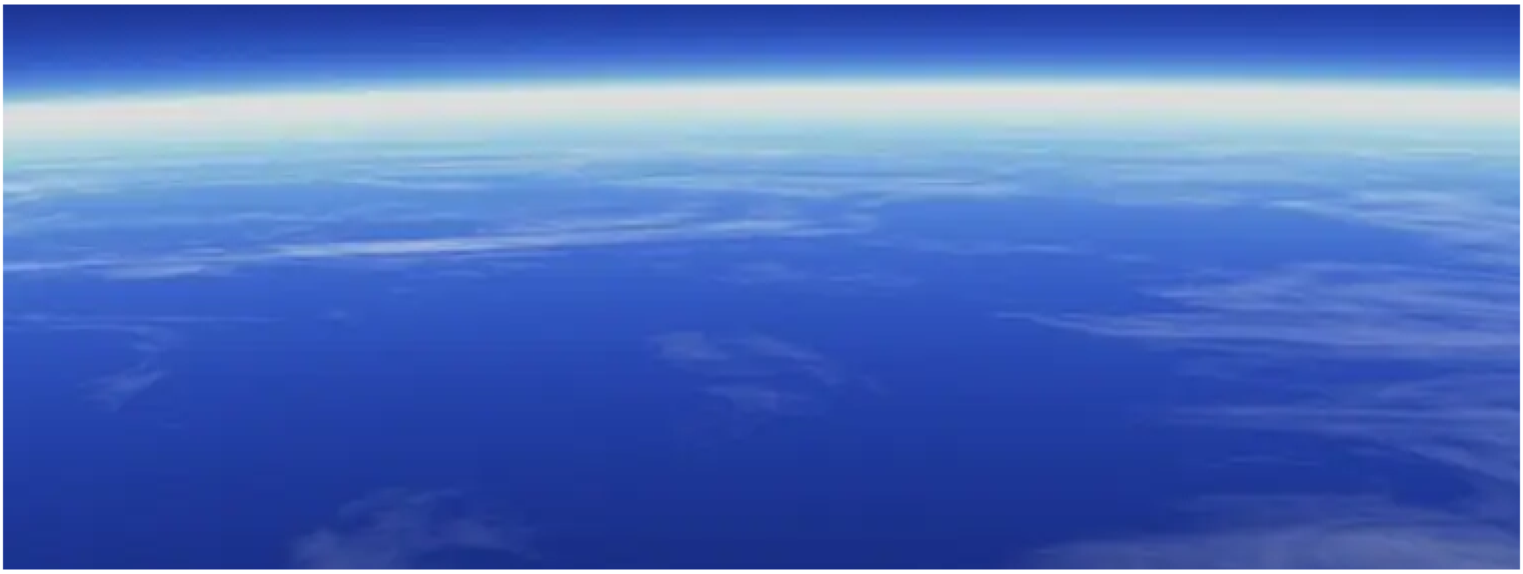


Key Takeaway:

Global sea levels are rising as a result of human-caused global warming, with recent rates being unprecedented over the past 2,500-plus years.

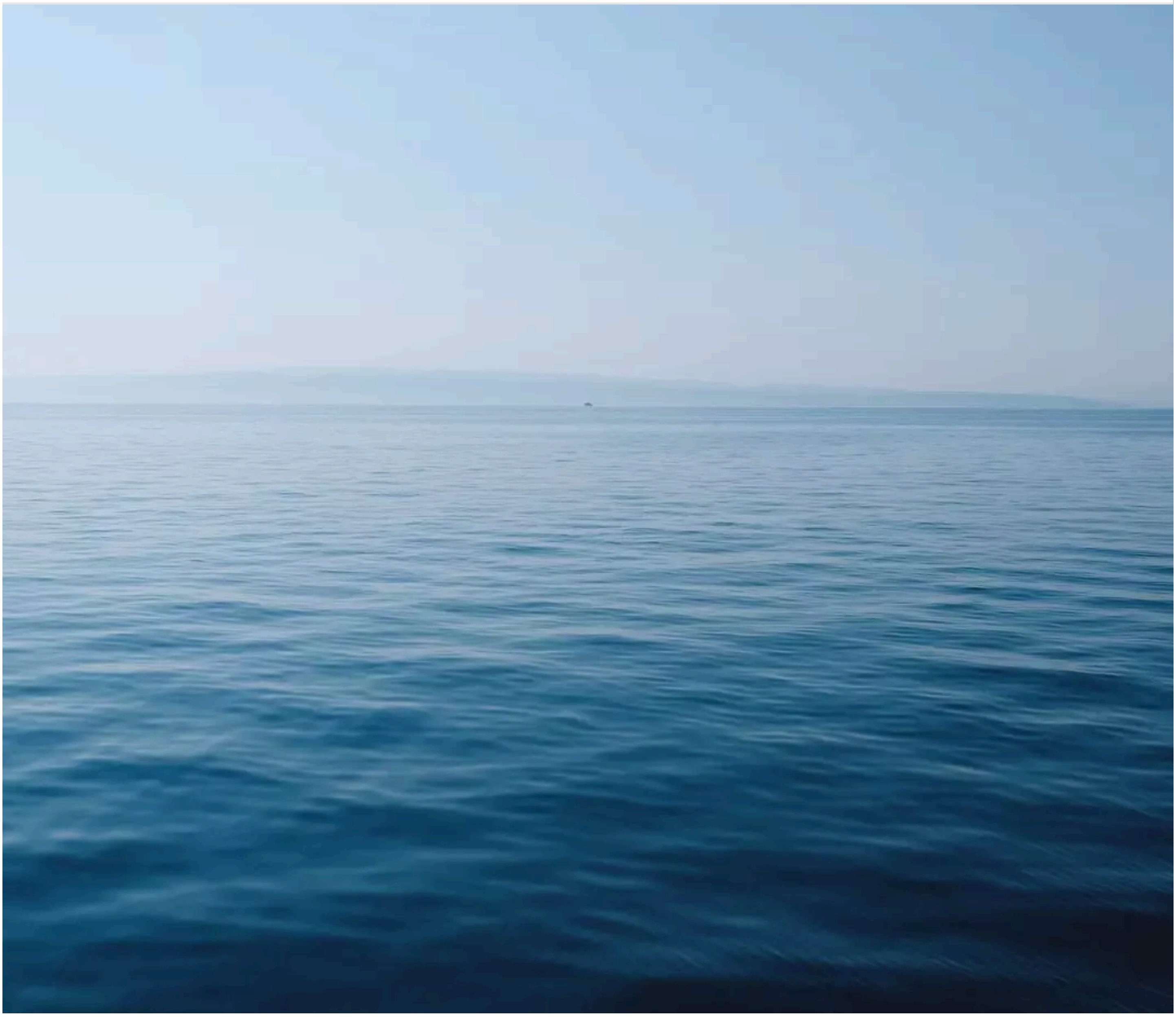
Sea level rise is caused primarily by two factors related to global warming: the added water from melting ice sheets and glaciers, and the expansion of seawater as it warms. The first



CLIMATE ACTION

Sea level rise: Everything you need to know

Mar 25, 2025



The two main drivers of sea level rise: melting glaciers and seawater expansion due to rising global temperatures.
Image: Unsplash/Thomas Vimare

Victoria Masterson
Senior Writer, Forum Stories

Stephen Hall
Writer, Forum Stories

Madeleine North
Senior Writer, Forum Stories

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This article has been updated.

- Rising sea levels caused by climate change are impacting 1 billion people worldwide.
- 2024 saw an unexpectedly fast rising of sea levels, which are already unprecedented.
- In the World Economic Forum's Global Risks Report 2025, 'Critical change to Earth systems', which includes sea level rise from collapsing ice sheets, is the third-biggest threat to the world in the coming decade.

Homes, livelihoods and, ultimately, lives are under threat from rising sea levels. Indeed, the United Nations (UN) calls it "a global crisis" - and one that is impacting 1 billion people worldwide.

Here's what you need to know.

What is sea level rise?

Sea level rise refers to the increase in the average height of the ocean's surface, measured from the centre of the Earth. This phenomenon is primarily driven by two main factors: the melting of glaciers and ice sheets, and the thermal expansion of seawater as it warms. As global temperatures rise due to climate change, ice sheets in Greenland and Antarctica are melting at an accelerated rate, contributing significantly to sea level rise.

Additionally, as seawater warms, it expands, further increasing the sea level. This rise in sea level is a critical indicator of climate change, with far-reaching impacts on coastal communities, ecosystems and economies worldwide.

analysis has found. Scientists were anticipating a rise of 0.43 centimetres, but instead recorded a rate of 0.59cm.

Pacific island nations like Tuvalu, Kiribati and Fiji have been battling rising sea levels for years now and NASA predicts they will experience a further 15cm of sea level rise in the next three decades, even if greenhouse gas emissions are brought under control.

Representatives from small-island and low-lying countries came together for the UN General Assembly's (UNGA) High-Level Week in 2024, which for the first time featured a dedicated meeting on Sea Level Rise to address this urgent issue.

"Today is our historical opportunity to turn the global tide and to embark on a common path that secures prosperity, dignity and rights to all affected countries and communities," said the Prime Minister of Tuvalu.

The key initiatives discussed at the meeting were:

- Creating a declaration on sea level rise in 2026
- Embracing AI and other innovations to help monitor risks associated with sea level rise
- Cooperation between scientists
- A treaty between Australia and Tuvalu to protect statehood in the case of eroded coastlines.

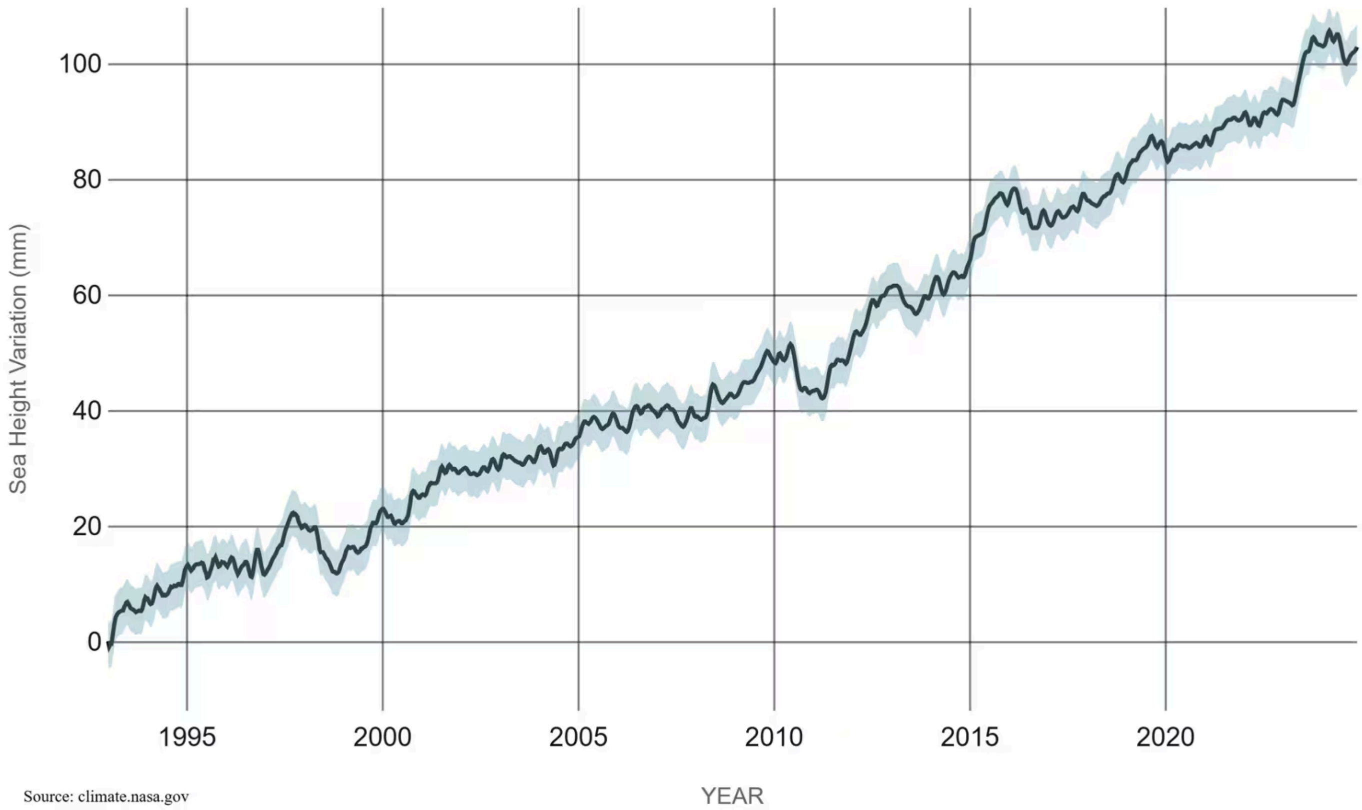
Have you read?

- **UNGA 2024: What is the UN General Assembly and what happens at the meeting?**
- **How Tuvalu is using technology to adapt to rising sea levels**
- **Vanishing shores: This is the impact of rising sea levels in Guinea-Bissau**

and harbours around the world. But now satellites can carry out this task more accurately by bouncing radar signals off the sea surface to measure changes in sea level.

Because local weather conditions and other factors can affect sea level, measurements are taken globally and then averaged out.

The World Economic Forum's work on Amplifying the Global Value of Earth Observation highlights monitoring changing sea levels as a key application of the technology to support vulnerability analysis.



Sea levels have risen by over 10cm between 1993 and 2024. Image: NASA's Goddard Space Flight Center

In 2021, scientists discovered a sea-level "fingerprint" from the Greenland ice sheet, confirming fears about the extent to which ice is melting.

…se fingerprints are "detectable patterns of sea level variability around the …rld resulting from changes in water storage on Earth's continents and in the according to the Geological Survey of Denmark and Greenland.

How much are sea levels rising?

With the ice sheet at “a tipping point of irreversible melting”, scientists currently expect an unavoidable sea level rise of 1-2 metres.

Global sea levels have already risen by over 10cm between 1993 and 2024, according to NASA, which says sea levels have been rising at unprecedented rates over the past 2,500 years.

While measuring in centimetres or even millimetres might seem small, these rises can have big consequences. This is particularly true where storm surges sweep further inland than they would have previously.

These 3 start ups are protecting and regenerating the world’s oceans

What causes sea level rise?

There are also likely negative feedback loops that could speed up glacier ice melt. For example, the Thwaites Glacier in Antarctica is disintegrating more quickly than anticipated. It's nicknamed the 'doomsday glacier' because sea levels could rise more than three metres without it and its supporting ice shelves.

Heat stored in the ocean is responsible for between a third and half of global sea level rise, NASA says. The past decade has been the ocean's warmest since at least 1800, and ocean temperatures reached a new high in 2023/2024.

Since 1971, oceans have absorbed over 90% of excess heat in the Earth system caused by rising greenhouse gas emissions.

The relationship between sea level rise and climate change

Climate change is the primary driver of global sea level rise.

Furthermore, the warming of the ocean causes the water to expand, a process known as thermal expansion, which also contributes to sea level rise.

The relationship between sea level rise and climate change is complex. Understanding it is crucial for predicting future sea level rise scenarios and developing strategies to mitigate its impacts.

As global warming continues, the rate of sea level rise is expected to accelerate, posing significant challenges for coastal regions around the world.

In the Forum's Global Risks Report 2025, 'Critical change to Earth systems' is the third-biggest threat to the world in the coming decade - and sea level rise from collapsing ice sheets is identified as a key contributing factor.

Effects of global sea level rise

The effects of global sea level rise are profound and multifaceted, impacting both human and natural systems. Rising seas threaten infrastructure, including roads, bridges and buildings, leading to increased costs for maintenance and repair.

As coastal flooding becomes more frequent and severe, it will exacerbate erosion and cause saltwater intrusion into freshwater sources, which can compromise drinking water supplies and agricultural productivity. The Forum's Water Futures: Mobilizing Multi-Stakeholder Action for Resilience white paper addresses the issue of water pollution as a result of extreme water-related events and lays out five pathways to water resilience.

Additionally, sea level rise poses a significant threat to coastal ecosystems such as mangroves, coral reefs and salt marshes, which provide critical habitats for numerous species.

Addressing these impacts requires comprehensive adaptation strategies to protect vulnerable communities and ecosystems.

Economic and social impacts

The economic and social impacts of sea level rise are significant and far-reaching. Rising seas can lead to increased costs for coastal protection measures, such as building sea walls and surge barriers, and repairing damage to infrastructure.

The loss of property and livelihoods due to coastal flooding and erosion can have devastating effects on communities, particularly in vulnerable regions. Additionally, sea level rise can exacerbate social and economic challenges by displacing people, disrupting economic activities and straining social services.

For example, communities that rely on tourism, fishing and agriculture may face significant economic losses as rising seas threaten their way of life.

Understanding these economic and social impacts is critical for developing effective adaptation strategies and mitigating the effects of sea level rise on vulnerable populations.

Past sea level rise and historical context

Throughout Earth's history, sea levels have fluctuated significantly, with major changes occurring during the last ice age and the subsequent warming period. However, the current rate of sea level rise is unprecedented.

Since 1890, the global average sea level has risen by approximately 21-24cm, a rate much faster than historical averages, according to the US National Oceanic and Atmospheric Administration. This rapid increase is largely attributed to human-

Understanding past sea level rise and its historical context is essential for predicting future changes and developing effective adaptation strategies.

By studying historical data, scientists can better understand the natural variability of sea levels and the extent to which current trends are influenced by human activities.

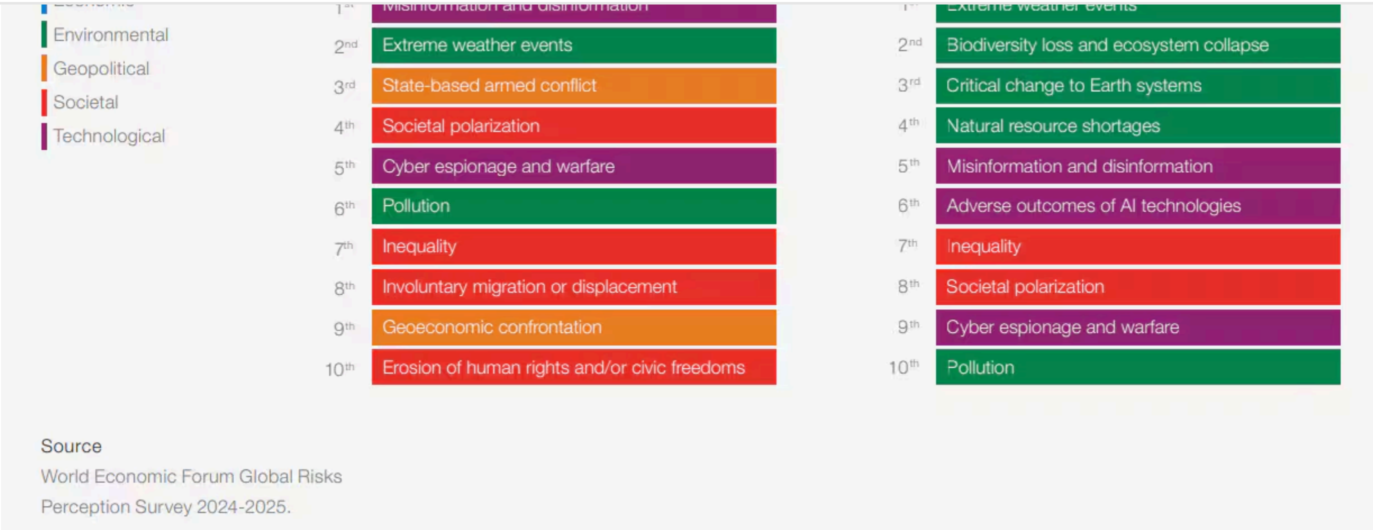
Which countries will be most affected by rising sea levels?

Bangladesh, China, India and the Netherlands were singled out by the UN in 2023 as being at high risk from rising sea levels, with nearly 900 million people living in low-lying coastal areas in acute danger.

NASA says the East Coast and Gulf Coast of the US, as well as Asia and islands, are at high risk from the rising ocean. But it's not just the changing sea level that's a threat, it says. "Storm surges are amplified by sea-level rise, causing them to hit higher water levels and allowing the surges to reach farther inland".

According to Reuters, sea levels around Tonga are rising at almost twice the global average rate. In Europe, sea level rise is expected to go above 10cm "prior to 2050", says the European Environment Agency.

While research in the US has found that almost 1,100 critical buildings in coastal communities could be at risk of monthly flooding by 2050. Some communities could become unliveable within two to three decades, the report says.



Sea level rise is one of the 'Critical changes to Earth systems' - the third-highest threat to the world in the coming decade. Image: World Economic Forum

How are areas at risk of rising sea levels adapting?

Developed nations need to double climate adaptation finance to at least $40 billion a year, according to the Glasgow Climate Pact. But even if this was achieved, the adaptation finance gap of $187-359 billion per year would only be reduced by 5%, says the United Nations Environment Programme.

In the meantime, countries and cities around the world are putting strategies into action. In New Zealand, climate adaptation policies are being designed to ensure public housing is not built near areas prone to climate hazards.

Sea walls, surge barriers and other coastal defences are being built and strengthened in several countries including Denmark, Germany and the United Kingdom.

South Korea and the islands of the Maldives in the Indian Ocean are erimenting with floating homes, while China, India and other nations are ding ways to absorb and store storm water for reuse.

The Guardian reports.

What are the 'positive tipping points' tha

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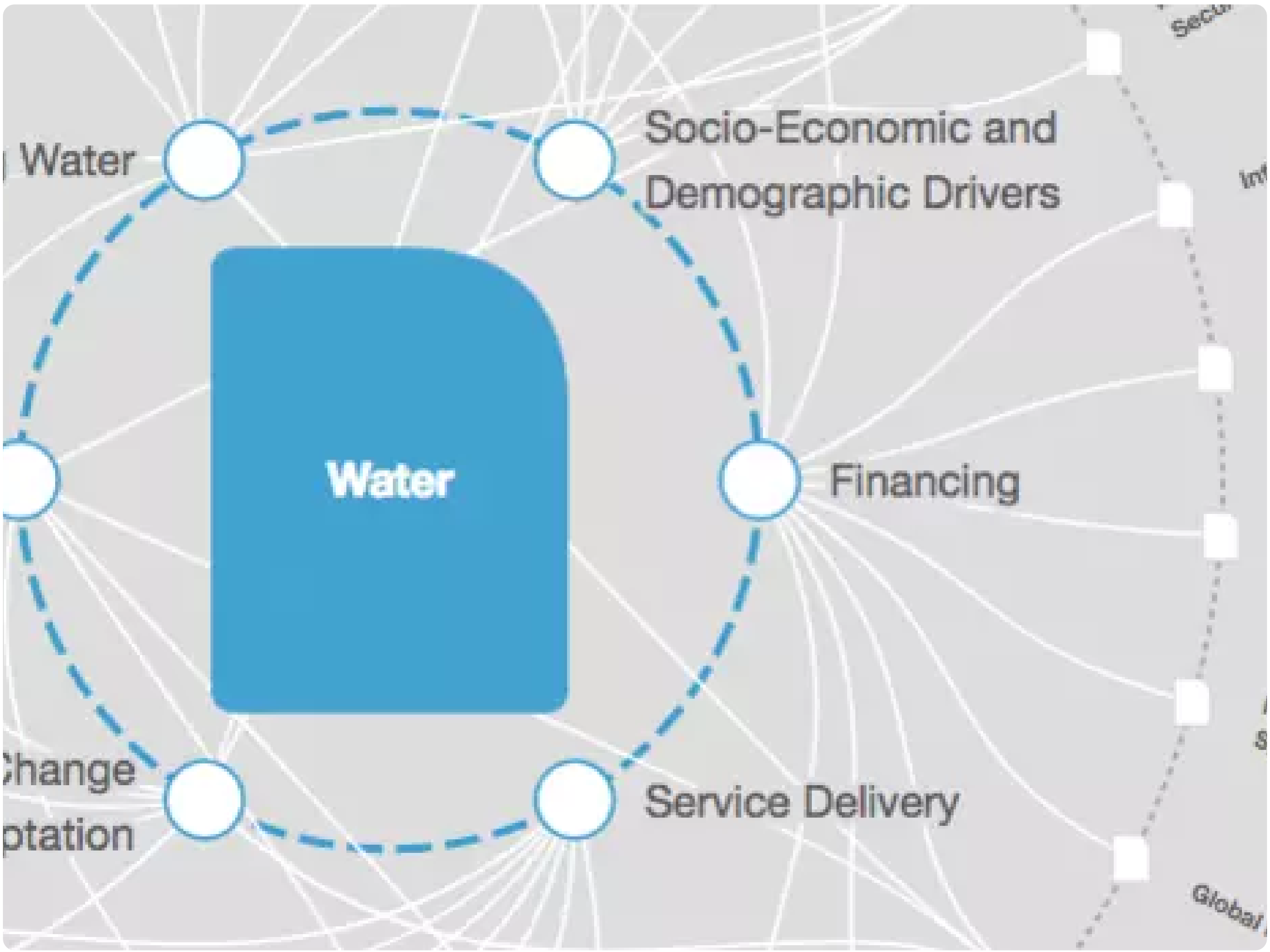

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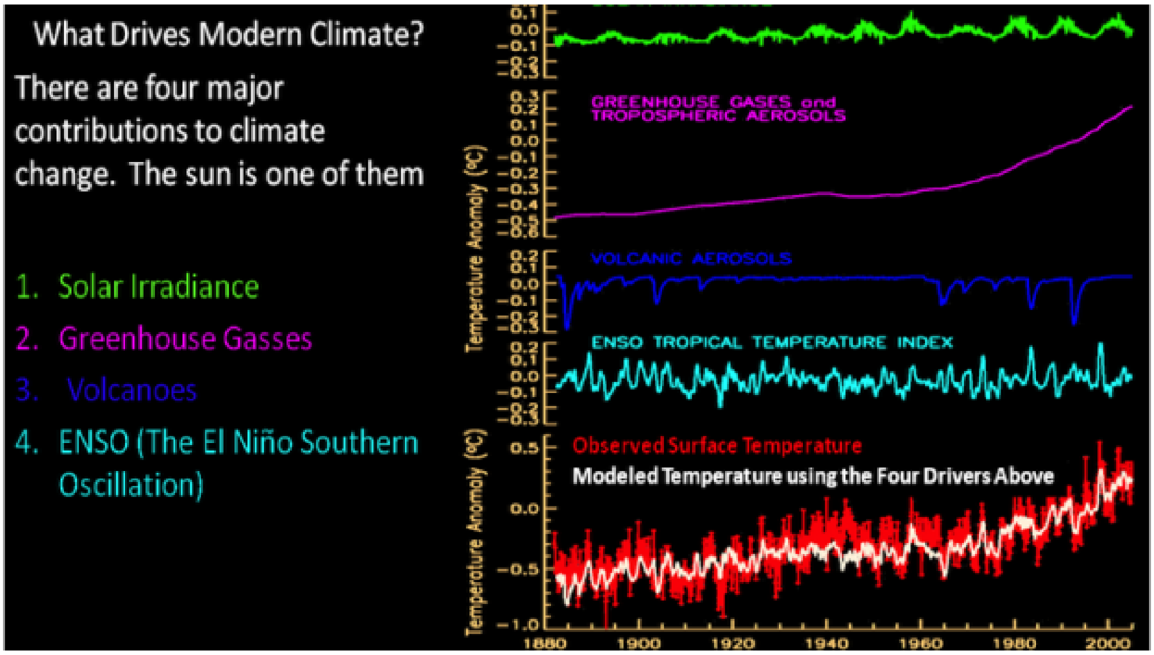

SPACE WEATHER IMPACTS ON CLIMATE

All weather on Earth, from the surface of the planet out into space, begins with the Sun. Space weather and terrestrial weather (the weather we feel at the surface) are influenced by the small changes the Sun undergoes during its solar cycle.

The most important impact the Sun has on Earth is from the brightness or irradiance of the Sun itself. The Sun produces energy in the form of photons of light. The variability of the Sun's output is wavelength dependent; different wavelengths have higher variability than others. Most of the energy from the Sun is emitted in the visible wavelengths (approximately 400 – 800 nanometers (nm)). The output from the sun in these wavelengths is nearly constant and changes by only one part in a thousand (0.1%) over the course of the 11-year solar cycle.

At Ultraviolet or UV wavelengths (120 – 400 nm), the solar irradiance variability is larger over the course of the solar cycle, with changes up to 15%. This has a significant impact on the absorption of energy by ozone and in the stratosphere. At shorter wavelengths, like the Extreme Ultraviolet (EUV), the Sun changes by 30% - 300% over very short timescales (i.e. minutes). These wavelengths are absorbed in the upper atmosphere so they have minimal impact on the climate of Earth. At the other end of the light spectrum, at Infrared (IR) wavelengths (800 – 10,000 nm), the Sun is very stable and only changes by a percent or less over the solar cycle.

The total wavelength-integrated energy from sunlight is referred to as the Total Solar Irradiance (TSI). It is measured from satellites to be about 1365.5 Watts/m2 at solar minimum to 1366.5 Watts/m2 at solar maximum. An increase of 0.1% in the TSI represents about 1.3 Watts/m2 change in energy input at the top of the atmosphere. This energy is scattered, reflected, and absorbed at various altitudes in the atmosphere, but the resulting change in the temperature of the atmosphere is measurable. It should be noted that the change in climate due to solar variability is likely small, but more research needs to be done.

There are other types of space weather that can impact the atmosphere. Energetic particles penetrate into the atmosphere and change the chemical constituents. These changes in minor species such as Nitrous Oxide (NO) can have long lasting consequences in the upper and middle atmosphere, however it has not been determined if these have a major impact on the global climate of Earth.

The duration of solar minimum may also have an impact on Earth's climate. During solar minimum there is a maximum in the amount of Cosmic rays, high energy particles whose source is outside our Solar system, reaching earth. There is a theory that cosmic rays can create nucleation sites in the atmosphere which seed cloud formation and create cloudier conditions. If this were true, then there would be a significant impact on climate, which would be modulated by the 11-year solar cycle.

Phenomena:

Solar EUV Irradiance

Galactic Cosmic Rays

Total Electron Content

Sunspots/Solar Cycle

Tags:

phenomena

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associate professor at the faculty of
Civil Engineering and Geosciences

TU Delft researchers: sea level rise along Dutch coastline accelerating

NEWS - 28 JUNE 2022 - WEBREDACTIE COMMUNICATION

Sea level rise along the Dutch coastline is accelerating. This is the conclusion of a new study carried out by researchers at TU Delft. A detailed analysis of the measurements at eight tidal stations along the Dutch coastline (including stations located at Maassluis, Delfzijl and Vlissingen) makes it clear that the average sea level rise – since the mid-1990s – has been 2.7 ± 0.4* millimetres per year. In comparison to the 70 proceeding years, this represents a significant increase of 1.0 ± 0.5 mm/year.

This is the first time that a significant acceleration was discovered in the data from tidal stations alongside the North Sea. However, the acceleration measured differs per station. For example, sea level rise is increasing twice as quickly in the Wadden Sea. Riccardo Riva, who in his day-to-day life carries out research into the interaction between the dynamic behaviour of the earth and sea level change, explains this as follows: ‘Measurements of the sea level at a tidal station – when viewed over the entire year – show quite large fluctuations. This is due to various factors such as the influence of wind, atmospheric pressure, and tides. Taking this into consideration, we developed a new method that utilises information about wind, pressure and tides. This enabled us to correct the measurements for “background noise” and to isolate the long-term oceanographic signal.’

A detailed analysis of the measurements at eight tidal stations along the Dutch coastline makes it clear that the average sea level rise – since the mid-1990s – has been 2.7 ± 0.4 millimetres per year. The findings of Riccardo Riva and colleagues were published in the leading journal Environmental Research Letters. The photo shows Riccardo Riva at the tidal station in Hoek van Holland.*

Dr. Riccardo Riva

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Civil Engineering and Geosciences

New method

Riva and colleagues applied the method to measurement series of 100 years. At the same time, they showed that it was possible to identify an acceleration in shorter series of at least 40 years if the measurement series continues for 20 years after the acceleration begins. Riva: 'The acceleration value depends in principle on the length of your analysis period, and is therefore rather arbitrary. That is also why, at a certain moment, we started searching for a "breakpoint", a sudden change in the behaviour of sea level change. Our search identified 1993 as such a point. In our research, we calculated the trend before as well as after this breakpoint. This demonstrated – for the first time – that the change in the sea level rise acceleration is larger than the (95%) confidence interval of both speeds (before and after the breakpoint). This is an interesting finding, since the period concerned is approximately 30 years. And that is also exactly the minimum length of time on the basis of which climate trends are determined.'

Mystery

The fact that sea level is rising is not new. Sea level has risen by approximately 13 cm over the 20th century. This rise measured can be explained in large part by the loss of mass from Greenland and glaciers in polar regions and the thermal expansion of the oceans. The latter is caused by the fact that the upper layer of water expands due to the increase in air temperature. As a result, the distance between the molecules of water increases. 'However', explains researcher Riva, 'an average global sea level rise does not, in itself, say all that much about the increase along our coastline. People tend to think that everything moves together, but a large part of the changes along the coast are caused by ocean currents. And what happens elsewhere in the ocean does not always have an effect on our small part of the North Sea. In principle, all kinds of things can take place here. So the question that intrigued us the most was: *What do we actually see happening along the Dutch coastline?'*

Eight tidal stations

To answer this question, Riva and colleagues started – at the end of 2019 – to study the measurement data from eight different tidal stations: at Vlissingen, Maassluis, Hoek van Holland, IJmuiden, Den Helder, Harlingen, Delfzijl and Cuxhaven (Germany). So why was Riva's research group the first one in the world to adopt this approach? Riva: 'Our research community is not very big. In addition, nowhere else in the world can you find such a good set of data. You have to realise that all eight tidal stations are more than 100 years old. And nowhere else in the world can you find so many stations at such a short distance from each other, together with an uninterrupted series of measurements, without any holes, over the last 100 years. That is simply not available elsewhere in the world.'

Cause for concern

Until now, it was not clear whether the sea level along our coastline is actually rising more quickly than in the previous century. Riva and colleagues have put an end to this uncertainty. Should we now be concerned? 'That is more a question for politicians', says Riva. 'However, I would advise other low-lying areas in the world to purchase measuring equipment as soon as possible and to carry out long-term measurements. After all, accurate information about the rate of our sea level rise is of crucial importance. It is crucial for the short term, for example with regard to the sand suppletion activities along the Dutch coastline, supplying extra sand to the beach or see bottom, as well as for the long term, whereby we have to take appropriate measures to protect our coastal areas against the effects of sea level rise.'

**) All uncertainties are calculated on the basis of 95% confidence intervals*

More information

If you have any questions about the acceleration of the sea level rise along the Dutch coastline or the acceleration of the energy transition, please feel free to contact:

- Dave Boomkens, media relations officer for the Energy transition TU Delft – [redacted]@tudelft.nl / [redacted]
- Dr. Riccardo Riva, associate professor at the faculty of Civil Engineering and Geosciences – [redacted]@tudelft.nl

Via this story you can read more about Riccardo Riva, who carries out research into the effects of moving water masses from one place to another.

And here you can read about the research based on an analysis of the measurements at eight tidal stations, which was just published in the leading journal Environmental Research Letters.

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