



Sea-level rise in Denmark: paleo context, recent projections and policy implications

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Abstract

We present the most recent Intergovernmental Panel on Climate Change Sixth Assessment Report (AR6) sea-level projections for four Danish cities (Aarhus, Copenhagen, Esbjerg and Hirtshals) under the Shared Socioeconomic Pathway (SSP) family of climate scenarios. These sea-level changes projected over the next century are up to an order of magnitude larger than those observed over the previous century. At these cities, year 2150 sea-level changes of between 29 and 55 cm are projected under the very low emissions scenario (SSP1-1.9), whilst changes of between 99 and 123 cm are projected under the very high emissions scenario (SSP5-8.5). These differences highlight the potentially significant impact of remaining opportunities for climate change mitigation. Due to this increase in mean sea level, the mean recurrence time between historically extreme events is expected to decrease. Under the very high emissions scenario, the historical 100-year storm flood event will become a 1- to 5-year event at most Danish harbours by 2100. There is considerable uncertainty associated with these sea-level projections, primarily driven by uncertainty in the future evolution of the Antarctic ice sheet and future steric dynamic changes in ocean volume. The AR6 characterises collapse of the West Antarctic ice sheet as a low-probability but high-impact event that could cause several metres of sea-level rise around Denmark by 2150. In climate adaptation policy, the scientific landscape is shifting fast. There has been a tremendous proliferation of diverse sea-level projections in recent years, with the most relevant planning target for Denmark increasing c. 50 cm in the past two decades. Translating sea-level rise projections into planning targets requires value judgments about acceptable sea-level risk that depend on local geography, planning timeline and climate pathway. This highlights the need for an overarching national sea-level adaptation plan to ensure municipal plans conform to risk and action standards.

Introduction

Future sea-level rise, which threatens coastal populations, ecosystems and infrastructures around the world, is highly dependent on society's choice of future climate pathway (Nauels *et al.* 2017). Denmark is a relatively low-lying nation — approximately 24% of the country lies within 10 m of sea level — with over 7000 km of coastline (Fig. 1). Presently, approximately 17% of the Danish population lives within 6 m of sea level (Fryd & Jørgensen 2020). This proportion is expected to increase with future population growth focused in coastal cities. The Danish coastline is dynamic and has been dramatically shaped by changes in sea level and sediment transport over the past 2000 years. In northern Jylland, at Skagen, relative sea level has fallen c. 4 m in the past two millennia (Hauerbach 1992; Clemmensen *et al.* 2001). In central Denmark, near Aarhus, as well as offshore in Kattegat and Øresund, relative sea level has fallen <1 m during the past 2000 years (Bennike *et al.* 2012, 2021; Clemmensen *et al.* 2012; Hede *et al.* 2015). In western Jylland, near Esbjerg, however, relative sea

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Abbreviations:

AR6: Sixth Assessment Report

CMIP6: Coupled Model Intercomparison Project Phase 6

DVR90: 1990 Danish Vertical Reference System

IPCC: Intergovernmental Panel on Climate Change

MIS: Marine Isotope Stage

PSMSL: Permanent Service for Mean Sea Level

RCP: Representative Concentration Pathway

SSP: Shared Socioeconomic Pathway

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Fig. 1 Overview map of Denmark with place names referred to in the text. Shaded areas designate areas below specified elevations, regardless of whether they have a direct connection to the ocean. This highlights potentially vulnerable areas, should the coastal barrier be breached. The digital elevation map is obtained from the Danish Agency for Data Supply and Infrastructure.

level has conversely risen c. 1.5 m during the same time (Gehrels *et al.* 2006; Szkornik *et al.* 2008). These contrasting relative sea-level changes, reconstructed over the past two millennia, primarily reflect spatial variations in the glacial isostatic adjustment of Earth's crust associated with deglaciation of the Scandinavian ice sheet. On longer timescales, the magnitude of sea-level change is even larger, reflecting absolute

increases in ocean volume and elevation associated with the deglaciation of land ice. Reconstructed sea-level curves indicate >30 m of local sea-level rise at several Danish sites during the mid-Holocene, between 12 000 and 6000 years ago (Bennike & Jensen 2011; Bennike *et al.* 2012, 2019, 2021). Coastal currents and associated sediment transport around Denmark play a major role in shaping the present-day

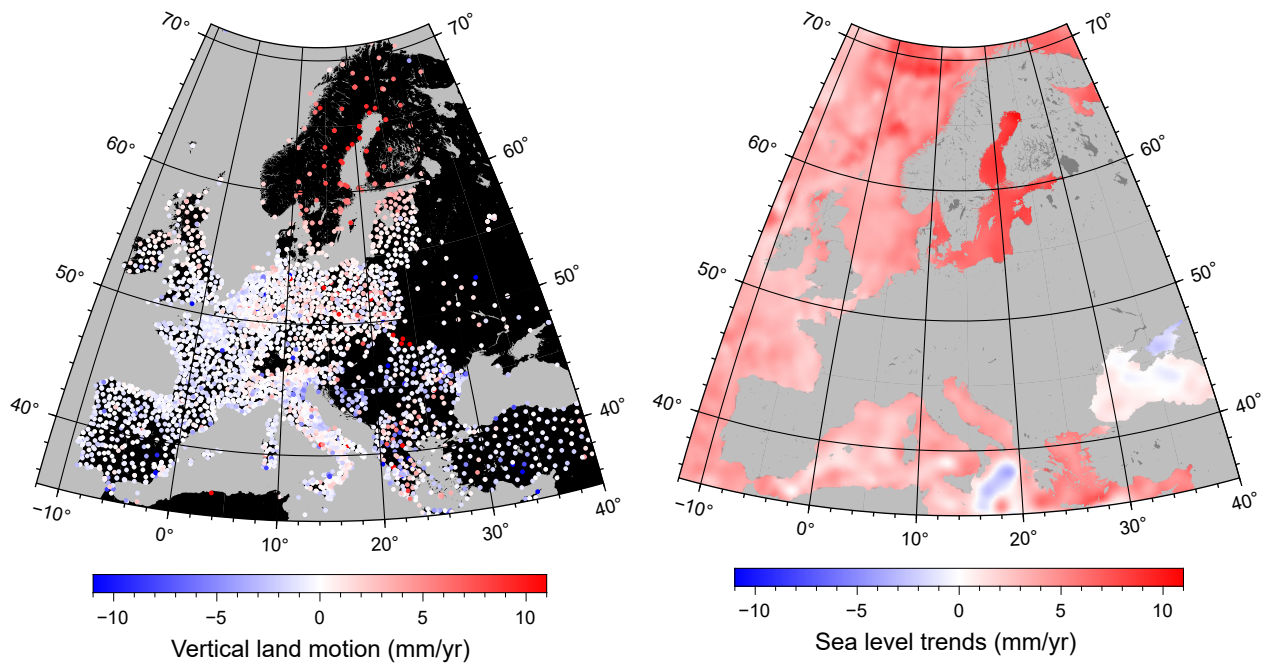


Fig. 2 Trends in European ocean and land elevation between January 1993 and December 2020. Left: Vertical land motion trend observed at fixed global positioning system sites (updated from Hammond *et al.* 2021). Right: Sea-level elevation trend observed from satellite radar altimetry (updated from Nerem *et al.* 2018).

shoreline (Kabuth *et al.* 2014). This underlines a complex history of sea-level change and shoreline position in Denmark.

Global sea level is now once again highly dynamic and increasing, in response to anthropogenic climate change. The rate of 21st century sea-level rise is expected to be faster than that for previous warm Holocene intervals, such as the Medieval Warm Period (c. 1000 to 1300 CE) and the Holocene Thermal Maximum (c. 6000 to 4000 BCE; Gehrels & Shennan 2015; Kaufman *et al.* 2020). Paleo studies also infer a consistently high sensitivity of global sea-level rise to atmospheric warming (Levermann *et al.* 2013). Specifically, global sea level was at least 6 m higher than present day during the last interglacial (Eemian; Marine Isotope Stage (MIS) 5e) when atmospheric temperatures were at least 1°C warmer than pre-industrial temperatures (Dutton *et al.* 2015). The rate of forthcoming Anthropocene sea-level rise may be comparable to some of the fastest periods of sea-level rise in the past 12 000 years (Weaver *et al.* 2003). Since 1993, global mean sea level has already risen 8 ± 1 cm (WCRP Global Sea Level Budget Group 2018). An acceleration in sea-level rise since 1993 is now readily detectable within the global satellite altimetry record, as well as within North Sea tide gauge data (Nerem *et al.* 2018; Steffebauer *et al.* 2022). There is tremendous spatial variability in recent vertical land motion and sea-level change across Europe (Fig. 2). There is a pronounced east-west trend in sea-level change across Scandinavia, with sea levels

in the Gulf of Bothnia rising twice as fast as those in the North Sea (Colgan *et al.* 2019).

The processes influencing recent and future sea-level changes at a specific city are complex. They include larger-scale processes, such as the transfer of land ice into the ocean, the thermal expansion of seawater and shifts in oceanic and atmospheric currents, as well as smaller-scale processes, such as vertical land motion and the redistribution of water masses (Nauels *et al.* 2017). Consequently, projected sea-level changes are globally non-uniform, and they vary from city to city (Jevrejeva *et al.* 2016). Here, we examine both the instrumental record of observed sea-level change and the sea-level change projected by the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), at four Danish cities (Holgate *et al.* 2013; Fox-Kemper *et al.* 2021). Our aim is to provide policy-relevant insight on local sea-level budgets that resolve all sea-level components, and their associated uncertainties, under the IPCC AR6 Shared Socioeconomic Pathway (SSP) climate scenarios. These scenarios have five fundamental storylines (O'Neill *et al.* 2020; Fig. 3). SSP1 characterises a 'sustainable' future with very low to low emissions and low challenges associated with climate change adaptation and mitigation. SSP2 characterises a 'middle of the road' future with intermediate emissions and challenges. SSP3 characterises a 'rocky road' with high emissions and challenges associated with growing regional rivalries. SSP4 characterises a future of 'inequality' and high emissions arising from clear regional pathways

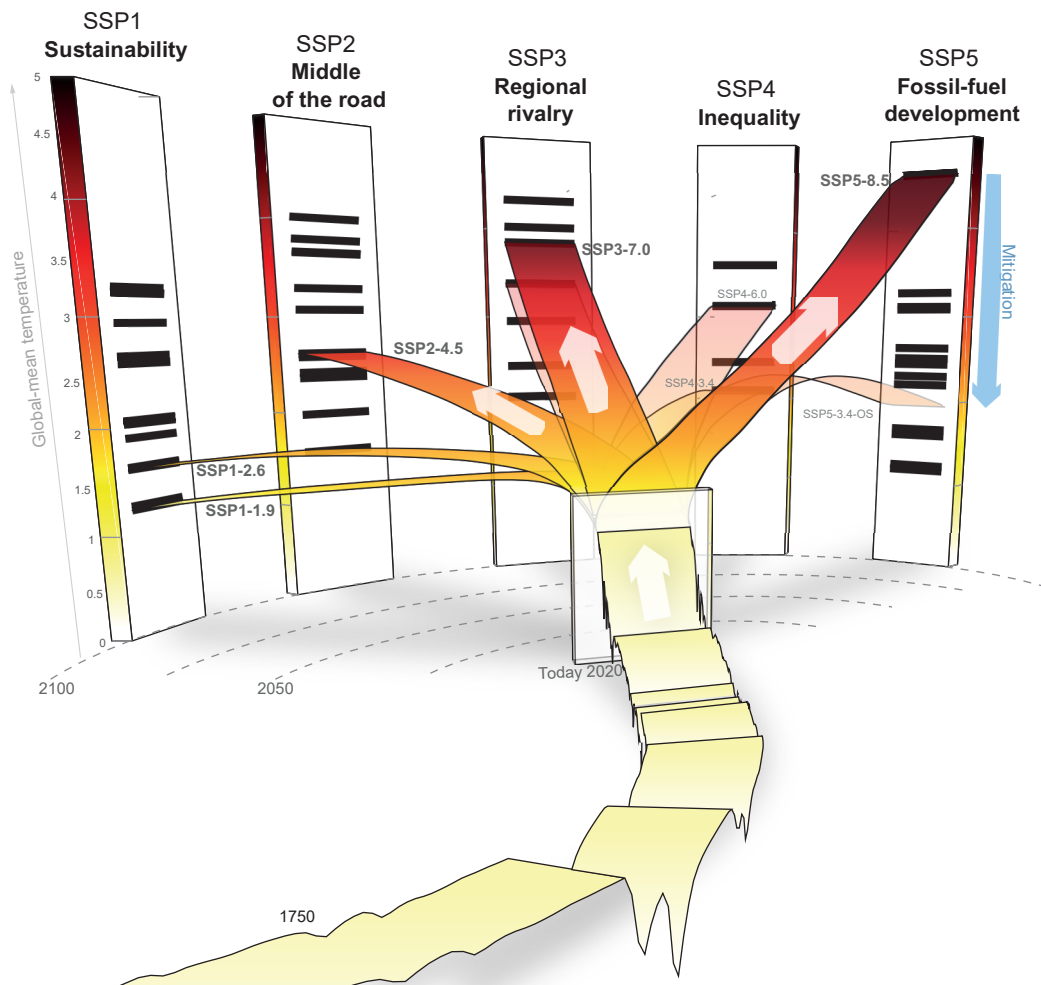


Fig. 3 The five SSP storylines with global-mean temperature illustrated relative to pre-industrial levels. The historical temperatures branch into the respective five SSP scenarios over the 21st century. The small black horizontal bars on the 2100 pillars for each SSP indicate illustrative temperature levels. The opaque bands over the 21st century indicate the five SSP scenarios SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 that are explored in this study. Other scenarios (SSP4-6.0, SSP4-3.4 and SSP5-3.4-OS) are not explored in this study. Modified slightly from Meinshausen *et al.* (2020).

dominated by adaptation challenges. Finally, SSP5 characterises a future taking the fast road of ‘fossil-fuel development’ and very high emissions dominated by mitigation challenges. These storylines incorporate broad assumptions about underlying social demographics and offer a wide range of future climates, including multiple alternative pathways to the same climate forcing (Fig. 3; Meinshausen *et al.* 2020). The differences in sea-level rise projected under this range of scenarios highlight the significant impact of remaining opportunities for climate change mitigation.

Methods

We employ sea-level projections made available through the IPCC AR6 Sea-Level Projection Tool at <https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool> (Fox-Kemper *et al.* 2021; Garner *et al.* 2021). The AR6 makes sea-level projections for Permanent Service for Mean Sea Level (PSMSL) reporting stations around the world

(Holgate *et al.* 2013). Within Denmark, four PSMSL stations are available: Aarhus (station 76), Esbjerg (station 80), Copenhagen (station 82) and Hirtshals (station 89; Fig. 1). AR6 selected these four stations from the 14 available PSMSL stations within Denmark to ensure globally homogeneous coverage that is representative of spatial variations in vertical land motion (Hansen 2018). At each of these four stations, the sea-level projection is estimated every 10 years between 2020 and 2150 using a local multi-component sea-level budget. The six components of this budget are (1) steric ocean-volume changes, (2) the Antarctic ice sheet, (3) the Greenland ice sheet, (4) mountain glaciers, (5) vertical land motion and (6) changes in land-water storage. Sea-level projections are made under five illustrative SSP scenarios: SSP1-1.9 (very low emissions), SSP1-2.6 (low emissions), SSP2-4.5 (intermediate emissions), SSP3-7.0 (high emissions) and SSP5-8.5 (very high emissions).

The AR6 provides relative sea-level projections as height changes relative to a 2005 baseline. We translate

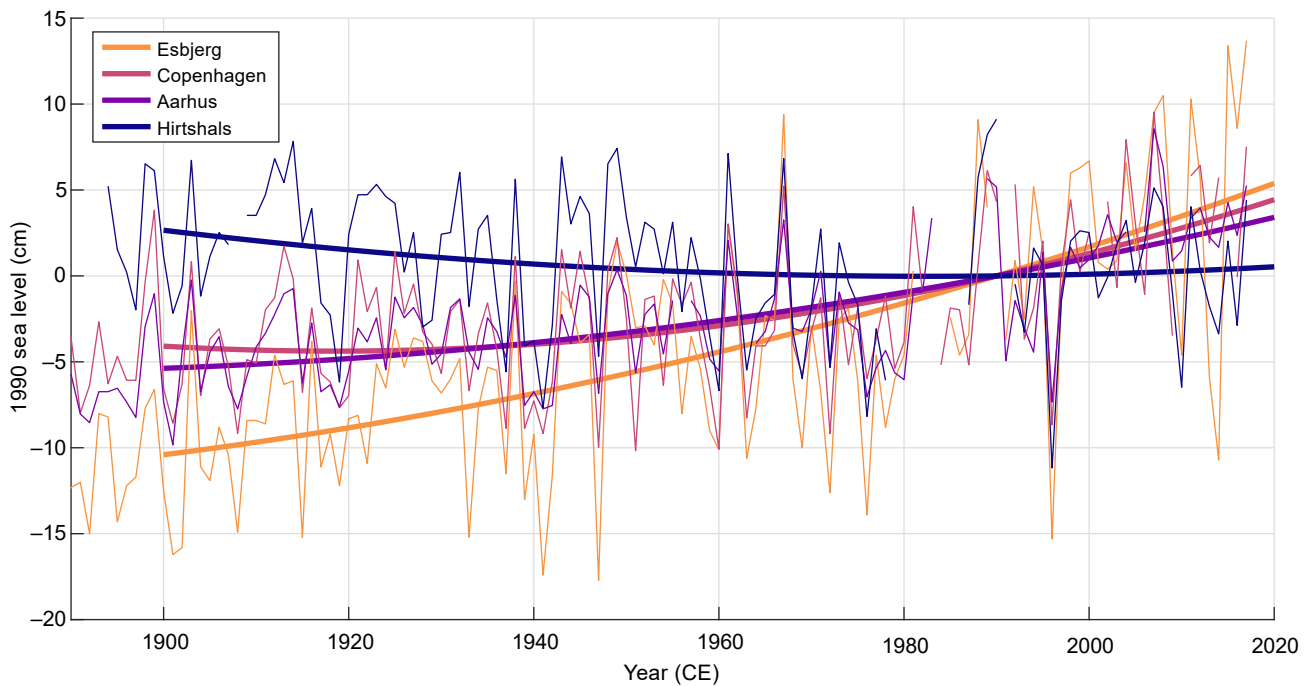


Fig. 4 Permanent Service for Mean Sea Level (PSMSL) records of sea-level elevation relative to 1900 at four Danish sites (Holgate *et al.* 2013). Thick lines are second-order polynomial fits that ignore missing data. These polynomial fits are used to correct the 2005 baseline of AR6 sea-level projections to the 1990 baseline of the Danish Vertical Reference System (DVR90).

these sea-level changes to a 1990 baseline by fitting a second-order polynomial curve to the mean annual sea-level elevation observed at each PSMSL station between 1900 and 2020. Our polynomial curve fitting ignores years with no data. Our polynomial approach deviates from the prevailing Danish Coastal Authority approach of applying linear best fit to historical data, which may cause small discrepancies in reported historical sea-level change (Ditlevsen *et al.* 2019). We estimate the change in sea-level baseline between 1990 and 2005 by differencing the respective annual values of our polynomial fit. This yields 2005 to 1990 baseline corrections to the AR6 relative sea-level changes of +0.2 cm at Hirtshals, +1.6 cm at Aarhus, +2.0 cm at Copenhagen and +2.6 cm at Esbjerg (Fig. 4). Translating these relative projections into absolute sea-level elevation in the standard 1990 Danish Vertical Reference system (DVR90) requires a further correction that reflects the offset between the 1990 baseline sea level and the reported DVR90 elevation for each station (Table 1). Aside from using a polynomial, rather than linear best fit, this DVR90 conversion conforms to the Danish Coastal Authority approach for linking local DVR90 datum to local sea-level elevation (Kystdirektoratet 2018).

Results

The PSMSL records at Aarhus, Esbjerg, Copenhagen and Hirtshals reveals a spatially complex pattern of sea-level change over the 1900–2020 period, even within the

Table 1 Year 1990 elevations of four Danish stations (PSMSL identification number in parentheses) in the 1990 Danish Vertical Reference System (DVR90).

Station	DVR90 (cm)
Aarhus (station 76)	6.0
Esbjerg (station 80)	20.1
Copenhagen (station 82)	10.9
Hirtshals (station 89)	1.1

relatively limited size of Denmark (Fig. 4). Hirtshals and Esbjerg are clear end members for this sea-level change. At Hirtshals, the relative sea level has fallen very slightly since 1900 (-2 ± 2 cm). At Esbjerg, by contrast, the relative sea level has increased sharply since 1900 ($+16 \pm 2$ cm). The distance between these two PSMSL sites is only c. 255 km. This sharp gradient in recent sea-level change is ultimately associated with the complex pattern of glacial isostatic adjustment following the relatively rapid deglaciation of the Scandinavian ice sheet, with Denmark becoming ice-free c. 16 000 years ago (Houmark-Nielsen & Kjær 2003). At Esbjerg, the Earth's crust is presently subsiding due to the collapse of the crustal forebulge that once ringed the Scandinavian ice sheet, whilst at Hirtshals, the crust is presently rebounding upwards due to ice unloading (Steffen & Wu 2011). The post-1900 sea-level changes at Copenhagen and Aarhus, both $+9 \pm 2$ cm, lie between these end members.

The inter-city differences in observed sea-level change are also generally reflected in the projected sea-level

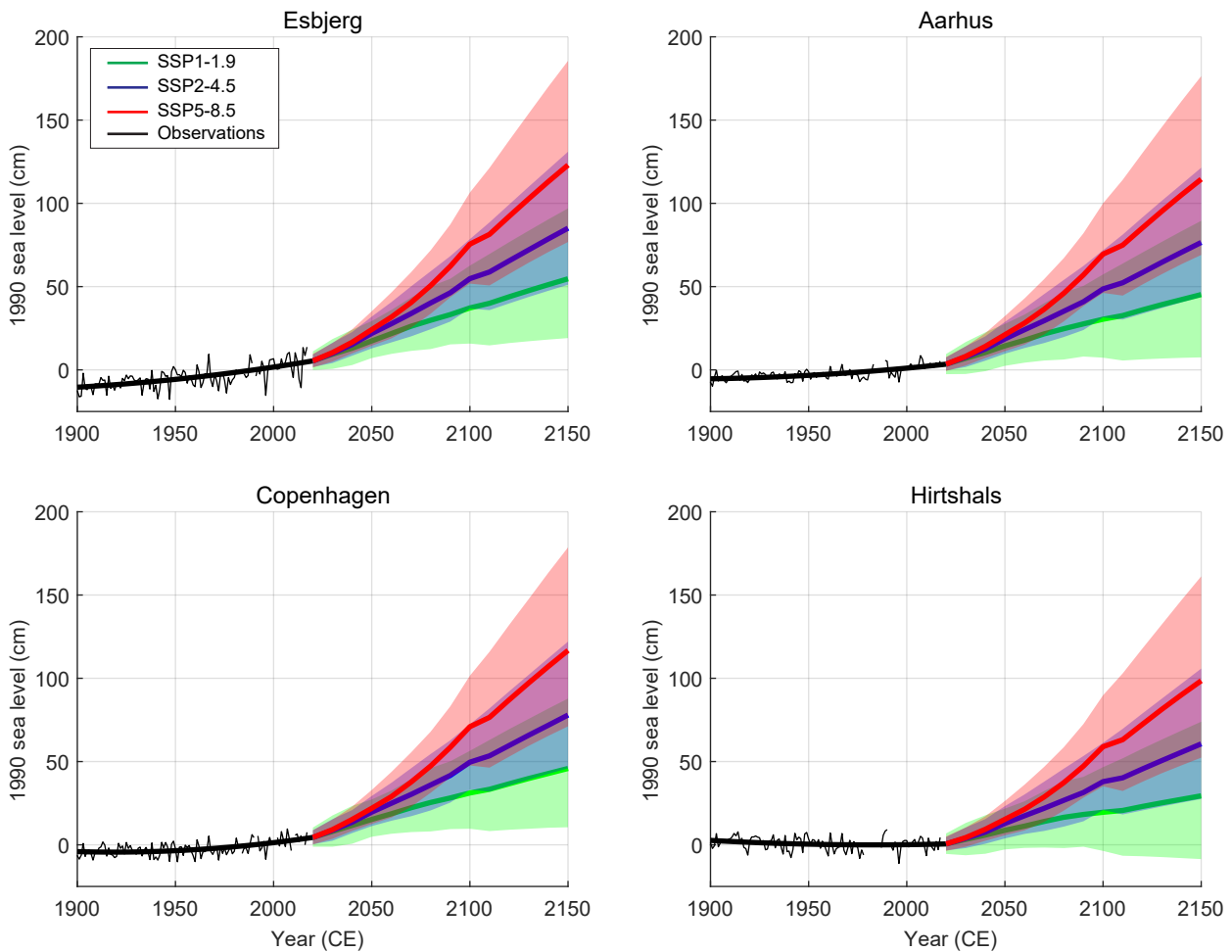


Fig. 5 Permanent Service for Mean Sea Level (PSMSL) observed sea-level change (1900–2020; Holgate *et al.* 2013) and AR6 projected sea-level change (2020–2150; Fox-Kemper *et al.* 2021) at four Danish cities, expressed relative to a 1990 baseline. Shaded areas denote the uncertainty associated with each projection. The SSP1-2.6 and SSP3-7.0 projections are omitted for clarity but appear tabulated in Table 2. The c. 2100 ‘bumps’ in projections are a known artifact associated with a decrease in available CMIP6 (Coupled Model Intercomparison Project Phase 6) simulations after 2100, in comparison to before 2100.

changes (Fig. 5). There can be, however, a non-physical inflection of observed and projected sea-level changes at the year 2020 observation-model transition. This is perhaps most evident at Hirtshals and likely results from vertical land motion not being treated consistently between observations and projections. Under all climate scenarios, the projected sea-level rise is systematically c. 25 cm higher at Esbjerg than at Hirtshals. This difference in sea-level rise associated with geography, however, is clearly smaller than the c. 70 cm difference associated with choice of climate scenario. Simply put, whilst presently non-trivial, with increasing warming, the vertical land motion component of sea-level change becomes small relative to the thermal expansion and cryospheric contributions to sea-level change. For example, at Aarhus, the year 2150 sea-level rise ranges from 45 (8–90) cm under the very low emissions scenario (SSP1-1.19) to 115 (69–176) cm under the very high emissions scenario (SSP5-8.5; Table 2). Here, the 90% confidence intervals indicate that there is a 95% chance that sea-level rise will be less than 90 cm under

SSP1-1.9 and less than 176 cm under SSP5-8.5. Clearly, however, the sea-level changes observed over the past century are an order of magnitude smaller than the sea-level changes expected over the next century.

Table 2 presents summary statistics to explicitly address four distinct elements of planning for sea-level change in Denmark. First, as discussed earlier, projected sea-level rise varies by location. Second, projected sea-level rise varies by year, or planning timeline, of interest. Third, projected sea-level rise varies with the choice of climate scenario. Finally, and perhaps most importantly, interpreting the appreciable 90% confidence uncertainty is ultimately a risk assessment. AR6 assesses the uncertainty associated with its sea-level projections based on ensemble spread, in both higher-complexity simulations and lower-complexity emulations, as well as structured expert judgment. Arguably, the most conservative approach for interpreting an upper-limit metric for sea-level rise planning is pessimistically assuming the very high emissions climate scenario (SSP5-8.5) with

Table 2 The sea-level changes, relative to a 1990 baseline, projected by the AR6 at four Danish cities under the five AR6 climate scenarios.

Climate scenario	Year	Esbjerg (cm)	Aarhus (cm)	Copenhagen (cm)	Hirtshals (cm)
SSP1-1.9	2050	17 (7–29)	14 (2–28)	15 (5–27)	9 (–3 to +22)
	2100	37 (16–63)	30 (7–57)	31 (10–56)	20 (–4 to +47)
	2150	55 (19–97)	45 (8–90)	46 (11–88)	29 (–9 to +74)
SSP1-2.6	2050	20 (11–30)	17 (7–27)	18 (9–28)	11 (1–22)
	2100	42 (23–65)	36 (18–58)	37 (19–58)	26 (8–48)
	2150	58 (26–99)	49 (21–87)	50 (21–87)	35 (5–73)
SSP2-4.5	2050	22 (13–32)	19 (10–29)	20 (11–29)	13 (4–23)
	2100	55 (37–78)	49 (32–72)	50 (33–72)	38 (21–61)
	2150	85 (51–131)	77 (44–121)	78 (46–122)	61 (28–106)
SSP3-7.0	2050	22 (12–32)	19 (9–29)	20 (10–30)	13 (3–24)
	2100	64 (42–92)	58 (36–86)	59 (38–86)	47 (26–75)
	2150	105 (64–159)	97 (55–150)	97 (58–150)	80 (39–134)
SSP5-8.5	2050	24 (15–35)	21 (11–32)	22 (13–33)	15 (6–26)
	2100	75 (52–106)	70 (46–100)	71 (48–102)	59 (35–90)
	2150	123 (77–186)	115 (69–176)	117 (71–179)	99 (52–161)

The 90% confidence interval is shown in parentheses. Within each city and climate scenario, projections are shown for 2050, 2100 and 2150. These relative changes can be translated into absolute DVR90 elevations by adding the city-specific corrections described in the methods.

the longest timeline (year 2150) and upper limit (95%) of the confidence interval. This yields upper limit metrics of +186 cm at Esbjerg, +179 cm at Copenhagen, +176 cm at Aarhus and +161 cm at Hirtshals. Conversely, the ambition of The Paris Agreement to limit climate change, combined with the need for nearer-term planning targets, can also justify the use of substantially lower planning metrics across Denmark. For example, assuming sea-level changes between +22 and +29 cm across all four cities, in the year 2050 under the SSP1-1.9 very low emissions scenario and 95% upper confidence limit. In short, translating the projections in sea-level rise presented here into planning targets requires making value judgements about the acceptable exposures and vulnerabilities to sea-level hazards that depend on geography, timeline and climate choices.

Discussion

Projection uncertainty

There are two main types of uncertainty associated with the AR6 sea-level projections (Fig. 6). The first type of uncertainty is the climate trajectory associated with the five AR6 climate scenarios: SSP1-1.9 (sustainability, very low emissions), SSP1-2.6 (sustainability, low emissions), SSP2-4.5 (middle of the road, intermediate emissions), SSP3-7.0 (regional rivalry, high emissions) and SSP5-8.5 (fossil-fuel development, very high emissions; O'Neill *et al.* 2020). These climate scenarios forecast how society's greenhouse gas emissions may evolve until 2150. Climate scenario uncertainty therefore clearly represents more of a social than physical uncertainty. Generally, however, the differences projected between scenarios highlight the significant impact of remaining opportunities for climate change mitigation. Simply put, society can still avoid substantial

future sea-level rise if we can divert from our current high-emissions climate pathway to a low-emissions climate pathway. The second type of uncertainty is the process-level uncertainty associated with each of the six components in the AR6 sea-level budget: (1) steric dynamic ocean-volume changes, (2) Antarctic ice sheet, (3) Greenland ice sheet, (4) mountain glaciers, (5) vertical land motion and (6) changes in global land-water storage. Both the magnitude and uncertainty of these latter two terrestrial processes are relatively small for all climate scenarios. Thus, terrestrial processes are not the main drivers of the sea-level changes projected around Denmark by the AR6. Next, we describe how other components of the sea-level rise budget influence Denmark.

The Greenland ice sheet contribution and associated uncertainty are an order-of-magnitude smaller than that of mountain glaciers across all five climate scenarios. This is perhaps counter-intuitive, as the Greenland ice sheet is a larger contributor to global mean sea-level rise than mountain glaciers. This apparent inversion, however, is an anticipated local consequence of shifting planetary gravity due to the redistribution of water and ice masses (Larour *et al.* 2017). Denmark is located within the regional gravitational weakening, and sea-level fall, associated with ice loss from Greenland. This makes the Greenland ice sheet contribution to sea-level rise disproportionately smaller around Denmark, in comparison to the global mean (Colgan *et al.* 2019). Denmark is conversely located well beyond the analogous regional gravitational weakening associated with Antarctic ice loss and, therefore, receives disproportionately more sea-level rise from the Antarctic, in comparison to the global mean. Danish sea-level projections therefore incorporate substantially more uncertainty associated with Antarctic ice loss, in comparison

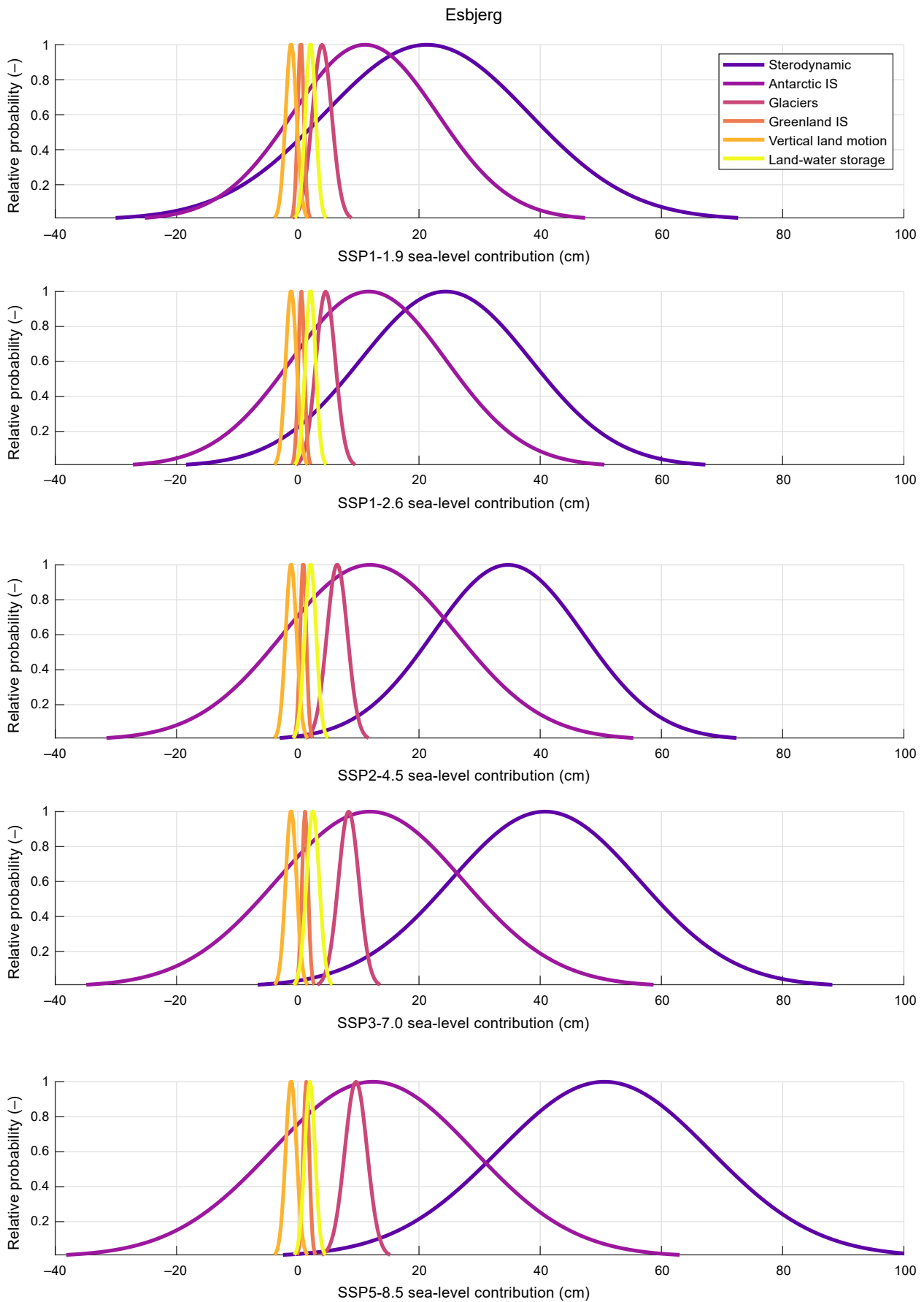


Fig. 6 Relative probability distributions of the six contributing terms for the 'medium confidence' year 2150 AR6 sea-level budget at Esbjerg (Fox-Kemper *et al.* 2021). The six components of sea-level change are shown under the five AR6 climate scenarios. The distributions shown here are broadly representative of other Danish cities.

to Greenland ice loss. Antarctic ice loss, which is a key source of uncertainty in both Danish and global projections, is discussed in Section 4.2.

There is also tremendous uncertainty associated with steric ocean-volume changes. These are the changes in ocean volume associated with the warming and expansion of ocean water, as well as the dynamic redistribution of ocean mass associated with changing currents. Across all climate scenarios, steric changes are one of the largest components within the AR6 sea-level budget, accounting for 30–40% of the total global sea-level rise, and within every climate scenario, there is substantial uncertainty (year 2150 standard deviation approximately ± 14 cm across the Danish sites; Fox-Kemper *et al.* 2021). Whilst the relation between water temperature and water density is well-known, and recent thermal expansion is well-observed, modelling the future thermal expansion of the ocean is challenging due to poor scientific understanding of how atmospheric heat is mixed into the near-surface ocean (Church *et al.* 1991; Zanna *et al.* 2019; Marti *et al.* 2022). So how deep will the ocean warm and expand due to spatially and temporally variable processes of downward heat advection and diffusion? The uppermost 700 m of the oceans has absorbed the vast majority of the anthropogenic climate energy associated with global warming since the industrial revolution, but how will the deeper oceans respond to future forcing? In the AR6 projections, the steric contribution is relatively large across all

climate scenarios, which reflects the substantial future thermal expansion committed by past global warming (Ehlert & Zickfeld 2018).

Ice-sheet collapse

Aside from steric ocean-volume changes, a second critical source of uncertainty in the AR6 projections is the Antarctic ice sheet contribution to sea-level rise. The projections described in Section 4.1 are regarded as ‘medium confidence’ by the AR6. This is a qualitative term used by the IPCC to convey medium validity based on the type, amount, quality and consistency of data. The AR6 also includes a ‘low confidence’ projection, which, by definition, conveys lower validity from underlying data that incorporates substantially higher near-term contributions from collapsing ice sheets. In comparison to the ‘medium confidence’ projection, which estimates a 5% chance of >230 cm of sea-level rise at Copenhagen in 2150, the ‘low confidence’ projection with additional ice-sheet collapse projects >450 cm at Copenhagen in 2150 (Fig. 7). Whilst the physical mechanisms associated with near-term ice-sheet collapse are qualitatively described, they are difficult to quantify in numerical models (Larour *et al.* 2021). The likelihood of such low probability, but high impact, events is, therefore, inherently difficult to assess beyond expert elicitation (Bamber *et al.* 2019).

The primary concern for ice-sheet collapse is the marine ice-sheet instability hypothesis, which fundamentally suggests that the retreat of glaciers grounded

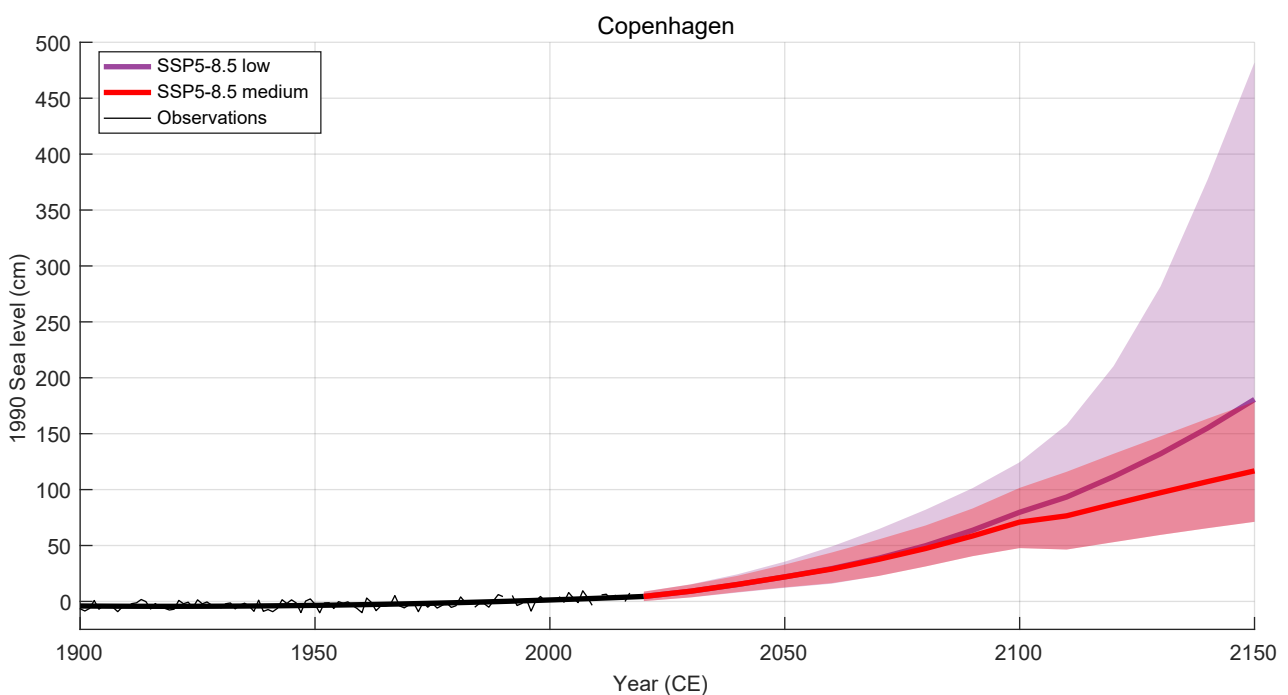


Fig. 7 AR6 SSP5-8.5 projections with ('low confidence') and without ('medium confidence') ice-sheet collapse at Copenhagen (Fox-Kemper *et al.* 2021). The projections shown here are broadly representative of other Danish cities.

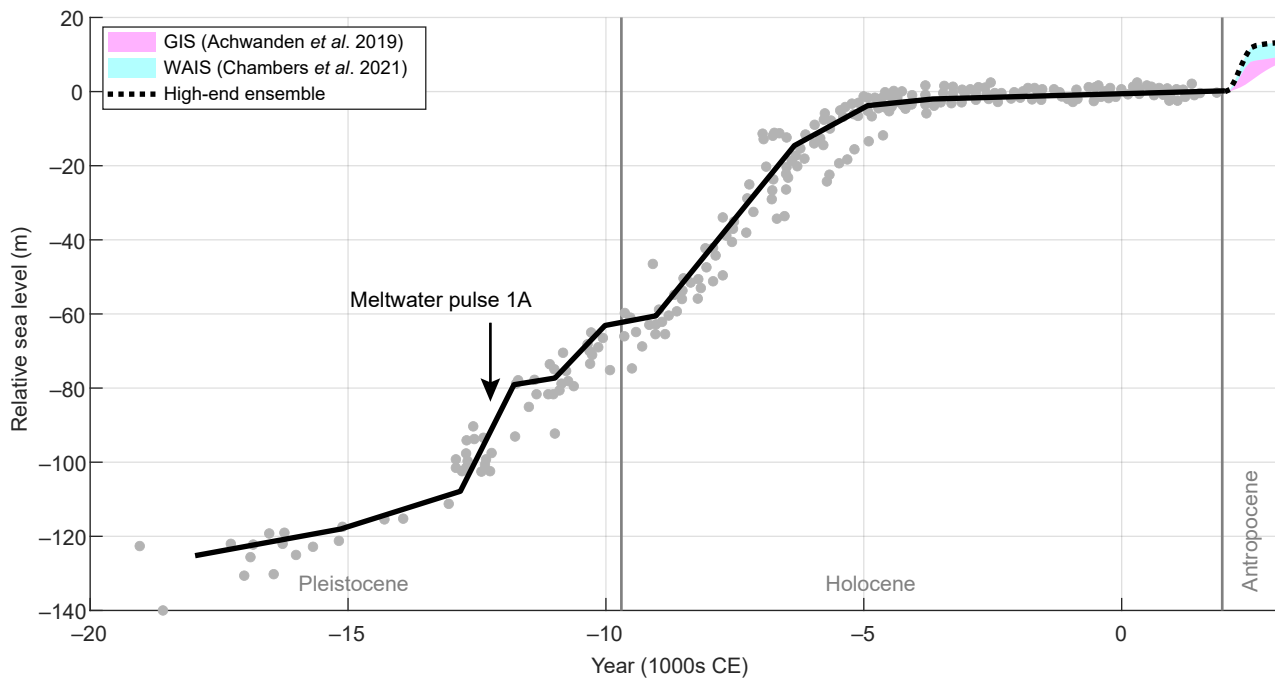


Fig. 8 Reconstruction of global mean sea-level since the Last Glacial Maximum, spanning the latter part of the Pleistocene and the Holocene, with the grey dots representing individual observations and black line representing trend after Fleming *et al.* (1998). Anthropocene high-emission (RCP8.5/SSP5-8.5) projections of Greenland ice sheet ('GIS'; Achswanden *et al.* 2019) and West Antarctic ice sheet ('WAIS'; Chambers *et al.* 2021) collapse are shown, ignoring associated sterodynamic effects, with the 'high-end' ensemble member denoted.

below sea level on retrograde bed slopes is irreversible on human time scales (Mercer 1978). For the West Antarctic ice sheet especially, which is largely grounded below sea level, this means that the retreat of major outlet glaciers can initiate a collapse of multi-metre sea-level equivalent over relatively short time scales (Bamber *et al.* 2009). There are growing observations of glacier retreat, thinning and acceleration that together suggest that a tipping-point threshold has been crossed, and ice-sheet collapse is already underway in the Amundsen Sea sector of West Antarctica (Joughin *et al.* 2014; Rignot *et al.* 2014; Voosen 2021). In a recently structured expert judgment from 23 global sea-level researchers, 5% of respondents expected West Antarctica's sea-level contribution over the 21st century to track a 'high-end' (i.e. high emissions) contribution consistent with marine ice-sheet instability (Bamber *et al.* 2019).

In the longer term, numerical ice-sheet projections under an SSP5-8.5 very high emissions scenario suggest that both the Greenland and Antarctic ice sheets are poised to deliver multi-metre sea-level rise for centuries to come (Fig. 8; Achswanden *et al.* 2019; Chambers *et al.* 2021). More specifically, the 'high-end' ensemble members within these projections suggest that complete loss of the Greenland ice sheet (c. 7.2 m sea-level equivalent) and West Antarctic ice sheet (c. 3.3 m sea-level equivalent) is possible by c. 2500 with

currently included model processes. This would raise global mean sea level by >10 m in five centuries, which may be up to half the deglaciation rate of meltwater pulse 1A, which occurred c. 14 500 years ago (Weaver *et al.* 2003; Liu *et al.* 2016). Whilst recently observed ice-sheet mass loss closely tracks the consensus RCP (Representative Concentration Pathway) 8.5 high emissions projection of the recent IPCC AR5 (The IMBIE Team 2020), there is emerging evidence that numerical ice-sheet simulations systematically underestimate the ice loss observed in the recent past (Achswanden *et al.* 2021). Ice-sheet models can suffer from uncertainty associated with boundary conditions, initial conditions, spatial and temporal resolution, parametric calibration and process inclusion. Community assessments derived from an ensemble of 'best estimate' models rarely probe these deeper inter-model uncertainties in a systematic fashion (Levermann *et al.* 2014). Generally, the scientific debate surrounding ice-sheet collapse has now moved beyond whether it is theoretically possible to whether it is realistically possible under sustained very high emissions.

Extreme events

Whilst we present and describe forecasted changes in mean sea level under differing climate scenarios, it is important to recall that local sea level can vary

substantially on daily timescales due to tidal and storm effects (Wahl *et al.* 2017; Thompson *et al.* 2021). The 1872 Baltic storm, which has been characterised as a once in 4500-year event, delivered extreme sea levels that were up to 280 cm above historical mean sea level in south-east Denmark (Clemmensen *et al.* 2014). Understanding extreme sea-level events, such as high tide or storm flooding, is critical to understand the inherent risk associated with sea-level rise. The risk of an extreme sea-level event is generally characterised by its recurrence interval. Tide gauge records are used to assess the magnitude of historical extreme events, for example characterising the height above mean sea level of the 100-year or 10-year events. As mean sea level around Denmark increases, however, the height of extreme sea-level events will also increase, which effectively decreases historical recurrence intervals (Su *et al.* 2021).

At Aarhus, the 100-year extreme sea-level event has been estimated as +163 cm above mean sea level, based on tide gauge observations during the 1981–2010 period (Fig. 9; Kystdirektoratet 2018; Thejll *et al.* 2021). Under the RCP8.5 high-emissions climate scenario, however, increases in mean sea level result in this same sea-level height recurring as a 5-year event during the 2071–2100 period. Su *et al.* (2021) suggest it will become a 1-year event. In short, sea levels equivalent to the historical 100-year event will occur at least 20 times more frequently during the last decades of the century under the RCP8.5 scenario. As a consequence, the annual duration of high water-level warnings at Aarhus will increase from c. 3 h per year in 1981–2010 to c. 1280 h per year (or c. 15% of the year) in 2071–2100 under the RCP8.5 high-emissions climate scenario median

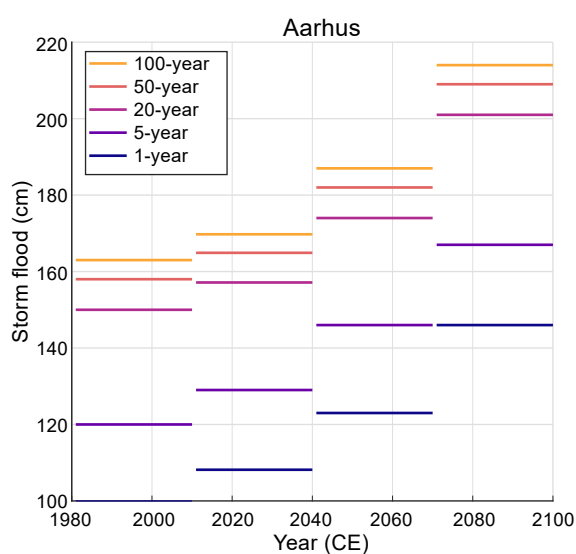


Fig. 9 Storm flood height above mean sea level (cm) for 1-, 5-, 20-, 50- and 100-year recurrence intervals at Aarhus. Calculated over different 30-year climatology periods until 2100 under the RCP8.5 high emissions climate scenario (Kystdirektoratet 2018; Thejll *et al.* 2021).

estimates (Thejll *et al.* 2021). This general pattern, characterised by decreasing extreme event recurrences and increasing duration of water-level warnings, is similar for other cities around Denmark (Kystdirektoratet 2018, 2022). These decreases in recurrence intervals are based on stationary statistics and ignore any changes in recurrence due to potential changes in storminess or seasonal cycle. They simply assume that future flooding events will be a composite of historical-type storm surges overlaid on projected sea-level rise.

The risk presented by these transient extreme sea-level events is currently managed with a variety of hard and soft solutions around Denmark (Fig. 10; Mangor *et al.* 2017). Hard solutions are engineered constructions of dikes, sluices, sea walls, floodgates and quay-terrain elevation, often with the primary purpose of maintaining the coastline position without any significant changes. Soft solutions typically use nature-based approaches, such as establishing new artificial islands, sand dunes or reefs and sand nourishment and/or revegetation along the coastline, with the primary purpose of reducing flood risk. Both types of solutions can play a key role in protecting existing and future developments and assets from coastal erosion and inundation (Farágó *et al.* 2018; Fryd & Jørgensen 2019). The choice between various hard and soft coastal management strategies is ultimately dependent on the municipal management strategy, which can range from the high-burden of 'hold-the-line' to low-burden of unmitigated retreat, as well as coastal morphology and the dominant coastal processes during extreme sea-level events.

Municipal planning

We provide a summary of previously published sea-level projections that are relevant for sea-level rise planning at Copenhagen in Fig. 11. These previous projections, which discount any scenarios of ice-sheet collapse, are collected from studies and assessments published since the 2007 IPCC Fourth Assessment Report (Table 3). All these sea-level projections correspond to a 'high' or 'very-high' emissions climate-change scenario (i.e. the previously published A1B, RCP8.5 scenarios or SSP5-8.5). The AR6 sea-level projections discussed here are the most recent projections available. Whilst previous IPCC assessments reported sea-level rise projections as tabulated global averages, AR6 now provides city-level sea-level projections. After accounting for the use of differing baseline years, these nine studies suggest that the best estimate, for planning purposes, of sea-level rise at Copenhagen increased c. 25 cm per decade between 2007 and 2021. There is, however, tremendous variability between studies. For example, the Danish Climate Atlas (Thejll *et al.* 2021) projects 22 cm less sea-level rise in the year 2100 than the AR6 (Fox-Kemper *et al.* 2021).



Fig. 10 Diversity of management options for extreme sea-level events. A: Coastal wetland in Roskilde Fjord, Sjælland. B: Earthen coastal protection dams near Rødby, Sjælland. C: Hardened shoreline at Copenhagen, Sjælland. D: High-water river lock on Ribe Å, Jylland.

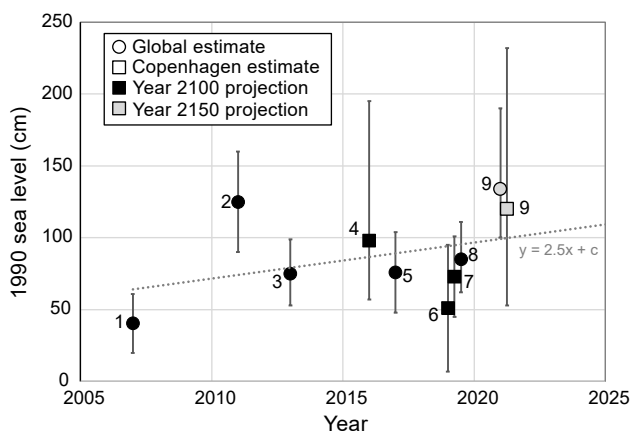


Fig. 11 Previously published sea-level projections of relevance for Copenhagen sea-level rise planning under a high-emissions climate change scenario. All studies expressed relative to 1990 sea level. Data labels are associated with specific previous studies in Table 3. Marker shape indicates global versus Copenhagen-specific projections. Marker colour indicates year 2100 versus 2150 projections. Dashed line denotes the sea-level projection for planning purposes increasing at $c. 2.5 \text{ cm/yr}$. The trend shown here is broadly representative of other Danish cities.

Additionally, these previous studies do not use the same confidence or uncertainty limits, which can make ‘high’ and ‘low’ estimates not directly comparable (Table 3). This underlines the need to continually update datasets and projections and make these available for planners, stakeholders and policy makers.

There are several reasons for the increasing trend in forecasted sea-level rise. Part of this trend reflects an extension of projections from year 2100 to year 2150 in AR6. As sea level rises through time, longer projections yield larger increases in relative sea level. AR6 projects Copenhagen-specific sea-level rise to be within $c. 10\%$ of the global mean projection. This suggests that adopting global projections for Copenhagen-specific planning purposes is generally valid with an additional uncertainty of $\pm 10\%$ relative to global projections. The shift from more global to more Copenhagen-specific projections over the past decade therefore does not explain the worsening sea-level rise forecast at Copenhagen. We instead suggest that the increasing trend of sea-level rise projections is primarily due to improved process-level understanding of the influence of climate change on sea-level change over time. It is reasonable to expect this trend to continue.

There are diverse sea-level adaptation challenges confronting different coastal municipalities around Denmark. The nature of these challenges depends on city layout and topography, as well as inland hydrological conditions (i.e. groundwater level) or coastal hydrodynamic conditions (i.e. tides and waves; Mangor *et al.* 2017). For example, a city situated within a fjord is confronted with a different flooding hazard than a city situated along an exposed shoreline. Consequently, the adaptation challenges confronting Danish

Table 3 Summary of previously published sea-level projections of relevance for Copenhagen sea-level rise planning under a high-emissions climate change scenario.

Data label	Study name	Study year	Projection baseline	Projection year	Projection type	Scenario	Low (cm)	Mean (cm)	High (cm)
1	AR4	2007	1990	2100	G	A1B +ice sheets	20	41	61
2	SWIPA2011	2011	1990	2100	G	A1B	90	125	160
3	AR5	2013	1996	2100	G	RCP8.5	52	74	98
4	Jevrejeva2016	2016	2005	2100	C	RCP8.5 (+5°C)	55	96	193
5	SWIPA2017	2017	2005	2100	G	RCP8.5	46	74	102
6	KlimaAtlas	2019	1996	2100	C	RCP8.5	6	50	94
7	Colgan2019	2019	1925	2100	C	RCP8.5	49	77	105
8	SROCC	2019	1996	2100	G	RCP8.5	61	84	110
9	AR6	2021	2005	2100	G	SSP5-8.5 (medium confidence)	63	77	101
9	AR6	2021	2005	2100	C	SSP5-8.5 (medium confidence)	48	71	102
9	AR6	2021	2005	2150	G	SSP5-8.5 (medium confidence)	98	132	188
9	AR6	2021	2005	2150	C	SSP5-8.5 (medium confidence)	51	118	230

Data labels correspond to Fig. 11 and literature references below the table. G: global; C: Copenhagen-specific. All studies are graphically depicted relative to a common 1990 baseline sea level in Fig. 4.

Data labels refer to the following studies: 1: Meehl *et al.* (2007). 2: AMAP (2011). 3: Church *et al.* (2013). 4: Jevrejeva *et al.* (2016). 5: AMAP (2017). 6: Thejll *et al.* (2021). 7: Colgan *et al.* (2019). 8: Oppenheimer *et al.* (2019). 9: Fox-Kemper *et al.* (2021).

municipalities span across sea-water flooding, river-water flooding, salt-water intrusion and rising groundwater levels. This highlights the need for site-specific solutions and adaptation strategies. In Denmark, sea-level rise planning has been decentralised since 2008, with at-risk coastal local municipalities each responsible for their own analyses of flood risks and developing prioritised climate change adaptation action plans. Since 2015, EU regulations have also required at-risk coastal municipalities to act to reduce flooding risks (European Parliament 2007).

Madsen *et al.* (2019) found that whilst Danish municipalities are, indeed, aware that rising sea levels will impact their infrastructure, precise municipal responses often remain poorly defined. Ergo, there is no national requirement to enforce consistent definitions or updates of municipal sea-level rise adaptation plans. This absence of sea-level rise adaptation plan standards creates the possibility for very different risk management and adaptation actions to occur in nearby municipalities with similar coastal geomorphology and coastal processes. It is evident that local adaptation plans must make critical choices, considering both site-specific hydrology challenges and the general issues of geography, timeline, climate choices and acceptable risk level. Arguably, however, there is a pressing need for an overarching common national sea-level adaptation plan to ensure that individual municipal plans conform to some standards in terms of risk analysis using systematically defined vulnerabilities, exposures and hazards.

Conclusions

Here, we review sea-level changes at four Danish cities during both a past instrumental period and a future projection period. Whilst these cities have experienced significant and differing sea-level changes over the instrumental period, the sea-level changes now confronting Denmark over the next two centuries are equivalent, or larger, than the sea-level changes experienced in the past two millennia. In a paleo context, the rate of forthcoming Anthropocene sea-level rise will likely be comparable to some of the fastest periods of sea-level rise during the Holocene, meaning the past c. 12 000 years. Translating the local sea-level rise projections presented here into planning targets, however, is challenging. This requires making value judgments about acceptable vulnerabilities and exposures to sea-level hazards that depend on geography, timeline, societal and climatic pathways and risk level.

The uncertainty associated with society's 21st century choice of SSP imparts a tremendous uncertainty on local projections of sea-level rise. The differences in sea-level rise projected under the range of scenarios highlight the potentially significant impact of remaining opportunities for climate-change mitigation. Aside from this social uncertainty, across all SSP scenarios, the largest physical uncertainty in projections is associated with the stereodynamic component of sea-level rise. Whilst Denmark is geographically closer to the Greenland ice sheet, uncertainty associated with the Antarctic ice sheet's response to climate change represents a

greater sea-level threat to Denmark. The IPCC scenarios analysed here, however, do not assess the likelihood or impact of rapid ice-sheet collapse. Over longer, multi-centennial, time scales, it is difficult to understate the sea-level threat confronting Denmark associated with ice-sheet collapse. The 'low-probability high-impact' scenario of ice-sheet collapse and c. 10 m sea-level rise by 2500 cannot be excluded under higher emission scenarios. Ice-sheet projections suggest that the only way to avoid certain ice-sheet collapse is to avoid a sustained higher emissions climate pathway.

The landscape of sea-level information available to Danish policymakers is shifting fast. Over the past two decades, the most relevant sea-level rise planning threshold for Copenhagen has been increasing at 25 cm per decade. This implies a continual need for updating sea-level projections using the state-of-the-art knowledge and translation of these projections to ensure usability for local stakeholders. There are a variety of hard and soft coastal management strategies already in use in Denmark today. The choice of these strategies is ultimately dependent on both municipal management strategy and coastal morphology or processes. Whilst sea-level rise planning has been decentralised to local municipalities since 2008, there now appears to be a clear need for an overarching national sea-level adaptation plan to ensure that individual municipal plans for at-risk coastal municipalities conform to both national and EU risk and action standards.

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Competing interests

The authors declare no competing interests.

Author contributions

All authors contributed to analysis, investigation, interpretation and writing. W.C. and K.K.K.: conceptualisation. W.C., H.J.H., S.R., A.Busck,

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Additional files

There are no supplementary files with this manuscript.

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