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LETTER

Future sea level rise dominates changes in worst case extreme sea levels along the global coastline by 2100

Svetlana Jevrejeva[1,*], **Joanne Williams**[1], **Michalis I Vousdoukas**[2] **and Luke P Jackson**[3]

[1] National Oceanography Centre, Liverpool L3 5DA, United Kingdom
[2] Department of Marine Sciences, University of the Aegean, University Hill, 81100 Mytilene, Greece
[3] Department of Geography, University of Durham, Durham, United Kingdom
[*] Author to whom any correspondence should be addressed.

E-mail: sveta@noc.ac.uk

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Abstract

We provide the magnitude of a worst case scenario for extreme sea levels (ESLs) along the global coastline by 2100. This worst case scenario for ESLs is calculated as a combination of sea surface height associated with storm surge and wave (100 year return period, the 95th percentile), high tide (the 95th percentile) and a low probability sea level rise scenario (the 95th percentile). Under these conditions, end-of-21st century ESLs have a 5% chance of exceeding 4.2 m (global coastal average), compared to 2.6 m during the baseline period (1980–2014). By 2100 almost 45% of the global coastline would experience ESLs above the global mean of 4.2 m, with up to 9–10 m for the East China Sea, Japan and North European coastal areas. Up to 86% of coastal locations would face ESLs above 3 m (100 year return period) by 2100, compared to 33% currently. Up to 90% of increases in magnitude of ESLs are driven by future sea level rise, compare to 10% associated with changes in storm surges and waves. By 2030–2040 the present-day 100 year return period for ESLs would be experienced at least once a year in tropical areas. This 100-fold increase in frequency will take place on all global coastlines by 2100.

1. Introduction

Coastal zones contain large human populations, significant socio-economic activities and assets, and fragile ecosystems. With climate change and sea level rise coastal communities face increasing risk of more frequent and severe coastal inundation, leading to huge economic losses (Jevrejeva *et al* 2018, Abadie *et al* 2020, Vousdoukas *et al* 2020, Brown *et al* 2021, IPCC 2021, 2022). While the focus of sea level change studies tends to be on quantifying the rate and magnitude of mean sea level rise, most threats of coastal flooding are governed by a combination of extreme sea levels (ESLs) due to storm surges and waves, and sea level rise (Vousdoukas *et al* 2018, Kirezci *et al* 2020, Tebaldi *et al* 2021). In the context of coastal management, adaptation planning and climate services such as insurance risk assessment require worst case scenarios, such as a low probability high impact (LPHI) ESL projections by 2100 (Cozannet *et al* 2015, Jevrejeva *et al* 2019, IPCC 2022). Specific examples that develop a worst case scenario for stakeholder engagement include Poumadère *et al* (2008) and Lonsdale *et al* (2008), which are used to support cross-sectoral stakeholder exploration of feasible adaptation responses. Alternatively, such worst case scenarios are also used within dynamic adaptive pathways planning as part of a suite of sea level pathways to stress-test national coastal guidance and policy (Lawrence *et al* 2018); this approach parallels stress-testing within insurance and financial sectors (Blaschke *et al* 2001).

In this study we construct a LPHI ESL projection that we interpret as a worst case scenario for ESLs given existing process knowledge and uncertainty of the 95th percentile of each components exceedance. We define the worst case scenario for ESLs as a combination of sea surface height associated with storm surges and waves (100 year return period, the 95th percentile), high tide (the 95th percentile) and low probability (the 95th percentile) sea level rise by 2100. This worst case scenario for ESLs assist with risk management, allowing planners, in planning for potential disasters, to consider the most severe possible outcome that can be reasonably projected, taking into account current understanding of uncertainties in ESL projections.

Recent studies (Vousdoukas *et al* 2018, Kirezci *et al* 2020, IPCC 2021, Tebaldi *et al* 2021) suggest that ESL events, associated with tropical cyclones, extratropical storm surges and waves, previously occurring once in 100 years could happen annually by the end of the century. In addition, there is a need to assess changing exposure and vulnerability in coastal areas due to sea level rise and climate change, and to estimate when the resilience capacity of each community could be exceeded, considering that ESLs will not just increase flood frequency, but also reduce time for post-storm recovery, challenging local capacities to maintain acceptable safety standards and appropriate expectations of economic damages (Brown *et al* 2021).

The aim of this study is to calculate the magnitude of worst case scenario for ESLs along the global coastline by 2100, taking into account evolution of ESLs due to future storm surges and waves and due to low probability sea level rise (e.g. 1.8 m global estimate of sea level rise) by 2100. We analyse the relative importance of the contributions from future storm surges and waves, sea level rise and tide to the changes in ESLs along the global coastline. We apply a probabilistic approach focussing on an ESL projection suitable for assessments of the economic impact of coastal floods, coastal defence design, and population exposure, among others. By providing the magnitude of a worst case scenario for ESLs our study complements previous studies (Vousdoukas *et al* 2018, Kirezci *et al* 2020, Tebaldi *et al* 2021), which focussed on the median, and/or most likely outcomes. In this study we utilise the LPHI sea level projections, with global mean sea level rise up to 1.8 by 2100 (Jevrejeva *et al* 2014, Jackson and Jevrejeva 2016). This is close to the low confidence SSP5-8.5 sea level rise scenario from the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (AR6 IPCC) (Fox-Kemper *et al* 2021).

2. Data and method

ESLs are calculated as a combination of sea surface height associated with storm surges and waves (100 year return period, the 95th percentile), high tide (the 95th percentile, figure SI 1) and low probability (the 95th percentile) sea level rise by 2100 (figures SI 2 and SI 3). We use high-end relative sea level projections for RCP8.5 (Jackson and Jevrejeva 2016) (more details are in the SI), which mimics the low probability sea level rise up to 1.8 m by 2100 in AR6 (IPCC 2021). Probability density functions for future waves and storm surges are from Vousdoukas *et al* (2018). These are produced from simulations using atmospheric forcing from ERA-INTERIM for the baseline (1980–2014) and a six-member CMIP5 global climate model ensemble for the future (table SI 1). Wind wave generation is simulated using the WW3 model (Mentaschi *et al* 2017) and storm surges using DFLOW FM (Vousdoukas *et al* 2018). For 4960 points along the coastline, all ESL components are combined in Monte Carlo simulations with 1000 ensembles and then fitted in combined pdf for each individual location.

3. Results

3.1. Changes in ESLs with LPHI sea level rise scenario

Figure 1 displays the magnitude of low probability ESLs (the 95th percentile, 100 year return period) and their changes by 2100. By the end of the 21st century, with global mean sea level rise of 1.8 m, there is a 5% probability of the global-coastal average ESL height for the 100 year return period exceeding 4.2 m, compared to 2.6 m during the baseline period (1980–2014). Figure 1(a) shows that almost 45% of global coastlines will experience ESLs above the global-coastal average, with the East China Sea, Japan, and Northern Europe seeing increases up to 9–10 m. By 2100 (figure 1(a)) up to 86% of coastal locations will experience ESLs above 3 m, compared to only 33% during the baseline period (figure 1(b)).

By 2100 the increase in global-coastal average ESLs along the coastline will be up to 1.6 m (figure 1(c)), compared to the baseline period (figure 1(b)); with 58% of coastline experiencing changes above the global average (figure 1(c)). About 83% of sites in the tropics and 74% of sites in Mediterranean Sea will experience an increase in ESLs above the global mean (table SI 2; figure SI 4 for the definition of selected regions). By the end of the 21st century, more than 95% of coastal locations will face an increase of 1–2 m in magnitude of ESLs compared to the extremes for the baseline period (figure 1(c)), while for 2% of the global coastline the rise in ESLs will reach up to 3 m. The above rise in ESL magnitudes translates also to a dramatic increase in frequency of extreme events. The entire global coastline will experience the baseline ESL with 100 year return period at least annually (figure 1(d)). Additionally, most of tropical areas, as well as the Mediterranean, Red and Black Seas will experience the baseline 100 year return period at least once a year by 2030–2040 (figure 1(d)).

3.2. Future ESLs due to climate change related alterations in storm surges and waves by 2100

The component of ESLs associated with storm surges and waves is mainly triggered by meteorological conditions (e.g. tropical/extratropical cyclones). Over the baseline period (1980–2014) the magnitude of sea

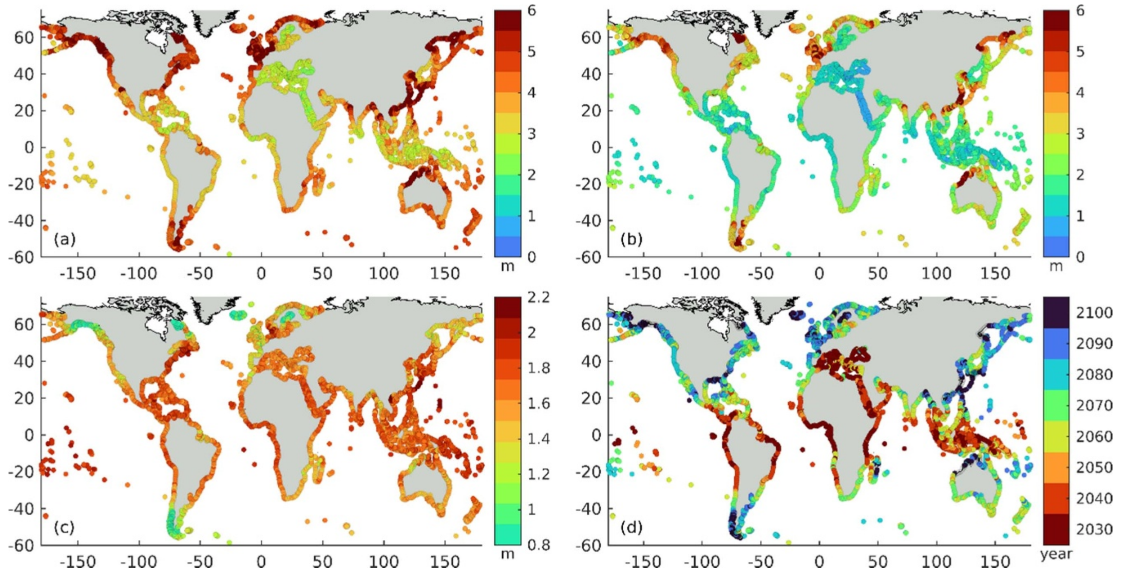

Figure 1. Projected magnitude of worst case scenario for ESLs (m) by 2100 (combination of the 95th percentile of sea surface height from storm surge and wave, 100 year return period for both, the 95th percentile of the tide, and the 95th percentile of sea level rise, where the 95th percentile for global sea level rise is 1.8 m), panel (a). Panel (b) is representing ESLs during the baseline period (1980–2014), combination of sea surface height from storm surge and waves (100 year return period), and the 95th percentile of tide (sea level rise is a few cm for baseline period). Panel (c) Changes (m) in projected low probability ESLs by 2100 relative to the baseline period (panels (a) and (b)). Panel (d) Decade of the magnitude of 100 year return period from baseline period projected to be at least once a year in the 21st century.

surface height for this component for the 100 year return period along the coast ranges from 0.5 m to 5 m, with global average of 1.7 m (figure SI 5(b)).

Figure 2 shows the projected 95th percentile of the 100 year return period of ESL height due to storm surge and waves at the end of the 21st century. By 2100 the global average magnitude of extreme sea surface height, associated with meteorological forcing only, is projected to increase by 0.2 m resulting in a 1.9 m estimate for the global average where the largest regional changes (increase/decrease) are projected along the coastline of the East China Sea, Australia and Northern Europe (figure 3).

Future increases in magnitude of ESLs, associated with storm surges and waves, assuming there is no sea level rise, thus contributes less than 10% to the total increase in ESLs by 2100 (figure 1(c)). This is mainly due to the moderate increase in magnitude in individual locations compensated with some decreases in other locations (figure 3(a)) leading to the global mean increase of 0.2 m, compared to overall increase in global mean ESLs up to 1.7 m.

3.3. Changes in ESLs due to future mean sea level rise

Up to 90% of changes in ESLs by 2100 (figure 1(c), figure SI 5(c)) are explained by future sea level rise, compared to 10% due to changes in extremes sea levels associated with storm surges and waves. In this study we use the 95th percentile of regional sea-level projections whose globally averaged sea level rise is 1.8 m by 2100 (figure SI 2). These projections show regional sea level rise up to 2.4 m, particularly in the tropics and northern hemisphere due to substantial Antarctic ice mass loss (figure SI 2; Jevrejeva *et al* 2016).

Examples of the change in 100 year return period for a given sea surface height due to projected regional mean sea level rise are demonstrated in figure 4. The sea surface height of 2.3 m reached by the 100 year return period event during the baseline period becomes almost annual by 2100 for Newlyn in the UK, North-West European Shelf (figure 4(a)). At Dakar (West Africa) the magnitude of 0.8 m, the baseline 100 year return period event, is exceeded more than five times in year under the 1.8 m of global sea level rise (figure 4(b)).

All sea level components contribute to the large uncertainties in future sea level projections, and the largest is associated with projections of the future contribution ice mass loss from the Antarctica ice sheet (IPCC 2021). Figure SI 6(a) shows changes in the magnitude of ESLs (100 year return period) by 2100 with future projections of ESLs associated with storm surges, waves and sea level rise, while the contribution from the Antarctic ice sheet is excluded. In this case ESLs will increase by 0.72 m globally (global average extreme) without the Antarctic contribution to future sea level rise, with 61% of locations above this global estimate of 0.72 m. Projected changes in ESLs by 2100 due to Antarctic ice mass loss alone (figure SI 6(b)) provides evidence that the Antarctic ice sheet contribution will increase the global average ESL by 0.95 m. For almost all coastlines there

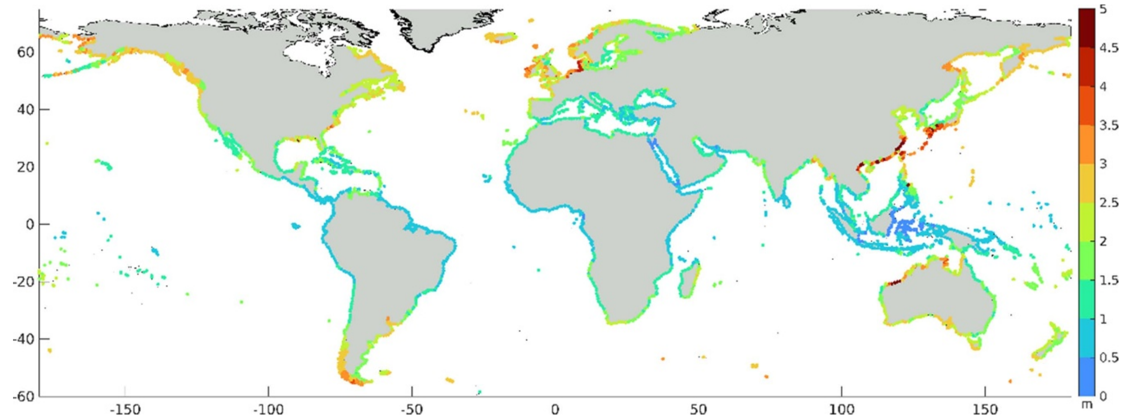

Figure 2. Magnitude (m) of ESLs due to storm surge and waves, 100 year return period, the 95th percentile by 2100 (no sea level rise and no tide).

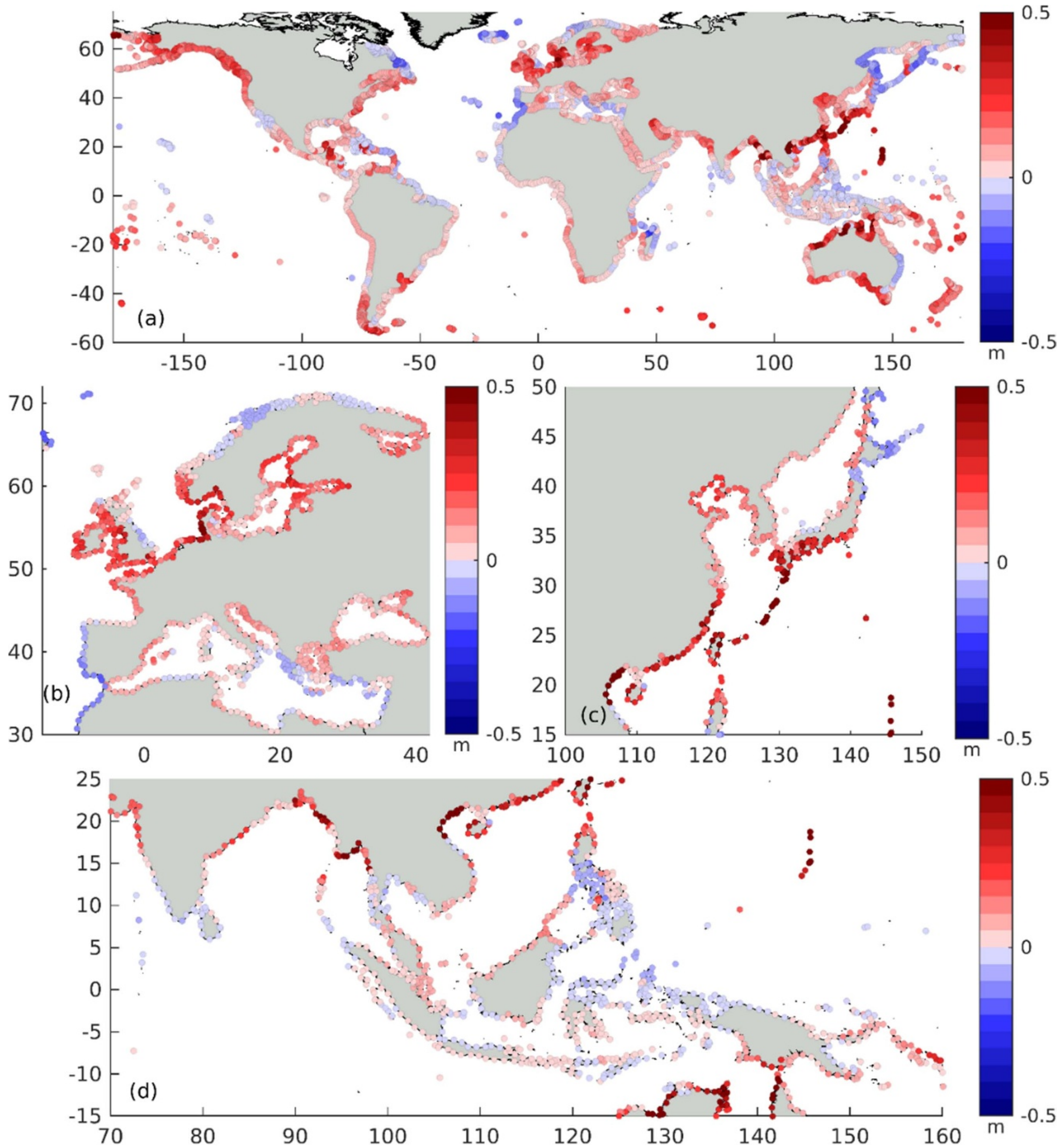

Figure 3. Changes (increase/decrease) in the 95th percentile of ESLs (m) by 2100, relative to baseline period (1980–2014), associated with changes in storm surges and waves only. Panels (b)–(d) changes in magnitude of the 95th percentile of ESLs (100 year return period) for the European coastline and China and Japan, South and South East Asia by 2100.

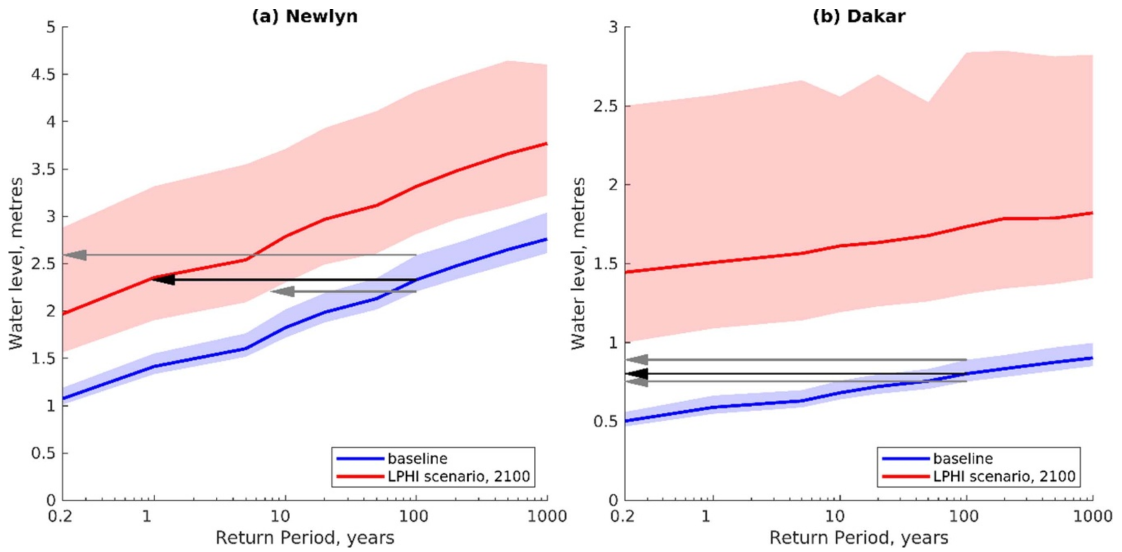

Figure 4. Changes (m) in projected low probability high impact (LPHI) extreme sea level rise by 2100 relative to the baseline period, in Newlyn (a) and Dakar (b). Thick line represents the median of the 100 year return period (no tide), with blue colour corresponding to the baseline period and the red- to the projections by 2100. In each panels the shaded areas are representing the 5–95th percentiles.

is an increase in ESLs (100 year return period) ranging from 0.4 m to 1.4 m, associated with the contribution of ice mass loss from Antarctica. We estimate that future ESLs due to this contribution could explain up to 55% (0.95 m due to Antarctic compared to 1.7 m from all sea level rise components) of changes in ESLs by the 2100 (figure SI 6(b)). Dramatic changes in ESLs are expected after 2050 (figure SI 7) with increased rate of sea level rise and increased uncertainties in sea level rise projections, specifically changing the tail of pdfs of sea level rise with time. For the global coastline reducing the uncertainties in projections of ice mass loss from Antarctica remains one of the keys to improve future ESL projections. In addition to changes in magnitude of ESLs by 2100, there is clear evidence of changes in frequency of 100 year extreme events, largely associated with mean sea level rise (figure 4). In addition to climate driven sea level components (e.g. ice mass loss from ice sheets and thermal expansion of the ocean) a contribution from scenario independent glacial isostatic adjustment (GIA) component is about a few cm to the global mean sea level rise by 2100, with sites in tropical regions are experiencing less than 5 cm. However, in Fennoscandia and some northern areas of North America up to almost 1 m of future sea level rise is masked by the land uplift (figure SI 3(b)) due to GIA, adjusting the changes in frequency of ESLs (figure 1(d)).

3.4. Role of the tide

Figure SI 1 shows that the tidal amplitude varies by coastline, from under 0.5 m in the Mediterranean, Baltic and Caribbean seas, to over 5 m in a few resonant estuaries and coastal locations on the continental shelf. In regions with a large tidal range, such as the North–West European Shelf and North West coast of Australia (figure SI 1), the most extreme water levels due to storm surge and waves can only occur in combination with high astronomical tide. Some regions have a fortnightly spring-neap variation in range of several metres, so storm surges occurring during neap tides may pass almost unnoticed, whilst spring tides can cause brief flooding even in the absence of a storm (Williams *et al* 2016). In this study we consider that tides will remain unchanged to 2100, assuming that most regions will be no more than a few percent of the direct effects of sea level rise (Idier 2017, Pickering *et al* 2017).

By 2100 the global mean increase in ESLs of 1.6 m is slightly lower to that without tide (1.7 m, figure SI 5). This is driven by the regions with high tidal amplitude (figure SI 1), for example, a median increase of 1.5 m in ESLs for North-West European Shelf with tide is lower compared to 1.6 m ignoring tides, suggesting that ESLs are moderated with low tide assurance in this region. Our tests show there is no net change in tidal range for the Mediterranean or Caribbean Seas.

4. Discussion

In this study, we focus on low probability ESL projections for global coastlines with specific emphasis on a worst case scenario to support adaptation planning in coastal areas. We have estimated the magnitude of the 100 year return periods for ESLs due to storm surges and waves, tide and a low probability future sea level rise by 2100. We attributed changes in coastal ESLs by considering the combined effect of future sea level rise (a), ESLs due to future changes in storm surge and waves (b) and tides, and estimated their relative importance.

The increase in magnitude of ESLs along the global coastline is not uniform, the regions with largest changes by 2100 being those in the tropics. The increase in magnitude of ESLs is largely driven by sea level rise, while changes in sea surface height due to storm surges and waves contribute up to 10% (increase in global average ESLs of 0.2 m) globally and with increase/decrease in magnitude up to 0.5 m in individual locations. These regional changes in ESLs due to storm surges and waves from our study are in good agreement with simulations of increased tropical cyclones and storm surges at areas of the Northern Hemisphere at latitude between 15–35 °N (Hemer *et al* 2013, Lin *et al* 2019, Mori *et al* 2019). For example, our calculated increase is extreme sea surface height up to 0.5 m by 2100 (100 year return period) due to storm surges and waves along the coast of East Asia and Japan is in a good agreement with projected 0.3–0.45 m increase of storm surge height with a 100 year return period in Mori *et al* (2019). These changes are attributed to the projected future alteration of extreme wind speeds; suggesting that future 100 year return values of wind speed increase up to 10% due to tropical cyclone activity in the East Asia region and along the coast of Japan (Mori *et al* 2019). Slight increases in ESLs along the USA coast due to future tropical and extra tropical cyclones were modelled by Lin *et al* (2019), and explain our changes in ESLs for the North Atlantic coast of the USA (figure 2). Theoretical and numerical models have consistently shown that the averaged intensity (i.e. maximum wind speeds) of tropical cyclones could shift toward stronger storms (IPCC 2021), with intensity increases of 2%–11% by 2100 (Grinsted *et al* 2013, Kossin *et al* 2014, Walsh *et al* 2016, IPCC 2021). The global proportion of tropical cyclones that reach very intense (Category 4 and 5) levels is projected to increase due to anthropogenic warming over the 21st century (Sobel *et al* 2016, IPCC 2021). However, large disagreements between the models in simulations of storm surges are remaining (IPCC 2021). In addition, changes in ESLs along the coast of low latitude areas of Pacific coast of South America and coastal areas in Australia (Southern ocean) are a good agreement with increase height of waves and increasing Southern Ocean swell propagation into tropical areas (Hemer *et al* 2013). Global high resolution modelling of extreme storm surges is expected to improve simulations of ESLs, however, currently the use of high resolution regional models is lacking in some specific regions (e.g. South East Asia).

Future sea level rise and the large uncertainties in sea level projections are the main drivers for dramatic changes in magnitude and frequency of ESLs by 2100. In our study global mean sea level rise is projected to be up to 1.8 m (the 95th percentile), which mimics the low probability sea level projections by AR6 (IPCC 2021). However, for 80% of coastline this estimate of 1.8 m could be exceeded (under this scenario), with the highest sea level rise for the small-island nations in the Pacific and Indian oceans, and North Atlantic coastline of USA (Jevrejeva *et al* 2016, Garner *et al* 2018, IPCC 2022; figure SI 2). The gravitational response to ice loss from the ice sheets in Greenland and Antarctica and isostatic rebound from previous glaciations result into the spatial patterns with sea level rise below the global mean expected around Greenland and Antarctica, some parts of the Arctic, Pacific Alaska and northern Europe (Jackson and Jevrejeva 2016, Kopp *et al* 2017). The non-uniform pattern of sea level rise thus shape the pattern and magnitude of projected 100 year return period ESLs by 2100 (figure 1(c)). Relatively modest changes in ESLs in high latitude can be explained by the moderation associated with the lowest sea level rise projections (Jackson and Jevrejeva 2016, Kopp *et al* 2017, IPCC 2021). For example, in high latitude areas of the Chilean coastline the smallest changes for ESLs occur in the low probability scenario (figure 1(c)). This is despite an increase in sea surface height due to changes in waves and storm surges up to 0.4 m (figure 3(a)).

Uncertainties in projected sea level rise vary spatially and temporally and the largest uncertainties are in future projections of Antarctica ice sheet contribution to sea level rise (Jevrejeva *et al* 2014, Rohmer *et al* 2019, van de Wal *et al* 2019, Siegert and Pearson 2021). Any scientific advance and refinement of future estimates of Antarctic and Greenland ice sheet mass loss will lead to the alteration of the magnitude of projected ESLs in coastal areas. In addition, further improvements to ocean dynamics and coastal sea level variability, for example including variability in seasonal and interannual time scale that is currently not represented in state of the art approaches for sea level projections (Jackson *et al* 2016, Kopp *et al* 2017, IPCC 2021), will lead to improved ESL projections. Recent publications (e.g. Vecchio *et al* 2019, Qu *et al* 2022) demonstrated that the range of seasonal and interannual variability in coastal sea levels is up to 70 cm (Qu *et al* 2022), leading to further amendments of ESLs in coastal areas. There are also regions where seasonal cycles in sea level must be included before the distribution of surges and tides are completely independent (Williams *et al* 2016), but as seasonality is not available in our surge dataset, we neglect that effect here. Understanding the future seasonality of these effects would be a very valuable next step in this work, with practical implications for coastal engineers regarding whether sites are likely to be flooded intermittently or only seasonally.

At a local scale, those ESLs constructed along coastlines with coastal megacities and settlements coincident with large river deltas are likely to be conservative because the regional sea level projections omit local enhanced subsidence from groundwater extraction, urbanization and tectonic activities. These locations are currently subject to local subsidence at rates equivalent to or greater than present-day sea level rise (e.g. Erkens *et al* 2015, Higgins 2016) and with potential contribution close or exceeding future sea level projections by 2100 (e.g. Bucx *et al* 2015, Anzidei *et al* 2020, Anzidei *et al* 2021). However, incorporating projections of anthropogenically induced subsidence or land movement due to tectonic activities is beyond the scope of this analysis, particularly given the non-linearity of the anthropogenic component should feasible policy intervene (e.g. Minderhoud *et al* 2017).

We produce worst case scenario of ESLs by 2100 for 4960 locations along the coast, using model simulations for storm surges, waves and sea level rise individually, which provide some limitations for our estimates. For example, we did not consider the interaction between sea level rise and extreme sea surface height associated with storm surges. Recent study (De Dominicis *et al* 2020) for Pearl River delta demonstrated that changes in ESLs generated by meteorological forcing (typhoon propagation) could increase/decrease ESLs by 0.5 m, with sea level rise up to 2 m, due to interaction between sea surface height and sea level rise. In addition, there are open questions about the interaction between waves and storm surges, their dependence/independence on meteorological forcing resulting in combined magnitude of ESLs, and interaction with sea level rise in time scale of seasonal and interannual variability (Jevrejeva *et al* 2019). Using selected tide gauge locations a study by Arns *et al* (2020) suggested that a magnitude of ESLs could be overestimated at some individual locations if storm surge and tide considered statistically independent (Arns *et al* 2020). According to Marcos *et al* (2019) the occurrence of high storm surges and wind waves is correlated for some areas along the global coastline, and neglecting this effect can underestimate the contribution of wave setup to ESLs (Marcos *et al* 2019).There are many challenging scientific problems based upon refinement of local ESL projections (Vousdoukas *et al* 2018), such as the overtopping of waves (Almar *et al* 2021). Locally, the implications of sea level rise to the changes in ESLs will differ, and adaptation decisions could need to consider unique local conditions for each coastal location. For example, improvement of future ESL simulations with high resolution modelling, taking into account changes in the beach profile and local forcing, has been demonstrated in case study for the Pyrgi region in Italy (Anzidei *et al* 2020). The need for high resolution modelling in specific locations to improve understating and simulations of ESLs has been suggested in several previous studies (Vousdoukas *et al* 2018, Tebaldi *et al* 2021).

5. Conclusion

We provide evidence that by 2100 with global sea level rise of 1.8 m, the global average magnitude of ESLs (100 year return period) along the global coastline will be 4.2 m, compared to 2.6 m during the baseline period (1980–2014). Almost 45% of global coastline will experience the magnitude of ESLs above the global estimate of 4.2 m, with up to 9–10 m for East China Sea, along the coast of Japan, Northern Europe and coastal areas of the USA. By 2100 the global average magnitude of extreme sea surface height, associated with meteorological forcing, is increasing by 0.2 m, with the largest changes up to $\pm$0.5 m (increase/decrease) are expected in individual locations. By 2100 magnitude of ESLs (100 year return period) due to storm surges and waves in individual locations is ranging from 0.5 m to 6 m, indicating the needs for high resolution modelling of ESLs in identified regions, e.g. South and South-East Asia. Challenges remain to incorporate the projections of anthropogenically induced subsidence or local land movement due to tectonic activities into future ESL projections.

Up to 90% of the magnitude of 4.2 m global average ESL (100 year return period) by 2100 will be due to sea level rise. The largest contribution up to 0.95 m (55%) is associated with projected ice mass loss from Antarctica ice sheet. Conversely, the large uncertainties in projections of sea level are leading to the challenges generating ESL projections for decision makers for adaptation in coastal areas. Communicating the progress with uncertainties in the ESL projections enable timely adaptation options, and our worst-case scenario for ESLs will be reviewed when the new information is available.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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ORCID iDs

Svetlana Jevrejeva https://orcid.org/0000-0001-9490-4665
Joanne Williams https://orcid.org/0000-0002-8421-4481

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