Journal of
Marine Science and Engineering

MDPI

Editorial

Coastal Sea Levels, Impacts, and Adaptation

Thomas Wahl [1,*], Sally Brown [2], Ivan D. Haigh [3] and Jan Even Øie Nilsen [4]

1 Department of Civil, Environmental, and Construction Engineering and National Center for Integrated Coastal Research, University of Central Florida, Orlando, FL 32816-2450, USA; t.wahl@ucf.edu
2 Faculty of Engineering and the Environment and Tyndall Centre for Climate Change Research, University of Southampton, Highfield, Southampton SO17 1BJ, UK; sb20@soton.ac.uk
3 Ocean and Earth Science, National Oceanography Centre, University of Southampton, European Way, Southampton SO14 3ZH, UK; I.D.Haigh@soton.ac.uk
4 Nansen Environmental and Remote Sensing Center, and Bjerknes Centre for Climate Research, 5006 Bergen, Norway; jan.even.nilsen@nersc.no
* Correspondence: t.wahl@ucf.edu

Received: 9 February 2018; Accepted: 11 February 2018; Published: 21 February 2018

Keywords: mean sea level; storm surges; waves; coastal zone management; impacts; coastal climate services; adaptation; communication; cross-sectorial collaboration; ECRA

1. Introduction

Sea-level rise (SLR) poses a great threat to approximately 10% of the world's population residing in low-elevation coastal zones (i.e., land located up to 10 m of present-day mean sea-level (MSL)) [1], as well as to the human and natural systems supporting these communities. In its Fifth Assessment Report (AR5), the Intergovernmental Panel on Climate Change (IPCC) projected, based on process-based model studies, the upper end of the likely range of global mean SLR, to be 98 cm at the end of the century with respect to 1986-2005 [2]. However, high-end scenarios of 2 m SLR, and more, by 2100 have been developed assuming unmitigated greenhouse gas emissions, and are recognized as a realistic possibility by the scientific community and many stakeholders and decision-makers (e.g., references [3–5] for the Netherlands, United Kingdom (UK), and the United States, respectively). It has been shown in multiple recent studies [6–8] that even moderate changes in MSL can lead to a significant increase in the number of extreme water level exceedances. These arise as a combination of mean sea-level, astronomical tides, storm surges (driven by tropical or extra-tropical storms), and a dynamic wave component (especially at open coastlines) leading to run-up at beaches and overtopping of built and natural coastal (defence) structures, such as dikes, sea walls, or dunes. Changes in the frequency of extreme sea levels will adversely impact coastal communities by increasing the risk of flooding and/or erosion of beaches and cliffs, and it will also impact ecologically and economically valuable marine ecosystems (such as productive estuaries, coastal wetlands, and coral reefs). Extensive adaptation plans and efforts are already underway in some parts of the world, particularly in high risk or urban areas (such as the Delta Works in the Netherlands or the Thames Barrier in the UK) and more will be necessary to mitigate the increasing risks.

By recognizing that combating the negative impacts of SLR presents a multidisciplinary challenge that requires cooperation of scientists from various fields, with stakeholders and decision-makers, the European Climate Research Alliance (ECRA) launched a Collaborative Program on Sea Level Changes and Coastal Impacts in 2012. During a series of workshops, scientists, practitioners, and stakeholders from across Europe came together to discuss solutions to the challenges outlined above. As a result, a white paper was released [9], where the following five themes were identified as research focus areas to facilitate improved sea-level predictions and projections, impact and adaptation assessments, and communication with stakeholders, policy makers, and the public:

1. Observations of MSL change and a better understanding of the contributing processes;
2. Modelling and projections of regional MSL;
3. Changes in extreme sea levels;
4. Potential impacts of, and adaptation strategies to, extreme sea levels and MSL change; and
5. Improved communication and collaboration.

In this Special Issue, 15 papers are published that can be grouped into these topical themes. For simplicity, topics 1 and 2 are merged into the broader topic "MSL changes". Each topic is discussed below in the context of the papers that have been submitted.

2. Mean Sea-Level Changes

Mean sea level changes, ranging from seasonal through multi-decadal variations to linear and non-linear long-term trends, have been studied extensively in the recent past. This is to better understand the processes involved in causing these changes at different temporal and spatial scales, develop models capable of simulating them, and ultimately derive more robust future projections to assess risks and adaptation needs. Four papers in the Special Issue address different aspects of MSL changes at various spatial and temporal scales.

Chafik et al. [10] analyse how sea levels, observed along northern European coastlines, are affected and modulated by large-scale climate features. They detect a non-stationary sea-level response to the North Atlantic Oscillation (NAO), which is explained by the influence of the East Atlantic (EAP) and Scandinavian (SCAN) teleconnection patterns on the NAO. Importantly, they find that coastal sea levels along different coastline stretches respond differently, depending on the phases of the NAO and teleconnection patterns (i.e., whether they are in a positive or negative state), but with variations that can reach the same magnitude as the observed MSL rise during the 20th century. Hence, it is crucial for climate models to be able to reproduce the relevant driving mechanisms acting at large spatial scales, in order to use this information to infer potential changes at the regional and local scale, in terms of both sea-level and flood risk.

Also at the continental scale, but focusing on Australia, Taylor and Brassington [11] introduce a new sea-level forecasting system that aggregates information from heterogeneous operational systems, including gridded ocean and atmosphere models and tidal predictions, to provide 7-day sea-level forecasts at different locations along the coast. Model bias is assessed and corrected for by including information from in-situ sea-level measurements. The system has the ability to provide meaningful forecasts under non-extreme conditions (i.e., storm surges are not captured), to support routine coastal decision processes, and offers a benchmark for future developments in MSL forecasting.

Breili et al. [12] undertake a regional study. They use a range of different data sets derived from tide gauges, satellite altimetry, Global Navigation Satellite System (GNSS), levelling campaigns, metrological stations, and model results, to investigate MSL changes along the Norwegian coast since the mid-20th century. They pay particular attention to spatial variability along the coast and its drivers, mainly vertical land movement caused by glacial isostatic adjustment (GIA) or anthropogenic impacts, and the inverse barometer effect. For example, they show that MSL trends along the Norwegian coast, when adequate corrections are applied for regional factors, are consistent with estimated global MSL trends for the last 30 to 50 years amounting to approximately 2 mm/year but increase to up to 3.5 mm/year for the more recent period from 1993 to 2016, again in accordance with an observed acceleration in global MSL rise.

Finally, the study by Watson [13] has a local focus and includes a detailed analysis of the long sea-level record from the Battery tide gauge in New York City. Observed rates of MSL rise over the last decade (again, after applying adequate corrections to filter out location specific temporal fluctuations) are compared with those derived from climate model projections from the Climate Model Intercomparison Project—Phase 5 (CMIP5) over the same time period (2007 to 2016). They find that the projected rates of rise are larger than the observed rates at the tide gauges. Such differences may be site specific for the particular location, but this highlights the need for in-depth validation of the model projections with in-situ measurements from tide gauges and remote sensing data from satellite altimetry.

3. Extreme Sea Levels

While the slow rise in MSL will eventually threaten many low lying and unprotected areas, the majority of the impacts to people, property, infrastructure, and the environment, will be felt through extreme sea-level events. Extreme sea levels arise as a combination of four factors: MSL, astronomical tides, storm surges, and waves. Three contributions in this Special Issue analyse extreme sea-level changes, including the dynamic wave component. Slangen et al. [14] undertake a global assessment of extreme sea-level allowances (i.e., the height a coastal structure needs to be elevated to keep the same frequency and likelihood of sea-level extremes under a certain sea-level rise scenario). Simpson et al. [15] and Malagon Santos et al. [16] undertake regional assessments of mean and extreme sea levels around Norway and extreme waves around the UK, respectively.

Slangen et al. [14] calculate sea-level allowances at the global scale using the Global Extreme Sea Level Analysis (Version 2) tide gauge database. In particular, they address one of the major uncertainties in future sea-level projections: the contribution of the ice sheets in Greenland and Antarctica to sea-level rise. Their results show that allowances increase significantly for ice sheet dynamics' uncertainty distributions that are more skewed, due to the increased probability of a much larger ice sheet contribution to sea-level rise. They find that allowances are largest in regions where a relatively small observed variability in the extremes is paired with relatively large magnitude and/or large uncertainty in the projected sea-level rise. This typically occurs around the equator. Finally, for the Representative Concentration Pathway (RCP) 8.5 sea-level rise projections, they show that the likelihood of extremes increases by more than a factor 10,000 at the majority of tide gauges analysed.

In their article, Simpson et al. [15] present new relative sea-level projections for Norway for the 21st century. The region is commonly perceived as being at low risk from sea-level rise, because the coastline is characterised by steep rocky topography. However, as the authors point out, most of Norway's major cities and numerous towns and villages are located in low-lying coastal areas and, hence, are vulnerable to sea-level rise and coastal flooding. To create their new projections, they use findings from the IPCC AR5 and CMIP5 model outputs and scale them to take into account spatial variations in ocean density, ocean mass redistribution, ocean mass changes and associated gravitation effects, and vertical land motion. Then, they calculate return heights for extreme sea levels around the coast using the average conditional exceedance rate (ACER) statistical method. Finally, they adapt the ACER method to also calculate sea-level allowances.

Malagon Santos et al. [16] carry out a spatial footprint and temporal clustering analysis of extreme storm-wave events around the coast of the UK using measurements from wave buoys. As the authors point out, economical, societal, and environmental impacts from extreme events are often correlated spatially. Furthermore, temporal clustering of extreme wave events may have important consequences for coastal structures as there may be insufficient time to properly repair structures between storms. These two issues have important financial and practical implications for the flood risk management sector and, yet, recognition and analysis of spatial and temporal wave characteristics is lacking. The authors identify six categories of spatial footprints of wave events and the distinct storm tracks that generated them. They find that the majority of large wave events occurred between November and March, with large inter-annual differences in the number of events per season associated with the West Europe Pressure Anomaly (WEPA).

4. Impacts and Adaptation

As outlined above, both observations and modelling studies point toward changes in mean and extreme sea levels on decadal to centennial time scales. Over the last few years, the scientific community has responded to this by focusing on sector specific studies or local scale studies to better understand potential impacts. Increasingly, adaptive response is becoming part of that process, with an emphasis on engineering (particularly encouraging natural methods) and societal response, including the role of decision-making. Six of the papers in this Special Issue reflect this range of advancements.

Some of the earliest effects of SLR are seen on beaches, which includes shifts in shoreline position and sediment redistribution. Kinsela et al. [17] describe an approach to estimate potential beach erosion and shoreline change on wave dominated sandy beaches in New South Wales, Australia. They find that sediment compartments help quantify sediment redistribution, including the source and sediment pathways. Exposure to coastal erosion is expected to increase, primarily due to SLR driven shoreline recession. This indicates that thousands of properties may be at risk from coastal erosion over this century. Similarly, Van De Lageweg and Slangen [18] assess changes in deltaic systems as a result of a combination of tides, waves, river-flow, and SLR. They use a set of models to quantify how different types of deltas respond to the abovementioned forcing factors and they evaluate related impacts, in the form of flooding, shoreline recession, and habitat change. Park et al. [19] investigate the effects of SLR and associated implications further inland. Focusing on Florida, they find that large amounts of land could be inundated unless adaptation is undertaken, including areas of marshland. SLR could have significant implications for coastal infrastructure and national parks in the region.

Whilst beaches erode, innovative methods are required to consider how to accrete sediment without causing knock-on problems down-coast. This need is particularly acute after rapid erosion events, as infrastructure is left exposed. Goreau and Prong [20] describe their findings on biorock electric reefs, which encourage damaged reefs to grow, thus having secondary impacts on coastal protection. From a case study in Indonesia, they find that after storm conditions, biorock reefs have allowed beaches to grow. If beach erosion is projected to increase with SLR, biorock reefs may encourage sedimentation along vulnerable shorelines.

Understanding how to respond to shoreline change is important, and the study by Hirschfield and Hill [21] is an example of how adaptation and decision-making, at the local scale in urban areas, is addressed. They analyse the San Francisco Bay shoreline and estimate unit costs for raising current infrastructure, taking into account the shoreline position and design heights, as well as the range of shoreline infrastructure. They conclude that defending the shortest length of shoreline might not be the best option. Although costs to protect a shorter shoreline stretch are lower, longer shoreline (which represents a boundary between saltwater habitat and freshwater habitat) protection could bring multiple ecosystem benefits. This paper has important implications for engineering, as it indicates that a wide range of options need to be considered when planning future defences, not just cost.

Being situated directly on the coast, ports are on the forefront of impacts from adverse weather conditions, including extreme events and SLR. However, even as a commercial business ports and harbours infrequently consider long-term (>100 years) climate change adaptation as they are more focused on day-to-day delivery. Becker et al. [22] recognise the need for long-term adaptation in port environments, such as raising infrastructure as sea-levels rise. Despite there being thousands of ports in need of long-term land raising, this paper is one of the first to estimate the volume of fill cost of materials to raise land. Focusing on 100 major ports in the United States, they estimate that 704 million m^3 of fill is required to raise land and infrastructure by 2 m at a cost of US$57–US$78 billion. For a large industry, these costs are achievable and suggestive that when the time comes, ports will be capable (from a technical and financial standpoint) to adapt to SLR.

5. Communication and Collaboration

The practical use of SLR information for coastal adaptation by governance and managers, is a challenge in its own right. Success requires extensive collaboration between all involved parties, from users to providers of SLR information. Separately, neither the specific requirements for, nor the usefulness of the provided climate information can be known a priori. For numerous places of the world, particularly in built up areas or those of high risk, the time for taking measures is now or in the near future. Hence, there is a dire need for establishing practices that facilitate the efficient use of SLR information for adaptation.

Two of the papers in this Special Issue address the challenge of improved communication (including the assessment of uncertainties inherent to coastal hazard assessments) and collaboration. Le Cozannet et al. [23] assess the translation of SLR information for efficient adaptation, while Stephens et al. [24] offer a framework for uncertainty identification and management and show, by practical example, how flexibility in decision-making for adaptation to future hazards can be supported by maps of the degree of hazard exposure.

Le Cozannet et al. [23] review the practices of coastal climate services (CCS) in France, the US, and Australia, by identifying current barriers and offering recommendations to overcome these. They find that coastal climate services based on sea-level projections are emerging in a scattered manner, and, overall, too slowly to meet the diversity of challenges. All the while the demand is there, driven by the user need to analyse the benefits of mitigation, to highlight research needs, and to support the many aspects of adaptation. The more technical barriers are the need for topical research into, for example, near- and long-term regional, relative sea-level projections and the uncertainties involved, as well as the gap between what sea-level science can provide and the methods of coastal engineers. In conclusion, the authors recommend and propose a framework involving all stakeholders, addressing issues of user interaction, decision-making, and uncertainties, as well as topical research on sea-level science, hydro- and morpho-dynamics, biology, demography, and economy.

Stephens et al. [24] explore the matter of uncertainty management for decision-making, with respect to coastal hazards and adaptation, addressing that near-term decisions need to build in flexibility, both in order to reduce exposure and to enable changes to actions, or pathways that can accommodate higher sea levels over longer timeframes. They outline a logical framework, starting from the land use situation, through the level of uncertainty, hazard scenarios in question, and complexity of the hazard modelling, to the decision (accept, adapt, or avoid). They also demonstrate enhancements to coastal flood exposure mapping by isolating both flooding depth and frequency, showing the degree of exposure and likelihood and how it will change with SLR, in an incremental manner. This gives flexibility in planning and helps inform when intolerable risks emerge. Together, the uncertainty framework and mapping techniques may improve the identification of trigger points for adaptation pathway planning and their expected time range, compared to traditional coastal flooding hazard assessments.

6. Conclusions

This Special Issue has emerged from the ECRA Collaborative Program on Sea Level Changes and Coastal Impacts and it provides a snapshot of the current state of research in the broad field of sea-level rise, its impacts, and adaptation. The 15 papers highlight the different challenges and pathways that can be taken to address either only one or multiple of the topical areas listed in the introduction, and how changes in both the physical drivers of coastal risks and our responses to it can happen at multiple temporal and spatial scales. Rising sea-levels will continue to pose challenges in many different coastal environments. In some coastal zones, lack of information is a key barrier, whereas in others, it is the lack of understanding of how to respond that leaves coastal communities, built infrastructure, and ecosystems vulnerable to changes in mean and extreme sea levels. Communicating these issues to decision-makers, stakeholders, and the general public is a major challenge, particularly when the threat is not always obvious to see, or a short-term solution is favoured but may reduce long-term sustainability that could be otherwise achieved or improved. This compendium shows that the community, including scientists from multiple fields, practitioners, and stakeholders, have made important advances, working side-by-side in order to make progress, but as sea levels continue to rise we will be facing major challenges in managing the coast for years to come.

Acknowledgments: The Collaborative Program on Sea Level Changes and Coastal Impacts thank ECRA, the Bjerknes Centre for Climate Research, and Nansen Environmental and Remote Sensing Center for support of the workshop where this Special Issue was conceived. All contributing authors and reviewers are thanked for their efforts.

Conflicts of Interest: The authors declare no conflict of interest.

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