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Editorial

Editorial: Adaptation to Coastal Climate Change and Sea-Level Rise

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1. Introduction to Climate Change in Coastal Zones

Climate change is already affecting many weather and climate extremes in every inhabited region across the globe. Scientific evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones and, in particular, their attributions to human influence have been strengthened in recent years [1]. The recent IPCC report provides further alerts of the widespread and rapid changes occurring in the atmosphere, ocean, cryosphere, and biosphere and adds more urgency to preparing adaptation actions and plans [1]. With global warming, every region is projected to increasingly experience concurrent and multiple changes in climatic impact drivers. Changes in several climatic impact drivers would be more widespread at 2 °C compared to 1.5 °C global warming and even more widespread and/or pronounced for higher warming levels. Coastal populations and their economies are particularly vulnerable to the impacts of climate change.

The heating of the global climate system and the ocean is raising mean sea levels through ocean thermal expansion and ice loss on land. Global mean sea level has increased by 0.20 m since 1901 but the rate has been increasing in recent decades. Thermal expansion explained 50% of sea-level rise (SLR) from 1971 to 2018, ice loss from glaciers contributed explained 22%, ice sheets explained 20%, and changes in land–water storage explained 8%; but the rate of ice-sheet loss increased by a factor of four between 1992–1999 and 2010–2019 [2]. Even if emissions are halted today, global mean sea level will continue to rise over the 21st century. Interannual events such El Niño and their effects on coastal hazards along many coastlines globally [3–6] also represent an example of how natural internal variability will also modulate climate changes, especially at regional scales and in the near term. These scales are also important to consider in planning adaptation in coastal zones.

Regional mean relative SLR (relative rise in sea level with respect to land movement) will continue throughout the 21st century except in a few regions with substantial geologic land uplift rates. Despite regional variations, approximately two-thirds of the global coastline has a projected regional relative SLR within ±20% of the global mean increase. The latest projections of global mean SLR by 2100 indicate increases of 0.28–0.55 m under very low GHG emission scenarios (SSP1-1.9) and 0.63–1.01 m under the very high GHG emissions scenario (SSP5-8.5). However, the global mean SLR above the likely range cannot be ruled out and values of 2 m by 2100 and 5 m by 2150 under a very high GHG emissions scenario (SSP5-8.5) could be possible given the deep uncertainty in ice-sheet processes [2].

In coastal cities, inundation from SLR would be only one of the effects of climate change. SLR and changes in storm surges, waves, and rainfall will significantly alter coastlines through inundation, flooding, erosion, and salt-water intrusion of low-lying areas globally. The combination of SLR with more frequent extreme sea level events (including through changes in storm surge) and extreme rainfall and river flow events will make flooding more probable. Extreme sea levels with a 1% historical annual probability

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are expected to become an annual event at 19–31% of the 634 global tide stations by 2050, and by 2100, they will become annual events at 60–82% of stations depending on climate scenarios [2]. Relative SLR also contributes to increases in the frequency and severity of coastal flooding in low-lying areas and to coastal erosion along most sandy coasts. Water levels during high tides also produce nuisance flooding and can challenge the efficiency of stormwater drainage and wastewater outfall under storm conditions. Water and other infrastructure, often located along the open coast or shorelines influenced by tides, will also be vulnerable to flooding and erosion from SLR and changes in wave action and storm surges. Rising sea levels will also aggravate or drive new saltwater intrusion into freshwater resources and aquifers. However, the consequences and local effects of climate change in coastal zones will vary globally depending on the rate of SLR relative to land elevation, local changes in storm activity, and coastal geomorphology. Many regions will also experience an increase in the probability of compound events with additional global warming [1].

Therefore, in addition to the global need to reduce and halt greenhouse gas emissions, the inertia in the climate system and the increasing costs of extreme weather events make the need to adapt to climate change and its impacts increasingly urgent, especially in coastal zones. Coastal areas are some of the most vulnerable to climate impacts because they concentrate high exposure of economic activity and population to the impacts of climate hazards [7,8]. As the link between land and the sea, coastal zones also host rich ecosystems and habitats that are increasingly important to human activities, employment, food security, recreation, and cultural values [9,10]. Yet, human and natural pressures, including rapid loss of ecosystems, unsustainable development, and intense use of coastal resources, further add sustainability challenges to global climate stressors on coastal zones globally [11–14]. The need to manage and adapt to these challenges is urgent.

2. Goal of This Special Issue

Climate change is a global issue, but it is felt on a local scale. Cities and municipalities are at the frontline of adaptation and require measures, experience, policies, and strategies that can integrate adaptation efforts into regional coastal policies and decisions (as well as plans for sustainable economic development) [15–17]. Global awareness has been rising, but coastal adaptation still lacks mainstreamed implementation and consistent procedures, practices, and policies. This Special Issue's goal is to present experiences and examples of case studies in different regions to illustrate how communities are effectively planning and implementing coastal adaptation in different contexts and landscapes.

This Special Issue includes one introductory (review) article on adaptation to climate change in coastal zones. The review article by Griggs and Reguero [18] provides an introductory description of some of the most important coastal hazards and their relevant timescales, including SLR, changes in wave energy, and other extreme sea levels. It provides a description of the main impacts on coastal areas but also an overview of potential solutions, adaptation responses, and the decision-making process. This overview can help communities and readers in preparing individual strategies. The review article may also help to identify challenges as it briefly outlines the main challenges to adaptation, which include technological, social conflict, economic, and financial barriers.

The research articles in the collection provide innovative insights into different aspects of adaptation to climate change in coastal zones and include research on exposure to coastal hazards and SLR; evaluation of adaptation solutions and strategies under uncertainty; and factors influencing effective adaptation, including communication and cultural biases. The highlights of these articles are summarized below.

3. Summary of Contributions

3.1. Exposure to Coastal Hazards

Gomez [19] provides critical insight on one impact of SLR that has been less examined in research. SLR hinders gravity flows of storm runoff discharge into the ocean, which may cause floodwater in low-lying depressions. This paper focuses on the influence of surface water inputs, geomorphology, and such hydrological effects, such as the case presented in Mana Plain in Kauai, Hawaii, where the majority of storm runoff relies on gravity flow to the ocean. This example calls for attention to multiple mechanisms of flooding as increasingly imminent threats to islands and low-lying urban areas. The author uses hydrological modeling to estimate runoff volumes, drainage and pumping needs using different annual exceedance probabilities, and provides validation against a recent 2020 storm. The critical variables controlling this process are the amounts of direct groundwater inflow and rainfall. The ~100-year-old drainage ditch system on the Mana Plain has helped prevent storm runoff from persistent ponding in low-lying areas, but SLR may compromise this system in the future. Estimates for this case study suggests the risk of flooding from surface water with 1 m of SLR likely being extended to 5.45 km^2 of land. By the end of this century, 25% of the agricultural land on the Mana Plain may be exposed to flooding as an indirect operational consequence of SLR. The recent ponding in 2020 covered 3 km^2 of land and required 17 days of pumping to lower the water level in the ditch system to its pre-storm elevation. This study points to the need to carefully maintain drainage, to increase pumping capacity and its operational ability, and to divert storm water away from sensitive land use areas. Adaptation strategies may also create storage or retention areas on agricultural land and open floodable spaces as a nature-based option for mitigating multi-mechanism flooding events.

In order to plan for adaptation, national and local governments need to first assess their coastal vulnerability to climate change. However, less information on vulnerability and adaptation is usually available for developing regions. When assessing flood and inundation risks, some critical data are topography, bathymetry, and socio-economic data. Acosta et al. [20] provided a review of datasets available for assessing exposure to coastal hazards in Jamaica in terms of resolution and costs. The article first compares available digital elevation models (DEM) for Jamaica considering spatial resolution (varying from 3 cm to 90 m), vertical accuracy (from 1 to 12 m), and costs (see Table 1 in [20]). The spatial resolution and vertical accuracy of elevation models directly influences the modeled coastal inundation area and estimates of population and infrastructure affected. The study finds more than a three-fold difference between datasets in the estimates of people and property affected for a 3 m flooding scenario. Information on socioeconomic exposure is also critical, as global datasets can greatly differ from locally sourced information. Such large differences emphasize the importance of the careful selection of appropriately scaled data for use in models that will inform climate adaptation planning, especially when considering SLR. This study also highlights the differences between Digital Surface Models and Digital Terrain Models (bare ground, with objects removed) when modeling flooding in low-lying coastal zones, especially in the presence of ecosystems, and reviews the recent attempts to remove vegetation in global elevation models. The article also describes how multiple scales of bathymetric data can be blended together, including global sources, nautical charts and local satellite-derived bathymetry, and the options available, including coastal ecosystems.

The majority of the climate change-induced SLR vulnerability and adaptation studies focused on highly urbanized and intensively developed coasts across the world. Yet, avoidance is a proactive approach that may prevent development or rebuilding in hazard zones, such as flood plains or areas that would be inundated by SLR. Davar et al. [21] presented a case study in Southern Iran, along the Gulf of Oman, which is a coastal area with a low level of development. The study uses types of lands exposed to the high-end estimates of SLR by 2100 as the primary criteria for determining adaptation approaches and ways to develop the coast in the future, identifying areas that could be developed but would be threatened by SLR, and including principles of spatial land management such as land evaluation, suitability, and planned use.

These articles demonstrate that, without proper understanding of data and limitations, project developers and decision makers may overvalue investments in adaptation and, as result, science may not necessarily translate into effective adaptation implementation. Acosta et al. demonstrated that precise digital elevation mapping (DEM) data are needed for targeted local-level decisions, but cost-effective, national data can be used by planners in the absence of high-resolution data to support adaptation action planning (e.g., as in [21]), possibly saving critical funding for project implementation.

3.2. Evaluating Adaptation Solutions and Uncertainties

Baseline information on vulnerability and exposure to coastal hazards can help prepare adaptation strategies and compare solutions. However, research has been more limited on how to evaluate strategies and uncertainties related to performance, timescales, and future pathways. Two articles in this collection, Mills et al. and Revell et al., provide important insight and scalable methodologies that identify and evaluate adaptation options in coastal communities.

First, Mills et al. [22] used a spatially explicit, agent-based modeling platform for different climate change scenarios to examine interactions between climate, human, and adaptation policy factors in Tillamook County, OR (USA). The article explores strategies that may reduce exposure to coastal hazards combining probabilistic simulation of coastal hazards with policy drivers, such as individual decisions and management policies. The study also compares the relative contribution and uncertainty from climate change and policy factors using three stakeholder-relevant performance metrics: flooding, erosion, and recreational beach access. Uncertainty was addressed by considering climate drivers (i.e., wave height and sea-level rise), human adaptation factors (i.e., development restrictions, construction of backshore protection structures), and future scenarios of climate change. The approach allows for direct comparisons of strategies under uncertainty.

Mills et al. determined that, in general terms, policy decisions introduced greater variability and uncertainty to the impacts of coastal hazards than the uncertainty sources associated with climate change. However, the case study illustrates a method to drive more robust and informed implementation of policies, as it highlights that some options provide more certain outcomes across scenarios and, therefore, may be more recommendable than others that do not provide consistent benefits across metrics and climate scenarios.

Revell et al. [23] presented a holistic framework for evaluating adaptation approaches to coastal hazards and SLR in a case study for Imperial Beach, California (USA). The article considers coastal flooding, erosion, and king tide flooding to develop a vulnerability assessment and compares five adaptation approaches—armoring, nourishment, living shorelines, groins, and managed retreat. The vulnerability assessment uses information on hazards and SLR scenarios to identify flooding and erosion risks, including estimates of direct damages to structures and how beach recreational, non-market values change with beach width. Adaptation solutions, identified by a steering committee and stakeholders, were modeled through physical responses to the public beach and private assets over time by linking physical changes in widths and water depths to damages, economic costs, and benefits from beach recreation and nature. The study provides a comprehensive benefit–cost framework based on project lifecycle costs and benefits that include the following: (i) flood damage prevention to property and infrastructure (public and private), (ii) recreation, and (iii) ecological value of beaches, measured as non-market and replacement cost values, respectively. The approach, therefore, assesses economic impacts associated with public trust recreation and ecosystem services over time, which represents a novel approach for assessing cost and benefits of adaptation strategies. Often, short-term adaptation armoring responses protect assets at the expense of the long-term health of public trust resources such as beach recreation and coastal ecosystems. Valuing public trust ecosystem services along with other adaptation benefits has been less evaluated in research thus far. However, this study for Imperial Beach also uses replacement cost as a proxy for ecosystem services, assigning economic values of development and infrastructure, recreation, and ecosystem services to each beach width. These estimates of replacement cost for loss of beach services, previously used on wetlands, are innovative and relevant for quantifying and tracking adaptation benefits of projects. This approach also allows for the inclusion of a managed retreat policy approach using a public buyout and rent-back option.

In Imperial Beach, Revell et al. identifies that coastal armoring can provide the least public benefits over time, while a cobble beach and a dune, in the form of a living shoreline approach, present the greatest public benefits among the protection strategies. Yet, the study shows that managed retreat, through a leaseback or long-term rental option, could be the best long-term adaptation strategy. Results from the physical analysis of beach width versus upland property also show that upland property would be maintained into the future, while the beach is eventually lost, but between nine and eleven nourishment cycles would be required by 2100 to maintain a recreational beach to accommodate 2 m of SLR and maintain beach width and protect upland property.

3.3. From Science to Action: Developing Actionable Adaptation

Information on hazards and solutions may facilitate progress for the coast's sustainable and resilient future, but effective adaptation requires careful consideration of many important aspects that intersect between sectorial activities; policies, public, and private property; and even communication. This Special Issue also presents some fresh perspectives from California, Florida, and Mexico on barriers, experiences, lessons, cultural views, and effective communication that influence effective adaptation.

First, communicating SLR and other coastal risks is not a simple task. Communicating adaptation needs is challenging because SLR is a phenomenon that is abstract to many people; climate change is a slow and temporally distant process; and the benefits of adaptation will only materialize in the future and may not always be tangible to everyone today. Calil et al. [24] showed that visualizing SLR simulations using Virtual Reality (VR) technology may offer a method to overcome some of these challenges, as it enables users to learn key principles related to climate change and coastal risks in an immersive, interactive, and safe learning environment. The article shows three key experiences of how VR has served to effectively facilitate new ways to engage with communities, communicate and visualize the impacts, and inform local action through multidisciplinary collaborations between scientists and communities. The article also reviews the literature on communication of environmental issues, which suggest that the context as much as the environmental issue is critical to promote pro-environmental behavior and attitudes. Calil et al. demonstrated that VR can play an important role in facilitating the local understanding of climate change impacts and solutions in coastal zones but also to effectively engage communities in planning adaptation measures. The recent technological advancements and decreases in the cost of technology elevate VR as a prime tool that could be mainstreamed in the future in adaptation efforts to engage communities in planning processes.

Similarly, managed retreat has often faced steady resistance in many communities. Managed retreat may represent a cost-effective option in the long term (e.g., as in Imperial Beach), but it is challenged by societal perceptions and the large cost in terms of private property loss. Bragg et al. [25] revised the process of seven California communities at imminent risk of SLR and categorized whether they were receptive or resistant to managed retreat as an adaptation strategy. Three prominent themes distinguished the two groups: (1) inclusivity, timing, and consistency of communication; (2) property ownership; and (3) stakeholder reluctance to change. Based on these cases, the authors provide recommendations for communicating managed retreat more effectively so that it does not stymy inclusion in adaptation plans.

However, findings in Stolz et al. [26] suggest that that adaptation views can be mediated by age, attachment to place, and worldviews. Stolz et al. evaluated fishing industry perspectives on SLR exposure and adaptation in three Florida coastal communities. In Florida, SLR stands to produce a significant impact on coastal communities, but the state's fishing industry will be affected in vulnerable areas through disruption of established patterns of fishery and marine resource uses. Florida boasts an abundance and diversity of saltwater fisheries along its 1920 km coastline, valued at over USD 12 billion between recreational and commercial fishing. This important industry is uniquely vulnerable to SLR and other effects of climate change given its physical exposure and high dependence on the resource. Using a semi-structured interview approach, the Stolz et al. study evaluated fishing industry perspectives on SLR risk and adaptation in three Florida coastal communities. The study shows that adaptation responses vary across industry sectors and communities and are strongly influenced by experience, community dynamics, and age. Generally, older fishers were found to be less willing to relocate due to social factors and strong place attachment compared to younger fishers, who are more likely to retreat and/or work from a less vulnerable location.

Escudero and Mendoza [27] provided a perspective on climate change adaptation in Mexico, where the coastline combines high population densities with economic dependence of coastal activities. The coast of Mexico is not only important for the national economy, but it also hosts a great diversity of ecosystems, which are threatened by anthropogenic and hydrometeorological stressors. The population is becoming progressively aware of the urgent need to adapt to the consequences of climate change. The article by Escudero and Mendoza reviews population perception to climate change and adaptation strategies in Mexico and highlight critical institutional and social barriers that have impeded effective implementation thus far. There are different examples of social, institutional, and physical adaptation activities. These activities also include successful ecosystem-based projects, especially on mangrove and coral reef restoration, which are of essential importance to consider for progressing on the path of a successful coastal adaptation in Mexico. The main difficulties encountered for effective implementation, however, include the following: institutional discrepancies in the implementation of strategies at the national and local level; weak governance structures that impede informed and effective participation of society; subordination of climate change strategies to economic growth objectives; overexploitation of natural resources; lack of information on hazards and monitoring; and challenges in resources and effective communication to society of the adaptation strategies. Strategies to climate change in Mexico may consider steps to address them, including economic resources, involvement of civil society and cultural values, effective regulation of land use, addressing environmental degradation, and developing information and communication to advance local adaptation actions.

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