A Global Survey of the application of Sea-Level Projections

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Abstract:

Including sea-level rise (SLR) projections in coastal adaptation is increasingly recognized as crucial. Here we analyze the first global survey on the use of SLR projections comprising 253 coastal practitioners engaged in adaptation/planning from 49 countries with time frames of 2050 and 2100. While recognition of the threat of SLR is almost universally recognized, only 71% of respondents currently utilize SLR projections. Generally, developing countries have lower levels of utilization. There is no global standard in the use of SLR projections: for locations using a standard structure, 53% are planning for a single projection, while the remainder are using multiple projections, with 13% considering an unlikely high-end scenario. Countries with long histories of adaptation and consistent national support show greater assimilation of SLR projections into adaptation decisions. This research proves insightful for improving sea-level science, and informs important ongoing efforts on the application of the science which are essential to promote effective adaptation.

Introduction:

The appropriate use of sea-level rise (SLR) projections in coastal decision-making is critical but challenging. The scenarios used (and the way in which they are used) will have profound impacts on our social, ecological, and economic coastal systems [1–3]. Hundreds of millions of people currently living in coastal zones face significant risks due to SLR, and the implementation of proactive adaptation measures would be prudent [4]. Coastal ecosystems are already under stress from ocean warming, acidification and SLR, compounded by human interventions, and expected responses over this century include habitat contractions, translocation, and loss of biodiversity and functionality [5]. Recent estimates suggest that coastal adaptation costs for the developing world will range from $26–89 billion a year by the 2040s [6]. Hence, the SLR scenarios used by decision-makers have substantial cost and risk implications, with the danger of overinvestment for unnecessary protection [7] versus underinvestment, leading to escalating inundation risk and emergency response challenges for vulnerable communities [8,9].

Sea-level science is a well-developed field of study with decades of scientific experience with increasing sophistication and new modeling platforms providing a deeper understanding of future sea-levels and associated uncertainties [2,10]. The Intergovernmental Panel on Climate Change (IPCC) has released six major assessments, based on an extensive body of literature [2,11]. Researchers have broadened work from a focus on median SLR estimates to the consideration of high-end SLR scenarios, increasing frequency of flooding, changing storm events, and waves to capture the widening uncertainty [2,11–15]. Global emissions in the coming decades and the sensitivity and tipping points of various SLR components drive uncertainty in projections, especially for the Greenland and Antarctic ice sheets[16–18]. This deep uncertainty challenges decision analysis [14,19]. Assimilation by practitioners, managers, and decision-makers of long-term SLR requires recognition and clear understanding of the widening uncertainties and how they can be articulated in planning [20–22].

Coastal and estuarine environments are highly dynamic, and communities living within them have a long history of adaptation [23,24]. Formal efforts to build a shared body of knowledge including frameworks to address SLR adaptation began with the first IPCC assessment and associated guidance in the 1990s [25–30]. Regional and local efforts to plan for future climates and implement adaptation measures have been undertaken by coastal managers for the last two decades and these efforts are still growing [31–33]. Increasing knowledge[34], public awareness, and programs to facilitate and promote adaptation[35] in some places puts pressure on decision-makers to incorporate sea-level science into planning efforts and guidance [23,36,37].

Successful coastal adaptation requires robust science-policy integration and well-designed climate services, both built on ensuring the usability of scientific information [38,39]. Building and designing these systems requires an understanding of how to make science-based decisions in the context of increasing uncertainties with time in SLR. With a few exceptions [40,41], however, there has been little assessment of adaptation practice in coastal areas, and especially the sea-level scenarios used by practitioners to inform the science-policy interface. Assessment of sea-level adaptation practices and accompanying scenarios will inform the future development of sea-level science, and would be accompanied by an improved understanding of how to translate uncertainty in sea-level projections into the decision environment.

Here we distributed the first global survey on this topic via a confidential questionnaire to coastal practitioners in every inhabited continent across the globe in eight different languages. The questionnaire asked for specific time horizon and projection information currently in coastal planning materials for areas under their jurisdiction, the science behind SLR projections used in policy, and how practitioners apply SLR projections. Through quantitative and qualitative analyses, we found spatial relationships between global coastal regions and the degree of use of sea-level science in plans. We found surprisingly that most coastal managers are using a single SLR projection rather than the recommended approach of considering a range of possible SLR values to account for uncertainty. We also learned that a wide range of future projections are in use and that there is no globally standardized approach to selecting and using SLR projections.

Results

Uneven Distribution of The Use of Sea-Level Science

We gained important insights at the global, continental, regional and country scales about whether and to what degree coastal managers are using SLR projections in their coastal planning. Working closely with partners and using a snowball sampling approach[42] we recruited 253 coastal managers each of whom completed our questionnaire. This sample represents the first global data collection on SLR use in decision making (Supplementary Table 1, Supplementary Table 2 & Supplementary Fig 1). Our analysis focuses on the information provided by our respondents about their use of sea-level science, not on the number of respondents per region. The distribution of responses in our samples, however, is clearly geographically uneven, which contributes to the fact that we did not note a strong correlation between the use of future sea-levels in planning and country level covariates including GDP, education levels, and the human development index. That is not to say that no relationship exists and further research with a different sampling approach and a greater number of respondents could better explore such relationships.

We found that 181 (72%) respondents are in Group 1, which means that they have formally adopted guidance materials, reports, or policy documents that include SLR projections in their coastal planning processes. This group represents areas with nearly half of the world's coastal population. We also found that 67 (26%) respondents are in Group 2 and are trying to use SLR projections; however, they do not have a formal policy in place yet. Finally, only 5 respondents (2%) are in Group 3, meaning that they are not trying to use SLR projections in their planning work (Supplementary Table 3).

At the continental scale (Fig 1A and Supplementary Table 4), we found that Europe, Australia/Oceania, and North America were the continents with the largest proportions of respondents using SLR projections in planning. Respectively, they had 87% (N=31), 84% (N=44) and 77% (N=126) of their respondents in Group 1. The continents with the lowest percentages of respondents in Group 1 are Asia and South America (36% (N=39) and 33% (N=3), respectively). Africa is intermediate, with 50% (N=10) of respondents in Group 1. Regionally (Fig 1B and Supplementary Table 4), we observe important differences within continents. In Europe we found that North and West Europe have 95% (N=20) of their respondents in Group 1, compared to only 50% (N=6) in Southern Europe (Northern Mediterranean). Continentally aggregated data obscures the North America dichotomy between the United States, where 80% (N=95) of respondents are in Group 1, and the Caribbean Islands, where only 20% (N=5) are in Group 1.

We found that certain countries are particularly high users of SLR projections in their coastal planning processes (Supplementary Table 4), such as New Zealand (90% of respondents). This is a reflection of the availability of SLR scenarios and clearly-articulated guidance for practitioner use created at the national level (see Lawrence et al. 2018). In another example, we found that in the United Kingdom, which has a long history of including relative SLR in infrastructure design pre-dating climate change concerns (e.g., Gilbert & Horner, 1984), 100% of respondents (N=8) use SLR projections in their planning processes. We infer from these examples that robust national guidance and a longer history of SLR integration in planning contribute to the ongoing use of SLR projections in current coastal planning.

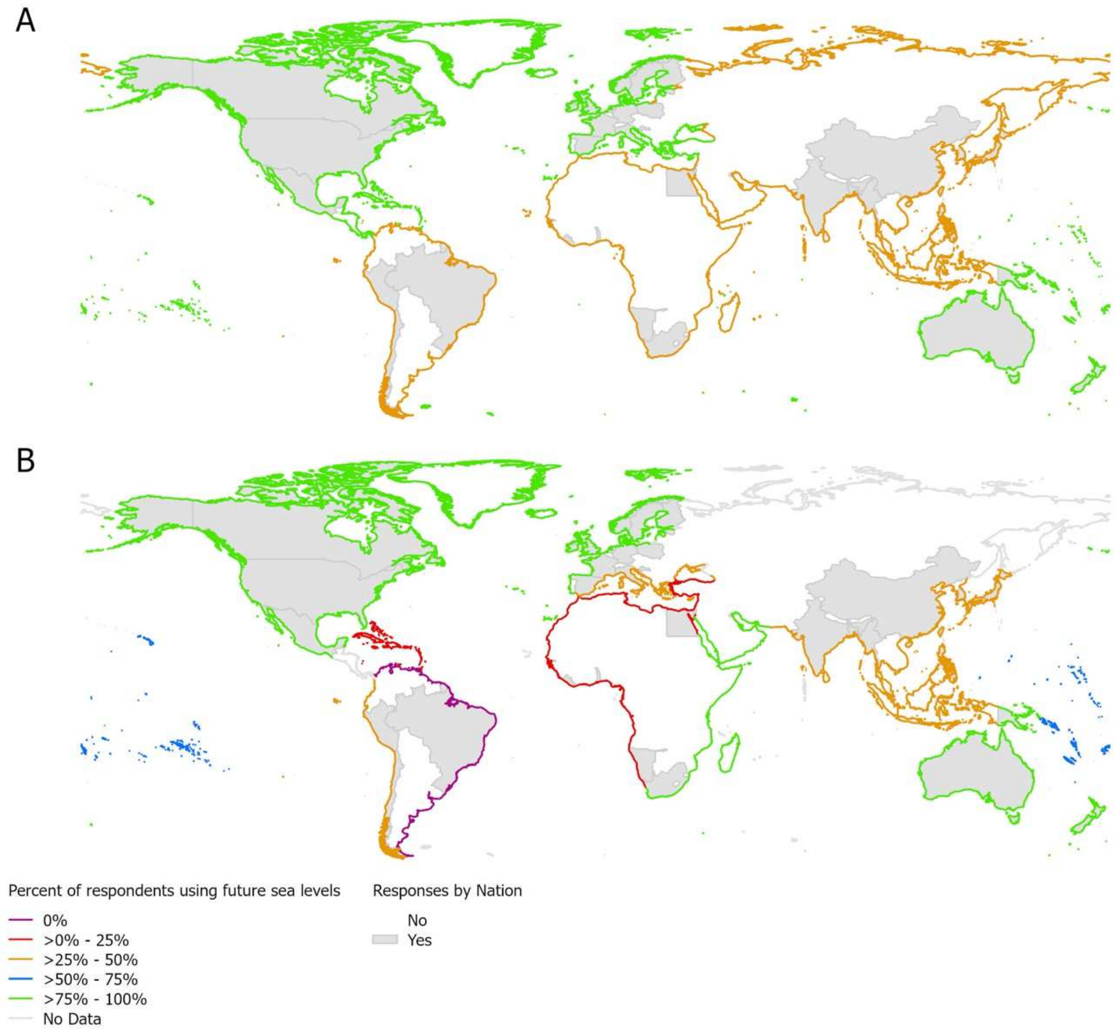

Fig. 1 Percent of respondents by continent (A) and coastal region (B) who are using sea-level rise in coastal planning processes and the countries (in grey) that provided responses

In contrast, we found certain regions and countries to have a low use of SLR projections (Supplementary Table 4). Japan, where 80% of respondents (N=5) were not using SLR projections in planning, has an extreme tsunami risk which was demonstrated in 2011 [43]. This extreme risk and recent experience, including rebuilding and adapting to tsunami risk, may overpower concerns about smaller SLR projections of between 1 and 2 meters. However, tsunami risk greatly increases with SLR and therefor SLR ought not to be ignored[44]. Other places, such as Western Africa, where none of our respondents said that SLR is part of planning, could be stymied by a lack of capacity for long-term planning (e.g., 2100 and beyond) and rather focus on the near term (i.e., next 10 – 20 years). These findings suggest that lack of capacity and competing priorities could both be playing a role in areas with low use of future SLR projections.

The Nature of Depicting the Future

We asked coastal managers if SLR projections fell under formal structures (A,B,C,D) for both 2050 and 2100. Of the 143 respondents that indicated use of these formal structures, the most common structure (A) is a singular estimate, which is used by 76 (53.1%) respondents (Fig 2). A low, intermediate, and high estimate was the second most common structure (C) used by 28 (19.6%) respondents, while 20 (14.0%) respondents used a low and high estimate (B). The least common structure (D), with 19 (13.3%) respondents, was the structure with a low, intermediate, high, and high-end estimate[*45]. In addition to these four common structures, forty respondents (16.0% of the original sample), are using unique structures tailored to their locations.

Notably, Structure A is used by most respondents on every continent for both 2050 and 2100. In Oceania, Asia, and Africa Structure A is used by 78.8%, 72.7%, and 66.7%, respectively. This finding contrasts with both guidance on SLR planning[19,37] and the work of the scientific community to refine and clarify the range of future sea levels and associated uncertainties [2]. Given the stark contrast between the use of a single projection by most practitioners surveyed and the widely recommended approach of considering a range of possible SLR values for any future period, the survey suggests that greater effort and investment is needed to provide more robust climate services to globally achieve coherent translation of sea-level projections and their uncertainties. Some coastal managers in the United States, Northern / Western Europe, New Zealand / Australia, and Northern Africa are using a high-end SLR scenario (Structure D) (Supplementary Fig 2). No other coastal regions in our sample are using this structure. The United States has the greatest use of high-end SLR scenarios, with 17 locations across the country using this type of scenario. The use of high-end SLR scenarios in plans provides an opportunity to understand the uncertainty, consider plausible high-end scenarios, and stress-test

[*] This was defined as the highest future sea level estimate based on extreme but plausible information. In some jurisdictions it is referred to as H++

long-term adaptation options to better bracket and plan adaptation and avoid maladaptation[11]. Conversely, adoption of this extreme value in planning can lead the public and policy makers to mistakenly anticipate more expensive and socially disruptive adaptation measures than are necessary, unless an adaptive approach is employed [37, 41, 48]. Hence, the survey identifies that more guidance concerning the use of high-end scenarios, including adaptive decision analysis, would be useful.

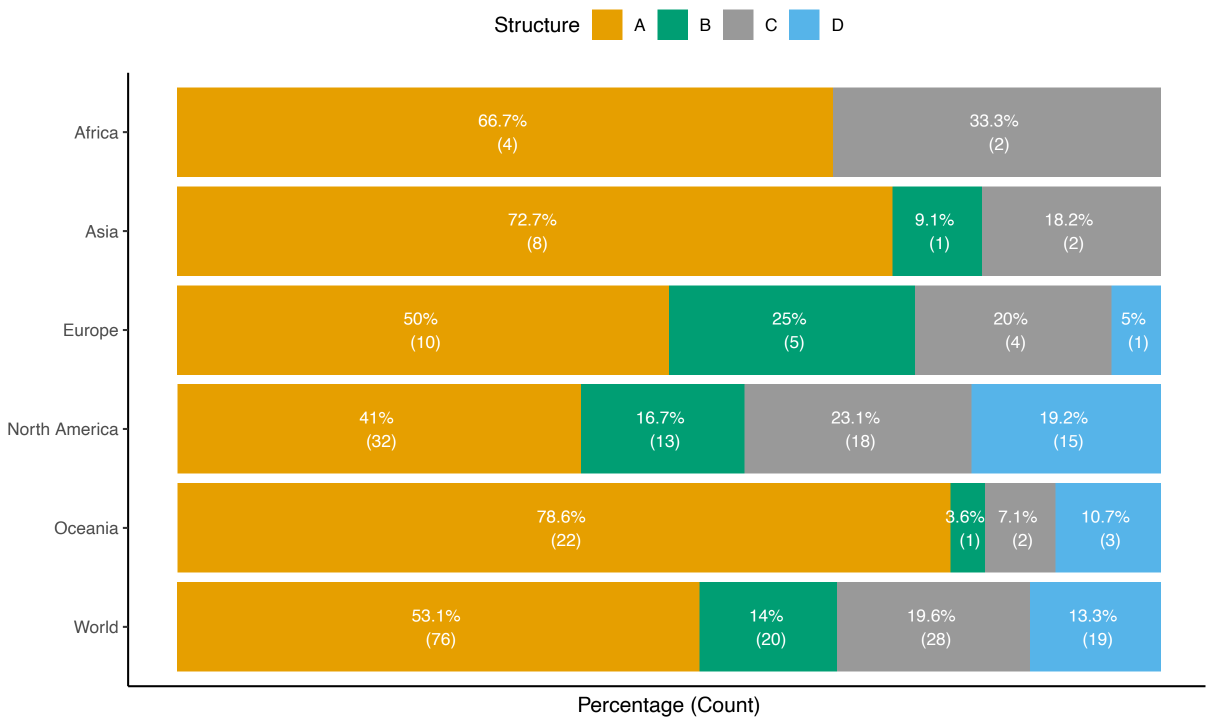

Fig. 2 Respondents structure the use of sea-level rise projections for planning purposes in four ways: A is a singular estimate, B is a low and a high estimate, C is a low, intermediate, and high estimate, and D is a low, intermediate, high, and high-end estimate. Shown are aggregated responses for five distinct geographical regions and the globe.

We observe an interesting difference between Canada and the USA. In Canada 16 places (84%) are using a single future estimate (A) and 3 places (16%) are using a low, intermediate, and high (C) SLR projections. Conversely, in the United States there is a much wider range of approaches: 14 places (24%) are using a single future estimate (A), 11 places (19%) are using a low and high estimate (B), 16 places (28%) are using a low, intermediate, and high estimates (C), and 17 places (29%) are using a low, intermediate, high, and high-end estimate (D). This difference is likely the result of national and regional guidance that emphasizes or de-emphasizes high-end estimates. For example, the State of California explicitly calls attention to the H++ scenario or 3 meters in 2100 and recommends its use in extreme risk averse decision contexts[46]. In contrast, British Columbia, where the majority of Canadian respondents were from, recommends consideration of 1 meter of sea-level rise at 2100 and 2 meter at 2200, adjusted for vertical land motion [47].

No Global Standard

Our findings indicate that a wide range of future projections are used by coastal managers to plan for SLR in both 2050 (Supplementary Fig 3 and Supplementary Table 5) and 2100 (Fig 3 and Supplementary Table 6). Here we focus on the sea-level rise projections[†] for 2100 used by respondents in the four scenario structures defined above. For Structure A (N=76) the median is 0.90 m, with a minimum of -0.15 m in Papua New Guinea and a maximum of 2.03 m in Hayward, California in the United States of America. For Structure B (N=20) the median low value is 0.60 m and the median high value is 1.40 m. Structure C (N=28) has a median low value of 0.51 m, a median intermediate value of 0.75 m, and a median high value of 1.21 m. The 19 respondents using Structure D had a median low value of 0.53 m, a median intermediate value of 1.19 m, a median high value of 1.91 m, and a median high-end value of 3.05 m. We observe that the values for those using Structure A cover almost the full range of values from structures B and C, indicating that this approach is not limited to median or low-end estimates. Finally, we did not find a robust statistical difference between the structure used and median projections; however, those using Structure D do have a higher median for their high estimate and have adopted a median high-end estimate that exceeds projections used in Structures A, B and C.

[†] We report numbers rounded to the nearest cm. Supplementary tables provide more precise numbers.

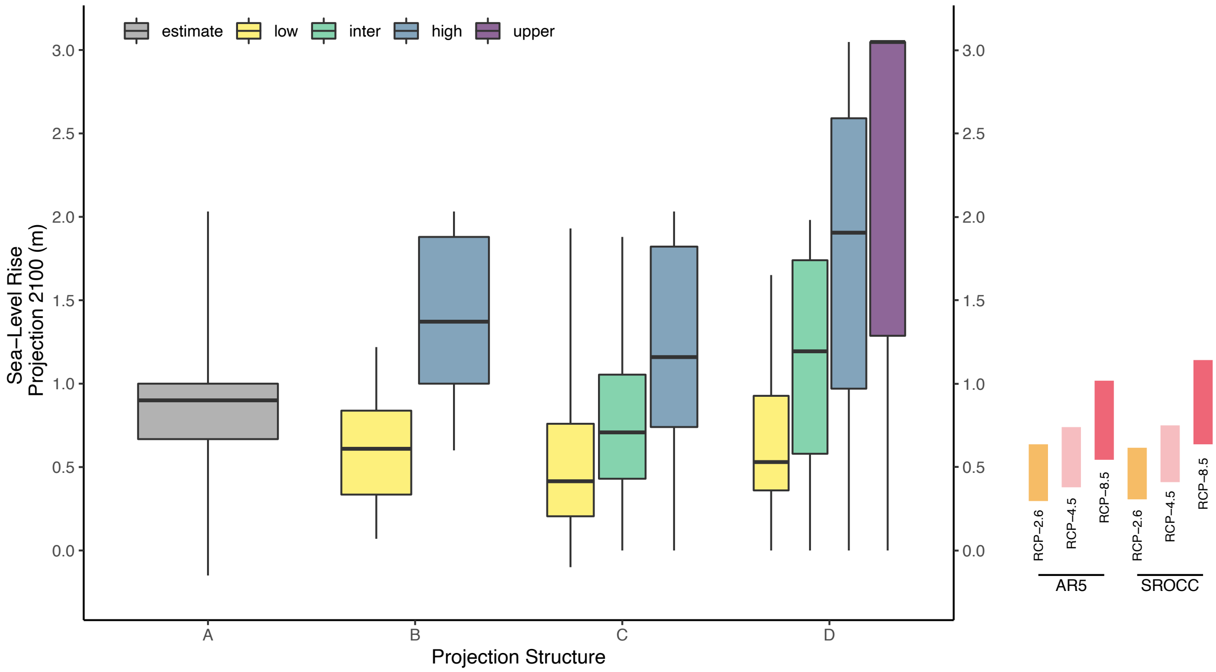

Fig. 3 Left: The SLR projections (in meters) for 2100, which respondents are using in their coastal plans and guidance documents. Projections are grouped by the four projection structures (A to D) shown in Fig 2 and shown as box plots with median values as the dark center line, the box representing the 25th to 75th percentiles, and the whiskers showing the full range of survey responses. Right: The IPCC Fifth Assessment Report (AR5)[1] and Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC)[5] global projections showing the "likely" ranges with the 17th and 83rd percentile.

We compared the projections provided in the survey with IPCC Fifth Assessment Report (AR5)[1] and Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC)[5], which are trusted global sources of SLR relevant to the timing of the survey (Fig. 3). Interestingly, many of the reported future sea levels for planning out to 2100 are lower or significantly higher than the range provided by AR5[1] and SROCC[5]. In total we received 119 responses above the RCP8.5 scenario of 0.98 m across all scenario types (see Supplementary Table 7). This variation may reflect respondents following regional guidance that suggests higher (or lower) SLR than the global IPCC projections based on the timing of the guidance, known regional variations, the use of relative SLR, or inclusion of larger amounts of projected sea-level rise using methods that were given low confidence by the IPCC

Discussion

Our findings reflect the respondents' interpretation of the questions we posed. We asked for sea-level values used for planning purposes. Respondents could have understood these values to include additional water height contributors such as storm surge, regional sea differences, and vertical land motion or they could have understood the value to be the global value that was then adjusted to local conditions. Thus, for some cases we may be comparing differing realizations of flood levels to the projections of mean sea-level change provided in the IPCC reports. However, here we are considering what coastal managers understand to be the future projections for which they are designing and planning. Investigation of the documents provided by survey respondents could provide further insight. Future versions of this survey should structure questions in such a way as to get greater clarity from survey respondents. A future survey could request, in addition to sea-level guidance used by the respondent, plans that were developed based on the guidance, to further investigate how the guidance is realized (e.g., The Bangladesh Delta Plan[48]).

The next step in this line of research could be to assess whether and how certain larger scale SLR guidance is assimilated into decisions. Specifically, does the design and regulatory environment of national guidance directly influence the local (i.e. city / county) level SLR planning? For example, does the national guidance in New Zealand, based on a dynamic adaptation pathways planning approach[37], provide local practitioners with more usable information? Additionally, more work is needed to understand the reasons behind the different approaches and progress in different communities. Interviews with practitioners across the globe would provide significant insights into the barriers encountered and opportunities available. Finally, more research is needed on how these policy and guidance documents inform the physical infrastructure and land-use planning decisions made by coastal managers.

As global sea levels continue to rise, planning, designing, and building resilient communities will become a more pressing societal challenge. This research provides global data on how coastal practitioners use sea-level science in adaptation planning of coastal lowlands. Consistent with past research on climate services, we find significant reliance on singular estimates (Fig 2) that do not account for the known uncertainties in the future projections and highly inconsistent approaches to assimilating sea-level science into decision making (Fig 3). This persistent disconnect raises concerns about coastal managers' ability to make informed adaptation decisions. The literature indicates that high quality translation services and peer learning through collaborative organizations improve practitioner use of sea-level science [20,50]. As implementation of SLR adaptation strategies is becoming more prevalent, we hope that this assessment triggers more such studies on the application of SLR science. The insights will create better bridges and shared understanding between science and coastal managers. Further improved surveys of the type described here are essential to inform and assess these efforts.

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A Global Survey of the Application of Sea-Level Projections

Methods

Recruitment and sample. To understand the nature and extend of sea-level science assimilation into decisions on adaptation for coastal lowlands (e.g., land use planning, infrastructure design, managed retreat), we recruited 253 coastal managers from every habitable continent using a combination of two sampling methods. First, we used a snowball sampling approach to reach as many geographic locations as possible. This sampling technique is ideally suited to circumstances where it can be difficult to adequately define the sampling frame[1]. We asked collaborating researchers and climate change specialists at national and regional levels to provide names and contacts at more localized jurisdictions that were known to be involved in sea-level rise (SLR) planning. The second method we used was to identify cities engaged with SLR planning and then target contacts directly within the city. To identify cities we used previous publications about SLR plans and websites (e.g. Climate Adaptation Knowledge Exchange, U.S Resilience Tool Kit, etc.) that provide case studies on SLR planning and design applications. For each location, one point of contact was identified from the official website or personnel database for that city. Some of the participants initially identified were not appropriate contacts due to organizational differences, retirement, or other factors. In these cases, the person usually provided replacement contacts.

Our respondents represent the first global data collection on SLR use in decision making. Though they were not evenly divided, no single continent represented over 50% of respondents (Supplementary Table 1). They comprised 10 (4.0%) from Africa, 39 (15.4%) from Asia, 31 (12.3%) from Europe, 126 (49.8%) from North America, 44 (17.4%) from Australia/Oceania, and 3 (1.2%) from South America. At the regional scale, North America Atlantic Ocean and North America Pacific Ocean had the greatest representation with 78 (30.7%) and 42 (16.6%) of the respondents, respectively. Pacific Ocean Large Islands, which include New Zealand and Australia, East Asia, North and West Europe and Pacific Ocean Small Islands represented between 7.9% and 14.6% of respondents. Africa Atlantic Ocean, Baltic Sea, Caribbean Islands, Northern Mediterranean, South Asia, and Southern Mediterranean made up between 2.0% and 3.2% of the respondents. The South-east Asia, South America Pacific Ocean, Africa Indian

Ocean, South America Atlantic Ocean, and Gulf states had the fewest respondents, each with less than 1%.

At the national scale, we received responses from people in 49 different countries. In forty of the countries we had between one and four respondents. In nine countries we had higher participation. China, Israel, and Japan each had 5 respondents and together they represent 6% of our respondents. In the middle was the United Kingdom, New Zealand, and South Korea with eight, ten and thirteen respondents, respectively. Australia, Canada, and the United States had the greatest number of respondents (26, 26, and 94, respectively). Within the broader context illuminated by the present analysis, we aim to conduct subsequent research activities to better investigate regions such as the Caribbean and Latin America, Africa, and South-east Asia, which were less represented in this research process.

Respondents represented a variety of jurisdictional scales but tended towards a local scale that afforded a unique and tangible perspective on climate adaptation efforts undertaken to directly address SLR threats. 163 respondents (65%) were from local governments (for example, cities, councils, municipalities, towns, and native settlements) with three (1.2%) from infrastructure specific settings (for example ports, airports, and ferries), and 60 (24.0%) respondents were from sub-national governments (for example districts, provinces, states, and territories). Only 24 (9.6%) of our respondents were from national governments. Sixteen (66%) of the national respondents were from island nations such as Nauru in Oceania and Trinidad and Tobago in the Caribbean while eight (33%) were from continental settings such as Bangladesh in Asia and Liberia in Africa. The high representation from local and sub-national respondents aligns with our objective of understanding the use of climate science by those with direct decision-making authority on infrastructure design and land use.

Respondents represent places that account for over 1 billion people. The places respondents answered for range widely in population. At the local government scale, Monhegan, Maine in the United States is the smallest place that we had a respondent from, with a population of 69. At the other end of the size spectrum, we had a local government response from Tianjin, China with a population of over 13 million. The mean population size for local government respondent is 1.04 million. At the sub-national scale, the largest place represented by a respondent was the State of

California in the United States, which has a population of over 39 million. The smallest sub-national respondent was from the Territory of Nunavut – Kugluktuk in Canada, which has a population of 1,491. The mean sub-national scale population is 3.7 million. Finally, at the national scale, the respondent from the smallest place was Niue with a population of 1,620, and the largest place was Bangladesh with 165 million people. The mean national scale population is 25 million. Gathering data from this wide range of populations allows us to gain insight into different places and their unique approaches to using SLR in planning.

Survey Design. The questionnaire ran from November 2020 to August 2021, which can be found in the Supplementary Information (Appendix 1). The questionnaire was designed for coastal managers across the globe to help us understand publicly available information about places and their management decisions relative to SLR planning. The questionnaire was conducted via an online survey platform, Qualtrics. The survey was written in English by the authors, several of whom are native speakers. The survey was then translated into 8 languages (Arabic, Chinese, French, Hebrew, Japanese, Korean, Portuguese, and Spanish) by professional translators. Native speakers of each language then verified the translations. The questionnaire was divided into four sections and consisted of 22 questions for respondents that are using SLR projections in planning. Section 1 was about the specific place and whether it has formally included future sea levels in its planning processes. Section 2 asked questions about formal local policies that include SLR projections, when the documents were developed, how much regulatory force they have, their specific projections for 2050 and 2100, and whether they consider sea level projections past 2100. Section 3 asked further questions about the science and physical processes included in the SLR projections used. Section 4 asked questions about the use of the SLR projections, such as whether the projections have affected development plans, what criteria go into the location's decision-making processes, what kind of planning approaches the location uses, and how often the projections are to be updated. For respondents that are not formally using SLR projections in planning the questionnaire consisted of 2 sections and a total of 5 questions. These respondents had the same first section as those that are using SLR projections. Their Section 2 asked general questions about coastal planning, hazards, and if they are engaged in a process to start to use SLR projections in the future.

Analysis. These data are not well suited to making robust statistical inferences since the snowball sampling method is intentionally non-random and therefore subject to bias. However, the sampling technique does lend itself well to an analysis that is more qualitative in nature. Therefore, the aim here was to present a descriptive overview of the survey data in such a way that it provided insight into our critical research questions. To that end, the analysis primarily focused on where survey respondents are based, the structure of the projections that the respondents are using and the projection values that they provided. We handled some anomalies in the data by switching zeros to NA, in cases where zero didn't make sense relative to other values provided. We also re-labelled 3 structures to reflect the data provided. In conducting the analysis, we spatially assessed the continents (Fig 1A) and regions (Fig 1B) with high and low utilization of SLR projections in planning. We considered the breakdown of projection structures (A, B, C, D) conditional on continent (Fig 2) and region (Supplementary Fig 2), to gain insight into the spatial variability of the structures being used. We summarised the projection values within the various projection structures (Fig 3, Supplementary Fig 3, Supplementary Tables 5 and 6) to investigate any notable internal consistency and/or external consistency. An example of internal consistency in this context would be seeing similarities in projections when comparing low/high estimates across structures B, C and D. An example of external consistency would be seeing projection ranges within the different structures align with IPCC or SROCC projections (Fig 3).

References

1. Atkinson, R. & Flint, J. Snowball Sampling. in *The SAGE Encyclopedia of Social Science Research Methods* (eds. Lewis-Beck, M., Bryman, A. & Futing Liao, T.) (Sage Publications, Inc., 2004). doi:10.4135/9781412950589.n931.

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