SEA LEVEL RISE II – GUIDANCE DOCUMENT

City and County of Honolulu Climate Change Commission May, 2022

PURPOSE

Pursuant to the Revised Charter of Honolulu ("RCH") Section 6-107(h), the City & County of Honolulu ("City") Climate Change Commission ("Commission") is charged with gathering the latest science and information on climate change impacts to Hawaiʻi. It provides advice and recommendations to the mayor, City Council, and executive departments as they draft policy and engage in planning for future climate scenarios as well as reduce Honolulu's contribution to global greenhouse gas emissions.

The purpose of this document is to provide a set of findings and recommendations to the City on sea level rise to augment decision-making. For example, in light of already apparent flooding that occurs during the convergence of extreme tides and rainfall (e.g., Dec. 5, 2021), how high will sea level rise, by when, and what are the hazards associated with sea level rise? Will sea level rise in Honolulu differ from the global mean and why? Are there sea level rise benchmarks on which to base design decisions for architectural, engineering, and nature-based solutions? This document describes the physical nature of sea level rise on the shores of Oʻahu, provides guidance on using on-line planning tools, and discusses uncertainties in sea level rise projections that should be considered in decision-making.

RECOMMENDATIONS

Based on research, the Commission recommends the following:

1. The IPCC AR6 states that global mean sea level will continue to rise for thousands of years, even if future CO_2 emissions are reduced to net zero and global warming halted. On this basis, community design professionals, government agencies, and all coastal stakeholders must recognize that sea level rise is an inevitable, dangerous, and fundamental condition that must be recognized in every element of coastal planning and management.
2. The City and County of Honolulu should adopt the interagency Intermediate High (1.78 m, 5.8 ft by 2100) sea level rise scenario for all planning and design.
3. The City and County of Honolulu should adopt the interagency High (2.41 m, 7.9 ft by 2100) sea level rise scenario for all planning and design of public infrastructure projects.
4. The communities of Miami-Dade County FL, Nantucket Island MA, and Pacifica CA have all adopted the interagency Intermediate High and High sea level rise scenarios in their planning (Appendix 1).
5. In light of new scientific findings (see Table 1), previous Commission Sea Level Rise Guidance[1] adopted June 5, 2018 on the use of 3.2 ft of sea level rise, should be understood to apply to the period 2070 to 2080 under the Intermediate High scenario and 2070 under the High scenario. The use of the 6 ft benchmark is applicable to the end of the century under the Intermediate High scenario, and to the period 2080 to 2090 under the High scenario.
6. With regard to Commision Guidance[2] on revisions to ROH Chapter 23 adopted December 23, 2019, new scientific findings underscore the sea level rise threat to coastal properties and assets and provide added urgency to implement our recommendations.
7. In implementing Intermediate High and High scenarios, all projects should use design elevations with mean higher high water as a datum. Projects with low tolerance for flood risk should add an additional 2 feet of elevation to account for compound events; 1 ft for extreme or "king" tides and 1 ft for runoff accumulation in light of drainage failure at high tides.

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[1] See https://www.resilientoahu.org/climate-change-commission/#guidance
[2] See https://www.resilientoahu.org/climate-change-commission/#guidance

FINDINGS

The Commission has conducted research on the problem of sea level rise and finds the following:

1. The IPCC states with high confidence that global mean sea level increased by 0.20 (0.15 to 0.25) meters over the period 1901 to 2018, with a rate of rise that has accelerated since the 1960's to 3.7 (3.2 to 4.2) millimeters per year for the period 2006–2018.
2. Global mean sea level will continue to rise for thousands of years, even if future CO_2 emissions are reduced to net zero and global warming halted, as excess energy due to past emissions continues to propagate into the deep ocean and as glaciers and ice sheets continue to melt.
3. By 2100, global mean sea level is projected to rise 0.28 - 0.55 meters to 0.63 - 1.01 meters, depending on model scenario, relative to the 1995–2014 average.
4. In a low-likelihood, high-impact storyline and a high carbon dioxide emissions scenario, ice-sheet processes characterized by deep uncertainty could drive global mean sea level rise up to about 2 meters by 2100, and 5 meters by 2150.
5. Given the long-term commitment, uncertainty in the timing of reaching different global mean sea level rise levels is an important consideration for adaptation planning.
6. Sea level rise will bring a range of flood types to coastal areas. These include groundwater inundation, storm-drain backflow, seasonal wave run-up, tropical cyclone storm surge, chronic coastal erosion (land loss), extreme tide flooding, intense rainfall, and compound events (e.g., heavy rain at high tide, a time where there is no drainage capacity in urban areas).
7. Hawai'i and other tropical Pacific locations will experience amounts of sea level rise that are greater than the global average (e.g., sea level fingerprinting, see Appendix 2). Due to global gravitational effects, estimates of future sea level rise in Hawai'i and other Pacific islands are about 15-20% higher than the global mean because of this phenomenon.[3]
8. A federal interagency task force has provided scenarios for designing adaptation to sea level rise (see Interagency Sea Level Rise Scenario Tool, https://sealevel.nasa.gov/task-force-scenario-tool). These represent global mean scenarios, as well as local scenarios reflecting sea level fingerprinting, for every US tide gauge.
9. It is advised that the use of a scenario should reflect project risk tolerance, with higher scenarios becoming appropriate for projects that do not tolerate high levels of coastal flood risk.
10. The Low and Intermediate Low scenarios are inappropriate to use for planning because the present-day rate of sea level rise acceleration is already on-track to produce higher water levels than projected by these two scenarios.
11. Scaled to the Honolulu tide gauge to account for sea level fingerprinting, the remaining three scenarios provide the following planning benchmarks (meters) by 2050 and 2100 (resp.): Intermediate 0.29/1.16, Intermediate High 0.37/1.78, and High 0.45/2.41.
12. The greatest short-term flooding will come from two types of events: tropical cyclone storm surge, and compound flooding by a convergence of rain, high tide, and other tpyes of flooding.

INTRODUCTION

According to Working Group I of the Sixth Assessment Report (AR6) from the Intergovernmental Panel on Climate Change[4] (IPCC) it is unequivocal that human influence has warmed the atmosphere, ocean, and land (**Figure 1**). As a result, widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred. The scale of recent changes across the climate system as a whole, and the present state of many aspects of the climate system, are unprecedented over many centuries to many thousands of years. Human-induced climate change is already affecting many weather and climate

[3] Sweet, W.V., et al. (2017) Global and Regional Sea Level Rise Scenarios for the United States. NOAA Technical Report NOS CO-OPS 083. NOAA/NOS Center for Operational Oceanographic Products and Services.

[4] IPCC (2021) Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of WGI to the AR6, IPCC [Masson-Delmotte, V., et al. (eds.)]. Cambridge Univ Press, Cambridge, UK and NY, USA, pp. 3−32, doi:10.1017/9781009157896.001.

extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since the last IPCC report[5] in 2013.

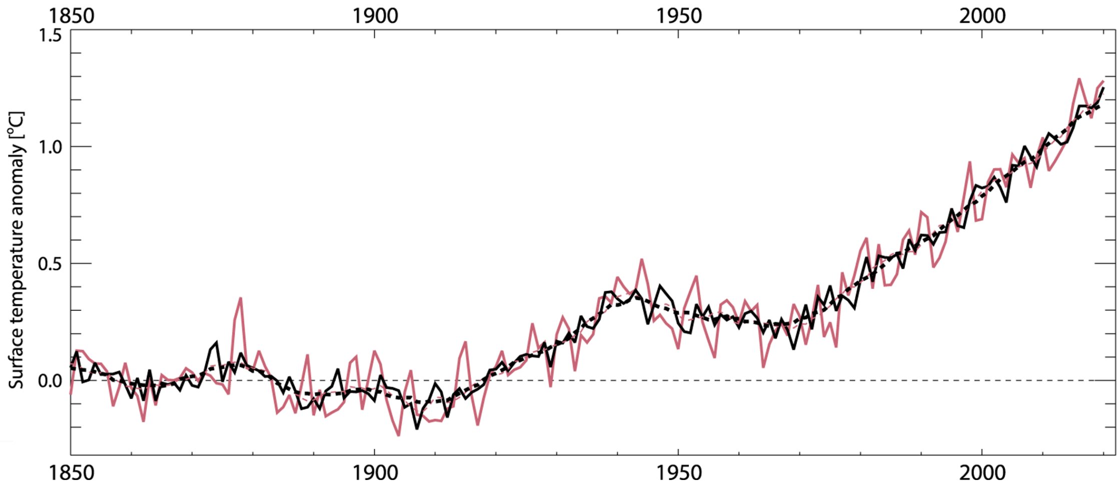

Figure 1. *Raw (red) and filtered (black) HadCRUT5[6] global mean surface temperature anomaly values, relative to 1850–1900. Based on filtered observations (2011-2020), the long-term rate of warming is 0.24 degrees Celsius per decade.[7]*

Global surface temperature will continue to increase until at least mid-century under all the emissions scenarios considered in AR6. Global warming of 1.5 degrees Celsius and 2 degrees Celsius will be exceeded during the 21st century unless deep reductions in carbon dioxide and other greenhouse gas emissions occur in the coming decades. Many changes due to past and future greenhouse gas emissions are irreversible for centuries to millennia, especially changes in the ocean, ice sheets and global sea level.

Climate change projections published in AR6 use scenarios of socio-economic global changes called "shared socio-economic pathways" (SSPs). Based on five narratives, the SSPs describe alternative socio-economic futures in the absence of climate policy intervention, comprising sustainable development (SSP1), middle-of-the-road development (SSP2), regional rivalry (SSP3), inequality (SSP4), and fossil-fueled development (SSP5). Each SSP explores possible future pathways of socio-economic activity, climate, policies, and other social and physical factors (**Figure 2**).[8]

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[5] IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the AR5 of the Intergovernmental Panel on Climate Change [Stocker, T.F., et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

[6] HadCRUT5 is a gridded dataset of global historical surface temperature measurements. Data are available for each month from January 1850 onwards, on a 5-degree grid and as global and regional average time series. The dataset is a collaborative product of the Met Office Hadley Centre and the Climatic Research Unit at the University of East Anglia, U.K. https://www.metoffice.gov.uk/hadobs/hadcrut5/

[7] Samset, B.H., Zhou, C., Fuglestvedt, J.S. et al. (2022) Earlier emergence of a temperature response to mitigation by filtering annual variability. Nat Commun 13, 1578. https://doi.org/10.1038/s41467-022-29247-y

[8] IPCC (2021) Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis.

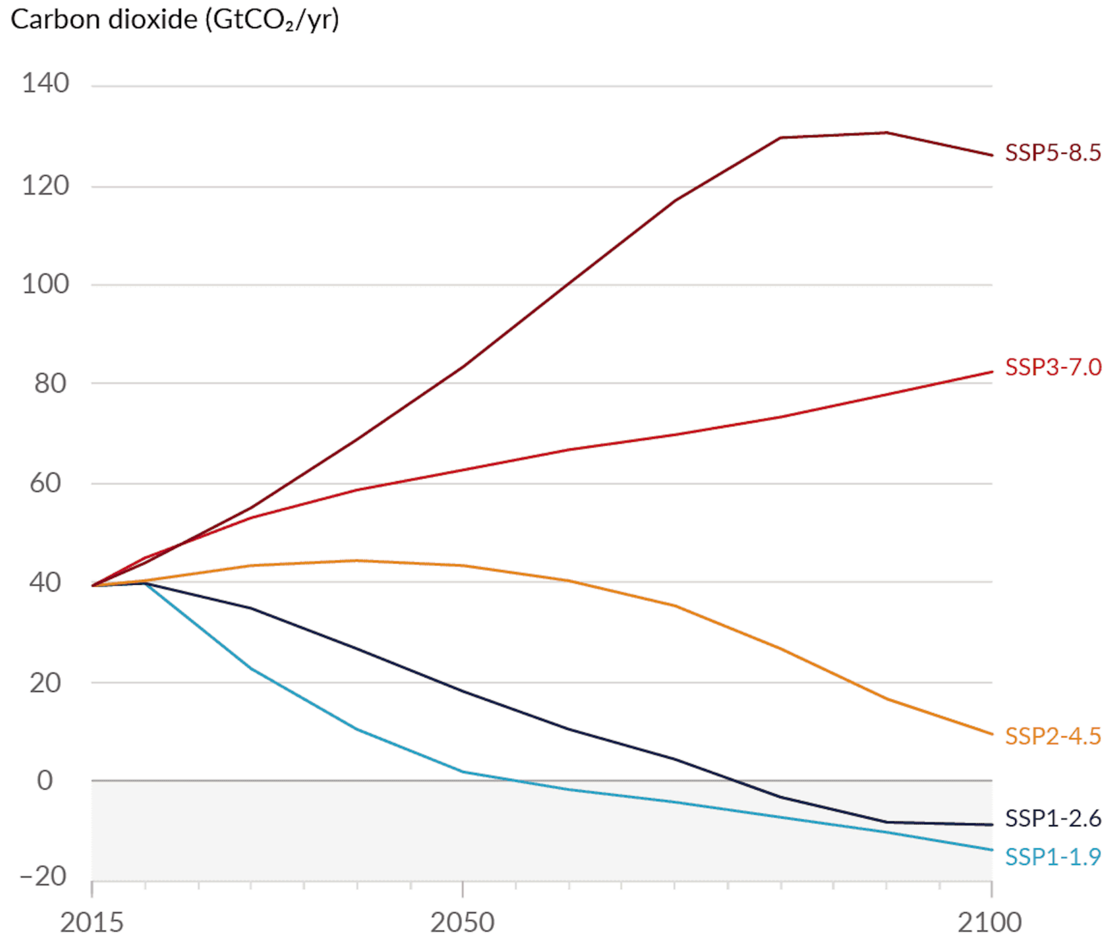

Figure 2. *Future annual emissions of carbon dioxide (Gigatonnes per year) across five shared socio-economic pathways (SSPs).[9] SSP2-4.5, reaching a best estimate of warming equal to 2.7 degrees Celsius by the end of the century, is the scenario currently projected to most closely match public emissions policies.[10]*

GLOBAL PROJECTIONS

The IPCC states with high confidence that global mean sea level increased by 0.20 (0.15 to 0.25) meters over the period 1901 to 2018, with a rate of rise that has accelerated since the 1960's to 3.7 (3.2 to 4.2) millimeters per year for the period 2006–2018. Observational evidence indicates that the individual components contributing to global mean sea level rise include expansion due to ocean warming (45.7 percent), melting of land-based snow and ice (43.5 percent), and anthropogenic groundwater mining, largely for irrigation, (10.8 percent). [11] It is virtually certain (99-100 percent probability) that global mean sea level will continue to rise over the 21st century in response to continued warming of the climate system.

By 2100, global mean sea level is projected to rise by 0.28 - 0.55 meters (66 - 100 percent probability) under SSP1-1.9, and 0.63 - 1.01 meters (66 - 100 percent probability) under SSP5-8.5 relative to the 1995–2014 average (**Figure 3**). However, scientists have criticized these results as being too conservative and

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[9] IPCC (2021) Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis.
[10] Meinshausen, M., Lewis, J., McGlade, C. et al. (2022) Realization of Paris Agreement pledges may limit warming just below 2 °C. Nature 604, 304–309. https://doi.org/10.1038/s41586-022-04553-z
[11] Frederikse, T., et al. (2020) The causes of sea-level rise since 1900, Nature 584, 393–397, https://doi.org/10.1038/s41586-020-2591-3

that actual sea level rise may be higher.[12] Under higher carbon dioxide emissions scenarios, there is deep uncertainty in sea level projections for 2100 and beyond associated with the ice-sheet responses to warming. In a low-likelihood, high-impact storyline and a high carbon dioxide emissions scenario, ice-sheet processes characterized by deep uncertainty could drive global mean sea level rise up to about 2 meters by 2100 and 5 meters by 2150. Given the long-term commitment, uncertainty in the timing of reaching different global mean sea level rise levels is an important consideration for adaptation planning.

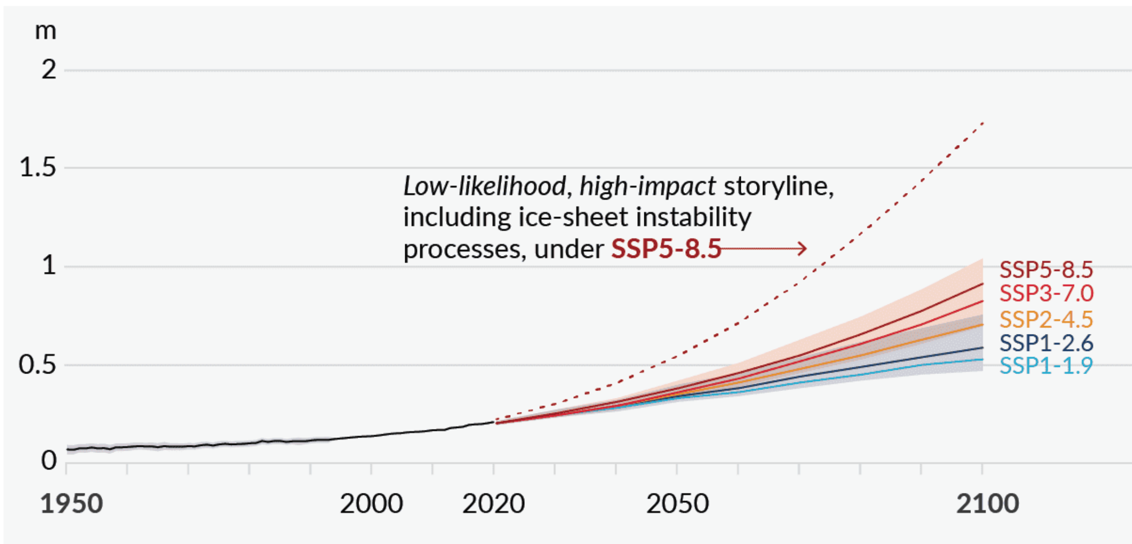

Figure 3. *Global mean sea level change (likely ranges in meters) relative to 1900. Only likely ranges (66 – 100 percent probability) are assessed for sea level changes due to difficulties in estimating the distribution of deeply uncertain processes. The dashed curve indicates the potential impact of these deeply uncertain processes. It shows the 83rd percentile of SSP5-8.5 projections that include low-likelihood, high-impact ice-sheet processes that cannot be ruled out.*[13]

Sea level responds to greenhouse gas emissions more slowly than global surface temperature. This slow response also leads to long-term committed sea level rise, associated with ongoing ocean heat uptake and the slow adjustment of the ice sheets. The IPCC states with high confidence that global mean sea level rise will continue over centuries and millennia long after emissions have ended.

> *"Global mean sea level will continue to rise for thousands of years, even if future CO_2 emissions are reduced to net zero and global warming halted, as excess energy due to past emissions continues to propagate into the deep ocean and as glaciers and ice sheets continue to melt."*[14]

Over the next 2000 years, global mean sea level will rise by about 2 to 3 meters if warming is limited to 1.5 degrees Celsius, 2 to 6 meters if limited to 2 degrees Celsius and 19 to 22 m with 5 degrees Celsius of warming, and it will continue to rise over subsequent millennia. Projections of multi-millennial global mean sea level rise are consistent with reconstructed levels during past warm climate periods: 5–10 meters higher than today around 125,000 years ago, when global temperatures were very likely 0.5–1.5 degrees Celsius higher than 1850–1900; and very likely 5–25 meters higher roughly 3 million years ago, when global temperatures were 2.5–4 degrees Celsius higher.[15]

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[12] Grinsted, A. and Christensen, J. H. (2021) The transient sensitivity of sea level rise, Ocean Sci., 17, 181–186, https://doi.org/10.5194/os-17-181-2021. https://os.copernicus.org/articles/17/181/2021/os-17-181-2021.html
[13] IPCC (2021) Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis.
[14] Arias, P.A., et al. (2021) Technical Summary. In Climate Change 2021: The Physical Science Basis. Contribution of WGI to the AR6 of the IPCC [Masson-Delmotte, V., et al. (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, pp. 33−144. doi:10.1017/9781009157896.002.
[15] Grinsted, A. and Christensen, J. H. (2021)

POTENTIAL FOR EXTREME SEA LEVEL RISE

The carbon dioxide level of the atmosphere has now increased by 50 percent compared to the eighteenth century.[16] Greenhouse gas emissions in the next few decades will strongly influence the long-term contribution of the Antarctic and Greenland ice sheets to global sea level (**Figure 4**).[17] As Earth warms, glaciers and sea ice are melting faster and faster. Earth is now losing an estimated 1.2 trillion tons of ice each year, a 60 percent increase in only 2 decades.[18] The global nature of glacier retreat, with almost all of the world's glaciers retreating synchronously since the 1950s, is unprecedented in at least the last 2000 years.[19] This is especially true in the Arctic.

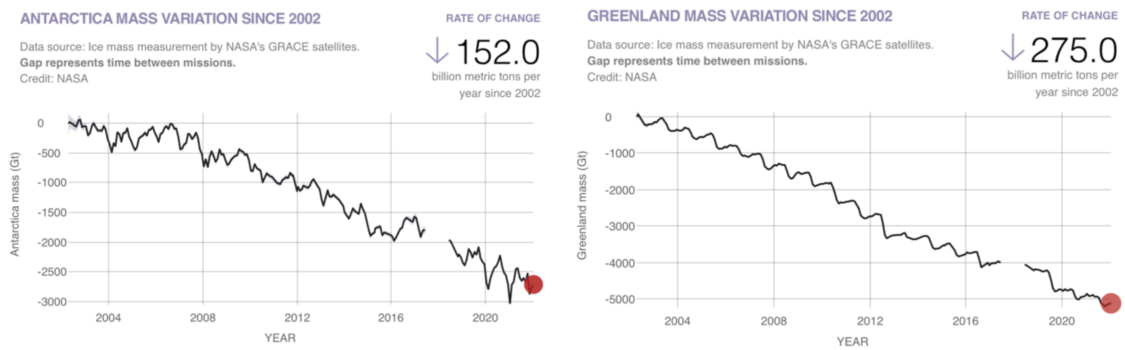

Figure 4. *Since 2002, Antarctica (left) has lost an average 152 billion metric tons of ice per year, and Greenland (right) has lost an average 275 billion metric tons of ice per year.*[20]

Although sea level rise projections under a high emissions scenario are about 1 meter by 2100, models lack capacity to simulate rapid ice sheet failure, and observations show that Greenland and Antarctic ice sheets are melting at accelerating rates. For instance, annual snowfall that normally replenishes the Greenland Ice Sheet can no longer keep pace with ice melt, triggering an irreversible feedback and very likely leading to an ice-free Greenland within a millennium.[21] Mass loss from the Greenland Ice Sheet is 7 times faster than it was in the 1990's,[22] and has quadrupled this decade.[23] Between July 30 and Aug. 2, 2019, approximately 90 percent of the surface of Greenland's ice sheet melted, causing about 55 billion tons of ice to melt into the ocean.[24] Greenland Ice Sheet meltwater has increased 250 to 575 percent in only 20 years.[25]

There is concern that with less than 0.5 degrees Celsius of additional warming, melting on Greenland will become unstoppable.[26] The Greenland Ice Sheet is vulnerable to a positive melt-elevation feedback that may reach a tipping point beyond which the ice sheet may become unstable. The nonlinear feedback

[16] UK MET Office (2021) https://www.metoffice.gov.uk/research/climate/ seasonal-to-decadal/long-range/forecasts/co2-forecast-for-2021
[17] Golledge, N.R., et al. (2015) The multi-millennial Antarctic commitment to future sea-level rise: Nature, 2015; 526 (7573): 421 DOI: 10.1038/nature15706.
[18] Slater, T., et al. (2021) Review article: Earth's ice imbalance, The Cryosphere, 15, 233–246, https://doi.org/10.5194/tc-15-233-2021
[19] Hugonnet, R., McNabb, R., Berthier, E. et al. (2021) Accelerated global glacier mass loss in the early twenty-first century. Nature 592, 726–731, https://doi.org/10.1038/s41586-021-03436-z
[20] NASA Vital Signs of the Planet, https://climate.nasa.gov/vital-signs/ice-sheets/
[21] Aschwanden, A., et al. (2019) Contribution of the Greenland Ice Sheet to sea level over the next millennium, Science Advances, 19 Jun: V. 5, no. 6, eaav9396, DOI: 10.1126/sciadv.aav9396. King, M.D., et al. (2020) Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat. Commun Earth Environ 1, 1. https://doi.org/10.1038/s43247-020-0001-2
[22] Shepherd, A., et al. (2019) Mass balance of the Greenland Ice Sheet from 1992 to 2018. Nature 579, 233–239. https://doi.org/10.1038/s41586-019-1855-2
[23] Bevis, M. et al. (2019) Accelerating changes in ice mass within Greenland, and the ice sheets sensitivity to atmospheric forcing. PNAS, 116, 1934-1939
[24] National Snow and Ice Data Center (2019) Europe's warm air spikes Greenland melting to record levels, http://nsidc.org/greenland-today/2019/08/europes-warm-air-spikes-greenland-melting-to-record-levels/
[25] Trusel, L.D., et al. (2018) Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming, Nature 564, 6 Dec: https://doi.org/10.1038/s41586-018-0752-4
[26] Climate tipping points—too risky to bet against, Nature (2019) https://nature.com/articles/d41586-019-03595-0

invokes melting that reduces ice sheet height, exposing the ice sheet surface to warmer temperatures, which further accelerates melting. Using ice cores to reconstruct ice sheet height, researchers warn[27] that the Western Greenland Ice Sheet has been losing stability in response to rising temperatures and that substantially enhanced melting, driven by the melt-elevation feedback, may develop in the near future.

Melting of the Antarctic ice sheet is also accelerating. The rate of melting has tripled in the past 5 years.[28] At 2 degrees Celsius of global warming, melting on the Antarctic Ice Sheet is projected to produce 1.3 meters of global mean sea level rise. Above 2 degrees Celsius, it will nearly double to 2.4 meters per degree of warming.[29] Researchers have concluded that irreversible collapse of Pine Island and Thwaites outlet glaciers in the Amundsen Sea sector of West Antarctica has already begun,[30] and that ice shelves holding them back "*…are showing new damage areas that are the first signs of structural weakening and precondition these ice shelves for disintegration*."[31] Pine Island and Thwaites glaciers, could raise global mean sea level by 1.2 meters.

Arctic Sea ice is in free-fall. Sea ice is Earth's refrigeration system because the white surface reflects sunlight back to space. But as the snow and ice are replaced by the dark water of the Arctic Ocean, the rate of regional warming has quadrupled compared to the rest of the planet.[32] In 1985, 33 percent of Arctic ice pack was very old ice (>4 years old), by March 2019 old ice constituted only 1.2 percent of the ice pack in the Arctic Ocean.[33] In 2011–2020, annual average Arctic Sea ice area reached its lowest level since at least 1850.[34] Late summer Arctic Sea ice area was smaller than at any time in at least the past 1000 years. Although loss of sea ice does not contribute to sea level rise, it does exert a strong regional climate control that influences stability of the Greenland Ice Sheet. Reductions in Arctic Sea ice, regional snow cover, and permafrost grow annually, and the transition from a snow- to rain-dominated Arctic in the summer and autumn may occur as early as 2040, with profound climatic, ecosystem and socio-economic impacts.[35]

PLANNING FOR SEA LEVEL RISE

IPCC AR6 projects larger ice loss from the Antarctic Ice Sheet than in previous studies, and uncertainty at the end of this century is mainly determined by the ice sheets, especially in Antarctica. AR6 also provides a low-likelyhood, high impact storyline resulting in multi-meter sea level rise this century. Importantly, the report acknowledges that processes controlling the timing of future ice-shelf loss and the extent of ice sheet instabilities, could increase Antarctica's contribution to sea level rise substantially higher than reported.

Mass loss from from the cryosphere, as well as thermal expansion of oceanwater as it absorbs excess heat trapped by greenhouse gases, are the primary drivers of global mean sea level rise. Acceleration of these in the near future will depend on two principle factors: 1) continued warming related to greenhouse gas emissions and the response of bio-physical systems;[36] and, 2) the nature of amplifying feedbacks in both

[27] Boers, N., and Rypdal, M. (2021) Critical slowing down suggests that the western Greenland Ice Sheet is close to a tipping point, PNAS, May, 118 (21) e2024192118; DOI:10.1073/pnas.2024192118
[28] The IMBIE team (2018) Mass Balance of the Antarctic Ice Sheet, Nature, 558, p. 219–222, https://doi.org/10.1038/s41586-018-0179-y
[29] Garbe, J., Albrecht, T., Levermann, A. et al. (2020) The hysteresis of the Antarctic Ice Sheet. Nature 585, 538–544. https://doi.org/10.1038/s41586-020-2727-5
[30] Joughin, et al. (2014) Marine Ice Sheet Collapse Potentially Underway for the Thwaites Glacier Basin, West Antarctica. Science; DOI: 10.1126/science.1249055. Rignot, E., et al. (2014) Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. Geophys. Res. Lett. 41, 3502–3509.
[31] Lhermitte, S., et al. (2020) Damage accelerates ice shelf instability and mass loss in Amundsen Sea Embayment. Proceedings of the National Academy of Sciences, Sept. 14; DOI: 10.1073/pnas.1912890117
[32] https://agu.confex.com/agu/fm21/meetingapp.cgi/Paper/898204.
[33] Perovich, D., et al. (2019) Sea Ice. NOAA Arctic Report Card 2019, J. Richter-Menge, M. L. Druckenmiller, and M. Jeffries, Eds., http://www.arctic.noaa.gov/Report-Card.
[34] IPCC (2021) Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis.
[35] McCrystall, M.R., et al. (2021) New climate models reveal faster and larger increases in Arctic precipitation than previously projected. Nat Commun 12, 6765 https://doi.org/10.1038/s41467-021-27031-y
[36] Duffy, K.A., et al. (2021) How close are we to the temperature tipping point of the terrestrial biosphere? Science, 13 Jan., v. 7, iss. 3, https://doi.org/10.1126/sciadv.aay1052

the air temperature response to emissions, and the ice response to increases in temperature. Both of these factors are unknown, or at least poorly understood.

Sea level rise intensifies the impact of storm surge, seasonal wave action, coastal erosion, groundwater inundation, and runoff flooding with consequences including infrastructure damage, and land loss (**Figures 5**).[37] For low-lying atoll communities, sea level rise threatens aquifers, the agro-forestry, roads, homes, and commercial districts. Future sea level rise is projected to affect human health and wellbeing, cultural and natural heritage, freshwater ecosystems and resources, biodiversity, agriculture, and fisheries.[38] In coming decades and centuries sea level rise will radically redefine the world's coastlines,[39] potentially displacing more than 600 million people this century.[40]

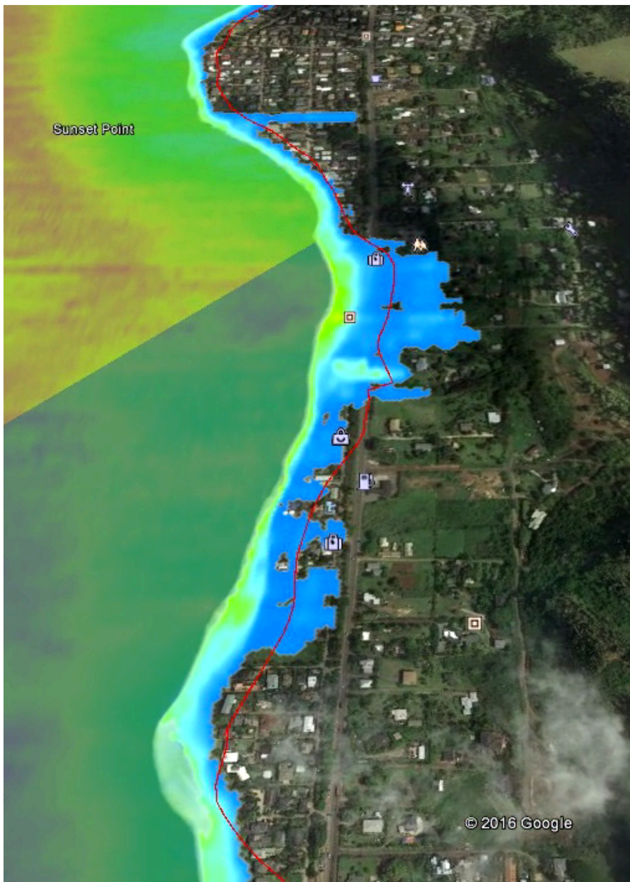

***Figure 5.** Model result showing the erosion (red line) and annual wave run-up (blue) under 98 cm of sea level rise at Sunset Beach, Oahu's North Shore. This is an oblique image of model results found at the Hawaiʻi SLR Viewer.[41]*

Several aspects of sea level rise are not widely known but should be taken into account when developing local adaptation plans:

1. Low-lying coastal areas may flood by groundwater inundation before direct marine flooding. Groundwater inundation creates wetlands, first at only the highest tides of the year, but in time with

[37] McMichael, C., Dasgupta, S., Ayeb-Karlsson, S., & Kelman, I. (2020) A review of estimating population exposure to sea-level rise and the relevance for migration. Environmental Research Letters, 15(12), 123005, https://doi.org/10.1088/1748-9326/abb398

[38] Norwegian Red Cross (2019) Overlapping vulnerabilities: the impacts of climate change on humanitarian needs, Oslo: Norwegian Red Cross.

[39] Hauer, M. E., et al. (2020) Sea-level rise and human migration. Nat. Rev. Earth Env.,1:28–39. doi: 10.1038/s43017-019-0002-9.

[40] Kulp S. A, Strauss B. H. (2019) New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nat. Comm., 10:4844. doi: 10.1038/s41467-019-12808-z.

[41] https://www.pacioos.hawaii.edu/shoreline/slr-hawaii/

increasing frequency, eventually becoming permanent. In urban areas, groundwater inundation is damaging to many types of public infrastructure and private assets.[42]

2. Engineered drainage systems may backflow salt water onto streets as part of sea level rise, especially during high tides. In Hawai'i, the frequency of local high tide flooding has increased from 6 to 11 days per year since the 1960's.[43]
3. Typically, the first evidence of sea level rise is chronic coastal erosion and high tide flooding. Both of these have already increased on O'ahu and elsewhere in Hawai'i, and the world.
4. Seasonal wave run-up, already a problem in some locations, will continue to grow as a threat to public and private assets in coastal communities.
5. Hawai'i and other tropical Pacific locations will experience amounts of sea level rise that are greater than the global average. Due to global gravitational effects, estimates of future sea level rise in Hawai'i and other Pacific islands are about 15-20% higher than the global mean.[44]

Modeling the statewide impacts of 0.98 m (3.2 ft) of sea level rise indicate that 25,800 acres of land will experience chronic flooding, erosion, and/or high wave runup (**Figure 6**).[45] One-third of this land is designated for urban use, and impacts include more than $19 billion in assets. Additionally, present day 100-yr extreme sea level events are projected to occur at least once a year by the end of the century, even under only 1.5 degrees Celsius of warming.[46]

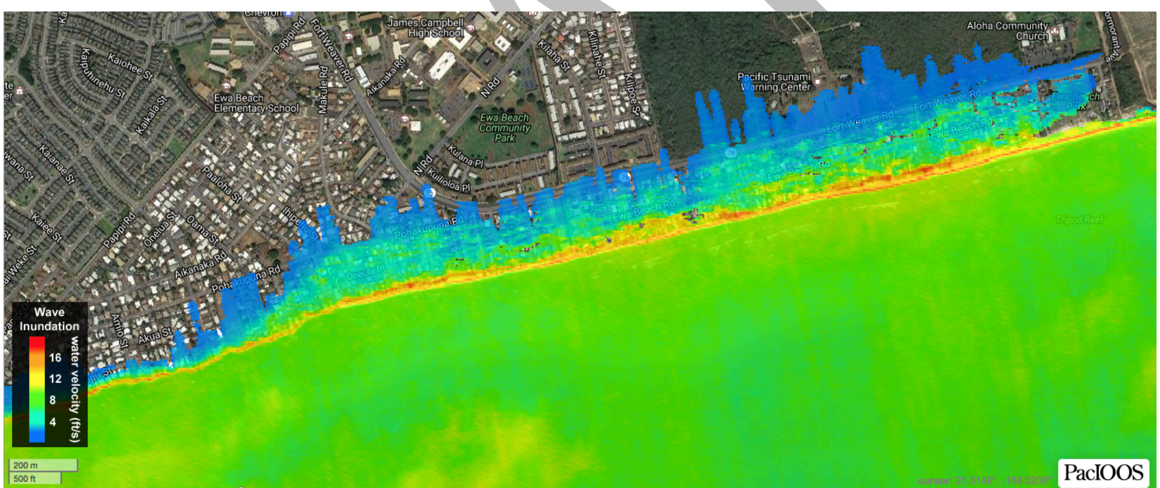

Figure 6. Model result of wave inundation under 98 cm of SLR on the Ewa Beach coastline.

Because no single physical model accurately represents all major processes contributing to sea level rise, scenarios have been developed under a multi-agency federal task force including NOAA and NASA that provide both global mean and local relative sea level rise scenarios to 2150.[47] These scenarios have been developed for community planning to frame risk tolerance for use by decison-makers (**Figure 7**).[48]

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[42] Habel, S., Fletcher, C., Anderson, T., & Thompson, P. (2020) Sea-Level Rise Induced Multi-Mechanism Flooding and Contribution to Urban Infrastructure Failure. Nature Scientific Reports, 10: 3796 DOI:10.1038/s41598-020-60762-4

[43] Marra, J.J., and Kruk, M.C. (2017) State of Environmental Conditions in Hawai'i and the U.S. Affiliated Pacific Islands under a Changing Climate: https://coralreefwatch.noaa.gov/satellite/publications/state_of_the_environment_2017_hawaii-usapi_noaa-nesdis-ncei_oct2017.pdf.

[44] Sweet, W.V., et al. (2017) Global and Regional Sea Level Rise Scenarios for the United States. NOAA Technical Report NOS CO-OPS 083. NOAA/NOS Center for Operational Oceanographic Products and Services.

[45] HI Sea Level Rise Vulnerability and Adaptation Report (2017) Tetra Tech, Inc. and the State of Hawai'i DLNR, OCCL, DLNR Contract No: 64064.

[46] Tebaldi, C., et al. (2021) Extreme sea levels at different global warming levels. Nat. Clim. Chang. 11, 746–751. https://doi.org/10.1038/s41558-021-01127-1

[47] See Interagency Sea Level Rise Scenario Tool, https://sealevel.nasa.gov/task-force-scenario-tool

[48] Sweet, W.V., et al. (2022) Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. NOAA, NOS, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nos- techrpt01-global-regional-SLR-scenarios-US.pdf

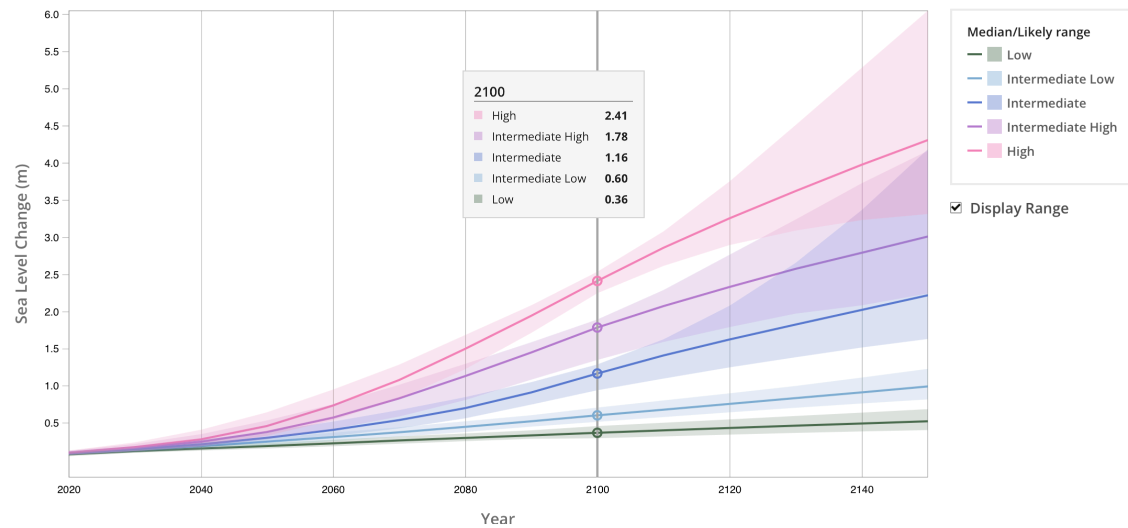

Figure 7. *Planning scenarios of future sea level rise, regionalized to the Honolulu tide gauge, developed by a federal interagency task force.*[49] *Median values are provided for each scenario, along with likely ranges represented by shaded regions showing the 17th-83rd percentile ranges. See https://sealevel.nasa.gov/task-force-scenario-tool for additional explanation.*

Each scenario is defined by a target value of global mean sea level rise by 2100 as follows: Low (0.3 m), Intermediate-Low (0.5 m), Intermediate (1 m), Intermediate-High (1.5 m), and High (2 m). These are then regionalized to provide the scenarios at individual tide gauges and on a 1-degree grid surrounding the U.S. coastlines. Files are available for global mean sea level, 11 regions around the U.S., 121 tide gauges around the U.S., and at 1-degree grid points. Figure 7 and Table 1 show Task Force products specific to the Honolulu tide gauge. The Low and Intermediate-Low scenarios are already exceeded by the observed acceleration of global sea level rise (0.65 ± 0.12 m).[50] Thus the Intermediate, Intermediate-high, and High scenarios represent a more realistic basis for planning and modeling impacts.

Each scenario provides planners with sea level rise targets at decadal frequency (**Table 1**). Sea level rise scenarios assist with planning in the face of uncertainty by providing a range of possible futures that represent a) potential future greenhouse gas emissions, and b) how Earth's bio-physical processes will respond to increased temperatures. These scenarios are different than the projections provided by the IPCC 6th Assessment Report. As opposed to constructing a projection around a particular emissions pathway, the scenarios specify a targeted amount of sea level rise at a time in the future. The trajectory for getting to that target value does rely on the same science and projection framework from the IPCC AR6.

[49] Sweet, W.V., et al. (2022) Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. NOAA, NOS, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nos- techrpt01-global-regional-SLR-scenarios-US.pdf
[50] Nerem, R.S., et al. (2018) Climate-change-driven accelerated sea level rise detected in the altimeter era, PNAS, 115, 2022-2025.

Sea Level Rise Scenarios from 2030 to 2150

Median Sea level projection values from years 2030 to 2150 for 5 sea level scenarios and the observation-based extrapolation, relative to a baseline of year 2000.

Values in meters

	Observation Extrapolation	Low	Intermediate Low	Intermediate	Intermediate High	High
Total (2030)	0.11	0.12	0.13	0.14	0.16	0.17
Total (2040)	0.16	0.15	0.18	0.21	0.24	0.27
Total (2050)	0.21	0.18	0.24	0.29	0.37	0.45
Total (2060)	—	0.22	0.30	0.40	0.57	0.73
Total (2070)	—	0.26	0.37	0.53	0.83	1.07
Total (2080)	—	0.29	0.44	0.69	1.13	1.49
Total (2090)	—	0.33	0.52	0.91	1.44	1.94
Total (2100)	—	0.36	0.60	1.16	1.78	2.41
Total (2150)	—	0.52	0.99	2.21	3.00	4.30

Table 1. *Decadal milestones of sea level rise specific to the Honolulu tide gauge for 5 planning scenarios and showing linear extrapolation of the observed water level trend. These scenarios allow stakeholders to consider future impacts and potential responses and ask "what if?" questions about the future to support planning and decision-making. Sea level rise scenarios are used to communicate how much sea level rise could occur, under what circumstances, and by when.*

SUMMARY

Other communities across the U.S. (see Appendix 1) have adopted the NOAA[51] sea level rise scenarios for their planning strategies. In every case the Intermediate scenario was avoided in favor of either the Intermediate High or the High scenario. Given that community planning is risk averse, and that investments in public infrastructure projects are expensive and typically designed to last a long-time, planning on the basis of higher-level scenarios is prudent.

Another way to look at this is to consider the flood potential of king tides and rain that may occur as a compound event (e.g., December 5, 2021 flooding of Kalakaua Avenue, Waikiki). By using the Intermediate High scenario for projects that have a 30 year design life (e.g., residential mortgages) a project gains a 3 inch freeboard at high tide (all sea level rise scenarios are applied relative to mean higher high water) compared to using the Intermediate scenario as a design criteria. Using the High scenario adds a 6.3 inch freeboard. These are incremental safety buffers that can reduce damage in coastal flood situations.

On the other hand, using one of the higher level sea level rise scenarios as a benchmark, and adding 1 foot of freeboard to accomodate a king tide and adding an additional foot of freeboard to accomodate heavy rainfall at high tide when there is no drainage capacity in the coastal zone, would provide an even greater buffer against flood damage.

[51] Sweet, W.V., et al. (2017)

APPENDIX 1 – SEA LEVEL RISE PLANNNING IN OTHER JURISDICTIONS

MIAMI-DADE

The Miami-Dade County Sea Level Rise Strategy[52] uses three sea level rise scenarios in their plan.

1. IPCC Assessment Report 5 (2013), median sea level projection under high emissions (RCP8.5) scenario. This projection reaches 21 inches (0.5 meter) by 2070.
    a. Applied to most infrastructure projects before 2070 or projects whose failure would result in limited consequences to others.
2. NOAA Intermediate High scenario (Sweet et al., 2017) that reaches 40 inches (1 meter) by 2070.
    a. Applied to projects in need of a greater factor of safety related to potential inundation. This includes evacuation routes, communications and energy infrastructure, and critical government and financial facilities or infrastructure that is designed to last 50 years or more.
3. NOAA High scenario (Sweet et al, 2017) that reaches 54 inches (1.4 meters) by 2070.
    a. Applied to planning critical projects including those that are hard to replace or remove or would have a catastrophic impact if they failed.

Several guiding principles emerged from an intensive community engagement process.

1. Adaptation investments make the community safer,
2. Reduce environmental pollution,
3. Be equitable,
4. Build with nature,
5. Be flexible, and
6. Be well aligned with other initiatives.

Following these pricicles, five specific project approaches were used to address higher water levels. They are as follows:

1. Build on fill,
2. Build like The Florida Keys (ie: building on stilts with yards and parks adapted to saltwater intrusion),
3. Build on high ground around transit,
4. Expand greenways and blueways, and
5. Create green and blue neighborhoods.

In the Miami-Dade Sea Level Rise Strategy document, these concepts are accompanied by images and graphics that capture each type of solution. An appendix is robust with examples of sea level rise impacts in South Florida and accompanying solutions and approaches to those challenges.

Miami-Dade also developed ten priority action areas they describe as the "*most impactful regulatory and policy changes, investments, and planning efforts they can engage in or enhance now to reduce future risk*."

1. Accelerate Adaptation Action Areas across the County
2. Require County projects be designed for sea level rise
3. Establish safer building and seawall elevation standards
4. Ensure development avoids flooding neighboring properties
5. Enhance flood protection by expanding greenways and blueways
6. Flood-proof the County's most vulnerable critical facilities
7. Integrate green infrastructure into County projects
8. Prepare for disaster recovery to accelerate inclusive adaptation
9. Address vulnerable septic systems

[52] See https://miami-dade-county-sea-level-rise-strategy-draft-mdc.hub.arcgis.com

10. Increase affordable, resilient housing on high ground within SMART Plan transit corridors

To help prioritize these projects, they developed the concept of Adaptation Action Areas (AAA), a flexible planning tool that allows the County to work directly with community members and other agencies to create a more detailed adaptation plan for the focus area. The plan further details funded and completed County resilience projects, totaling approximately $1.7 billion. It also outlines unfunded projects that the County is seeking resources to complete. In addition to the main report, there are three supporting documents or "mini-guides". Each shows how to tailor adaptation approaches to different areas across the County, giving readers of the plan a higher granularity for understanding and implementing the projects.

NANTUCKET ISLAND

The Nantucket Coastal Resilience Plan (CRP)[53] and the Nantucket Coastal Risk Assessment and Resiliency Strategies[54] use two SLR scenarios from NOAA: High and Medium High depending on the risk tolerance of projects. A community engagement process for Nantucket found challenges and tensions on the island. The CRP used these as a guide to prioritize projects, define community assets and shape the final resilience and adaptation strategies.

Ultimately three strategies were adopted in their plan:

1. Protect (resist the sea),
2. Adapt (live with the sea), and
3. Relocate (move away from the sea).

Each specific project area in the report describes the strategy or multiple strategies that are planned to be deployed. For example, their downtown commerical region is designated as "protect" and "adapt" since it is more urban and would be difficult to implement a retreat strategy. Less dense areas are planned for pure "adaptation" or blended with the "relocate" strategy. The plan also categorizes "nature-based approaches", "non-structural approaches" and "structural approaches". The strategy of "Protect" is more structural and "Relocate" is non-structural. In addition to these criteria the plan overlays a risk framework that includes a scale of urgency from most urgent "Priority Action Areas of Extreme Coastal Risk" to less urgent "Lower Coastal Risk Areas" and two moderate risk designations in between.

Finally, the plan includes evaluation criteria (STAPLEE-Social, Technical, Administrative, Political, Legal, Economic and Environmental) from FEMA that the authors used to help the community decide the best approach for priority projects. This process led to the identification of strategies that scored the highest for priority areas based on the evaluations.

The remainder of the plan speaks to the specific strategies for the chosen priority areas laying out detailed road maps for how sea level rise will be handled in the Nantucket community. In total there are recommendations for 40 projects to be advanced across the island over the next 10-15 years. It also includes an implementation roadmap that has higher granularity for project phasing.

PACIFICA, CALIFORNIA

The Pacifica Adaptation Plan sea level rise projections use the high emissions scenario (IPCC, 2013 - RCP 8.5) when looking at projects for which plans need to be executed before 2050. The author's explanation for this is that the world is currently on the RCP 8.5 trajectory, and differences in sea level rise projections

[53] https://www.nantucket-ma.gov/DocumentCenter/View/40279/Nantucket-Coastal-Resilience-Plan-Existing-Conditions--Coastal-Risk-Assessment---November-2021-PDF
[54] https://www.nantucket-ma.gov/DocumentCenter/View/35045/Coastal-Risk-Assessment-and-Resiliency-Strategies-Report-January-2020-PDF

under different scenarios are minor before 2050. The plan considers a wider range of sea level rise scenarios for future projects with time frames that look beyond 2050.

The Pacifica plan discusses the community's history of coastal armoring that has been the primary strategy to mitigate erosion and flood hazards. This strategy has had mixed results in terms of protecting property. Beaches and access have largely diminished where there is armoring and shoreline erosion continues seaward of armoring; beaches are absent even at low tides in some armoring locations. In the future, the feasibility of hardening against sea level rise and the cost associated may make the strategy unsustainable. The plan articulates that as the beach erodes, greater wave loading on the armoring and increased overtopping has led to higher maintenance costs of the structures as well as damage of landward assets.

Similar to the Nantucket Plan, the Pacifica plan identifies three general categories of adaptation: “protect”, “accommodate”, and “retreat”. In the plan, these adaptation actions are triggered when certain thresholds are reached. The thresholds include sea level rise amount, flooding and storm damage frequency (using photographs, community reporting and official city data), beach width, and bluff top offset (distance between the edge of the bluffs and assets such as streets and infrastructure). The triggers are intended to reduce risk by creating an impetus for action.

Within the adaptation strategies is the topic of “managed retreat”. This would require the removal or relocation of structures and infrastructure to realign assets landward with the migrating shore, and can include shore protection structures (e.g. seawalls), sand placement and accommodation such as raising buildings on pile-foundations. Despite the bundle of tactics that this type of retreat uses, often the language is alarming, especially for private property owners in coastal areas.

APPENDIX 2 – SEA LEVEL FINGERPRINTING

All of the worlds ice centers are losing mass: Greenland, W. Antarctica, E Antarctica, glacier systems in SE Alaska, the Himalayas, Patagonia, and others.[55] As each of these locations lose mass, the gravitational pull of the ice on the ocean surface decreases. Normally, the North Atlantic water surface slopes up toward the Greenland ice sheet, and the North Pacific water surface slopes up toward the mountain glaciers in SE Alaska. The same is true adjacent to all glacier systems. However, mass loss diminishes the gravitational attraction associated with the ice and the water surface relaxes downward. Compared to global mean sea level, melting can actually lead to sea level fall near the ice centers. Elsewhere (known as the “far field”) localized sea level rise exceeds the global mean sea level rise.

This phenomenon is called sea level fingerprinting **(Figure 2-1**) because melting at each ice center causes an associated distant area to experience sea level rise that is greater than the global mean. The tropical Pacific, where Hawai‘i and other Polynesian and Micronesian island groups are located, is the site of multiple, overlapping, sea level fingerprints. For instance, the interagency sea level rise working group describe the Intermediate scenario of global mean sea level rise that reaches 40 inches (1 meter) by the year 2100. However, because of sea level fingerprinting, local relative sea level rise at the Honolulu Tide Station is a full 6 inches higher at 46 inches (1.16 meters (**Table 1**).

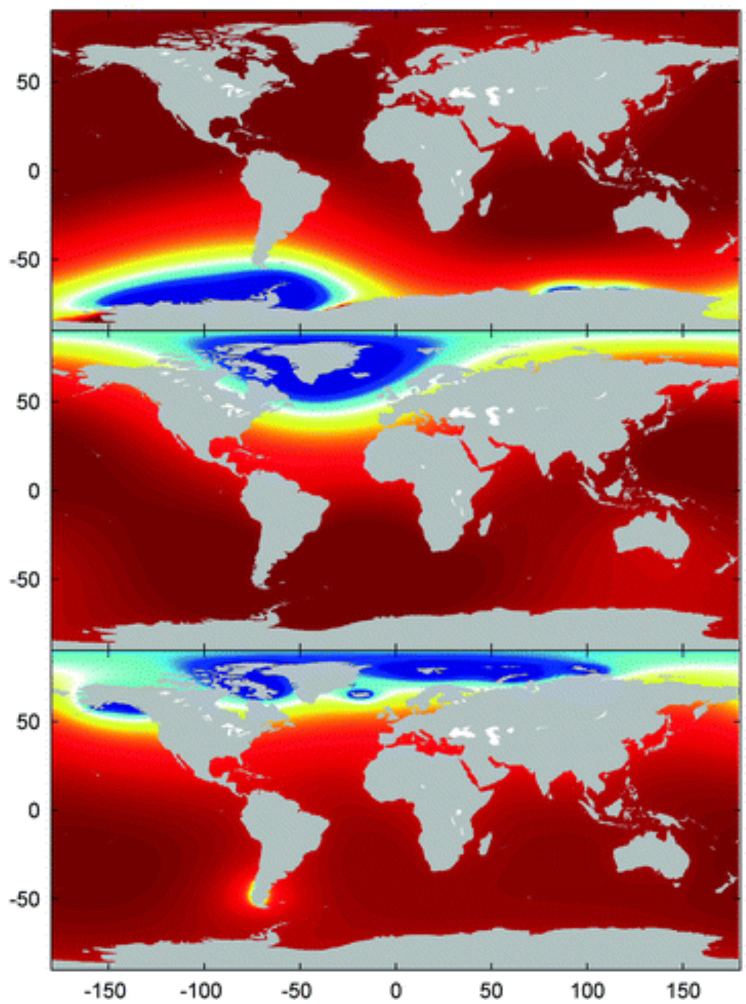

Figure 2-1. *The spatial fingerprint of sea-level rise expressed as a ratio to the global mean sea level equivalent loss from:* ***Top -*** *the Antarctic ice sheet;* ***Middle -*** *the Greenland ice sheet;* ***Bottom -*** *mountain glaciers and ice caps.*[56]

[55] Ciracì, E., et al. (2020) Continuity of the mass loss of the world's glaciers and ice caps from the GRACE and GRACE Follow-On missions. Geophysical Research Letters, 47, e2019GL086926. https://doi.org/10.1029/2019GL086926

[56] Grinsted A. (2015) Projected Change—Sea Level. In: The BACC II Author Team (eds) Second Assessment of Climate Change for the Baltic Sea Basin. Regional Climate Studies. Springer, Cham. https://doi.org/10.1007/978-3-319-16006-1_14