SEA LEVEL RISE II – GUIDANCE DOCUMENT
City and County of Honolulu Climate Change Commission
Adopted June 5, 2018
Updated July 29, 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 Hawai'i. 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 pertaining to the federal interagency task force recommendations on sea level rise (SLR).

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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 should recognize that sea level rise is an inevitable, dangerous, and fundamental condition to be recognized in every element of coastal planning and management.
2. The City and County of Honolulu should set as a planning and policy benchmark the interagency Intermediate (1.16 m, 3.8 ft by 2100) sea level rise scenario, as modeled[1] for the Honolulu Tide Station, as the minimum scenario for all planning and design, and that the City continue to utilize the 3.2 ft SLR-XA until updated SLR-XA map data is available.
3. The City and County of Honolulu should set as a planning and policy benchmark the interagency Intermediate High (1.78 m, 5.8 ft by 2100) sea level rise scenario for all planning and design of public infrastructure projects and other projects with low tolerance for risk, and that the City continue to utilize the 6 ft passive flooding map layer from NOAA until updated map data is available.

[1] 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. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nos- techrpt01-global-regional-SLR-scenarios-US.pdf

4. With regard to Commision Guidance[2] on revisions to ROH Chapter 23 concerning shoreline setbacks (adopted December 23, 2019), new scientific findings underscore the threat that sea level rise presents to coastal properties and assets, and provide added urgency to implement the recommendations.
5. In implementing Intermediate and Intermediate High sea level rise scenarios, all projects should apply design elevations to mean higher high water (MHHW) as a datum. Projects with low tolerance for flood risk should add additional design elevation to account for compound events (e.g., an additional 1 ft for extreme or “king” tides, 1 ft for runoff accumulation in light of drainage failure at high tides).

FINDINGS

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

1. Since the early 20th Century, global mean sea-level has risen 0.12–0.21 m (0.4-0.7 ft).
2. Global mean sea level is projected to rise 0.44-0.76 m (1.4-2.5 ft) to 0.63-1.01 m (2.1-3.3 ft) by 2100.
3. Because of deep uncertainty regarding ice sheet processes, sea level rise (SLR) approaching 2 m (6.6 ft) by 2100 and 5 m (16.4 ft) by 2150 cannot be ruled out.
4. Hawai‘i and other tropical Pacific locations are projected to experience SLR that is 16 to 20% higher than the global average.
5. Due to the growing instability of the Antarctic and Greenland ice sheets, there is an increasing probability of a high impact SLR outcome this century.
6. 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 temperature increases are halted.
7. Given the long-term commitment and costs associated with implementing adaptation projects, uncertainty in the timing of reaching different global mean sea level rise levels is an important consideration for planning.
8. Published energy policies put the global climate on track to warm at least 2.7-3.5 ^{o}C (4.9-6.3 ^{o}F) by 2100.
9. A US-federal “Interagency Task Force” provides a range of scenarios for designing adaptation to SLR. For the year 2100, these scenarios depict global mean SLR as:
    a. Low (0.3 m, 1 ft)
    b. Intermediate Low (0.5 m, 1.6 ft)
    c. Intermediate (1 m, 3.3 ft)
    d. Intermediate High (1.5 m, 5 ft)
    e. High (2 m, 6.6 ft)
10. The use of a scenario should reflect the risk tolerance of a given project, with higher scenarios becoming appropriate for projects that do not tolerate high levels of coastal flood risk.
11. The Low and Intermediate-Low scenarios are inappropropriate to use for planning because present-day SLR acceleration is already on-track to exceed these water levels by 2100 (0.7 m, 2.3 ft).[3]
12. According to the Interagency Task Force:
    a. At all warming levels, there is at least a 92% chance of exceeding the Low scenario in 2100.
    b. At a warming level of 3 ^{o}C there is at least an 82% chance of exceeding the Intermediate-Low scenario, and a 5% chance of exceeding the Intermediate scenario.
    c. Given the growing instability of the Greenland and Antarctic ice sheets it is prudent to plan for a high impact outcome.
    d. In a high impact outcome, there is at least a:
        i. 96% probability of exceeding the Intermediate-Low scenario, nearly a
        ii. 50% chance of exceeding the Intermediate scenario, a
        iii. 20% chance of exceeding the High scenario (1.5 m, 5 ft), and an
        iv. 8% probability of exceeding the High scenario (2 m, 6.6 ft).

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

[3] Nerem, R. S., Frederikse, T., & Hamlington, B. D. (2022). Extrapolating empirical models of satellite-observed global mean sea level to estimate future sea level change. Earth's Future, 10, e2021EF002290. https://doi. org/10.1029/2021EF002290

13. 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 tidal flooding, intense rainfall, and compound events (e.g., heavy rain at high tide, a time where there is no drainage capacity in urban Honolulu – for instance Dec., 2021).[4]
14. Scaled to the Honolulu tide gauge, interagency scenarios provide the following benchmarks by 2050 and 2100 (respectively): Intermediate 0.29/1.16 m, Intermediate High 0.37/1.78 m, and High 0.45/2.41 m.
15. 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 types of flooding.

GLOBAL AND REGIONAL TRENDS IN SEA LEVEL RISE

At present, climate change causes sea level rise[5] (SLR, **Figure 1**[6]) predominantly through[7] thermal expansion (45.7%) and melting of land-based snow and ice (43.5%). Anthropogenic groundwater depletion, largely for irrigation, contributes the remainder (10.8%). Since the early 20th Century, global mean sea-level has risen 0.12–0.21 m (0.4-0.7 ft).[8] Sea level rise acceleration is projected to increase with continued global warming.[9]

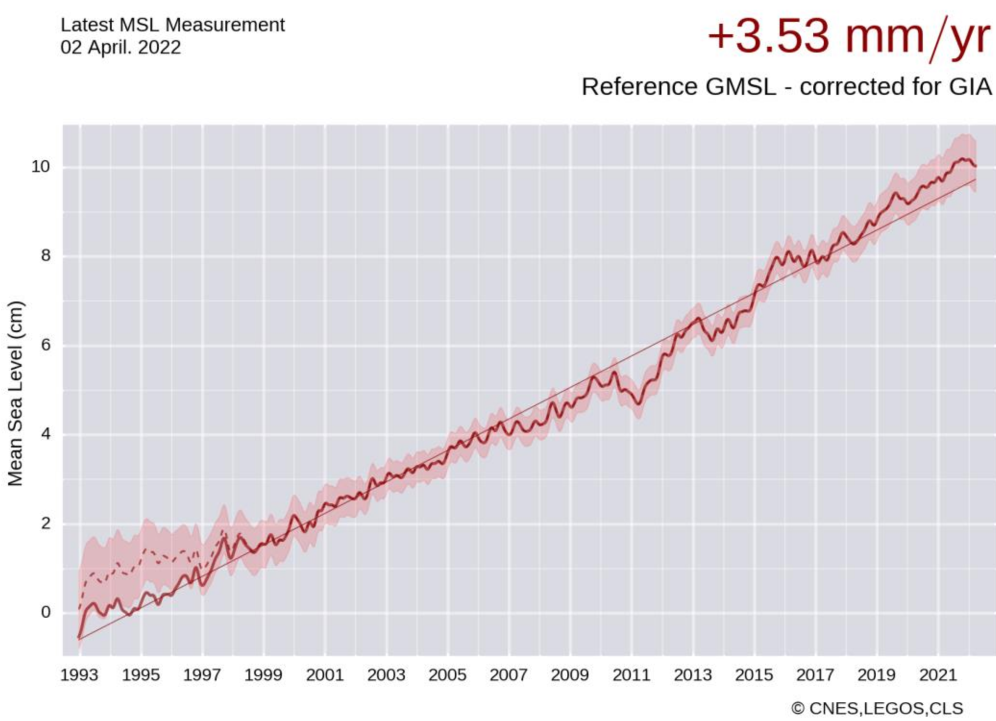

Figure 1. *Global mean sea level and trend measured by satellite altimetry (Jan. 1993-Dec. 2021). The uncertainty envelope (red shaded area) is given at the 90% confidence level. Data – French National Centre for Space Studies (CNES), Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO).*[10]

[4] https://twitter.com/graceleesunrise/status/1468255669954375682?lang=en
[5] Guérou, A., et al. (2022) Current observed global mean sea level rise and acceleration estimated from satellite altimetry and the associated uncertainty, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2022-330.
[6] https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html
[7] 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
[8] IPCC (2019) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, et al. (eds.)]. In press.
[9] Dangendorf, S., et al. (2019) Persistent acceleration in global sea-level rise since the 1960s. Nat. Clim. Chang. 9, 705–710. https://doi.org/10.1038/s41558-019-0531-8
[10] https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html

According to the 6th Assessment Report (AR6) of the International Panel on Climate Change (IPCC),[11] global mean sea level is projected to rise 0.44-0.76 m (1.4-2.5 ft) to 0.63-1.01 m (2.1-3.3 ft) by the end of the century. However, a rise approaching 2 m (6.6 ft) by 2100 and 5 m (16.4 ft) by 2150 cannot be ruled out, as there remains deep uncertainty regarding ice sheet processes (Appendix 1). Locally, models indicate that Hawaiʻi and other tropical Pacific sites will experience SLR that is 16% to 20% higher than the global average.[12]

Recent findings[13] suggest that the present acceleration of mass loss from the Antarctic ice sheet may mark the beginning of an ice sheet retreat period that will contribute to substantial global SLR for centuries to millennia. Data show that West Antarctic "*ice shelves are showing new damage areas that are the first signs of structural weakening and precondition these ice shelves for disintegration*".[14]

On Greenland, annual snowfall that normally replenishes the 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.[15] Mass loss from the Greenland Ice Sheet is 7 times faster than it was in the 1990's,[16] and has quadrupled this decade.[17] Between July 30 and August 2, 2019, approximately 90 percent of the surface of Greenland's ice sheet experienced temporary melting, causing about 55 billion tons of ice to melt into the ocean.[18] Greenland Ice Sheet meltwater has increased 250 to 575 percent in only 20 years.[19] In aggregate, the growing instability of the Antarctic and Greenland ice sheets signal that the probability of SLR exceeding 1 m (3.3 ft) this century is increasing.

Sea level responds to greenhouse gas emissions more slowly than global surface temperature. This slow response also leads to long-term committed SLR, associated with ongoing ocean heat uptake and the slow adjustment of the ice sheets. The AR6 states with high confidence that global mean SLR 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*."[20]

PLANNING SCENARIOS AND TIMING FOR HONOLULU

Because no single physical model accurately represents all major processes contributing to SLR, five scenarios have been developed under a multi-agency federal task force including NOAA, USGS, the Army, and NASA that provide both global mean and local relative SLR scenarios to 2150.[21] These scenarios have been developed for community planning to frame risk tolerance for use by decision-makers.[22] The choice of which scenario to use for planning should be determined through an assessment of risk tolerance associated with any individual project or asset.

[11] IPCC (2021) Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson- Delmotte, V., et al. (eds.)]. Cambridge Univ. Press. In Press.
[12] 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. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nos- techrpt01-global-regional-SLR-scenarios-US.pdf
[13] Weber, M.E., et al. (2021) Decadal-scale onset and termination of Antarctic ice-mass loss during the last deglaciation. Nat Commun 12, 6683. https://doi.org/10.1038/s41467-021-27053-6
[14] Lhermitte, S., et al. (2020) Damage accelerates ice shelf instability and mass loss in Amundsen sea Embayment, PNAS, 117 (40), https://doi.org/10.1073/pnas.1912890117
[15] 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
[16] 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
[17] Bevis, M. et al. (2019) Accelerating changes in ice mass within Greenland, and the ice sheets sensitivity to atmospheric forcing. PNAS, 116, 1934-1939
[18] 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/
[19] 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
[20] 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.
[21] Interagency Sea Level Rise Scenario Tool, https://sealevel.nasa.gov/task-force-scenario-tool
[22] Sweet, W.V., et al. (2022)

Each of the five scenarios is defined by a target value of global mean sea level rise by 2100 as follows: Low (0.3 m, 1 ft), Intermediate-Low (0.5 m, 1.6 ft), Intermediate (1 m, 3.3 ft), Intermediate-High (1.5 m, 5 ft), and High (2 m, 6.6 ft). 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 2** and **Table 1** show task force products specific to the Honolulu tide gauge. *Note:* Projections from the Low and Intermediate-Low scenarios are already lower than the observed acceleration of global mean sea level rise which is on trajectory to reach 0.7 m (2.3 ft) by the year 2100.[23] Hence, the Intermediate, Intermediate-High, and High interagency scenarios represent a more realistic basis for planning and modeling impacts.

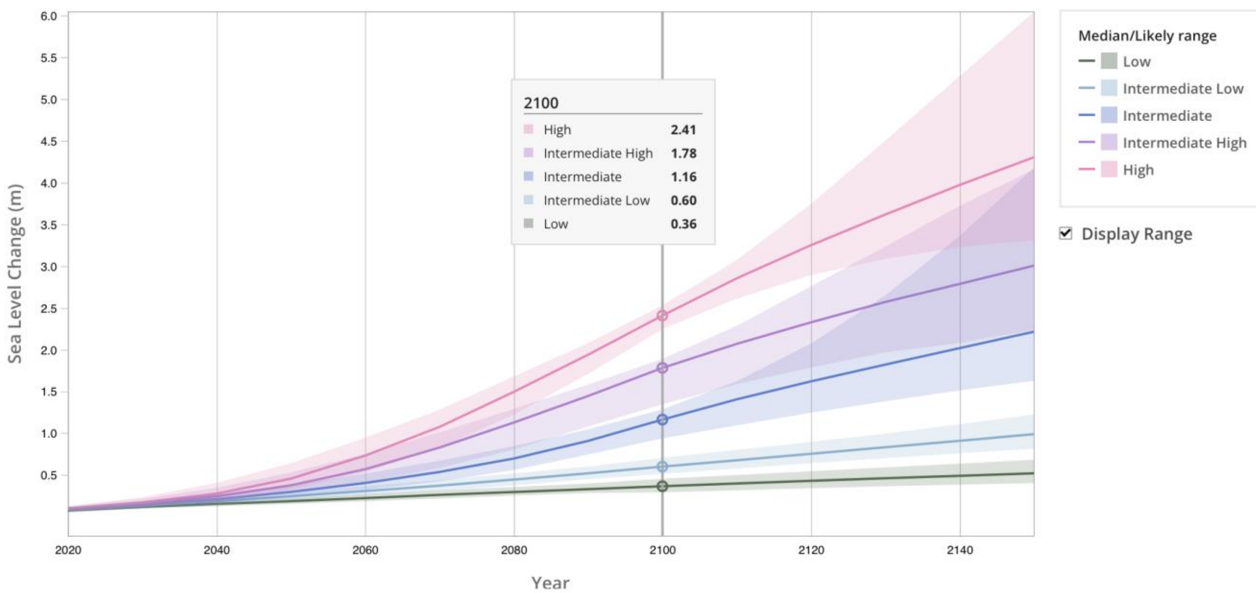

Figure 2. *Future SLR planning scenarios for the Honolulu Tide Gauge, developed by a federal interagency task force.[24] Median values are provided for each scenario, along with likely ranges represented by shaded regions showing the 17th-83rd percentile ranges. See https://sealevel.nasa.gov/task-force-scenario-tool for additional explanation.*

Each scenario provides planners with SLR targets at decadal frequency. 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 (e.g., melting of permafrost, rainforest ecosystem function, etc.). These scenarios are different than the projections provided by the IPCC 6th Assessment Report.[25] As opposed to constructing a projection around a particular emissions pathway, the scenarios specify a targeted amount of SLR at a time in the future (**Table 1**). The trajectory for getting to that target value relies on the same science and projection framework from the IPCC AR6.

[23] Nerem, R. S., et al. (2022)
[24] Sweet, W.V., et al. (2022)
[25] IPCC (2021) Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis.

Table 1. Sea Level Rise (m, ft) Scenarios 2030-2150 for Honolulu, Interagency Task Force[26]					
Median sea level projection values (m, ft) from years 2030-2150 for five sea level scenarios, relative to year 2000.					
Decade	Low	Intermediate Low	Intermediate	Intermediate High	High
2030	0.12, 0.39	0.13, 0.43	0.14, 0.46	0.16, 0.52	0.17, 0.56
2040	0.15, 0.49	0.18, 0.59	0.21, 0.69	0.24, 0.79	0.27, 0.88
2050	0.18, 0.59	0.24, 0.79	0.29, 0.95	0.37, 1.21	0.45, 1.48
2060	0.22, 0.72	0.30, 0.98	0.40, 1.31	0.57, 1.87	0.73, 2.40
2070	0.26, 0.85	0.37, 1.21	0.53, 1.74	0.83, 2.72	1.07, 3.51
2080	0.29, 0.95	0.44, 1.44	0.69, 2.26	1.13, 3.71	1.49, 4.89
2090	0.33, 1.08	0.52, 1.71	0.91, 2.98	1.44, 4.72	1.94, 6.36
2100	0.36, 1.18	0.60, 1.97	1.16, 3.81	1.78, 5.84	2.41, 7.91
2150	0.52, 1.70	0.99, 3.25	2.21, 7.25	3.00, 9.84	4.30, 14.11

HOW ARE THE INTERAGENCY SCENARIOS CONNECTED TO CHANGES IN TEMPERATURE IN THE IPCC-AR6 OUTCOMES?

Warming levels projected in IPCC-AR6 are compared to the five interagency SLR scenarios by assessing the probability that a given SLR value in 2100 will be exceeded for a particular warming level (**Table 2**). At all warming levels, there is at least a 92% chance of exceeding the Low scenario in 2100. The probability for exceeding the Intermediate-Low (0.5 m) scenario drops for all warming levels when compared to the probability for exceeding the Low scenario. For the Intermediate, Intermediate-High, and High scenarios, the exceedance probability drops more with each warming level. Consistent with the framing of the five scenarios in this report, greater warming and higher emissions are generally needed to arrive at the Intermediate through High scenarios in 2100.

[26] Sweet, W.V., et al. (2022)

Table 2. *IPCC warming level–based global mean sea level projections. Global mean surface air temperature anomalies are projected for years 2081–2100 relative to the 1850–1900 climatology. Sea level anomalies are relative to a 2005 baseline. The probabilities are imprecise probabilities, representing a consensus among all projection methods applied. For imprecise probabilities >50%, all methods agree that the probability of the outcome stated is at least that value; for imprecise probabilities <50%, all methods agree that the probability of the outcome stated is less than or equal to the value stated.*[27]

Global Mean Surface Air Temperature 2081–2100	1.5°C	2.0°C	3.0°C	4.0°C	5.0°C	Unknown Likelihood, High Impact – Low Emissions	Unknown Likelihood, High Impact – Very High Emissions
Closest Emissions Scenario–Based GMSL Projection	Low (SSP1-2.6)	Low (SSP1-2.6) to Intermediate (SSP2-4.5)	Intermediate (SSP2-4.5) to High (SSP3-7.0)	High (SSP3-7.0)	Very High (SSP5-8.5)	Low (SSP1-2.6), *Low Confidence* processes	Very High (SSP5-8.5), *Low Confidence* processes
Total (2050)	0.18 (0.16–0.24)	0.20 (0.17–0.26)	0.21 (0.18–0.27)	0.22 (0.19–0.28)	0.25 (0.22–0.31)	0.20 (0.16–0.31)	0.24 (0.20–0.40)
Total (2100)	0.44 (0.34–0.59)	0.51 (0.40–0.69)	0.61 (0.50–0.81)	0.70 (0.58–0.92)	0.81 (0.69–1.05)	0.45 (0.32–0.79)	0.88 (0.63–1.60)
Bounding Median Scenarios in 2100	Low to Intermediate-Low	Intermediate-Low to Intermediate	Intermediate-Low to Intermediate	Intermediate-Low to Intermediate	Intermediate-Low to Intermediate	Low to Intermediate-Low	Intermediate-Low to Intermediate
Probability > Low (0.3 m) in 2100	92%	98%	>99%	>99%	>99%	89%	>99%
Probability > Int.-Low (0.5 m) in 2100	37%	50%	82%	97%	>99%	49%	96%
Probability > Int. (1.0 m) in 2100	<1%	2%	5%	10%	23%	7%	49%
Probability > Int.-High (1.5 m) in 2100	<1%	<1%	<1%	1%	2%	1%	20%
Probability > High (2.0 m) in 2100	<1%	<1%	<1%	<1%	< %	<1%	8%

WHAT IS THE CURRENT GLOBAL TEMPERATURE PATHWAY?

Updated national pledges under the United Nations Framework Convention on Climate Change Paris Climate Agreement only cut emissions 7.5% by 2030, leaving a 34% probability of staying below 2 °C (3.6 °F) and a 1.5% probability of staying below 1.5 °C (2.7 °F).[28] However, the current energy policies associated with the nations reveal that emissions will be greater than these pledges, putting the climate on track to warm 2.7-3.5 °C (4.9-6.3 °F) by 2100. Additionally, on average, global emissions are underreported by ~23%[29], with an estimated 70% under-reporting of methane emissions alone.[30] There is also growing evidence that global carbon sinks such as Arctic permafrost[31] and tropical rainforests[32] are emitting more greenhouse gases than they sequester annually. Energy economists[33] project that new energy demand will continue to increase anthropogenic greenhouse gas emissions to mid-century. Analysts at Climate Action Tracker state that renewable energy has failed to take a central position in

27 Sweet, W.V., et al. (2022)

28 Ou, Y., et al. (2021) Can updated climate pledges limit warming well below 2°C? Science, 5Nov, v374, Iss.6568, DOI:10.1126/science.abl8976

29 Mooney, C., et al. (Nov. 7, 2021) Countries' climate pledges built on flawed data, Post investigation finds; Washington Post, https://www.washingtonpost.com/climate-environment/interactive/2021/greenhouse-gas-emissions-pledges-data/

30 IEA (2022), Global Methane Tracker 2022, IEA, Paris https://www.iea.org/reports/global-methane-tracker-2022

31 Natali, S.M., Watts, J.D., Rogers, B.M. et al. (2019) Large loss of CO_2 in winter observed across the northern permafrost region. Nat. Clim. Chang. 9, 852–857. https://doi.org/10.1038/s41558-019-0592-8

32 Feng, Y., Zeng, Z., Searchinger, T.D. et al. (2022) Doubling of annual forest carbon loss over the tropics during the early twenty-first century. Nat Sustain. https://doi.org/10.1038/s41893-022-00854-3

33 Newell, R., Raimi, D., Villanueva, S., and Prest, B. (2021) Global energy outlook 2021: Pathways from Paris, Report 21-11, June, Resources for the Future (RFF), https://media.rff.org/documents/RFF_GEO_2021_Report_1.pdf

post-COVID recovery,[34] and the Global Carbon Project found fossil fuel use increasing faster than renewables.[35] These indicators suggest that the current global temperature pathway is on track to exceed 3 °C (5.4 °F).

PICKING A LOCAL SLR SCENARIO FOR PLANNING

Table 2 provides guidance in picking a global mean SLR planning scenario. At all warming levels, there is at least a 92% chance of exceeding the Low scenario in 2100. Assuming a warming trajectory of at least 3 °C (discussion above), there is at least an 82% chance of exceeding the Intermediate-Low scenario, and a 5% chance of exceeding the Intermediate scenario. Given the growing instability of the Greenland and Antarctic ice sheets (discussion above and Appendix 1) it would be prudent to plan for a high impact outcome (right column) for long-term infrastructure or high-risk assets. In this case there is at least a 96% probability of exceeding the Intermediate-Low and nearly a 50% chance of exceeding the Intermediate scenario.

SLR HAZARDS

The impacts of SLR are potentially catastrophic. As sea levels rise so does the risk of flooding,[36] damage by extreme weather events,[37] and permanent land loss.[38] Because of the extremely low relief of the coastal zone, small increases in mean sea level generate nonlinear impacts by storms and compound events involving rain and extreme tides.[39] Flooding originates from multiple sources: groundwater inundation,[40] extreme high tides,[41] direct wave run-up (**Figure 3**),[42] storm surge,[43] extreme precipitation events,[44] and others. Salinization of coastal aquifers leads to ecosystem loss, corrosion of buried and surface infrastructure, and contamination of freshwater supplies.[45]

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[34] https://climateactiontracker.org/publications/glasgows-2030-credibility-gap-net-zeros-lip-service-to-climate-action/

[35] Jackson, R.B., et al. (2022) Global fossil carbon emissions rebound to near pre-COVID-19 levels, Environmental Research Letters, v17, no3, https://doi.org/10.1088/1748-9326/ac55b6

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

[37] Tebaldi, C., Strauss, B.H., and Zervas, C.E. (2012). Modelling sea level rise impacts on storm surges along US coasts. Environmental Research Letters, 7(1, Jan-March), 014032. doi: 10.1088/1748- 9326/7/1/014032

[38] Limber, P.W., et al. (2018) A model ensemble for projecting multidecadal coastal cliff retreat during the 21st century. Journal of Geophysical Research: Earth Surface, 123, 1566-1589: https://doi.org/10.1029/2017JF004401.

[39] Rohmer, J., et al. (2019) Increased extreme coastal water levels due to the combined action of storm surges and wind waves. Geophys. Res. Lett. 46(8), 4356–4364.

[40] Befus, K.M. et al. (2020) Increasing threat of coastal groundwater hazards from sea-level rise in California. Nat. Clim. Chang. 10, 946–952. https://doi.org/10.1038/s41558-020-0874-1

[41] Thompson, P. R., et al. (2019). A Statistical Model for Frequency of Coastal Flooding in Honolulu, Hawaii, During the 21st Century. Journal of Geophysical Research: Oceans, 124(4), 2787–2802. https://doi.org/10.1029/2018JC014741

[42] Vitousek, S., et al. (2017) Doubling of coastal flooding frequency within decades due to sea-level rise: Nature Scientific Reports, https://doi.org/10.1038/s41598-017-01362-7.

[43] Rohmer, J., et al. (2019)

[44] 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

[45] Storlazzi, C.D., et al. (2018) Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding: Science Advances, v. 4, eaap9741, DOI: 10.1126/sciadv.aap9741

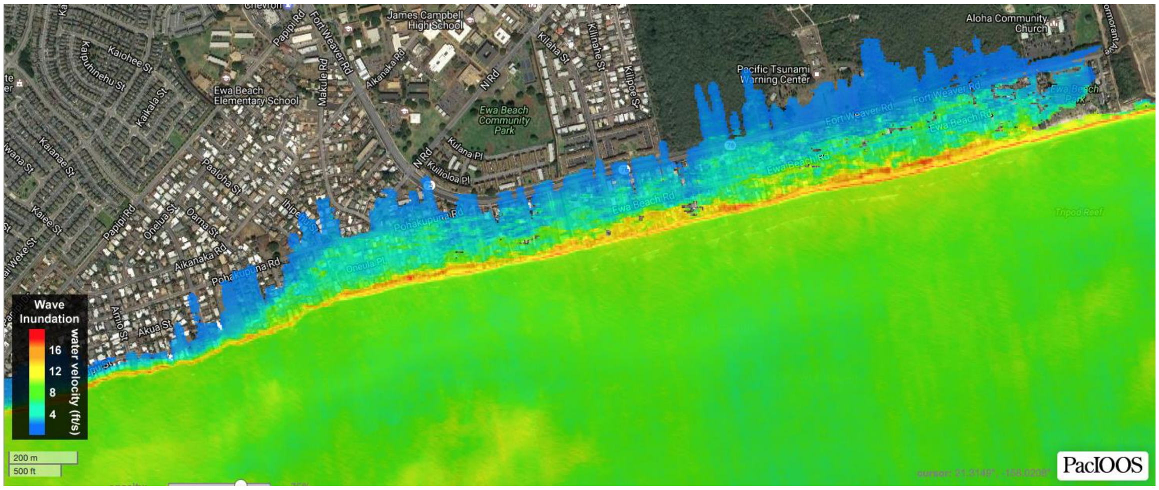

Figure 3. *Model result of wave inundation under 98 cm (3.2 ft) of SLR on the Ewa Beach coastline.*

Several aspects of SLR are not widely known but should be taken into account when developing local adaptation plans (Appendix 3): 1) Low-lying coastal areas may flood by groundwater inundation before direct marine flooding,[46] 2) Engineered drainage systems may backflow salt water onto streets especially at high tide due to SLR,[47] 3) Typically, the first evidence of SLR is coastal erosion (**Figure 4**) and high tide flooding both of which have already increased in Hawaiʻi,[48] 4) Tropical Pacific locations (including Hawaiʻi) will experience amounts of SLR flooding that are greater than the global average.[49]

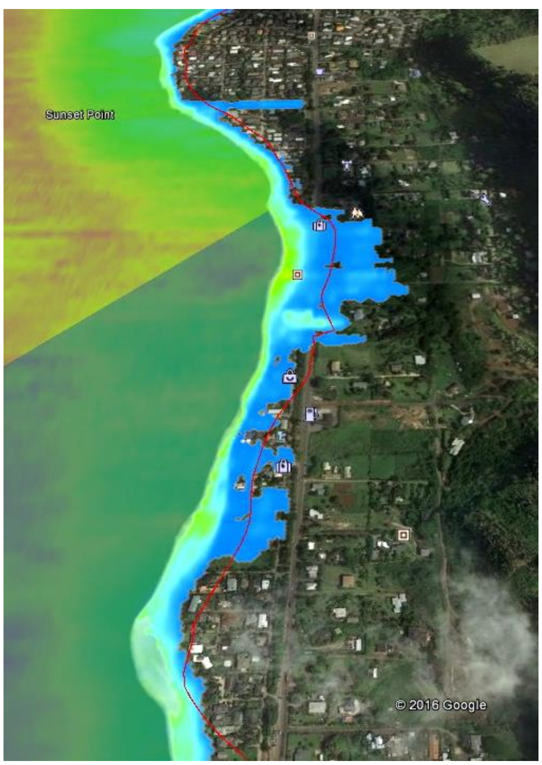

Figure 4. *Model result showing the erosion (red line) and annual wave run-up (blue) under 98 cm (3.2 ft) of sea level rise at Sunset Beach, Oahu's North Shore. This is an oblique image of model results found at the Hawaiʻi SLR Viewer.*[50]

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46 Habel, S., Fletcher, C., Rotzoll, K., El-Kadi, A., & Oki, D. (2019) Comparison of a simple hydrostatic and a data-intensive 3D numerical modeling method of simulating sea-level rise induced groundwater inundation for Honolulu, Hawai'i, USA. Environmental Research Communications, 1(4), 041005. DOI:10.1088/2515-7620/ab21fe
47 Habel, S., Fletcher, C., Anderson, T., & Thompson, P (2020)
48 Summers, A., Fletcher, C.H., Spirandelli, D. et al. (2018) Failure to protect beaches under slowly rising sea level. Climatic Change 151, 427–443. https://doi.org/10.1007/s10584-018-2327-7
49 Vitousek, S., et al. (2017)
50 https://www.pacioos.hawaii.edu/shoreline/slr-hawaii/

SUMMARY

Other communities across the U.S. (see Appendix 2) have adopted the NOAA[51] sea level rise scenarios for their planning strategies. 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 Intermediate or higher scenarios is appropriate. Using the Intermediate or higher level sea level rise scenario as a benchmark, adding 1 ft of freeboard[52] to accomodate a King Tide, and adding an additional 1 ft 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.

ACKNOWLEDGEMENTS

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

[52] “Freeboard” is a factor of safety usually expressed in feet above a flood level for purposes of floodplain management. "Freeboard" tends to compensate for the many unknown factors that could contribute to flood heights greater than the height calculated for a selected size flood and floodway conditions, such as wave action, bridge openings, and the hydrological effect of urbanization of the watershed. https://www.fema.gov/glossary/freeboard see also https://www.fema.gov/sites/default/files/2020-08/fema_freeboard-deficient-procedure.pdf

APPENDIX 1 – POTENTIAL FOR EXTREME SEA LEVEL RISE

The carbon dioxide level of the atmosphere has now increased by 50 percent compared to the eighteenth century.[53] 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 1-1).[54] 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.[55] 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.[56] This is especially true in the Arctic.

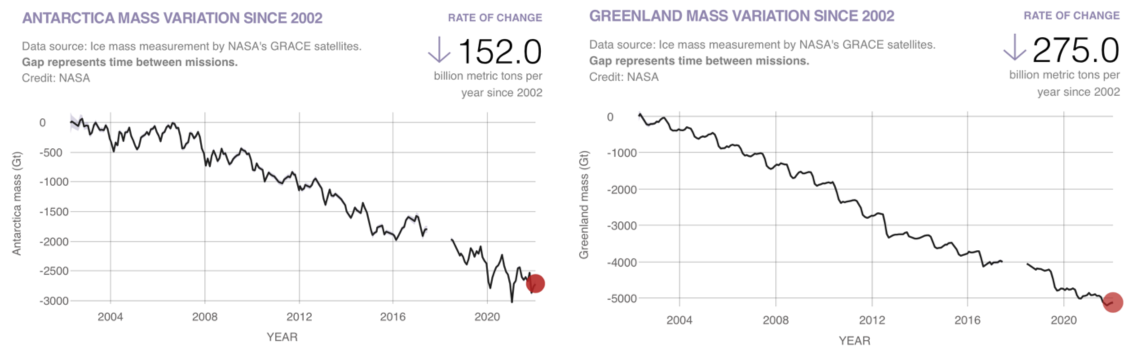

***Figure 1-1**. Since 2002, Antarctica (left) has lost an average 152 billion metric tons of ice per year, and Greenland (right) has lost an average 275 billion metric tons of ice per year.[57]*

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.[58] Mass loss from the Greenland Ice Sheet is 7 times faster than it was in the 1990's,[59] and has quadrupled this decade.[60] 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.[61] Greenland Ice Sheet meltwater has increased 250 to 575 percent in only 20 years.[62]

There is concern that with less than 0.5 degrees Celsius of additional warming, melting on Greenland will become unstoppable.[63] 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 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[64] that the Western Greenland Ice Sheet has been losing

[53] UK MET Office (2021) https://www.metoffice.gov.uk/research/climate/ seasonal-to-decadal/long-range/forecasts/co2-forecast-for-2021
[54] 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.
[55] 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
[56] 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
[57] NASA Vital Signs of the Planet, https://climate.nasa.gov/vital-signs/ice-sheets/
[58] 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
[59] 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
[60] Bevis, M. et al. (2019) Accelerating changes in ice mass within Greenland, and the ice sheets sensitivity to atmospheric forcing. PNAS, 116, 1934-1939
[61] 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/
[62] 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
[63] Climate tipping points—too risky to bet against, Nature (2019) https://nature.com/articles/d41586-019-03595-0
[64] 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

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.[65] 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.[66] Researchers have concluded that irreversible collapse of Pine Island and Thwaites outlet glaciers in the Amundsen Sea sector of West Antarctica has already begun,[67] 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*."[68] 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.[69] 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.[70] In 2011–2020, annual average Arctic Sea ice area reached its lowest level since at least 1850.[71] 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.[72]

[65] 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
[66] 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
[67] 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.
[68] 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
[69] https://agu.confex.com/agu/fm21/meetingapp.cgi/Paper/898204.
[70] 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.
[71] IPCC (2021) Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis.
[72] 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

APPENDIX 2 – SEA LEVEL RISE PLANNNING IN OTHER JURISDICTIONS

MIAMI-DADE

The Miami-Dade County Sea Level Rise Strategy[73] 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
10. Increase affordable, resilient housing on high ground within SMART Plan transit corridors

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

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)[74] and the Nantucket Coastal Risk Assessment and Resiliency Strategies[75] 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

Sea level rise planning[76] for the City of Pacifica, CA 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 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.

[74] https://www.nantucket-ma.gov/DocumentCenter/View/40279/Nantucket-Coastal-Resilience-Plan-Existing-Conditions--Coastal-Risk-Assessment---November-2021-PDF
[75] https://www.nantucket-ma.gov/DocumentCenter/View/35045/Coastal-Risk-Assessment-and-Resiliency-Strategies-Report-January-2020-PDF
[76] https://www.cityofpacifica.org/departments/planning/sea-level-rise

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 3 – 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.[77] 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 3-1)** 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 Hawaiʻi 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**).

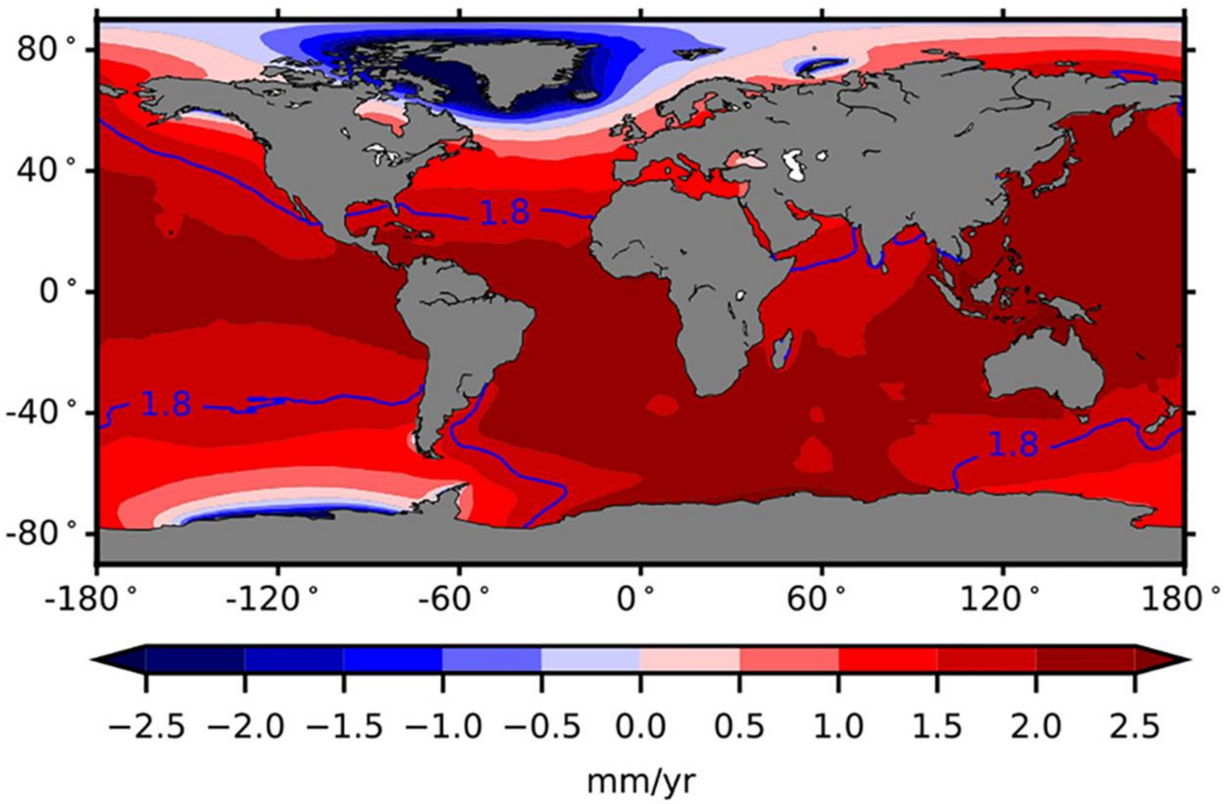

***Figure 3-1**. Sea level fingerprints (patterns of variation in sea level rise) calculated from GRACE satellite observations, 2002-2014. The blue contour (1.8 millimeters per year) shows the average sea level rise if all the water added to the ocean were spread uniformly around Earth. Credit: NASA/UCI.*[78]

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[77] 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
[78] https://climate.nasa.gov/news/2626/evidence-of-sea-level-fingerprints/