CLIMATE CHANGE BRIEF 2023

City and County of Honolulu Climate Change Commission

PURPOSE

Pursuant to the Revised Charter of Honolulu ("RCH") Section 6-107(h), the City and County of Honolulu ("City") Climate Change Commission (Commission) is charged with gathering the latest science and information on climate change impacts in O‘ahu, Hawai‘i, and globally and providing advice and recommendations to the mayor, City Council, and executive departments as they draft policy and engage in planning to improve community resiliency and sustainability.

To establish the scientific basis for observations and future consequences of climate change, the Commission adopts this CLIMATE CHANGE BRIEF 2023, which has been updated from the first version released in 2018. The document presents the findings of peer-reviewed scientific literature on past, present, and projected climate change, including trends, events, and observed and anticipated impacts. It highlights both global conditions and those specifically known to O‘ahu and Hawai‘i using credible, data-based sources and peer-reviewed model results. This brief provides a foundation for guidance and recommendations from the Commission, and a resource for community to understand and assess the types and timing of climate change impacts.

The Commission views this brief as a comprehensive overview of the best-available science on climate change but acknowledges that more detailed information and guidance is needed to adequately address the full range of current and projected climate-related impacts to the City. In response, the Commission also produces topically-focused guidance documents for the City. Current guidance documents have included topics such as: sea level rise, a "one-water collaboration framework" for climate resiliency, climate change and financial risk, climate change and social equity, social cost of carbon, reducing greenhouse gas emissions from buildings, and urban heat. This document will be updated every several years and topically-focused guidance documents will be produced as new information becomes available and the City continues to implement climate adaptation and mitigation projects.

Contents

INTRODUCTION

This Climate Change Brief is updated every several years, with this update being prompted by the release of peer-reviewed research and several national and multinational climate change reports. The Intergovernmental Panel on Climate Change (IPCC) released three Special Reports since the 2018 Climate Change Brief: Global Warming of 1.5 C (2018), Climate Change and Land (2019), and The Ocean and Cryosphere in a Changing Climate (2019).[1] The IPCC began releasing The Sixth Assessment Reports (AR6) in 2021 beginning with: The Physical Science Basis (2021); Impacts, Adaptation and Vulnerability and Mitigation of Climate Change (2022); and finally the AR6 Synthesis Report in March 2023; collectively providing an overview of the state of knowledge on the science of climate change.[2] The Fifth US-National Climate Assessment (NCA5), released in draft form at the time of writing this brief and expected to be released in 2023, will provide an updated analysis of the impacts of global climate change in the United States, including chapters focused on earth systems, national topics, regions, and responses, with the draft regional chapter on Hawai‘i and the US Affiiated Pacific Islands identifying sea level rise as one of the most concerning climate change-related impacts for the region.[3] In 2022, National Oceanic and Atmospheric Administration (NOAA) released an updated interagency Sea Level Rise Technical Report for the United States incuding Alaska and Hawai‘i that synthesizes the best-available science on sea level rise including providing updated sea level rise planning scenarios out to 2150.[4] This 2023 update to the Climate Change Brief emphasizes local climate change observations and projected impacts for O‘ahu and Hawai‘i followed by global observations and projected impacts. Each section also includes progress and next steps to highlight recent and ongoing efforts addressing these impacts at the island, state, and global scales.

COMMONLY USED ACRONYMS, ABBREVIATIONS, AND TERMS

CO_2	Carbon Dioxide
ENSO	El Niño Southern Oscillation
FEMA	Federal Emergency Management Agency
ft	feet
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
m	meters
MMTCO2e	Million Metric Tons of Carbon Dioxide Equivalent
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
City	The City & County of Honolulu
CCSR	City Office of Climate Change, Sustainability, and Resiliency
Commission	The City Climate Change Commission
ppb	Parts per billion
ppm	Parts per million
USGS	United States Geological Survey

1 Intergovernmental Panel on Climate Change, Reports: https://www.ipcc.ch/reports/
2 Intergovernmental Panel on Climate Change, Sixth Assessment Report: https://www.ipcc.ch/assessment-report/ar6/
3 U.S. Global Change Research Program, Fifth National Climate Assessment: https://www.globalchange.gov/nca5
4 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-nostechrpt01-global-regional-SLR-scenarios-US.pdf

CLIMATE CHANGE INDICATORS AND IMPACTS

Energy and Greenhouse Gases

Greenhouse gas (GHGs) emissions resulting from human activities are the main driver of global warming in the modern era, and include carbon dioxide (CO_2), methane, nitrous oxide, and various synthetic fluorinated gases. Rising concentrations of GHGs are causing extra heat to be trapped in the atmosphere, with resulting rising temperatures leading to a range of direct and indirect impacts. Carbon dioxide is the most closely-monitored gas because it is the primary GHG emitted through human activities, currently accounts for the greatest portion of the warming associated with human activities, and is particularly long-lived in the Earth's climate system (up to thousands of years).[5] Burning fossil fuels for energy production, transportation, and industry, and release of GHG's from land use practices associated with food and timber production that destroy natural carbon reservoirs through deforestation and soil mismanagement have raised the concentration of carbon dioxide in the Earth's atmosphere by 140 parts per million (ppm), or about fifty percent, over atmospheric concentration of 280 ppm prior to the industrial revolution.

Local Observations

- Oʻahu produced 16.2 million metric tons of GHGs (Carbon Dioxide Equivalent, MMTCO2e) in 2019 (the most recent data available), a decrease of 16% from 2005 when local measurements became available.[6]
    - Approximately 80% of Hawaiʻi's GHG emissions come from Oʻahu (16.2 MMTCO2e / 19.6 MMTCO2e).[7, 8]
    - Emissions from electricity production is the largest single source of GHG emissions at 48% of the total.
    - Emissions from transportation-related combustion of gasoline, diesel, and jet fuels, among other fuels, represent the second largest source at 37%; other energy industries' emissions including oil and gas refining are 11%.
    - The remaining 15% of GHG emissions come from other industrial processes (3%), solid waste and wastewater (5%), and land use changes (7%) including agricultural and forestry.
- Oʻahu's per capita CO_2 emissions (about 14 MMTCO2e) are lower than the national average (about 18 MMTCO2e) but more than twice the global average (about 6 MMTCO2e).[9]

Global Observations

- CO_2 levels in the Earth's atmosphere have passed 420 ppm compared to pre-industrial levels of 280 ppm – an increase of over 50% (Figure 1).[10] Levels are now comparable to the "Pliocene Climatic Optimum" 4.1 to 4.5 million years ago.[11]
- Global energy-related carbon dioxide emissions increased by 6% in 2021 to the highest level ever as the world economy rebounded strongly from the COVID-19 pandemic. This rebound relied strongly on coal (40% of the overall increase in emissions) in part because of record high natural gas prices related to the war in Ukraine.[12]
- Atmospheric methane, the second biggest contributor to human-caused global warming after CO_2, increased by a record amount in 2021 (17 parts per billion (ppb)) for the second year in a row (2020 was 15.3 ppb).[13] Atmospheric methane levels averaged 1,895.7 ppb during 2021, which is 162% greater than pre-industrial levels (Figure 2).

5 United States Environmental Protection Agency: https://www.epa.gov/report-environment/greenhouse-gases

6 City & County of Honolulu, Office of Climate Change, Sustainability and Resilience (2019) Greenhouse Gas Emissions Inventory: https://www.resilientoahu.org/greenhouse-gas-inventory.

7 City & County of Honolulu, Office of Climate Change, Sustainability and Resilience (2019)

8 Hawaiʻi State Department of Health (2021) Hawaii Greenhouse Gas Emissions Report for 2017: https://health.hawaii.gov/cab/hawaii-greenhouse-gas-program/

9 City & County of Honolulu, Office of Climate Change, Sustainability and Resilience (2019) One Climate One Oahu, City & County of Honolulu Climate Action Plan 2020-2025: https://www.resilientoahu.org/climate-action-plan

10 NOAA Global Monitoring Laboratory (2023) Trends in Atmospheric Carbon Dioxide: https://gml.noaa.gov/ccgg/trends/. Last viewed 2/9/2023.

11 NOAA News & Features (2022) Carbon dioxide now more than 50% higher than pre-industrial levels: https://www.noaa.gov/news-release/carbon-dioxide-now-more-than-50-higher-than-pre-industrial-levels

12 International Energy Agency (2022) Global Energy Review: CO2 Emissions in 2021: https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2

13 NOAA News & Features (2022) Increase in atmospheric methane set another record during 2021: https://www.noaa.gov/news-release/increase-in-atmospheric-methane-set-another-record-during-2021

- In 2019, fossil fuels fed about 85% of energy consumption, nuclear energy 4.4%, and renewable sources about 11%. Renewables incuded hydro (62.8%), wind (19%), geothermal and biomass (9.4%), and solar (8.8%).[14, 15] Despite rapid recent growth, renewables still make up a small fraction of the global energy consumption (Figure 3).
- Natural factors such as volcanic eruptions and changes in solar activity have had a negligible effect on global surface temperatures over the past 170 years.[16]

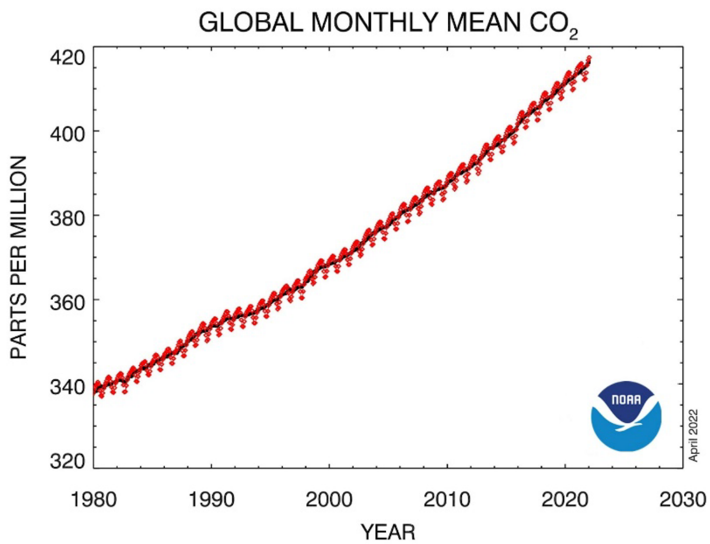

Figure 1. Global atmospheric carbon dioxide concentration (black line) measured from NOAA's Mauna Loa Observatory.[17] Natural seasonal variability is visible in the monthly data (red dots).

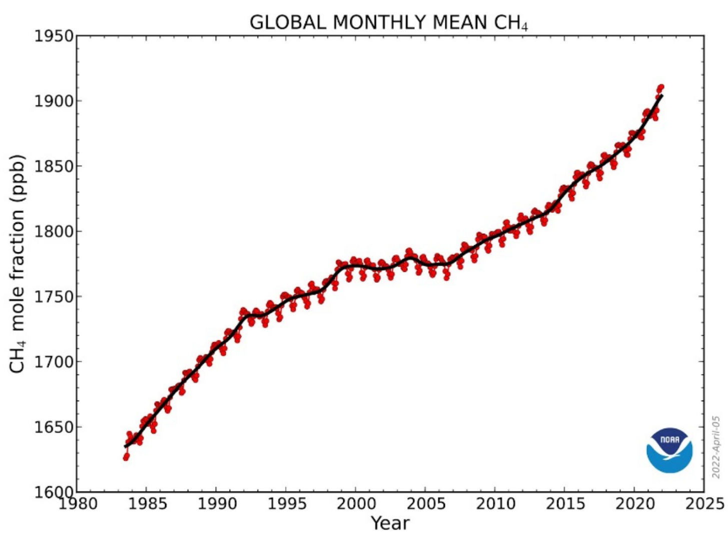

Figure 2. Global atmospheric methane concentration (black line) measure from NOAA's Mauna Loa Observatory.[18] Natural seasonal variability is visible in the monthly data (red dots).

14 Sato, M. and Hansen, J. (2021) Updating the climate science: What path is the real world following? http://www.columbia.edu/~mhs119/

15 BP Statistical Review of World Energy (2022) https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

16 IPCC (2021) Climate Change 2021: The Physical Science Basis

17 NOAA Global Monitoring Laboratory (2023) Trends in Atmospheric Carbon Dioxide: https://gml.noaa.gov/ccgg/trends/. Last viewed 2/9/2023.

18 NOAA Global Monitoring Laboratory (2023) Trends in Atmospheric Methane: https://gml.noaa.gov/ccgg/trends_ch4/. Last viewed 2/9/2023.

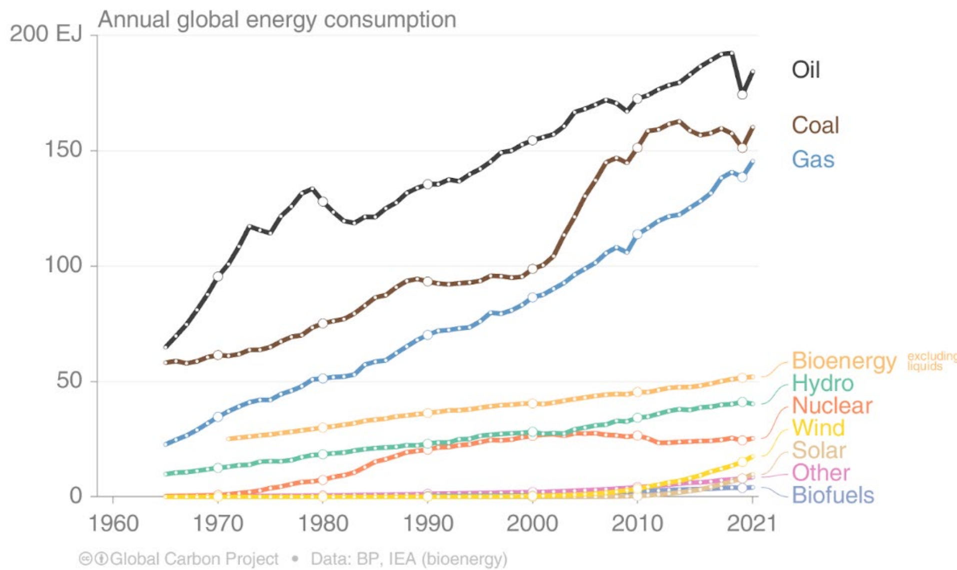

Figure 3. Global energy use by source. Renewable energy is growing rapidly but has been offset in recently by increasing coal and natural gas use.[19]

Projected Impacts

- To hold global temperature below an increase of 2°C (3.6°F) per the 2015 Paris Climate Agreement, it is necessary to decrease carbon emissions by 50% per decade until net-zero emissions are reached in the 2080s (Figure 4). [20, 21]

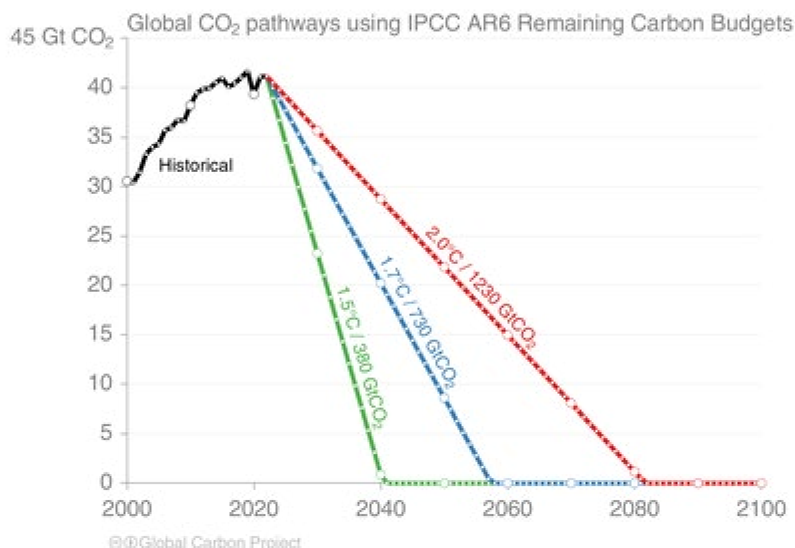

Figure 4. Global CO_2 emissions pathways to stabilize global mean temperature at 1.5 or 2.0° C require dramatic reductions in emissions starting in this decade.[22]

19 Global Carbon Project (2022) Global Carbon Budget: https://www.globalcarbonproject.org/carbonbudget/index.htm
20 Friedlingstein, P., et al. (2022) Earth System Science Data, 14, 4811–4900, 2022, DOI: 10.5194/essd-14-4811-2022.
21 Global Carbon Project (2022) Carbon budget and trends 2022. www.globalcarbonproject.org/carbonbudget
22 Global Carbon Project (2022) Carbon budget and trends 2022. www.globalcarbonproject.org/carbonbudget

- Projections of energy use by the International Energy Association (IEA) and U.S. Energy Information Association (EIA) show there is still a large gap between projected reductions in GHG emissions, based on pledges and projected implementation, and a 1.5° C stabilization.
    - The IEA projects the following global energy patterns in its 2022 World Energy Outlook[23]:
        - The world is in the midst of its first global energy crisis related to Russia's invasion of Ukraine. A key question is whether the crisis will hamper or catalyze faster action on clean energy transitions.
        - By 2030 investments in clean electricity generation will increase by 50% globally and 250% in the U.S, which is sufficient to outpace growth in total electricity generation, reducing the contribution of fossil fuels for power.
        - Based on prevailing policy and demand, total demand for fossil fuels declines steadily from the mid-2020s. Global demand for coal peaks in the next few years, natural gas demand peaks by the end of the decade, and oil demand levels off in the mid-2030s but remains high.
        - These projected gains based on economic and policy trends equate to a reduction of only 13% in annual CO_2 emissions by 2050, which is insufficient to avoid the most serious modeled impacts of climate change.
    - The U.S. Energy Information Administration (EIA) projects the following energy patterns in the U.S. to the year 2050[24]:
        - Petroleum and natural gas remain the most-consumed sources of energy but renewable energy is the fastest growing.
        - Energy-related CO_2 emissions drop through 2035 before climbing again through 2050 as population and economic growth outpaces gains in efficiency.
        - U.S. production of natural gas and petroleum rises with growing demand for exports and industrial uses.

Progress & Next Steps

- Hawai'i and its four counties are committed through State legislation to the 2015 Paris Climate Agreement, with the main aim of limiting global average temperature rise this century to 1.5° C above pre-industrial levels.[25]
- Hawai'i is approaching climate change adaptation through the adoption of the United Nations Sustainable Development Goals (SDGs)[26] and has made progress toward meeting 24 out of 35 local SDG metrics as of 2021.[27]
- Hawai'i established 100% renewable portfolio standards for the electricity sector, to be achieved by no later than 2045[28] and established a net-negative emissions target by 2045.[29]
- The City's 2020-2025 Climate Action Plan, adopted by Ordinance 20-47, assesses O'ahu's GHG emissions and charts a course through specific strategies and actions for a transition to 100 percent renewable energy and net-carbon emissions within the City by 2045, consistent with State law.[30]
- O'ahu produced 16.2 million metric tons of GHGs (Carbon Dioxide Equivalent, MMTCO2e) in 2019 (the most recent data available), a decrease of 16% from 2005 when local measurements became available.[31]
- O'ahu's sole remaining coal-fired electricity generation plant was closed in September 2022, with lost energy production to be replaced by renewable sources.

23 International Energy Agency (2022) World Energy Outlook 2022: https://www.iea.org/reports/world-energy-outlook-2022/key-findings
24 U.S. Energy Information Administration (2022) Annual Energy Outlook 2022: https://www.eia.gov/outlooks/aeo/narrative/introduction/sub-topic-01.php
25 State of Hawai'i Act 32 (Senate Bill 559), Session Laws of Hawai'i, 2017
26 United Nations Office for Disaster Risk Reduction (2015). United Nations Office for Disaster Risk Reduction Annual Report 2015. United Nations Office for Disaster Risk Reduction, Geneva, Switzerland.
27 Hawaii Green Growth. (2022). 2021 Annual Sustainability Scorecard | Aloha Challenge. https://alohachallenge.hawaii.gov/pages/2021-annual-sustainability-scorecard
28 State of Hawai'i (2015) Act 97, Session Laws Hawai'i 2015.
29 State of Hawai'i (2018) Act 15, Session Laws Hawai'i 2018.
30 City & County of Honolulu, Office of Climate Change, Sustainability and Resilience (2019) One Climate One Oahu, City & County of Honolulu Climate Action Plan 2020-2025: https://www.resilientoahu.org/climate-action-plan
31 City & County of Honolulu, Office of Climate Change, Sustainability and Resilience (2019) Greenhouse Gas Emissions Inventory: https://www.resilientoahu.org/greenhouse-gas-inventory.

- O'ahu reached 34.4% renewable electricity use by customers as a percentage of total utility sales in 2022, up from 32.8% in 2021.[32, 33]
- Rapid growth of rooftop solar generation, centralized solar, battery storage, wind power, and pumped hydropower storage is enabling a transition away from an oil-predominant grid.[34]
- In response to a mayoral request, the Commission's 2021 Social Cost of Carbon Guidance Document provides an overview of carbon pricing mechanisms and how those might apply to City decision-making and enabling City programs' progress toward decarbonization.
- The Commission's 2022 Guidance Document on Reducing Greenhouse Gas Emissions from Building Operation provides recommendations based on an overview of key design influences including codes, policies and practices, incentives, education approaches, and sustainable and resilient design strategies incorporating feedback from a stakeholder focus group.

Atmosphere and Ocean Warming

The Intergovernmental Panel on Climate Change (IPCC) stated in its Fifth and Sixth Assessment Reports that "It is unequivocal that the increase of CO_2, methane, and nitrous oxide in the atmosphere over the industrial era is the result of human activities and that human influence is the principle driver of many changes observed across the atmosphere, ocean, cryosphere, and biosphere" It continues: "Since systematic scientific assessments began in the 1970s, the influence of human activity on the warming of the climate system has evolved from theory to established fact."[35, 36] These statements are supported by similar findings from leading national scientific societies including the American Association for the Advancement of Science, the American Chemical Society, the American Geophysical Union, the American Meteorological Society, and the U.S. National Academy of Sciences.[37]

Local Observations

- Average air temperature has risen by about 1.1°C (2°F) statewide and by 1.4°C (2.6°F) in Honolulu since 1950 with a sharp increase in warming over the last decade (Figure 5).[38]
- 2015 and 2016 were the warmest years on record in Hawai'i.[39]
- Average sea level air temperature in Hawai'i increased 0.12° C (0.22° F) per decade over the past century (1905-2017),[40,41] similar to global average temperature increase.
- Statewide, the number of hot days and very warm nights between 2015 and 2020 were more than double the respective long-term averages.[42]
- The rate of temperature increase is greatest at high elevations, far exceeding the global average rate of change.[43]
- 2019 saw the 1st, 2nd, and 3rd hottest calendar days on record in Honolulu[44] related to a record-setting marine heatwave, which was the result of weak atmospheric circulation and calm wind patterns.[45]

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32 Hawaii Electric (2021) 2021 Renewable Portfolio Standard Status Report
33 Hawaii Electric (2022) 2022 Renewable Portfolio Standard Status Report
34 Hawai'i State Energy Office, 2020. Hawai'i's Energy Facts and Figures.
35 IPCC (2014) Fifth Assessment Report, Summary for Policymakers, SPM 1.1.
36 IPCC (2021) Sixth Assessment Report, Working Group 1.
37 NASA Global Climate Change: https://climate.nasa.gov/scientific-consensus/ (last viewed 2/9/2023).
38 NOAA National Centers for Environmental Information (2022) State Climate Summaries 2022: Hawai'i
39 McKenzie, M.M. (2016) Regional temperature trends in Hawai'i: A century of change, 1916–2015 (MS thesis). Dept. of Geog., University of Hawai'i at Mānoa.
40 Kagawa-Viviani, A. K., and Giambelluca, T. W. (2020). Spatial patterns and trends in surface air temperatures and implied changes in atmospheric moisture across the Hawaiian Islands, 1905–2017. Journal of Geophysical Research: Atmospheres, 125, e2019JD031571. https://doi.org/10.1029/2019JD031571
41 McKenzie, MM, Giambelluca, TW, Diaz, HF. Temperature trends in Hawai'i: A century of change, 1917–2016. Int J Climatol. 2019; 39: 3987– 4001. https://doi.org/10.1002/joc.6053
42 NOAA National Centers for Environmental Information (2022)
43 NOAA National Centers for Environmental Information (2022)
44 Washington Post, Hawaii goes 20 days in a row setting a heat record during its hottest summer ever: https://www.pennlive.com/nation-world/2019/09/hawaii-goes-20-days-in-a-row-setting-a-heat-record-during-its-hottest-summer-ever.html
45 Amaya, D.J., et al. (2020) Physical drivers of the summer 2019 North Pacific marine heatwave. Nature Communications; 11 (1) DOI: 10.1038/s41467-020-15820-w

- During the strong El Niño of 2015, Honolulu set or tied 11 days of record heat.[46] This compelled the local energy utility to issue emergency public service announcements to curtail escalating air conditioning use that stressed the electrical grid.[47]

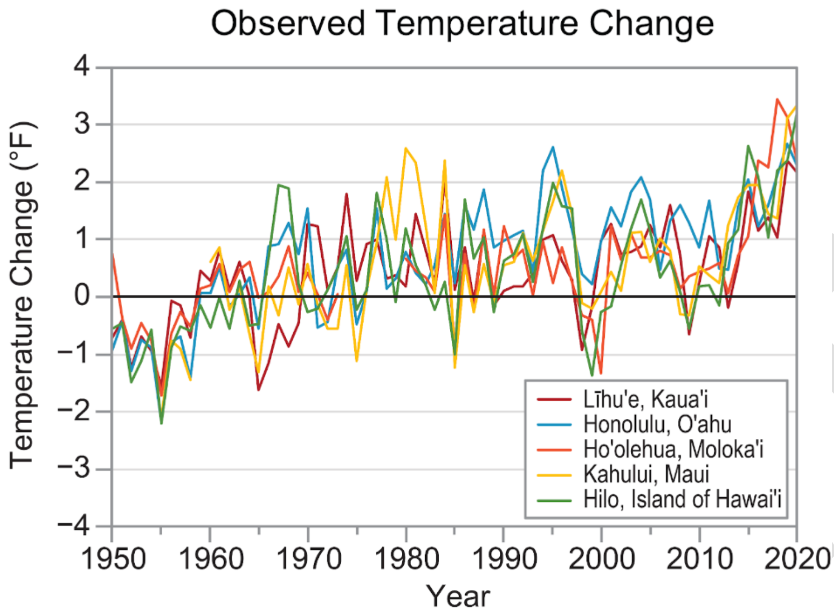

Figure 5. Average annual temperatures have increased significantly statewide and in Honolulu (blue line) over the past century compared to the 1951-1980 average. Natural variability from ENSO and other processes is also apparent in the record (Figure credit: NOAA-NCEI).[48]

Global Observations

- Global surface air temperature has risen between 1.1° and 1.2° C (2.0° and 2.2° F) since the preindustrial era (Figure 6). [49, 50, 51].
- 2022 tied for the fifth warmest year in the instrumental record (1880-2022), which is particularly notable since the tropical Pacific Ocean was in a third successive year of a La Niña cool phase of the El Niño / La Niña (ENSO) cycle that dominates global temperature variability from year-to-year.[52, 53]
- The past nine years were the nine warmest years on record with 2020 as the warmest on record (+1.29°C, 2.3°F).[54]
- Global warming is accelerating, but the rate of warming is not evenly distributed around the planet. Warming over land is about 60% faster than over the ocean,[55] and warming is greatest in the Arctic at over four times the global rate,[56]
- Humans are causing the climate to change an estimated 170 times faster than natural forces.[57]

46 New York Times weather chart: https://www.nytimes.com/interactive/2016/02/19/us/2015-year-in-weather-temperature-precipitation.html#honolulu_hi.
47 http://www.hawaiinewsnow.com/story/26551141/hawaiian-electric-asks-oahu-customers-to-conserve-power-tonight
48 NOAA National Centers for Environmental Information (2022) State Climate Summaries 2022 – Hawaiʻi. https://statesummaries.ncics.org/chapter/hi/
49 NASA Global Climate Change, Vital Signs for the Planet: https://climate.nasa.gov/ (last viewed 2/10/2023).
50 NOAA Climate.gov, Climate Change: Global Temperature: https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature
51 Hansen J.; Sato, M.; Ruedy, R. (2023) Global Temperature in 2022, unpub. ms. http://www.columbia.edu/~jeh1/mailings/2023/Temperature2022.12January2023.pdf
52 Hansen J.; Sato, M.; Ruedy, R. (2023)
53 Data from: NASA Goddard Institute for Space Studies, Surface Temperature Analysis (GISTEMP v4): https://data.giss.nasa.gov/gistemp/ (last viewed 2/10/2023)
54 Hansen J.; Sato, M.; Ruedy, R. (2023)
55 Wallace, C.J. and Joshi, M. (2018) Comparison of land–ocean warming ratios in updated observed records and CMIP5 climate models, Environmental Research Letters, 13, 114011: https://doi.org/10.1088/1748-9326/aae46f
56 Rantanen, M., Karpechko, A.Y., Lipponen, A. et al. (2022) The Arctic has warmed nearly four times faster than the globe since 1979. Commun Earth Environ 3, 168 (2022). https://doi.org/10.1038/s43247-022-00498-3
57 Gaffney, O., and Steffen, W. (2017) The Anthropocene equation, The Anthropocene Review, http://dx.doi.org/10.1177%2F2053019616688022

- Globally-averaged sea surface temperature (SST) increased by 1.0°C (1.8°F) over the past 100 years. Half of this rise has occurred since the 1990s. North Central Pacific averaged SST trends follow the globally averaged trend. Over the last 5 years almost the entire tropical Pacific, in particular areas along the equator, have seen temperatures warmer than the 30-year average.[58]
- Marine heatwaves have doubled in frequency since 1982 and are increasing in intensity.[59]
- The deep ocean (below 2000 m, 13,123 ft) has also warmed in recent decades, especially in the Southern Ocean.[60]
- Over 90% of the heat trapped by greenhouse gases since the 1970's has been absorbed by the oceans and today the oceans absorb heat at twice the rate they did in the 1990's.[61,62]

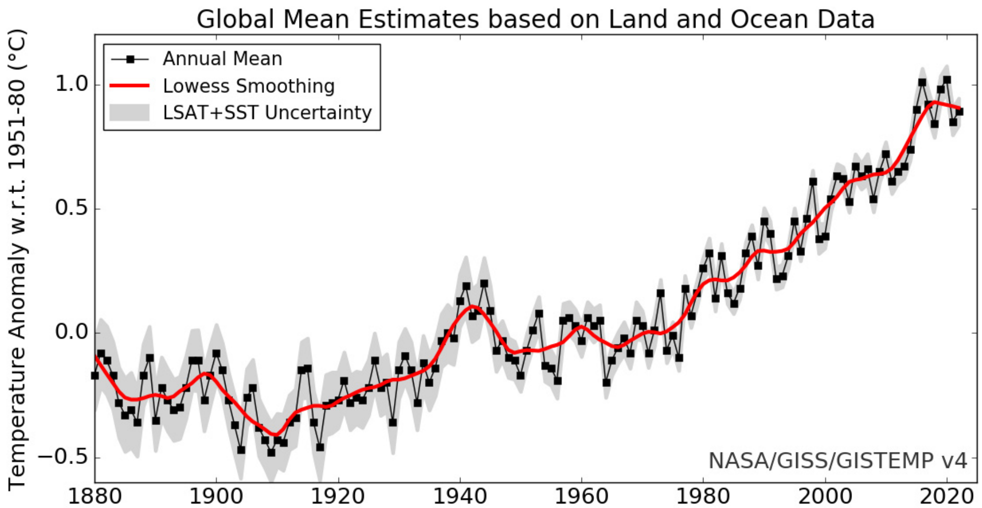

Figure 6. Global surface temperatures relative to 1880-1920 (Source: NASA GISS).[63]

Projected Impacts

- Global temperatures in 2023 will likely be notably warmer than 2022 as the cooling effects of the three-year La Niña phase of the El Niño / La Niña cycle is unlikely to continue. 2024 may approach 1.5°C (2.7°F) if the tropical Pacific shifts to an El Niño warm phase.[64]
- The World Meteorological Organization projects that there is about a fifty-fifty (48%) chance that annual global mean temperature will exceed 1.5°C above preindustrial levels by 2026.[65]
- The last time global climate matched today's temperatures, approximately 125,000 years ago, global sea level was about 6.6 m (20 ft) higher.[66, 67, 68]
- Beyond the next few decades, the magnitude of climate change impacts depends on continued emissions of greenhouse gases and the sensitivity of the climate system. Projected changes for the end of this century range from

58 Marra, J.J.; Kruck, M.C. (2017) State of Environmental Conditions in Hawaii and the U.S. Affiliated Pacific Islands under a Changing Climate: 2017: https://pirca.org/2017/11/30/state-of-environmental-conditions-in-hawaii-and-the-u-s-affiliated-pacific-islands-under-a-changing-climate-2017/
59 IPCC (2019) Special Report on the Ocean and Cryosphere in a Changing Climate: https://www.ipcc.ch/srocc/
60 IPCC (2019)
61 Cheng L., et al (2015) Global upper ocean heat content estimation: recent progress and the remaining challenges. Atmospheric and Oceanic Science Letters, 8. DOI:10.3878/AOSL20150031.
62 Glecker, P.J., et al. (2016) Industrial era global ocean heat uptake doubles in recent decades. Nature Climate Change.
63 National Aeronautics and Space Administration, Goddard Institute for Space Studies, Surface Temperature Analysis (v4). https://data.giss.nasa.gov/gistemp/graphs_v4/ (last viewed March 21, 2023)
64 Hansen J.; Sato, M.; Ruedy, R. (2023)
65 World Meteorological Organization (2022) Global Annual to Decadal Climate Update, Target years 2022 and 2022-2026.
66 Hoffman, J.S., et al. (2017) Regional and global SST's during the last interglaciation, Science, 355(6322), 276-279, doi: 10.1126/science.aai8464.
67 Kopp, R.E, et al. (2009) Probabilistic assessment of sea level during the last interglacial stage, Nature, 462, 863-867, doi: 10.1038/nature08686.
68 Dutton, A., et al. (2015) Sea-level rise due to polar ice-sheet mass loss during past warm periods, Science, v. 349, Is. 6244, DOI: 10.1126/science.aaa4019.

1.0° to 1.8°C (1.8° to 3.2°F) under very low emissions scenario, 2.1° to 3.5°C (3.8° to 6.3°F) under intermediate emissions scenarios, to 3.3° to 5.7°C (5.9° to 10.3°F) under very high emissions scenarios.[69]

- Model projections for late 21st century for Hawai'i indicate that surface air temperature over land will increase 2° to 4°C (1.8° to 7.2°F) with the greatest warming at the highest elevations and on leeward sides of the major islands. [70] [71] [72]
- Under continued ("business as usual") greenhouse gas emissions, elevations above 3,000 m (9,800 ft) in Hawai'i are projected to reach up to 4° to 5°C (7.2° to 9°F) warmer temperatures by the late 21st Century.[73]
- The deep ocean and large ice sheets lag behind in their response to changing climate conditions at Earth's surface. It takes hundreds to thousands of years for the deep ocean to turn over, i.e., fully circulate, and ice sheets may require thousands of years to recover lost ice. These "committed" changes to the deep ocean and cryosphere mean that some changes are irreversible on the timescales relevant to human society (decades to centuries).[74]

*For progress and next steps, see: Energy and Greenhouse Gases

Precipitation and Streamflow

Water in all its forms is central to the sustainability, resilience, and socio-economic fabric of Hawai'i. Recognizing the critical importance of managing water resources appropriately in a changing climate, the Commission produced a One Water for Climate Resiliency White Paper for the City in 2020. The paper recognizes that "water, in all forms, is critical to Hawai'i's built and natural environment and managing it sustainably will be essential as the pressures of development, aging infrastructure, climate change, and sea level rise increase over time. A majority of climate change impacts involve water - usually resulting from too much or too little of it." Interactions of tradewinds and storms with Hawai'i's complex topography make rainfall patterns highly geographically variable and complicates efforts to model future changes with climate change. See Appendix 1: El Niño-Southern Oscillation (ENSO) Variability for more on the relationships between ENSO and interannual variability in precipitation in Hawai'i.

Local Observations

- Over 90% of Hawai'i experienced a decline in rainfall from 1920-2012, with changes in precipitation varying on each island (Figure 6). The period since 2008 has been particularly dry.[75]
- Rainfall has declined in both the wet and dry seasons on all the major islands. On O'ahu, the largest declines have occurred in the northern Ko'olau Mountains.[76]
- Drought frequency, duration, and magnitude has increased statewide and on O'ahu from 1920-2019.[77]
- Consecutive wet days and consecutive dry days are both increasing in Hawai'i.[78, 79]
- Streamflow in Hawai'i has declined over approximately the past 100 years, consistent with observed decreases in average annual rainfall and leading to an increase in the number of no-flow days in drier areas.[80, 81]

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69 IPCC, 2021: 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., P., et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

70 Xue, L., Wang, Y., Newman, A.J. et al. How will rainfall change over Hawai'i in the future? High-resolution regional climate simulation of the Hawaiian Islands. Bull. of Atmos. Sci.& Technol. 1, 459–490 (2020). https://doi.org/10.1007/s42865-020-00022-5

71 Timm, O.E. (2017) Future Warming Rates over the Hawaiian Islands Based on Elevation-Dependent Scaling Factors. Int. J. Clim., doi:10.1002/joc.5065.

72 Zhang, C., Y. Wang, K. Hamilton, and A. Lauer, 2016: Dynamical Downscaling of the Climate for the Hawaiian Islands. Part II: Projection for the Late Twenty-First Century. J. Climate, 29, 8333–8354, https://doi.org/10.1175/JCLI-D-16-0038.1.

73 Timm, O.E. (2017) Future Warming Rates over the Hawaiian Islands Based on Elevation-Dependent Scaling Factors. Int. J. Clim., doi:10.1002/joc.5065.

74 IPCC (2019) Special Report on the Ocean and Cryosphere in a Changing Climate: https://www.ipcc.ch/srocc/

75 Frazier, A.G. and Giambelluca, T.W. (2017) Spatial trend analysis of HI rainfall from 1920 to 2012. Int. J. Climatol, 37: 2522-2531, DOI: 10.1002/joc.4862.

76 Frazier, A.G. and Giambelluca, T.W. (2017)

77 Frazier, Abby G.,et al. (2022). "A Century of Drought in Hawai'i: Geospatial Analysis and Synthesis across Hydrological, Ecological, and Socioeconomic Scales" Sustainability 14, no. 19: 12023. https://doi.org/10.3390/su141912023

78 Kruk, M. C., et al. (2015)

79 Chu, P., Y. R. Chen, and T. A. Schroeder, 2010: Changes in Precipitation Extremes in the Hawaiian Islands in a Warming Climate. *J. Climate*, **23**, 4881–4900, https://doi.org/10.1175/2010JCLI3484.1.

80 Bassiouni, M., and D. S. Oki (2013) Trends and shifts in streamflow in Hawai'i, 1913–2008. Hydrological Processes, 27 (10), 1484–1500. doi:10.1002/hyp.9298

81 Clilverd, HM, Tsang, Y-P, Infante, DM, Lynch, AJ, Strauch, AM. Long-term streamflow trends in Hawai'i and implications for native stream fauna. *Hydrological Processes*. 2019; 33: 699– 719. https://doi.org/10.1002/hyp.13356

- In Hawai‘i, El Niño and La Niña phases of ENSO can dramatically affect precipitation, air and ocean temperature, and trade winds.[82] Total rainfall is higher and extreme precipitation events are more frequent in La Niña years, with the opposite trend in El Niño years.[83, 84, 85] Most droughts are associated with El Niño events.[86] See Appendix 1: El Niño-Southern Oscillation (ENSO) Variability.

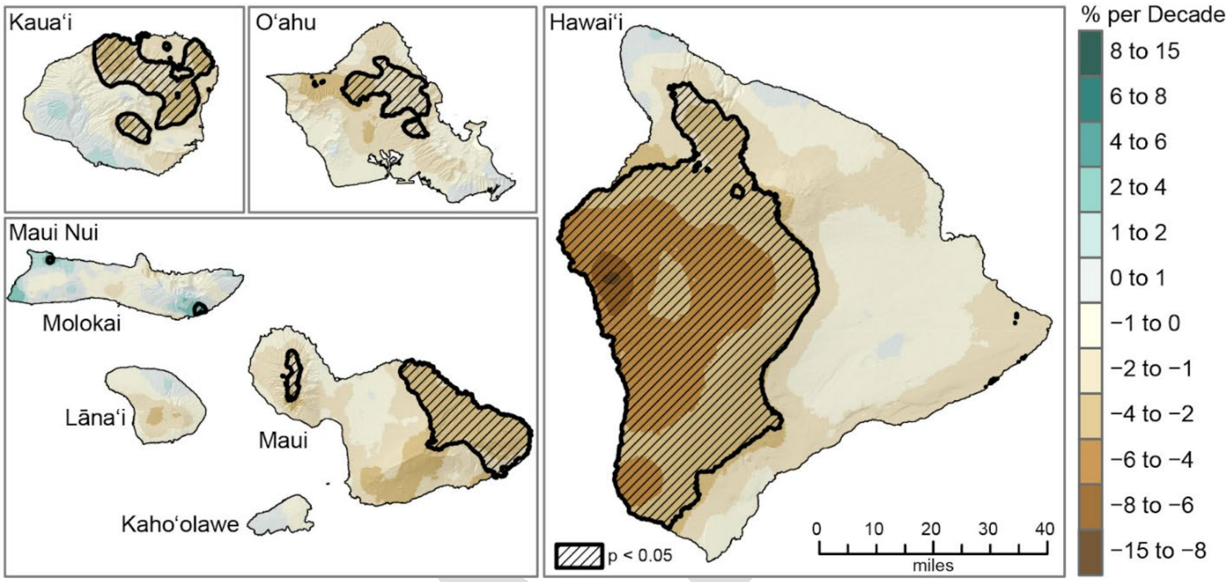

Figure 6. Most of O‘ahu and the State of Hawai‘i has seen a decrease in average annual rainfall since 1920 (tan to brown areas) with statistically significant decrease in rainfall (black hatching) over the Central and Northern Ko‘olau Mountains (Adapted from the Fourth National Climate Assessment, USGCRP; Source: adapted from Frazier & Giambelluca 2017, © Royal Meteorological Society).[87]

Global Observations

- Globally, the percentage of area in drought has increased about 10%.[88]
- Heavy downpours are more intense and frequent; the global occurrence of extreme rainfall has increased 12%.[89, 90]
- Storm tracks are shifting poleward with consequences for precipitation patterns.[91]
- In the Pacific Basin, heavy rainfall has become more common, increasing runoff, erosion, and flooding in already wet locations.[92]
- Droughts and water shortages have become more common in already dry areas in the Pacific Basin.[93]

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82 Keener, V.W., et al. (2018) Chapter 27: Hawai`I and Pacific Islands. Impacts, Risks, and Adaptation in the United States: The Fourth National Climate Assessment, Volume II. U.S. Global Change Research Program. https://doi.org/10.7930/NCA4.2018.CH27

83 Chu, P., and H. Chen, 2005: Interannual and Interdecadal Rainfall Variations in the Hawaiian Islands. J. Climate, 18, 4796–4813, https://doi.org/10.1175/JCLI3578.1.

84 Chu, P., Y. R. Chen, and T. A. Schroeder, 2010: Changes in Precipitation Extremes in the Hawaiian Islands in a Warming Climate. J. Climate, 23, 4881–4900, https://doi.org/10.1175/2010JCLI3484.1.

85 Chen, Y. R.; Chu, P.-S. (2014) Trends in precipitation extremes and return levels in the Hawaiian Islands under a changing climate. Int. J. Climatol, 34, 3913-3925.

86 Frazier, Abby G.,et al. (2022)

87 USGCRP (2018) Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. doi: 10.7930/NCA4.2018.

88 Dai, A. (2011) Characteristics and trends in various forms of the Palmer drought severity index during 1900–2008, Journal of Geophysical Research 116.

89 Lehmann, J., et al. (2015) Increased record-breaking precipitation events under global warming. Climatic Change, doi: 10.1007/s10584-015-1434-y

90 See NOAA, https://www.climate.gov/news-features/featured-images/heavy-downpours-more-intense-frequent-warmer-world.

91 Bender, F. A-M, et al. (2012) Changes in extratropical storm track cloudiness 1983–2008: Observational support for a poleward shift, Climate Dynamics 38.

92 Kruk, M. C., et al. (2015) On the state of the knowledge of rainfall extremes in the western and northern Pacific basin, Int. J. Climatol., 35(3), 321–336.

93 Kruk, M. C., et al. (2015)

Projected Impacts

- Projected changes in total rainfall for Hawaiʻi are not consistent across recent studies with different models predicting increases or decreases in annual precipitation over various timespans within this century.[94, 95, 96, 97]
  - Compared to Oʻahu's 1978 – 2007 estimated mean annual precipitation of 64.7 inches,[98] end-of-century projections using different models over a range of IPCC intermediate (RCP4.5) and very high scenarios (RCP8.5) encompass dryer futures 50 – 54 inches[99] per year, to wetter scenarios of 63 – 64 inches per year.[100]
- Projected changes in heavy rainfall events are also not consistent across recent studies with some research predicting an increase in frequency in heavy rainfall events[101, 102, 103, 104] for portions of Oʻahu while another study predicts a reduction in heavy rain events[105] in this century under a range of climate change scenarios.
- Projected changes in streamflow on Oʻahu are not consistently described, following the inconsistency in projections for total rainfall in the later part of this century. Some studies predict increases [106, 107, 108] while another study predicts decreases.[109] Low flows are maintained by groundwater discharge to streams, which is affected by total rainfall and groundwater use, further complicating modeling efforts.[110]

Progress & Next Steps

- A City One Water Panel, composed of key agency officials and codified as a City climate adaptation policy in Ordinance 20-47, recognizes that collaboration is key for climate change adaptation and successful water quality and quantity management in the face of climate change.[111]
- The City Office of Climate Change, Sustainability, and Resiliency produced a website "Get Flood Ready" containing tools to help residents understand flood risks and safety, insurance, and building guidance.[112]

94 Xue, L., Wang, Y., Newman, A.J. et al. (2020) How will rainfall change over Hawaiʻi in the future? High-resolution regional climate simulation of the Hawaiian Islands. Bull. of Atmos. Sci.& Technol. 1, 459–490. https://doi.org/10.1007/s42865-020-00022-5

95 Timm, O., and H. F. Diaz, 2009: Synoptic-Statistical Approach to Regional Downscaling of IPCC Twenty-First-Century Climate Projections: Seasonal Rainfall over the Hawaiian Islands. J. Climate, 22, 4261–4280, https://doi.org/10.1175/2009JCLI2833.1.

96 Elison, Timm, O., Giambelluca, T. W., and Diaz, H. F. (2015)

97 Mizukami, N., et al. (2022) New projections of 21st century climate and hydrology for Alaska and Hawaiʻi, Climate Services, Volume 27, 100312, ISSN 2405-8807, https://doi.org/10.1016/j.cliser.2022.100312.

98 Giambelluca, T.W., Q. Chen, A.G. Frazier, J.P. Price, Y.-L. Chen, P.-S. Chu, J.K. Eischeid, and D.M. Delparte, (2013) Online Rainfall Atlas of Hawaiʻi. Bull. Amer. Meteor. Soc. 94, 313-316, doi: 10.1175/BAMS-D-11-00228.1.

99 Elison Timm et al., (2015)

100 Zhang, C., Wang, Y., Hamilton, K., and Lauer, A., 2016, Dynamical Downscaling of the Climate for the Hawaiian Islands. Part II: Projection for the Late Twenty-First Century: Journal of Climate, v. 29, no. 23, p. 8333–8354.

101 Norton, C. W., Chu, P.-S., and Schroeder, T. A. (2011), Projecting changes in future heavy rainfall events for Oahu, Hawaii: A statistical downscaling approach, J. Geophys. Res., 116, D17110, doi:10.1029/2011JD015641.

102 Fandrich, K. M., Timm, O. E., Zhang, C., & Giambelluca, T. W. (2022). Dynamical downscaling of near-term (2026–2035) climate variability and change for the main Hawaiian Islands. Journal of Geophysical Research: Atmospheres, 127, e2021JD035684. https://doi.org/10.1029/2021JD035684

103 Zhang, C., Wang, Y., Hamilton, K., and Lauer, A., (2016)

104 Xue, L., Wang, Y., Newman, A.J. et al. (2020)

105 Elison Timm, O., Takahashi, M., Giambelluca, T. W., and Diaz, H. F. (2013), On the relation between large-scale circulation pattern and heavy rain events over the Hawaiian Islands: Recent trends and future changes, J. Geophys. Res. Atmos., 118, 4129– 4141, doi:10.1002/jgrd.50314.

106 Safeeq, M. and Fares, A. (2012), Hydrologic response of a Hawaiian watershed to future climate change scenarios. Hydrol. Process., 26: 2745-2764. https://doi.org/10.1002/hyp.8328

107 Olkeba Tolessa Leta, Aly I. El-Kadi, Henrietta Dulai, Kariem A. Ghazal (2016) Assessment of climate change impacts on water balance components of Heʻeia watershed in Hawaiʻi, Journal of Hydrology: Regional Studies, Volume 8, 2016, Pages 182-197, ISSN 2214-5818, https://doi.org/10.1016/j.ejrh.2016.09.006.

108 Leta, Olkeba Tolessa, Aly I. El-Kadi, and Henrietta Dulai. 2018. "Impact of Climate Change on Daily Streamflow and Its Extreme Values in Pacific Island Watersheds" *Sustainability* 10, no. 6: 2057. https://doi.org/10.3390/su10062057

109 Naoki Mizukami, Andrew J. Newman, Jeremy S. Littell, Thomas W. Giambelluca, Andrew W. Wood, Ethan D. Gutmann, Joseph J. Hamman, Diana R. Gergel, Bart Nijssen, Martyn P. Clark, Jeffrey R. Arnold (2022) New projections of 21st century climate and hydrology for Alaska and Hawaiʻi, Climate Services, Volume 27, 100312, ISSN 2405-8807, https://doi.org/10.1016/j.cliser.2022.100312.

110 Izuka, S.K., Engott, J.A., Rotzoll, Kolja, Bassiouni, Maoya, Johnson, A.G., Miller, L.D., and Mair, Alan, 2018, Volcanic aquifers of Hawaiʻi—Hydrogeology, water budgets, and conceptual models (ver. 2.0, March 2018): U.S. Geological Survey Scientific Investigations Report 2015-5164, 158 p., https://doi.org/10.3133/sir20155164.

111 https://www.resilientoahu.org/onewater

112 https://www.resilientoahu.org/get-flood-ready

- The City is studying options for a future storm water utility as a reliable funding mechanism for managing storm water on O‘ahu.[113]
- The City prepared a Repetitive Loss Area Analysis for areas that have experienced multiple flood events and resulting insurance losses, in preparation for an application to join the Community Rating System (CRS) under FEMA's National Flood Insurance Program (NFIP).[114] The City is currently rated in CRS Class 8 of 10, qualifying residents for a 10% discount (premium reduction) on NFIP flood insurance.

Sea Level Rise and Coastal Impacts

The City Climate Change Commission provided updated guidance on sea level rise in July, 2022, finding that the impacts of sea level rise are potentially catastrophic for O‘ahu.[115] As sea levels rise so does the risk of flooding, damage by extreme weather events, and permanent land loss. Because of the extremely low relief of the coastal zone, small increases in mean sea level generate nonlinear or compound impacts from rain and extreme tides. Flooding originates from multiple sources: groundwater inundation, extreme high tides, direct wave run-up, storm surge, extreme precipitation events, and others. Salinization of coastal aquifers leads to ecosystem loss, and corrosion of buried and surface infrastructure. See Appendix 2: Global Cryosphere Indicators for more on the relationships between global ice melt and sea level rise.

Local Observations

- The long-term rate of sea level rise at the Honolulu tide station is 1.55 mm (0.061 in) per year with a 95% confidence interval of ±0.21 mm (0.008 in) per year based on monthly mean sea level data, 1905 to 2021. This is equivalent to a change of 15.5 cm (6.1 in) over the past 100 years.[116]
- Record high monthly mean sea levels were measured on the Honolulu tide gauge in summer and fall of 2020 and January to February 2021. Numerous record-high daily extreme water levels were also observed during these months.[117, 118]
- The frequency of high tide flooding in Honolulu since the 1960's has increased from 6 days per year to 11 per year.[119]
- Over 70% of beaches in Hawai‘i and 60% of beaches on O‘ahu are in a state of chronic erosion.[120] This is likely related to long-term sea level rise as well as coastal hardening and other harmful land use practices.[121, 122]
- Coastal hardening of chronically eroding beaches caused the combined loss of 9% (21.5 km, 13.4 mi) of the length of sandy beaches on Kaua‘i, O‘ahu, and Maui. Of that, 8% (8.7 km, 5.5 mi) of beaches have been lost on O‘ahu.[123]
- Increasing flooding and coastal erosion from sea level rise is impacting traditional and customary practices in Hawai‘i including fishpond maintenance and cultivation of salt, impairing shoreline access for gathering from nearshore fisheries, and threatening ‘iwi kūpuna (ancestral bones) buried along shorelines.[124]

Global Observations

- Global mean sea level has risen about 200 mm (8 in) since 1900.[125]

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113 https://www.stormwaterutilityoahu.org/
114 https://www.resilientoahu.org/get-flood-ready
115 https://www.resilientoahu.org/climate-change-commission/#guidance
116 NOAA Tides & Currents, Relative Sea Level Trend for Honolulu Hawaii, Station #1612340: https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=1612340 (last viewed 2/16/2023)
117 University of Hawaii Sea Level Center, Station Explorer; Station #57, Honolulu, Hawaii: https://uhslc.soest.hawaii.edu/stations/?stn=057#climatology
118 M.J. Widlansky, personal communication, August 26, 2022
119 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.
120 Fletcher, C.H., et al. (2012) National Assessment of Shoreline Change: Historical shoreline change in the Hawaiian Islands. USGS OFR 2011-1051, 55p.
121 Romine, B.M., et al. (2013) Are beach erosion rates and sea-level rise related in Hawaii? Global and Planetary Change, 108: 149-157.
122 Romine, B.M. and Fletcher, C.H. (2012) Armoring on eroding coasts leads to beach narrowing and loss on O‘ahu, HI. DOI 10.1007/978-94-007-4123-2_10.
123 Fletcher, C.H., et al. (2012)
124 Sproat, D. K. (2016) An Indigenous People's Right to Environmental Self-Determination: Native Hawaiians and the Struggle Against Climate Change Devastation. Stanford Environmental Law Journal, 35.
125 NASA Global Climate Change, Vital Signs for the Planet, Sea Level: https://climate.nasa.gov/vital-signs/sea-level/ (last viewed 2/16/2023)

- Sea level is rising at an accelerating rate over recent decades based on satellite altimetry data.[126] Global mean sea level is presently rising at 3.56 mm/yr (1.40 inches per decade).[127]
- Between 1993 and 2014, the contribution from melting of the Greenland Ice Sheet to global sea level rise increased from 5% in 1993 to 25% in 2014.[128]
- The amount of sea level rise due to melting of mounting glaciers and ice sheets from 2005-2013 was nearly twice the amount of sea level rise due to thermal expansion of ocean water.[129]
    - Ice loss from the Greenland Ice Sheet increased seven-fold from 34 billion tons per year between 1992 and 2001 to 247 billion tons per year between 2012 and 2016.
    - Antarctic ice loss nearly quadrupled from 51 billion tons per year between 1992 and 2001 to 199 billion tons per year from 2012 to 2016.

Projected Impacts

- Global mean sea level is expected to rise as much over the next 30 years as it has in the last 100.[130] The present rate of sea level rise acceleration is projected to lead to a minimum of 23 cm (9 inches) of global mean sea level rise by 2050 (relative to the year 2000).[131] Continued global warming is expected to increase this rate of acceleration.
- Rapid increases in tidal flooding are expected to begin in Hawaiʻi by the mid-2030's as a result of ongoing sea level rise in combination with natural cyclicity in tidal amplitudes, i.e., natural variations in the highest high tides.[132]
- A 2022 report from a multi-agency federal task force including the National Oceanic and Atmospheric Administration (NOAA), US Geological Survey (USGS), Army Corps of Engineers, and National Aeronautics and Space Administration (NASA) based on IPCC AR6 emissions scenarios and finds[133]:
    - Hawaiʻi and other tropical Pacific sites are expected to experience sea level rise that is 16% to 20% higher than the global average.
    - There is a 92% chance of exceeding 0.4 m (1.3 ft) of sea level rise for Honolulu in 2100 in all greenhouse gas emissions scenarios and at all warming levels (greater than 1.5° C or 2.7° F global mean surface air temperature by 2100).
    - There is an 82% chance of exceeding 0.6 m (2.0 ft) of sea level rise for Honolulu by 2100 in an Intermediate to High emissions scenario leading to 3.0° C or 5.4° F.
    - There is a 23% probability of exceeding 1.16 m (3.8 ft) of sea level rise in Honolulu by 2100 (relative to the year 2000) in a Very High emissions scenario that leads to 5.0° C (9.0° F) of warming*. The probability increases to 49% in a High Impact – Very High Emissions scenario. The City Climate Change Commission, in its updated sea level rise guidance document, recommends the City use this as the scenario for most planning and design.
    - There is a 2% probability of exceeding 1.78 m (5.8 ft) of sea level rise in Honolulu by 2100 (relative to the year 2000) in a Very High emissions scenario that leads to 5.0° C (9.0° F) of warming*. The probability increases to 20% in a High Impact – Very High Emissions scenario. The City Climate Change Commission, in its updated sea level rise guidance document, recommends the City use this as the scenario in planning and design of public infrastructure projects and other projects with low tolerance for risk.

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126 Nerem, R.S., Frederikse, T. and Hamlington, B.D., 2022. Extrapolating Empirical Models of Satellite-Observed Global Mean Sea Level to Estimate Future Sea Level Change. Earth's Future, 10(4), p.e2021EF002290.

127 AVISO+ Satellite Altimetry Data – Mean Sea Level: https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html#c15723 (last viewed: March 20, 2023)

128 Chen, X., et al. (2017) The increasing rate of global mean sea-level rise during 1993–2014, Nature Climate Change. DOI: 10.1038/nclimate3325

129 NOAA Climate Change, Global Sea Level Rise: https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level (last viewed 2/16/2023)

130 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.

131 Nerem, R.S.; et al. (2022)

132 Thompson, P.R.; et al. (2021) Rapid increases and extreme months in projections of United States high-tide flooding. Nature Climate Change, 11(7), pp.584-590.

133 Sweet, W.V.; et al. (2022)

- Sea level rise is not projected to stop at in 2100 under current emissions trajectories. Rather, global mean sea level is projected to continue to rise for thousands of years, even if future CO_2 emissions are reduced to net zero and global warming halted.[134]
- For O‘ahu, 0.98 m (3.2 ft) of sea level rise will lead to chronic (annual to permanent) flooding of 9,400 acres of land and 3,880 structures, displace over 13,000 residents, cause $12.9 billion in losses of private land and structures (2016 dollars), and flood 17.7 miles of major roads; by far the greatest impacts, by those measures, among the islands statewide.[135]
- About 550 Hawaiian cultural sites are exposed to chronic flooding with a sea level rise of 0.98 m (3.2 ft).[136]

**The Low to Very High emissions scenarios in the NOAA 2022 interagency report do not consider the possibility of poorly understood ice instability processes, which the High Impact – Very High Emissions scenario includes. Acceleration of ice flow and retreat in Antarctica, which has the potential to lead to sea level rise of several meters within a few centuries, is observed in the Amundsen Sea Embayment of West Antarctica and in Wilkes Land, East Antarctica. These changes may be the onset of an irreversible ice sheet instability*.[137]

Progress & Next Steps

The Hawai‘i Sea Level Rise Vulnerability and Adaptation Report 2022 Update provides a detailed assessment of progress in preparing the State and Counties for sea level rise including the following, which are particularly relevant to the City & County of Honolulu[138]:

- Honolulu Mayor Directive 18-02 (July 16, 2018) requires all City departments to use the City Climate Change Commission’s Guidance and the 2017 State of Hawai’i Sea Level Rise Vulnerability and Adaptation Report and associated Hawai`i Sea Level Rise Viewer in permitting and planning.
- The Climate-Ready O‘ahu Web Explorer features best-available map data from the City, state, and federal governments for a variety of climate change stressors and other regulatory layers in support Mayor’s Directive 18-2.
- Communities and Honolulu Department of Planning and Permitting (DPP) are integrating climate change and sea level rise considerations into processes updating Community Development Plans and Sustainable Community Plans following the State Planning Act – Climate Change Adaptation Priority Guidelines[139] and Mayor’s Directive 18-2 (2018).[140]State Act 16 (SLH 2020) updated the State Coastal Zone Management Act (CZMA, HRS 205A), strengthening protections for beach and other coastal environments, prohibiting private shoreline hardening structures and minimizing public shoreline hardening structures, and increasing the minimum shoreline setback to 40 feet. City DPP requires an evaluation of a project’s vulnerability to sea level rise and consistency with each of the objectives in the CZMA with Special Management Area (SMA) Applications consistent with State Act 16 until relevant ordinances are updated.
- State Environmental Impact Statement Rules (HAR 11-200.1) were updated per State Act 17 (SLH 2018) to include consideration of the sea level rise-XA in determining whether an action may have a significant effect on the environment. City DPP created new guidance on the breadth and quality of information that these documents should contain including for shoreline properties exposed to sea level rise hazards.[141]
- The City’s 2020 Multi-Hazard Pre-Disaster Mitigation Plan includes a chapter on climate change effects including sea level rise, incorporating best-available science and map data.[142]

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134 IPCC (2021) AR6

135 Hawai‘i Climate Change Mitigation and Adaptation Commission (2017) Hawai‘i Sea Level Rise Vulnerability and Adaptation Report. Prepared by Tetra Tech, Inc. and the State of Hawai‘i Department of Land and Natural Resources, Office of Conservation and Coastal Lands, under the State of Hawai‘i Department of Land and Natural Resources Contract No: 64064.

136 Hawai‘i Climate Change Mitigation and Adaptation Commission (2017)

137 IPCC (2019) The Ocean and Cryosphere in a Changing Climate, Summary for Policymakers

138 Hawai‘i Climate Change Mitigation and Adaptation Commission (2022) Hawai‘i Sea Level Rise Vulnerability and Adaptation Report, 2022 Update

139 §226-109, Hawai‘i Revised Statues; Climate Change Adaptation Priority Guidelines

140 For examples see: Primary Urban Center Development Plan: https://www.pucdp.com/ and North Shore Sustainable Communities Plan: https://www.northshorescp.com/

141 https://www.honolulu.gov/dpp/dpp-announcements/48990-july-12,-2022-environmental-assessment-and-environmental-impact-statement-instructions-now-available.html

142 https://www.resilientoahu.org/hazard-mitigation-plan

- The O‘ahu Resilience Strategy (2019) recommended actions to address impacts related to sea level rise include protecting beaches and public safety with revised shoreline management rules.
- The City released Climate Adaptation Design Principles identifying recommended tools and best practices to consider in designing building sites and structures that are more resilient to sea level rise, flooding, extreme heat, and groundwater inundation.
- In 2021, the State of Hawai‘i enacted an update to the Mandatory Seller Disclosures in Real Estate Transactions Law, codified within Hawai`i Revised Statutes §508D-15, requiring that real estate transactions within the State must disclose any risk of sea level rise (up to and including the 3.2-feel sea level rise scenario) to the property.
- City Council and the Mayor approved Bills 41 and 42 in 2023 increasing shoreline setbacks beyond the state minimum in Chapter 23, Revised Ordinance of Honolulu (ROH), and updating the Special Management Area (SMA) Ordinance, Chapter 25, ROH, to address coastal hazards impacts with sea level rise.
- The Honolulu Office of Climate Change, Sustainability and Resiliency (CCSR) is developing a Climate Adaptation Strategy assessing climate change and sea level rise hazards and their impacts to City services and assets critical to neighborhoods island-wide.
- State Act 223 (SLH 2022) expands the authority of the counties to transfer development rights for the relocation of development from areas at higher risk of sea level rise, coastal erosion, storm surge, and flooding associated with climate change to areas of lower risk. City Bill 10 (2022, not passed) included provisions that would further expand the authority of the City to use transfer of development rights to support retreat from areas at risk of flooding and coastal erosion, which could be incorporated in future City legislation.
- State Act 208 (SLH 2022) expands the purpose and rationale for Special Improvement Districts (SIDs) to include financing of climate change and sea level rise adaptation. The City can develop SIDs beyond Waikīkī to engage community and develop local financing for sea level rise adaptation.
- CCSR has a current grant-funded project to develop a Long-Term Disaster Recovery plan and tools by the end of 2023 to help O`ahu organize and recover more quickly from disasters.
- The Climate Resilience Collaborative at the University of Hawai‘i is studying and modeling various flood risks, coastal erosion and land loss, groundwater inundation and storm drain failure, community design, extreme weather, and compound events, all through the lens of sea level rise. Updated sea level rise exposure map data is expected over the next 3-5 years.

Extreme Weather

The devastating impact of extreme events and natural hazards are well-documented across Hawai‘i and the greater Pacific Islands region and include tropical cyclones, extreme rainfall, floods, droughts, and wildfires. Climate change affects the frequency and intensity of extreme weather events, which in turn affects how communities experience, prepare for, respond to, and recover from hazards. When extreme events compound spatially and temporally there can be disproportionate impacts on populations that have been made more physically and socioeconomically vulnerable. At a global scale, extreme climate events such as extreme daily temperatures and daily precipitation extremes are increasing in frequency and intensity.[143] For example, the number of global weather disasters is up 14% since the 1995-2004 period and has doubled since 1985-1994.[144] The Pacific Islands region has historically experienced a high burden of such climate disasters, sometimes resulting in wide-ranging impacts on food and water security, human health and safety, infrastructure, coral reefs and other ecosystems, and geopolitical stability.[145] The direct and indirect burdens of these events are often underestimated and are projected to increase with climate

143 Stott, P. (2016) How climate change affects extreme weather events. Science, 352, 1517–1518, doi:10.1126/science.aaf7271

144 Centre for Research on the Epidemiology of Disasters, UN International Strategy for Disaster Reduction, http://reliefweb.int/report/world/human-cost-weather-related-disasters-1995-2015.

145 The World Bank (2013). Acting on Climate Change and Disaster Risk for the Pacific. 16 p. Retrieved from: https://www.worldbank.org/content/dam/Worldbank/document/EAP/Pacific%20Islands/climate-change-pacific.pdf

change.[146,147] Whereas on an absolute scale, deaths from flood events in Hawaiʻi are low, the state ranks third highest in the nation when deaths are normalized by geographic area, and Kauaʻi currently holds the national record for total 24-hour rainfall.[148]

Local Observations

Tropical Cyclones and Wind

- Average daily wind speeds have undergone a non-statistically significant decline in Honolulu and Hilo, while remaining steady across western and southern Pacific sites.[149,150]
- Observations from the Honolulu International Airport show that trade winds have shifted from northeasterly to easterly.[151] Northeast trade wind days that occurred 291 days per year in 1973 occurred only 210 days per year in 2009, while the frequency of east trade winds increased.[152] Northeast trade winds impact wave height, cloud formation, and precipitation across the state.
- The frequency of gale-force winds (sustained winds between 39 – 54 mph) has increased in the western and south Pacific but decreased in the central Pacific.[153,154]
- Since 1980 in the Central North Pacific basin, trends in the number of named storms have remained constant, with no significant trend in observed tropical cyclone frequency.[155,156]

Extreme Rainfall

- Historical extreme rainfall trends across the state vary with the definition of "extreme" and the time and spatial scales and periods of reference used.
  - One study shows an increase in the frequency of extreme daily rainfall from 1940 – 2010 at rain gages across the state, including at several on Oʻahu, and that consecutive wet days and consecutive dry days are both increasing statewide;[157]
  - Other studies show that from 1980 - 2007, rainfall patterns on Oʻahu have shifted towards more frequent light and less frequent moderate and heavy rainfall, and decreased daily rainfall intensity.[158]
  - Analysis of heavy rainfall patterns during the wet season (October to April) from 12 stations across the state showed a decrease in the frequency of heavy rainfall events from 1977 – 2010, as compared to 1958 -1976.[159]

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146 Noy, I. (2015). Natural Disasters and Climate Change in the Pacific island Countries: New non-monetary Measurements of Impacts. Victoria University of Wellington: Wellington, 29 p. Retrieved from: http://researcharchive.vuw.ac.nz/bitstream/handle/10063/4200/Working%20paper.pdf

147 Keener, V., Helweg, D., Asam, S., Balwani, S., Burkett, M., Fletcher, C., Giambeluca, T., Grecni, Z., Nobrega-Olivera, M., Polovina, J., & Tribble, G. (2018). Ch 27: Hawaiʻi and US-Affiliated Pacific Islands. In Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, & B.C. Stewart (Eds) Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. U.S. Global Change Research Program: Washington, DC, pp. 1242–1308. https://doi.org/10.7930/NCA4.2018.CH27

148 Corrigan, T. J., and S. Businger, 2022: The Anatomy of a Series of Cloud Bursts that Eclipsed the U.S. Rainfall Record. Mon. Wea. Rev., 150, 753–773, https://doi.org/10.1175/MWR-D-21-0028.1.

149 Marra, J.J., and Kruk, M.C. (2017) State of Environmental Conditions in Hawaiʻi 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.

150 Marra, J.J., Gooley, G., Johnson, M-V.V., Keener, V.W., Kruk, M.K., McGree, S., Potemra, J.T., and Warrick, O. [Eds.] (2022). Pacific Climate Change Monitor: 2021. The Pacific Islands-Regional Climate Centre (PI-RCC) Network Report to the Pacific Islands Climate Service (PICS) Panel and Pacific Meteorological Council (PMC). DOI: 10.5281/zenodo.6965143

151 Wentworth, C.K. (1949). Directional shift of trade winds at Honolulu. Pacific Science. 3(1): 86-88. http://hdl.handle.net/10125/8917

152 Garza, J.A., Chu, P.S., Norton, C.W, and Schroeder, T.A. (2012) Changes of the prevailing trade winds over the islands of Hawaii and the North Pacific. JGR Atmospheres, 117(D11). https://doi.org/10.1029/2011JD016888.

153 Marra, J.J., and Kruk, M.C. (2017) State of Environmental Conditions in Hawaiʻi 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.

154 Marra et al. (2022)

155 Marra et al. (2022)

156 Murakami et al. (2015) INVESTIGATING THE INFLUENCE OF ANTHROPOGENIC FORCING AND NATURAL VARIABILITY ON THE 2014 HAWAIIAN HURRICANE SEASON [in: Explaining Extremes of 2014 from a Climate Perspective]. Bull. Amer. Meteor. Soc., 96 (12), S115-S119. https://journals.ametsoc.org/downloadpdf/journals/bams/96/12/bams-d-15-00119.1.pdf

157 Kruk, M. C., et al. (2015), On the state of the knowledge of rainfall extremes in the western and northern Pacific basin, Int. J. Climatol., 35(3), 321–336.

158 Chu, P.S., Chen, Y.R., and Schroeder, T.A. (2010). Changes in Precipitation Extremes in the Hawaiian Islands in a Warming Climate. Journal of Climate, 23(18): 4881 – 4900. https://doi.org/10.1175/2010JCLI3484.1

159 Elison Timm, O., Takahashi, M, Giambelluca, T.W., and Diaz, H.F. (2013). On the relation between large-scale circulation pattern and heavy rain events over the Hawaiian Islands: Recent trends and future changes. JGR Atmospheres, 118(10): 4129-41. https://doi.org/10.1002/jgrd.50314

- On the Island of Hawai‘i, a rare storm with daily precipitation of 300 mm (equivalent to a 20-year return period) in 1960 was a common storm event (equivalent to a 3–5-year return period) in 2009. On the other hand, rainfall extremes were found to be less frequent on the Islands of Maui and O‘ahu in the last 5-decades.[160]

- Across the state of Hawai‘i, extreme precipitation events are more frequent in La Niña years and less frequent in El Niño years.[161]

Drought and Wildfire

- From 1920 – 2012, over 90% of the state experienced significant drying trends.[162] The worst statewide droughts occurred during 1920 – 2019 and 2007 – 14.[163] (Figure 7)
- Drought frequency, duration, and magnitude have increased statewide in both the wet and dry seasons and have affected all the major islands. On O‘ahu, the worst drought on record occurred during 1998 - 2002, with the most severe drought conditions occurring in the northern Ko‘olau Mountains.[164,165]
- Wildfire in Hawai‘i is a growing problem related to drying, invasive grasses, and human-caused ignitions. Statewide, non-native, flammable grasses and shrubs cover 25% of the total land.[166]
- Total burned area statewide has increased more than fourfold in the last century and fire propagates rapidly in dry nonnative grasslands.[167] The causes of most fires are unknown. Out of 12,000 recorded incidents statewide from 2000 to 2011, only 882, or about 7%, had a determined cause. Of those, 72% were accidental, which also means they're preventable.[168]
- Two strategies are expedient to address the increase in wildfires:[169]
  - Target reducing ignitions through public education;
  - Manage vegetation to reduce highly flammable areas.
- During El Niño, summers often have more rainfall which prolongs the growing season and increases potential fuel loads for fires. Drought throughout the following winter months causes vegetation to dry out and raise wildfire risk. In the 1997-1998 El Niño, which was the strongest to date, wildfires in Hawai‘i burned over 37,000 acres.

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160 Chen, Y. R., P.-S. Chu (2014) Trends in precipitation extremes and return levels in the Hawaiian Islands under a changing climate. *Int. J. Climatol*, 34, 3913-3925.

161 Chen, Y. R., P.-S. Chu (2014)

162 Frazier and Giambelluca (2017)

163 Frazier, A.G.; Giardina, C.P.; Giambelluca, T.W.; Brewington, L.; Chen, Y.-L.; Chu, P.-S.; Berio Fortini, L.; Hall, D.; Helweg, D.A.; Keener, V.W.; Longman, R.J.; Lucas, M.P.; Mair, A.; Oki, D.S.; Reyes, J.J.; Yelenik, S.G.; Trauernicht, C. (2022). A Century of Drought in Hawai‘i: Geospatial Analysis and Synthesis across Hydrological, Ecological, and Socioeconomic Scales. Sustainability, 14, 12023. https://doi.org/10.3390/su141912023

164 Frazier and Giambelluca (2017)

165 Frazier et al. 2022.

166 Trauernicht, C., et al. (2015) The Contemporary Scale and Context of Wildfire in Hawai‘i. Pacific Science, v. 69, no 4, October, pp. 427–444. https://doi.org/10.2984/69.4.1.

167 Trauernicht, Clay, & Elizabeth Pickett (2016) Pre-fire planning guide for resource managers and landowners in Hawai‘i and Pacific Islands, Forest and Natural Resource Management, College of Tropical Agriculture and Human Resources, https://www.ctahr.hawaii.edu/oc/freepubs/pdf/RM-20.pdf.

168 Restoration of Forest Key to Fire Control, Feb. 12 (2019) https://www.hawaiiwildfire.org/news-center/tag/Maui+%28West%29

169 Dr. Clay Trauernicht, wildland fire specialist Univ. of HI at Mānoa: https://www.nrem-fire.org/clay-trauernicht

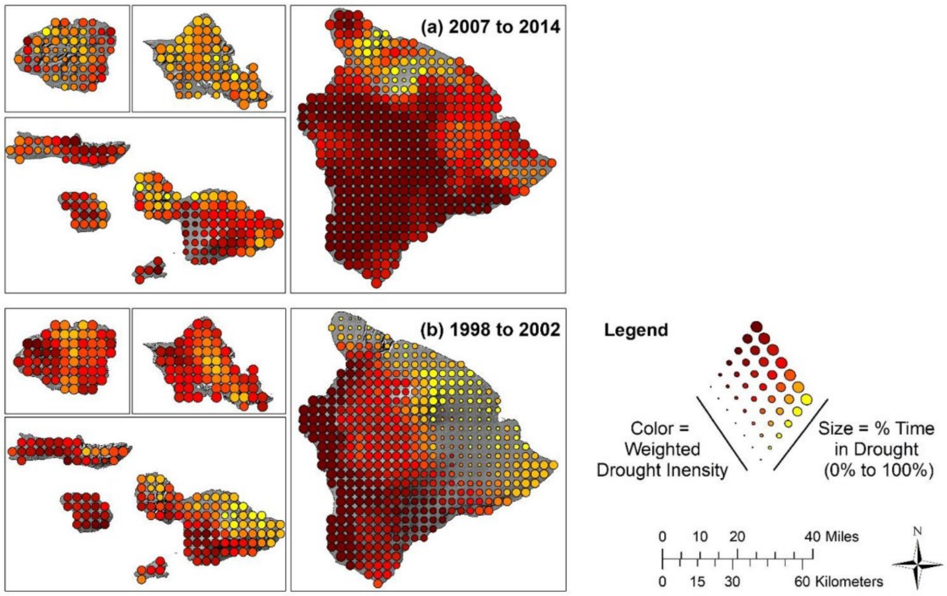

Figure 7: These statewide drought maps show the 12-month Standardized Precipitation Index for the two worst droughts on record: (a) 2007–2014; (b) 1998–2002. Color indicates weighted proportion of drought intensity (mild drought in yellow to extreme drought in dark red). Size of points indicates proportion of time spent in drought (smallest points: 0–25% time in drought, largest points: 85–100% time in drought during drought years).[170]

Global Observations

Tropical Cyclones and Wind

- The global satellite record of tropical cyclones from 1979-2009 shows a significant increasing trend in intensity.[171]
- Storm tracks are shifting poleward. Concurrently, overall tropical cyclone activity is migrating towards coasts and the areas of maximum intensity are moving closer to land.[172,173]
- 2020 was an historic year for tropical cyclones.
    - The Atlantic hurricane season goes from June to November, and the 2020 season had the highest number of storms in the shortest time span in history.[174]
    - The Atlantic had five simultaneous, active tropical cyclones, which last occurred in 1971.[175]

Extreme Rainfall

- It is likely that the number of heavy precipitation events over land has increased on average. Observations suggest that the burning of fossil fuels have contributed to more intense heavy precipitation over the second half of the 20th century.[176]

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170 Frazier et al., 2022
171 Kossin, J.P., Knapp, K.R., Olander, T.L. and Velden, C.S. (2020). Global increase in major tropical cyclone exceedance probability over the past four decades. PNAS, 117(22): 11975-11980. https://doi.org/10.1073/pnas.1920849117
172 Bender, F. A-M, et al. (2012) Changes in extratropical storm track cloudiness 1983–2008: Observational support for a poleward shift, Climate Dynamics 38.
173 Wang, S. and Toumi, R. (2021). Recent migration of tropical cyclones towards coasts. Science, 371(6528): 514-17. DOI: 10.1126/science.abb9038
174 "We've Run out of Hurricane Names. What Happens Now?" Nationalgeographic.com. N.p., 21 Sept. 2020. Web. 7 Oct. 2020. https://www.nationalgeographic.com/science/2020/09/weve-run-out-of-hurricane-names-what-happens-now/#close
175 Chinchar, Allison. "5 tropical cyclones are in the Atlantic at the same time for only the second time in history." CNN. N.p., 14 Sept. 2020. Web. 7 Oct. 2020. https://www.cnn.com/2020/09/14/weather/atlantic-ocean-5-active-tropical-cyclones/index.html
176 IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

- Heavy downpours are more intense and frequent, and the global occurrence of extreme rainfall has increased 12%.[177, 178]
- Extreme rainfall of both short (<1 day) and long durations (>1 day) are intensifying, but the degree of intensification varies by geography and atmospheric circulation patterns. Sub-daily rainfall intensification may substantially increase the risk of local flash flooding.[179]
- Half a degree Celsius (0.9ºF) of global warming has increased occurrences of heat waves and heavy rains in many regions of the planet.[180]

Drought and Wildfire

- Globally, some regions have experienced increased agricultural and ecological droughts due to increased evapotranspiration, though there is low confidence in the observed global-scale drought trends.[181]
- Models have shown that the driving factor of global fire trends for the 21st century is temperature-driven in contrast with the precipitation-driven regime in the pre-industrial period. This shift in the global fire regime results in a newly fire-prone global environment.[182]
- The increase in wildfire frequencies related to fire regime sensitivity is due to changes in climate.[183] Research on the western U.S. shows a clear connection between forest fire area and fuel aridity (a combination of temperature and precipitation). About 75% of annual differences in burned area are due to fuel aridity.[184]
- 85% of wildfires in the US are caused by humans, the rest are typically caused by lightning (or lava).[185]
- 3.7 million US homes were identified to be at high or extreme risk of wildfire in 2022, with almost half in California.[186]
- In 2021, there were 58,968 wildfires in the US that burned over 7.1 million acres of land.[187]

Projected Impacts

Tropical Cyclones and Wind

- With 2°C (3.6°F) of additional warming, global climate models project a 10-15% increase in the average precipitation rate within 100 km of a storm.[188]
- Globally, the proportion of tropical cyclones reaching Category 4 and 5 levels will likely increase.[189] Hurricanes have already become bigger and more destructive in the U.S.[190] There is low confidence in the global number of future Category 4 and 5 storms, since modeling studies show decreasing global frequency of all tropical cyclones combined.[191]

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177 Lehmann, J., et al. (2015) Increased record-breaking precipitation events under global warming. Climatic Change, doi: 10.1007/s10584-015-1434-y

178 See NOAA, https://www.climate.gov/news-features/featured-images/heavy-downpours-more-intense-frequent-warmer-world.

179 Fowler, H.J., Lenderink, G., Prein, A.F. et al. (2021)Anthropogenic intensification of short-duration rainfall extremes. Nat Rev Earth Environ 2, 107–122. https://doi.org/10.1038/s43017-020-00128-6.

180 Schleussner, C-F, et al. (2017) In the observational record half a degree matters, Nature Climate Change. DOI: 10.1038/nclimate3320.

181 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., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, doi:10.1017/9781009157896.001.

182 Pechony, O., and D. T. Shindell. "Driving Forces of Global Wildfires over the Past Millennium and the Forthcoming Century." Proceedings of the National Academy of Sciences 107.45 (2010): 19167–19170. Web. 6 Oct. 2020.

183 "Factcheck: How Global Warming Has Increased US Wildfires | Carbon Brief." Carbon Brief. N.p., 9 Aug. 2018. Web. 29 Sept. 2020. https://www.carbonbrief.org/factcheck-how-global-warming-has-increased-us-wildfires

184 Abatzoglou, John T., and A. Park Williams. "Impact of Anthropogenic Climate Change on Wildfire across Western US Forests." Proceedings of the National Academy of Sciences 113.42 (2016): 11770–11775. Web. 29 Sept. 2020. https://www.pnas.org/content/113/42/11770

185 "Facts + Statistics: Wildfires | III." Iii.org. N.p., 2021. Web. March 1, 2023. https://www.iii.org/fact-statistic/facts-statistics-wildfires.

186 "Facts + Statistics: Wildfires", 2023.

187 "Facts + Statistics: Wildfires", 2023.

188 Global Warming and Hurricanes, an Overview of Research Results (2020) Geophysical Fluid Dynamics Laboratory, Princeton University, NOAA: https://www.gfdl.noaa.gov/global-warming-and-hurricanes/

189 Global Warming and Hurricanes, an Overview of Research Results (2020).

190 Grinsted, A., et al. (2019) Normalized US hurricane damage estimates using area of total destruction: 1900-2018; PNAS: http://dx.doi.org/10.1073/pnas.1912277116

191 Global Warming and Hurricanes, an Overview of Research Results (2020).

- Overall, the impact of tropical cyclones is expected to increase with further warming through increased maximum wind intensity, a greater proportion of tropical cyclones of higher intensity, more intense rainfall, and making landfall on the background of higher sea levels.[192]
- Global models project a 1-10% increase in tropical cyclone intensity for warming of 2°C (3.6°F), implying increasing destructive potential, assuming no reduction in storm size.[193]
- Studies indicate there will be future changes to winds and waves due to climate change, which affects ecosystems, infrastructure, freshwater availability, and commerce.[194]
- More frequent tropical cyclones are projected near Hawai'i, though models are uncertain. This is not necessarily because there will be more storms forming in the east Pacific; rather, it is projected that storms will follow tracks that bring them into the region of Hawaiʻi more often.[195,196,197]
- Tropical Pacific Islands, including Hawaiʻi, will likely experience a larger number of tropical cyclones during future El Niño events, and reduced occurrences during La Niña events.[198]

Extreme Rainfall

- Models show a range of projected changes in future extreme rainfall depending on the methods and the future timescale used:
    - Some models suggest increased future frequency of heavy rainfall mid-century but decreased intensity for the south shore of Oʻahu;[199]
    - By the mid to late 21st century, however, several models show moderate to substantial increases in extreme rainfall during wet and dry seasons by 10 - 20% at many locations across the state.[200,201,202]
- Generally, windward sides of the major islands will become cloudier and wetter by 2100. The dry leeward sides will generally have fewer clouds and less rainfall.[203]
- Models project a near doubling in the frequency of future extreme La Niña events, associated with extreme rainfall in Hawaiʻi, from one in every 23 years to one in every 13 years.[204]

Drought and Wildfire

- Globally, the total land area subject to drought will increase and droughts will become more frequent and severe over the 21st century.[205]

192 Marra et al, 2021.
193 Marra et al, 2021.
194 Storlazzi, C.D., et al. (2015). Future wave and wind proj. for US and US-API, USGS OFR No. 2015–1001, http://dx.doi.org/10.3133/ ofr20151001.
195 Murakami, H., Wang, B., Li, T. et al. (2013) Projected increase in tropical cyclones near Hawaii. Nature Clim Change 3, 749–754. https://doi.org/10.1038/nclimate1890
196 Murakami et al. (2015)
197 Knutson, T. R., J. J. Sirutis, M. Zhao, R. E. Tuleya, M. A. Bender, G. A. Vecchi, G. Villarini, and D. Chavas, 2015: Global Projections of Intense Tropical Cyclone Activity for the Late Twenty-First Century from Dynamical Downscaling of CMIP5/RCP4.5 Scenarios. Journal of Climate, 28(18), DOI:10.1175/JCLI-D-15-0129.1.
198 Cai, W., Santoso, A., Collins, M. et al. Changing El Niño–Southern Oscillation in a warming climate. Nat Rev Earth Environ 2, 628–644 (2021). https://doi.org/10.1038/s43017-021-00199-z
199 Norton, C.W., Chu, P-S., Schroeder, T.A. (2011). Projecting changes in future heavy rainfall events for Oahu, Hawaii: A statistical downscaling approach. JGR Atmospheres, 116(D17). https://doi.org/10.1029/2011JD015641.
200 Zhang, 2016
201 Xue, L., Wang, Y., Newman, A.J., Ikeda, K., and others. (2020). How will rainfall change over Hawaiʻi in the future? High-resolution regional climate simulation of the Hawaiian Islands. Bull. Atm. Sci. Tech. 1: 459–490. doi.org/10.1007/s42865-020-00022-5.
202 Fandrich, K.M., Elison Timm, O., Zhang, C., and Giabelluca, T.W. (2021). Dynamical Downscaling of Near-Term (2026–2035) Climate Variability and Change for the Main Hawaiian Islands. JGR Atmospheres, 127(2). https://doi.org/10.1029/2021JD035684.
203 Zhang et al (2016)
204 Cai, W., et al. (2015) Inc. freq. of extreme La Niña events induced by greenhouse warming, Nature Climate Change, 5, 132–137, doi: 10.1038/nclimate2492.
205 Arias et al., 2021: Technical Summary. 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., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33−144. doi:10.1017/9781009157896.002.

- The frequency of extreme El Niño events, which is correlated with heat and drought in Hawaiʻi[206], is projected to double in the 21st century, with the likelihood of extreme El Niño events occurring roughly once every decade.[207]
- There is disagreement regarding total precipitation at the end of the century in Hawaiʻi.[208] Model projections range from small increases to increases of up to 30% in wet areas, and from small decreases to decreases of up to 60% in dry areas.[209, 210]
- Future drying in Hawaiʻi would likely shift peak wildfire risk to higher elevations.[211]
- Increased incidence of wildfire will result in less native forest cover, increased erosion and runoff, more coastal brownouts, and more at-risk communities.[212]

Progress & Next Steps

- Action #12 in the Ola Oʻahu Resilience Strategy encourages a program to provide incentives to retrofit pre-1995 homes to be more resilient to storm impacts for the most vulnerable residents. Next steps on implementing this program should be taken as soon as possible, as over 71% of single-family homes on Oʻahu lack sufficient wind resistance.
- Action #13 in the Ola Oʻahu Resilience Strategy recommends increasing flood insurance affordability for Oʻahu residents. Honolulu was accepted into the National Flood Insurance Program's (NFIP) Community Rating System (CRS), which will help achieve savings for the community while providing protection in case of disaster.
- In 2021, the City was awarded over $2,000,000 in FEMA grant funding for hazard mitigation, disaster risk reduction, and other flood analysis projects.
- Action #19 in the Ola Oʻahu Resilience Strategy is to develop a Long-Term Disaster Recovery and Post-Disaster Mitigation Plan (LTDR Plan), which will assist in planning for and utilizing funds in the event of a disaster. Currently, CCSR is standing up a citizen's advisory board to help guide the LTDR Plan.
- CCSR received a FEMA planning grant to initiate engagement on Action #15 in the Ola Oʻahu Resilience Strategy. This action develops a network of community resilience hubs which will provide focal points for community services and coordination in the case of a disaster. A full set of recommendations is anticipated at the end of 2023.
- To address the impacts of increased extreme rainfall, the City has created the One Water Panel, which creates a cross-department team to coordinate and integrate the management of water systems. Next steps should continue to establish and implement the proposed Storm Water Utility, which will give the city greater ability to manage storm water runoff on both communities and the environment.
- The Commission's 2020 Financial Risk Guidance Document recommends that the City reexamine the adequacy of City property insurance relative to climate change shocks.[213] Currently, the City spends almost $4 million annually to purchase approximately $300 million in property insurance. As of 2020, the total value of City property is $3.8 billion.

Food Systems

The majority of food in Hawaiʻi and the greater Pacific Islands region is imported,[214] leaving food supply chains vulnerable to climate-related disasters and other disasters .[215] Industrial-scale agriculture often includes negative ecological impacts such as fertilizer and pesticide pollution, soil degradation, loss of biodiversity and pollinators, and significant greenhouse gas emissions,

206 Keener et al 2018
207 Cai, W., et al. (2015) Inc. frequency of extreme El Niño events due to greenhouse warming. Nature Climate Change 4, 111–116, doi:10.1038/nclimate2100.
208 PIRCA (2016) Expert Consensus on Downscaled Climate Projections for the Main Hawaiian Islands. PIRCA Information Sheet, HI. http://bit.ly/2yoY0Il.
209 Zhang et al (2016)
210 Timm, O.E., et al. (2015), Stat. downscaling of rainfall changes in HI, based on CMIP5 model proj., JGR Atmos, 120(1), 92–112, doi:10.1002/2014JD022059.
211 Trauernicht, C. (2019). Vegetation—Rainfall interactions reveal how climate variability and climate change alter spatial patterns of wildland fire probability on Big Island, Hawaii. Science of The Total Environment. Volume 650, Part 1, Pages 459-469, https://doi.org/10.1016/j.scitotenv.2018.08.347.
212 Trauernicht, C. (2017). Climate Change Impacts on Wildfires in Hawaii. Infographic: https://www.hawaiiwildfire.org/fire-resource-library-blog/climate-change-wildfire-hawaii-infographic
213 City and County of Honolulu Climate Change Commission, (Adopted: July 14, 2020). Climate Change and Financial Risk Guidance.
214 Keener et al., 2018
215 Barnett, J. (2020). Climate Change and Food Security in the Pacific Islands. In J. Connell & K. Lowitt (Eds.), Food Security in Small Island States (pp. 25–38). Springer. https://doi.org/10.1007/978-981-13-8256-7_2

which reduce resilience to climate shocks and contribute to additional warming.[216] Increasing air and ocean temperatures will have negative impacts on agriculture and agroforestry, fisheries production and health, and lead to increased invasive species, pests, and diseases, while increasing sea levels, more intense tropical cyclones, and saltwater intrusion will affect local food production and security.[217] Proximity and access to healthy food is also an issue of environmental and social equity, with areas of lower socioeconomic status often linked to fewer varieties of nutritious food.[218] New and innovative plans, policies, and systems are urgently needed to optimize local food production, ensure access to quality food, promote public health and nutrition, and improve commercial and emergency food to realize food system resilience and ensure O'ahu's food security under current and future climate conditions.[219,220]

Local Observations

- The most comprehensive estimate for the quantity of food imported into the State of Hawai'i was published in 2008. It estimates that Hawai'i imports approximately 85-90% of its food. From 199-2005, all foods besides beef and fresh vegetables declined in production rate, meaning Hawai'i's overall level of food production and the contribution of agriculture to the state's GDP has significantly decreased.[221, 222] The real value of agricultural products sold by Hawai'i farms over the last 40 years has decreased by nearly 73%.[223]
- At any given time, the Hawai'i Emergency Management Agency reports that there is a 5- to 7-day supply of food in the state, which significantly limits the resilience of Hawai'i's food system to increasing climate-related disasters and other disaster events. Honolulu Harbor is the only port in the state that can unload incoming freight of the magnitude needed to supply current levels of imported food to all the Hawaiian Islands.[224]
- In 2020, one in three children in Hawai'i lived in a food insecure household. As of March 2021, 48% of Hawai'i families reported experiencing food insecurity, and 15% said they did not have enough food in the last week.[225] Given global projections for climate change impacts to food systems and food pricing, this could further negatively affect food security in Hawai'i. [226]
- While the state of Hawai'i has more than 7,000 farms, 90% of those are small niche growers that are not commercially viable. Most local produce comes from only about 100 farms.[227]
- Warmer nighttime temperatures and saltwater intrusion will increase damage from disease on staple regional crops such as taro, bananas, and breadfruit.[228] In Hawai'i, recent severe drought is the main cause of crop loss.[229]

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216 Rockström, J., Edenhofer, O., Gaertner, J., and DeClerck, F. (2020). Planet-proofing the global food system. *Nature Food*. 1, 3–5. doi: 10.1038/s43016-019-0010-4

217 Pörtner, H.- O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., et al. (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

218 Look, M. A., Soong, S., & Kaholokula, J. K. (2020). Assessment and priorities for the health and well-being in Native Hawaiians and Pacific Islanders. University of Hawai'i, John A. Burns School of Medicine, Department of Native Hawaiian Health.

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220 Tendall, D. M., Joerin, J., Kopainsky, B., Edwards, P., Shreck, A., Le, Q. B., et al. (2015). Food system resilience: defining the concept. *Global Food Secur.* 6, 17–23. doi: 10.1016/j.gfs.08,001.

221 Leung, Pingsun, and Matthew Loke. Economic Issues Economic Impacts of Increasing Hawai'i's Food Self-Sufficiency. N.p., 2008. Web. 13 Oct. 2020.

222 La Croix, S., & Mak, J. (2021). Reviving Agriculture to Diversify Hawai'i's Economy. *UHERO Research Brief*, *21*.

223 La Croix (2021)

224 "Critical Systems: Vulnerabilities Overview." State of Hawai'i Department of Defense, 8 Mar. 2018, dod.hawaii.gov/hiema/files/2018/04/HI_EMA-vulnerability-presentation.pdf.

225 Pruitt, A. S., Zhang, W., Wu, Y., Bird, O., Nakamura, B. & Barile, J. P. (2021). Addressing Hunger & Food Insecurity among Hawai'i's Families. Prepared for the College of Social Sciences, UH Mānoa and First Insurance Company of Hawai'i, Honolulu, HI. https://drive.google.com/file/d/1e3MkhACuaFYxULdsfwx56Jp1psCMAm4t/view

226 Romanello, M., McGushin, A., Napoli, C., Di Drummond, P., Hughes, N., Jamart, L., et al. (2021). The 2021 report of the *Lancet* Countdown on health and climate change: code red for a healthy future. *Lancet* 398, 1619–1662. doi: 10.1016/S0140-6736(21)01787-6

227 La Croix (2021)

228 Taylor, M., Mcgregor, A., Dawson, B., 2016. Vulnerability of Pacific Island Agriculture and Forestry to Climate Change 550.

229 Frazier, A. G., Giardina, C. P., Giambelluca, T. W., Brewington, L., Chen, Y.-L., Chu, P.-S., Berio Fortini, L., Hall, D., Helweg, D. A., Keener, V. W., Longman, R. J., Lucas, M. P., Mair, A., Oki, D. S., Reyes, J. J., Yelenik, S. G., & Trauernicht, C. (2022). A Century of Drought in Hawai'i: Geospatial Analysis and Synthesis across Hydrological, Ecological, and Socioeconomic Scales. Sustainability, 14(19), 12023. https://doi.org/10.3390/su141912023

- Restoring native agroecosystems is one important way to diversify Hawaiian food systems.[230] By using three models of Kānaka Maoli agroecosystems under current and future climate change scenarios, it was found that Hawai'i has the capability to support 250,000 acres of native farming systems and produce over 1 million metric tons of food per year, similar to food demands in Hawai'i today.[231]
- Local cattle production contributes to Hawaiʻi's greenhouse gas emissions. In 2016, there were 0.25 MMT of CO_2 equivalent of methane emissions from enteric fermentation (a digestive process in ruminant animals like cattle, sheep, and goats), which accounts for 18% of Agricultural, Forestry and Other Land Uses (AFOLU) sector emissions. Manure management of livestock resulted in 0.04 MMT of CO_2 equivalent of methane emissions in 2016, which is 3% of the state's AFOLU sector emissions.[232]
- Though currently being considered by the state legislature, unlike 18 U.S. states and regions, Hawaiʻi does not have a comprehensive and formal state-level food system plan or governance structure to guide and monitor the development of the food system to address the range of pressing ecological, social equity, public health and economic challenges presented above.[233,234,235]

Global Observations

- Global food system accounts for an estimated 30% of total global Green House Gas emissions.[236] Animal agriculture alone accounts for nearly 1/2 (14.5%) of this total.[237] Agriculture contributes nearly 50% of global anthropogenic methane (CH_4) and 75 % of the total nitrous oxide (N_2O) emissions.[238]
- Climate change has increased agricultural production risks by disrupting growing zones and growing days, which are dependent on precipitation, air temperature, and soil moisture.
- Pathogens emerging from and amplified through agriculture are also anticipated to increase along with human population and the expansion and intensification of production strategies.[239,240]
- Climate change is projected to reduce the availability and affordability of nutritious food. Rising concentrations of CO_2 decreases the nutrient and protein content of wheat, leading to a 15% decline in yield by mid-century.[241]
- Higher concentrations of CO_2 are lowering amounts of protein, iron, zinc, and B vitamins in rice with potential nutrition and health consequences for a global population of approximately 600 million.[242]

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230 Kurashima, N., Fortini, L. & Ticktin, T. The potential of indigenous agricultural food production under climate change in Hawaiʻi. *Nat Sustain* **2**, 191–199 (2019). https://doi.org/10.1038/s41893-019-0226-1

231 Kurashima et al, 2019.

232 Hawaiʻi Greenhouse Gas Emissions Report for 2016 Final Report. N.p., 2019. https://health.hawaii.gov/cab/files/2019/12/2016-Inventory_Final-Report_December2019-1.pdf

233 Participatory State and Regional Food System Plans and Charters in the U.S.: A Summary of Trends and National Directory: https://www.canr.msu.edu/resources/participatory-state-and-regional-food-system-plans-and-charters-in-the-us

234 See SB420: https://legiscan.com/HI/bill/SB420/2023

235 Fanzo, J., Haddad, L. K., Schneider, R., Béné, C., Covic, N. M., Guarin, A., et al. (2021). Viewpoint: rigorous monitoring is necessary to guide food system transformation in the countdown to the 2030 global goals? *Food Policy* 104, 102163. doi: 10.1016/j.foodpol.2021.102163

236 Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., & Leip, A. J. N. F. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, *2*(3), 198-209. https://www.nature.com/articles/s43016-021-00225-9

237 Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., ... & Tempio, G. (2013). *Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities*. Food and Agriculture Organization of the United Nations (FAO). https://www.fao.org/news/story/en/item/197623/icode/

238 Tubiello, F. N., Karl, K., Flammini, A., Gütschow, J., Conchedda, G., Pan, X., ... & Torero, M. (2022). Pre-and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems. *Earth System Science Data*, *14*(4), 1795-1809. https://essd.copernicus.org/articles/14/1795/2022/essd-14-1795-2022.html

239 Rohr, J. R., Barrett, C. B., Civitello, D. J., Craft, M. E., Delius, B., DeLeo, G. A., et al. (2019). Emerging human infectious diseases and the links to global food production. *Nat. Sustain.* 2, 445–456. doi: 10.1038/s41893-019-0293-3

240 Brooks, D. R., Hoberg, E. P., Boeger, W. A., and Trivellone, V. (2022). Emerging infectious disease: an underappreciated area of strategic concern for food security. *Transbound. Emerg. Dis.* 69, 254–267. doi: 10.1111/tbed.14009

241 Myers, S.S., et al. (2014) Increasing CO2 threatens human nutrition, Nature, 510, 139-142, doi: 10.1038/nature13179. Feng, Z., et al. (2015) Constraints to nitrogen acquisition of terrestrial plants under elevated CO2, Global Change Biology, 21(8), 3152-3168, doi: 10.1111/gcb.12938.

242 Zhu, C., et al. (2018) Carbon dioxide (CO2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries, Science Advances, 23 May, v. 4, no. 5, DOI:10.1126/sciadv.aaq1012.

- Without changes to policy and improvements to technology, food productivity in 2050 could look like it did in 1980 because at present rates of innovation, new technologies won't be able to keep up with the damage caused by climate change in major growing regions.[243]
- Approximately 56 billion livestock are consumed annually, and this number is expected to double by 2050. Animal agriculture globally contributes to 9% of the world's total CO_2 emissions, with the production of chemical fertilizer alone emitting 41 MMT of CO_2 per year. Additionally, livestock feed requires a minimum of 80% of global soybean crop and over 50% of global corn crop. 35-40% of yearly anthropogenic methane emissions are a result of animal agriculture due to enteric fermentation and manure.[244]

Projected Impacts

- Small coral-reef fisheries provide Pacific Islands communities with 50 – 90% of their dietary protein, and climate change impacts are redistributing ocean fish stocks.[245],[246] By 2050 under a high emissions scenario, fisheries catch in the Pacific region are projected to decline by 40% relative to the early 2000s.[247]
- Crop failure due to drought, flood, or some other extreme weather event in the course of a growing season, increases disproportionately between 1.5 and 2°C (2.7 and 3.6°F) of global warming.[248] For maize, risks of multiple breadbasket failures increase the most, from 6% to 40% at 1.5°C to 54% at 2°C of warming. In relative terms, the highest simultaneous climate risk increase between 1.5°C and 2°C of warming is for wheat (40%), followed by maize (35%) and soybean (23%). Limiting global warming to 1.5°C would reduce the risk of simultaneous crop failure for maize, wheat, and soybean by 26%, 28% and 19% respectively.
- By 2050, climate change will lead to per-person reductions of 3% in global food availability, 4% in fruit and vegetable consumption, and 0.7% in red meat consumption. These changes will be associated with 529,000 climate-related deaths worldwide.[249]
- Harvests of staple cereal crops, such as rice and maize, could decline by 20 to 40% as a function of increased surface temperatures in tropical and subtropical regions by 2100.[250] This will exacerbate existing food security issues, as one billion people are currently classified as food insecure.[251]

Progress & Next Steps

- In 2014, Governor David Ige set a goal of doubling Hawai'i's food production by 2020. With little progress made, in 2016 he changed the date for doubling food production to 2030. A greater integration of the above support structures combined with the restoration of indigenous agroecology practices and traditional food ways can help increase food system resilience and security, promote public health, support conservation, and strengthen communities.[252]

243 Liang, X.Z., et al. (2017) Determining climate effects on US total agricultural productivity, PNAS, www.pnas.org/cgi/doi/10.1073/pnas.1615922114
244 "Global Farm Animal Production and Global Warming: Impacting and Mitigating Climate Change." Environmental Health Perspectives. N.p., 2020. Web. 13 Oct. 2020.
245 Bell, J.D., Kronen, M., Vunisea, A., Nash, W.J., Keeble, G., Demmke, A., Pontifex, S., Andréfouët, S., 2009. Planning the use of fish for food security in the Pacific. Mar. Policy 33, 64–76. https://doi.org/10.1016/J.MARPOL.2008.04.002
246 Farmery, A.K., Scott, J.M., Brewer, T.D., Eriksson, H., Steenbergen, D.J., Albert, J., Raubani, J., Tutuo, J., Sharp, M.K., Andrew, N.L., 2020. Aquatic Foods and Nutrition in the Pacific. Nutr. 2020 Vol 12 Page 3705 12, 3705. https://doi.org/10.3390/NU12123705.
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249 Springmann, M., et al. (2016) Global and regional health effects of future food production under climate change: a modeling study, The Lancet.
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251 Barrett, C.B. (2010) Measuring food insecurity. *Science* 327, 825–828.
252 Bremer, L.L., Falinski, K., Ching, C., Wada, C.A., Burnett, K.M., Kukea-Shultz, K., Reppun, N., Chun, G., Oleson, K.L.L., Ticktin, T., 2018. Biocultural restoration of traditional agriculture: Cultural, environmental, and economic outcomes of Lo'i Kalo restoration in He'eia, O'ahu. Sustain. Switz. 10. https://doi.org/10.3390/SU10124502

- Previous analysis estimated that an island nation would have to produce at least 50% of its own staple crops to be self-sufficient in disaster conditions, which was last true in the 1960s in Hawaiʻi.[253],[254] Though unlikely to be realized before 2030, to advance toward this goal, more economically viable farms, better financial support, new markets, more technology to aggregate, process, and transport the food, and new emergency and commercial food storage systems are needed.
- To help meet these goals, the *Transforming Hawaiʻi's Food System Together* initiative seeks to build statewide capacity and create a more robust, sustainable, and resilient food system through best practices, education, and policy analysis and recommendations.[255]
  - One of these recommendations was to fund and position a Food Security and Sustainability Program Manager in CCSR, which was done in 2020.
- A comprehensive state-level food system plan and governance structure is currently under consideration at the state legislature to guide and monitor the development of the food system of Hawaiʻi to address the range of pressing climate, ecological, cultural, social equity, public health and economic development challenges above.[256] Relevant components of the proposed food system plan address the following: (1) Food as a human right and healthy food for all persons; (2) Social equity and food justice; (3) Food system resilience; and (4) Agriculture and food system sustainability, among others.
- A plan is needed to fund and build commercial and emergency food storage infrastructure in the case of climate and other events along with a formal coordination strategy for use in state-wide emergency food distribution. Examples underway include a collaboration between HIEMA-Hawaiʻi Foodservice Alliance-and the US DoD.
- Actions in the City's Ola Oʻahu Resilience Strategy recommend a dual approach to addressing food insecurity on the island. Accelerating implementation of this two-pronged approach must be accelerated.
  - Decreasing reliance on imports by developing urban farming and partnering government agencies with nonprofits to test projects, and;
  - Establishing an on-island emergency food supply and storage strategy overseen by an Emergency Feeding Task Force to manage the supply and map out available resources.
- Mapping tools can guide communities and investments in accessing and creating a more affordable and equitable food system. A story map by the Honolulu CCSR outlines key aspects of food access on Oʻahu, from the location of emergency food assistance programs to community gardens.

Human Health

The impacts of climate change affect human health both directly and indirectly in Hawaiʻi. For example, climate change impacts people through direct injury from extreme events such as wildfires, floods, storms, heat, and droughts, and indirectly through decreased food and water security, diminished air quality, reduced ecosystem services, spread of vector-borne disease, access to healthcare, and mental and spiritual health.[257,258] These harms are exacerbated by persisting systemic socioeconomic inequities and disproportionately impact marginalized, low-wealth communities, the elderly, young children, and disabled populations.[259] In order to better address the cross-cutting impacts of climate change on human health, a One Health framework that embraces a collaborative, multisectoral, and transdisciplinary approach to community health recognizing the connection between people, climate, and ecosystems can be a useful resilience tool.

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253 State of Hawaiʻi Office of Planning, Department of Business Economic Development and Tourism. (2012). Increased food security and food self sufficiency strategy volume II: A history of agiriculture in Hawaiʻi and technical reference document. https://files.hawaii.gov/dbedt/op/spb/Volume_II_History_of_Agriculture_in_Hawaii_and_Technical_Reference_Document_FINAL.pdf

254 Terrell, J. (January 27, 2021) Hawaii's food system is broken. Now is the time to fix it. Civil Beat. https://www.civilbeat.org/2021/01/hawaiis-food-system-is-broken-now-is-the-time-to-fix-it/

255 https://transforminghawaiifoodsystem.org/

256 See SB420: https://legiscan.com/HI/bill/SB420/2023

257 Romanello et al. The 2022 report of the Lancet Countdown on health and climate change. Lancet 2022;400:1619-54 https://www.thelancet.com/action/showPdf?pii=S0140-6736%2822%2901540-9

258 CDC. Climate Effects on Health: https://www.cdc.gov/climateandhealth/effects/default.htm

259 Romanello et al. 2022

Local Observations

- Impacts from tropical cyclones, droughts, heat, wildfires, and floods have negative impacts on human health across the state:
  - Since 1949, at least 29 people have died in and hundreds have been injured in Hawai‘i because of tropical cyclones. Seven of the deaths occurred during Hurricane Iniki in 1992.[260]
  - A community heat assessment coordinated by CCSR found in August 2019 that many neighborhoods on O‘ahu had afternoon heat indices (apparent temperature considering humidity) between 100 – 107ºF.[261]
  - Severe wildfires, which occur primarily during drought in Hawai‘i, directly threaten physical safety and can create respiratory hazards.[262]
  - Deaths and injuries occur from flash flooding resulting from intense and extreme rainfall.[263],[264]
- In the aftermath of a natural hazard such as a storm or a flood, medical facilities and infrastructure to access them such as roads can be damaged, hindering access to needed care.
- Exposure to floodwaters can create hazards by exposing people to dangerous bacteria from overflowing sewage and flooded cesspools as well as other waterborne infections such as leptospirosis. Cleaning homes and buildings after floods or storms can also expose people to a variety of dangerous toxins and molds.[265]
- An increase in the incidence of vector-borne diseases such as malaria and dengue in the Pacific Islands has been linked to climate variability drought and flood cycles and is expected to increase further as a result of climate change.[266]
  - A cluster of 264 cases of dengue on Hawai‘i Island in 2015 – 2016 was the first incidence of locally-acquired disease since a handful of people were sickened in 2011 on O‘ahu.[267]

Global Observations

- The health of all communities is vulnerable to climate change impacts; however, some populations including children, elders, the disabled, and low-wealth communities face the greatest risks.[268]
- Extreme temperature increase can lead to illness and death from heat stroke and dehydration, especially in those who work outdoors or lack air conditioning. People with cardiovascular and/or respiratory chronic illnesses are particularly vulnerable to high temperatures.[269]
- According to the IPCC AR6 report published this year, 143 million people across the globe are likely to be uprooted by rising seas, drought, searing temperatures and other climate catastrophes in the next 30 years. Forced migration is already occurring in many parts of the world and having massive impacts on cultural traditions, community cohesiveness, medical resources and health equity.[270]
- Often the areas that face the worst impacts from climate change are also socially vulnerable. Low-wealth communities and communities of color are often more likely to live near a facility emitting hazardous local co-pollutants.

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260 NOAA. (1993). Natural Disaster Survey Report Hurricane Iniki September 6 - 13,1992. https://www.weather.gov/media/publications/assessments/iniki1.pdf
261 City and County of Honolulu Office of Climate Change, Sustainability, and Resiliency (CCH CCSR). "O‘ahu Community Heat Map," 2019. https://cchnl.maps.arcgis.com/apps/View/index.html?appid=ff1b73d836074cf6b2aca420fffbd930.
262 Trauernicht, C., Pickett, E., Giardina, C.P., Litton, C.M., Cordell, S., Beavers, A., 2015. The Contemporary Scale and Context of Wildfire in Hawai'i. Pac. Sci. 69, 427–444. https://doi.org/10.2984/69.4.1
263 https://www.khon2.com/local-news/investigation-underway-following-maui-firefighter-death/
264 https://www.khon2.com/local-news/woman-loses-husband-friend-in-flash-flood-says-visitor-education-needed/
265 CDC – Natural Disasters and Severe Weather – Clean up safely after a disaster. https://www.cdc.gov/disasters/cleanup/facts.html
266 CDC. (2021). Regional Health Effects – Hawaii and US Affiliated Islands. https://www.cdc.gov/climateandhealth/effects/HawaiiandPacificIslands.htm
267 https://health.hawaii.gov/docd/dengue-outbreak-2015/
268 Medical Alert! Climate change is Harming Our Health, report by the Medical Society Consortium on Climate and Health, 24p. https://medsocietiesforclimatehealth.org/wp-content/uploads/2017/03/medical_alert.pdf.
269 Medical Alert! Climate change is Harming Our Health, report by the Medical Society Consortium on Climate and Health, 24p. https://medsocietiesforclimatehealth.org/wp-content/uploads/2017/03/medical_alert.pdf.
270 Cissé, G., R. McLeman, H. Adams, P. Aldunce, K. Bowen, D. Campbell-Lendrum, S. Clayton, K.L. Ebi, J. Hess, C. Huang, Q. Liu, G. McGregor, J. Semenza, and M.C. Tirado, 2022: Health, Wellbeing, and the Changing Structure of Communities. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1041–1170, doi:10.1017/9781009325844.009.

Neighborhoods within 2.5 miles of a GHG emitter, like a power plant, have 22% higher proportion of residents of color and a 21% higher proportion of residents under the poverty line than neighborhoods further than 2.5 miles from such a facility.[271]

Projected Impacts

- Projected increases in air temperature are among the most certain impacts of climate change, and current urban heat island effects across Oʻahu already indicate dangerously high temperatures.[272] The risk for heat related illness will continue to increase across the island, with high elevation areas warming the most rapidly.[273]
- When coupled with rising temperatures. projected decreases in tradewind days will exacerbate the risks of heat related illness.[274]
- Increases in sea surface temperature create a more hospitable environment for Vibrio Vulnificus bacteria, leading to a projected increase in exposures and devastating Vibrio vulnificus skin infections.[275,276]
- By comparing the state's Hazard Evaluation and Emergency Response Office map of contaminated sites with the Hawaiʻi state sea level rise viewer and NOAA flood maps, scientists were able to quantify the impact of projected sea level rise and increased flooding on chemically contaminated areas. At over 800 sites across Hawaiʻi, projected increases in sea level rise and flooding could release contaminants in stormwater that would expose the public to potential health risks.[277,278]
- Climate-induced migration from affected areas in Asia and the Pacific[279] will increase utilization of Hawaiʻi's health care system as well as potentially increase exposure to infectious diseases that are not commonly seen in Hawaiʻi.
- As the environment degrades, people may lose access to traditional food sources and increase their reliance on canned, processed, and imported foods, which will have significant downstream impacts on people's health. In 2010, the US Affiliated Pacific Islands (USAPI) declared a state of emergency[280] due to non-communicable, chronic diseases like diabetes and heart disease.[281]
- Mental health impacts from climate change are extensive and understudied and may worsen as severe weather events and climate impacts increase. Current and projected resources are not adequate to address these increases in mental health impacts.[282]

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271 Cushing, Lara et al. "Carbon Trading, Co-Pollutants, and Environmental Equity: Evidence from California's Cap-and-Trade Program (2011–2015)." Ed. Jonathan Patz. PLOS Medicine 15.7 (2018): e1002604. Web.

272 CCH CCSR, 2019.

273 Keener et al. 2018

274 SOEST 2014 Climate Change Impacts in Hawaii. seagrant.soest.hawaii.edu/wp-content/uploads/2018/05/smFINAL-HawaiiClimateChange.pdf

275 Camilo Mora, Tristan McKenzie, Isabella M. Gaw, Jacqueline M. Dean Hannah von Hammerstein, Tabatha A. Knudson, Renee O. Setter, Charlotte Z. Smith, Kira M. Webster, Jonathan A. Patz and Erik C. Franklin. (2022). Over half of known human pathogenic diseases can be aggravated by climate change. Nature Climate Change. https://doi.org/10.1038/s41558-022-01426-1

276 Jessica A. Bullington Abigail R. Golder Grieg F. Steward Margaret A. McManus, Anna B. Neuheimer, Brian T. Glazer Olivia D. Nigro , Craig E. Nelson.(2022). Refining real-time predictions of Vibrio vulnificus concentrations in a tropical urban estuary by incorporating dissolved organic matter dynamics. Science of the total environment 829. https://www.sciencedirect.com/science/article/pii/S0048969722011676?via%3Dihub

277 Felton, D. and van der Zander, I. (2021). Risks of Sea Level Rise and Increased Flooding on Known Chemical Contamination in Hawaii (updated June 2021). State of Hawaii Department of Health Memo, File: 179731 DF

278 https://www.civilbeat.org/2022/12/flooding-sea-level-rise-could-release-chemicals-at-hundreds-of-hawaii-sites-say-health-experts/

279 Krzesni, D. & Brewington, L. (2022). Climate Change, Health, and Migration in the Marshall Islands: Profiles of Resilience and Vulnerability. East-West Center, Honolulu, HI, 70 pp. Available from: https://www.eastwestcenter.org/publications/climate-change-health-and-migration-profiles-resilience-and-vulnerability-in-the

280 https://ncdalliance.org/news-events/news/pacific-islands-declare-health-emergency-due-to-ncds

281 Tuitama LT et al. (2014). Acting on the Pacific Crisis in NCDs. The Lancet VOLUME 384, ISSUE 9957, P1823-1824, https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(14)61824-9/fulltext

282 Palinkas and Wong. (2020). Global Climate change and mental health Current Opinion. Psychology 202,32:12-16 https://dworakpeck.usc.edu/sites/default/files/2020-10/Palinkas%20Wong.pdf

Progress & Next Steps

- The ability of communities to better endure disasters and the health impacts of climate change is linked to higher social connectedness and social capital. Community initiatives planning for flood impacts on Kauaʻi and Hawaiʻi Island provide examples of these types of networks.[283]
    - Action #15 in the Ola Oʻahu Resilience Strategy develops a network of community resilience hubs, which will provide focal-points for community services and coordination in the case of a disaster, including access to health services and public cooling centers. Progress including securing initial planning funding from FEMA and creating a Resilience Hubs planning team has been made.
- Action #33 in the Ola Oʻahu Resilience Strategy aims to increase tree canopy coverage to provide shade and decrease urban heat, reducing impacts of heat on community health. In 2021, the city passed the halfway point to its goal of planting 100,000 trees.
- Develop criteria for identification of contaminated sites at high-risk of causing significant harm due to rising sea level and flooding. This can include incorporating the impacts of sea level rise and related effects on contamination in State, County, and Local Masterplans, including harbors, and considering potential contamination in relation to awarding building permits.[284]
- Continue to assess climate related health impacts in Hawaiʻi with research on heat-related illness, vibrio vulnificus infections, vector borne illnesses and other Hawaiʻi-specific hazards. Data from these projects will help prioritize resiliency and adaptation resources.
- Enhance culturally appropriate mental health services in Hawaiʻi, particularly for youth and underserved communities.
- Synchronize City climate and health initiatives with Hawaiʻi's State Department of Health utilizing CDC's Building Resilience Against Climate Effects (BRACE) Framework.[285]
- Implementing a One Health framework that embraces a collaborative, multisectoral, and transdisciplinary approach to community health that recognizes the connection between people, climate, and ecosystems can be a useful resilience tool.

Disproportionately Impacted Communities

While climate change will expose weaknesses in all societal systems, the impacts are not experienced equally, and vary by geographic location, socioeconomics, demographics, colonial history, and militarization, among other factors. Disproportionately impacted communities are those that are experiencing the most immediate and severe impacts of climate change and are least able to adapt, and often include low-income populations, communities of color, and Indigenous peoples. Equitable adaptation to climate change must include an analysis of how and why these communities experience increased risk, both to address past injustices and to ensure that adaptation plans do not create new inequities. Increasing social cohesion within and across communities can increase adaptive capacity and reduce the risk of maladaptation, that is, reducing the risk of affecting vulnerability in harmful and unintended ways.[286]

Local Observations

- Frontline communities on Oʻahu that may suffer first and worst from the impacts of climate change include those living in high-risk areas for flood or urban heat island effects, populations with limited mobility, low-income households, renters, persons with disabilities or pre-existing health conditions, immigrants or non-native English speakers, children, or the elderly.[287]
- Low-income individuals tend to lack the resources needed to respond and recover from hazard events, such as being less likely to have access to a vehicle or insurance and more likely to live in substandard housing. In 2020, 33% of

283 Buehler, J. (2020). The Storm, the Flood, and the Future – Hawaii Sea Grant. Ka Pili Kai. https://seagrant.soest.hawaii.edu/the-storm-the-flood-and-the-future/
284 Felton et al, 2021.
285 CDC BRACE https://www.cdc.gov/climateandhealth/BRACE.htm
286 Eriksen, S. et al. (2021) Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? World Development, doi:10.1016/j.worlddev.2020.105383
287 City and County of Honolulu Climate Change Commission, (Adopted: December 8, 2020). Climate Change and Social Equity Guidance.

Hawai‘i’s households were classified as “asset limited, income constrained, employed” (ALICE), with 9% living below the federal poverty level.[288]

- Indigenous peoples of Hawai‘i and the Pacific have been forced into settler colonial systems that have marginalized and disenfranchised them, as evidenced in sociodemographic indicators.[289,290]
- Indigenous populations with reliance on natural resources for sustenance will be disproportionally impacted by climate change. Native Hawaiians have a connection to the land and its resources which can be traced back to the creation story in the Kumulipo, which is a chant that connects the birth of Kānaka Maoli to all living things in Hawai‘i. Hawaiian culture embodies this idea of kuleana of caring for Hawai‘i’s resources.[291]
- About 550 Hawaiian cultural sites are exposed to chronic flooding with a sea level rise of 0.98 m (3.2 ft).[292]
- Sea level rise impacts on traditional and customary practices (including fishpond maintenance, cultivation of salt, and gathering from the nearshore fisheries) have been observed.[293]
- Because of flooding and sea level rise, indigenous practitioners have had limited access to the land where salt is traditionally cultivated and harvested. Salt harvests at Hanapēpē have been minimal in the past few years compared to the 20-25 five-gallon bucket yields from each summer harvest 20 years ago.[294]
- In Hawai‘i, climate change impacts, such as reduced streamflow, sea level rise, saltwater intrusion, episodes of intense rainfall, and long periods of drought, threaten the ongoing cultivation of taro and other traditional crops.[295]
- Indigenous Pacific Islanders have the highest rates of obesity and chronic diseases in the region, which are correlated to a dependence on imported food which is further correlated to climate stressors and other socioeconomic factors.[296]

Global Observations

- Evidence shows that around the world, climate impacts are inequitably distributed to individuals and communities based on their social identities, including race, ethnicity, access to authority, geography, economic status, and ability.[297,298]
- Disproportionately impacted populations have the most urgent need for adaptation. The most vulnerable regions are in East, Central and West Africa, South Asia, Micronesia and Melanesia, and in Central America, characterized by compound challenges of high levels of poverty, a significant number of people without access to basic services, such as water and sanitation, and wealth and gender inequalities, as well as governance challenges. Needed investments increase with higher emissions scenarios.[299]

288 Aloha United Way. (2020). ALICE in Hawaii: A Financial Hardship Story. 2020 Hawaii Report, https://www.auw.org/sites/default/files/pictures/2020ALICEReport_HI_FINAL.pdf

289 Rohrer, Judy. Staking Claim Settler Colonialism and Racialization in Hawai‘i . The University of Arizona Press, 2016.

290 Kagan J.A., Ronquillo J.C. (2019) Ho‘oponopono and the Kānaka Maoli: The Elusive Quest for Social Equity in the Hawaiian Islands. In: Johansen M. (eds) Social Equity in the Asia-Pacific Region. Palgrave Macmillan, Cham.

291 Sproat, D. Kapua'ala. "An Indigenous People's Right to Environmental Self-Determination: Native Hawaiians and the Struggle against Climate Change Devastation." Stanford Environmental Law Journal, vol. 35, no. 2, 2016, p. 157-222. HeinOnline, https://heinonline.org/HOL/P?h=hein.journals/staev35&i=194.

292 Hawai‘i Climate Change Mitigation and Adaptation Commission (2017).

293 Sproat, D. K. (2016) An Indigenous People’s Right to Environmental Self-Determination: Native Hawaiians and the Struggle Against Climate Change Devastation. Stanford Environmental Law Journal, 35.

294 Ku`uwehi Hiraishi. “Traditional Hawaiian Salt Makers Combat Climate Change.” @hipubradio, 2017, www.hawaiipublicradio.org/post/traditional-hawaiian-salt-makers-combat-climate-change#stream/0.

295 Sproat (2016)

296 CDC, 2021.

297 Martinich, J., Neumann, J., Ludwig, L., & Jantarasami, L. (2013). Risks of sea level rise to disadvantaged 33 communities in the United States. Mitigation and Adaptation Strategies for Global Change, 18(2), 169-185.

298 Fussell, Elizabeth, Sara R. Curran, Matthew Dunbar, Michael A. Babb, LuAnne Thompson, and Jacqueline Meijer25 Irons. (2017). “Weather-related hazards and population change: A study of hurricanes and tropical storms in 26 the U.S., 1980-2012.” Annals of the American Academy of Political and Social Sciences, 669: 146-167

299 Birkmann, J., E. Liwenga, R. Pandey, E. Boyd, R. Djalante, F. Gemenne, W. Leal Filho, P.F. Pinho, L. Stringer, and D.Wrathall, 2022: Poverty, Livelihoods and Sustainable Development. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1171–1274, doi:10.1017/9781009325844.010.

- Globally, the right to self-determination enhances the ability of Indigenous peoples to more effectively adapt to the impacts of climate change. This right has been undermined by the legacy of colonialism and continuing low levels of funding and administrative support for Indigenous community self-determination.[300,301]

Projected Impacts

- Under all future IPCC emissions scenarios, climate change reduces capacities for adaptive responses. Higher levels of global warming lead to greater constraints, especially on disproportionately impacted communities. Observed societal impacts such as mortality due to floods, droughts, and storms, are much greater for regions with high vulnerability compared to regions with low vulnerability.[302]
  - Under the IPCC's projected inequality scenario (Shared Socioeconomic Pathway (SSP) 4) the projected number of people living in extreme poverty may increase by 122 million by 2030.[303]
  - Higher emissions scenarios and increasing climate hazards also increase the potential for social tipping points, with vulnerable populations experiencing increased livelihood insecurity that can compound with shock events and humanitarian crises.[304]
- Multicausal, climate change is already contributing to human migration in the Pacific Islands region, for example though coastal erosion, drought, and sea level rise-driven inundation,[305,306] and is expected to accelerate as hazards compound. As a frontline population, migrant populations are at higher risk from climate change impacts.[307]

Progress & Next Steps

- The City's Climate Action Plan, adopted in 2020, recommends a set of guiding implementation principles, the first of which is to center environmental and economic justice considerations by seeking guidance from disproportionately impacted community leaders, create and track metrics in an equity framework, and offer justice training to implementation staff. Steps to operationalize these principles should be taken as soon as possible.
- Identify frontline communities that potentially have, are, or will be experiencing chronic climate or socioeconomic stressors that could worsen the impact of climate change-induced shocks.[308]
- Collaborate with communities to share resources and information about community risks, needs, and abilities. Encourage holistic, community-scale approaches to building resilience by partnering with communities, nonprofits, allied professionals, and technical experts to identify and communicate about areas of high-risk.[309]
  - Groups across Hawai'i are building resilience to climate change through local cultural community-building. On Kaua'i, Hawai'i, and Moloka'i Islands, community-based subsistence fishing, forest areas, and energy cooperatives are examples of place-based natural resource management through traditional and customary skills and networks.[310,311,312]

300 Cozzetto, K., Marks-Marino, D., & Status of Tribes and Climate Change Working Group. (2021). Executive Summary. In D. Marks-Marino (Ed.), Status of Tribes and Climate Change Report. Institute for Tribal Environmental Professionals.

301 Whyte, K. (2013). Justice forward: Tribes, climate adaptation and responsibility. Climatic Change, 120(3), 517- 530.Whyte, K., Maldonado, J., McNeeley, S., Mullen, H., & Novak, R. (2021). History of Indigenous Peoples in National Climate Assessments. In D. Marks-Marino (Ed.), Status of Tribes and Climate Change Report (pp. 29– 29 35). Institute for Tribal Environmental Professionals.

302 Birkmann et al, 2022.

303 Birkmann et al., 2022.

304 Birkmann et al, 2022.

305 Storlazzi, C.D., Gingerich, S.B., Dongeren, A. van, Cheriton, O.M., Swarzenski, P.W., Quataert, E., Voss, C.I., Field, D.W., Annamalai, H., Piniak, G.A., McCall, R., 2018. Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. Sci. Adv. 4. https://doi.org/10.1126/sciadv.aap9741

306 Krzesni, D., Brewington, L., 2022. Climate Change, Health, and Migration in the Marshall Islands: Profiles of Resilience and Vulnerability. Honolulu: The East West Center. DOI 10.5281/zenodo.6555170.

307 Birkmann et al, 2022.

308 CCSR, 2020.

309 CCSR, 2020.

310 Mehana Blaich Vaughan, Peter M. Vitousek. (2013) "Mahele: Sustaining Communities through Small-Scale Inshore Fishery Catch and Sharing Networks," Pacific Science, 67(3), 329-344. https://doi.org/10.2984/67.3.3

311 Kamelamela, K.L., Springer, H.K., Keakealani, R.K., Ching, M.U., Ticktin, T., Ohara, R.D., Parsons, E.W., Adkins, E.D., Francisco, K.S., Giardina, C., 2022. Kōkua aku, Kōkua mai: An Indigenous Consensus-driven and Place-based Approach to Community Led Dryland Restoration and Stewardship. For. Ecol. Manag. 506. https://doi.org/10.1016/J.FORECO.2021.119949

312 Ho'āhu Energy Cooperative, (Accessed March 2023), https://hoahuenergy.coop/.

- Continue to focus on outreach to underserved communities through expanding accessibility options and providing information in the preferred format and languages of the island's diverse communities.[313]

Terrestrial and Marine Ecosystems

Climate change now threatens the stability of major marine and terrestrial biophysical systems.[314] Climate change and other impacts of human activities are triggering irreversible changes in major ice systems, Atlantic circulation, the Amazon Rainforest, boreal forests, coral reefs, and permafrost. Given the scale and interconnectedness of these complex systems, regime shifts[315], or large, abrupt, and persistent critical transitions in the function and structure of ecosystems, may be triggered by continued GHG emissions and potentially commit the world to changes that are irreversible over timescales of centuries to millennia. Tipping points, such as with permafrost melting or deforestation, can trigger abrupt carbon release back to the atmosphere. This can amplify climate change and reduce the probability of stopping global warming at defined targets.

Climate change impacts have been documented across every ecosystem on Earth, including shifts in species ranges, shrinking body size, changes in predator-prey relationships, new spawning and seasonal patterns, and modifications in the population and age structure of marine and terrestrial species; despite current average warming of only about 1° C so far.[316] In 2017, over 15,000 scientists published a "Warning to Humanity". They said humans have pushed Earth's ecosystems to their breaking point and are well on the way to ruining the planet.[317] Researchers have labeled global ecosystem impacts, including from climate change, "biological annihilation," and identify that a "sixth major mass extinction" is underway as a result of dwindling population sizes and range shrinkages among vertebrates.[318]

Local Observations

Terrestrial Ecosystems and Biodiversity

- Hawai'i is home to 31% of the nation's plants and animals listed as threatened or endangered, and less than half of the landscape on the islands is still dominated by native plants. Studies indicate that endemic and endangered birds and plants are highly vulnerable to climate change and are already showing shifting habitats.[319]
- Greenhouse gas sinks, mainly from forest ecosystems, offset about 33% of statewide emissions in 2016.[320]
- Combined impacts of invasive species, pests and diseases, and habitat destruction from development and altered disturbance regimes have greatly reduced the distribution and abundance of Hawai'i's native species while causing extinctions.[321,322,323,324,325,326]
- Warming air temperatures are bringing mosquito-borne diseases to previously disease-free upland forests, driving several native bird species toward extinction.[327]
- Sea level rise is altering coastal habitats throughout Hawai'i.[328]

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313 CCSR, 2020.

314 Lenton, T.M., et al. (2019) Climate tipping points — too risky to bet against. Nature; 575 (7784): 592 DOI: 10.1038/d41586-019-03595-0

315 Rocha, J.C., et al. (2018) Cascading regime shifts within and across scales, Science, 21 Dec., DOI: 10.1126/science.aat7850

316 Scheffers, B.R., et al. (2016) The broad footprint of climate change from genes to biomes to people. Science, Nov., DOI: 10.1126/science.aaf7671.

317 Ripple, W.J., et al. (2017) World Scientists' Warning to Humanity: A Second Notice. BioScience.

318 Ceballos, G., et al. (2017) Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines, PNAS, 114 (30) E6089-E6096; doi:10.1073/pnas.1704949114

319 Jacobi, J.D., et al. (2017) Baseline land cover. In Selmants, P.C., et al., eds., USGS, http://pubs.er.usgs.gov/publication/pp1834.

320 Hawaii Greenhouse Gas (GHG) Emission Report for 2016: Summary of Key Results. 1990, doi:10.3133/pp1834.

321 Wilcove, D.S.; et al. (1998) Quantifying threats to imperiled species in the United States: Assessing the relative importance of habitat destruction, alien species, pollution, overexploitation, and disease. BioScience 48, 607–615. https://doi.org/10.2307/1313420/2/48-8-607.PDF.GIF

322 Blackburn, T.M.; et al. (2004) Avian extinction and mammalian introductions on oceanic islands. Science 305, 1955–1958. https://doi.org/10.1126/SCIENCE.1101617/SUPPL_FILE/BLACKBURN.SOM.PDF

323 Pyšek, P., Jarošík, V., Hulme, P.E., Pergl, J., Hejda, M., Schaffner, U., Vilà, M., 2012. A global assessment of invasive plant impacts on resident species, communities and ecosystems: the interaction of impact measures, invading species' traits and environment. Glob. Change Biol. 18, 1725–1737. https://doi.org/10.1111/J.1365-2486.2011.02636.X

324 Fortini, L.B.; et al. (2015) Large-scale range collapse of Hawaiian forest birds under climate change and the need for 21st century conservation options. PLOS ONE 10, e0140389. https://doi.org/doi:10.1371/journal.pone.0140389

325 Leclerc, C.; Courchamp, F.; Bellard, C. (2018) Insular threat associations within taxa worldwide. Sci. Rep. 2018 81 8, 1–8. https://doi.org/10.1038/s41598-018-24733-0

326 Fernández-Palacios, J.M.; et al. (2021) Scientists' warning – The outstanding biodiversity of islands is in peril. Glob. Ecol. Conserv. 31, e01847. https://doi.org/10.1016/J.GECCO.2021.E01847

327 Paxton, E.H., et al. (2016) Collapsing avian community on a Hawaiian island. Science Advances, 2, e1600029.

328 Hawai'i Department of Land and Natural Resources. 2015. Hawai'i's State Wildlife Action Plan. Prepared by H. T. Harvey and Associates, Honolulu, Hawai'i.

- Prolonged drought conditions are affecting wildlife populations by reducing native habitat, vegetative structure, and food production in Hawaiʻi.[329]
- Wildfire has increased fourfold from the early 1900s in Hawaiʻi, in terms of area burned annually, and is most prevalent in nonnative grasslands and shrublands, which allow wildfires to propagate rapidly into forested margins threatening native habitat, watersheds, and human safety.[330]

Marine Ecosystems and Biodiversity

- Nearly 30 years of oceanic pH measurements collected from deepwater Station ALOHA 100 km north of Oʻahu show an 8.7% increase in ocean acidity since 1988.[331]
    - Increasing ocean acidity reduces the ability of marine organisms to build calcareous shells and other hard structures. This adversely impacts coral reefs and threatens marine ecosystems more broadly.[332]
- The first documented, large-scale coral bleaching event occurred in 1996, and was most prevalent in Kāneʻohe Bay, Oʻahu.[333] An intense Pacific wide ocean heat wave between 2014 and 2017 led to the most severe and widespread coral bleaching event observed in Hawaiʻi.[334] Reefs on the south shore of Oʻahu between Diamond Head and Pearl Harbor are the most impacted in Hawaiʻi due to co-occurrence of stressors including direct human impact, fishing, habitat destruction, invasive algae, and urban runoff. Reefs in other parts of South Oʻahu and in southern Kāneʻohe Bay are also heavily impacted.[335]

Global Observations

Terrestrial Ecosystems and Biodiversity

- Climate-related local extinctions have already occurred in hundreds of species, including 47% of 976 species surveyed.[336]
- Plant and animal species are migrating poleward and to higher elevations consistent with climate change predictions.[337]
- Tree lines in Alaska's boreal forests are shifting poleward consistent with global vegetation models considering climate change.[338]
- Springtime temperatures are coming sooner affecting the natural seasonal cycles of some plant species in the Arctic, while other species are delaying their emergence amid warmer winter temperatures. The changes are associated with diminishing sea ice.[339]
- The tropical climate zone has expanded north and south.[340]

Marine Ecosystems and Biodiversity

- Marine ecosystems are under extreme stress.[341] The world's richest areas for marine biodiversity are also those areas mostly affected by both climate change and industrial fishing.[342, 343]

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329 Hawaiʻi Department of Land and Natural Resources. 2015. Hawaiʻi's State Wildlife Action Plan. Prepared by H. T. Harvey and Associates, Honolulu, Hawaiʻi.
330 Trauernicht, Clay, et al. "The Contemporary Scale and Context of Wildfire in Hawaiʻi." Pacific Science, vol. 69, no. 4, 2015, p. 427–, https://doi.org/10.2984/69.4.1.
331 Marra and Kruk (2017)
332 Marra and Kruk (2017)
333 Hawaiʻi Department of Land and Natural Resources. 2015. Hawaiʻi's State Wildlife Action Plan. Prepared by H. T. Harvey and Associates, Honolulu, Hawaiʻi.
334 Marra and Kruk (2017)
335 Gove JM, Maynard JA, Lecky J, Tracey DP, Allen ME, Asner GP, Conklin, C, Couch C, Hum K, Ingram RJ, Kindinger TL, Leong K, Oleson KLL, Towle EK, van Hooidonk R, Williams GJ, Hospital J. 2022. 2022 Ecosystem Status Report for Hawaiʻi. Pacific Islands Fisheries Science Center, PIFSC Special Publication, SP-23-01, 91p. doi:10.25923/r53p-fn97
336 Wiens, J.J. (2016) Climate-related local extinctions are already widespread among plant and animal species, PLOS Biology, 14(12), e2001104.
337 Parmesan, C. & Yohe, G. (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421, 37–42.
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339 Post, E., et al. (2016) Highly individualistic rates of plant phenological advance associated with arctic sea ice dynamics, Biology Letters, 12(12), 20160332.
340 Seidel, D.J., et al. (2008) Widening of the tropical belt in a changing climate, Nature Geoscience, 1, 21-24, doi: 10.1038/ngeo.2007.38.
341 McCauley, D.J.; et al. (2015) Marine defaunation: Animal loss in the global ocean, Science, 347(6219), 16, Jan. Henson, S.A.; et al. (2017) Rapid emergence of climate change in environmental drivers of marine ecosystems, Nature Communications, 8, 14682, doi: 10.1038/ncomms14682.
342 Ramírez, F.; et al. (2017) Climate impacts on global hot spots of marine biodiversity. Science Advances; 3 (2): e1601198 DOI: 10.1126/sciadv.1601198.
343 Heron, S.F.; et al. (2016) Warming trends and bleaching stress of the world's coral reefs 1985-2012, Scientific Reports, 6, 38402, doi: 10.1038/srep38402.

- The number of coral reefs impacted by bleaching has tripled over the period 1985-2012. [344]
- Dissolved oxygen in the oceans is declining because of warmer water.[345] [346] Oxygen levels in the ocean have declined by 2% over the past five decades because of global warming, risking habitat loss for many fish and invertebrate species.[347]
- Globally, average pH of ocean water fell from 8.21 to 8.10, a 30% increase in acidity since the start of the industrial era. [348] Ocean water is becoming more acidic from increased dissolution of atmospheric CO_2, which drives reductions in pH that will increasingly negatively affect marine organisms.

Projected Impacts

Terrestrial Ecosystems and Biodiversity

- Climate change is likely to accelerate range contractions (shrinking habitat) and extinction rates of native species in Hawaiʻi.[349]
- Even under moderate warming, 10 of 21 existing native forest bird species are projected to lose over 50% of their range by 2100. Of those, three may lose their entire ranges and three others are projected to lose more than 90% of their ranges making them of high concern for extinction.[350]
- Plant and animal extinctions, already widespread, are projected to increase from twofold to fivefold in the coming decades.[351]
- Overall, climate change is anticipated to exacerbate the spread of invasive species.[352,353,354,355]
- Anticpated reductions in dry-season streamflow[356] would result in loss of habitat and connectivity between habitants.[357]

Marine Ecosystems and Biodiversity

- Under climate change, ocean warming is projected to cause annual coral bleaching in some areas, for example in the central equatorial Pacific Ocean, as early as 2030 and almost all reefs by 2050.[358,359,360] This will not only devastate local coral reef ecosystems but will also have profound impacts on ocean ecosystems in general. Ultimately it will threaten the human communities and economies that depend on a healthy ocean, including Hawaiʻi.[361]

344 Heron, S.F.; et al. (2016)
345 L. Stramma; et al. (2011) Expansion of Oxygen Minimum Zones May Reduce Available Habitat for Tropical Pelagic Fishes, Nature Climate Change 2: 33–37.
346 Sekerci, Y. and PetrovskII (2015) Mathematical modeling of Plankton-Oxygen dynamics under the climate change. Bulletin of Mathematical Biology.
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348 NOAA State of the Science Fact Sheet – Ocean Acidifiation: https://www.pmel.noaa.gov/co2/files/noaa_oa_factsheet.pdf.
349 Fortini, L.B.; et al. (2015)
350 Fortini, L., et al. (2015)
351 Wiens, J.J. (2016)
352 Ainsworth, A., Drake, D.R. (2020) Classifying Hawaiian plant species along a habitat generalist-specialist continuum: Implications for species conservation under climate change. PLOS ONE 15, e0228573. https://doi.org/10.1371/JOURNAL.PONE.0228573
353 Sommer, R.M., Cowie, R.H. (2020) Invasive traits of veronicellid slugs in the Hawaiian Islands and temperature
29 response suggesting possible range shifts under a changing climate. J. Molluscan Stud. 86, 147–155.
30 https://doi.org/10.1093/mollus/eyz042
354 Louppe, V.; et al. (2020) The globally invasive small Indian mongoose Urva auropunctata is likely to spread with climate change. Sci. Rep. 2020 101 10, 1–11. https://doi.org/10.1038/s41598-020-7 64502-6
355 Veazey, L.; et al. (2019). Present-Day Distribution and Potential Spread of the Invasive Green Alga Avrainvillea amadelpha Around the Main Hawaiian Islands. Frontiers in Marine Science, 6, 402. https://doi.org/10.3389/FMARS.2019.00402/BIBTEX
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357 Tsang, Y.-P., 2019. Identifying high value areas for conservation_ Accounting for connections among terrestrial, freshwater, and marine habitats in a tropical island system. J. Nat. Conserv.
358 Heron, S.F., et al. (2016)
359 Van Hooidonk, R., et al. (2014) Opposite latitudinal gradients in projected ocean acidification and bleaching impacts on coral reefs. Global Change Biology, 20.
360 van Hooidonk, R., J., et al. (2020) Projections of future coral bleaching conditions using IPCC CMIP6 Models: climate policy implications, management applications, and regional seas summaries. United Nations Environmental Programme
361 Marra and Kruk (2017)

- By 2050 over 98% of coral reefs will be afflicted annually by bleaching-levels of thermal stress.[362]
- Bleaching and acidification will result in loss of reef structure. Reef collapse leads to lower fisheries yields and loss of coastal protection and habitat.[363]
- Fisheries, coral reefs, and the livelihoods they support are threatened by higher ocean temperatures and ocean acidification.[364]
- Annual severe bleaching of coral reefs is projected to occur in the main Hawaiian Islands between 2030 and 2066 under and range of GHG emissions scenarios. [365,366]
- Of 75 reef sites assessed on Oʻahu for vulnerability to projected future climate impacts, 18 (24%) were found to be highly vulnerable and the remainder were found to have low-medium or medium-high vulnerability. High vulnerability sites were found all around Oʻahu.[367]

Progress & Next Steps

Conservation and management of terrestrial and marine ecosystems falls primarily under state and federal jurisdiction. However, many of the impacts of climate change cross jurisdictional boundaries at shorelines and watersheds. The challenges we're facing in our watersheds and coastal ecosystems are inextricably linked to land use practices within City jurisdiction. Cooperation is key to addressing these issues, including through the initiatives listed below.

Terrestrial Ecosystems and Biodiversity

- 173,000 acres of watershed forest area are part of protected watersheds in Hawaiʻi as of 2022, "near target" for the Aloha+ Challenge Goal for Natural Resource Management aligned with the United Nations Sustainable Development Goals (SDGs).[368]
- The Ola Oʻahu Resilience Strategy includes a recommended action of Enhancing the Community Forest by increasing the tree canopy across Oʻahu's communities to 35% by 2035.[369] Over 50,000 trees have been planted on Oʻahu in recent years in support of City Council Resolution 18-55 to increase the City's urban tree canopy and as tracked by the City's 100,000 Trees Oʻahu survey and mapping tool.[370]
- Invasive species and climate change are having interactive and compounding impacts on Hawaiʻi's terrestrial ecosystems.[371] The Hawaiʻi Interagency Biosecurity Plan (HIBP) is intended to address the most pressing invasive species issues in Hawaiʻi. To-date, 68% of the 147 actions have started.[372]

Marine Ecosystems and Biodiversity

- The Hawaiʻi Coral Reef Strategy 2030 guides coral reef conservation and management by the Hawaiʻi Department of Aquatic Resources in partnership with NOAA[373]. The related 2023 Makai Restoration Action Plan provides specific goals to increase the ecological function and integrity of coral reefs and identifies Kāneʻohe Bay, Hanauma Bay, Waialae-Kahala, and reef adjacent to the Waīkikī Aquarium as priority candidate restoration areas.[374]
- The State Department of Aquatic Resources' Holumua Initiative conducted a pilot community-based planning approach to guiding marine resource management on Maui in 2022.[375]

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362 Heron, S.F.; et al. (2016)
363 Yates, K. K.; et al. (2017) Divergence of seafloor elevation and sea level rise in coral reef ecosystems, Biogeosciences, 14, 1739-1772, https://doi.org/10.5194/bg-14-1739-2017.
364 Keener, V.; et al. (2018)
365 van Hooidonk, R., J., et al. (2020) Projections of future coral bleaching conditions using IPCC CMIP6 Models: climate policy implications, management applications, and regional seas summaries. United Nations Environmental Programme
366 Gove J.M., et al. (2022)
367 Gove J.M., et al. (2022)
368 https://alohachallenge.hawaii.gov/
369 Oahu Resilience Strategy (2019) https://www.resilientoahu.org/resilience-strategy
370 100,000 Trees Oahu: https://arcg.is/O9u4X
371 Burgett J, Martin C, Kerkering H, Arnott C. 2021 . When Invasive Species and Climate Change Intersect: Survey of Hawaiʻi Natural Resource Managers. Honolulu: The Pacific Regional Invasive Species and Climate Change Management Network.
372 Hawaii Invasive Species Council Support Program (2023) Hawaii Interagency Biosecurity Plan, January 2023 Progress Report.
373 State of Hawaii Department of Land and Natural Resources, Division of Aquatic Resources (2020) Hawaii Coral Reef Strategy 2030
374 Hawaii Department of Land and Natural Resources – Division of Aquatic Resources (2023) Hawaii Coral Reef Strategy 2030: Makai Restoration Action Plan
375 Department of Land and Natural Resources – Division of Aquatic Resources, Holumua Initiative: https://dlnr.hawaii.gov/holumua/

- To ensure public health and improve the water quality in watersheds and coastal waters, the State Department of Health was directed by Act 132, Session Laws Hawaiʻi 2018 to establish a cesspool conversion working group to develop a long-range plan for conversion of all cesspools statewide by 2050.[376]

Areas for Future Research

This climate change brief aims to include the most current and comprehensive science information on climate change and related impacts. However, in the writing of the brief, there were areas of further research identified. Next-generation modeling of coastal erosion and flooding impacts is needed to continue to improve site-specific preparedness for sea level rise. Downscaling of global climate change models for projected temperature, precipitation, and other climate indicators remains a challenge for Hawaiʻi and other island locations with steep and varied topography and high natural shorter-term climate variability. Relatedly, research on historical and projected trends of extreme rainfall in Hawai'i, colloquially known as "rain bombs", has not provided consistent results and needs further investigation. Furthermore, data on food systems and human health in Hawai'i related to climate change is scarce, specifically on the climate resiliency and GHG contributions of the local food sector. Due to the scarce amount of literature quantifying the disproportionate impact of current and projected climate change scenarios on vulnerable populations, like those with pre-existing conditions or those with low socioeconomic status, in Hawai'i, the Commission recommends further research in this area.

Some key areas for future research identified by the Commission:

- Observations and projections for extreme rainfall levels in Hawaiʻi, specifically "rain bombs", as well as a more precise and consistent definition of what constitutes "extreme" rainfall.
- Additional research and modeling are needed to reduce uncertainty in projections of future precipitation in Hawaiʻi at smaller spatial and temporal scales.
- Modeling of flooding impacts with increasing precipitation combined with sea level rise and considering rising coastal groundwater with sea level rise.
- Next-generation coastal erosion and wave run-up modelling considering two-dimensional alongshore processes and at various timescales.
- Robust and accepted methods for ecosystem valuation to track and compare benefits of conservation of natural ecosystems such as reefs, beaches, and forested lands with other actions or pathways.
- More research is needed on the impacts of future climate change on local food systems and human health in Hawai'i, to increase resilience in the event of a disaster event, increase sustainable local food production, and improve the resilience of disproportionately-affected communities.
- The Commission recommends additional research quantifying the current and future impacts of climate change on human health and on disproportionately impacted communities. The State initiated an important assessment of climate impacts on health in 2015, which highlighted vector borne disease, heat, and the need to address key vulnerabilities on populations with pre-existing conditions that can be exacerbated by climate change.
- The Commission notes the ongoing need for and importance of continuous monitoring of climate data including physical variables such as extreme temperatures, precipitation, streamflow, groundwater, and sea level, and socioeconomic variables and impacts such as community health, food security, ecosystem health and biosecurity, and equitable distribution of adaptation resources. In addition to supporting statewide initiatives that monitor water resources and climate[377,378], we recommend increasing the scope of socioeconomic climate data collection.

376 State of Hawaii, Department of Health. Cesspool Conversion Working Group: https://health.hawaii.gov/wastewater/home/ccwg/

377 Cheng, C. L., Izuka, S. K., Kennedy, J., Frazier, A. G., & Giambelluca, T. W. (2021). Water-resource management monitoring needs, State of Hawaiʻi (Report No. 2020–5115; Scientific Investigations Report, p. 114). USGS Publications Warehouse. https://doi.org/10.3133/sir20205115

378 https://www.hawaii.edu/news/2021/10/10/hawaii-mesonet-project/

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The content of this paper rests solely with the Honolulu Climate Change Commission.

Appendix 1: El Niño-Southern Oscillation (ENSO) Variability

The El Niño-Southern Oscillation (ENSO) is a semi-regular fluctuation (about every 2-7 years) in sea surface temperatures and atmospheric air pressure across the equatorial Pacific Ocean that affects weather conditions in Hawai'i, throughout the Pacific Basin, and in many parts of the world.[379] ENSO is a primary cause of inter-annual variability in long-term Pacific regional and global climate records. El Niño conditions are characterized by warmer surface waters in the equatorial Pacific and weaker than average easterly tradewinds. The opposite conditions, La Niña, is characterized by cooler-than-average equatorial ocean waters and stronger easterly tradewinds. Intermediate conditions are termed ENSO-neutral.

- For Hawai'i, El Niño generally brings more rain in the beginning of the season followed by rapid decline in rainfall, weaker tradewinds, increased wave runup occasionally combined with anomalously high sea levels, warmer ocean conditions, and increased risk of tropical cyclones.[380]
- For Hawai'i, extreme precipitation events are more frequent in La Niña years and less frequent in El Niño years.[381]
- During the strong El Niño of 2015, Honolulu set or tied 11 days of record heat.[382]
- During El Niño, summers often have more rainfall which prolongs the growing season and increases potential fuel loads for fires. Drought throughout the following winter months causes vegetation to dry out and raise wildfire risk. In the 1997-1998 El Niño, which was the strongest to date, wildfires in Hawai'i burned over 37,000 acres.[383]
- Frequency of intense El Niño events is projected to double in the 21st century, with the likelihood of extreme events occurring roughly once every decade.[384]
- Models project a near doubling in the frequency of future extreme La Niña events, from one in every 23 years to one in every 13 years. Approximately 75% of the increase occurs in years following extreme El Niño events, thus projecting more frequent swings between opposite extremes from one year to the next.[385]

Appendix 2: Global Cryosphere Indicators

The cryosphere refers to the frozen components of the Earth System at and below the land and ocean surface, including snow cover, glaciers, ice sheets, ice shelves, icebergs, sea ice, lake ice, river ice, permafrost, and seasonally frozen ground. The ocean and cryosphere are interconnected with other components of the Earth's climate system through exchanges of water, energy, and carbon. These interconnections are particularly important for human communities in coastal environments, on small islands, in polar areas, and on high mountains. The 2019 IPCC Special Report on the Ocean and Cryosphere in a Changing Climate assesses the best-available scientific literature on the topic and provides the following observations with *high* to *very high confidence* level (80-100% degree of confidence in being correct, unless otherwise noted) [386]:

- Over the last decades, global warming has led to widespread shrinking of the cryosphere, with mass loss from ice sheets and glaciers, reductions in snow cover and Arctic sea ice extent and thickness, and increased permafrost temperature.
- Between 2006 and 2015, the Greenland Ice Sheet lost ice mass at an average rate of 278 ± 11 Gt yr–1 (equivalent to 0.77 ± 0.03 mm yr–1 of global sea level rise), mostly due to surface melting.
- Between 2006 and 2015, the Antarctic Ice Sheet lost mass at an average rate of 155 ± 19 Gt yr–1 (equivalent to 0.43 ± 0.05 mm yr–1 of global sea level rise), mostly due to rapid thinning and retreat of major outlet glaciers draining the West Antarctic Ice Sheet.
- Arctic June snow cover extent on land declined by 13.4 ± 5.4% per decade from 1967 to 2018, a total loss of approximately 2.5 million km^2, predominantly due to surface air temperature increase.

379 NOAA National Centers for Environmental Information: El Niño/Southern Oscillation (ENSO): https://www.ncei.noaa.gov/access/monitoring/enso/technical-discussion
380 NOAA National Weather Service, El Nino and its Impact on Hawai'i: https://www.weather.gov/media/peac/one_pagers/El%20Nino%20Impacts%20on%20Hawaii.pdf
381 Chen, Y. R., P.-S. Chu (2014)
382 New York Times weather chart: https://www.nytimes.com/interactive/2016/02/19/us/2015-year-in-weather-temperature-precipitation.html#honolulu_hi.
383 El Niño and Long-Lead Fire Weather Prediction for Hawaii and US-affiliated Pacific Islands PFX Fact Sheet 201 5_1. N.p. Web. 13 Oct. 2020.
384 Cai, W., et al. (2015) Inc. frequency of extreme El Niño events due to greenhouse warming. Nature Climate Change 4, 111–116, doi:10.1038/nclimate2100.
385 Cai, W., et al. (2015) Inc. freq. of extreme La Niña events induced by greenhouse warming, Nature Climate Change, 5, 132–137, doi: 10.1038/nclimate2492.
386 IPCC (2019) The Ocean and Cryosphere in a Changing Climate, Summary for Policymakers

- September Arctic sea ice coverage decreased 12.8 ± 2.3% per decade between 1979 and 2018.
- Permafrost temperatures increased 0.29°C ± 0.12°C from 2007 to 2016 averaged across polar and high-mountain regions globally. Arctic and boreal permafrost contain almost twice the carbon in the atmosphere (*medium confidence*). There is *medium evidence* with *low agreement* whether northern permafrost regions are currently releasing additional net methane and CO_2 due to thaw.
- Acceleration of ice flow and retreat in Antarctica, which has the potential to lead to sea level rise of several meters within a few centuries, is observed in the Amundsen Sea Embayment of West Antarctica and in Wilkes Land, East Antarctica. These changes may be the onset of an irreversible ice sheet instability.