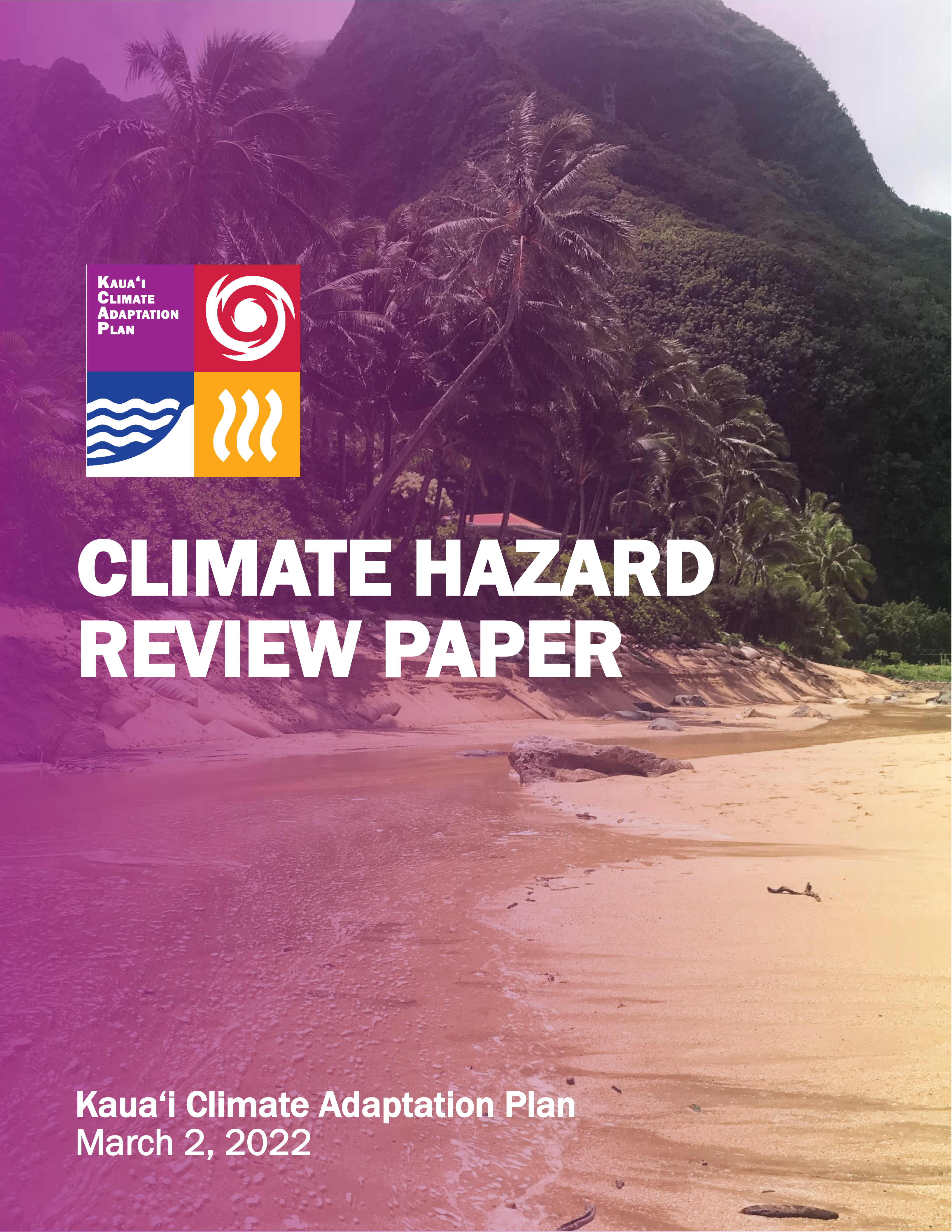


CLIMATE HAZARD REVIEW PAPER

Kauaʻi Climate Adaptation Plan
March 2, 2022

This page left intentionally blank.

Table of Contents

TABLE OF FIGURES

TABLE OF TABLES

CLIMATE HAZARD REVIEW PAPER

The Climate Hazard Review Paper synthesizes the current scientific knowledge of the climate change hazards that Kauaʻi, and Hawaiʻi at large, face now and in the future. It builds on scientific studies and existing local plans to provide a comprehensive baseline understanding of climate change, which will inform the next steps of the Kauaʻi Climate Adaptation Plan.

Key Findings

1. Compared to the late 1800's, human greenhouse gas (GHG) emissions have warmed average annual air temperature at Earth's surface by 1.1 to 1.3°C (2 to 2.3°F). Climate change is likely accelerating, and impacts are growing in frequency and magnitude.
2. Kauaʻi is facing unavoidable, costly, and dangerous impacts from climate change and the islands future socio-economic viability is at risk.
3. In the County of Kauaʻi, climate change hazards are expressed as both shocks and stressors related to an accelerated water cycle.
4. Five climate change hazards stand out above others as warranting special concern and the need to develop specific adaptation plans and policies:
    a. Increasing ambient and extreme **heat** bringing new challenges to emergency response, grid resilience, public health, community design, and ecosystems;
    b. **Declining rainfall**, expanding **drought**, and related hazards such as **wildfire** and threats to **food production**;
    c. Growing **storminess**, and related hazards such as **landslides**, **floods**, **infrastructure damage**, and **public safety**;
    d. **Sea level rise**, lasting millennia, punctuated by **extreme tides**, **compound events** (e.g., high tide plus heavy rain, waves, onshore winds, and others), and ultimately requiring the community to **retreat from the coast**; and
    e. Expanding **supply chain disruptions** as ports, manufacturing centers, global bread baskets, and transportation systems experience growing climate change impacts.

1. Executive Summary

Human activities are polluting the atmosphere with "greenhouse" gases that trap heat and warm the air.[1] Compared to the late 1800's, these emissions have warmed average annual air temperature at Earth's surface by 1.1 to 1.3°C (2 to 2.3°F).[2] Climate change is accelerating, and related hazards are growing in frequency and magnitude. According to the Intergovernmental Panel on Climate Change,[3] it is *unequivocal* that human influence has warmed the atmosphere, ocean, and land. As a result, widespread, unprecedented, and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.

Rising temperatures are causing phenomena such as loss of sea ice and ice sheet mass, sea level rise, longer and more intense heat waves, and shifts in plant and animal habitats and behaviors. Understanding these long-term climate trends is essential for preserving the safety and quality of human life, allowing humans to adapt to the changing environment in ways such as planting different crops, new ways of managing water resources, designing resilient, low carbon communities, and preparing for extreme weather events.

Global surface temperature will continue to increase until at least mid-century regardless of any changes in Human-made emissions.[4] Global warming of 1.5°C (2.7°F) and 2°C (3.6°F) will be exceeded during the 21st Century unless there are deep and rapid reductions in carbon dioxide (CO_2) and other emissions. Even though the pace of climate change has been rapid and the impacts severe, until recently, few people have noticed. Now, however, a range of key socio-economic sectors (e.g., investors, public agencies, supply-side community) show broadening acceptance of the need to act quickly.[5] But progress remains too slow to avoid dangerous levels of warming.[6]

1.1. CLIMATE CHANGE HAZARDS

1.1.1. Global Climate System

Many changes in the climate system become larger in direct relation to increasing global surface temperature. These include increases in the frequency and intensity of hot extremes,[7] the risk and extent of vector-borne

---

[1] See Appendix I for discussion of Human-made global warming.
[2] NASA *2021 Tied for Sixth Warmest Year in Continued Trend, NASA Analysis Shows*, https://www.giss.nasa.gov/research/news/20220113/; See also Global Warming index, https://www.globalwarmingindex.org
[3] IPCC (2021) Summary for Policymakers (SPM). 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. et al. (eds.)]. In Press.
[4] IPCC (2021) SPM
[5] "Get ready for ESG Investing to Quadruple by End of Decade" Dec. 6, 2021: https://www.nasdaq.com/articles/get-ready-for-esg-investing-to-quadruple-by-end-of-decade
[6] Fletcher, C. (2021) COP26 has failed our children - political compromise cannot be the answer, https://thehill.com/opinion/energy-environment/582048-cop26-has-failed-our-children-political-compromise-cannot-be-the
[7] Ma, F., and Yuan, X. (2021) Impact of climate and population changes on the increasing exposure to summertime compound hot extremes, *Science of The Total Environment*, v772, https://doi.org/10.1016/j.scitotenv.2021.145004.

disease,[8] marine heatwaves,[9] heavy precipitation,[10] compound events,[11] agricultural and ecological droughts,[12] extreme rainfall and the chance of floods,[13] and the proportion of intense tropical cyclones.[14] Arctic Sea ice,[15] snow cover[16] and permafrost[17] decline annually, and the transition from a snow- to rain-dominated Arctic in the summer and autumn may occur as early as 2040, with profound climatic, ecosystem and socio-economic impacts.[18]

Many changes due to past and future greenhouse gas emissions are irreversible for centuries to millennia, especially changes in the ocean, ice sheets and global sea level.[19] Low-likelihood outcomes, such as ice sheet collapse, abrupt ocean circulation changes, some compound extreme events, and warming substantially larger than those assessed in the "very likely" range (>90%), cannot be ruled out.[20]

1.1.2. Local Context

Climate on the island of Kaua'i is embedded in the larger Pacific and global climate system. Changes in atmospheric circulation (e.g., the Polar Jet Stream), the ocean (e.g., North Pacific sea surface temperatures), and in bio-physical systems such as tropical forests, permafrost, and others, will be seen in some fashion as changes in the climate on Kaua'i as well.

For instance, loss of Arctic summer sea ice drives Arctic Amplification[21] wherein the Arctic warms 4 times[22] faster than the global average. This reduces Northern Hemisphere atmospheric circulation which depends on regional gradients (differences) in temperature. Researchers hypothesize that the Polar Jet Stream has become unstable as a result[23] and large meanders in the jet stream generate frontal lows associated with severe weather events. Jet stream meanders may cause Kaua'i to experience stormy weather such as happened on December 6, 2021 when Līhu'e Airport recorded 8.31 cm (3.27 in) of rain, a record for that date.[24] **Figure ES-1** shows that a deep meander in the jet stream on that date created a frontal low, generating

---

[8] Science Brief (2021) paper compilation on "Climate change increases the risks and extent of vector-borne diseases," https://sciencebrief.org/topics/climate-change-science/vector-borne-diseases
[9] Laufkötter, C., *et al.* (2020) High-impact marine heatwaves attributable to human-induced global warming, *Science*, https://doi.org/10.1126/science.aba0690
[10] Fowler, H.J., Lenderink, G., Prein, A.F. *et al.* (2021) Human-made intensification of short-duration rainfall extremes. *Nat Rev Earth Environ* 2, 107–122. https://doi.org/10.1038/s43017-020-00128-6
[11] Robinson, A., *et al.* (2021) Increasing heat and rainfall extremes now far outside the historical climate, *Climate and Atmospheric Science*, https://doi.org/10.1038/s41612-021-00202-w
[12] Pokhrel, Y., Felfelani, F., Satoh, Y. *et al.* (2021) Global terrestrial water storage and drought severity under climate change. *Nat. Clim. Chang.* 11, 226–233. https://doi.org/10.1038/s41558-020-00972-w
[13] Blenkinsop, S., *et al.* (2021) Science Brief Review: Climate change increases extreme rainfall and the chance of floods. In: *Critical Issues in Climate Change Science*, edited by: C. Le Quéré, P. Liss & P. Forster. https://doi.org/10.5281/zenodo.4779119
[14] Knutson, T. R., *et al.* (2021) Science Brief Review: Climate change is probably increasing the intensity of tropical cyclones. In: *Critical Issues in Climate Change Science*, edited by: Corinne Le Quéré, et al. https://doi.org/10.5281/zenodo.4570334
[15] Andersson, T.R., *et al.* (2021) Seasonal Arctic Sea ice forecasting with probabilistic deep learning. *Nat Commun* 12, 5124. https://doi.org/10.1038/s41467-021-25257-4
[16] Niittynen, P., *et al.* (2020) Decreasing snow cover alters functional composition and diversity of Arctic tundra, *PNAS*, 117 (35) 21480-21487; DOI:10.1073/pnas.2001254117
[17] Plaza, C., *et al.* (2019) Direct observation of permafrost degradation and rapid soil carbon loss in tundra. *Nat. Geosci.* 12, 627–631. https://doi.org/10.1038/s41561-019-0387-6
[18] McCrystall, M.R., *et al.* (2021) New climate models reveal faster and larger increases in Arctic precipitation than previously projected. *Nat Commun* 12, 6765 https://doi.org/10.1038/s41467-021-27031-y
[19] IPCC (2021) Headline statements SPM, https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Headline_Statements.pdf
[20] Ibid.
[21] Previdi, M., *et al.* (2021) Arctic amplification of climate change: a review of underlying mechanisms, *Environmental Research Letters*, v16, n9, https://doi.org/10.1088/1748-9326/ac1c29
[22] https://public.wmo.int/en/media/press-release/wmo-recognizes-new-arctic-temperature-record-of-38^{0}c
[23] Francis, J.A. and Vavrus, S.J. (2012) Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters*. 39 (6): L06801. doi:10.1029/2012GL051000.
[24] https://www.weather.gov/wrh/Climate?wfo=hfo

extreme rain. This illustrates that global and regional climate change can have meaningful localized impacts on the island of Kaua'i.

Figure ES - 1. Weather Map December 6, 2021

A deep meander in the Polar Jet Stream (gray band) generated record precipitation of 8.31 cm (3.27 in) at Līhuʻe Airport. Researchers have tied these meanders to Arctic Amplification caused by global warming.

Source: Honolulu Star Advertiser

1.1.3. Local Climate Change Hazards

Kaua'i is facing unavoidable, costly, and dangerous impacts from climate change. Studies[25] show that the impacts of climate change fall disproportionately on vulnerable populations. The remote and currently vulnerable socio-economic framework of Kaua'i, and Hawai'i at large (demonstrated by critical reliance on imported goods and services), constitutes a significant weakness. This was starkly illustrated by the severe environmental and socio-economic impacts caused by Hurricane Iniki.[26] Growing exposure to tropical cyclones and the effects of marine and atmospheric warming, put Kauai's food and water security and economy at risk. These risks are more than sufficient to motivate deep inspection and analysis of island policies with the intention of enacting transformational changes to ensure strengthened resilience and sustainability.

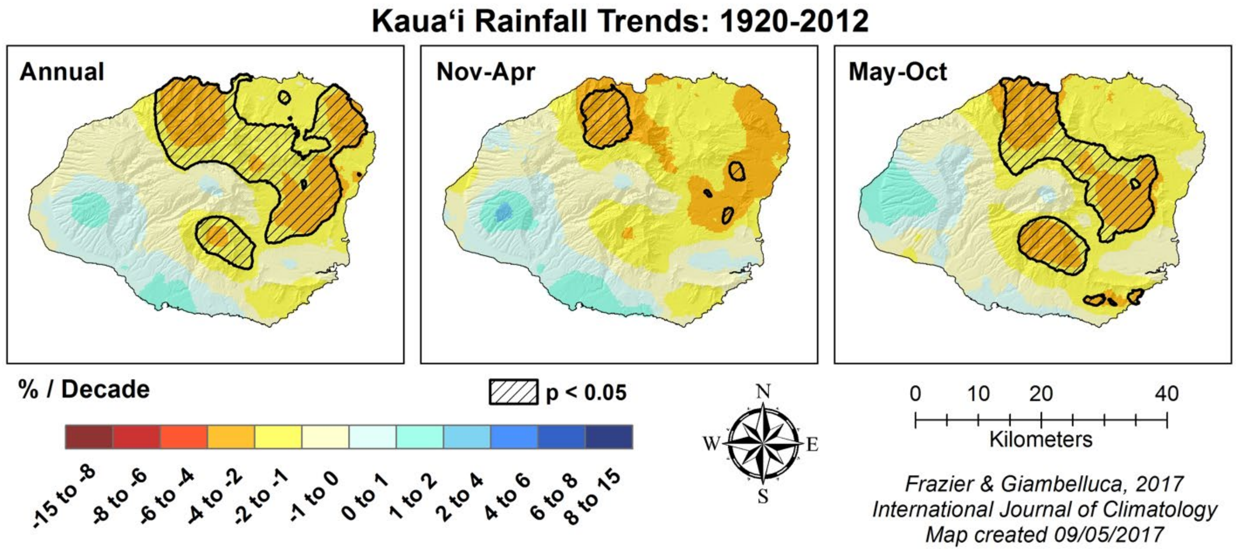
As an isolated, and remote group of islands without the capacity to rapidly exchange critical resources such as freshwater, food, or medical supplies with neighboring communities, the state of Hawai'i, and Kaua'i specifically, are especially vulnerable to the accelerating impacts of climate change. Five impacts stand out above others as warranting special concern and the need to develop specific adaptation plans and policies: 1.) Increasing ambient and extreme heat, 2.) Declining rainfall and expanding drought, 3.) Growing storminess, 4.) Sea level rise, and 5.) Supply chain disruptions. These five represent direct challenges to long-term sustainability (declining rainfall, drought, supply chain disruptions), public health and safety (heat, storminess), and chronic and growing socio-economic disruption (sea level rise).

---

[25] UN (2020) World Social Report 2020: Inequality in a Rapidly Changing World, https://www.un.org/development/desa/dspd/wp-content/uploads/sites/22/2020/01/World-Social-Report-2020-FullReport.pdf

[26] Coffman, M. and Noy, I. (2009) A hurricanes long-term economic impact: the case of Hawaii's Iniki, *Working Paper No. 09-5*, June. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.366.1272&rep=rep1&type=pdf

Figure ES - 2. Annual Average Rainfall



Average annual rainfall is declining on Kaua'i at a rate of about 1% per decade (Scale- % change rainfall per decade). *Source: Frazier, A. G., and Giambelluca, T. W. (2017)*

Several major categories illustrate the breadth of impacts to Kaua'i:

1. **Global Tipping Points** - Some major global bio-physical systems (e.g., terrestrial Carbon sinks) show early indications of abrupt, potentially irreversible change that could accelerate warming and related climate change impacts.[27]
2. **Global Disease** - Climate change alters the range of pathogens, allowing infections, particularly vector-borne infections, to expand to new locations. The continued uptick in global travel, trade and mobility transports pathogens rapidly. Even relatively remote locations such as Kaua'i are at risk from an emerging class of zoonotic diseases related to habitat and biodiversity loss, extreme weather, and expanded vector range.
3. **Accelerated Sea Level Rise** - Collapse of Thwaites Glacier ice shelf could rapidly accelerate sea level rise. Thwaites Ice Shelf has doubled its outflow speed over the last 30 years, and its base has eroded rapidly. Thwaites could raise global sea level by >61 cm (2 ft) and could lead to 3 m (10 ft) if it draws surrounding glaciers with it. New giant fractures have been observed, and researchers are concerned that part of the shelf could shatter within 5 years.[28]
4. **Sea Level Rise Flooding** - Sea level rise, extreme tide flooding, and compound coastal flood events are increasing.[29] Coastal erosion and land loss is increasing with growing threats to private and public

[27] Steffen, W. et al. (2018) Trajectories of the Earth system in the Anthropocene, *PNAS – Perspective*, Aug. 14, v115, no33, 8252-8259, www.pnas.org/cgi/doi/10.1073/pnas.1810141115
[28] Giant cracks push imperiled Antarctic glacier closer to collapse (2021) https://www.nature.com/articles/d41586-021-03758-y *Nature*, Dec. 14.
[29] Hawai'i Sea Level Rise Vulnerability and Adaptation Report (2017) Tetra Tech, Inc. and the State of Hawai'i DLNR, OCCL, DLNR Contract No: 64064.

property, transportation systems, bridges and other forms of public infrastructure, and when shoreline armoring is used to mitigate erosion, loss of beaches,[30] a public trust.[31]

5. **Ocean Heat Content** - Last year (2021) was the warmest year on record for ocean heat content, which increased markedly between 2020 and 2021.[32] The oceans absorbed the heat equivalent of seven Hiroshima atomic bombs detonating each second, 24 hours a day, 365 days a year.[33] Studies document increasing sea surface temperature with growth in marine heat waves as well as compound heat, acidification, and deoxygenation events.[34]

6. **Declining Rainfall** - In Hawaiʻi, on average, there has been a decline of 1.78% of annual rainfall per decade since 1920. A significant downward trend in annual rainfall per decade is seen in mountainous regions of Kauaʻi, while leeward areas mostly show no trend in annual rainfall. Wet season, and dry season precipitation has decreased in mountainous and windward areas of Kauaʻi.[35]

7. **Water Resources** - Climate change has fundamentally altered the water cycle on tropical islands which is a critical driver of freshwater ecosystems and water resource renewal.[36] Long-term decreases in precipitation result in negative impacts to water resources, stream discharge, watershed and coastal ecosystems, and mauka to makaʻi watershed connectivity. Streamflow has declined with increasing numbers of perennial streams running dry between direct rain events.[37] Kauai's water supply is mainly derived from groundwater.[38] The probability of chronic water shortages may grow as rainfall decreases and the water requirements of a growing population increase.

8. **Drought** - Drought has increased with longer and drier periods between rain events. Leeward areas are projected to experience significant drying, temperatures will continue to rise, and drought severity and frequency in the future will increase because of greater evaporative demand. Already-dry, drought-prone leeward areas are projected to become drier. These leeward areas are expected to be at high risk for drought in the future.[39] The frequency of extreme El Niño events is projected to increase which will likely result in more extreme drought.[40]

9. **Variability and Storminess** - Extreme precipitation and rainfall intensity have increased with related flooding.[41] Exposure to hurricanes has increased as they have become larger, wetter, more intense,

---

[30] Summers, A., Fletcher, C.H., Spirandelli, D., *et al.* (2018) Failure to protect beaches under slowly rising sea level. *Climatic Change* 151, 427–443. https://doi.org/10.1007/s10584-018-2327-7
[31] Lee, C. A. (2021). Eliminating the Hardship Variance in Honolulu's Shoreline Setback Ordinance: The City and County of Honolulu's Public Trust Duties as an Exception to Regulatory Takings Challenges. *University of Hawai'i Law Review*, 43(2), 464-518.
[32] Cheng, L., Abraham, J., Trenberth, K.E., *et al.* (2022) Another Record: Ocean Warming Continues through 2021 despite La Niña Conditions. *Adv. Atmos. Sci*. https://doi.org/10.1007/s00376-022-1461-3
[33] https://thehill.com/changing-america/sustainability/climate-change/589187-oceans-absorbed-heat-equivalent-to-7-hiroshima
[34] Gruber, N., *et al.* (2021) Biogeochemical extremes and compound events in the ocean. *Nature* 600, 395–407.
[35] Frazier, A.G. and Giambelluca, T.W. (2017) Spatial trend analysis of Hawaiian rainfall from 1920 to 2012, *International Journal of Climatology,* 37, 2522-2531, DOI: 10.1002/joc.4862
[36] Leta, O.T., *et al.* (2018) Impact of climate change on daily streamflow and its extreme values in Pacific Island watersheds, *Sustainability*, 10, 2057, doi:10.3390/su10062057
[37] Bassiouni, M., and D. S. Oki (2013) Trends and shifts in streamflow in Hawaiʻi, 1913–2008. *Hydrological Processes*, 27 (10), 1484–1500. doi:10.1002/hyp.9298
[38] Oki, D. S., *et al.* (1999) Hawaii. *Ground Water Atlas of the United States*, Segment 13, Alaska, Hawaii, Puerto Rico, and the U.S. Virgin Islands. Miller, J. A., et al., Eds., U.S. Geological Survey, Reston, VA, N12–N22, N36.
[39] Longman, R.J., *et al.* (2015) Sustained increases in lower-tropospheric subsidence over the Central Tropical North Pacific drive a decline in high-elevation rainfall in Hawaii. *Journal of Climate*. 28(22): 8743–8759. See also: Zhang, C., *et al.* (2016) Dynamical downscaling of the climate for the Hawaiian Islands. Part II: Projection for the late 21st century. *Journal of Climate.* 29(23): 8333–8354.
[40] Wang, G., *et al.* (2017) Continued increase of extreme El Niño frequency long after 1.5 °C warming stabilization. *Nature Climate Change*. 7(8): 568–572. See also: Cai, W., *et al.* (2014) Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change*. 5(2): 1–6.
[41] Chen, Y.R. and Chu, P.-S. (2014) Trends in precipitation extremes and return levels in the Hawaiian Islands under a changing climate, *International Journal of Climatology*, 34, 3913-3925, DOI: 10.1002/joc.3950

and are migrating poleward.[42] On Kauaʻi and across Hawaiʻi, extreme precipitation events are more frequent in La Niña years and less frequent in El Niño years.[43] The frequency and intensity of large El Niño and La Niña events is projected to increase bringing more extreme weather to Hawaiʻi and Kauaʻi.[44]

10. **Compound Events** - The probability of compound events such as hurricanes followed by heat waves, and the co-incidence of intense rain-king tide-and large swell are increasing.[45]

11. **Heat** - Human communities globally are experiencing increased heat stress, and extreme weather events.[46] State-wide, there has been an increase in air temperature with growth in record-setting hot days, rising urban heat, increased general heat stress, and increases in compound heat and humidity.[47]

12. **Winds** - The frequency of Hawaiian northeast trade wind days has decreased, and the frequency of east trade winds has increased.[48] Changes in wind direction from NE to E bring warmer air than in the past and interact with ridgelines in ways that reduce precipitation.[49]

13. **Wildfire** – Wildfire frequency & size has increased,[50] often related to invasive grasses that act as tinder and fuel.[51]

14. **Ecosystems** - Land and ocean *ecosystem* impacts associated with changes in precipitation, water availability, ambient temperature, ocean acidification and sea surface warming, extreme events, disease, and recovery time are numerous and widespread.[52]

Table ES-1 provides a list of key observed and projected climate change hazards and threats to Kauaʻi.

---

[42] Sharmila, S., and Walsh, K.J.E. (2018) Recent poleward shift of tropical cyclone formation linked to Hadley cell expansion. *Nature Clim Change* 8, 730–736. https://doi.org/10.1038/s41558-018-0227-5
[42] Kossin, J.P., *et al.* (2020) Global increase in major tropical cyclone exceedance probability over the past four decades. *PNAS*, DOI: 10.1073/pnas.1920849117
[43] Chen, Y. R., P.-S. Chu (2014)
[44] Cai, W., *et al.* (2014) Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change*. 5(2): 1–6.
[45] December 6, 2021: National Weather Service, https://twitter.com/WMO/status/1468530412163149824
[46] IPCC, 2021, SPM
[47] Keener, V., *et al.* (2018)
[48] Garza, J. A., P.-S. Chu, C. W. Norton, and T. A. Schroeder (2012), Changes of the prevailing trade winds over the islands of Hawaii and the North Pacific, J. Geophys. Res., 117, D11109, doi:10.1029/2011JD016888.
[49] Marra, J.J. & 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.
[50] Trauernicht, C., *et al.* (2015) The Contemporary Scale and Context of Wildfire in Hawaiʻi. Pacific Science, v. 69, no 4, October, pp. 427–444. https://doi.org/10.2984/69.4.1
[51] Trauernicht, Clay, & Elizabeth Pickett (2016) Pre-fire planning guide for resource managers and landowners in Hawaiʻi 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
[52] Keener, V., *et al.* (2018)

Table ES - 1. Historical and Expected Climate Hazards on Kaua'i

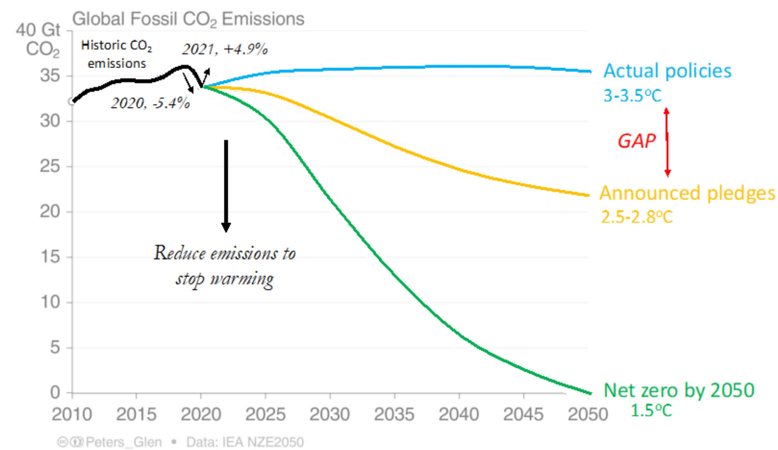
Climate Hazard	Past Trend	Future Trend	Confidence
Average Rainfall	↓ Declining (last 100 years)	↓ Decreasing wet and dry season rain	High
Heavy Rainfall Events	↑ Increasing (last 100 years)	↑ Increasing	Moderate
Drought	↑ Increasing length	↑ Increasing with changing rainfall and temperature	Moderate
Stream flow	↓ Decreasing (last 20 years)	↓ Decreasing with declining rainfall	Moderate
Wildfire	↑ Increasing (last 50 years)	↑ Increasing with changing rainfall and temperature	High
Average Temperature	↑ Increasing (last 70 years)	↑ Increasing	High
Warm Days & Nights	↑ Increasing (last 45 years)	↑ Increasing	High
Trade Winds	↓ Decreasing, turning easterly	↑ Continuing	Moderate
Sea Level Rise	↑ Increasing (last 65 years)	↑ Increasing	High
Tidal Flooding	↑ Increasing	↑ Increasing with higher SLR	High
Tropical Cyclones	↑ Increasing (last 40 years)	↑ Increasing	Moderate
Marine Heatwaves	↑ Increasing (last 40 years)	↑ Increasing	High
Global Disease	↑ Increasing (last 40 years)	↑ Increasing	High

1.2. GLOBAL PROGRESS IN MITIGATING EMISSIONS

In the 2015 Paris Climate Agreement,[53] parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreed to stop global warming before 2ºC (3.6ºF) and pursue efforts to end warming before 1.5ºC (2.7ºF). To what degree is progress being made on these goals?

- To stop warming at 1.5ºC, GHG emissions must decrease 50% by 2030, and emissions must end by 2050 (**Figure ES-3**).[54]
- Updated national pledges cut emissions only 7.5% by 2030, leaving a 34% probability of staying below 2ºC and a 1.5% probability of staying below 1.5ºC.[55]
- As of the beginning of 2022, *national pledges* under the Paris Agreement put the climate on track to warm 2.5 to 2.8ºC (4.5 to 5ºF) globally by the end of the century.[56]
- *National energy policies* put the climate on track to warm 3 to 3.5ºC (5.4 to 6.3ºF) by 2100.[57]
- On average, global GHG emissions are underreported by 23%.[58] Global emission assessments generally underestimate future temperature pathways.
- The terrestrial biome, historically responsible for sequestering over 30% of human-made CO_2 emissions, is nearing, and has already temporarily crossed, a photosynthetic maximum and is projected to grow increasingly unstable potentially losing 50% capacity as a carbon sink by 2040.[59]
- Global GHG emissions dipped 5.4% in 2020 and rebounded 4.9% in 2021, reaching 36.4 $GtCO_2$, only 0.8% below their pre-pandemic high of 36.7 $GtCO_2$ in 2019.[60]

Figure ES - 3. Global Fossil CO_2 Emissions



Global fossil CO_2 emissions and temperature projections based on national policies (blue), UNFCCC pledges (yellow), and modeled pathway to limit warming to 1.5ºC.

Source: International Energy Agency (2021)

[53] The Paris Agreement is a binding international treaty on climate change adopted by 196 Parties at COP 21 in Paris on 12 December 2015 and entered into force on 4 November 2016: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement
[54] International Energy Agency (2021) Net Zero by 2050: https://www.iea.org/reports/net-zero-by-2050
[55] Ou, Y., *et al.* (2021) Can updated climate pledges limit warming well below 2ºC? *Science*, 5Nov, v374, Iss.6568, DOI:10.1126/science.abl8976
[56] UNEP (11/4/21) Addendum to Emissions Gap Report: https://wedocs.unep.org/bitstream/handle/20.500.11822/37350/AddEGR21.pdf
[57] Ibid.
[58] Mooney, C., *et al.* (Nov. 7, 2021) Countries' climate pledges built on flawed data, Post investigation finds; Washington Post, https://www.washingtonpost.com/climate-environment/interactive/2021/greenhouse-gas-emissions-pledges-data/
[59] Duffy, K.A., *et al.* (2021) How close are we to the temperature tipping point of the terrestrial biosphere? *Science Advances*, v.7no.3, DOI: 10.1126/sciadv.aay1052
[60] Friedlingstein, P., *et al.* (2021) Global Carbon Budget 2021, *Earth Syst. Sci. Data Discuss*. [preprint], https://doi.org/10.5194/essd-2021-386, in review.

2. Kaua‘i Climate Hazards

2.1. INTRODUCTION

Scientists worked out the basic physics of Earth's climate in the 1800's[61] and made the first quantitative prediction of *global warming* in 1896[62] from the combustion of *fossil fuels* and the release of *carbon dioxide* (CO_2). Although CO_2 makes up just a small fraction of the atmosphere, it is effective at trapping some of the planet's heat before it escapes into space. This warms the air which increases *humidity*. *Water vapor* (H_2O) is even more effective at trapping heat than CO_2, leading to an *amplifying feedback* that raises Earth's surface temperature. This phenomenon has been named the *greenhouse effect*.

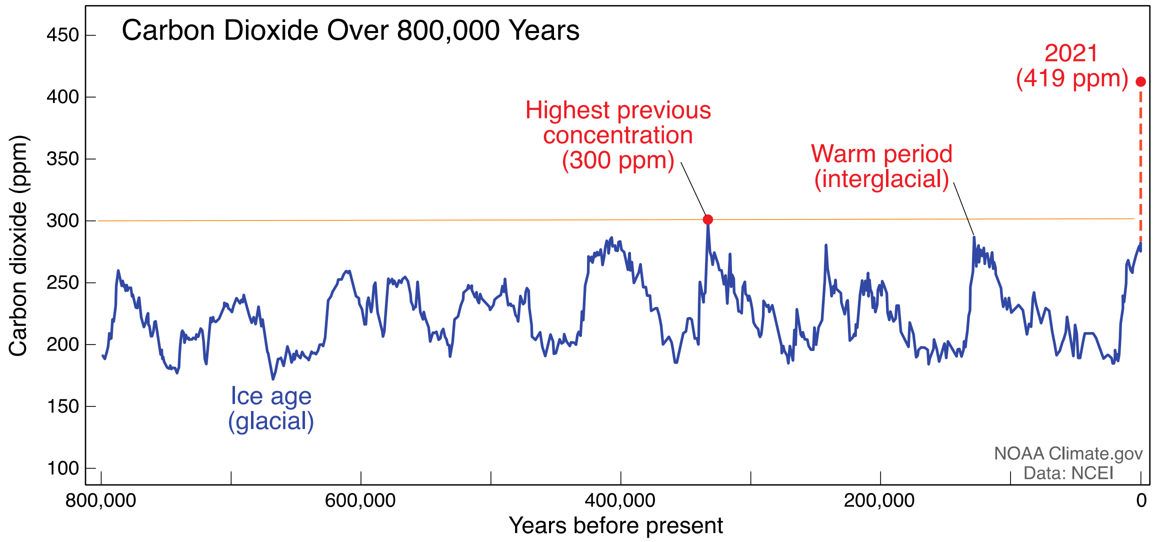
A natural greenhouse effect is why Earth, so far from the Sun, has liquid water and life, without it the average surface temperature would be below freezing and life as we know it would not be possible. During the *Industrial Revolution*, people burned increasing volumes of coal and other fossil fuels to power factories, smelters and steam engines, which added more *greenhouse gases* (GHG) to the atmosphere and increased the natural greenhouse effect. We call this enhanced effect *global warming* and the resulting impacts of global warming are called *climate change*.

For most of human history, the amount of CO_2 in the troposphere, the lowest layer of Earth's atmosphere, remained in a stable range between 260 to 280 parts per million (ppm).[63] However, during the past 200 years, increased combustion of fossil fuels, cement production, deforestation, and other human activities that produce GHG's[64] have raised the average concentration of CO_2 in the atmosphere. A record 419 ppm[65] was measured in 2021 – higher than any time in at least 800,000 years.[66] Notably, more than half of all human emissions of CO_2 have occurred since 1988, a period in which the occurrence, causes, and impacts of climate change have been widely known and understood.[67]

---

[61] Foote, E. (1856) Circumstances affecting the heat of the Sun's rays: Art. XXXI, *The American Journal of Science and Arts*, 2nd Series, v. XXII/no. LXVI, November, p. 382-383. https://ia800802.us.archive.org/4/items/mobot31753002152491/mobot31753002152491.pdf
[62] Arrhenius, S. (1896) XXXI. On the influence of carbonic acid in the air upon the temperature of the ground, *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, 41:251, 237-276, DOI: 10.1080/14786449608620846
[63] Lourantou, A., *et al.* (2010) Changes in Atmospheric CO_2 and Its C Isotopic Ratio During the Penultimate Deglaciation, 29 *QSR*,1983.
[64] Friedlingstein, P., *et al.* (2020) Global Carbon Budget 2020, *Earth Syst. Sci. Data*, 12, 3269–3340, https://doi.org/10.5194/essd-12-3269-2020
[65] NOAA Global Monitoring Laboratory (2021) Trends in Atmospheric Carbon Dioxide, https://gml.noaa.gov/ccgg/trends/weekly.html
[66] Masson-Delmotte, V., *et al.* (2013) Information from Paleoclimate Archives. In: *Climate Change 2013: The Physical Science Basis.* Contribution WG I to AR5, IPCC [Stocker, T.F., et al. (eds.)] Cambridge University Press, Cambridge, UK and New York, NY, USA.
[67] Frumhoff, P.C., *et al.* (2015) The climate responsibilities of industrial carbon producers. *Climatic Change* 132, 157–171, https://doi.org/10.1007/s10584-015-1472-5

Figure 1: CO_2 concentrations over the last 800,000 years

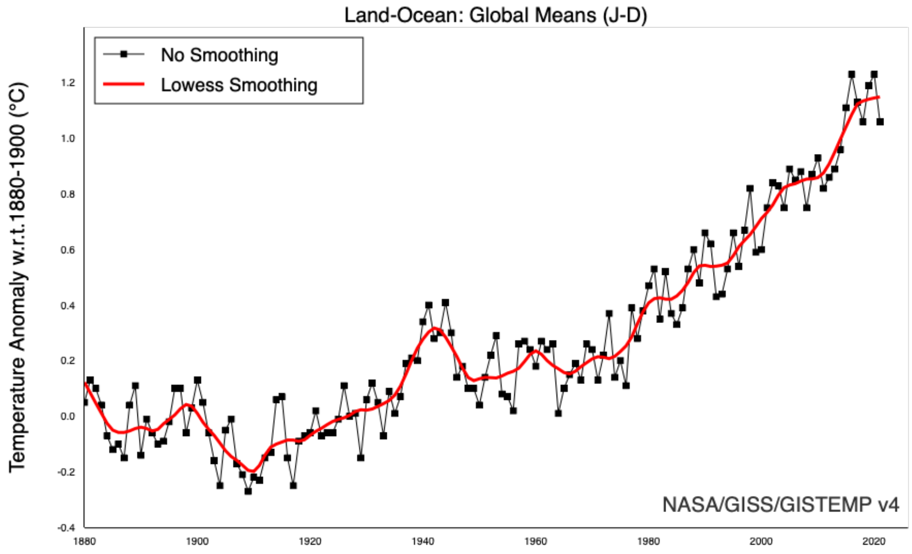


Geologic CO_2 levels from ice core data. Red Dot - peak 2021 concentration from Mauna Loa Observatory.

Source: Modified from NOAA

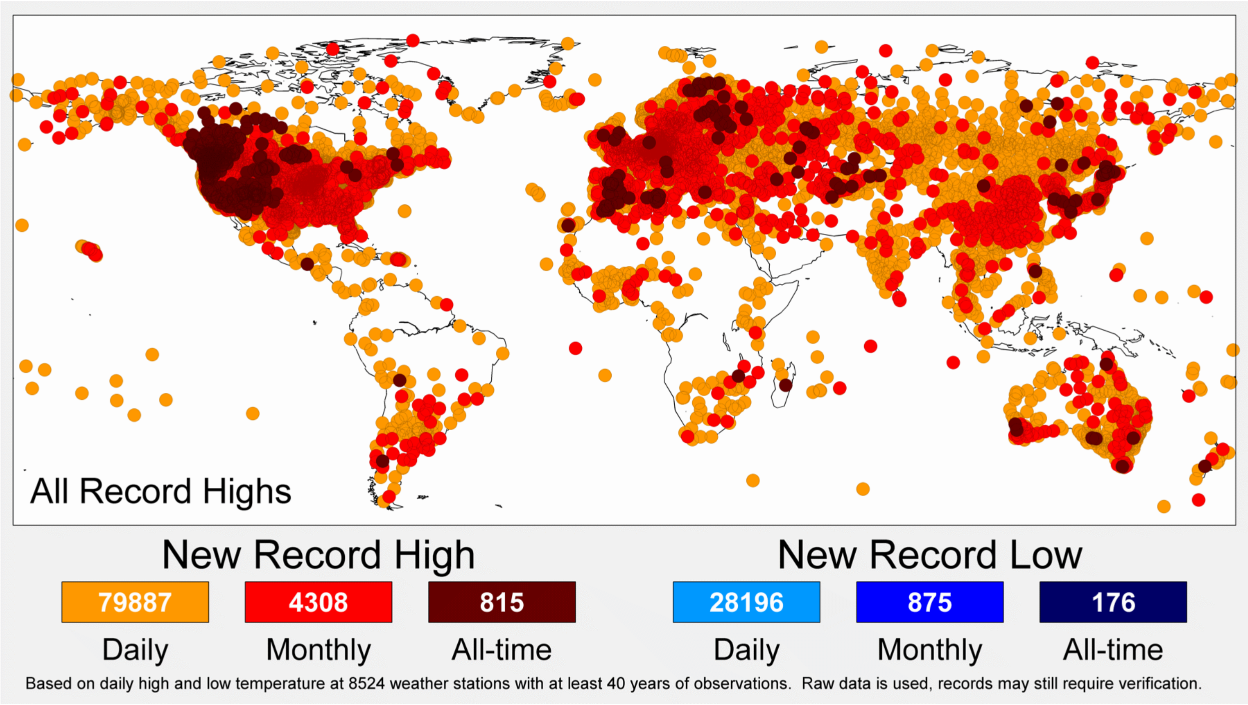
The global rise of GHG has continued to heat the planet. We know this is true thanks to an overwhelming body of evidence that begins with temperature measurements taken at weather stations and on ships starting in the mid-1800s. Now satellites and clues about climate change in geologic deposits add to the evidence. Together, these data all tell the same story: Earth's surface temperature is getting hotter (Figure 2).

Figure 2. Global Temperature since the late 1800's



Compared to the late 1800's, human GHG emissions have warmed average annual air temperature at Earth's surface 1.1 to 1.3ºC (2 to 2.3ºF).[68] Climate change is accelerating, and impacts are growing in frequency and magnitude. According to the 2021 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC),[69] it is *unequivocal* that human influence has warmed the atmosphere, ocean and land. As a result, widespread, unprecedented, and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred. Land areas have warmed more than the sea surface and the Arctic has warmed the most — by more than 2.2ºC (4ºF) just since the 1960s. Temperature extremes have also shifted. Globally all-time record high temperatures exceeded all-time record low temperatures by more than 4 to 1 in 2021 (Figure 3).[70]

Figure 3. Long-term weather stations that saw new record high temperatures in 2021.



Given weather variability, it is normal to see both new highs and new lows, but due to global warming, new highs have become significantly more common than new lows. Earth's temperature has risen by 0.08ºC (0.14ºF) per decade since 1880, and the rate of warming over the past 40 years is more than twice that: 0.18ºC (0.32ºF) per decade since 1981.[71] The past seven years have been the hottest in recorded history, and global temperatures in 2021 were among the highest ever observed, with 25 countries setting new annual records. From 1900 to 1980, a new temperature record was set on average every 13.5 years; from 1981–2019, a new record was set every 3 years.[72]

[68] NASA *2021 Tied for Sixth Warmest Year in Continued Trend, NASA Analysis Shows*, https://www.giss.nasa.gov/research/news/20220113/; See also Global Warming index, https://www.globalwarmingindex.org
[69] IPCC (2021) SPM
[70] https://twitter.com/RARohde/status/1490991224198955009.
[71] NOAA Climate Change: Global Temperature, https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature
[72] Ibid.

2.2. GLOBAL CLIMATE CHANGE IMPACTS

Raising Earth's surface temperature[73] has led to devastating consequences that threaten human habitability, especially in the tropics and the Arctic.[74] Global warming risks food[75] and water[76] availability with the global land area and human population in conditions of extreme to exceptional drought more than doubling by 2100 under a scenario of continued emissions. Climate change threatens natural ecosystems that provide life-sustaining resources,[77] human security,[78] and livable conditions for human communities.[79]

With only 1.2^oC (2.16^oF) of warming, we see nearly one-third of the world population exposed to deadly heat waves,[80] a nine-fold increase in large North American wildfires,[81] animal and plant extinctions projected to increase 2 to 5-fold in coming decades,[82] and a weakened global ecosystem,[83] described in one paper with over 15,000 co-authors, as "pushed to its breaking point."[84]

We have now increased the CO_2 level of the atmosphere by 50% compared to the eighteenth century.[85] As Earth warms, polar ice is melting faster and faster. The global nature of glacier retreat, with almost all of the world's glaciers retreating synchronously since the 1950s, is unprecedented in at least the last 2000 years.[86] This is especially true in the Arctic. Greenland has started losing ice seven times faster than it did in the 1990s,[87] and between July 30 and Aug. 2, 2019, approximately 90% of the surface of Greenland's ice sheet melted, causing about 55 billion tons of ice to melt into the ocean.[88] There is concern that with less than 0.5^oC (0.9^oF) of additional warming, melting on the Greenland ice sheet will become unstoppable.[89]

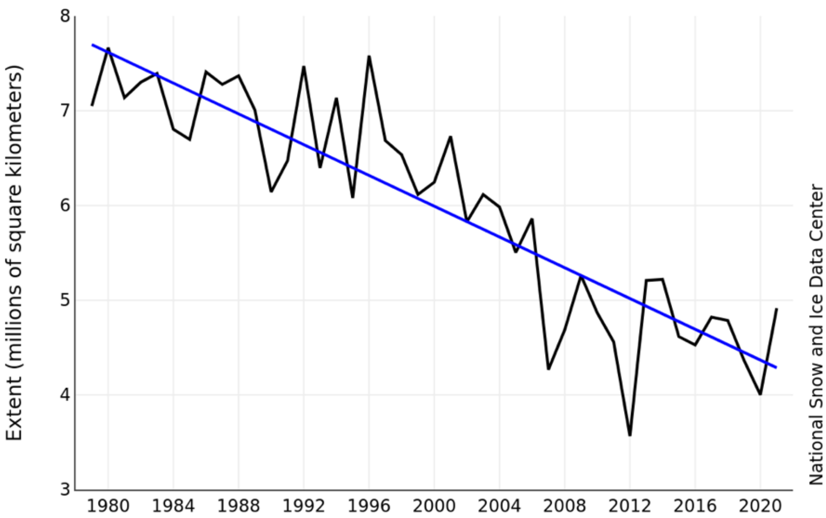
Arctic Sea ice is in free-fall (Figure 4). Sea ice is Earths refrigeration system as the white surface reflects sunlight back to space. But as the snow and ice are replaced by the dark water of the Arctic Ocean, the rate of warming in the Arctic has quadrupled compared to the rest of the planet.[90] In 1985, 33% of Arctic ice pack was

---

73 Haustein, K. *et al.* (2017) A global warming index. *Nature Scientific Reports*, doi:10.1038/s41598-017-14828-5
74 Xu, C., *et al.* (2020) Future of the human climate niche. *PNAS* May, 117 (21) 11350-11355; DOI: 10.1073/pnas.1910114117
75 Belay, T. (2021) Impact of Climate Change on Food Availability—A Review. *International Journal of Food Science and Agriculture*, 5(3), 465-470. DOI: 10.26855/ijfsa.2021.09.017
76 Pokhrel, Y., *et al.* (2021) Global terrestrial water storage and drought severity under climate change. *Nat. Clim. Chang*. 11, 226–233. https://doi.org/10.1038/s41558-020-00972-w
77 Nolan, C., *et al.* (2018) Past and future global transformation of terrestrial ecosystems under climate change. *Science*, 31 Aug., doi: 10.1126/science.aan5360
78 Brock, S., *et al.* (2021) The World Climate and Security Report 2021. Expert Group of the International Military Council on Climate and Security. Sikorsky, E. and Femia, F. (eds) Center for Climate and Security, an institute of the Council on Strategic Risks. June.
79 Clement, V., *et al.* (2021) Groundswell Part 2: Acting on Internal Climate Migration. World Bank, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/36248 License: CC BY 3.0 IGO.
80 Mora, C., *et al.* (2017) Global risk of deadly heat, *Nature Climate Change*; DOI: 10.1038/NCLIMATE332
81 Abatzoglou, J.T., Williams, A.P. (2016) Impact of Human-made climate change on wildfire across western U.S. forests. *PNAS*; 201607171 doi: 10.1073/pnas.1607171113
82 Wiens, J.J. (2016) Climate-related local extinctions are already widespread among plant and animal species, *PLOS Biology*, 14(12), e2001104, doi: 10.1371/journal.pbio.2001104
83 Diaz, S., *et al.* (2019) Pervasive human-driven decline of life on Earth points to the need for transformative change, *Science*, 13 Dec., v. 366, iss. 6471, https://doi.org/10.1126/science.aax3100
84 Ripple, W.J., *et al.* (2017) World Scientists' Warning to Humanity: A Second Notice. *BioScience*. DOI: 10.1093/biosci/bix125
85 UK MET Office (2021) https://www.metoffice.gov.uk/research/climate/ seasonal-to-decadal/long-range/forecasts/co2-forecast-for-2021
86 Ibid.
87 Shepherd, A., *et al.* (2019) Mass balance of the Greenland Ice Sheet from 1992 to 2018. *Nature*. https://doi.org/10.1038/s41586-019-1855-2
88 National Snow and Ice Data Center (2019) Europe's warm air spikes Greenland melting to record levels, http://nsidc.org/greenland-today/2019/08/europes-warm-air-spikes-greenland-melting-to-record-levels/
89 Climate tipping points—too risky to bet against Nature (2019) https://nature.com/articles/d41586-019-03595-0
90 https://agu.confex.com/agu/fm21/meetingapp.cgi/Paper/898204.

very old ice (>4 years old), by March 2019 old ice constituted only 1.2% of the ice pack in the Arctic Ocean.[91] In 2011–2020, annual average Arctic Sea ice area reached its lowest level since at least 1850.[92] Late summer Arctic Sea ice area was smaller than at any time in at least the past 1000 years.[93] Reductions in Arctic Sea ice, regional snow cover, and permafrost grow annually, and the transition from a snow- to rain-dominated Arctic in the summer and autumn may occur as early as 2040, with profound climatic, ecosystem and socio-economic impacts.[94]

Figure 4. Average Monthly Arctic Sea Ice Extent (Sept. 1979 - 2021)



September sea ice extent has declined 12.7% per decade relative to the 1981 to 2010 average. September marks the month of the largest linear trend in ice extent, both in absolute terms and percentage loss. Overall, since 1979, September has lost 3.49 million km² (1.35 million mi²) of ice, based on the linear trend values. This is equivalent to about twice the size of Alaska. *Source: Arctic Sea Ice News and Analysis (2021)*

2.2.1. Future Global Impacts

The extent and characteristics of future climate change depend in part on the amount of Human-made GHG emissions now and in the future, and on *climate feedbacks* that can either amplify (a positive feedback) or diminish (a negative feedback) the effects of GHG emissions. Reports from the IPCC have concluded that the combined effects of all feedbacks are likely to be significantly positive.[95] Additionally, scientists have expressed concern that self-reinforcing feedbacks in the climate system could push Earth toward a planetary threshold beyond which the climate cannot be stabilized at intermediate temperatures.[96]

Human emissions are driven by economic development, extractive land use, transportation and energy systems, and other social, economic, and political factors. As such, climate scientists cannot be certain how emissions and the climate will change in the future. To reduce this uncertainty, scientists use numerical models to simulate specific socio-economic futures and assess their impact on global climate processes.

[91] Perovich, D., *et al.* (2019) Sea Ice. *NOAA Arctic Report Card 2019*, J. Richter-Menge, M. L. Druckenmiller, and M. Jeffries, Eds., http://www.arctic.noaa.gov/Report-Card.
[92] IPCC (2021) SPM
[93] Ibid.
[94] McCrystall, M.R., *et al.* (2021) New climate models reveal faster and larger increases in Arctic precipitation than previously projected. *Nat Commun* 12, 6765 https://doi.org/10.1038/s41467-021-27031-y
[95] 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.
[96] Steffen, W., *et al.* (2018)

GHG Emissions

Scientists use model scenarios of socio-economic global changes up to 2100 called *shared socio-economic pathways* (SSPs). These are used to project GHG emissions under different policies and from there derive a future climate. The scenarios are: SSP1: Sustainability, SSP2: Middle of the Road, SSP3: Regional Rivalry, SSP4: Inequality, SSP5: Fossil-fueled Development. Each SSP is a logical quantitative description that relates national populations, urbanization, and per capita GDP. Each SSP explores possible future pathways of socio-economic activity, climate, policies, and other social and physical factors. The latest modeling was published in IPCC Assessment Report 6 (Figure 5).[97]

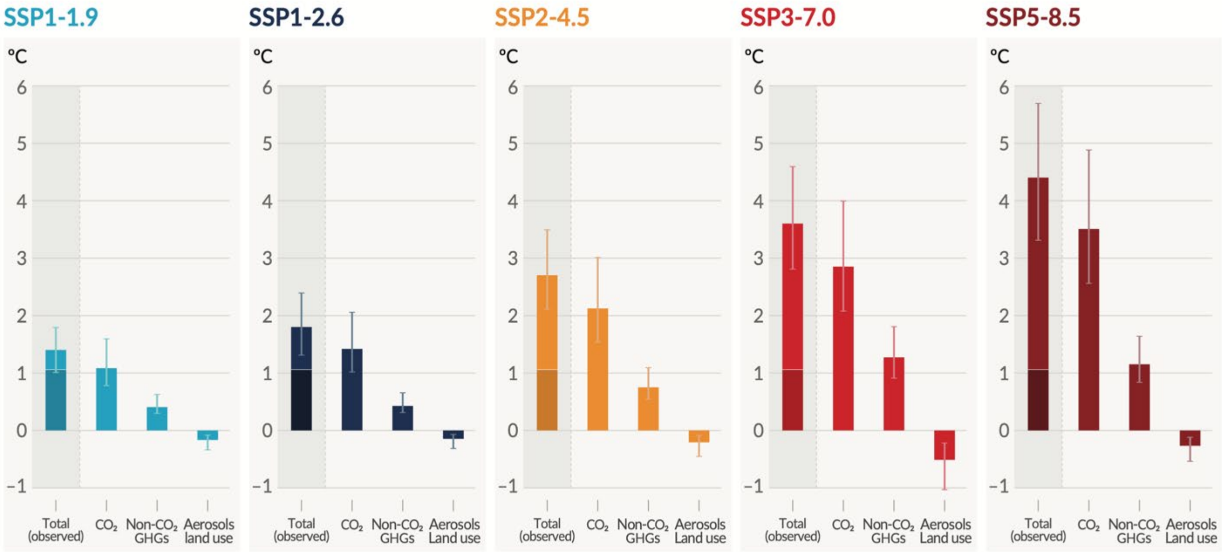


Figure 5. Warming Contributors by Groups of Human-made Drivers by SSP Scenario

Warming contributions by groups of Human-made drivers and by SSP scenario, shown as the change in global surface temperature (°C) in 2081–2100 relative to 1850–1900, with indication of the observed warming to date. Bars and whiskers represent median values and the "very likely" range, resp. Within each scenario bar plot, the bars represent: total global warming (°C, 'total' bar); warming contributions (°C) from changes in CO_2 ('CO_2' bar) and from non-CO_2 greenhouse gases (GHGs, 'non-CO_2 GHGs' bar: comprising well-mixed greenhouse gases and ozone); and net cooling from other Human-made drivers ('aerosols and land use' bar: Human-made aerosols, changes in reflectance due to land-use and irrigation changes, and contrails from aviation). The best estimate for observed warming in 2010–2019 relative to 1850–1900 is indicated in the darker column in the 'total' bar.[98] *Source: IPCC (2021)*

[97] IPCC (2021) SPM
[98] Ibid. Figure SPM.4, p. 13

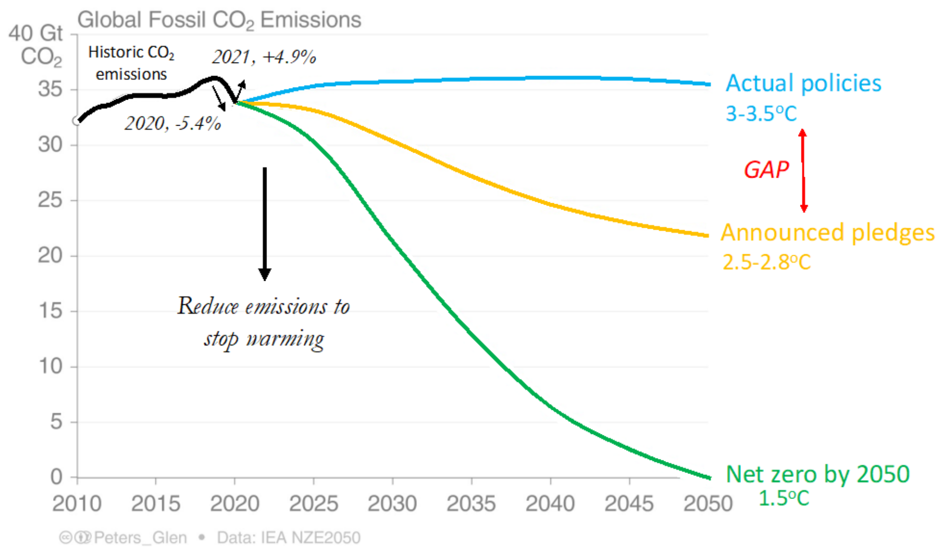
In the 2015 Paris Climate Agreement,[99] parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreed to stop global warming before 2ºC (3.6ºF), and pursue efforts to end warming before 1.5ºC (2.7ºF). In 2018, the IPCC[100] published *Global Warming of 1.5ºC*[101] from which the world learned that warming from the pre-industrial period to the present will persist for centuries to millennia with increases in severe impacts to human communities, threats to global security and world trade, increased human inequality, damage to global terrestrial and marine ecosystems, and increased extreme weather events including drought, heat waves, and flooding.

Following the 2018 report, the default target for reducing emissions became 1.5ºC (2.7ºF). What is the emissions pathway to this goal, and to what extent is progress being made?

- To stop warming at 1.5ºC, emissions must decrease 50% by 2030, and end by 2050 (Figure 6).[102]
- Updated national pledges only cut emissions 7.5% by 2030, leaving a 34% probability of staying below 2ºC and a 1.5% probability of staying below 1.5ºC.[103]
- As of the beginning of 2022, national pledges under the Paris Agreement put the climate on track to warm 2.5 to 2.8ºC (4.5 to 5ºF) globally by the end of the century.[104]
- Publicly stated energy policies put the climate on track to warm 3 to 3.5ºC (5.4 to 6.3ºF) by 2100.[105]
- On average, global emissions are underreported 23%,[106] and therefore these pledges and policies generally represent underestimates of future temperature.
- The terrestrial biome, historically responsible for sequestering about 30% of Human-made CO_2 emissions, is nearing a photosynthetic maximum and projected to grow increasingly unstable potentially losing 50% capacity as a carbon sink by 2040.[107]
- Emissions dipped 5.4% in 2020 and have rebounded 4.9% in 2021, reaching 36.4 $GtCO_2$, only 0.8% below their pre-pandemic high of 36.7 $GtCO_2$ in 2019.[108]

[99] The Paris Agreement is a binding international treaty on climate change adopted by 196 Parties at COP 21 in Paris, on 12 December 2015 and entered into force on 4 November 2016: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement
[100] The IPCC is an organization of governments that are members of the United Nations Environmental Program or the World Meteorological Organization. The IPCC has 195 members. The objective of the IPCC is to provide governments at all levels with scientific information that they can use to develop climate policies. IPCC reports are also a key input into international climate change negotiations, https://www.ipcc.ch/about/
[101] IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., et al. (eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 pp.
[102] International Energy Agency (2021) Net Zero by 2050: https://www.iea.org/reports/net-zero-by-2050
[103] Ou, Y., *et al.* (2021) Can updated climate pledges limit warming well below 2ºC? *Science*, 5Nov, v374, Iss.6568, DOI:10.1126/science.abl8976
[104] UNEP (11/4/21) Addendum to Emissions Gap Report: https://wedocs.unep.org/bitstream/handle/20.500.11822/37350/AddEGR21.pdf
[105] Ibid.
[106] Mooney, C., *et al.* (Nov. 7, 2021) Countries' climate pledges built on flawed data, Post investigation finds; Washington Post, https://www.washingtonpost.com/climate-environment/interactive/2021/greenhouse-gas-emissions-pledges-data/
[107] Duffy, K.A., *et al.* (2021) How close are we to the temperature tipping point of the terrestrial biosphere? *Science Advances*, v.7no.3, DOI: 10.1126/sciadv.aay1052
[108] Friedlingstein, P., *et al.* (2021)

Figure 6. Global Fossil CO2 Emissions



Global fossil CO_2 emissions and temperature projections based on national policies (blue), UNFCCC pledges (yellow), and modeled pathway to limit warming to 1.5°C.

Source: International Energy Agency (2021)

2.2.2. Abrupt Change and Global Context

Scientists speculate[109] that because of Human-made warming, certain aspects of future climate may be beyond our control. Some major global bio-physical systems (e.g., West Antarctic Ice Sheet and Shelves) show early indications of abrupt, potentially irreversible change that could accelerate many climate change impacts (Table 1). This would mean that, despite efforts to mitigate GHG emissions, some aspects of planetary climate change may become self-actuated and continue on their own, placing global security and socio-economic structures at risk, possibly beyond our control.[110]

According to the IPCC AR6,[111] the way that the Earth system is responding to warming is currently

> "*...proportionate to the rate of recent temperature change*", but "*...some aspects may respond disproportionately*".[112]

There is evidence of abrupt change in Earth history that was associated with significant changes in the global climate, such as deglaciations when an ice age came to an end. According to AR6

> *"Such events changed the planetary climate for tens to hundreds of thousands of years, but at a rate that is actually much slower than projected Human-made climate change over this century, even in the absence of tipping points."*

Paleoclimate evidence has fueled concern that continued emission of GHGs could tip the global climate into a permanent hot state. However, IPCC-AR6 counters this thinking

[109] Lenton, T., *et al.* (2019) Climate tipping points – too risky to bet against. *Nature*, 575, 592-595: https://doi.org/10.1038/d41586-019-03595-0
[110] Steffen, W., *et al.* (2018)
[111] IPCC (2021) SPM
[112] CarbonBrief (2021) In-depth Q&A: The IPCC's sixth assessment report on climate science, https://www.carbonbrief.org/in-depth-qa-the-ipccs-sixth-assessment-report-on-climate-science

> *"…there is no evidence of such non-linear responses at the global scale in climate projections for the next century, which indicate a near-linear dependence of global temperature on cumulative GHG emissions."*

Nonetheless, the report notes with *high confidence* that abrupt responses and tipping points in the climate system

> "*…cannot be ruled out*" and that it is *virtually certain* that "*irreversible, committed change is already underway for the slow-to-respond processes as they come into adjustment for past and present emissions*".

The report states:

> "*For global climate indicators, evidence for abrupt change is limited, but deep ocean **warming**, **acidification**, and **sea level rise** are committed to ongoing change for millennia after global surface temperatures initially stabilize and are irreversible on human time scales (very high confidence).*"

Table 1: Earth system components susceptible to abrupt change, irreversibility, and projected 21st Century change[113]

Earth System Component	Potential Abrupt Change?	Irreversibility	21st Century Change with Continued Warming
Global Monsoon	Yes w/AMOC[114] collapse, medium confidence	Reversible within years to decades, medium confidence	Medium confidence, Global monsoon increase; Asian-African strengthening & North American weakening
Tropical Forest	Yes, Low confidence	Irreversible for many decades, medium confidence	Medium confidence, Decreasing carbon storage depending on human disturbance
Boreal Forest	Yes, Low confidence	Irreversible for many decades, medium confidence	Medium confidence, Offsetting lower latitude dieback & poleward extension depending on human disturbance
Permafrost Carbon	Yes, High confidence	High confidence	Virtually certain, Decline in frozen carbon; Low confidence in net carbon change
Arctic Summer Sea Ice	No, high confidence	Reversible within years to decades, High confidence	Likely complete loss

[113] Lee, J. Y., *et al.* (2021) Future Global Climate: Scenario-Based Projections and Near-Term Information. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., et al. (eds.)]. Cambridge University Press. In Press.
[114] AMOC – Atlantic Meridional Overturning Circulation, also known as the conveyor belt current of the North Atlantic.

Arctic Winter Sea Ice	Yes, High confidence	Reversible within years to decades, High confidence	High confidence in moderate winter declines
Antarctic Sea Ice	Yes, Low confidence	Unknown, Low confidence	Low confidence in moderate winter and summer declines
Greenland Ice Sheet	No, High confidence	Irreversible for millennia, High confidence	Virtually certain mass loss under all scenarios
West Antarctic Ice Sheet and Shelves	Yes, High confidence	Irreversible for decades to millennia, High confidence	Likely mass loss under all scenarios; Deep uncertainty in projections above 3°C
Global Ocean Heat Content	No, High Confidence	Irreversible for centuries, very high confidence	Very high confidence oceans will continue to warm
Global Sea Level Rise	Yes, High confidence	Reversible within years to decades, High confidence	High confidence in moderate winter declines
Atlantic Overturning Circulation (AMOC)	Yes, Medium confidence	Reversible within centuries, High confidence	Very likely decline; Medium confidence of no collapse
Southern Overturning Circulation (MOC)	Yes, Medium confidence	Reversible within decades to centuries, Low confidence	Medium confidence in decrease in strength
Ocean Acidification	Yes, High confidence	Reversible at surface; irreversible for centuries to millennia at depth, very high confidence	Virtually certain to continue with increasing CO_2; Likely polar aragonite undersaturation
Ocean Deoxygenation	Yes, High confidence	Reversible at surface; irreversible for centuries to millennia at depth, very high confidence	Medium confidence in deoxygenation rates and increased hypoxia

2.3. CLIMATE SHOCKS AND STRESSORS

The impacts of climate change can be broadly categorized into those that happen suddenly, a *shock*, and those that happen gradually, a *stressor* (Table 2). Climate change brings to the County of Kaua'i both shocks and stressors related to an accelerated water cycle. Climate-related shocks are rapidly developing, high impact events such as hurricanes, wildfires, heat waves, and extreme rainfall. Climate-related stressors are persistent, slowly developing negative influences, such as sea level rise that exacerbates chronic coastal erosion and flooding, rising ambient heat, expanding drought, and declining rainfall.

Table 2: Climate Change Shocks & Stressors in Hawaiʻi.[115] To the extent that shocks and stresses are related, they are listed within the same row.

Shocks	Stressors
Tropical Cyclones (TC) – Rising intensity, high winds, waves, storm surge, heavy rainfall & flooding, shifting into Hawaiian waters[116]	
Extreme Rainfall and Flooding – Increasing frequency, floods & “brown water” alerts[117]	**Declining Precipitation** - Stress to aquifer recharge, watershed & forest ecology, streams & aquatic ecosystems, increasing aridity, new wildfire-prone land, Ag. impacts[118]
Drought - Temperatures are expected to increase, drought severity and frequency will increase because of increased evaporation. Already-dry, drought-prone leeward areas are projected to become drier and at high risk for future drought.	
Landslides and Rock Falls – Related to extreme rainfall and localized geology and topography[119]	**Soil Erosion** – Especially heavy rainfall events, cumulative impact to aquatic ecosystems and coastal water quality
High Winds[120] (Not TC) –Windstorms, local topography can create especially vulnerable “wind speed-up” areas[121]	**Declining Trade Winds**[122] - Poor air circulation & quality, physical discomfort, reduced renewable energy capacity
Heat Waves[123] – More days with high temperature; impacts to health, transportation, energy, agriculture, and construction sectors	**Rising Heat Stress** – Amplifies urban heat island effect, increased power demand, physical discomfort; increasing health problems with elderly, ill and young
Wildfire[124]– Burned area has increased over 4x in the past century, fire propagates rapidly in dry nonnative grasslands	**Growing Aridity** – Increasing wildfire & associated costs (personnel, air quality), impacts food production & native ecosystems
Extreme Tides – coastal erosion, increased high tide flooding, high surf, damage from tsunami & storm surge increased[125]	**Sea Level Rise & Chronic Coastal Erosion** – Rising demand for seawalls & retreat strategies, at-risk buried infrastructure, drainage failure, polluted groundwater, flooding[126]

[115] Honolulu Climate Change Commission (2020) Climate change financial risk: https://resilientoahu.org/climate-change-commission/#guidance
[116] Widlansky, M. J., *et al.* (2018) Tropical Cyclone Projections: Changing Climate Threats for Pacific Island Defense Installations. Weather, Climate, and Society, 11(1), 3–15. https://doi.org/10.1175/WCAS-D-17-0112.1
[117] Keener, V., *et al.* (2018)
[118] Ibid.
[119] Stephen D. E., *et al.* (1995) Relation of slow-moving landslides to earth materials and other factors in valleys of the Honolulu District of Oahu, Hawaii. *USGS Open-File Report 95-218*. https://pubs.usgs.gov/of/1995/0218/report.pdf
[120] https://www.staradvertiser.com/2019/02/09/breaking-news/weekend-storm-to-bring-damaging-winds-and-destructive-surf-to-hawaii/
[121] https://dod.hawaii.gov/hiema/files/2018/06/Draft-Section-4.10-High-Wind-Storms.pdf
[122] Chu, P.-S. (2002). Large-Scale Circulation Features Associated with Decadal Variations of Tropical Cyclone Activity over the Central North Pacific. *Journal of Climate*, 15(18), 2678.
[123] Keener, V., *et al.* (2018)
[124] Trauernicht, C., *et al.* (2015) Contemporary Scale and Context of Wildfire in Hawaiʻi. *Pac Sci*, 69(4), 427–444 https://doi.org/10.2984/69.4.1
[125] Keener, V., *et al.* (2018)
[126] Ibid.

Marine Heat Waves and Compound Events[127] – heat/deoxygenation/acidification, increasing frequency, regionally associated with El Niño	**Coral Bleaching** – Bleaching, reef collapse, impacts to fish & ecosystems, sea surface temperature & ocean acidification[128]
Compound Events - Tropical Cyclone + Heat Wave[129]; Tropical Cyclone + Wildfire[130] Extreme High Tide +Large Swell + Large-Scale Intense Precipitation; Multiple Large-Scale Wildfires	
El Niño (extreme) - frequency of events doubles under the 1.5^{o}C Paris target and continues to increase long after global temperatures stabilize due to emission reductions[131]	
Distant Events[132]- potential trade and supply-line interruptions with global impacts; Simultaneous Crop Failure,[133] Wheat, Maize, Soybean, Rice micronutrient losses; Saltwater flooding of major Ag areas (e.g., Mekong Delta); Blackouts at key west coast ports; Global trade reductions; Global disease	
Disease[134] - Rapidly warming climate is a threat to global public health. The risks to health of increases above 1.5°C are now well established. Indeed, no temperature rise is "safe." In the past 20 years, heat-related mortality among people over 65 years of age has increased by more than 50%. Higher temperatures have brought increased dehydration and renal function loss, dermatological malignancies, tropical infections, adverse mental health outcomes, pregnancy complications, allergies, and cardiovascular and pulmonary morbidity and mortality. Harms disproportionately affect the most vulnerable, including children, older populations, ethnic minorities, poorer communities, and those with underlying health problems	

Compound events are related to the overlap, or end to end sequencing of shocks. For example, a hurricane that produces damaging storm surge which partially incapacitates government services and exceeds the resilience capacity of local communities would be a disaster of significant scale. Potentially electrical, waste handling, freshwater, and transportation services might all become unavailable for a period of days to weeks. Because heat waves develop at the same time of the year as hurricanes, a heat wave developing in the aftermath of a hurricane constitutes a potential compound event in Hawaiʻi. In this case extreme daytime heat, in the absence of cooling evening and nightime temperatures (a projected reality[135]) can lead to mortality among the elderly, young, and ill in this compound event.

Climate impacts that affect Kauaʻi can be of distant origin, such as the simultaneous failure of two breadbaskets. The global food distribution system is sufficiently robust that a single breadbasket failure can be absorbed by its inherent resilience. However, the probability of two failures in one Northern Hemisphere summer is growing.[136] This would send shock waves across global trade with ripple effects leading to price spikes, food shortages, and enhanced potential for conflict in fragile communities. If the world continues on a

[127] Gruber, N., *et al.* (2021) Biogeochemical extremes and compound events in the ocean. *Nature* 600, 395–407, https://doi.org/10.1038/s41586-021-03981-7
[128] Ibid.
[129] Chen Y, *et al.* (2019) Half-a-degree matters for reducing and delaying global land exposure to combined daytime-nighttime hot extremes, *Earth's Future* 7 953–66
[130] Alison D. Nugent, *et al.* (2020) Fire and Rain: The Legacy of Hurricane Lane in Hawaiʻi. *Bulletin of the American Meteorological Society*; 101 (6): E954 DOI: 10.1175/BAMS-D-19-0104.1
[131] Chowdhury MR, Chu P-S. (2019) A study of the changing climate in the US-Affiliated Pacific Islands using observations and CMIP5 model output. *Meteorol Appl*.;1–14. https://doi.org/10. 1002/met.1781
[132] Gaupp, F., Hall, J., Hochrainer-Stigler, S. *et al.* (2020) Changing risks of simultaneous global breadbasket failure. Nat. Climate Change, 10, 54–57. https://doi.org/10.1038/s41558-019-0600-z
[133] Janetos, A., *et al.* (2017) The risks of multiple breadbasket failures in the 21st Century: A science research agenda, F. S. Pardee Center for the Study of the Longer-Range Future: https://www.bu.edu/pardee/files/2017/03/Multiple-Breadbasket-Failures-Pardee-Report.pdf
[134] https://www.nejm.org/doi/full/10.1056/NEJMe2113200?query=featured_home
[135] Chen Y, *et al.* (2019)
[136] Janetos, A., *et al.* (2017)

high GHG pathway that fails to hold warming to under 1.5ºC, there are almost no parts of the world where agriculture will be unaffected.[137]

2.4. CLIMATE CHANGE IMPACTS TO KAUAʻI

This review synthesizes existing scientific research relevant to developing an improved understanding of climate change hazards on Kauaʻi. However, Hawaiʻi, and Kauaʻi-specific data are limited. Thus, this is a living document that can incorporate additional data through the planning process. In addition, localized endemic knowledge can make a significant contribution to mitigation, adaptation, and sequestration efforts.

In light of the continued upward trajectory of global GHG emissions, Kauaʻi is facing unavoidable, costly, and dangerous impacts from climate change and the islands future socio-economic viability is at risk. The impacts of climate change fall disproportionately on vulnerable populations.[138] As an isolated, and remote group of islands without the capacity to exchange critical resources such as freshwater, food, or medical supplies with neighboring states, Hawai'i, and specifically Kauaʻi, are especially vulnerable to the impacts of climate change. Several major categories illustrate the breadth of risk to Hawaiʻi: Global change, Air temperature, Heat, Marine heat waves, Ocean warming and acidification, Trade winds, Drought, Wildfire, Precipitation, Streamflow, Tropical cyclones, Sea level rise, and Disease.

2.4.1. Global Change

Climate on the island of Kauaʻi is embedded in the larger Pacific and global climate systems. Changes in atmospheric circulation (e.g., the Polar Jet Stream), the ocean (e.g., North Pacific sea surface temperatures), and in bio-physical systems such as tropical forests, permafrost, and others, will be seen in varying degrees of intensity and impact, as changes in the climate on Kauaʻi as well.

For example, loss of Arctic summer sea ice drives Arctic Amplification[139] wherein the Arctic warms 4 times[140] faster than the global average. This reduces Northern Hemisphere atmospheric circulation which depends on regional differences (gradients) in temperature. The Polar Jet Stream has become unstable as a result and large southerly meanders in the jet stream may cause Kauaʻi to experience stormy weather. This is exactly the set of circumstances that occurred on December 6, 2021 when Lihue Airport recorded 8.3 cm (3.27 in) of rain, a record for that date. Figure 7 shows that a deep meander in the jet stream on that date was associated with that extreme weather event. This serves to illustrate the point that global and regional climate change can have meaningful localized impacts on the island of Kauaʻi, and Hawaiʻi in general.

---

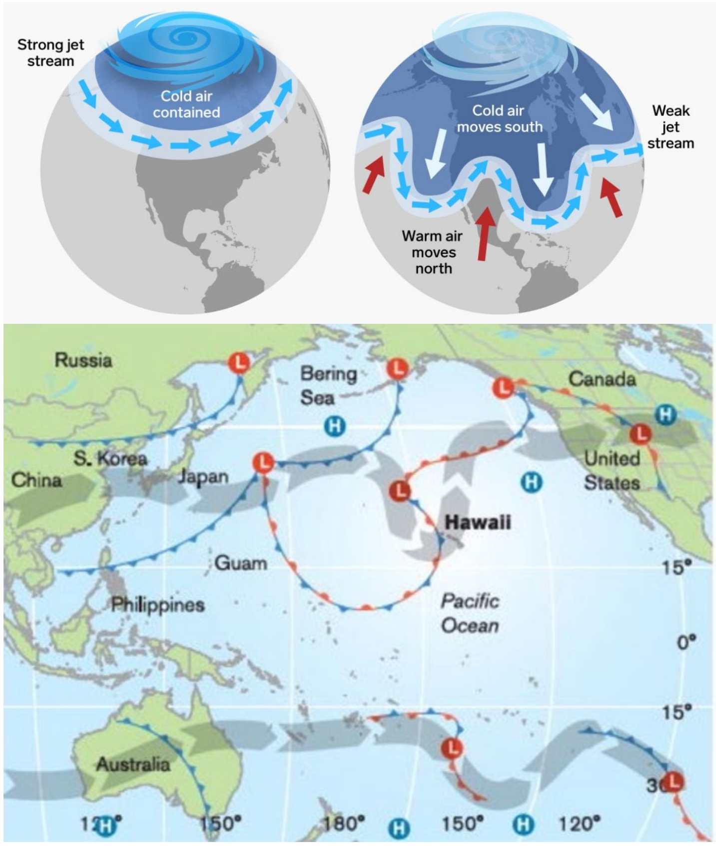
[137] Jägermeyr, J., Müller, C., Ruane, A.C. *et al.* (2021) Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nat Food* 2, 873–885. https://doi.org/10.1038/s43016-021-00400-y

[138] UN (2020) World Social Report 2020: Inequality in a Rapidly Changing World, https://www.un.org/development/desa/dspd/wp-content/uploads/sites/22/2020/01/World-Social-Report-2020-FullReport.pdf

[139] Previdi, M., *et al.* (2021) Arctic amplification of climate change: a review of underlying mechanisms, *Environmental Research Letters*, v16, n9, https://doi.org/10.1088/1748-9326/ac1c29

[140] https://public.wmo.int/en/media/press-release/wmo-recognizes-new-arctic-temperature-record-of-38ºc

Figure 7. Jet Streams and Extreme Weather Events



Top left – stable jet stream without Arctic Amplification. Top right – Unstable jet stream caused by Arctic Amplification. Bottom - Weather map December 6, 2021. A deep meander in the Polar Jet Stream (gray band) associated with record precipitation of 3.27 inches at Lihue Airport.[141] *Source: Honolulu Star Advertiser (2021)*

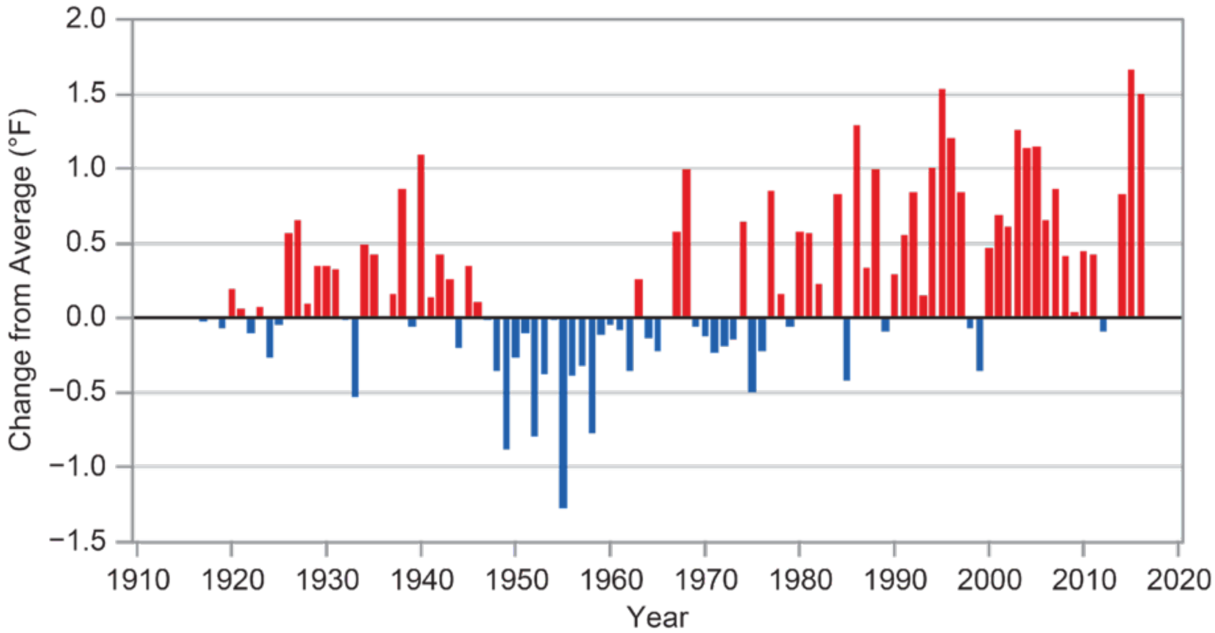
2.4.2. Air Temperature

In Hawaiʻi, the rate of air temperature increase has accelerated in recent years.[142] At a rate of 0.17°C (0.31°F) per decade, the air is warming four times faster than half a century ago.[143] Statewide, the average air temperature has risen by 0.42°C (0.76°F) over the past 100 years, and 2015 and 2016 were the warmest years on record (Figure 8).[144]

---

[141] Honolulu Star Advertiser Print Replica for December 6, 2021(A12), https://printreplica.staradvertiser.com/?token=8e39557241d765a62e7a4400521a2856
[142] Giambelluca, T.W., *et al.* (2008) Secular Temperature Changes in Hawaiʻi, *Geophysical Research Letters*, 35:L12702.
[143] Ibid.
[144] McKenzie, M.M. (2016) Regional temperature trends in Hawaiʻi: A century of change, 1916–2015 (MS thesis). Dept. of Geog., University of Hawaiʻi at Mānoa.

Figure 8. Difference in Annual Average Temperature Compared to the Average from 1944-1980 in Hawai'i



Although both warming and cooling periods have occurred, the average annual temperature change in Hawai'i over the past century shows a statistically significant warming trend. Red bars-years with above average temperatures; Blue bars-years with below average temperatures. *Source: Keener, V., et al. (2018)*

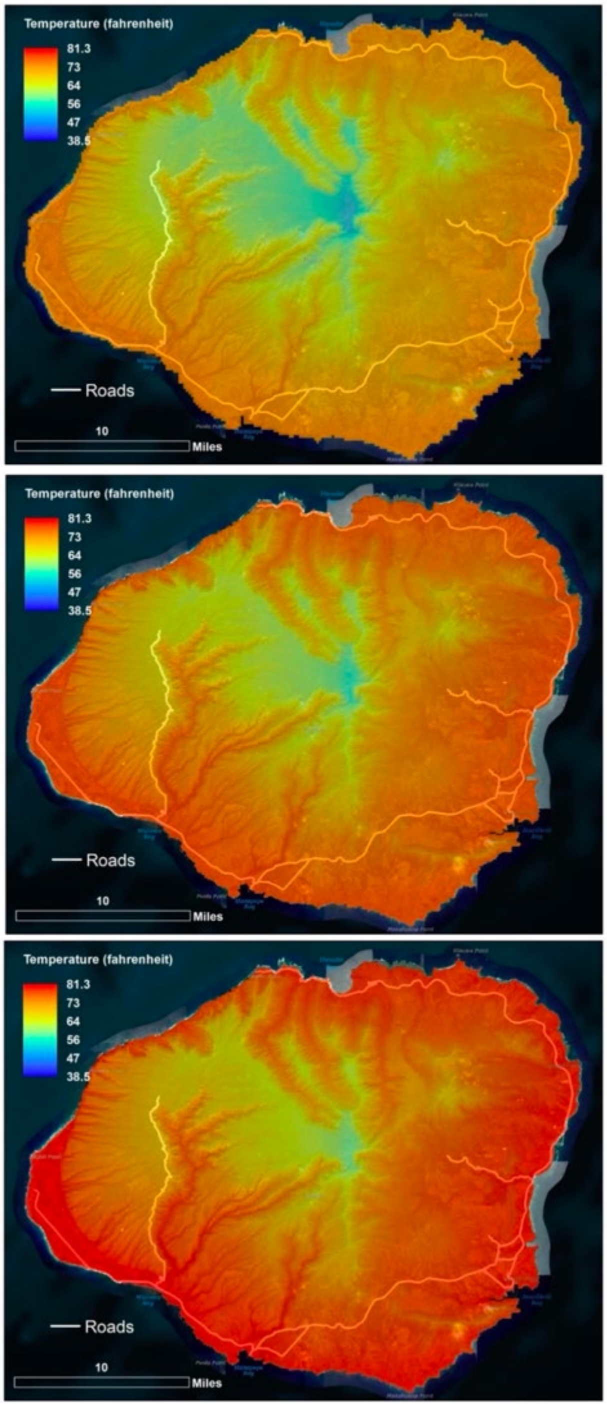
Rapidly increasing air temperature is detrimental to the delicate balance of Hawaii's ecosystems.[145] Modeling[146] results suggest that for every 1^{o}C (1.8^{o}F) temperature change projected at sea level, the high elevation zones of Kaua'i may experience 1.2^{o}C (2.16^{o}F) change near 1500 m elevation and about 1.5^{o}C (2.7^{o}F) warming at 4000 m elevation (Figure 9). Rapid warming increases thermal stress on native flora and fauna, sets the stage for increased invasive plant and animal life, increases the likelihood of wildfire, threatens human health, and impedes precipitation (the source of Hawaii's freshwater).[147]

[145] Fortini, L., *et al.* (2013) A Landscape-Based Assessment of Climate Change Vulnerability for all Native Hawaiian Plants. Hawai'i Cooperative Studies Unit. University of Hawai'i at Hilo. Technical Report HCSU-044

[146] 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.

[147] University of Hawai'i Sea Grant College Program (2014) Climate Change Impacts in Hawai'i-A summary of climate change and impacts to ecosystems and communities. UNIHI-SEAGRANT-TT-12-04.

Figure 9. Mean Annual Temperature Values for Kauaʻi



Historical

Mid-Century

End-of-Century

Downscaled 97.5th percentile ensemble mean temperature changes (°C) for RCP 8.5[148] scenario. The highest mountain elevations warm by a factor 1.5±0.2 compared to the surface temperature at sea level. In scenario RCP 8.5, high elevations above 3000 m reach up to 4–5 °C (7.2–9 °F) warmer temperatures by the late 21st century.

Source: Hawaii Highways, Climate Adaptation Plan, Exposure Assessments (April, 2021) based on projections by Timm, O.E. (2017)

---

[148] RCP or Representative Concentration Pathway, is a GHG concentration trajectory adopted by the IPCC and used in projecting future climate change. Four RCPs were modeled in the IPCC 5th Assessment Report (2014). Their use has been continued and expanded in SSP models used in the IPCC 6th Assessment Report (2021). The RCPs describe possible climate futures depending on the volume of GHGs emitted in the years to come. The RCPs – originally RCP 2.6, RCP 4.5, RCP 6, and RCP 8.5 – are labelled after radiative forcing (net heating) values in the year 2100 (2.6, 4.5, 6, and 8.5 W/m^2, resp.). RCP 8.5 is now considered unlikely given the rapid deployment of renewable technologies that have replaced traditional fossil fuels, but still possible as feedbacks are not well understood.

As air temperature rises, the impact of El Niño events also grows. During the strong El Niño of 2015/16, where Honolulu experienced 11 days of record heat,[149] the local energy utility was compelled to issue emergency public service announcements asking residents and businesses to curtail escalating use of air conditioning that stressed the electrical grid.[150] El Niño years affect Hawai'i specifically by hosting record-breaking hot windless days, intense rains, active hurricane seasons, and spikes in sea surface temperatures.[151]

Climate models project that there will be increasing frequency and strength of El Niño[152] and La Niña[153] events as a result of continued warming in the 21st Century. Strong El Niño events are associated with extreme rainfall and flooding, drought, high heat, extreme tides, active hurricane seasons, high sea surface temperatures and coral bleaching, extraordinary high waves on north-facing shores, and compound events such as intense rain at high tide which lead to urban flooding (Figure 10).

Figure 10. Compound flooding – king tide, intense rain, El Niño 2015

El Niño and La Niña years tend to have episodes of intense rainfall. When these occur in urban settings during high tide, flooding is likely. *Source: Honolulu Star Advertiser*

[149] New York Times https://www.nytimes.com/interactive/2016/02/19/us/ 2015-year-in-weather-temperature-precipitation.html# honolulu_hi.
[150] http://www.hawaiinewsnow.com/story/26551141/hawaiian-electric-asks-oahu-customers-to-conserve-power-tonight
[151] Keener, V., *et al.* (2018)
[152] 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.
[153] Cai, W., *et al.* (2015)

Models project a near doubling in the frequency of future extreme La Niña events, from once every 23 years to once every 13 years.[154] 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.

2.4.3. Heat

Records were set across Hawai'i in the summer of 2019.[155] At Lihue, temperatures of 32.8°C (91°F) on August 25 and 31 tied the all-time record high previously set on seven other occasions (twice in July 1918, once in September 1936, and once each in October 1926, 1930, and 2012). The average temperature for August, 28.6°C (83.5°F) made it the warmest single month on record (previously 28.2°C [82.7°F] in August 2017) and of the 92 days of summer (June 1-Aug. 31), a total of 31 days set or tied daily record highs. An amazing 21 of these were in August alone, which may itself be a record for so many daily heat records in a single month at any site in the U.S. with a long period of record.

A total of 33 daily max/min records were set that summer in Lihue, including all-time record-warm minima of 27.2°C (81°F) on Aug. 3, 12, 21, and 24 (beating 26.7°C [80°F] from multiple previous occasions). As of September 9, every day since August 24 had either broken or tied the site's daily record high, 17 consecutive days. Weather experts comment that for a site with a period of record since 1905, that level of persistent warmth is astonishing.[156] Furthermore, five consecutive days of the all-time record of 32.8°C (91°F) were measured on September 4-8.

Of four long-running weather monitoring stations in Hawai'i, three saw their warmest summer on record. Only Hilo, did not. In Lihue, Aug 24 to Sept 12 set daily heat records. In July, Aug, and Sept, 48 days set record highs, 44 nights set record high lows, and zero days or nights set record lows. Over 300 records were tied or broken in 2019. Only 5 of these were for record lows, revealing a strong warming shift in median temperature across Hawai'i. The likely cause, a record-setting marine heat wave, was the result of weak atmospheric circulation that produced very calm wind patterns.[157]

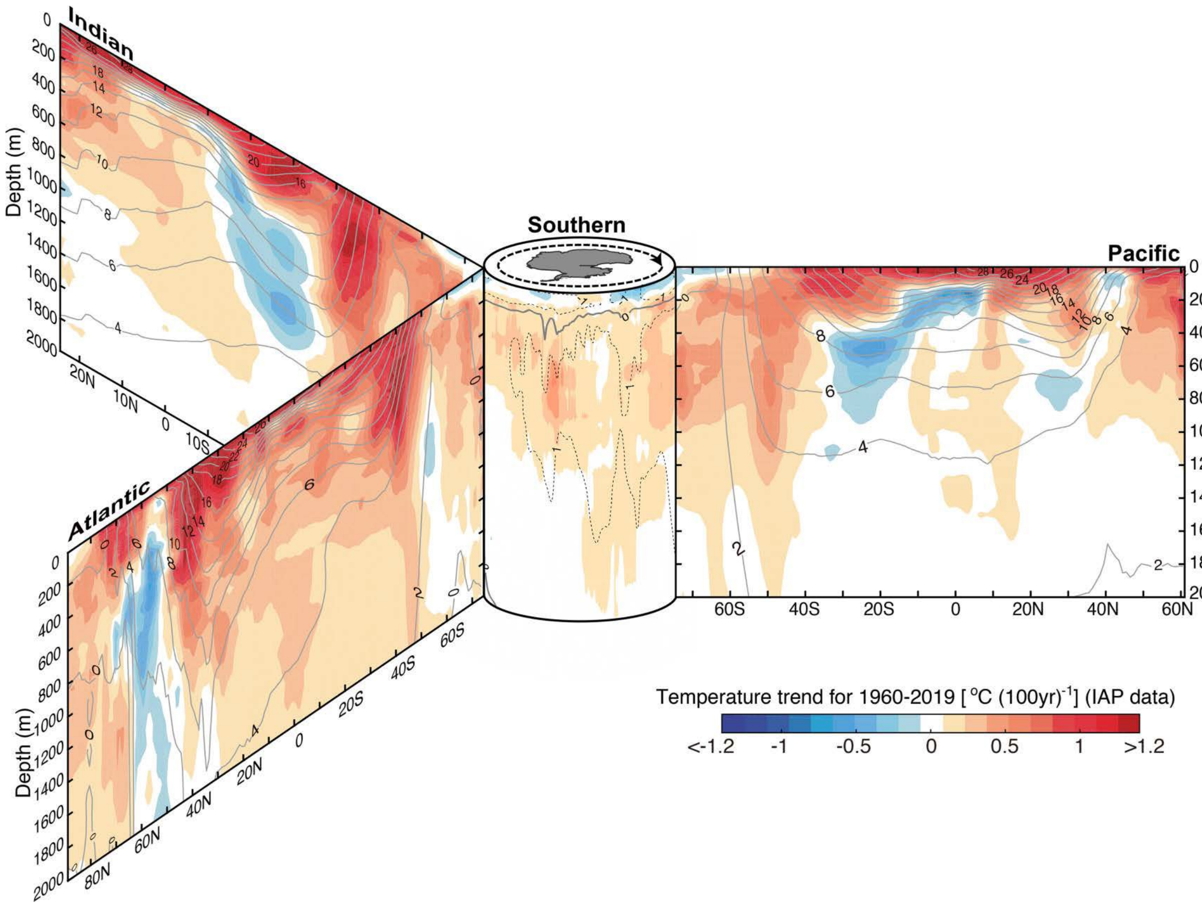
2.4.4. Marine Heat Waves

Ocean waters were abnormally warm in 2019 (Figure 11).[158] August 2019 was the warmest month for global ocean water temperatures on record, with records to 1854. 2019 also saw the weakest North Pacific atmospheric circulation patterns in at least the last 40 years.[159] 2019 was the warmest year for global ocean water temperatures on record.

---

[154] Ibid.
[155] 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
[156] Wunderground.com (September 10, 2019) Hawaii's warmest summer on record, https://www.wunderground.com/cat6/Hawaiis-Warmest-Summer-Record-and-Alaskas-Second-Warmest
[157] 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
[158] Cheng, L., *et al.* (2020) Record-Setting Ocean Warmth Continued in 2019. *Adv. Atmos. Sci*. 37, 137–142. https://doi.org/10.1007/s00376-020-9283-7
[159] Amaya, D.J., *et al.* (2020)

Figure 11. Ocean Temperature Trends from the Sea Surface to 2000 m 1960-2019



Shown are the zonal (E-W) mean sections in each ocean basin organized around the Southern Ocean (south of 60°S) in the center. Black contours show mean temperature with intervals of 2°C (3.6°F) (in the Southern Ocean, 1°C (1.8°F) intervals are provided in dashed contours). *Source: Cheng, L., et al. (2020)*

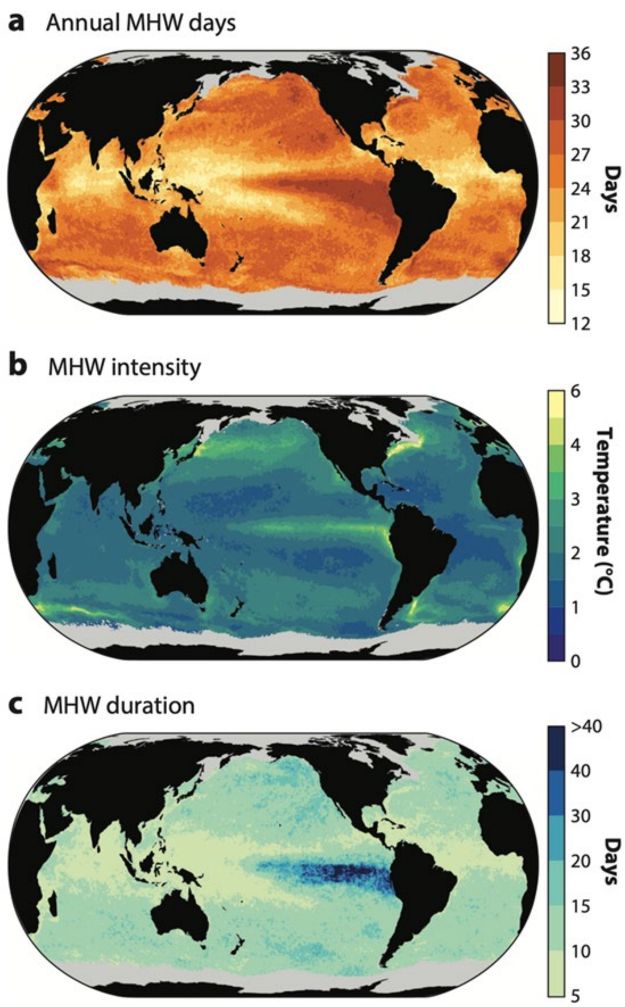
The record setting air temperatures in Hawaiʻi during the summer of 2019 were caused by a marine heatwave located in regional Hawaiian waters. A marine heatwave is a short period of abnormally high sea surface temperatures. Marine heatwaves are caused by a variety of factors and have been associated with severe biodiversity changes such as sea star wasting disease, toxic algal blooms, and mass mortality of benthic communities.[160] Marine heatwaves can be caused by a whole range of factors, and not all factors are important for each event. The most common drivers of marine heatwaves include ocean currents which can build up areas of warm water and air-sea heat flux, or warming through the ocean surface from the atmosphere.

---

160 Oliver, E.C.J., *et al.* (2021) Marine Heatwaves, *Annual Review of Marine Science*, 13:1, 313-342, https://www.annualreviews.org/doi/pdf/10.1146/annurev-marine-032720-095144

Studies[161] find that from 1925 to 2016, global average marine heatwave frequency and duration increased by 34% and 17%, respectively, resulting in a 54% increase in annual marine heatwave days globally (Figure 12). Importantly, these trends can largely be explained by increases in mean ocean temperatures, suggesting that we can expect further increases in marine heatwave days under continued global warming.

Figure 12. Statistical Properties of Historical Marine Heatwaves



Source: Oliver, E.C.J., et al. (2021)

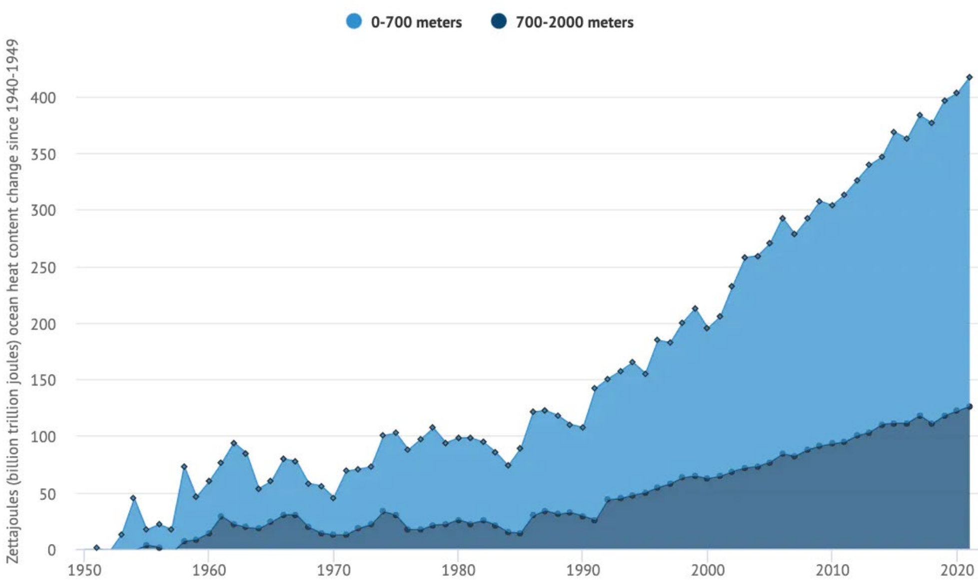
Increases in ocean temperature reduce dissolved oxygen in the ocean and significantly affect sea life, particularly corals and other temperature- and chemistry-sensitive organisms. Warming increases evaporation, and the extra moisture in the warmer atmosphere nourishes heavy rains and promotes flooding. Increased heat and evaporation leads to a more extreme hydrological cycle and more extreme weather, in particular hurricanes. The warm ocean water of 2019 is one of the key reasons why Earth experienced increasing catastrophic fires in the Amazon, California, and Australia in 2019.

[161] Oliver, E.C.J., et al. (2018) Longer and more frequent marine heatwaves over the past century. *Nat Commun* 9, 1324. https://doi.org/10.1038/s41467-018-03732-9

2.4.5. Ocean Warming and Acidification

Because of climate change, the oceans are becoming warmer and more acidic.[162] 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 1990s.[163] Globally averaged, sea surface temperatures have already increased by 1.0ºC (1.8ºF) over the past 100 years, with half of this rise occurring during the 1990s.[164] In 2021, the world ocean was the hottest ever recorded by humans (Figure 13).[165]

Figure 13. Ocean Heat Content 1950 through 2021



Annual global ocean heat content (in zettajoules – billion trillion joules, or 10^21 joules) for the 0-700 m and 700-2000 m layers. Data from Cheng et al 2021. Ocean warming is attributed to increased GHG concentrations. Ocean warming has far-reaching consequences and should be incorporated into climate risk assessments, adaptation, and mitigation. *Source: Climate Brief https://www.carbonbrief.org/state-of-the-climate-how-the-world-warmed-in-2021*

In addition to warming, an average 26% of annual Human-made CO_2 emissions are dissolved in ocean water causing ocean acidification. This is because of the chemical reaction that occurs when water bonds with CO_2. Data collected from station ALOHA regarding marine pH levels portray an 8.7% increase in ocean acidity over the past 30 years. Ocean acidification interferes with natural processes of marine organisms and ecosystems. It reduces the ability of marine organisms to build shells and other hard structures. It also contributes to coral bleaching where entire coral reefs turn white and are more vulnerable to mortality.

[162] Barton, A., *et al.* (2012) The Pacific oyster, Crassostrea gigas, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects, *Limnology and Oceanography* 57(3), 698-710.
[163] 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. Glecker, P.J., et al. (2016) Industrial era global ocean heat uptake doubles in recent decades. *Nature Climate Change*.
[164] Marra and Kruk (2017)
[165] Cheng, L., Abraham, J., Trenberth, K.E. *et al.* (2022) Another Record: Ocean Warming Continues through 2021 despite La Niña Conditions. *Adv. Atmos. Sci.*. https://doi.org/10.1007/s00376-022-1461-3

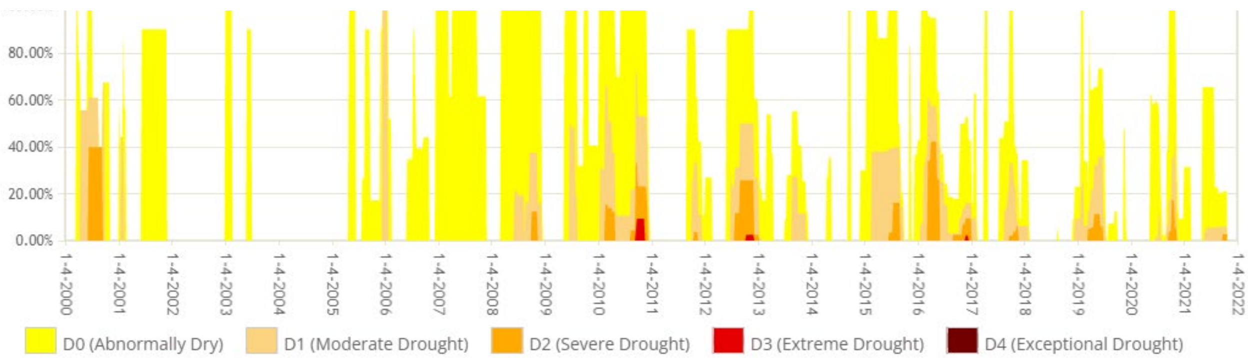
2.4.6. Trade Winds

Average daily wind speeds are declining on Kaua'i and statewide. Winds have declined regionally in the North Central Pacific but have remained steady across Western and South Pacific sites.[166] Already, trade winds interact with ridgelines in ways that produce less cloud cover and less rainfall, resulting in reduced water supply and higher water demand.[167]

2.4.7. Drought

Droughts are becoming more common in Hawai'i and on Kaua'i, with longer periods of drought experienced more recently. Continued changes in precipitation patterns (decline in rainfall, higher intensity events) may increase drought frequency, intensity, and duration. Figure 14 indicates that frequent periods of abnormally dry to severe drought characterize the past two decades.

Figure 14. Drought Severity History for Kaua'i County 2000-2022



Source: National Integrated Drought Information System

All areas on Kaua'i are susceptible to drought and the effects of heat may be worse in urban areas due to the urban heat area effect. Future temperatures in Hawai'i are expected to increase,[168] and periods of reduced cloud formation and drying are projected to become more frequent, particularly at high elevations.[169] If humidity increases, windward areas are expected to show slight increases or no changes in precipitation, while leeward areas are projected to experience significant drying.[170] Even if rainfall does not change in the future, rising temperatures will increase drought severity and frequency because of increased evaporation. Already-dry, drought-prone leeward areas are projected to become drier and at high risk for future drought.

Rainfall patterns are strongly controlled by climate variability, including the El Niño Southern Oscillation (ENSO) which consists of two modes – El Niño and La Niña. El Niño events are typically associated with drier-than-average winter wet seasons and wetter dry seasons, whereas La Niña events often result in wetter-than-

[166] Marra, J.J. & Kruk, M.C. (2017)
[167] 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.
[168] Elison Timm, O. (2017) Future warming rates over the Hawaiian Islands based on elevation-dependent scaling factors. *International Journal of Climatology*. 37(S1): 1093–1104. See also: Lauer, A., *et al.* (2013) Downscaling of climate change in the Hawaii region using CMIP5 results: on the choice of the forcing fields. *Journal of Climate*. 26(24): 10,006–10,030. See also: Zhang, C., *et al.* (2016) Dynamical downscaling of the climate for the Hawaiian Islands. Part II: Projection for the late 21st century. *Journal of Climate*. 29(23): 8333–8354.
[169] Longman, R.J., *et al.* (2015) Sustained increases in lower-tropospheric subsidence over the Central Tropical North Pacific drive a decline in high-elevation rainfall in Hawaii. *Journal of Climate*. 28(22): 8743–8759. See also: Zhang, C., et al. (2016) Dynamical downscaling of the climate for the Hawaiian Islands. Part II: Projection for the late 21st century. *Journal of Climate*. 29(23): 8333–8354.
[170] Elison Timm, O. (2017), Zhang, C., *et al.* (2016)

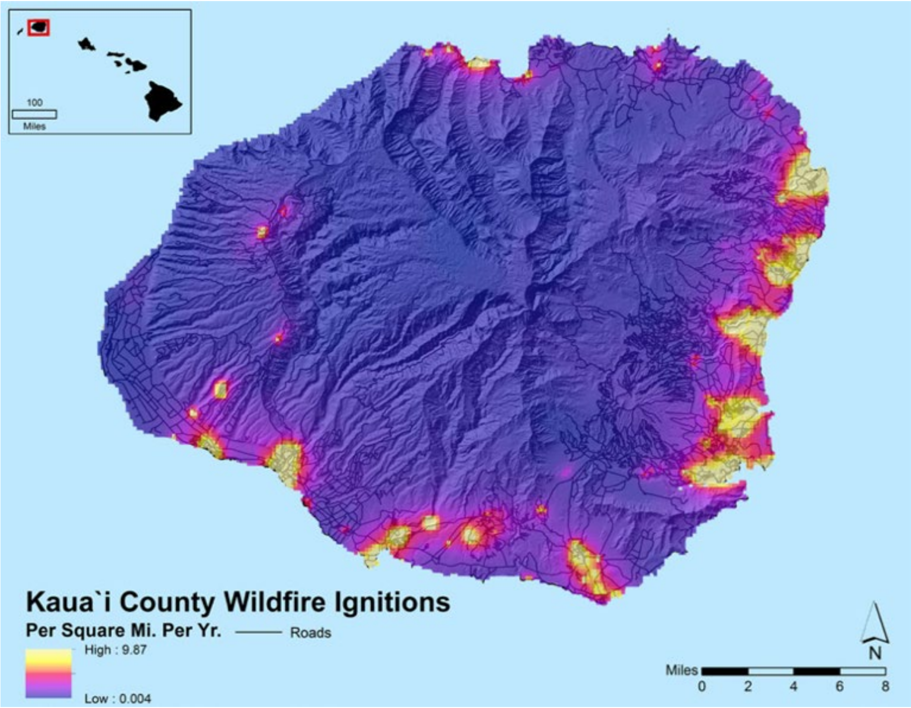
average wet seasons and drier dry seasons. The frequency of extreme El Niño events is projected to increase,[171] which will likely result in more extreme drought in the region.

2.4.8. Wildfire

Wildfire is a growing problem related to drying, invasive grasses, and human ignition.[172] Total burned area statewide has increased more than fourfold in the last century and fire propagates rapidly in dry nonnative grasslands.[173] 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 (Figure 15). Of those, 72% were accidental, which also means they're preventable.[174]

Public education on the risks of fire and how to avoid sparking a fire is an important part of the solution to wildfire. Statewide, non-native, flammable grasses and shrubland cover 25% of the total land. Effective strategy includes permanently converting flammable vegetation to something less likely to burn, such as planting trees to shade grasses out.

Figure 15. Wildfire Ignition Density



Kauaʻi County wildfire ignition density (number of ignitions per unit area) from point-based wildfire location data. The variation in ignition density over a landscape provides an illustration of where ignitions are most frequent using a straightforward, quantitative value (e.g., number of ignitions per square mile per year).
Source: Trauernicht and Lucas (2016)

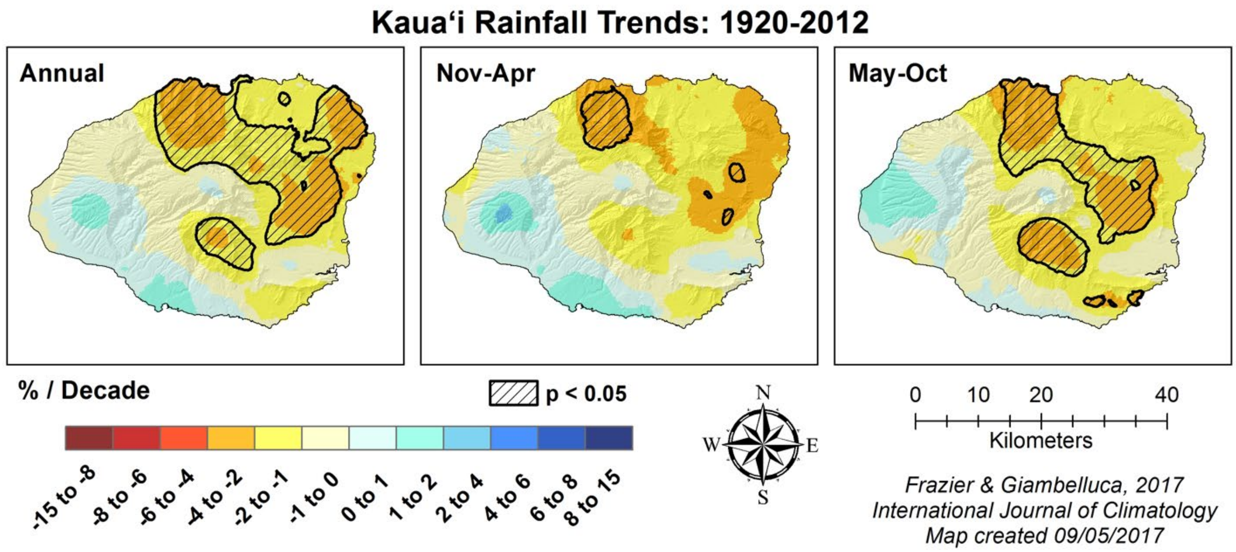
---

[171] Wang, G., *et al.* (2017) Continued increase of extreme El Niño frequency long after 1.5 °C warming stabilization. *Nature Climate Change*. 7(8): 568–572. See also Cai, W., *et al.* (2014) Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change*. 5(2): 1–6.
[172] Trauernicht, C., E. *et al.* (2015) The contemporary scale and context of wildfire in Hawaii. *Pacific Science* 69:427-444
[173] Trauernicht, C., *et al.* (2015) See also Trauernicht, C., & Elizabeth Pickett (2016) Pre-fire planning guide for resource managers and landowners in Hawaiʻi 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.
[174] Restoration of Forest Key to Fire Control, Feb. 12 (2019) https://www.hawaiiwildfire.org/news-center/tag/Maui+%28West%29

2.4.9. Precipitation

Precipitation patterns are being disturbed on Kaua'i due to climate change. Hawai'i has seen an overall decline in rainfall (Figure 16) over the past 30 years, with a particularly dry period ensuing from 2008 to present.[175] Consecutive wet days and consecutive dry days are both increasing.[176] The heavy rainfall and drought periods have intensified, increasing runoff, erosion, flooding, and water shortages.[177] On Kaua'i there have been over 81 flood events between 2005 and 2020, with especially severe flooding occurring in 2018 and 2020.

Figure 16. Annual Average Rainfall



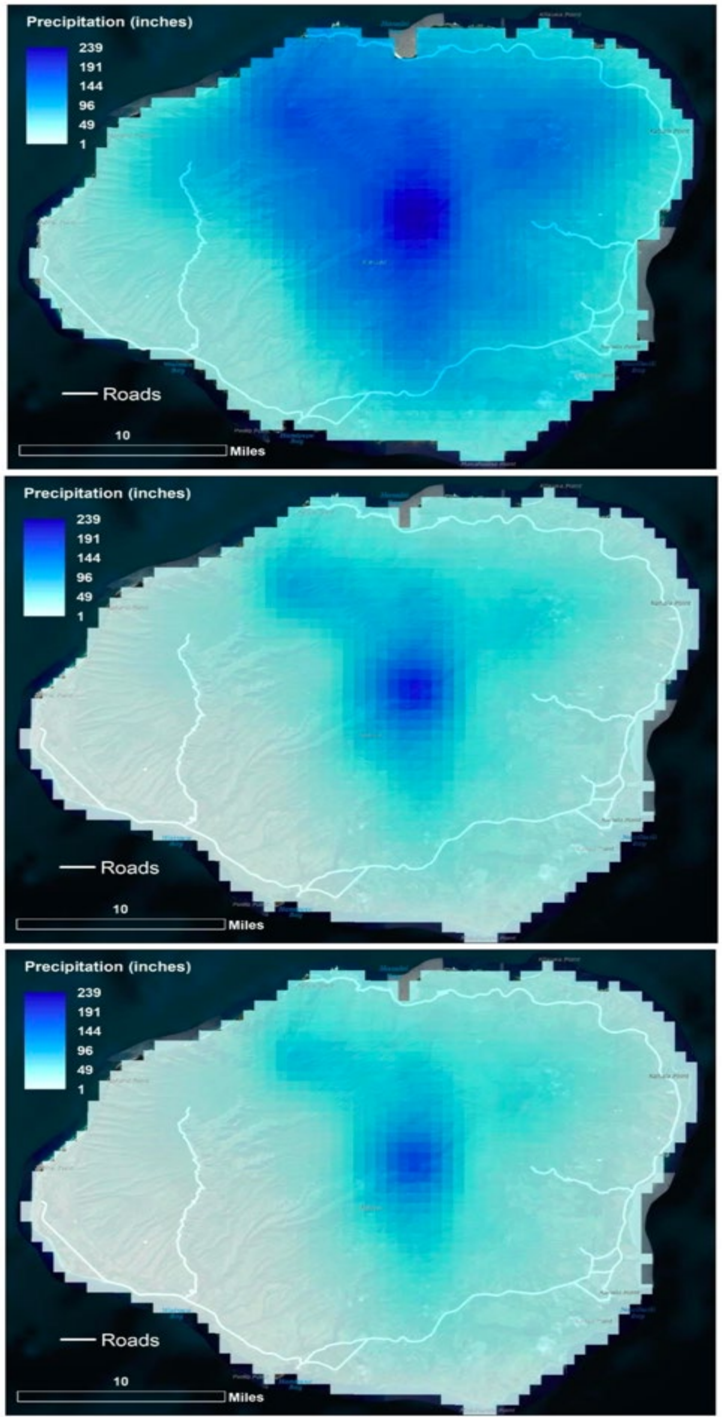
Average annual rainfall is declining on Kaua'i at a rate of about 1% per decade. (Scale- % change rainfall per decade). Source: Frazier, A. G., and Giambelluca, T. W. (2017)

Modeling does not necessarily do a good job of projecting high frequency flooding (e.g., 10-year floods). However, windward Kaua'i, where ridgelines capture trade wind moisture and form orographic clouds, may see an increase in wet season flooding with a changing climate (Figure 17). This trend could be detrimental to freshwater availability as intense precipitation is less effective at recharging aquifers than extended (less intense) wet weather. Drought, declining wet weather, and reduced recharge has also depleted stream flow, which indicates declining groundwater levels.

Kauai's water supply is mainly derived from groundwater.[178] Chronic water shortages may grow in probability as rainfall decreases and the water requirements of a growing population increase. On Kaua'i and across the state, extreme precipitation events are more frequent in La Niña years and less frequent in El Niño years.[179]

[175] Bassiouni, M., and D.S. Oki. 2013. Trends and shifts in stream flow in Hawai'i, 1913-2008. Hydrological Processes 27(10):1484-1500.
[176] Kruk, M.C., et al. (2015)
[177] Ibid.
[178] Oki, D. S., *et al.* (1999)
[179] 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.

Figure 17. Wet Season Precipitation



Historical

Mid-Century

End-of-Century

Downscaled wet season ensemble mean precipitation changes (inches) using the RCP 8.5 scenario.

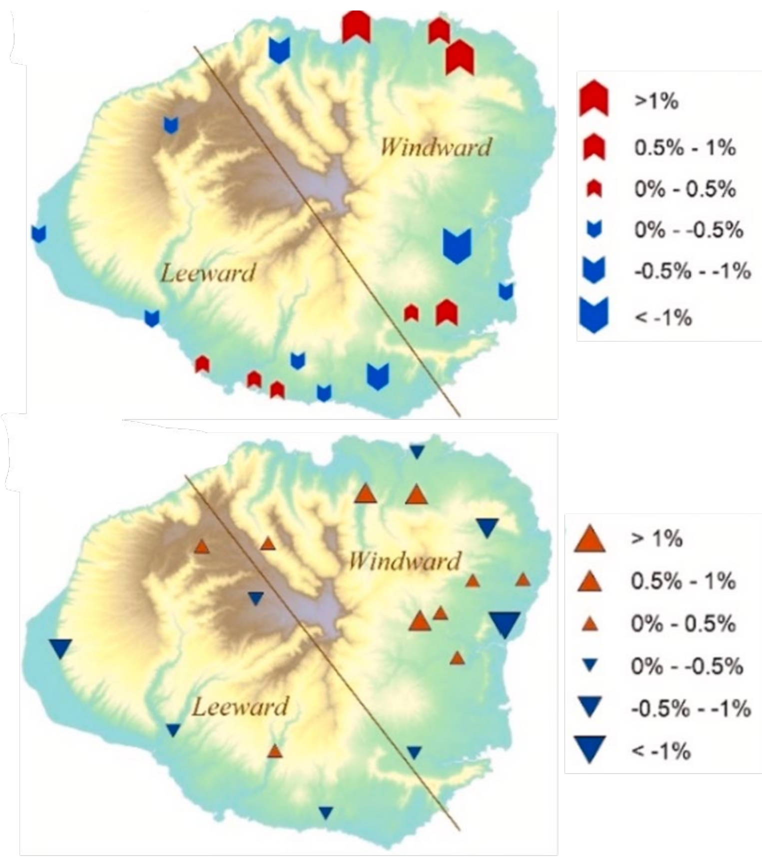
Source: Hawaii Highways, Climate Adaptation Plan, Exposure Assessments (April, 2021) based on projections by Timm, O.E. (2017)

2.4.10. Streamflow

Streamflow in Hawaiʻi has generally declined over the past century, consistent with observed decreases in rainfall.[180] Trends showing low flows becoming lower indicate declining groundwater levels. On all islands, water supply is mainly derived from groundwater.[181] If these declines continue due to further reductions in rainfall and/or increases in evaporation, groundwater availability will be impaired. Chronic water shortages are possible as rainfall decreases and both evaporation and the water requirements of a growing human population increase.

An analysis[182] of extremes in rainfall and streamflow on Kauaʻi, found that increasing trends in annual maximum daily rainfall (RFmax) were primarily located on the windward side, whereas there were no discernable differences in RFmax between leeward and windward on other Hawaiian islands. Overall (island wide), decreasing trends in RFmax dominated on Oahu, Maui, and Hawaiʻi, while no particular trend prevailed on Kauaʻi. Annual peak streamflow generally increased on the windward side of Kauaʻi, but island-wide, a decreasing trend was observed (Figure 18).

Figure 18. Trends in Precipitation and Streamflow Extremes 1970-2005

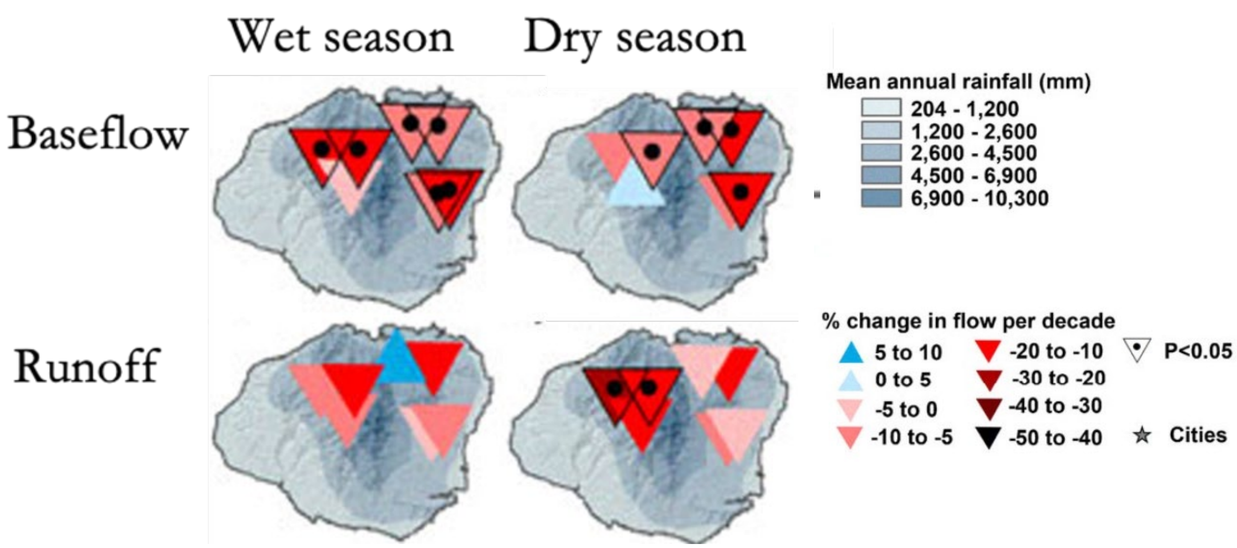


Arrows - Annual maximum daily rainfall. Triangles – Annual peak flow. Blue = decreasing trends, red = increasing trends. Brown line = physiographic division of windward (northeast) and leeward (southwest) regions. *Source: Huang, Y-F, et al. (2021)*

[180] Bassiouni, M., and D. S. Oki (2013) Trends and shifts in streamflow in Hawaiʻi, 1913–2008. *Hydrological Processes*, 27 (10), 1484–1500. doi:10.1002/hyp.9298
[181] Oki, D. S., et al. (1999)
[182] Huang, Y-F, et al. (2021) Shifting magnitude and timing of streamflow extremes and the relationship with rainfall across the Hawaiian Islands, *Journal of Hydrology*, https://doi.org/10.1016/j.jhydrol.2021.126424

Studies[183] show that streamflow has declined in association with a general drying across the islands. In particular, significant declines in low flow conditions (baseflows), were experienced in 57% of streams, compared with a significant decline in storm flow conditions for 22% of streams. Downward trends were more significant for recent decades, with an average decline in baseflow and run-off of 10.90% and 8.28% per decade, (resp.). A significant decline in dry season flows (May–October) has increased the number of no-flow days in drier areas, indicating that more streams may become intermittent. This has important implications for mauka to makai (mountain to ocean) hydrological connectivity and management of Hawai'i's native migratory freshwater fauna (Figure 19).[184]

Figure 19. Mean Annual Baseflow and Runoff Trends 1987-2016



Mean annual baseflow trends (top panels) and runoff trends (bottom panels) from 1987 to 2016 for wet season (November–April; left panels) and dry season (May–October; right panels). Trend magnitudes expressed as a percentage of the 1978–2007 reference period. Significant trends ($p < 0.05$) are highlighted with • Source: Clilverd, H.M., et al. (2019)

Climate change has fundamentally altered the water cycle in tropical islands, which is a critical driver of watershed ecologies. Natural ecosystems are the key to aquifer recharge. Indigenous vegetation that captures cloud water is responsible for nearly 40% of groundwater recharge.[185]

---

[183] Clilverd, H.M., et al. (2019) Long-term streamflow trends in Hawai'i and implications for native stream fauna, *Hydrological Processes*, v33(5), https://doi.org/10.1002/hyp.13356
[184] Ibid.
[185] Giambelluca, T.W., et al. (2013) Online Rainfall Atlas of Hawaiʻi. Bull. Amer. Meteor. Soc. 94, 313-316, doi: 10.1175/BAMS-D-11-00228.1.

2.4.11. Tropical Cyclones

The global zone of tropical cyclone (TC) formation is shifting poleward. This is linked to Hadley Cell expansion.[186] Major TC's have become 15% more likely over the past 40 years.[187] Climate models project an increase in TC's near Hawai'i.[188] A global-average migration of TC activity is taking place as storms move away from the tropics at a rate of about one degree of latitude per decade.[189] With 2°C (3.6°F) of additional warming, climate models project a 10-15% increase in the average precipitation rate within 100 km of a storm.[190] As oceans warm, there is less cold, subsurface water to serve as a braking mechanism for hurricanes.[191]

Sea level rise is causing higher coastal inundation levels for TC storm surge. The proportion of TC's reaching Category 4 and 5 levels will likely increase. Hurricanes have already become bigger and more destructive in the U.S.[192] 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. The forward speed of TC's is decreasing.[193] Model simulations suggest that future global warming could lead to a significant slowing of hurricane motion.

Sea surface temperature increase has intensified in areas of TC genesis relevant to Hawai'i suggesting a connection with strengthened storminess.[194] Increased heat and evaporation contribute to a more extreme hydrological cycle and more extreme weather, in particular hurricanes. More frequent tropical cyclones are also projected for waters near Hawai'i because of the new tracks that storms will likely follow as a result of climate change.[195] There will be an increase in average cyclone intensity (Figure 20), and in the number and occurrence days of very intense category 4 and 5 storms in most basins and in tropical cyclone precipitation rates.[196]

---

[186] Sharmila, S., and Walsh, K.J.E. (2018) Recent poleward shift of tropical cyclone formation linked to Hadley cell expansion. *Nature Clim Change* 8, 730–736. https://doi.org/10.1038/s41558-018-0227-5

[187] Kossin, J.P., *et al.* (2020) Global increase in major tropical cyclone exceedance probability over the past four decades. *PNAS*, DOI: 10.1073/pnas.1920849117

[188] 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

[189] Kossin, J., Emanuel, K. & Vecchi, G. (2014) The poleward migration of the location of tropical cyclone maximum intensity. *Nature* 509, 349–352. https://doi.org/10.1038/nature13278

[190] 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/

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

[192] 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

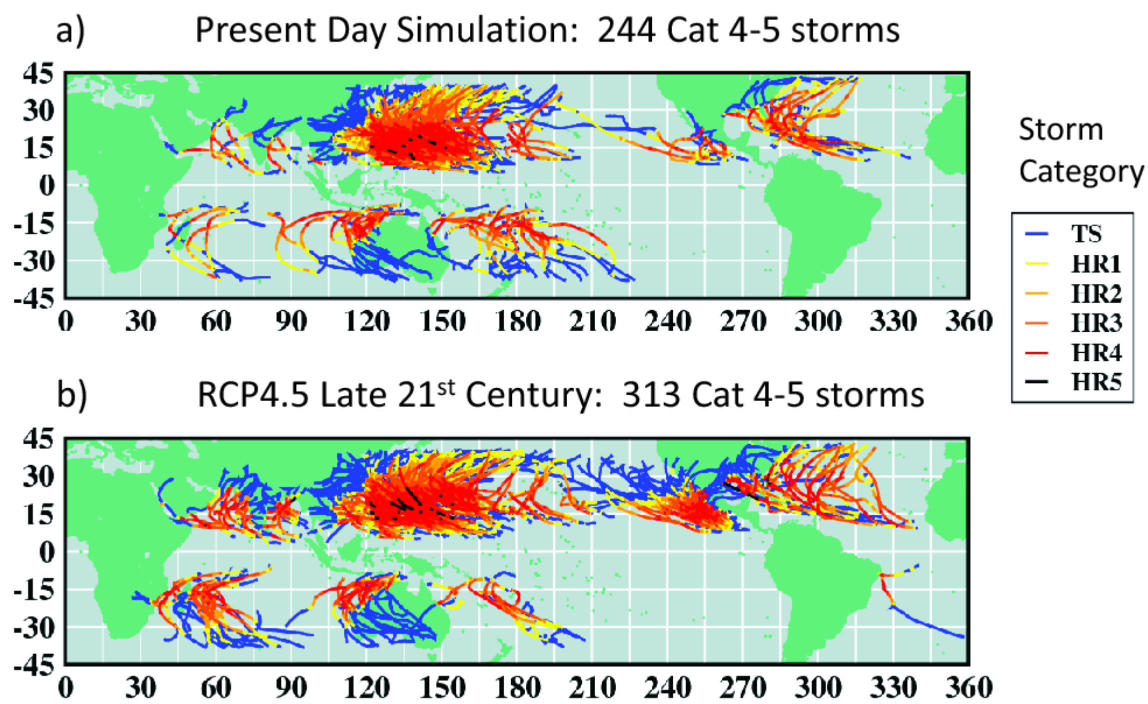
[193] Zhang, G., *et al.* (2020) Tropical Cyclone Motion in a Changing Climate, *Science Advances*, DOI: 10.1126/sciadv.aaz7610

[194] Defforge, C.L., Merlis, T.M. (2017) Observed warming trend in sea surface temperature at tropical cyclone genesis, *Geophys. Res. Lett.*, 44, 1034–1040, doi:10.1002/2016GL071045.

[195] Murakami, H., *et al.* (2013)

[196] Knutson, T., *et al.* (2020) Tropical Cyclones and Climate Change Assessment: Part II: Projected Response to Human-made Warming, *Bull. Amer. Meteor. Soc.* (2020) 101 (3): E303–E322: https://doi.org/10.1175/BAMS-D-18-0194.1

Figure 20. Simulated Cat. 4-5 Tropical Cyclone Tracks



Tracks of simulated category 4-5 tropical cyclones for (a) present-day or (b) late twenty-first century under conditions of decreasing greenhouse gas emissions in the second half of the century (RCP4.5[197]). Storm categories on the Saffir–Simpson scale are depicted by the track colors, varying from tropical storm (blue) to category 5 (black; see legend). The number and intensity of storms in Hawaiian waters significantly increases.

Source: Knutson, T.R., et al. (2015)

Tropical cyclone intensities globally will likely[198] increase. Climate models project that there will be increasing frequency and strength of El Niño[199] and La Niña[200] as a result of continued warming in the 21st Century.[201] Strong El Niño events have been associated with certain local impacts in the past: extreme rainfall and flooding, drought, high heat, extreme tides, active hurricane seasons, high sea surface temperatures and bleaching, extraordinary high waves on North-facing shores, and compound events such as intense rain at high tide which lead to urban flooding.

[197] RCP4.5 or RCP6 are more realistic modeling scenarios compared to RCP8.5 due to the accelerated deployment of renewable energy sources. See Hausfather, Z. and Peters, G.P. (2020) Emissions – the "business as usual" story is misleading. *Nature*, v577, 30 Jan., p618-620: https://doi.org/10.1038/d41586-020-00177-3

[198] The term "likely" is used to denote 66-100% likelyhood.

[199] Wang, G., *et al.* (2017) Continued increase of extreme El Niño frequency long after 1.5 °C warming stabilization. *Nature Clim Change* 7, 568–572. https://doi.org/10.1038/nclimate3351

[200] Cai, W., et al. (2015)

[201] Cai, W., et al. (2015) ENSO and greenhouse warming. *Nature Clim Change* 5, 849–859. https://doi.org/10.1038/nclimate2743

2.4.12. Sea Level Rise

Global mean sea level rise (SLR) is driven by melting of Greenland (~15.2%) and Antarctic (~9%) ice sheets, melting mountain glaciers (~19.3%), expansion of warming ocean water (~45.7%), and groundwater mining and discharge to the ocean (~10.8%).[202] Measured[203] over 28 years of global altimetry missions (1993-2021), the rate of SLR is 3.51 mm/year (1.38 in/decade). Over the past decade (2011-2021), the rate is a higher 4.43 mm/year (1.74 in/decade).

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

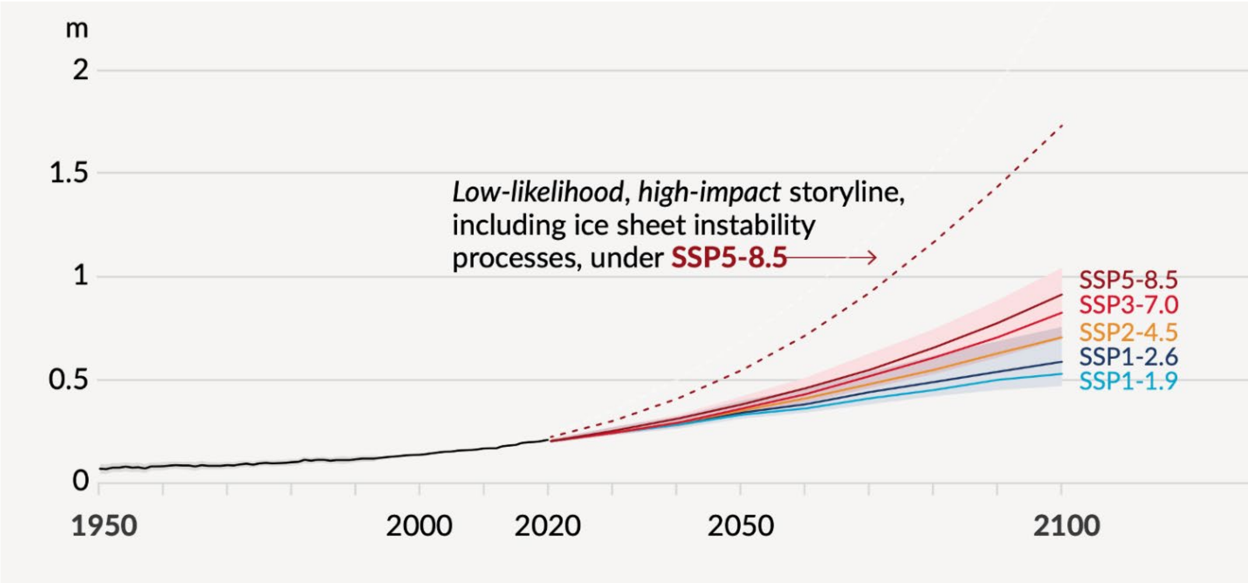
1. Low-lying coastal areas may flood by groundwater inundation before direct marine flooding;
2. Engineered drainage systems may backflow salt water onto streets as part of SLR;
3. The first evidence of SLR is coastal erosion and high tide flooding both of which have already increased on Kaua'i and elsewhere in Hawai'i;
4. Hawai'i and other tropical Pacific locations will experience amounts of SLR that are greater than the global average.

The frequency of local high tide flooding has increased from 6 to 11 days per year since the 1960's.[204] Due to global gravitational effects, estimates of future sea level rise in Hawai'i and other Pacific islands are about 20-30% higher than the global mean.[205] Modeling the statewide impacts of 0.98 m (3.2 ft) of sea level rise indicate that 25,800 acres of land will experience chronic flooding, erosion, and/or high wave runup.[206] One-third of this land is designated for urban use, and impacts include more than $19 billion in assets.

Acceleration of SLR[207] is likely to increase with continued global warming.[208] Global mean sea level is projected[209] to rise 0.44-0.76 m (1.4-2.5 ft; SSP2-4.5) to 0.63-1.01 m (2-3.3 ft; SSP5-8.5) by the end of the century (Figure 21). However, a rise approaching 2 m (6.6 ft) by 2100 and 5 m (16.4 ft) by 2150 cannot be ruled out, as there remains deep uncertainty regarding ice sheet processes.[210] Recent findings[211] suggest that the present mass loss acceleration of the Antarctic ice sheet may mark the beginning of an ice sheet retreat period that will contribute to substantial global SLR for centuries to millennia.

[202] Frederikse, T., *et al.* (2020) The causes of sea-level rise since 1900, *Nature* 584, 393–397, https://doi.org/10.1038/s41586-020-2591-3
[203] AVISO Satellite Altimetry Data, Mean Sea Level Products, https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level/data-acces.html
[204] Marra and Kruk (2017)
[205] Sweet, W.V., *et al.* (2017) Global and Regional Sea Level Rise Scenarios for the United States. NOAA Technical Report NOS CO-OPS 083. NOAA/NOS Center for Operational Oceanographic Products and Services.
[206] Hawai'i Sea Level Rise Vulnerability and Adaptation Report (2017) Tetra Tech, Inc. and the State of Hawai'i DLNR, OCCL, DLNR Contract No: 64064.
[207] Nerem, R. S. *et al.* (2018) Climate-change–driven accelerated sea-level rise detected in the altimeter era. *PNAS*, 115, 2022–2025.
[208] Dangendorf, S., *et al.* (2019) Persistent acceleration in global sea-level rise since the 1960s. *Nat. Clim. Chang*. 9, 705–710. https://doi.org/10.1038/s41558-019-0531-8
[209] IPCC (2021) SPM
[210] Ibid.
[211] Weber, M.E., *et al*. (2021) Decadal-scale onset and termination of Antarctic ice-mass loss during the last deglaciation. *Nat Commun* 12, 6683. https://doi.org/10.1038/s41467-021-27053-6

Figure 21. IPCC-AR6 Global Mean Sea Level Change (m) Relative to 1900



Historical observations from tide gauges and altimeters. Future changes projected with ice sheet, glacier, thermal expansion and Human-made use models. Likely ranges shown for SSP1-2.6 and SSP3-7.0. Dashed curve shows 83rd percentile of SSP5-8.5 projections that include low-likelihood, high-impact ice sheet processes that cannot be ruled out. *Source: IPCC (2021)*

Thwaites Glacier in West Antarctica could rapidly increase the rate of sea level rise if its floating ice shelf collapses. Several observations are especially concerning: it has doubled its outflow speed over the last 30 years, its base has eroded rapidly, new giant fractures have been observed, and researchers are concerned that part of the shelf could shatter within five years.[212] Thwaites holds enough water to raise sea level by >60 cm (2 ft) and could lead to 3 m (10 ft) of SLR if it draws surrounding glaciers with it.

Concerns that IPCC modeling focus on the low end of possible outcomes,[213] thus detracting attention from plausible high-end impacts, are consistent with observations of accelerated melting of the Greenland[214] Ice Sheet, and the West Antarctic Ice Sheet.[215] Observations[216] show accelerating ice discharge in the Amundsen Sea sector, lending further credence to concerns about multi-meter sea level rise this century.[217] Given key

[212] Giant cracks push imperiled Antarctic glacier closer to collapse (2021) https://www.nature.com/articles/d41586-021-03758-y Nature, Dec. 14.
[213] Siegert, M., et al. (2020) Twenty-first century sea-level rise could exceed IPCC projections for strong-warming futures. One Earth 3, 691–703.
[214] Aschwanden, A., et al. (2021) Brief communication: A roadmap towards credible projections of ice sheet contribution to sea-level, *The Cryosphere Discuss*. https://doi.org/10.5194/tc-2021-175
[215] DeConto, R. M., et al. (2021) The Paris Climate Agreement and future sea-level rise from Antarctica. Nature 593, 83–89.
[216] Joughin, I., et al. (2021) Ice-shelf retreat drives recent Pine Island Glacier speedup. Sci. Adv. 7.
[217] Hansen, J., et al. (2016) Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming could be dangerous. Atmos. Chem. Phys. 16, 3761–3812.

uncertainties[218] in ice sheet mass loss[219] and long-term responses to warming,[220] this issue continues to motivate coastal communities to engage in planning for unique and demanding scenarios[221] for which few professionals have formal training.[222]

The local expression of SLR can differ significantly from global mean SLR.[223] In addition to vertical land motion and spatially varying patterns of ocean heat storage, gravitational effects related to mass loss produce unique local and regional sea level deviations.[224] Additionally, present day 100-yr extreme sea level events are projected to occur at least once a year by the end of the century, even under only 1.5 °C of warming.[225]

For Kauaʻi, Table 3 provides estimates of local SLR at key milestones this century.[226]

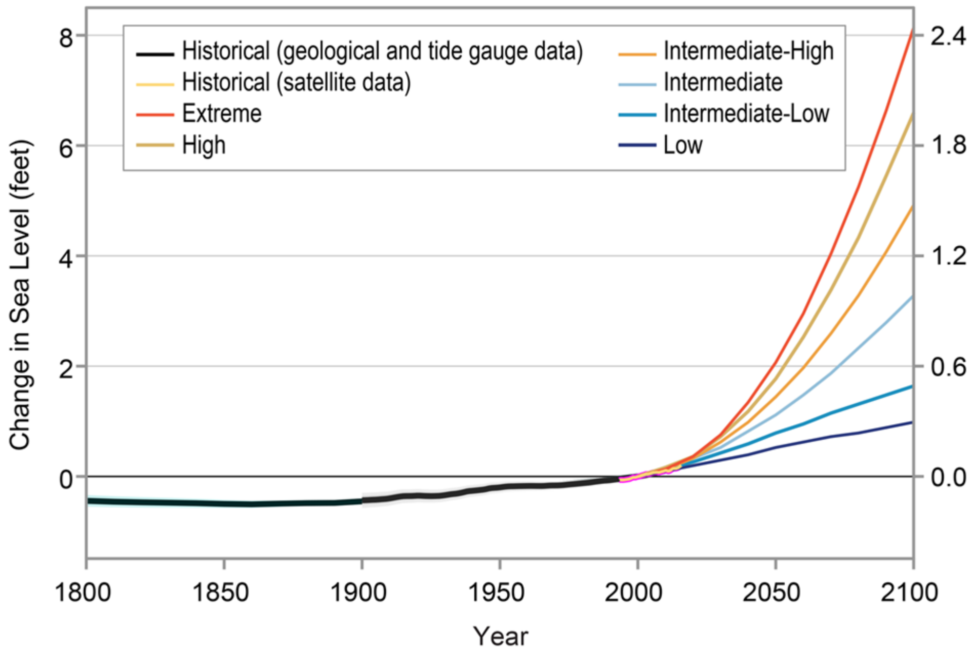
Table 3: Local SLR projections (m), Nawiliwili in the SSP5-8.5 scenario, median (17th, 83rd)

2030	2050	2090	2100
0.12 (0.08, 0.16)	0.26 (0.20, 0.35)	0.73 (0.56, 1.00)	0.89 (0.69, 1.22)

Because no single physical model accurately represents all major processes contributing to sea level rise, scenarios have been developed by NOAA for both global mean and local relative scenarios to 2100 that frame risk tolerance for use by planners (Error! Reference source not found.).[227] However, their Low and Intermediate-low scenarios are already exceeded by the observed acceleration of global SLR (0.65 ± 0.12 m).[228] Thus the Intermediate, Intermediate-high, and High relative SLR values represent more realistic scenarios for modeling impacts.

[218] Choi, Y., et al. (2021) Ice dynamics remain a primary driver of Greenland ice sheet mass loss over the next century. Commun Earth Environ 2.
[219] Pattyn, F. & Morlighem, M. (2020) The uncertain future of the Antarctic Ice Sheet. Science 367, 1331–1335.
[220] Clark, P.U. et al. (2016) Consequences of 21st century policy for multi-millennial climate & SLR change. Nature Clim Change 6, 360–369.
[221] Day, J.W., et al. (2021) Diminishing Opportunities for Sustainability of Coastal Cities in the Anthropocene: A Review. Front. Environ. Sci. 9:663275. doi: 10.3389/fenvs.2021.663275.
[222] Nicholls, RJ, et al. (2021) Integrating new sea-level scenarios into coastal risk and adaptation assessments: An ongoing process. WIREs Clim Change; 12:e706. https://doi.org/10.1002/wcc.706
[223] Kopp, R. E. et al. (2014) Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. Earth's Future 2, 383–406.
[224] Adhikari, S., et al. (2019) Sea-level fingerprints emergent from GRACE mission data. Earth Syst. Sci. Data 11, 629–646.
[225] Tebaldi, C., et al. (2021) Extreme sea levels at different global warming levels. Nat. Clim. Chang. 11, 746–751. https://doi.org/10.1038/s41558-021-01127-1
[226] Fox-Kemper, B., et al. (2021) Ocean, Cryosphere and Sea Level Change. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the 6th Assessment Report of the IPCC [Masson-Delmotte, V., et al. (eds.)]. Cambridge University Press. In press.
[227] Sweet, W.V., et al. (2017).
[228] Nerem et al. (2018)

Figure 22. Representative Global Mean SLR Scenarios (ft, left, and m, right)



Six representative global mean SLR scenarios for 2100 (6 colored lines) relative to historical geological, tide gauge and satellite altimeter reconstructions from 1800–2015 (black and magenta lines).

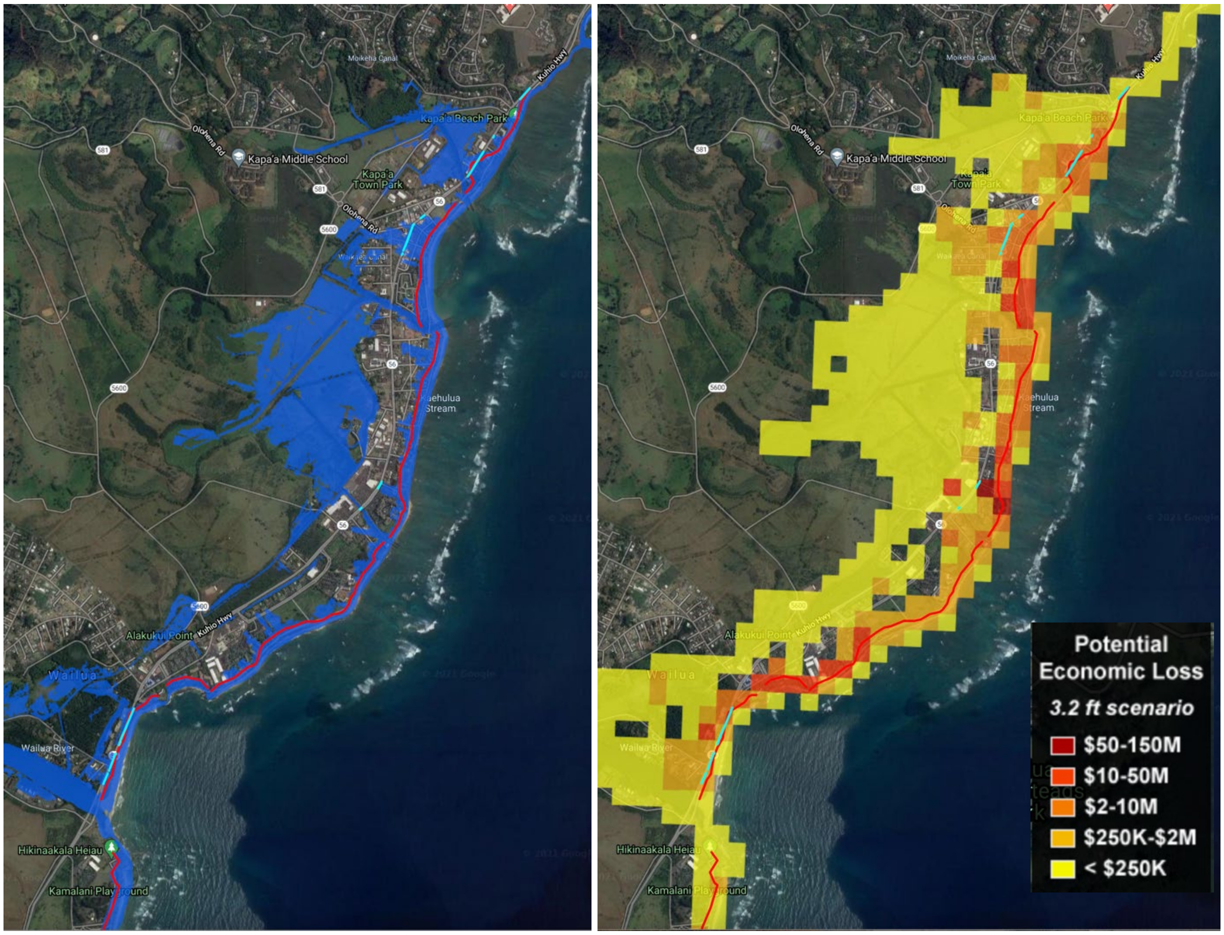
Source: Sweet et al. (2017)[229]

Low-lying elevation areas in Hawaiʻi already flood during extreme tides and are projected to worsen over the next decade.[230] High water levels develop for multiple reasons, such as when eddy-like anomalies are coincident with high background sea levels.[231] Under these conditions, there is greater exposure to seasonal wave inundation,[232] coastal erosion,[233] groundwater inundation,[234] and drainage system blockage.[235] These and other impacts can be simulated by numerical modeling. The Pacific Islands Ocean Observing System (PacIOOS) Hawaiʻi Sea Level Rise Viewer provides users with visualizations and downloadable GIS digital files showing SLR impacts including coastal erosion, hydrostatic flooding, annual wave run-up, and potential economic loss (Figure 23).[236]

---

[229] Sweet, W.V. (2017) Sea level rise. In: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., et al. (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 333-363, doi: 10.7930/J0VM49F2.
[230] Thompson, P.R., et al. (2019) A Statistical Model for Frequency of Coastal Flooding in Honolulu, Hawaii, During the 21st Century. J. Geophys. Res. Oceans 124, 2787–2802. See also Thompson, P.R. et al. (2021) Rapid increases and extreme months in projections of United States high-tide flooding. Nat. Clim. Chang. 11, 584–590.
[231] Firing, Y.L., and M.A. Merrifield (2004) Extreme sea level events at Hawaii: Influence of mesoscale eddies. Geophys. Res. Lett.,31, L24306, https://doi.org/10.1029/2004GL021539
[232] Guiles M, et al. (2019) Forecasts of Wave-Induced Coastal Hazards in the United States Pacific Islands: Past, Present, and the Future. Front. Mar. Sci. 6:170. doi: 10.3389/fmars.2019.00170
[233] Anderson, T.R., (2015) Doubling of coastal erosion under rising sea level by mid-century in Hawaii. Nat Hazards 78, 75–103.
[234] Habel, S., et al. (2019) Comparison of a simple hydrostatic and a data-intensive 3D numerical modeling method of simulating sea-level rise induced groundwater inundation for Honolulu, Hawaiʻi, USA. Environ. Res. Commun. 1, 041005.
[235] Habel, S., et al. (2020) Sea-Level Rise Induced Multi-Mechanism Flooding and Contribution to Urban Infrastructure Failure. Sci Rep 10.
[236] Anderson, T., et al. (2018) Modeling multiple sea level rise stresses reveals up to twice the land at risk compared to strictly passive flooding methods. Nature Scientific Reports 8: 14484 DOI:10.1038/s41598-018-32658-x

Figure 23. 3.2 ft SLR Impacts in Kapa'a



Left – Blue = wave and hydrostatic flooding, Red = 80%ile coastal erosion. Right – Potential economic loss. According to Table 3, under the SSP5-8.5 scenario of the IPCC 6th Assessment Report, this level of flooding is projected for the final two decades of the 21st Century. However, under the NOAA High, or Intermediate High scenarios, this flooding would occur sooner. *Source: PacIOOS Hawaii SLR Viewer*

2.4.13. Disease

In September 2021, over 200 medical journals issued a joint statement[237] that the rapidly warming climate is a threat to global public health. The editorial, published in leading journals such as *The Lancet*, *The New England Journal of Medicine* and the *British Medical Journal*, urged world leaders to cut heat-trapping emissions to avoid "catastrophic harm to health that will be impossible to reverse." The editorial continued:

> *"The risks to health of increases above 1.5 °C are now well established. Indeed, no temperature rise is "safe." In the past 20 years, heat-related mortality among people over 65 years of age has increased by more than 50%. Higher temperatures have brought increased dehydration and renal function loss, dermatological malignancies, tropical infections, adverse*

[237] https://www.nejm.org/doi/full/10.1056/NEJMe2113200?query=featured_home

mental health outcomes, pregnancy complications, allergies, and cardiovascular and pulmonary morbidity and mortality. Harms disproportionately affect the most vulnerable, including children, older populations, ethnic minorities, poorer communities, and those with underlying health problems."

The editorial not only identified the effects of climate change but also the consequences of global biodiversity loss.[238] Together, climate change and biodiversity loss constitute an environmental crisis with impacts that fall disproportionately on communities that are least responsible for the problem and least able to mitigate the harms. While wealthy nations may shield themselves from negative impacts, allowing the consequences to fall disproportionately on the most vulnerable will breed more conflict, food and water insecurity, forced displacement, and infectious disease — with severe implications for all countries and communities. As with the Covid-19 pandemic, we are globally as strong as our weakest member.

Because of climate change, expanding agriculture and population centers, mining, and other disruptions, only 15% of the planet's forests remain intact. The rest have been cut down, degraded or fragmented to the point that they disrupt the natural ecosystems that depend on them. As forests die, and grasslands and wetlands are also destroyed, biodiversity sharply decreases. The United Nations warns that the number of species on the planet has already dropped by 20% and that more than a million animal and plant species now face extinction.

Losing species has translated directly to a rise in infectious disease. As larger mammals suffer declines at the hands of hunters or loggers or shifting climate patterns, smaller species, including bats, rats, and other rodents, are thriving, either because they are more resilient to the degraded environment, or they are able to live better among people. It is these small animals, the ones that manage to find food in garbage cans or build nests in the eaves of buildings, that are proving most adaptable to human interference and happen to spread disease. Rodents alone accounted for more than 60% of all the diseases transmitted from animals to people, researchers have found.

Warmer temperatures and higher rainfall associated with climate change — coupled with the loss of predators — are bound to make the rodent problem worse, with calamitous implications. In 1999, for example, parts of Panama saw three times as much rainfall as usual. The rat population exploded, and so did the viruses rats carry, along with the chances those viruses would jump to people. That same year, a fatal lung disease transmitted through the saliva, feces and urine of rats and mice called hantavirus pulmonary syndrome emerged in Panama for the first time.

As the planet heats up, infectious diseases that were once confined to warmer latitudes are slowly expanding their range. In particular, the number of zoonotic diseases – diseases that spread from animals to humans – has skyrocketed. A new emerging disease surfaces five times a year. One study estimates that more than 3,200 strains of coronaviruses already exist among bats, awaiting an opportunity to jump to people. These diseases may have always been there, buried deep in wild and remote places out of reach of people.

Today, climate warming is driving a catastrophic loss in biodiversity that, when coupled with reckless deforestation and aggressive conversion of wildland for economic development, pushes farms and cities closer to the wild and opens the gates for the spread of disease. There are three ways climate influences emerging diseases.

---

[238] Díaz S, Settele J, Brondízio ES, *et al.* (2019) The global assessment report on biodiversity and ecosystem services: summary for policymakers. Bonn, Germany: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (https://ipbes.net/sites/default/files/2

1) Roughly 60% of new pathogens come from animals — including those pressured by diversity loss — and roughly one-third of those can be directly attributed to deforestation and habitat loss.[239]

2) Vector-borne diseases[240] — those carried by insects like mosquitoes and ticks and transferred in the blood of infected people — are also on the rise as warming weather expands climate zones into northerly regions. Ticks and mosquitoes now thrive in places they'd never ventured before. As tropical species move northward, they are bringing dangerous pathogens with them.

3) Extreme weather events including floods, wildfire, heatwaves, and others, drives animals (and their diseases) and people together in typically unsanitary conditions.[241] Making things worse, the trauma humans experience during extreme weather events can lower immunity and open vulnerabilities to pathogenic diseases.

As the global population surges to 10 billion over the next 35 years, and the capacity to farm food is stressed further again by the warming climate, the demand for land will only get more intense. Already, more than one-third of the planet's land surface, and three-quarters of all its fresh water, go toward the cultivation of crops and raising of livestock. These are the places where infectious diseases spread most often.

How does the rising risk of disease affect Kaua‘i? Climate change, rapid urbanization, deforestation, and expanding agriculture will increase the global probability of emerging diseases in coming decades (Figure 24). Disease control experts on Kaua‘i need to be aware that climate change may alter the range of pathogens, allowing infections, particularly vector-borne infections, to expand to new locations. A continued uptick in global travel, trade and mobility will transport pathogens rapidly. However, increased investment in outbreak response could help mitigate the threat from future emerging infections.

A changing world requires changing science to evaluate future risks from infectious disease. More forward-looking research, to contend with possible future outcomes, is required in addition to the retroactive analyses that typically dominate the field of epidemiology. Increasing attention needs to be paid to pathogens currently circulating in both wild and domestic animal populations, especially in cases where agriculture is expanding into native species' habitats and, conversely, invasive species are moving into populous regions due to climate change. Future research needs to align with a global view of disease risk. In an increasingly connected world, the risk from infectious disease is globally shared. The COVID-19 pandemic, including the rapid global circulation of evolved strains, highlights the need for a collaborative, worldwide framework for infectious disease research and control.[242]

---

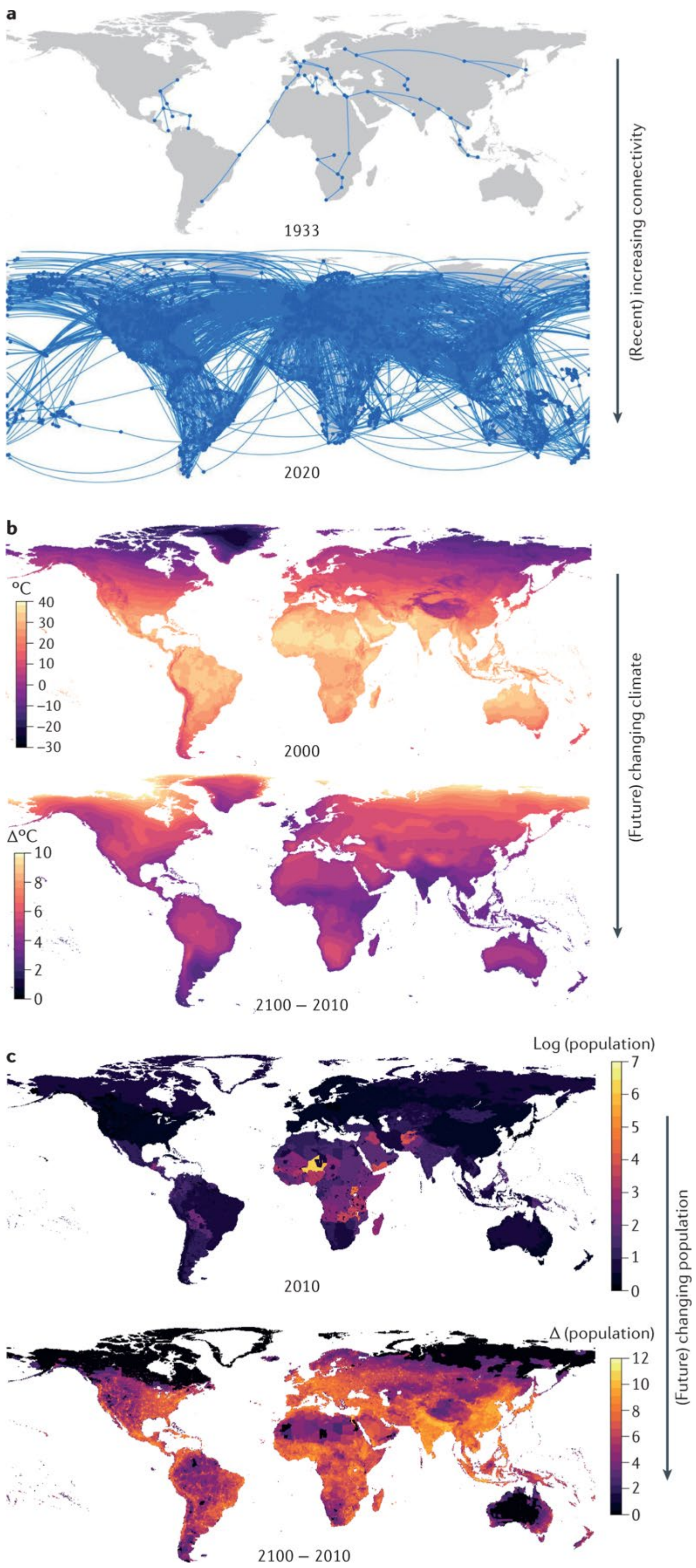
[239] Jones, K., Patel, N., Levy, M. *et al.* Global trends in emerging infectious diseases. *Nature* 451, 990–993 (2008). https://doi.org/10.1038/nature06536

[240] Ryan SJ, Carlson CJ, Mordecai EA, Johnson LR (2019) Global expansion and redistribution of *Aedes*-borne virus transmission risk with climate change. PLoS Negl Trop Dis 13(3): e0007213. https://doi.org/10.1371/journal.pntd.0007213\

[241] Garten, R., *et al.* (2018). Update: Influenza Activity in the United States During the 2017-18 Season and Composition of the 2018-19 Influenza Vaccine. *MMWR. Morbidity and mortality weekly report*, *67*(22), 634–642. https://doi.org/10.15585/mmwr.mm6722a4

[242] Baker, R.E., *et al.* (2021) Infectious disease in an era of global change. *Nat Rev Microbiol*. https://doi.org/10.1038/s41579-021-00639-z

Figure 24. Climate change and global disease transmission



Climate change and the globally connected nature of modern disease transmission. a. The global international air travel network expanded substantially from 1933 to 2020. b. Average monthly maximum temperature in 1970–2000) and difference between 2070–2100 and 1970–2000 averages (Shared Socioeconomic Pathway 3 (SSP3)). c. Population projections under SSP3 in 2010 and relative population change projected until 2100. *Source: Baker, R.E., et al. (2021)*

2.5. CONCLUSION

It is unequivocal that human influence has warmed the atmosphere, ocean, and land.[243] Hawai'i is one of the world's most vulnerable locations. Even under the most ambitious emissions reductions scenario, the world's oceans will continue to rise as the climate system comes into balance with the increase in atmospheric carbon dioxide concentration caused by Human-made combustion of fossil fuels. Studies show that with less than 1 m (3.3 ft) of sea level rise Kaua'i is exposed to severe flooding,[244] environmental loss,[245] and economic damage.[246] There is no plausible emissions reduction scenario where Kaua'i or Hawai'i at large can avoid the substantial cost of adapting to and protecting itself from rising seas, declining rainfall, increased exposure to tropical cyclones, expanding drought, record-setting heat, disease transmission, and marine devastation that result from the combustion of fossil fuels.[247]

---

[243] IPCC (2021) Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of WGI to the AR6 of the IPCC [Masson-Delmotte, V., et al. (eds.)]. Cambridge Univ. Press. In Press.
[244] Habel, S., Fletcher, C., Anderson, T., & Thompson, P. 2020. Sea-Level Rise Induced Multi-Mechanism Flooding and Contribution to Urban Infrastructure Failure. Nature Scientific Reports, 10: 3796 DOI:10.1038/s41598-020-60762-4
[245] Tavares, K., Fletcher, C.H. & Anderson, T.R. 2020. Risk of shoreline hardening and associated beach loss peaks before mid-century: O'ahu, Hawai'i. Nature Scientific Reports, 10: 13633. DOI:10.1038/s41598-020-70577-y
[246] Anderson, T., Fletcher, C., Barbee, M., Romine, B., & Lemmo, J. 2018. Modeling multiple sea level rise stresses reveals up to twice the land at risk compared to strictly passive flooding methods. Nature Scientific Reports 8: 14484 DOI:10.1038/s41598-018-32658-x
[247] Heede, R. (2020) Update Carbon Majors 1965-2018 [Press Release], Climate Accountability Institute (9 Dec.) https://climateaccountability.org/pdf/CAI%20PressRelease%20Dec20.pdf.

Appendix A: Human-made Global Warming Discussion

Humans burn coal, oil, and natural gas (collectively known as "fossil fuels") to make electricity, move vehicles, heat buildings, and for other uses. Fossil fuel burning releases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) into the air. These gases act as a partial blanket that blocks heat emitted by Earth's surface and the atmosphere, that would otherwise radiate to space. These same gases are also released by deforestation, wildfire, damming rivers, and aspects of agriculture such as manure management, soil disturbance, rice farming, livestock management, and more.

Excess heat trapped by "greenhouse gases" enhances a natural process called the "greenhouse effect."[248] Human-made pollution by greenhouse gases has raised the air temperature at Earth's surface about 1.1 to 1.3°C above the late 1800's. About 50% of the natural greenhouse effect is attributed to water vapor (H_2O), about 25% to clouds, and about 20% to CO_2.[249] Methane, nitrous oxide, other gases present in the atmosphere in small amounts also contribute to the greenhouse effect.

Water vapor and CO_2 are both powerful absorbers of heat emitted from surfaces warmed by sunlight. However, condensation and precipitation limit the residence of H_2O in the atmosphere to only 8-10 days,[250] which is too short to drive climate change. Carbon dioxide, with a longer residence time, naturally cycles between the atmosphere, the oceans, and the land biosphere. Its removal from the atmosphere involves a range of processes with different time scales.[251] About 50% of an increase in CO_2 will be removed from the atmosphere within 30 years, and a further 30% will be removed within a few centuries. The remaining 20% may stay in the atmosphere for many thousands of years.[252] Because of its long residence time, CO_2 is considered the primary driver of climate change, responsible for about 79% of Human-made global warming.[253]

The average concentration of CO_2 in the air has risen from a natural level of 277 parts per million (ppm) to 419 ppm, the highest in human history. The rate of CO_2 accumulation in the atmosphere is accelerating; it increased from less than 1 ppm per year in the 1960's to more than 2 ppm per year averaged over the past two decades. Today's rate of CO_2 release is about ten times faster than the most rapid event of any time since

---

248 The "greenhouse effect" operates as a partial blanket that blocks heat emitted by Earth's surface and the atmosphere, that would otherwise radiate to space. Much of this heat is absorbed by water vapor, including clouds, carbon dioxide and reradiated in all directions – including back to Earth, amplifying the warming already provided by the Sun. This trapped heat raises the surface temperature and warms the air. The key gases are water vapor, carbon dioxide, methane, nitrous oxide, and fluorinated gases.

249 Schmidt, G.A., et al. (2010) Attribution of the present-day total greenhouse effect, *J. Geophys. Res.*, 115, D20106, doi:10.1029/2010JD014287.

250 Gimeno, L., et al. (2021) The residence time of water vapor in the atmosphere. *Nat. Rev. Earth Environ.* 2, 558–569. https://doi.org/10.1038/s43017-021-00181-9

251 Denman, K.L., et al. (2007) Couplings Between Changes in the Climate System and Biogeochemistry (p.501). In: *Climate Change 2007: The Physical Science Basis*. Contribution of WGI to AR4 of the IPCC [Solomon, S., et al. (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.

252 Ibid.

253 Figure 7.6; Forster, P., et al. (2021) The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. 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., et al. (eds.)]. Cambridge University Press. In Press.

66 million years ago when an asteroid impact caused the extinction of the dinosaurs.[254] The last time CO_2 levels were this high, about 3 million years ago (during the Pliocene Period), Earth's climate was radically different; the global average temperature was 2 to 3°C warmer, beech trees grew near the South Pole, there was no Greenland ice sheet, no West Antarctic ice sheet, and there is evidence that global sea level was 5.6 to 19.2 meters higher than today.[255]

Because of warming, widespread and rapid changes in the atmosphere, ocean, cryosphere, and biosphere have occurred. Earth's surface is reacting to the release of Human-made CO_2 much as originally calculated by Nobel Prize winning chemist Arrhenius Svante in 1896.[256] Since those early days, an extensive body of careful observations and modeling unmistakably tells us that CO_2, and the amplifying feedbacks it generates, are raising Earth's surface temperature[257] with devastating consequences that threaten human habitability.[258] Global warming risks food[259] and water[260] availability with the global land area and human population in conditions of extreme to exceptional drought more than doubling by 2100 under a scenario of continued emissions. Climate change threatens natural ecosystems that provide life-sustaining resources,[261] human security,[262] and livable conditions for human communities.[263]

---

[254] Zeebe, R.E., et al. (2016) Human-made carbon release rate unprecedented during the past 66 million years, Nature Geoscience, doi: 10.1038/ngeo2681
[255] Dumitru, O.A., et al. (2019) Constraints on global mean sea level during Pliocene warmth. Nature, DOI: 10.1038/s41586-019-1543-2
[256] Arrhenius, S. (1896) XXXI. On the influence of carbonic acid in the air upon the temperature of the ground, The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 41:251, 237-276, DOI: 10.1080/14786449608620846
[257] Haustein, K. et al. (2017) A global warming index. Nature Scientific Reports, doi:10.1038/s41598-017-14828-5
[258] Xu, C., et al. (2020) Future of the human climate niche. PNAS May, 117 (21) 11350-11355; DOI: 10.1073/pnas.1910114117
[259] Belay, T. (2021) Impact of Climate Change on Food Availability—A Review. International Journal of Food Science and Agriculture, 5(3), 465-470. DOI: 10.26855/ijfsa.2021.09.017
[260] Pokhrel, Y., et al. (2021) Global terrestrial water storage and drought severity under climate change. Nat. Clim. Chang. 11, 226–233. https://doi.org/10.1038/s41558-020-00972-w
[261] Nolan, C., et al. (2018) Past and future global transformation of terrestrial ecosystems under climate change. SCIENCE, 31 Aug., doi: 10.1126/science.aan5360
[262] Brock, S., et al. (2021) The World Climate and Security Report 2021. Expert Group of the International Military Council on Climate and Security. Sikorsky, E. and Femia, F. (eds) Center for Climate and Security, an institute of the Council on Strategic Risks. June.
[263] Clement, V., et al. (2021) Groundswell Part 2: Acting on Internal Climate Migration. World Bank, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/36248 License: CC BY 3.0 IGO.