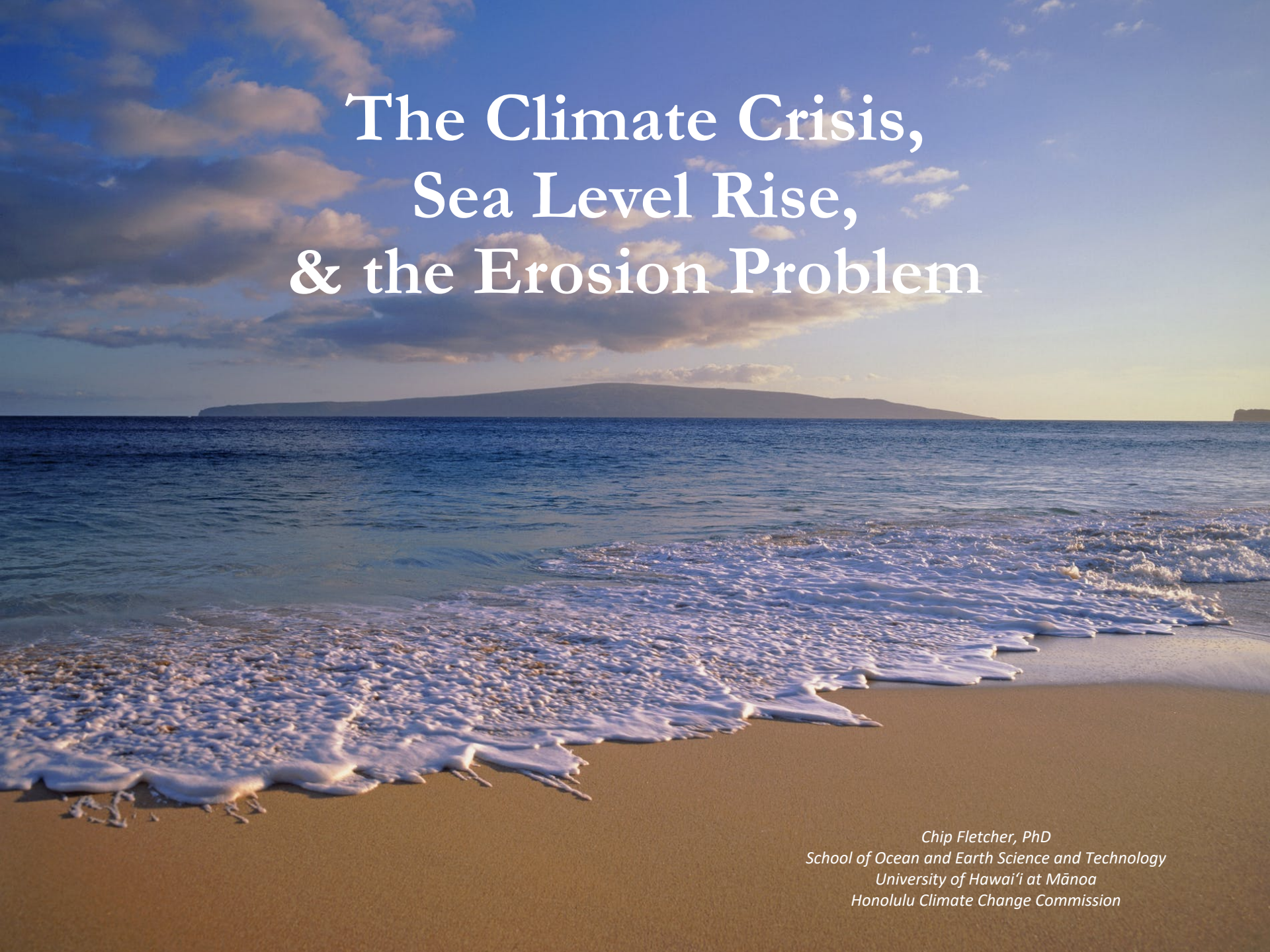
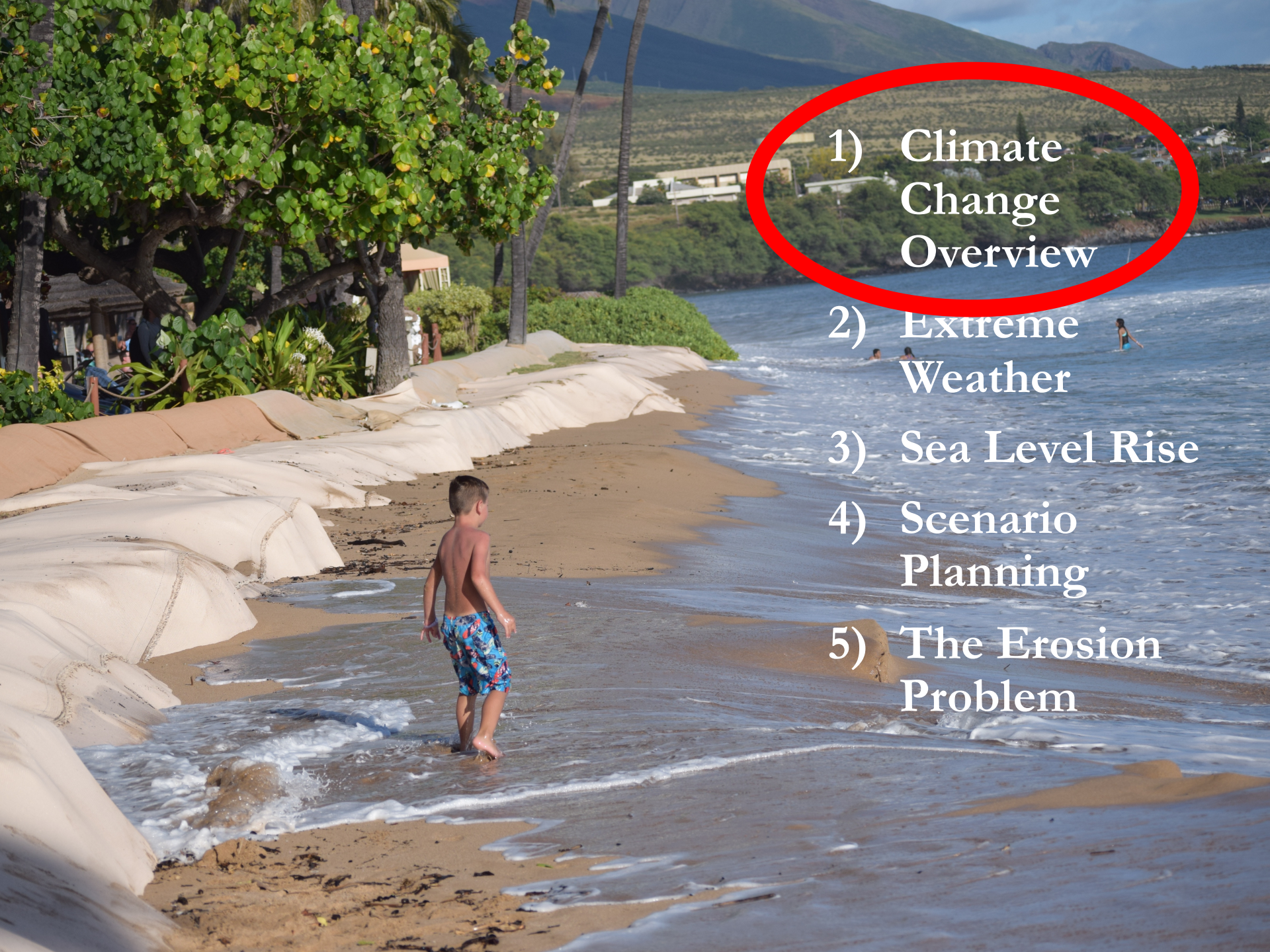


The Climate Crisis, Sea Level Rise, & the Erosion Problem

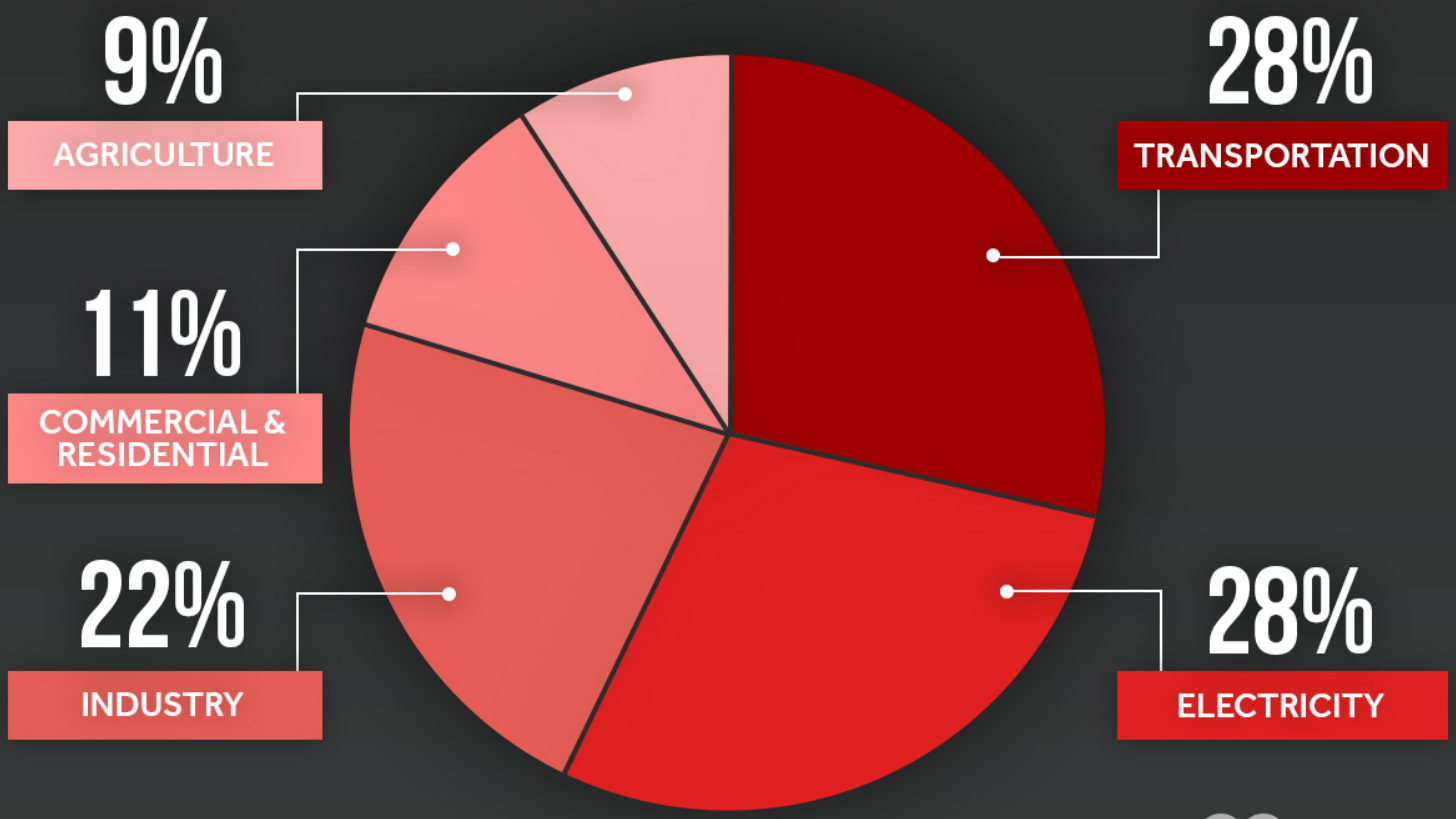
Chip Fletcher, PhD
School of Ocean and Earth Science and Technology
University of Hawai'i at Mānoa
Honolulu Climate Change Commission


1) Climate Change Overview
2) Extreme Weather
3) Sea Level Rise
4) Scenario Planning
5) The Erosion Problem

The Greenhouse Effect

GREENHOUSE GAS SOURCES

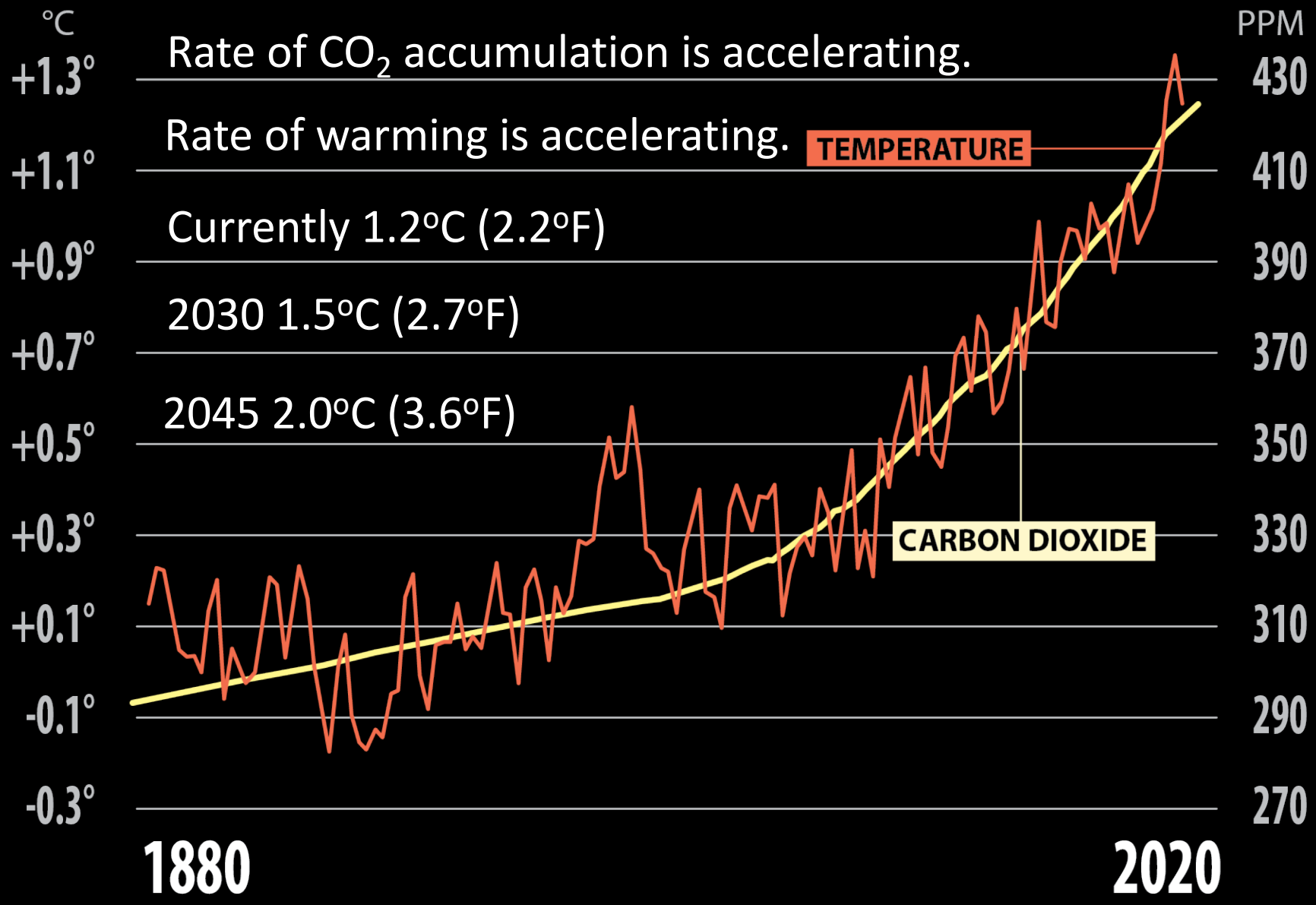
United States Greenhouse Gas Emissions by Sector



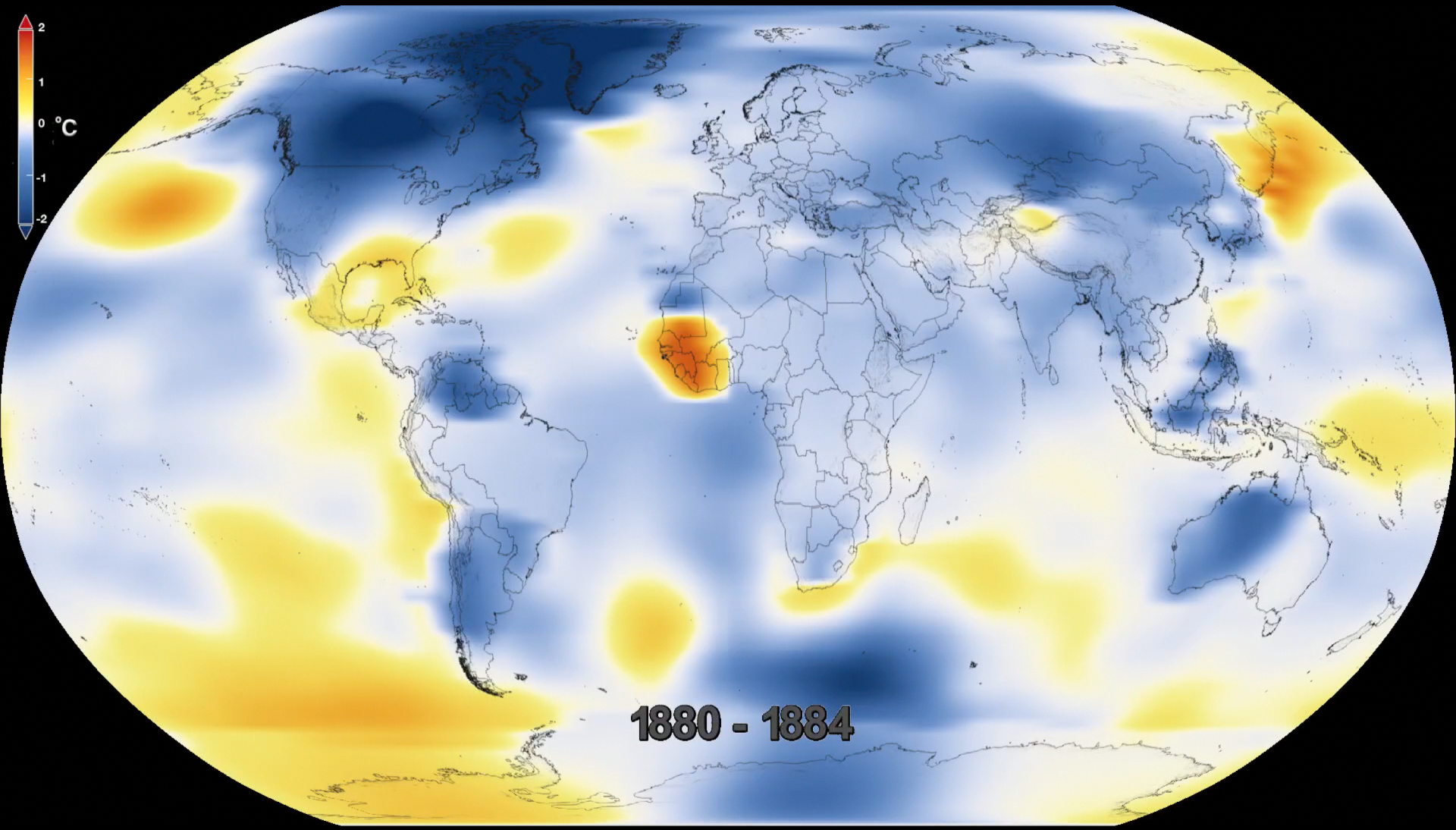
Source: US EPA

CLIMATE CENTRAL

GLOBAL TEMPERATURE & CARBON DIOXIDE



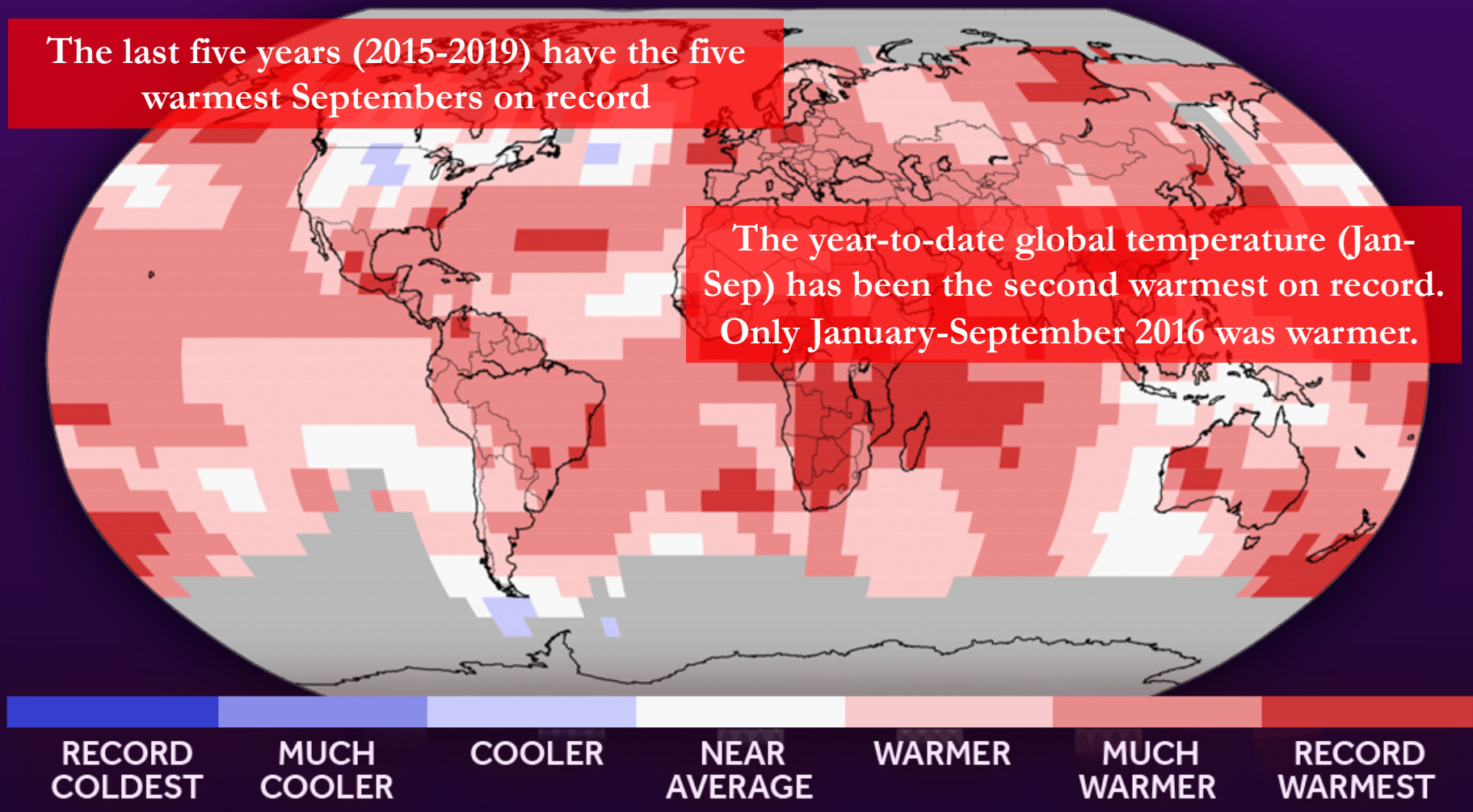
Carbon dioxide has warmed the air 1.2°C (2.2°F)



https://www.youtube.com/watch?v=Z4bSxb5THm4

2019 GLOBAL TEMPS

January-September Land and Ocean Temperature

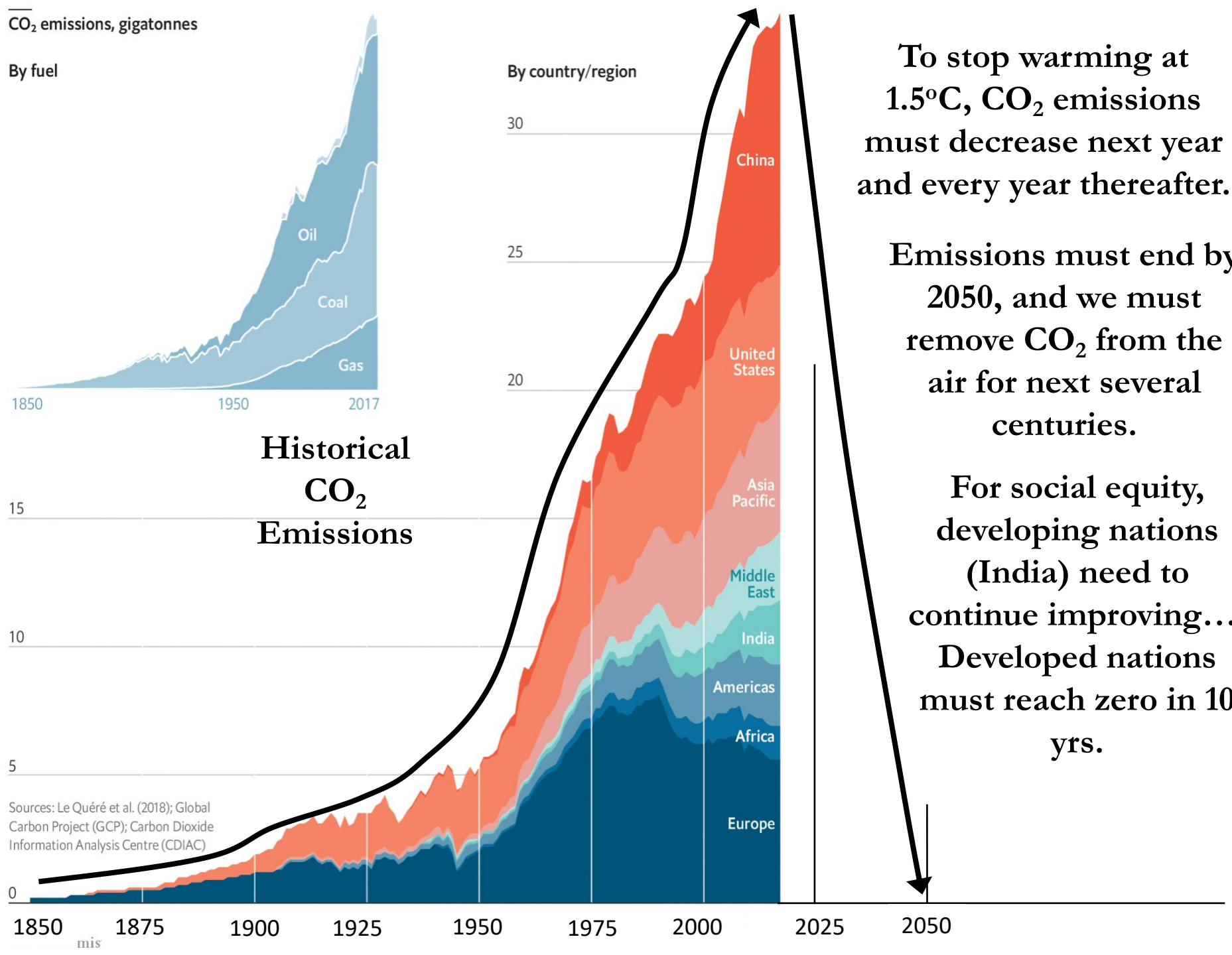


Data as of 10/16/2019
Source: NOAA/NCEI Climate at a Glance

CLIMATE CENTRAL

With only 1°C of global warming so far, researchers have already documented:

1. Sea level rise with 10% probability of 2 m by 2100
2. Antarctica melting 3x faster than last decade
3. Greenland melting 2x faster than last decade
4. Arctic sea ice volume down 50 - 70% ~1979
5. 12% global increase in extreme rainfall
6. 10% global increase in the land area under drought
7. Decrease in atmospheric circulation, unstable jet stream
8. Decrease in ocean vertical circulation
9. Ocean warming, acidification, loss of dissolved oxygen
10. Marine and terrestrial extinctions
11. Hurricanes are bigger, wetter, slower, and intensifying literally overnight



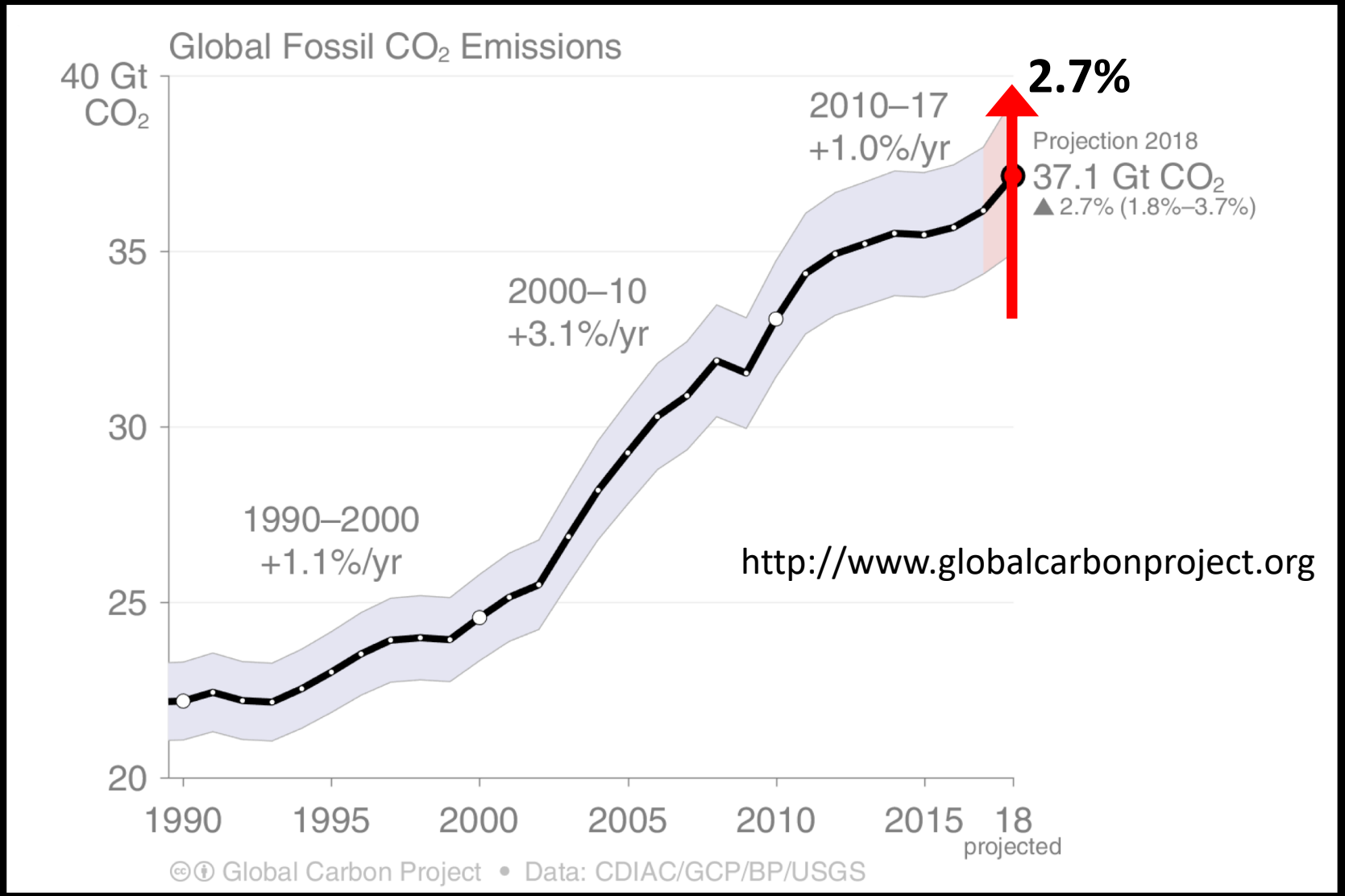
Historical CO_2 Emissions

To stop warming at 1.5°C, CO_2 emissions must decrease next year and every year thereafter.

Emissions must end by 2050, and we must remove CO_2 from the air for next several centuries.

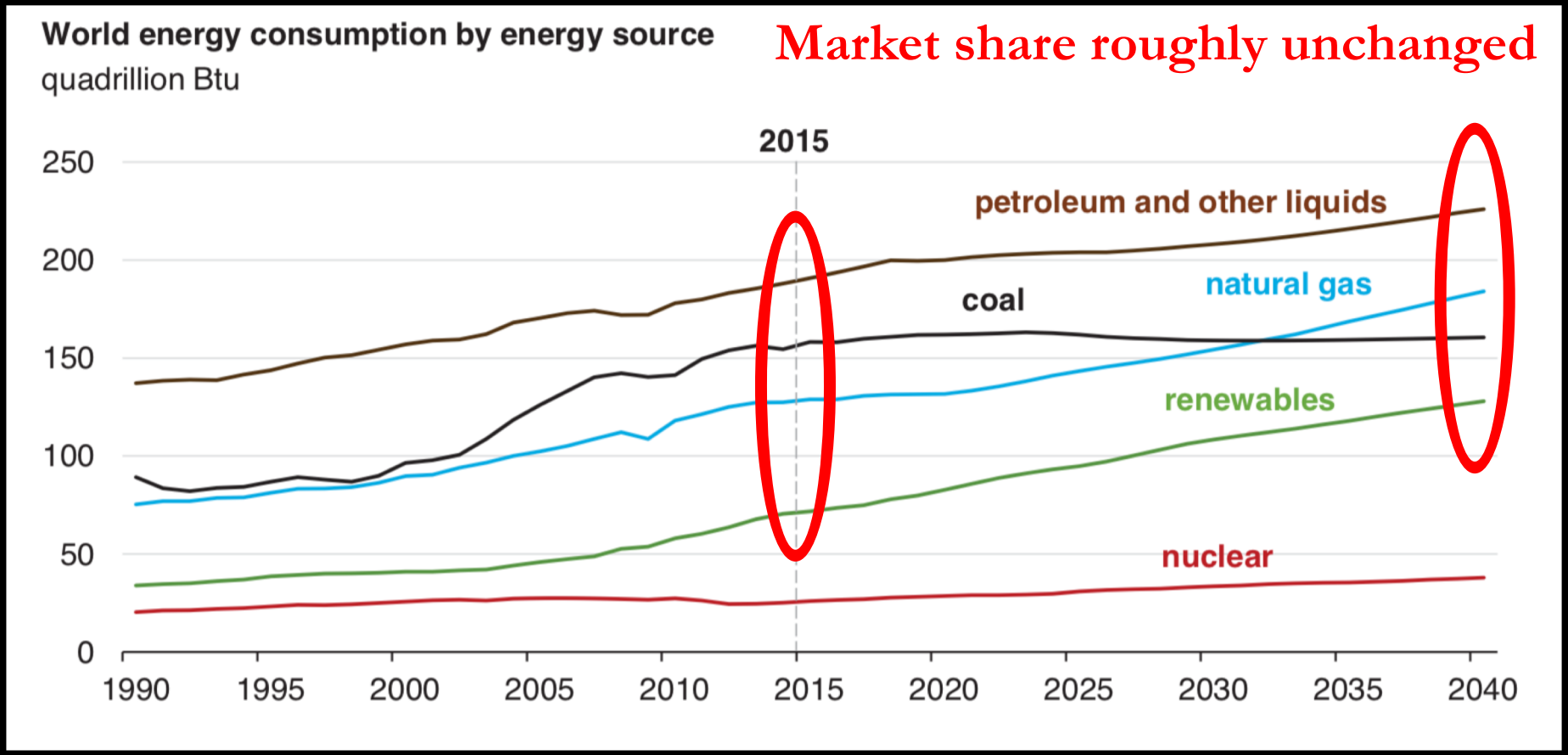
For social equity, developing nations (India) need to continue improving…. Developed nations must reach zero in 10 yrs.

CO_2 emissions are rising at record levels



U.S. Energy Information Administration

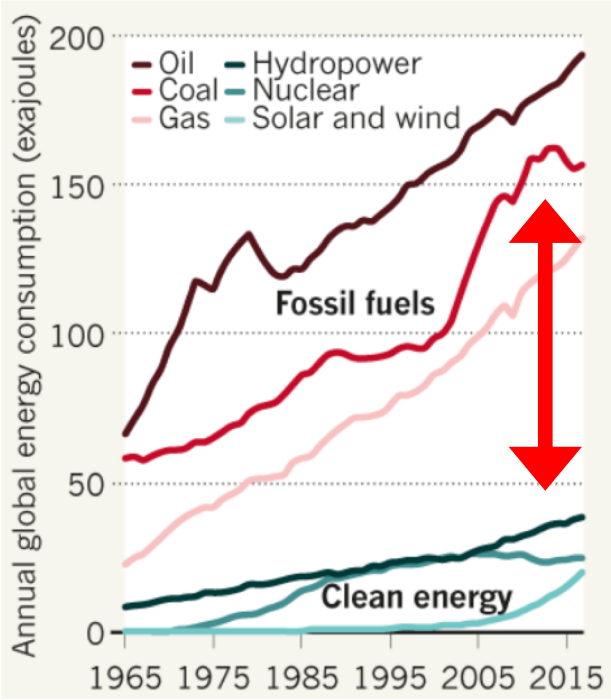
Energy Consumption increases to 2040 for all fuels but coal



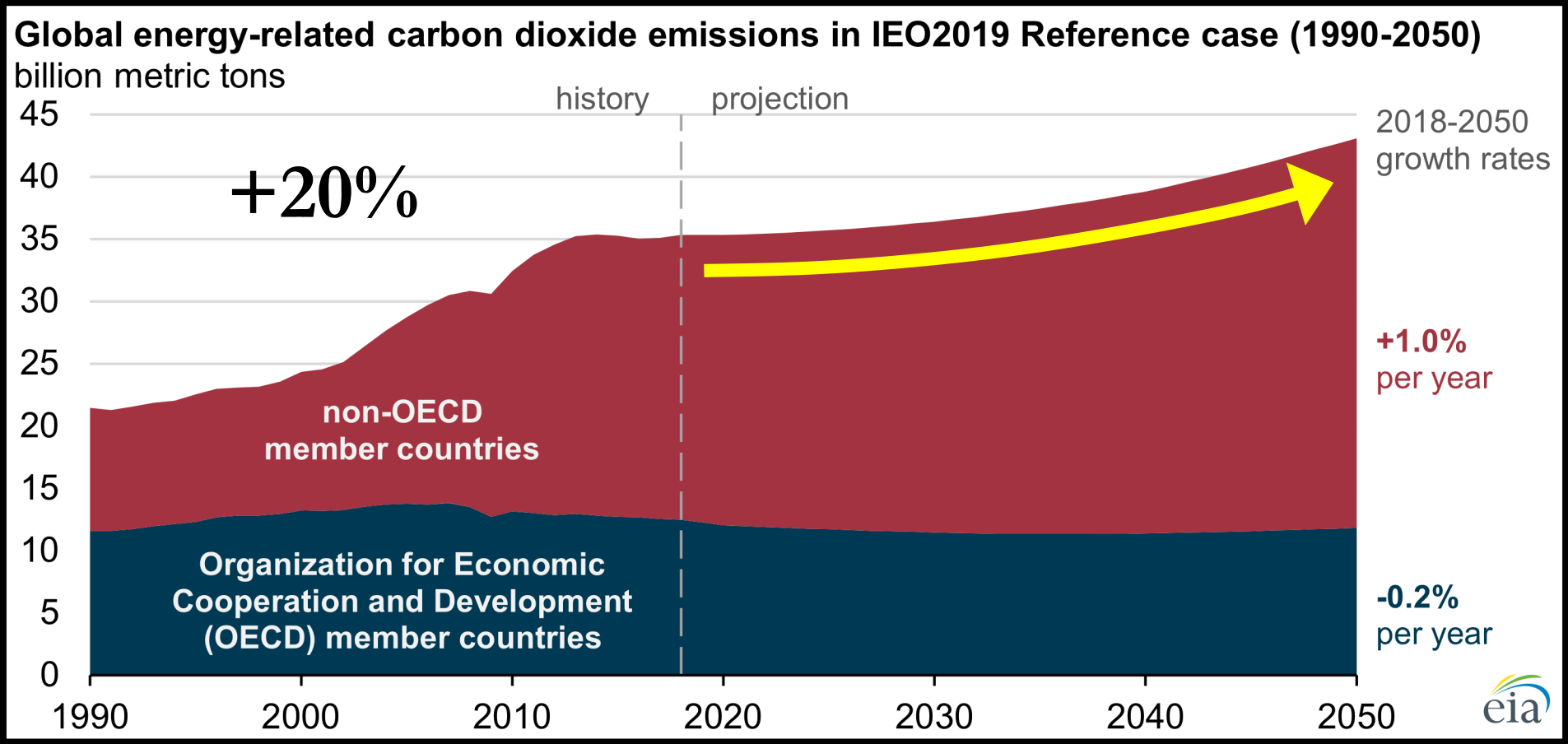
https://www.eia.gov/outlooks/ieo/exec_summ.php

Conventional approaches to mitigating climate change are not working

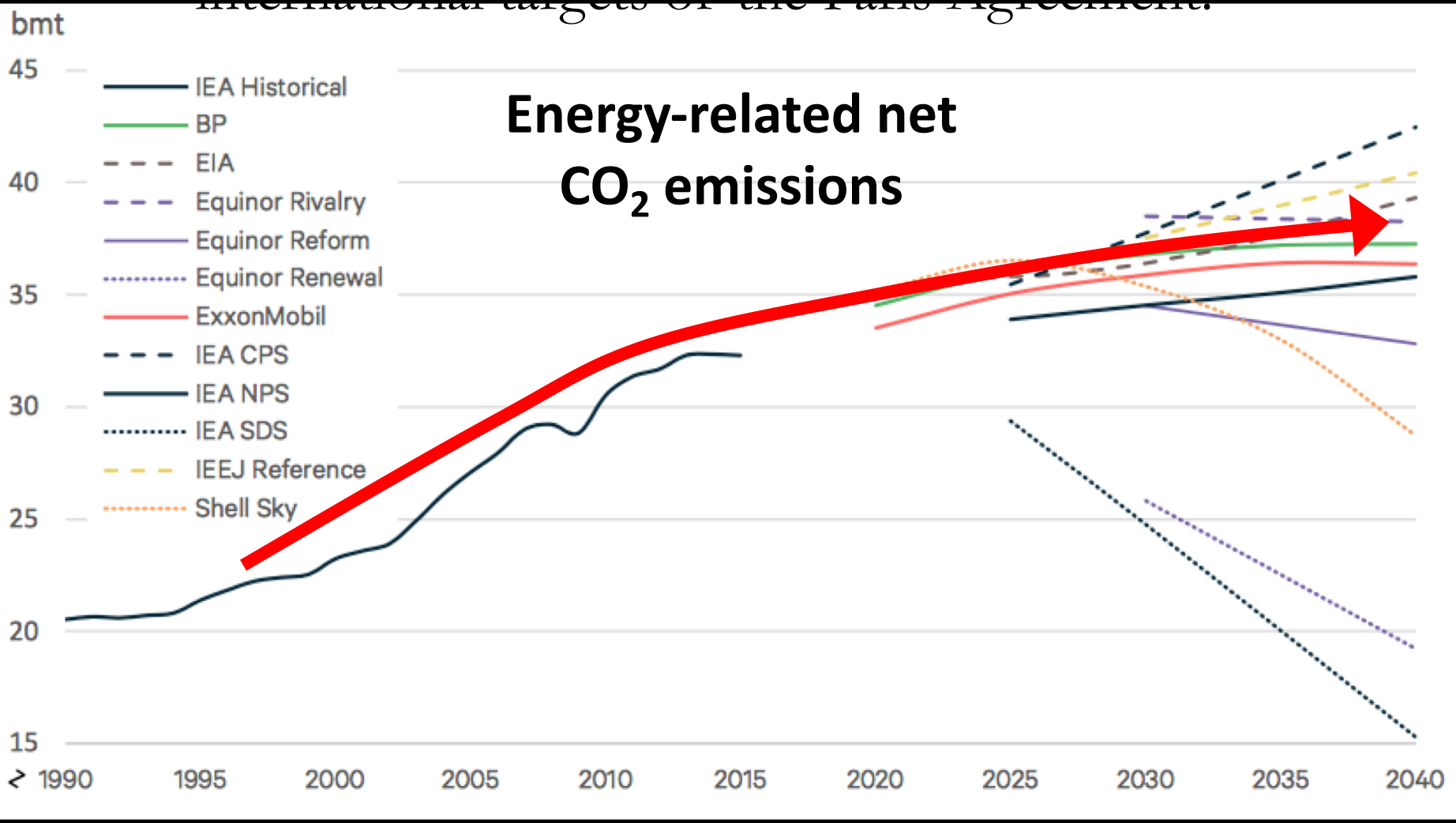
- Progress is falling well short of the Paris Agreement.
  - < 1/3 of needed reductions,
  - < 1% population in full compliance
- Fossil fuel use is accelerating faster than renewable energy
- Solutions by sector are geographically and temporally irregular.
- Solutions must simultaneously:
  - 1) End carbon emissions,
  - 2) Sequester 1 trillion tons of CO_2, and
  - 3) Adapt to centuries of growing weather disasters.
- Any one of these represents an expensive and radical change in current socio-economic practices.



U.S. Energy Information Administration
Energy-related global CO_2 emissions will grow 0.6% per year from 2018 to 2050 in its Reference case.



https://www.eia.gov/todayinenergy/detail.php?id=41493

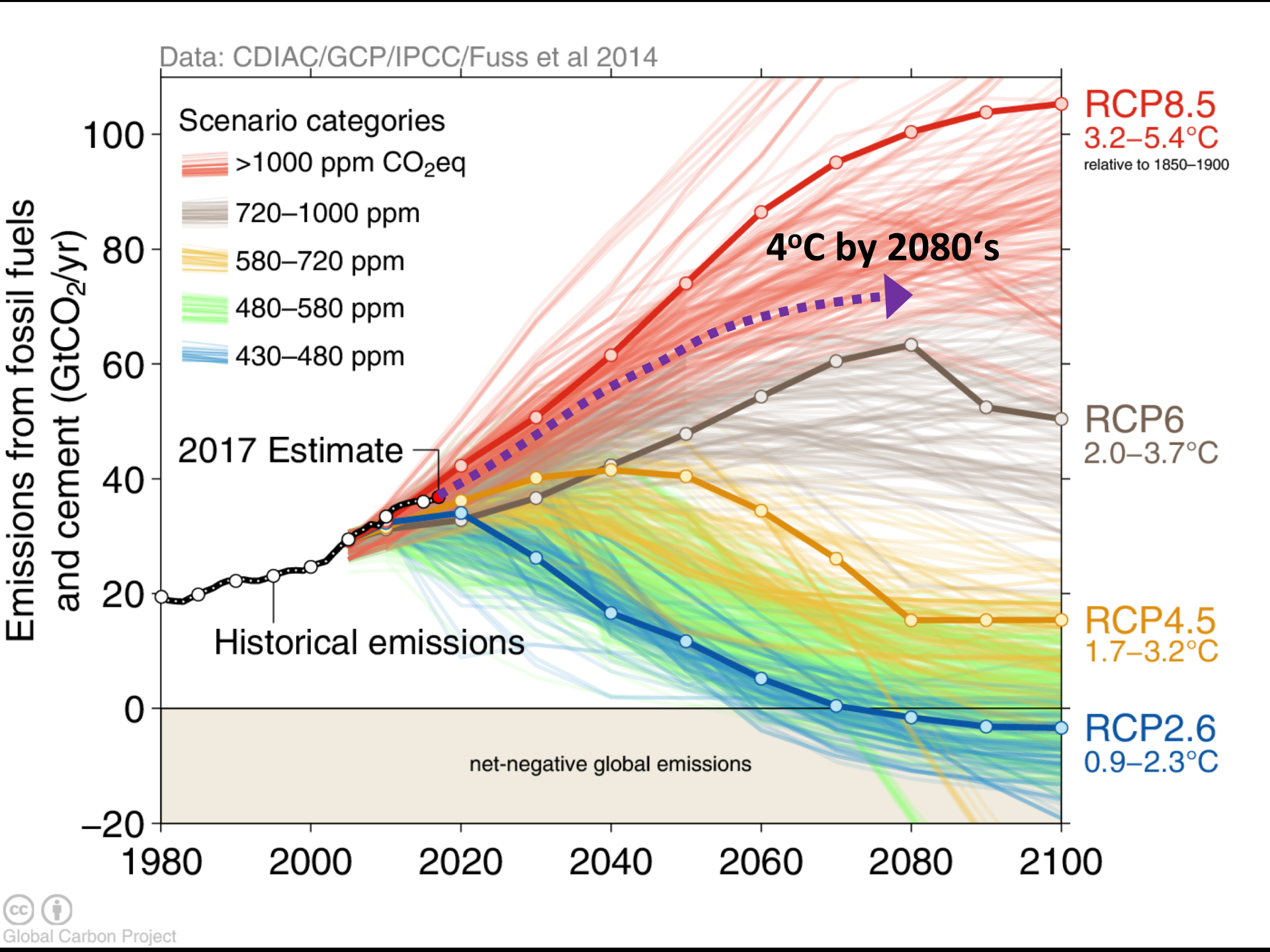

bmt
45
40
35
30
25
20
15
IEA Historical
BP
EIA
Equinor Rivalry
Equinor Reform
Equinor Renewal
ExxonMobil
IEA CPS
IEA NPS
IEA SDS
IEEJ Reference
Shell Sky
Energy-related net
CO_2 emissions
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040

We must reject the assumption that scaling up clean energy will automatically replace fossil fuels.

Historically, new energy sources have *added* to older ones. Oil and gas didn't replace coal; they were added on top.

The same is happening right now with new clean energy.

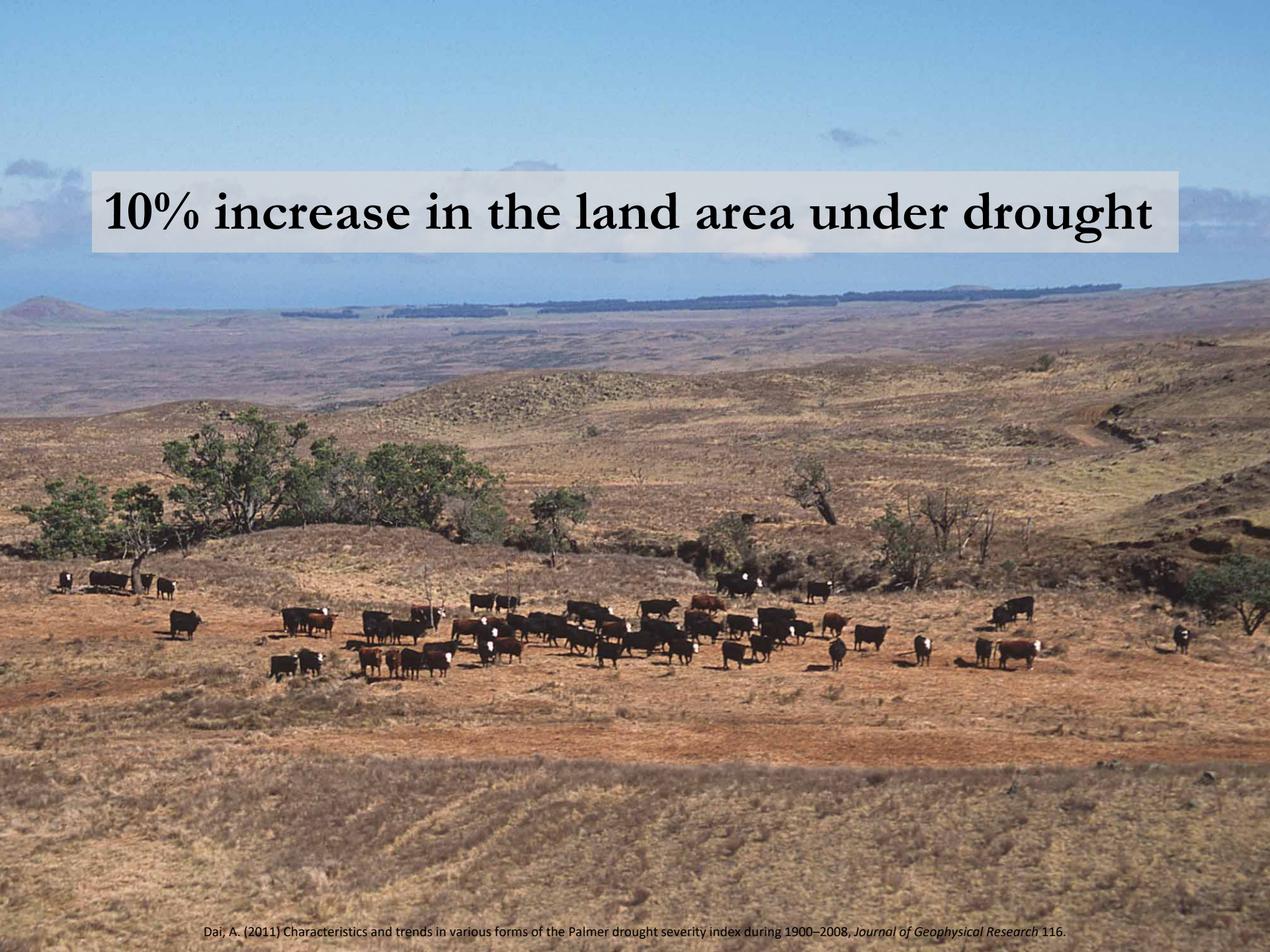
Jason Hickel @jasonhickel



Global Carbon Project

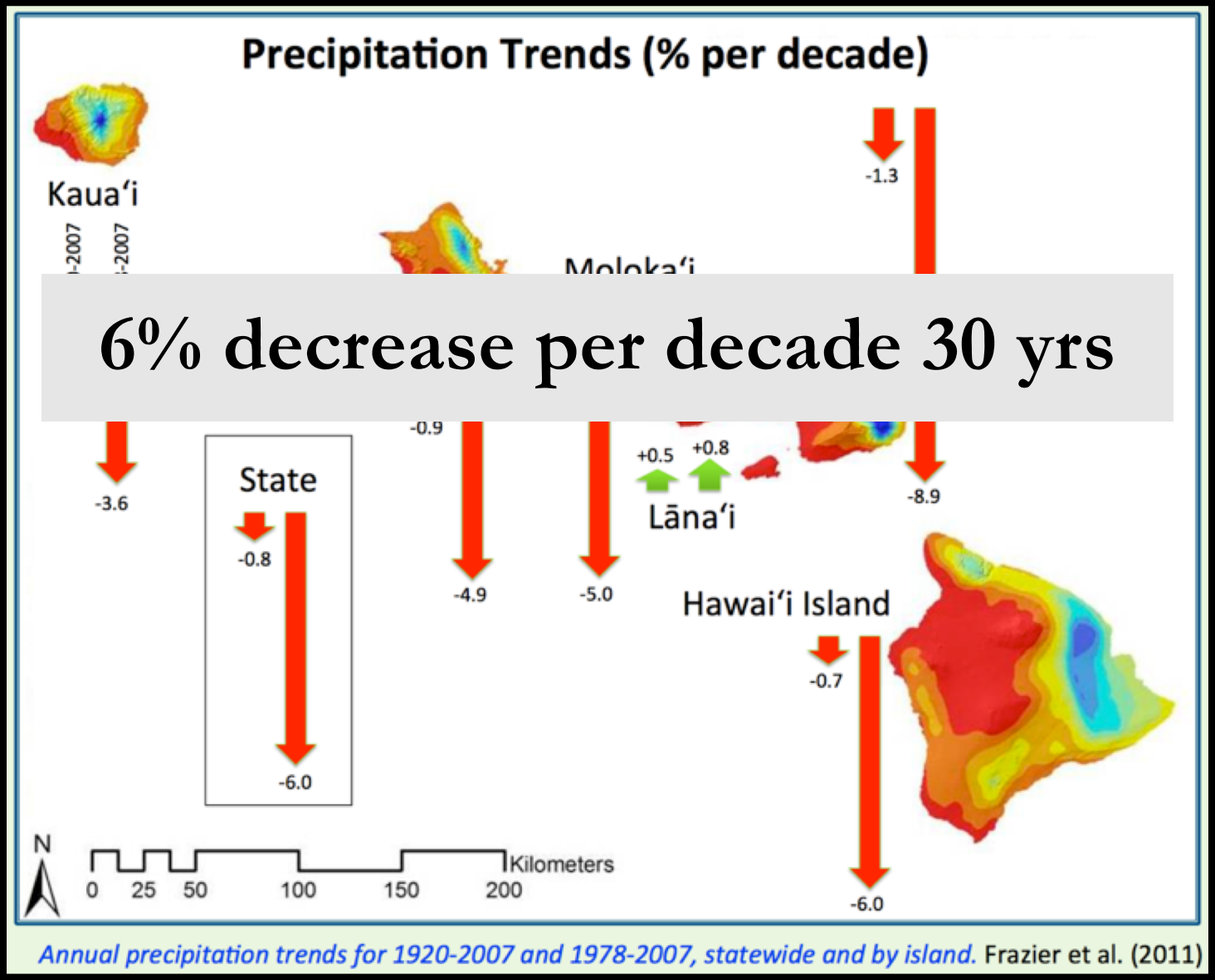
Extreme
Weather

10% increase in the land area under drought



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

Hawai‘i is getting drier

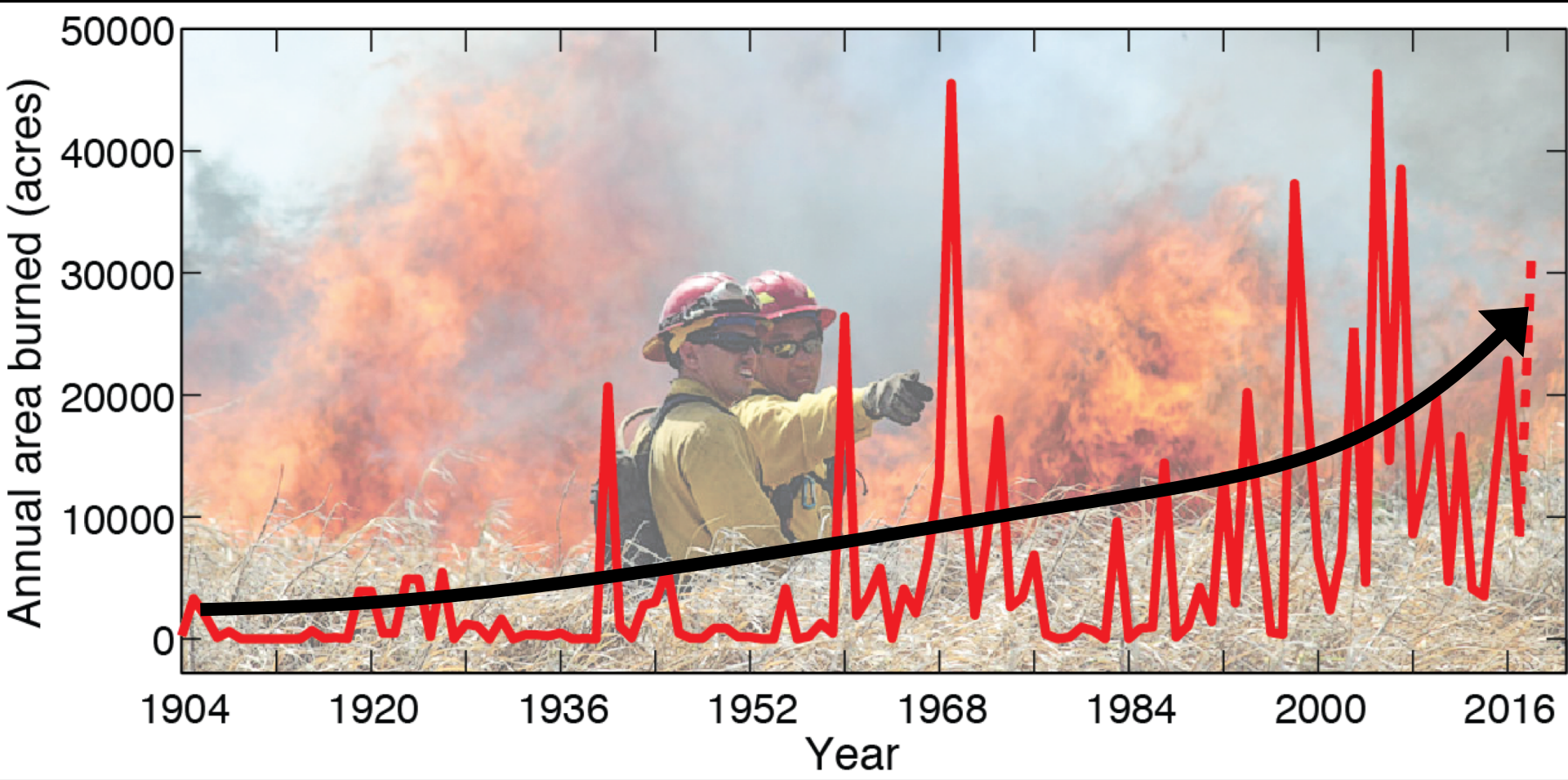


6% decrease per decade 30 yrs

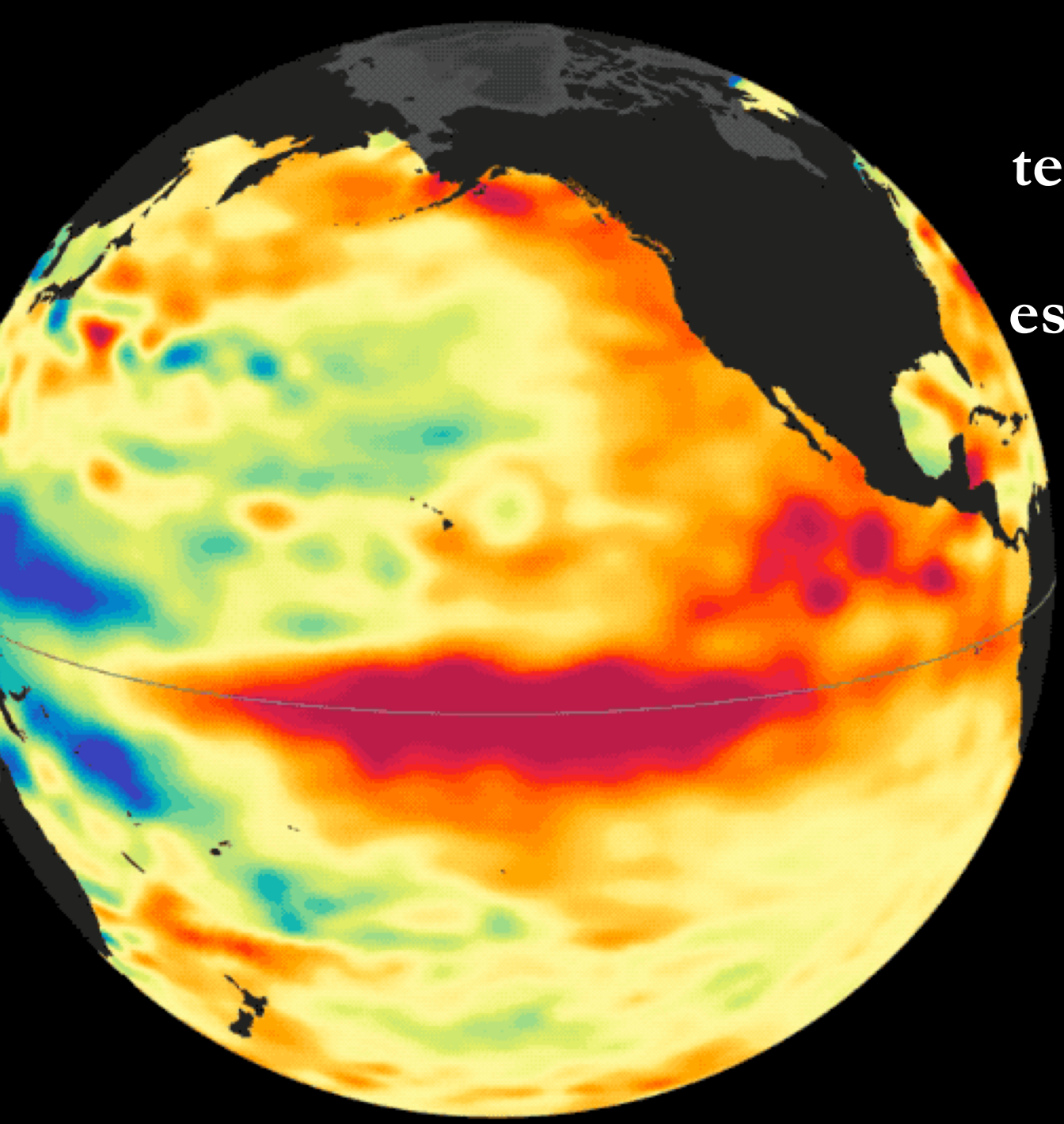
Annual precipitation trends for 1920-2007 and 1978-2007, statewide and by island. Frazier et al. (2011)

Giambelluca, T.W., Diaz, H.F., Elison Timm, O., Takahashi, M., Frazier, A.G., and Longman, R. 2011. Regional climate trends in Hawai‘i. American Geophysical Union Fall Meeting, San Francisco, December 2011.

400% increase in wildfire on O'ahu since 1960's

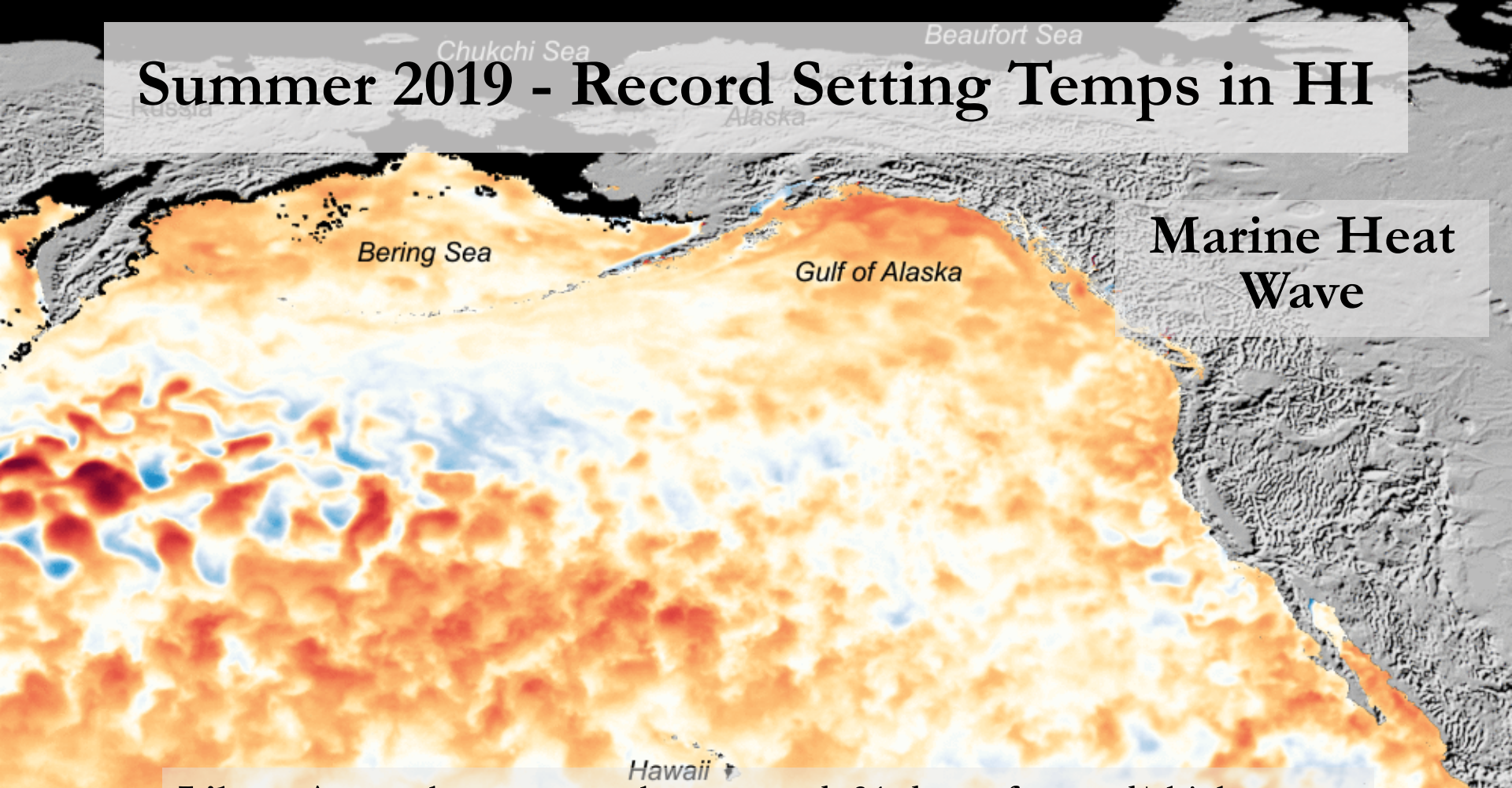


Trauernicht, C., E. et al. 2015 The contemporary scale and context of wildfire in Hawaii. Pacific Science 69:427-444



Sea surface temperatures are rising – especially during El Niño

Summer 2019 - Record Setting Temps in HI



Lihue–August hottest month on record; 31 days of record* highs.

Honolulu–Aug. 31 tied all time record high (95°); 29 days of record* highs.

Kahului–July 29 97° may be highest ever HI temp; 41 days of record* highs.

Hilo – August hottest month on record; 15 days of record* highs.

Weekly Sea Surface Temperature Departure January 2019

https://www.nesdis.noaa.gov/content/marine-heat-wave-reminiscent-blob-lingers-us-west-coast?utm_source=Social%20Media&utm_medium=Twitter&utm_campaign=Marine%20Heatwave%20Article%2020191008

https://www.wunderground.com/cat6/Hawaiis-Warmest-Summer-Record-and-Alaskas-Second-Warmest

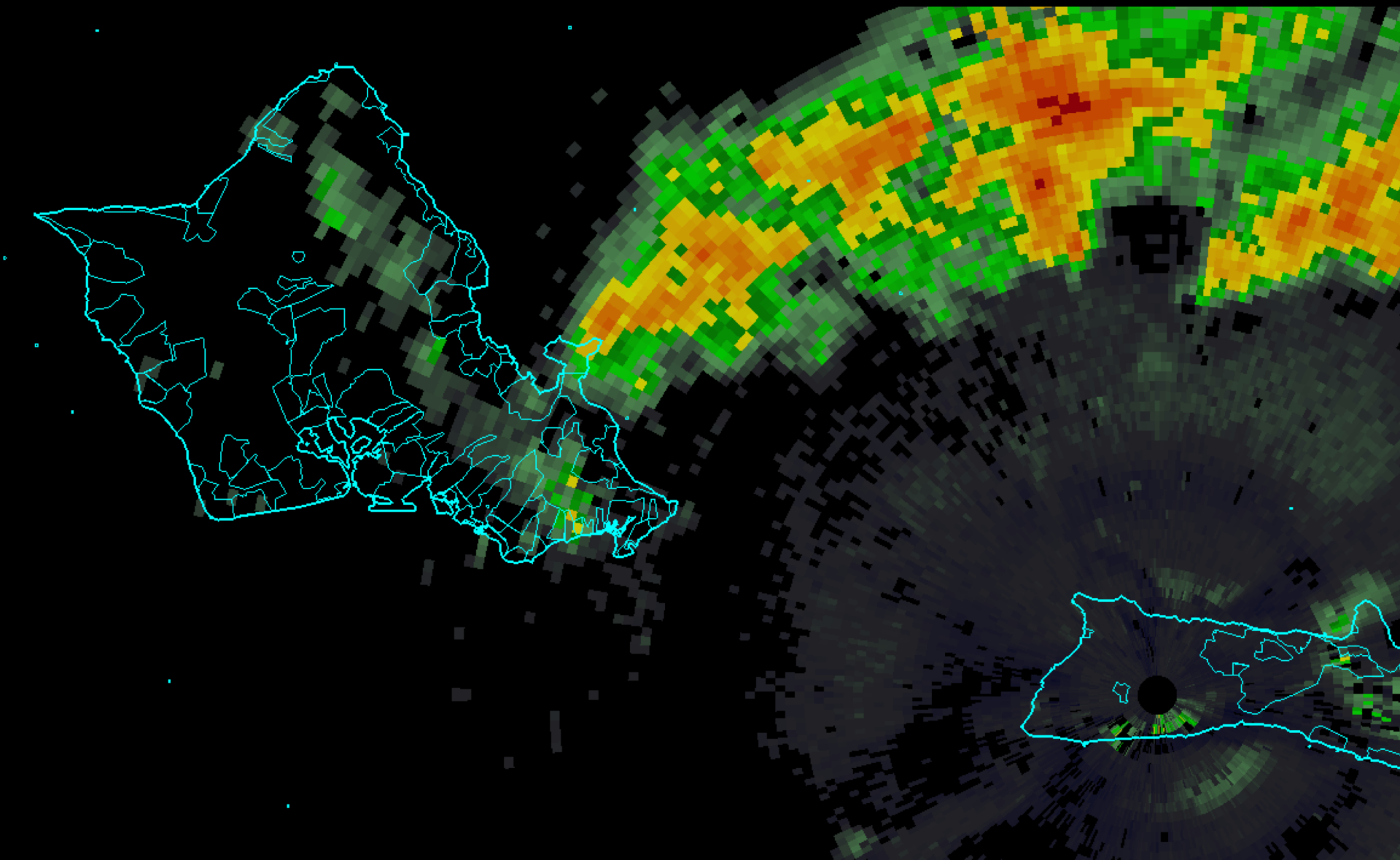
Global extreme rainfall has increased 12%

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

Global extreme rainfall has increased 12%

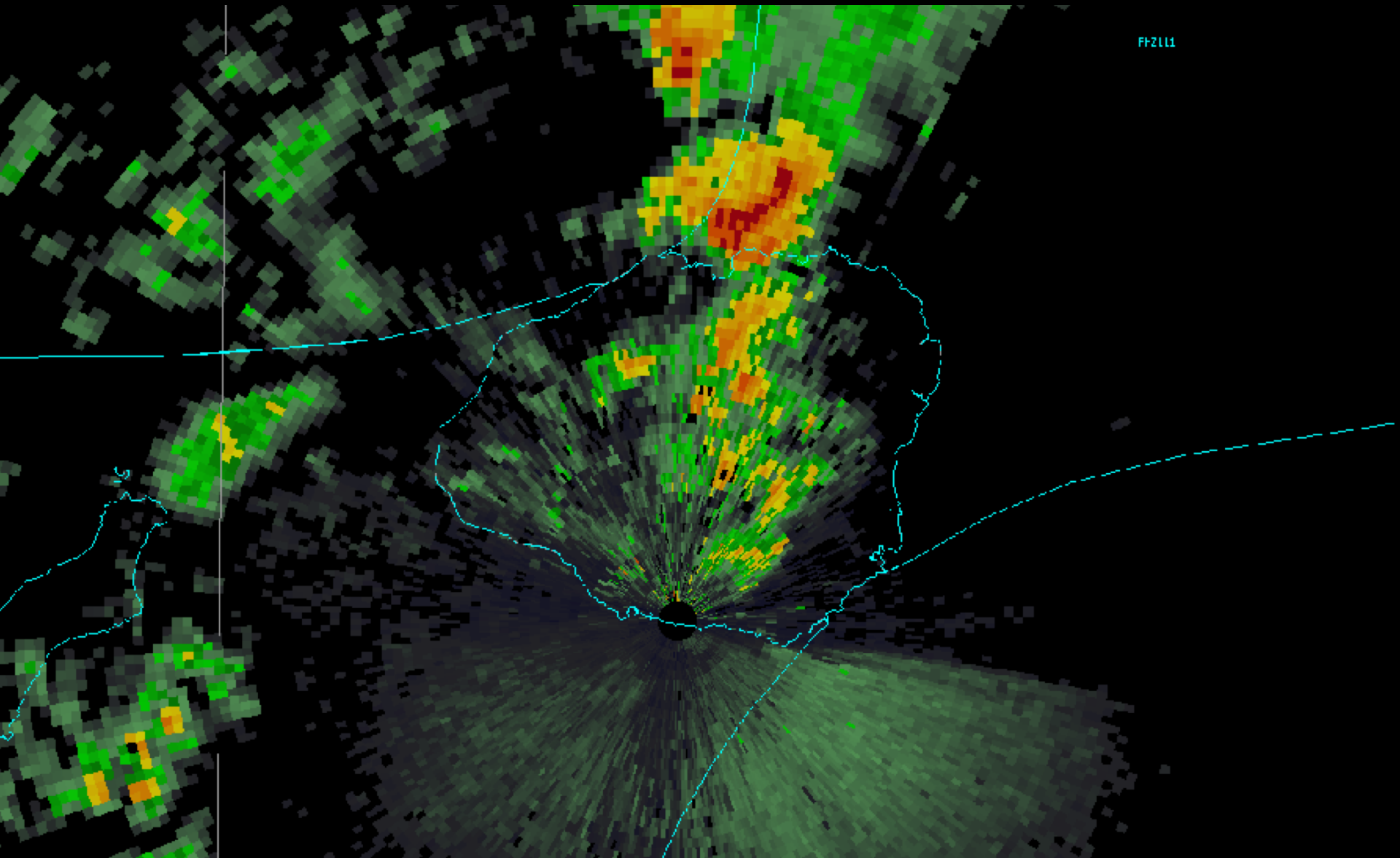
Lehmann, J., et al. (2015) Increased record-breaking precipitation events under global warming, *Climatic Change*, doi: 10.1007/s10584-015-1434-y

O‘ahu, April 2018
State of Emergency, $124 million



O‘ahu, April 2018
Water in Wailupe Gulch rose 8 ft

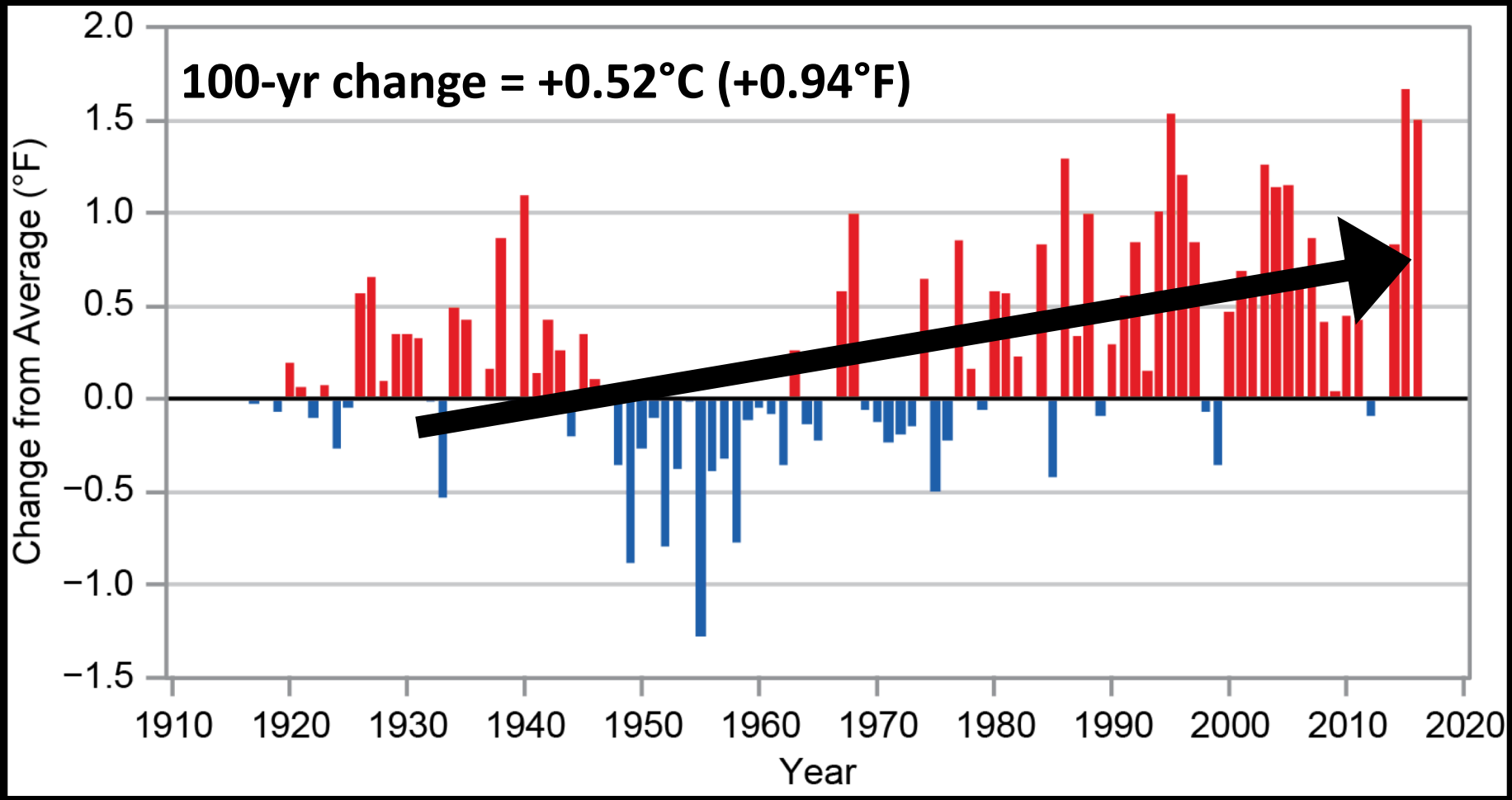
Kaua‘i, April 2018
49.69 inches in 24-hour, national record



Kaua‘i, April 2018
Hanalei River rose 15 feet

Kaua‘i, April 2018
Hanalei River jumped its bank and carved a new channel

Hawai‘i is getting warmer

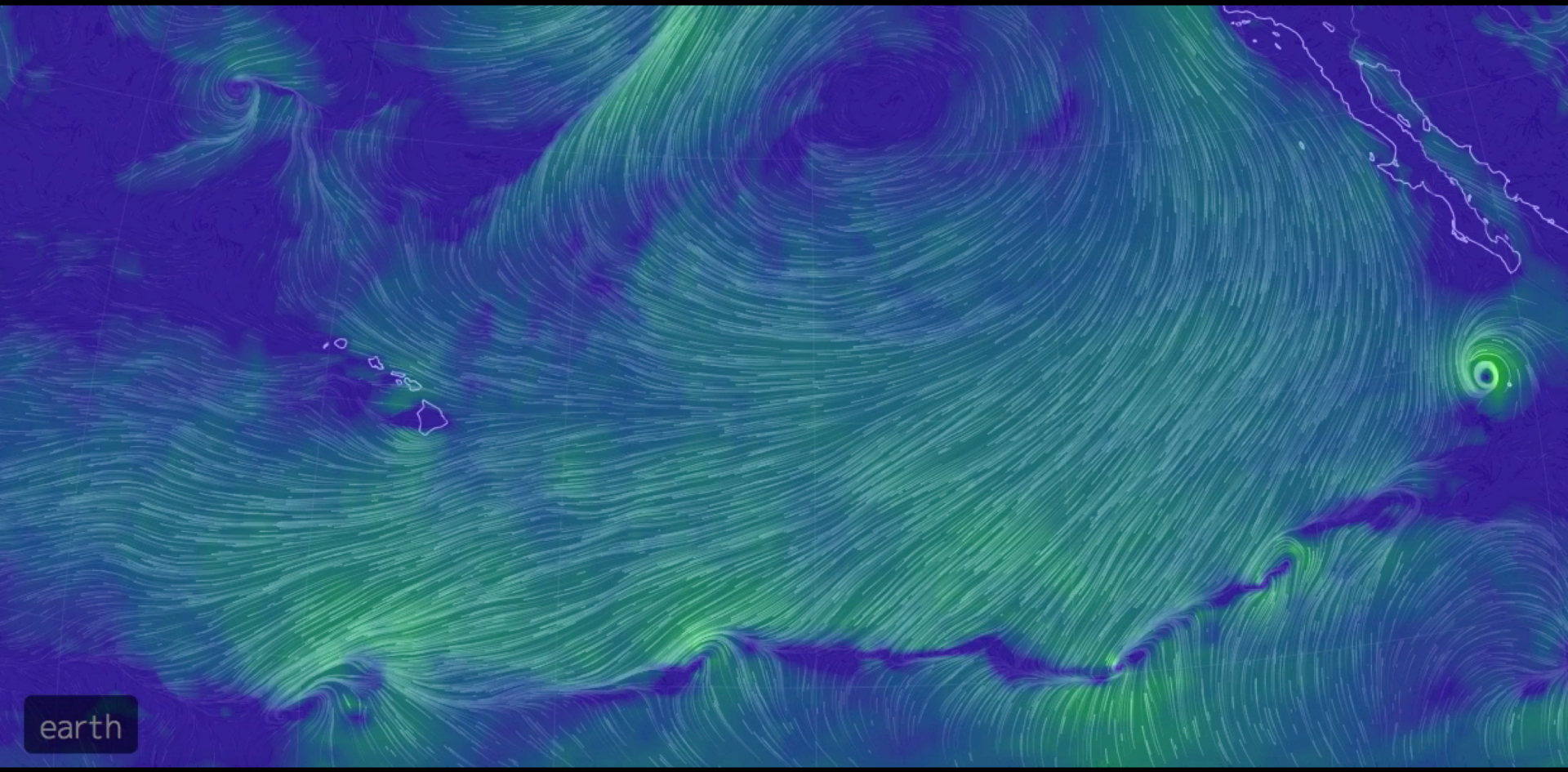


McKenzie, M.M., Giambelluca, T.W., and Diaz, H.F. Accepted. Regional temperature trends in Hawai‘i: a century of change, 1917-2016. *International Journal of Climatology*.

Average daily wind speeds are declining

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

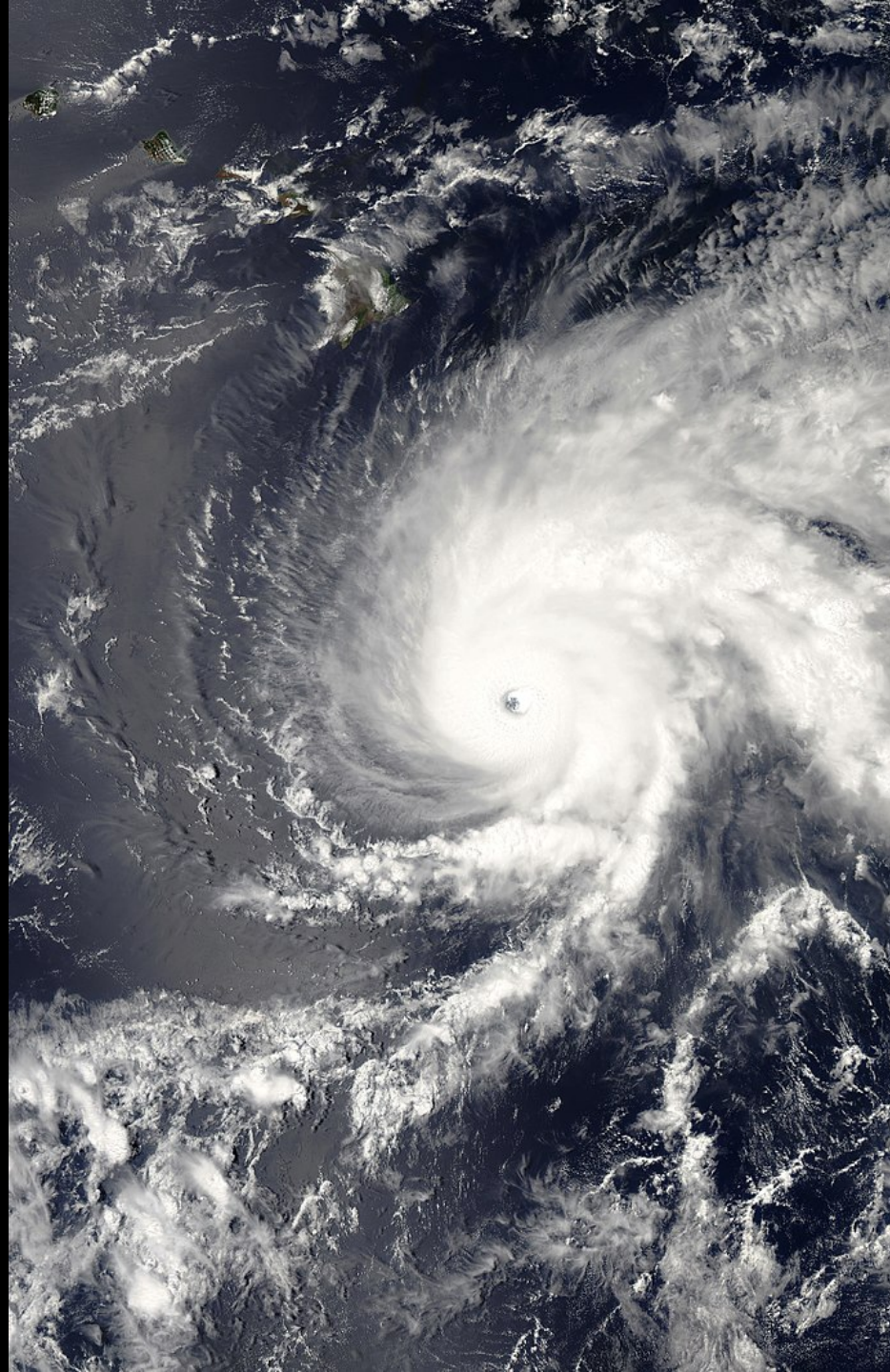
Trade winds easterly, warmer, less rain



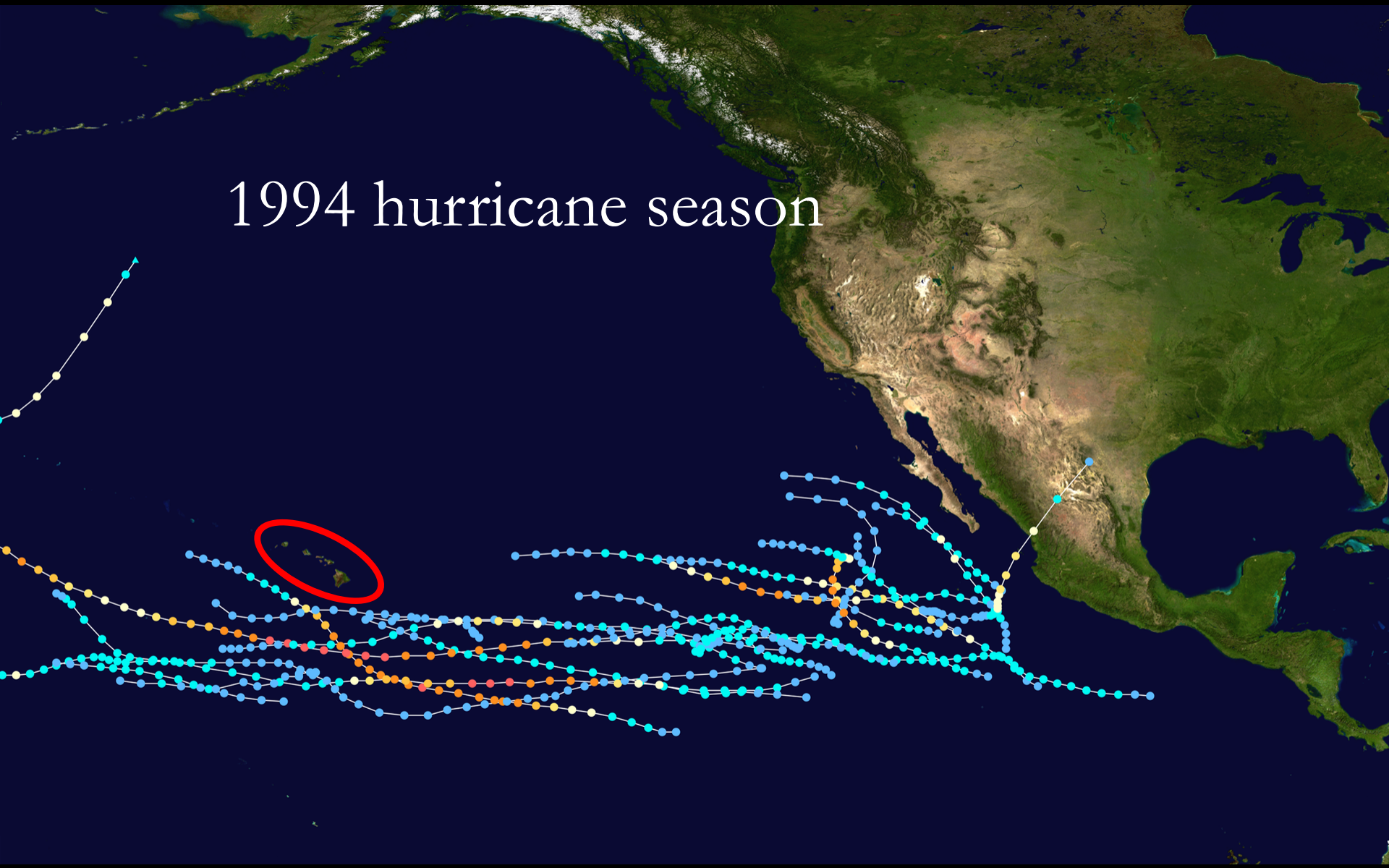
Marra, J.J., and Kruk, M.C. (2017) State of Environmental Conditions in Hawai'i and the U.S. Affiliated Pacific Islands under a Changing Climate: https://coralreefwatch.noaa.gov/satellite/publications/state_of_the_environment_2017_hawaii-usapi_noaa-nesdis-ncei_oct2017.pdf.

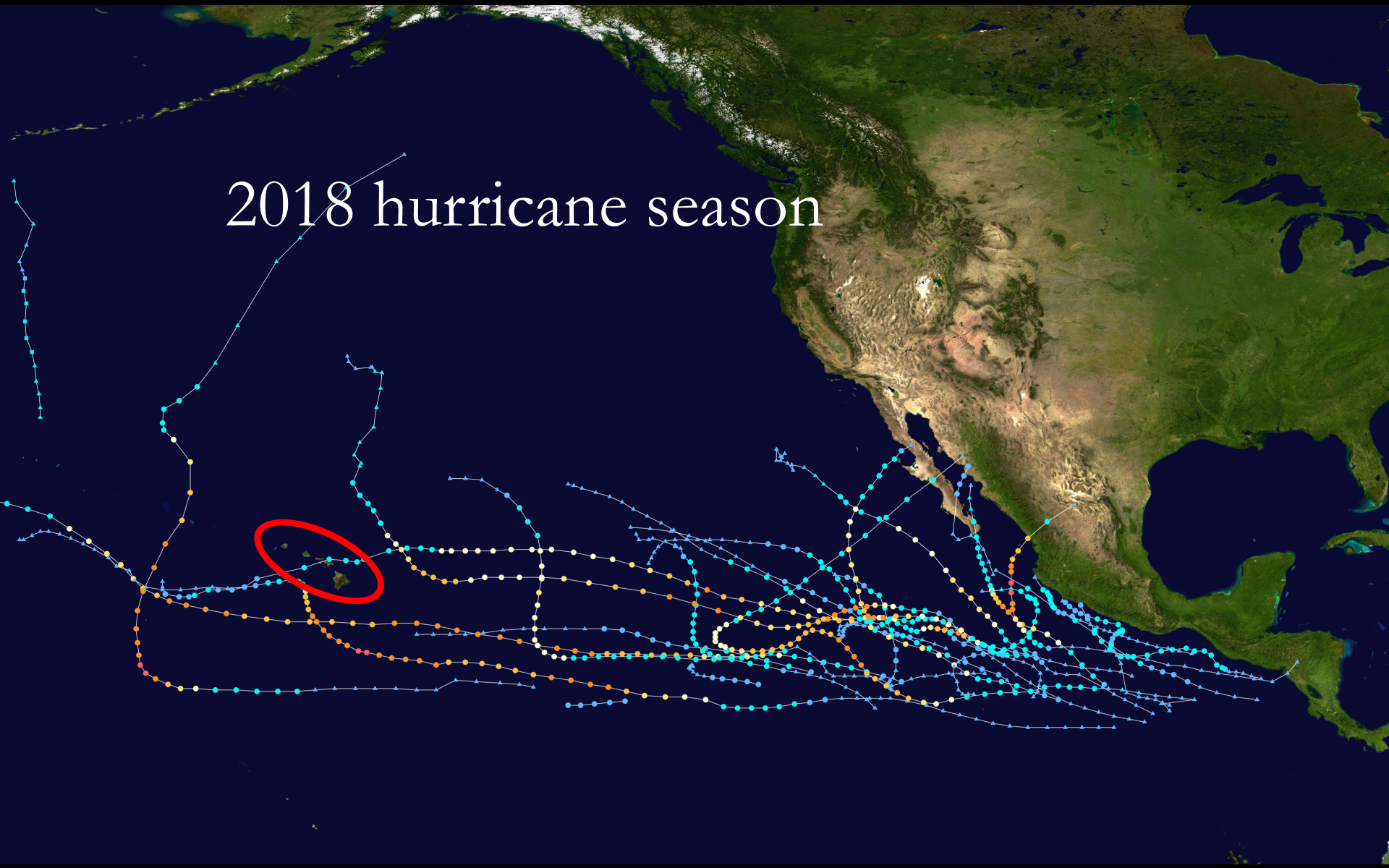
Hurricanes and Climate Change

- Warmer water = More fuel
- Larger
- More rain
- Stronger wind = Higher category
- Slower = More damage
- Higher storm surge
- Shifting away from equator

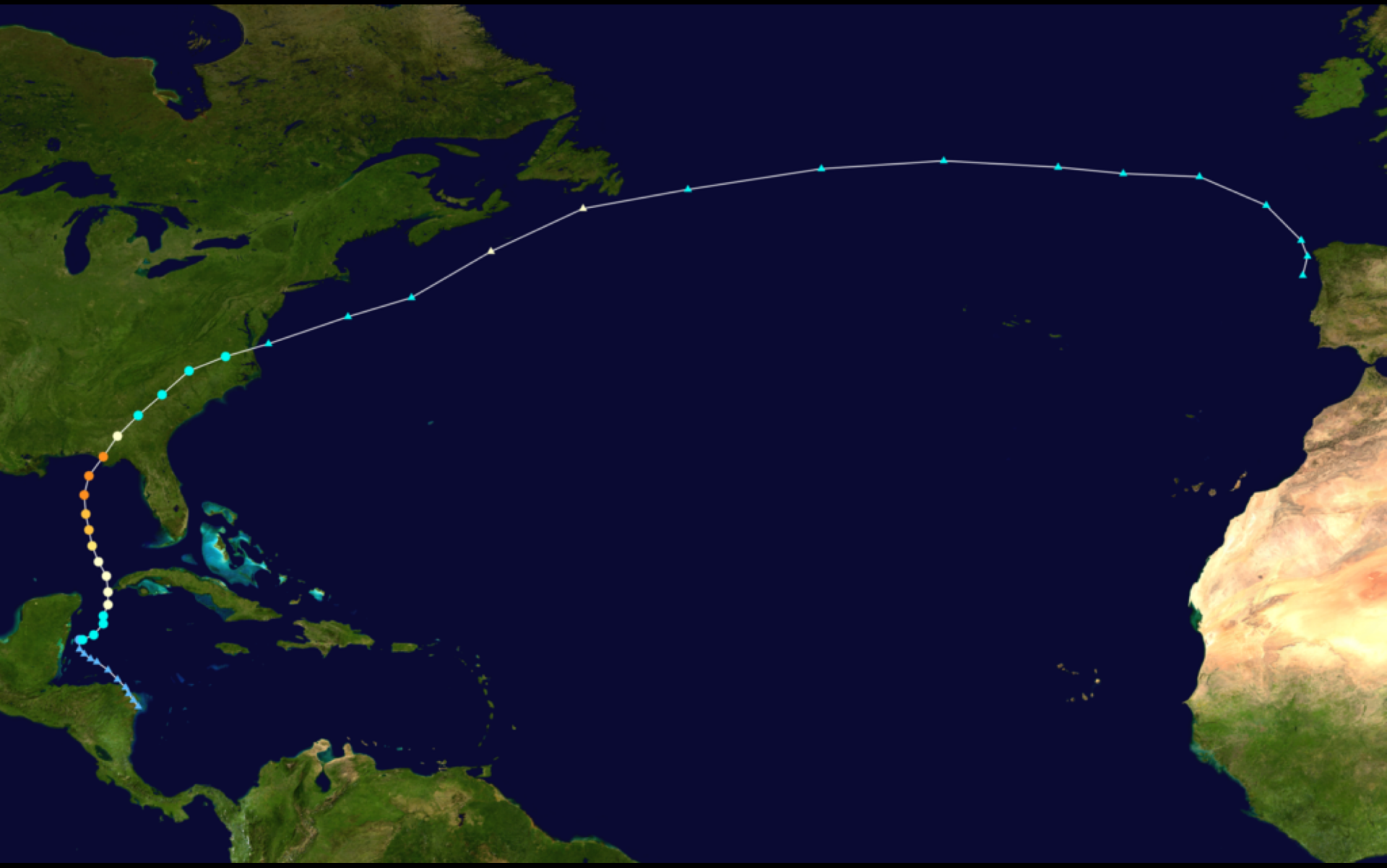


Does Global Warming Make Hurricanes Stronger? http://www.realclimate.org/index.php/archives/2018/05/does-global-warming-make-tropical-cyclones-stronger/


1994 hurricane season


2018 hurricane season

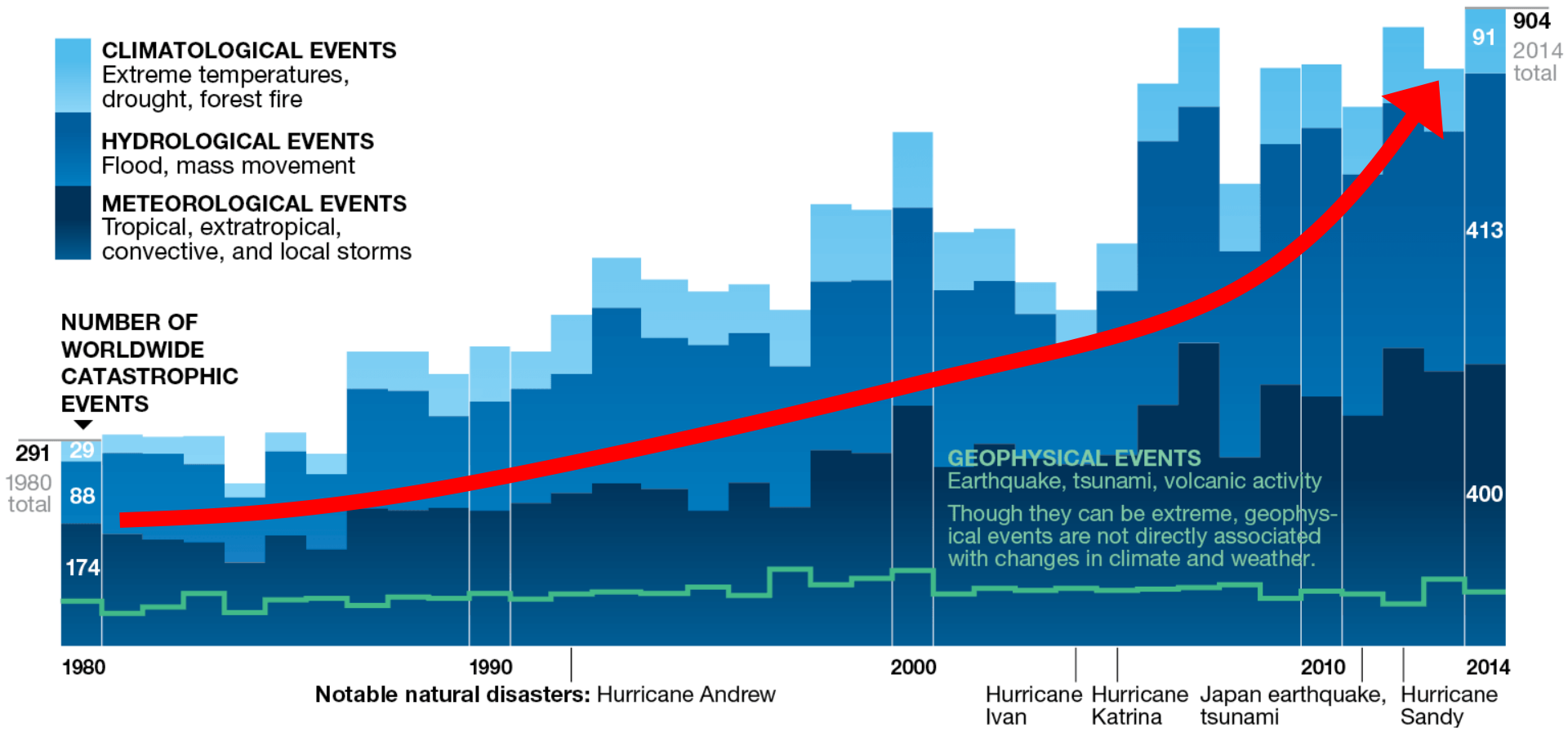
Hurricane Michael, Florida Panhandle, October, 2018



Global weather disasters have tripled in two decades

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

Global weather disasters have tripled in two decades



Sea Level
Rise

Sea Level Rise has been accelerating since the 1960‘s

nature climate change

ARTICLES

https://doi.org/10.1038/s41558-019-0531-8

Persistent acceleration in global sea-level rise since the 1960s

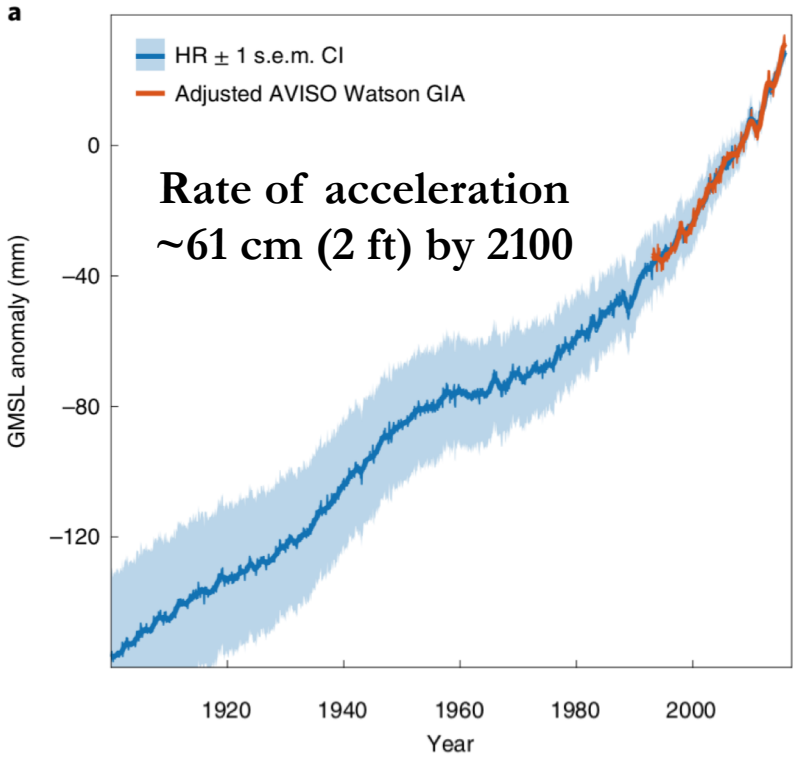
Sönke Dangendorf[1,2*], Carling Hay[3], Francisco M. Calafat[4], Marta Marcos[5], Christopher G. Piecuch[6], Kevin Berk[7] and Jürgen Jensen[1]

Previous studies reconstructed twentieth-century global mean sea level (GMSL) from sparse tide-gauge records to understand whether the recent high rates obtained from satellite altimetry are part of a longer-term acceleration. However, these analyses used techniques that can only accurately capture either the trend or the variability in GMSL, but not both. Here we present an improved hybrid sea-level reconstruction during 1900–2015 that combines previous techniques at time scales where they perform best. We find a persistent acceleration in GMSL since the 1960s and demonstrate that this is largely (~76%) associated with sea-level changes in the Indo-Pacific and South Atlantic. We show that the initiation of the acceleration in the 1960s is tightly linked to an intensification and a basin-scale equatorward shift of Southern Hemispheric westerlies, leading to increased ocean heat uptake, and hence greater rates of GMSL rise, through changes in the circulation of the Southern Ocean.

Understanding twentieth-century global and regional sea-level changes is of paramount importance, as they reflect both natural and anthropogenic changes occurring in the Earth's climate system (through changes in land-ice and ocean heat uptake) and affect the livelihood of hundreds of millions of people in the world's coastal regions. Satellite altimetry shows that GMSL has been rising at an average rate of about 3.1 ± 0.3 mm yr^{-1} since 1993, whereas complementary observations from profiling floats (observing density changes in the upper 2,000 m of the ocean) and gravimetric satellites (measuring mass changes from space) have enabled the attribution of the GMSL signal to its density and mass contributions with an accuracy of ~0.3 mm yr^{-1} since about 2005 (ref. [1]). Recent altimetry-based studies also report that the pace of GMSL has been accelerating since 1993 (refs. [2–4]), which is consistent with independent estimates of increasing mass contributions from Greenland and Antarctica over the last two decades[5,6]. However, when this acceleration started and what processes contributed the most to it remains unclear, as satellite altimetry only covers the short period since 1993. A complementary source of sea-level information comes from the network of tide gauges. Although confined to the coast and containing data gaps, tide-gauge records in some places date back to the Industrial Revolution. Synthesizing the tide-gauge record with satellite altimetry requires statistical techniques that allow for sparse data coverage and the treatment of systematic differences between the two observing systems[7–9].

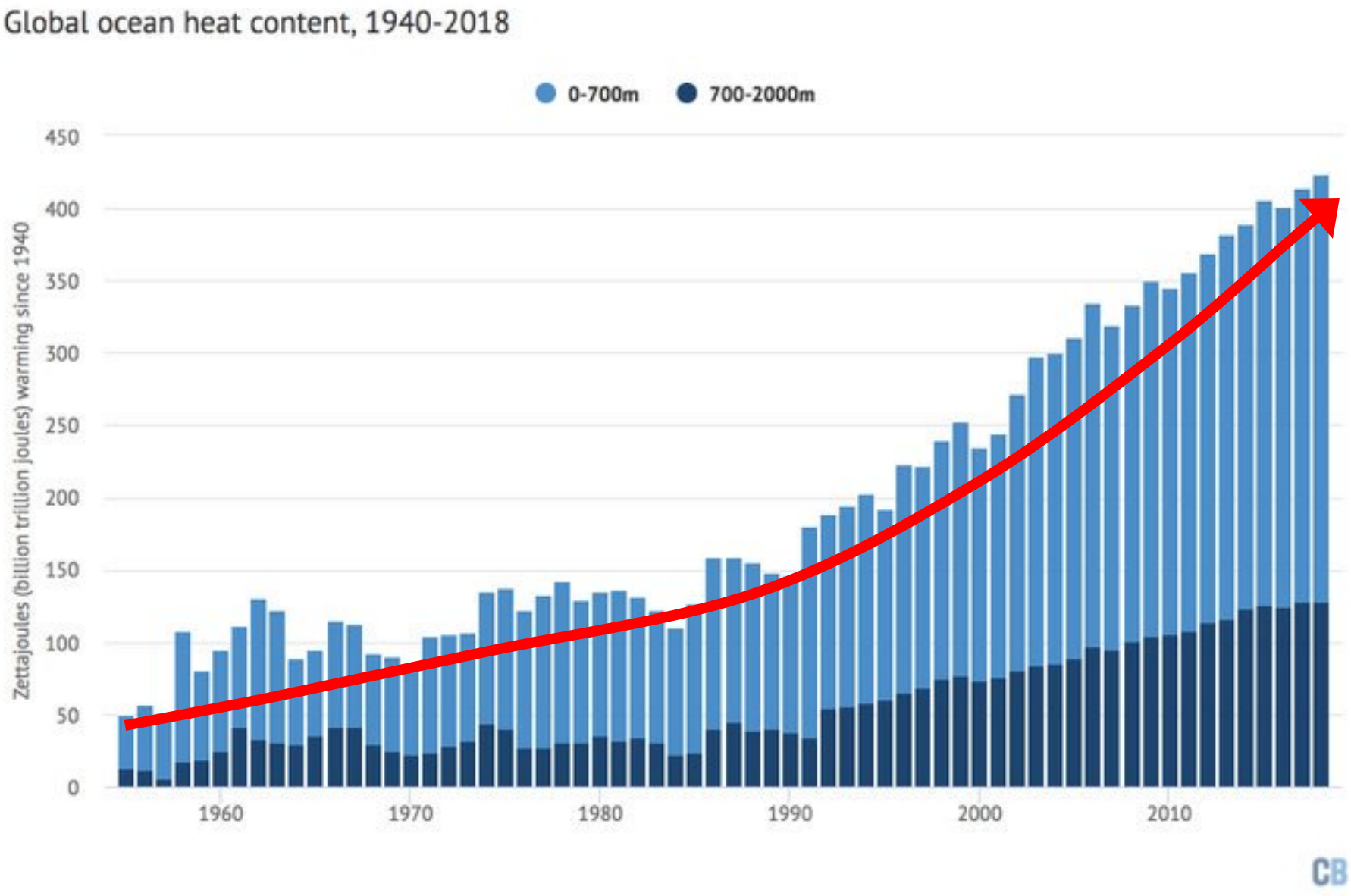
Several approaches have been developed to reconstruct the geometry of past sea-level change with similar spatial coverage as satellite altimetry and spanning the same period as the tide-gauge record[10–12]. These can roughly be divided into two types of approaches: probabilistic techniques based on the Kalman Smoother (KS) or Gaussian Process Regression[12–14], which fit known spatial patterns of individual sea-level contributors[15], also known as fingerprints, to tide-gauge records, and Reduced Space Optimal Interpolation (RSOI) techniques, which reconstruct the temporal amplitudes of a truncated set of empirical orthogonal functions (EOFs) calculated from satellite altimetry using tide-gauge data[10,11,16]. Probabilistic techniques provide robust and smooth reconstructions of long-term changes in sea level (including more realistic modelling of uncertainties) even if only a few tide gauges are available[12–14], but in their current set-up they fail in realistically reconstructing the interannual variability[17]. RSOI reconstructions, on the other hand, are generally capable of reconstructing interannual to decadal sea-level changes[18–20], although they have their limitations in accurately estimating long-term trends[14]. Consequently, while both groups of techniques have their individual advantages, neither is (as currently configured) able to reconstruct the full spectrum of global and regional sea-level change[18]. This conundrum contributes to the large differences between individual reconstructions before the 1970s[21,22] and therefore hampers placing the recent acceleration into the historical context of the twentieth century.

Our aim here is to combine low-frequency sea-level information from the KS[12] with high-frequency information from RSOI reconstructions to generate a hybrid reconstruction (HR) of global and regional sea-level during 1900–2015, which uses the techniques only at those time scales where they perform best. This is achieved by taking the low-frequency signal of the KS reconstruction (smoothed with a cut-off period of 15 years) at individual sites as a trend correction for each tide-gauge record. The residuals (with spectral power remaining at periods below 15 years) are then used in an iterative RSOI reconstruction with similarly detrended satellite altimetry data (see also Supplementary Fig. 1). The latter step also includes a gap-filling algorithm based on stepwise regression models with surface wind stress, sea-level pressure (SLP), sea surface temperature (SST), and neighbouring sites as predictors for minimizing gap-induced biases in the RSOI reconstruction (see Methods). Combining the low-frequency KS field with the high-frequency residual RSOI reconstruction provides a novel HR including high latitudes in the Arctic Ocean and around Antarctica. The HR of GMSL presented is based on the assimilation of 479 carefully selected tide-gauge records (see Methods).



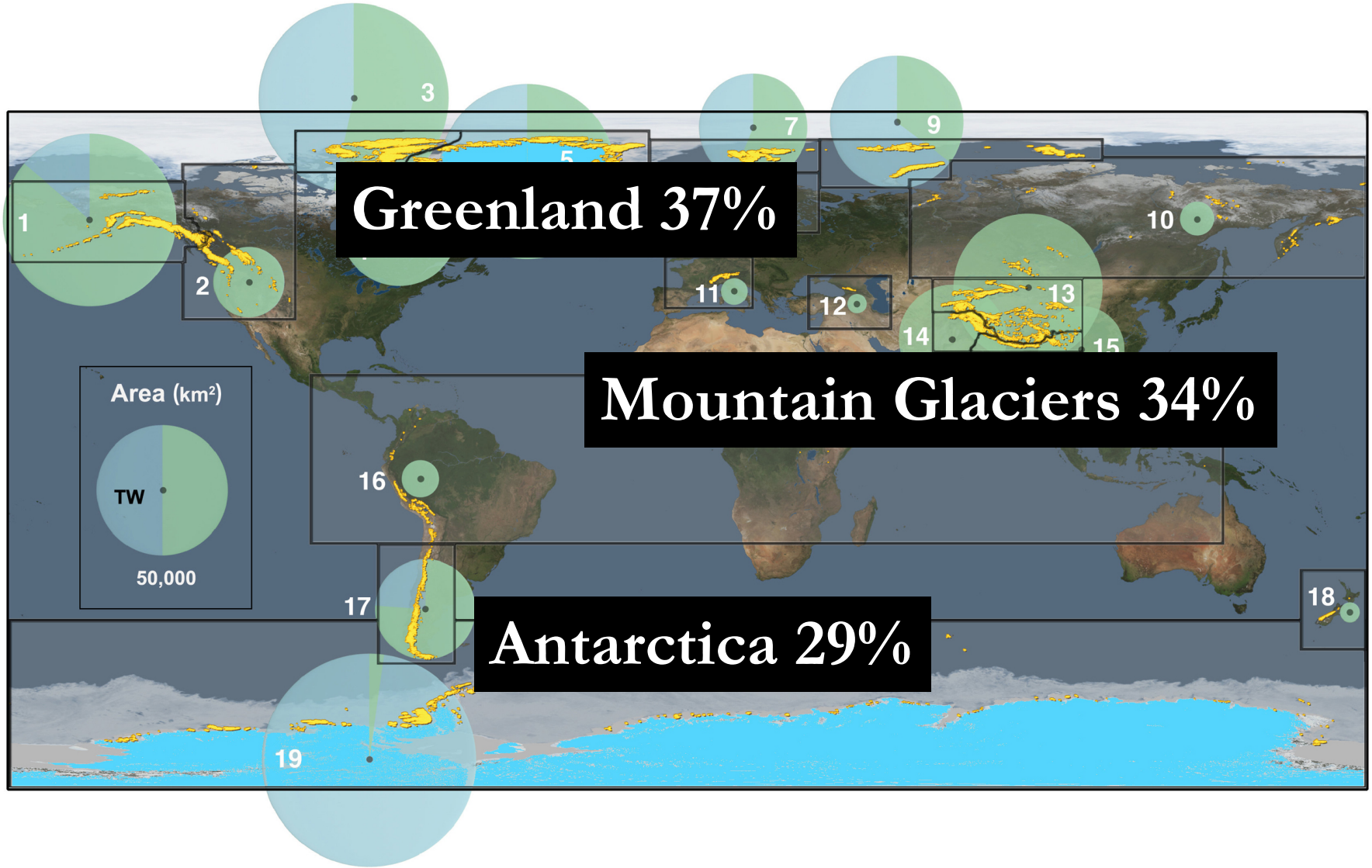
Dangendorf, S. et al. (2019) Persistent acceleration in global sea-level rise since the 1960s, Nature Climate Change: http://dx.doi.org/10.1038/s41558-019-0531-8. R. S. Nerem el al., "Climate-change–driven accelerated sea-level rise detected in the altimeter era," *PNAS* (2018). www.pnas.org/cgi/doi/10.1073/pnas.1717312115

The ocean is 40% hotter than previously thought.



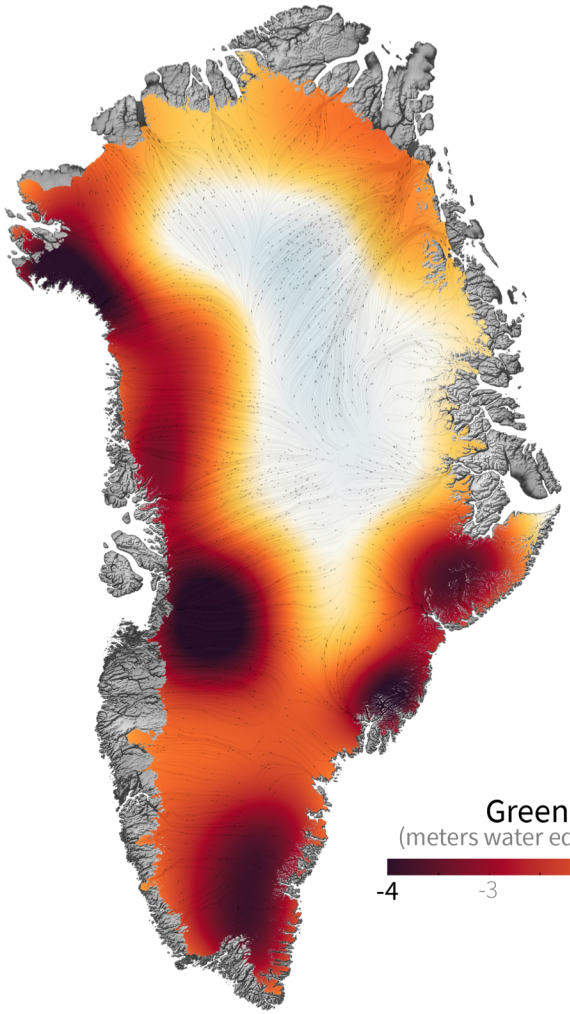
Cheng, L., et al. (2019) How fast are the oceans warming? *Science*, 2019 DOI: 10.1126/science.aav7619; Cheng L. J. Zhu, and J. Abraham, 2015: Global upper ocean heat content estimation: recent progress and the remaining challenges. Atmospheric and Oceanic Science Letters, 8. DOI:10.3878/AOSL20150031. ; Glecker, P.J., et al. (2016) Industrial era global ocean heat uptake doubles in recent decades. Nature Climate change. doi:10.1038/nclimate2915

665 Billion Tons of Ice Melt Each Year

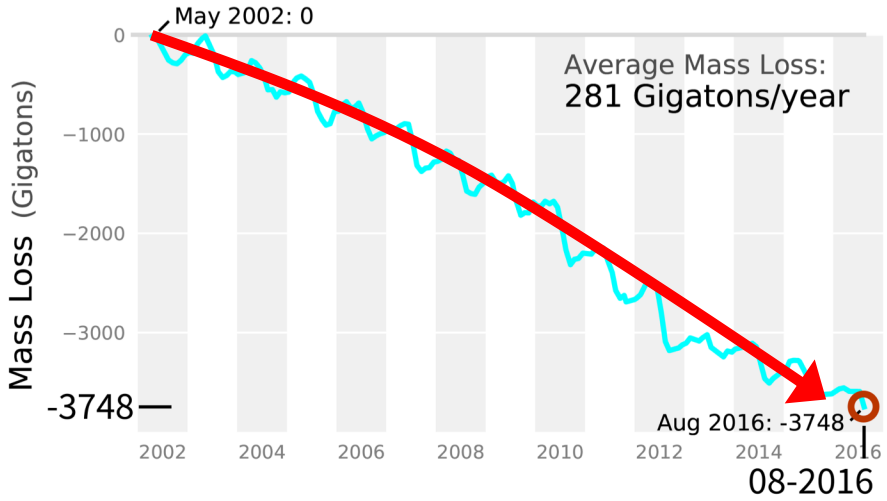


Bamber, J.L., et al (2018) The land ice contribution to sea level during the satellite era, Environ. Res. Lett. 13 https://doi.org/10.1088/1748-9326/aac2f0

Greenland faces a 66% chance that melting will become unstoppable at 1.8ºC

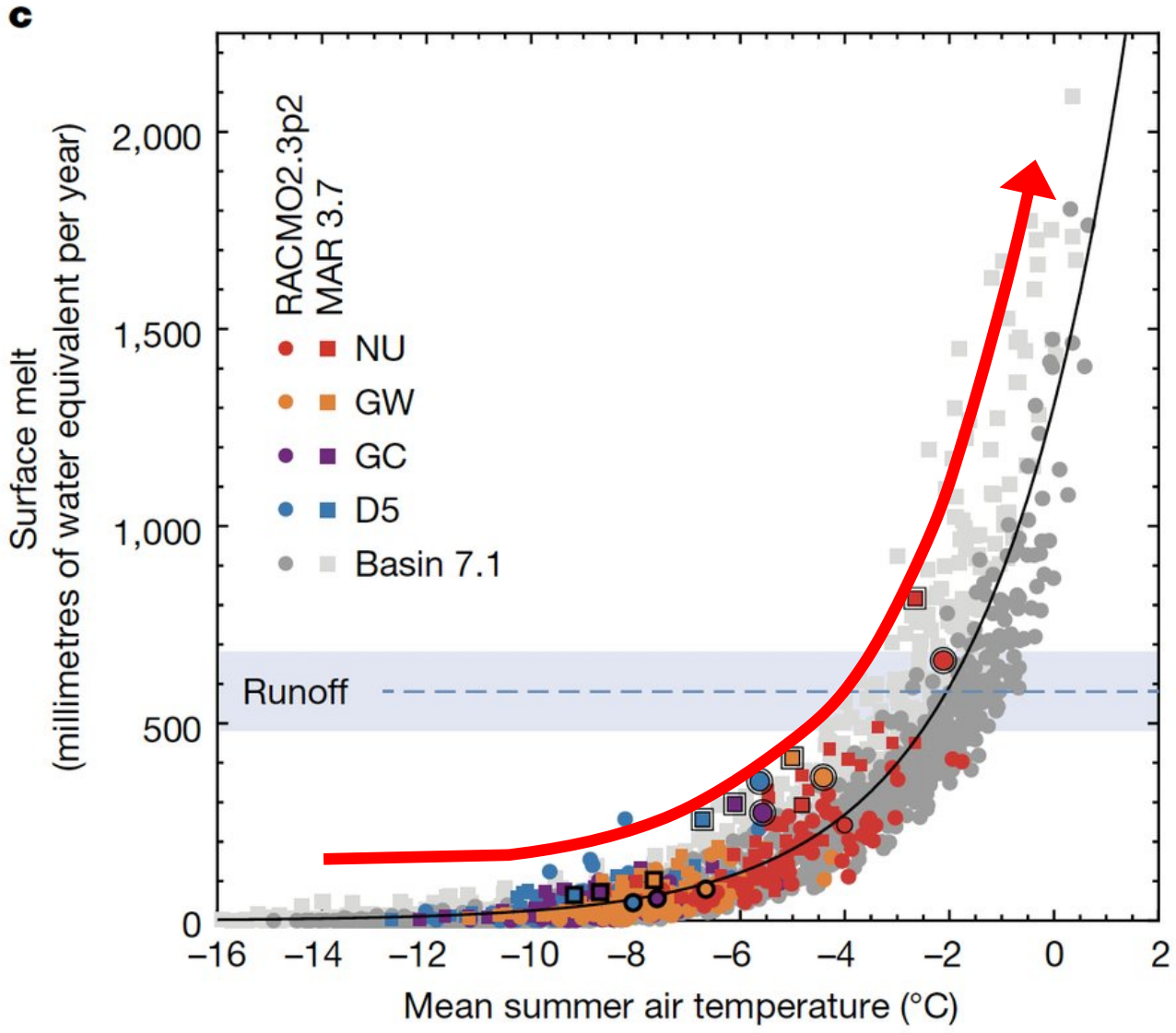


Ice loss, Gigatons



Trusel, et al., 2018 Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming, 104, *Nature*, v564, 6 December: https://doi.org/10.1038/s41586-018-0752-4

Greenland is exponentially melting

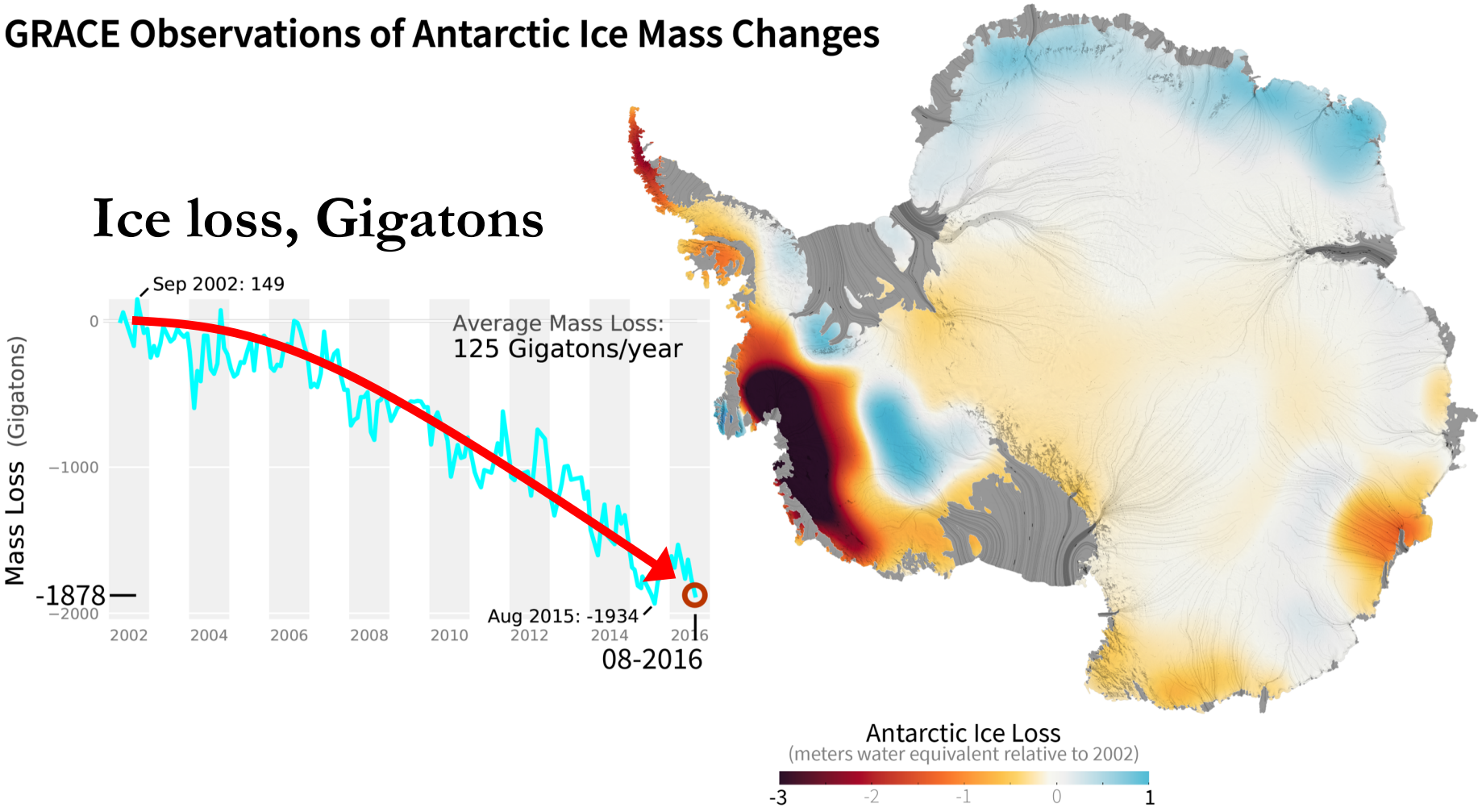


Melting 50% more than pre-industrial

33% more than 20th century

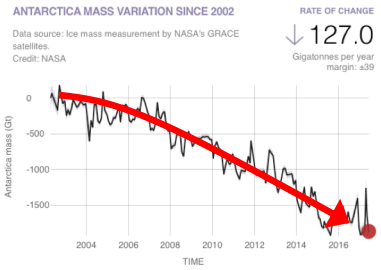
Trusel, et al., 2018 Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming, 104, *Nature*, v564, 6 December: https://doi.org/10.1038/s41586-018-0752-4

Antarctic ice melt has ‘tripled over the past five years’



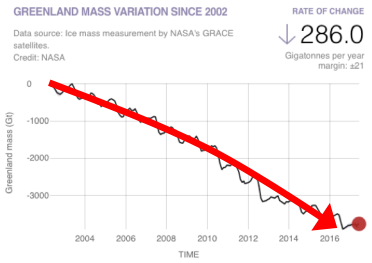
The IMBIE team (2018) Mass Balance of the Antarctic Ice Sheet, *Nature*, 558, pages219–222, https://doi.org/10.1038/s41586-018-0179-y

1 m only reflects past and current warming. We are still emitting GHG's and there is more warming (and faster melting) to come.



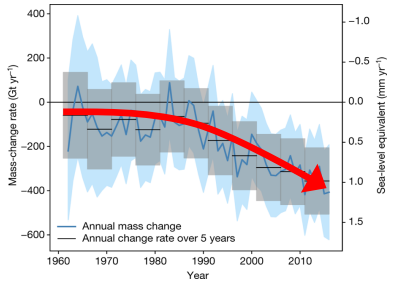
Antarctic ice loss

+



Greenland ice loss

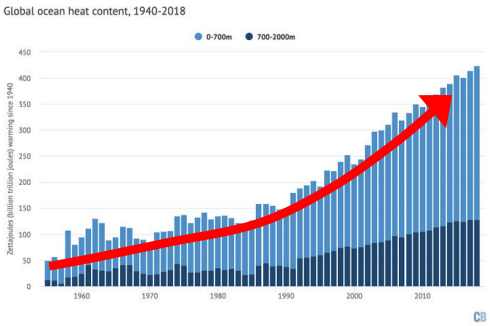
+



Mountain glacier ice loss

= 0.8 m

0.8 m +



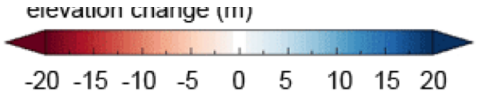
Thermal expansion

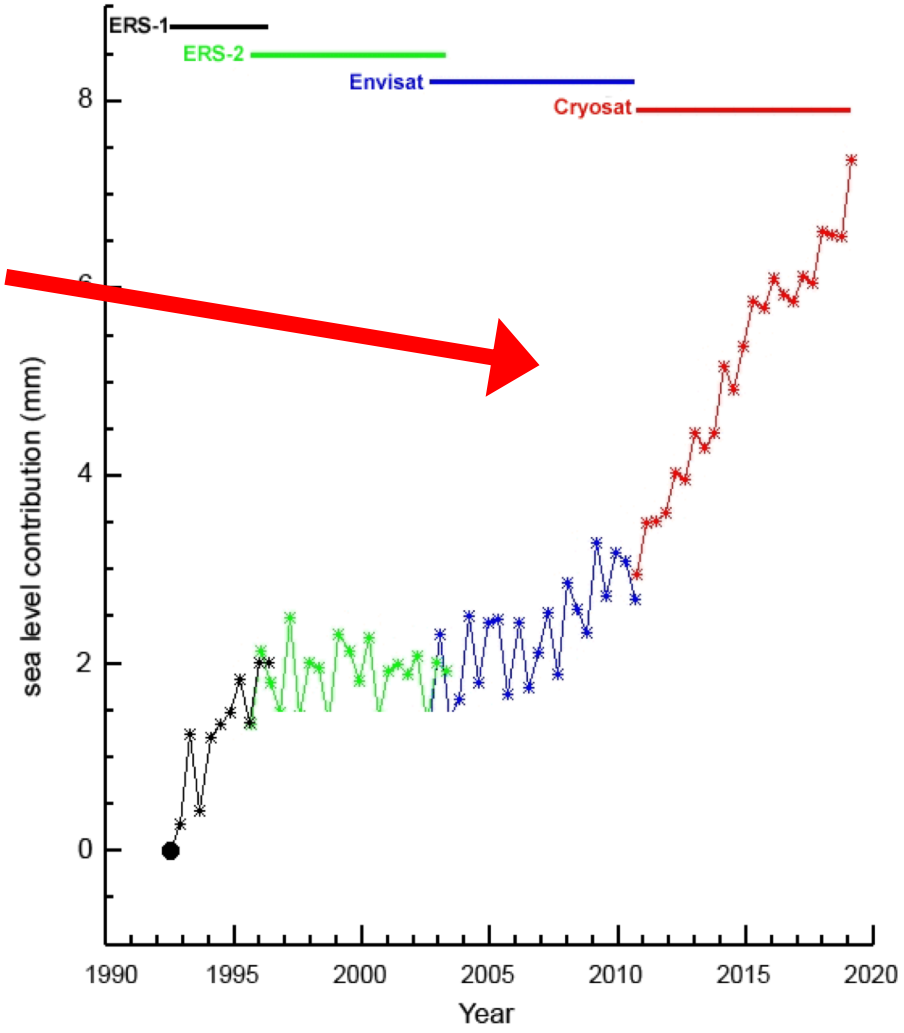
= 1 m by 2100

E. Rignot (2019) pers. comm.: http://sites.nationalacademies.org/SSB/SSB_191179

West Antarctica is losing ice 5 times faster than in the 1990s, more than 100m of thickness gone in some places

Is this a long-term accelerating trend, or is this variability?





Shepherd et al. (2019) Trends in Antarctic Ice Sheet Elevation and Mass. *Geophysical Research Letters*, May 16, 2019; DOI: 10.1029/2019GL082182

The Antarctic ice sheet remains the largest single source of uncertainty in projections of future sea-level rise.

Coastal communities cannot wait for Antarctic science to clear up.

Development projects are continuously ongoing and require long lead times.

Ice sheet contributions to future sea-level rise from structured expert judgment

Jonathan L. Bamber[a,1], Michael Oppenheimer[b,c], Robert E. Kopp[d,e], Willy P. Aspinall[f,g], and Roger M. Cooke[h,i]

[a]School of Geographical Sciences, University of Bristol, Bristol BS8 1SS, United Kingdom; [b]Department of Geosciences, Princeton University, Princeton, NJ 08544; [c]The Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ 08544; [d]Department of Earth & Planetary Sciences, Rutgers University, New Brunswick, NJ 08854; [e]Institute of Earth, Ocean, and Atmospheric Sciences, Rutgers University, New Brunswick, NJ 08901; [f]School of Earth Sciences, University of Bristol, Bristol BS8 1RJ, United Kingdom; [g]Aspinall & Associates, Tisbury SP3 6HF, United Kingdom; [h]Land, Water, and Nature, Resources for the Future, Washington, DC 20036; and [i]Department of Mathematics, Delft University of Technology, 2600 GA, Delft, The Netherlands

Edited by Stefan Rahmstorf, Potsdam Institute for Climate Impact Research, Potsdam, Germany, and accepted by Editorial Board Member Hans J. Schellnhuber April 8, 2019 (received for review October 5, 2018)

Despite considerable advances in process understanding, numerical modeling, and the observational record of ice sheet contributions to global mean sea-level rise (SLR) since the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change, severe limitations remain in the predictive capability of ice sheet models. As a consequence, the potential contributions of ice sheets remain the largest source of uncertainty in projecting future SLR. Here, we report the findings of a structured expert judgement study, using unique techniques for modeling correlations between inter- and intra-ice sheet processes and their tail dependences. We find that since the AR5, expert uncertainty has grown, in particular because of uncertain ice dynamic effects. For a +2 °C temperature scenario consistent with the Paris Agreement, we obtain a median estimate of a 26 cm SLR contribution by 2100, with a 95th percentile value of 81 cm. For a +5 °C temperature scenario more consistent with unchecked emissions growth, the corresponding values are 51 and 178 cm, respectively. Inclusion of thermal expansion and glacier contributions results in a global total SLR estimate that exceeds 2 m at the 95th percentile. Our findings support the use of scenarios of 21st century global total SLR exceeding 2 m for planning purposes. Beyond 2100, uncertainty and projected SLR increase rapidly. The 95th percentile ice sheet contribution by 2200, for the +5 °C scenario, is 7.5 m as a result of instabilities coming into play in both West and East Antarctica. Introducing process correlations and tail dependences increases estimates by roughly 15%.

sea-level rise | climate predictions | ice sheets | Greenland | Antarctica

Global mean sea-level rise (SLR), which during the last quarter century has occurred at an accelerating rate (1), averaging about +3 mm·y^{-1}, threatens coastal communities and ecosystems worldwide. Adaptation measures accounting for the changing hazard, including building or raising permanent or movable structures such as surge barriers and sea walls, enhancing nature-based defenses such as wetlands, and selective retreat of populations and facilities from areas threatened by episodic flooding or permanent inundation, are being planned or implemented in several countries. Risk assessment for such adaptation efforts requires projections of future SLR, including careful characterization and evaluation of uncertainties (2) and regional projections that account for ocean dynamics, gravitational and rotational effects, and vertical land motion (3). During the nearly 40 y since the first modern, scientific assessments of SLR, understanding of the various causes of this rise has advanced substantially. Improvements during the past decade include closing the historic sea-level budget, attributing global mean SLR to human activities, confirming acceleration of SLR since the nineteenth century and during the satellite altimetry era, and developing analytical frameworks for estimating regional and local mean sea level and extreme water level changes. Nonetheless, long-term SLR projections remain acutely uncertain, in large part because of inadequate understanding of the sheets and their responses to future global climate change. This limitation is especially troubling, given that the ice sheet influence on SLR has been increasing since the 1990s (4) and has overtaken mountain glaciers to become the largest barystatic (mass) contribution to SLR (5). In addition, for any given future climate scenario, the ice sheets constitute the component with the largest uncertainties by a substantial margin, especially beyond 2050 (6).

Advances since the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (7) include improved process understanding and representation in deterministic ice sheet models (8, 9), probabilistic projections calibrated against these models and the observational record (10), and new semiempirical models, based on the historical relationship between temperature and sea-level changes. Each of these approaches has limitations that stem from factors including poorly understood processes, poorly constrained boundary conditions, and a short (~25 y) satellite observation record of ice sheets that does not capture the time scales of internal variability in the ice sheet climate system. As a consequence, it is unclear to what extent recent observed ice sheet changes (11) are a result of internal variability (ice sheet weather) or external forcing (ice sheet climate).

Significance

Future sea level rise (SLR) poses serious threats to the viability of coastal communities, but continues to be challenging to project using deterministic modeling approaches. Nonetheless, adaptation strategies urgently require quantification of future SLR uncertainties, particularly upper-end estimates. Structured expert judgement (SEJ) has proved a valuable approach for similar problems. Our findings, using SEJ, produce probability distributions with long upper tails that are influenced by interdependencies between processes and ice sheets. We find that a global total SLR exceeding 2 m by 2100 lies within the 90% uncertainty bounds for a high emission scenario. This is more than twice the upper value put forward by the Intergovernmental Panel on Climate Change in the Fifth Assessment Report.

Author contributions: J.L.B., M.O., and R.E.K. designed research; J.L.B., M.O., R.E.K., W.P.A., and R.M.C. performed research; W.P.A. and R.M.C. analyzed data; and J.L.B. and M.O. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission. S.R. is a guest editor invited by the Editorial Board.

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Data deposition: The data sets and workshop materials are available from the University of Bristol permanent repository, https://data.bris.ac.uk/data/dataset/23k1jbtan6sjv2huakf63cqgav.

[1]To whom correspondence may be addressed. Email: j.bamber@bristol.ac.uk.

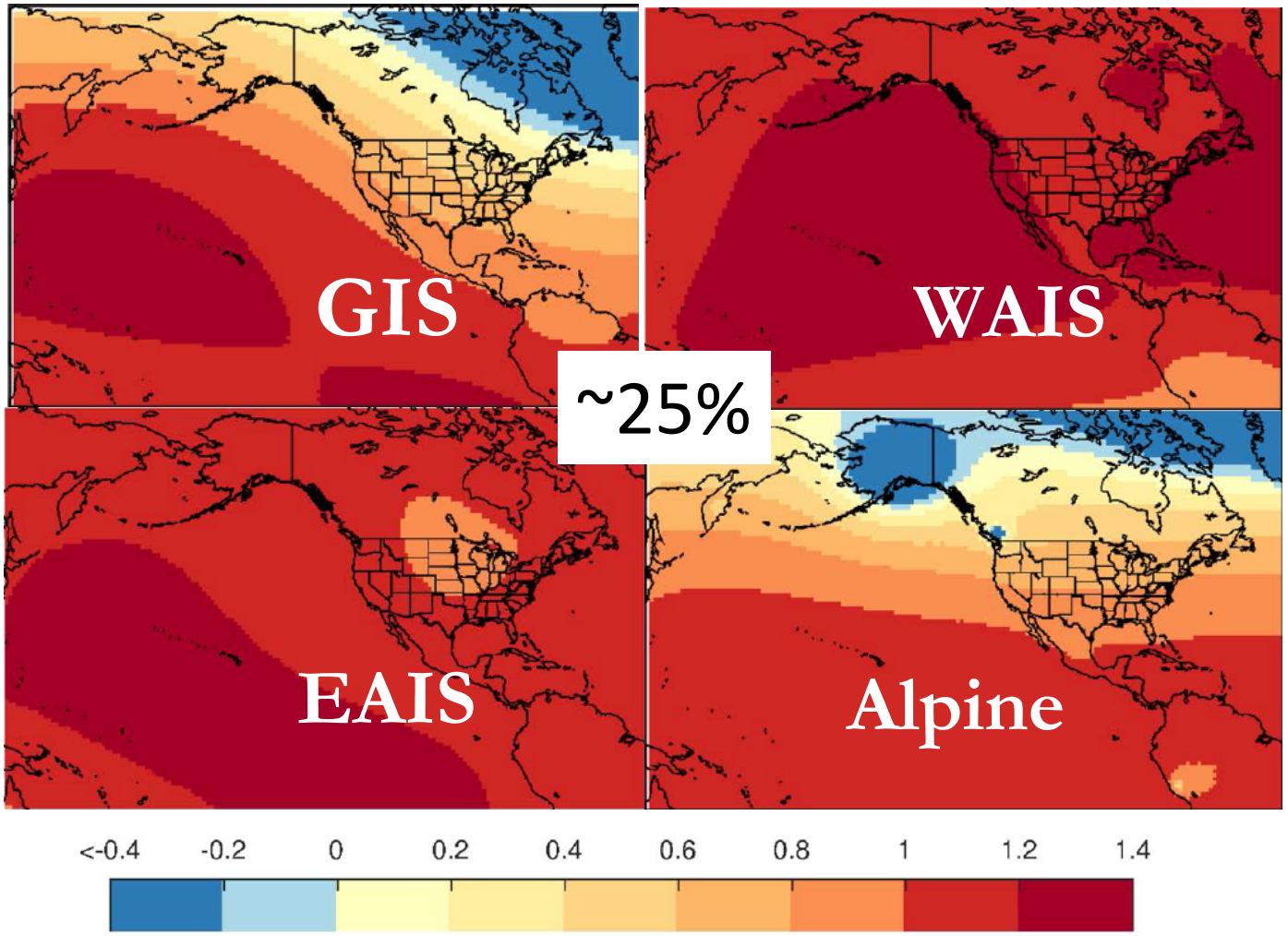
This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.

A survey of global experts found a 10% chance of sea level exceeding **2 m (6.5 ft) by 2100**.

On our current emissions path, sea level will exceed **7.5 m by 2200** and **9.7 m by 2300**.

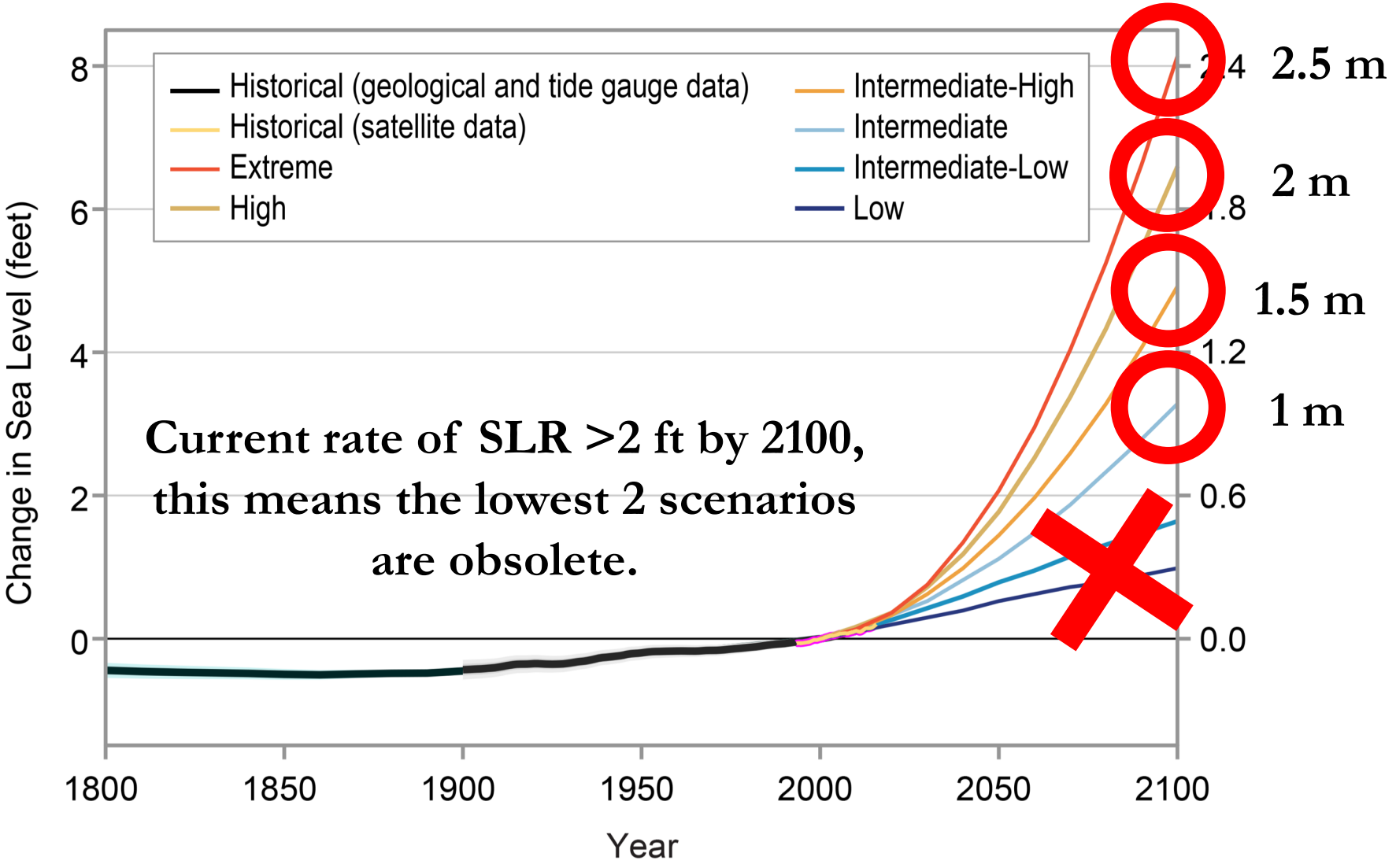
J. L. Bamber, et al. (2019 Ice sheet contributions to future sea-level rise from structured expert judgment. *Proceedings of the National Academy of Sciences*, May 20, 2019; DOI: 10.1073/pnas.1817205116

Hawai‘i can expect SLR greater than the global mean



Scenario
Planning

NOAA & 4thNCA SLR Scenarios



Sweet, W.V., et al. 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, https://science2017.globalchange.gov/chapter/12/

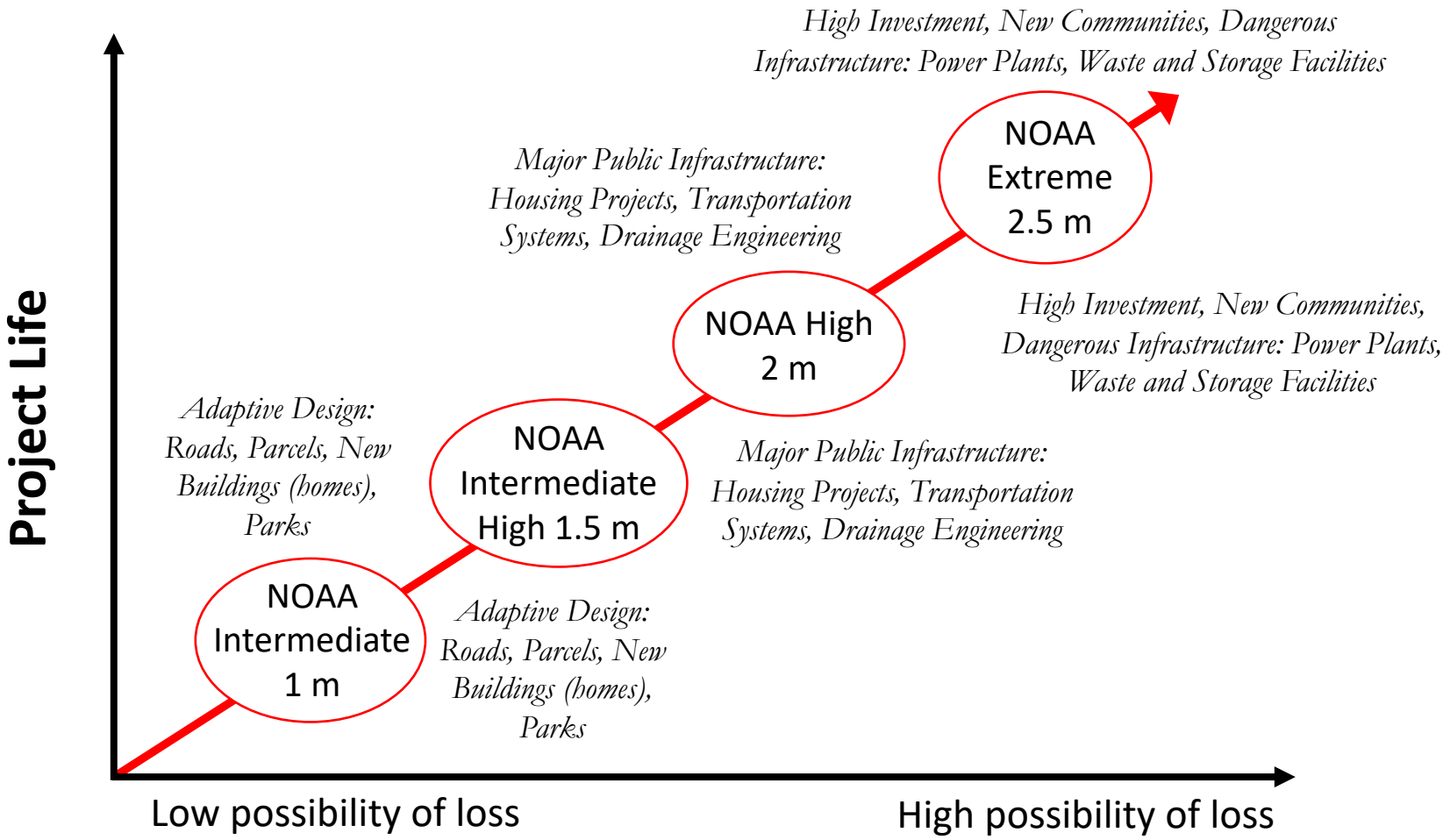
SLR Scenario Timing NOAA

GMSL Scenario (m)	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2120	2150	2200
Low	0.03	0.06	0.09	0.13	0.16	0.19	0.22	0.25	0.28	0.30	0.34	0.37	0.39
Intermediate-Low	0.04	0.08	0.13	0.18	0.24	0.29	0.35	0.4	0.45	0.50	0.60	0.73	0.95
Intermediate	0.04	0.10	0.16	0.25	0.34	0.45	0.57	0.71	0.85	1.0	1.3	1.8	2.8
Intermediate-High	0.05	0.10	0.19	0.30	0.44	0.60	0.79	1.0	1.2	1.5	2.0	3.1	5.1
High	0.05	0.11	0.21	0.36	0.54	0.77	1.0	1.3	1.7	2.0	2.8	4.3	7.5
Extreme	0.04	0.11	0.24	0.41	0.63	0.90	1.2	1.6	2.0	2.5	3.6	5.5	9.7

Sweet, W.V., et al. 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, https://science2017.globalchange.gov/chapter/12/

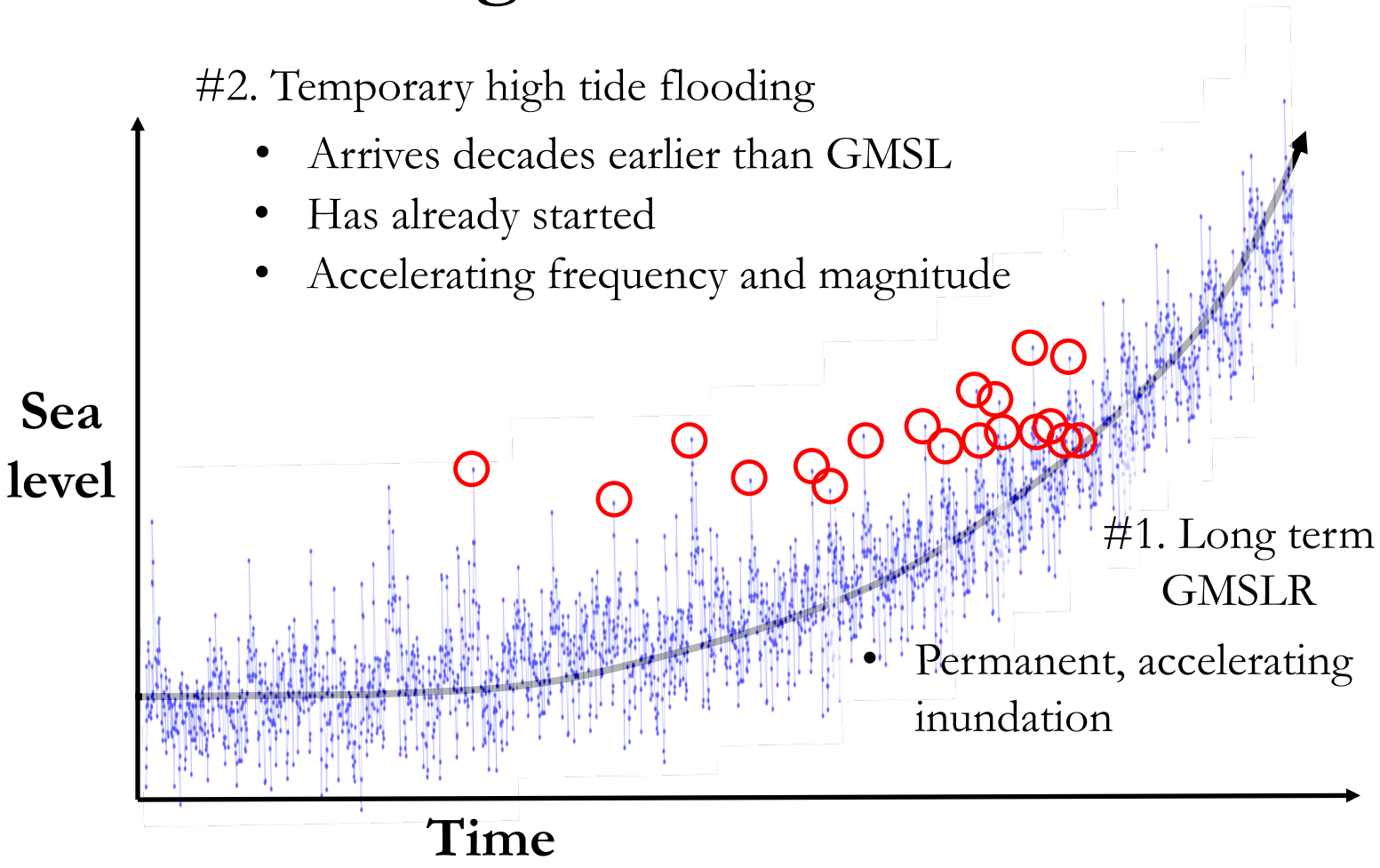
SLR Scenario Planning

decision-making under conditions of uncertainty



Risk – Possibility of losing something of value

SLR Flooding: Nuisance and Permanent



JGR Oceans

RESEARCH ARTICLE
10.1029/2018JC014741

A Statistical Model for Frequency of Coastal Flooding in Honolulu, Hawaii, During the 21st Century

Philip R. Thompson[1], Matthew J. Widlansky[2], Mark A. Merrifield[3], Janet M. Becker[3], and John J. Marra[4]

[1]Department of Oceanography, University of Hawai'i at Mānoa, Honolulu, HI, USA, [2]Joint Institut
Atmospheric Research, University of Hawai'i at Mānoa, Honolulu, HI, USA, [3]Scripps Institution o
University of California, San Diego, San Diego, CA, USA, [4]NOAA/NESDIS/National Centers for En
Information, Inouye Regional Center, Honolulu, HI, USA

Key Points:
- The highest sea level events in Honolulu tend to cluster together in time
- Decadal modulations of tidal amplitude temporarily reduce or enhance impacts of sea level rise
- Transitions from occasional to chronic threshold exceedance can occur in less than a decade

Supporting Information:
- Supporting Information S1

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P. R. Thompson,
philiprt@hawaii.edu

Citation:
Thompson, P. R., Widlansky, M. J., Merrifield, M. A., Becker, J. M., & Marra, J. J. (2019). A statistical model for frequency of coastal flooding in Honolulu, Hawaii, during the 21st century. *Journal of Geophysical Research: Oceans*, *124*. https://doi.org/10.1029/2018JC014741

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Abstract The state of Hawaii and city of Honolulu experienced an unprecedente
flooding episodes during 2017 due to the combination of seasonal high tides an
levels. To quantify the impact of sea level rise on the tendency for floodin
we developed a hierarchical statistical model describing the numbe
exceeds a prescribed threshold in Honolulu as a function of an
of the highest tides. Based on this model, we generate pr
for the 21st century, which show pronounced infle
interaction between sea level rise and long-p
of the projections demonstrates how pla
flooding impacts during inevitabl
expected in a probabilistic sense. The projections also show the potential for rapid, subdecadal transitions from occasional to chronic threshold exceedance during the second half of the century, suggesting that implementation of adaptation and mitigation strategies may need to begin prior to the emergence of occasional minor impacts in affected areas.

Transitions from occasional to chronic flooding can occur in less than a decade.

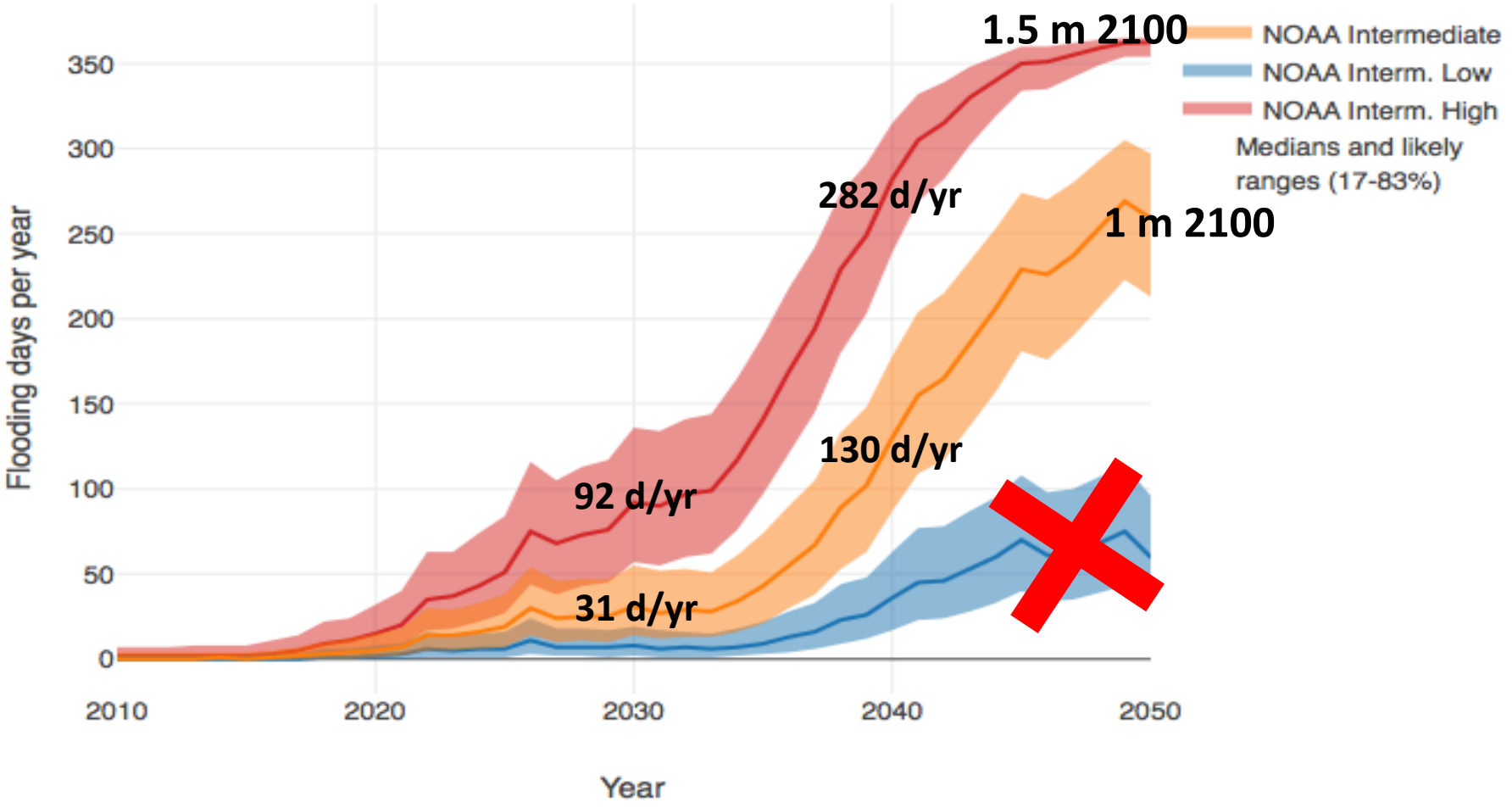
1. Introduction

The state of Hawaii and the city of Honolulu face considerable challenges from sea level rise (SLR) due to the concentration of residents, infrastructure, high-value assets, and economic activity in the coastal zone (Hawai'i Climate Change Mitigation and Adaptation Commission, 2017). Despite these vulnerabilities, most of Hawaii has not yet experienced the routine, disruptive flooding that affects many coastal urban areas on the U.S. Atlantic Coast, such as the cities of Miami (Wdowinski et al., 2016), Norfolk (Hall et al., 2016; Sweet et al., 2014), and Boston (Ray & Foster, 2016). During 2017, however, the city of Honolulu and locations around the state of Hawaii experienced an unprecedented number of high-water episodes (Yoon et al., 2018), which included the highest hourly water level recorded by the tide gauge in Honolulu Harbor (1905 to present, Figure 1a). These events resulted in repeated overwash of famed Waikiki Beach and minor flooding of inland roads and parking lots, generating significant media attention and prompting concern about the impending impacts of SLR across the state (e.g., LaFrance, 2017).

The greatest flooding impacts experienced in Honolulu during 2017 occurred when sea levels reached approximately 35 cm above mean higher high water (MHHW), which is a vertical datum defined as the average of daily maximum water levels during the U.S. National Tidal Datum Epoch (NTDE, 1983–2001). The 35-cm threshold was qualitatively established by matching time stamps of photographs from a citizen science project documenting flooding impacts (University of Hawai'i Sea Grant College Program, 2016) to water levels recorded by the tide gauge in Honolulu Harbor. Since the gauge was established in 1905, the 35-cm threshold has been exceeded for at least 1 hr on 37 distinct days (referred to herein as *exceedance days*). Fifteen (or 40%) of these days occurred during a single 5-month period from April to August 2017.

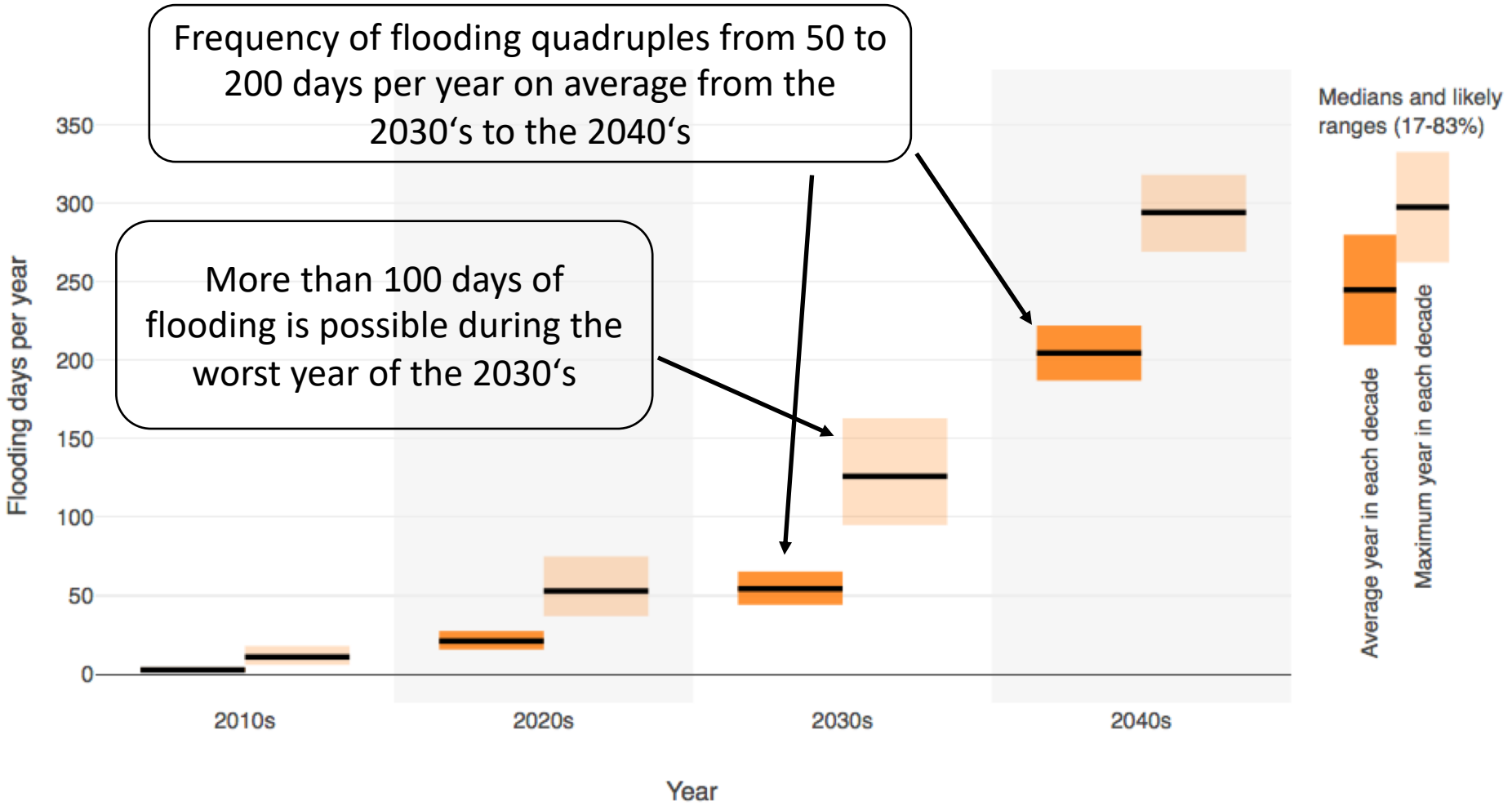
Tallying the exceedance days in calendar years demonstrates the anomalous nature of 2017 compared to previous years, as no other year experienced more than four exceedance days above the 35-cm threshold (Figure 1b). The effect of ongoing SLR manifests in the absence of exceedances prior to the 1960s, but

High Tide Flooding in Coastal Honolulu by Decade



Thompson et al. (2019) A statistical model for frequency of coastal flooding in Honolulu Hawaii, during the 21st Century, JGR Oceans, 10.1029/2018JC014741
UH Sea Level Center: https://uhslc-flooding-test.soest.hawaii.edu

High Tide Flooding in Coastal Honolulu by Decade



Thompson et al. (2019) A statistical model for frequency of coastal flooding in Honolulu Hawaii, during the 21st Century, JGR Oceans, 10.1029/2018JC014741
UH Sea Level Center: https://uhslc-flooding-test.soest.hawaii.edu

High tide flooding is occurring with greater frequency

Storm Drain Backflow

At high tide the water table is only 60 cm below the ground surface in Waikiki

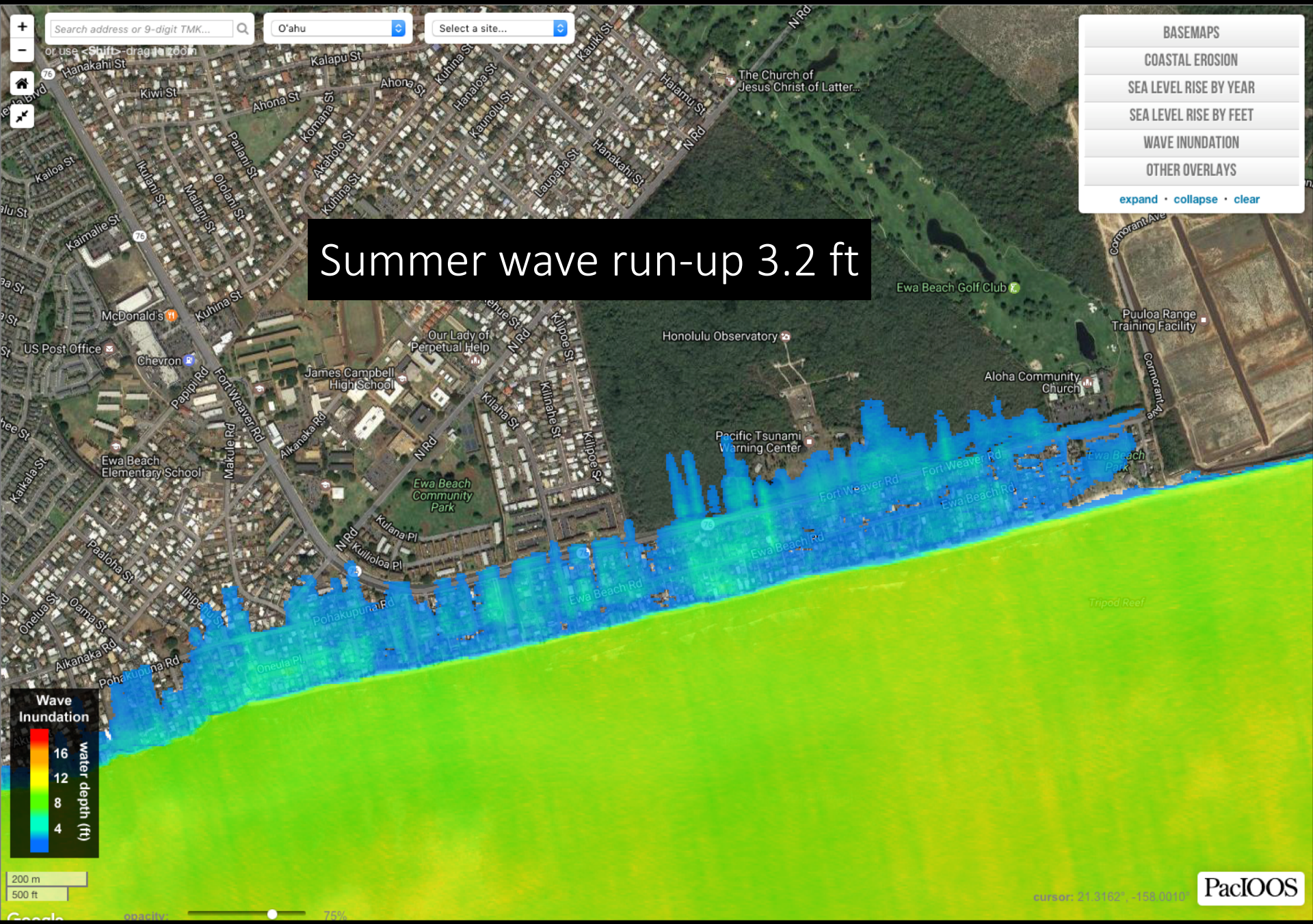
Groundwater Inundation

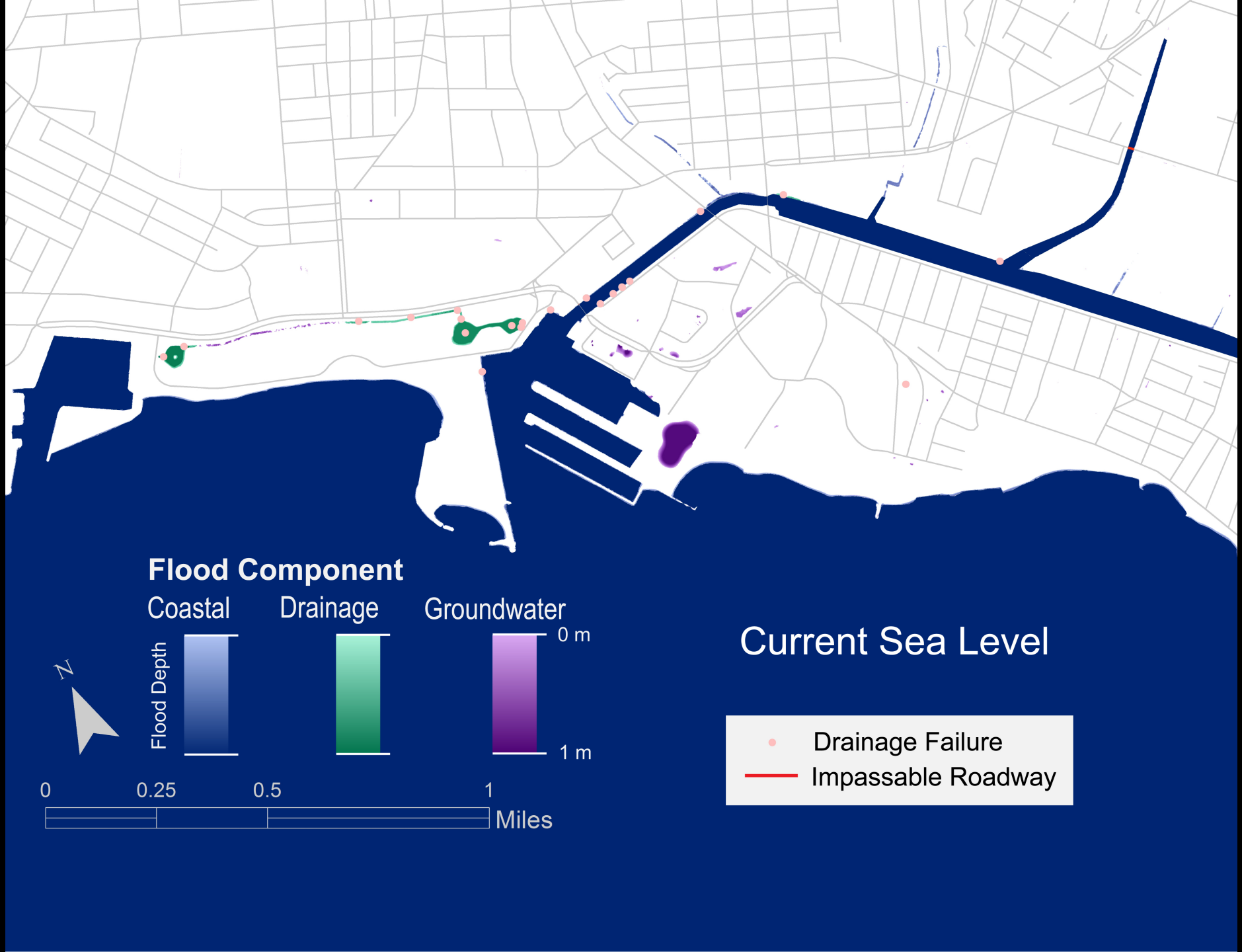
Heavy rains at high tide cause urban flooding

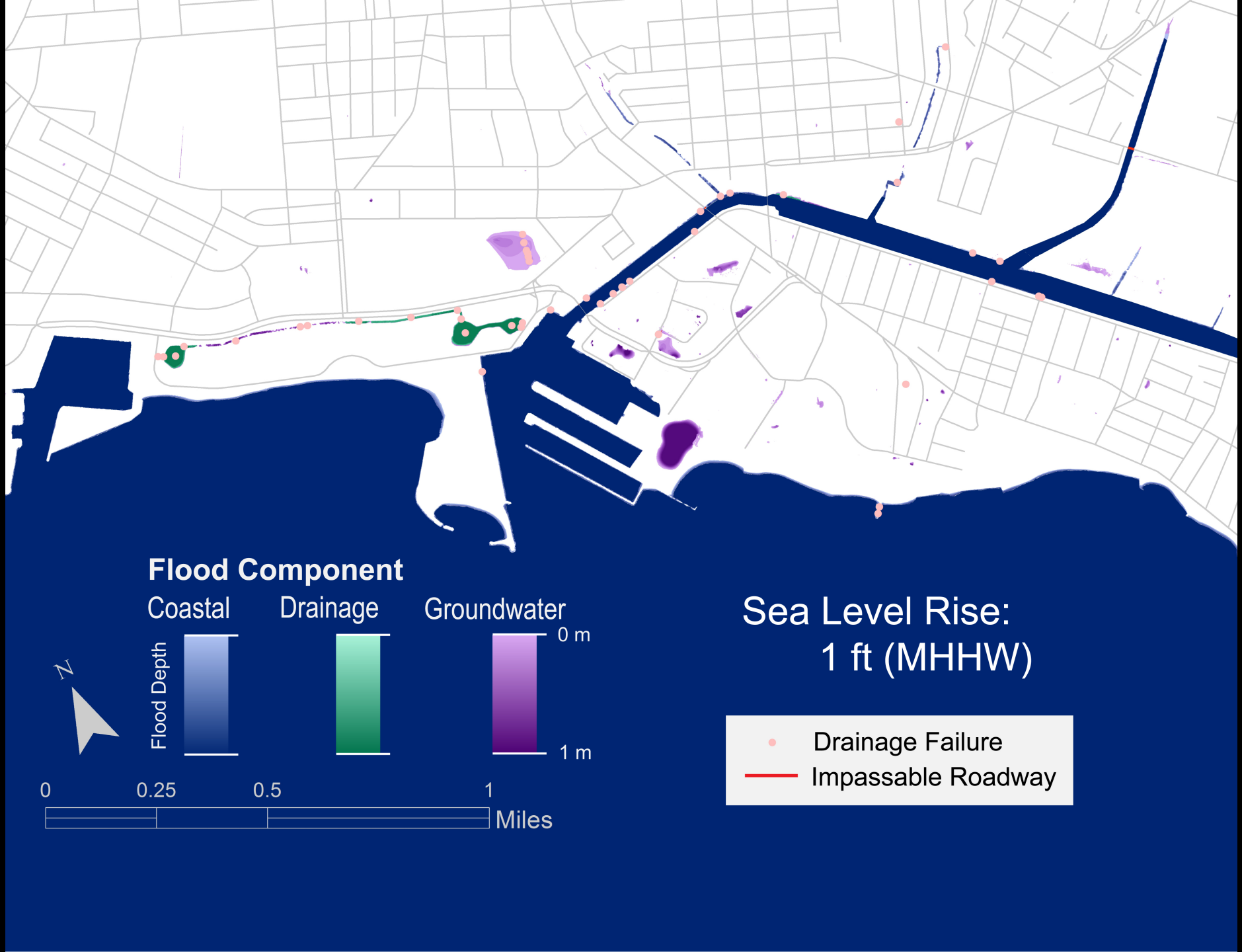
Disruptive High Tide Flooding rapid increase over next 1 to 3 decades

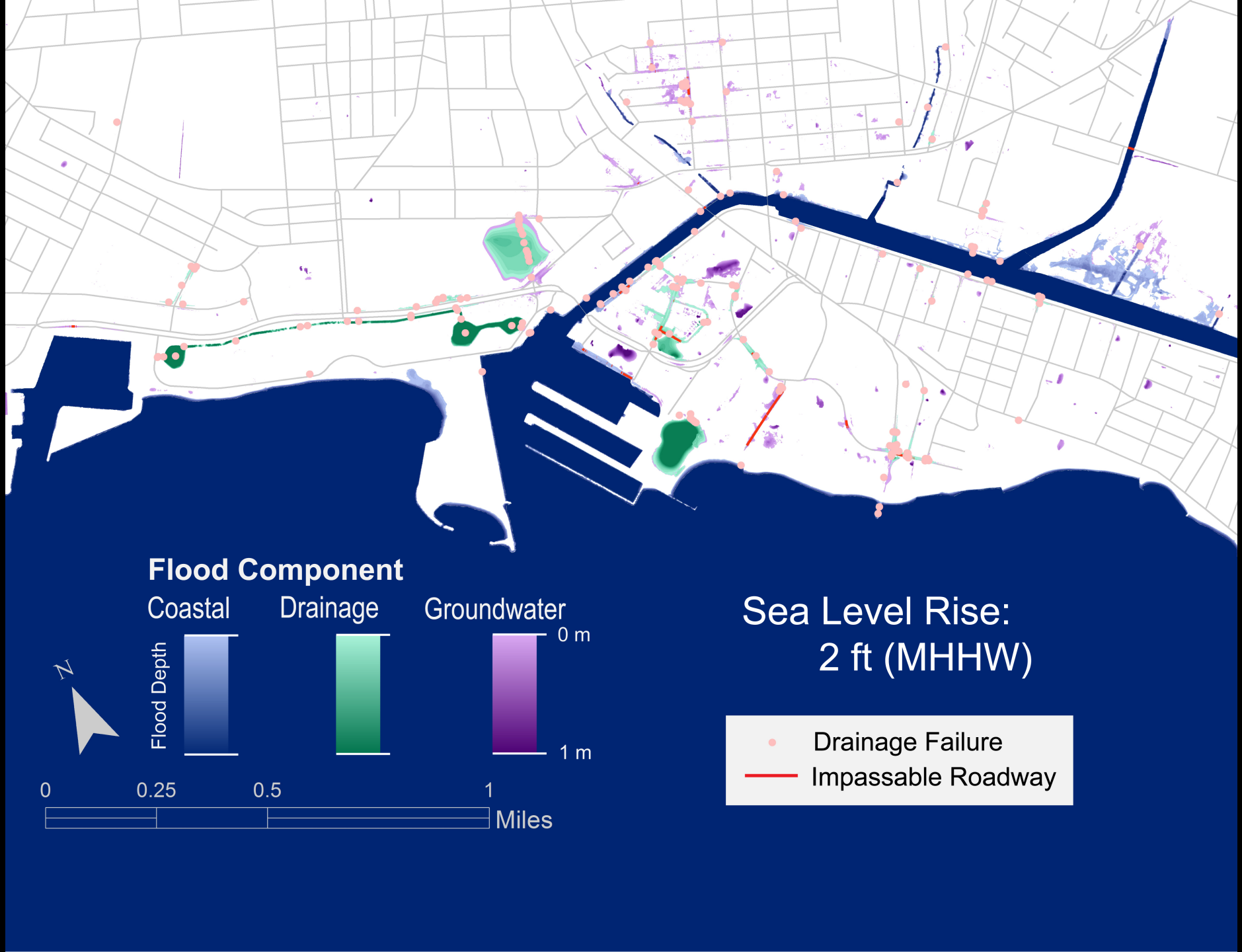
Groundwater Pollution

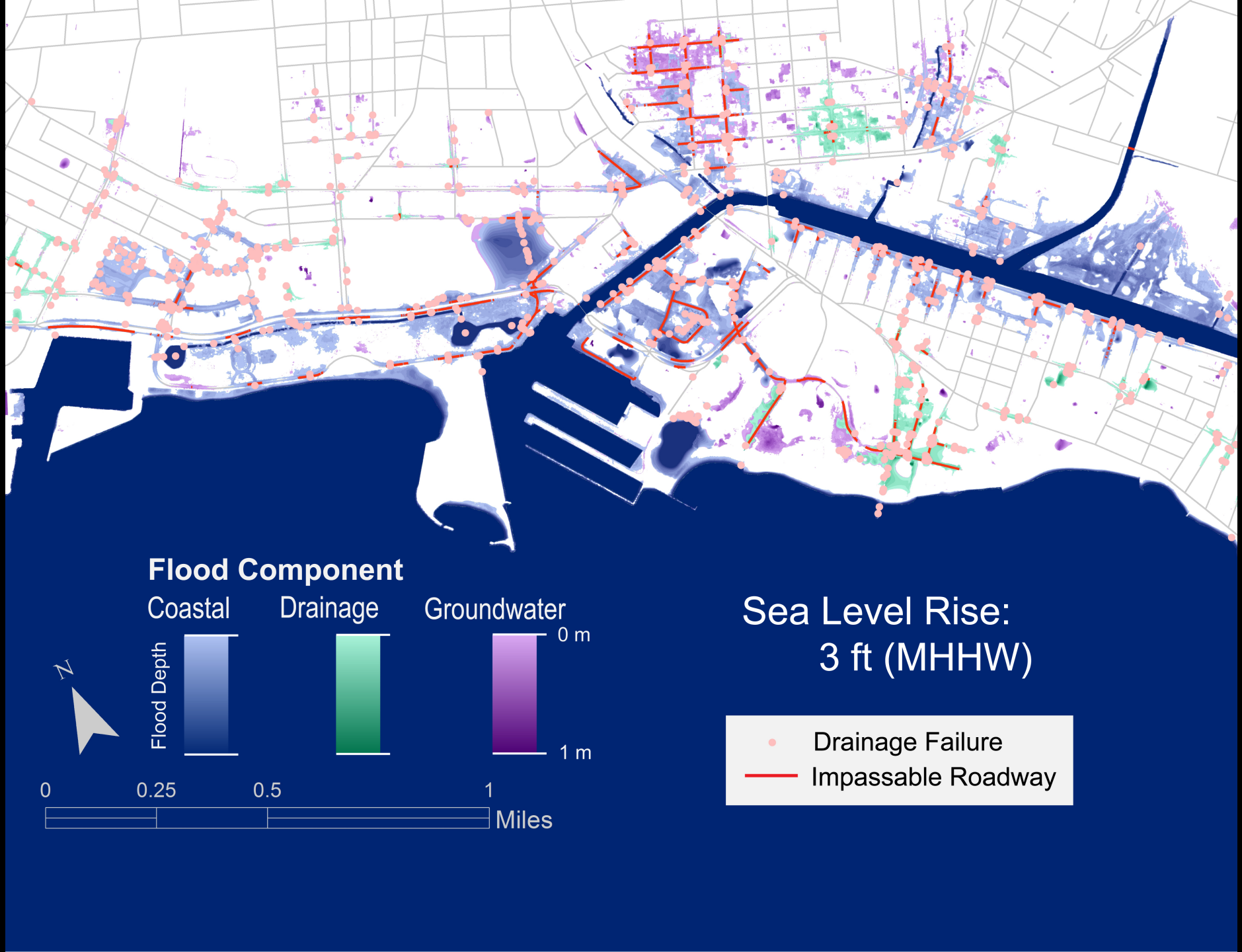
Search address or 9-digit TMK...
or use <Shift>-drag to zoom
O'ahu
Select a site...
BASEMAPS
COASTAL EROSION
SEA LEVEL RISE BY YEAR
SEA LEVEL RISE BY FEET
WAVE INUNDATION
OTHER OVERLAYS
expand • collapse • clear
Summer wave run-up 2ft
Wave Inundation
16
12
8
4
water depth (ft)
200 m
500 ft
PacIOOS

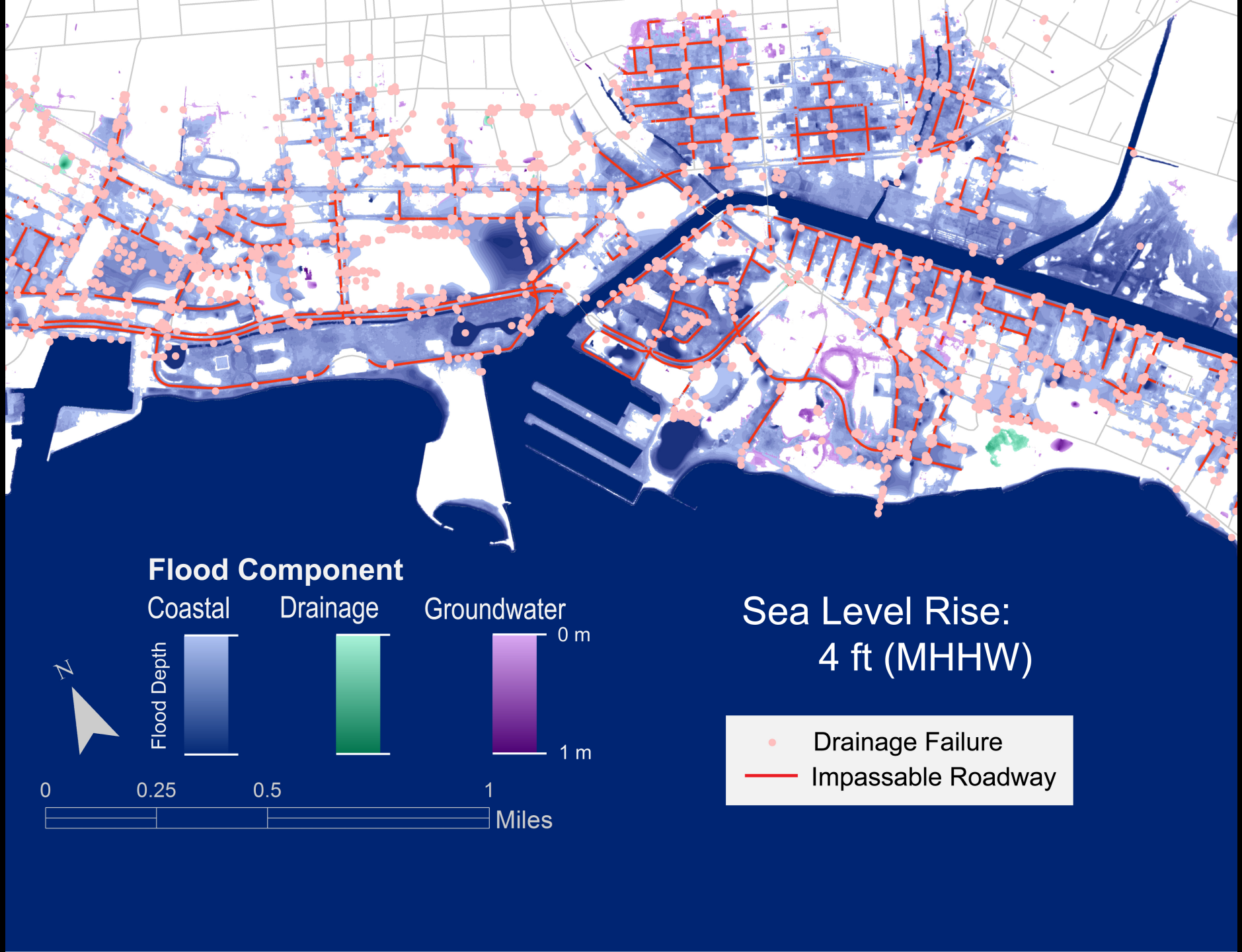

Search address or 9-digit TMK...
or use <Shift>-drag to zoom
O'ahu
Select a site...
BASEMAPS
COASTAL EROSION
SEA LEVEL RISE BY YEAR
SEA LEVEL RISE BY FEET
WAVE INUNDATION
OTHER OVERLAYS
expand • collapse • clear
Summer wave run-up 3.2 ft
Wave Inundation
16
12
8
4
water depth (ft)
200 m
500 ft
opacity:
75%
cursor: 21.3162°, -158.0010°
PacIOOS

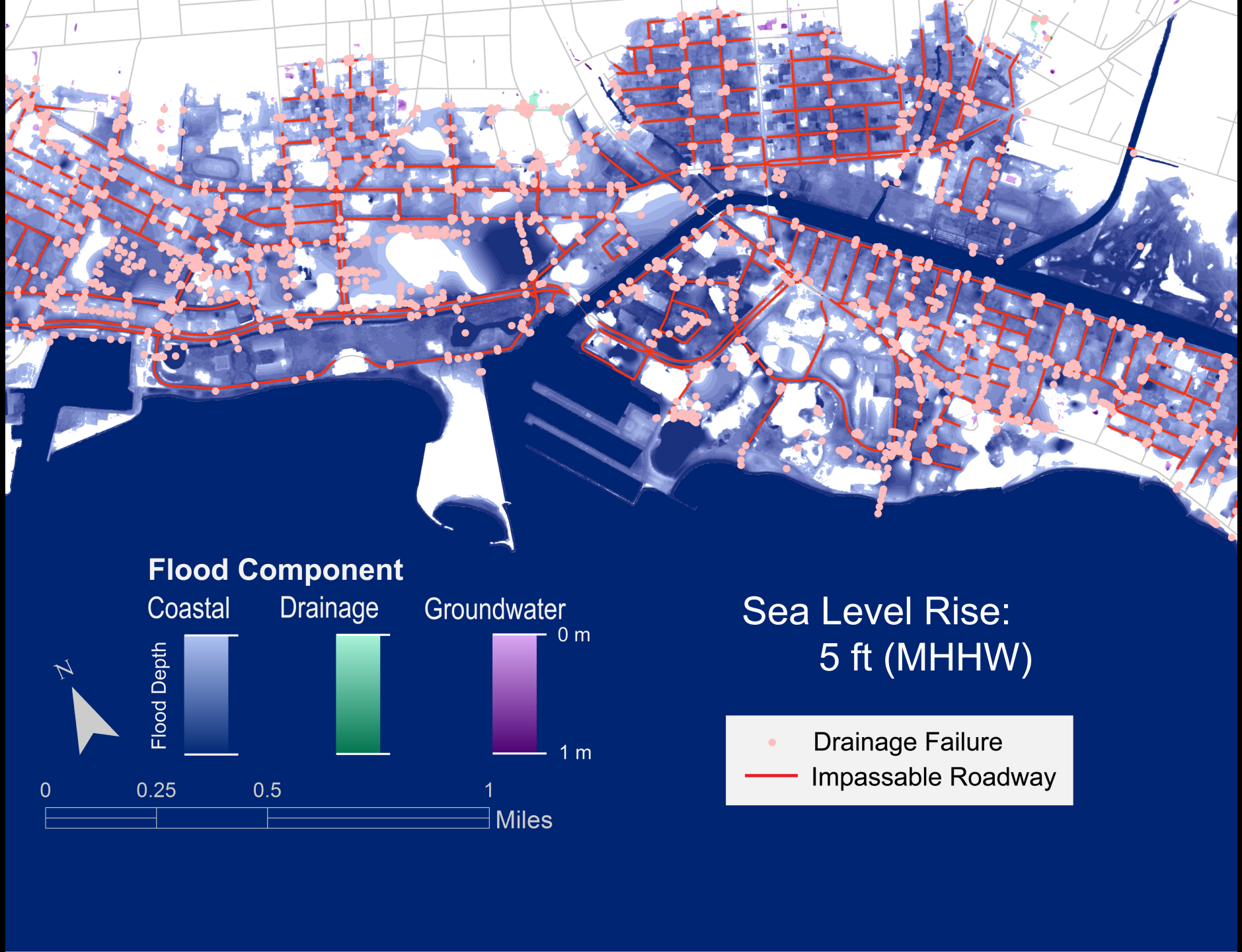

Flood Component
Coastal
Drainage
Groundwater
Flood Depth
0 m
1 m
N
0
0.25
0.5
1
Miles
Current Sea Level
Drainage Failure
Impassable Roadway


Flood Component
Coastal
Drainage
Groundwater
Flood Depth
0 m
1 m
N
0
0.25
0.5
1
Miles
Sea Level Rise:
1 ft (MHHW)
Drainage Failure
Impassable Roadway


Flood Component
Coastal
Drainage
Groundwater
Flood Depth
0 m
1 m
N
0
0.25
0.5
1
Miles
Sea Level Rise:
2 ft (MHHW)
Drainage Failure
Impassable Roadway


Flood Component
Coastal
Drainage
Groundwater
Flood Depth
0 m
1 m
N
0
0.25
0.5
1
Miles
Sea Level Rise:
3 ft (MHHW)
Drainage Failure
Impassable Roadway


Flood Component
Coastal
Drainage
Groundwater
Flood Depth
0 m
1 m
N
0
0.25
0.5
1
Miles
Sea Level Rise:
4 ft (MHHW)
Drainage Failure
Impassable Roadway


Flood Component
Coastal
Drainage
Groundwater
Flood Depth
0 m
1 m
N
0
0.25
0.5
1
Miles
Sea Level Rise:
5 ft (MHHW)
Drainage Failure
Impassable Roadway

The Erosion
Problem

Honokowai Kaanapali Beach Club

Honokowai Kaanapali Beach Club

Honokowai Kaanapali Beach Club

Honokowai Kaanapali Beach Club

Kaanapali Hyatt

Kaanapali Hyatt

Kaanapali Beach Hotel

Kahana Reef

Royal Kahana

Royal Kahana

Royal Kahana

Kahana Sands

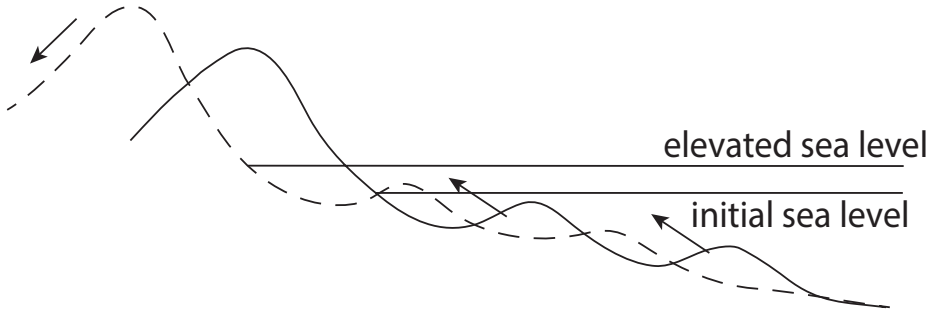
Kahului Wastewater Plant

Kihei, Halama Street

Chronic Erosion

- 140 miles
- 120 bridges
- 10-15% all roads
- $7.5M per lane mile
- $14M per bridge
- $15B total

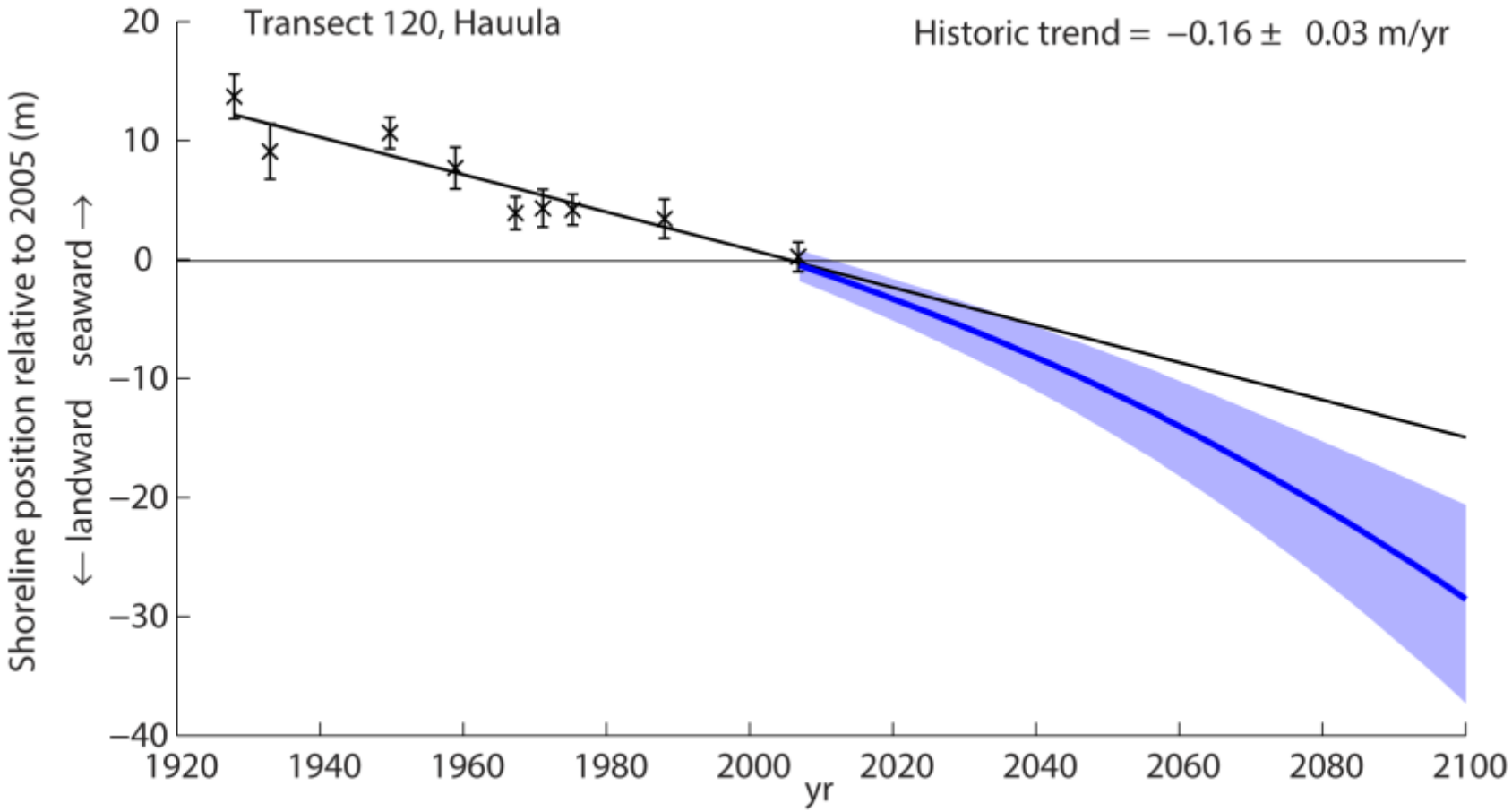
Modeling Shoreline Change with SLR



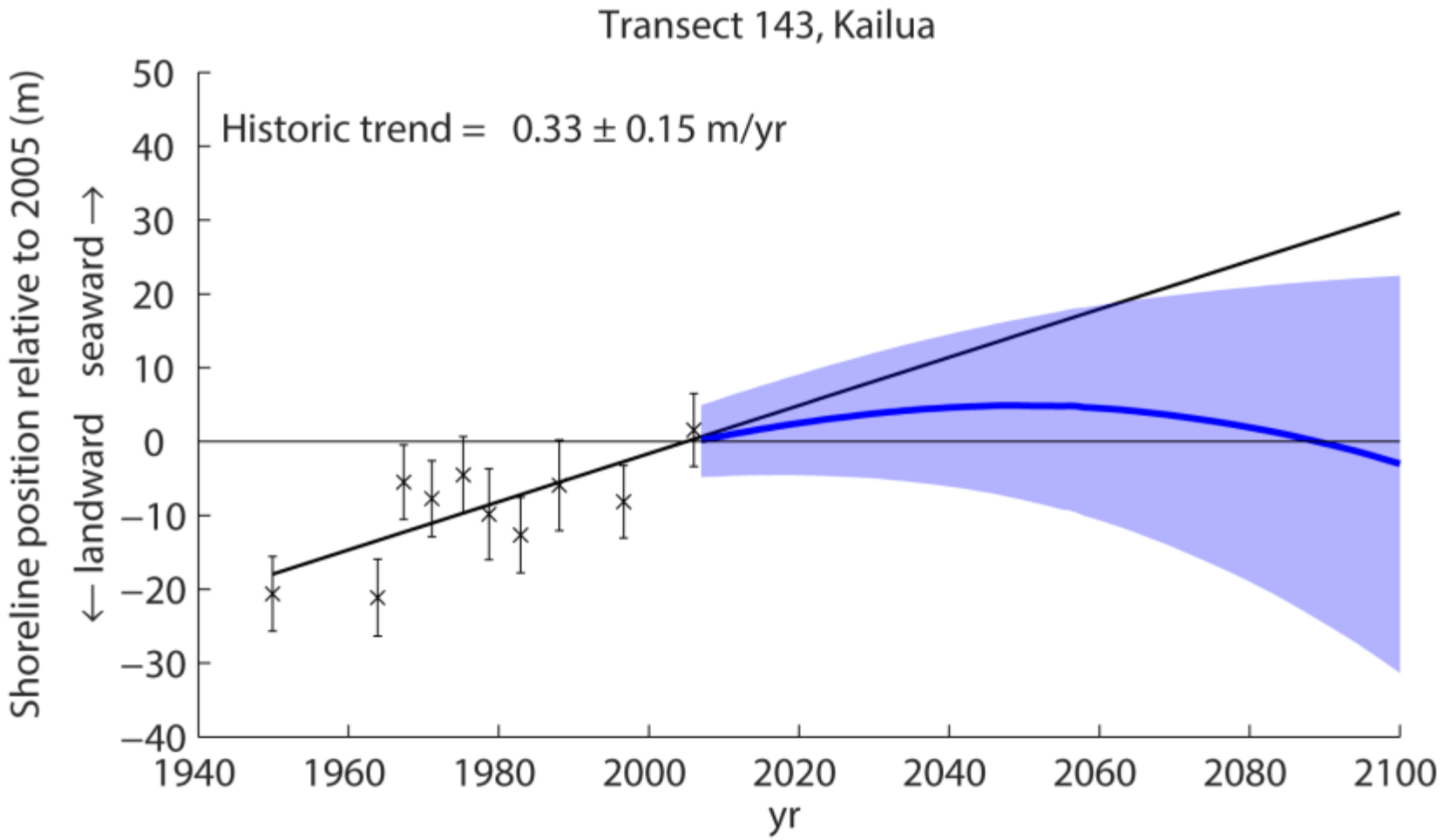
Davidson-Arnott (2005) model of shoreline response to changes in sea level

- Represents past behavior - does not include future increases in SLR
- Use a geometric model to account for additional changes due to increased SLR, and combine with historical change

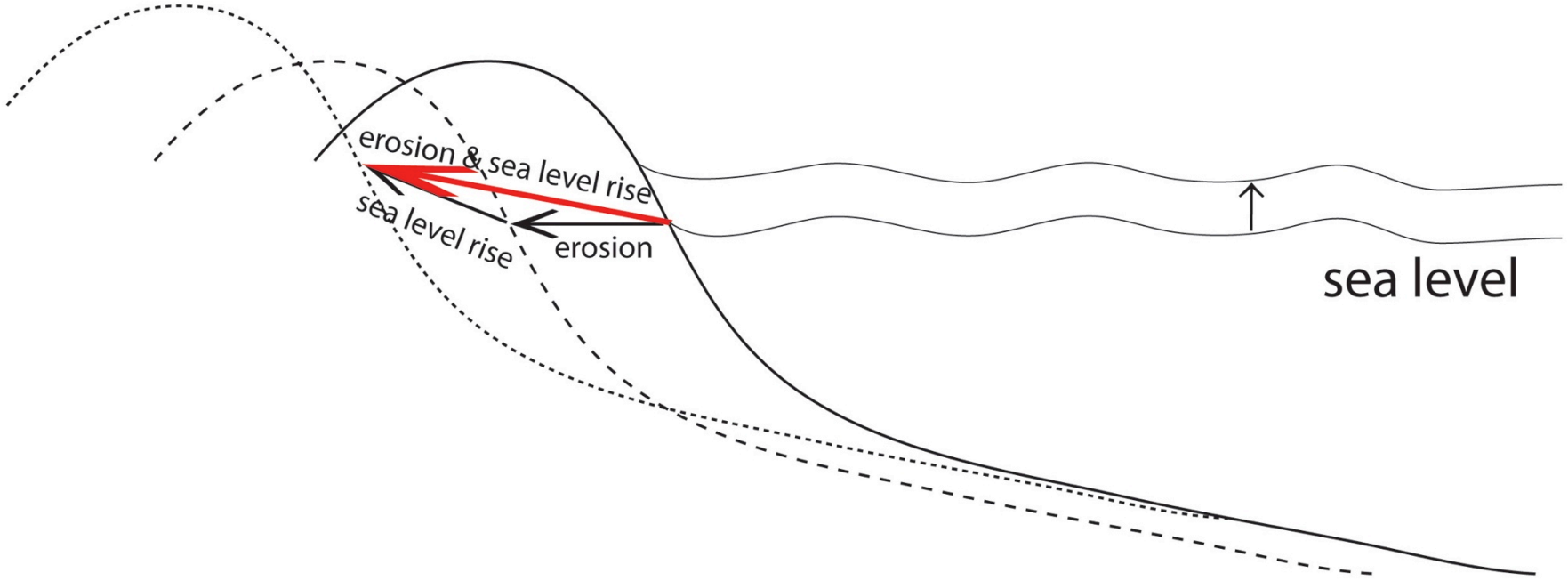
Example: Retreating shoreline



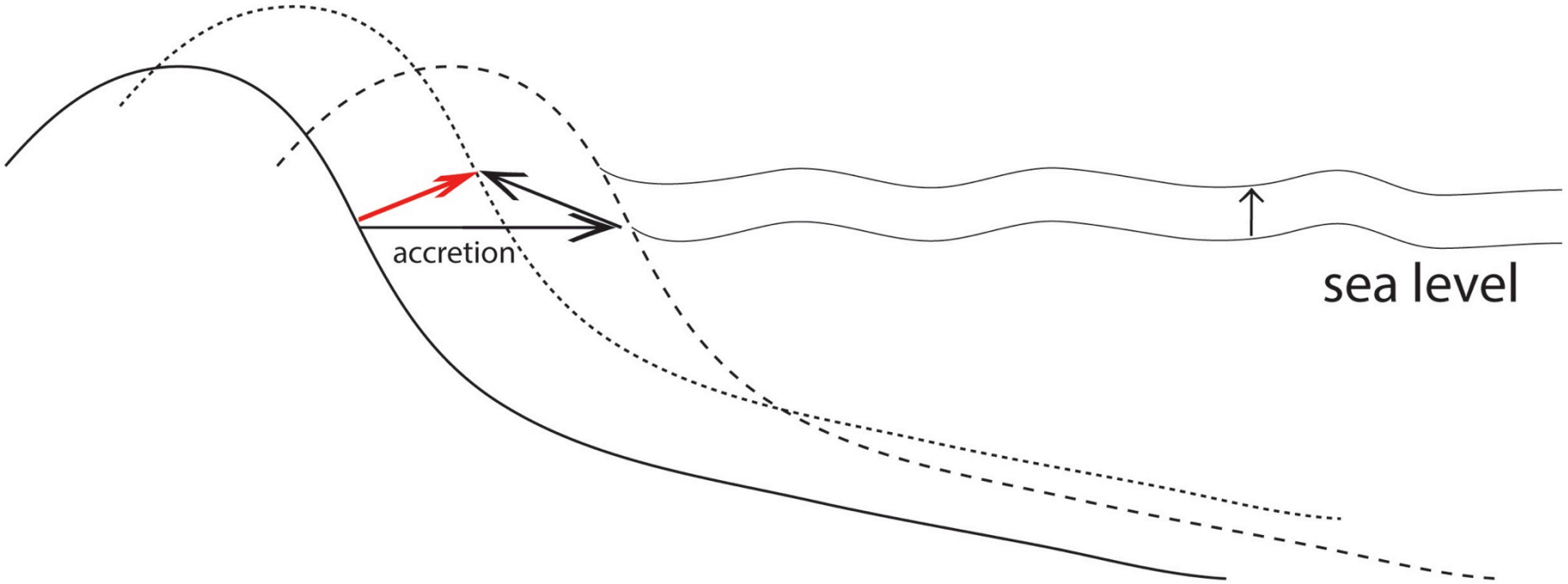
Example: Advancing shoreline



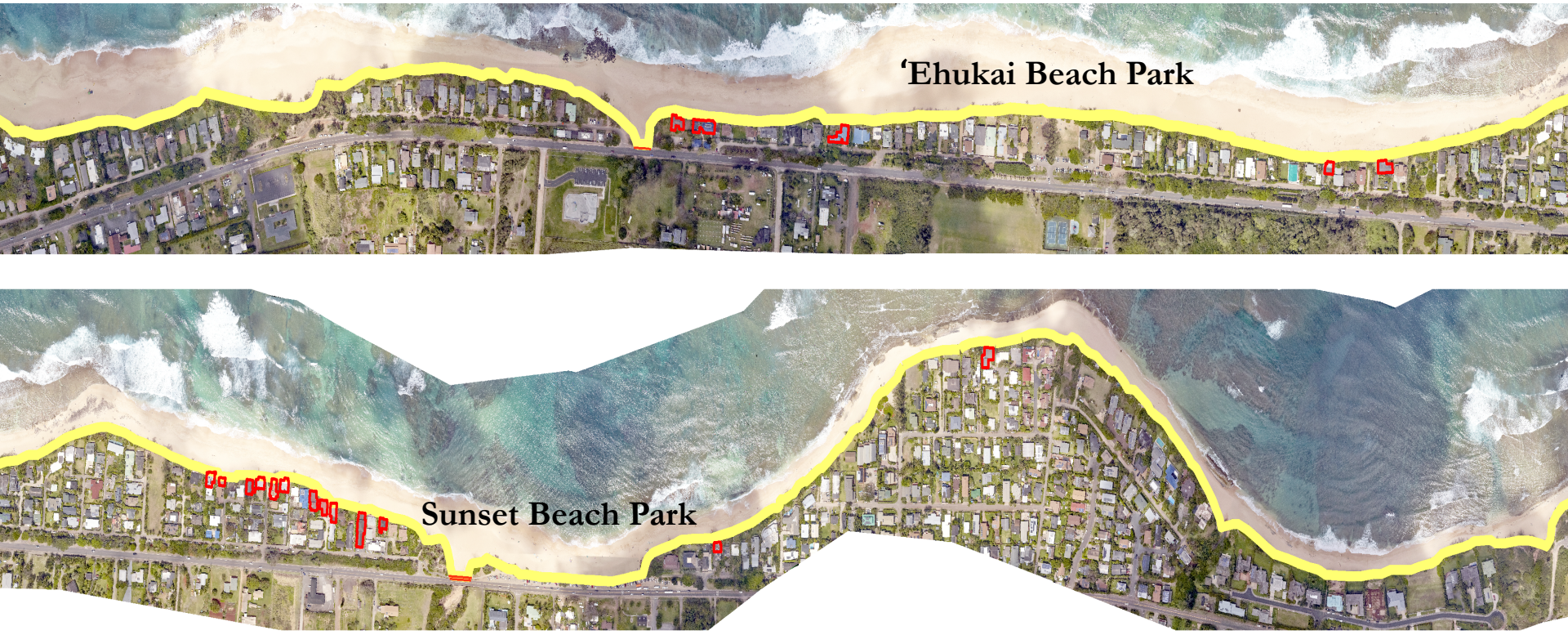
Sediment loss with sea level rise



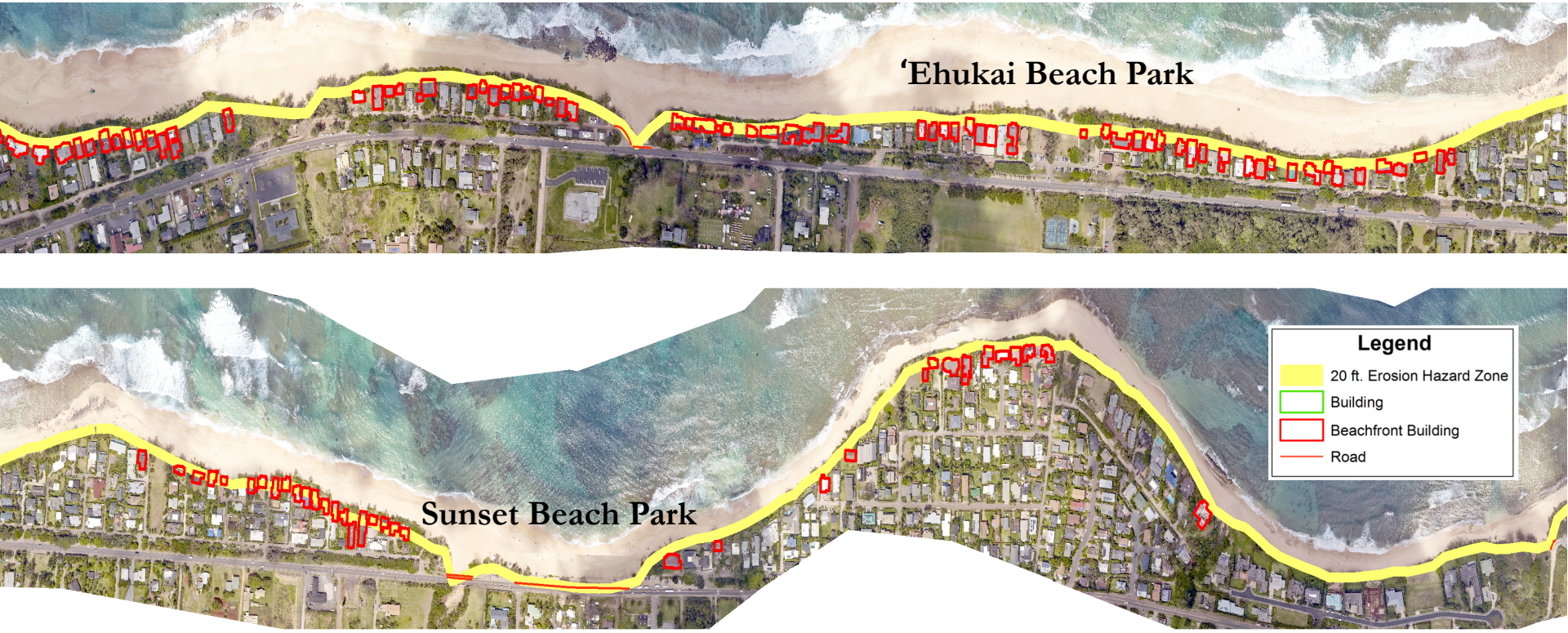
Sediment gain with sea level rise



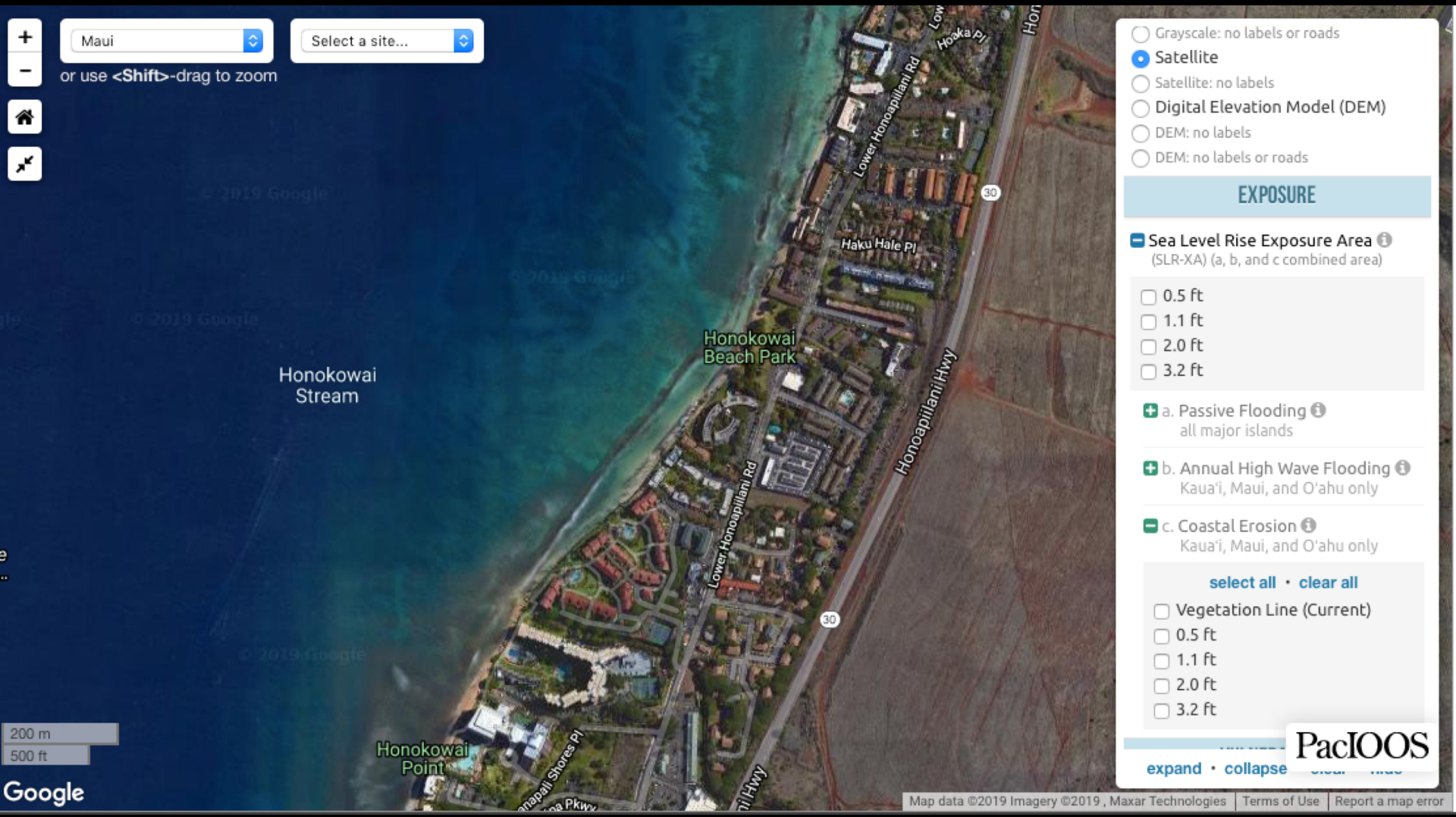
Coastal Erosion
Today - 18 buildings (10%) 0.04 miles of road



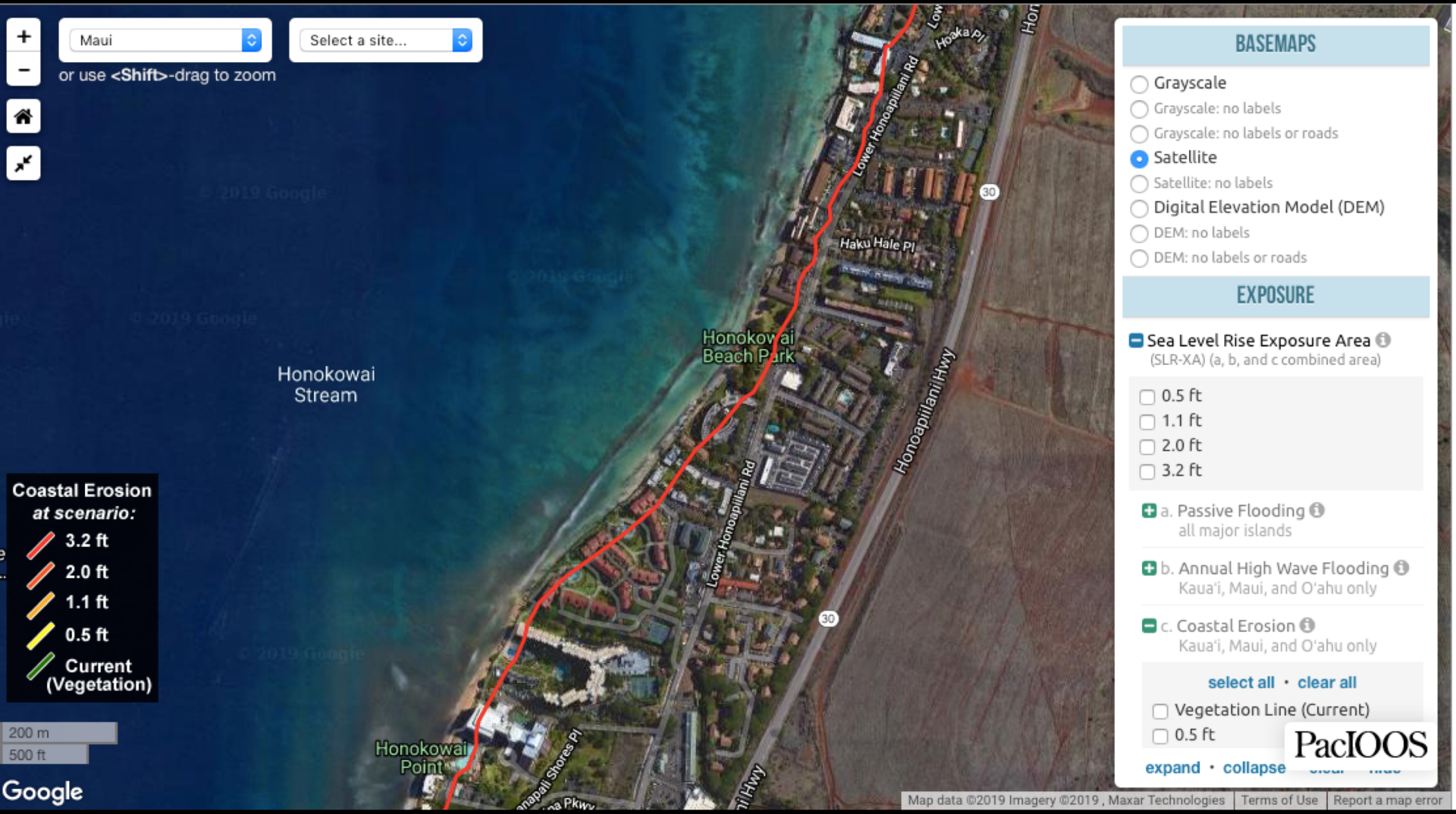
Coastal Erosion
1 ft SLR - 109 buildings (60%) 0.2 miles of road



Hawaii SLR Viewer



Hawaii SLR Viewer



Sunset Beach 3.2 ft SLR
Paumalū Gulch
Rocky Point
Kamehameha Hwy
Girl Scout Camp Rd
Sunset Beach Park
Annual wave Run-up
'Ehukai Beach Park
Erosion
Kālunawaika'ala Stream
Banzai Rocks
Sunset Beach Neighborhood Park
Pūkea Rd
Opae Rd

3.2 ft of SLR - Honolulu

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Modeling reveals up compared methods

Tiffany R. Anderson, (no &
Jade M.S. M. S. Delevau

Scientific Reports **8**, Arti

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Abstract

Planning community resilience to sea level rise (SLR) requires information about where, when, and how SLR hazards will impact the coastal zone. We augment passive flood mapping (the so-called "bathtub" approach) by simulating physical processes posing recurrent threats to coastal infrastructure, communities, and ecosystems in Hawai'i (including tidally-forced direct marine and groundwater flooding, seasonal wave inundation, and chronic coastal erosion). We find that the "bathtub" approach, alone, ignores 35–54 percent of the total land area exposed to one or more of these hazards, depending on location and SLR scenario. We conclude that modeling dynamic processes, including waves and erosion, is essential to robust SLR vulnerability assessment. Results also indicate that as sea level rises,

Hawai´i Sea Level Rise Vulnerability and Adaptation Report

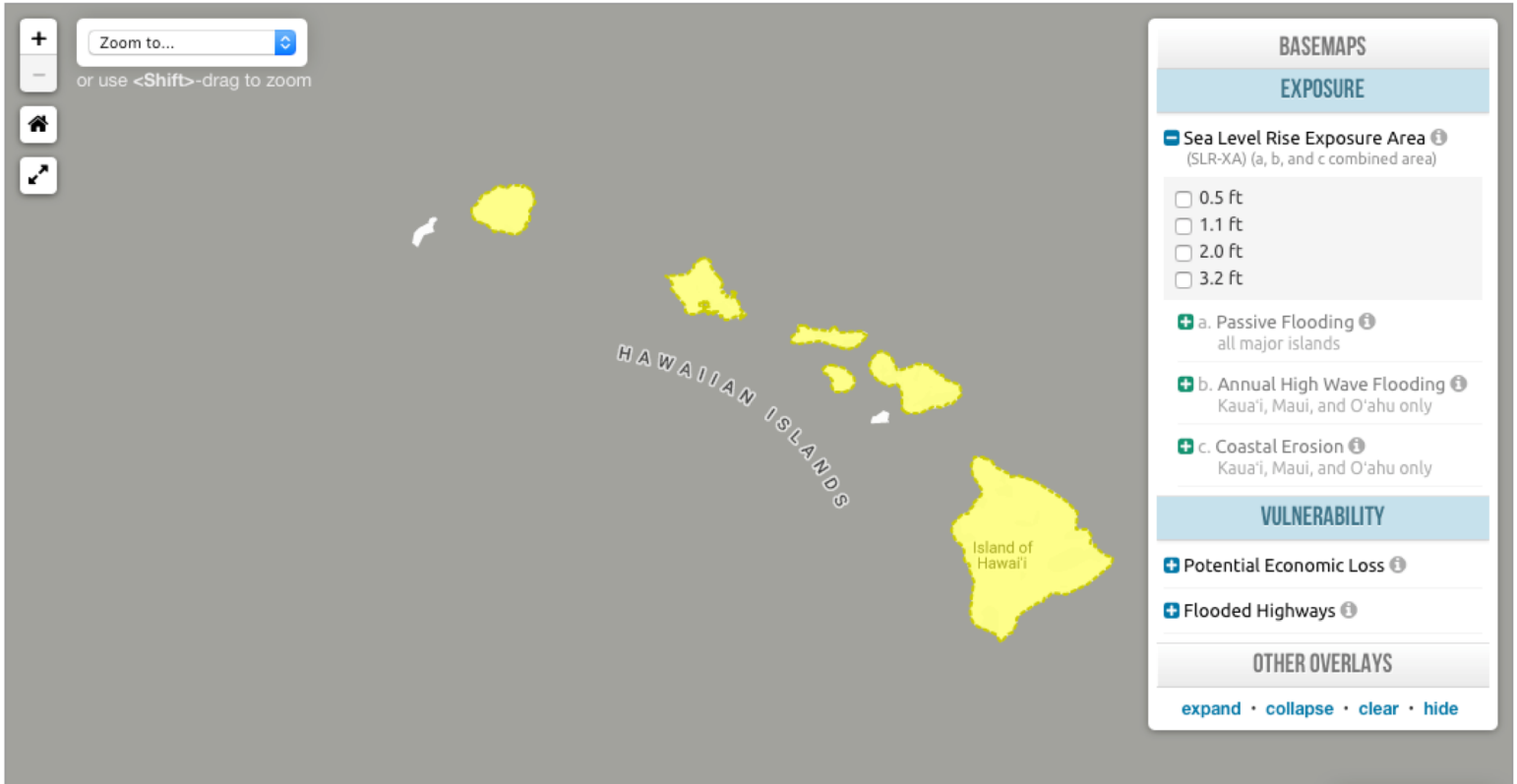
State of Hawaii, Office of Planning

TETRA TECH

PICSC

Sea Level Rise : Hawai‘i Sea Level Rise Viewer

view full-screen map



The 1 m SLR-XA
King Tide Flooding & Permanent Inundation

Chip Fletcher, PhD
School of Ocean and Earth Science and Technology
University of Hawai'i at Mānoa
Honolulu Climate Change Commission

“If you wage war with water, you will lose.”

Grief

1. Shock
2. Denial
3. Anger
4. Negotiation
5. Acceptance

Thank you for your time