Global and Local Impacts of Climate Change

Chip Fletcher, University of Hawai'i at Mānoa

Progress on the problem of climate change

Paris Agreement, 2015

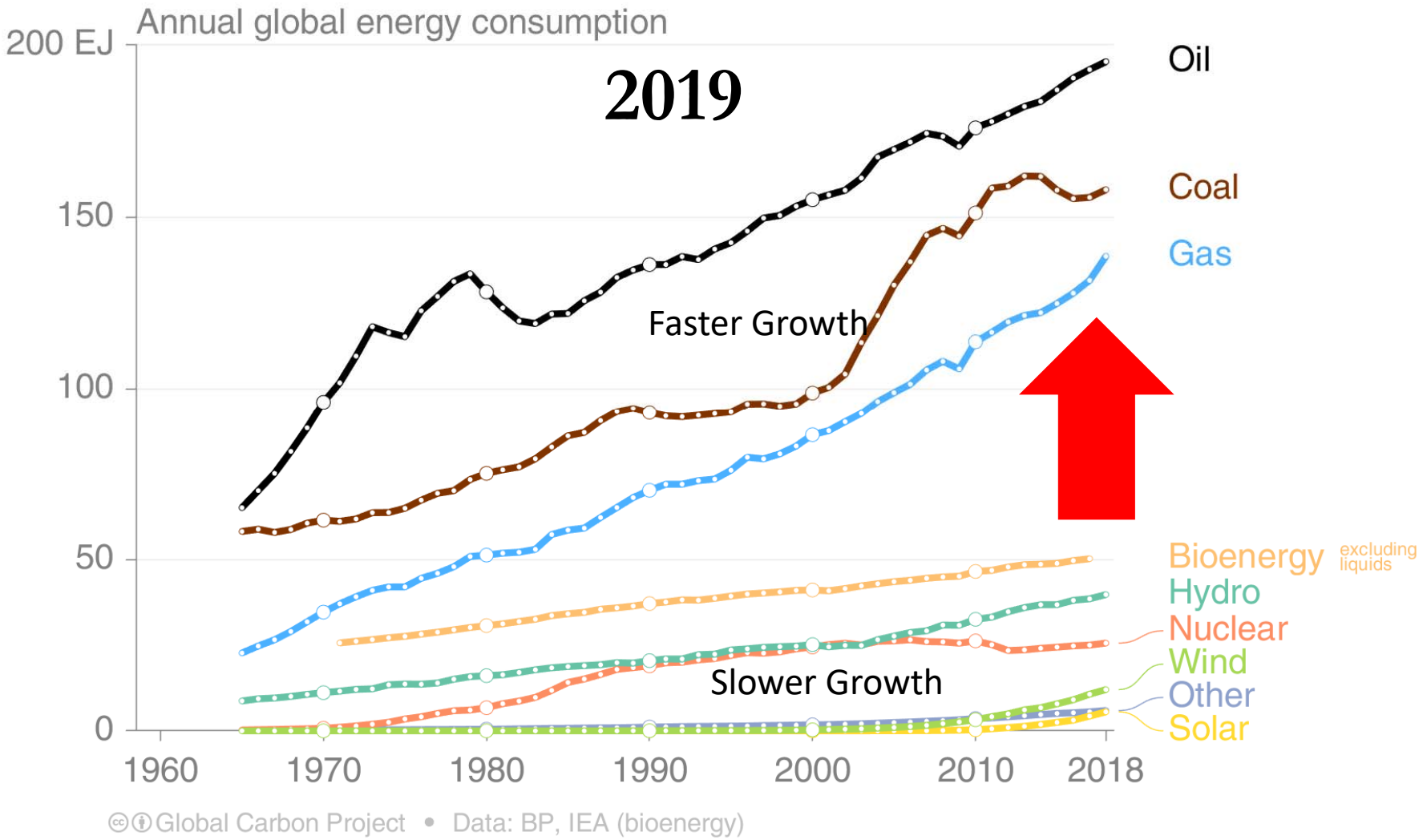
United Nations Framework Convention on Climate Change

Stop global warming before *2°C*

Pursue efforts to end warming before *1.5°C*

Fossil fuel use is accelerating faster than renewable fuel use

Renewable energy is not replacing fossil fuels, it is helping meet the demand for NEW energy

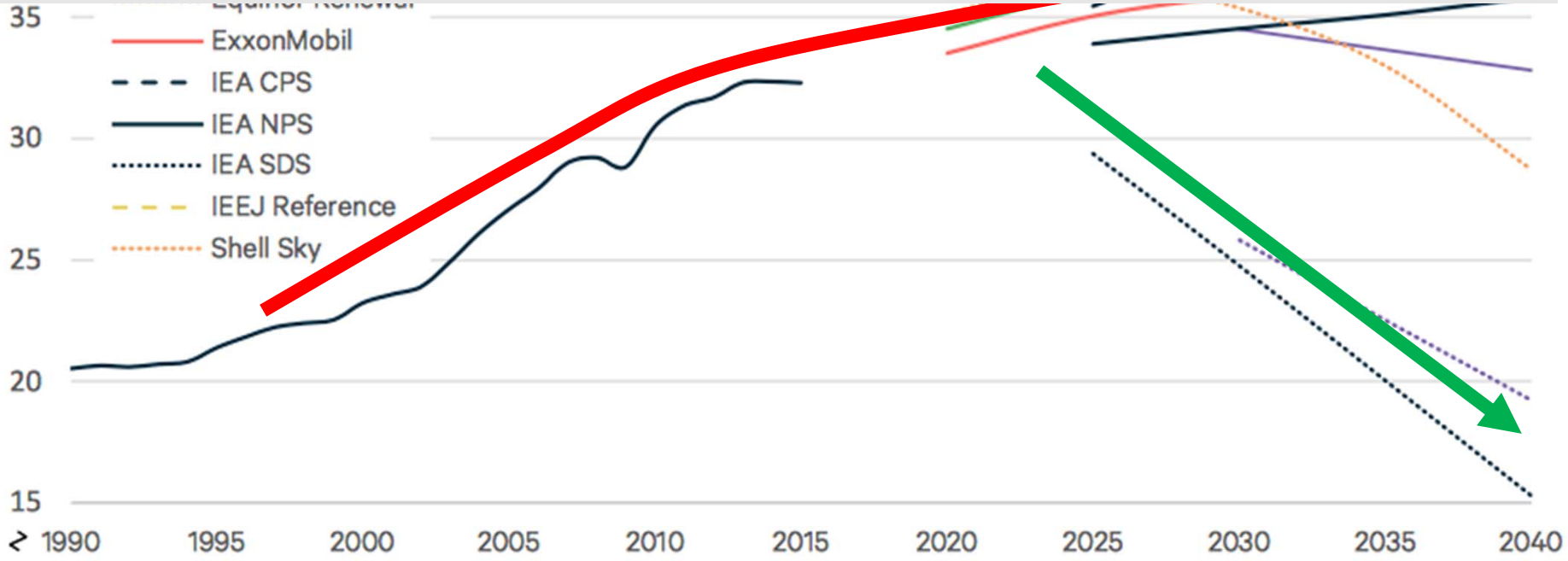


Global Carbon Project (2019) Global energy growth is outpacing decarbonization: https://www.globalcarbonproject.org

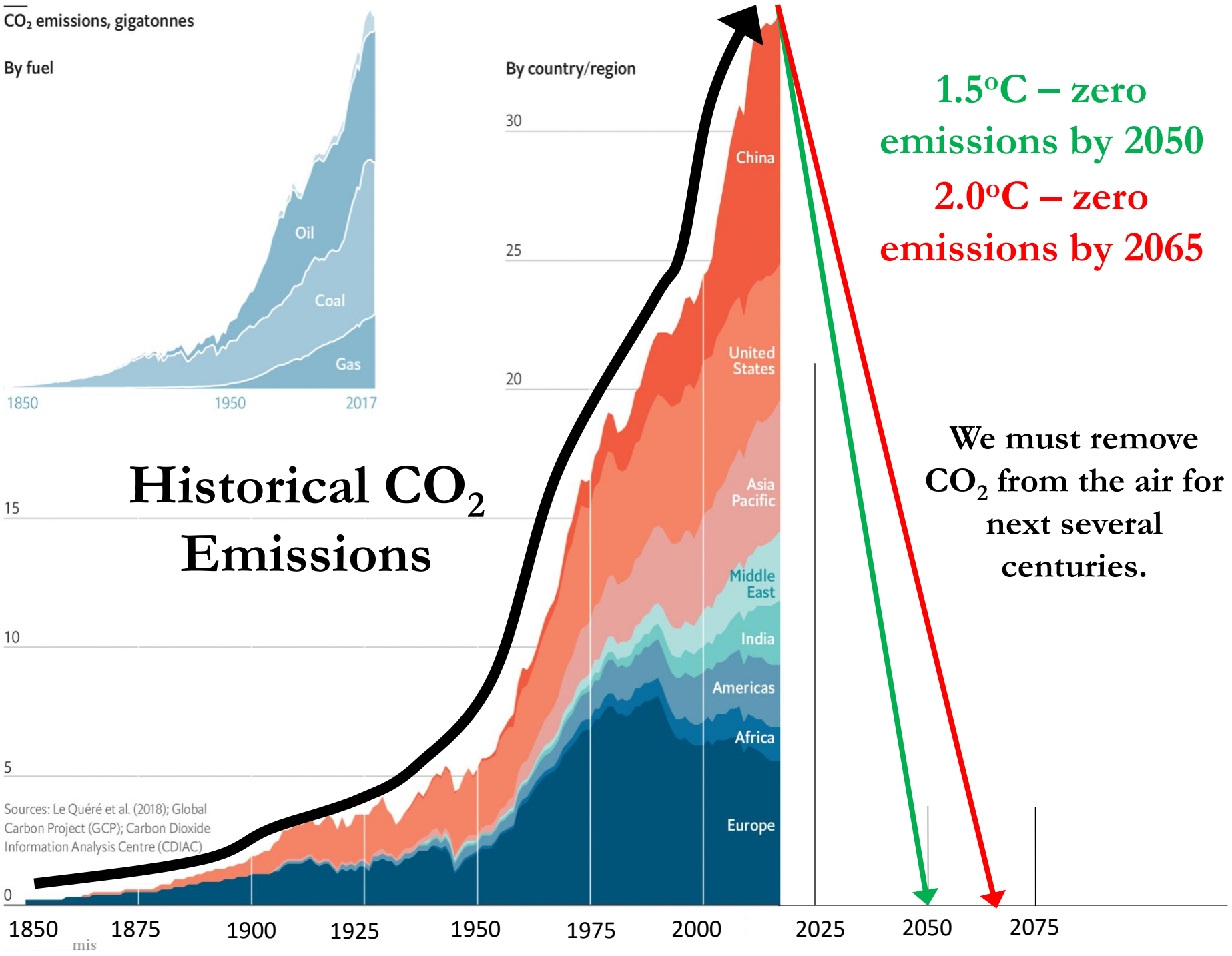
CO_2 emissions are on a path to far exceed the Paris Agreement.

"Under most scenarios, **carbon dioxide (CO_2)** emissions from the global energy system are on a path to far exceed international targets of the Paris Agreement."

Resources for the Future Institute – non-partisan Congressional Think Tank, 2019
https://www.rff.org



Global Energy Outlook 2019, The Next Generation of Energy: https://media.rff.org/documents/GEO_Report_7-19-19.pdf

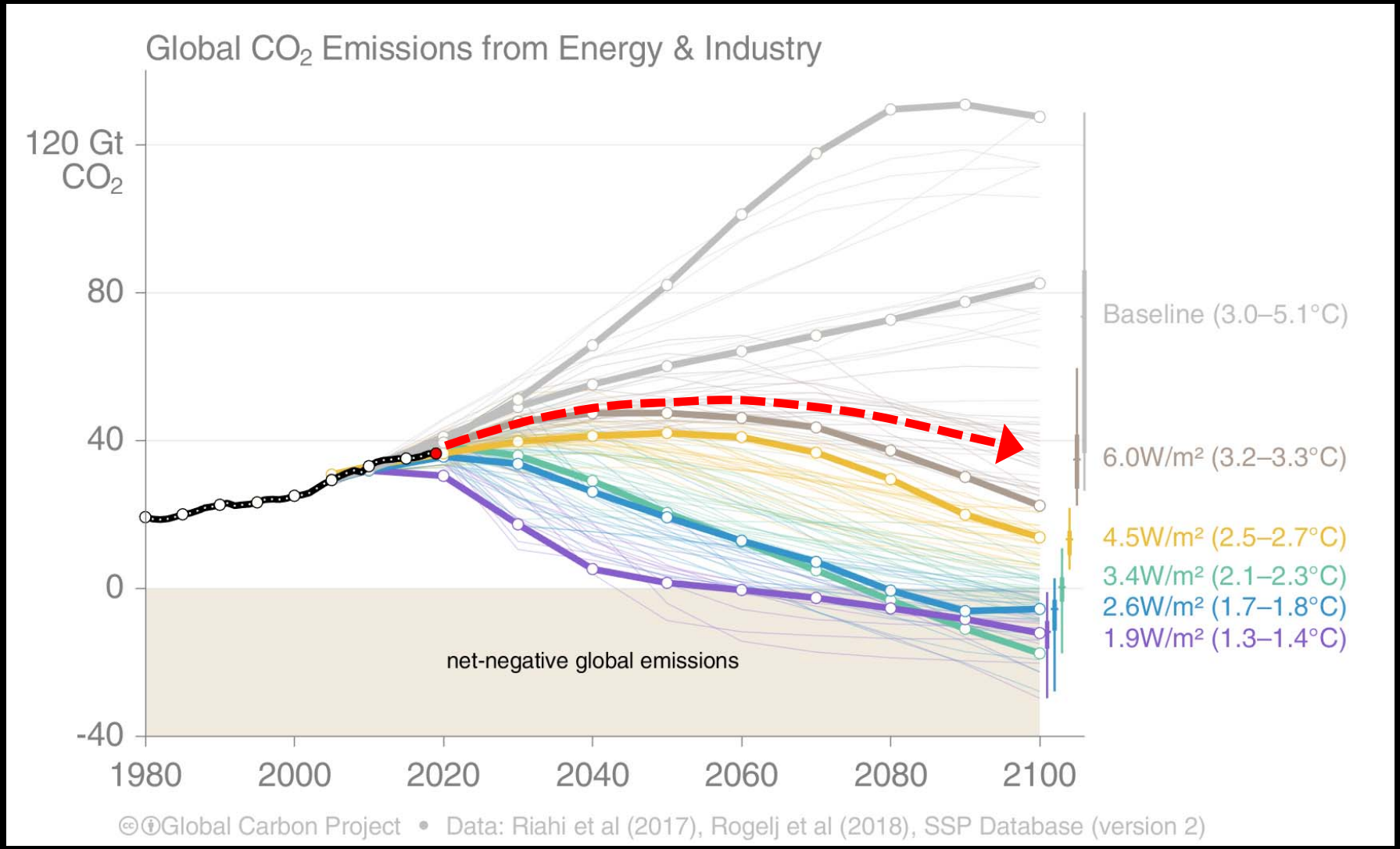

CO_2 emissions, gigatonnes
By fuel
Oil
Coal
Gas
1850
1950
2017
By country/region
30
25
20
15
10
5
0
China
United States
Asia Pacific
Middle East
India
Americas
Africa
Europe
Sources: Le Quéré et al. (2018); Global Carbon Project (GCP); Carbon Dioxide Information Analysis Centre (CDIAC)
1850
1875
1900
1925
1950
1975
2000
2025
2050
2075
Historical CO_2 Emissions
1.5°C – zero emissions by 2050
2.0°C – zero emissions by 2065
We must remove CO_2 from the air for next several centuries.

Renewable energy provides only 10% of global power

- Fossil-fuel producing nations have announced plans to produce 50% more fossil fuels by 2030 than compatible with stopping at 2^{o}C.
- China is building more new coal plants than the rest of the world combined.
- India is opening 41 new coal mines as part of its post-COVID recovery plans.
- Coal remains the single largest source of power generation, accounting for 36% of global power in 2019.
- Renewable energy provides only 10% of global power.
- To get to net zero by 2050, the world requires 2020-like reductions in carbon emissions every other year for the next 25 years.
- This can only be achieved by a radical shift in all our behaviors. COVID is forcing us to make this shift.
- What will the post-COVID economy look like?
    - Will it coming roaring back powered by fossil fuels?
    - Will it come back slower but powered by renewables?
    - Is COVID here to stay as a quasi-permanent condition that suppresses economic growth?

https://insideclimatenews.org/news/20112019/fossil-fuel-production-climate-change-goals-subsidies-policies-un-report
https://www.wired.com/story/china-is-still-building-an-insane-number-of-new-coal-plants/
BP, 2020, Statistical Review of World Energy: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

We are on-track for 3 - 3.5°C warming before end of the century



Global Carbon Project (2019) Global energy growth is outpacing decarbonization: https://www.globalcarbonproject.org

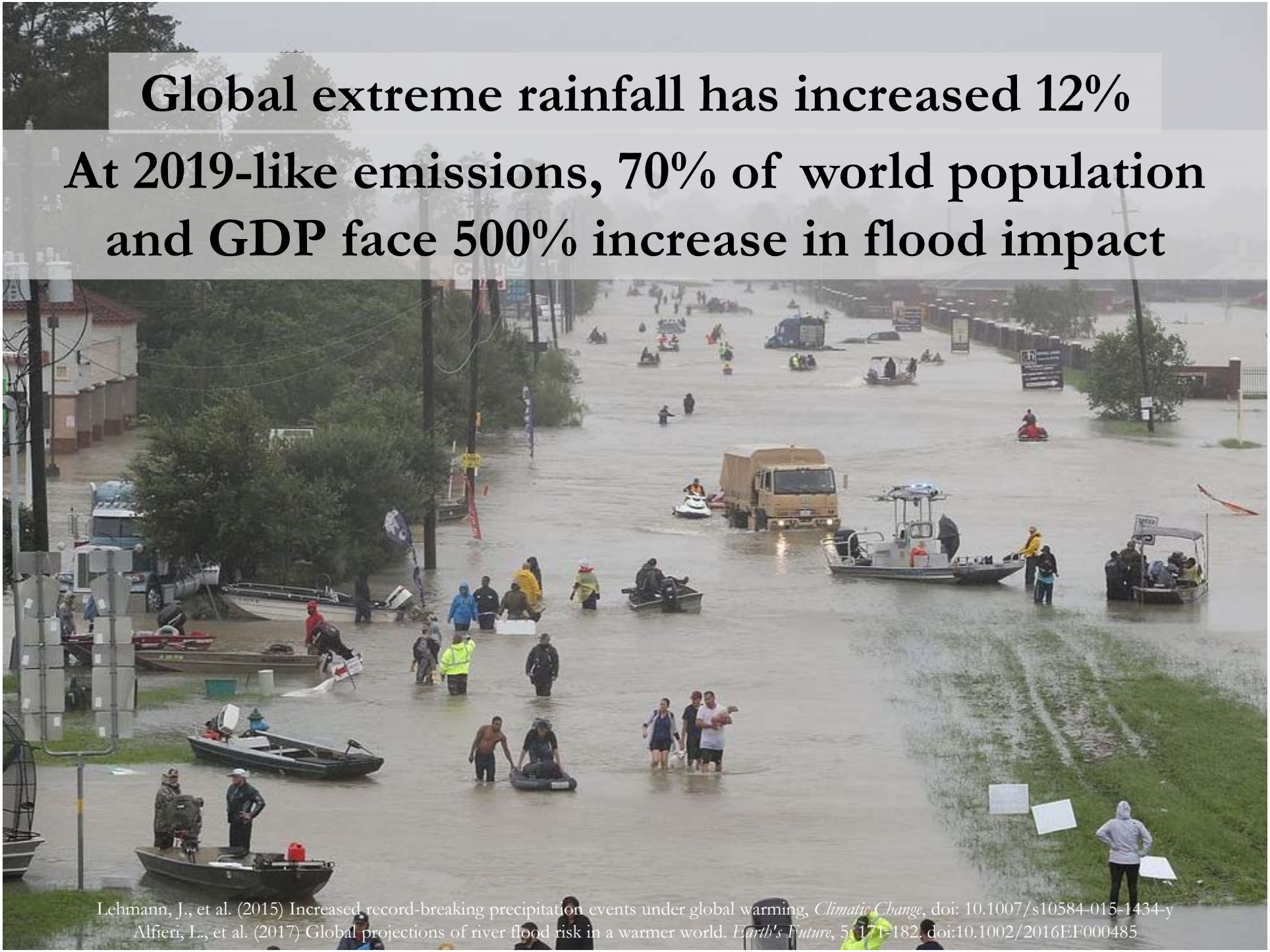
Physical Impacts

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

Kitzberger T, et al.(2017) Direct and indirect climate controls predict heterogeneous early-mid 21st century wildfire burned area across western and boreal North America. PLoS ONE 12(12). https://doi.org/10.1371/journal.pone.0188486
Abatzoglou, J.T., Williams, A.P. (2016) Impact of anthropogenic climate change on wildfire across western U.S. forests. *Proceedings of the National Academy of Sciences*; 201607171 doi: 10.1073/pnas.1607171113

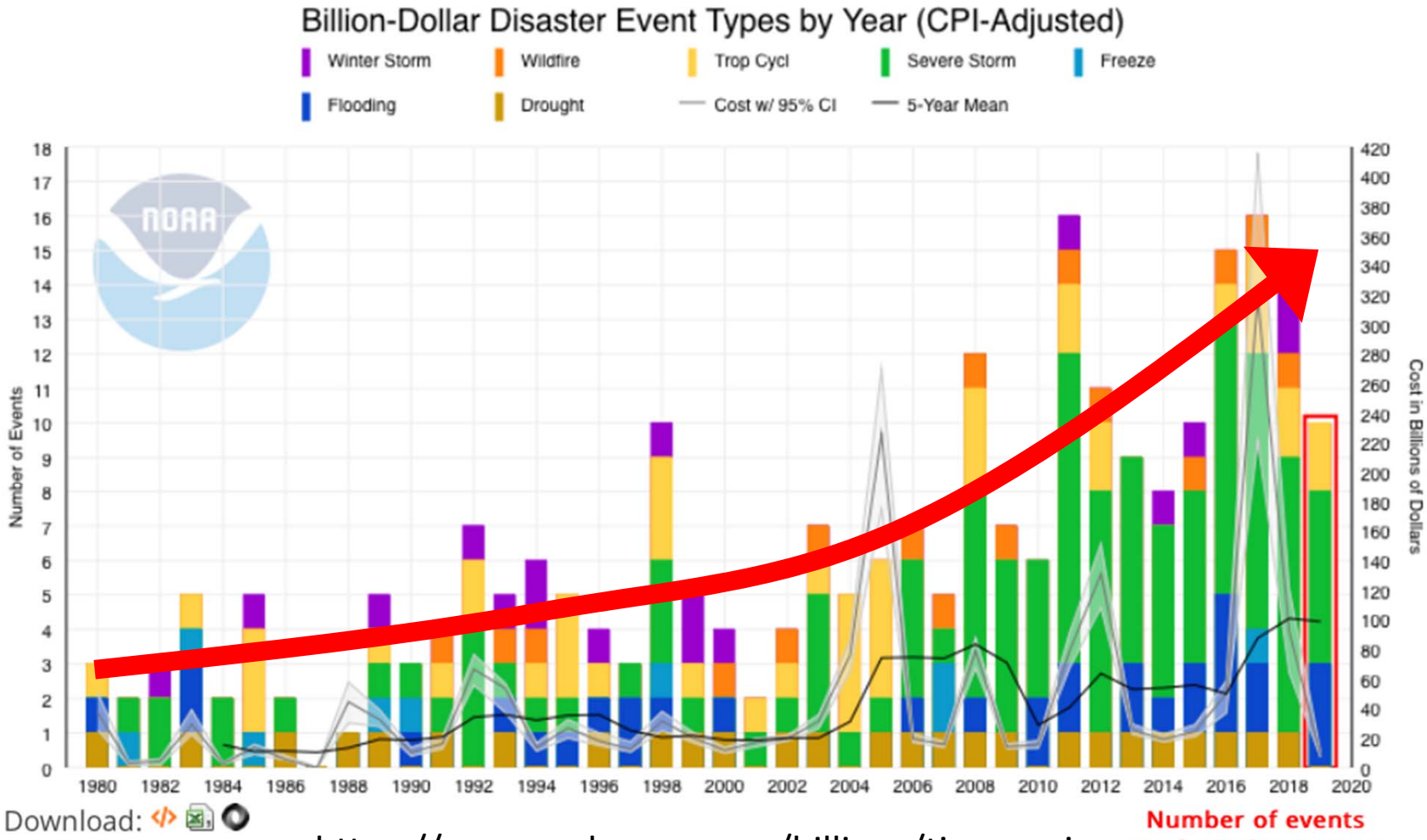
Global extreme rainfall has increased 12%

At 2019-like emissions, 70% of world population and GDP face 500% increase in flood impact



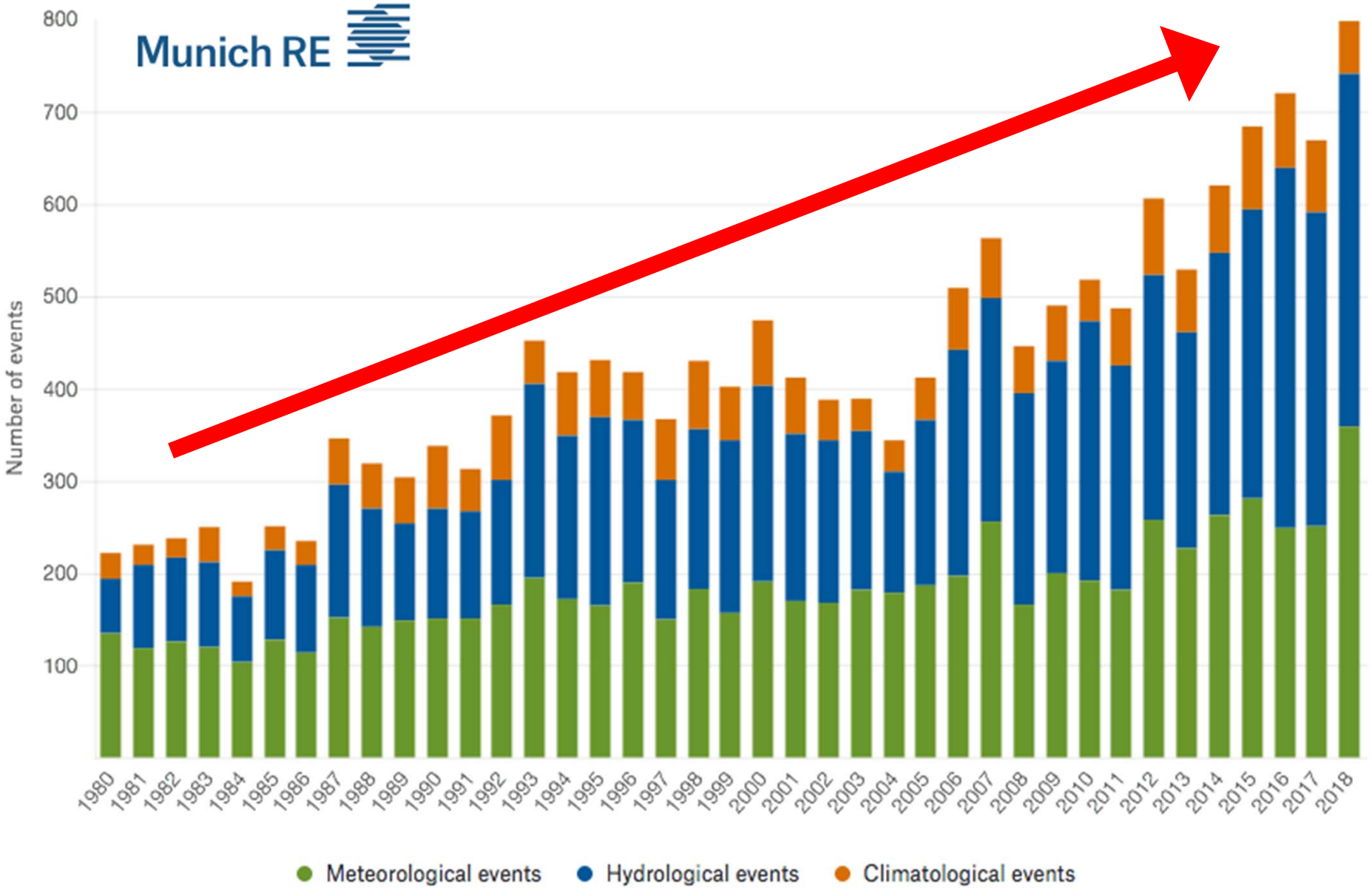
Lehmann, J., et al. (2015) Increased record-breaking precipitation events under global warming, *Climatic Change*, doi: 10.1007/s10584-015-1434-y
Alfieri, L., et al. (2017) Global projections of river flood risk in a warmer world. *Earth's Future*, 5: 171-182. doi:10.1002/2016EF000485

Billion Dollar Disasters in the US are on the Rise



https://www.ncdc.noaa.gov/billions/time-series

Weather related loss events worldwide 1980-2018

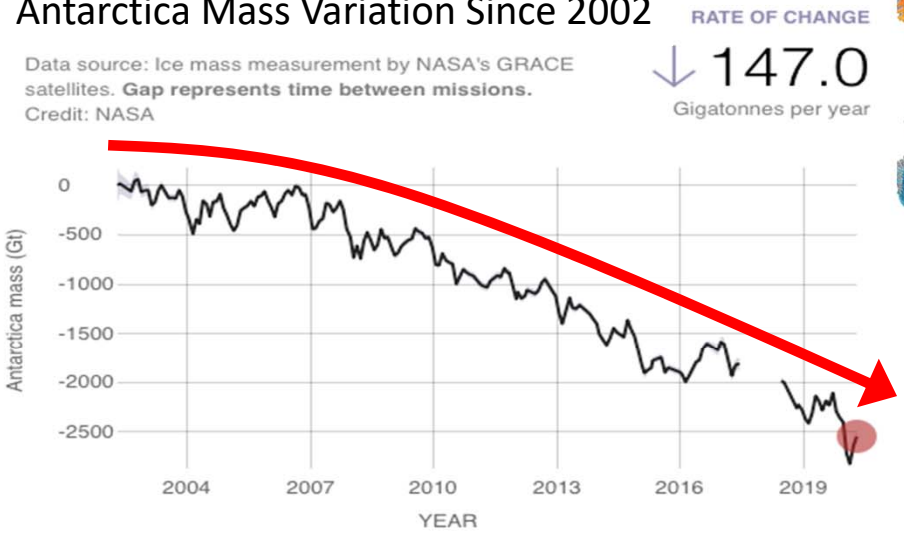


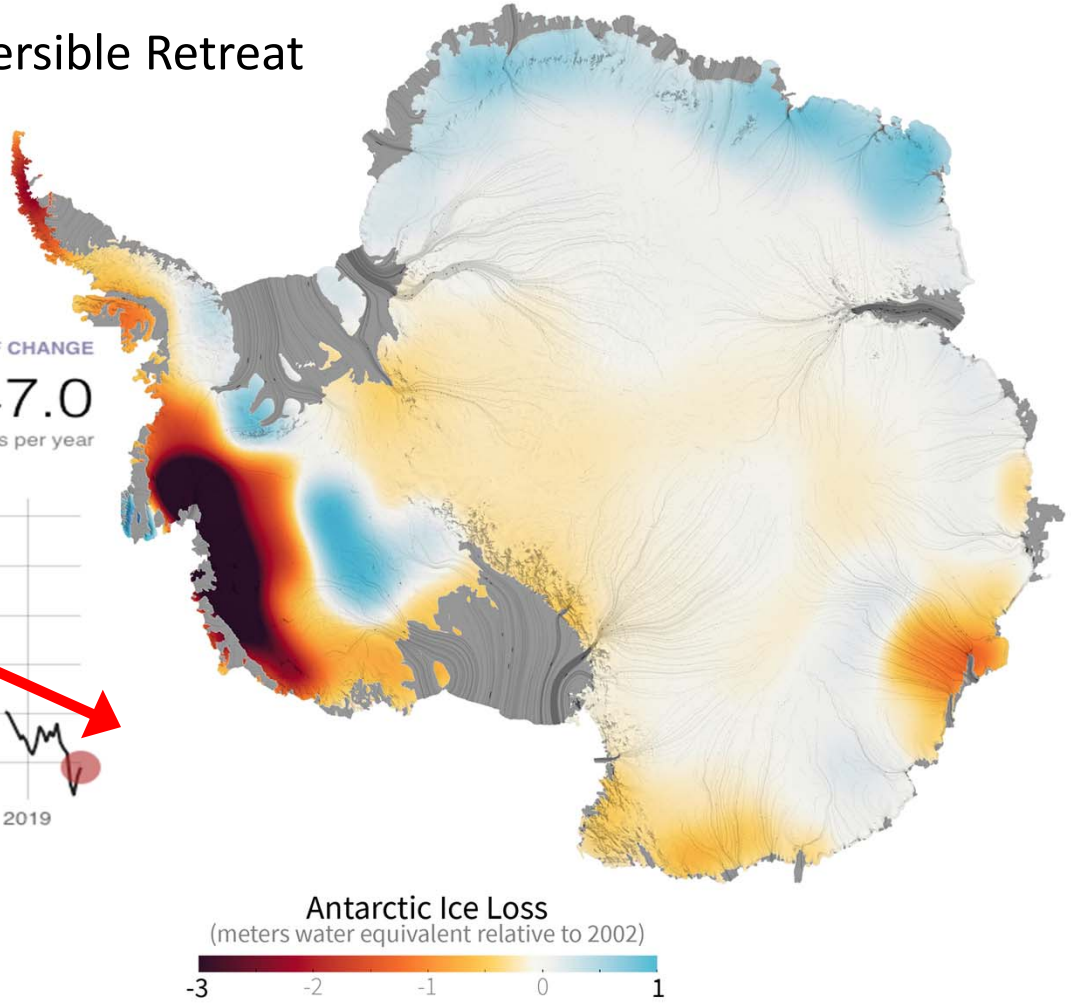
Antarctic ice melt has tripled over the past five years

West Antarctic Glaciers are in Irreversible Retreat

Ice loss, Gigatonnes

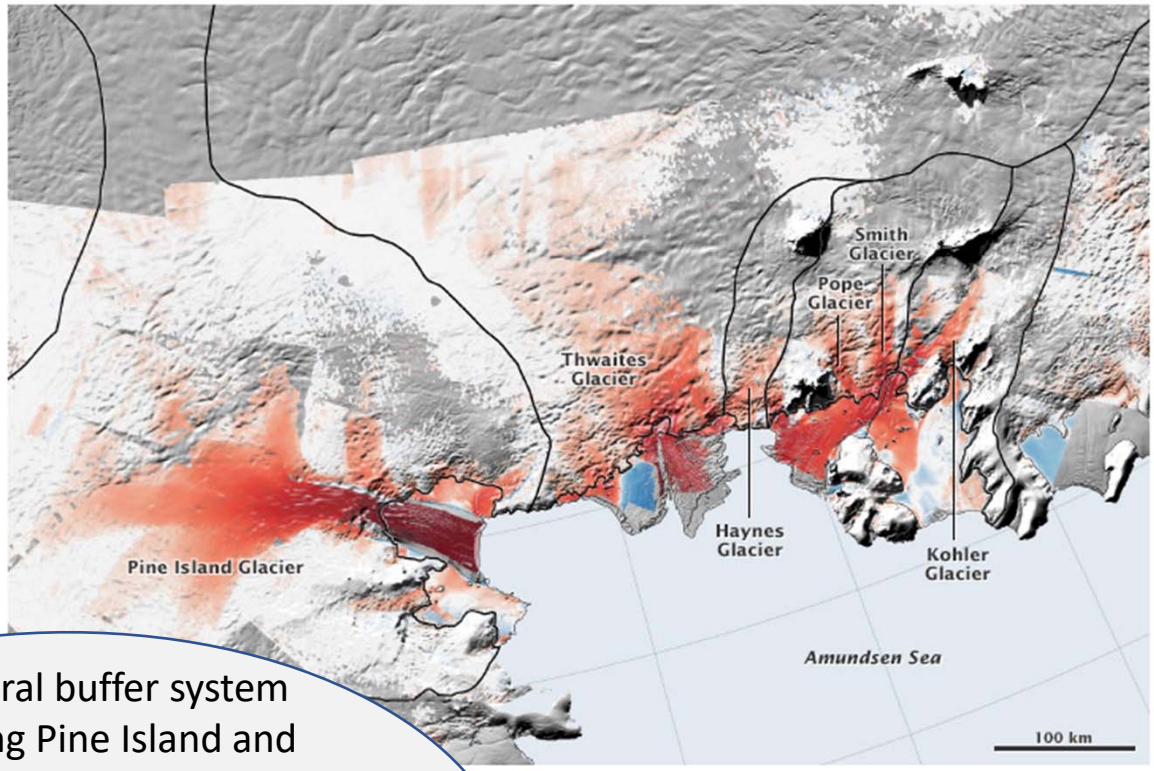
Antarctica Mass Variation Since 2002





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

Decline of West Antarctic Glaciers Appears Irreversible



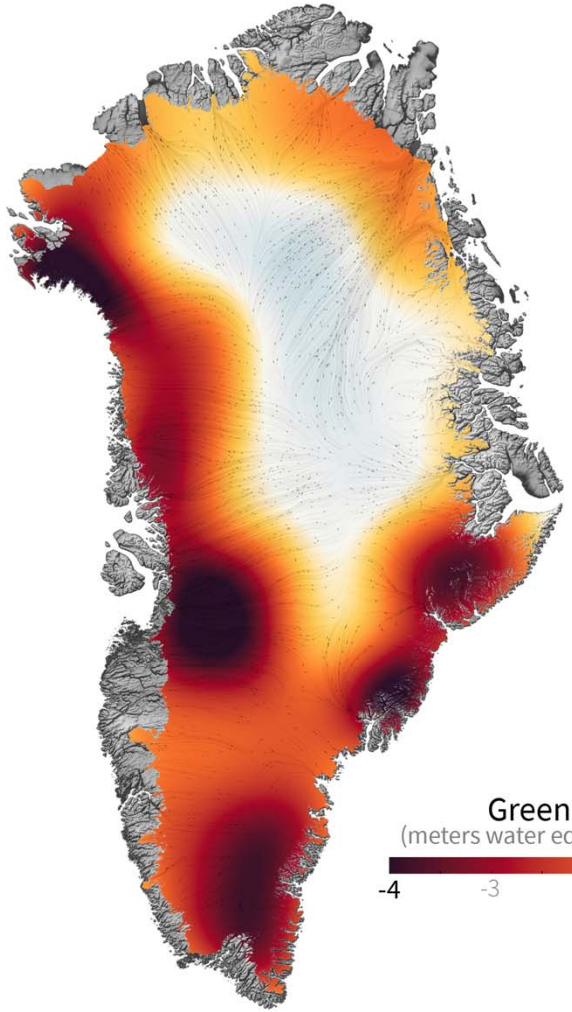
The natural buffer system preventing Pine Island and Thwaites glaciers from flowing rapidly is **breaking down**. The ice shelves are showing **new damage areas** that are the first signs of structural weakening and precondition these ice shelves for **disintegration**.

onclude that a section of the West Antarctic
vitable collapse, an event that would
n a meter (three-plus feet). The first study,
sion Laboratory, used NASA satellite and
ow glaciers have been retreating in the
in of the University of Washington,
el to compare obse ns of recent melting with
melt scenarios to see which matches reality best so far. Both studies conclude that the Amundsen Sea segment of the ice sheet has begun an irreversible decline that will result in its loss, possibly as soon as the next few

Lhermitte, S., et al. (2020) Damage accelerates ice shelf instability and mass loss in Amundsen Sea Embayment. *Proceedings of the National Academy of Sciences*, Sept. 14; DOI: 10.1073/pnas.1912890117

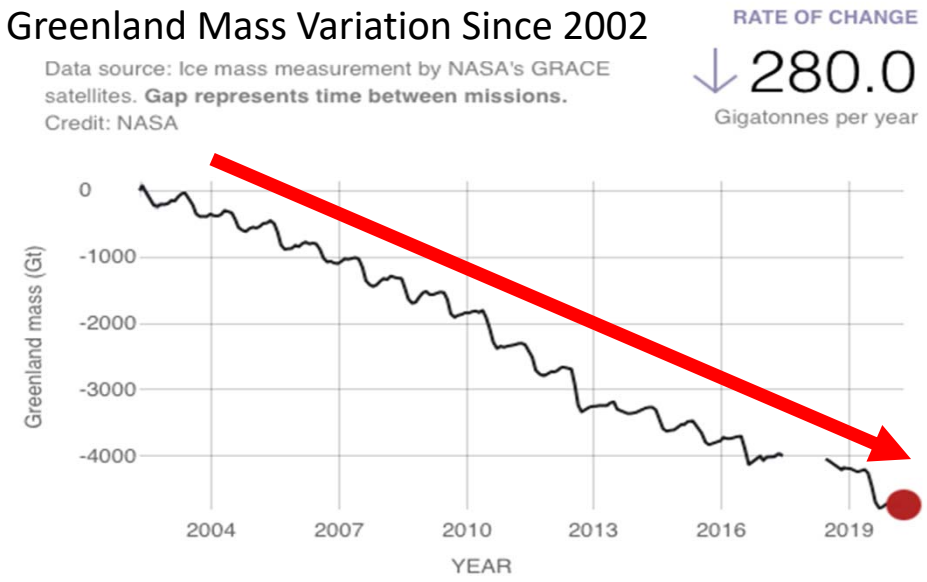
Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., Scheuchl, B. 2014. Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophys. Res. Lett.* 41, 3502–3509.

Greenland melting has quadrupled over the past decade



Greenland Ice Loss
(meters water equivalent relative to 2002)
-4 -3 -2 -1 0 0.5

Ice loss, Gigatonnes



Bevis, M. et al. (2019) Accelerating changes in ice mass within Greenland, and the ice sheets sensitivity to atmospheric forcing. PNAS, 116, 1934-1939.

Greenland's Melting Ice Sheet Has 'Passed The Point of No Return', Scientists Say

Greenland's ice sheet may have hit a tipping point that sets it on an
path to completely disappearing.

Snowfall that normally replenishes Greenland's glaciers each ye
keep up with the pace of ice melt, according to resea
University.

That means that the Greenland ice sheet - the world's second-largest ice body - would continue to lose ice even if global temperatures stop rising.

In their study, published Thursday in the journal *Nature*, the scientists reviewed 40 years of monthly satellite data from more than 200 large glaciers that are draining into the ocean across Greenland.

Snowfall that normally replenishes Greenland's glaciers each year can no longer keep up with the pace of ice melt

King, M.D., Howat, I.M., Candela, S.G. *et al.* Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat. *Commun Earth Environ* **1,** 1 (2020). https://doi.org/10.1038/s43247-020-0001-2

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.

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.

"Coastal decisions require long lead times. It would be nice if we could wait for the science to clear up, but we can't."

5-10% chance of sea level exceeding 6.5 ft (2 m) by 2100

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

Social Aspects

PNAS Proceedings of the National Academy of Sciences of the United States of America

Keyword, Author,

Home | Articles | Front Matter | News | Podcasts | Authors

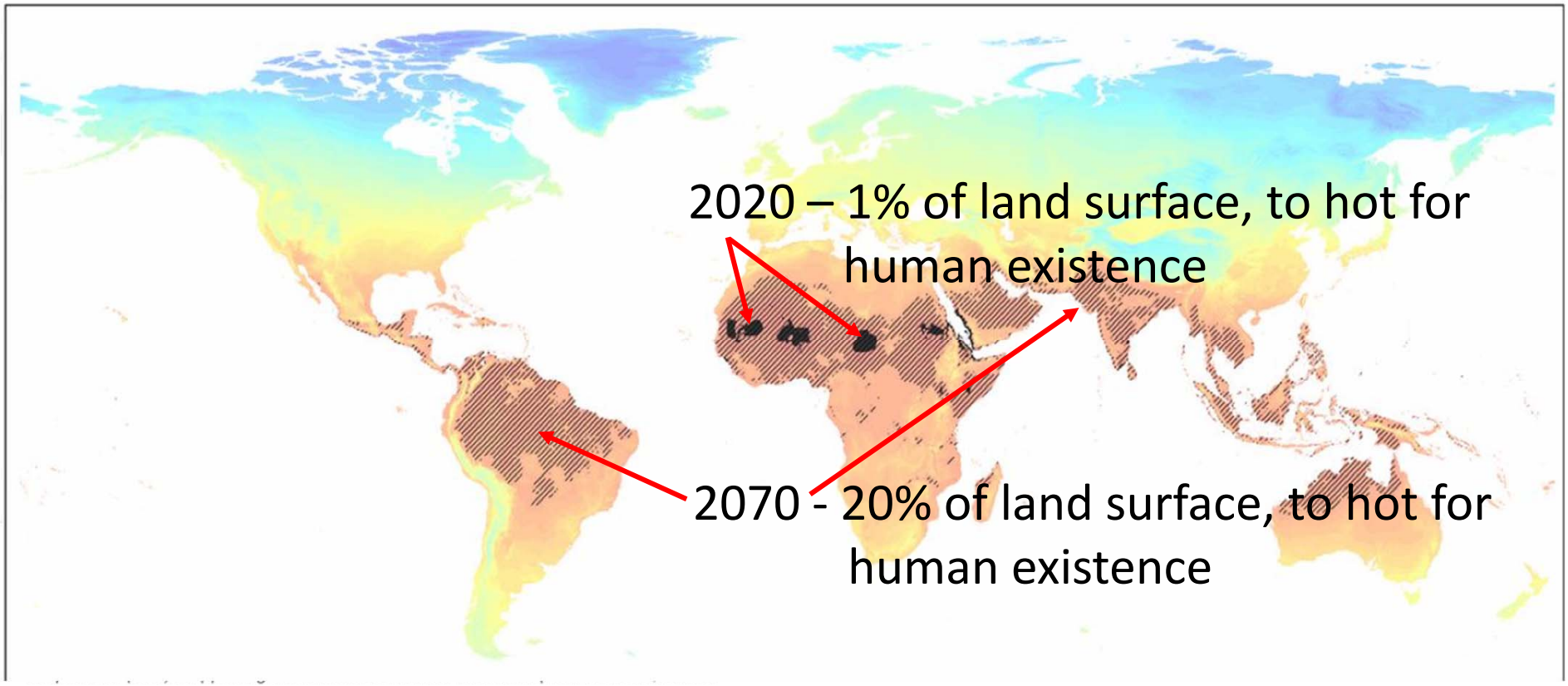
NEW RESEARCH IN Physical Sciences | Social Sciences

RESEARCH ARTICLE

Future of the human climate niche

Chi Xu, Timothy A. Kohler, Timothy M. Lenton, Jens-Christian Svenning, and Marten Scheffer

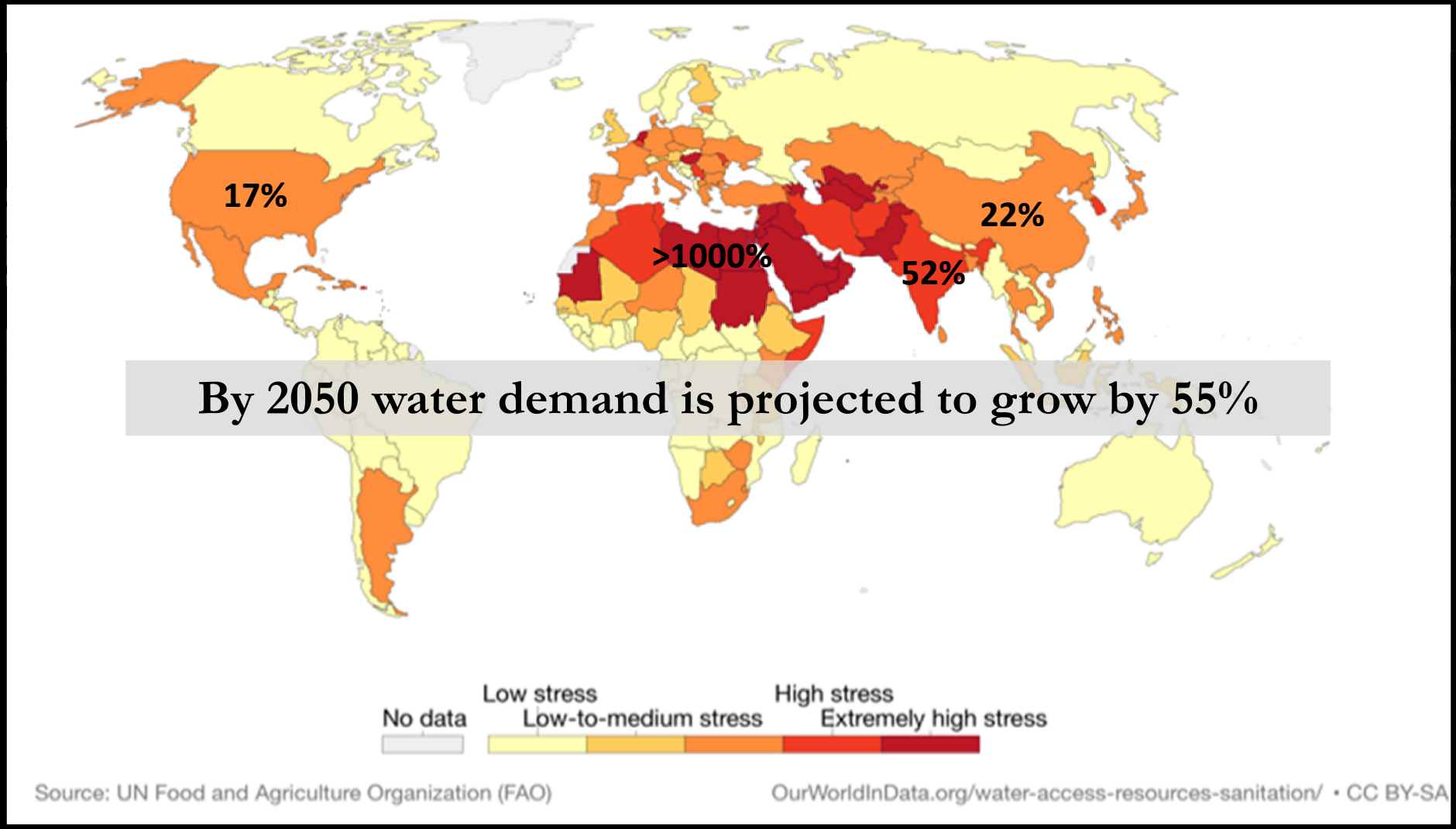
Over the next 50 yrs, 1 of every 3 people will be living in a climate too hot for humans to exist without air conditioning.



production of crops and livestock is largely limited to the same conditions, and the same optimum has been [illegible] countries through analyses of year-to-year variation. We show that in a business-as-

Xu, C., et al. (2020) Future of the human climate niche, *PNAS*, May 2020, 201910114; DOI:10.1073/pnas.1910114117

Freshwater withdrawals are exceeding internal sources



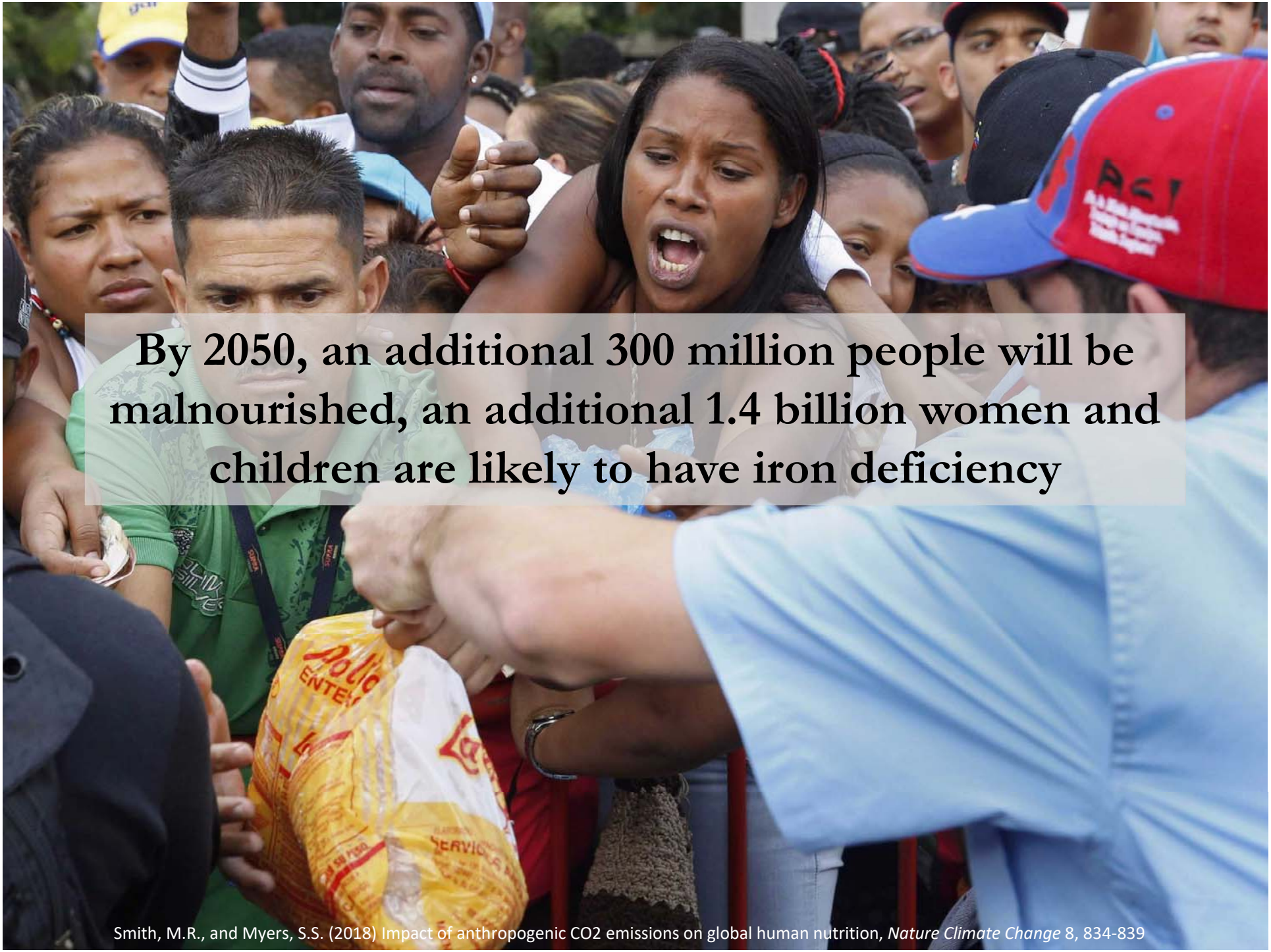
https://ourworldindata.org/water-access-resources-sanitation#water-stress-and-scarcity

Chunwu, Z et al (2018) Carbon dioxide levels (CO2) this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries, *Science Advances*, May 23, v. 4, no. 5. Myers, S.S., et al. (2014) Increasing CO_2 threatens human nutrition, *Nature*, 510, 139-142, doi: 10.1038/nature13179.

Food Shortages

- Global wheat provides 20% of human protein.
  - Yield is threatened by drought, flood, higher CO_2
  - By 2050 demand will increase by 60% (9 billion people)
  - But wheat yields will decline by 15%.

Deutsch, C.A., et al. (2018) Increase in crop losses to insect pests in a warming climate, *Science*, 31 August, v. 361, Iss. 6405, p. 916-919
Springmann, M. et al. Global and regional health effects of future food production under climate change: a modelling study. The Lancet, March 2, 2016 DOI: 10.1016/S0140-6736(15)01156-3. Myers et al, 2014 Increasing CO_2 threatens human nutrition, Nature 510, 139-142. Feng et al, 2015 Constraints to nitrogen acquisition of terrestrial plants under elevated CO_2, Global Change Biology, DOI: 10.1111/gcb.12938



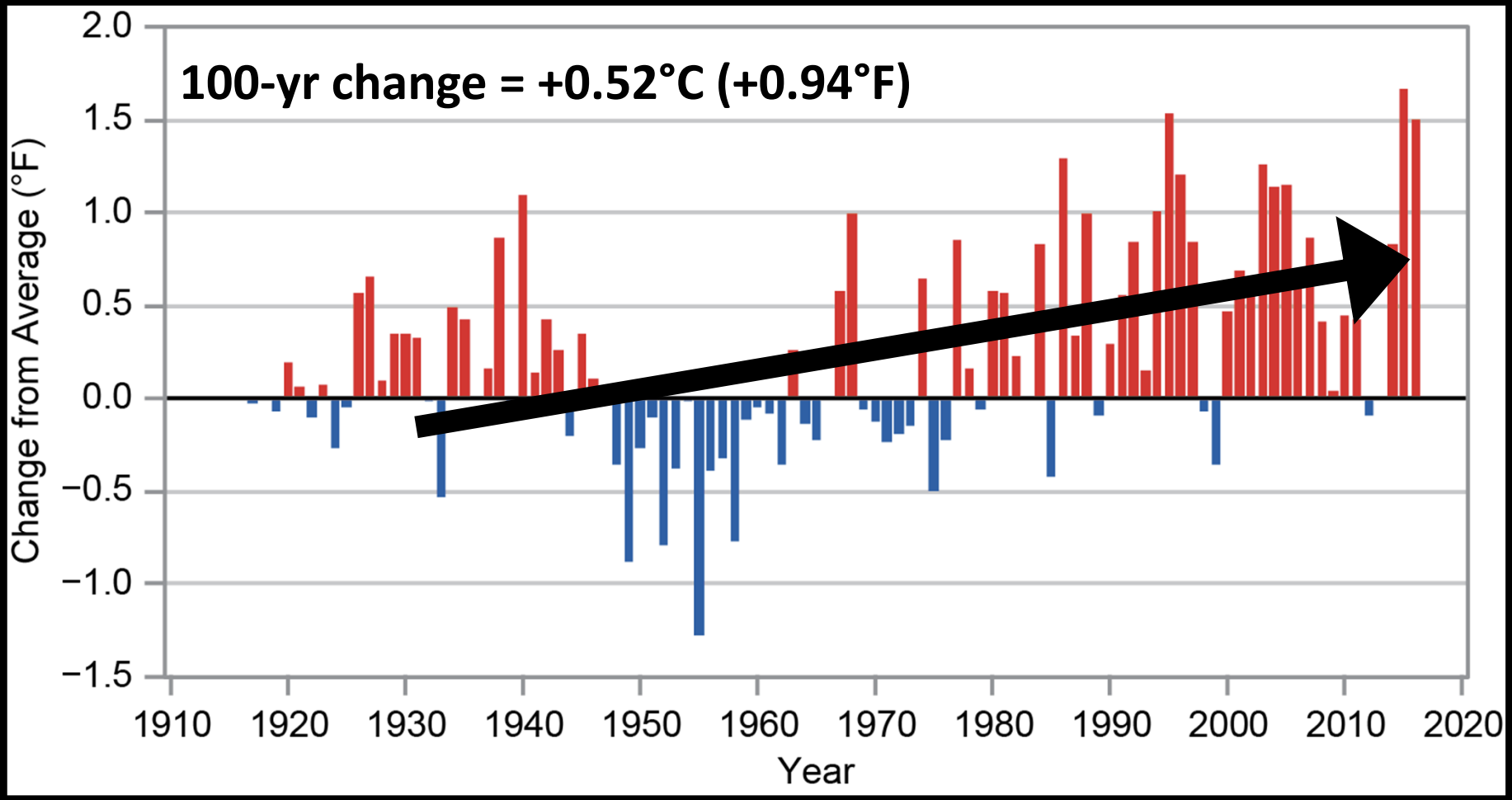
Smith, M.R., and Myers, S.S. (2018) Impact of anthropogenic CO2 emissions on global human nutrition, *Nature Climate Change* 8, 834-839

Food and water shortages can lead to violent conflict

Mora, C., et al. (2017) **Global risk of deadly heat.** *Nature Climate Change*; DOI: 10.1038/NCLIMATE3322

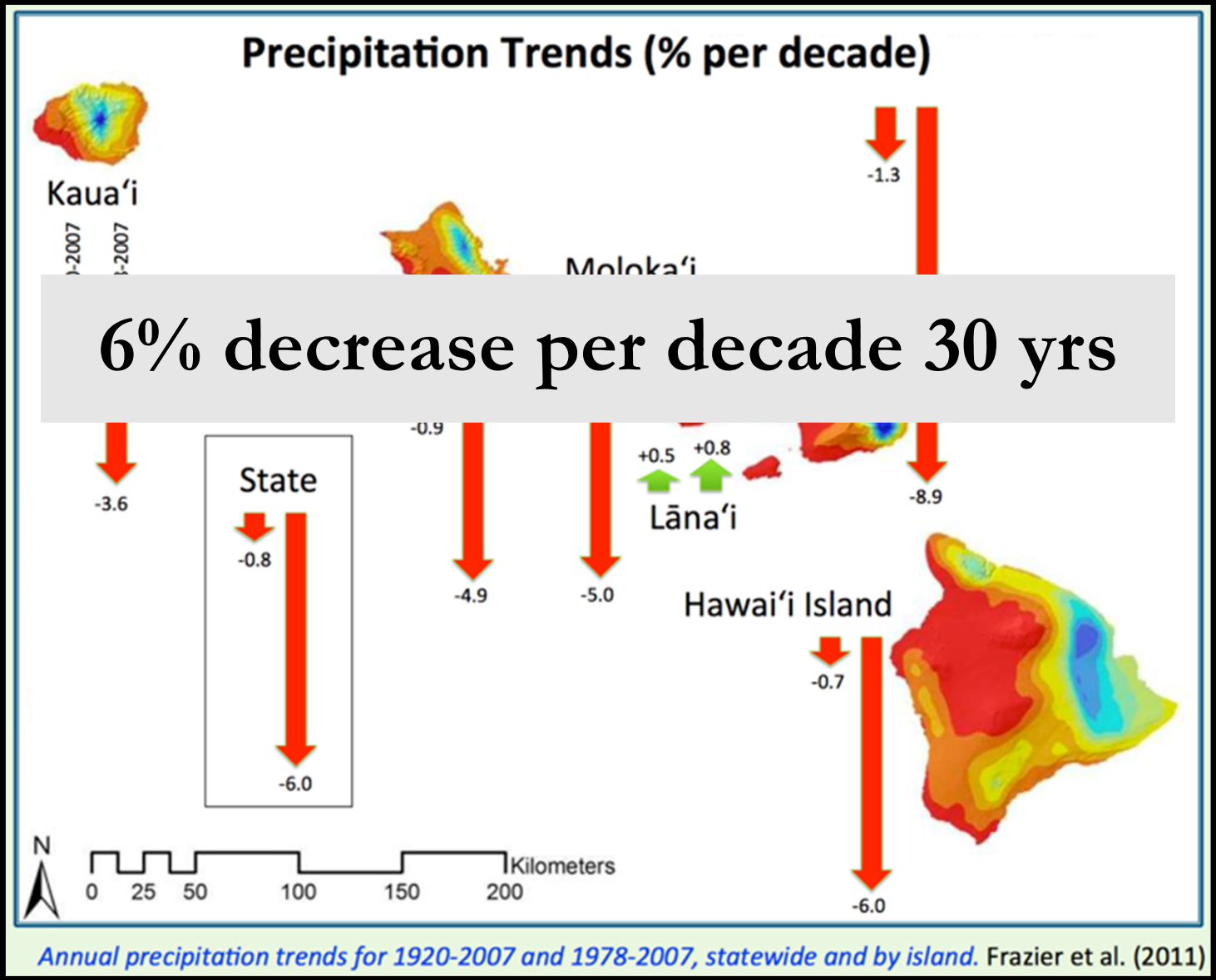
Local Climate Change Impacts

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*.

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.

Rainfall Trends in Hawai‘i (1920 to 2012)

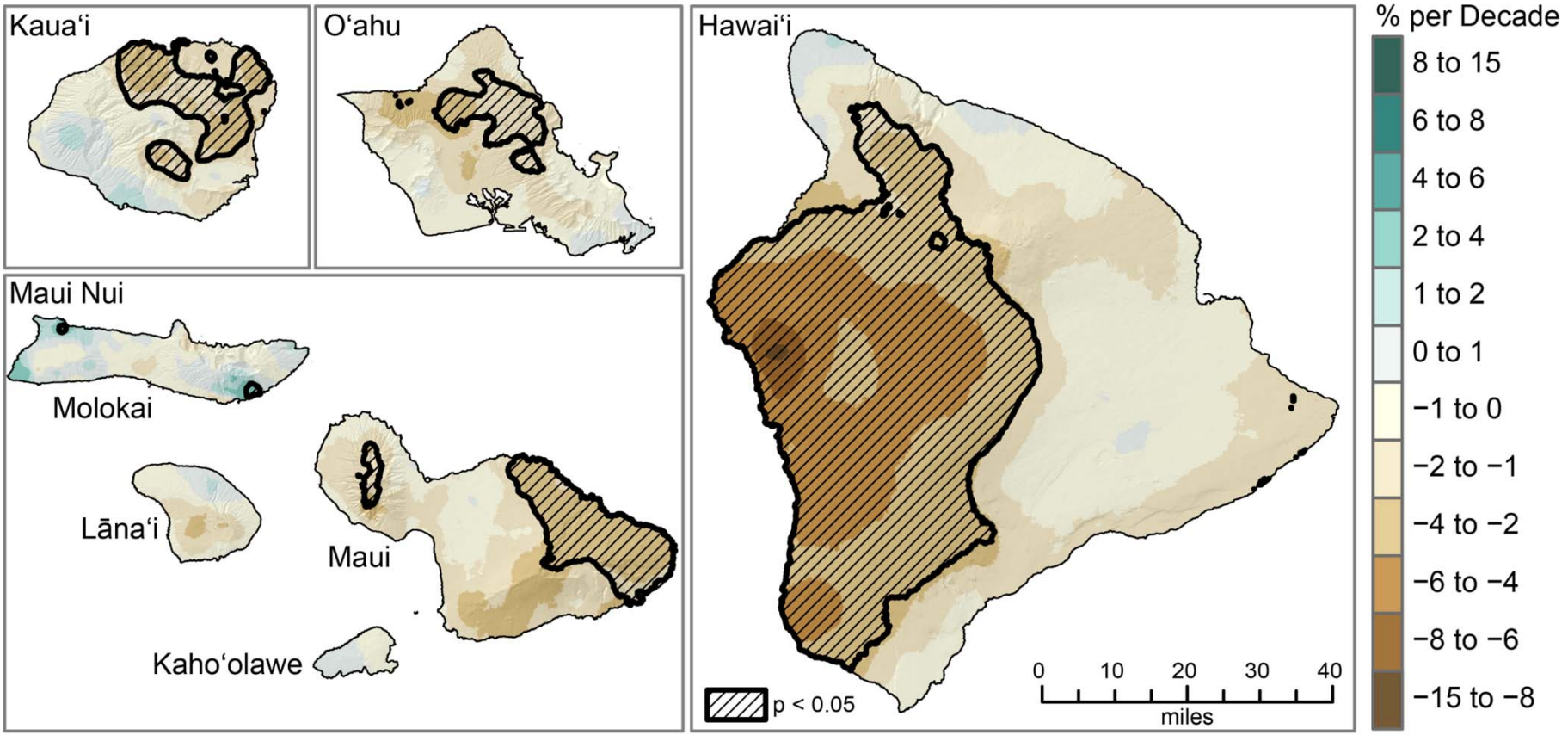


Fig. 27.6

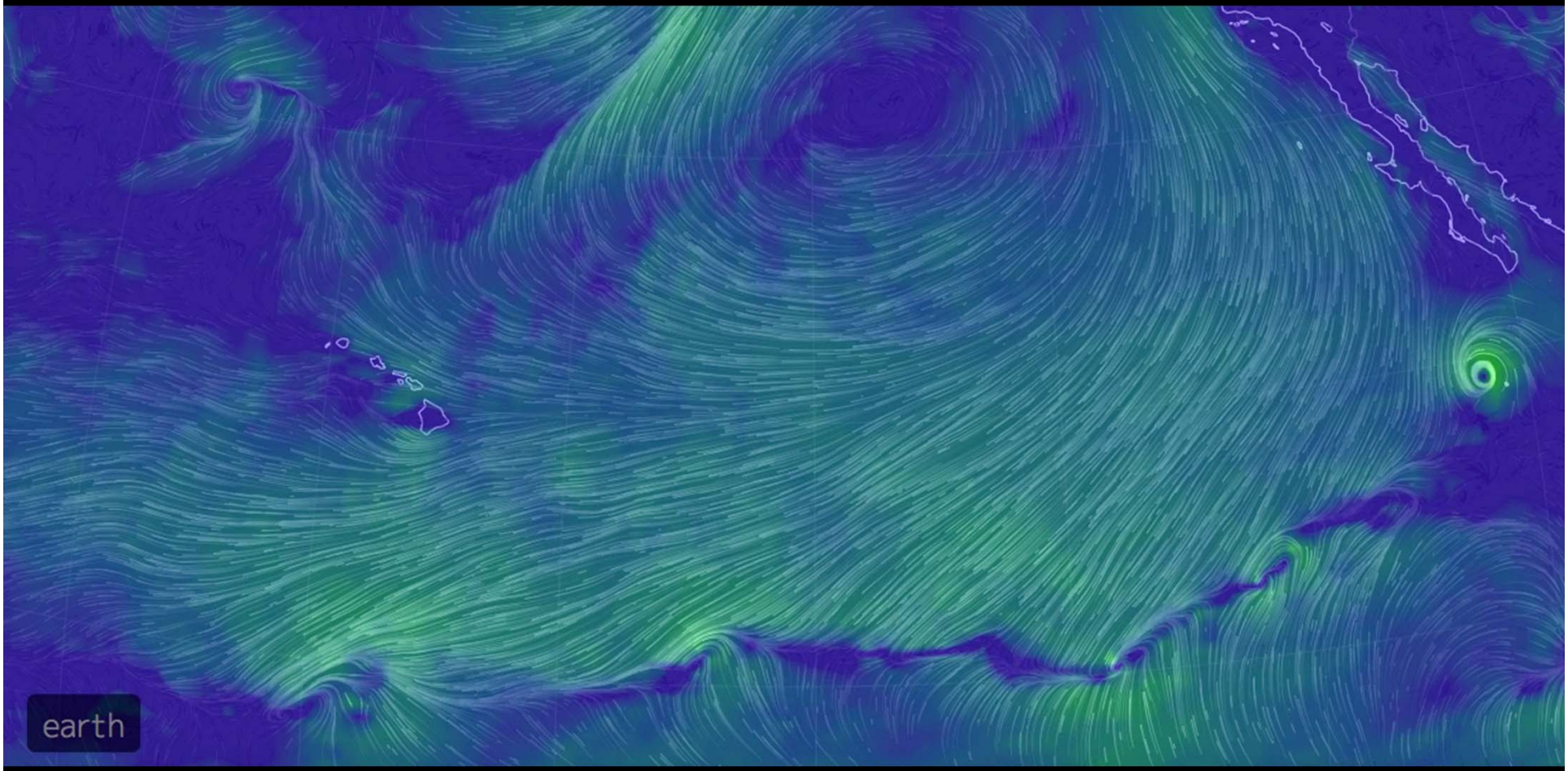
- Statewide drying trend with more consecutive dry days AND wet days
- Increased frequency of 1-day extreme rain events (90th percentile - Oahu, 1940-2010)

4th National Climate Assessment, 2018

Average daily wind speeds are declining

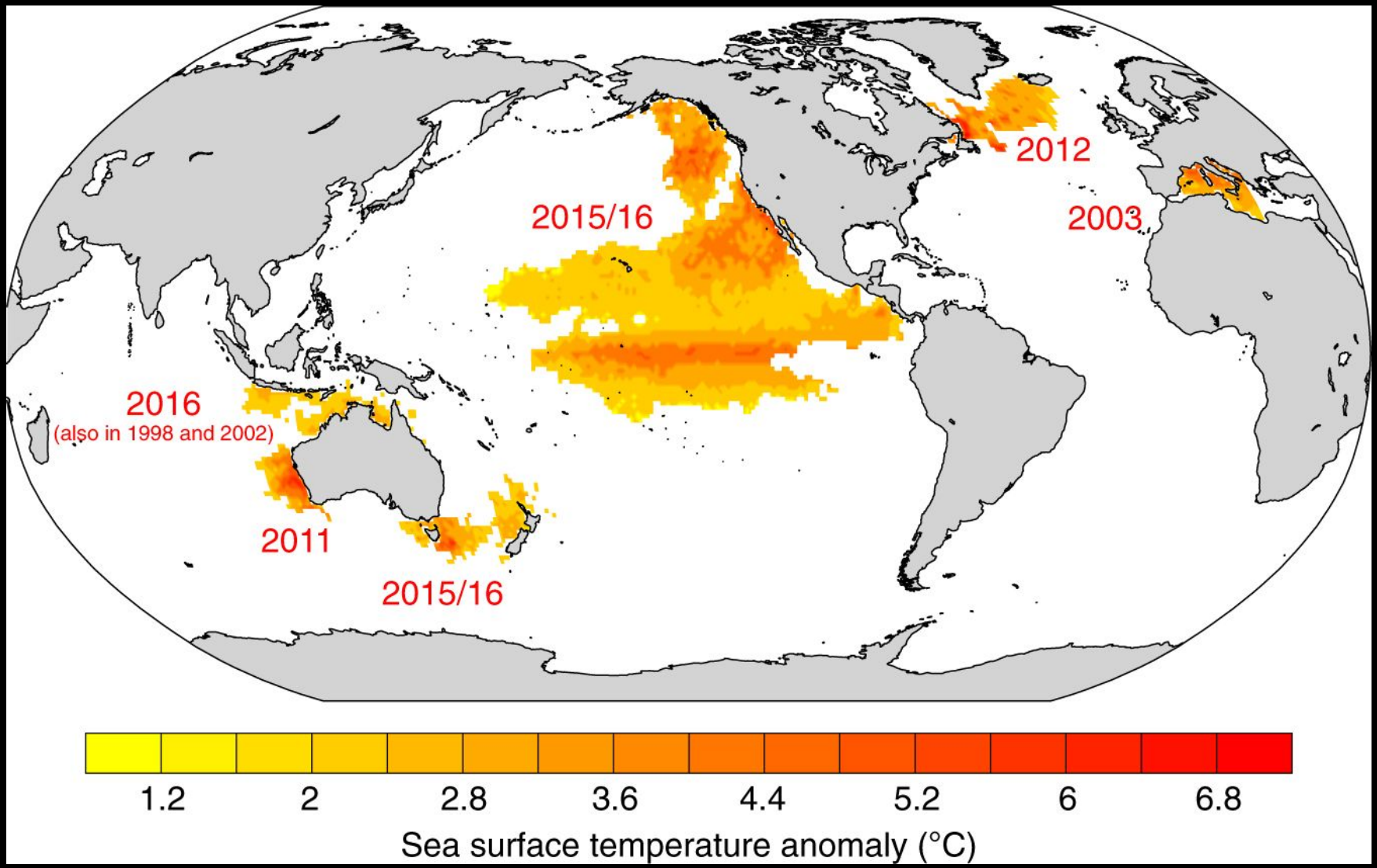
Marra, J.J., and Kruk, M.C. (2017) State of Environmental Conditions in Hawai'i and the U.S. Affiliated Pacific Islands under a Changing Climate: https://coralreefwatch.noaa.gov/satellite/publications/state_of_the_environment_2017_hawaii-usapi_noaa-nesdis-ncei_oct2017.pdf.

Trade winds easterly, warmer, less rain



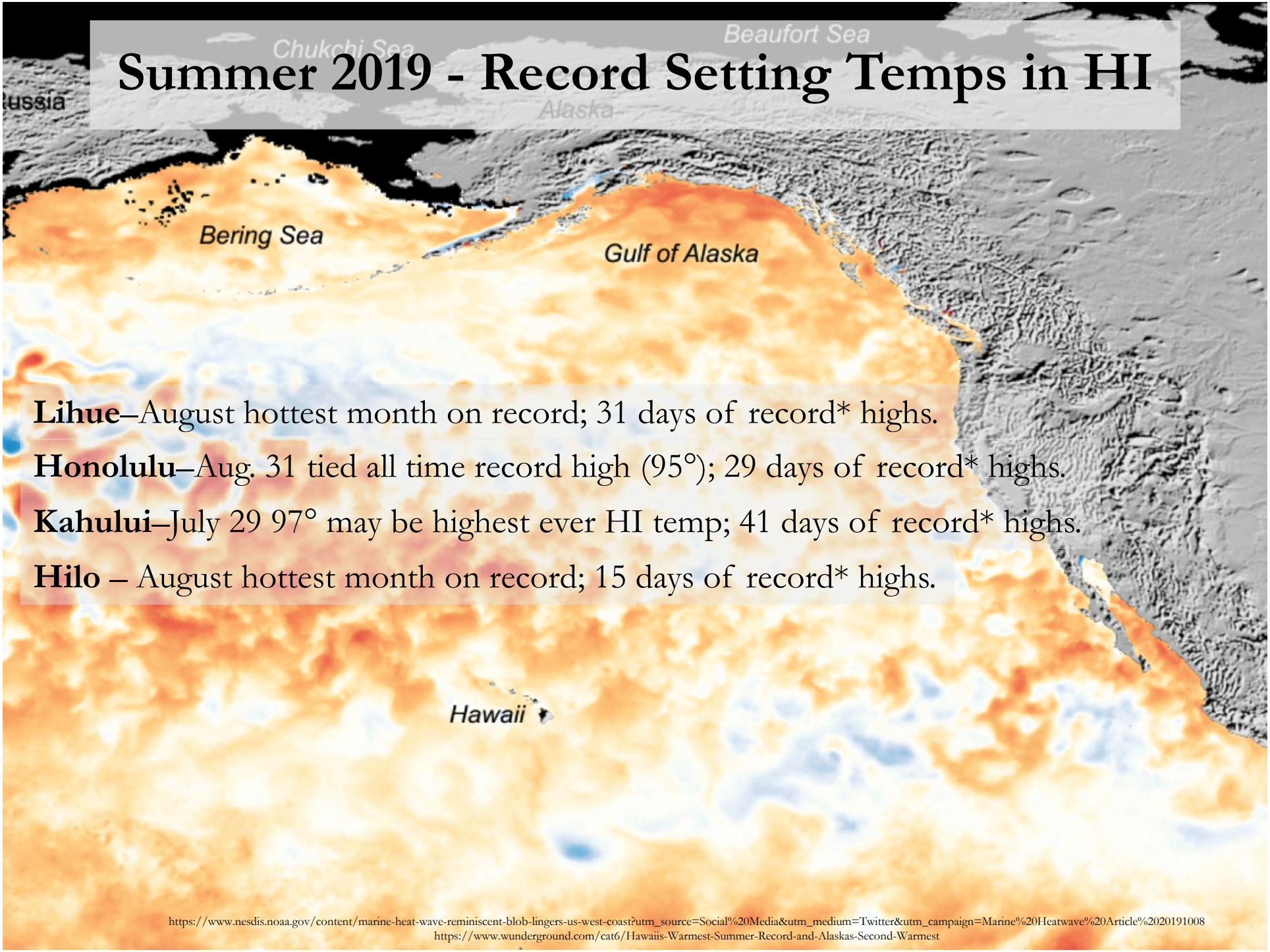
Marra, J.J., and Kruk, M.C. (2017) State of Environmental Conditions in Hawai'i and the U.S. Affiliated Pacific Islands under a Changing Climate: https://coralreefwatch.noaa.gov/satellite/publications/state_of_the_environment_2017_hawaii-usapi_noaa-nesdis-ncei_oct2017.pdf.

Marine Heatwaves 54% increase since 1925



Eric C. J. et al. (2018) Longer and more frequent marine heatwaves over the past century. *Nature Communications*, 2018; 9 (1) DOI: 10.1038/s41467-018-03732-9
Frölicher, T.L., Laufkötter, C. Emerging risks from marine heat waves. *Nat Commun* **9,** 650 (2018) doi:10.1038/s41467-018-03163-6

Summer 2019 - Record Setting Temps in HI



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

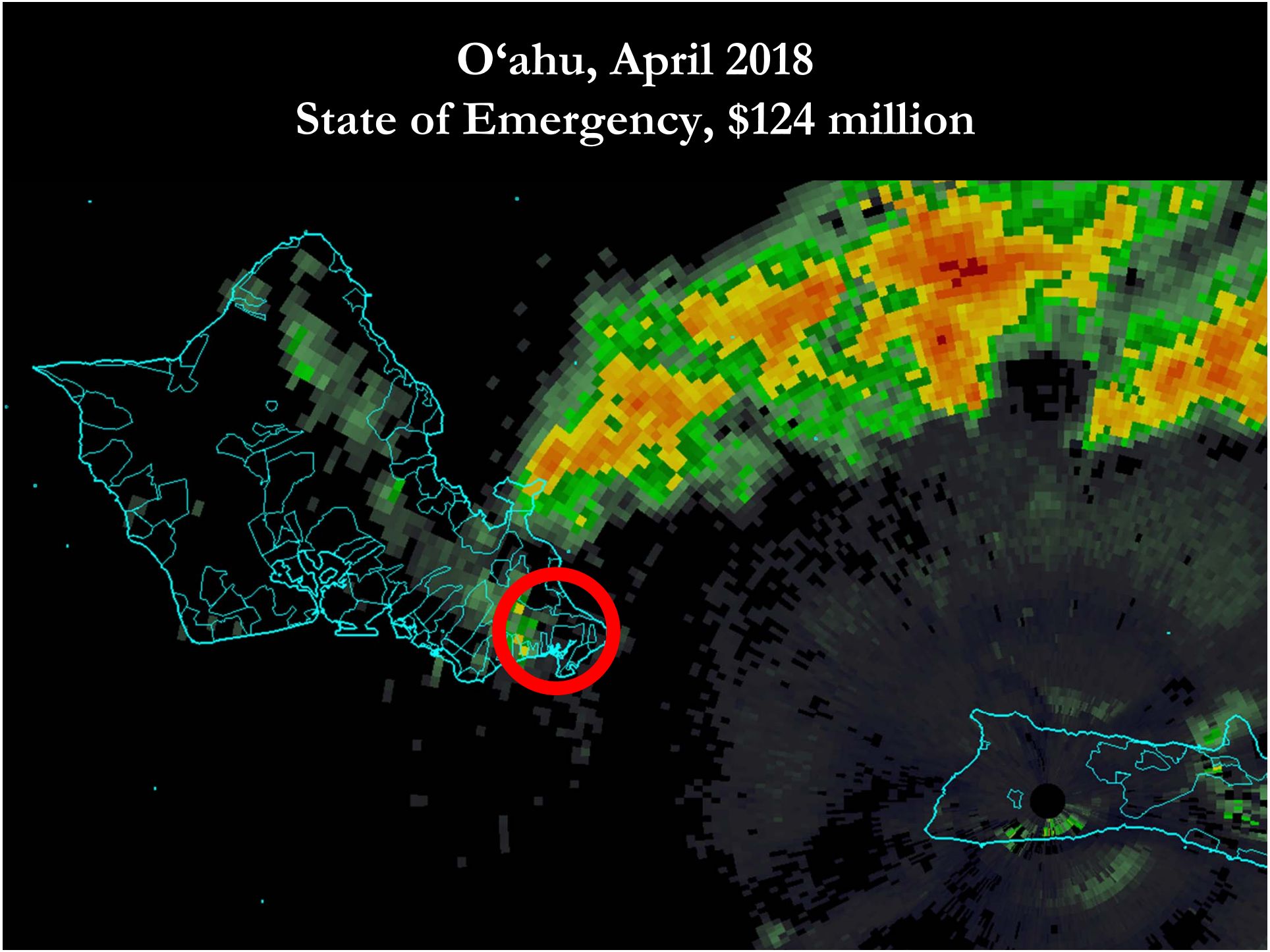
Honolulu–Aug. 31 tied all time record high (95°); 29 days of record* highs.

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.

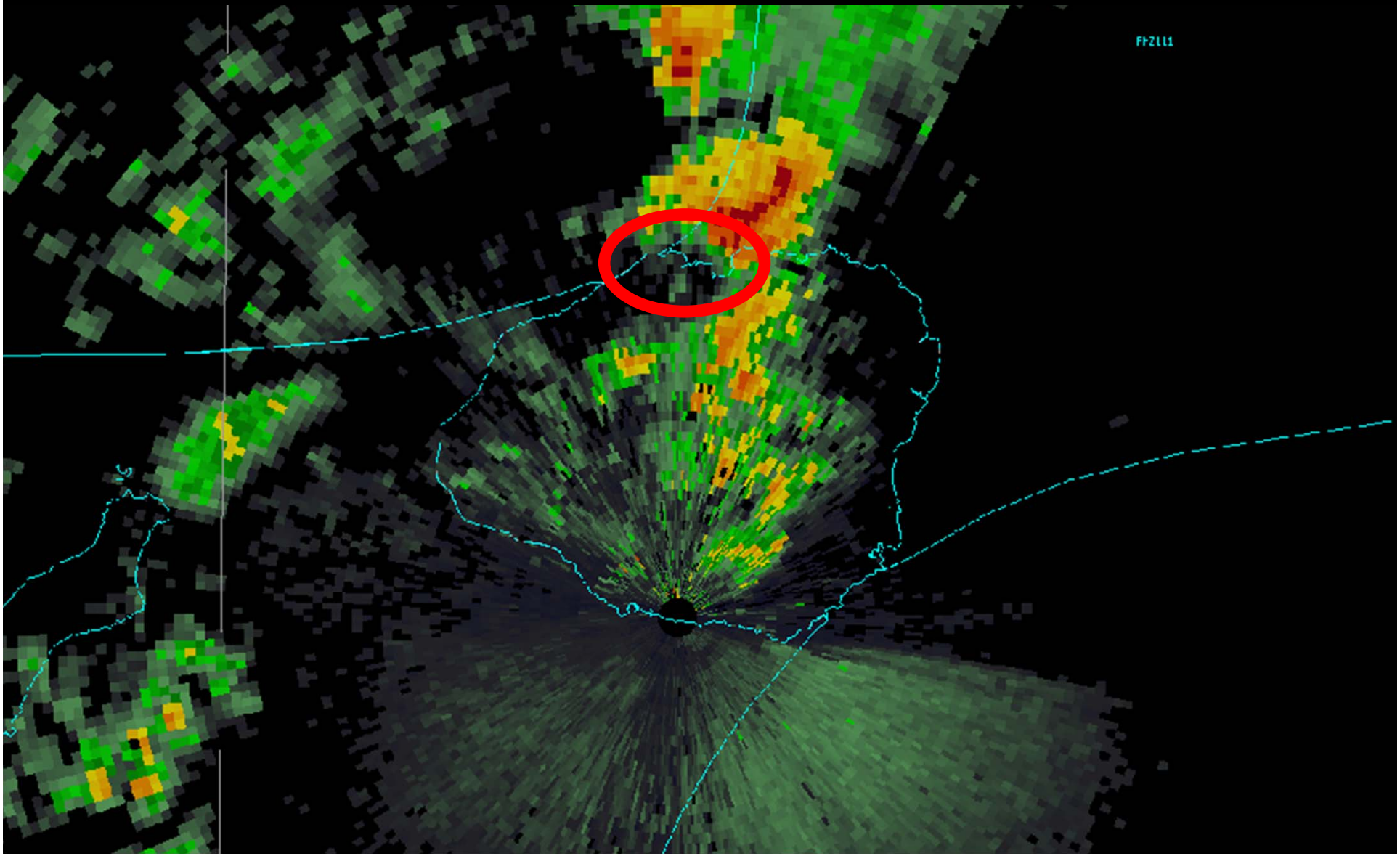
https://www.nesdis.noaa.gov/content/marine-heat-wave-reminiscent-blob-lingers-us-west-coast?utm_source=Social%20Media&utm_medium=Twitter&utm_campaign=Marine%20Heatwave%20Article%2020191008
https://www.wunderground.com/cat6/Hawaiis-Warmest-Summer-Record-and-Alaskas-Second-Warmest

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



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

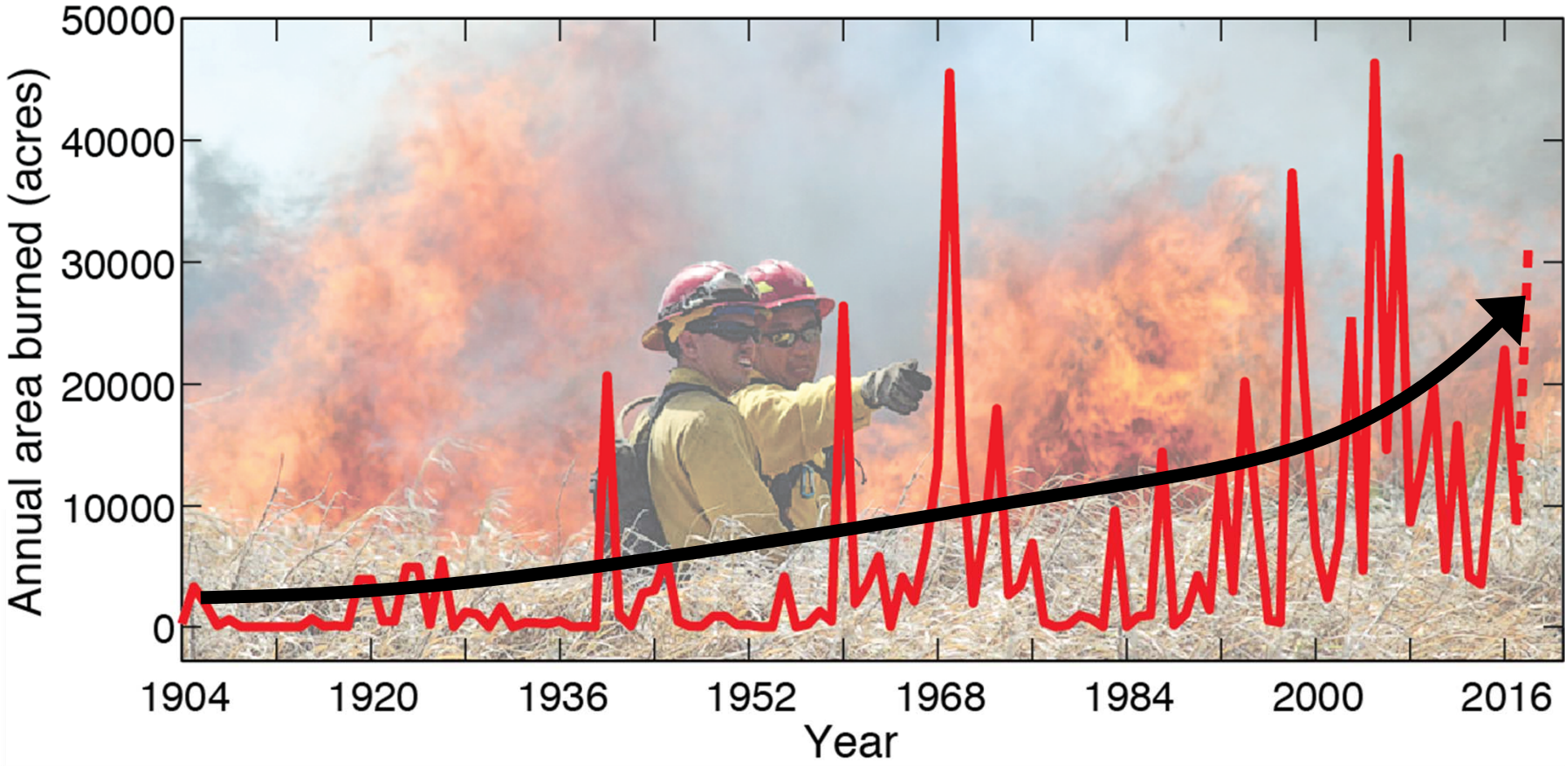
Kaua‘i, April 2018
49.69 inches in 24-hour, national record



Kaua‘i, April 2018
Hanalei River rose 15 feet

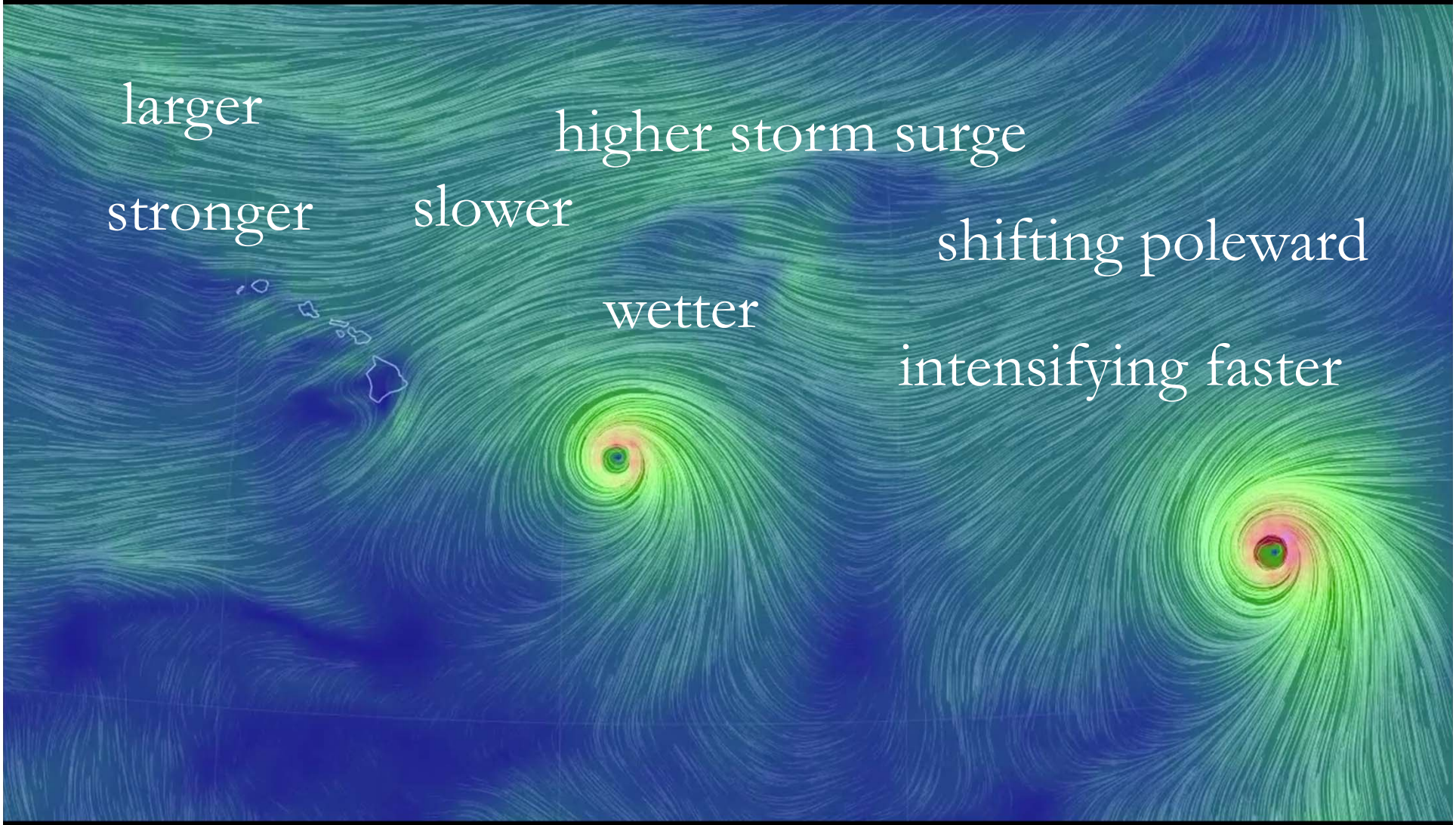
Kaua‘i, April 2018
Hanalei River jumped its bank and carved a new channel

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



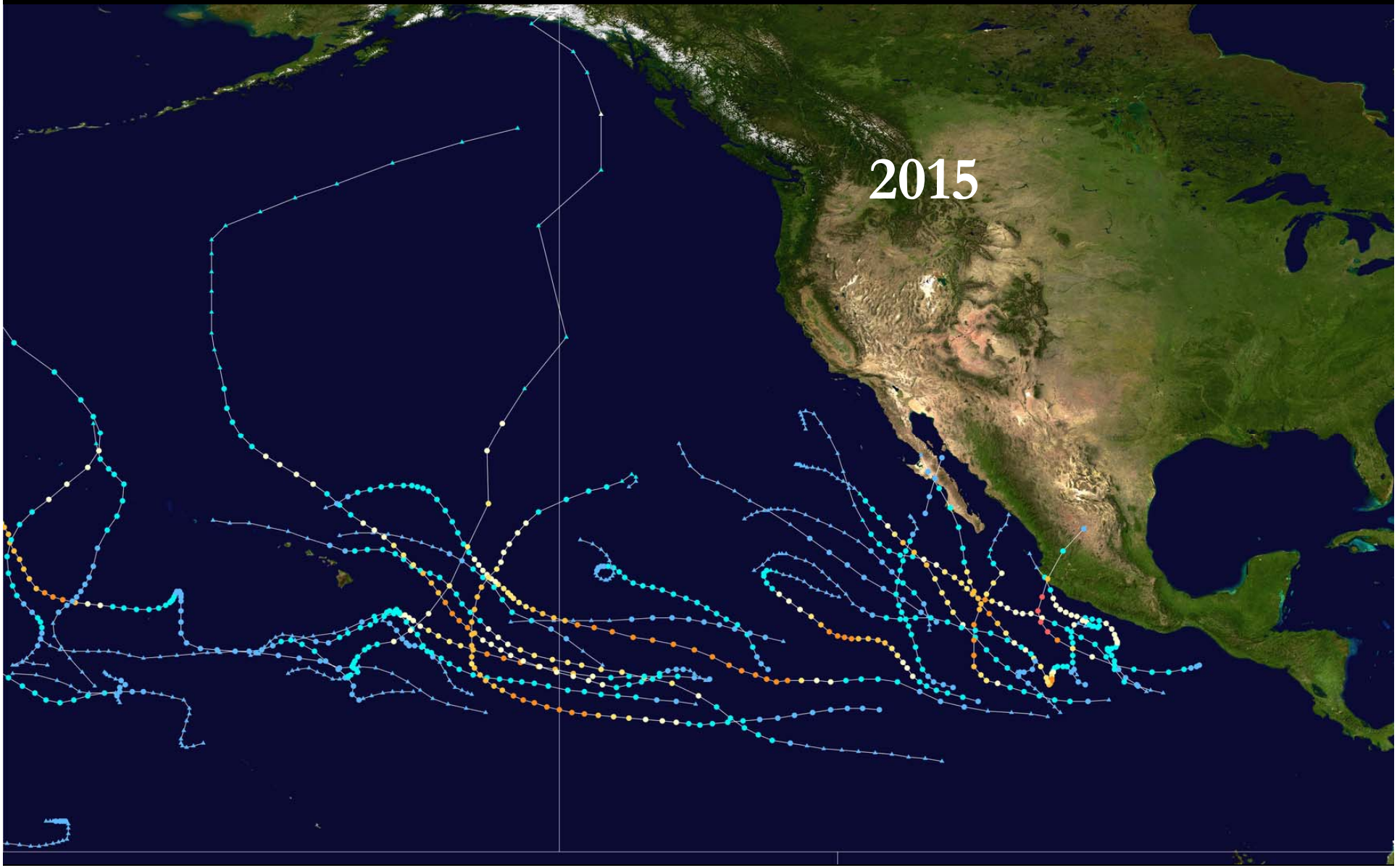
Trauernicht, C., E. et al. 2015 The contemporary scale and context of wildfire in Hawaii. Pacific Science 69:427-444

Hurricanes

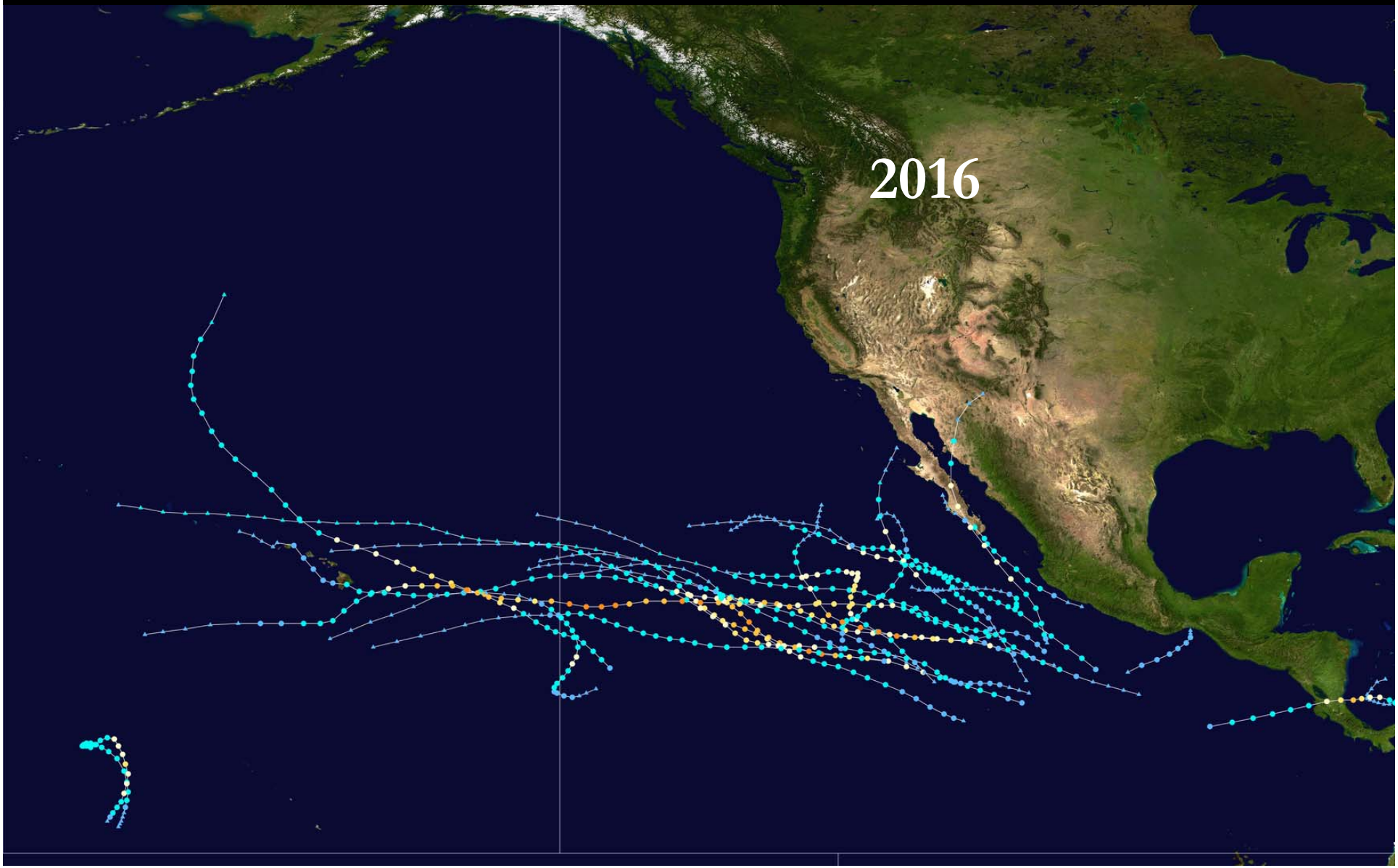


Does Global Warming Make Hurricanes Stronger? http://www.realclimate.org/index.php/archives/2018/05/does-global-warming-make-tropical-cyclones-stronger/

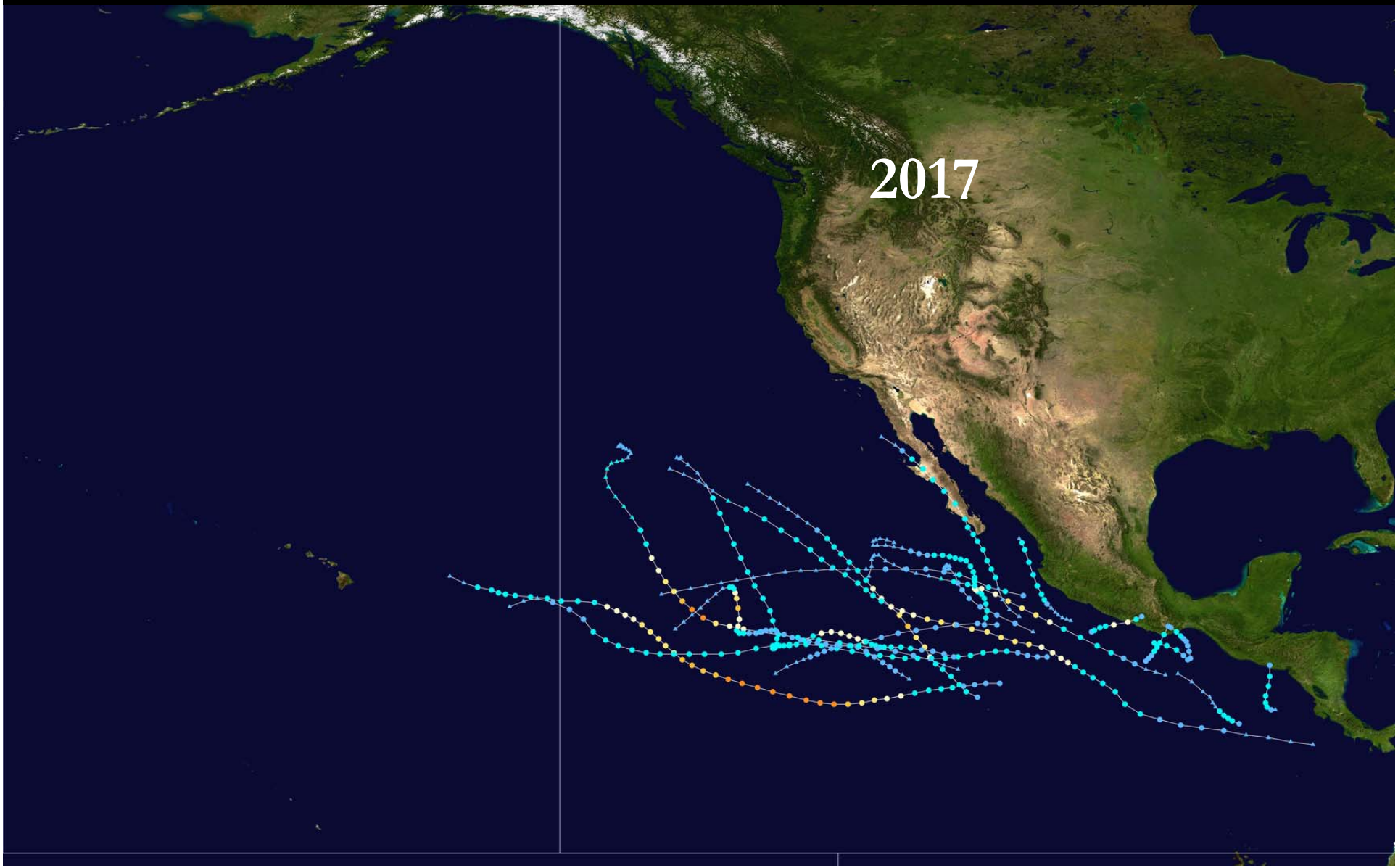
Recent Hurricane Seasons



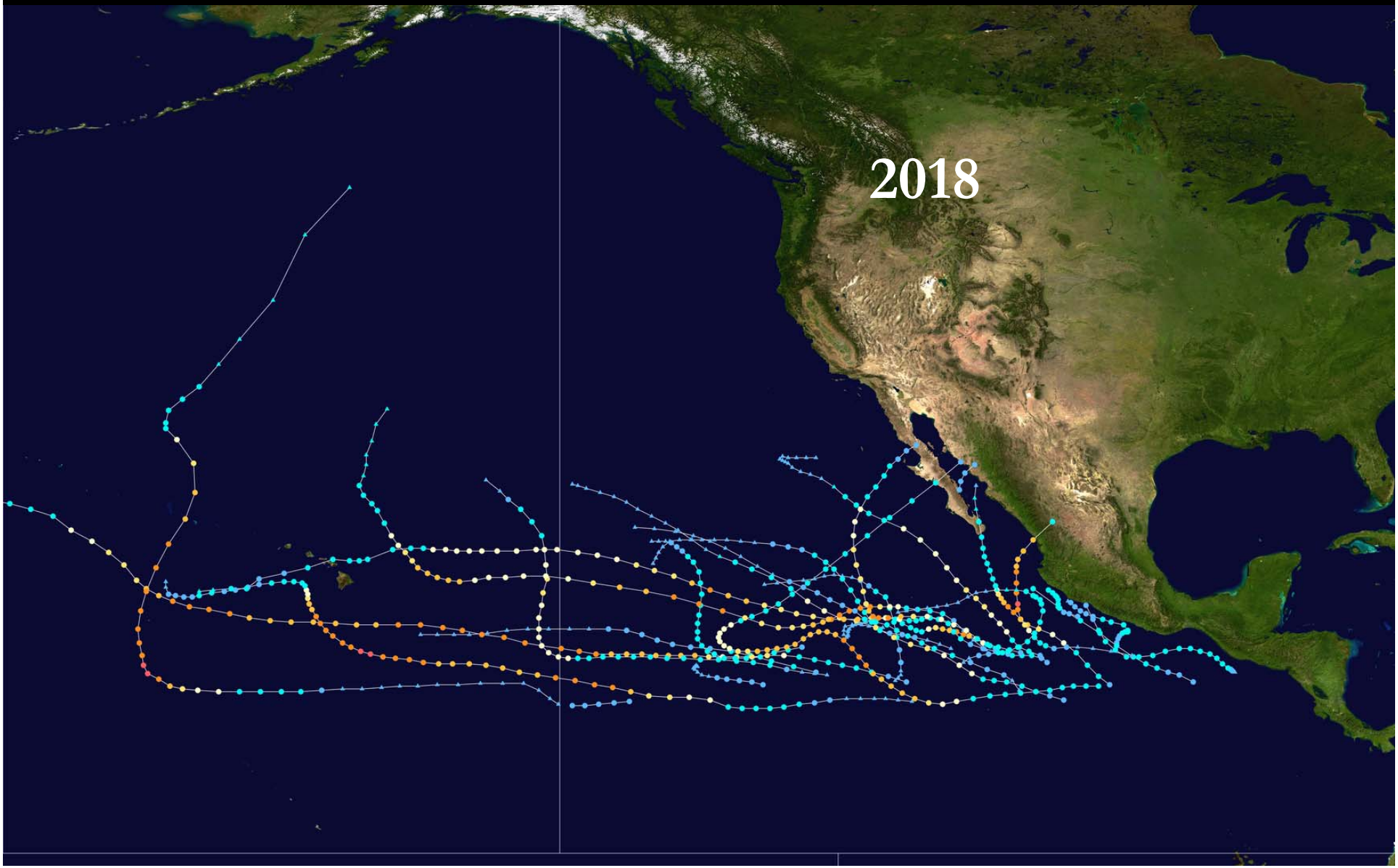
Recent Hurricane Seasons



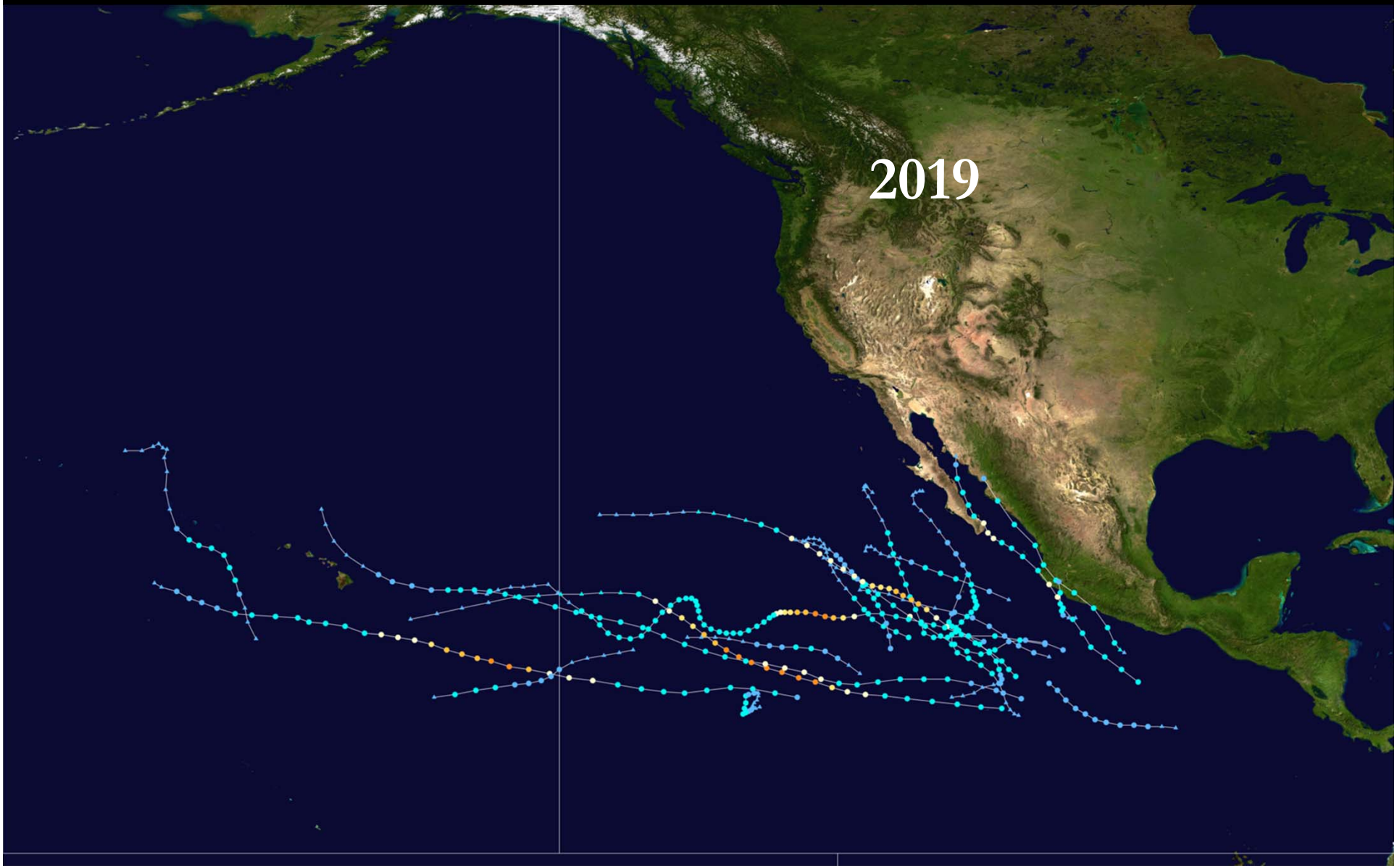
Recent Hurricane Seasons



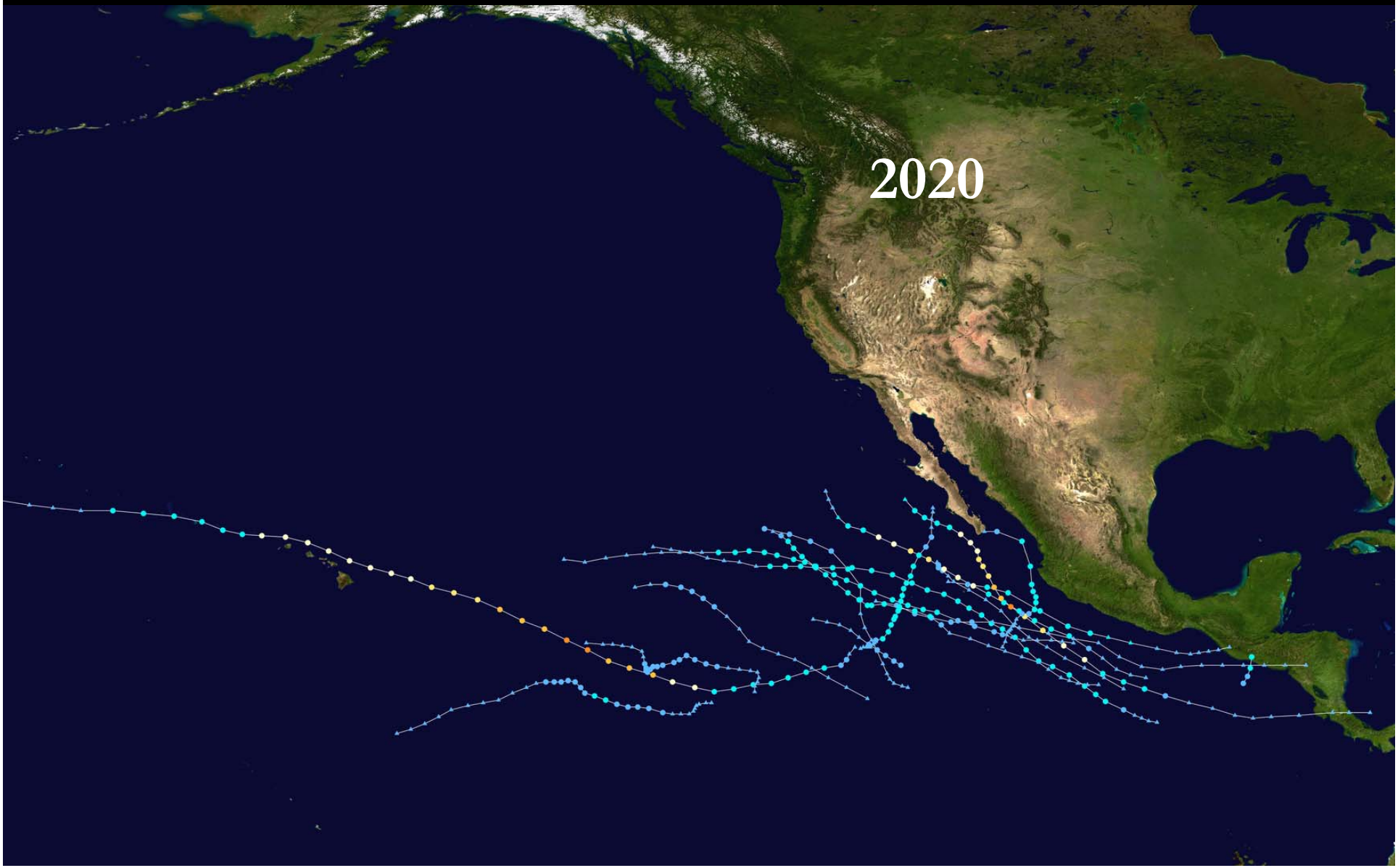
Recent Hurricane Seasons



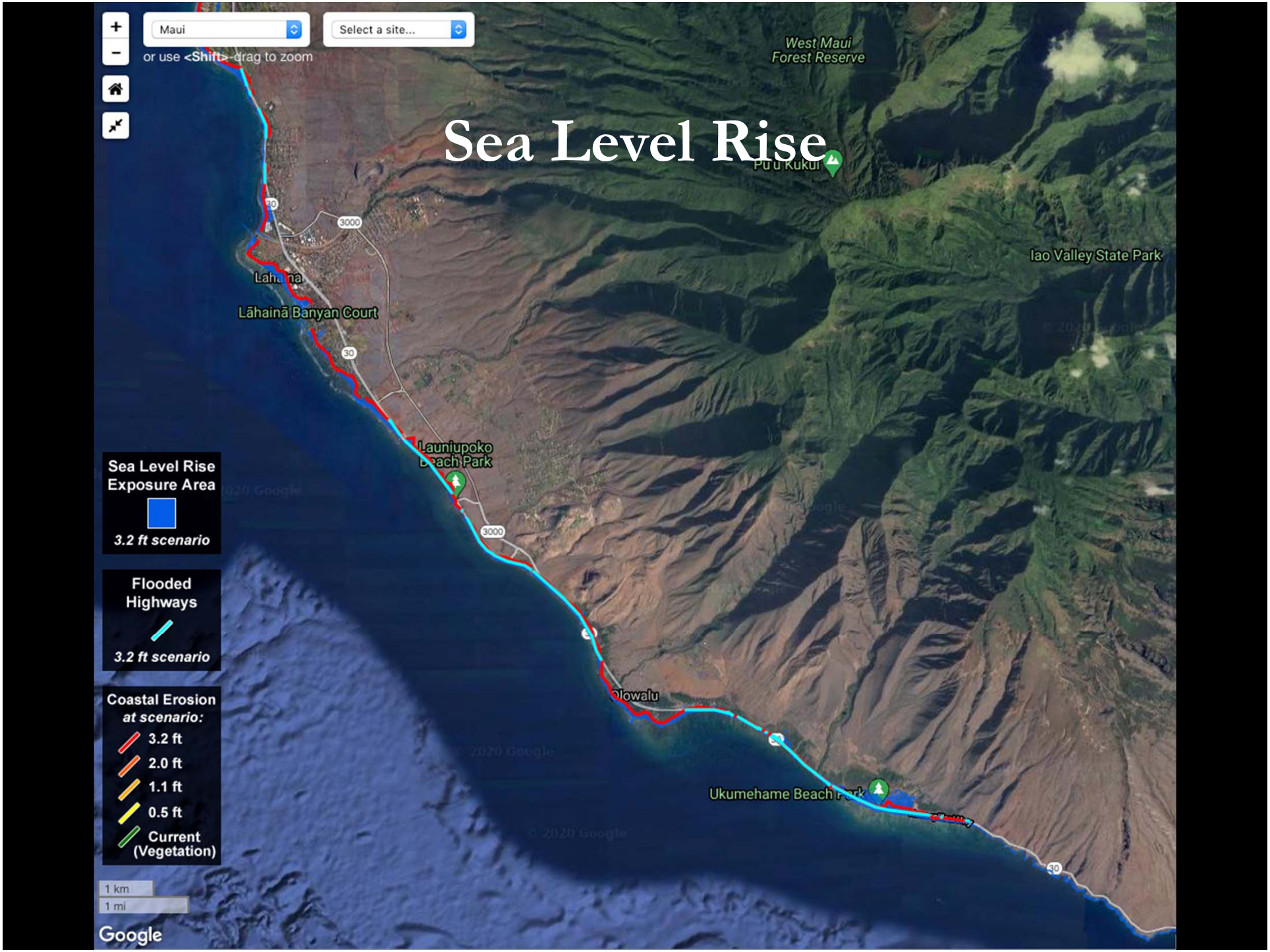
Recent Hurricane Seasons

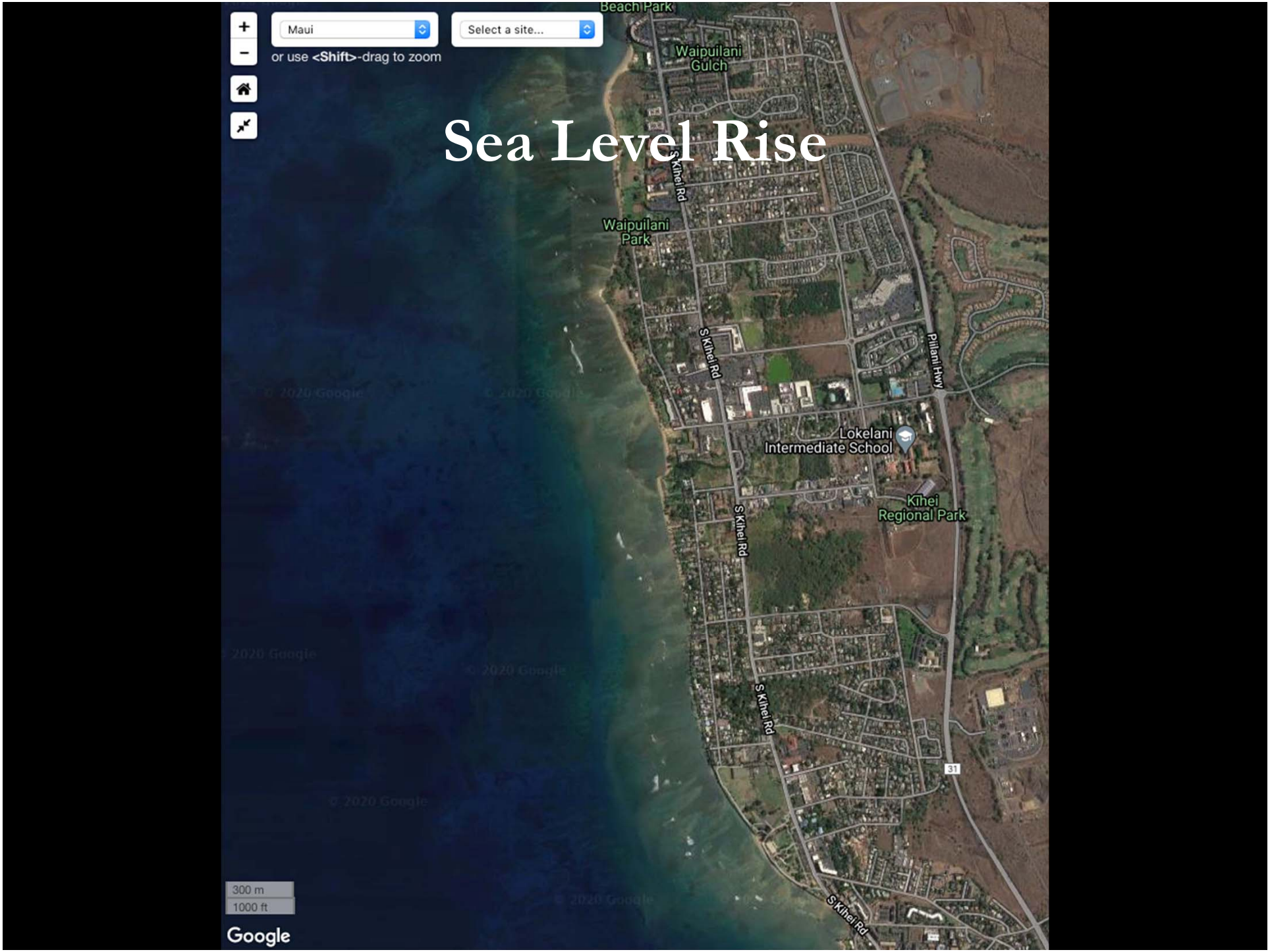


Recent Hurricane Seasons




Maui
Select a site...
or use <Shift>-drag to zoom
Sea Level Rise
West Maui
Forest Reserve
Pu'u Kukui
Iao Valley State Park
Lahaina
Lāhainā Banyan Court
Launiupoko
Beach Park
Olowalu
Ukumehame Beach Park
Honoapiilani Hwy
30
3000
1 km
1 mi
Google

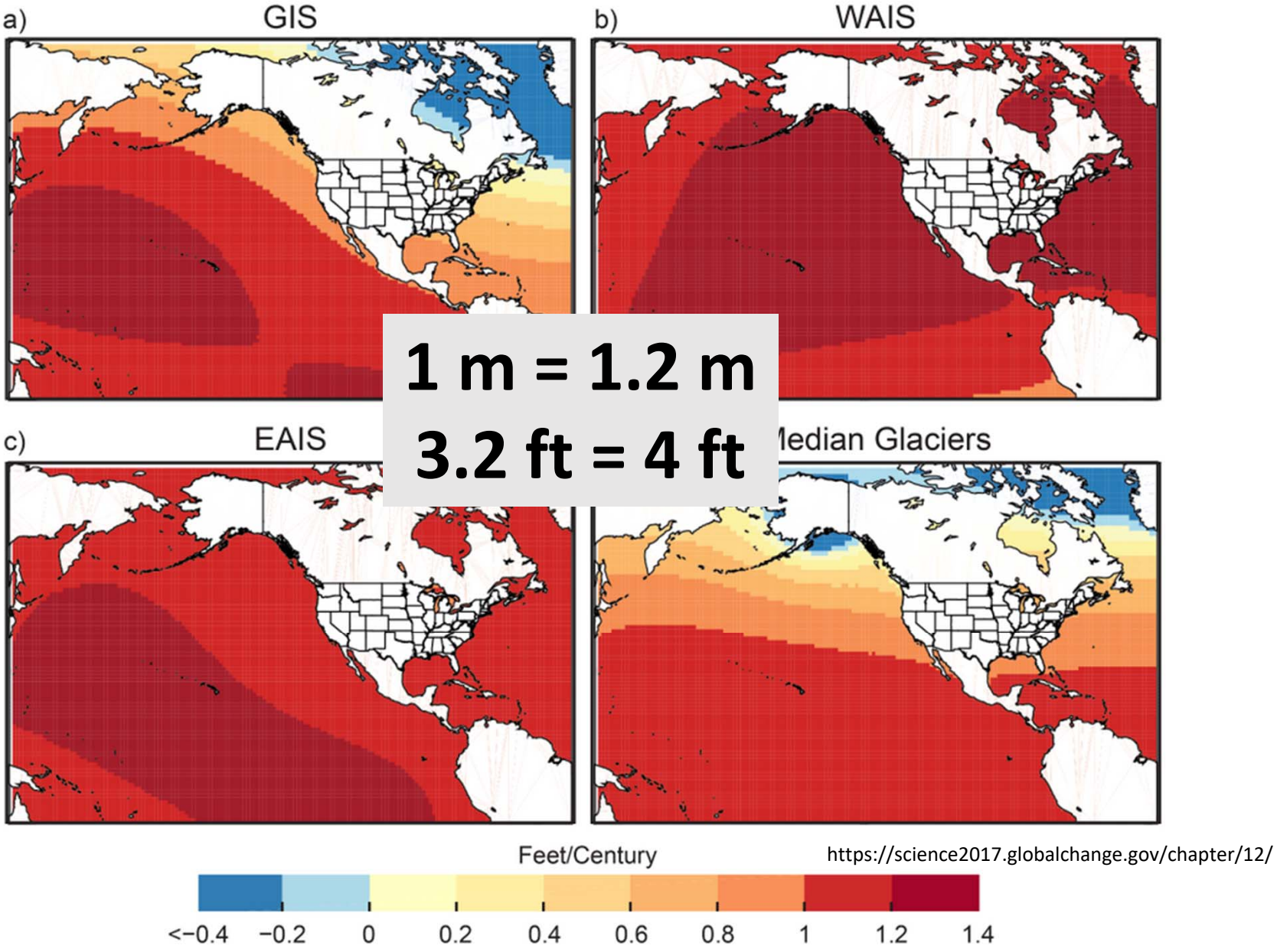

Maui
Select a site...
or use <Shift>-drag to zoom
Sea Level Rise
West Maui Forest Reserve
Pu'u Kukui
Iao Valley State Park
Lahaina
Lāhainā Banyan Court
Launiupoko Beach Park
Olowalu
Ukumehame Beach Park
3000
30
Sea Level Rise Exposure Area
3.2 ft scenario
Flooded Highways
3.2 ft scenario
Coastal Erosion at scenario:
3.2 ft
2.0 ft
1.1 ft
0.5 ft
Current (Vegetation)
1 km
1 mi
Google


Maui
Select a site...
or use <Shift>-drag to zoom
Sea Level Rise
Beach Park
Waipuilani Gulch
S Kihei Rd
Waipuilani Park
Piilani Hwy
Lokelani Intermediate School
Kihei Regional Park
31
300 m
1000 ft
Google


Maui
Select a site...
or use <Shift>-drag to zoom
Sea Level Rise
Waipuilani Gulch
S Kihei Rd
Pi'ilani Hwy
Lokelani Intermediate School
Kihei Regional Park
31
Sea Level Rise Exposure Area
3.2 ft scenario
Coastal Erosion at scenario:
3.2 ft
2.0 ft
1.1 ft
0.5 ft
Current (Vegetation)
Flooded Highways
3.2 ft scenario
300 m
1000 ft
Google

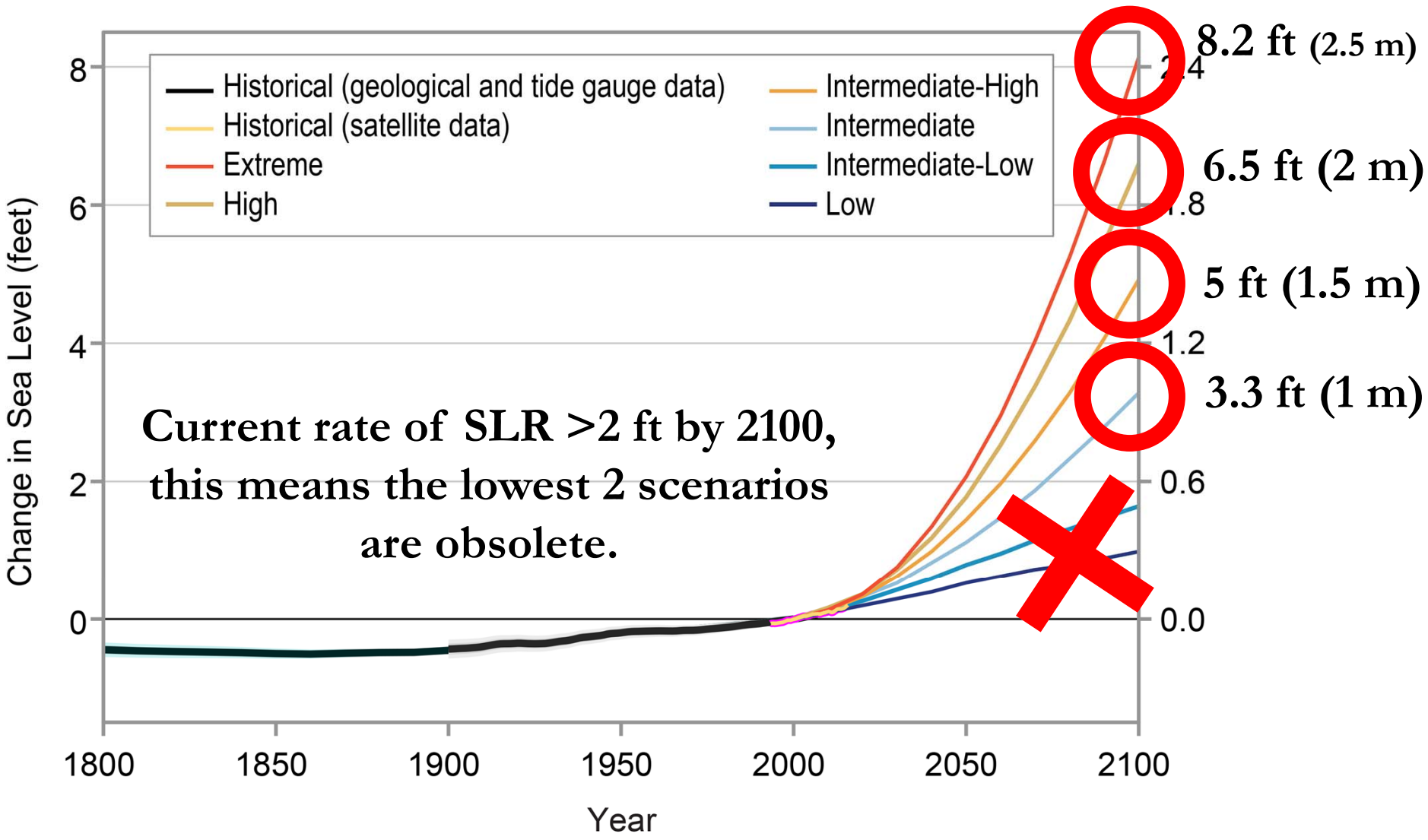
Thank you
I'm happy to take questions

Sea Level Fingerprinting



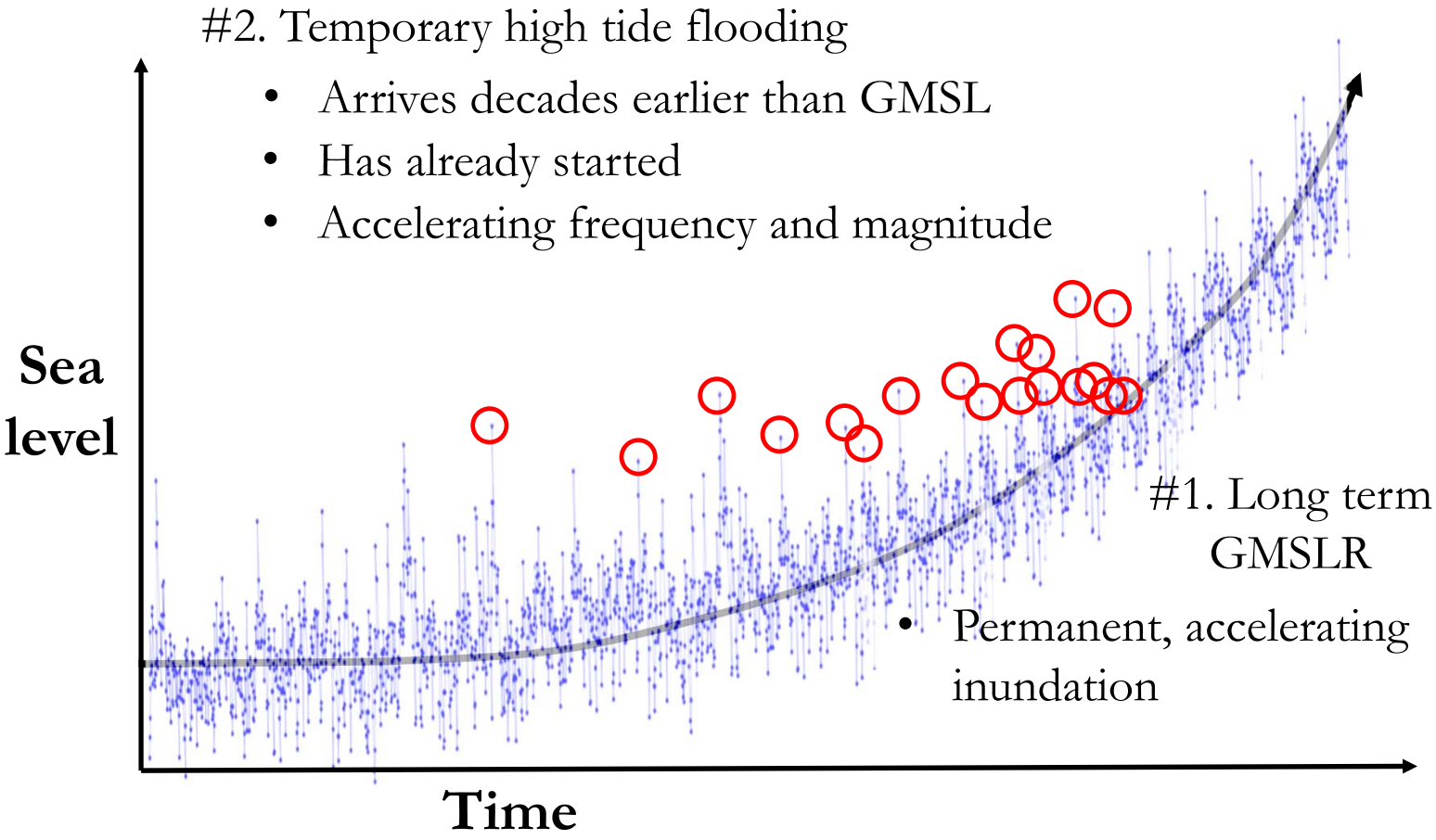
https://science2017.globalchange.gov/chapter/12/

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 Flooding: Nuisance and Permanent



Storm Drain Backflow at High Tide

Groundwater Inundation

Rain + High Tide = Flooding

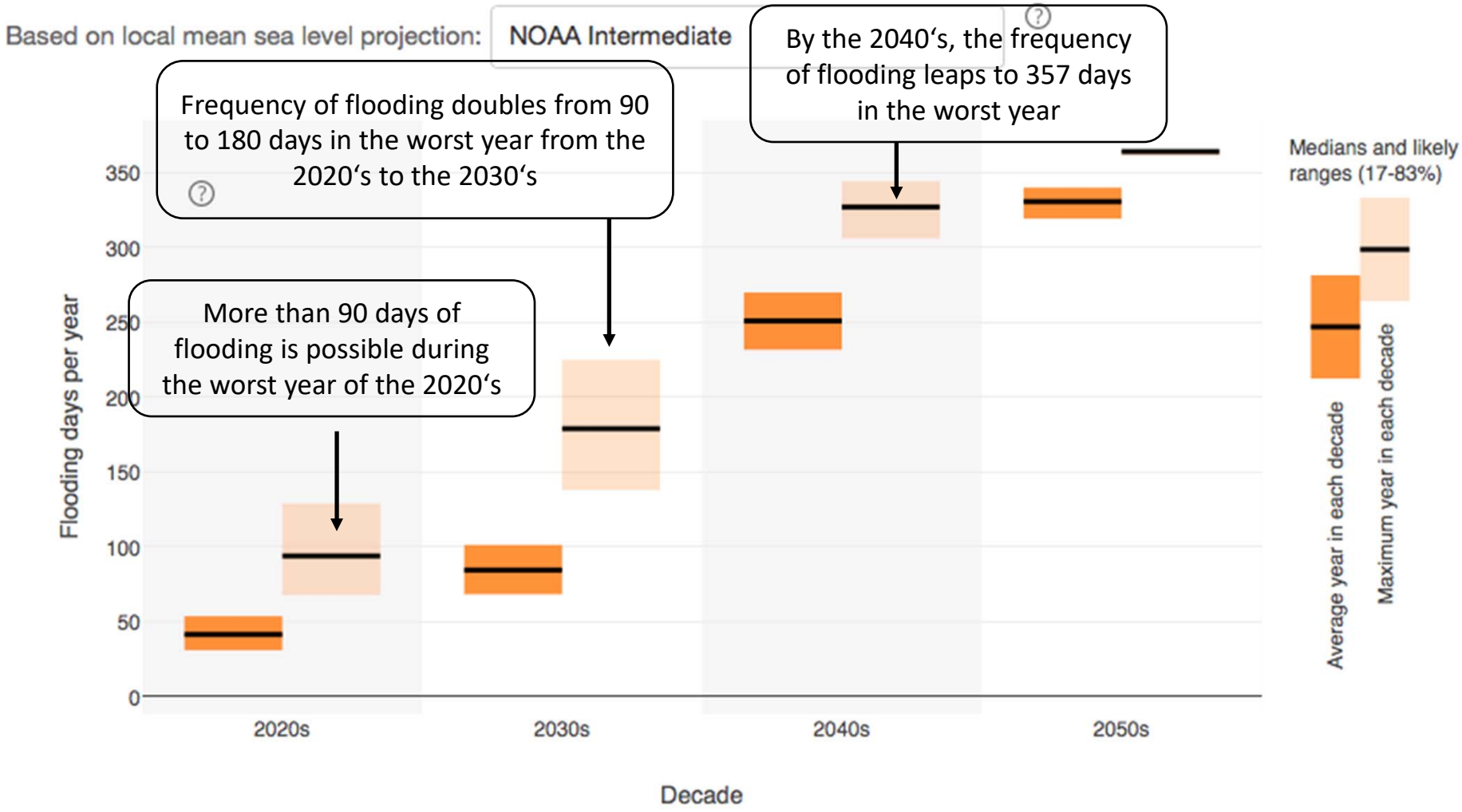
High Tide Flooding will bring polluted groundwater to the surface

Groundwater Pollution

King Tides today are rare, but are projected to rapidly increase to dozens of times per year within only 20-30 yrs

King Tides today are rare, but are projected to rapidly increase to dozens of times per year within only 20-30 yrs

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