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Thank you, Chairman Whitehouse, Ranking Member Grassley, and committee members for inviting me to speak today.

I am a Professor at the University of Wisconsin-Madison in the Department of Geoscience. I am a geologist and paleoceanographer who conducts research on past climate and sea-level change using marine sediments. My research focuses on the behavior of sea level and polar ice sheets during past warm periods to better inform us about future sea-level rise. I am an international expert in this area and my accomplishments have been widely recognized: as a MacArthur Fellow, a Fulbright Scholar, and a Fellow of the Geological Society of America.

Human-caused climate change that is driven primarily by the burning of fossil fuels poses formidable challenges to maintain the health of our oceans and coastlines. This impacts a wide range of economic, cultural, environmental, and social interests.

Climate impacts on the oceans that have major repercussions for marine life include:

- marine heatwaves that are increasing in frequency and intensity[1,2],
- more acidic seawater as the carbon dioxide we pump into the atmosphere gets absorbed by the oceans,[3,4] and
- lower levels of oxygen in seawater.[5]

Some additional impacts on the oceans include:

- changes in ocean currents that impact weather patterns extending far inland,[6]
- warmer oceans that fuel more intense hurricanes and can lead to rapid intensification of hurricanes before they make landfall,[7] and
- accelerating rates of sea-level rise and coastal inundation.[4]

These are just a few examples, but they give a flavor of the profound and far-reaching impacts of climate change on the oceans, marine life, and human life that will produce knock-on effects for our coastal and national budgets and economies. To better grasp the scope of these impacts, the remainder of my testimony provides more depth on two of these climate impacts: sea-level rise and marine heatwaves.

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[1] Marine heatwaves have increased by 54% over the last century.
[2] 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 Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362.
[3] About 25% of human carbon dioxide emissions have been absorbed by the oceans.
[4] Canadell, J.G. et al., 2021: Global Carbon and other Biogeochemical Cycles and Feedbacks. 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, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 673–816.
[5] Canadell, J.G. et al., 2021, IPCC.
[6] Fox-Kemper, B. et al., 2021, IPCC.
[7] Garner, A.J., 2023, Observed increases in North Atlantic tropical cyclone peak intensification rates. *Scientific Reports,* **13**, 16299.

Sea-level rise

Sea-level rise threatens the safety and security of the United States.[8]

Sea-level rise impacts coastal ecosystems and infrastructure that underpin the blue economy and also poses economic risks related to many topics that this committee has held hearings on, including supply chains, real estate, infrastructure, agriculture, insurance markets, health costs and more.

Sea level is not just rising, it is accelerating. Coastal communities are already struggling to keep up with sea-level rise; yet future rates of sea-level rise will outpace those of the present, which have already accelerated at least 3-fold in comparison to 20th century rates.[9] Coastal flooding frequency along U.S. coastlines has already increased by a factor of 2-3 along most of the Atlantic and Gulf coast between 1990 and 2020 and the occurrence of high tide flooding events is accelerating (Fig. 1).[10]

Sea level is rising due to the combined impacts of the expansion of seawater as the ocean continues to warm and the melting of land-based ice such as glaciers and ice sheets.[2] The polar ice sheets of Greenland and Antarctica are melting at accelerating rates and will become the increasingly dominant factor contributing to sea-level rise this century.[2]

- ### Rapid Jumps and Tipping Points

My research focuses on reconstructing sea-level change during past warm periods to constrain how quickly and how much sea-level rises as temperatures warm. The record of past sea-level change has taught us some important lessons about what to expect for the future.

We have learned that as ice sheets melt, sea level can experience sudden jumps as sectors of the ice sheet collapse.[5] **This potential for sudden pulses in sea level as ice sheets deteriorate means that if we are relying on average projections of future sea-level rise to estimate risk, then we will be unprepared for the much greater damages when such events unfold**.

If we delay action to slash carbon emissions, **we risk triggering physical instabilities known to exist in ice sheets; crossing these tipping points will commit us to accelerating rates of sea-level rise and continued ice loss that cannot be reversed on human timescales.[2,11]** Once that threshold is crossed, mass loss of ice will further accelerate and could commit us to rates of sea-level rise 10 times faster than today by the end of this century.[11]

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[8] Department of Defense, Office of the Undersecretary for Policy (Strategy, Plans, and Capabilities). 2021.
[9] Gulev, S.K. et al., 2021, Changing State of the Climate System. 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, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 287–422.
[10] USGCRP, 2023: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA.
[11] DeConto, R.M. et al., 2021, The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature* 593, 83–89.

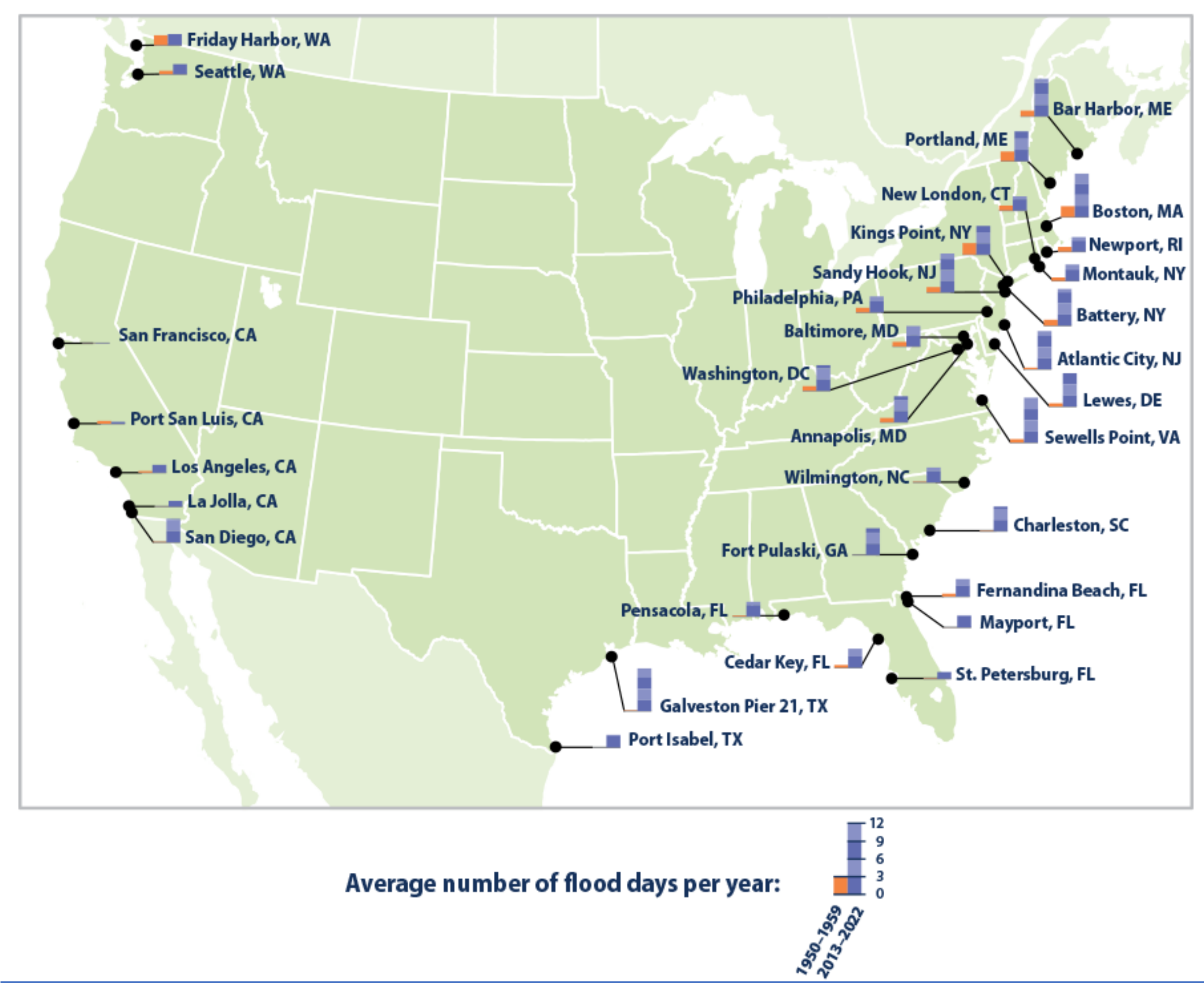

Figure 1. The average number of days per year when coastal waters rose above a local threshold for flooding. The small bar graphs for each of the 33 sites compares the number of flood days per year for 1950-1959 in orange compared to the 2013-2022 time window in purple.[12,13]

There is considerable evidence that portions of the West Antarctic Ice Sheet may be near such a tipping point, whereby the grounded ice margin could retreat past the ledge of the deep basin in which it sits, causing the ice sheet to become unstable and retreat rapidly down this slope.

Both data and modeling suggest that some of these thresholds for rapid melting and retreat in Greenland and Antarctica are somewhere between 1 and 2 °C of warming[14] and could commit us to tens of feet of sea level rise. For reference, last year warming reached 1.4 °C above the preindustrial baseline.

[12] Data from NOAA (National Oceanic and Atmospheric Administration). 2023. Tides and currents: CO-OPS derived product API. https://api.tidesandcurrents.noaa.gov/dpapi/prod
[13] Figure from https://www.epa.gov/climate-indicators/climate-change-indicators-coastal-flooding
[14] Warming is relative to the preindustrial baseline.

In comparison to past warming events, we are warming the ice sheets faster now than at any point in geologic history and we are heating both poles simultaneously[15]. Both of these factors may push the ice sheets and sea-level rise to respond even more quickly than in the past.

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When will we cross ice sheet tipping points? Even with the best models and the best data imaginable, we won't truly be certain where these tipping points are until we are past them.

A key takeaway is that because there are known tipping points in ice sheets, there is an urgency to reducing carbon emissions sooner rather than later. While we can negotiate with each other until we are blue in the face, we cannot negotiate with the ice sheets. The physics is simple: sustained global warming melts more ice. And there is much at risk on our coastlines.

- **What the 'long tail' means for economic risk**

Sea-level rise projections have been developed according to different carbon emission scenarios to help us understand the probable response of sea level (one example is shown in Fig. 2A). These are useful for planning, but reliance on the most probable or central estimate outcome masks the true risk in what is referred to as the long tail (Fig. 2B).

Long-tailed (skewed) distributions have uncertainties that are unequally distributed around the central estimate. In the case of sea-level rise (and many other climate impacts) **this means that the central estimate more likely greatly underestimates the true risk rather than overestimates it.**

I have just provided several examples (sea-level pulses, tipping points in ice sheets, and rapid and bi-polar climate forcing) of reasons why sea level may rise both higher and faster than the 'central estimate' or range of 'consensus values' that are often the focus in research studies and reports. This helps to understand why the uncertainty for future sea-level has a very long tail on the high end.

Most economic models are unable to fully account for this long tail. To address this, in one study, a spatial analysis of eight climate tipping points showed that passing these tipping points would increase economic losses almost everywhere and increase the overall level of risk in the global economy.[16] Even in that case, the authors warn that their results are "probable underestimates" of the actual risk.

[15] Greenhouse gas emissions heats both poles simultaneously in contrast to some past examples of warming and ice sheet retreat that were caused by small changes in Earth's orbit, where increasing solar insolation in one hemisphere corresponds to less in the other hemisphere.
[16] Dietz et al., 2021, Economic impacts of tipping points in the climate system, *Proceedings of the National Academy of Sciences*, 118 (34) e2103081118.

Another factor that leads to underestimated risk is how sea-level projections are interpreted and implemented in coastal planning. Relative sea level projections for a particular location are typically taken to represent how long a community might have until sea level reaches a particular elevation. Unfortunately, this is incorrect and leads to a gross underestimation of risk.

In brief, for any magnitude of sea-level rise shown on a projection curve, sea level will reach that level before the time indicated on the graph.[17] At first it may only be once or a few times a year, but the frequency of sea level reaching that elevation will increase until this becomes the average position of sea level.

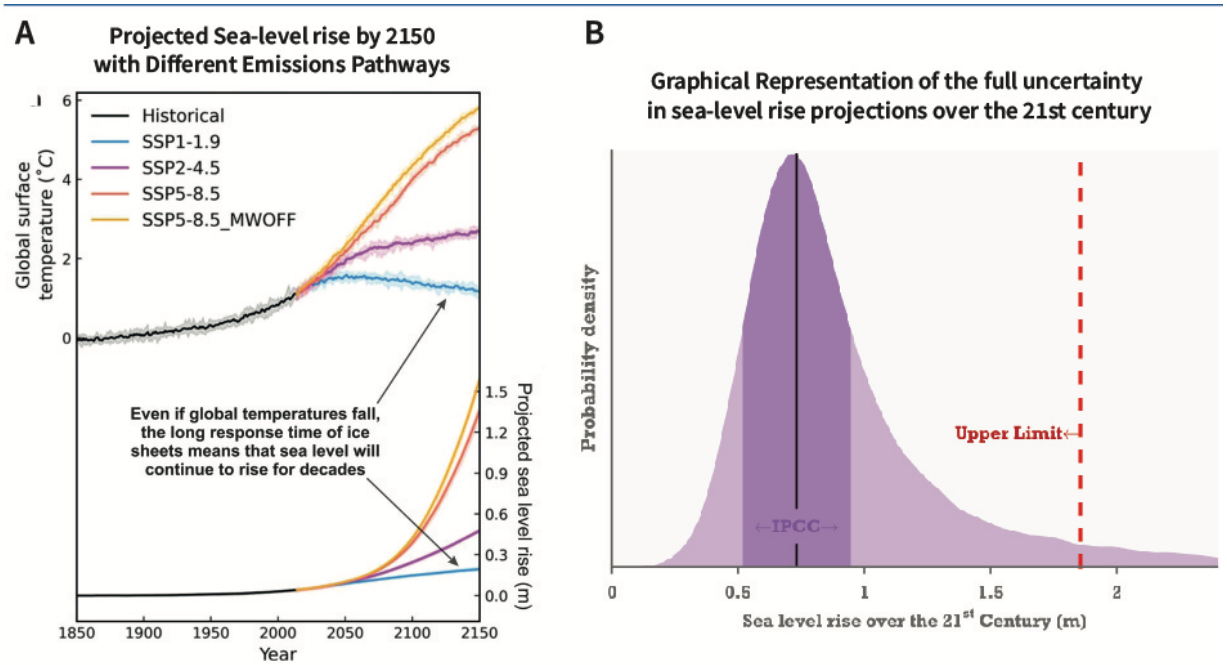

Figure 2. (A) The top of panel A displays global surface temperature (in degrees Celsius) for four future pathways that are distinguished by different emissions scenarios. The lower portion of the panel displays the corresponding projected pathway of global mean sea-level rise for each scenario. Only the "very low" fossil fuel emissions pathway (blue line) that peaks before 2030 (peak temperature 1.6°C, SSP1-1.9) would slow and stabilize sea-level rise, preserving many coastal communities and giving others time to adapt.[18] (B) Representation of the "long-tail" of uncertainty on the high side of sea-level rise projections that translates to lower probability but extremely high potential risks. The dark purple shading represents the *likely* (67% probability) amount of sea-level rise projected by the now-outdated IPCC AR5 report and the light purple area represents the other 33% probability that is unevenly distributed around that.[19]

[17] For example, see the global sea level projections in Figure 2A.
[18] Park et al., 2023, Future sea-level projections with a coupled atmosphere-ocean-ice-sheet model. *Nature Communications* 14, 636. Figure notations added by ICCI, 2023. State of the Cryosphere 2023 – Two Degrees is Too High. International Cryosphere Climate Initiative (ICCI), Stockholm, Sweden. 62 pp.
[19] Jevrejeva, S. et al., 2014, Upper limit of sea level projections, *Environmental Research Letters*, 9, 104008.

As an example, if a community is planning for sea-level to rise 2 feet by the year 2060, sea-level will reach 2 ft. long before 2060 and will do so with increasing frequency until that is the average position. If a house is flooded more than once a year, it may no longer be habitable much sooner than 2060. Hence, the tolerance of residents and infrastructure for flood frequency at 2 feet therefore will likely be reached long before 2060.

Some adaptations may create even more risk rather than lowering it. For example, there are already social inequities arising between communities that can afford to build sea walls and those that cannot. Building sea walls is inherently risky, because the water will come, and eventually those walls will be breached. Building walls is another form of delay, and it builds in a level of complacency for communities behind the wall that think they are safe and increases risk in the long term. It also builds in fierce social inequities, because all that water has to go somewhere and seawalls will push the water into the areas where there is no protection, making adjacent communities without seawalls even more vulnerable.

- **Summary for sea-level rise**

When the coastal real estate market collapses—not if, but when—the impacts will cascade through our national economy.

While the recent pandemic taught us something about supply chain vulnerabilities, accelerating rates of sea-level rise will create more persistent challenges for our supply chains as ports struggle to maintain their infrastructure in the face of retreating coastlines. Many major transportation corridors are coastal, compounding these challenges.

The accelerating trend and potential for larger jumps in sea level as ice sheets and glaciers decay is cause for concern for industries operating in the coastal zone and for the 40% of Americans who live in coastal communities[20]. Without policies and resources in place to remove or adapt infrastructure from retreating coastlines, we will continue to lose houses, condos, and other buildings into the ocean. Is our plan really to stand by and continue to allow buildings to collapse into the ocean, adding debris and toxic chemicals into the water, disrupting tourism, recreation, marine ecosystems, and maritime operations?

Policy decisions that are made today on future greenhouse gas emissions will in turn determine the rate of future sea-level rise along with associated risks to development and security for millennia to come. To maintain the possibility of not passing critical tipping points in ice sheets we need to fully commit to the Paris Agreement goals. To do otherwise, leaders would be effectively making a decision to erase many coastlines, displacing hundreds of millions of people, sooner than many think.

[20] https://coast.noaa.gov/digitalcoast/data/acs.html

Marine Heatwaves

You may have heard in the news recently that 2023 was the warmest year on record[21]. However, the warming we measure in the atmosphere only represents 1% of the total heating in our climate system. It turns out that the oceans absorb approximately 91% of that heat, with the remaining 8% being absorbed by land and ice.

This in itself is a remarkable statistic. The oceans have also absorbed 25% of anthropogenic carbon dioxide emissions. By absorbing both heat and carbon dioxide the oceans have been buffering the amount of warming that has occurred in our atmosphere. This may seem like a good thing, but each additional increment of ocean warming is having an increasingly devastating impact.

Ocean heat content has been steadily increasing, with five of the warmest years on record occurring in the past 5 years.[22] Last year a record high was reported for upper ocean heat content, which is a key metric for tracking the warming of our planet given that the oceans absorb most of the excess heat in the Earth system[23].

In 2023, temperatures in Florida Bay reached >100 °F,[24] possibly the highest seawater temperatures ever recorded.[25] A record-breaking marine heatwave also took hold in the northeast Atlantic Ocean in 2023, with temperatures that were off the charts.[26]

Heatwaves in the ocean are different than those in on land because seawater absorbs and releases heat more slowly than air. Hence marine heatwaves can last for much longer and cover vast expanses of the ocean. Marine heatwaves have approximately doubled in frequency since the 1980s and they have become more intense and longer.[27]

Marine heatwaves can result in impacts on marine ecosystems that are both severe and persistent, including mass mortality of benthic organisms, toxic algal blooms, and decline in fisheries catch and mariculture.[28] In 2015, one of the largest and longest duration marine heatwaves occurred in the Northeast Pacific Ocean. This resulted in shifts in marine species distribution and abundance and a bloom of toxic algae off the West Coast of the United States. Impacts cascaded through the food web, including decline of the California kelp forests and the collapse of the abalone industry.[29]

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[21] https://www.ncei.noaa.gov/news/global-climate-202312
[22] https://www.ncei.noaa.gov/news/global-climate-202312
[23] Cheng et al., New Record Ocean Temperatures and Related Climate Indicators in 2023, *Advances in Atmospheric Sciences*, 2024.
[24] For reference, average hot tub temperatures are 100-102 °F.
[25] https://www.nesdis.noaa.gov/news/extreme-ocean-temperatures-are-affecting-floridas-coral-reef
[26] https://earthobservatory.nasa.gov/images/151743/the-ocean-has-a-fever
[27] Fox-Kemper, B. et al., 2021, IPCC.
[28] Smale, D.A. et al., 2019, Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change,* 9, 306–312, 2019.
[29] Cooley et al., Oceans and Coastal Ecosystems and Their Services. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 379–550.

One particular concern is that marine heatwaves threaten the continued existence of corals reefs on our planet. Coral reefs are a cradle of marine biodiversity. Though they occupy less than 1% of the sea floor, coral reefs are home to 25% of marine life. Extreme heat is toxic to corals because it causes them to lose their colorful microscopic algae – an event referred to as coral bleaching. Severe bleaching events result in coral death with major repercussions on marine ecosystems.

Between 2016 and 2020, the Great Barrier Reef in Australia experienced three major bleaching episodes within a five-year span due to extremely high seawater temperatures.[30] You may remember the Australian bushfires during the austral summer 2019-2020[31]. After the Australian bush burned, what you did not see under the water was another mass mortality event that played out as corals bleached and died.

I recently wrote a paper about the Great Barrier Reef, which is the largest coral reef system on our planet. It has existed for hundreds of thousands of years, spanning warm periods and intervening ice ages.[32] Despite this long-lived history, the burning of fossil fuels is increasing the frequency of marine heatwaves and leaving mass mortality of corals in its wake. Our pathway to saving the Great Barrier Reef and reef systems around the globe is unquestionably to slash fossil fuel emissions as quickly as possible.

Scientists have warned of a developing mass extinction unfolding beneath the waves, but the good news is that they also project that we could cut these losses by 70% if we reverse greenhouse gas emissions trends.[33]

This is just one example of how extreme heat in our oceans is impacting marine life, with immediate knock-on effects for fisheries, tourism, food availability, shoreline protection, and coastal economies.

The way forward

An important point in this conversation is that we cannot just adapt to climate change. My testimony has highlighted ways in which marine life is already reaching thresholds of survival. Human bodies similarly have physical limits in terms of the temperature extremes that can be tolerated. Such limitations mean that while climate change may seem like a gradual, slow-moving problem, once we cross critical thresholds the impacts can be sudden, widespread, and devastating.

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[30] Pratchett et al., 2021, Recurrent Mass-Bleaching and the Potential for Ecosystem Collapse on Australia's Great Barrier Reef, in *Ecosystem Collapse and Climate Change,* [Canadell, J.G. and R.B. Jackson(eds.)]. Springer International Publishing, Cham, pp. 265–289.
[31] Abram, N.J. et al., 2021, Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Communications Earth & Environment,* 2(8). https://doi.org/10.1038/s43247-020-00065-8
[32] Braithwaite et al., 2004, The Great Barrier Reef: The Chronological Record from a New Borehole. Journal of Sedimentary Research; 74 (2): 298–310. doi: https://doi.org/10.1306/091603740298
[33] Penn, J.L. and Deutsch, C., 2022, Avoiding ocean mass extinction from climate warming, *Science*, 376, 524–526.

Keeping our oceans healthy and protecting our economy means not investing in more fossil fuel infrastructure and transitioning to renewable energy sources as rapidly as possible. These energy sources are less expensive and create less pollution, translating to immediate financial and health benefits for Americans.

This transition, while already underway, is not happening quickly enough. While I applaud the current administration for the steps they have taken to curb emissions, our actions have yet to scale with the urgency of the problem.

Because risks increase with every increment of warming, the costs of inaction are far greater than the costs of action. If we choose to delay mitigation and adaptation, we will increase losses and damages, lock in high-emissions infrastructure, and increase the risks of stranded assets.

However, we are not powerless to change our climate change trajectory.

The most important part of my message today is that because humans are driving the rapid warming of our planet, that means that we are also the solution to this problem. Our climate future is not just a place that we get to go to, it is a place that we get to create together.

Thank you.