Dr. Twila A. Moon

Research Scientist, National Snow and Ice Data Center
Cooperative Institute for Research in Environmental Sciences
University of Colorado Boulder

Dr. Twila Moon is a Research Scientist at the National Snow and Ice Data Center, part of the University of Colorado Boulder's Cooperative Institute for Research in Environmental Sciences, a world leader in Earth science. Dr. Moon's expertise is in contemporary changes in glaciers and ice sheets, and the connections among ice, climate, ocean, and ecosystem. While she has conducted work across the globe, her primary focus is on the Greenland Ice Sheet and the Arctic.

Dr. Moon's research uses tools ranging from satellite remote sensing to field work to computer simulations. Her work has been published in high-impact journals such as *Science* and *Nature*, and received extensive media coverage; for example, National Public Radio, the Associated Press, and the BBC. She is an accomplished science communicator and is leading efforts to improve science and knowledge co-production between scientists and stakeholders.

Dr. Moon has a BS in Geological and Environmental Sciences (Stanford) and an MS and PhD in Earth and Space Sciences (University of Washington). Subsequently, she was a U.S. National Science Foundation Postdoctoral Fellow (Ocean Sciences Division) at the University of Oregon and a Cooperative Institute for Research in Environmental Sciences Postdoctoral Fellow at the University of Colorado Boulder. She then held the position of Lecturer in Cryospheric Sciences at the University of Bristol, England, before returning to the National Snow and Ice Data Center. She serves on the Acting Committee for the Greenland Ice Sheet - Ocean Interactions Science Network. Additional information on her work is available at www.changingice.com.

Rapid Land Ice Loss and Impacts for the United States

Statement of

Twila A. Moon
Research Scientist, National Snow and Ice Data Center
Cooperative Institute for Research in Environmental Sciences
University of Colorado, Boulder

before the

Committee on Science, Space, and Technology
U.S. House of Representatives

for the hearing

Earth's Thermometers: Glacial and Ice Sheet Melt in a Changing Climate
11 July 2019

Chairwoman Johnson, Ranking Member Lucas, and members of the House Committee on Science, Space, and Technology, thank you for the opportunity to testify on the critical issue of rapid global land ice loss, its implications, and the challenges and opportunities for moving forward. I am heartened to see the Committee taking up this topic; sea-level rise and other impacts from land ice loss have serious consequences within the United States and across the globe. I am honored to inform the Committee's knowledge and actions via my testimony. I am a Research Scientist at the National Snow and Ice Data Center[1] and the Cooperative Institute for Research in Environmental Sciences[2] at the University of Colorado Boulder, and my testimony today is as an expert in glacier and ice sheet science. My comments represent the views of a scientific expert, not those of the University of Colorado. Since I aim to synthesize science information within this testimony, I have provided academic paper references sparingly, but would be happy to provide additional resources on any topics or statements contained herein.

[1] For more information: nsidc.org
[2] For more information: cires.colorado.edu

The Importance of Land Ice

The title of this hearing refers to glaciers and ice sheets - Earth's land ice - as "Earth's thermometers". It may be more accurate to describe glaciers and ice sheets as Earth's water towers. Only 2.5% of the world's water is fresh water, and more than two thirds of this fresh water is contained in glaciers and ice sheets[3]. These global water towers are critical as sources of fresh water and as long-term reservoirs to store it.

Glaciers around the world provide water for drinking, irrigation, energy, and other uses. And because warm, sunny weather produces ice melt, glacier-produced fresh water is often an abundant and vital resource during dry seasons or drought. For example, roughly 800 million people in Asia, including less geopolitically stable regions across Pakistan, Afghanistan, and India, depend on glacier melt as an important water source. During average years, land ice in the region provides a small percentage of the total water supply, but in drought years glacier melt becomes much more important, sustaining millions of people and the economies they depend on. Glacier melt is important in the production of hydropower as well[4]. However, ice in the region is melting more quickly than it is being resupplied. This provides a temporary bump in water availability, but future water and energy shortages due to glacier loss are certain.

As a source of cold water, **glacier melt helps to regulate stream temperatures and sustain ecosystems**. In Glacier National Park, for example, glacier melt is critical to maintaining the cooler water temperatures needed for native fish species and for a cascade of invertebrates that form a fundamental portion of the food web[5]. Glacier melt also helps to cycle nutrients by eroding rocks and transporting sediments underneath the ice to river and ocean ecosystems. In Alaska, the roughly $1B salmon fishing industry depends strongly on the nutrients and water properties of the Alaska Coastal Current. Roughly half of the Alaska Coastal Current waters come from seasonal glacier melt[6]. But Alaska is losing ice; the region is the second largest contributor to ice loss in the Arctic (after Greenland). Ongoing ice loss is likely to affect the future of the salmon industry and the many people who depend on it.

---

[3] Shiklomanov, I. (1993), World fresh water resources in 'Water in crisis: A guide to the world's fresh water resources'. P. H. Gleick (ed.).

[4] Case study details: Pritchard, H. D. (2019), Asia's shrinking glaciers protect large populations from drought stress, *Nature*, 1–20, doi:10.1038/s41586-019-1240-1.

[5] For example: Clark, A. M., J. T. Harper, and D. B. Fagre (2018), Glacier-Derived August Runoff in Northwest Montana, *Arct Antarct Alp Res*, *47*(1), 1–16, doi:10.1657/AAAR0014-033.

[6] Case study details: O'Neel, S. et al. (2015), Icefield-to-Ocean Linkages across the Northern Pacific Coastal Temperate Rainforest Ecosystem, *BioScience*, *65*(5), 499–512, doi:10.1093/biosci/biv027. For a more accessible summary: https://alaska.usgs.gov/products/pubs/2014/2014_Timm_ONeel_etal_ACCC_website_factsheet.pdf

As the world's water towers, **Earth's glaciers and ice sheets protect our coastal communities and economies from a myriad of impacts related to sea-level rise**, including coastal erosion, frequent or permanent flooding, saltwater inundation of fresh water resources, disruption of storm water systems, and destruction of infrastructure including schools, homes, superfund sites, and military bases[7]. These impacts are already evident within the U.S. and across the globe as a result of almost 3 inches of sea-level rise during the last 25 years. But additional sea-level rise from ice contained within Greenland, Antarctica, and the rest of the Earth's glaciers will likely dwarf what is currently being experienced. Midrange projections for additional sea level rise by 2100 are 17 inches for IPCC RCP2.6, 21 inches for RCP4.5, and 29 inches for RCP8.5, often referred to as the 'business as usual' pathway[8]. Note that these projections do not include mechanisms for potential accelerated ice loss that scientists are currently studying, particularly in Antarctica.

Recent & Rapid Global Land Ice Loss

Creation of the world-leading American economy has come about, in part, because of a stable and reliable climate. Development has depended upon and reinforced well defined coastal margins, allowing 39% of the U.S. population to thrive and prosper in shoreline counties[9], driving the U.S. economy and providing stable locations to base infrastructure for shipping, military activities, and other functions vital in today's connected global economy. This stability, however, is at risk. Since 1993, global average sea-level has already risen almost 3 inches. But sea-level rise is not evenly distributed around the world, and some communities have already experienced much higher sea-level rise than the global average. In the United States, for example, coastal erosion related to sea-level rise is displacing communities in Louisiana, drinking water problems are affecting California, and there is increased regular flooding across the Gulf Coast and Eastern Seaboard[10] (Figure 1). Similar impacts are being felt around the world.

---

[7] For more information on the military and sea level rise: climateandsecurity.org/militaryexpertpanel

[8] IPCC (2013), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. p. 1180.

[9] oceanservice.noaa.gov/facts/population.html

[10] Moon, T. A. et al. (2019), The expanding footprint of rapid Arctic change, *Earth's Future*, 1–13, doi:10.1029/2018EF001088. And references therein.

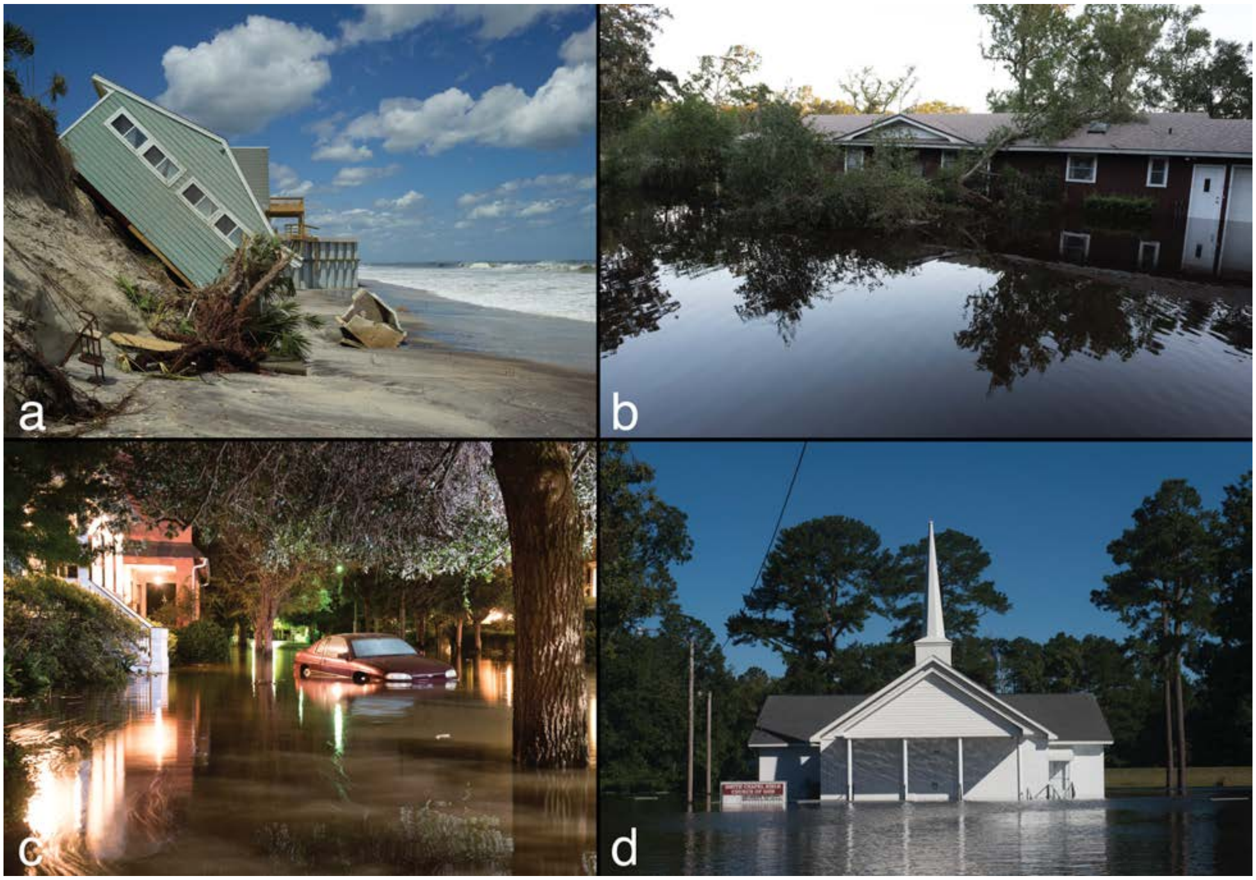

Figure 1. Flooding and storm damage in the US are connected to rapid global land ice loss. a) South Ponte Vedra Beach, Florida, b) Black Creek area near Jacksonville, Florida, c) Charleston, South Carolina, and d) Lumberton, North Carolina. Images: James Balog/Earth Vision Institute[11].

As noted, sea-level rise is not the same everywhere. Local sea-level rise is due to the combined effects of local vertical land motion (some land is sinking, some is rising, depending on various factors), ocean and atmospheric currents moving ocean waters towards or away from the coast, additions of groundwater to the ocean, expansion of ocean water as it warms, and added ocean water due to loss of land ice. Today, the largest of these contributors is land ice loss. **Land ice loss has increased quickly and across the globe since the mid-20th Century, with contemporary rates - and extents - of ice loss unprecedented over human history**.

Satellites are a critical tool for studying contemporary changes in ice mass. The NASA GRACE and GRACE-FO (Gravity Recovery and Climate Experiment / -Follow On) satellites directly measure ice loss via changes created in the gravitational pull of the ice mass. The NASA ICESat and ICESat-2 (Ice, Cloud, and land Elevation) satellites use lasers reflected off

[11] Figure from: Moon, T. A. et al. (2019), The expanding footprint of rapid Arctic change, Earth's Future, 1–13, doi:10.1029/2018EF001088.

of the Earth surface to measure the changing surface elevations of glaciers and ice sheets. Data from the joint NASA/USGS Landsat satellites are used to measure the surface speed of land ice and to map its extent. Combining these speed measurements with observed and modeled precipitation and ice thickness information tells us how much snow is accumulated on an ice sheet versus how much ice is lost from melting and calving of icebergs into the ocean. Subtracting the losses from the gains tells us how much the ice mass has changed. These techniques alone provide three methods to independently and accurately measure ice mass changes, and results from these techniques give a consistent picture of rapid worldwide ice loss that has accelerated. This conclusion is supported by other data, including long-term measurements of glacier advance/retreat from committed individuals and institutions, examination of historical photographs, and deduction from geologic records. **It is now unequivocal that contemporary ice loss is a direct result of warming air and warming ocean water due to human-caused climate change.**

Role of the Greenland Ice Sheet

The Greenland Ice Sheet reaches more than two miles thick at its center, with hundreds of fast-moving outlet glaciers along its edges, which act as conveyor belts to move ice from the ice sheet interior to the ocean. Smaller glaciers and ice caps (regions of land ice that are smaller than ice sheets, but include areas of ice connecting multiple glaciers) began losing ice due to climate change earlier in the 20th century. The Greenland Ice Sheet was mostly in balance through the 1980s, but that changed in the late 1990s[12]. **During the 21st century, Greenland has lost ice at an increasing tempo.**

Greenland ice is being lost through melt on the ice sheet surface and where the ice contacts the oceans along its edge. Ice is also being lost as large and small icebergs that break or 'calve', into the ocean. While glaciers and ice caps continued to add the most water to the world's ocean up into the early 21st century, ice loss from the Greenland Ice Sheet has recently reached the same level[13], with a reservoir of potential future sea-level rise that eclipses small glaciers and ice caps.

There are several indicators of current rapid ice loss in Greenland. Widespread surface thinning and ice edge retreat is observed around the entire ice sheet, exposing new land and ocean water. While personally conducting ship-based field work in northwestern Greenland in August 2018, our ship's navigation map did not show the elevation of the ocean seafloor underneath us. Instead, because the ice sheet edge in the area had retreated

[12] For example: Mouginot, J. et al. (2019), Forty-six years of Greenland Ice Sheet mass balance from 1972 to 2018, *Proc National Acad Sciences*, doi:10.7280/D1MM37.
[13] For example: Chen, X., X. Zhang, J. A. Church, C. S. Watson, M. A. King, D. Monselesan, B. Legresy, and C. Harig (2017), The increasing rate of global mean sea-level rise during 1993–2014, *Nature Climate change*, *7*(7), 492–495, doi:10.1038/nclimate3325.

almost two miles since 2000, the map showed our ship ostensibly motoring across the ice sheet itself (Figure 2)! Individual glacier retreat of multiple miles since 2000 is common[14]. Along with adding ice to the ocean, the speed at which the Greenland coastal environment is changing may increase risk across valuable industries like tourism and resource extraction.

Figure 2. Rapid retreat of the Greenland ice sheet edge is changing coastal boundaries in Greenland, and in the U.S., where ice loss creates rising sea levels. Here, a science research ship appears to be traveling across the ice sheet itself because navigational maps are not keeping pace with the fast ice edge retreat. Image: Twila Moon.

The rapid ice loss in Greenland is akin to the rapid melt you see in your kitchen when placing an ice cube in a water glass or leaving it lying on the countertop. The ice sheet is melting in response to warming air temperatures and ocean temperatures that are warming at depths that matter to ice (~600-1300 ft). This handy analogy has its limits, however, as the Greenland Ice Sheet system is much more complex than a household block of ice and understanding its behavior requires continued research:

- Depending on the season, the ice sheet surface is a mix of bright, reflective new snow; darker and often dirty bare glacier ice; and very dark melt lakes fed by an extensive system of surface streams. The character of the surface, which changes from region to

[14] The NASA MEaSUREs (Making Earth System Data Records for Use in Research Environments) Program provides valuable data on a variety of Greenland Ice Sheet metrics, including glacier advance/retreat. To overview NASA MEaSUREs data at NSIDC: nsidc.org/data/measures.

region and over time, helps to determine how much energy, or heat, the ice sheet absorbs to melt more ice or reflects, minimizing the amount of melt. Research indicates that there will be more surface melt in the future, but also that year-to-year variations in the quantity of surface melt will span a wider range than in the past. How will the ice sheet surface transform in coming decades and respond to year-to-year variations in weather?

- Underneath the ice sheet is an entire landscape of mountains and valleys. In some areas, the ice sheet is frozen to the land, or 'bed', beneath it while in other areas liquid water and water-saturated sediments sit between the ice and the bed, affecting how easily the ice moves (or slides) over the land. Understanding the properties, and even the shape, of the bed beneath the ice is challenging, but it also vital to determining how the ice sheet moves. Will small topographic features not yet mapped speed up or slow down ice loss? How will the ice sheet be affected by increasingly large amounts of meltwater flowing underneath it?
- Some areas of the ice sheet edge end on land, but there are also hundreds of fast-moving outlet glaciers that connect directly to the ocean, each with their own unique width, depth, slope, and flow path. These areas where the ice sheet interacts with the ocean are hot spots for activity. This is where melt water discharges from underneath the glaciers into the ocean, warm ocean water at depth contacts the glacier edge, and icebergs calve into the ocean. The ocean plays a substantial role in determining how quickly an outlet glacier can retreat and flush its ice into the sea. If the elevation of the land underneath the glacier drops further inland, retreat can create a cascade of glacier speedup and thinning that drives further retreat and may create a self-reinforcing cycle of ice loss. How will interactions between the ice sheet and ocean change the speed of ice loss? How will the fresh water from Greenland transform the ocean water, ocean currents, and marine ecosystems?

Ice loss from Greenland has impacts in addition to sea-level rise. The additional fresh water added to the ocean is changing the temperature and salinity of ocean water, and also changing the quantity and cycling of important nutrients[15]. It is likely that these changes are influencing plants and animals around Greenland, including in areas supporting important commercial fisheries. The fresher and colder water that Greenland adds to the ocean may also alter ocean currents in the North Atlantic region. North Atlantic ocean currents help to determine the climate in North America and Europe, and research is

[15] For example: Cape, M. R., F. Straneo, N. Beaird, R. M. Bundy, and M. A. Charette (2018), Nutrient release to oceans from buoyancy-driven upwelling at Greenland tidewater glaciers, *Nat Geosci*, 1–8, doi:10.1038/s41561-018-0268-4.

ongoing to understand how quickly and to what degree ocean currents may change, and the contributing role of Greenland Ice Sheet melt.

The past two decades have seen strong advances in characterizing, understanding, and predicting changes in the Greenland Ice Sheet. In the early 1990s our knowledge of the large ice sheets was so limited that the science community did not consider them major players in climate change on decadal timescales. Today, we understand that ice sheets are major players, and changes in Greenland are already impacting U.S. communities and the U.S. economy. The Greenland Ice Sheet, however, remains a remote and difficult place to study, and **increasing our ability to predict what will happen to the Greenland Ice Sheet in coming decades will require investment in observing systems, understanding the physical processes controlling ice sheet change, and building scientific capacity and stakeholder connections**.

Understanding the Future of Greenland Ice Loss: The Powerful Impact of Science

Satellite observations in the early 2000s revealed that the Greenland Ice Sheet was starting to respond to climate change. Since then, the science community has made substantial progress in understanding the behavior of the ice sheet and projecting future changes, and watched as the initial changes became much larger and more rapid. The United States has played a key role in these advances, supported via investment in satellites, in airplane- and ship-based surveys, and through advances in modeling. It is clear that while there may be short-term (less than a decade) departures from the current trend of ice loss, there is no expectation of a long-term (multi-decadal) re-stabilization under current greenhouse gas emission rates.

There remains, however, a large range in projections of ice loss for each individual future greenhouse gas emissions scenario. This spread is due to remaining limitations in our knowledge of ice sheet physics and ice sheet - atmosphere - ocean interaction, and the challenges in fully incorporating newly discovered physical relationships into computer models. The spread in the range of projected ice loss adds to the difficulty in pinpointing how much sea-level rise our nation, states, counties, and cities should plan for when making infrastructure investments. Knowing when two feet of sea-level rise will arrive to the Texas coast, for example, is essential for planning for improvements to coastal infrastructure or adjusting regional flood mitigation and planning.

Glaciology (the study of land ice) and the general study of the Earth's cryosphere (all things frozen) is a fairly young field of research, given the historic difficulty of access and vast expanse of land ice. Current resources support only a limited number of cryosphere scientists. Yet, we are trying to understand one of the most rapidly changing elements on our planet. The Arctic is warming at more than double the speed of the global average.

Additional glaciological research is necessary if we want to narrow the range of future ice loss projections and inform our Nation and the world about the ramifications for sea-level rise, water resources, etc., and the associated implications for decision-making. **The United States can lead this effort via focused support to: 1) conduct research in challenging locations and understand the physics of Earth's land ice and its interactions with the atmosphere and ocean, 2) foster iterative research to connect observations and computer models to improve projections, and 3) create new and stronger connections across scientific disciplines and with decision makers through knowledge co-production so that science can advance quickly while serving societal needs.**

Critical Research in Challenging Locations

Harsh weather, remote locations, large distances, and sparse infrastructure conspire to make studying Earth's land ice challenging and expensive. Yet understanding how massive ice sheets behave and how physical processes work at critical interfaces, like the ice-ocean boundary, is imperative for improving our projections of ice loss and impacts such as sea-level rise. Strengthening funding for focused research on processes controlling ice sheet behavior is vital. Through these efforts, we will increase understanding of ice-ocean interactions, ice sheet surface properties, ice sheet hydrology, and iceberg calving to improve future projections. Increased support must also include developing long-term observations that span all seasons over multiple decades. The U.S. Arctic Observing Network (AON) and international Sustaining Arctic Observing Networks (SAON) can play a valuable role in supporting these observations for the Arctic.

Connecting Current Observations to Future Projections

Observations fundamentally inform scientific knowledge about land ice processes, and are critical in developing better computer models to help scientists explore the causes of observed changes and project what will happen in coming decades. Not all physics can be seamlessly included in computer models - some processes must be captured using approximations, or 'parameterizations', that are created through observational analysis. Consistent and efficient information sharing between modeling research and observational research can fast track scientific understanding. Achieving this will require sustained support and encouragement of science that integrates these tools.

Building Collaborations to Lead

Understanding the expansive and compounding impacts of land ice loss require that new collaborations be created across different research disciplines, including areas of Earth science, social sciences, and infrastructure and economy research. Old approaches that silo science within specific disciplines must be broken down. The United States has the opportunity to be a world leader in creating strong collaborations between scientists and stakeholders. These collaborations need to be fostered via long-term, repeat interactions so that the United States can form and champion co-production of scientific knowledge and rapid information sharing. This should include support to coordinate science and stakeholder communities so that decisions at all levels are informed by the most robust science, not simply the latest headline. U.S. federal action that can support these advances by increasing coordinated opportunities for interagency funding and actively funding activities that integrate scientists with decision makers and planners. In my experience, the most effective stakeholder-scientist partnerships fully support participation across all groups.

International collaboration is also key. Land ice loss and sea-level rise are not just U.S. concerns, and coordinating research in the U.S. with international efforts will serve all. The current 17-nation MOSAiC mission[16] and the U.S. - U.K. International Thwaites Glacier Collaboration[17] are excellent examples. Research in Greenland is also enhanced via strong partnerships with Greenland, Denmark, and other Arctic nations.

Creating the Future of Greenland Ice Loss:
The Powerful Impact of Mitigation

The impacts of land ice loss are visible today. More difficult to comprehend is that our climate has not caught up with the greenhouse gases that have already been added to the atmosphere, meaning that more warming and additional ice loss is certain. Continued sea-level rise over the next several decades is guaranteed and will require **adaptation**. If greenhouse gas emissions are reduced, however, sea-level rise can still be kept to a more manageable level.

The full power of **mitigation** to create the future of Earth's land ice is underappreciated. U.S. leaders, including Congress, must think beyond the short time scales of politics and realize the power they now hold for fundamentally creating the world our grandchildren and their grandchildren will live in. Recent research using a cutting-edge Greenland Ice Sheet computer simulation tells us that choosing to lead the world on a path of reduced

---

[16] For more information: mosaic-expedition.org
[17] For more information: thwaitesglacier.org

greenhouse gas emissions can be the difference between maintaining most of the Greenland Ice Sheet or allowing it to melt completely within the next 1000 years (Figure 3).

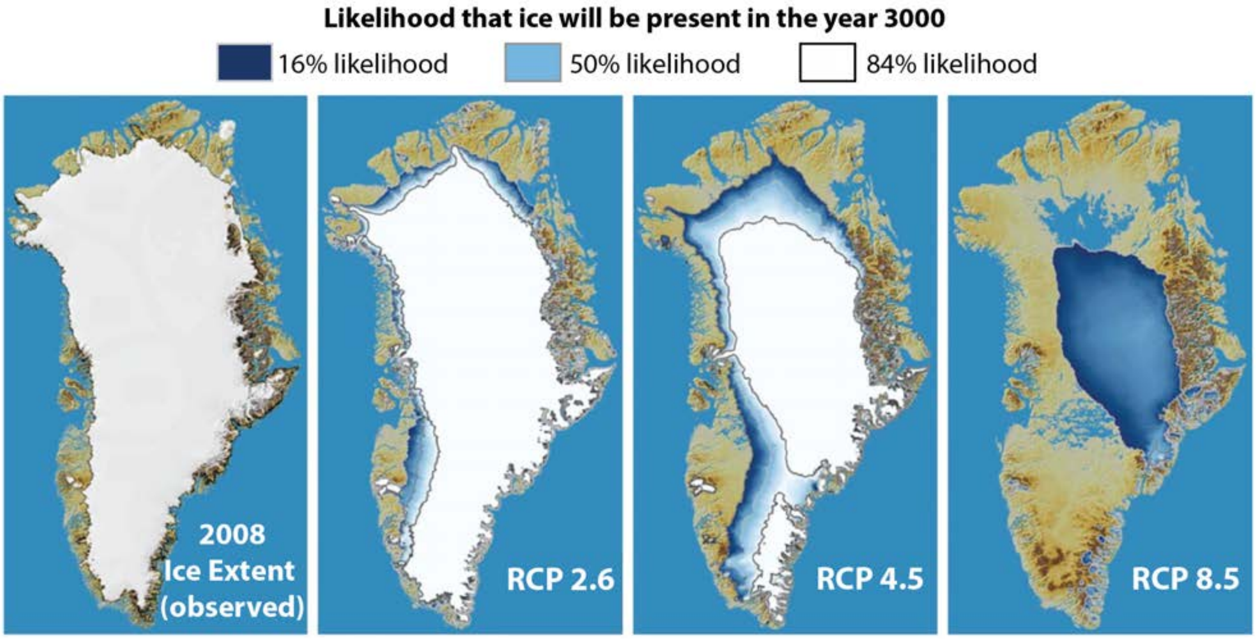

Figure 3. Computer simulations show that greenhouse gas emissions pathways followed this century will result in dramatically different Greenland Ice Sheet extents in the year 3000. All ice lost will contribute to global sea-level rise[18].

Let me be clear here about how I see the various roles of science, policy, and leadership. Increasing scientific knowledge is essential to more accurately project what the future is likely to bring given that we are on a particular greenhouse gas emissions pathway. But policy has the power to determine which emissions pathway we take. **Embarking on a lower emissions strategy will make a fundamental difference in how quickly - and how much - land ice disappears. U.S. leadership on mitigation within our lifetimes will reverberate to positively impact the world for millennia**.

Communicating Scientific Urgency

Challenges remain for communicating with decision makers, planners, and the public about land ice loss and its impacts, including within the United States. The language of science can be difficult to understand. For example, the public meaning of 'positive feedback' is a good response or praise, while the scientific meaning of 'positive feedback' is a self-reinforcing cycle, often with negative consequences[19]. This disconnect is a problem. Fostering

---

[18] Figure modified from: Aschwanden, A., M. A. Fahnestock, M. Truffer, D. J. Brinkerhoff, R. Hock, C. Khroulev, R. Mottram, and S. A. Khan (2019), Contribution of the Greenland Ice Sheet to sea level over the next millennium, Sci Adv, 5(6), eaav9396, doi:10.1126/sciadv.aav9396.
[19] Somerville and Hassol, Physics Today 64, 10, 48 (2011); https://doi.org/10.1063/PT.3.1296.

interactive and sustained connections between scientists and decision making and public communities via intentional funding can create a shared language for clear understanding and informed planning.

It is also critical that decision makers and the public understand that land ice loss at the poles has strong impacts on low and mid-latitude countries, including the United States. These impacts are also not confined to coastal regions. For example, if limited federal resources are being used to respond to sea-level rise in coastal states, interior states may find it more difficult to secure resources to address other priorities or emergencies.

That mitigation today will not immediately stop ice loss and sea-level rise poses a challenge for maintaining momentum on mitigation while at the same time adapting to change. But strong mitigation today can reduce the worst outcomes of ice loss. America can not only lead the world in understanding and projecting ice loss. America can also lead on actually determining the future of land ice and the extent to which ice loss will impact our citizens and the citizens of the world.

Thank you for the opportunity to testify today on glacier and ice sheet melt in Greenland and across the globe. I look forward to answering your questions and ensuring that the Committee has the most complete and up-to-date information on the science of ice loss and its impacts in the United States and around the world.