COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES

HEARING CHARTER

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

Thursday, July 11, 2019
10:00 a.m.
2318 Rayburn House Office Building

PURPOSE

The purpose of this Full Committee hearing is to discuss the current state of the science on glacier and ice sheet melt. The hearing will focus on the science to understand the physical processes and projections of mass loss of the major ice sheets in Greenland and Antarctica, as well as of mountain and other land-based glaciers. The Committee will receive expert testimony on current projections of glacier mass loss due to anthropogenic climate change, and in turn how that will affect sea level. Additionally, this hearing will provide an opportunity to discuss the major sources of uncertainty related to glacial and ice sheet melt including research gaps, risks to communities from local glacier melt, as well as global risks from ice sheet instability and sea level rise, and the need for adaptation and mitigation.

WITNESSES

- **Dr. Richard B. Alley,** Evan Pugh Professor of Geosciences and Associate of the Earth and Environmental Systems Institute, Pennsylvania State University
- **Dr. Robin E. Bell**, Lamont Research Professor, Lamont-Doherty Earth Observatory, Columbia University
- **Dr. Twila A. Moon**, Research Scientist, National Snow and Ice Data Center's (NSIDC) Cooperative Institute for Research in Environmental Sciences
- **Dr. Gabriel J. Wolkon,** Research Scientist and Manager, Climate and Cryosphere Hazards Program, Division of Geological & Geophysical Surveys, Alaska Department of Natural Resources
- **Dr. W. Tad Pfeffer,** Fellow, Institute of Arctic and Alpine Research, University of Colorado Boulder

OVERARCHING QUESTIONS

- How is anthropogenic climate change, particularly rising temperatures, affecting glaciers and ice sheets?
- How do glaciers and ice sheets act as "Earth's thermometers" and what can past climates tell us about current rates of change?
- How much do melting glaciers and ice sheets contribute to sea level rise and what are the projections for future sea level changes?
- What methods do scientists use to study glaciers and ice sheets, and what are the major challenges and sources of uncertainty in understanding glacial and ice sheet melt?
- What is our understanding of "tipping points" or "thresholds" in ice sheet and glacial melt, such as at the Western Antarctic Ice Sheet?

- Globally, how does mountain glacial melt impact human society?

Background

Glaciers are defined as persistent, land-based, dense ice formations that form when accumulation of snow exceeds its ablation (melting and other forms of loss) over many years.[1] The world's approximately 198,000 glaciers cover less than one percent of Earth's land surface,[2] yet glacial ice is the largest reservoir of freshwater on Earth[3] and is an important source of water for plants, animals, and humans where they occur in temperate regions and release meltwater in the summer. Glaciers and ice sheets play a critical role in Earth's air and water cycles, ecosystem support through providing nutrients and shelter for plants and animals, and climate system.

Glaciers that are larger than 50,000 km^2 (20,000 mi^2) are called ice sheets, or continental glaciers.[4] The Earth's only two present day ice sheets are in Antarctica and Greenland.[5] Ninety percent of the Earth's ice mass is contained in the Antarctic ice sheet, the world's largest single ice mass, covering almost 14 million km^2 (5.4 million mi^2) and containing 30 million km^3 of ice.[6] The Greenland and Antarctic ice sheets hold enough water to raise sea levels by 65 m (over 213 ft); however, complete melting of the ice sheets is not expected to happen.[7]

Ninety-nine percent of glacial ice is contained in ice sheets in the polar regions, but mountain glaciers exist on every continent except Australia.[8] In the U.S., glaciers can be found in Washington, Oregon, California, Montana, Wyoming, Colorado, and Nevada, with the majority occurring in Alaska.[9] Glaciers are sometimes called "Earth's thermometers" because they are very sensitive to, and therefore indicators of, climatic changes.[10] Glaciers are also indicators of past climates because trapped air bubbles reveal past atmospheric conditions from thousands of years ago.[11] Glaciers and ice sheets have a slow response time to global warming, and glaciers have not yet caught up to the heat additions made in the past decades. Therefore, even if global carbon emissions stopped entirely today, glaciers are locked in to a certain amount of melt. Thousands of studies conducted by researchers around the world have documented melting glaciers, diminishing snow cover, and rising sea levels.[12]

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[1] "What is a glacier?" National Snow & Ice Data Center. https://nsidc.org/cryosphere/glaciers/questions/what.html

[2] Davies, B. "Mapping the world's glaciers." 2017. http://www.antarcticglaciers.org/glaciers-and-climate/glacier-recession/mapping-worlds-glaciers/

[3] "Ice, Snow, and Glaciers and the Water Cycle." USGS. https://www.usgs.gov/special-topic/water-science-school/science/ice-snow-and-glaciers-and-water-cycle?qt-science_center_objects=0#qt-science_center_objects

[4] "What is an ice sheet?" National Snow & Ice Data Center (NSIDC). https://nsidc.org/cryosphere/quickfacts/icesheets.html

[5] Ibid.

[6] Amos, Jonathan (2013-03-08). "BBC News - Antarctic ice volume measured". Bbc.co.uk.

[7] Shepherd, A. et al. *Science*. 338: 1183-1189 (2012).

[8] "State of the Cryosphere: Mountain Glaciers." NSIDC. https://nsidc.org/cryosphere/sotc/glacier_balance.html

[9] USGS. "Where are glaciers found in continental North America?" https://www.usgs.gov/faqs/where-are-glaciers-found-continental-north-america?qt-news_science_products=0#qt-news_science_products

[10] Moon, T. *et al.* 2018. "Rising oceans guaranteed: Arctic land ice loss and sea level rise." *Current Climate Change Reports.* https://doi.org/10.1007/s40641-018-0107-0

[11] "Glaciers and climate change." NSIDC. https://nsidc.org/cryosphere/glaciers/questions/climate.html

[12] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp (IPCC AR5)

This hearing is focusing on land-based ice, as opposed to sea ice. Arctic sea ice is also diminishing at rapid rates due to anthropogenic warming,[13] but as it melts, it does not contribute to sea level changes unlike glacial and ice sheet melt.[14]

State of the Science on Glacial and Ice Sheet Melt

Globally, land-based ice is deteriorating. According to the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5), a diverse range of observational evidence from multiple data sources and independent analysis techniques provide consistent evidence of substantial retreat of mountain glaciers since the 1960s, and the increased surface melting of the Greenland ice sheet since 1993, due to warmer temperatures. According to satellite data, Greenland lost an average of 269 gigatons[15] of ice, equivalent to about 71 trillion gallons of water, per year between 2002 and 2016, with the pace accelerating in recent years (**Figure 1**).[16] Increased surface melt, runoff, and outlet glacier discharge from warmer air temperatures are the primary contributing factors. The portion of the Greenland Ice Sheet experiencing annual melt has increased since 1980, including through significant melting events. For example, an unprecedented 98.6% of the Greenland Ice Sheet surface experienced melt on a single day in July 2012.[17] While there are seasonal patterns of warm-weather ice melt and re-freezing in winter months, when seasonal melt outpaces re-freezing, there is net annual ice mass loss. Just last month, the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado reported that the Greenland Ice Sheet appears to have experienced its biggest mid-June melt event on record.[18]

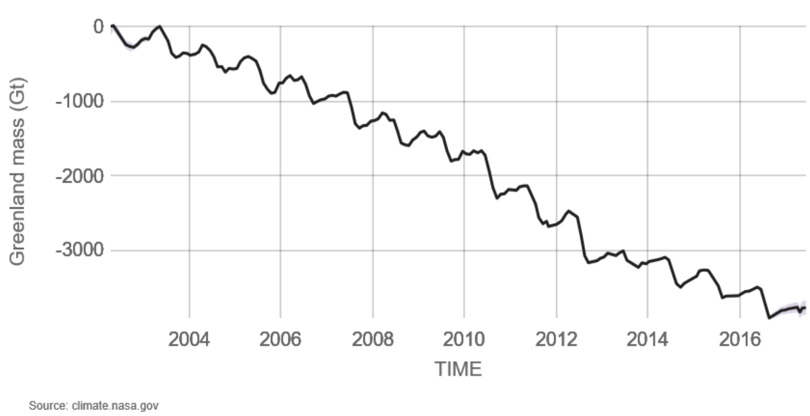

Figure 1: Greenland ice sheet mass variation since 2002, showing loss of 286 gigatons ice per year. Data source: Ice mass measurement by NASA's Gravity Recovery and Climate Experiment (GRACE) satellites. Credit: NASA.

[13] "Arctic sea ice minimum." NASA. https://climate.nasa.gov/vital-signs/arctic-sea-ice/

[14] Appell, D. "Loss of land ice (not sea ice) = more sea level rise." 2014. https://www.yaleclimateconnections.org/2014/11/loss-of-land-ice-not-sea-ice-more-sea-level-rise/

[15] 1 gigaton = 10^9 tons

[16] IPCC AR5

[17] Ibid.

[18] Samenow, Jason. June 14, 2018. "Temperatures leap 40 degrees above normal as the Arctic Ocean and Greenland ice sheet see record June melting." https://www.washingtonpost.com/weather/2019/06/14/arctic-ocean-greenland-ice-sheet-have-seen-record-june-ice-loss/?utm_term=.2f92ed415b9d

The Western Antarctic Ice Sheet (WAIS), the portion of the Antarctic ice sheet that covers the western part of the continent, is considered the most vulnerable ice sheet on Earth because its bed lies thousands of feet below sea level and is exposed to warm ocean currents.[19] In 2018, a major joint U.S.-UK research collaboration was initiated to study the possibility of “marine ice sheet instability” and “marine ice cliff instability” of the WAIS, focusing on the marine-terminating Thwaites Glacier.[20] Marine ice cliff instability is when a tall cliff that might form at the front of the glacier begins to calve and break in a runaway fashion. Marine ice sheet instability is an inherently unstable architecture caused by atmospheric and ocean warming, which could result in a positive feedback loop of rapid melting of the WAIS, triggering rapid sea level rise. The Thwaites Glacier has increased speed of movement and simultaneously experienced rapid ice thinning. Multiple studies indicate that this collapse is underway in the WAIS and may also be a cause of rapid ice front retreat occurring in Greenland.[21,22]

The WAIS has been experiencing mass loss since the early 1990s, and melt rates have more than tripled in the last 25 years.[23] Recent observed rapid mass loss from West Antarctica’s floating ice shelves is attributed to increased glacial discharge rates due to diminishing ice shelves caused by the surrounding ocean becoming warmer.[24] Antarctica as a whole lost more than 3 trillion tons of ice between 1992 and 2017.[25] More recent gravity data collected from space using NASA’s Gravity Recovery and Climate Experiment (GRACE) satellites show that Antarctica has been losing more than one hundred km^3 (24 mi^3) of ice each year since 2002 (**Figure 2**).[26] A chunk of ice the size of Delaware broke off on July 12, 2019 from the Larsen C Ice Shelf of the WAIS, which might destabilize the entire ice shelf.[27]

[19] Fox, Douglas. “The West Antarctic Ice Sheet Seems to Be Good at Collapsing.” *National Geographic*, National Geographic Society, 13 June 2018, www.news.nationalgeographic.com/2018/06/west-antarctic-ice-sheet-collapse-climate-change/

[20] The International Thwaites Glacier Collaboration, https://thwaitesglacier.org/about/itgc

[21] Moon, Twila. May 2017. “Saying goodbye to glaciers: Glacier volume is shrinking worldwide, with wide-ranging implications for society.” Science. Vol. 356, Issue 6338.

[22] BBC 30 April 2018. “Thwaites Glacier: Biggest ever Antarctic field campaign.” By Jonathan Amos https://www.bbc.com/news/science-environment-43936372

[23] Harvey, C. “Antarctic Melt Rate Has Tripled in the Last 25 Years.” June 14, 2018. https://www.scientificamerican.com/article/antarctic-melt-rate-has-tripled-in-the-last-25-years/

[24] IPCC AR5

[25] Harvey, C. “Antarctic Melt Rate Has Tripled in the Last 25 Years.” June 14, 2018. https://www.scientificamerican.com/article/antarctic-melt-rate-has-tripled-in-the-last-25-years/

[26] Conway, E. “Is Antarctica melting? – Climate Change: Vital Signs of the Planet.” September 16, 2014. https://climate.nasa.gov/news/242/is-antarctica-melting

[27] Fox, Douglas. “The West Antarctic Ice Sheet Seems to Be Good at Collapsing.” *National Geographic*, 13 June 2018, www.news.nationalgeographic.com/2018/06/west-antarctic-ice-sheet-collapse-climate-change/

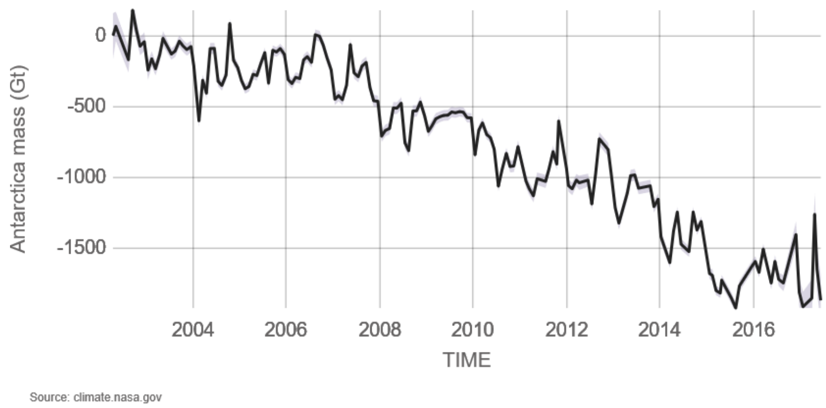

Figure 2: Antarctic ice sheet mass variation since 2002, showing loss of 127 gigatons ice per year. Data source: Ice mass measurement by NASA's GRACE satellites. Credit: NASA.

The IPCC AR5 predicts that global glacier volume, excluding glaciers on the periphery of Antarctica and the Greenland and Antarctic ice sheets, is projected to decrease by 15 to 55% if we limit global temperature rise to 2 degrees Celsius (RCP2.6) and by 35 to 85% under a high emissions scenario (RCP8.5). However, uncertainties remain in the quantification and modeling of key physical processes that contribute to the acceleration of land ice melting. Climate models are unable to capture the rapid pace of observed land ice melt over the last 15 years; a major factor is our inability to quantify and accurately model the physical processes driving the accelerated melting.[28]

The vast majority of global mountain glaciers are losing mass at significant rates. The annually averaged ice mass from 37 global reference glaciers has decreased every year since 1984. Annual average near-surface air temperatures across Alaska and the Arctic have increased over the last 50 years at a rate more than twice as fast as the global average temperature. Due to increasing temperatures, Alaska is losing about 75 billion tons of ice each year.[29]

A recent study provides the clearest picture of Himalayan glacier loss to date, using declassified U.S. spy satellite data from the past 40 years and combining it with contemporary satellite data.[30] The study found that the Himalayas lost 25% of their ice in the last 40 years, equivalent to eight billion tons of water each year. Glacial melt rates tracked temperature increases during the time period studied, meaning the melting can be attributed to warmer temperatures.

Methods for Studying Ice Loss

Measuring mass loss of glaciers is not straightforward but can be estimated used many types of observations, namely, the gravitational pull of the ice, surface elevation of ice sheets, and difference between ice accumulation and loss. The modern study of mass change in glaciers and ice sheets occurs over many spatiotemporal scales, from paleo-glaciological records dating back hundreds of thousands of years, to centimeter-scale in situ measurements, to global images using

[28] IPCC AR5

[29] Fountain, H. "When the Glaciers Disappear, Those Species Will Go Extinct." April 17, 2019. https://www.nytimes.com/interactive/2019/04/16/climate/glaciers-melting-alaska-washington.html

[30] Maurer, J.M. et al. 2019. "Acceleration of ice loss across the Himalayas over the past 40 years." Science Advances. Vol 5, no. 6. DOI: 10.1126/sciadv.aav7266

satellites.[31] Field studies enable detailed sampling and long-term monitoring and involve the use of various instruments. Global Positioning System (GPS), weather stations, seismometers, time-lapse cameras, and radar instruments elucidate glacier hydrology, subsurface environments, and glacier dynamics on time scales of minutes to months.[32] Challenges in observational work are that it is time-consuming, involves travel to remote and difficult to access locations, is expensive, and involves physically demanding work in harsh environments.

The advent of satellite monitoring in the 1990s was a major advancement for studying large ice sheets, allowing for improvements in the ability to estimate ice mass loss. NASA's GRACE satellite mission (2002-2017) and GRACE Follow On (launched May 2018)[33] help estimate ice mass variations, altimetry satellites (e.g. NASA's Ice, Cloud, and land Elevation Satellite, ICESat (2003-2009) and ICESat-2 (launched 2018)[34] and the European CryoSat (1999-2005) and CryoSat-2 (launched 2010))[35] detect changing surface elevations, and optical and radar imaging satellites measure ice motion, monitor glacier advance and retreat, and observe surface properties, including melt. Aerial surveys are able to cover inaccessible regions such as glacial crevasses and help with data collection in between satellite missions.[36]

Observations of ice sheets and glaciers and past records of glaciation are important for understanding Earth's climate system. Observational data is important in validating models in order to predict future changes. Ice sheets are important to the climate system, and incorporating ice sheet models into global climate models will improve projections. However, this is a challenge given ice sheet models are very high resolution and the climate models cannot currently accommodate that level of detail.[37]

Resulting Sea Level Rise

Sea levels have risen over eight inches (23 cm) since the Industrial Revolution and continue to rise 0.13 inches (3.2 mm) each year.[38] One third of current sea level rise is due to thermal expansion of seawater, one third is from ice sheet melt, and one third is from mountain glacial melt. The contribution to sea level rise from Antarctic and Greenland ice sheet melt has gone up from one-tenth just two decades ago, mostly due to Greenland ice losses.[39] The Fourth National Climate Assessment (NCA4) predicts global mean sea level will rise an additional 1.0-4.3 feet by 2100, depending on a low or high emissions scenario.[40] Even with a low emissions scenario and

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[31] Moon, Twila. May 2017. "Saying goodbye to glaciers: Glacier volume is shrinking worldwide, with wide-ranging implications for society." Science. Vol. 356, Issue 6338.
[32] Moon, T. *et al.* 2018. "Rising oceans guaranteed: Arctic land ice loss and sea level rise." *Current Climate Change Reports.*
[33] The NASA GRACE mission concluded in June 2017 and GRACE's successor mission, GRACE Follow-On, is launching in the summer of 2019.
[34] NASA ICESat and ICESat-2, https://icesat.gsfc.nasa.gov/
[35] European Satellite Agency, CryoSat and CryoSat-2, https://www.esa.int/Our_Activities/Observing_the_Earth/CryoSat/Introducing_CryoSat
[36] Moon, T. *et al.* 2018. "Rising oceans guaranteed: Arctic land ice loss and sea level rise." *Current Climate Change Reports.*
[37] Fourth National Climate Assessment.
[38] Nunez, C. 2017. "Sea level rise, explained." https://www.nationalgeographic.com/environment/global-warming/sea-level-rise/
[39] Shepherd, A. et al. Science. 338: 1183-1189 (2012).
[40] NCA4; Volume I; Ch. 12

not considering additional contribution from ice sheet melt, we are locked in to approximately 1 foot of global sea level rise by the end of the century.[41]

Over the last two decades, significant progress has been made in understanding ice sheet dynamics through combined field and satellite observations and improving numerical models to capture responses of ice sheets to environmental change. However, there is major uncertainty in the amount of additional sea level rise that could occur due to melting of Greenland and Antarctic ice sheets, due to the possibility of marine ice sheet and marine ice cliff instability. Collapse of the WAIS could contribute an additional 11 feet of sea level rise.[42] Sea level rise threatens coastal communities in the U.S. and worldwide and will increase the frequency and extent of extreme flooding associated with coastal storms, such as hurricanes and nor'easters.[43]

Other Impacts of Glacial and Ice Sheet Melt

Glacial and ice sheet mass loss will also have other direct and indirect impacts on humans and ecosystems, including on the climate system and weather patterns, ocean circulation, Earth's rotation, drinking water, and certain fisheries. Mountain glaciers are an important drinking water supply for many people around the world, especially in India, Nepal, and some countries in South America. Approximately 800 million people depend on glacial meltwater from the high mountains of Asia alone.[44] Glacial melt leads to rapid, catastrophic floods and debris flows for these downstream communities.[45]

Recent research suggests ice sheet melt may substantially slow down the major ocean conveyor belt of heat, known as the Atlantic meridional overturning circulation, which helps regulate the climate and affects global weather patterns.[46] There is satellite evidence that ice sheet melt is also responsible for a slight decrease in the speed of the Earth's rotation. This is because ice sheets are at high latitudes, and when they melt, the water is redistributed toward lower latitudes in a phenomenon called "polar wander."[47]

Loss of glacial streams and meltwater will lead to extinction of small creatures that rely on them. If glacial meltwater continues to decline and stream temperatures rise, larger fish populations like salmon and similar fish may also be affected.[48]

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[41] Ibid

[42] Fox, Douglas. "The West Antarctic Ice Sheet Seems to Be Good at Collapsing." *National Geographic*, National Geographic Society, 13 June 2018, www.news.nationalgeographic.com/2018/06/west-antarctic-ice-sheet-collapse-climate-change/

[43] IPCC AR5

[44] Pritchard, H.D. 2019. "Asia's shrinking glaciers protect large populations from drought stress." Nature, Vol 569. https://doi.org/10.1038/s41586-019-1240-1

[45] Ibid

[46] Harvey, C. 2019. "Melting ice sheets could worsen extreme weather." https://www.scientificamerican.com/article/melting-ice-sheets-could-worsen-extreme-weather/

[47] Dunham, W. 2015. "Melting glaciers blamed for subtle slowing of Earth's rotation." https://www.reuters.com/article/us-science-rotation-idUSKBN0TU2F720151212

[48] Ibid