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

For

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Introduction

Chairwoman Johnson, Ranking Member Lucas, Members of the House Science Committee, thank you for inviting me and my esteemed colleagues to speak today on this important topic- the melting ice on our home planet. This change is happening at the ends of our planet but is lapping at our doorsteps now. I am Robin Elizabeth Bell, and I am the PGI Lamont Research Professor at Lamont-Doherty Earth Observatory of Columbia University and a member of the Earth Institute faculty. At Lamont, I direct programs in ice sheet dynamics, lead efforts to develop innovative technology and work to improve the scientific culture especially for women. I have led ten major expeditions to the polar regions, to both Greenland and Antarctica resulting in discoveries ranging from active volcanism beneath the West Antarctic Ice sheet, to large deep lakes encased by two miles of ice to hidden mountain ranges buried by ice where water under the pressure of thick ice is forced uphill. I was the first women to chair the National Academy of Science's Polar Research Board (2002-2008) where I was instrumental in launching the International Polar Year 2007-9 that brought together over 50,000 scientists from around the globe. The International Polar Year fostered major expeditions, new international collaborations and discoveries that were only possible because of the partnerships between 60 nations. The polar regions are still a challenging place to work and science remains an international team sport. I also co-chaired the recent National Academy report *A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research* (2015) that set the priorities for Antarctic science. This report identified changing ice as the highest priority science in Antarctica. Recently, I chaired the National Academy of Science Review of the Draft Fourth National Climate Assessment – a comprehensive undertaking by U.S. scientists and citizens documenting the impacts of climate change around the country(USGCRP 2018). Currently, I have the great honor of serving as the President of the American Geophysical Union, or AGU as we all refer to it. Formed 100 years ago, AGU is the society of over 60,000 Earth and space scientists from around the globe who together promote discovery for the benefit of humanity. Today, I am honored to speak about the changing ice sheets with you. Thirty years ago when I first flew over Antarctica in a Naval Research Laboratory P-3 it seemed unimaginable to me that the vast ice sheet below could change. Now we know those white expanses are changing and these changes matter to our homes and communities around the globe. The changing polar ice is tightly linked to the changing coastlines. Although I speak to you today in my capacity as a private citizen, my testimony is based on my decades of experience studying our planet's ice.

Evidence for Changing Ice

The surprising wakeup call for the polar science community came in early 2002. This buzzing alarm came from the Antarctic Peninsula, the part of Antarctica that is the furthest north, jutting towards South America. This is also the destination of Antarctic cruises which over 14,000 Americans visit each year The Antarctic Peninsula is where global temperatures have risen the most - more than 7°F over 50 years. We had thought ice sheets and the state-sized ¼-1/2 mile thick pieces of floating ice that pin them in place changed really slowly. These floating extensions of continental ice sheets are called ice shelves. But by 2002, warming temperatures had started to produce more meltwater on top of the ice. The floating Larsen B Ice Shelf, the size of Rhode Island, developed hundreds of lakes. Suddenly the ice shelf disintegrated into thousands of icebergs over the course of two weeks (Scambos, Hulbe et al. 2003). The change occurred before our very eyes. The Larsen B ice shelf had been in place for over 10,000 years (Domack, Duran et al. 2005). Once the floating ice shelf disintegrated, the glaciers that flowed into the ice shelf sped up, pushing more ice into the ocean (Rignot, Casassa et al. 2004, Scambos, Bohlander et al. 2004). Glaciers are the earth's conveyor belts delivering ice to the ocean and an ice shelf controls the speed– if an ice shelf collapses, the conveyor belt speeds up. The satellite images of this collapse were printed in major newspapers around the globe (for example: The Charleston Gazette, St Louis Post, The Gazette – Ft. Wayne Indiana, The Patriot – Harrisburg, PA, Chicago Tribune, Rocky Mountain News, The Economist, The Wall Street Journal, The New York Times, Toronto Star, Calgary Herald, The Press - New Zealand, Belfast Telegraph, The Australian, China Daily, The Statesman- India). Suddenly, changing ice was newsworthy. Together scientists and the public from Harrisburg to India learned Antarctic ice could change faster than we imagined. The Antarctic conveyor belt had sped up. For the first time many around the world saw the link between blue meltwater on the ice shelf surface, the glacier conveyor belt speeding up and sea level rising.

Over the ensuing decades, the evidence for the changing ice on our planet has become very clear. I will focus on the grounded ice, the large ice sheets in Antarctica and Greenland where thick ice, in places over two miles thick, rests on solid ground although the ground may be well below sea level. Melting these ice sheets will raise sea level around the globe. Antarctica holds 200 feet of potential sea level rise and Greenland 20 feet of sea level rise– although no scientists are suggesting they will completely disappear any time soon. These very thick ice sheets are distinct from the relatively thin floating sea ice (around 10 feet) that covers much of the Arctic Ocean and rings the Southern Ocean close to Antarctica. Sea ice is like the layer of ice cubes floating in a punch bowl. The Arctic sea ice has been steadily shrinking over the past two decades and recently the Antarctic sea ice has begun to retreat. Changing sea ice shifts the Earth's albedo and weather patterns, impacts food available to wildlife from penguins to polar bears, and opens new shipping routes. But shrinking sea ice itself will not cause sea level to rise, since sea ice is already floating in the water. The major source of future sea level rise are the grounded ice sheets. Melting ice sheets are like the kid with a new twenty-pound bag of ice at the picnic who pours the entire bag into the bowl without thinking. The glaciers are conveyor belts of ice being delivered to the ocean, and we see them speeding up.

I often get asked "do you believe the ice is changing?" My response is – changing ice is not a belief but knowledge that emerges from three independent observations. These independent observations are primarily based on satellite measurements enabled by NASA working with other space agencies around the globe. The first measurement is how fast the ice moves. Several parts of the Antarctic Ice Sheet (key parts of the conveyor belts) have doubled their speed in the past two decades, showing that the ice is speeding up (Rignot, Mouginot et al. 2011). The second measurement is the height of the ice surface, and is made using laser and radar instruments from a satellite or aircraft. In the same places where the ice is speeding up the ice surface is getting lower. Ice, like mozzarella cheese atop a pizza, is getting thinner and lower because it is stretching. The third measurement is ice sheet mass, or weight, which is calculated from observations from a pair of identical satellites chasing each other and measuring changes in the gravity field(Velicogna, Sutterley et al. 2014, Harig and Simons 2015). In the same places that the ice is speeding up and lowering, it is losing mass. These three measurements together demonstrate in more detail than ever before how the ice in Greenland and Antarctica is changing.

Scientists from around the globe have used these three key observations to quantify how fast the ice sheets are changing. To quantify the change over a large continent like Antarctica, the size of the lower 48 states, requires careful examination of each measurement and resolving issues such as how the snow that falls on Antarctica turns into ice. After much lively debate and testing of assumptions by a team of 77 scientists from around the world, the clear signal is that Antarctica is losing ice, as is Greenland. The current mass loss from the ice sheets is contributing one millimeter of sea level rise globally each year (Shepherd, Ivins et al. 2018) although this rise is not evenly distributed around the globe. Antarctica is now losing mass at twice the rate it was in the 1990s. For these calculations, the team broke Antarctica up into three parts, the Peninsula where the Larsen B Ice Shelf was; West Antarctica, the ice sheet that rests on low-lying topography and is exposed to changes in the ocean temperature and East Antarctica, the large ice sheet where the South Pole is that sits on higher topography. Each region stores different amounts of ice, has a different history and a different susceptibility to a warming world. The West Antarctic Ice Sheet is the most susceptible to warming oceans and atmosphere as it sits lower and is in direct contact with the ocean. West Antarctica is where the greatest changes have occurred over the past decade. Most of the 0.3 inches (8 mm) of sea level rise from Antarctica in the last decade has come from West Antarctica. This region was the highest priority in the 2015 National Academy report *A Strategic*

Vision for NSF Investments in Antarctic and Southern Ocean(National Academies of Sciences and Medicine 2015).

Evidence for Changing Coastlines

Why did the changing ice emerge as the highest priority in the National Academy Report? We are beginning to see the melting ice, including from Antarctica, at the tide gauges along our coastline. Globally, average sea level has risen 8-9 inches since 1880, with the global rise since 1993 being 3 inches (Hay, Morrow et al. 2015, Nerem, Beckley et al. 2018). Right here at the dock along the bike path in Southeast Washington sea level has risen a foot in since 1919 (https://tidesandcurrents.noaa.gov/sltrends). I put my hand on my leg just below my knee and realize the water level has risen that far since my father was born.

At most locations around the globe sea level is rising now, although the ocean turns out to be more complicated than the punch in the punchbowl. At a few locations, sea level is actually falling. Three major components make up the change at an individual coastal city: the change in ocean temperature, the melting ice and whether the land the city rests on is rising or sinking. Up to now the warming of the ocean waters by 1.3°F since 1960 is the major signal that has appeared at our coasts. But, melting ice has the greatest potential for new rapid sea level rise globally. To complicate things further, the melting ice contribution to changes sea level is modulated by the self-gravitation of the ice sheets. Already the modulation of the impact of melting ice in Greenland by the self-gravitation is apparent in the tide gauges along the east coast of the United States. Because of this gravitational effect, sea level is rising faster in the Southeastern US than in New England. Atop these signals are local impacts. The land cities and towns are built on can be rising or sinking, impacting local sea level. In cities like Juneau and Stockholm (Milne, Davis et al. 2001) the land is rising due to the loss of ice 20,000 years ago while cities like Norfolk, Virginia and New Orleans are sinking due to removal of groundwater (Sweet, Kopp et al. 2017). Every community is going to see a different future sea level depending the ocean temperature, the changing ice, and whether the land is rising or falling. Linking the changing ice to the changing coastlines is a challenge that will require collaboration from the ice to the shorelines.

Impacts of Changing Coastlines Now and Looking Ahead

So we have begun to witness the melting ice and see the impact along our shorelines. The higher sea level made the impact of recent major storms like Maria, Harvey, Irma and Sandy more devastating. For example, close to my home 30 miles from the Atlantic Ocean they used bulldozers to clear boats from the roads after Superstorm Sandy. Because of the sea level rise over the past century, 45,000 more people were impacted by Sandy’s flooding. The impact of rising sea level is not just during major storms. All around the US we are seeing increased nuisance flooding. Nuisance flooding is called sunny day flooding where high tides in fair weather make it difficult to get home because the roads are flooded. Miami and Norfolk are both experiencing this and are working to adapt to this. Scientists are working to provide these cities with the forecasts of future sea level they need to adapt.

Looking Ahead: Current Ice Sheet Change Projections

Looking ahead the scientific community is scrambling to provide answers to how fast and how much will sea level rise in each community from ice sheet melt. Suddenly city managers, architects, reinsurance companies and resiliency officers care about Antarctic ice. The efforts to answer the how-fast-how-much question range from simple exercises to frame the problem to quizzing experts locked in a room (Bamber and Aspinall 2013) to probabilistic projections (Edwards, Brandon et al. 2019) and full-blown ice sheet models (Feldmann and Levermann 2015, DeConto and Pollard 2016). These models are like weather models only for ice. In contrast to weather and hurricane models, these models are still in the early stages of development. Ice sheet modeling scientists have made big advances in these efforts, such as figuring out how to capture mathematically the changing forces when ice goes afloat and using the latest supercomputing resources to allow the models to include many of the important stresses at play within the ice. The ice sheet models are now linked to different futures, whether temperatures go up a little, a lot or a huge amount. These different futures will be determined by how much CO_2 we release into the atmosphere. The science community is working through this collaboratively and through peer review, the way good science happens. An idea is published, the community tests it and new ideas are advanced. Since scientists have never watched an ice sheet disappear, we use records from the past We know sea level rises when temperature rise --- Miami is built on rocks formed in a shallow sea very similar to the Bahamas today. The hills of Miami formed 120,000 years ago when the planet was warm and sea level was 19-30 feet higher than it is now. The other point we use to calibrate our models is from three million years ago, the last time CO_2 was as high as it is now sea level was 19-65 feet higher than it is now.

The challenges the scientists working on the models face include that is that we are still learning so much about how ice sheets work. For example, while we are all familiar with how water flows across our familiar landscape, we are just now working to understand what happens when water collects on Antarctica. Greenland wears a necklace of blue ponds every summer and has water hidden in crevasses and in the snow. What happens if Antarctica warms until it looks like Greenland(Bell, Banwell et al. 2018)? Will all the new water make the remaining ice shelves disintegrate like the Larsen B, triggering more glaciers/conveyor belts to accelerate, or will rivers form atop the ice(Kingslake, Ely et al. 2017)? Will we will see giant ice cliffs that become unstable causing a sudden runaway collapse of the ice switching the glacier conveyor belts to hyper-fast? These are the ice processes that might produce drastically accelerate sea level rise. Models with lots of meltwater and collapsing cliffs predict close to six feet of sea level rise from Antarctica by 2100. More recent publications suggest that the number might be closer to 1-1.5 feet (45 cm). As we discover new important processes and discover more, these numbers will change. Our knowledge-base and our models are evolving. My family has a boat on the Hudson and we worry about hurricanes every summer. Thirty years ago the hurricane models could not tell us whether the hurricane was going to hit Maine or our New York home, now we can plan much better. We knew Sandy was possibly coming ten days out and were able to prepare. The improvement in hurricane prediction illustrates that the ice predictions can improve if we work on it by building our knowledge base, deepening the bench of scientists and fostering interdisciplinary and international collaborations.

Three Essentials to Improve Ice Sheet Melt Projections

The Antarctic melt projections for 2100 range from just below my knee or over my head, or, quantitatively 1-6 feet. How can we narrow down this answer about how Antarctica will melt in the coming decades? My neighbors are asking me. There are three critical things essential to improving the predictions: knowledge of processes (or how ice sheets work), people (to explore, discover, model and communicate, and fostering collaboration: 1) Processes: We have never witnessed an ice sheet collapse and improving our predictions requires getting up close and personal with the ice sheets to better understand how ice sheets work and intense efforts to decide how best to describe these processes in ice-sheet models. 2) People: The community studying ice around the world has grown but the community is still really small. 3) Collaboration: Because changing ice is controlled by the ocean, the atmosphere, the underlying geology and ice physics and Antarctica are huge, this work requires collaboration across disciplines and nations.

Our understanding of the process of how ice sheets work has made huge advances. Prior to the International Geophysical Year in 1958, we did not even know how much ice there was in Antarctica. By the 1980s we began to understand why those giant conveyor belts of ice can deliver so much ice to the ocean (Alley 1986). These conveyor belts can be over 60 miles wide and in Antarctica move up to about 1.5 miles per year. In Greenland the conveyor belts move even faster – more than 7.5 miles a year. In the 1990s we began both to drill through the ice sheet and to study extensive regions with aircraft and we discovered that the geology underneath matters. In the 2000s we realized there were extensive networks of water beneath the ice including large lakes, one the size of New Jersey (Kapitsa, Ridley et al. 1996), smaller lakes that will slowly fill and drain (Fricker, Scambos et al. 2007), and water networks that move the water. Where the water goes matters because the water is part of the basal lubrication system. Some of the big unknowns include: what is happening in this hidden environment beneath the ice, how will the warming ocean and atmosphere attack the ice sheet and will surface water trigger collapse of all the major ice shelves?

We have discovered a lot but there remains a lot to be learned. We as a species have lived with changing weather and have a deep knowledge of weather systems behave. Our grandmothers understood the wispy angular clouds they called mare's tails meant rain soon, but we can now predict to the hour when the rain will arrive. We as a species have far less experience with collapsing ice sheets. To improve our models, we must get up close and personal with the ice sheets. The satellite record has clearly shown us that change is happening but it is the work in Antarctica from surface ships and aircraft that is essential to foster the advances in understanding of how ice sheets work that will improve our projections. NASA's Operation Icebridge is an example of the importance of comprehensive imaging of the ice sheets that fostered a new norm of freely available open data. The National Science Foundation has responded to the 2015 National Academy report by launching a major program collaboratively with the United Kingdom's Natural Environment Research Council (NERC), the International Thwaites Glacier Collaboration. Thwaites Glacier, one of the largest conveyor belts, is considered one of the most unstable pieces of ice on the planet. Thwaites Glacier is wide and is perched on a topographic ridge where the warming ocean is known to be thinning the ice. Because this glacier can deliver a lot of ice to the ocean fast and because it is already showing signs of thinning and shrinking it is a major threat and a high priority (NAS). The major NSF/NERC initiative (Scambos, Bell et al. 2017) this as an example of the type of work that is essential to launch around all of Antarctica. Advancing the basic understanding of how the ice sheets work and the processes that control their melting, will improve our predictions. Think of Antarctic scientists as the hurricane hunters for sea level.

The second critical need to improve our projections is people. As President of AGU and as former President of the Cryosphere Section (the best job title ever), I am acutely aware of how small our community is. Now, the AGU Cryosphere section has 1,492 members. This number includes scientists from around the globe studying ice, snow and sea ice. To put that in perspective in 2010, there were about 140,000 people enrolled in law school in the US. In a single year, 100 times more people were studying law than the entire global community studying changing ice. There is an acute personnel problem. We need more scientists working on this problem if we are to improve our projections. Science and the science of melting ice from the Arctic to the South Pole must be an open welcoming community. The science is remarkable and the discoveries to be made remarkable. We have barely started to scratch the surface of the ice sheets.

The third need is to fully embrace ice as part of the changing earth and enable truly convergent work. When your child is in the hospital with a sudden ailment you really want the specialists to be working together to provide the best care. The ice community is coming to the realization that we need to take a similar approach. We recently completed ROSETTA, a study of the largest ice shelf in Antarctica, the Ross, just a little smaller than Texas. Using Recovery Act funding, in partnership with the New York Air National Guard, we repurposed military imaging technology for ice studies. After three years of flying the IcePod over the Ross Ice Shelf we realized that it was impossible to understand how the ice will melt without bringing all the specialists to the table. We learned that the geology is in essence protecting that sector of West Antarctica from the warming global ocean but the vulnerability is to heat pumped under the ice shelf from the shallow ocean waters by strong winds(Tinto, Padman et al. 2019). It took scientists from many disciplines working together on the same data sets to converge on these complex processes. We were acting like that team of specialists working together for the good for a patient. It is essential to foster this convergent work for the planet and our species. To move the Antarctic work forward will require interdisciplinary and international collaboration as fostered by NSF in the ITGC program but on a larger scale. Ice science must also be more tightly linked to our changing coastlines so each community will know how to respond and adapt. I am hopeful. With investment the hurricane forecasts have improved. We can improve the melt forecasts and provide better information to our neighbors.

Thank you for inviting me to speak today. I am heartened that the House Science Committee is considering this very important issue. We are very fortunate as a species to have the capacity to see how our home planet works and have the capacity to address this issue both scientifically and technically. If we continue to foster collaborative science across disciplines, the science community will be able to provide our communities with accurate projections of how sea level will rise. If ice scientists work with coastal scientists, we can develop tailored projections for each community. I am also heartened as I see individuals, communities, state governments and professional societies taking action to reduce the underlying cause of the changing ice – our greenhouse gas emissions. The AGU community is very proud of our headquarters on Florida Avenue. This building, long known for the planets in the sidewalk, is Washington DC's first net-zero emissions building renovation. Reaching net zero required multiple technologies from solar panels to heat exchange with the sewer system to green walls. Similarly, using the same multi-pronged strategy, we as a species can address the issue of climate change and ice melt with broad concerted efforts, from individuals, communities and governments.

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