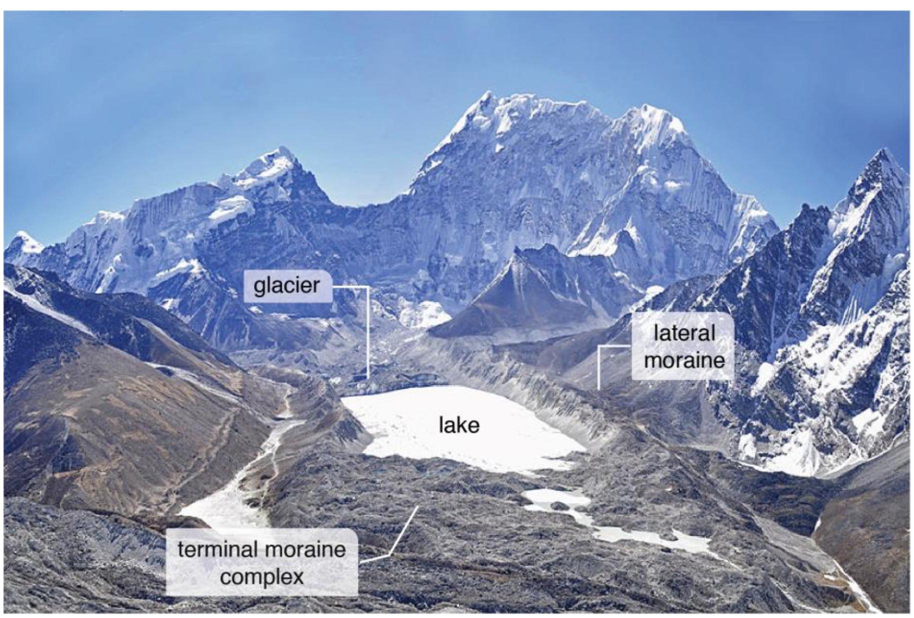
Personal Introduction and Background: My name is William Tad Pfeffer. I am a glaciologist employed by the University of Colorado at Boulder, where I am a Professor of Civil, Environmental, and Architectural Engineering, and a Fellow of the University's Institute of Arctic and Alpine Research (INSTAAR). I have been at UC Boulder for 31 years, and have been an active glaciological researcher for 40 years. My particular sphere of expertise is in the study of the world's "small" glaciers – meaning all of the world's ca. 200,000 glaciers exclusive of the two ice sheets covering Greenland and Antarctica. I have worked extensively in glaciological laboratory experiments, numerical modeling, and theoretical analysis, and have conducted hundreds of field expeditions over 35 years in the Continental USA, Alaska, Canadian Arctic, Svalbard, Greenland, Antarctica, the Himalayas, and Africa. I have published over 60 papers in the refereed scientific literature, including several seminal and highly-cited studies of glacier physics and of global glacier contributions to sea level rise. I served as a co-author of the 2012 National Research Council Report "Sea Level Rise for the Coasts of California, Washington, and Oregon: Past, Present, and Future." I was also a Lead Author for Chapter 13 (Sea Level Change) of the IPCC Fifth Assessment (AR5), Working Group 1, in 2013. Most recently, I have shifted my focus to science planning and policy and to the historical development of glaciological and sea level research. Starting in 2013, I was a founding editor of the Oxford University Press Handbook Series on Planning for Climate Change Hazards. I also served in 2015-16 as a National Academy of Sciences Jefferson Fellow; in this capacity, I worked at USAID in Washington DC as a senior science advisor in the Office of Energy and Infrastructure, Europe and Eurasia.

My testimony reflects my own views and scientific judgement, and does not represent the views or positions of any institution or agency, including the University of Colorado.

While the potential for rapid sea level rise from the earth's two major ice sheets tends to be the most visible sphere of snow and ice research, there are other issues of concern to glaciologists involving ice in its many forms at the earth's surface. Ranging from permafrost in Siberia and Alaska to seasonal river ice in New England, from seasonal snow in Colorado's ski country to glacier lake outburst floods (or "GLOFs") in the Himalayas, and from glacier-fed rivers in India to sea ice blocking shipping routes across the Canadian Northwest Passage, ice is a crucial element of our environment anywhere on earth where freezing occurs. As temperatures rise, melting ice mobilizes liquid water, weakens previously strong frozen materials, increases the permeability of thawing soils, speeds aqueous chemical reactions, and drives a multitude of other processes, all with the potential to dramatically alter our environment. In this testimony I will focus in problems directly involving glaciers (leaving aside some equally important issues involving permafrost, river ice, and sea ice) and briefly summarize a few of what I view as the most important outstanding environmental problems. I will also concentrate on those problems that affect the United States directly, or indirectly through economic and political reactions to environmental changes elsewhere in the world.

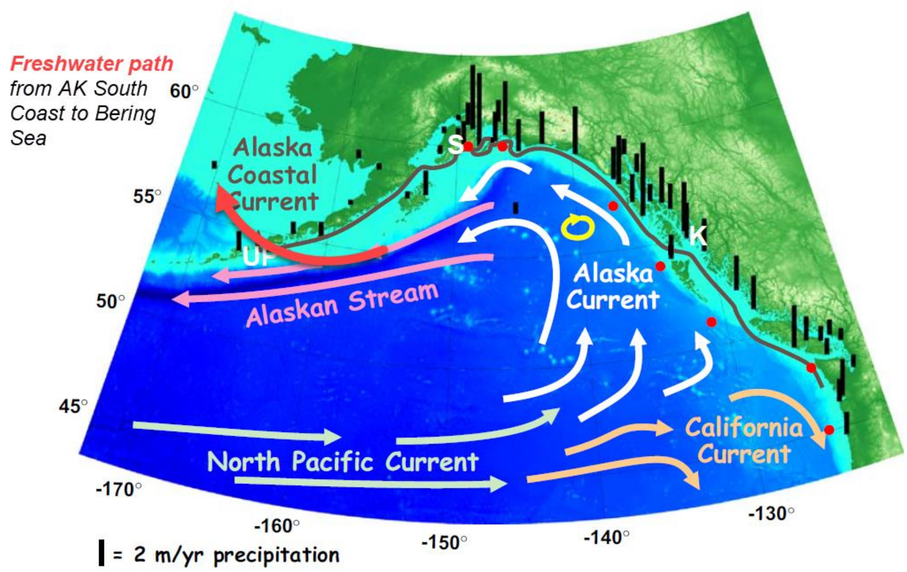
- **Seasonal snow and glacier runoff as a water resource**. Society everywhere in earth depends critically on freshwater for domestic use (cooking, cleaning, washing, etc.) as well as for agricultural irrigation, industrial use, and hydropower generation. All fresh water moving on the earth's surface starts as rain or snow, but that fraction falling at high elevations as snow will remain in place (either seasonally as snow or for many years as ice) until melting conditions at the surface allow the water to move downslope. Water stored in the mountains as snow and ice acts as a reservoir, delaying the drainage of precipitation, which may arrive in very imbalanced "wet season/dry season" cycles, until later in the season. This benefits users of the water by spreading the downstream arrival of water throughout the year and storing water as glacier ice during wet years to be released during dry years. This is a critically important benefit for agriculture anywhere (including the Western US), but no more so than in the Indian Subcontinent, where very large populations depend upon crops irrigated by runoff from the Himalayas. Recent research (Maurer et al, 2019) indicates that the glaciers of the Himalayas are experiencing losses at rates that have doubled over the past 40 years. The economic and political effects of major seasonal water shortages in India and neighboring countries – a probable consequence of continued snowpack depletion and glacier losses – could be profound and global in its indirect consequences.

- **Glacier recession and geohazards**. People and infrastructure living in the immediate vicinity of glaciers are exposed to natural hazards including flooding, landslides, and rockfalls, all associated with slopes destabilized by the removal of glacier ice (Richardson and Reynolds, 2000) Such risks are global in extent but are particularly concentrated in parts of the world with high population densities in mountain regions, and specifically on the south side of the Himalayas (Bhutan, India, Nepal, Pakistan) and in the Andes on the west coast of South America (Harrison et al, 2018). These regions (along with virtually all of the earth's mountain regions) are subject to landslide and rockfall hazards, but glacier retreat dramatically magnifies these hazards. Advancing glaciers disaggregate rocks and soil at their base and margins and plow this material forward and the margins of the glacier, creating *moraines* that surround the glacier terminus and valley sides. When a glacier retreats, the moraines are left behind, and "proglacial" lakes frequently form in the enclosed depression formed between the retreating terminus and the inner side of the moraine wall. Moraines are intrinsically weak materials, being composed of an incohesive mixture of soil and rocks of many sizes; they also typically have very steep slopes. These factors all favor the incidence of slope failures and landslides, and when proglacial lakes are formed, additional hazards are created due to the easily eroded



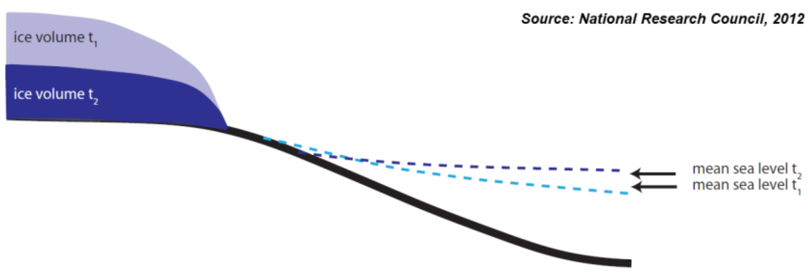
Imja Tsho (or Imja Lake) in eastern Nepal, dammed by a terminal moraine complex. The lake has been growing rapidly since the 1960s as the Imja Glacier has retreated. Photo: Sharad Joshi, Wikimedia Commons, Edited by J.Bendle. Source: http://www.antarcticglaciers.org/glacier-processes/glacial-lakes/glacial-lake-outburst-floods/

Glacier runoff and ocean salinity. One of the most significant and rapidly changing effects of present day warming is the depletion of sea ice in the Arctic Ocean (Mueller et al, 2018). The loss of sea ice in the arctic has profound implications on local and global scales, ranging from accelerated coastal erosion on Alaska's arctic coast to alterations of the planetary energy balance as the reflectivity of the Arctic Basin drops with increasing open water. The formation and maintenance of sea ice depends on the surface energy balance of the arctic and also on the salinity of Arctic Ocean water (McPhee et al, 1998). Water entering the Arctic Basin via Bering Strait (between Alaska and Siberia) is one of the primary sources of low-salinity sea water in the Arctic Ocean. The salinity of this Pacific sea water is influenced to a significant but poorly constrained degree by the Alaskan Current (Woodgate and Aagaard, 2005), which in turn carries fresh water draining into the Gulf of Alaska from the glaciers of Alaska's south coastal mountains (Chugach & St. Elias Ranges) and interior mountains (Alaska Range, Wrangell Mountains) northward and through Unimak Pass into the Bering Sea (see Figure). The retreat of Alaska's glaciers thus has an effect – probably significant but at this point not well known – and arctic sea ice. Glacier losses in the Canadian Arctic may have a similar influence (Dimitrenko et al, 2017). The influence of Alaska's glaciers on conditions in the Arctic is not well established in part because of the absence of any comprehensive program of observations of freshwater runoff to the Gulf of Alaska. This is one of many examples of the significance of Alaska's glaciers both locally and globally, and the need to invest in research in this area.



Alaskan coastal transport carrying glacier runoff from coastal mountains in the Bering Sea. Adapted from Weingartner et al (2005)

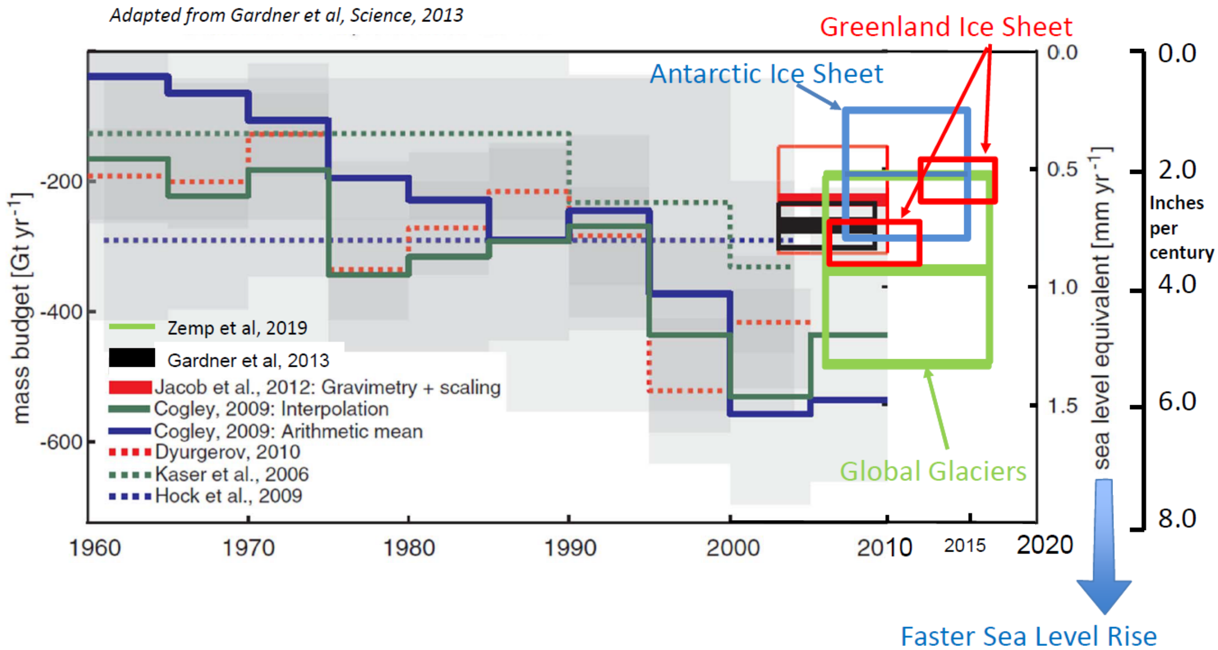
- **Glacier retreat and gravitational fingerprinting**. Like a magnet drawing metal filings around its edges, the large mass of glaciers and ice sheets on land (e.g. the Greenland and Antarctic ice sheets and the glaciers in Alaska) exerts a gravitational pull that draws ocean water toward them. This creates a non-uniform sea level surface, with sea level slightly elevated adjacent to any large mass concentration and slightly lowered elsewhere. This distortion on the mean sea level surface is unique to each ice mass given its size and location, and is informally referred to as the gravitational "fingerprint" of that ice mass. When glaciers shrink, however, the magnitude of their gravitational pull decreases, and the combined result of the melting of any given ice mass is to raise the total amount of water in the ocean (raising global average sea level) and to reduce that particular "fingerprint" distortion of the sea level surface. The combined effect of the gravitational fingerprints from Alaska and, to a lesser extent, Greenland, causes relative sea level to fall all along the west coast of the United States, whereas melting from Antarctica causes a relative sea level rise. The net effect of losses from Alaska, Greenland, and Antarctica on the US west coast is reduce the local sea level rise relative to the global mean value by values ranging from ca. 40% in Washington State to ca. 15% in southern California (National Research Council, 2012). Again, Alaska's glaciers have significant effects both globally and locally.



Gravitational "Fingerprint" of a terrestrially-based ice mass: Globally averaged sea level increases as any terrestrially-based glacier shrinks, but *relative* sea level change is negative adjacent to the declining ice mass and positive away from it.

- **Rising sea level from the earth's 200,000-plus glaciers**. The total potential sea level rise from these glaciers is very small: only a bit more than 1 foot (Farinotti et al, 2018). However, the present-day *rate* of loss from the glaciers is as great as that coming from the ice sheets, and will in all likelihood continue to match the ice sheet losses for at least the next few decades, when near-term decision making requires the highest level of confidence in projections.

  Since the beginning of comprehensive global observations, virtually all glaciers on Earth have been in a state of mass loss, contributing 0.71 ± 0.08 mm yr^{-1} over the period 2003-2009 (Gardner et al., 2013) corresponding to 29±13% of the observed sea-level rise during that period. The most recent assessment of glacier losses (Zemp et al, 2019) finds a global total loss rate for the period 2006-2016 to be 0.92 ± 0.39 mm yr^{-1}. For context, the most recent ice sheet loss rate assessments show Antarctic contributing 50 ± 26 mm yr^{-1} (2008-2015) and Greenland contributing 0.77 ± 0.005 mm yr^{-1} (2007-12) and 0.53 ± 0.05 mm yr^{-1} (2012-2017).



Global glacier loss rate assessments, 1960 to the present. The most recent loss rates from the Greenland and Antarctic Ice Sheets are included for comparison.

Because of their large number and small size, assessments of all 200,000+ glaciers on earth has been difficult, and the calculated aggregate loss rate has varied significantly over time, partly due to limitations in observational methods and partly due to the fact that the rates change over time. Recent research programs have benefitted from rapid developments in remote sensing, including NASA's ICESat satellite (2003 – 2009), the NASA-GFZ GRACE gravity twin satellite mission (2002-2017). Further missions, including the GRACE Follow-On (GRACE-FO), launched in May of 2018, and ICESat-2, launched in September of 2018. These mission investments have aided global glacier assessments enormously and testify to NASA's commitment to earth science generally and glacier monitoring in particular. However, remote sensing methods cannot work alone to continue accurate and validated observations of glacier change, nor can they be used in isolation to solve the numerous outstanding problems faced by modelers seeking to project future glacier behavior. Integration of field and remote sensing observations with model simulations is necessary to accurately project future trends in glacier contribution to sea level. Conventional field observations of mass balance at "benchmark" glaciers, especially those in Alaska, should remain a high priority to ensure the continuity of long-term records, some of which extend back to the 1957-58 International Geophysical Year. Ground-truthing programs are particularly important for large glacierized regions with steep gradients in environmental conditions, where the distant view of an orbiting satellite becomes a liability. Field studies at these and other sites should be expanded to include detailed observations of surface and dynamic processes. Improved parameterization of surface albedo, which controls the dominant term in the surface radiation budget, can be achieved through studies of snow and ice crystal grain sizes (Painter et al., 2009) and parameterization of the impacts of dust/black carbon (Flanner and Zender, 2006) and debris cover (Reznichenko et al., 2010) on surface melt rates. The conversion of volume to mass change in geodetic remote sensing assessments remains a large source of uncertainty (Huss, 2013) and can be informed through field measurements of near-surface densification rates. Glaciers that terminate in lakes or the ocean have the potential for rapid changes through poorly-understood calving mechanisms (Moholdt et al., 2012; Willis et al., 2018), requiring expanded observations of ice thickness, grounding line locations and lake/fiord conditions. Finally, field programs should include observations of stream discharge where possible since this provides valuable information on the integrated water balance of glacierized watersheds.