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Savor the Cryosphere

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ABSTRACT

This article provides concise documentation of the ongoing retreat of glaciers, along with the implications that the ice loss presents, as well as suggestions for geoscience educators to better convey this story to both students and citizens. We present the retreat of glaciers—the loss of ice—as emblematic of the recent, rapid contraction of the cryosphere. Satellites are useful for assessing the loss of ice across regions with the passage of time. Ground-based glaciology, particularly through the study of ice cores, can record the history of environmental conditions present during the existence of a glacier. Repeat photography vividly displays the rapid retreat of glaciers that is characteristic across the planet. This loss of ice has implications to rising sea level, greater susceptibility to dryness in places where people rely upon rivers delivering melt water resources, and to the destruction of natural environmental archives that were held within the ice. Warming of the atmosphere due to rising concentrations of greenhouse gases released by the combustion of fossil fuels is causing this retreat. We highlight multimedia productions that are useful for teaching this story effectively. As geoscience educators, we attempt to present the best scholarship as accurately and eloquently as we can, to address the core challenge of conveying the magnitude of anthropogenic impacts, while also encouraging optimistic determination on the part of students, coupled to an increasingly informed citizenry. We assert that understanding human perturbation of nature, then choosing to engage in thoughtful science-based decision-making, is a wise choice. This topic comprised "Savor the Cryosphere," a Pardee Keynote Symposium at the 2015 Annual Meeting in Baltimore, Maryland, USA, for which the GSA recorded supporting interviews and a webinar.

INTRODUCTION

The cryosphere is the portion of Earth that is frozen, which includes glacial and periglacial environs on land, where ice, permafrost, or snow cover dominate, as well as ice-covered sea. Geographically, arctic regions and the higher elevation portions of alpine regions at lower latitudes are included. We assert that the retreat of glaciers—the loss of ice—is emblematic of the recent, rapid contraction of the cryosphere. Because relatively few people visit such places due to their remoteness, we note the difficulty that many non-specialists have in recognizing the scope of this issue. Our response is to explain ice loss in tangible terms that feature multimedia, as well as to provide geoscience educators with information for doing so themselves. We presented this topic as "Savor the Cryosphere," a Pardee Keynote Symposium at the 2015 Annual Meeting of the GSA in Baltimore, Maryland, USA. Archival interviews are available at https://www.youtube.com/watch?v=d1-jzYuea9E, and a webinar is available at https://attendee.gotowebinar.com/recording/5467381313092358658 (no charge to register to see the information). Our approach here is to document glacial retreat, noting that rising air temperature is the principal cause of it (coupled with warming sea water and changes in ocean currents in areas with tidewater glaciers), then to review the implications of ice loss, and finally to present the legacy that the loss of ice will pass to the future. The extent of ice can be measured by satellites or by ground-based glaciology. While we provide a brief assessment of the first method, our focus on the latter is key to informing broad audiences of non-specialists. The cornerstone of our approach is the use of repeat photography so that the scale and rate of retreat are vividly depicted. Science is grounded in observation, so science education will benefit from displaying the recently exposed landscapes. We close by prompting people to value the cryosphere and to recognize the consequences of fossil fuel consumption.

RETREAT OF GLACIERS

Earth is losing ice. The instances of glacial retreat far exceed those of advance. Zemp et al. (2015) reported glaciological and geodetic observations of over 5,200 glaciers from nineteen regions around the world, showing that the rates of early twenty-first–century ice mass loss are without precedent, at least for the few-century observational period. The compilation of Zemp et al. (2008) shows that, since 1900, retreating glaciers have been more common than advancing ones (see http://www.grid.unep.ch/glaciers/img/5-1.jpg). These inventories are based upon a variety of different approaches to measurement; hence, we present both remote and close observation.

Space-Based Observation

Satellites are useful for studying glaciers for many reasons. Ice loss can be assessed by repeat gravimetry, which quantifies changes in ice mass, or by altimetry, which contributes to measuring changing surface elevation, coupled together with repeat

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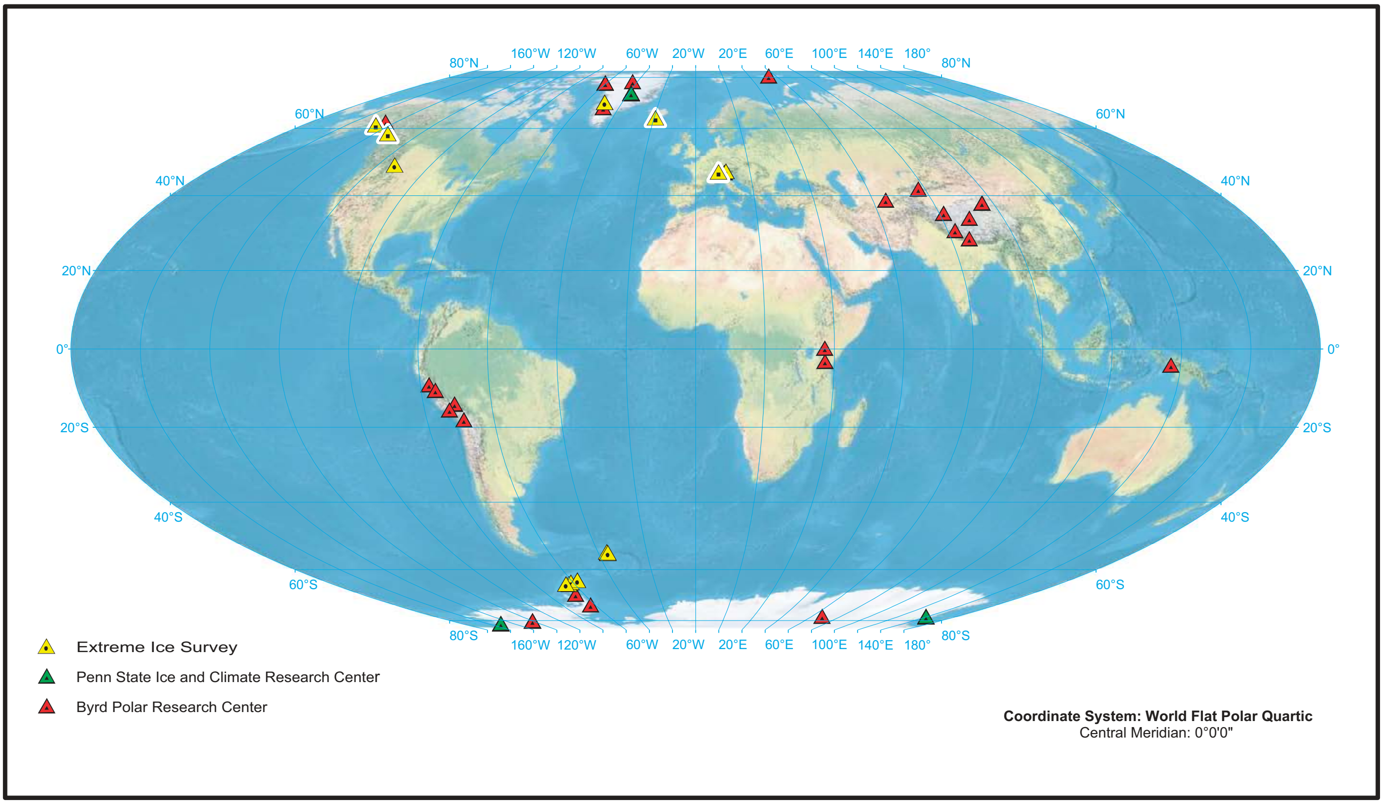

Figure 1. Global distribution of glaciers studied by the co-authors.

imagery that displays changes in coverage area (Gardner et al., 2013). As we shall see, comparison between results determined by various tools lends confidence to the findings. Remote sensing is advantageous because glaciated terrain is remote and difficult to access (Luthcke et al., 2008). Kääb (2008) also notes that spaceborne techniques are sustainable for global-scale monitoring of glaciers because satellites can remain operational for decades.

These observations provide robust documentation of ice loss. Arendt et al. (2013) reported a mass-balance for glaciers in the Gulf of Alaska of −65 ± 11 Gt/a from 2003 to 2010 from the Gravity Recovery and Climate Experiment (GRACE), which compared well with their determination of −65 ± 12 Gt/a from the Ice, Cloud, and land Elevation Satellite (ICESat) based upon glacier elevation changes. Kääb (2008) compared a digital elevation model from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite optical stereo to elevation data from ICESat and an earlier topographic map to report elevation change at two ice caps in eastern Svalbard of −0.55 or −0.61 m/a between 1970 and 2002 (ASTER) and 2006 (ICESat), respectively. Kääb et al. (2012) used satellite laser altimetry and a global elevation model to report widespread loss of ice in the Himalayas. While one recent study suggested slight growth of the Antarctic ice sheet as an ongoing response to the increase in snowfall at the end of the last ice age (Zwally et al., 2015), a study using a wider range of analytical techniques (Shepherd et al., 2012) indicates shrinkage at both poles. Several additional studies as summarized by Scambos and Shuman (2016) support and extend the record of Antarctic mass loss. Jacob et al. (2012) used GRACE results to calculate global ice change of –536 ± 93 Gt/a between 2003 and 2010 by summing the mass balance of twenty glaciated regions around the planet. Thus, satellites are very useful for assessing changes in glaciers, both regionally and over time.

Land-Based Glaciology

Our documentation of ice loss, like that of other groups working on this problem, integrates art with science, by focusing upon glaciologic study that is enriched through photography. Figure 1 displays the global network of monitoring completed by the co-authors' collaborators. The authors assess findings from six continents, where inquiry spans the study of ice sheets, ice caps, and mountain glaciers. The researchers at the Byrd Polar and Climate Research Center (BPCRC) and Penn State Ice and Climate Exploration have extracted, or helped to extract, ice cores at the sites indicated. The ice cores provide histories of annual net balance and of precipitation chemistry. The Extreme Ice Survey provides extensive archives of time-lapse photography for a multitude of glaciers, which reveal changes in the lateral extent and thickness of ice.

Examples of ice loss are abundant and well documented. Since 1974, investigators at the BPCRC have monitored glaciers in South America, Africa, and Asia. In Tanzania, the total surface area of the ice fields on top of Mount Kilimanjaro decreased by 88.3% from 1912 to 2013; however, the rate of retreat has recently accelerated—from 2000 to 2013, they decreased by 40%. The three remaining ice fields on its summit and slopes are also losing volume vertically at a rate of 0.5 m/a (Thompson et al., 2009, 2011). In Papua, New Guinea, several small glaciers exist in the vicinity of Puncak Jaya. From 1850 to 2005, their total surface area decreased from 19.3 km^2 to 1.72 km^2, representing a 91% loss (Kincaid, 2007). From 2000 to 2002 alone, surface area decreased from 2.326 km^2 to 2.152 km^2, or by 7.48% (Klein and Kincaid, 2006). The rate of retreat accelerated from 1988 to 2005, even while precipitation (partly as rain) actually increased (Kincaid, 2007). When ice contracts in area and thickness, the ice within the glacier can also be affected by melting. Snow pits and cores at the Quelccaya ice cap in southern Peru reveal that since the late 1970s the seasonal oxygen isotopic ($\delta^{18}O$) variations have been homogenized by meltwater percolating through the top 20 to 30 m of firn. This homogenization compromises the long-term seasonally resolved record of past climate variations. This finding is consistent with analyses of shallow cores throughout the Cordillera Blanca of northern Peru (Davis et al., 1995). Radiocarbon dates from wetland plants exposed by the retreating margins of Quelccaya ice demonstrate that, for >~6,300 years, this ice cap has not been smaller than it is today (Thompson et al., 2013). Rapid retreat of the ice margin continues to expose such evidence.

Photography

Our collaboration features the work of the Extreme Ice Survey (EIS), a nongovernmental organization founded to photograph the retreat of glaciers. Photo couplets of ice retreat have been both coincidentally and intentionally collected. Ernest Shackleton's expedition on HMS *Endurance*, for example, collected historic photos of the extent of ice on South Georgia that can be compared to modern photos (see https://vimeo.com/125634374). Figure 2 presents photo couplets of glacial retreat in Alaska, Iceland, Switzerland, and Peru, where lateral retreat and thinning are apparent. In a similar vein, the EIS has amassed >1.1 million images recorded by 43 cameras observing 24 glaciers in Alaska, the Rockies, the Andes, South Georgia, Antarctica, the Alps, Iceland, and the Himalayas. *Ice: Portraits of Vanishing Glaciers* (Balog, 2012) provides graphic evidence in print form. Such time-lapse imagery has also been assembled into videos that display ice retreat, such as "Extreme Ice" (https://www.youtube.com/watch?v=6scs-Q-Ut_E). The film *Chasing Ice* is critically acclaimed for its portrayal of glacial retreat. The film captured spellbinding imagery of perhaps the largest calving event ever witnessed, when Greenland's Ilulissat glacier discharged a section of its terminus that measured ~5 km wide, 1 km thick, and 1.5 km long.

CAUSES OF ICE LOSS

Extensive literature shows that the ongoing loss of mass from glaciers is being caused primarily by warming over those glaciers and that this warming is, in turn, being caused primarily by the rising CO_2 concentrations in the atmosphere. The reports of the Intergovernmental Panel on Climate Change (IPCC) provide useful starting points for understanding the linkage between temperature and the mass balance of a glacier (e.g., Lemke et al., 2007), and IPCC (2013) examines the history and causes of warming. Glaciers can respond to changes in accumulation of snowfall, seasonality of temperature, cloudiness, and other factors. The advance or retreat of a single glacier may be difficult to interpret without targeted studies, but literature summarized in these sources shows that for a large suite of glaciers ending on land, retreat is primarily driven by atmospheric warming.

Paleoclimate information contributes in fundamental ways to the strong evidence that warming temperature is the primary driver of the recent acceleration of ice retreat (Thompson et al., 2011, 2013). For example, evidence for warming is associated with ice retreat in the tropical Andes (Rabatel et al., 2013). Arendt et al. (2013) found that mean summer temperatures derived from ground and lower troposphere records were good predictors of GRACE-derived summer mass balances in Gulf of Alaska glaciers, capturing 59% and 72% of the variability. In the context of the ice retreat in New Guinea from 1972 to 1987, mean monthly atmospheric temperature was the only climate variable that changed in a statistically significant way (+0.24 °C; Klein and Kincaid, 2006). Warming is also seen throughout the Tibetan Plateau (now sometimes characterized as the Third Pole [TP]), where meteorological data show that surface temperatures are rising faster at higher elevations than at lower elevations (Liu and Chen, 2000). On average, the temperature on the TP has been increasing at a rate of 0.16 °C annually and 0.32 °C per decade during winter.

On decadal and longer time scales, climate models project that greenhouse-gas–forced warming will drive temperatures to rise faster with elevation, with this vertical amplification being greatest in the tropics due to feedbacks involving upper-tropospheric humidity, as well as snow albedo and surface-based and water-vapor feedbacks (Ramaswamy et al., 2006; Randall et al., 2007; Pepin et al., 2015). Results from general circulation models indicate that the combined water-vapor/lapse-rate feedback provides the largest positive radiative reaction and that this effect alone roughly doubles the warming in response to forcing by greenhouse gases. As a result, the projected changes in mean annual free-air temperatures show twice as much warming at higher elevations in the tropics as is predicted at Earth's surface generally (Bradley et al., 2006). These projections are consistent with the recently documented rise of the free-air 0 °C isotherm in the tropical atmosphere (Bradley et al., 2009). Furthermore, as more dark land surface is exposed, absorption of the intense higher-elevation radiation increases, thus accelerating the melting (Bradley et al., 2006).

Low- to mid-latitude glaciers are extremely susceptible to such warming. In accord with model predictions of warming, high-elevation tropical glaciers appear to be responding with an accelerating rate of glacier loss (Coudrain et al., 2005; Thompson et al., 2006). Smaller glaciers respond more rapidly to climate changes, and these mountain glaciers are generally much smaller than their polar counterparts. These ice masses are also particularly sensitive to small changes in ambient temperatures, because they already exist very close to the melting point.

We again emphasize that many environmental factors affect glaciers, and one glacier may change for many reasons. As glaciers shrink, the insulating effect of a debris cover that slows further melting may become more important, joining other factors influencing glaciers, some of which are mentioned above. Thus, proper characterization of ongoing trends requires monitoring of many glaciers in many places, together with targeted studies of selected glaciers to better characterize controls. Taken together, though, the full scholarship as summarized above gives high confidence that warming caused primarily by human release of greenhouse gases is causing the retreat of glaciers.

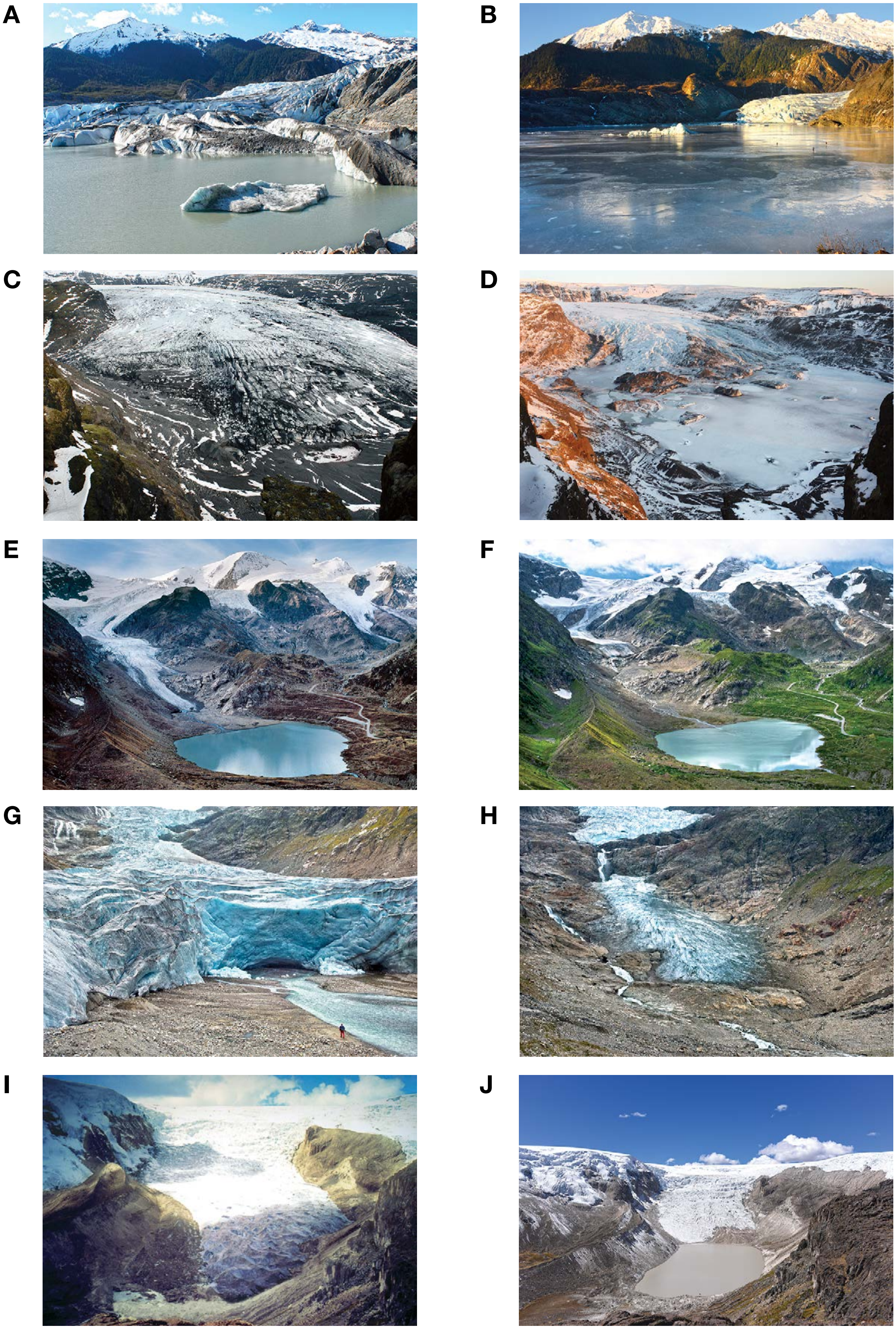

Figure 2. Time-lapse photo couplets of glaciers revealing retreat. (A–B) Mendenhall Glacier, Alaska, retreat of ~550 m from 2007 to 2015. (C–D) Solheimajokull, Iceland, retreat of ~625 m from 2007 to 2015. (E–F) Stein Glacier, Switzerland, retreat of ~550 m from 2006 to 2015. (G–H) Trift Glacier, Switzerland, retreat of ~1.17 km from 2006 to 2015. (I–J) Qori Kalis Glacier, an outlet of the Quelccaya Ice Cap, Peru, retreat of ~1.14 km from 1978 to 2016. Photo credits: (A–H) James Balog and the Extreme Ice Survey; (I–J) Lonnie Thompson.

IMPLICATIONS OF ICE LOSS

Global Sea Level

The most widespread and economically important global impact of ice loss is sea-level rise. As summarized by the IPCC (2013), sea level has recently been rising at just over 3 mm/year. A longer view shows that this rise has accelerated and that further acceleration is likely with continuing warming. Recent contributions to ocean volume have come from a combination of the expansion of ocean water due to its warming, retreat of mountain glaciers, shrinkage of the Greenland and Antarctic ice sheets through faster flow of land-originated ice into the ocean, and, primarily in Greenland, increasing surface melting and runoff. Relevant studies show accelerated flow in coastal regions in response to warming ocean waters that reduce the buttressing of ice shelves (IPCC, 2013). The Shepherd et al. (2012) synthesis estimated that sea-level rise from the ice sheets accelerated between 1992 and 2011, with an average over that interval of 0.59 ± 0.20 mm/yr. Complete loss of the ice sheets would raise sea level ~60 m, so at this average rate, more than 100,000 years would be required for complete ice-sheet removal. As discussed below, however, much shorter time scales may be involved.

Some studies estimate the costs of sea-level rise to be relatively small. These estimates are, in part, based upon using the most-likely IPCC projections of a slow, small, and well-anticipated rate, as well as the assumption of an efficient response to the rise (e.g., Darwin and Tol, 2001). Growing knowledge about the ongoing evolution and behavior of the primary outlet glaciers in Greenland and Antarctica, however, raises the possibility that future increments of sea-level rise may not, in fact, be slow, small, or well-anticipated (e.g., Joughin et al., 2014; Pollard et al., 2015; DeConto and Pollard, 2016).

As reviewed in Alley et al. (2015), the distribution of possible rates of sea-level rise includes values with slightly slower, slightly faster, or a much faster rise than the central IPCC projections. Of particular concern is marine instability in West Antarctica, especially the drainage through Thwaites Glacier into the Amundsen Sea (National Research Council, 2013). Extensive retreat may already have been triggered or may be imminent (Joughin et al., 2014; Parizek et al., 2013). In cold environments, ice flowing into the ocean typically forms attached, floating ice shelves. Friction between ice shelves and fjord walls, or local sea-floor highs, slows ice-shelf flow, in turn slowing the flow of non-floating ice into ice shelves. Warming ocean waters thin shelves, reducing this ice-shelf buttressing, allowing faster flow of non-floating ice into ice shelves. Beyond some warming threshold, ice shelves typically break off completely, leaving tidewater cliffs (reviewed in Alley et al., 2015). Material strength limits the height of cliffs (e.g., Fig. 3); ice cliffs much taller than ~100 m are likely to be unstable and break rapidly (Hanson and Hooke, 2003; Bassis and Walker, 2012). Retreat of Thwaites Glacier, West Antarctica (Joughin et al., 2014; DeConto and Pollard, 2016), could generate a cliff much higher than this limit, suggesting that very rapid retreat could follow. Implementation of a parameterization for these processes in a well-characterized ice-flow model produced ice-sheet collapse more than one century after initiation of rapid retreat, with >3 m of sea-level rise from this one source alone (Pollard et al., 2015; DeConto and Pollard, 2016). The full parameter space for such cliff instability has not been extensively explored, and faster collapse cannot be eliminated (Alley et al., 2015). Even if such rapid cliff collapse is not triggered, warming during the next one to a few centuries could commit the world to a very much larger long-term rise of sea-level (Pollard et al., 2015), possibly including complete loss of the ice sheets (Winkelmann et al., 2015). Uncertainties remain great, with potentially very large impacts upon human society and economies. The importance of this topic was highlighted by the recent studies from the National Research Council/National Academies (2013, 2015).

Water Supply

The loss of ice will have direct impact on local populations through changes in water availability, particularly during dry periods. The glacial-fed streams in the Andes, and elsewhere, are essential for hydroelectric production, irrigation, and municipal water supplies. Indeed, the glaciers across the TP are sometimes referred to as the "water towers" for southern Asia, where >100,000 km^2 of glaciers contain one of the largest glacial stores of fresh water outside of the Greenland and Antarctic ice sheets (Yao et al., 2012; Bolch et al., 2012). These glaciers discharge meltwater into the largest rivers in south Asia (Fig. 4), which are critical water resources in the populous regions surrounding the Himalayas. In 2009, the Third Pole Environment (TPE) program was launched in part to study the response of this remote region to climate change (http://www.tpe.ac.cn). The TPE program includes a strong educational component, as well as an integrated study of paleo-records to develop the context essential to assess and address the impact of anthropogenic activities. Beside the larger-scale impacts that are yet to unfold, people who live in areas affected by glacial retreat are already experiencing the consequences. For example, in 2006, a lake that had grown from the melting of Quelccaya's Qori Kalis outlet glacier (see Fig. 2J) breached its moraine dam after an avalanche and flooded the valley below, drowning herds of grazing alpacas. Emblematic of these concerns, the National Research Council of the National Academies also conducted a study to assess the role of Himalayan glaciers within the context of climate

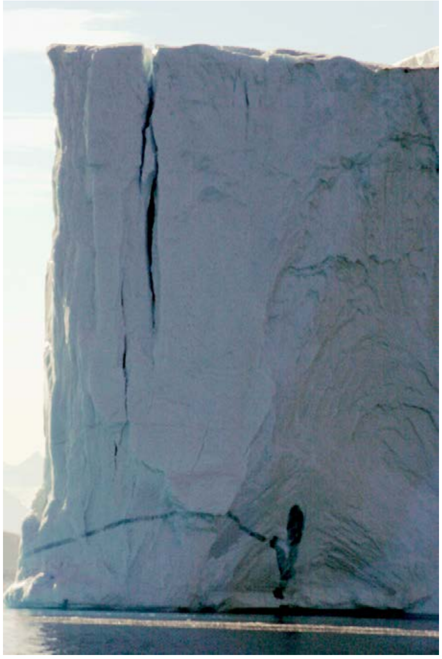

Figure 3. Ice that enters the ocean typically forms cliffs that then fracture, as shown for this iceberg with an approximate 60 m cliff face, in Scoresby Sound, Greenland. Higher cliffs have larger stress imbalances and so are more likely to break rapidly. Ice cliffs of ~100 m height appear to be near the highest that can support themselves. Retreat in West Antarctica, particularly at Thwaites Glacier, could produce taller cliffs that would fail rapidly, accelerating the retreat and its contribution to sea-level rise.

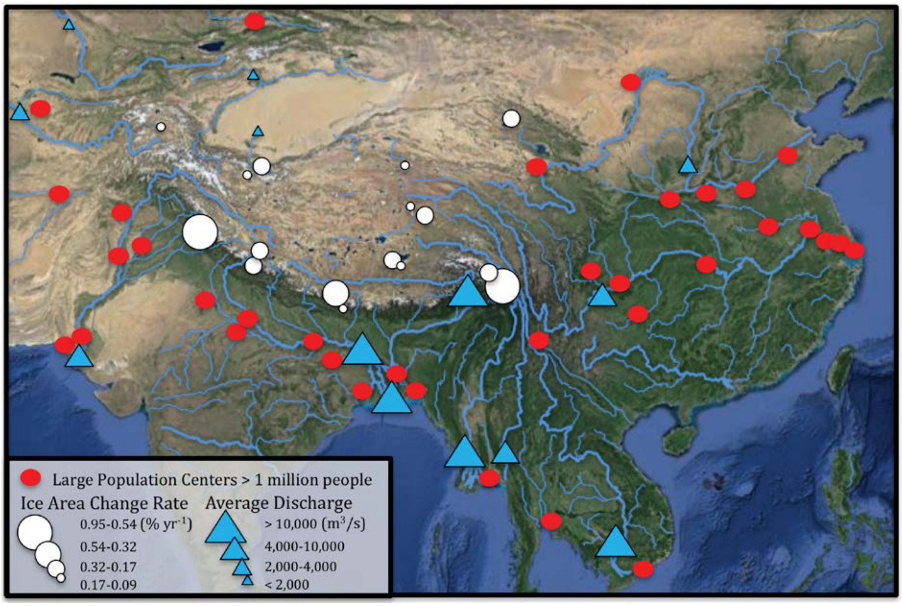

Figure 4. Earth's "Third Pole" (TP, also known as the Tibetan Plateau). Melted snow and ice from the TP generates major river systems including the Indus, Ganges, Salween, Mekong, Yangtze, and Huang He. Red dots—population centers with > 1,000,000 people that are served by these major river systems; white dots—areas of glacier loss as measured on 7,090 glaciers across the TP from the 1970s to 2000s (modified from Yao et al., 2012); blue triangles—average discharge of rivers. The base map and population centers are modified from Google Earth and the river drainages are modified from International Rivers database.

change, water resources, and water security (http://www.nap.edu/catalog.php?record_id=13449).

Loss of Natural Environmental Archives

Glaciers serve as both recorders and indicators of climate change, as the ice contains archives of environmental conditions that prevailed throughout their existence. Ice-core paleoclimatology plays an important role here, because the chemical and physical properties preserved within the glacial ice provide an essential long-term context for twentieth- and twenty-first–century changes. The history of links between climate change and humans, and indeed the rise and fall of entire civilizations, is well documented in low latitude ice cores (e.g., Thompson and Davis, 2014). Snowfall that accumulates to metamorphose into ice incorporates dust, volcanic ash, smoke, and other atmospheric constituents, as well as isotopic variations. Changes in the concentration of these constituents can reveal changes in the distribution of land mass, ocean currents, deserts, wetlands, and human activity. As the snow accumulates into annual layers that add mass to a glacier, a record of all these environmental conditions is preserved. Alley (2000) discussed the array of analyses that reveal the natural and anthropogenic history contained within the ice, which in the Greenland ice cap extends back over 100,000 years. The EIS film *Chasing Ice* and the multimedia production *Earth: The Operators' Manual* (Alley, 2011) vividly display the preservation of paleo-atmospheres within a glacier, as well as the loss of that archive that occurs during melting.

SUMMARY, LEGACY, AND CHALLENGE

Both satellite measurements of ice mass and ground-based observations indicate that Earth is losing ice; related studies show that warming temperatures are triggering this dramatic response in the world's ice cover. The characterization of rapid retreat of glaciers across Earth is well documented. Melting ice is contributing to sea-level rise, with concomitant disruption of shoreline communities. It is apparent that feedback mechanisms, such as loss of buttressing near calving faces, can rapidly accelerate this rise in human timeframes. Since glaciers are reservoirs for frozen water, the retreat of ice has other powerful implications. As glaciers are lost, rivers receiving meltwater will increasingly be susceptible to low flows during dry seasons and drought, stressing societies that rely upon those resources. Ice loss is also destroying environmental archives, much to the disadvantage of our scientific understanding of natural history.

In some places, the legacy of ice loss may be one of barren landscapes, as terrain that witnessed the passing of thousands of years during burial by advancing glaciers is now being rapidly exposed by substantially accelerating rates of retreat. It is likely that these recently deglaciated landscapes will not be re-occupied by ice during foreseeable human timeframes. In other places, forests or other vegetation may rapidly colonize such landscapes. Photographic records, such as those included here, provide an outstanding avenue for education, because they display a record of ice that may never be seen again.

This project has focused upon conveying captivating imagery of ice loss to the public, through which we highlight the forcing that the human combustion of fossil fuels is exerting upon terrestrial systems. Society is committed to additional warming, perhaps moving well past the 1.5–2 °C target from the recent Paris Agreement, unless strong actions are taken, perhaps growing from that accord. The rate at which glaciers are retreating provides one of the clearest indications that time is of the essence if human impacts are to be limited. As geoscience educators, we attempt to present the best scholarship as accurately and eloquently as we can to address the core challenge of conveying the magnitude of anthropogenic impacts, while also encouraging optimistic determination on the part of students, coupled to an increasingly informed citizenry. We assert that understanding human perturbation of nature, then choosing to engage in thoughtful science-based decision making, is a wise choice. Let us endeavor to tell the story better. Savor the cryosphere.

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