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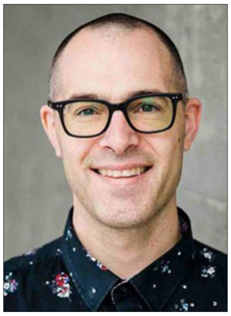
DOI: https://doi.org/10.56315/PSCF9-25Pimentel



Sam Pimentel

Have You Seen the Storehouses of the Snow? Glaciers in the Anthropocene

Sam Pimentel

Within Christian theology, the beauty and grandeur of glaciated regions on Earth are seen as reflections of God's glory. These landscapes have spiritual significance in reminding us of God's power and majesty, as well as of the humility of our own humanity in relation to these awe-inspiring parts of God's creation. Yet, the current state and future prognosis of these regions also reflect humanity's desecration of God's glory in them. Projections indicate that with 1.5°C warming above preindustrial levels, 49% of the world's glaciers will disappear between 2015 and 2100. These losses have profound implications for society, particularly for the poor and vulnerable, including rising sea levels, diminished freshwater resources, and increased exposure to natural hazards. Any reduction in the ongoing temperature increase that can be achieved by humanity matters for the survival of glaciers. We must choose our future responsibly and embody God's care for these majestic parts of his creation and all who benefit from them. Christians, as witnesses to the God who creates and loves the world, have the privilege of advancing climate solutions that bring reconciliation to the world and maintain a place for glaciers within the community of creation.

Keywords: glaciers, climate change, Anthropocene, reconciliation, creation care, climate action, climate justice, water resources, sea level rise

Glaciers have shaped some of the most spectacular landscapes on Earth (fig.1).[1] In Christian theology, all of creation is viewed as a gift, loved into existence by God,[2] and glaciers are one of its most striking expressions. Everything in creation is intended by God to be a revelation, a self-disclosure; the world is full of God.[3] The sheer beauty and grandeur of glacierized regions of Earth reflect God's glory; they embody something of the divine presence.[4] They burst with joy in celebration of God's redeeming and renewing work.[5] The vast expanses of ice express the enormity and power of God. There is the unrelenting force of a glacier to level mountains and carve out valleys, to mold and make the landscape on such grand scales, and in its wake to leave the fertile places that sustain human and ecological communities.[6] Consideration of the spiritual significance of glaciers offers us an opportunity to ponder God's beauty, his power and his majesty, as well as the humility of our humanity in relation to these awe-inspiring parts of God's creation.[7] As biblical scholar Terence Fretheim writes, "the natural order provides raw materials for human praise … Human beings give voice to nonhuman praise, to a world charged with wonder and praise."[8] Glaciers are one such stunning example of this.

The Current State of Glaciers

Glacier ice represents by far the largest planetary store of freshwater. Nearly 90% of Earth's land ice is contained within Antarctica, with most of the remainder

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held in the Greenland Ice Sheet. In fact, only about 1% of the total volume of glacier ice is stored outside these ice sheets. Nonetheless, land ice masses that are separate from the continental ice sheets—hereafter referred to as "glaciers"—play an outsized role with respect to societal significance and are the focus of this article. For instance, according to one estimate, mountain glaciers account for 18.4% of the freshwater considered accessible for sustainable human use.[9] Glaciers are typically situated in steep, localized mountain environments and are of much smaller size; thus they are highly sensitive to climate change, responding to atmospheric and oceanic warming on shorter time scales, when compared to the ice sheets. As such, glaciers are one of the most visible indicators of a warming world and the ill effects of ice mass loss from glaciers are more immediately apparent. For example, ice melt from glaciers is contributing about 25% of the currently observed global sea level rise.[10]

The Randolph Glacier Inventory records 274,531 glaciers and ice caps on Earth,[11] located on mountain ranges from the tropics to the polar regions (see figs. 1 and 3) and encompassing an area of 706,744 km^2. The global glacier ice volume (apart from the ice sheets) is estimated to be 140,600±40,400 km^3.[12] If all this ice were to melt completely, it would raise global sea levels by 0.311 ± 0.099 m.[13] This potential contribution is referred to as sea level equivalent (SLE).[14]

As evidenced by repeat photography, glaciers around the globe have been losing mass and retreating over recent decades (fig. 2). Changes in glacier mass have been carefully observed by multiple *in situ* monitoring programs. Although only a relatively small number of glaciers (a few hundred) are sampled with instrumentation, they form an important historical record of glacier change; in some cases, these glaciological measurements go back over 100 years.[15]

With the advent of geodetic methods that use precise geospatial techniques we can utilize spaceborne observations to monitor glaciers at the global scale, including in remote locations. Optical and radar sensors allow for the derivation of digital elevation models (DEM) of glacier surface topography. With repeat mapping and DEM differencing, we can determine multiyear trends in glacier elevation and track volume change for all glaciers in the world. Laser and radar altimetry are also used to provide higher temporal resolution along linear tracks, which can then be extrapolated to ascertain regional changes. Scientists have also utilized satellite gravimetry for determining glacier mass change by measuring changes in Earth's gravitational field which, after correcting for solid Earth and hydrological effects, reveal regional ice mass changes.

The combination of these methods—glaciological, DEM differencing, altimetry, and gravimetry—provides a robust and comprehensive picture of contemporary global glacier changes. By combining results from all major studies using these different techniques, it is estimated that the world has lost about 5% of its glacier ice since the year 2000.[16] The total amount of ice present is not uniformly distributed across regions, and there is considerable regional variability in glacier mass

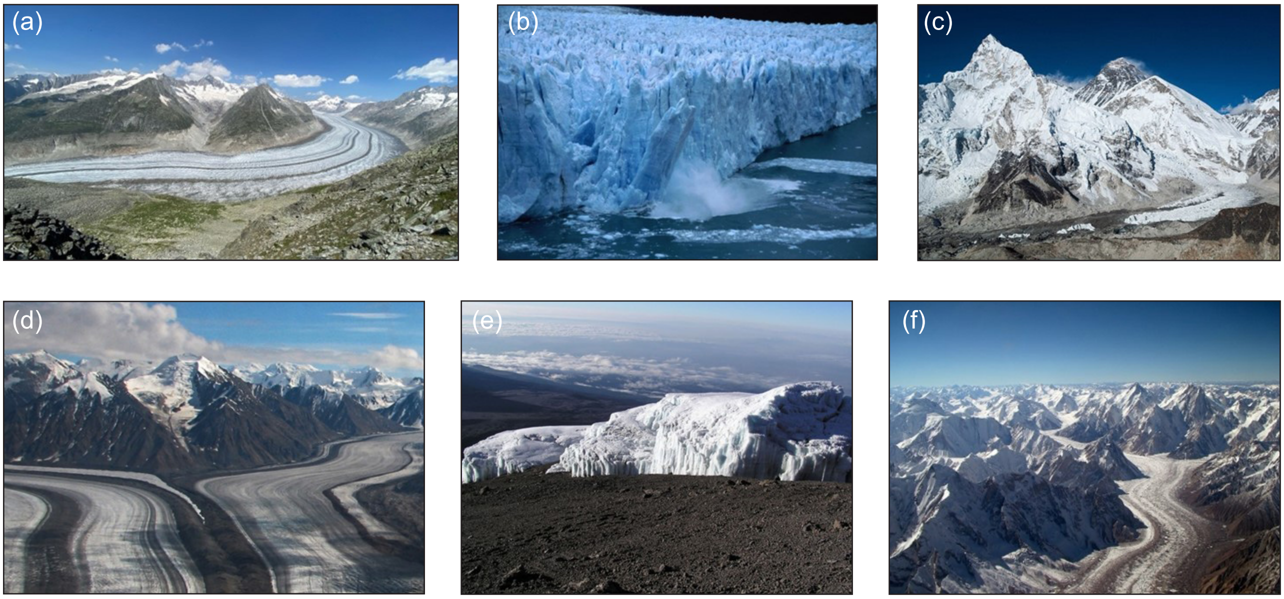

Figure 1. (a) Aletsch Glacier,[17] Switzerland; (b) Perito Moreno Glacier,[18] Argentina; (c) Khumbu Glacier,[19] Mount Everest, Tibet; (d) Kaskawulsh Glacier,[20] Yukon, Canada; (e) Rebmann Glacier,[21] Mount Kilimanjaro, Tanzania; (f) Baltoro Glacier,[22] Pakistan.

changes. For example, regions with comparatively large glacier volumes, such as the periphery of Antarctica and subantarctic, Arctic Canada North, and the Greenland periphery, experienced relatively modest losses between 2000 and 2023: approximately 2%, 3%, and 7%, respectively. In contrast, regions with smaller total ice volumes, such as Western Canada and USA, Central Europe, and New Zealand, saw much larger percentage losses over the same period: about 23%, 39%, and 29%, respectively.[23]

Hugonnet et al. provided the first globally complete and consistent estimate of 21st-century glacier mass change, using highly resolved estimates based on differencing DEM.[24] In light of this and several other studies, the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6) concludes that the global mass loss rate during the period 2000–2019 is 267 ± 16 Gt/year (Gt = gigatonne = 1,000,000,000 tonnes or 1 billion metric tons, where 1 metric ton = 1000 kg).[25] This means that each year glaciers lose roughly the same amount of mass as the total water consumed by every person on Earth over 30 years.[26] The mass loss rate has increased from 240 ± 9 Gt/year during 2000–2009 to 290 ± 10 Gt/year in 2010–2019.[27] It can be concluded, with very high confidence, that glaciers lost more mass during 2010–2019 than in any previous decade since the beginning of the observational record.[28]

The Human Influence on Glacier Change

The key variable connecting glaciers to climate is the mass balance of gain to loss over time. Throughout the year, a glacier can gain mass through snow accumulation and lose mass due to melt and other processes. The net result of these gains and losses, the balance of inputs to outputs, determines any change to the size of the glacier. A positive mass balance causes a glacier to thicken and advance, while a negative mass balance leads to thinning and retreat. As such, the mass balance is the most critical measure of a glacier's health and a direct indicator of its response to climate change.

Over geological timescales, Earth has experienced multiple glaciation events during which continental-scale ice sheets have covered much of the planet, profoundly reshaping the landscape. These glacial-interglacial cycles are a natural feature of the unfolding of God's creation and a fundamental characteristic of Earth's history over the past 2.5 million years (the Quaternary Period). Long-term climate variability is driven primarily by changes in Earth's orbit, known as the Milankovitch cycles. The past 11,700 years demarcate the latest interglacial period, that is, the current geological epoch called the Holocene. During this time, glaciers retreated to their minimum extent about 6,000 to 8,000 years ago, followed by a gradual expansion that culminated in a new maximum between the mid-15th to late 19th centuries.[29]

Over the past century or so, humanity has emerged as a planetary force, driving profound environmental changes—a shift often referred to as the Anthropocene.[30] Human activities, principally the burning of fossil fuels, have caused concentrations of atmospheric greenhouse gases to rise to levels unprecedented in at least the last 800,000 years.[31] As a result, global average surface temperatures rose to 1.1ºC above the 1850–1900 baseline during the 2011–2020 period.[32] This atmospheric warming is the primary driver of contemporary global glacier recession. In some regions, precipitation changes or internal glacier dynamics have also modified the temperature-induced glacier response.

Today, the vast majority of the world's glaciers have a negative mass balance; hence, they are out of equilibrium with the current climate and are losing mass. Furthermore, because the response is lagged, even if global temperatures stabilize, glaciers will continue

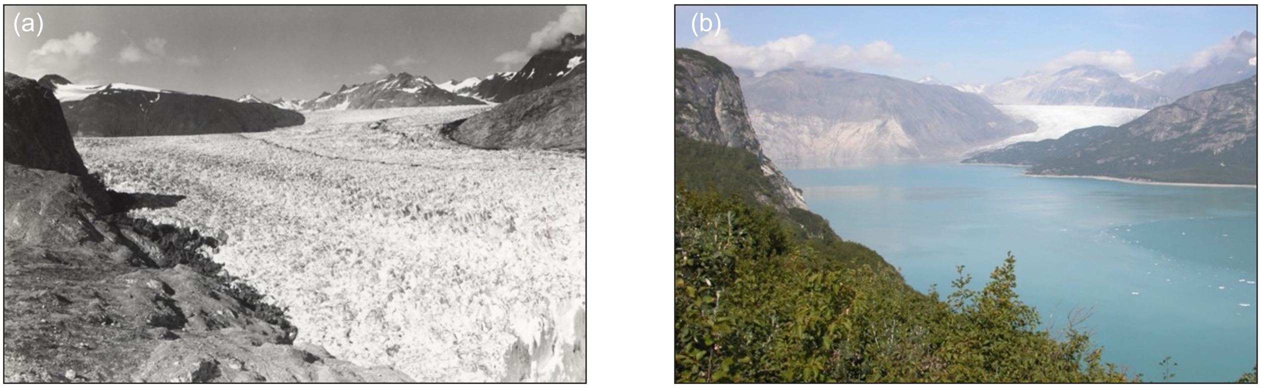

Figure 2. Muir Glacier, Alaska, USA, in (a) 1941,[33] and (b) 2004.[34]

to lose mass in the near future. The reason: although glacier mass loss is directly connected to increasing atmospheric temperatures, a glacier's response to those changes can take decades.

Attribution studies have demonstrated that the observed centennial-scale retreat of glaciers far exceeds the length fluctuations that would have occurred due to natural climate variability alone.[35] For alpine valley glaciers, it has been estimated that 85–130% of the observed cumulative mass loss since 1850 is a result of anthropogenic warming (a value over 100% indicates that, in the absence of human influence, glaciers would have gained mass).[36] Hence, contemporary glacier retreat and mass loss are entirely a consequence of human-caused climate change, which has fundamentally disrupted the patterns of natural variability.

Glaciers at the End of the Twenty-First Century

The future of glaciers is dependent on greenhouse gas emission scenarios. A recent comprehensive study by Rounce et al. have run individual model simulations of every glacier on Earth.[37] For each glacier, an ice dynamic model is "forced" with a suite of potential future climates out to 2100. This study projects that glaciers are set to lose between 26 ± 6% (+1.5°C warming) to 41 ± 11% (+4°C warming) of their mass by 2100, relative to 2015, depending on the global temperature change scenario (fig. 3).[38] This corresponds to the disappearance of 49 ± 9% (+1.5°C) to 83 ± 7% (+4°C) of the world's glaciers; note that most glaciers are small and thus inherently more vulnerable.[39]

Impacts of Glacier Loss

The ongoing decline of glaciers due to climate change will have major societal and ecological outcomes. Melting glaciers are a significant contributor to contemporary sea level rise. Sea level rise includes a steric component (thermal expansion) and a mass component (melt from glaciers and ice sheets, as well as land water storage changes). Melt specifically from glaciers contributes about a quarter of the total sea level rise.[40] The projected loss of glacier ice mass by 2100 corresponds to

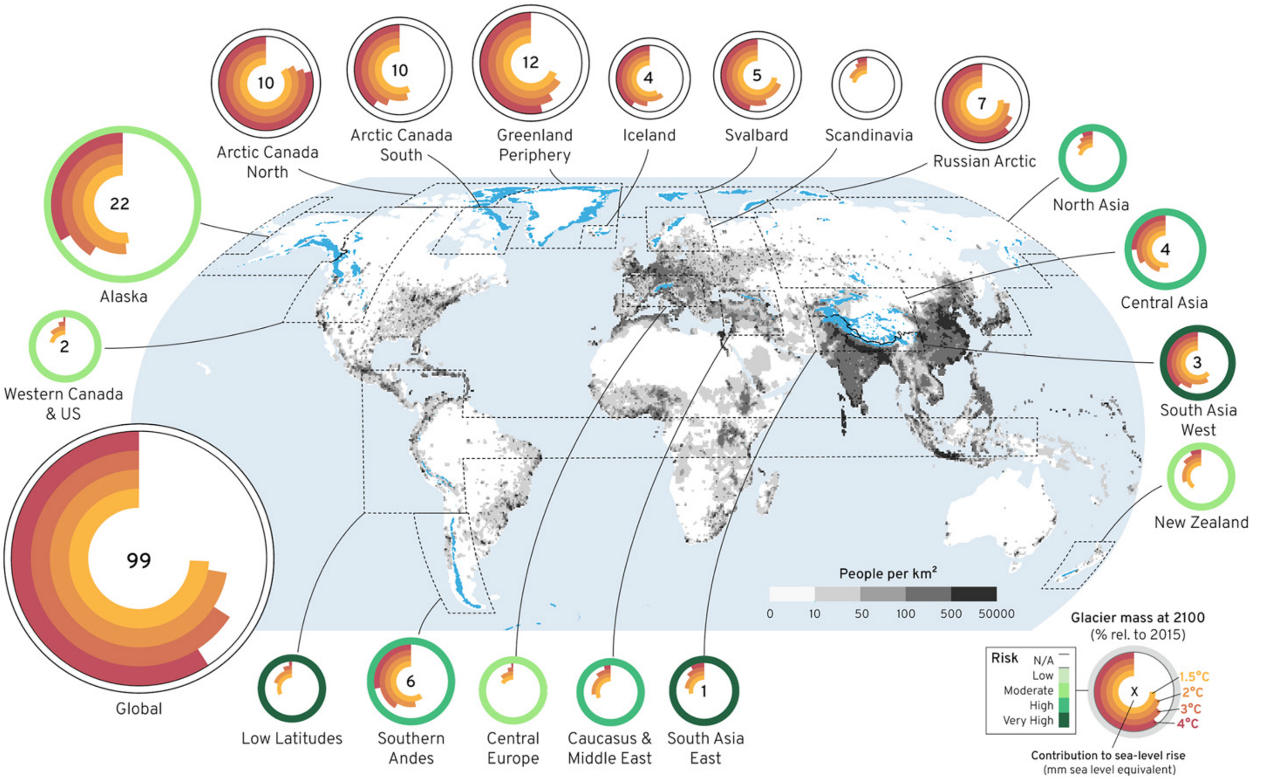

Figure 3. Regional glacier mass change and contributions to sea-level rise from 2015 to 2100. Disks show global and regional projections of glacier mass remaining by 2100, relative to 2015, for global mean temperature change scenarios. Disks are scaled based on each region's contribution to global mean sea-level rise from 2015 to 2100 for the +2°C scenario by 2100 relative to preindustrial levels. Nested rings are colored by temperature change scenarios showing normalized mass remaining in 2100. Regional sea-level rise contributions larger than 1 mm sea-level equivalent (SLE) for the +2°C scenario are printed in the center of the ring charts. The color of the rings for each region indicates the risk to livelihoods and the economy from changing mountain water resources between 1.5 and 2°C global warming. The gridded population density (people per km^2) is also shown (grey scale). Glaciers are shown in blue.[41]

an expected sea level rise of 90 ± 26 mm under a +1.5°C scenario, and 154 ± 44 mm under a +4°C scenario (see fig. 3).[42] It is estimated that 190 million people currently live on land that is projected to be below the high-tide mark in 2100 under a low emission scenario.[43] These coastal communities will become increasingly vulnerable to storm surges and flooding events, putting infrastructure and livelihoods at risk.[44]

Glaciers are effective water towers, as they play a critical role in the storage and supply of freshwater that is vital for many mountain regions (fig. 4). It is estimated that at least 1.9 billion people live in or downstream of mountain areas that receive water from glaciers.[45] This includes the high population density in the regions of High Mountain Asia, which are particularly vulnerable as they rely on glaciers for water, energy, and food security (see fig. 3). Glacier melt is seasonal and can play a buffering role as it delays the supply of melt water, compensating for water shortages during the dry season, and thus reducing drought frequency and severity. The loss of these vast storage containers of freshwater (mountain water towers) depletes regional freshwater resources as the ability of glaciers to retain and release water is diminished.

The decline and loss of glaciers affects the local mountain environment causing changes in water flow and sediment transport, and creating slope instabilities that can trigger landslides.[46] Their melting leads to increased geohazards putting local populations at risk. As glacial ice mass loss accelerates, we are witnessing an increase

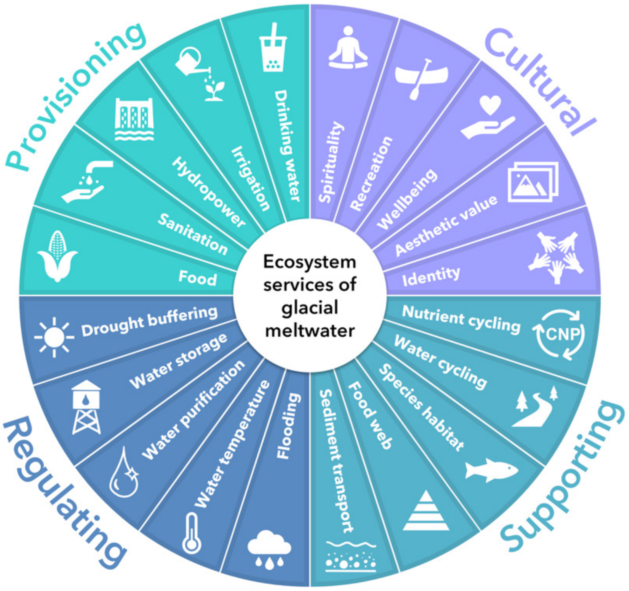

Figure 4. Examples of the cultural, provisioning, regulating, and supporting ecosystems services provided by glacial meltwater in mountain regions.[47]

in glacial lakes, exposing around 15 million people to serious damage from potential glacial lake outburst floods.[48]

Many hydroelectric power plants are principally glacier fed. As glacier runoff declines, the reduction in streamflow will reduce hydropower output, putting at risk a major source of renewable energy. Hydropower infrastructure is also vulnerable to the destabilization of the local landscape due to glacier loss that can produce slope failures and increased sediment fill.[49]

Glaciers preserve important records of past climates. Isotope content and soluble impurities trapped in the ice can be sampled through ice cores and used to reconstruct the regional environmental conditions of the past. However, the valuable "memory" stored in these natural archives is being permanently lost or contaminated due to melt caused by climate change.[50]

Glaciers hold deep cultural value.[51] For example, of the 247 natural World Heritage sites listed for their outstanding universal value,[52] 46 contain glaciers.[53] For five of those sites, glaciers are the principal reason for their status, and for 28 sites, they are a contributing factor.[54] However, for between 8 and 21 of those World Heritage sites, glaciers will become extinct through mass wastage by 2100, depending on the future emission scenario.[55] Glaciers also hold profound cultural and spiritual significance for many Indigenous cultures around the world and are an important feature in oral histories and storytelling. The disappearance of glaciers on ancestral lands represents a profound loss to cultural heritage and identity, not to mention the glaciers' life-sustaining water and ecosystem services that will disrupt the traditional ways of life for Indigenous communities.

The global retreat of glaciers is altering terrestrial and marine biodiversity. Mountain glacier ecosystems host diverse habitats, but rising temperatures and the loss of meltwater are modifying environmental conditions and putting these communities at risk.[56] As glaciers recede, proglacial and postglacial habitats emerge in the newly exposed ice-free terrain, creating opportunities for ecological succession and colonization.[57] In alpine river catchments, the diminishing glacial influence reduces cold-water inputs, affecting species adapted to stable, low-temperature environments.[58] In marine settings, tidewater glaciers function as nutrient delivery systems, enriching fjord waters with macro- and micronutrients that support plankton, fish, and seabirds. Consequently, changes in glacial meltwater delivery may undermine the productivity and viability of these communities.[59]

Climate Justice

The Anthropocene has brought about worldwide glacier retreat and decline. This is unequivocally a result of atmospheric warming driven by anthropogenic emissions. At the heart of this lies a justice issue, as those who have contributed least to this crisis are the ones who are most vulnerable to current and future changes. The poorest, the least protected, and the least resilient populations will bear the heaviest burdens.[60] Risks are not evenly distributed, and there is disproportionate exposure to harm (see fig. 3). Those living in low-lying coastal zones are in direct danger from sea-level rise driven by glacier melt. Meanwhile, communities downslope of glacierized mountain regions suffer from the loss of critical seasonal freshwater from mountain water towers. Moreover, future generations will live in a world with far fewer glaciers. They will not have contributed to this loss, yet they will nonetheless be impoverished by it. This raises the question of intergenerational justice, of what we owe to those who come after us, and of the fairness in the provision and legacy we leave behind. There is also the sense of the justice we owe to the glaciers themselves, to the ecological spaces they shape, and to the habitats they sustain. We must ask whether our interaction with the world allows glaciers to fulfill their fitting role within creation, or whether it disrupts their God-given purpose. These glaciological systems carry something of God's intention and invitation; they are an expression of God's gift to us. We should care about the glaciers because God does. It is not simply about human concerns, but justice for the whole community of creation, doing what is fair and true and fitting.

Reconciliation and Climate Action

Figure 3 illustrates that each projected increase in global mean temperature is associated with corresponding glacier mass loss.[61] Our policies and actions to curb greenhouse gas emissions are directly linked to the extent to which glaciers survive. Indeed, it has been calculated that every kilogram of CO_2 emission would eventually be responsible for about 16kg of glacial ice loss.[62] It is inevitable that we will continue to experience glacier loss and retreat; however, the differences between a 2-, 3-, and 4-degree world to global glacier coverage is stark (see fig. 3). We choose the differences now by the policies we enact today. These findings call for urgent and concrete actions to limit anthropogenic climate change.

Glacier mass loss can be halted only when glaciers are in balance with their climate and have had the necessary time to return to equilibrium. Global average temperatures must be stabilized to slow the acceleration of ice mass loss and the resulting consequences. Reaching net-zero[63] anthropogenic CO_2 emissions is a requirement to stabilize human-induced global temperature increase at any level. Transformative actions are required to achieve this, including improving energy efficiency; transitioning to renewable energy sources, particularly wind and solar; reducing deforestation and promoting reforestation; limiting the release of short-lived climate pollutants; and implementing technologies to remove and store CO_2 from the atmosphere—all whilst adapting to unavoidable changes.[64] Many of these actions have health and economic co-benefits.

Efforts to save glaciers, such as glacier blanketing—the practice of laying geotextiles across glacier surfaces to reduce ablation,[65] and building ice stupas—a form of glacier grafting to create artificial glaciers built to store winter water for spring irrigation,[66] demonstrate both human ingenuity and a commitment to environmental stewardship. These interventions reflect values such as care for creation, justice for climate-affected local populations, and community responsibility to future generations. Adaptive measures, while valuable, cannot prevent all losses or damages, which will continue to be unequally distributed and concentrated among the poorest and most vulnerable populations.[67]

Psalm 1:1[68] describes a transition from walking to standing to sitting. Where are we, as a society and as individuals, on our moral journey when it comes to climate change? Are we becoming increasingly sedentary with inaction as we sit around paying heed to the climate naysayers? Do we scoff or stand about as we wait for our scientific predictions to come true? Or should we walk the narrow path in pursuit of the kinds of choices that climate justice calls for, living with honesty and humility, and seeking Christ-like ways to relate to the world that God has entrusted to us?[69] What future climate pathway will we choose?[70] How many glaciers will we bequeath to future generations? What an awesome responsibility and challenge! Rather than fearing or denying climate change, we can embrace it as an opportunity for reconciliation.

Christian faith gives us well-grounded hope. Throughout scripture the Christian hope is directed toward what is not yet visible, a "hoping against hope." Despite human-driven degradation of glaciers and glacierized habitats, the life-giving Spirit of God remains at work. For example, receding glaciers give rise to new proglacial and postglacial landscapes, quickly pioneered by species, forming new habitat niches.[71] The recession of marine-terminating glaciers opens up new spawning routes for salmon.[72] The loss of glacier tourism instead might result in new recreational activities such as hiking routes in the newly uncovered territory.[73] Melting glacier margins sometimes reveal remains that can shed light on past societies and ecosystems, spurring a new subdiscipline called ice patch archeology.[74]

In the words of Saint Paul in Romans, the whole of creation groans in frustration as it awaits redemption.[75] Applying his anthropomorphic characterization of nature, as glaciers recede and become remnants of their former stature, they yearn to be set free, to flourish, to be in harmony with their climate, to become a place of healing and reconciliation, and to be a visible reflection of God's glory.

God's grace is inbuilt into creation. With a favorable climate, over time glaciers can be restored and regrow. For example, in the decades following the cataclysmic eruption in 1980 of Mount St. Helens, Washington, USA, heavy winter snowfall and avalanches led to the rapid growth and formation of a new glacier within the deeply shaded niche of the crater. This newly formed glacier is now the largest on Mount St. Helens exceeding all other remaining glaciers in extent.[76]

Continuing scientific endeavors to monitor and simulate glaciers is vital for understanding the impact of climate change and accurately projecting future freshwater resources and sea-level rise. The work of glaciologists helps us live out our calling as co-creators by equipping us to make informed decisions that shape a future of flourishing for glaciers, humanity, and the whole community of creation.[77] Transformative actions, both mitigation and adaptation, to limit glacier loss and care for those most at risk are urgently needed to protect life and promote well-being, global equity, and safety.

Notes

[1]The title is a reference to Job 38:22, "*Have you entered the storehouses of the snow or seen the storehouses of the hail …?*" Although the verse isn't explicitly referring to glaciers, it seems an apt title. The writer of Job here imagines some great cache for storing these primal meteorological forces of nature from which God can dispense weather's wrath. Glaciers form from snowfall accumulated over many years. As layers of snow build up, they are compacted into firn (an intermediate stage between snow and glacial ice), and with continued compression and recrystallization, glacier ice is formed. Eventually, the mass of ice deforms and flows under the force of gravity. Although it can snow in Jerusalem and surrounding areas, there are no glaciers in the biblical geographical region. The closest would be the glaciers that are present in Turkey and extremely remote regions of Iran. As such, the biblical authors would presumably be unaware of the existence of glaciers. It is interesting to imagine how the writer of Job, who is so attuned to describing the natural world, would have described glaciers. For example, Job 6:15–18:

My brothers betrayed like a wadi,
like the channel of brooks that run dry.
They are dark from the ice,
snow heaped on them.
When they warm, they are gone,
in the heat they melt from their place.
The paths that they go on are winding,
they mount in the void and are lost.

is a beautiful and perceptive passage comparing Job's portrayal to a wadi, a desert stream that dries up. The author describes the seasonal cycle with the ice and snow heaped on top followed by warming that melts the snow and so on. Presumably the author of Job here has in mind the Lebanese mountains where there is significant seasonal snowfall.

[2]See, for example, Simon Oliver, *Creation: A Guide for the Perplexed* (Bloomsbury, 2017).

[3]See, for example, "The whole earth is full of God's glory" (Isa. 6:3); "The Lord's kindness fills the earth" (Ps. 33:5); "Do I not fill heaven and earth? says the LORD" (Jer. 23:24).

[4]The Christian tradition has held that the manifestation of the divine is through both the natural world and the biblical world. In the words of Thomas Berry, "to save Earth is an essential part of saving the pristine divine presence" (Thomas Berry, *The Christian Future and the Fate of Earth* [republished by Maryknoll, 2009], **38**). In the context of this article, it would be appropriate and relevant to replace "Earth" with "glaciers" in the above quote.

[5]See Isa. 55:12: "… the mountains … burst into song …"

[6]See, for example, Job 14:18–19:

"… the mountain falls and crumbles away,
and the rock is removed from its place;
the waters [ice!?] wear away the stones;
the torrents wash away the soil of the earth …"

[7]See, for example, the Psalmist's humility in response to God's awe-inspiring creation, "What are human beings that you are mindful of them?" (Ps. 8:4). A more in-depth exploration of this theme can be found in a chapter on wonder and humility in Steven Bouma-Prediger, *Earthkeeping and Character: Exploring a Christian Ecological Virtue Ethic* (Baker Academic, 2020), 29–50.

[8]Terence Fretheim, *God and World in the Old Testament: A Relational Theology of Creation* (Abingdon Press, 2005), 284.

[9]Matthew Mccartney et al., "Change in Global Freshwater Storage," *International Water Management Institute (IWMI)*, IWMI Working Paper 202, 2022, https://www.researchgate.net/publication/359586409_Change_in_Global_Freshwater_Storage.

[10]Romain Hugonnet et al., "Accelerated Global Glacier Mass Loss in the Early Twenty-First Century," *Nature* 592, no. 7856 (2021): 726–31, https://doi.org/10.1038/s41586-021-03436-z.

[11]RGI Consortium, "Randolph Glacier Inventory—A Dataset of Global Glacier Outlines, Version 7," NASA National Snow and Ice Data Center Distributed Active Archive Center, 2023, https://doi.org/10.5067/F6JMOVY5NAVZ.

[12]Romain Millan et al., "Ice Velocity and Thickness of the World's Glaciers," *Nature Geoscience* 15 (2022): 124–29, https://doi.org/10.1038/s41561-021-00885-z; Regine Hock et al., "What Is the Global Glacier Ice Volume Outside the

Ice Sheets?," *Journal of Glaciology* 69, no. 273 (2023): 204–10, https://doi.org/10.1017/jog.2023.1.

[13]Millan et al., "Ice Velocity and Thickness of the World's Glaciers"; and Hock et al., "What Is the Global Glacier Ice Volume?"

[14]To calculate SLE, the total ice volume above flotation is used—that is, the portion of the glacier ice that is not already displacing seawater. Approximately 15% of the global glacier volume is already submerged below sea level at grounded tidewater termini and thus would not contribute to sea level when melted. The above flotation volume is converted to the equivalent volume it would occupy in the ocean, accounting for the difference in density between ice and seawater, and this volume is then divided by the total surface area of the world's oceans to produce SLE. A commonly used approximation is that 361.8 gigatonnes (Gt) of ice correspond to 1 millimetre (mm) of global mean sea level rise.

[15]WGMS Global Glacier Change Bulletin No. 5 (2020–2021) (ISC(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service, 2023); https://doi.org/10.5904/wgms-fog-2023-09. The longest continuous mass-balance monitoring program is at Claridenfirn, Switzerland, with measurements dating from 1914.

[16]The GlaMBIE Team, "Community Estimate of Global Glacier Mass Changes from 2000 to 2023," *Nature* 639 (2025): 382–88, https://doi.org/10.1038/s41586-024-08545-z.

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[22]Photo taken October 23, 2005, by Guilhem Vellut, shared under the Creative Commons License.

[23]The GlaMBIE Team, "Community Estimate."

[24]Hugonnet et al., "Accelerated Global Glacier Mass Loss."

[25]IPCC, *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, ed. V. Masson-Delmotte et al. (Cambridge University Press, 2021).

[26]Assuming a daily water intake for 1 person is 3 litres, total daily water intake of 8 billion people is 24 billion litres; total water intake of 8 billion people for thirty years is 263 trillion litres (or 263 gigatonnes). This is less than the 273 gigatonnes of glacier ice mass lost annually over the period 2000 to 2023 (see The GlaMBIE Team, "Community Estimate").

[27]IPCC, *Climate Change 2021: The Physical Science Basis*.

[28]IPCC, *Climate Change 2021: The Physical Science Basis*.

[29]Olga N. Solomina et al., "Holocene Glacier Fluctuations," *Quaternary Science Reviews* 3 (2015): 9–34, http://dx.doi.org/10.1016/j.quascirev.2014.11.018.

[30]Although not formally recognized as a geological epoch, the Anthropocene remains an important and widely used concept across many disciplines. See, for example, Jan Zalasiewicz et al., "The Meaning of the Anthropocene: Why It Matters Even Without a Formal Geological Definition," *Nature* 632 (2024): 980–84, https://doi.org/10.1038/d41586-024-02712-y.

[31]According to the IPCC (2023), atmospheric CO_2 concentrations are now higher than any time in at least 2 million years, while methane and nitrous oxide levels are at their highest in at least 800,000 years. See "Summary for Policymakers," in *Climate Change 2023: Synthesis Report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, ed. Core Writing Team, H. Lee, and J. Romero (IPCC, 2023), 1–34, https://doi.org/10.59327/IPCC/AR6-9789291691647.001.

[32]IPCC, "Summary for Policymakers."

[33]William Osgood Field, 1941. Muir Glacier: From the Glacier Photograph Collection. Boulder, Colorado USA: National Snow and Ice Data Center, digital media, https://nsidc.org/data/glacier_photo/search/image_info/muir1941081301.

[34]Bruce F. Molnia, 2004. Muir Glacier: From the Glacier Photograph Collection. Boulder, Colorado USA: National Snow and Ice Data Center. Image courtesy of the U.S. Geological Survey.

[35]Gerard H. Roe et al., "Centennial Glacier Retreat as Categorical Evidence of Regional Climate Change," *Nature Geoscience* 452 (2017): 95–99, https://doi.org/10.1038/ngeo2863.

[36]Gerard H. Roe et al., "On the Attribution of Industrial-Era Glacier Mass Loss to Anthropogenic Climate Change," *The Cryosphere* 15, no. 4 (2021): 1889–1905, https://doi.org/10.5194/tc-15-1889-2021.

[37]David R. Rounce et al., "Global Glacier Change in the 21st Century: Every Increase in Temperature Matters," *Science* 379, no. 6627 (2023): 78–83, https://doi.org/10.1126/science.abo1324.

[38]Rounce et al., "Global Glacier Change."

[39]Rounce et al., "Global Glacier Change."

[40]Martin Horwath et al., "Global Sea-Level Budget and Ocean-Mass Budget, with a Focus on Advanced Data Products and Uncertainty Characterisation," *Earth System Science Data* 14, no. 2 (2022): 411–47, https://doi.org/10.5194/essd-14-411-2022; and Hugonnet et al., "Accelerated Global Glacier Mass Loss."

[41]Figure taken from Mercedes Bustamante et al., "Ten New Insights in Climate Science 2023," *Global Sustainability* 7 (2023): e19, https://doi.org/10.1017/sus.2023.25, which makes use of source data from Rounce et al., "Global Glacier Change"; and IPCC, *Climate Change 2022: Impacts, Adaptation, and Vulnerability,* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, ed. H.-O. Pörtner et al. (Cambridge University Press, 2023). Reproduced under the Creative Commons License.

[42]Rounce et al., "Global Glacier Change."

[43]Scott A. Kelp and Benjamin H. Strauss, "New Elevation Data Triple Estimates of Global Vulnerability to Sea-Level Rise and Coastal Flooding," *Nature Communications* 10 (2019): 4844, https://doi.org/10.1038/s41467-019-12808-z.

[44]Kelp and Strauss, "New Elevation Data"; see also B.C. Glavovic et al., "Cross-Chapter Paper 2: Cities and Settlements by the Sea," in *Climate Change 2022*, 2163–94, https://doi.org/10.1017/9781009325844.019.

[45]W. W. Immerzeel et al., "Importance and Vulnerability of the World's Water Towers," *Nature* 577 (2020): 364–69, https://doi.org/10.1038/s41586-019-1822-y.

[46]See, for example, John J. Clague and Dan H. Shugar, "Impacts of Loss of Cryosphere in the High Mountains of

Northwest North America," *Quaternary* 6, no. 1 (2023): 1, https://doi.org/10.3390/quat6010001.

[47]Figure taken from Caroline Clason et al., "Contribution of Glaciers to Water, Energy and Food Security in Mountain Regions: Current Perspectives and Future Priorities," *Annals of Glaciology* 63, no. 87–89 (2022): 73–78, https://doi.org/10.1017/aog.2023.14. Reproduced under the Creative Commons License.

[48]Caroline Taylor et al., "Glacial Lake Outburst Floods Threaten Millions Globally," *Nature Communications* 14 (2023): 487, https://doi.org/10.1038/s41467-023-36033-x. The observed increase in the number and size of glacier lakes may result in an associated increase in glacial lake outburst flood (GLOF) hazards; however, this relationship is complex. For example, Georg Veh et al., "Progressively Smaller Glacier Lake Outburst Floods Despite Worldwide Growth in Lake Area," *Nature Water* 3 (2025): 271–83, https://doi.org/10.1038/s44221-025-00388-w. Furthermore, the risks associated with GLOFs are highly context-dependent, influenced by the size and economic vulnerability of exposed populations.

[49]Dongfeng Li et al., "High Mountain Asia Hydropower Systems Threatened by Climate-Driven Landscape Instability," *Nature Geoscience* 15 (2022): 520–30, https://doi.org/10.1038/s41561-022-00953-y.

[50]See, for example, C. J. Huber et al., "High-Altitude Glacier Archives Lost Due to Climate Change-Related Melting," *Nature Geoscience* 17 (2024): 110–13, https://doi.org/10.1038/s41561-023-01366-1.

[51]For an interesting discussion of evolving views within glacier–mining interactions, see Caroline White-Nockleby and Scott Odell, "From Obstacles to Heritage: The Shifting Status of Glaciers Across 150 Years of Mining Research," *Energy Research & Social Science* 121 (2025): 103953.

[52]That is, their natural beauty or importance for geological and biological diversity and processes.

[53]J.-B. Bosson et al., "Disappearing World Heritage Glaciers as a Keystone of Nature Conservation in a Changing Climate," *Earth's Future* 7, no. 4 (2019): 469–79, https://doi.org/10.1029/2018EF001139.

[54]Bosson et al., "Disappearing World Heritage Glaciers."

[55]Bosson et al., "Disappearing World Heritage Glaciers."

[56]Scott Hotaling et al., "Microbial Ecology of Mountain Glacier Ecosystems: Biodiversity, Ecological Connections and Implications of a Warming Climate," *Environmental Microbiology* 19, no. 8 (2017): 2935–48, https://doi.org/10.1111/1462-2920.13766.

[57]J. B. Bosson et al., "Future Emergence of New Ecosystems Caused by Glacial Retreat," *Nature* 620 (2023): 562–69, https://doi.org/10.1038/s41586-023-06302-2; and Gentile Francesco Ficetola et al., "The Development of Terrestrial Ecosystems Emerging After Glacier Retreat," *Nature* 632 (2024): 336–42, https://doi.org/10.1038/s41586-024-07778-2.

[58]M. A. Wilkes et al., "Glacier Retreat Reorganises River Habitats Leaving Refugia for Alpine Invertebrate Biodiversity Poorly Protected," *Nature Ecology and Evolution* 7 (2023): 841–51, https://doi.org/10.1038/s41559-023-02061-5.

[59]Mayumi L. Arimitsu et al., "Influence of Glacier Runoff on Ecosystem Structure in Gulf of Alaska Fjords," *Marine Ecology Progress Series* 560 (2016): 19–40, https://doi.org/10.3354/meps11888.

[60]Although glaciers are not a focus, see Christiana Zenner, *Just Water: Theology, Ethics, and Fresh Water Crises*, rev. edition (Orbis Books, 2018), for a lens on climate justice issues related to water more broadly, one that is rooted in the Catholic ecological thought of Pope Francis's *Laudato Si': On Care for Our Common Home* (Paulist Press, 2015).

[61]Rounce et al., "Global Glacier Change."

[62]Ben Marzeion et al., "Limited Influence of Climate Change Mitigation on Short-Term Glacier Mass Loss," *Nature Climate Change* 8 (2018): 305–8, https://doi.org/10.1038/s41558-018-0093-1.

[63]Net zero means the amount of CO_2 that humans emit into the atmosphere is matched by the amount removed by natural or technological means.

[64]IPCC, *Climate Change 2022: Mitigation of Climate Change*, contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, ed. P.R. Shukla et al. (Cambridge University Press, 2022).

[65]Carey Clouse, "Glacier Blanketing: Two Approaches in the European Alps," *Journal of Landscape Architecture* 17, no. 3 (2022): 70–83, https://doi.org/10.1080/18626033.2022.2195246.

[66]Carey Clouse, "The Himalayan Ice Stupa: Ladakh's Climate-Adaptive Water Cache," *Journal of Architectural Education* 71, no. 2 (2017): 247–51, https://doi.org/10.1080/10464883.2017.1340781.

[67]"'Truly I tell you, whatever you did for one of the least of these brothers and sisters of mine, you did for me'" (Matt. 25:40).

[68]"Blessed is the one
who does not walk in step with the wicked
or stand in the way that sinners take
or sit in the company of mockers" (Ps. 1:1).

[69]For a theological framing of Christ-like ways of responding to climate change, see Gijsbert van den Brink, "King, Priest, Prophet, and Climate Science: Ecological Implications of the Threefold Office," *Perspectives on Science and Christian Faith* 76, no. 3 (2024): 154–64, https://doi.org/10.56315/PSCF12-24vandenBrink. See also Katharine Hayhoe, *Saving Us: A Climate Scientist's Case for Hope and Healing in a Divided World* (Atria/One Signal Publishers, 2021), especially for the role of shared values and relational trust in motivating climate action.

[70]"All the LORD's paths are kindness and truth,
for the keepers of His pact and His precepts" (Ps. 25:10).

[71]See Bosson et al., "Future Emergence."

[72]Kara J. Pitman et al., "Glacier Retreat Creating New Pacific Salmon Habitat in Western North America," *Nature Communications* 12 (2021): 6816, https://doi.org/10.1038/s41467-021-26897-2.

[73]Examples of popular glacier tourism sites include Athabasca Glacier in Alberta, Canada, and Bashui Glacier No. 1 in Yunnan, China, which have attracted millions of visitors, as well as cruise ships visiting Glacier Bay National Park in Alaska, USA.

[74]See, for example, Lisa Baril, *The Age of Melt: What Glaciers, Ice Mummies, and Ancient Artifacts Teach Us About Climate Change* (Timber Press, 2024).

[75]Romans 8:22–23.

[76]Steve P. Schilling et al., "Posteruption Glacier Development Within the Crater of Mount St. Helens, Washington, USA," *Quaternary Research* 61 (2004): 325–29.

[77]"Human beings are God's created co-creators whose purpose is to be the agency, acting in freedom, to birth the future that is most wholesome for the nature that has birthed us" from Philip Hefner, *The Human Factor: Evolution, Culture, and Religion* (Fortress Press, 1993), 27.