This is an Accepted Manuscript for *Journal of Glaciology*. Subject to change during the editing and production process.

DOI: 10.1017/jog.2024.29

For whom and by whom is glaciology?

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ABSTRACT. Glacier and ice sheet research is frequently justified on the basis of potential benefits to those communities that are most vulnerable to glacier change. In this glaciology research, funding priorities and communication to the broader public are strongly affected by the experiences and values of glaciology researchers. Using population data and newly available survey data from research organizations including glaciologists, we show that there is a substantial misalignment between the demographics of those who stand to benefit from glaciological research and those who produce glaciological knowledge. We discuss the potential negative consequences of this misalignment, which causes scientific research to be less effective, valuable and usable for communities. We conclude by outlining twenty evidence-based strategies that individuals and organizations can adopt to improve the recruitment and retention of a more representative group of scientists in glaciological research and encourage co-production with communities.

INTRODUCTION

The pursuit of glaciological knowledge has multiple objectives. Many consider it an intrinsically valuable goal to understand the rules that govern the natural world that humans inhabit. Another common justification for the expenditure of public resources on the training and employment of glaciologists is the practical benefit of glaciology research to the broader public. Glaciers and snow near communities provide important benefits in the form of water for drinking and irrigation, habitats for local flora and fauna, and as loci for tourism and culture (Xiao and others, 2015; Cook and others, 2021). Loss of ice from glaciers and ice sheets also contributes to sea level rise and other climate impacts, damaging established infrastructure, homes, and habitats in coastal communities and other locales far from glaciated regions (Moon and others, 2019). For some communities and entire countries, glacier loss and sea level rise are existential threats that will potentially displace entire populations from land that they have historically inhabited.

Despite the centrality of human impacts in justifying glaciological research as an essential scientific pursuit, less attention has been paid to the consideration of two questions: (1) who comprises the communities that stand to benefit from advances in glaciology research? and (2) who comprises the glaciology research community? We start by summarizing a deep body of literature which argues that the composition of scientific research communities is critical in determining what types of research are prioritized, the value of the research to the public, and how the results from research are communicated to the public. We then survey available data on the composition of communities that stand to benefit from glaciology research and the glaciology research community itself. We conclude by suggesting steps towards improving the representation of potentially impacted communities within the glaciology research community through structural changes, recruitment and retention strategies, and co-production. Though throughout we focus on glaciology research and communities affected by glacier and ice sheet change, we emphasize here that many of the same arguments can be applied more broadly within the cryospheric sciences, including those communities affected by sea ice and snow loss.

WHY DO THE DEMOGRAPHICS OF RESEARCH COMMUNITIES MATTER?

The alignment between communities that conduct scientific research and those that stand to benefit from the research is important for a variety of reasons. According to "Standpoint Theory", a longstanding branch of the philosophy of science, knowledge is informed by the social, cultural, and political positions within which the knowledge was created (Crasnow, 2013). Standpoint theory is one form of the "social constructivist" view of science (e.g., as argued by Thomas Kuhn, Bruno Latour and others; Kuhn, 1962; Latour and Woolgar, 1979) that development of knowledge is, at least partly, determined by social forces within society and scientific communities. Therefore, the knowledge itself is not borne solely from an inherent reality, but instead it is dependent upon systems of power and privilege. A fundamental tenet of Standpoint theory is that those who experience intersecting forms of oppression in society have a unique and beneficial perspective that must be accounted for in the generation of scientific questions as well as in the translation of knowledge into practical action (Longino, 1993). This also points to the importance of an intersectional lens in accounting for complex forms of disadvantage and their impact on how individuals and groups experience the social world and contribute to the scientific enterprise (Collins, 1986).

While the social-constructivist view of science is certainly not universally held, we make the more modest claim that patterns of funding, citation, and acclaim (awards, conference/seminar invitations, solicited manuscripts, etc.) determine the types of scientific questions that receive the most attention with research communities. Indeed, many studies have shown that the cultural and personal values and lived experiences of researchers play a strong role in determining which research topics are prioritized for funding and in requests for funding (Karlsson and others, 2007; Nash, 2022). These value systems are informed, in part, by the manner in which researchers come to understand the risks faced by communities on the front lines of environmental change and how these risks intersect with other social, economic, and governance issues outside of the traditional purview of physical science (Miller, 2013). Due to differences in local values and less availability of research funding, environmental researchers from communities most affected by climate change are more likely to prioritize issues of social, economic and inter-general inequity when formulating research questions (International Development Research Centre, 1991; Agarwal and others, 1992). Thus, the current set of glaciological research priorities are informed at least as much by who is doing the research as by their likely impact on those communities most affected by glacier change.

Imposing the values of “outside” researchers on communities affected by glacier and sea level change can be considered a form of “scientific colonialism” if research questions and methods have not been designed in concert with communities or by scientists with lived experiences of the complex issues at stake in communities. Indeed, historically, many large governmental investments into field-based glaciological research have served national priorities around colonization, exploration, resource extraction, and projection of military power (Bloom, 1993; Dodds and Nuttall, 2016). These past priorities continue to influence research through the location of research installations and logistical capabilities. As discussed above, the value of glaciers to local communities is highly variable and depends on socioeconomic vulnerability and local political and cultural contexts. However, research priorities do not necessarily follow this vulnerability. For example, Taylor and others (2023) find that regions with the highest vulnerability to glacial lake outburst floods are the least studied, and those with the lowest vulnerability are the most studied. When research planning, funding and execution are all carried out by scientists and funding agencies with no lived experience in the communities that may benefit from the knowledge, this context is often not incorporated

https://doi.org/10.1017/jog.2024.29 Published online by Cambridge University Press

into the scientific process.

Studies show that the most effective forms of science communication to the public are informed by the lived experiences of the communities most impacted by the issues under examination (Davies and others, 2019; Kearns, 2021). Thus, glaciologists from those most affected communities (or similar communities) are likely to be more effective in communicating knowledge developed from glaciology research through the power of personal anecdotes and by virtue of being a “trusted source” for these communities. For these same reasons, such local glaciologists can also be effective intermediaries in designing research projects. Furthermore, studies have shown that locally generated data facilitates the provision of contextually relevant advice by local experts and increases the likelihood that local governments acknowledge the existence and magnitude of environmental change (Karlsson and others, 2007; Pasgaard and others, 2015). Thus, when researchers from distant institutions communicate about research implications to local communities without prior input or context from community members, local knowledge gain and action are less likely.

There is a substantial body of quantitative evidence indicating that more diverse teams, across a wide range of contexts (within science and elsewhere), are more effective at solving problems, innovating, and making predictions (all skills which are particularly relevant to glaciology; AlShebli and others, 2018; Page, 2019). In particular, scientific research teams that are diverse across a wide range of dimensions tend to be more productive in producing well-cited publications when intra-team communication and sensitivity are actively taught and practiced (Adams, 2013; Cheruvelil and others, 2014). Of particular relevance to scientific research that is intended for use by communities, knowledge produced by a more diverse and representative population increases the value of that knowledge because it can be used in a wider range of contexts and by a wider range of people (Forero-Pineda and Jaramillo-Salazar, 2002).

Finally, a simple fact of geography is that those who live near glaciers or in coastal areas stand to lose the most, in terms of resources and cultural heritage, due to glacier loss. As the population with the most at stake, it stands to reason that these communities should have a voice in determining which scientific questions about these potential losses are prioritized and how research on these problems is carried out. Such communities can be a part of this decision making either by producing scientists who work on these problems or by being valued partners in the design and execution of research. In sum, an overwhelming body of researched evidence emphasizes the development of diverse research teams that are representative of the broader population that they seek to benefit through production of new knowledge is critical to the success of research and usability of this new knowledge. In the following two sections, we focus on the

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extent to which glaciology researchers in particular are representative of the communities that stand to benefit from glaciological research.

FOR WHOM IS GLACIOLOGY?

Glaciological change directly affects two populations: communities near or directly downstream of glaciers and more distant communities at risk from sea level rise and other climate impacts. The character of these impacts is varied and goes far beyond the most commonly cited risks of water scarcity (Immerzeel and others, 2020; Clason and others, 2023) and coastal inundation (Kulp and Strauss, 2019). In glacier-proximal regions, glaciers play an important role in natural hazards, ecosystems, agriculture, hydropower generation, tourism, and culture (Carey and others, 2017). In coastal regions, sea level rise from glacier melt can cause disruptive impacts before complete inundation occurs, including saltwater intrusion into aquifers (Werner and Simmons, 2009), shifts in property values (Keenan and others, 2018), increasing insurance premiums (Eaves and others, 2023), reduced efficacy of coastal protection structures (Nunn and others, 2021), and community isolation from critical services (Logan and others, 2023), among many others. Populations affected by these impacts can be identified by their geographic distribution, and their demographic characteristics can be quantified. Their geographic and demographic characteristics can then be compared to those of researchers studying the impacts of glacier and ice sheet change. Understanding the intersection of geographic, demographic, and (where possible) cultural identities is critical in understanding how the potential harms of glacier change on communities may be compounded by economic, political, colonial, and cultural forms of oppression (Goodrich and others, 2019; Versey, 2021). The current state of demographic data for communities vulnerable to glacier change make it difficult to understand intersectionality or complex disadvantage (that is, disadvantages across multiple domains, such as discrimination, poverty, disability, etc. Crenshaw, 1990), and so we have endeavoured to survey the available information in this study.

Populations that are likely to be affected by glacier and ice sheet change are distributed over a geographically diverse range. One-third of humans worldwide reside in hydrological drainage basins which depend on glacier runoff for some of their drinking and irrigation water supply (Huss and Hock, 2018; Immerzeel and others, 2020). Most of this population is concentrated in relatively few highly populated regions downstream of high-altitude heavily glacierized watersheds, including: High-Mountain Asia (e.g., India, Pakistan, China and Nepal) and the Southern Andes (e.g., Peru, Bolivia, Chile, and Argentina).

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Glacier-proximal communities in, for example, Canada, Alaska, East Africa, Iceland and the European Alps are also likely to be significantly affected by glacier changes through a loss of cultural heritage, hydropower resources, and tourism. In many regions, particularly in the Arctic and sub-Arctic, substantial indigenous communities have already experienced considerable negative effects of changes in the cryosphere, including glacier, sea ice and permafrost loss. However, specific demographic statistics quantifying the scale of impacts to indigenous communities are challenging to quantify due to the widely varying definition of "indigenous" between countries and poor census coverage in remote regions (Monitoring and Program, 2021).

Beyond geographic distribution, there have been few systematic studies published that focus on the demographic characteristics (i.e., gender, race/ethnicity, social class) of the population living in glacier-proximal or glacier-dependent regions globally or in specific regions. Taylor and others (2023) studied the social and economic vulnerability of communities exposed to risk from glacial lake outburst floods, finding substantial risk to communities with limited resources in High-Mountain Asia and the Southern Andes. Here, we use demographic data derived from the United States (US) Census to estimate the demographics of communities that are vulnerable to glaciological changes. For consistency with other US-oriented demographic studies and associated survey instruments from scientific societies, we use US census terminology to refer to racial and ethnic groups: Hispanic, non-Hispanic Black, non-Hispanic White and other historically excluded groups (mainly including Asian-American, Pacific Islander, and Native American groups). Hereafter, we refer to "White" and "Black" to mean non-Hispanic members of those racial and ethnic groups. Additionally, the term "historically excluded groups" is used throughout to signify those groups that have been excluded from participating in scientific research through either explicit or implicit discriminatory practices by government agencies, academic institutions, and scientific societies. Prior studies show that such historically excluded groups are likely to experience greater disruption from environmental changes due to: historical disinvestment in protective measures (Hendricks and Van Zandt, 2021), proximity to potentially mobile toxic chemical pollution (Herreros-Cantis and others, 2020), residential segregation (Handwerger and others, 2021), and lack of adaptive capacity (Marino, 2018). Here, we focus on the US because census data is easily accessible, interpreted and comparable to statistics from a US-based scientific society (in the next section). However, we note that: (1) racial and ethnic categorizations aggregate groups together in ways that do not always align with how people in these groups self-identify (Maghbouleh and others, 2022), and (2) there is substantial variation in the history of exclusionary practices and

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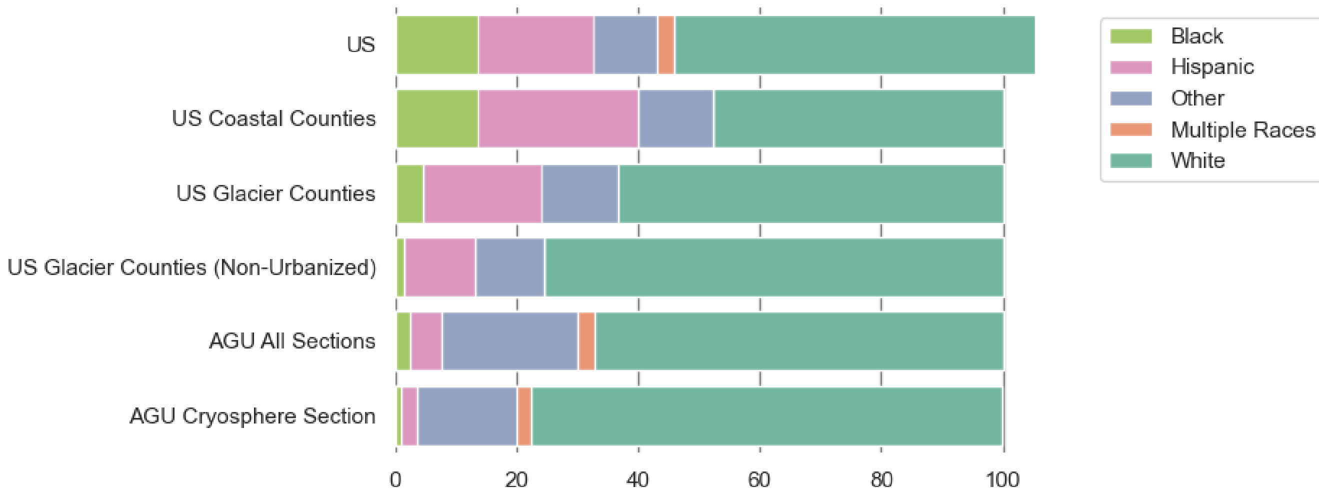

Fig. 1. Racial and ethnic composition of (top to bottom) the US population in 2020, US counties with an ocean coastline in 2020, US counties with a RGI-registered glacier in 2020, US counties with a RGI-registered glacier and less than 100,000 residents in 2020, all sections of the American Geophysical Union in 2022, and just the Cryosphere Section. The US Census requires those listing "multiple races" (approximately 2%) to also specify at least one race, and so the US total is above 100%. County-based data is based on estimates for 2020 based on 2016 US census data (Hauer, 2019). Data for AGU provided by AGU staff and provided in aggregate form in supplementary material.

self-identification of race and ethnicity between the US and other countries (Bulmer, 2016). These caveats should be accounted for when interpreting the data presented in the remainder of this analysis.

We start by using the census-based population estimates of Hauer (2019) to determine the aggregate demographic characteristics of US counties with at least one existing glacier (according to the RGI standard for classification, Pfeffer and others, 2014). Figure 1 shows the aggregate race and ethnicity of residents of these counties using 2020 US census data (labeled as "US Glacier Counties"), noting that this population is primarily from a few high-population counties, encompassing parts of Seattle, Fresno and Portland. Compared to the US as a whole, these "glacier counties" include a similar proportion of Hispanic (19.5%) and other historically excluded groups (12.5%), but a lower proportion of Black (4.5%) residents. In "glacier counties" with less than 100,000 residents, the proportion of all historically excluded groups is lower yet, in line with the known demographic makeup of rural counties throughout the Mountain West and Pacific Northwest. These are compared to the US population as a whole (top bar), which has total population greater than 100% because the US Census requires those listing "multiple races" to also specify at least one race.

Different classification schemes may be used to analyze the population that is exposed to sea level rise.

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Hauer and others (2022) aggregated the current demographics of US coastal counties and coastal counties by vulnerability to sea level rise, and also projected how these demographics would change over the 21st century. The Furman Center (Yager and Rosoff, 2017) analyzed the population of US census tracts in floodplains, which includes both coastal communities and inland communities (which may also be affected by sea level rise through increased river flooding; Bates and others, 2021). Hauer and others (2022) found that the population of US coastal communities (see "US Coastal Counties" in Figure 1) is more racially and culturally diverse compared to the US population overall, and that the counties most vulnerable to sea level rise (i.e., coastal and low-lying) are more diverse still. This disparity is projected to continue or widen in the future as the population of Hispanic and other historically excluded groups grows both in the US and in coastal counties exposed to sea level rise. The Furman report (Yager and Rosoff, 2017) similarly found that census tracts in the combined US floodplain (100-year and 500-year floodplains using FEMA definitions) includes a greater proportion of Asian and Hispanic populations and moderate/high poverty communities than in non-floodplain regions. Future work could consider smaller political units (e.g., census tracts in the US) and populations outside the US to make this analysis a more accurate representation of communities vulnerable to glaciological change.

Global analyses have generally focused on the geographic distribution of populations vulnerable to sea level rise. Kulp and Strauss (2019) found that more than 70% of the total global population vulnerable to inundation from sea level rise in the 21st century are in eight Asian countries: China, Bangladesh, India, Vietnam, Indonesia, Thailand, the Philippines, and Japan. Most of the remaining vulnerable coastal populations are spread among the Middle East (Egypt, Iraq), Africa (Nigeria, Senegal), North America (US, see above discussion) and Europe (Netherlands, UK and Germany). Small Island States, while low in population compared to the aforementioned countries, are particularly vulnerable due to the large proportion of their population exposed to sea level rise (Thomas and Benjamin, 2018). For these countries, sea level rise is an existential threat to their continued existence on land that holds historical and cultural importance to indigenous communities (Storlazzi and others, 2015).

Analyses of coastal and glacier-proximal communities suggest that the gender composition in communities most vulnerable to glacier and ice sheet change is not statistically different from the broader population. Studies of adaptation and glacier hazards in High Mountain Asia indicate that vulnerability to these hazards is inextricable from gender (Goodrich and others, 2019) and in organizations where women are excluded from planning activities important gendered context is missing (Shrestha and oth-

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ers, 2016). Furthermore, anthropological research shows that women and non-binary community members actively engage in research that provides localized information about glaciers and coastal change. This knowledge is enhanced by their time spent managing glacier-dependent livestock and agriculture (Bolin, 2009; Dunbar and Marcos, 2012; Carey and others, 2016; Caine, 2021) and communal water supply (Drew, 2012; Christmann and Aw-Hassan, 2015). Such knowledge is typically not included in externally produced global assessments, which are likely to be less effective as a result (Williams and Golovnev, 2015; Carey and others, 2016; Caine, 2021).

BY WHOM IS GLACIOLOGY?

As argued above, the value systems of those participating in research are an important determinant of how knowledge is produced and which research questions are prioritized (Collins, 1986; Crasnow, 2013). Some glaciologists may be motivated by a desire for uncovering fundamental knowledge about the natural world, but are still strongly incentivized to justify potential public allocation of resources to their research on the basis of potential return to the public. Researchers may have deep lived experiences of these risks, or they may have come to know risks by working and communicating directly with affected communities, or as an outside observer (through field work or remote sensing) in the course of their science, or with limited connection to conditions in particular locations (e.g., model, laboratory or mathematical approaches). To best understand how these experiences inform the production of glaciological knowledge, we must first understand who designs and carries out glaciological research.

There are some prior studies on the gender composition of the glaciological community. Recent surveys indicate that women comprise: 34% of members affiliated with the Cryosphere section of the American Geophysical Union (AGU - the largest scientific society representing the geosciences broadly in the United States) in 2022, 39% of the British Antarctic Survey (BAS), which includes many scientists working on non-glaciological topics (British Antarctica Survey, 2021), and 41% of scientists participating in the International Thwaites Glacier Collaboration (Karplus and others, 2023). The 2022 AGU survey was recently broadened to include a “nonbinary umbrella” survey option, which made up 0.6% of the Cryosphere section. The AGU survey also indicates a slowly increasing trend over the past decade as compared to a prior AGU survey (2015) in which 27% of Cryosphere section members were women. Where demographic statistics are available by career stage, the gender distribution is closer to even among early-career than among later-career scientists (Koenig and others, 2016), reflecting a widely observed trend of higher attrition rates

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among women than men across career stage in the US (Ranganathan and others, 2021). Similar underrepresentation of women in glaciology and polar science has been found among authors of published papers in the *Journal of Glaciology* and *Annals of Glaciology* (approximately 16% of all authors in 2009; Hulbe and others, 2010), editorship of cryosphere journals (about 33% of *Journal of Glaciology* editors were women in 2019, the first female IGS Chief Editor in 72 years was appointed in 2019 and the first for The Cryosphere was appointed in 2020; Jiskoot, 2019), grants awards by the US National Science Foundation Office of Polar Programs (24% of PIs and co-PIs from 2007-2009; National Research Council and others, 2012), PIs and co-PIs involved in the International Thwaites Glacier Collaboration (16% in 2023; Karplus and others, 2023), and awards for senior glaciologists in the Cryosphere section of the American Geophysical Union (AGU) (14% of Nye Lecturers, 5% of Cryosphere AGU Fellows in 2016; Koenig and others, 2016).

The geographic distribution of recently active glaciologists can also be inferred from publications. Scopus lists 2215 studies published between 1993 and 2023 that include the terms "'sea-level rise" and "glacier" or "ice sheet" in their abstracts. Of those, more than half (62%, 1371 studies total) had author affiliations in the USA or UK. More than 75% (1729 studies) had author affiliations in one of six countries: the USA, the UK, Germany, the Netherlands, France, or Canada. Additionally, all of the glacier and ice sheet modeling groups participating in recent voluntary community efforts to project ice sheet contributions to sea level rise (Seroussi and others, 2020; Goelzer and others, 2020) originate in North America, Western Europe or Japan. A recent survey of attendees to the virtual Global Seminar Series of the IGS (Murray and others, 2021) finds that 49% were based in Europe, 39% in North America, 5% in Asia, 4% in Australia/Oceania, 2% in South America and 0.6% from Africa or the Arctic. All of these statistics indicate that on the basis of both individual participation and publications, a substantial majority ($> 85\%$) of current glaciological research is conducted in Europe and North America.

As noted in the previous section, a complete analysis of those performing and potentially benefiting from glaciological research requires an "intersectional" lens, which acknowledges the overlapping identities and complex forms of disadvantage that inform communities' vulnerability to glacier change (Versey, 2021) and barriers to advancement within the scientific community (Seag and others, 2020). Unfortunately, beyond gender, there is very little data available in the published literature on the demographic composition of glaciologists, internationally, though surveys of smaller groups within the glaciology community exist. The same demographic survey of BAS employees cited above (British Antarctica Survey, 2021) also found that just 3% of BAS employees were from Black, Asian and Minority Ethnic (BAME) backgrounds, as

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compared to the 16% of the total UK population, and 16% of "UK Higher Education STEM" population from this classification group. A 2023 demographic survey of 76 participants in the International Thwaites Glacier Collaboration (composed of glaciologists based in the US and UK) indicates that 84% of respondents identify as "White/Caucasian", 7% identify as "Asian", and 8% identify as any of "Pacific Islander, Indigenous, Native American, Black, African, African-American" (Karplus and others, 2023). The same IGS Global Seminar survey (Murray and others, 2021) found that among respondents 14.3% identified as any of BIPOC (Black or Indigenous or Person of Colour), BAME, or Underrepresented Minority. The fraction of students participating in this survey (25%) appears to be comparable to the fraction of students (24%) comprising the AGU Cryosphere section in 2022.

Since 2014, AGU has been asking members renewing their membership to voluntarily provide information on their race and ethnicity, in addition to long-standing survey questions on gender, nationality and career stage. Adding this information to their existing survey provides an intersectional lens through which to investigate who comprises the membership of AGU (compared to prior data gathering which has focused on gender) and potential biases within sections. Figure 1 shows self-identified race and ethnicity of US-based members of the AGU cryosphere section in 2022, that has not previously been publicly available (upon request, it was provided to the authors by AGU staff). For ease of comparison, we have regrouped the survey categories to correspond to US census classifications (Hauer, 2019) and omitted respondents who did not specify any race or ethnicity or listed "unknown". The fraction of respondents in the latter two categories is non-trivial (9.4% and 4.3%, respectively). However, they are within the range of such classifications in other surveys (Ford and others, 2020), which suggest that they are not likely to qualitatively influence the conclusions drawn here (Moreno and others, 2005). Full survey statistics with original categories used in the survey are available in the supplementary material.

Among US-based members of the AGU Cryosphere section, White respondents comprise 77%, Hispanic respondents comprise 3%, respondents listing "Multiple Races" make up approximately 3%, and Black respondents comprise approximately 1% of all included respondents. The "other" category, composing 16% of respondents, includes categories of: "Asian or Asian American", "Indigenous Peoples", "Middle Eastern or North African", "Native of Indian subcontinent", and "Not listed". Of these categories, the largest fraction of respondents are from "Asian or Asian American" (10%) and "Not listed" (4%). It should be noted that among the anonymized text responses among "Not listed", a small fraction of respondents (<1% of total) have listed a race or ethnicity that is, under US census definitions, one of the listed categories.

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For this survey, the most comparable grouping to the BIPOC, BAME or "underrepresented minority" classifications used in the BAS and IGS surveys includes all race/ethnicity categories except "White, Euro-American, or European" or other not specified in the included AGU respondents. This group comprises 22.4% of the total survey group. However, it is important to note the limitations discussed in the previous section in aggregating race and ethnicity across groups which do not always self-identify as members of the same group, and also comparing self-identification across nationalities where labels for groups may differ. We follow the available survey instruments in their use of specific terminology (BAME for the UK-based IGS and BIPOC and related US Census classifications for US-based AGU) because the design of these surveys makes it challenging to disaggregate these groups for the purpose of comparison. Future surveys of glaciologists would also benefit from a design that allows such cross-national comparison by systematically surveying across a more international group (e.g., IGS or IACS membership) and an intersectional analysis of participants by allowing multiple selections and self-identification.

In 2022, White members comprised 68% of students in the AGU Cryosphere section, Hispanic student members comprised nearly 5%, respondents listing "Multiple Races" make up 4.6%, Black respondents comprised 1.9%, and other historically excluded groups comprised the remaining 20% (with the largest two groups again being "Asian or Asian American" at 11% and "Not listed" at 5%). Comparing to the above statistics, we find that the fraction of AGU Cryosphere members from historically excluded groups decreases from early to more senior career stages. This pattern is common throughout the sciences, and indicates that there are issues both in recruiting students into glaciology at undergraduate and graduate levels, and also retention within science.

Prior studies have identified underrepresentation of historically excluded groups as a problem across the geosciences (Bernard and Cooperdock, 2018). To determine the extent to which the AGU cryosphere section reflects broader demographic composition across AGU, it is instructive to compare section-level data to all sections where data are gathered using the same methodology. Figure 1 (row 5) also plots 2022 data for all AGU section across all career levels (again omitting respondents who did not specify any race or ethnicity or listed "unknown"). Across all AGU sections, White respondents comprised 67%, Hispanic respondents comprised 5%, respondents listing "Multiple Races" comprised 2.7%, Black respondents comprised approximately 2.4%, and other historically excluded groups comprised the remaining 22% (with the largest two groups again being "Asian or Asian American" at 14% and "Not listed" at 6.5%). This comparison indicates that the AGU cryosphere section includes proportionally fewer members from historically

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excluded groups than AGU as a whole, which is itself already unrepresentative of the US population.

All of these survey statistics point to a single conclusion: there is a stark difference between the geographic, racial, and ethnic composition of those who are vulnerable to the effects of glacier and ice sheet change (rows 2-4 in Figure 1) and those who conduct research on glacier and ice sheets as represented in the BAS, IGS and AGU surveys (row 6 in Figure 1). Statistical measures gathered by scientific societies or organizations based in the US, UK and Europe (even those which are nominally "international") may introduce geographic bias into these demographic measures. Nevertheless, these potential biases cannot explain the lack of representation among glaciologists of vulnerable communities from within their own countries. This points to a clear need for more robust efforts to expand the glaciological research community by including more scientists from highly exposed regions in Asia, Africa and South America and from affected communities in North America and Europe. As discussed in this and the previous section, the former group are disproportionately exposed to glacier and sea level change (Huss and Hock, 2018; Kulp and Strauss, 2019), but are poorly represented in the international glaciological research community. In the next section, we suggest steps to remedy this misalignment going forward.

STEPS FORWARD

Many of the structural barriers to diversification of the glaciological workforce are rooted in broader problems within the geosciences, where scientists from historically excluded groups are also underrepresented relative to the broader population and even other scientific fields (Bernard and Cooperdock, 2018). Widespread exclusionary behavior has been identified as a key cause of the lack of representation in geosciences, including: harassment (sexual and otherwise), exclusion from professional opportunities, and lack of mentorship and role models (Nash and Nielsen, 2020; Berhe and others, 2022). However, as we have shown above, underrepresentation of historically excluded groups is more pronounced in glaciology than in the geosciences as a whole. In recent years, many prominent examples of exclusionary acts have been brought to the fore of glaciology in particular, including: documented exclusion, harassment and bullying throughout Antarctic field programs (Nash, 2021; US Antarctic Program, 2022; Langin, 2023); poor gender and racial representation among AGU Cryosphere award nominees (Koenig and others, 2016); and highly public questioning of policies enacted to promote diversity in virtual scientific community spaces (e.g., Cryolist, AGU Connect). Additionally, a systematic review of responses by National Antarctic field programs to pervasive harassment and bullying in field settings has shown few explicit or structural changes

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to field manuals or programmatic policies (Nash, 2021). Until these structural issues are resolved, efforts to recruit and retain scientists from underrepresented communities are unlikely to yield success. Achievement of such improvements is fundamentally a matter of ensuring that scientific working environments are physically and psycho-socially safe for all participants. Indeed, prior efforts to improve the gender diversity of academic faculty in geosciences and nominees for cryosphere awards have had limited success due to continued structural barriers towards the advancement and recognition of women and non-binary scientists within research institutions (Ranganathan and others, 2021) and scientific societies (Koenig and others, 2016; Harvey, 2021). In the remainder of this section, we suggest steps (numbered and illustrated in Figure 2) that can be undertaken by individuals and organizations that hope to improve the representation of communities affected by glacier and ice sheet loss in the glaciology research community. This list is not meant to be exhaustive, but rather summarizes a substantial literature on evidence-based strategies for improving diversity in science.

The first step to improving the representation of communities affected by glacier and ice sheet change within glaciology is to change the culture of glaciology in the institutions where glaciological research is performed and at the community level through scientific societies (IGS, IACS, AGU, EGU, etc.). Organizational policies towards bullying and harassment that are focused on legal compliance have been shown to be unsuccessful at reducing bullying and harassment (National Academies of Sciences, Engineering, and Medicine, 2018). Fortunately, the literature on bullying and harassment in academic and research settings has clear messages about how to effectively reduce such misconduct. Cultural change within organizations requires moving beyond the focus on mitigating risk and harm from harassment to a model of proactive prevention by eliminating the conditions under which harassment occurs. First, evidence shows that organizational cultures should train leaders (including faculty at universities) on effective methods for deterring harassment and other exclusionary behaviors (S1) to set an example for members of organizations and reduce the incidence of harassment within organizations (Gruber, 1998). Second, diffusing power and organizational values among members reduces the likelihood that inappropriate behavior will persist out of view of leaders and supervisors within organizations (S2) (Nelson and others, 2017). Third, transparency and accountability are promoted when policies (e.g., conference and organization codes of conduct, research group guidelines) are easy to understand and provide clear, escalating consequences for violation, and reasonable time frames for investigation of allegations (S3; Buchanan and others, 2014; Euben and Lee, 2005).

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Fig. 2. Illustration of selected strategies for increasing diversity in glaciology, created by TreVaughn Ellis.

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In addition to the lack of geographic and racial diversity across career levels within glaciology, there is little diversity amongst those entering glaciological studies. This suggests that the glaciology community needs to change how it recruits students into glaciological research and how it conducts outreach to younger students. This may take the form of initiating new efforts, and also refocusing existing outreach and training efforts towards reaching communities most affected by glacier and ice sheet change. Evidence from other scientific disciplines indicates that many students from the secondary through graduate level, and particularly those from historically excluded groups, are drawn to scientific research by the potential to produce knowledge that can directly help solve problems in their own communities (Thoman and others, 2015; McGee, 2016). The same is true in geosciences in particular (and presumably glaciology, though specific evidence is lacking in the literature), where students identifying as underrepresented gender or ethnic minorities rate "helping people/society/environment" as the most important factor in picking an "ideal" career (Carter and others, 2021). Such altruistic motives for pursuing careers in the geosciences are also strongly linked to childhood experiences with nature and outdoor activities (Broom, 2017), which are disproportionately inaccessible to historically excluded groups as a whole, though significant variations exist between subgroups depending on geographic distribution and economic circumstance (Chavez and others, 2008).

To capitalize on the potential usability of glaciological knowledge, efforts to provide a wider range of research "on-ramps" into glaciology research groups (S4), even those that are not squarely within the traditional area of focus for a research mentor, can attract potential glaciologists with a more diverse range of motivations than those traditionally pursuing glaciological research as a career (Chaudhary and Berhe, 2020). Another potentially effective action is to provide incentives for students to participate or lead community outreach and engagement through fellowships, awards, and programmatic policies that consider outreach on the same level as PhD research (S5; Bernard and Cooperdock, 2018). Additionally, organizations can support sustained outreach programs that provide support for repeated contact over months or years between scientists and the same group of young students (S6), which have been shown to be more effective than one-time efforts (Shepherd and others, 2020).

There are several established programs, such as the Inspiring Girls Expeditions, Juneau Icefield Research Program (JIRP), and Research Experiences for Undergraduates (REU), which aim to introduce students below the graduate level to glaciers and glaciology research. Inspiring Girls Expeditions, focused on secondary school students, pay strong attention to inclusion and equity in their programs by being fully

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tuition free, providing most travel costs and equipment, and selecting teams that are diverse across many dimensions (Carsten Conner and others, 2018; Young and others, 2020). JIRP serves a mainly undergraduate student audience, providing experience in glaciological field work and research. JIRP has successfully launched many undergraduate students into careers in glaciological research, but also had a variable tuition level for participating undergraduates over its nearly 70-year history. Recent funding shortfalls have made access to this program a challenge for students without personal access to funding for field programs. Across sciences and engineering disciplines, REU programs provide paid research internships for undergraduates at universities and laboratories in the US, with variable efficacy in connecting students from historically excluded groups to research and preparing them for graduate studies (Ahmad and Al-Thani, 2022).

Longstanding summer-school programs for graduate students, including those in Karthaus, McCarthy, and Chile, play an important role in helping students develop community and connection within the glaciological research community and beyond their own institutions, which can play an important role in their persistence within careers in glaciological research. Funding agencies and scientific societies could reduce barriers to entry for such introductory glaciology programs by increasing funding for scholarships and more competitive stipends for REU programs (S7) (comparable to internships in industry). Additionally, these introductory programs can distribute advertising more widely, and adopt more inclusive admissions processes (S8) from programs like Inspiring Girls to improve the diversity of students entering these programs. Providing opportunities for visiting glaciological field sites (S9) without participants needing to provide their own field equipment (i.e., through community repositories that lend field equipment and apparel free-of-charge) and through experiences that are approachable to potential participants without any prior hiking or camping experience, may increase the accessibility of field-based on-ramps to those from historically excluded groups. Organizations and programs within the glaciology research community do provide funding support to graduate summer schools. However, the continued lack of diversity, even among early-career glaciologists, indicates the need for more aggressive and focused funding efforts to improve the diversity of these programs, in addition to more extensive recruiting efforts aimed at undergraduate and high school students.

Mentorship programs for early career scientists from historically excluded groups have recently been developed through organizations that support glaciologists, including Polar Impact and AGU. However, in fields such as glaciology, where there are very few potential mentors in senior roles from historically excluded groups, developing effective mentorship programs can place a disproportionate burden on the few senior scientists who are willing to devote (typically uncompensated) time to mentoring activities (Hirshfield and Joseph, 2012). In such circumstances, mentoring between those at a similar career level has been shown to be highly effective, particularly when organized around developing specific technical, professional or leadership skills (Johannessen, 2016; Dickson and others, 2021). In recent years, several groups in glaciology and the geosciences more broadly, have had initial success focusing on such peer mentoring programs, including the IGS Early-Career Glaciologists Group (EGG), the aforementioned Polar Impact program, Polar Pride, and the Code-to-Communicate initiative of the international GeoLatinas group. Organizational, administrative and financial support for peer-mentorship groups to lead events at conferences or on their own (S10) is another way that scientific societies can support the diversification of glaciology among early career researchers.

Academic institutions with glaciology research groups can take steps to attract prospective students from historically excluded groups into glaciology, including offering targeted fellowships (S11), using the Masters Degree as a pathway to the PhD (S12), engaging with Bridge-to-PhD Programs (S13) like those administered by AGU, and developing recruitment partnerships with minority-serving institutions (S14). All academic institutions can hire glaciologists from historically excluded groups into permanent faculty positions with the appropriate resources to recruit and retain graduate students and introduce undergraduates to glaciological research (S15). Additionally, promoting a wider range of career pathways beyond academic faculty positions, including long-term positions focused on research, outreach, or translation of glaciological research into actionable information (S16; e.g.,cooperative extension or CAP/RISA programs in the US) can retain more glaciologists with a diverse array of motivations within our discipline. Increasing the security, prestige and prevalence of such non-academic positions also increases the likelihood that glaciologists can find positions in proximity to support networks and family members, which are important factors in retaining those from historically excluded groups within the glaciology community (McGee and others, 2021).

Scientific societies could choose to provide specific funding for undergraduate and graduate students from historically excluded groups to attend conferences and summer school programs, including financial and administrative support for obtaining appropriate visas for travel (S17). These societies could also choose to provide more substantial funding to send large cohorts of glaciologists across different career stages to conferences and events specifically catering to students from historically excluded groups (S18), such as (in the US) the Society for Advancement of Chicanos/Hispanics and Native Americans in Science

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(SACNAS) and the National Association of Black Geoscientists (NABG). These efforts would require provision of funds available to organizations putting on conferences either by redirecting funds from other organizational activities, raising fees for publications and conferences, or applying for funding for such programs from funding agencies at the national level. Though there are trade-offs to any such efforts to raise funding, we strongly argue that the current lack of diversity within glaciological research merits an aggressive and focused response from our community and structures within it.

Beyond taking steps to diversify the research workforce, glaciology groups can align research with the priorities of communities vulnerable to glaciological change by working with them directly through iterative "co-production" of knowledge or by coordinating with "science intermediaries" (S19) (Dilling and Lemos, 2011; Beier and others, 2017; Ultee and others, 2018). Disseminating expertise and training across national boundaries could also be accomplished through increasing support for bi-lateral research exchanges by funding agencies, including funded coordination efforts by organization such as International Centre for Integrated Mountain Development (ICIMOD; S20). We anticipate that collaboration with practitioners in communities near glaciers and coastlines will be necessary even as the glaciology workforce becomes more diverse, for two main reasons. First, adaptation decision-making is very localized, such that a glaciologist from one community may have direct personal experience of concerns faced by another community, but they could not be expected to have a full understanding of the decision landscape in that community. Second, it is unjust to recruit members of historically excluded groups into the discipline with the expectation that they take on responsibilities greater than those of their colleagues from historically over-represented groups, or that they engage in research and activities that are prized by the current majority-dominated system (Hirshfield and Joseph, 2012). There have been successful efforts working with indigenous communities to co-produce research on sea ice in Alaska (Mahoney and others, 2021), and on snowpack in the Chilean Andes (MacDonell and others, 2022). However, developing meaningful relationships with communities affected by glacier and sea level change takes time and commitment, often beyond the typical time scales associated with research grants and career advancement within university or laboratory settings. Initial efforts to promote co-production through research enterprises such as the "Navigating the New Arctic" program at the US National Science Foundation required substantial reworking after indigenous community groups reported that "true collaboration had not occured" along the lines of NSF objectives (Stone, 2020; Carey and Moulton, 2023). It falls to all members of the glaciology research community to ensure that the needs of communities affected by glaciological change are reflected in the research they conduct.

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Finally, viewing concerns of glacier change in a broader context is a necessary step in connecting glaciology research with community needs. These issues are exacerbated by colonialism, economic and racial inequities, and other socioeconomic issues. Describing glacier change and sea-level rise as solely a physical threat to communities can conceal the socioeconomic issues that exacerbate the risks posed by climate change. Many studies describe the long history of adaptation to climate changes in Arctic communities through technological development and mobility (Cruikshank, 2001; Ford and Smit, 2004; Holm, 2010; Eicken, 2010; Buijs, 2010; Eerkes-Medrano and Huntington, 2021). This mobility has been affected by colonialism (for example, the movement of Inuit communities from mobile to fixed settlements in the 20th Century; Ford and Smit, 2004). This is compounded by economic hardships, suppressed local and traditional knowledge, and related political shifts (Ford and Smit, 2004). Besides being an important reason why scientific research, environmental movements and activism cannot be disentangled from colonialism, this illustrates the importance of deeply understanding the context of the problems glaciologists seek to describe, quantify or potentially contribute to solving. Researching and teaching about climate impacts without incorporating this context leads to an incomplete understanding of the problem as a whole. The question of "what are the impacts of cryosphere change on communities" transcends individual disciplines, and this should shape the way glaciologists teach and research glaciology.

Glaciological researchers occupy an increasingly important role in being capable of generating knowledge that can help billions of people adapt to coming glacier and ice sheet changes. However, until glaciologists critically examine and change their own community, its composition, and its influence on how research is designed, conducted and communicated, they cannot claim that glaciological research is truly useful to the broader public. Glaciologists have all the tools needed to effect such changes. Now is the time to make that change in this necessary scientific endeavour.

ACKNOWLEDGEMENTS

We would like to thank the staff of the American Geophysical Union for sharing anonymized survey data with the author team, and answering many questions about the survey design. We would also like to thank Tavi Murray for discussing the IGS Global Seminar survey with the author team, and Mathew Hauer for providing further context on the analysis of census data. Thanks to TreVaughn Ellis, who was commissioned to illustrate Figure 2. All code used to generate Figure 1 and analyze data is available at a GitHub repository: https://github.com/aarobel/ForWhomByWhomGlaciology.

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