IDP Ice Core Working Group (IDP-ICWG)
Paleoclimate Ice Core Research Priorities in Antarctica

June 4, 2020

A white paper produced as a result of the IDP-ICWG Science Planning Meeting 2020

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Summary

The ice-coring priorities for Antarctica are driven by global-scale questions about the forcing mechanisms of Earth's climate system as well as Antarctic-centric questions concerning how much and how fast Antarctica will contribute to future sea-level rise. Antarctica's unique climate and glaciological settings preserve records of the past atmosphere that can be obtained nowhere else on Earth. Understanding the causes of past climate changes as preserved in the Antarctic ice sheets is a primary research goal across all Antarctic science disciplines (NASEM 2015). The future of the West Antarctic Ice Sheet (WAIS) is of particular concern because irreversible ice loss contributing to sea level rise may already be underway (Joughin et al. 2014, Rignot et al. 2013). Improvements in technology have increased the scientific return from Antarctic ice cores by allowing seasonal-scale determinations of temperature, precipitation, and other climate variables, as well as measurement of microbes, organic carbon, ultra-trace gases, and isotopic composition of greenhouse gases. The purpose of this white paper is to provide community guidance for ice core science occurring in Antarctica over the next 5-10 years, focused on the most pressing scientific questions about Earth's climate.

<u>Antarctic ice coring projects will provide insight into:</u>
Ice sheet stability: Projects will place constraints on the timing, speed, and magnitude of ice loss, as well as the forcing mechanisms. Investigations will include ice-sheet instability during past interglacial periods – analogs for our current and future climate – as well as climate forcing during past centuries and millennia that have set the stage for current mass loss.

Oldest Ice: Antarctica provides the opportunity to recover a continuous "oldest ice" record, extending back more than 1 million years. Investigations will include novel records of past atmospheric greenhouse gases, the Mid-Pleistocene transition when glacial-interglacial cycles of 40 kyr duration shifted to 100 kyr cycles, and climate sensitivity under differing boundary conditions. Both a deep core in the East Antarctic interior

and surface cores from blue-ice areas, preserving multi-million year old ice that has migrated to the surface of the ice sheet, will be targeted.

Glacial-Interglacial Climate Dynamics: Our understanding of the mechanisms driving glacial-interglacial cycles and abrupt climate change remains incomplete. Atmospheric gas records, coupled with mm-scale resolution of trace impurities and isotopes in ice, will allow for testing of different hypotheses of the forcing mechanisms and dynamics of the global climate system.

Driving Scientific Questions

Ice Sheet Stability: The West Antarctic Ice Sheet (WAIS) is expected to contribute substantially to future sea level rise, but the magnitude and speed of these changes is uncertain

1) How rapidly and how extensively did WAIS respond to warming during the Eemian interglacial period, Marine Isotope Stage (MIS) 5e, and other prior interglacials?
2) How have WAIS ice shelves and coastal regions responded to Pacific ocean-atmosphere forcing in recent decades/centuries/millennia?
3) How are modern estimates of sea level rise impacted by uncertainties in firn compaction?

Oldest Ice: Antarctica preserves multi-million year old ice that has been scarcely studied. Advances in technology, including new proxies and improved measurement resolution, will allow for unprecedented examination of Earth's climate system.

1) How does equilibrium climate sensitivity (ocean and air temperature *vs.* CO_2) of the 40 ka world compare to the 100 ka world? What was the relationship between greenhouse gases, aerosols, climate, and sea level?
2) What climate feedbacks explain the 100 ka world transient response, such that 100 ka glacials are colder than 40 ka glacials, yet the temperatures of 100 ka interglacials exceed maximum 40 ka temperatures?

Glacial-Interglacial Climate Dynamics: Observations of past glacial-interglacial cycles provide constraints for understanding natural climate variability, yet very little ice is available for study by US scientists that is older than the middle of last glacial period. New, high-quality ice cores are needed to place modern and past climate variability in context.

1) What drives the initiation and termination of glacial cycles? How are greenhouse gases, biomass burning, ocean circulation, solar, and volcanic forcing interrelated?
2) How does the last glacial cycle differ from prior cycles? Does the lack of a warming hiatus (i.e. Antarctic Cold Reversal) in older glacial terminations contribute to a climate "overshoot" and a warmer interglacial?
3) What was the magnitude, speed, and timing of abrupt climate change events in the earlier part of the last glacial period (~120-78 ka) and older glacial periods, including warming associated with Dansgaard-Oeschger Events and abrupt carbon dioxide and methane increases during deglaciations? What changes in biogeochemical cycles drove the greenhouse gas responses?
4) What processes and mechanisms drive the Earth from an interglacial (warm, high sea level, high CO_2) to a glacial (cold, low sea level, low CO_2).
5) How do anthropogenically driven changes to modern atmospheric chemistry compare to natural variability prior to the industrial revolution?

Scientific Rationale

Ice Sheet Stability: One of the great challenges facing society is how to adapt to rising sea levels that will ultimately displace millions of people from coastal cities. Predictions of the rate and scale of sea level rise are limited by the lack of data from time periods in Earth's past when sea level was higher (e.g. the last interglacial, ~130 ka) and when human activity had not dominated the climate system (e.g. the pre-industrial).

Recent changes: Coastal areas of the WAIS are changing rapidly: Pine Island Glacier (PIG) and Thwaites Glacier (TG) are thinning extensively (Pritchard et al. 2009); upwelling warm Circumpolar Deep Water (CDW) is causing extensive melting beneath the Amundsen Sea ice shelves (Jacobs et al. 2013); sea ice is shifting westward (Cavalieri and Parkinson 2008); and the air temperature across the WAIS has increased (Steig et al. 2009). The climate of the Amundsen Sea region is strongly linked to the tropical Pacific Ocean, and strong El Niño events may have contributed to the onset of current PIG and TG ice shelf retreat (Steig et al. 2012). Atmosphere-ocean modeling suggests a human role in 20th century wind trends which promote warm anomalies in the Amundsen Sea region (Holland et al. 2019). Few observations exist prior to the last several decades, hampering the ability to distinguish anthropogenic-forced change from natural variability. Ice core records, strategically placed on ice domes along the Amundsen Sea coast, will provide high-resolution (annual) records, at least 2000 years long, of natural variability in ice, ocean, and atmospheric dynamics in which to place the recent observations in context. These cores can also be used to improve firn densification models needed to accurately estimate Antarctica's contribution to sea level from satellite altimetry (Smith et al. 2020).

WAIS at the Last Interglacial: Ice core research provides a longer-term context for modern changes and rates of change, and provides boundary conditions and validation for ice sheet models. During the last interglacial period, sea level was 5.5 to 9 m higher than present. It is difficult to close the sea level budget without substantial ice loss from West Antarctica (Dutton et al. 2015). Yet evidence for major mass loss from the WAIS is at best indirect. Two important questions emerge: if WAIS did collapse, how fast did the collapse occur? And if WAIS did not collapse, under what climate conditions was it stable? Attempts to obtain MIS5e ice from West Antarctica have been largely unsuccessful, with the low resolution, "horizontal" Mt. Moulton ice core the sole record. Among potential new drill sites, Hercules Dome has emerged as an ideal study site for last interglacial ice. Hercules Dome is in East Antarctica, but receives moisture primarily from the West Antarctic sector. Hercules Dome is not likely to have changed elevation significantly, and the aerosol and isotope composition of snowfall will provide constraints on changes in the elevation of the WAIS at the last interglacial (Steig et al. 2015). Site selection activities began at Hercules Dome in the 2018-19 field season and will conclude in the 2020-21 field season.

A core through the last interglacial would also *per force* provide a record of the onset of the last glacial period, for which high quality ice core samples do not exist in the US collection. (The oldest high quality ice, from WAIS Divide, dates to 68 ka). Filling the gap between the end of last interglacial (~120 ka) and 68 ka will provide an opportunity to examine in detail the processes that control why the Earth enters an ice age (a major long standing climate science question), for example through synchronized records of greenhouse gases, deep ocean temperature, and local Antarctic temperatures.

Physics of Firn Compaction: Robust and consistent physics-based models of firn-compaction rate and pore-closure are needed to correctly convert ice sheet elevation changes (measured by satellite altimetry) into ice-mass changes, which contribute to sea-level rise in a warming climate. Current firn-compaction models show substantial discrepancies in predictions of the firn-air content and its evolution (Lundin et al. 2017), resulting in varying ice-sheet mass-balance estimates and even disagreement about the sign of the mass change (e.g. Richter et al. 2014; Zwally et al. 2015, 2016; Scambos and Schuman 2016). Developing a physically-based firn-compaction model requires observations from sites where temperature and accumulation are decoupled, allowing the effects of each on the firn column to be quantified.

Oldest Ice: For the last ~50 million years, Earth's climate has been cooling in fits and starts. This cooling, recorded best in the $\delta^{18}O$ of benthic foraminifera, is characterized by periods of relatively stationary climates bounded by transitions. During stationary intervals, and in particular during the ice-house climates of the last 15 million years, climate variability has been largely concentrated into periods associated with cycles of eccentricity, precession, and tilt (400 kyr and 100 kyr, 21 kyr, and 41 kyr, respectively). Northern hemisphere ice sheets first extended to sea level around 3 Ma. For the next 2 Myr, Earth's climate was characterized by 40 kyr cycles paced by tilt (Raymo et al. 2006). Between 0.8-1.2 Ma, corresponding to the Mid-Pleistocene Transition (MPT), glacial-interglacial cycles lengthened to the period of ~100 kyr that persists until the present. Hypotheses to explain the MPT include a drop in atmospheric CO_2 that caused cooling and larger ice sheets, or a change in ice sheet basal lubrication due to gradual removal of soil (the "regolith hypothesis") that ultimately enabled larger northern hemisphere ice sheets to grow.

Understanding the links between orbital forcing, greenhouse gas concentrations, climate, and ice sheet mass balance over the last 3 million years is a central goal of paleoclimate science. Events of this period helped shape the modern surface environment and the warmer intervals are often seen as plausible geologic analogues for near-term future climates under business as usual CO_2 emission scenarios (IPCC, 2014). Ice cores are the gold standard for reconstructing the composition of ancient atmospheres and many other aspects of Earth's climate system. However, at present, continuous deep ice core records extend back only to 800 ka, and the oldest published age of clean glacial ice is about 1 Ma (Higgins et al. 2015, Yan et al. 2019). The absence of older ice core samples is a major limitation in our ability to characterize and understand climate change during earlier warm periods.

Glacial-Interglacial Climate Dynamics: Past climate states, and their associated forcing mechanisms, provide robust boundary conditions to benchmark, test, and validate climate models. Some of the largest changes in boundary conditions occur during deglaciations, across glacial-interglacial cycles, and at specific times as the Earth descends into ice ages. These changes are largely driven by orbital dynamics, partly driven by internal Earth dynamics, and sometimes exhibit abrupt, step-like changes. Other shorter-wavelength, millennial-scale events occur prominently, especially in glacial periods (e.g. Dansgaard-Oeschger Events). Higher frequency signals, on the order of centennial, decadal, interannual, and even seasonal scales, are now routinely measured in ice cores, such as CO_2, CH_4, water isotopes, and impurities. A picture of climate at all timescales (orbital to seasonal), as well as of the quantitative impact of varying forcing mechanisms, is emerging from these studies (e.g., Brook and Buizert 2018, WAIS Divide Project Members 2013, Marcott et al. 2014, Rhodes et al. 2015, Jones et al. 2018).

Magnitude of glacial-interglacial change: Glacial cycles are driven primarily by orbital forcing, while other forcings, such as greenhouse gas concentration and volcanism, can affect the magnitude of change. Currently, the magnitude of glacial-interglacial temperature change in Antarctica is not fully understood. The canonical value of about 9°C from East Antarctic cores for the most recent termination has been challenged by analysis of borehole temperature and empirically derived Δage (i.e. the gas-age ice-age difference), indicating temperature changes of only 4-5°C (Buizert et al. in prep, 2020). This uncertainty inhibits our ability to evaluate climate models (e.g. Masson-Delmotte et al., 2013). Existing and new techniques, such as the diffusion of water isotopes (Kahle et al. in prep. 2020, Jones et al. 2017), promises to improve our understanding of past climate sensitivity in Antarctica during the most recent and prior termination. These new methods for determining temperature and other properties rely on firn densification modeling and motivate more physically-based models constrained by in situ measurements of densification rates rather than depth-density profiles. Furthermore, water isotope records suggest interglacial periods are warmest at the beginning and that terminations do not always have a hiatus in warming akin to the Antarctic Cold Reversal (Wolff et al. 2009). New records are needed to establish whether there are differences in the timing and mechanisms of warming and greenhouse gas change during glacial terminations. Existing greenhouse gas isotopic data suggest substantial and puzzling differences between the most recent and the previous glacial termination (Eggleston et al. 2016, Bock et al. 2017).

Abrupt change: In the last glacial period, abrupt warming events in Greenland (DO Events) and the associated onset of cooling in Antarctica (AIM Events) have been extensively studied (WAIS Divide Project Members 2015). Were these abrupt shifts in glacial temperatures and deglacial greenhouse gas concentrations also a fixture of prior glacial-interglacial cycles older than MIS 5e (123 ka)? For at least the past 1 Ma, there is widespread evidence for millennial-scale variability (Jouzel et al. 2007, McManus et al. 1999, Martrat et al. 2007), of which the timing, speed, and amplitude is influenced by differing boundary conditions. New Antarctic ice cores, coupled with improvements to technology and novel proxy records, can substantially enhance our understanding of millennial-scale climate variability older than 123 ka. Continuous high-resolution methane records from new Antarctic ice cores can define the amount and magnitude of DO Events in older glacials. Then, using multi-proxy records, the relationship to Antarctic and southern hemisphere climate can be established. Improved chronology and inter-core synchronization using volcanic markers will eventually provide regional insights from varying sectors of Antarctica.

Recent studies have also shown abrupt step-like changes in CO_2 during the last deglaciation, and abrupt jumps in CH_4 (Marcott et al. 2014, Rhodes et al. 2015). Although the history of greenhouse gases is well known for the last glacial termination, the influence of greenhouse gases on climate during prior glacials, the last interglacial, and the last glacial inception is poorly understood. Atmospheric CO_2 and Antarctic temperatures vary asynchronously during multiple periods in MIS5 (Bereiter et al., 2012). New records of the isotopic composition of CO_2 will provide constraints on the mechanisms of CO_2 change, distinguishing among changes in the biological pump, release of respired CO_2 from the deep ocean, and changes in ocean temperature or carbonate chemistry. Measurements of ultra-trace gas carbonyl sulfide will yield information on carbon uptake by land plants (Aydin et al. 2016). Ice core measurements of ethane, acetylene, carbon monoxide and its stable isotopes (Nicewonger et al. 2019), when combined with records of the $\delta^{13}C$ of CH_4, will yield constraints on gaseous emissions from biomass burning through the last glacial period. Additionally, organic carbon characterizations have the potential to help differentiate past carbon sources (D'Andrilli et al. 2017) .

Solar Variability: The interaction of cosmic rays with atoms in the atmosphere and at Earth's surface results in production of nuclides such as ^{14}C, ^{10}Be, ^{26}Al and others. Records of these nuclides in ice cores, tree rings and bedrock cores have been used to study past variations in solar activity (an important climate driver) and ice dynamics. These studies typically rely on the assumption that the galactic cosmic ray flux is constant. However, this assumption is uncertain by 30% or more (Wieler et al. 2013). The ^{14}C is produced in situ in ice grains by secondary cosmic ray neutrons and muons. In situ ^{14}C in the CO phase (^{14}CO) at low-accumulation ice core sites can act as a record of changes in the historical flux of galactic cosmic rays (BenZvi et al. 2019). A model of in situ cosmogenic ^{14}CO production indicates that ice core samples from Dome C would be able to detect long-term variations in the galactic cosmic ray flux of ≈15% or better, considerably reducing uncertainties in the assumption of a constant flux (BenZvi et al. 2019).

Stratospheric Ozone: Studies are needed to establish proxies of stratospheric ozone in snow chemicals. The most promising candidates are isotopes of nitrogen, oxygen, and sulfur in nitrate, sulfate, and other trace snow impurities (McCabe et al. 2007). The proxy-ozone relationship can be studied with shallow ice cores during the period (1970-present) when Antarctic ozone levels have been continuously monitored. After such proxies are established and verified, long records of stratospheric ozone can be reconstructed from deep ice cores.

Atmospheric Oxidizing Capacity: Atmospheric oxidizing capacity (AOC) controls the atmospheric lifetime of methane and other trace greenhouse gases (Thompson 1992). As a result, variation in AOC can directly impact climate. Research has provided evidence of AOC proxies in Antarctic ice cores (Alexander et al. 2003). Additional research is needed to establish the validity of AOC proxies in ice cores. Such proxies can be used to investigate the relationship between climate and AOC and contribute to future climate model development.

Project Requirements and Logistics

Community Projects for Intermediate and Deep Ice Cores

Hercules Dome: A variety of sites may preserve ice from the Last Interglacial that records the history of WAIS. Potential locations are Hercules Dome, Whitmore Saddle, areas in Marie Byrd Land, and coastal domes of the Filchner-Ronne. Of these, Hercules Dome is the preferred site because the Last Interglacial ice is the most likely to be thick, undisturbed, and record a signature of WAIS collapse if it occurred. Drilling at Hercules Dome is an immediate priority (<5 yr). Site selection began in the 18/19 field season, continued in 19/20, and will be completed in 20/21. The ice thickness is ~2000 m. Repeat phase sensitive radar measurements at the ice divide observed a vertical deformation pattern typical of ice divides, indicating the bed is likely frozen. Radioecho sounding has imaged layers within tens of meters of the bed, and Last Interglacial is likely preserved. In the 20/21 field season, the optimal drilling location will be identified. Drilling at Hercules Dome is best accomplished with the FORO3000 drill. Replicate coring of last interglacial ice located near the bed would enhance the project.

Allan Hills: A 1170-m long ice core drilled to bedrock in the Allan Hills (AH), Antarctica is needed to further understand the glaciological setting of this Blue Ice Area (BIA) and to develop paleoenvironmental reconstructions covering several glacial-interglacial cycles, potentially extending well beyond 800,000 years. The project will expand on existing research at AH that has already yielded the largest collection of Antarctic meteorites and the oldest direct measurements of trapped atmospheric gases. The site is logistically more accessible than most deep ice core sites. In the event that there is a continuous record extending to the MPT, it will provide the first continuous paleo-climate and -atmospheric record with the temporal resolution needed to investigate the change in the dominant periodicity of glacial-interglacial cycles from 41 to 100 kyr. The project will use the US intermediate-depth drilling (FORO1500) system, will require two drilling seasons (23/24, 24/25) and is part of a pending Science and Technology Center proposal (NSF #2019719) (COLDEX - Center for Oldest Ice Exploration).

Deep core from East Antarctic Plateau: The recovery of ice cores from the Early to Mid-Pleistocene is a leading objective of the international ice core and paleoclimate community. Two complementary strategies have emerged to recover ice >1 Ma. The first strategy involves surveying and drilling in a region where stratigraphically continuous ice may extend to ages of 1 to 1.5 Ma, ideally with the Rapid Access Ice Drill (RAID) to verify the site before commencing a full deep drilling program. The likely timing for this project is 2025-28, due to the need for reconnaissance and thorough site characterization prior to initiation of this deep ice core. A pending Science and Technology Center proposal (NSF #2019719; COLDEX) may serve to focus US efforts in finding appropriate sites on the East Antarctic Plateau where accumulation rates, temperatures, and geothermal heat flows are extremely low, all of which improve the chances of preservation of old ice. Drilling would likely use the FORO3000 and replicate coring capability would be extremely valuable.

Shallow/Agile Projects

WAIS Coastal Domes: Understanding the destabilization of the WAIS and its effects on sea level rise (how much, how fast) is time-sensitive, so this project has a near term goal of <5 yrs. Initial recovery of 100-200 m cores, using Foro or Eclipse drills, from one or two WAIS coastal domes is needed to investigate paleoclimate proxy preservation, spatial variability in climate dynamics along unsampled 1,200 mile coastline, and reveal century-scale atmospheric variability with implications for coastal upwelling and ice shelf stability. Example candidates include:

1) *Guest Peninsula (76.3ºS, 148ºW).* 580 m elevation. Directly influenced by Amundsen Sea Low. Known LC-130 landing zone located nearby.
2) *Martin Peninsula (74.3ºS, 114.5ºW).* 670 m elevation. Accessible by ground traverse. Snow accumulation linked to high-pressure blocking over the Bellingshausen Sea.

Equipment must be light and transportable by Twin Otter. Shallow coring is first priority; deeper drilling will require a partially fluid-filled hole. Equipment likely cannot be left over winter due to extreme snowfall (>1 m/yr ice equiv.). Weatherproof drilling infrastructure is essential (existing IDP drill tents). If ground traverse is the only possible logistical option, Martin Peninsula is the best site accessible over land from WAIS Divide.

Blue Ice Areas: Measurements of $^{40}Ar/^{38}Ar/^{36}Ar$ of trapped gases indicate that ice with well-preserved gases as old as 2-2.6 Myr exists in the Allan Hills BIA, Antarctica. This discovery shows that very old ice, perhaps reaching back into the Pliocene (5.3 to 2.6 Ma), may exist at shallow (<200 m) depths in the ice sheet. In the Allan Hills, bedrock topography and strong katabatic winds lead to the exhumation of old ice from depth to the surface. Similar BIAs cover approximately 1% of the Antarctic surface and there are a number of promising targets for future drilling. Shallow drilling (<200m) with the Blue Ice Drill (large diameter) in the Allan Hills is currently ongoing (19-20 and 20-21 field seasons). A follow-up project with the pending COLDEX Science and Technology Center proposal (NSF #2019719) would extend drilling in the Allan Hills BIA for another 3 years (through 2024) and expand to include other Antarctic BIA drilling targets through 2026.

<u>Dome C:</u> Shallow dry ice coring to 300 m at the French-Italian Concordia station is proposed for the 22-23 season, for studies of past cosmic ray variability, requiring a 4" drill or FORO 400 for dry drilling. A weatherproof drilling structure is required, as well as a ground traverse (via French program) for transport of drills and heavy scientific equipment. Fixed-wing support is needed for transport of team members and some light equipment between McMurdo and Concordia.

<u>South Pole:</u> Snowpits and shallow 100-200 m ice cores can provide high-resolution (sub-annual) chemical records to establish ozone proxies and document ozone fluctuations during and prior to the development of the Antarctic stratospheric ozone hole.

<u>Taylor Dome:</u> The large accumulation gradient and near-constant temperature across Taylor Dome make it an ideal location for investigating the role of accumulation rate on firn evolution. Firn cores drilled to pore close-off are needed at 4 sites across the dome, with accumulation spanning 2 to 25 cm yr^{-1}. Additional drilled holes are needed at each site to install a thermistor string and 4 vertical strain meters to measure in-situ firn-compaction.

Existing Ice
When possible, existing ice core from projects such as WAIS Divide or South Pole, stored at the NSF Ice Core Facility, will be utilized. For example, atmospheric Oxidizing Capacity (AOC) proxy validation can be studied with existing ice cores from East Antarctica. Long records of AOC will likely be constructed from new deep East Antarctica cores.

Improving Community Diversity and Inclusivity

Ethnic, racial, and gender diversity in the geosciences is a persistent problem which has not improved at the PhD level for the past 40 years, with people of color holding less than 5% of tenured or tenure track positions at the top 100 ranked geoscience departments (Bernard and Cooperdock 2018). Increasing diversity and inclusion is beneficial for the scientific community, as individuals from a broad diversity of backgrounds and life experiences may have perspectives that can result in unique research questions or approaches that move the field forward (Medin and Lee 2012). There are issues with biases and barriers in polar science that prevent diverse participation, ranging from harassment and implicit bias (Gay-Antaki and Liverman, 2018; Starkweather et al. 2018; Bell and Koenig 2017), long field seasons in Greenland and Antarctica requiring sacrifices from researchers with varying degrees of caretaking responsibilities (Lynn et al. 2018, Nash et al. 2019), and the misconception that polar fieldwork requires a masculine body type (Nash et al. 2019). Further, the individuals' choice to pursue a professional or academic career path in polar science may be influenced or constrained by subtle social cues that discourage an individual's feeling of belonging (Dasgupta 2011). Improving the culture of diversity and inclusivity in the ice core community is a key goal. Working towards this goal, we propose to have participants (undergraduates, graduate students, postdoctoral scholars, early career to senior faculty) involved in workshops and discussions at future Ice

Core Planning Meetings to collect information on experiences, culture, climate, and to identify areas of improvement and/or opportunities for facilitating a more diverse and inclusive participation. As the issue was raised whether certain participants would feel comfortable speaking up in a group setting, we propose that a formal reporting mechanism be set in place to allow for individuals to have an equal voice, and a mechanism for them to voice concerns relating to equity, diversity, and inclusion in the ice core community.

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