IDP Ice Core Working Group (IDP-ICWG)

Alpine Glaciers and Ice Caps

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Summary

This white paper details opportunities to expand ice core studies of Alpine glaciers and ice caps (outside Antarctica and Greenland) to address multiple research questions and enrich the paleoclimate framework. Alpine drill sites from the Northern and Southern Hemisphere provide high resolution climate records which are highly sensitive to the complex atmospheric processes and changes such as modern warming. Often, the potential ice core archive at lower elevation sites is under threat from increasing atmospheric temperature and loss of stored climate signals. The proposed areas of investigation include the Sub-Antarctic Islands, North Pacific coastal mountain ranges, and the Karakoram in Asia. The scientific goals include a variety of research questions linked to hydroclimate variability, climate feedbacks, past extension of high-altitude glaciers and aerosol deposition. Ultralight and light drilling equipment will be necessary to extract ice cores from extremely remote locations with limited available logistics such as the Sub-Antarctic Islands and Karakoram. Some developing or existing drill equipment (FORO 700 and the improved IDP 3 thermal drill) will need to be used in the relatively more accessible North Pacific drilling sites. A strong increase in the promotion of inclusion and diversity and minorities is planned, broadening research fields and opportunities for minorities with the extension of national programs involving students in field operation in the US North Pacific territory and through the development of international collaborative programs with Australia and Pakistan. Finally, this working group recommends that adequate support for preliminary geophysical activities will be made available in order to optimize the selection of the ice core drilling sites and maximize the linked scientific output.

1 Driving scientific questions, motivations and time sensitivity

1.1 Research questions

Sub-Antarctic region:

- What is the spatial variability of the margin of the Antarctic sea ice at different time scales?
- How did the position of the polar front change through time?
- How did the intensity of the circumpolar westerlies (Southern Annular Mode) change at decadal, centennial and millennial timescales?

North Pacific region:

- What is the nature of North Pacific hydroclimate variability and how well this is captured by climate models throughout the Holocene?
- Are events observed in the Alaska Range (e.g. large 20th century increases in snowfall) seen further south at the opposite extreme of precipitation dipole in British Columbia?
- Is the high amplitude stable isotope and glacio-chemical variability observed in Yukon a robust spatial feature in the North Pacific during the Holocene?
- Does the Holocene Thermal Maximum (~9000-5000 BP) have a distinct signal in the North Pacific?
- Did the 8200 and 4200 BP events have a broad impact in the North Pacific?
- What is the relationship between tropical Pacific forcing and North Pacific hydroclimate response during the Holocene?
- What is the role of North Pacific volcanism on the different components of the climate system?

High Mountain Asia region:

- What are the climate mechanisms driving the "Karakoram Anomaly" and over what timescales do they operate?
- What is the natural variability in aerosols (dust and black carbon) over the Holocene, and how does this variability and magnitude compare to the Industrial age?
- What fraction of high elevation precipitation is controlled by winter westerly disturbances versus summer monsoon dynamics?
- How does the hydroclimate of the Holocene in the eastern Himalayas compare to that of the western Himalayas, and how closely linked is Himalayan hydroclimate to climate dynamics of the tropics versus mid-to-high latitudes?
- When and how often was the High Mountain Asia Region of the Karakoram ice free?

1.2 Motivations from prior work

Sub-Antarctic region: A large suite of ice cores have been recovered from East and West Antarctica and are most often used to infer climatic and environmental changes occurring in the Southern Ocean. However, no long ice core records have been retrieved from the ice caps in the Sub-Antarctic Islands that are ideally located to record climate variability in the Southern Ocean.

North Pacific region: Recent observational and modeling studies have demonstrated a connection between Pacific multidecadal variability and Arctic warming during the early 20th century and since the 1970s (Svendsen et al., 2018). Previous ice core work (e.g., Winski et al., 2017; 2018; Osterberg et al., 2017) demonstrates that the observed doubling of snow accumulation and 60-fold increase in summer melt during the industrial era (since ca. 1850 C.E.) is linked to Pacific multidecadal variability and is likely unique in the last millennium. It is important to confirm if the same drivers are relevant for the entire Holocene, which can be accomplished through the recovery and analysis of a high-resolution (sub-decadal) ice core record from the region.

As with the Yukon and Alaska records, snow accumulation from mountains in British Columbia (as all along the British Columbia coast) largely reflects Aleutian Low variability (Neff et al., 2012). However, the sign of this relationship is opposite to that of the more northerly sites – i.e., when snowfall is greater to the north, it is lower to the south. Having a long record of snow accumulation from British Columbia would be a valuable complement to the Alaska records, and would aid in better understanding accumulation changes observed there.

Finally, the archive of the surface-to-bedrock core drilled at Mt. Logan PRCol in 2002 (Fisher et al., 2008) was lost during a 2017 freezer malfunction at the Canadian Ice Core Lab. A new ice core from the same vicinity on PRCol is required to address many of the science questions articulated above.

High Mountain Asia region: In this region glaciers, ice caps, and snowpack exist in a wide range of climate settings within a single geographic region: from extreme summer precipitation associated with the Indian summer monsoon to the extremely dry peaks surrounding the Taklamakan Desert. This is thus an ideal place to understand glacier and climate sensitivity to climate forcing.

While glacier mass loss rates over the Himalayan range have accelerated over the past several decades, the Karakoram glaciers have remained relatively stable, dubbed the Karakoram Anomaly (Brun et al., 2017; Maurer et al., 2019; Shean et al., 2020). Numerous hypotheses have been proposed to explain this anomaly (increasing precipitation, cooling trend, decrease in light-absorbing aerosol fluxes, increases in irrigation), yet lack of data and uncertainty in modeling in this complex terrain has hampered our ability to assess either the the mechanism(s) or the timescale of this glacier mass anomaly (Kok et al., 2018; Farinotti et al., 2020).

An ice core strategically drilled in the Karakoram would provide critical data for understanding the anomaly, as well as reconstructing the role of summer monsoons versus winter storms in the interior regions of the High Mountain Asia region, assessing the penetration of aerosols into high mountain regions, and providing the first record of climate and aerosols in this region.

1.3 Time sensitivity

Projected changes in hydroclimate in a warming world challenge water resource managers across all inhabited continents. Alpine glacier-fed hydrology controls water flow for hydropower schemes, stream temperature and turbidity affecting fisheries (e.g. salmonids), and water quality (Moore et al., 2009). Ice core records of historic snow accumulation and other proxy records can contextualize 21st century changes and provide resource managers with a more complete decision-making environment for developing adaptive management strategies where alpine water flow is essential (e.g. western North America, Andes, European Alps, High Mountain Asia). This is required as soon as possible to best manage alpine hydrological resources.

A critical lack of data has also hindered in particular analyses and modeling of climate, snowpack, and glaciers in the High Mountain Asia region giving rise to significant uncertainties in how future climate change will impact water resources in the coming decades and centuries. New reliable ice core data are urgently needed from this region to inform models of adaptation and mitigation strategies.

Climate change is also affecting the Sub-Antarctic Islands and their glaciers are receding rapidly (e.g. Thost and Truffer, 2008). For instance, glacial tongues are retreating at Heard Islands since at least 1947 with an acceleration in the 1988-2000 time period (Cogley et al., 2014). Because of their low elevations, these ice caps are more exposed to possible imminent surface melting and percolation. It is fundamental to retrieve long ice core records from this region before the unique climatic signal embedded in these glaciers could be overprinted.

2 Intellectual merit

Sub-Antarctic region: The Southern Ocean represents one of the key components of the climate system because of its role in distributing energy in the Southern Hemisphere and in providing feedbacks through changes in sea ice albedo (Mayewski et al., 2009) and the ventilation of CO_2 as a consequence of changes in forcing of the circumpolar westerlies (Anderson et al., 2009). Knowledge of climate feedback mechanisms at centennial, millennial and orbital time scales provide key information on the natural variability of the global climate system.

North Pacific region: The impact of Pacific multidecadal variability on Arctic climate has considerable implications for sea ice extent, and hence the possible linkage between Arctic amplification, sea ice loss, and enhanced mid-latitude winter variability. In addition, a dipole in precipitation, reflecting changes in the mean position of the Aleutian Low, is a well-established control on glacier mass balance across the North Pacific Region (e.g., Bitz and Battisti, 1999; Christian et al., 2016). Establishing how the Pacific-Arctic teleconnection and the dipole in precipitations responded during warm intervals and abrupt events outside of the instrumental period and last millennium (early/mid Holocene warmth and across abrupt changes such as the 4200 and 8200 year events) would provide valuable insight into the sensitivity of the global climate system.

High Mountain Asia region: Climate change is affecting High Mountain Asia and the billions of people living within and downstream of these mountains. This region hosts also more snow and ice outside of the polar regions than anywhere else on earth. These so-called water towers of Asia provide critical water resources to a large and vulnerable population of the world (Immerzeel et al., 2019). However, this region is plagued with a paucity of in situ observations within which to understand the climate, pollution, and glacier dynamics that alter these high mountain water resources. For example, the Karakoram hosts the majority of glacier ice in High Mountain Asia and serves as the dominant source of water to the Indus River. Knowing past hydroclimatic conditions, including those under which this region was ice free, is an important target for modeling the availability of glacier ice and water resources under future climate scenarios, and can link the Karakoram to on-going work in the Arctic and Antarctic regions.

3 Sampling sites, drilling requirements and timelines

3.1 Potential drilling sites

Sub-Antarctic region: Heard Island. Among the Sub-Antarctic island glaciers, a promising ice cap is located next to Mawson Peak (2745 m, 53°6′ S 73°31′ E), the summit of Heard Island, a remote uninhabited Australian territory in the Indian sector of the Southern Ocean that can be reached in two weeks of navigation from Australia. Thanks to its relatively high latitude (53° S) and high altitude (2400 m, -10 °C calculated average annual air temperature), this ice cap has the potential to contain cold or polythermal ice. Measured precipitations at sea level are 1380 mm/y with an expected lower annual snow accumulation at 2400 m due to significant wind drift. Under these conditions an ice thickness in the order of 100 m can be expected on this ice cap. An annual resolved record may be obtained thanks to the expected strong seasonality of proxies of the close Antarctic sea ice margin.

North Pacific region:
Eclipse Icefield (Kluane National Park, Yukon Territory, Canada; 3010 m a.s.l., 60.68º N, -139.78º W). In 2016 and 2017 ground-penetrating radar data (Kochtitzky et al., 2020) were collected that revealed >600 m ice depth with strong horizontal layers and lack of flow perturbations at the central Eclipse Icefield ice divide. Velocity and vertical strain rate at the

deepest location at the divide was estimated and permits an estimation of the basal ice age of at least 8000 years, and potentially much longer, if the true ice depth is close to 650 m, as geophysical evidence suggests. Based on the well-preserved chemical, isotopic, and volcanic signals at Eclipse (Yalcin et al., 2006; 2007; Kelsey et al., 2012) a seasonal resolution to at least 1700 years ago, annual resolution to at least 4000 years ago and sub-decadal resolution sampling through the remainder of the Holocene are possible with current analysis technology. Recovery of basal ice (i.e., coring to bedrock) will be critical, so that radiogenic and cosmogenic isotope analyses (on englacial sediment) can be performed.

Mt. Logan (Kluane National Park, Yukon Territory, Canada; 5300 m a.s.l., 60.59 º N -140.5º W). The high elevation summit plateau of Mt. Logan has been the site of ice core recovery at NWCol in 1980 (Holdsworth et al., 1992) and PRCol in 2002 (Fisher et al., 2008). Given the high elevation of the summit plateau, there is no summer melting and relatively low snow accumulation (~0.3 mwe/year), and the site is sensitive to regional and long-range moisture and aerosol transport (Osterberg et al., 2008). The 188 m surface-to-bedrock core from PRCol has a maximum age of ~30,000 years (Zdanowicz et al., 2014), and is the best candidate site for new core recovery on Mt. Logan. As with the Eclipse Icefield site, recovery of ice to the bedrock interface will be critical to access the longest possible climate record.

Mt. Waddington (Combatant Col; 3000 m a.s.l., 51.385ºN, 125.258ºW). Outside the polar regions and the highest mountains (e.g., Andes, Himalaya), the ice in most glaciers is temperate (at or near the melting point). Combatant Col is unique in that it is both at sufficient elevation to maintain low annual-average temperature, and near enough to coastal moisture to maintain high annual snowfall. The very high snowfall prevents significant alteration of snow stratigraphy by summer melt, preserving valuable paleoclimate information that is usually unavailable from temperate ice (Neff et al., 2012). An ice core drilled to 141 m in 2010 demonstrated unambiguous seasonal cycles in water stable isotopes, dust particles, lead and black carbon, making Combatant Col the southernmost ice core site in North America with preserved annual stratigraphy. Extrapolation of the existing Combatant Col ice core depth-age scale to the bed indicates that ice dating to more than 200 years, and likely more than 500 years old, is retrievable at this site.

High Mountain Asia region: Geopolitical instability likely prohibits drilling in the east Karakoram. However, the west Karakoram within Pakistan is logistically more reasonable. Potential core sites in Pakistan are accessible from the Karakoram Highway, which remains one of the safest routes in the region. In the Karakoram, there are at least three potential drilling locations that extend from the Karakoram Highway in the west to a broad icefield near Kent Ganghi in the east. They are all located in a region that reliably receives both summer and winter precipitation, thus providing an ideal candidate for reliable dating.

Pakistani Karakoram: the two initial target sites in this area occur at 5300 and 5700 m and require a highly technical ice traverse for the drilling team with some potential helicopter support for the lower elevation portion. Both sites are located in broad saddles (36.033ºN, 75.74ºE and 36.11ºN, 75.57ºE). The lower elevation site is estimated to be ~180 m deep and, based on assumed accumulation rates and preliminary ice flow modeling, seasonal to annual resolution is likely achievable back 300-700 years. The higher site at 5600 m is deeper, ~250 m, and annual resolution will likely be possible back 500-1000 years.

Eastern Karakoram: The third deeper core, ~600 m deep, is possible in the eastern Karakoram, but is located at 6200 m and is along disputed borders that are not currently accessible due to extreme geopolitical instability.

3.2 IDP technological requirements/support

There are several common requirements for the proposed sites: portable drill systems, limited use of drilling fluid, and need to address the potential presence of liquid water in the borehole. Below we specify the specific equipment needed.

Sub-Antarctic region: Due to the extreme remoteness of Heard Island and very unstable weather conditions, to drill successfully and safely the Heard Island glacier, it is necessary to plan a one-shot operation without aviation support involving a small independent team to climb, drill and descend this ice cap by transporting both equipment and ice on foot. The key factor is to have the availability of an ultra-light drill system (total weight ~50 kg) that would core deeply to bedrock (possibly 150 m deep or shallower) small diameter (4-6 cm) continuous ice core sections. A mechanical and/or thermo-drill like this may be acquired by IDP in the framework of this drilling operation and kept for future uses of the US ice core community for surveys and full drilling operations in the most remote and logistically difficult areas.

North Pacific region:

Eclipse Icefield
1) FORO 700 drill. Science requirements for the FORO 700 drill have been developed for the broadest possible community use in alpine and polar environments, and conceptual design is underway; IDP should prioritize moving this drill to the next stage of development. For the Eclipse project, the key attributes are: recovery of a ~650 m surface-to-bedrock core in a single 60-day field season; Twin Otter support, with a logistically feasible number of flights; drill setup, operation, and break down by a small team (5 people) with limited logistics (e.g., no heavy equipment); core quality requirements similar to the IDP Intermediate Drill.
2) Drill fluid considerations. Minimizing the quantity of drill fluid needed for Eclipse Icefield drilling with the FORO 700 system is necessary to reduce logistics, comply with environmental

regulations, and satisfy national park permit conditions. In particular, we assume that drill fluid will have to be removed from the borehole and retrograded at the end of the field season. IDP should prioritize the development of drilling techniques that utilize limited amounts of drilling fluid, such as drilling with a reduced fluid column (Mulvaney et al., 2014; Triest et al., 2014; Sheldon et al., 2014).

Mt. Logan
None. The existing Canadian ECLIPSE drill will be used to drill at PRCol.

Mt. Waddington
Due to the presence of liquid water in a "firn aquifer" below ~40 m depth, the improved IDP 3" thermal drill is required for recovering an ice core to bedrock at Mt. Waddington. Testing of this system at the Juneau Icefield in summer 2019 reaching 294 m depth, demonstrated its suitability for the wet temperate ice at Combatant Col which is estimated at less than 250 m depth based on previous Ground Penetrating Radar (GPR) data.

High Mountain Asia region: Reconnaissance GPR and shallow cores need to be completed in order to determine the likelihood of retrieving a high-quality core from this region. Developing portable, lightweight technologies to drill to and through bedrock in remote, high elevation, difficult access terrain should be an IDP priority. In the future, ice drilling requirements and support in High Mountain Asia are likely similar to that of the planned operations on the Eclipse Icefield or Heard Island (see above).

Other Potential Opportunities:
It should be noted that each potential drill site listed above requires substantial effort and cost in terms of reconnaissance and drilling. Therefore, use of each remaining borehole for other potential applications should be fully considered by funded science teams, and news of funded projects should be disseminated to the broader community for potential development of additional opportunistic research activities. This includes but is not limited to:
1) considering borehole geophysics which may provide numerical constraints on ice temperature and ice flow deformation rates (which are valuable for reconstructing accumulation variability, among answering other chemistry related questions)
2) completing radiocarbon or cosmogenic nuclide analyses of any debris captured in the core at the ice-bedrock interface or sub-glacial bedrock drilling to improve understanding of previous long-term deglaciation events.
These two topics are outside the scope of this whitepaper. However, building such collaborations between the ice core, glaciology, and geomorphology communities are necessary strategies to maximize scientific information while broadening research diversity in the future at each Alpine core site.

3.3 Timelines

Sub-Antarctic region: Heard Island. During the next few years (possibly as early as summer season 2021-2022) the Australian Antarctic Division will conduct a large multidisciplinary scientific expedition that will provide the logistic to reach the coast of Heard Island from Australia. As soon as the naval expedition will be confirmed by the Australian Antarctic Division, a proposal will be submitted to NSF to acquire a drill for coring and analyzing an ice core from the Heard Island glacier in collaboration with Australian Colleagues (Dr. Mark Curran).

North-Pacific region:
Eclipse Icefield. A NSF proposal will be submitted (to either Arctic Natural Science or P2C2) in 2020. The proposed project will include a field season in 2022 for additional geophysics and final site selection, and drilling a surface to bedrock core in 2023 with the FORO 700 drill.

Mt. Logan. A combined geophysics-site selection and drilling season will occur on PRCol in 2021. Funding is through the University of Alberta (insurance settlement) and the NSF P2C2 program (EAGER award). Assuming successful core recovery in 2021, a NSF proposal will be submitted in late 2021 to analyze and interpret the core.

Waddington. An NSF proposal has been submitted to conduct radar geophysics in summer 2020 and ice coring in summer 2021, with Canadian support for logistics (University of Northern British Columbia). Due to COVID-19, the summer 2020 season has been postponed. Proposals for analyses beyond water stable isotopes and snow accumulation will be submitted after the ice core recovery.

High Mountain Asia region: A proposal will be submitted to complete preliminary reconnaissance work at the three locations in the western Karakoram along the Karakoram Highway in Pakistan. This will include GPR, shallow ice cores, and drone mapping of lower reaches of the glaciers. These do not need IDP support.

A larger NSF proposal would be submitted the year following the reconnaissance work assuming there is a high probability of obtaining a high-quality core in the region. The deep core could be completed with the FORO 700 drill or similar, but an ultra-light portable drill that minimizes or eliminates the need for drilling fluid could be essential for successful recovery of ice cores in this remote region. IDP technical support will be required also for the drill setup/dismantling, drilling, and core recovery.

4 Opportunities to enhance community diversity and inclusivity

The ice coring community should actively pursue more initiatives supporting early career under-represented community members including women, non-binary, first generation college students, and minority populations. This will contribute in diversifying the scientist population and indirectly will also broaden the science fields. Note, this pursuit will require partial funding within individual projects to be shifted towards diversity and inclusion budgets to support these community members because participation in the sciences by these communities is limited, in many cases, due to financial limitations. When possible, outreach activities targeting also local communities located on the way to and near the drilling sites, will be planned.

Sub-Antarctic region: The program to Heard Island will allow to build a long-term scientific collaboration with the Australian colleagues implying the exchange of international students. This ice core project will also be performed in the framework of the Ice Memory program https://www.ice-memory.org/program/program-571158.kjsp further enhancing the international breath and possibilities of inclusion of this project in particular with additional students from Europe and Asia.

North-Pacific region: Diversity and inclusivity within the ice coring community can be developed by engaging with existing field programs fostering such activities such as the Juneau Icefield Research Program (JIRP) where greater than 60% of the students have been women between 2017-2019 (https://juneauicefield.org/). Alpine and ice cap ice coring in North America can indeed be a more accessible avenue for getting diverse students into the fieldwork setting. This can also serve as a pipeline to polar programs, training students in field scientific skills, remote communications, group dynamics, field safety, and more.

High Mountain Asia region: An USAID grant has been awarded to the proposers to help increase capacity at Pakistani institutions. U.S. ice core collaboration with Pakistan would provide a means to further increase ice core education, resources, and collaborations in the US and Pakistan. Pakistani involvement would provide a network of colleagues living in and downstream of the very region being studied, and help increase diversity and inclusivity within the ice core community.

A final note is linked to the importance of programs for ice storage (e.g. NSF-ICF, Ice Memory) for the study and conservation of ice cores by the future generation of scientists as a novel form of intergenerational inclusion. It is of fundamental importance that every Alpine program will consider, if possible, the extraction of extra ice for this purpose.

5 Future Drill Site Selection and Development Considerations

Geophysical, remote sensing, and numerical modeling (e.g. Campbell et al., 2012; Campbell et al., 2013; Licciulli et al., 2020) capabilities have evolved significantly over the past two decades. This evolution allows for more sophisticated pre-analysis of potential ice core or subglacial access drill sites, providing assurances that science objectives will be met and that benefits of each core or borehole are maximized.

For example, GPR now provides rapid lateral and vertical 3-dimensional structural glaciological observations in detail that was not available in the early part of the century. Concurrently, high resolution digital elevation models through stereo imagery, LiDAR, or Structure-from-Motion, terrestrial surface velocity observations from GPS, ground-based interferometry (GBI), or satellite techniques, and vertical velocities observable from autonomous phase sensitive radar (ApRES), when combined, provide unprecedented quantitative data for incorporation in numerical models addressing drill site suitability. These field and remote sensing observations also provide detailed opportunities for model validation, post-coring. This is important, particularly considering the cost and logistics associated to extract and process each ice core record.

We encourage NSF to consider investing in geophysical equipment (e.g. GPR, ApRES, Interferometry) and associated expertise which would be made available to the ice coring community for core site selection and analysis. Wider access to this equipment/expertise funded ice coring and sub-glacial drilling proposals would also promote smaller academic or research programs that typically do not have this kind of in-house instrumentation. We also recommend that, if possible, geophysical characterization of potential drill sites should be conducted prior to drilling works to reduce uncertainties and maximize benefits.

Finally, boreholes linked to alpine ice core drilling programs are also a unique opportunity that so far has been only rarely and partially exploited (e.g. Gabrielli et al. 2016). In synergy with the Borehole Logging Working Group (BLWG), boreholes can be used for additional geophysical investigations (e.g englacial temperature, glacier dynamics; Vincent et al. 2007), in situ measurements (e.g dust, Bramall et al.2005) and to investigate life signature that could inform researchers of ice regions for further targeted analyses taking ice as an analog for environments of other planetary bodies (Eshelman et al.2019).

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