Draft white paper for additional community input

Please email suggestions to Erich Osterberg Erich.C.Osterberg@dartmouth.edu before June 4, 2020

IDP Ice Core Working Group (IDP-ICWG)

Ice Core Research Priorities in Greenland

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IDD Intermediate Drill testing camp at Summit, Greenland in 2014. Credit: Jay Johnson.

Summary

Rapid warming is profoundly affecting Arctic ecosystems, accelerating Greenland Ice Sheet (GrIS) melting, reducing sea ice cover, raising sea level and endangering coastal societies and infrastructure. However, large uncertainties remain about the projected rate and magnitude of Arctic cryosphere and ecosystem change in the coming decades under plausible 21st century emissions scenarios. Greenland ice cores revolutionized our understanding of climate change when they revealed a series of abrupt climate change events (CCEs) in the glacial and Holocene. The paleorecord indicates that Arctic processes (e.g. deep-water formation and sea ice) played a central role in past CCEs, but we still lack a comprehensive understanding of their triggers and dynamics. Climate model projections suggest that warming and increased meltwater runoff will weaken the Atlantic circulation in the 21st century, a scenario similar to past CCEs. Understanding how such processes occurred in the past is needed to better predict nonlinear responses to anthropogenic warming that will have impacts well beyond the Arctic. It is particularly challenging to quantify the impact of human activities on Arctic systems because of the extremely short instrumental period, often limited to the satellite era since 1979. Details of pre-instrumental Arctic processes over the Common Era and the evolution of human impacts from the onset of industrialization are needed to clarify future vulnerabilities.

These critical knowledge gaps can be addressed by a series of new ice cores and state-of-the-art, high-resolution analyses that are developed in a convergent framework that incorporates a diverse research community. This new approach will focus on the following research priorities:

1) **Arctic Change and GrIS Instability during Warm Periods:** The Holocene Thermal Maximum (HTM; ca. 5,000-9,000 years BP) and Eemian interglacial (130,000-115,000 years BP) are periods when Arctic summers were at least 3-5°C warmer than today, making them valuable analogs for future warming. A strategy that involves ice cores to bedrock in Northern and Southern Greenland will target the GrIS response to these past warm intervals.

2) **Mechanisms of Abrupt Climate Change:** The regional and global expression of abrupt climate change events (CCEs) during the last glacial period (Dansgaard-Oeschger and Heinrich events) and Holocene (8.2 ka event, Medieval Climate Anomaly/Little Ice Age, and the Industrial Era) provide a critical perspective on the complex interaction of various Earth System components. The spatial pattern and detailed anatomy of CCEs across Greenland remain elusive, but can be accessed with a combined shallow/intermediate/deep drilling approach.

3) **The Evolution of Human Impacts on the Arctic:** The complex interaction of human emissions (greenhouse gases, pollutants) and activities (biomass burning) with natural forcing and feedbacks (volcanic eruptions, oceanic and atmospheric circulation, sea ice, GrIS mass balance, sea level) must be resolved on a seasonal basis throughout Greenland with agile drilling of shallow cores. Societally-relevant predictions regarding future changes in the coupled human/natural system require these data.

Driving Scientific Questions

The Arctic climate, atmosphere, ecosystems and cryosphere will continue to respond to anthropogenic forcing in ways that strongly impact local and global societies. Our research questions focus on specific aspects of ***past*** *Arctic change that provide the most useful insights into future coupled human/natural systems in the North.*

Question Group 1: Arctic change and GrIS instability during warm periods

Motivation: The Arctic spatial response during interglacial periods warmer than today provides analogs for potential Arctic cryosphere and ecosystem change in the near future.

A. What was the magnitude, timing and seasonality of peak Arctic warmth during the early Holocene thermal maximum and Eemian?
B. How did Arctic sea ice, weather patterns, GrIS mass balance, and ecosystems respond during past warmer periods?
C. How much, and how quickly, did the GrIS melt and raise sea level?
D. How accurately do global climate models and ice sheet models capture the variability of interglacial climate forcing and cryosphere and ecosystem response?

Question Group 2: Mechanisms of abrupt climate change events

Motivation: Understanding the triggers, feedbacks, and system instabilities involved in abrupt climate change events (CCEs) is crucial to clarify fundamentals of nonlinear Arctic processes.

A. Did past CCEs (e.g. Dansgaard-Oeschger Events, Heinrich events, Younger Dryas, 8.2 ka Event, Medieval Climate Anomaly/Little Ice Age) occur synchronously across Greenland, or were there regional differences in their magnitude, timing and seasonality?
B. Can the detailed anatomy of CCEs, including the relative phasing of changes in the cryosphere, ocean circulation, atmospheric circulation, and greenhouse gases, reveal fundamental insight into their governing processes?
C. What can we learn about anthropogenic climate change from the record of past natural CCEs during the glacial period and Holocene?

Question Group 3: The evolution of human impacts on the Arctic

Motivation: Greenland ice preserves a history of human activities and their impact on Arctic systems, providing insight to future vulnerabilities and clarifying human/natural interactions.

A. What are the time-evolving and spatially variable impacts of human activities on the Arctic climate, atmosphere, cryosphere and ecosystems over the Common Era?
B. How does the Arctic response to anthropogenic forcing differ from the response to natural forcing, including the Little Ice Age and Medieval Climate Anomaly?

C. When did human signatures emerge from the range of natural variability in the Arctic?

Scientific Rationale

A new network of Greenland ice cores combined with state-of-the-art analytical techniques would provide the critical data needed to address the questions above. We envision an expanded model of open source, community-driven ice core data collection, analysis and sharing which will enhance collaboration and promote community diversity and inclusivity.

Over the next decade, the U.S. ice core community is primarily focused on regions close to the periphery of the GrIS where the amplitude of past climate variability and the magnitude of GrIS response is larger than in central Greenland. Cores drilled to bedrock (1400-2400 m deep) in northwest Greenland ('Qaanaaq site') and south Greenland ('South Dome') would clarify the magnitude of warming and GrIS response during the early Holocene and Eemian. Combined with existing records from the Greenland interior (GISP2, GRIP, NGRIP, NEEM, EGRIP), the Qaanaaq and South Dome cores would provide a north-south gradient of records during CCEs, allowing us to test hypotheses about their ultimate cause and gain insight about the impacts of human-induced climate change. Access to basal ice and underlying sediment and bedrock would incorporate a broad community of multidisciplinary researchers who could explore GrIS stability and terrestrial ecosystems during older interglacials, and would provide information about basal boundary conditions (geothermal flux, ice-sediment coupling) essential to constrain ice sheet models.

Shallow ice cores (20 - 700 m deep) collected from the GrIS percolation zone and peripheral ice caps would reveal the evolution and spatial signature of human impacts on the Arctic over recent decades to millennia. High-resolution records of surface mass balance (SMB), temperature, atmospheric composition, and sea ice extent, among others, are vital for extending the limited Arctic instrumental record back to pre-anthropogenic times and validating remotely sensed data and climate models. A distributed network of shallow ice cores is needed from north-to-south along the western and eastern GrIS percolation zones to constrain the spatial signature of human impacts. As independent glacier domes, peripheral ice caps provide opportunities to collect regional Arctic climate records even further back through the Holocene and potentially into the glacial with agile ice drilling systems (400-700 m). The study of atmospheric gases (e.g. CH_4) using ice cores and firn air is an important exception to the focus on the GrIS percolation zone and peripheral ice caps. The cold, dry conditions of Summit, Greenland are optimal for such studies.

Target Ice Core Sites

Intermediate Core from Northwest Greenland ('Qaanaaq Site')

A new intermediate-depth (1400-1800 m) ice core from Northwest (NW) Greenland would provide an excellent opportunity to improve our understanding of the HTM and Eemian climate forcing and the magnitude and rate of GrIS retreat. As a long-duration (~10,000 year) warm period, the Eemian represents an opportunity to quantify the ice sheet's "Equilibrium Response" to warmer conditions, as there was sufficient time for GrIS mass loss to stabilize at the warmer mean state. As a shorter and more recent (~5-9 ka) warm period, the HTM is an opportunity to quantify the GrIS "Transient Response" to warming; to reconstruct seasonally-resolved changes in climate forcing and the detailed ice sheet response *through time*. Ice sheet models require constraints on both the equilibrium (Eemian) and transient (HTM) response to warmer conditions, and *an intermediate-depth NW Greenland ice core would capture both responses in a single record.*

Northwest Greenland is of particular interest to the community because limited published data suggest that the region experienced strong (4-8^{o}C) summertime warming during both the HTM and the Eemian (McFarlin et al., 2018; Lecavalier et al., 2017). The northwest GrIS is also a particularly dynamic region of the ice sheet. HTM warming is hypothesized to have caused 600-1000 m of thinning at the Camp Century site (Vinther et al., 2009; Lecavalier et al., 2017), and the NW GrIS is currently losing mass faster than any other region of the ice sheet (2010-2018; Mouginot et al, 2019). Existing ice core chemistry in NW Greenland confirms that changes in temperature, precipitation (snowfall), and sea ice extent in Baffin Bay are accurately recorded (Dansgaard et al., 1969; Osterberg et al., 2015; Wong et al., 2015). Combining the distinctive Baffin Bay record from the Qaanaaq Site with Greenland Sea and North Atlantic records from the EGRIP and South Dome cores, respectively, would clarify the spatial evolution of Arctic climate variability.

Critically, the Camp Century ice core collected in 1963-1966 demonstrated that Eemian-age ice is present near the bed at a depth of only ~1400 m (Johnsen et al., 2001). This is well within the depth range of the Intermediate Depth Drill (IDD) developed by the U.S. Ice Drilling Program and successfully used to collect the South Pole Ice Core (1751 m). The ability to sample the sub-glacial sediment and bedrock, and the proximity to ice-marginal lakes and a planned IODP drilling campaign, provide unique opportunities to bring together researchers across disciplines to address our critical research questions. The proposed Qaanaaq coring location will furthermore be synergistic with the recent NSF-funded Petermann glacier experiment (Mix et al., 2016 AGU abstract). Finally, the proximity to Thule and an existing over-ice traverse route simplifies logistical planning for an intermediate ice core project in NW Greenland.

Deep Core from South Dome

Abrupt Climate Change events (CCEs) in the last glacial period are closely linked to variations in the Atlantic Ocean circulation (Liu et al., 2009; Lynch-Stieglitz, 2017). The seminal ice cores drilled in central and northern Greenland have provided unique records of CCEs, yet are further from the location of deep water formation in the North Atlantic than southern Greenland. Heinrich events are indistinguishable from other stadial events in Greenland climate records despite their prominent signatures in Antarctic and tropical records. Given the expected pattern of Heinrich cooling, a southern Greenland ice core would provide the best opportunity to observe a unique signature of Heinrich events in Greenland climate for the first time. Dye-3 is the only ice core in southern Greenland that is continuous from the last glacial period to modern times. In the 1970s, it was sited based on its proximity to the Dye-3 early warning station rather than for its glaciological characteristics; the Dye-3 ice deeper than 1915 m (~42,000 years BP) is impossible to interpret due to stratigraphic disturbance. The lack of high resolution records from southern Greenland leave fundamental questions about abrupt climate change and sea level rise unanswered.

The $\delta^{18}O$ record at Dye-3 suggests that high-resolution records could be collected from a nearby site at South Dome (>2000 m deep) back to at least 40,000 years ago; it is likely that, with modern radar imaging and site-selection expertise, older ice can be found in stratigraphic order near the dome's divide. With present-day drilling expertise and high-resolution analytical capabilities, important scientific questions concerning the magnitude and timing of CCEs in southern Greenland can be addressed (Ganopolski and Rahmstorf, 2001; Buizert et al., 2014; Badgeley et al., 2020). In addition, the climate records from a South Dome ice core would be critical for creating boundary conditions for ice-sheet models, which are needed for interpreting past rates of sea level rise and for providing context for modern and projected changes (Badgeley et al., 2020; Briner et al., submitted).

CCEs, such as the Dansgaard-Oeschger cycles, likely involve migration of the summertime position of the polar front across Greenland. New climate records from South Dome would show whether southern Greenland climate change is synchronous with central and northern sites; in other words, did the polar fronts move abruptly or slowly across Greenland? Similar to the Qaanaaq location, a South Dome core would have a relatively low surface elevation, allowing studies of past melt frequency and intensity to answer questions related to the timing, magnitude and seasonality of the HTM. Like the Dansgaard-Oeschger events, the timing and magnitude of the HTM may differ significantly between the north and south of Greenland. New cores at both Qaanaaq and South Dome will resolve the zonal gradient of climate from the last glacial to present. South Dome additionally presents a unique opportunity to learn about ice sheet stability. Modeling studies suggest that a southern dome may persist in warm climates (e.g. Fyke et al., 2014). Along with climate records from the ice core, measurements from the basal ice (e.g., Willerslev et al., 2007) and bedrock (Schaefer et al., 2016) collected beneath South Dome would address questions of ice sheet stability.

Shallow/Agile Ice Core Sites

Greenland Ice Sheet Percolation Zone: New cores from the GrIS percolation zone provide an opportunity to reconstruct past snowfall and surface melt across a geographically expansive region of the GrIS (Graeter et al., 2018; Trusel et al., 2018). Ideal sites are those where surface melt occurs on an annual or near-annual basis (preserved as refrozen melt layers), but in small enough quantities that the seasonal stratigraphy is not destroyed by meltwater percolation. Recent evidence indicates that much of Greenland has experienced a decrease in snow accumulation since the mid 1990s contrary to model projections (Lewis et al., 2019), whereas northwest Greenland has experienced an increase in snowfall over the same time period (Hawley et al., 2014; Wong et al., 2015). Furthermore, regional climate models suggest that the largest SMB decline over recent decades occurred in southwest Greenland (Mouginot et al, 2019). Confirming these observations and testing hypotheses for their cause requires collecting a series of shallow (20-400 m) ice cores from the percolation zone in NW and SW Greenland. Such records can also provide spatially-distributed records of sea-ice extent (Osterberg et al., 2015), marine productivity (Osman et al., 2019), atmospheric circulation (Mosley-Thompson et al., 2005), and atmospheric chemistry/pollution (McConnell and Edwards, 2008) during the crucial late Holocene transition from the pre-anthropogenic to industrial ages.

Das2 Site, SE Greenland: The Das2 site in SE Greenland is an excellent target for Greenland research requiring high snow accumulation (~90 cm ice equivalent per year) and unusually high temporal resolution (e.g. Pedro et al., 2012). For example, hydroxyl radicals (OH) are the main tropospheric oxidant and their concentration ([OH]) determines the lifetime of methane and most other trace gases in the atmosphere, thereby controlling the amount of greenhouse warming that emissions of these gases can produce (e.g., Brasseur et al., 1999). Changes in [OH] in response to large changes in reactive trace gas emissions (which may happen in the future) are uncertain. Atmospheric ^{14}CO measurements over the last ~30 years have been successfully used to help monitor changes in [OH] (Manning et al., 2005). A complicating factor for ice cores is the added production of ^{14}CO by cosmic rays directly in glacial ice. Recent work (Petrenko et al., 2016) shows that at ice core sites with very high accumulation rates, the in situ cosmogenic ^{14}CO signal would be relatively small and can be corrected for.

Peripheral Ice Caps: Glaciologically independent ice caps around the margin of Greenland provide opportunities to collect long records (500-125,000 years) of regional Arctic climate using agile coring technology (200-700 m depth), as demonstrated by cores from Renland Ice Cap, Flade Islbink, and Nuussuaq Ice Cap (e.g. Johnsen et al., 2001; Lemark and Dahl-Jensen, 2010; Trusel et al., 2018). Ice Caps of particular interest include North Ice Cap and Prudhoe Land Ice Cap (informal name) near Thule and Qaanaaq, respectively, which are far enough north that summer melt percolation does not eliminate seasonal stratigraphy. Previous studies show a strong coast-to-interior gradient in NW Greenland precipitation increases (Wong et al., 2015); ice cores from these peripheral ice caps would capture this stronger coastal climate variability, including sea ice extent. Shallow ice cores drilled to the ice cap bed could leverage logistics and provide synergy with the subglacial exposure age community, which has also prioritized Prudhoe Land Ice Cap for future study. The Renland ice core shows that such ice caps may preserve ice from the last interglacial, providing further impetus for drilling in these locales.

Summit: Shallow cores from Summit are a high priority, particularly for the ice core gas community, due to its cold, dry-snow conditions and simplified logistics. For example, atmospheric methane is the second most important driver of anthropogenic warming due to its 2.5-fold mole fraction increase since the preindustrial (Shindell et al., 2009). Interestingly, the growth rate of methane paused for almost a decade beginning in the late 1990s before rapid growth resumed starting in 2007 (Schaefer et al., 2016). The cause of this most recent rapid increase in methane is not well understood and is currently the subject of an intense scientific debate (e.g., Turner et al., 2017). Methane isotopes (^{14}C, ^{13}C, dD) can help to identify the causes of the methane increase, but relatively few measurements of dD and 14C of methane over the last ~15 years are available. Air in the firn column provides a well-preserved archive of the atmosphere from the last few decades. A new shallow core to ~85 m depth from Summit, accompanied by firn air sampling, would enable a detailed reconstruction of recent isotopic history of atmospheric methane and help to solve the puzzle of the current rapid methane rise.

Improving Community Diversity and Inclusivity

The U.S. ice core community is committed to increasing the participation of female, underrepresented minority, and early-career researchers. The Qaanaaq and South Dome projects outlined above would expand upon the successful model developed for community ice cores recently drilled in Antarctica (e.g. WAIS Divide and SPICEcore). Each year, we will host a science coordination meeting in Washington D.C. This meeting will be open to all so that researchers across disciplines can contribute to the discussion. Travel funds will be prioritized for early-career scientists, and remote participation (e.g. via Zoom) will be available and optimized so that virtual attendees feel equally included in the discussion. International collaborations, particularly with researchers from Greenland and Denmark, are already established within collaborative science teams. Community input during meetings early in the project will drive the allocation of the ice core samples based on scientific priorities. In later years, the meetings will focus on new scientific results. Because the ice recovered during these projects is intended to serve as a community resource into the future, we will encourage collaborative research that can produce a wide array of measurements while using minimal ice to satisfy the science goals of the community.

There are also several exciting opportunities to enhance diversity and inclusivity through interface with Northern communities. As an example, several U.S. ice core institutions are members of the University of the Arctic (UArctic), a cooperative network of over 200 universities, colleges, research institutes and other organizations concerned with education and research in and about the North. UArctic has several programs to foster international student exchange among member institutions. These programs could be a valuable way to encourage Northern indigenous students to become engaged in ice core science. In addition, developing new capacity (building community and resources) for a next generation approach to ice core data product development for future Arctic decision making could be achieved by hosting workshops bridging ice core, modeling, and regional Northern community knowledge experts (pending NSF NNA Track 2 project). Outcomes of these workshops could include a focus on Northern indigenous student inclusion in ice core science.

Sampling Requirements and Drilling Parameters

Ice Drilling Program (IDP) Drill Systems

All of the target ice cores discussed above can be collected using drilling systems that are either in the IDP inventory or are currently being developed by IDP. The **Intermediate Depth Drill (IDD)**, used to successfully collect the SPICEcore, would be used to collect the Qaanaaq ice core. The **FORO3000** is the most appropriate drill for collecting the South Dome Ice Core as the ice thickness will likely be greater than 2000 m. This drill is currently being constructed by IDP for anticipated use at Hercules Dome in Antarctica. Shallow ice core sites will utilize a range of drills including **hand augers,** the **Blue Ice Drill,** the **Eclipse Drill,** the **FORO400**, and the **700 Drill**. The 700 drill conceptual design is currently being developed by IDP, and it would be well suited for drilling cores from Greenland peripheral ice caps.

Replicate Coring from High-Value Depths

There will be strong demand in the U.S. community for Greenland ice, particularly surrounding important climate events such as the Younger Dryas, glacial CCEs, and the Eemian. Replicate coring for the intermediate and deep drilling projects (IDD and FORO3000 drills), similar to what was performed at WAIS Divide in Antarctica, will be highly desirable. The interpretation of the compressed basal ice (likely Eemian in age) with potential irregular layering would be improved with larger sample volumes and the ability to better understand potential stratigraphic disruptions with replicate cores. For these studies, drill orientation data would be valuable for improving interpretations.

High-Quality Core from the Brittle Ice Zone

Obtaining minimally fractured ice core sections through the brittle ice zone is a high priority. Much of the brittle ice zone across the Greenland Ice Sheet includes mid-early Holocene strata which represent a high-priority analog for 21st century conditions. Recent IDP advances in drilling and core handling techniques have produced high-quality core in brittle ice from the South Pole and the Northeast Greenland Ice Stream (Danish EGRIP project).

Sub-Glacial Sediment and Rock Coring

Another priority for the U.S. community is improving our capability to collect sediment and rock cores (up to 10 m long) beneath intermediate (Qaanaaq) and deep (South Dome) ice cores. These samples provide critical information about ice sheet extent during prior interglacials, interglacial and pre-glacial climate and ecosystems, subglacial erosion rates, and data needed to constrain ice sheet models including heat flux and till rheology. As an indication of the value of such samples, an October 2019 workshop to discuss results from Camp Century basal sediment (collected in 1966) attracted 33 researchers from around the globe (Voosen, 2019). Improving sub-glacial sampling beneath the Qaanaaq and South Dome ice cores would thus increase the science impact and further broaden the disciplinary range of researchers on these projects.

Target Timeline

2021-2026: Site selection of the Qaanaaq and South Dome sites could be combined with agile drilling campaigns focused on surface mass balance and the evolution of human impacts (2021-2023; proposal in development). Agile ice coring and firn sampling at Summit (2021-2023), peripheral ice caps (2021-2025), and Das2 (2024-2025) are all being proposed over the next few years. Annual science coordination meetings for the Qaanaaq project would be planned as part of a science coordination and drilling proposal (in development), with drilling at Qaanaaq targeted to span two seasons, potentially 2023-2024 or 2024-2025.

2026-2031: Analysis and interpretation of the Qaanaaq core would continue with annual community meetings to discuss research results and publications. Planning for deep drilling at South Dome would be incorporated into these meetings, with drilling targeted to span three seasons, potentially 2026-2028 or 2027-2029.

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