

# Sustaining the Science Impact of Summit Station, Greenland

*A white paper produced from the Summit Station Science Summit.*



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## Executive Summary

Summit Station, Greenland is, and should remain, a multi- and interdisciplinary science research hub that has served as a crucial component of the observing system for the Arctic region for nearly three decades (Summit's relevance to science is detailed in **Section 1**). Summit is the site where the Greenland Ice Sheet Project Two (GISP2) ice core showed that temperatures have changed by several degrees Celsius in a handful of years and remains the only site on the Greenland ice sheet with a long enough suite of climatologic, atmospheric and glaciologic measurements to understand and model if these dramatic change processes of the past are occurring today or will occur in the future. Summit provides evidence to show that accumulation on the ice sheet is not compensating for melt and ablation leading to accelerating mass imbalance over the ice sheet and contributing to the rising seas of today. The comprehensive, high quality, long-term records tied to the GISP2 ice core are critical to understanding current changes and processes across the ice sheet and the Arctic. The scientific research at Summit goes beyond glaciology and includes process-based scientific discovery from science questions spanning from the outer reaches of space to the bedrock below the Greenland ice sheet, transforming our research and knowledge (Science questions are detailed in **Section 2**). Studies and observations obtained from the station are currently used across the research spectrum, including for numerical weather prediction, atmospheric reanalyses, surface process models for understanding ice-sheet mass balance, models of clouds and atmospheric water vapor, tropospheric and stratospheric chemistry modeling, regional climate and general circulation models, and to investigate the early universe (The state of scientific discovery and research is detailed in **Section 4**).

In this report, we conclude that *Summit Station is scientifically powerful because it leverages a suite of scientific measurements, co-located over time and at one point in space, allowing researchers to go beyond their own study and put their research into the larger climate perspective.* This perspective allows process-based discovery to contribute to an assessment of climate that is necessary for understanding and modeling the changing Arctic system. As we envision future paths for sustaining the science impact of Summit (**Section 3**) our recommendations emphasize leveraging the broad suite of long-term measurements, the only measurements capable of deciphering climate change from natural variability over an ice sheet containing over 6 meter of potential sea level rise, to ensure science discovery across multiple disciplines. Given the climatological importance of Summit and the devastating societal impacts if sea levels were to rise faster than predicted, we specifically recommend the future logistics scenarios of Increased Operations, Business as Usual, Minimum Personnel, Multiparty or Reduced Operations with

winter power (**Section 3**) to maintain year-round observations of the key processes that effect our abilities to measure and predict change. Maintaining year-round measurements for processes that directly relate to improving atmospheric, climate and ice sheet models, calibrating satellites and determining long-term trends and variability for key scientific questions (**Section 2**) are essential for scientists to analyze and predict change. We recommend the expansion of Summit for future astrophysics studies and emphasize the importance of maintaining a clean snow and air sector at Summit (**Section 3**). Furthermore, we strongly recommend continued efforts to collect and disseminate Summit data sets as quickly and broadly as possible to further scientific discovery (**Section 3**).

This report uniquely identifies and describes the most-critical measurements taken at Summit and how many could be automated given sufficient financial and schedule support (**Section 4**). We recommend at least one year of overlap between automated and currently manned measurements (**Section 3**) to maintain climate quality records. We recommend that future National Science Foundation (NSF) solicitations highlight the need to develop technologies to automate Summit and enable reductions in cost and staff of Summit in the future.

We recommend that the NSF recognize the vital importance of the climate records at Summit to a broad swath of the scientific research and modeling communities and establish it as a protected site, similar in stature to the Long Term Ecological Research Sites, with a core set of community measurements which we specify in this report (**Section 3**). The measurements are necessary for large community-wide studies, including but not limited to, understanding the Greenland ice sheet's contributions to sea level rise, the changing arctic atmospheric and boundary layer over an ice sheet and the impact of clouds on accelerating land ice melt. We recommend that future NSF solicitations highlight the major science questions that can best be addressed by scientific research at Summit described in this report (**Section 2**) and encourage researchers from disciplines outside of the cryosphere community to consider proposals using Summit as a research site (e.g. following guidance from the NSF Antarctic solicitation). The recommendations in this report direct science towards the next major discoveries to benefit society including determining: What are the hemispheric and global impacts of atmospheric change on radiative forcing, including effects of clouds; Whether the Arctic has passed a tipping point; How much will sea-level rise due to Greenland's contributions by 2050, or 2100; Are we approaching a dramatic mode change in the climate system as seen in the past; and What are the physics of the early universe?

## 1.0 The Science Domain of Summit Station

Earth's polar Ice Sheets, in Antarctica and Greenland, are pristine, high altitude observatories that host researchers seeking to answer fundamental Earth and Space Science questions including: how has Earth's climate, sea level and atmospheric composition changed in the past, what future changes should societies anticipate, and how did the Universe begin? The geography of ice sheets in the Northern and Southern Hemisphere provide insight



**Figure 1.1:** GISP2 Borehole at Summit Station, Greenland in 2011.

into the timing, magnitude and causes of glacial/interglacial cycles, allow for monitoring the dynamics of atmospheric circulation and widen the views of our galaxy for telescopes.

Summit Station, Greenland ( $72^{\circ}35'46.4''\text{N}$   $38^{\circ}25'19.1''\text{W}$ , 3216 m a.s.l.), hereafter Summit, is an anchor in this rich global and historic scientific context, serving as *the longest continually operating station on the Greenland ice sheet, since ~1989, with extensive, historical paleoclimate ice core records from the Northern Hemisphere dating back over 100,000 years and spanning a glacial cycle.* The time series at Summit makes it the only site on the Greenland ice sheet with a long enough suite of climatologic, atmospheric and glaciologic measurements to understand, model and validate change processes. The station benefits from its unique geography as a highly representative location for surface climate conditions over the Greenland ice sheet dry snow zone. The presence of a virtually unlimited, pristine snowfield and *low internal climate variability allows for small regional and larger-scale trends to be detected quickly.*

Scientific discoveries at Summit have directly benefited society in many ways. Notably, the high-resolution climate record in the Greenland Ice Sheet Project Two (GISP2) ice core revealed that our climate can change by several degrees Celsius in a handful of years – far more abruptly than previously thought, alerting us to the many feedbacks and thresholds in the climate system. Likewise, ice mass changes recorded in satellite data, made possible by calibrations at Summit, have drawn attention to the Arctic impacts of climate change on the ice sheet and the potential sea level rise. Long term measurements of atmospheric trace gases at this pristine site show the seasonal prevalence of atmospheric non-methane hydrocarbons, which impact air quality, and have shown that ethane levels, the most prevalent and longest-lived non-methane hydrocarbons (NMHC), have been steadily increasing in recent years due to oil and natural gas



production in the United States (US).

Today Summit is a multi- and interdisciplinary science hub utilized by government agencies, primarily but not limited to, the National Science Foundation (NSF), The National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA), to further the United States of America's research and education agendas. International researchers supported by the governments of Denmark, Norway, Germany and the European Union are also part of the Summit science community. Each summer Summits hosts the Joint Science Education Project (JSEP), a cultural and science exchange that brings together Greenlandic, Danish and US Students for a hands-on polar science research experience that continues the tradition of international cooperation and education at the site. Summit has proven a safe, inclusive field camp where senior researchers work alongside undergraduate students, fostering a collaborative work environment that produces valuable, unquantifiable science results, trains the next generation of scientists and enables transformative research.

The Summit infrastructure, which simultaneously enables process-oriented work and climate studies, provides a breadth of scientific measurements and critical, often unknown at the time, synergisms that are matched at few other locations. *Summit Station is scientifically powerful because it leverages a suite of scientific measurements, co-located over time and at one point in space, allowing researchers to go beyond their own study and put their research into the larger climate perspective.* While this synergism is difficult to quantify, it is clearly evident in: paleo-climatologists' continued campaign science at the site of GISP2; the inclusion of Summit by glaciologists in transects to understand mass balance of the entire ice sheet; why modelers include Summit data in efforts to validate and improve numerical weather predictions, global chemical transport models, and modeling of paleoclimates including glacial/interglacial cycles; NASA's selection of Summit as a calibration site for Operation IceBridge and the Ice, Cloud, and land Elevation Satellite Two (ICESat-2) missions; and astrophysicists choosing Summit as a site to investigate how different snow/firn conditions capture neutrons.

Summit should remain a crucial component of the observing system for the Arctic region. Observations obtained from the station serve scientists across the research spectrum, including numerical weather prediction, atmospheric reanalyses, surface process models for understanding ice-sheet mass balance, models of clouds and atmospheric water vapor, tropospheric and stratospheric chemistry modeling, and regional climate and general circulation models. Observations from Summit contribute to global predictions of sea level rise and Arctic change through the Intergovernmental Panel on Climate Change (IPCC). **Table 1.1** provides a snapshot of the science that has been accomplished at Summit and significant outstanding science questions for each of the major scientific disciplines present at Summit.

**Table 1.1:** The Scientific fields that conduct research at Summit, an example of one of their leading scientific discoveries and their high level scientific questions still to answer.

<b>Scientific field</b>	<b>Major discovery</b>	<b>Still to answer</b>
Earth Systems Modeling	The Arctic is warming two times faster than the rest of the globe.	Has the Arctic passed a tipping point? Is the albedo feedback irreversible? How much and how fast will global sea-level rise?
Astrophysics	The Central Greenland ice sheet is an ideal location for cosmic ray background studies and the global network of telescopes.	What are the physics of the early universe? Do Black Holes have spin? How do Black Holes launch jets? Does General Relativity hold near a Black Hole?
Atmospheric Science	Aerosols reaching Greenland have declined in response to regulations and economic changes in North America and Europe, while Greenhouse Gases continue to rise. Supercooled liquid clouds occur frequently over Greenland. Effects of radiative forcing manifest in extensive surface melt events.	What are the hemispheric and global impacts of atmospheric change on radiative forcing, including effects of clouds? Will growing emissions of aerosol and precursor gases in southeast Asia reverse current trends and radiative impacts?
Atmosphere and Snow Interactions	Vigorous two-way exchange of water, energy and chemicals have profound effects on both the snow and the atmosphere.	Is the record 2012 melt event an indication that the dry snow zone of the Greenland ice sheet is imperiled?
Glaciology	The Greenland ice sheet is losing ~300 gigatons of mass per year, contributing to sea level rise.	Will recent trends of accelerating mass loss continue, or speed up further? How much will sea-level rise due to Greenland’s contributions by 2050, or 2100?
Paleoclimatology	Our climate can abruptly- increase several degrees celsius on decadal-scales.	Are we approaching similar dramatic mode changes in the climate system?

Summit is in a strong position to continue its vital role in US research agendas. As detailed in this report, Summit research is poised to contribute to the high-level “Grand Challenges” of protecting human health and exploring the universe at all scales by improving models of Arctic, atmospheric and sea level change, improving our understanding of the global water cycle, and providing a Northern Hemisphere location for studying the Universe. Summit directly addresses, and should continue to address, the two main objectives of the Interagency Arctic Research Policy Committee (IARPC), Glacier Ice 5-Year plan to 1) Coordinate and integrate observations to improve understanding of the processes controlling the mass balance of Arctic land ice and 2) Improve numerical models to enhance projection of ice loss from Arctic

land ice and the consequent impact on global sea level, and to better understand the predictability of these processes. The research at Summit supports the findings of the Fairbanks Declaration signed by the US and Arctic Council members in May of 2107 and can continue to support the declaration's future directions by monitoring black carbon and methane and contributing to the observations by joining the World Meteorological Organization's Global Cryosphere Watch. Cloud and atmosphere research conducted at Summit is part of the upcoming international Year of Polar Prediction (YOPP) effort, one of seven US-lead YOPP endorsed projects. And, finally, Summit's scientific research is aligned with 5 of the 10 Big Ideas the National Science Foundation has proposed for future research directions including Navigating the New Arctic, Windows on the Universe: The Era of Multi-messenger Astrophysics, Enhancing Science and Engineering through Diversity, Work at the Human-Technology Frontier: Shaping the Future, and Growing Convergent Research.

As we look to the future for Summit, it is important to review lessons from history. Summit currently maintains the longest time series of data from the interior of the Greenland ice sheet, a site of low climate variability, yet extremely high societal impacts if accelerated warming occurs. Decades ago, Byrd and Siple Dome Stations in West Antarctica were analogs to Summit today. Both were eventually closed. We know that science was hindered by losing the continuity once maintained at these stations. Bromwich et al. (2013) clearly articulates that the incomplete temperatures records from West Antarctica slowed the realization that West Antarctica had indeed been warming over the past decades. This underscores the point that time series must be maintained so history doesn't repeat itself in the Arctic where temperatures are now rising at double the rate for the rest of the globe (Richter-Menge et al., 2016). For perspective, the accuracy lost for a monthly temperature record when a manned temperature station with a ventilated housing that is monitored daily is replaced by automatic weather station with an unventilated housing is  $\sim 0.5$  °C (Shuman et al., 2014a; Shuman et al., 2014b), or equivalent to the last decade of warming over the Greenland ice sheet surface (Hall et al., 2013).

This report begins with the fundamental science questions we seek to answer (**Section 2**) at Summit and how they relate to NSF's Big Ideas ([https://www.nsf.gov/about/congress/reports/nsf\\_big\\_ideas.pdf](https://www.nsf.gov/about/congress/reports/nsf_big_ideas.pdf)) to understand our universe and provide fundamental, process, and systems-level understanding of the changing Arctic and the future impacts of these changes on society. Our recommendations and future vision (**Section 3**) directly emerge from our science questions to enhance the contribution of Summit to transformative science that benefits society. Finally, we provide specific details, by scientific discipline, on how each discipline contributes to the scientific questions, recommendations, critical nature of the science investigations and societal benefit of the science (**Section 4**). The appendixes include the background, data, statistics and publications that support this report and its recommendations. **Appendix A** contains the results from a public survey on Summit, **Appendix B** data on Science User Days at Summit, **Appendix C** publications using Summit data, **Appendix D** download statistics for Summit data, and **Appendix E** the scientific measurements made at Summit in 2016.

## 2.0 Science Questions and Relation to NSF's Big Ideas

The NSF's Big Ideas for Future Investments provides a structure for ensuring the process-based scientific questions investigated at Summit contribute to the overarching scientific goals set by NSF. The research infrastructure at Summit and the longstanding culture of welcoming diverse, multi-, inter-, and transdisciplinary teams promotes synergy as multiple projects collect data at the same location and time. This history places Summit and its' user community in a strong position to respond to NSF's interest in Growing Convergence Research, where *"Convergence can be characterized as the deep integration of knowledge, techniques, and expertise from multiple fields to form new and expanded frameworks for addressing scientific and societal challenges and opportunities (NSF, 2017)."* NSF specifically recognizes that Navigating the New Arctic in the face of rapid ongoing change is ripe for a convergent approach, and *"challenges the research community to join together the diverse perspectives of physical, biological, and social and behavioral sciences with computer science, engineering, and education to define the key challenges and research imperatives facing humans and the environment in the Arctic region (NSF, 2017)."*

Here, we describe high level science questions that are central to three of the NSF Big Ideas to which the Summit community is currently investigating; Navigating the New Arctic; Windows on the Universe: The Era of Multi-messenger Astrophysics; and Work at the Human-Technology Frontier: Shaping the Future. We recommend that when appropriate NSF include these questions in future proposal calls. It is clear from the Big Ideas that future in understanding are dependent on the transdisciplinary approaches already employed by the Summit community, and the understanding of the earth systems impacting Summit based on data records built by 30 years of related research at the site. While physical scientists constitute the largest fraction of the Summit community, educators are also well represented, computer scientists and engineers are critical members of many teams, suggesting this community is well placed to embrace convergent research. Moving past inter- and transdisciplinary research to convergent research will also require that NSF, and specifically the Arctic Science section of the Division of Polar Programs, assess and possibly refine funding priorities and the criteria and procedures applied in review of proposals (NAS, 2004; NRC, 2014; McNutt, 2017). In fact, the convergent approach may lead to new funding models including more partnerships between funding agencies, including non-federal sources (NRC, 2014). We recommend that through the funding process NSF recognize the vital importance of the climate records at Summit to a broad swath of the scientific research and modeling communities and establish it as a protected site similar in stature of the Long Term Ecological Research Sites, with a core set of community measurements which we specify in this report (**Section 3**).

## *Navigating the New Arctic*

1. What is the history of the ice and atmosphere at Summit and how can this history inform our understanding of current climate and atmospheric change and variability in the Arctic and beyond?
  - 1.1. How is water vapor transported globally in the atmosphere and what are the effects on the interpretations of past and present proxies?
  - 1.2. What are the important physical processes of the Arctic atmospheric hydrological cycle and how are these important for future Arctic climate?
  - 1.3. How is change in climate recorded in the snow, firn, and atmospheric observations at Summit, and how does the observed change compare to the past changes in rate and magnitude?
  - 1.4. What are the influences of long-range intercontinental transport on the ice sheet, processes and composition in the surface boundary layer, and overlying atmosphere?
  - 1.5. How are arctic-wide fluxes of naturally-emitted trace gases influencing climate, tropospheric (i.e. near surface) and stratospheric ozone changing in response to reduced ice coverage and changes in climate?
  - 1.6. How is the chemical and physical state of the atmosphere in the Arctic changing over time?
2. How much is the Arctic warming and how does this affect weather patterns Greenland-wide, Arctic-wide and World-wide?
  - 2.1. How do past and present observations at Summit inform us about the climate and environmental conditions in the mid-latitudes and tropics?
3. What processes drive change on ice sheets, how do they operate and what are the impacts for future sea level?
  - 3.1. What is the variability of the surface mass balance of the Greenland ice sheet and how will changes impact future sea level?
  - 3.2. How do recent warm Arctic winters influence surface properties in the dry-snow zones of the Greenland ice sheet?
4. How are clouds changing in the Arctic and what are the effects of this change?
  - 4.1. How do changes in cloud properties affect the mass and energy balance of the ice sheet?
  - 4.2. How do changes in aerosol properties impact clouds and precipitation over the Greenland ice sheet and the Arctic?

5. How is the state of the climate, mean state and variability, reflected in the chemical and isotopic characteristics of the snow and firn?
  - 5.1. How do air/snow exchange and other post-depositional processes change physical, chemical, and isotopic characteristics of snow and firn?
6. How well can we predict past, present and future atmospheric, temperature and glaciological conditions?
  - 6.1. How well do models reproduce cloud and aerosol properties and associated radiative and moisture fluxes?
  - 6.2. How well can chemistry transport models capture inter-annual variability in atmospheric composition observed in the Arctic?
7. How accurate/precise are satellite retrievals over land ice?
8. What differences exist between the Northern and Southern Hemisphere, particularly in polar regions where dramatic changes are expected in the future?
9. What processes are occurring in ice and the crust beneath that cause earthquakes or other seismic signals?

### ***Windows on the Universe: The Era of Multi-messenger Astrophysics***

10. What are the observational characteristics of Super Massive Black Holes?
11. What is the physics of the early universe, what are the properties of neutrinos, what is the nature of dark energy?
12. What are the sources of the highest energy neutrinos?
13. How do stars form, and what are the physical processes regulating the stellar feedback in the interstellar medium?
14. What is the nature of gamma-ray burst sources?

### ***Work at the Human-Technology Frontier: Shaping the Future***

15. How do instruments, equipment, robots, and Unmanned Aerial Systems (UASs) operate in cold/extreme environments and what measurement quality can they achieve?

16. What clean energy sources can be used to autonomously operate scientific equipment through the darkness and extreme weather of polar winters?

**Section 4** specifically addresses how these questions lead to process-based scientific discovery from the outer reaches of space to the bedrock below the Greenland ice sheet to transform our research and knowledge.

### 3.0 Science Recommendations and Future Vision

The following recommendations are made for Summit Station.

#### *Science Enabling Recommendations*

1. Maintain year-round measurements of temperature, precipitation, the atmospheric boundary layer (10's to 100's of meters above surface), cloud properties, aerosol concentrations to understand clouds and precipitation, flask measurements for greenhouse gases and halocarbons, water vapor isotopes, snow surface elevation, accumulation and snow density.
2. Maintain the accuracy and timing of all Summit data used in weather predictions, reanalysis and Earth-system, regional and global modeling. These primarily include temperature, pressure/geopotential height, water vapor, wind speed, short- and long-wave radiative fluxes and cloud fraction.
3. Maintain the clean air and snow sector of Summit to not degrade the pristine characteristics, which make it suitable for process-based investigations and, in the future, could be utilized for determining change implemented by international policy decisions.
4. Continue to serve as a calibration site for national and international remote sensing programs for Earth Science research, including Operation IceBridge, ICESat-2, SPOT-VGT, Proba-V, Sentinel 2 and 3, and other satellite measurements for atmospheric composition and optical and snow properties.
5. Continue supporting Summertime, campaign style process-based science, at Summit.
6. Continue supporting surface mass balance calculations of the Greenland ice sheet, which require measurements of accumulation and snow densification at a dry-snow zone site. And support surface mass balance models of the Greenland ice sheet which require additional calibration and process studies from an accumulation zone site, as they are still not accurately capturing accumulation, the single input value to ice sheet mass balance.
7. Restore/Maintain the GISP2 Borehole so Summit researchers have access to investigate processes from the bedrock beneath the ice all the way up to other galaxies.
8. If manned operations are replaced by autonomous systems for any period of time, there should be a minimum of one year of overlap between historically manned measurements and their automated replacement measurements in order to observe and capture the variation and offset of the measurements in each season with confidence.



9. Summit should become an engineering test bed for both the public and private sector, including the energy sector, for researching and developing energy systems for extreme environments, battery capabilities, unmanned aerial system development, robotics and planetary exploration.

### *Infrastructure Related Recommendations*

10. The infrastructure at Summit today is adequate for the science questions outlined in **Section 2**, excluding the infrastructure for a new telescope (**Section 2** - Questions 10-14). Beyond the deployment of a telescope, additional infrastructure is not requested at this time.
11. If infrastructure is improved at Summit, focus on upgrades for clean energy, lower power requirements, and more automated scientific measurements on elevated or mobile platforms. (See Scoping Document, Summit Redevelopment)
12. Increased data transfer rates will allow Summit to host a global network telescope and contribute Arctic Change data to Big Data initiatives.

### *Recommendations for Governance*

13. Continue and expand efforts to collect and disseminate data sets collected at Summits as quickly and widely as possible for broad community use.
14. Recognize the vital importance of the climate records at Summit to a broad swath of the scientific research and modeling communities and establish it as a protected site, similar in stature to the Long Term Ecological Research Sites, with a core set of community measurements (Recommendations 1 and 2).
15. Future solicitations should highlight the major science questions that can best be addressed by scientific research at Summit (**Section 2**) and encourage researchers from disciplines outside of the cryosphere community to consider proposals using Summit as a research site (e.g. following guidance from the NSF Antarctic solicitation).
16. Future solicitations should highlight the need to develop technologies to automate Summit and enable reductions in cost and staff of Summit in the future.

## 3.1 Envisioned Future Logistics Scenarios

We evaluate science at Summit Station moving forward under the following logistics scenarios and quantify the impact of each to science (**Section 4**). These scenarios have different consequences for the

different areas of scientific interest and are, therefore, evaluated for each sub discipline (**Section 4 and Figure 3.1**). Considering the impacts to all sub discipline, we provide a general recommendation to minimize the impact to all Summit science. *Following from Figure 3.1, to minimize impact to science, we recommend the future scenarios of Increased Operations, Business as Usual, Multiparty, Minimum Personnel and Reduced Operations with winter power.*

**The definitions for the Future Logistics Scenarios are:**

**Increased Operations** - Additional infrastructure would be developed for Summit including the telescope observatory.

**Business as usual** - Similar operations to Summit in 2015 with a manned camp year round and 2-3 science technicians to run equipment or take measurements.

**Multiparty** - Summit is run as a partnership with multiple US agencies, private-public businesses, and other countries. Though management would change operations would be similar to Summit in 2015.

**Minimum Personnel** - Summit would be maintained year round by the minimum personnel to safely maintain the station. Personnel would have both station and science duties, reducing time for maintenance of science equipment or measurements.

**Reduced Operations - Power** - No human presence from approximately Nov 1- Jan 30, however, an autonomous power source capable of running similar science equipment to operations in 2015 would be available.

**Reduced Operation - No Power** - No human presence or power source from approximately Nov 1- Jan 30.

**Campaign Only** - Summit would only open when campaign science was funded. Runway would not be maintained.

**Robotic Measurements** - New technologies including robotic, automation and Unmanned Aerial Systems (UASs) are used to make measurements and collect samples at Summit which would, likely, not require station infrastructure.

	Earth System Modeling	Astrophysics	Atmospheric Science	Atmosphere/Snow Interactions	Glaciology	Paleoclimate
Increased Operations	=	+	=	+	+	+
Business as Usual	=	=	=	=	=	=
Multiparty	=	=	=	+	+	+
Minimum Personnel	=	=/-	=	=	=	=
Reduced Operations - Power	-	N	-/=	-	-	=/-
Reduced Operations – No Power	-	N	-	-	-	-
Campaign Only	-	N	-	-	-	-
Robotic Measurements	-	N	F	F	F	=/-

**Figure 3.1** - Broad impact to science for each scenario where + is positive impact, = is neutral impact, - is negative impact, N is not possible and F is possible with future developments in technology. For further detailed information see **Section 4**.

**Figure 3.1** provides a broad summary of the impact to science given the different logistics scenarios. **Section 4** provide the specifics for each discipline but in general the future scenarios of Increased Operations has a positive effect on Summit science. Business as Usual, Minimum Personnel and Multiparty have a neutral effect. Reduced Operations with winter power has slightly negative effect. Reduced Operations with no winter power and Campaign Only would have strongly negative impacts for science. While a transition to fully Robotic Measurements is not currently possible, this scenario should remain as a future path that will require investments in technology and collaboration between science and engineering pursuits.

## 4.0 Science Justification for Recommendations by Discipline

All disciplines contributed to the specific Recommendations for Governance (**Section 3**) 13-16.

### 4.1 Earth Systems Modeling

*Earth Systems Modeling addresses science questions (Section 2) 1, 2, 3, 4, and 6.*

*Research in this area contributed to specific recommendations (Section 3) 1, 2, 6, 7, 8, and 12.*

#### *Critical Nature of Research*

Summit plays a critical role as a component of the observing system for the Arctic region. Observations obtained from the station are important to various aspects of environmental modeling. Activities that have leveraged Summit data include numerical weather prediction and atmospheric reanalyses, surface process models, clouds and atmospheric water vapor, tropospheric and stratospheric chemistry modeling, regional climate models, and global coupled models. The utility of the station for modeling is based on its location, near the center of the ice sheet and at the highest elevation with low variability, and the variety of instrumentation and high quality (i.e. continuous, calibrated, low uncertainty) data available.

Summit provides a crucial boundary condition for atmospheric models over the data-sparse Greenland ice sheet. The spatial homogeneity of the Summit location combined with the variety of available measurements allows for the investigation of questions associated with the climate of the Greenland ice sheet in combination with models and satellite data. *Fyke et al. (2014) determined Summit to be an optimal location to examine changes in surface mass balance (SMB) due to the long-term baseline climate record obtained from ice cores. This record and the previous low variability also suggested **Summit as one of the best global locations for assessing evolving anthropogenic climate change. Fyke et al. (2014) and the studies of Fettweis (2007) and appraisal of Ohmura (2001) all find Summit to be regionally representative, and thus the key location for understanding changes in the ice sheet (e.g., Fettweis, 2007).***

#### *Societal Impact of Research*

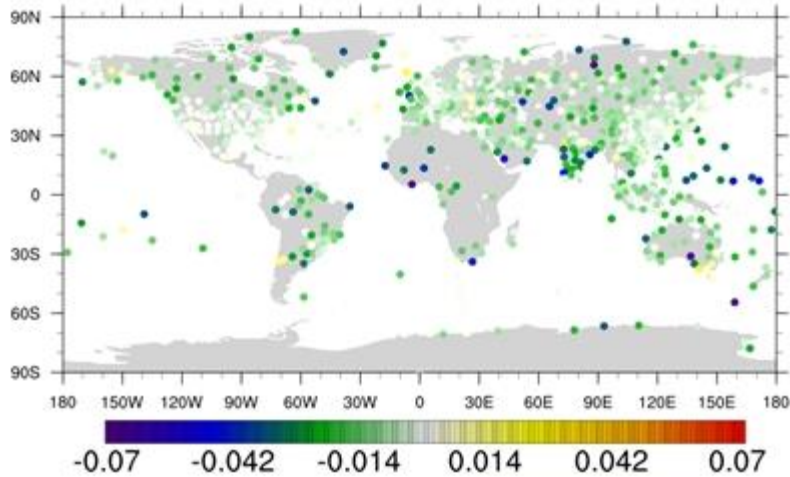
The documentation of Greenland ice sheet climate conditions through reanalyses and the prediction of conditions on synoptic, seasonal, and interannual time scales has important societal implications, ranging from the improvement of numerical weather prediction to an understanding of the present and future impact of the Greenland ice sheet on sea level.

## *The State of the Science and Measurements*

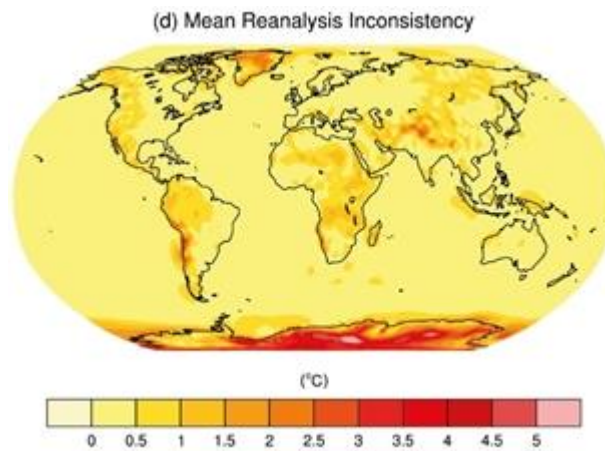
### **Numerical weather prediction**

For numerical weather prediction and atmospheric reanalyses, conventional station data are particularly important in polar regions, as geostationary satellites have poor coverage, and polar orbiting satellite infrared soundings of the lower troposphere have difficulty distinguishing cloud temperatures from the underlying snow and ice covered surface. Passive microwave sounding data also have difficulty in the lower troposphere due to ambiguity in surface emissivity over snow and ice surfaces. For weather prediction analyses, or reanalyses, in situ observations serve as an important tie between the background model surface representation and mid-tropospheric radiance data. Observations including pressure, air temperature, humidity, and winds from surface meteorological stations and from upper air rawinsondes are transmitted in near-real time to weather forecasting centers via the global telecommunications system (GTS) for inclusion as initial conditions in weather forecasting. These data are then archived for climate analysis and potential use in retrospective analyses. Records at the US National Climate Data Center indicate surface meteorological observations have been transmitted from Summit (station ID 044160) intermittently since 1998, with gaps in 1998-1999 and 2003-2004, and reduced reporting frequency in 2011-2012. Twice-daily rawinsonde observations (WMO ID 04417) have been continuously archived since 18-January 2012, while the nearby Summit GC-Net automatic weather station (ID 044180) briefly transmitted from 2011 until 2013.

Anecdotally, upper air stations in Greenland have been thought to have an important impact on analyses in winter due to their proximity to the North Atlantic storm track and the regional scarcity of other stations. The overall impact on a global analysis is difficult to quantify. As noted by Baker and Daley (2000; see also Zhu and Gelaro 2008), an efficient method of estimating the impact of observations on an analysis is available from use of the adjoint of a data assimilation system. An application of this method is shown in **Figure 4.1.2** for January 2016 using the NASA GMAO Forward Processing near-real time system. Of approximately 670 upper air stations, Summit ranks within the top 10 percent. In other seasons examined, the impact of Summit is marginal. The figure illustrates the regional scarcity of conventional data in the vicinity of Greenland. Summit is the only routinely-transmitting station over the central ice sheet. The GC-Net automatic weather stations have intermittently transmitted data through the GTS, but mainly rely on the Argos system, which is not available in real time to weather forecasting centers. Archived GTS data are widely used in reanalyses; observations archived elsewhere would necessitate special efforts for inclusion into reanalyses. The importance of observations may be further seen in **Figure 4.1.2**, which shows the mean inconsistency between reanalyses that assimilate near-surface air temperature observations for the period 1979-2001. The paucity of observations over the full time period, and difficulties in the modeled representation of glaciated surfaces account for the large discrepancies over the polar ice sheets, including the Greenland ice sheet. The difficulties for models to produce correct temperatures over the Greenland ice sheet is further shown **Figure 4.1.3** which compares the mean temperature modeled from 8 different models.

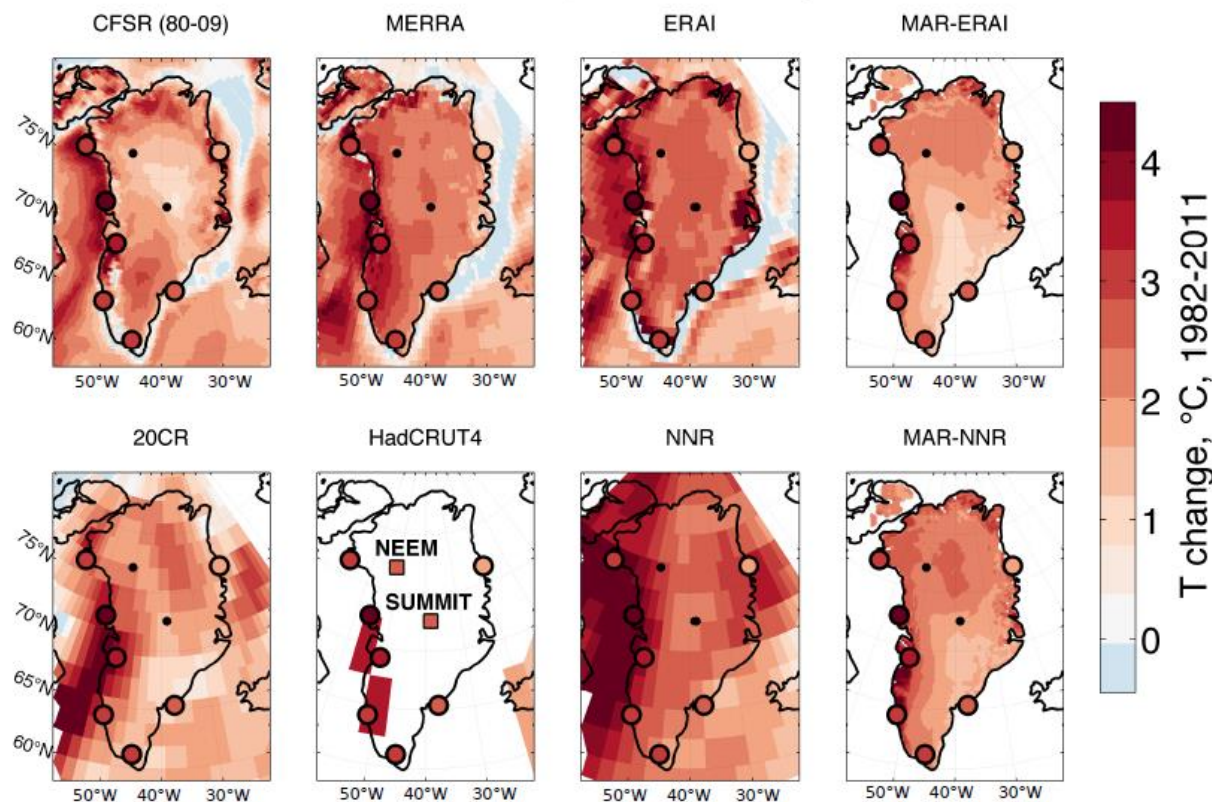


**Figure 4.1.1** - Cumulative rawinsonde impact scores for January 2016 from the NASA GMAO Forward Processing data assimilation system after Zhu and Gelaro (2008), in  $J\ kg^{-1}$ . Scores are computed from the daily 00Z analysis. Negative values denote a beneficial impact on the analysis and Summit ranks in the top ten percent of stations for this time period.



**Figure 4.1.2** - Mean inconsistency between ERA-Interim, ERA 40-year reanalysis (ERA40) and Japanese 25-year ReAnalysis (JRA-25) products as the mean of the absolute pairwise differences between those fields for their common period (1979–2001). From Flato et al., 2013. Showing large inconsistencies over Summit suggesting station measurements of temperature are needed.

## Surface temperature change, 1982-2011



**Figure 4.1.3** - Maps illustrating the importance of temperature datasets for model validation by showing the variations between 8 models. Thirty year [1982 -2011] surface temperature change over Greenland from various reanalyses (Orsi et al. In press): NCEP- CFSR [ Saha et al., 2010], NASA-MERR A [Rienecker et al., 2011], ERA-interim [Dee et al.,2011], NCEP-20CR-v2c [Compo et al., 2011] , NCEP-NCAR reanalysis ( NNR ) [Kalnay et al.,1996; Kistler et al., 2001], and as well as the outputs of the regional model MAR forced by either ERA-Interim or NNR [Fettweis et al., 2013], and the surface temperature reconstruction from HadCRUT4 [Morice et al., 2012]. The circles are trends calculated from all available weather stations having continuous measurements over the time period 1982-2011 [ Cappelen, 2014]. The squares show the 30-year warming trend at NEEM (Orsi et al. in press) and at Summit [McGrath et al., 2013], the latter being based on the combination of firn temperatures and weather station data.

### Surface processes and surface mass balance

As noted by Ohmura (2001), the location of Summit is ideal for studies related to the atmospheric boundary layer and surface processes due to the large distances from anthropogenic emission sources and the homogeneous nature of the snow surface. The large homogeneous footprint, low interannual variability (Fyke et al., 2014), and availability of co-located temperature and energy flux measurements allows for reduced ambiguity in model evaluation. For these reasons, the modeling of snow processes and SMB in regional climate models including RACMO2 (Ettema et al., 2010) and MAR (Fettweis, 2007), and global

models (Cullather et al., 2014; Punge et al., 2012; Smith, 1999) have frequently utilized Summit data. Adequate model validation is critical to understanding and predicting future changes in SMB and its associated eustatic impact (Science Question 3.1). As noted by Fettweis (2007), snowfall at Summit is an excellent indicator of the total ice sheet snowfall variability. Thus model SMB evaluation is primarily associated with consideration of the dry snow zone conditions at Summit, and ablation conditions on the Kangerlussuaq transect.

### **Clouds, surface radiative fluxes, and atmospheric chemistry**

Clouds in the Arctic have historically been difficult to model (e.g., Randall et al., 1998). There has been increased attention on the role of mixed phase clouds in surface warming based on modelling studies, satellite data, and in situ observations (Morrison et al., 2012), as the importance of clouds in total surface energy budget of the Arctic becomes more apparent. Summit, along with Eureka and Barrow, has been characterized as a “supersite” that has provided invaluable cloud and radiation observations (Shupe et al. 2013), and evaluation of cloud theory in combination with atmospheric models (Kay et al., 2016a). Summit observations in combination with satellite data have been used to understand and diagnose cloud parameterizations in global climate models (e.g., Kay et al., 2016b).

Summit serves as an important validation site for atmospheric chemistry and transport models for both the US and international partners (e.g., Shindell et al., 2008; Monks et al., 2015; and including the Danish Eulerian Hemispheric Model (DEHM), Community Earth System Model (CESM), and SOCOL (Solar Climate Ozone Links) chemistry-climate model). As noted by Shindell et al. (2008), the Summit location is particularly useful in delineating the local Arctic seasonality in ozone concentrations in combination with Barrow. The two stations are typically out of phase in springtime. At Barrow, the impact from the sea-ice Bromine explosions events appear as extremely low ozone episodes in springtime, but these events are not observed at Summit. In the Arctic, atmospheric pollutants and aerosols can have significant influence on climate through radiative impacts and by changing cloud properties (Science Questions 4.1, 6.1). Studies including Kay et al. (2016b) have highlighted the need for careful treatment of cloud phase to adequately reproduce radiative fluxes in models. Current model development has employed the use of an explicit representation of cloud water glaciation through the interaction with model aerosols. Further development of these microphysical parameterizations relies on an improved understanding of aerosols and cloud properties in locations where mixed-phase clouds have been observed, including Summit (Shupe et al. 2013; Science Question 4, 4.1).

### *Science Impact Under Future Scenarios*

**Increased Operations, Business as usual, Multiparty and Minimum Personnel:** These scenarios likely have no significant impact on modelling as the measurements required for models/reanalysis would not lose accuracy, precision or their time series.

**Reduced Operations- Power or No Power, Campaign Only, and Robotic Measurements:** Under these scenarios there is significant risk to winter-time measurements which are vitally important for modeling. It



is important to note that observed temperature trends at Summit vary considerably between seasons, with winter months displaying the largest variability in temperature and opposite trends when compared to summer months over the last 10 years. While the 2012 summer melt event was momentous and necessitated detailed study, changing wintertime conditions on the Greenland ice sheet are likely to continue to be an important research topic, and one that is particularly not well understood. Automation of surface meteorological stations has been adequately performed at various polar locations, including Greenland, although comparison with manned observations has identified significant shortcomings, especially in winter months due to technological and equipment failures. The difference between manned and unmanned monthly temperatures for Summit is  $\sim 0.5$  °C, or the warming of the Greenland ice sheet surface over the past decade. The GC-Net weather stations around Greenland have a data loss rate of  $\sim 10\%$  due to malfunctions with the Summit GC-net station performing slightly better (Konrad Steffen, personal communication). The automation of upper air soundings, surface energy budget measurements, and atmospheric chemistry observations pose significant technical challenges and would likely be lost under these scenarios.

## 4.2 Astrophysics

*Astrophysics addresses science questions (Section 2) 10, 11, 12, 13 and 14.*

*Research in this area contributed to specific recommendations (Section 3) 10 and 12.*

### *Critical Nature of Research*

Understanding the physics of the early universe, the physics that drives the expansion of the universe, and the physics that lies deep inside energetic sources in the universe are some of the most exciting questions in cosmology and astrophysics today. Summit is poised to answer these questions.

### *Societal Impact of Research*

Through astrophysics and cosmology research, we explore the universe on its biggest scales, and learn about the physics that describes the way the universe works. Asking and answering questions on the largest scales inspires generations of scientists to pursue STEM careers.

### *The State of Science and Measurements*

#### **Greenland Telescope Project**

The Greenland telescope project is a collaboration between the Smithsonian Astrophysical Observatory and Academia Sinica Institute of Astronomy and Astrophysics. The project plans to install a high precision 12 m diameter radio telescope at the Summit in 2020, operating at submillimeter wavelengths. Currently, the antenna is under construction at the Thule Air Base (**Figure 4.2.1**) (Raffin et al., 2016). In phase-1 of the project, Very Long Baseline Interferometry (VLBI) observations at 86 and 230 GHz will be carried out from Thule. In phase-2, the antenna will be relocated to the Summit in 2020. This high altitude, dry and stable site will allow VLBI observations at 345 GHz, to image the silhouette of the super-massive black hole in M87, as part of the Event Horizon Telescope project, as well as other submillimeter science which require extremely good atmospheric transparency at high frequencies approaching THz.



**Figure 4.2.1:** (Left, and inset): The Greenland telescope antenna under construction at the Thule Air Base (cluster pad 1, and hangar 6). The Alt-Az antenna mount, dish back up structure and quadrapod feed legs are fully assembled, as of August 2016. The antenna construction will be completed in August 2017. (Right): The ALMA prototype antenna at NRAO JVLAsite near Socorro, NM, in 2011.

There are only two supermassive black hole sources that can be studied observationally with direct VLBI imaging: SgrA\*, the black hole at the center of our Milky Way galaxy, and the black hole at the center of the galaxy M87. SgrA\* black hole has a mass of about 4 million  $M_{\text{sun}}$ , and it is at a distance of about 8.5 kpc. M87 is much farther away, at the distance of about 16 Mpc, but its black hole has a mass of about 6.6 billion  $M_{\text{sun}}$ . The angular size of the event horizon for both these black holes are similar, about 40 microarcseconds. The pioneering VLBI observations by Doelman et al. (2008) measured the size of  $37^{+16}_{-10}$  microarcseconds of SgrA\* at 1.3 mm wavelength. A global network of several radio telescopes, from Mauna Kea Hawaii, to Atacama in Chile, have just completed an observing campaign of the Event Horizon Telescope, observing both the sources SgrA\* and M87 (10-14 April 2017). These observations were carried out at 230 GHz. Future observations (which the Greenland telescope will be part of), will be carried out at 345 GHz. The higher frequency is critical for better imaging of the shadow of the black hole, to avoid interstellar scattering effects. The northern baselines approaching 9000 km length, to the Greenland telescope, are critical for the high angular resolution of about 20 microarcseconds, as well as high imaging fidelity (Inoue et al., 2014; Broderick and Loeb, 2009) for the imaging of the black hole shadow in M87 (Science question 10).

VLBI observations are typically carried out only about 10% of the total observing time in a year. The Greenland telescope will be used for single-dish observations at submillimeter wavelengths which allow probing cold gas and dust in interstellar clouds, and permits detections of distant dusty galaxies. Studies of star-forming regions require observations of dust emission (which peaks at submm wavelengths at temperatures of few 10s to 100 K), and molecular lines such as the high excitation CO and ionized

Nitrogen lines (Hirashita et al., 2016). Other single-dish submillimeter science studies will include surveys of submillimeter galaxies at red-shifts of 1~2, and observations of gamma-ray burst afterglows (Science questions 12,13).

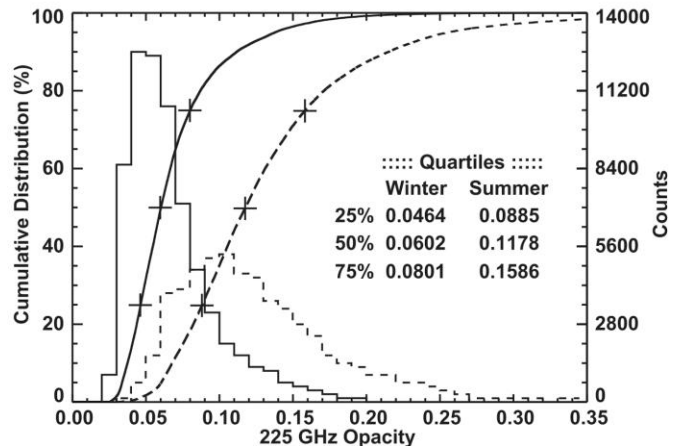
Measurements of atmospheric opacity at 225 GHz at Summit, were carried out by ASIAA over a period of 3.5 years. These data (Figure 4.2.2) show that the Summit site is significantly better compared to the Mauna Kea site for submillimeter astronomy. The South Pole site remains the best in all seasons. In summers, the Summit site is better than the ALMA site, but in winter, both sites are comparable.

### Cosmic Microwave Background Measurements

Precision measurements of the Cosmic Microwave Background (CMB) probe the physics of the early universe, the properties of neutrinos, and the nature of dark energy (Science Question 11). Current world-leading CMB experiments are located at the South Pole and in Chile, and a next-generation CMB experiment (CMB-S4) would benefit from full-sky coverage, only possible with the addition of a Northern site. Full-sky coverage is especially important for learning about the properties of dark energy, neutrinos, and other relic particles, and Summit may be the best place in the Northern hemisphere to make low-noise CMB measurements, due to its high altitude and dry, stable atmosphere.

### Searches for Ultra-High Energy Neutrinos

The detection of the highest energy astrophysical neutrinos would reveal the sources of the highest energy particles in our universe and illuminate the physics that drives the central engines in the highest energy accelerators. The highest energy neutrinos can be detected via the radio emission that is created when they induce charged particle cascades in large volumes of dielectric material, such as glacial ice. Summit is an appealing place to put a radio detector for the highest energy neutrinos, but is slightly worse



**Figure 4.2.2:** (From Matsushita et al. 2017) (Left) 225 GHz tipping radiometer at the Summit camp (Mobile Science Facility). (Right) Cumulative distribution plots and histograms of 225 GHz opacity in winter (solid lines) and summer (dashed lines). Crosses mark the quartiles of each season.

than the South Pole in terms of radio clarity of ice, which is the main environmental quality that determines the sensitivity of a given set of radio detectors at a given location. If detectors that are currently being built discover these highest energy neutrinos when deployed in Antarctica in the coming years, then a complementary detector at Summit would allow observation of sources in the Northern sky.

### *Science Impact Under Future Scenarios*

**Increased Operations:** Summit could be home to a ~5m aperture telescope that is part of the worldwide network of telescopes that will constitute CMB-S4, with identical sister telescopes in Chile and at the South Pole. The telescopes would require year-round operation, ~50kW of power, ~10GB/day of data transmission (which would only transmit ~2% of the data taken in quasi-real time, requiring the other 98% to be flown out twice yearly on disk), one dedicated winter support staff, a dedicated Dark Sector where radio communications transmission is limited, support for 5-10 summer deployments for scientists each year of operation, flight support for significant cargo during the initial deployment season, and a dedicated structure and laboratory space to house the telescope. Up to 10x higher bandwidth for data transmission would be useful to expedite science results. This would require Increased Operations with possible modifications to the communications, data transmission, and addition or modification of a structure to house the telescope. Additionally, it could house the 12 m VLBI, Greenland Telescope. The Greenland Telescope can only operate at Summit under Increased Operations.

**Increased Operations, Business as Usual, Multiparty, Minimum Personnel:** Another path forward for CMB science would be to locate a smaller, ~0.5m aperture telescope at Summit that targets the large angular scale features to facilitate measurements of early universe physics. This would require year-round operation, ~15kW of power, ~5GB/day of data transmission (which is only ~10% of the total data collected, and the remaining 90% would be flown out twice yearly), a winter support staff member who could be shared with other experiments, a dedicated Dark Sector, support for 3-5 summer deployments for scientists each year of operation, flight support for modest cargo during the initial deployment, and a dedicated laboratory space and space to house the telescope (possibly a cargo container or similar). This would require less demand on the power, cargo, personnel, and data infrastructure would be smaller than the first option presented.

**Reduced Operations, Campaign Only, Robotic Measurements:** Reduced operation in winter would significantly diminish the science returns from any telescope at Summit. Since the best observing is during the middle of the winter, cutting out those months of operation is a disproportionately large hit to the science data. It is not possible to fully automate the operation of either a CMB or submillimeter telescope.

**Increased Operations, Business as Usual, Multiparty, Minimum Personnel:** A radio detector for high energy neutrinos would consist of a system of semi-autonomous stations near Summit. There would be minimal power requirements, minimal lab space requirements to host computers, ~1 GB/day of data transfer year-round, and modest cargo and summer deployment requirements, and a dedicated Dark Sector to site the instruments. Such an experiment would be possible full-time in all scenarios except for scenarios where

there is no power in the winter on Station. Having on-call winter support on station, as in Business as Usual or Minimum Personnel would help with potential problems with computing and communications to the instruments. The loss of data that we would have with a loss of power on station during a winter break would only be proportional to the fraction of time that power was down on station, so the sensitivity would only suffer moderately under the Reduced Operations- Power scenario.

## 4.3 Atmospheric Science

*Atmospheric Science addresses science questions (Section 2) 1, 2, 4, 6, 7 and 8.*

*Research in this area contributed to specific recommendations (Section 3) 1, 2, 3, 4, 8, 9, 10, 11, 12, 14 .*

### *Critical Nature of Research*

Summit represents the most pristine measurement site in the Arctic and Northern Hemisphere. The remoteness of Summit, as well as its high latitude and high elevation location, enhances its values to atmospheric science as a location from which long-term trends and large-scale atmospheric processes can be clearly identified without confounding local effects. Summit is typically removed from anthropogenic and local coastal influences relative to other Arctic observatories, thus, providing vital baseline measurements of the free troposphere for the northern hemisphere. It is far from infrastructure and anthropogenic pollution sources, and this isolation is not likely to change in the future.

Understanding the broad-scale Arctic response to climate change and how these changes in turn affect climate, tropospheric and stratospheric ozone in the northern hemisphere isn't possible without measurements at Summit. Results from Summit provide a spatially-integrated view of Arctic-wide (even hemispheric in some cases) changes that aren't possible at coastal Arctic sites, and thus provide the critical information for understanding how the Arctic is changing overall in response to a warmer climate, reduced ice cover, and an increased anthropogenic presence. Likewise, Summit is one of the best locations in the northern hemisphere to document and understand trends in the amount of trace gases in the atmosphere. Many of the trace gases studied directly force climate processes, impacting key large-scale environmental systems, and many reactive halogen species profoundly impact the Arctic environment through the destruction of ozone. Many of these species can be traced to natural or anthropogenic sources, which helps us to understand the impact of human activity on large scales.

### *Societal Impact of Research*

Atmospheric research at Summit targets improved understanding of the connections between nearly all components of the earth system. Atmospheric observations at Summit are ingested into weather forecasting systems, and have been shown to improve the skill of these models. Research focused on trends in surface, tropospheric and stratospheric ozone, amount of greenhouse and ozone depleting gases in the atmosphere, and studies on coupled aerosol and cloud processes provide important insight into processes that are essential to improve the next generation of climate and weather models. Trace gas measurements made at Summit are critical to understanding trends in the amount and sources of natural and man-made pollution in the atmosphere. Many of these gas species not only directly impact the climate and act as climate forcers, but they can act as tracers of human activity, and cause far-reaching feedback processes within the Arctic environment. For example, reactive halogen species such as bromine and iodine cause ozone destruction within the troposphere, which can have positive human and plant health impacts reducing a toxic constituent of smog and source of greenhouse gas; and within the stratosphere has a negative human

impact by reducing protection from solar radiation. Atmospheric data are incorporated into glaciological studies and calculations for ice sheet surface mass balance (**Section 4.5**). The combination of modern atmospheric measurements, snow/firn processes and paleo-atmospheric records in ice cores, have shown that the ice sheet and the atmosphere affect each other in ongoing dynamic ways.

### *The State of Science and Atmospheric Measurements*

While a comprehensive review of Summit atmospheric science is beyond the scope of this report, we provide here a few key examples of transformational science that stem from on-going atmospheric measurements and have altered our understanding of climate dynamics. **Appendix G** lists the specific atmospheric measurements taken at Summit in 2016.

#### **Atmospheric water vapor, clouds and surface energy balance**

Atmospheric water vapor, clouds, and precipitation greatly affect the surface energy and cryospheric mass balances in the Arctic, and are responsible for much of the variability in these balances. Since clouds are such a strong modulator of atmospheric radiation they are drastically effecting the Arctic. It is thought that recent rapid melting of Arctic sea ice may be driven, in part, by changes in cloud cover and radiation (e.g., Perovich et al. 2007; Kay et al. 2008; Persson et al. 2016; Mortin et al. 2016) and, over the Greenland ice sheet, with immediate sea level implications, clouds have been shown to enhance surface melting by one-third (van den Broeke et al. 2009; de la Peña et al. 2015; Van Tricht et al. 2016). Bennartz et al. (2013). Solomon et al. (2017) directly linked the 2012 surface melt event which involved almost the entire ice sheet, and caused the first surface melt at Summit since 1889, to the impact of supercooled, low-level liquid bearing clouds emphasizing the roll of clouds in the accelerating negative mass balance of the ice sheet.

Cloud-related processes and feedbacks are known to be one of the greatest sources of uncertainty in global climate models, and shortcomings in the representation of clouds have been clearly identified in model simulations over the Arctic (e.g., Gorodetskaya et al. 2008; Tjernstrom et al. 2008). Clouds are poorly represented over Greenland. For example, the Community Earth System Model (CESM) fails to accurately represent the cloud composition and therefore cloud radiative effects on the surface of Greenland. A few of the most important, yet highly uncertain, Arctic cloud-atmosphere processes include:

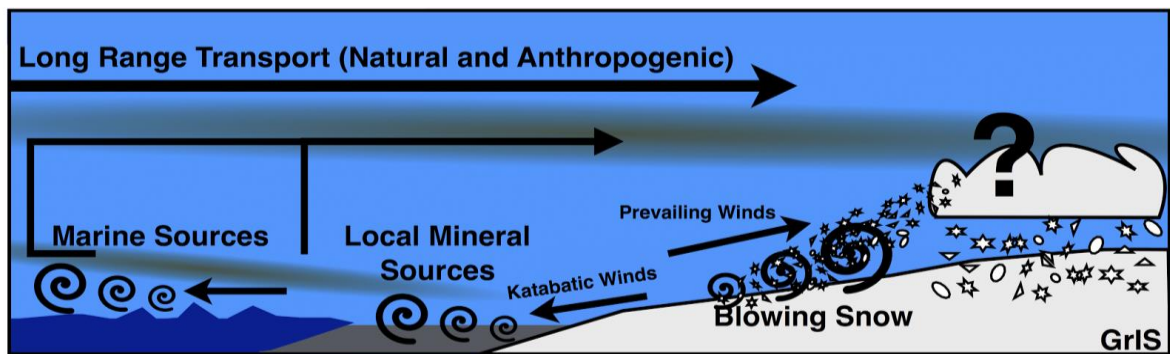
- Low-cloud persistence – Stratiform clouds are extensive and persistent in the Arctic (Shupe et al. 2006, 2011), they interact with atmospheric thermodynamics (e.g., Curry 1986), and impart significant radiative effects on the atmosphere (e.g., Zuidema et al. 2005) and surface (e.g., Shupe and Intrieri 2004). While it is clear that these clouds are self-maintaining through processes like radiative cooling (e.g., Pinto 1998, Morrison et al. 2012), many of the process-level details that lead to their remarkable persistence are unknown.



- Cloud-phase partitioning – Many Arctic clouds are mixed-phase (e.g., Turner 2005, Shupe 2011), containing both supercooled liquid water and ice. The partitioning of these condensed phases influences the cloud lifetime, radiative effects (Sun and Shine 1994), and precipitation efficiency (e.g., Harrington and Olsson 2001), yet it is unclear what determines this partitioning.
- Precipitation partitioning – Arctic precipitation comes from two basic sources, the frequent, slow precipitation from shallow, stratiform clouds and the more substantial, yet less frequent, precipitation resulting from episodic frontal storm systems. Additional surface accumulation can result from direct vapor deposition onto frozen surfaces, clear-sky ice precipitation (diamond dust), and blowing snow. However, the relative contributions of these processes are unknown.

One of the largest uncertainties in global climate models is the indirect effect atmospheric aerosols have on cloud properties. In particular, very little is known about how aerosols and clouds interact in the Arctic and over the Greenland ice sheet. Due to the lack of simultaneous measurements of cloud-active aerosols with cloud microphysical properties (e.g., profiles of liquid water content, ice water content, hydrometeor size, etc), it is unclear how aerosols impact clouds over Greenland. Furthermore, we lack the observations and knowledge to assess just how badly climate models represent these aerosol-cloud interactions over the Greenland ice sheet.

The above paragraphs outline the scientific justification that lies at the heart of scientific questions 2, 3, 4, 5 and 6. To address these questions in a manner that will allow for significant advances in how models represent key atmospheric drivers of the Greenland ice sheet energy and mass budgets, co-located and contemporaneous measurements of the atmospheric state, surface energy budget, clouds, precipitation, and aerosols are needed. Such observations specifically include cloud macro-physical (height, thickness, fraction, motions) and micro-physical (phase, liquid water content, ice water content, hydrometeor size) properties, profiles of atmospheric state (temperature, humidity, and wind profiles), and aerosol properties (ideally number, size distribution, and cloud-active constituents). High temporal and vertical resolution profiles of hydrometeor velocity are needed to understand turbulence in clouds and also many of the



**Figure 4.3.1-** Depiction of possible sources of cloud condensation nuclei (CCN) and ice nucleating particles (INP) along the west coast of Greenland.

characteristics of precipitation (including fall speed). Accompanying surface measurements must include upwelling and downwelling longwave and shortwave radiation fluxes, latent and sensible heat fluxes, ground temperature and heat flux, surface meteorology, and surface precipitation (including amount, rate, and density).

The primary processes that drive the surface energy and mass budgets vary over the annual cycle and this variability ultimately controls the evolving state of the Greenland ice sheet. For example, water vapor advection depends on season, and, along with variations in temperature, impacts the annual variability of cloud phase partitioning and occurrence. Precipitation intensity and accumulation vary substantially between winter and summer (Castellani et al. 2015). There is a strong seasonal dependence in aerosol properties related to seasonal controls on large-scale circulation, seasonality in aerosol sources, and the role of sunlight in certain chemical processes, all of which may be shifting in the Arctic due to climate change (Browse et al. 2012; 2014). The partitioning of energy at the surface also shows important annual variation. For example, the conductive flux of heat into the ice sheet surface responds differently to atmospheric radiative forcing in winter relative to summer (Miller et al. 2017). All of these processes, and their annual variability, must be measured so they are accurately represented in models. While these measurements do not necessarily need to be made at Summit, it is important that they are made over the Greenland ice sheet to help develop a holistic, process-based understanding of cloud-atmosphere impacts on the surface energy/mass budgets in that region.

An observatory such as Summit is also a hub for large international science campaigns. The Suomi-NPP Arctic validation mission was specifically flown over Summit because of its comprehensive suite of atmospheric and cloud measurements. Also ESA's recent ADM-Aeolus WindVAL Campaign used observations from Summit to validate remotely-sensed wind retrievals that are difficult over snowy, low aerosol regions. Another upcoming campaign includes the United Kingdom's proposed Greenland Aerosol Cloud Experiment (GrACE) that will make repeated flights over Summit to make in situ observations of aerosol and cloud particles above, within, and below clouds across the Greenland ice sheet. Tying the GrACE observations to the continuous, year-round cloud-atmosphere observations being made at Summit is key to creating a process-based budget of moisture over the ice sheet. We reiterate that understanding the radiation and moisture budget over the ice sheet directly relates to improved sea level predictions.

### **Surface Energy Balance**

The surface energy budget is a critical integrator of atmospheric interactions with the Greenland ice sheet surface and ultimately controls surface temperature and melt processes. Energy budget processes vary substantially in both space and time, and serve as a key factor influencing the surface mass budget. The observational components required to measure the surface energy balance include incoming and outgoing fluxes of short and longwave radiation, sensible and latent heat, and inputs from precipitation and ground heat flux. The fundamental meteorological observations taken at Summit allow for the annually

changing surface energy budget to be calculated. To continue these measurements, at minimum a robust record of net radiation, temperature, pressure, winds, and humidity is required at two levels. From these observations, it is possible to use the Bowen Ratio to calculate sensible and latent heat flux and the surface energy balance. Ideally, more sophisticated measurements of high-frequency winds, temperature, and moisture would be made to more accurately quantify surface energy fluxes. Due to challenging environmental conditions over the Greenland ice sheet, robust measurements of surface energy budget terms are difficult to make autonomously. Additional investment into development of autonomous surface flux measurements would enable the future collection of these critical measurements at lower net cost.

The basic meteorological observations recorded at Summit, which have an increased accuracy over automatic weather stations, are fundamental to virtually all process studies conducted at Summit. Long term records providing a robust measure of diurnal and seasonal variability as well as observational histories that allow for the analysis of trends, are critical when framing short-term experiments into a larger Arctic-wide and global context. More detailed, comprehensive measurements of the components of the surface energy balance are required for numerous studies and provide essential forcing data for modeling. For example, using available data from multiple projects at Summit, Miller et al. (2017) derived a complete surface energy budget product for at least one full year. This enabled a detailed analysis of the relationships among different energy budget terms, their variability throughout the annual cycle, and their sensitivity to radiative impacts from clouds and the solar cycle. Such process relationships are currently being used to quantify model deficiencies in representing snow density, surface albedo, boundary layer structure and other important processes.

## **Aerosols**

Aerosols measured at Greenland Summit are key factors in two vitally important questions: 1) What effect did aerosols have on the initiation and continuation of recent ice ages as measured by dust in Greenland cores (McConnell et al., 2002)? and 2) because aerosols represent approximately 70% of the total uncertainty in Global Climate Models in the Arctic, the region most impacted by climate change (IPCC, 2015), how can measurements at Summit Greenland provide a better constraint to climate models?

Aerosol particles are important climate forcers, but the sign and magnitude of their forcing effect is highly uncertain and depends not just on the aerosol optical properties but also their location with respect to clouds and different surface albedo types (e.g., snow vs ocean) (e.g., Myhre et al., 2013). One example of the role aerosol particles play in the complex climate system is that deposition of absorbing aerosols from the atmosphere to the cryosphere can decrease the surface albedo resulting in faster melting (e.g., Flanner et al., 2009). The Arctic is particularly sensitive to changes in surface albedo which subsequently impacts sea ice (less ice, more open water), snow cover, and ultimately surface temperature (e.g., Serreze and Barry, 2011; Serreze et al., 2009). The two most recent IPCC assessments also suggested that improved understanding of the atmospheric effects of aerosol particles on radiation, clouds, and circulation is essential to improve skill of climate and weather models. Emissions in the Arctic are likely to increase in the future due to expected decreases in sea ice, making the region more readily accessible for activities such as energy

extraction, shipping and tourism (e.g., Aliabadi et al., 2015). More research in the Arctic, particularly on processes and trends/variability connecting the spheres (atmosphere, cryosphere, etc.), is necessary to better understand what is changing, why it is changing, how it might change in the future and the local and global impacts of such change.

A critical difference between aerosol and climatically important trace gases is that the lifetime of particles tends to be quite short, on the order of days to weeks, so aerosol spatial distributions are more heterogeneous and change more quickly than most gases. While Summit is remote it can be affected by long-range transport from mid-latitude regions. We are able to track and identify Saharan dust, natural and man-made aerosols from China, North America and European aerosols, and a volcanic eruption halfway around the world (VanCuren et al., 2012). This capability would be lost at low elevation sites. Stohl et al. (2006), for example, showed that Siberian forest fire smoke transported across the Arctic created a sharp influx of black carbon at Summit (as well as at other lower altitude observatories (e.g., Barrow, Alert, Ny Alesund). Interestingly, the well-documented springtime Arctic Haze phenomenon does not appear to occur at Summit because Summit is generally above the layers carrying the haze aerosol.

Aerosol measurements at Summit are vital because the Arctic atmosphere has proven challenging to global modelers (Shindell et al., 2009; Eckhardt et al., 2015; Schwarz et al., 2010). Models frequently have difficulties simulating the observed seasonality and/or the magnitude of aerosol in the Arctic. Summit occupies an important, undersampled region in the Arctic, and is the only station making continuous, long-term free tropospheric measurements. Of particular importance is developing an accurate predictive capability (through models) of climate response (i.e., surface temperature increase) in the Arctic. This would have profound effects on our ability to accurately predict snow/ice mass loss from the Greenland Ice Sheet, sea ice melting, surface albedo changes, sea level rise, and several other climate-related effects.

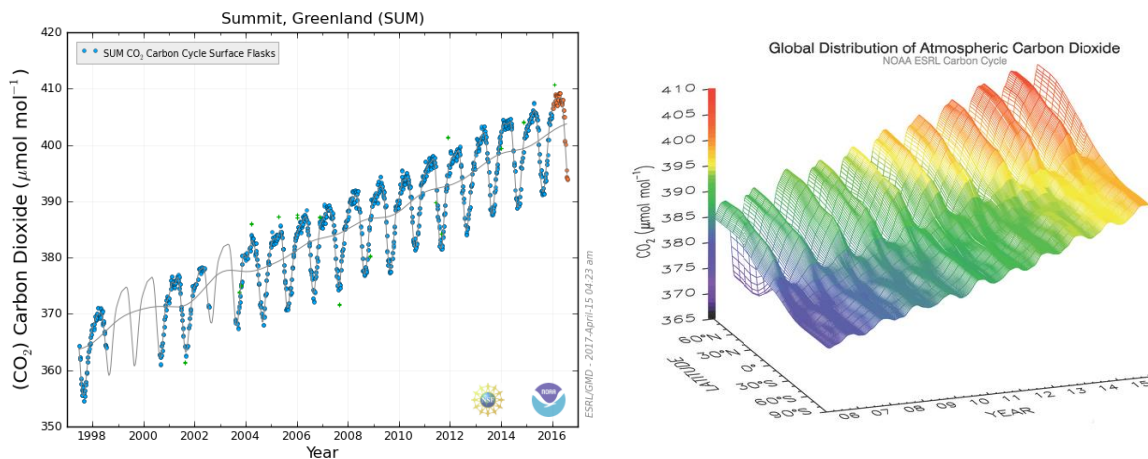
Aerosols are measured at Summit using a diverse array of in situ instruments utilizing optical light scattering methods as well as drum samplers and radionuclide concentrations of Be-7 and Pb-210 on filter samples. Aerosol contributions of scattering and absorption to the total light extinction is an important climate forcing variable and can determine the sign (e.g., warming/cooling) of forcing. The radionuclide tracers provide insight into vertical mixing on both short and seasonal time frames. Over decadal scales Be-7 reflects solar-terrestrial links. Aerosol composition aids in source attribution of air masses reaching Summit. Combined with snow composition data they improve understanding of atmosphere to snow transfer processes.

### **Trace Gases**

In the northern hemisphere, industrial emissions due to large human populations and natural effects caused by larger land masses, dominate the emission of many atmospheric trace gases. The emissions are responsible for enhancements in ozone concentrations in the boundary layer that are harmful to the human health and environment. In addition, climate warming has been observed to be occurring disproportionately

in the Arctic. These combined effects make sampling sites in the high northern latitudes important to understanding sources and sinks of major greenhouse gases. As an example, **Figure 4.3.2** shows the global distribution of carbon dioxide and measurements from Summit. Trends in  $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{N}_2\text{O}$  show similarities. Unlike nearly all other sampling stations in the Arctic, Summit provides a means to measure trace-gas concentrations in the free troposphere (due to its high altitude), but from the surface; Summit is the only site of this type in the Arctic. Summit is also one of a few locations in the Arctic that launches routine ozonesondes, dating back to 2005 (Shams et al, 2017). Routine ozonesonde profiles are useful for detecting Arctic ozone hole events.

Long-term measurements at Summit, provide the primary means to reliably measure Arctic-wide changes in concentrations and fluxes of a wide range of important trace gases and to understand the variability and gradients over space and time. Given that most other surface locations in the Arctic are impacted by local sources, measurements at the low-altitude, coastal sites mainly reflect local processes. Results from such sites provide a measure of Arctic changes, but are likely to be highly variable and site-specific when compared to Summit. A complete list of trace gases measured at Summit can be found in **Appendix G**.



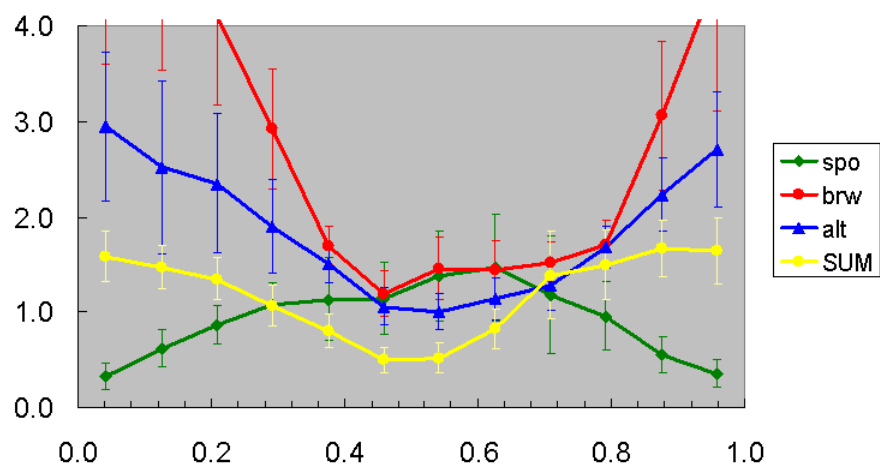
**Figure 4.3.2** - Time series of atmospheric  $\text{CO}_2$  concentrations globally, and at Summit, Greenland showing the important role of high latitude northern hemisphere sites. (source NOAA, CMDL <https://www.esrl.noaa.gov/gmd/ccgg>).

## Halocarbons

In addition to trace gases, halocarbons provide distinctive insights into more complicated but societally relevant processes. Halocarbon measurements at Summit are particularly useful for understanding transport and chemical processes in the arctic. For example bromoform ( $\text{CHBr}_3$ ) and methyl bromide ( $\text{CH}_3\text{Br}$ ) are measured at Summit (and globally) because they are significant sources of reactive bromine in the stratosphere, where they contribute to rapid ozone depletion and increased health concerns over the reduction in solar radiation protection. In general, reactive halogens such as bromine and iodine profoundly impact the Arctic environment in many ways, and particularly in the springtime, including causing ozone depletion in the troposphere, which is beneficial to human and plant health, and ozone depletion in the stratosphere, which on the other hand, increases exposure to solar radiation. Similarly, bromine is believed to oxidize elemental mercury to reactive gaseous mercury that deposits through snowfall, and is detrimental to the environment. Many questions remain about the impact of these species to the overall Arctic system, particularly through atmosphere-surface snow-ice interactions, and the seasonality of these interactions, which are very much not well understood.

An example of just one of the gas species currently measured at Summit is bromomethane, or methyl bromide, an ozone-depleting agent, which is naturally occurring, but was more prevalent in the recent past as an extensively-used, industrially-produced fumigation agent in the US and Europe before being phased out by the Montreal Protocol in 1989. Methyl bromide is steadily decreasing in the Arctic, with similar trends being observed at three other North American sites participating in the NOAA flask network. The Summit results suggest that the seasonal patterns in methyl bromide at Barrow and Alert are strongly impacted by local processes (e.g., the frequency of shallow inversions during spring at coastal sites) and, therefore, seasonal variations at these coastal stations are not representative of changes in the methyl bromide flux throughout the Arctic.

Another species measured at Summit is bromoform, which has natural oceanic sources, exhibits relatively strong seasonality with annual minima in the summer reflecting loss due to photolysis and attack by OH, as is clearly demonstrated by comparing monthly averages between the Arctic and Antarctic (**Figure 4.3.3**).



**Figure 4.3.3** Bromoform (monthly mean dry-air mole fraction as ppt in ambient air) in Polar regions.

Winter-time peak concentrations in bromoform at Barrow and Alert are much higher than observed at South Pole, which could be suggesting much stronger emissions from natural sources in the northern hemisphere. If results from Barrow and Alert were taken to reflect hemispheric concentrations of bromoform, they could suggest a significant asymmetry in the role of tropospheric bromine chemistry on ozone in the two hemispheres. However, the winter peaks at Barrow and Alert are much higher than observed at Summit (**Figure 4.3.4**). In fact, the annual mean and amplitude of seasonal variations at Summit and South Pole are nearly identical, suggesting bromoform concentrations in the free troposphere of both hemispheres are very similar. Given that bromoform production in the Arctic is associated with sea ice, enhanced concentrations at Barrow and Alert during the winter mainly reflect the proximity of these stations to the Arctic Ocean and locally significant emissions. Without Summit it would be difficult to see through this local signature and assess any true hemispheric gradients in bromoform. Questions do remain about the seasonality of this cycle and the processes involved for both this gas and methyl bromide.

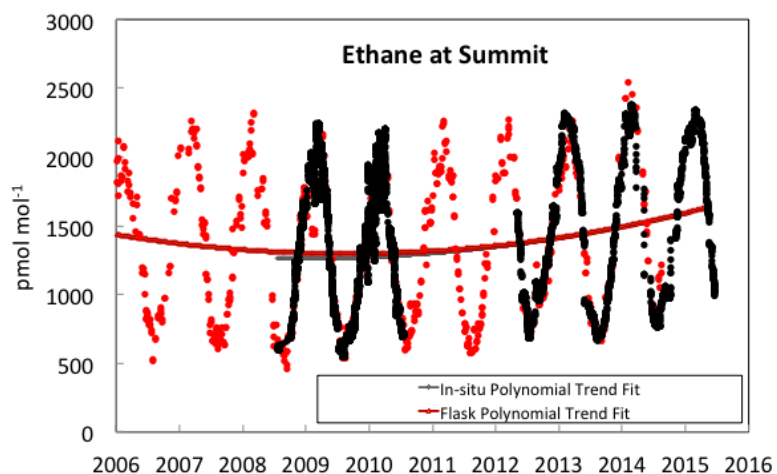
### Ethane

The long time-series of atmospheric measurements at Summit revealed a recent reversal of atmospheric ethane and propane trends (Figure 9) largely attributed to US oil and natural gas production and believed to be globally representative (Helmig et al., 2016). The record presented in Figure 9 demonstrates the use of Summit as the key calibration site in a global volatile organic compound (VOC) network consisting of 44 sites. Summit is the only reference surface site with remote in situ measurements, with the overlap of flasks and in situ measurements serving as the calibration 'hub' of the entire global network. Having co-located in situ and discrete flask measurements of several species allows comparison of the high time resolution (every 6 hours) in situ measurements to the lower time resolution (weekly) flask records in order to determine that weekly measurements at the VOC network sites do reflect the overall trend. The in situ data collected at Summit provide better accuracy and precision, particularly for the measurement of VOC, with about 6 times better precision in comparison to the flask measurements. The

time resolution of the in situ measurements also allows transport analyses, which the flask sampling does not allow.

### Stratosphere-Troposphere exchange

The exchange of air between the stratosphere and troposphere affects the chemical and physical state of our atmosphere. Stratospheric ozone transported to the troposphere is a main source of tropospheric ozone, and long-lived greenhouse gases like CFCs and  $N_2O$  are destroyed only after they are transported from the troposphere into the stratosphere. Ozone sonde profiles at Summit were collected since 2005. Analyses of ozone-sonde observations over Greenland have identified significant stratosphere and troposphere exchange in the summer of 2008 (Ancellet et al., 2016). Authors found that persistent cyclonic activity over Baffin Bay was related to the strat-trop exchange events. They also found a positive 12 ppbv gradient in tropospheric ozone over Greenland (4-8 km) that was influenced by long-range transport of biomass-burning emissions from North America, Europe and Asia. Changes in strat-trop exchange are expected in the future as greenhouse gas concentrations increase. These changes are difficult to assess from surface measurements, but strat-trop exchange does leave an imprint on trace gases measured in the Arctic: It creates a seasonal variation in trace gases with substantial stratospheric loss such as  $N_2O$  and the CFCs. This seasonal variation is primarily the result of two processes: seasonal dynamics in the lower atmosphere in the presence of emissions and seasonal downwelling of stratospheric air. Measurements at Summit are more isolated from lower tropospheric influences and, therefore, seasonal changes measured there are more directly influenced by strat-trop exchange processes. Hence, year-round results (capturing the full seasonal cycle) from Summit provide the best measure available from surface sites of strat-trop exchange in polar regions and how it could evolve over time.



**Figure 4.3.4** - Ethane concentrations at Summit from two different and independent programs. Black data represent ~6 hourly measurements with an in situ gas chromatograph at the site. The red data points are results from weekly whole air sample collection done by NOAA. The graph also shows best-fit polynomial trend curves to both data sets, falling mostly on top of each other, indicating the increase in ethane and good agreement between both data sets and their trend results.



Sampling for only a fraction of the entire year at Summit would substantially compromise the usefulness of these data by not allowing for a true estimate of an annual mean mixing ratio. Furthermore, it would not allow the full annual cycle amplitude to be estimated. In many analyses performed with trace gas data, a careful analysis of the full annual cycle is central to the analysis leading to improved understanding. The examples mentioned above demonstrate that point. The importance of a full year of data in the Arctic is also apparent in the recent analysis of the seasonal amplitude of CO<sub>2</sub> in the Arctic. A substantial increase has been observed in the seasonal amplitude for CO<sub>2</sub> in the Arctic, based on results obtained at Barrow, in particular (Graven et al., 2013). Unfortunately, the record from Summit isn't as long as it is at Barrow, but one could easily imagine that having results from Summit over that period would have helped add understanding to the underlying causes of the increased seasonality observed for CO<sub>2</sub>.

Long-term measurements are conducted to answer fundamental questions regarding atmospheric chemistry and composition, and how the chemical and physical state of the atmosphere are changing over time. These states are changing today in important ways, particularly as a result of human activities and particularly in the Arctic, and we expect even larger changes in the future. Long-term measurements allow the detection of changes and can enable an understanding of the underlying causes for those changes. A robust and diverse sampling network enables one to better understand observed trace gas concentrations and distributions, to better diagnose changes observed in these concentrations and distributions over time, and to better predict how they might change in the future. Summit is a cornerstone of our “robust and diverse” sampling network, primarily because it is the only Arctic sampling site far removed from local sources of naturally-emitted trace gases affecting climate and stratospheric ozone. The long-term ozonesonde record at Summit provides valuable information about large scale stratosphere-troposphere exchange in the Arctic and its seasonal and interannual variability (Shams et al, 2017). The changes observed at Summit are representative of a large portion of the Arctic, not just the local surrounding environment.

### **Atmospheric Boundary Layer**

Through much of this discussion of atmospheric processes and research, the importance of the atmospheric boundary layer (ABL) has been implicit. While Summit is often considered to be representative of the free troposphere, the near-surface atmosphere is usually stably stratified (Miller et al. 2013) as a result of the interplay of strong surface cooling and generally warm air advection aloft. Thus, the actual link between surface-measurements at Summit and the free troposphere is not entirely clear. Low-level ABL structure plays a role in vertical mixing processes, which are important for determining the association between large-scale advection and local near-surface measurements of many parameters including atmospheric gases, aerosols, moisture, etc. The ABL structure constrains surface fluxes of energy and gas exchange. It also influences, and is influenced by, cloud and precipitation processes. Thus, much of the atmospheric science conducted at Summit requires knowledge of the ABL structure.

ABL structure measurements at Summit are currently made most robustly by twice-daily radiosonde profiles. Additional measurements on meteorological towers (10 and 50m) and retrievals from

passive microwave and infrared measurements at the surface also provide supporting information. While routine radiosonde profiles made at coastal Greenland stations may provide a reasonable constraint on the free tropospheric thermodynamic structure over central Greenland, these coastal radiosoundings will not represent central Greenland ABL structure extending from the surface up to typically 100s of meters. Radiosoundings, and/or other measurements of the ABL structure, therefore provide critical context for much of the atmospheric science at Summit.

### *Science Impact Under Future Scenarios*

**Increased Operations:** Continue weekly (carbon cycle) and bi-weekly to weekly (halocarbons) sampling. Continue surface energy balance, meteorological, cloud, and aerosol measurements year-round, with daily inlet cleaning, and instrument stewardship. Continue NOAA surface ozone measurements year-round, 5 minute resolution, with weekly zero level calibrations. Twice-daily radiosonde measurements will continue with additional measurements in the near-surface layer. However, significant cost savings could be realized in the radiosonde program by deploying a small hydrogen generator that would generate gas daily for radiosonde balloons; this would eliminate the considerable costs of procurement and transportation of helium to Summit.

**Business as Usual:** Continue weekly (carbon cycle) and bi-weekly to weekly (halocarbons) sampling. Continue NOAA aerosol measurements year-round, with daily inlet cleaning. Continue aerosol and cloud measurements from Universities. Continue NOAA surface ozone measurements year-round, 5 minute resolution, with once a month zero level calibrations. Continue twice-daily radiosonde program. Measurements of SEB continue to provide valuable context for short term campaigns, long term analysis of trends, satellite algorithm development, transfer function research, aerosol-snow exchange studies, studies of water vapor transport, cloud process studies, and virtually all other studies interested in any process level understanding of the surface of the Greenland ice sheet and the overlying atmosphere.

**Multiparty:** Continue weekly (carbon cycle) and bi-weekly to weekly (halocarbons) sampling. Continue NOAA aerosol and surface ozone measurements year-round, with daily inlet cleaning. Continue aerosol and cloud measurements from Universities. Continue twice-daily radiosonde program.

**Minimum Personnel:** Continue sampling weekly and/or bi-weekly via PFP system (engineering necessary), if TAWO/sampling site is powered. Requires limited technician intervention/maintenance to continue sampling with current timeline. Continue NOAA aerosol measurements year-round, but design/install new inlet (heated/larger) for decreased technician time requirements. Continue surface ozone measurements year-round with once a year calibration checks. Continue current University aerosol observations. Consider the level of cloud observations that will be possible. Continue the radiosonde program but consider the scientific impact of dropping to one per day. Generally, SEB instrumentation would present very little workload for techs overwintering at Summit. The reliability of power would furthermore ensure high quality data and having local personnel on site would greatly reduce the impact of weather processes (rime) on the observations.

**Reduced Operations - Power:** Reduce sampling frequency during reduced-operations periods (to bi-weekly?), using re-engineered PFP for carbon cycle and halocarbon flasks. Conditioning sampling protocols and equipment compatibility not yet demonstrated. Continue year-round aerosol and surface ozone measurements as power will allow while accepting the inherent risk to data and facilities (risk of prolonged data loss, risk of pumps overheating/fire/etc when unmonitored). NOAA to design/install new heated/larger inlet, better remote monitoring/control for pump, and video/webcam. Likely lose some University aerosol and cloud measurements while some could continue, with risk to data loss if problems occur. Consider continuation of 1-2 radiosondes per day during manned periods, but discontinue during unmanned periods. As mentioned above, the deployment of a small hydrogen generator for balloon gas could significantly reduce the overall cost of the radiosonde program. So long as continuous reliable power is available at Summit it may be possible for reasonable quality SEB observations to be made. There would likely be a reduction in quality during winter months due to riming and other challenges of the instrumentation, however, if heated sensors could be used, and monitored with remote infrared and visible cameras, data could continue to be collected and post-processing using the monitoring cameras could allow for identification of potentially troublesome periods.

**Reduced Operations - No Power:** Data lost during dark period, a measure of the full seasonal cycle is lost. Discontinue NOAA aerosol and surface ozone measurements at Summit. Lose University aerosol observations during cold months, continue during manned months. Lose many cloud observations as it is not feasible to re-deploy each year. Consider continuation of 1-2 radiosondes per day during manned periods, but discontinue during unmanned periods. SEB Observations from Summit would provide valuable data for campaign research, but would lose value for placing activities into the context of the full seasonality. In particular, as a model validation and benchmark site, the lack of winter operations would create a significant gap in validation capacity. Storm intensity, cloud processes, and surface snow processes are all quite unique and highly variable during the winter. This gap would pose substantial difficulties for system studies.

**Campaigns Only:** Discontinue all flask sampling if summer operations only. Discontinue all aerosol, cloud, and surface ozone measurements. In campaign-only mode, SEB would continue presumably as a GC-NET style station. With this, would come the associated uncertainty and data loss that is associated with fully remote autonomous observations. Could perform radiosoundings on an as-needed basis.

**Robotic Operations:** Continue bi-weekly sampling via Manned aircraft or UAS with PFP for carbon cycle and halocarbon flasks (engineering necessary- significant effort required). Discontinue NOAA aerosol and surface ozone measurements. Discontinue some University aerosol measurements and most cloud measurements. Could lose the vital late winter early spring aerosol transport window, but could continue if power is available (instrument needs sample collection substrate replaced every 9 months). Risk to data loss if problems. UAS or Robotic operations offer potential possibilities for SEB but engineering is needed to maintain the current temporal resolution. UAS platforms could provide intermittent observations of atmospheric boundary layer structure, but would not be useful for operational models.

Much of the instrumentation that typically make measurements needed to improve understanding of cloud processes, and especially cloud/aerosol interactions, is very sophisticated and has not been operated autonomously; routine attention from operators is required to ensure instrument stability and optimal operation, to replace consumables, and to mitigate adverse effects on the measurements from harsh Arctic conditions. Additionally, an autonomous approach has not yet been developed to replace radiosonde measurements as a backbone of meteorological science and operational modeling. It should be noted that many research communities are interested in the temperature and humidity structure of the lowest few hundred meters of the atmosphere, which is currently only available from radiosondes. Continuation of cloud studies would probably only continue under operational scenarios that included year-round staffing, and might not be possible under the Minimum Personnel option.

## 4.4 Atmosphere and Snow Interactions

*Atmosphere and Snow Interaction Research addresses science questions (Section 2) 1, 4, 5, 8, 15 and 16.*

*Research in this area contributed to specific recommendations (Section 3) 1, 3, 5, 6, 8, 9 and 11.*

### *Critical Nature of Research*

The state of the Arctic environment is changing right now. The summer sea ice is predicted to disappear in the near future and will further impact the climate and the hydrological cycle in the Arctic and across most of the Northern Hemisphere mid-latitudes. As the Arctic continues to warm and sea level research stations experience more snow/ice-free conditions, the high-altitude observatory at Summit will play an increasingly important role in providing critical information on the ice-sheet albedo and snow-air chemistry.

### *Societal Impact of Research*

The atmosphere not only influences the snow, the snow also influences the atmosphere. These influences have both local as well as long-range hemispheric-effects. For societies and stakeholders it is crucial to be able to understand these changes in order to prepare for changes in the climate and environment in order to understand these physical processes as societies and stakeholder rely on accurate and precise projections of future climate. The understanding of the physical processes gained from process-oriented studies at Summit can be implemented directly in global climate models to make such models more accurate.

### *The State of Science and Measurements*

The chemical and physical processes occurring at the cryosphere-atmosphere boundary are not unique to central Greenland; they occur throughout the Arctic, Antarctic, and seasonally snow-covered mid-latitudes. This significantly increases the relevance of the process studies conducted at Summit, since even small chemical fluxes between the snow and atmosphere measured at Summit can have major impacts on Arctic biogeochemical cycles when scaled to the whole Arctic. However, it does raise the important question: “Why go to Summit to study something that happens in many of our backyards every winter?” There are a number of reasons why Summit is the best location for studying these boundary layer processes as is detailed below.

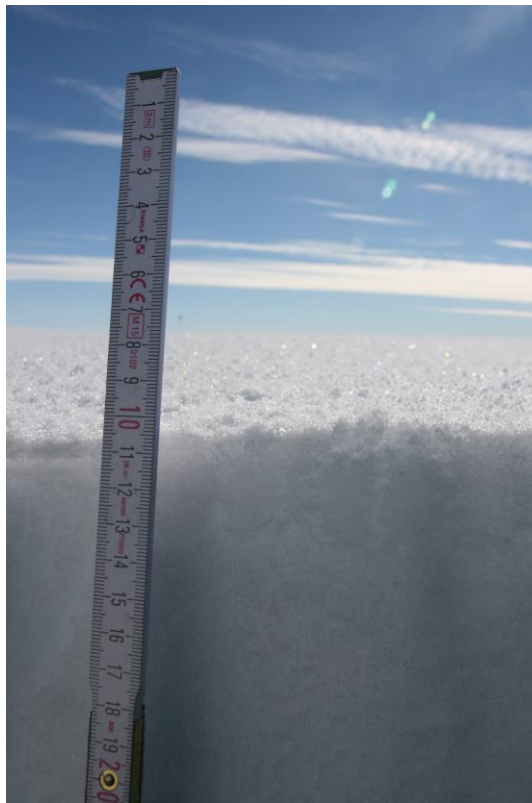
Summit’s position at the top of the Greenland ice sheet means that it is more often impacted by long-range transport from both the Arctic and mid-latitudes within the free troposphere than any other Arctic stations. Its 3000-m elevation and distance from significant point sources of most atmospheric species results in a “background” atmospheric signal that is more representative of the wider Arctic. Summit is perhaps the best northern hemisphere location from which to monitor the temporal evolution of atmospheric climate forcers, including short-lived pollutants such as methane, ozone, aerosols (especially

absorbing components of the aerosol like dust and black carbon) as well as the well-mixed greenhouse and other trace atmospheric gases. Summit's atmosphere and snow chemical concentrations are generally low, simplifying the chemical processes. In contrast, stations near sea level and along coasts are dominated by high concentrations of marine aerosols and gases which mask contributions from more distant locations and can overwhelm chemical reactions involving non-marine species.

Summit's position within the dry snow zone removes much of the complexity associated with snowpack melting, freeze/thaw cycles, and meltwater migration that can convolve the processes of interest. However, experiments investigating the effect of freeze/thaw and melt can be conducted at Summit by artificially introducing meltwater to the system under controlled conditions (Wong et al. 2013) and taking advantage of infrequent natural melt events. Furthermore, dry-snow conditions throughout the year allow photochemical experiments to be conducted under a wide range of photon fluxes.

Air-snow boundary layer experiments have been conducted at Summit since the early 1990's after collection of the GISP2 and GRIP ice cores. This multi-decadal sample and data legacy is invaluable for evaluating how these processes are evolving through time under changing environmental/climate conditions. Furthermore, this legacy means that we often have data from a particular snowfall event beginning with the atmospheric conditions and chemical signature during the event, the chemical and physical attributes immediately after initial deposition, its progressive post-depositional evolution during advection down into the snowpack, and it can be resampled in the future to evaluate longer-term post-depositional processes. This archive of atmospheric, surface snow, and snow pit samples spanning more than a decade is not available at any other cryospheric location, allowing studies to be developed at Summit that would be impossible anywhere else. These past atmospheric and snow studies can be further used to relate to the ice core records at Summit in order to have a real understanding of past climate signals.

Summit's position on the Greenland ice sheet increases its relevance because of societal concern about Greenland's current and projected mass loss and the consequential impacts on global sea level. As one example, Summit-based studies focused on changes in snow albedo due to changes in snow grain properties and impurity concentrations provide critical constraints on Greenland surface energy and mass



**Figure 4.4.1** - Measurement of surface hoar showing the cycling of chemicals and vapor between the snow and atmosphere.

balance. Studies focused on climate-driven changes to snow metamorphism and densification processes also have important implications for satellite altimeter estimates of Greenland mass balance.

Perhaps the greatest advantage of conducting these studies at Summit is the GISP2 and GRIP ice cores spanning the past 100,000 years of climate and atmospheric history, arguably the two most important ice cores in the Northern Hemisphere. Air-snow boundary layer studies provide critical information for correctly interpreting chemical and physical signatures in the deep Summit ice cores. The ice cores, in turn, provide a unique, long-term record from the same location for comparison to modern measurements.

In recent years, the atmosphere-cryosphere boundary layer measurements have included a year-round sampling regime, conducted with the aid of science technicians using strict sampling methods including:

- ***Surface/fresh Snow Samples:*** Replicate samples of surface snow have been collected every 3-10 days (including the winter) since 2003 for a suite of chemical and isotopic analyses. These samples are collected from the clean air sector by Summit science technicians and returned frozen to institutions for analyses.
- ***Snowpit Samples:*** 1-m deep snowpits have been sampled at 3-cm resolution for chemical concentrations, isotope ratios and physical properties (temperature, density, stratigraphy) on a monthly basis (including the winter) since at least 2003. The snowpits are excavated and sampled in the clear air sector by Summit science technicians, and chemistry samples are returned frozen to institutions for analyses.
- ***Aerosol Sampling:*** Since 2005, a rotating 8-stage Davis Rotating-drum Unit for Monitoring (DRUM) aerosol sampler has measured aerosols by size, time and composition. The instrument provides data every 12 hours in 8 different size modes from 10 to 0.9 micrometer in diameter over the entire year. Compositional analyses are completed by synchrotron induced x-ray fluorescence (S-XRF), optical spectroscopy, proton electron scattering analyses (PESA), and soft beta ray transmission (VanCurren et al., 2012). Summit science technicians ensure that the DRUM sampler remains operational over the year. Aerosol sampling was also conducted at Summit over shorter intervals during individual research campaigns prior to 2005, mostly during the summer season when PIs were on-site at Summit.
- ***Vapor Isotope Sampling:*** In addition to measuring surface snow and snowpit samples for stable water isotope ratios, water vapor was continuously analyzed for stable isotopes over a 4-meter vertical profile in the Summit clean air sector from July 2012-July 2014 (Berkelhammer et al., 2016). This instrument was maintained by Summit science technicians.
- ***Firn Air Sampling:*** Gases and water vapor isotopes have been sampled from Summit firn air during summer campaign-style studies.
- ***Meteorological Data:*** Meteorological data are a critical component of cryosphere-atmosphere boundary layer studies, and are detailed in the “Surface Energy Balance” chapter of this report.

## *Science Impact Under Future Scenarios*

**Increased Operations:** With expanded operations, one might prioritize additional sampling locations to evaluate spatial variability, and particularly increase aerosol and vapor sampling at several different elevations to better understand boundary layer dynamics and their impact on atmospheric chemistry and air-snow transfer.

**Business as Usual:** Under a Business as Usual scenario with year-round science technicians, the atmospheric and snow/ice sampling regimen that has been in place since 2003 will continue. This will extend this completely unique and valuable record into the coming years as anthropogenic climate change continues to increase in magnitude. The long-term baseline allows for even subtle changes in chemical, physical and isotopic air and snow properties to be statistically identified and their causal processes explored.

**Multiparty:** The multiparty option would likely have a positive effect on science with additional collaborative parties. Much of the work US PI's do in regards to process studies would be enhanced through collaboration with international PI's with complementary expertise.

**Minimum Personnel:** Surface snow and snowpit sampling has typically been conducted by two personnel over the winter, so it would be feasible to continue BAU under this option. However, the ramifications for personnel safety and the ability for only two personnel to maintain life support systems in the Station over winter are unclear.

**Reduced Operations- Power:** With winter power, some sampling of aerosols and water vapor might be possible, but would pose significant engineering challenges and investments to ensure faithful collection of data over the winter during challenging conditions. However, the collection and preservation of representative surface snow samples and snowpit samples during the winter would not be possible without personnel. An automated surface snow collection system could be developed with considerable engineering development and expense. However, an automated system to collect snowpit samples is not likely feasible at this time. More feasible would be an automated ice core collection system by robot that would collect a 1-m ice core at a set time and preserve it for later analyses. This technology also does not currently exist and would require significant engineering development and expense. As a summertime campaign activity, ice air sampling would be unaffected by this option.

**Reduced Operations- No Power:** Without winter personnel or power, the current surface snow sampling, snowpit sampling, aerosol sampling, and vapor isotope sampling would not be possible over the winter months. Summer campaigns provide significant insights into some of the research questions outlined above, especially related to snow photochemistry, but miss critical long-range transport variability and markedly different deposition and post-depositional processes during the winter. Specific processes that have important seasonal variations include, but are not limited to: atmospheric temperature, moisture advection, vertical atmospheric stratification, vertical mixing of the boundary layer and free troposphere,



surface radiative and turbulent heat fluxes, conductive fluxes in the near-surface snow/ice, trace gas and aerosol concentrations, pollution transport, precipitation fluxes, stratosphere-troposphere interactions, wind speed and direction, rates and timing of snow accumulation, metamorphism, and firn compaction. Knowledge of these processes based on summertime observations is not sufficient to understand how these processes manifest throughout the rest of the year. Air-snow exchange processes are undoubtedly affected by ambient conditions, hence these processes must be investigated under as wide a range of environmental conditions as possible. As a summertime campaign activity, firn air sampling would be unaffected by this option.

**Campaigns Only:** Without winter sampling, the physical and chemical processes specific to the winter months when no sunlight exists will not be possible to quantify. Further, the summer May-August present campaign season represents only  $\frac{1}{3}$  of the year and a smaller fraction of the range of ambient climate conditions that significantly impact the air-snow boundary processes of interest and their rates. As a result, our understanding of these processes will be incomplete, as will their ability to perform correctly in global models. Furthermore, the intensified atmospheric circulation during the winter months intensifies long-range transport of aerosols from the tropical and mid-latitudes, which would be missed under this option. For example, marine aerosol species (sodium) have peak wintertime concentrations, and dust concentrations (transported from Asian deserts) peak in March-April. This option would significantly curtail researchers' ability to address cryosphere-atmosphere boundary research questions.

**Robotic Operations:** As discussed in the Winter Power No Personnel option above, robotic solutions for surface snow sampling and shallow (1 m) core sampling may be possible with considerable development, but do not currently exist. Measuring aerosols by UAV would provide the opportunity to collect data at multiple elevations above Summit, which would significantly advance the air-snow-transfer research at Summit. Drone-mounted aerosol sampling platforms are currently in development (see Bates et al., 2013; Brady et al., 2016), but currently only have the ability to measure a few analytes due to weight constraints. This technology should be monitored to see if drone-based aerosol sampling would be advantageous at Summit.

## 4.5 Glaciology

*Glaciology addresses science questions (Section 2) 1, 5, 6, 7, 8, 9, 15 and 16.*

*Research in this area contributed to specific recommendations (Section 3) 1, 2, 4, 5, 6, 7, 8, 9, 10 and 11.*

### *Critical Nature of Research*

One of the defining questions associated with ice sheets is their mass balance; that is, how much mass is gained or lost. Mass lost from an ice sheet goes to the ocean, raising sea level. The Greenland ice sheet contains enough water locked up as ice to raise sea level roughly 7 meters, inundating many coastal locations. Studies have shown increases over recent decades in ice-stream velocities and extent of surface ablation zones, contributing to observed drawdown of coastal and interior ice in Greenland (e.g., Abdalati and others, 2001; Krabill et al., 2004; Luthcke and others, 2006; Velicogna and Wahr, 2006; Stearns and Hamilton, 2007; Howat and others, 2007; Kahn and others, 2010).

Whether the Greenland ice sheet ice loss continues and accelerates in the coming decades depends on the highly variable surface mass balance and the dynamic response of the ice sheet to recent and future climate changes. The mass balance of the Greenland ice sheet depends on accumulation and ablation (or mass gain and loss). Accelerating mass loss from faster flow of outlet glaciers, such as Jakobshavn Isbrae and Helheim Glacier, has been widely documented and is likely to continue (eg. Thomas and others, 2000; Joughin and others, 2004; Rignot and others, 2010). Additional work has addressed the increasing melting in the ablation zone of the glacier, and the resulting enhancement of runoff, sometimes in dramatic ways (e.g., Das et al., 2008). Less dramatic, but of similar or even greater importance, is knowledge of changes in snowfall. Most of the accumulation data for the Greenland ice sheet comes from snow pits and shallow cores <15 years in length, and many were collected during early ice sheet traverses in the 1950s, 1960s and 1990s (e.g. Ohmura and Reeh, 1991; Ohmura and others, 1999; Bales and others, 2001; Mosley-Thompson et al., 1998).

### *Societal Impact of Research*

The most significant societal impact of ice-sheet change is the associated change in mean sea level directly affecting the nearly one billion people on Earth living in low lying areas (less than 10 m above sea level). Measuring the mass balance of the ice sheet entails determining volume change, which can be translated into change in global sea level rise. A key component of ice sheet mass balance is documentation of surface-height change. When combined with detailed understanding of ice density, changes in surface height allow accurate accounting of gains and losses of mass from different regions of the ice sheet. The societal impact of determining the mass balance of ice sheets is shown in the major US government investment in the ICESat-2 satellite scheduled to launch in 2018. One of the objectives of ICESat-2 is to make repeated measurement of surface height over both polar ice sheets. The orbit for ICESat-2 was adjusted to align with Summit in order to use the long record of very precise surface height made at Summit by repeated kinematic GPS surveys to validate surface height measurements made from the satellite.

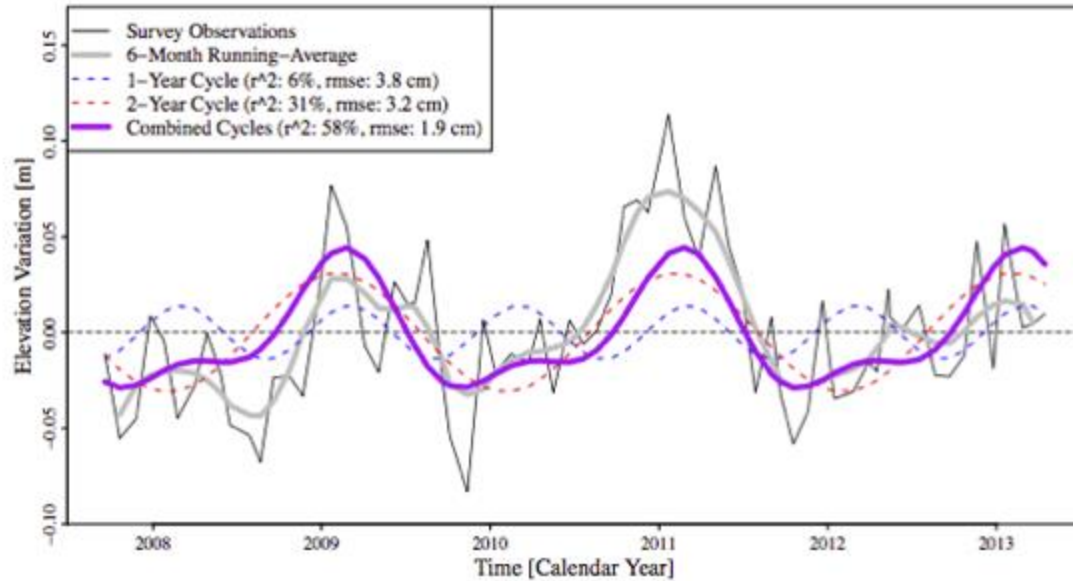
## *The State of Science and Measurements*

Spatially and temporally extensive accumulation time series are needed to quantify robustly any recent temporal trends, evaluate relationships with regional climate patterns, and constrain the impact on Greenland ice sheet mass balance. Long accumulation records have been obtained from the deep ice core sites (e.g. Camp Century, GISP2, GRIP, DYE3, NEEM, NGRIP; e.g., Alley et al., 1991; Cuffey and Clow, 1997), and from a series of shallow (15-30 m) firn core sites mostly in the southern and western sectors of the Greenland ice sheet as part of the Program for Regional Arctic Climate Assessment (PARCA; McConnell and others, 2000, 2001; Mosley-Thompson et al., 2001; Thomas and others, 2001). The Summit accumulation record, however, explicitly covers spatial variability over scales from 10 m to 10 km, and temporal variability, on scales from weeks to decades to millennia (GISP2). The length and breadth of this record are important for providing context for shorter or more localized records; for example, one must characterize the variability from snowdrifts to know how much of the variability in a single core could arise from drifts. Assessing such variability at Summit supplies prior and ongoing studies needed context.

Since 2006, a monthly assessment of surface height is currently being made near Summit along an 11-km traverse, referred to as the ICESat traverse (**Figure 4.5.1**). This assessment has been used as a ground-based validation of airborne and satellite assessments, including NASA's Operation IceBridge and ICESat, which leads to an ice-sheet wide assessment of change and allows for a quantification of mean sea level rise. The monthly ICESat traverse represents the most temporally long and dense in situ observation of ice-sheet elevation change. Since its inception, this traverse has evolved such that there are uniform survey strategies and data processing methods. Common sampling and processing strategies have led to cm-level internal consistency (precision) of the ground-based GPS data.

While this assessment could be made elsewhere in Greenland, or in Antarctica, the long-term observations of surface height, accumulation, and firn densification at Summit are key measurements for understanding surface mass balance. From a sampling perspective, Greenland is changing faster than Antarctica, and has a stronger seasonal signal. Both factors make this type of assessment easier to accomplish at Summit.

Surface height measurements are just one piece of the more complex question associated with how our ice sheets are changing (and the impact of that change on mean sea level). When these measurements are coupled with other measurements (e.g., AWS estimates of accumulation; automated SWE measurements; upward-looking radar; the bamboo forest and the ICESat traverse assessments of accumulation; radar-based estimates of precipitation) we gain a better understanding of the surface change and how that relates to the longer-term trend in the changes of the Greenland ice sheet.



**Figure 4.5.1** - ICESat traverse data showing significant accumulation variability by elevation variation. The variability is too large and too unpredictable to model at the cm level for the future ICESat-2 calibration and, therefore, requires ground validation.

Kuipers Munneke et al. (2015) highlight some limited but significant (i.e. above uncertainty levels) thickening of the high interior firn layer, by  $\sim 0.01\text{-}0.05\text{ m yr}^{-1}$ , during 1980-2014, which they ascribed mainly to increased accumulation; this increase migrated from the east and north-east interior to the Greenland ice sheet centre where it stagnated in the last years, while south-east Greenland accumulation overall decreased during this period. NEEM accumulation increased by  $0.016\text{ m yr}^{-1}$ , during 1979-2007 (Masson-Delmotte, 2015). There tends to be an antiphase in precipitation/accumulation trends between inland and coastal regions (Mernild et al., 2015), which merits more attention in terms of causal mechanisms. Regarding observations, Summit is an optimal long-term accumulation observation site due to the availability of long control records from firn/ice cores and the relatively low accumulation variability compared with lower elevations, which reduces the emergence time of a global-warming related Greenland surface mass balance signal; the latter may already be happening as Fyke et al. (2014) report recent interior accumulation (slight) increases.

Current accumulation measurements at Summit are collected in five distinctly different ways, which can be characterized as either automated or manual:

***Automated:***

1) AWS estimates of accumulation- As part of the GC-Net network, an Automated Weather Station is in place at Summit. Part of the AWS suite of instruments is a Sonic Ranger, an instrument that uses sound waves to determine the distance between the sensor and the snow surface. This measurement is collected at a single location, but at frequent time intervals. This instrument generally requires little to no intervention by a scientific technician through a year. The instrument runs on an independent renewable energy system of batteries and solar panels. It is required that the tower supporting the Sonic Ranger stays vertical, so the

ranger is pointed straight down, for quality measurements which requires some periodic maintenance for leveling.

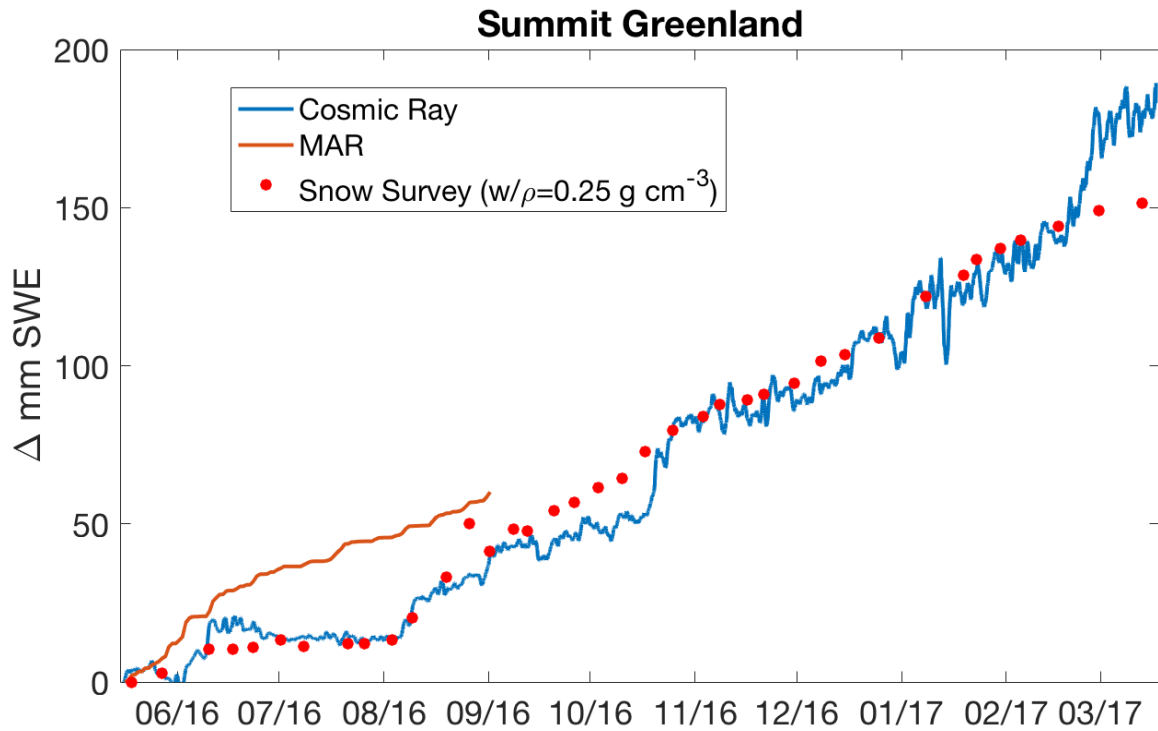
2) Automated Snow-Water-Equivalent (SWE) measurement by the attenuation of high-energy particles associated with cosmic rays. This instrument is buried in the snow at Summit and continuously measures the number of impacts by fast-moving neutrons generated from cosmic radiation, which are attenuated by water molecules (**Figure 4.5.2**). As the thickness of water, in any phase, increases above the sensor, the number of neutrons contacting the sensor per time decreases as a consistent function, regardless of the density of the water molecules. Once corrected for atmospheric moisture content, using a local barometer, and background variability using the Bartol reference station at Thule, the neutron impact count per time gives a measure of the Snow Water Equivalent (SWE) accumulation (i.e. surface mass-balance). The effective measurement footprint of the sensor is a several meter diameter circle. This instrument does not require science tech intervention. It is currently operated on station power but has a low power draw (< 100 mA at 12 V) and has been successfully deployed autonomously for two years at another location on the ice sheet. This is a single (point) measurement, not co-located with the AWS.

3) Upward-looking radar- this is a commercial-grade ground penetrating radar unit buried in the snow, looking up. The radar can easily detect the snow/air interface. This instrument requires station power, operates at a single point (coincident with Cosmic Ray SWE measurements) and can make temporally frequent measurements of snow depth. The radar requires a measurement of snow density either in conjunction with the Cosmic Ray SWE measurements or from manual measurements or modelling studies.

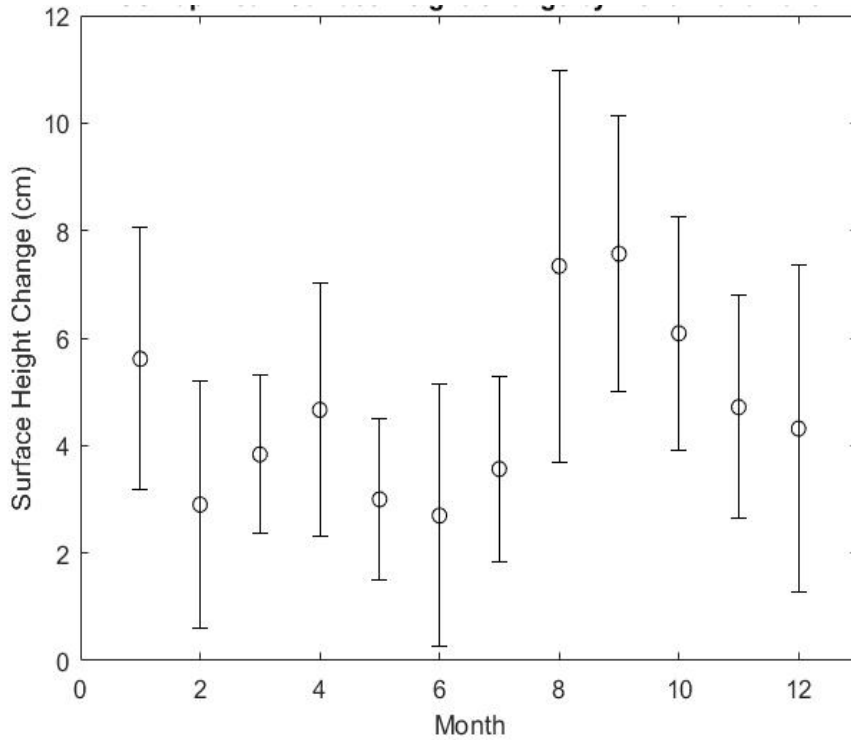
**Manual:**

4) The Bamboo Forest- this is a grid of bamboo poles, ~100 m on each side, with spacing of ~10 m between each pole. On a weekly basis, the science technicians visit the poles on skis and manually measure the distance from a fiducial mark on the pole to the snow surface. The difference between one measurement and the previous measurement indicates the amount of snow gained or lost during the interval. This is the longest time series of surface accumulation on the Greenland ice sheet. **Figures 4.5.3 and 4.5.4** show the largest variance in the Bamboo Forest surface height occurs August through December while the largest variance in density used to determine SWE is from June to August.

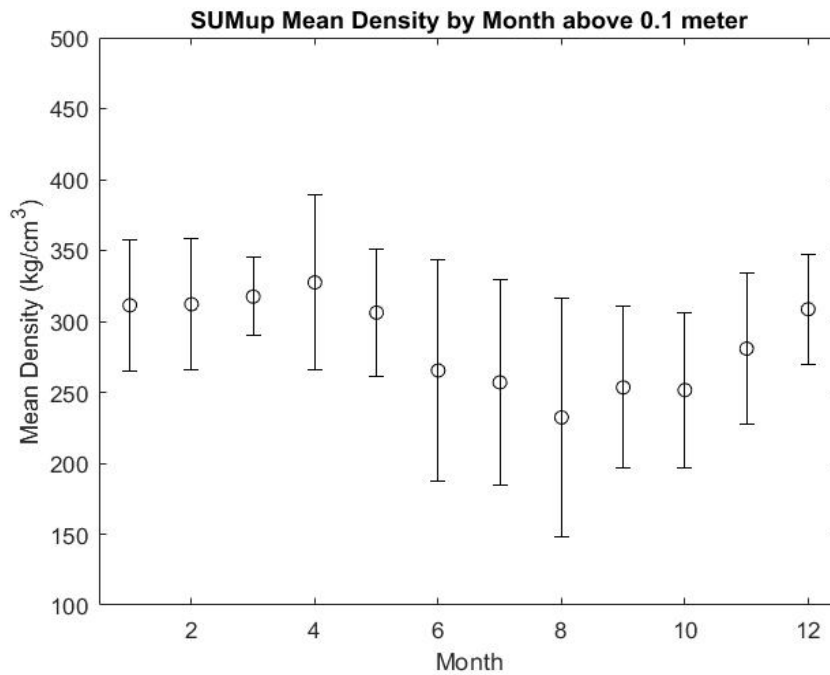
5) The ICESat transect- this is a line of 122 bamboo poles along a ~10 km zig-zagging track that covers a linear distance of ~6.5 km along ICESat orbital track 412. On a monthly basis, science techs visit each pole via snowmachine, measuring with the same technique as in the bamboo forest above. It is important to note that of the above methods, only method 2) the Cosmic Ray SWE, provides a completely independent measure of SMB. Each of the other methods is a measurement of surface height change, and to calculate SMB from these measurements requires an estimate of density, which is obtained by direct measurement in a snowpit, which are currently dug monthly. This is an example of the synergistic nature of many of the measurement programs at Summit- one dataset often depends on another for interpretation or for ancillary measurements to make its findings complete.



**Figure 4.5.2** - Cosmic Ray SWE measurements (blue) are a promising automated measurement that is serviceable over short time periods. The Bamboo Forest (red dots) is currently being used to validate Cosmic Ray SWE measurements. The time series of ~ 9 months is not long enough to assess the differences between the Cosmic Ray SWE measurements and the more traditional Bamboo Forest stake measurements from Summit.



**Figure 4.5.3** - Surface height change from Bamboo Forest measurements showing the largest variance and change from August through December.



**Figure 4.5.4** - Surface density change at Summit Station from the SUMup dataset showing the largest variance June through August.

## *Science Impact Under Future Scenarios*

**Increased Operations:** Under increased operations, we would expand the grid of accumulation measurements; the current ICESat line roughly follows a contour line. This could be increased to include poles 10, 20, 30 km out from Summit, up to the actual high point to the East and in all other directions. We would continue the surface height time series and the accumulation (stake measurement) time series, and would introduce better methods for determining firn densification. Given these synergetic measurements, we could make better assessments of SMB. GPS reflectometry from a tower could be used to characterize the snow surface, providing important data on the snow surface and structure of upper layers of firn, perhaps aided by an active radar system. Firn densification could be tracked to study time-dependent changes that could cause surface-elevation changes mimicking accumulation-rate changes.

**Business as Usual:** Under the Business as Usual scenario, nothing changes for Glaciological measurements. We continue to have time- and space-series of accumulation measurements via multiple methods, all of which can corroborate and support one another. We would continue the surface height time series and the accumulation (stake measurement) time series important for the calibration of ICESat-2 and other altimetry missions.

**Multiparty:** Under this scenario, Glaciological measurements could proceed unaltered.

**Minimum Personnel:** Under this scenario, Glaciological measurements could proceed unaltered. This assumes that travel away from station is deemed acceptably safe.

**Reduced Operations - Power:** Under this scenario, the impact is similar to the Reduced Operations - No Power described below, however, the upward-looking GPR (method 3 above) would be enabled. This scenario does not provide any spatial information on accumulation, and provides data that partially overlaps with those from method 1) above. The ICESat line traverse requires more than just power to keep it going and would suffer significant data gaps and is therefore not a viable solution to continue this time series. Seismometer measurements would continue.

**Reduced Operation - No Power:** This scenario would introduce gaps into the time series from the two manually-operated accumulation measurements and from the upward-looking GPR, which requires station power. Methods 1) and 2), described above, would be unaffected by a wintertime closure, except in the case of instrument failure that could not be repaired until the next human visit. Loss of the manually-operated measurements would result in a total loss of data on the spatial variability of accumulation for that time period. **Figure 4.5.1** shows a climatology of accumulation at Summit, based on the measurements of the ICESat transect; clearly visible is the difference in accumulation between December, January, and February. Losing the mid-winter months would mean losing the ability to discern changes in this pattern.



If the surface height assessments were not made for some number of months in the winter, the time series would be blind to some of the largest seasonal and annual changes in elevation and density (**Figure 4.5.1**). Seismometer measurements would continue.

**Campaign Only:** Under the Campaign Only scenario, the value of the accumulation and surface elevation data sets would be significantly reduced, summertime only data sets would have nearly no scientific value for mass balance studies or satellite validation within just a few years after the winter-time measurements were terminated. Descoping the temporal or spatial coverage of our key measurements decreases the value of investments already made to satellite missions such as ICESat-2. This scenario would lead to significant data gaps and is therefore not a viable solution to continue the time series. As seen in **Figure 4.5.1** the temporal variability of the accumulation on the ICESat line is large outside the summer period. Seismometer measurements would continue.

**Robotic Measurements:** With time and investment many of the glaciological measurements could be achieved by robotic means. Indeed there are already research and engineering projects into these areas and we detail them here. If an infrastructure investment were made in advanced techniques for measurement of accumulation and SMB at Summit, the primary methods improved would be methods 4 and 5, as the others are already largely or entirely autonomous. The ICESat transect is an ideal candidate for one of the several autonomous rovers that have been tested at Summit. These rovers could make monthly measurements, each month 'waking up' and driving the route with an operating DGPS. Measurements of surface height change relative to the stakes could be made by one of several different tactics, from low-tech to high-tech- a camera could capture the snow surface, and a set of fiducial marks (rather than just 1) could be marked on the pole, effectively making the pole into a measuring stick. Or the fiducial mark on the pole could be an RFID chip, readable by the robot when the robot brings the sensor up to the height of the chip; the robot then measures the displacement of the arm required to trigger the chip reader. Such a solution would also work for the bamboo forest, and in fact would be simpler since the driving distance is shorter. The key challenges to a rover-deployed ICESat transect are access and power. Power is easy to provide for the rover during the summer months, using solar panels. Currently there is no existing solution to providing sufficient power during the winter months. This could be solved by employing wind power, or under the Reduced Operations- Power scenario, by allowing the rover to plug into the Summit power grid. Another challenge to a rover-deployed ICESat transect is the time that it would take to develop and deploy such rovers. While a rover may provide data through a period when there is reduced infrastructure, and thus sustain a continuous annual time series, getting to that point will require more instrument development. Another alternative would be independent sensors at each accumulation pole. This would require replicating something like an AWS of GPS stations a total of 122 times for each stake along the traverse. Other potential engineering solutions exist; for example, a small, microcontroller-based GPS and sonic range logger could be constructed and replicated the 122 times for the ICESat line and 100 times for the bamboo forest. This would also require some investment in development, but is likely a solvable problem.

UASs and rovers represent a rapidly evolving technology that could be implemented for surface height and snow accumulation. Instruments already take these measurements on manned aircraft and some UASs, including lidars and near-surface radars. Significant developments need to be made in the UASs field to overcome existing hurdles, which include: cold-start of UASs in the winter; ensuring a rover can keep itself moving (and not get stuck in sastrugi) and return to base; and data download and transfer. Further, an implementation plan would have to be created, whereby the traditional traverse and a UAS or rover traverse would be conducted simultaneously for some length of time to ensure that a UAS implementation was achieving similar or acceptable results (with respect to accuracy and precision of the kinematic GPS post-processed position solutions for the UAS in particular). If the overlap between the traditional and UAS traverse is only feasible for a short period of time, the traverse should be conducted more frequently to develop a statistical assessment of the UAV results. Seismometer measurements would continue but would need to be automatically leveled.

## 4.6 Ice Core and Firn Paleoclimate Research

*Ice Core and Firn Paleoclimate Research addresses science questions (Section 2) 1, 2, 3, 5, 6, and 8.*

*Research in this area contributed to specific recommendations (Section 3) 1, 2, 3, 5, 6, 7, 8, 10.*

### *Critical Nature of Research*

A pre-industrial Holocene baseline for atmospheric composition and climate is needed as context for understanding modern environmental change. Summit ice cores have provided results that have been critical in constructing a baseline for Arctic temperature and atmospheric composition (e.g., Brook et al., 1996; Mann et al., 1999).

### *Societal Impact of Research*

Abrupt climate change has the potential to inflict catastrophic damage on society, particularly in some Arctic and sub-Arctic regions, because of the possibly rapid (1 – 2 decades) rate of climate change and very large shifts in regional climate (e.g., 10°C mean annual temperature). Summit ice cores have greatly improved our understanding of abrupt climate change, providing some of the best-dated records of these events that illustrated when these events have occurred and at what frequency (e.g., Grootes et al., 1993). Summit ice cores also provided the best estimates of magnitude as well as the remarkably rapid rate of these events (e.g., Alley et al., 1993; Severinghaus et al., 1998; Severinghaus and Brook, 1999).

### *The State of Science and Measurements*

Records of impurities from Summit ice cores provided critical information about changes in past atmospheric circulation during the last ice age (Mayewski et al., 1994) and over the Holocene (O'Brien et al., 1995). They revealed the nature of long-range atmospheric transport of dust from Asian deserts (Biscaye et al., 1997), a Northern Hemisphere record of volcanic emissions representing a key natural climate forcing mechanism (Zielinski et al., 1994), and the history of Northern Hemisphere pollution from sulfur and nitrogen acids (Mayewski et al., 1990) and toxic heavy metals (Boutron et al., 1991; Hong et al., 1996).

Summit ice cores also yielded results that help to elucidate key patterns of global climate change and large-scale ocean and atmospheric teleconnections. For example, the GISP2 and GRIP ice cores in comparison with the Byrd, WAIS Divide and other ice cores from Antarctica clearly illustrated the “bipolar see-saw” behavior of glacial periods (Blunier and Brook, 2001; WAIS Divide Project Members, 2015). These records also provided evidence that linked north Atlantic climate to low-latitude monsoon intensity (e.g., Chappellaz et al., 1993).

Sea level is one of the most fundamental environmental parameters and is of great societal importance. The Greenland ice sheet is an important player in global sea level, currently containing ≈7 m of sea level rise equivalent. Summit ice cores provided evidence that during the previous interglacial (when

Greenland was several degrees warmer than today) some ice was still present on or near the Summit region, as ice from that time is preserved in the cores (e.g., Grootes, et al., 1993; Suwa et al., 2006; Bender et al., 2011). Deep ice core boreholes also offer access to basal ice and underlying bedrock. Samples of bedrock from below Summit recently provided evidence that Greenland may have been almost completely ice-free during several interglacials during the Pleistocene (Schaefer et al., 2016). Studies of basal ice have revealed important paleoclimatic and glaciological insights (e.g., Willerslev et al., 2007; Bierman et al., 2014).

Despite the apparent maturity of some parts of paleoclimatic reconstructions, rapid and important advances continue unabated. For example, a recent study by Steiger et al. (2017) revisited ice core isotope records and showed how model-data assimilation can be used to deconvolute past climate variability not only for the local Greenland region but globally.

### **Potential for Future Ice Core and Related Studies at Summit**

The Summit site has served, and can serve, as a staging site for additional surveys in the vicinity. The borehole remains an important target for ice-flow and geophysical-calibration studies. And, additional sampling of ice and bed could yield important rewards. While a comprehensive overview of future possibilities is beyond the scope of this document, we provide some examples here.

The great antiquity of some disturbed ice in the base of the Greenland ice sheet (Yau et al., 2016; Suwa et al., 2006; Bender et al., 2011), together with the clear evidence for exposure of the bedrock beneath GISP2 to cosmic rays within the last ~1 million years (Schaefer et al., 2016), place limits on the sensitivity of the ice sheet to warming and its history over recent glacial-interglacial cycles. However, those limits still leave important questions, and the small sample sizes available results in limited analyses that could be conducted. The Summit site could be used as a staging point for additional nearby coring, perhaps using a rapid access drill, to obtain larger and more diverse samples of basal ice and the rock beneath to address these critical questions--the implication that temperatures similar to modern removed almost all of the ice sheet (Schaefer et al., 2016) is of great societal relevance.

Perhaps the easiest such sampling would be to re-core the base of the GISP2 hole. The last entry of the hole indicated that it was partially blocked by partial failure of the casing through the firn, but that might be penetrated readily by reaming. Below, the hole should be present to or near the bed. Deformation in the borehole concentrated near the bed (Clow and Gundestrup, 1997; also see Bender et al., 2011) may have made penetration completely to the bed difficult, but this could open the opportunity for easily drilling into a slightly different part of the bed, obtaining unique samples of basal ice and substrate.

Diversion drilling from an existing borehole was successfully completed in the WAIS Divide deep coring project. Application in the GISP2 hole would allow resampling of key ages such as the onset and termination of the Younger Dryas and other rapid climate change events (Dansgaard-Oeschger events), allowing new studies with improved instrumentation but without the expense of drilling a complete new hole.

The deformation of the borehole holds important information on ice-flow processes (e.g., Bender et al., 2011; Clow and Gundestrup, 1997), so re-logging could be conducted to yield further useful findings. Geophysical measurements in the borehole, and between the borehole and the surface, using new and improved instrumentation could more accurately characterize such issues as attenuation of radar and seismic waves in ice and their dependence on temperature, with the possibility of measuring temperature remotely (Peters et al., 2012). Many additional experiments could be proposed.

Such an ambitious effort of coring and measurement in the GISP2 hole would require some coordination and probably a workshop to discuss ways forward, as well as better assessment of the integrity of the hole especially through the damaged casing. Nonetheless, large scientific returns might be obtained at much lower cost than if a new site were developed.

As noted just above, the Summit site can anchor additional regional surveys collected to supplement the central records. For example, excitement was created by the spread of surface melting across the Summit region in 2012, but this was not a unique event in the Holocene as shown by analysis of melt layers in the GISP2 core (Alley and Anandakrishnan, 1995). Despite subsequent studies extending this work, much detail is still lacking; additional networks of cores could track the regional and time evolution of melting, and accumulation rate, chemical impurity deposition, and much more.

### *Science Impact Under Future Scenarios*

**Increased Operations:** This would likely enhance opportunities for exciting new ice core projects because of increased logistical synergies with other projects/routine operations.

**Business as usual:** no significant impact

**Multiparty:** This would likely enhance opportunities for exciting new ice core projects at Summit by attracting more international research groups.

**Minimum Personnel:** If atmospheric and snow sampling and measurements are able to continue through the winter with reduced personnel, no significant impacts are expected.

**Reduced Operations -Power:** if atmospheric measurements are able to continue throughout the year, and flight accessibility is maintained in the summer, no significant impacts are expected on the trace gas model tuning research. However, snow sampling would not be possible without over-winter personnel and would have the same negative impact as full station winter shut-down for the snow chemistry and isotope air-snow transfer studies.

**Reduced Operations-No Power:** Future firm air studies would be impacted because full-year trace gas records from Summit are used for tuning with the firm gas diffusion models. Snow chemistry studies at Summit aimed at improving interpretations of the ice core impurity (dust, sea salt, soot, etc.) and stable isotope records would also be negatively impacted because of the importance of winter processes (see Atmosphere and Snow Interactions, **Section 4.4**, for further details). This would significantly impair our

ability to understand and quantify the transfer function between the climate and the climate signal recorded in the ice cores. However, studies of older ice / air below the firn zone have summer operations and would not be impacted, nor would be the drilling operations.

**Campaign Only:** This is likely to affect Summit accessibility by C-130 aircraft, making ice core campaigns more difficult, particularly for larger projects that attempt to drill deeper or to recover large volumes of ice. Future firn air studies would be impacted because full-year trace gas records from Summit are used for tuning with the firn gas diffusion models. Similarly, the interpretation of past and future ice core records from Summit would be negatively impacted from the lack of air-snow transfer studies over the year.

**Robotic Measurements:** No impact if this is restricted to winter months. If this extends to summer months and results in reduction in Summit's ability to receive flights and support campaign science, then a major negative impact on future firn and ice core studies is possible (field campaigns would be more difficult to get approved).

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## Appendix A - Summit Science Summit Survey

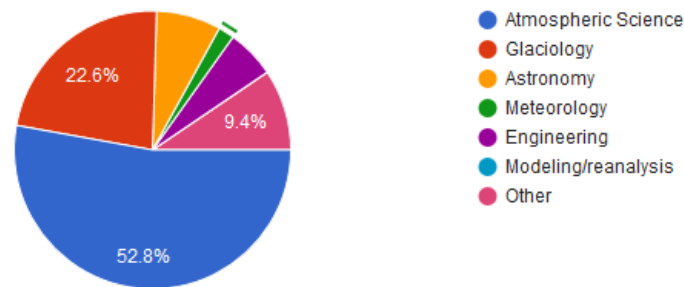
A survey on scientific use of Summit a sent out to all meeting participants and broadly to the Arctic Community through postings on the list serves Cryolist ([www.cryolist.org](http://www.cryolist.org)) and Arctic Info ([www.arcus.org/arctic-info](http://www.arcus.org/arctic-info)) and was posted to the International Arctic Science Committee's (IASC) Facebook page and sent to the Association of Polar Early Career Scientists (APECS) for inclusion in their newsletter. This survey was meant to get a broad sampling of how the science community uses Summit Station and was not conducted to be scientifically significant. In total there were 54 responses to the survey. While names and institutions were collected, however, all results posted here will remain anonymous. All results are compiled below and a quick summary is in the following paragraph.

The Summit Summit Survey had 54 total responses from 30 institutions by April 22, 2017. Affiliates with the University of Colorado represented the largest institution with 10 members likely due to the large NOAA atmospheric studies, modeling and Glaciological studies that are affiliated with the University of Colorado. The largest fields of study identified at Summit are Atmospheric Science with just over 50% followed by Glaciology with just under 25%. The research topics submitted were all represented in Section 2 of the report, however, many were more detailed/specific. All dataset collected at Summit were mentioned broadly or specifically in the survey responses. The majority of responses were using datasets going back 5 or more years. 4 times as many respondents would have a negative impact, as compared to no impact, to their science if Summit operated seasonally. While it is clear some measurements can not be automated the responses show that increased automation could be achieved with additional engineering. Approximately one third of respondents had submitted a proposal to work and Summit in the past 3 years, had been awarded a proposal in the past 3 years and planned on submitting a proposal in the next 3 years. Most Respondents report between 3 and 10 publications with 10's up to 100's or citations. The Summit Summit Survey responses aligned with the recommendations and analysis of the meeting attendees and report coauthors leading us to believe that the sample of scientists that wrote the report and attended the Summit Station Science Summit were representative of the larger Arctic Science Community.

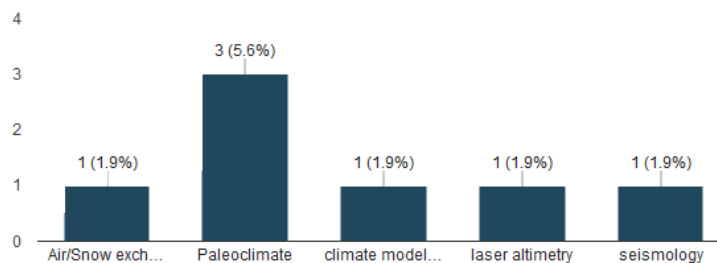
### Summit Summit Survey-Questions and Responses

Please answer the following questions to help us assess the major science questions investigated at Summit Station. This survey is for use of the Summit Station Science Summit Organizing Committee for informational purposes among colleagues and the data collected may be used, anonymously, for the final white paper and/or a summary publication on the workshop. Short answers are appropriate here. Thank you, we appreciate your time. This should take approximately 10 minutes.

### Primary field of study (53 responses)



### If you answered Other above please fill in primary field of study. (7 responses)



### Briefly state the scientific question(s) you are investigating.

- Understand energy and mass balance on top of GIS
- Snow & firn physics, ice core interpretation
- How do snow photochemical processing and early metamorphism degrade ice core records and impact atmospheric chemistry above Summit. What processes control albedo of snow on the Greenland ice sheet
- Ice-sheet futures and sea-level rise; climate histories in ice sheets; erosion and sedimentation by ice sheets
- Tropospheric chemistry - source contributions to atmospheric composition, role of long-range transport.
- Photochemistry in snow and impacts on atmosphere and snow composition
- Atmospheric Composition. Climate Change, Snow Photochemistry
- Surface mass balance, air-snow chem and isotope transfer, chem-phys snowpack interactions
- Impact of present-day and future climate change on ice sheets
- The role of snow/ice in Arctic atmospheric chemistry
- How changes in atmospheric composition reflect or impact on atmospheric processes.
- The role of clouds, atmospheric state, and precipitation on the GIS surface energy and mass budgets

- Temperature records and melt events in central Greenland
- My research at Summit has focused on understanding the deposition of nitrate to Summit (today and in the past) and investigating post-depositional processing of nitrate in surface snow.
- Atmospheric circulation, water balance and climate.
- What are the means, variability and trends of the climate forcing properties of aerosol particles at a high latitude, high altitude site?
- Use of area near Summit station as a calibration target for ICESat-2
- Albedo and energy balance of the Greenland Ice Sheet
- Climate monitoring of the Greenland ice sheet
- 1) What are the temporal and spatial variations of the boundary-layer temperature and humidity structure across the Arctic Ocean? How do these variations compare with those predicted by models (both forecast and reanalyses)? 2) What are the macrophysical (cloud fraction, cloud-base height) and microphysical (particle phase, optical depth, effective particle size) properties of clouds over the Arctic Ocean, as measured at the surface? How do these properties vary spatially across the Arctic Ocean? 3) How do the concentrations of greenhouse gases (water vapor, methane, carbon monoxide, nitrous oxide, nitric acid, CFCs) vary temporally and spatially across the Arctic Ocean? How do biomass burning and industrial activity in the northern hemisphere affect the concentrations of greenhouse gases?
- Tropospheric trace gas spatial distributions and emissions
- How and why is the chemical composition of the atmosphere changing over time?
- Long-term Surface ozone variability in the Arctic
- VLBI imaging of M87 Black Hole and submm/THz single-dish astronomy
- How is GrIS surface mass balance changing with time, and what influences SMB?
- Currently, C-N interactions in the gas-particle phase
- Global sources and sinks of greenhouse gases, climate change
- What physical processes of the hydrological cycle in the Arctic is important; How does the atmospheric hydrological cycle change as climate change; How do we infer accurately the past climate variability from ice core records
- What are the impacts of particulate matter on the energy balance of the Greenland Ice Sheet?
- History of Global Carbon Monoxide Budget. Production of C-14 in ice by cosmic rays. Potential of  $^{14}\text{CH}_4$ ,  $^{14}\text{CO}$  and  $^{14}\text{CO}_2$  in glacial ice as paleoclimatic and paleoatmospheric tracers
- How do atmospheric processes drive the surface energy and mass budgets of the central Greenland Ice Sheet? What is the annual variability of central Greenlandic cloud properties and their radiative effects? How do cloud properties and large-scale advection of moisture impact precipitation over the central Greenland Ice Sheet?
- Cosmic Microwave Background (what happened in the early universe and how did particle physics properties affect structure formation in the universe) and ultra-high energy neutrino physics (looking for the most energetic particles in the universe)
- How is the ice-sheet surface changing at Summit on seasonal and multi-year timescales; how can

we use this information to validate and interpret ICESat-2 surface-change assessments.

- The interaction between clouds and the Greenland ice sheet
- ice surface elevation change, mass balance
- ice dynamics
- I investigate biomass burning recorded in ice cores and surface snow using specific organic markers.
- Firn Compaction
- emergence of an anthropogenic signal over the GrIS
- How does the microstructure of firn impact gas transport mechanisms that are critical to the formation of ice core records? How accurately do remote sensing snow products represent ground based measurements of temperature, albedo, and grain size? What are the dominant controls on surface snow grain structure and albedo in the dry snow zone?
- Air-snow transfer and water isotopes
- Transfer function, aerosols to ice cores; current aerosols and sources
- development of melt probe for logistically light instrument emplacement within and beneath ice sheets
- Sources of pollution to the Arctic, understanding past climate change
- Understanding the polarized emissions from the Milky way to allow measurements of primordial CMB polarization
- pan-Arctic analyses, net radiation, cloud radiative forcing, fogs, subsurface and boundary-layer processes, clouds properties and cloud-surface interactions
- Lifecycle of stars and planets in the universe
- How much new snow is being deposited on the Greenland Ice Sheet each year? How much snow is being redistributed on the Greenland Ice Sheets?
- Ground heat flux variability in the Arctic, and also surface ozone variability in the Arctic
- accumulation, compaction, snow studies, albedo
- Quantifications of factors that affect solar UV radiation at Summit. Factors include: stratospheric ozone, clouds, long-range pollutants and aerosols, surface albedo, galactic cosmic rays, atmospheric cycles (e.g., AO, QBO), solar variability.
- How do clouds and the atmospheric moisture budget impact
- Nature and occurrence of oriented ice crystals, mixed phase cloud occurrence and properties
- The feed back between climate and air Pollution

**What is/are the primary dataset(s) you use that are collected at Summit Station?**

- ICECAPS Multi-sensor data
- Firn structure, remotely sensed images, weather data
- Mainly our own (and those of collaborators) collected in focused process studies
- Right now, not much. I am a veteran of GISP2, worked extensively on processes controlling

archival of atmospheric signals in ice, on ice flow, and recently helped in a study that used cosmogenic isotopes in the GISP2 rock core to learn the history of ice-sheet loss

- CO, O<sub>3</sub>
- Nothing recently. Actinic fluxes from others in past.
- Atmospheric trace gases and aerosols, meteorological variables, ozone sondes
- Snowpit samples, accumulation data, vapor isotope data, ice core data, weather data
- atmospheric cloud data, surface radiation data, weather data
- GSHOX, long term observations from NOAA
- The remaining GMD observations would be flask collection for halocarbons (steel flasks), carbon cycle gases (glass flasks), continuous aethelometer for black carbon, continuous surface ozone.
- ICECAPS dataset, NOAA meteorology obs, radiosonde launches, surface radiation datasets
- Manned and automated temperature records and firn profiles
- The primary data was collected by our group(s) including air, snow, and ice core sample collection during field campaigns. In addition to that, we have utilized meteorological data and ozone concentrations collected at Summit.
- Basic meteorology, radiation, accumulation, trace gas concentrations, our collected data on micrometeorology and isotope ratios
- In-situ measurements of spectral aerosol scattering and absorption; also 'Black Carbon' concentrations.
- ground based GPS surveys, ground-based accumulation rate measurements, upward looking lidar from ICECAPS MPL station
- I use Summit primarily as an ice sheet access point. I also use data collected there by others such as atmospheric aerosols in air and snow, AOD, snow albedo, accumulation, basic met data.
- Meteorological data
- Many datasets acquired by the ICECAPS experiment (radar, lidar, sondes, infrared spectra, ...)
- The various Flask and GC measurements of greenhouse gases, halocarbons, hydrocarbons and CFCs
- Flasks are collected and I analyze them in my laboratory for 30+ trace gases
- surface ozone, meteorological parameters, CO/CO<sub>2</sub> time series
- Our telescope is still under construction at Thule Air base; expected to be installed at Summit station only after 2019.
- Meteorological variables from surface station and upper air sounding; surface energy fluxes.
- They're older and to my knowledge not collected regularly -- WSOC data, particle size distribution data from mid 2000s.
- weekly (duplicate) flask samples analyzed for GHGs and other gases
- Currently the primary dataset for my research would be continuous water vapor isotope observations together with snow surface isotopes and precipitation isotopes. Currently the atmospheric water vapor isotopes are not collected on continuous basis.
- Aerosol optical properties including wavelength dependent light scattering and absorption



coefficients.

- Trace gas measurements (mainly CO, CH<sub>4</sub>, CO<sub>2</sub>). Physical weather parameters (mainly T, P, wind) - for firn air modeling and field planning
- Radar, lidar, broadband radiation, radiosondes, microwave radiometer, IR spectrometer, precipitation sensors, surface height change (snow stake field)
- I've done two different things, only one of which I am currently pursuing. 1) Measured the radio attenuation length of the ice at 200-1200 MHz to see if it is a good site for a radio detector for high energy neutrinos, and subsequently deployed a prototype instrument to monitor the station environment and test our hardware. 2) deployed a 183 GHz Water Vapor Radiometer in 2016 that scans in azimuth and dips in elevation to measure atmospheric fluctuations on timescales and angular scales relevant for Cosmic Microwave Observations from the ground. This is a site characterization study to see how the noise from the atmosphere at Summit would compare to that at South Pole and Chile (Where CMB telescopes are currently sited).
- Ground-based 'ICESat' 6-km GPS traverse
- MWR, Ceilometer, AWS, MMCR
- monthly GPS ground measurements along ICESat ground track #412
- seismic
- I used data from a 6 meter snow pit and associated surface meteorological data.
- Temperature, annual accumulation
- accumulation variability records (e.g. van der Veen and Bolzan, 1999)
- Spectral albedo, IR surface temperature, optical grain size, 2 m air temperature, millimeter cloud radar data, wind speed, incoming/outgoing shortwave and longwave radiation, firn cores collected at Summit
- Temperature, humidity.
- Aerosol data; meteorology;
- I hope to collect an ice core, and compare to available meteorological data, comparison to trace gas/aerosol measurements
- Weather data (PWV, Cloud cover, wind), and data we will collect ourselves (10 GHz map of the sky)
- ICECAPS, Noone, ETH radiation/tower, GMD met
- Spectral maps of the local galaxy
- None yet but the upcoming proposal will focus on deploying snow gauges and particle size sensors to help determine the difference between falling versus blowing snow.
- Temp, atmospheric fluxes, soil fluxes, surface ozone
- snow accumulation
- Global spectral irradiance in the UV and visible range.
- ICECAPS, GMD, radiation and ice core
- ICECAPS remote sensing instruments
- We are using atmospheric data reported to AMAP for modelling validation

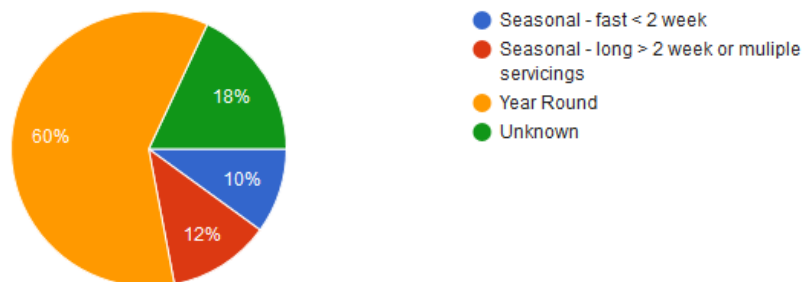
### What is the time frequency of your dataset and the length of time covered?

- going back to 2011. Data between twice daily and once every 5 sec
- sporadic
- Depends on the campaign. We also have long term (1997 to present) record of Be-7 and Pb-210 at nominal 2 day resolution.
- Various
- Hourly resolution during light season is great.
- Faster than Hourly frequency. Prefer at least a decade of
- hourly to monthly, over past decade or so except longer ice cores
- I usually use monthly means, averaged from hourly data. Dataset is about 3 years long.
- Hourly, 2000-present
- decades
- ICECAPS started July 2010 and is current slated to continue until Summer 2018 (although we are going to propose extending it two more years). Our observations occur every minute
- Since ~1987, at the highest resolution available, currently 1 minute averages
- Air and surface snow datasets were campaign based -- typically 4-6 weeks in spring and summer. Other datasets utilized were daily data over several months.
- 3 years existing(2011-2014), 5 years proposed (2018-2022)
- data are continuously collected at 1min freq. black carbon measurements started 2003, scattering and absorption started 2011
- frequency is mainly monthly, length of time is ~10 years
- The datasets vary. Continuous data over long time periods is necessary for many studies of trends.
- Every second, averaged over 1 or 10 min since 2000
- ICECAPS -->July 2010 - current; most datasets are at a frequency of 5-10 measurements per hours; radiosondes are twice daily
- Variable/past summer campaigns and year-round
- Samples are collected weekly to every other week. They have been collected on an ongoing basis since 2004.
- 1 minute averages, since 2000
- Hourly to daily; since 2008.
- Weekly, regular data start in 2004, intermittent data 1997-2003
- Water vapor isotopes and precipitation isotopes on 6 hourly resolution. Snow surface isotopes on daily basis.
- hourly data beginning roughly in 2012.
- Time frequency is variable between a few months (upper firn) and decades (deeper ice). Coverage for current projects is from modern to ≈1700 AD
- Multiple. Mostly covered from 2010 to present

- I'll talk about number 2) from above in the questions below: The Water Vapor Radiometer (WVR) has been operating since July 2016. We will retro it for a repair in April and potentially re-deploy it in August 2017 for one more season of observation. The data consists of 360 degree azimuth scans (continuous) and elevation dips from zenith to ~20 degrees.
- Monthly; 2006-Present
- 2007-2010, finest possible temporal resolution
- monthly repeat measurements since August 2006
- 2 yr
- The dataset was continuous over three years.
- Daily, May 2015 - Current
- multiple years (e.g. enough to properly characterize variability+change)
- Frequency: subhourly for most parameters, daily for albedo and grain size. Length of time: 1-2 months during summer
- daily
- 2003- 2013; 2014 - present; 12 hr data
- pre-industrial to present
- Our preliminary data will be 4 weeks continuous observations, future work could involve 5- 10 years of (nearly) continuous observation
- post 2010, base frequency generally minutes, but monthly/seasonal/annual statistics are important, all months of the year are important
- A mapping survey would typically take one year minimum to cover the full visible sky
- climatology, multi-decadal
- One spectrum every 15 minutes since 2004.
- 1 minute from 2010 and all historical data available from GMD, radiation and ice core datasets
- Approximate minute resolution since 2015
- Typically daily averages

**What are the maintenance requirements of your instrument, or what is the the temporal nature of your work?**

(50 responses)



**What would be the impact to your research if Summit Station operated seasonally. Please quantify, if possible.**

- Would lose data continuity. Would not be able to contribute to Year of Polar Prediction
- n/a
- Minor or none except for the long term radionuclide record
- N/A
- This wouldn't affect my work.
- Data would be lost.
- No impact on current research. Potential impact on future proposals that are hard to quantify
- Potential of instrument failure would lose its measurement capability during the winter.
- It's very important that the long term observations (met and ozone) are maintained, I think for these Summit needs to be open year round
- No value of seasonal observations.
- The impact would be huge. We desire to understand the role of clouds and atmospheric state on the ice sheet during all seasons. We have fewer observations during the winter already due to challenges in the first few years of ICECAPS in getting the instruments to work properly under the harsh conditions. We have overcome this now, and are collecting good data year-around. We desire to have several more winters, if possible.
- The best available, climate quality temperature data set from NOAA would be compromised.
- My research at Summit is project based (i.e. not continuous). However, with funded work, sample collection in every season would be fantastic and would expand our understanding of nitrate evolution in surface snow, which is currently limited to spring/summer.
- Significant impacts on measuring season cycles, thus limiting capacity to properly evaluate climate and climate processes in central greenland. If power was available year round, completely autonomous measurement systems could be designed (but both at higher cost and with much higher risk of failure with out tech support)
- we would stop measurements. we would not be able to evaluate trends. while the instruments can run unattended for long periods of time there are some aspects that require human intervention - clearing rime from the inlet every few days and changing filters every few months. there are also monthly calibrations to ensure data quality.
- We become unable to calibrate ICESat-2 elevation measurements over Greenland in the months the survey is not conducted.
- My direct data collection efforts would not be impacted. Quality and continuity of datasets that I use would likely be significantly impacted. It is unlikely that atmospheric aerosols, AOD, albedo, or high quality met data would be collected on a continuous basis without a manned presence at the station. I also think there are likely impacts on the station workload to be considered if camp opening and closing replace year-round occupancy. These large pushes in workload could impact my deployment to the field during camp opening phases, when my past deployments have been.
- My radiation measurements from the Baseline Surface Radiation Network (BSRN) would not be

possible without daily maintenance

- The ICECAPS experiment would end; we require a year-round technician at Summit Station.
- We would not have data available to compare with our background aircraft and surface (Pacific) long-term (quarterly) data sets.
- We would lose the ability to discern changes over time in seasonal variations in trace gas concentrations. Seasonal trends are key for providing and understanding of underlying causes to change. We would also lose the ability to accurately determine an annual mean concentration at the site, which is another important reason why we make measurements there.
- surface ozone has seasonal sources of local production and transport, therefore loss of year-around measurements impacts on full understanding of parameters that contribute to the air-quality in the Arctic.
- Greenland rawinsonde stations are known to have a significant impact on global weather forecast skill, although I have not quantified the impact for Summit as yet. Comparison of manned observations with nearby AWS have highlighted deficiencies in the AWS instruments, which can vary seasonally. Summit is also one of the few locations of Arctic surface energy budget measurements lasting for any length of time.
- None
- The data would lose most of their value. Note to the previous question: our required maintenance at Summit is minimal
- We would have no way to quantify the changes in the hydrological cycle of the atmosphere during the winter.
- If Summit were to operate seasonally we would lose the continuous record of optical properties.
- Our group's sampling would be unaffected if Summit only operated in the summer season (e.g., April - August). Interpretation of our firn air data would be more uncertain, however, as we would have to estimate the winter surface signals from other Arctic stations.
- We would not operate. The ICECAPS experiment operates sophisticated instruments that require the stability of an operational camp. Additionally, the instruments are large and take significant time to set up and calibration. It would not be very feasible to operate these on a "summer" schedule. Additionally, the scientific benefit of these measurements would be substantially limited by not being year-round: interactions between the atmosphere and ice sheet occur year round, must be represented by models year round, and therefore must be observed year round in order to develop the needed process understanding.
- The main goal of our current research is to see if Summit would be a good place to put a CMB telescope - the CMB community is moving toward a large experiment called CMB-S4, which would benefit from full sky coverage. To do that, a Northern site is required, and Summit looks like our best bet. If summit were seasonal only, this would not be possible.
- We would be blind to surface change in the winter months; we would only see snapshots of a sine wave.
- Severe impact, year-round observations would not be warranted

- lack of coincident data with airborne data acquisition
- less reliable data coverage
- The deposition of aerosols onto the Greenland Ice Sheet are strongly influenced by the same conditions that create the Arctic Haze. If Summit was only open seasonally there is the potential to lose vital information regarding the seasonal change from winter to summer aerosol depositional conditions.
- Primarily we'd lose the high-quality temperature and accum data sets.
- I am mostly interested in annual integrated accumulation variability/change
- Work that I have done so far has not depended upon Summit Station being open beyond the summer, however there are some projects down the line that I could envision benefiting from year-round operation to maintain instruments. Perhaps a single proposal that I would write in the next 5 years would benefit from Summit operating year round.
- I have no CURRENT research. Impact would be great on planned research.
- Loss of most of the spring aerosol transport period that dominates all aerosol concentrations and deposition into the snow
- We anticipate proposing to NSF to conduct instrument tests beginning in April (perhaps 2020), with continual instrument emplacement (but without a need for tending) for a period of a year.
- Our current work is a seasonal precursor to a hoped for year-round operation, which would require year round operations of Summit. If Summit were to be seasonal only, we would not pursue further use of the site for deep CMB cosmology studies
- My work involving Summit involves (1) process understanding, (2) analysis of climate extremes and (3) pan-Arctic studies. Regarding (1), processes involving exchanges of moisture and energy between the firm, surface and atmosphere have distinct seasonal characteristics (and thus winter data are important), but a great deal of observations have already been collected and some of the data sources I listed above are grant-funded and have either ended or are scheduled to end within the next few years. Many research pursuits of interest to me are possible with the data already available. Regarding (2) and (3), collection of data from atmospheric instrument suites comparable to those at other Arctic stations (namely Barrow, Oliktok, Tiksi, Alert, Eureka and Ny-Alesund) are important for ongoing research on how the Arctic is impacted by, and responds to individual weather events, climate extremes and long-term change/variability. With such limited coverage around the Arctic and Greenland, the loss of wintertime data could have an impact on those inquiries, noting again that some data streams of interest to me are not from permanent installations so this impact will be felt to some extent regardless of whether Summit becomes seasonal or not.
- If power remains available remote operation is an option but we would have to invest in reliability/redundancy.
- Likely minimal as most of what is planned could be remotely monitored.
- Loss of climatological record, loss of Arctic variability datasets
- hard to quantify in one line....these data are not available by any other means.

- Closing the station during winter months would likely mean that all power would be switched off. Since our equipment must not freeze, this would mean that it would have to be removed for warm storage before season close and reinstalled when the station is reopened. The chance for damaging the equipment in the process would be high and could jeopardize the resumption of accurate measurements in March, the month when spring-time ozone losses may lead to large changes in surface UV radiation.
- Would not be able to capture the seasonal changes of moisture and clouds. Instrument deployment and maintenance costs would increase by \$20000 a year at least(not including logistics at Summit for 2 people traveling there 2 times years for at least a week each time.)
- It wouldn't be worth staying.
- The trend in observation will be lost. Summit is the only station that measured in the free troposphere, therefore it will make it more difficult to validate models

**Can your measurements be automated or the process modeled?**

- no
- Mostly not
- N/A
- Already automated.
- Measurements can be automated.
- Some (met station) are automated, but others like snow pit sampling can not
- In principle they are already automatic.
- This is a question for NOAA, who makes the measurements
- ozone and aethelometer are automated. It's possible that flask samples could be, but would depend upon the operating environment.
- Most of our instruments are automated, but being that they are advanced remote sensors, they still require occasional maintenance by staff onsite.
- Not well so far based on research in preparation
- No.
- Maybe, probably yes - this would be risky. I worry it may also change the spirit of the type of work that could be done in a university setting. Rather than supporting grad students to collect and analyse data, we'd need to budget for additional engineering staff. For this to be a robust human resources model, such new engineering positions would need to have an on-going support model which exceeds that which can be assured from a single grant. (The processes can be modeled, but not well, which is why we need the observations)
- some can but not all.
- No. The high frequency variability of accumulation in space and time make it impossible to model to the precision level required (~2 cm).
- It would be very challenging to collect high quality observations of aerosols or snow surface albedo autonomously. Autonomous albedo stations I have deployed as well as those of others (e.g. GC-NET) suffer from icing, calibration drift, and becoming out of level.

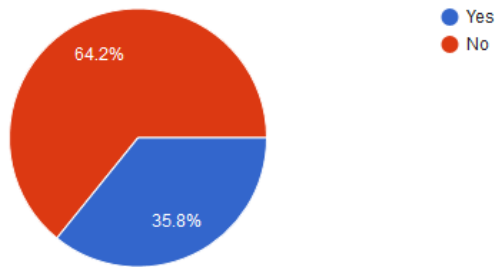
- no
- No.
- potentially the flask collection process could be automated
- surface ozone measurements are already automated
- Possibly.
- No
- We would consider installing automated sampling outside of the summer season
- If we can develop a way to have continuous power during the winter.
- I think it would be difficult to continue measurements without roughly weekly maintenance.
- No, as everything involves firm and ice drilling
- It would be very difficult to automate our observations as they are already difficult to make with people and a camp. Modeling of the atmosphere and clouds over Greenland is very problematic in most (all?) models. For example, we know that CESM struggles to correctly represent clouds over Greenland, as does a regional model like MAR. Additionally, our results have show that reanalyses like ERA-Interim and the operational NOAA model CFSv2 have significant deficiencies in representing the surface energy responses to atmospheric radiative forcing of the central Greenland surface. Prior to ICECAPS measurements there has been little information with which to assess and evaluate the cloud-atmosphere-surface process representations in models.
- To have a real CMB telescope operating, winter support is needed.
- Automated would be tough; and these measurements are used to validate satellite data used as input for process models.
- no, since it involves driving on a snow mobile
- somewhat
- Unfortunately (or perhaps fortunately), digging snow pits is not yet automated.
- Sort of. Ours is a model validation experiment.
- Yes (modelled in GCMs)
- Most of the measurements could be automated. Firn core collection could not, but is seasonal work anyhow.
- Partly
- Sampler needs occasional drum changes - can not automate
- yes
- It's unlikely that our measurements could be so automated that there would be no need for technicians or scientists on site.
- I have served as a technician for ICECAPS and Noone projects, but am not a PI for the instruments. At this time my role is primarily that of an a data user. The instruments are largely autonomous (some more so than others), but the data quality suffers in the absence of routine maintenance (again, some require more attention than others). Improved process modeling is one of the goals of the research.



- Remote operation is a good option
- Yes
- observations are needed to validate the models
- modeled? no automated? possibly....but expensive
- Measurements \*are\* mostly automated, but the instrument parts exposed outside have to be regularly cleaned (e.g., snow removed). Calibration are performed every two weeks and cannot be automated.
- It has been automated as much as possible. Balloon launches still require technicians. Advanced remote sensors need human intervention from time to time that cannot be automated (changing laser flash lamps; cleaning windows).
- Measurements are automated to the extent possible.
- Yes measurements are automated. The data are needed for validating models

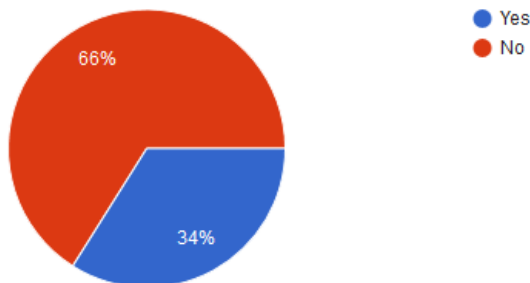
**In the past 3 years have you submitted a proposal to work at Summit Station?**

(53 responses)



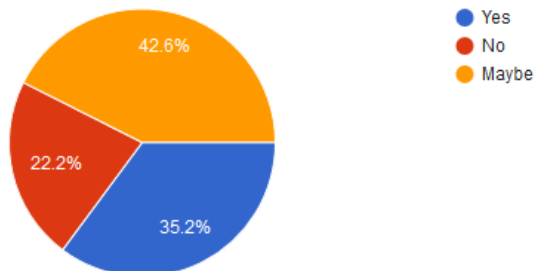
**In the past 3 years have you had a funded proposal for Summit Station?**

(53 responses)



## In the next 3 years do you plan on submitting an NSF proposal to work at Summit Station?

(54 responses)



## How many of your publications, including dataset publications, have used Summit Station Data?

- 4 first or co-author; more than twenty using the ICECAPS dataset
- 6
- Around 50
- Well, if you include GISP2... dozens
- 2
- 7
- 10+
- Hard to answer - depends what you call Summit "Station" data. 1 published using ice core from Summit (2010 100m core); 1 on snowmelt experiments at summit; 1 accepted using shallow summit ice core data; 1 other in review using Owen core;
- 3 (2015, 2016 x2)
- 10
- The ICECAPS project team has at least two dozen publications that use obs collected at Summit
- Lead or co-author on 19 publications
- 10
- 6 (all 2016, 2017)
- 4
- 3
- At least 5 in the past 4 years.
- > 20
- 11
- 7
- many... I regularly post 15 different datasets from SUM to the web
- 1-2
- Four.

- 3
- Summit data are incorporated in many of our data products that are regularly updated: GlobalView (multiple species), CarbonTracker (CO<sub>2</sub>, CH<sub>4</sub>), ObsPacks (machine readable data distributions)
- 2
- ~5
- 3; but there are none yet from currently funded projects
- 15 papers over the last 4 years
- 2
- 2
- 3
- 1
- 2
- 3 (plus one in prep)
- 1 so far
- 2
- 3
- 3
- 7, including 5 GMD meetings
- at least 2 in preparation, possibly a third.
- 1
- 9 published (2 first author) and 2+ in prep, my dissertation
- 0
- None
- at least 4
- We have used data from Summit in four regular journal papers. In addition, data have also been featured in the NOAA Arctic Report Card, and the State of the Climate Reports published annually in the Bulletins of the American Meteorological Society (BAMS). Summit data have also been used by following AON projects: “Photochemical formation of oxidants and destruction of organic compounds in the snowpack at Summit, Greenland” (NSF Award 0455055), “High Resolution, Active Remote Sensing of Cloud Microphysics at Summit, Greenland with Polarized Raman Lidar” (NSF Award 1303864), “Direct radiative forcing over central Greenland - assessment of the coupled effect of light absorbing aerosols and snow albedo variability” (NSF Award 1023227).
- 7(25% of my current body of work)
- 2 completed, 4 in review, 2 planned
- >5

**If known, please give the number of citations for your publications?**

- Four papers are cited one-hundred and one (101) times as per Web of Science 3/20/2017

- More than 2200 (I only checked the top 100 of my papers (out of ~240), ranked by citations, 25 out of this top 100 were Summit based and these had 2157 citations per Web of Science)
- And, if you include GISP2, thousands (I can get numbers if you need, but GISP2 did pretty well...)
- 165
- 18
- ~41
- Two most recent, >30 total; two oldest > 120 total
- 402
- 8 (all papers published 2016, or in press now)
- 104
- 32
- I guess about 100 or higher
- about 225
- more than 380
- Order 30
- Too many to count. For example, almost all publications about CO<sub>2</sub> and CH<sub>4</sub> using satellite data need to use calibrated in-situ data provided by us, incl. Summit, to keep their retrieved column integrals believable. Without our data they would produce nonsense.
- 1 (published 2016); 6 (published 2015)
- 19
- Unknown, but at least 150 over the past 4 years
- 10
- 28
- 11
- 13
- 50
- significant
- 185
- At least 60
- 70

## Appendix B - Summit User Days

User day statistics, including information about the number of field party participants per project and funding source are maintained by Polar Field Services. Here, we have compiled user data for the past 16 years according to source of funding (NSF, NOAA, NASA, a European source, or other), timing of the project (year round vs. summer only campaign science), and broad category of science research. Some of the variations in user days are due to the classification of the station science technicians as a science user vs. a logistics provider. Also, the classification of one of the science technicians was funded by NOAA from 2005 through 2015, so the sharp drop in NOAA user days reflects a change from funding from NOAA to NSF.

One important trend in the user day population is that user days at Summit are nearly directly tied to budget trends. Uptick in user day for NSF is seen for the IPY years 2007 and 2008, with a sharp decrease in 2009 during recession years following the end of several large (in terms of user days as represented by large, summer-long research projects) summer-time campaigns. ARRA funding also contributed to increases in NSF programs, most notably AON funded projects.

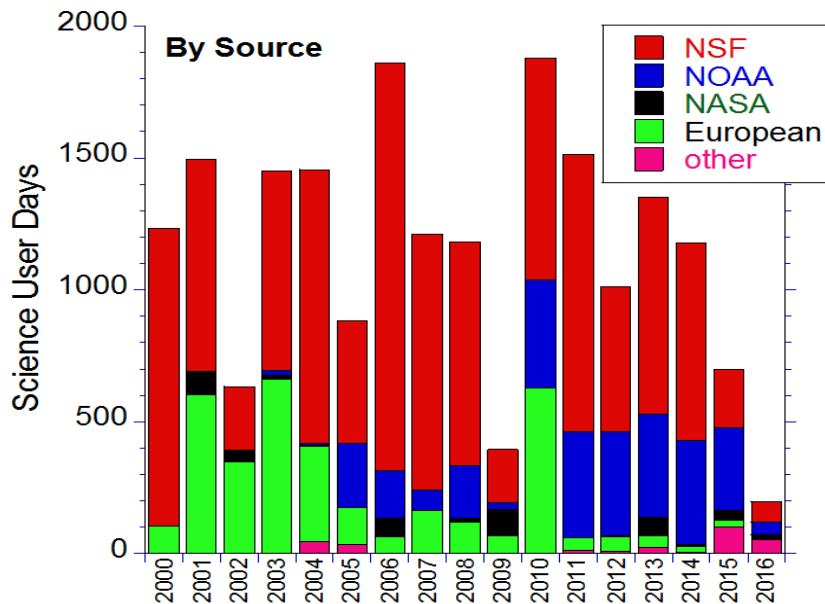
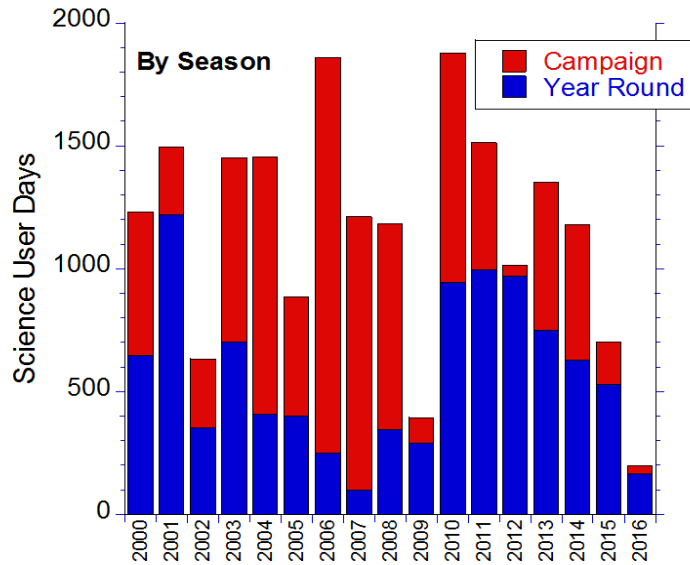
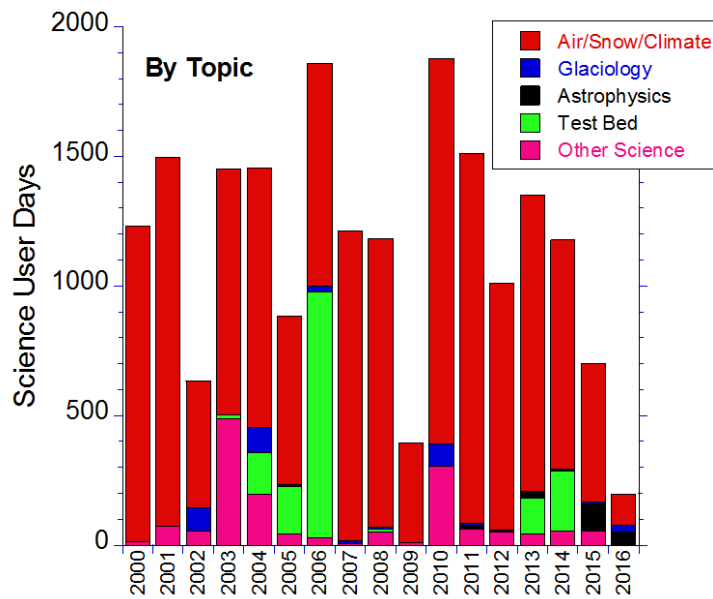


Figure B.1 - Science User Days by funding source.



**Figure B.2 - Science User Days by duration.**

Of note in the user day trends is the increase in year round user days, as primarily influenced by science tech time on station, due to the addition of a year round science tech for the ICECAPS project.



**Figure B.3 - Science User Days by science topic.**

Process studies of air, snow and climate interactions still remain the core of broad science interest, along with observing projects, with increases in user days for astrophysics related projects.

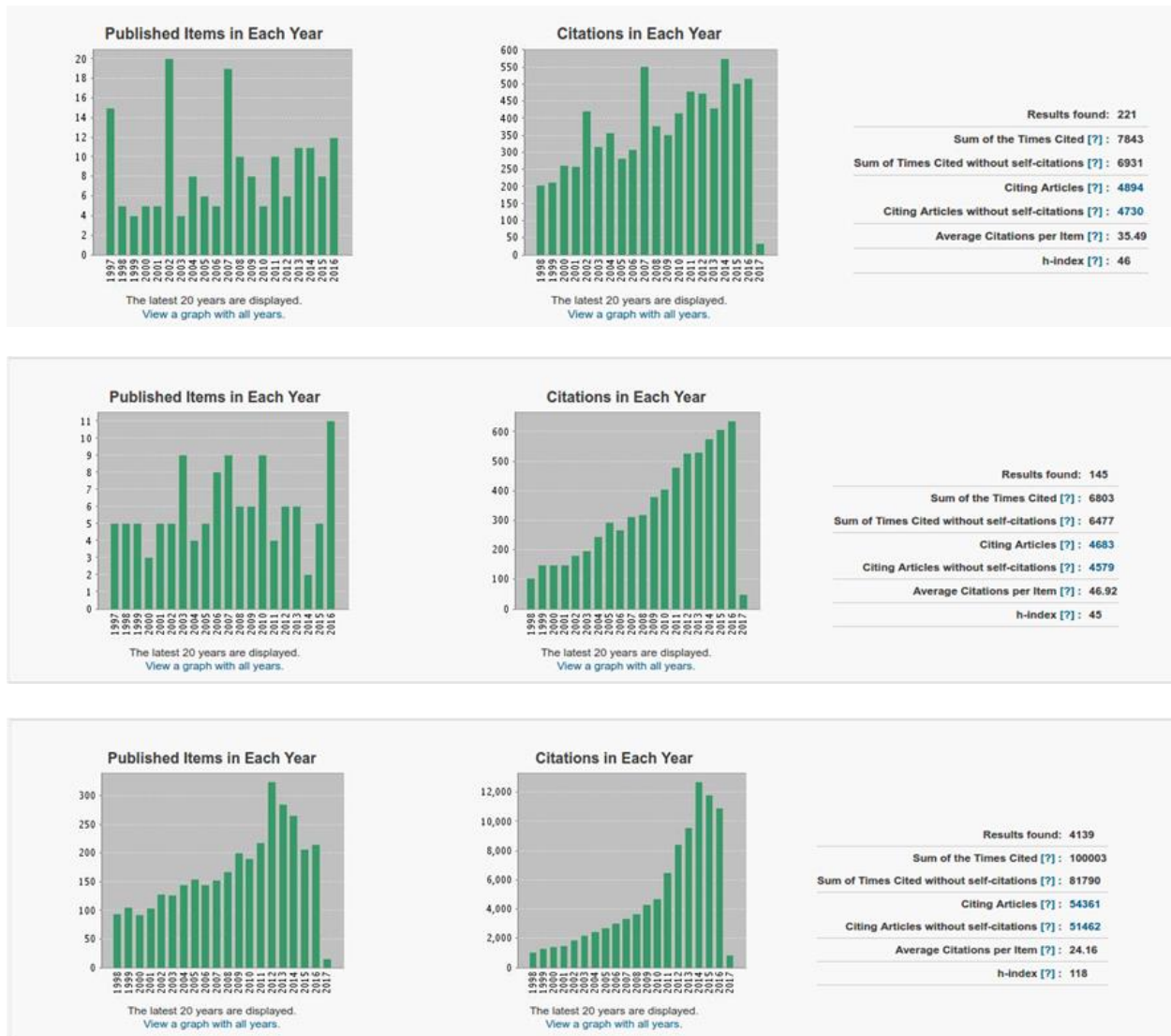
## Appendix C - Science Impact of Summit from Publications

In order to quantify trends of the impact of Summit related science, we tracked trends in publications, both number and citations per broad topical areas using Summit science data from a variety of search engines (e.g. Google Scholar, ISI Web of Science).

As a broad overview, searching for the term “summit greenland” in the Web of Science returns 221 results, which are cited 7843 times (6931 times without self-citations). 4894 articles cite “summit greenland” (4730 times without self-citations). The average number of citations per item is 35.49, with an h-index of 46. A similar search for the term “GISP2” results in over 14,000 citations. GISP2 data is used in a variety of climate reanalysis simulations and in comparison to other proxy climate records. GISP2 data are used in publications that discuss a range of topics from the first human inhabitants in Western Greenland to the record of volcanism. Over 40 Science or Nature publications have been published based on Summit research since 1995.

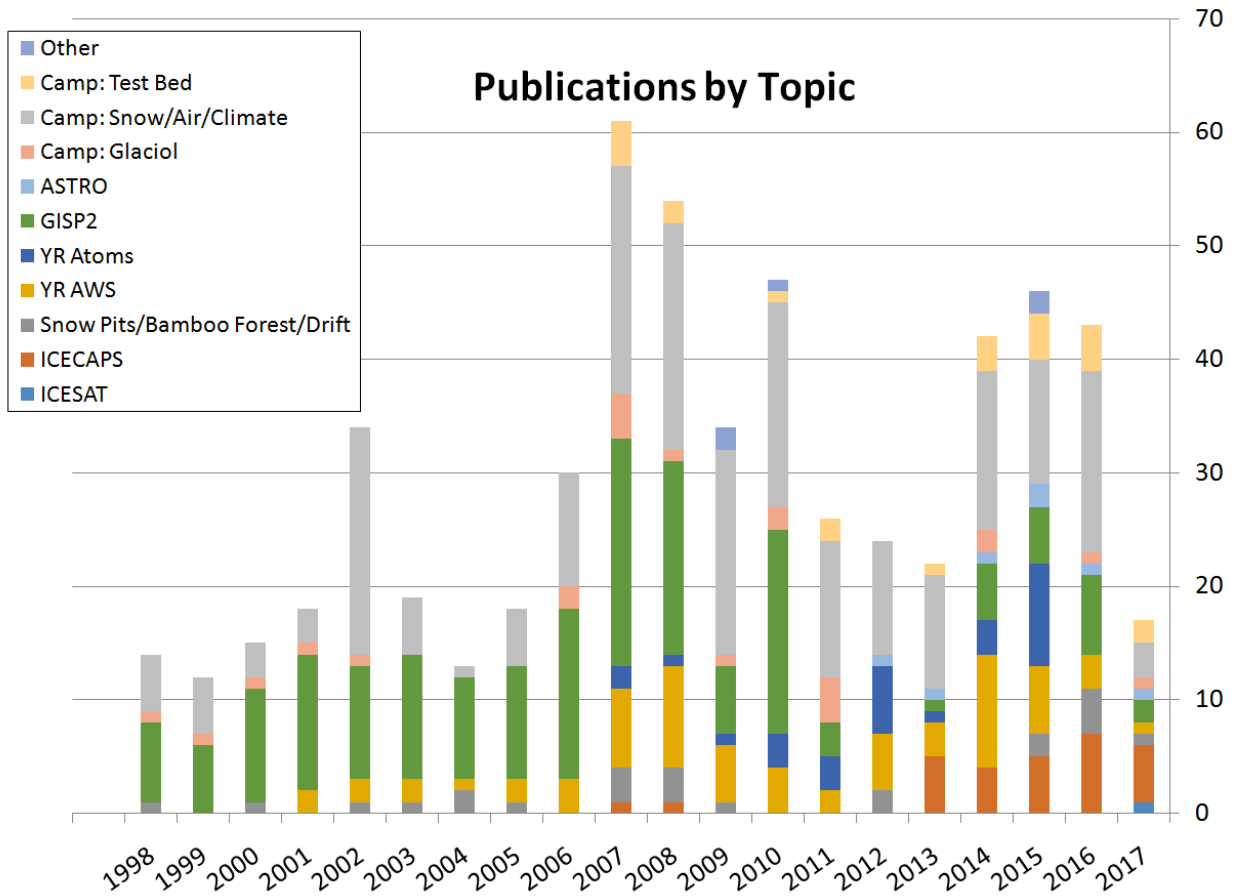
We also compared publication trends for Summit Station data to other polar stations maintained by NSF, Toolik Lake and South Pole Station (**Figure C.1**). Note that the scale bars on the following figures are different. Summit and Toolik Lake publication numbers are similar, with more Summit publications and citations. South Pole station publications outnumber Summit and Toolik Lake publications by an order of magnitude, but also represents a much larger logistical draw, in terms of station population, facilities and operations.

Tracking trends in publication by broad science topics studied at Summit for the past 20 years reveals a few important features (**Figure C.2**). Namely, GISP2 data have in the past when first published, and continue to be, cited frequently in current modeling studies to validate GCM of past and future climate predictions. GISP2 data are also used in a surprising variety of studies where past climate conditions are needed, including studies needing snow depth-density profiles (i.e. ground penetrating radar studies) and long-term past temperature records (i.e. human migration patterns). Campaign science studies of snow/air interactions represent another large amount of publications, with process studies of nitrate and photochemistry being a large portion of publications and citations, as several key discoveries in these areas have been made at Summit. Year round meteorology data are also used in many publications, with increases in publications following extreme, unexpected events, such as the 2012 melt event.



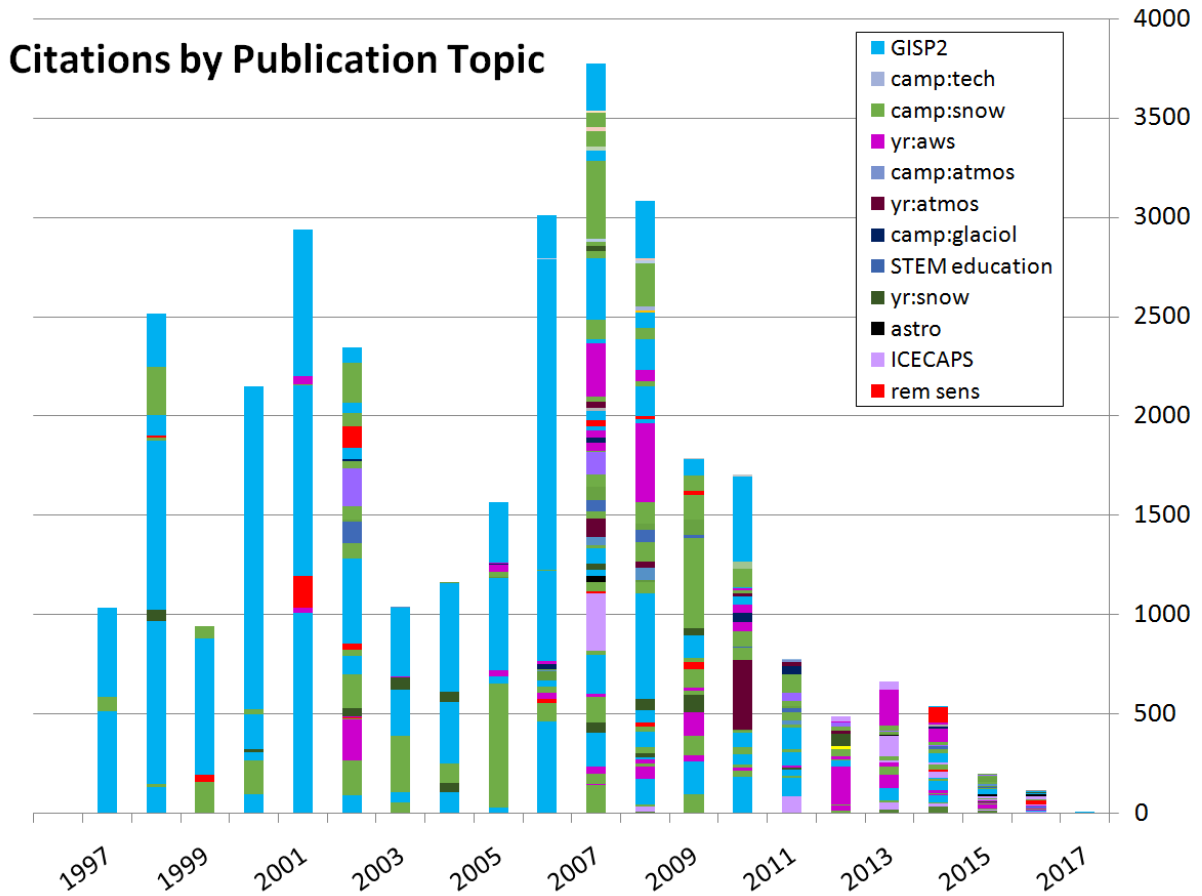
**Figure C.1-** Web of Science comparisons of Summit (top), Toolik Lake (middle) and South Pole based publications and citations for the last 20 years.





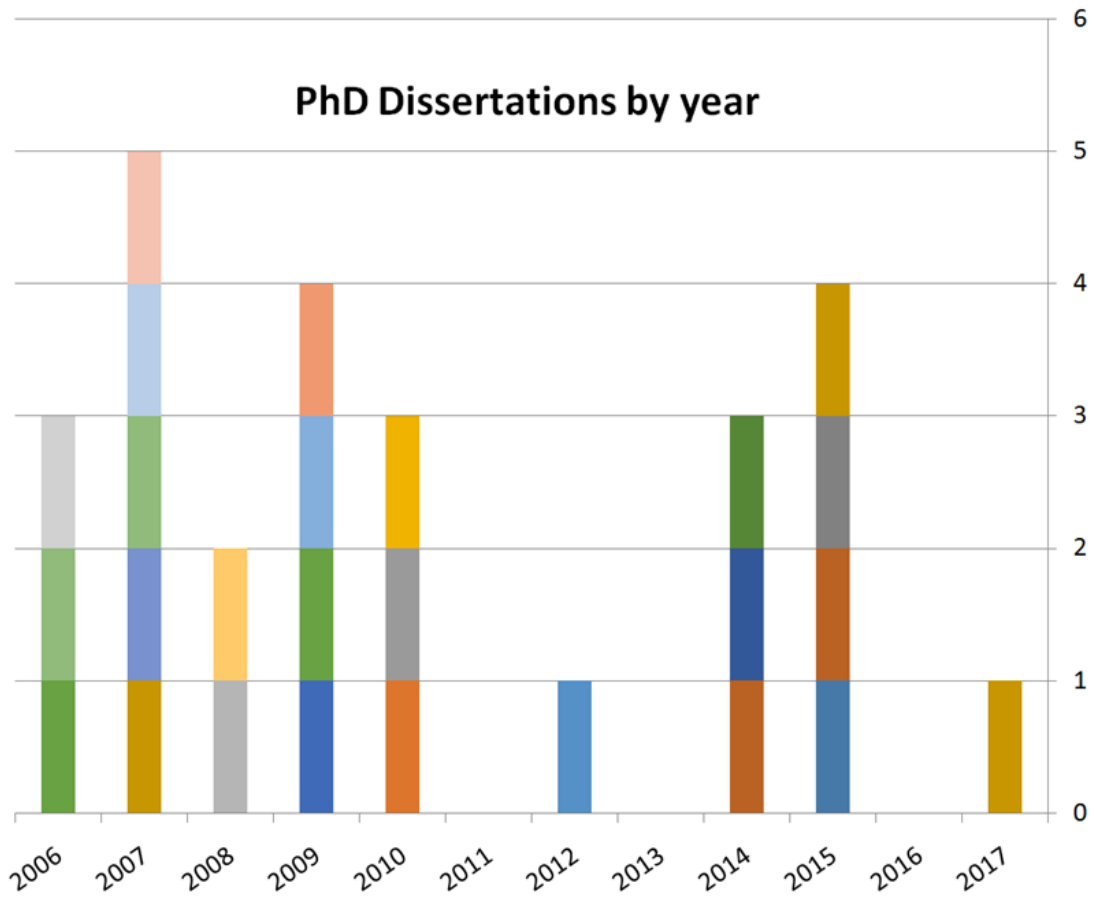
**Figure C.2-** Number of publications per broad science topic. “Camp” refers to projects and resulting that were conducted in a summer-time only campaign project. “YR” refers to year round data.

In the last 5 years, including 2017, the number of publications using GISP2 data has decreased, while publications from year round projects, including ICECAPS, year round measurements of meteorology and atmospheric gas measurements have increased. Publications based on campaign science, and particularly those studies focused on air/snow interactions and processes continue to make up a large number of Summit-based publications.



**Figure C.3-** Citations per publication and sorted by broad science topic.

Summit-based data and publications are used in a diverse range of research work. For instance, ICECAPS snowflake crystals, used to help interpret lidar signals of precipitation in the atmosphere, have been used by several physicists studying the crystallographic formation of solids. ICECAPS cloud and atmospheric data represent one of the most complete examination of polar clouds in both the northern and southern hemisphere and are used to compare studies from Antarctica in addition to Greenland. GISP2 data have been used in over 14,000 publications from past climate reconstruction to volcanic records to understanding human migration patterns.

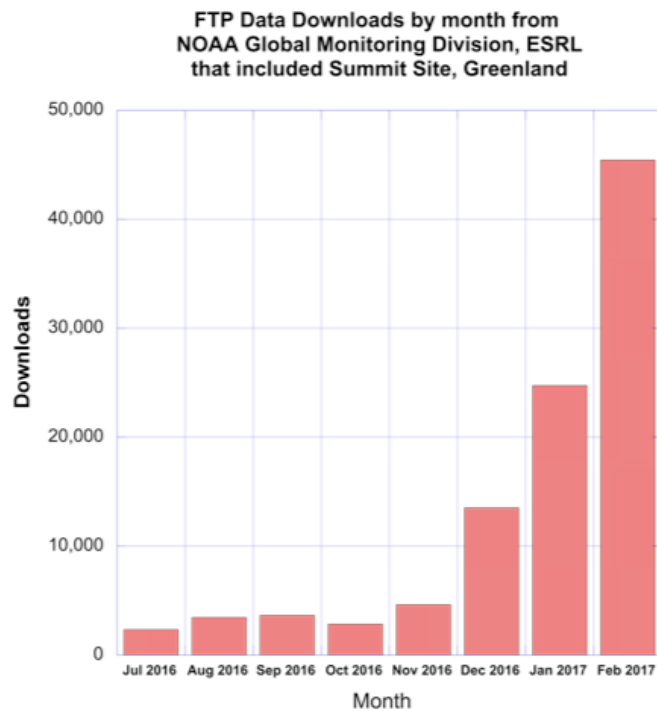


**Figure C.4-** Number of dissertations published based on Summit science per year.

Summit remains an important location for the next generation of polar scientists to be trained. As shown in **Figure C.4**, several graduate dissertations have been completed at Summit.

## Appendix D - Science Impact of Summit from Data Downloads

Data from Summit Station is housed in multiple locations making it difficult to get reliable statistics on data use. Here, we present the download metrics that are readily available. In most instances the PIs and co authors of this report feel that these numbers are low and should be looked at in context with the publications topics in **Appendix C** to see broader use. Discussion during the Summit and at telecons after identified problems with Summit data including that NSF data have been housed at a multiple data center, PIs having difficult getting there data in the data centers and PIs releasing their own data to the community through other websites that are not tracked here. Additionally, the GeoSummit website FTP data does not track downloads and is a primary download site for many scientists. **Figure D.1** shows the downloads from the NOAA Global Modeling Division for the atmospheric measurement for the entire network that includes Summit. Note the significant jump in Dec 2016-Feb 2017 corresponds with the Trump Administration being elected and assuming power in the United States and is consistent with other spikes in data downloads across US government agencies.



**Figure D.1-** Data downloads of NOAA Global Monitoring Division data that includes Summit Station.

Files downloaded from 2010 till now	
Datastream	Files Downloaded
smtsondewnpnX1.b1	49962
smtmwrlosX1.a1	19390
smtmplpolX1.a1	14512
smtvceil25kX1.b1	6566
smtaerich2C1.b1	6080
smtaerich1C1.b1	6059
smtaerich1X1.b1	4982
smtaerich2X1.b1	3537
smtmmcrmomX1.b1	2848
smtaerich1nf1turnX1.c1	1186
smtaerich2nf1turnX1.c1	1182
smtecmwfsfc1IX1.c1	476
smtecmwfvarX1.c1	267
smtecmwfsfceX1.c1	231
smtecmwfflxX1.c1	219
smtecmwftenX1.c1	187
smtaerisummaryX1.b1	167
smtecmwfsfcmIX1.c1	135
smtecmwfx1.00	127

Figure D.2- ICECAPS data downloads from DOE ARM website.

Figure D.2 shows downloads of the ICECAPS projects data by file from the Department of Energy’s, Atmospheric Radiation Measurements (ARM) website. There are no estimates of data downloads from the NOAA ESRL data archive for this dataset that is currently downloadable from at least 4 locations.

Table D.1 was assembled by L. Koenig from Summit data housed at the NSF’s Arctic Data Center. The Arctic Data Center could not provide statistics directly as they were having technical difficulties. Using a locational search at Summit and the surrounding ~30 km 100 datasets were retrieved. Many of the datasets are duplicates since each new version is given a different doi. The downloads for each dataset were totaled. Some datasets had one file and others had hundreds of files. Therefore, 100 downloads could represent 1 file downloaded 100 time or 100 files each downloaded once. The downloads are from 2009 to today, meaning that downloads from the previous data center, ACADIS, are included. The duplicity of data and many dataset not containing science data, only metadata, illustrates the difficulties scientist can have extracting Summit data leading to them getting the data directly from the PIs and, thus, likely undercounting actual use of these data. The top downloads are for cloud/radiative properties, atmospheric and snow measurements consistent with top publication and research topics at Summit shown previously in this document.

**Table D.1**-Dataset title and downloads since 2009 from the Arctic Data Center.

<b>Dataset from Arctic Data Center</b>	<b>Downloads</b>
<a href="#">Matthew Shupe. 2010. Ceilometer Cloud Base Height Measurements at Summit Station, Greenland. NSF Arctic Data Center. doi:10.18739/A2FT27.</a>	4100
<a href="#">Germar Bernhard. 2009. UVSIMN Version2 Summit Spectra. NSF Arctic Data Center. doi:10.18739/A2G028.</a>	2332
<a href="#">NSF Arctic Data Center. 2009. Core Atmospheric and Snow Measurements at Summit, Greenland Environmental Observatory: Atmospheric Chemistry. NSF Arctic Data Center. doi:10.18739/A2MK6W.</a>	2033
<a href="#">Germar Bernhard. 2009. UVSIMN Version2 Summit. NSF Arctic Data Center. doi:10.18739/A2B60B.</a>	991
<a href="#">Ryan Banta. 2009. Core Atmospheric and Snow Measurements at Summit Greenland Environmental Observatory: Firn Air. NSF Arctic Data Center. doi:10.18739/A2HS48.</a>	762
<a href="#">Matthew Shupe. 2011. Ceilometer Cloud Base Height Measurements at Summit Station, Greenland. NSF Arctic Data Center. doi:10.18739/A2KM3S.</a>	718
<a href="#">Nathan Chellman. 2009. Core Atmospheric and Snow Measurements at Summit Greenland Environmental Observatory: Surface Snow Chemistry. NSF Arctic Data Center. doi:10.18739/A2NG65.</a>	693
<a href="#">Ryan Banta. 2009. Core Atmospheric and Snow Measurements at Summit, Greenland Environmental Observatory: AWS. NSF Arctic Data Center. doi:10.18739/A2W020.</a>	390
<a href="#">Ryan Banta. 2009. Core Atmospheric and Snow Measurements at Summit Greenland Environmental Observatory: Soundings. NSF Arctic Data Center. doi:10.18739/A2D02N.</a>	387
<a href="#">NSF Arctic Data Center. 2009. Core Atmospheric and Snow Measurements at Summit Greenland Environmental Observatory: Snow Accumulation. NSF Arctic Data Center. doi:10.18739/A2S89G.</a>	383
<a href="#">Matthew Shupe. 2012. Ceilometer Cloud Base Height Measurements at Summit Station, Greenland. NSF Arctic Data Center. doi:10.18739/A2B37Z.</a>	365
<a href="#">Ryan Banta. 2009. Core Atmospheric and Snow Measurements at Summit Greenland Environmental Observatory: Clean Air Traffic. NSF Arctic Data Center. doi:10.18739/A20S37.</a>	361
<a href="#">Nathan Chellman. 2009. Core Atmospheric and Snow Measurements at Summit Greenland Environmental Observatory: Snow Pit. NSF Arctic Data Center. doi:10.18739/A2888F.</a>	341

<a href="#">Gordon Oswald. 2014. Subglacial Water Intrusion in Greenland. NSF Arctic Data Center. doi:10.18739/A2MW60.</a>	330
<a href="#">Jihong Cole-Dai, A.L. Lanciki, and D.G. Ferris. 2013. Chemistry (major ions) data of 2007 Summit ice cores. NSF Arctic Data Center. doi:10.18739/A24627.</a>	318
<a href="#">Germar Bernhard. 2009. UVSIMN Version2 Summit Wavelength Accuracy. NSF Arctic Data Center. doi:10.18739/A2002X.</a>	285
<a href="#">Germar Bernhard. 2009. UVSIMN Version2 Summit Spectral Irradiance. NSF Arctic Data Center. doi:10.18739/A2QG75.</a>	279
<a href="#">Michael Bergin. 2012. Monthly Averages of Aerosol Properties in Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A2694N.</a>	270
<a href="#">Germar Bernhard. 2009. UVSIMN Version2 Summit Flags. NSF Arctic Data Center. doi:10.18739/A26G64.</a>	270
<a href="#">Ryan Banta. 2009. Core Atmospheric and Snow Measurements at Summit Greenland Environmental Observatory: Fog and Fresh Snow Measurements. NSF Arctic Data Center. doi:10.18739/A2GS3K.</a>	258
<a href="#">Germar Bernhard. 2009. UVSIMN Version2 Summit Cloud Optical Depth. NSF Arctic Data Center. doi:10.18739/A27G7T.</a>	256
<a href="#">Dorothy L. Fibiger, M.G. Hastings, and J.E. Dibb. 2014. Surface snow ion concentrations and nitrate isotopic composition. NSF Arctic Data Center. doi:10.18739/A2QP77.</a>	253
<a href="#">Germar Bernhard. 2009. UVSIMN Version2 Summit Integrals Doserates. NSF Arctic Data Center. doi:10.18739/A2V592.</a>	249
<a href="#">Ryan Banta. 2009. Core Atmospheric and Snow Measurements at Summit Greenland Environmental Observatory: Snow Temperature. NSF Arctic Data Center. doi:10.18739/A2R88S.</a>	234
<a href="#">J.E. Dibb, Dorothy L. Fibiger, and C.A. Corr. 2014. Concentrations of gas phase nitric and nitrous acids and soluble bromide at Summit in summers 2010 and 2011. NSF Arctic Data Center. doi:10.18739/A2VD02.</a>	232
<a href="#">Andrei Kurbatov. 2014. Searching for Abrupt Climate Change Precursors Using Ultra High Resolution Ice Core Analysis. NSF Arctic Data Center. urn:uuid:2498c4df-4932-4369-8849-96932beade98.</a>	229
<a href="#">NSF Arctic Data Center. 2014. Sub-millimeter resolution chemical analysis by LA-ICP-MS. NSF Arctic Data Center. doi:10.18739/A2F64S.</a>	217
<a href="#">Germar Bernhard. 2009. UVSIMN GUV Summit 15 Minute Data. NSF Arctic Data Center. doi:10.18739/A22P5K.</a>	206

<a href="#">Dorothy L. Fibiger, M.G. Hastings, and J.E. Dibb. 2013. The oxygen isotopic composition of nitrate in surface snow at Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A2KW59.</a>	190
<a href="#">Germar Bernhard. 2009. UVSIMN Version2 Summit Model Log. NSF Arctic Data Center. doi:10.18739/A23P4H.</a>	175
<a href="#">Matthew Shupe. 2016. Cloud occurrence and layering at Arctic atmospheric observatories: Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A2S09Q.</a>	156
<a href="#">Ryan Banta. 2009. Core Atmospheric and Snow Measurements at Summit Greenland Environmental Observatory: Flux Measurements. NSF Arctic Data Center. doi:10.18739/A24G7W.</a>	153
<a href="#">NSF Arctic Data Center. 2013. Summit 2010 Ice Core. NSF Arctic Data Center. doi:10.18739/A2306C.</a>	132
<a href="#">Germar Bernhard. 2009. UVSIMN GUV Summit. NSF Arctic Data Center. doi:10.18739/A2T60P.</a>	121
<a href="#">Germar Bernhard. 2009. UVSIMN GUV Summit 1 Minute Data. NSF Arctic Data Center. doi:10.18739/A2Z017.</a>	102
<a href="#">Germar Bernhard. 2009. UVSIMN Version2 Summit Ozone. NSF Arctic Data Center. doi:10.18739/A2KP4V.</a>	86
<a href="#">Germar Bernhard. 2009. UVSIMN Version2 Summit Daily Dose. NSF Arctic Data Center. doi:10.18739/A2C59Q.</a>	56
<a href="#">Detlev Helmig. 2013. Collaborative Research: A Synthesis of Existing and New Observations of Air-Snowpack Exchanges to Assess the Arctic. NSF Arctic Data Center. urn:uuid:478b7fc5-df07-40f5-926c-48cc538aa22d.</a>	30
<a href="#">Dexian Chen, L Greg Huey, and David J Tanner. 2016. Concentration of gas-phase NO/NOy and BrO in the boundary layer at Summit Station, Greenland. NSF Arctic Data Center. doi:10.18739/A20H1Q.</a>	24
<a href="#">Detlev Helmig, David Boulter, and Donald James. 2016. Vertical Boundary Layer Profiles for Ozone and Meteorological Parameters at Summit, Greenland, 2000. NSF Arctic Data Center. doi:10.5065/D6TX3CH3.</a>	22
<a href="#">James W. C. White. 2016. GISP2 Stable Isotopes (Deuterium, Deuterium Excess, and Oxygen). NSF Arctic Data Center. doi:10.5065/D6JW8C0F.</a>	21
<a href="#">Jihong Cole-Dai. 2017. Perchlorate record from Greenland ice cores. NSF Arctic Data Center. doi:10.18739/A26H3B.</a>	16
<a href="#">Michael Ram and John Jr. Donarummo. 2016. Data Correlating the Shallow GISP2 Dust Profile with the Wolf Sunspot Number Series. NSF Arctic Data Center. doi:10.5065/D6DJ5CRG.</a>	15



<a href="#">Paul A. Mayewski and Sallie Whitlow. 2016. Snow Pit Data from Greenland Summit, 1989 to 1993. NSF Arctic Data Center. doi:10.5065/D6NP22KX.</a>	15
<a href="#">Charles Stearns. 2016. Automated Weather Station Data for Greenland Ice Core Locations. NSF Arctic Data Center. doi:10.5065/D6DJ5CSX.</a>	12
<a href="#">Jeffrey Severinghaus and Vasilii Petrenko. 2016. Cosmogenic 14C in Shallow Firn at Summit, Greenland. NSF Arctic Data Center. doi:10.5065/D62V2D8G.</a>	11
<a href="#">Paul A. Mayewski and Sallie Whitlow. 2016. Snow Pit Data from Greenland Summit, 1987. NSF Arctic Data Center. doi:10.5065/D63X84RQ.</a>	11
<a href="#">Edward Zeller. 2016. Nitrate and Conductivity Data from the GISP H Core. NSF Arctic Data Center. doi:10.5065/D6JH3JB9.</a>	11
<a href="#">NSIDC, World Data Center (WDC) for Paleoclimatology, National Geophysical Data Center, NOAA, and Greg Scharfen. 2016. Greenland Summit Ice Cores. NSF Arctic Data Center. doi:10.5065/D6QR4V8G.</a>	11
<a href="#">Becky Alexander. 2016. Greenland Ice Sheet Project 2 sulfate and nitrate isotopes. NSF Arctic Data Center. doi:10.18739/A23T0C.</a>	9
<a href="#">NSF Arctic Data Center. 2014. Nitrogen Oxides from GEOsummit Station, Greenland. NSF Arctic Data Center. doi:10.18739/A2K60H.</a>	8
<a href="#">David H. Bromwich. 2016. Influence of Ocean Surface Conditions on the Regional Climate of the Northernmost Atlantic, 1988-2004. NSF Arctic Data Center. doi:10.5065/D6V69GQC.</a>	7
<a href="#">Edward Brook. 2016. Summit, Greenland lock in zone methane and total air content data. NSF Arctic Data Center. urn:uuid:2d6c7992-9100-49ea-bd8b-f08dfb5948a5.</a>	5
<a href="#">Michael Bergin. 2015. Monthly Averages of Aerosol Properties in Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A2T36X.</a>	4
<a href="#">Matthew Shupe. 2015. Ceilometer Cloud Base Height Measurements at Summit Station, Greenland. NSF Arctic Data Center. doi:10.18739/A21M3T.</a>	3
<a href="#">Meredith Hastings. 2016. Isotopic composition of nitrate in atmospheric mist chamber samples. NSF Arctic Data Center. doi:10.18739/A24640.</a>	3
<a href="#">Matthew Shupe. 2014. Ceilometer Cloud Base Height Measurements at Summit Station, Greenland. NSF Arctic Data Center. doi:10.18739/A25D64.</a>	3
<a href="#">Matthew Shupe. 2013. Ceilometer Cloud Base Height Measurements at Summit Station, Greenland. NSF Arctic Data Center. doi:10.18739/A2696D.</a>	3
<a href="#">Michael Bergin. 2013. Hourly Averages of Aerosol Properties in Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A2DT05.</a>	3
<a href="#">Michael Bergin. 2015. Daily Averages of Aerosol Properties in Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A2FT0G.</a>	3

<a href="#">Matthew Shupe. 2016. Ceilometer Cloud Base Height Measurements at Summit Station, Greenland. NSF Arctic Data Center. doi:10.18739/A2WX0J.</a>	3
<a href="#">Michael Bergin. 2014. Monthly Averages of Aerosol Properties in Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A2XT0T.</a>	3
<a href="#">Edwin D. Waddington and Bob Hawley. 2016. Borehole Optical Stratigraphy measurements through 4 full years at Summit, Greenland. NSF Arctic Data Center. doi:10.5065/D6XK8CPQ.</a>	3
<a href="#">Vasilii Petrenko, Jeffrey Severinghaus, and Edward Brook. 2016. Greenland Summit 14C and close-off studies. NSF Arctic Data Center. urn:uuid:4d549744-fe00-46a5-a8ef-77f92a0d438a.</a>	3
<a href="#">Michael Bergin. 2013. Monthly Averages of Aerosol Properties in Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A22M2R.</a>	2
<a href="#">Michael Bergin. 2015. Hourly Averages of Aerosol Properties in Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A25D4C.</a>	2
<a href="#">Michael Bergin. 2014. Hourly Averages of Aerosol Properties in Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A29368.</a>	2
<a href="#">Michael Bergin. 2012. Hourly Averages of Aerosol Properties in Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A2JM23.</a>	2
<a href="#">Michael Bergin. 2012. Daily Averages of Aerosol Properties in Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A2V367.</a>	2
<a href="#">Michael Bergin. 2011. Monthly Averages of Aerosol Properties in Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A2B36K.</a>	1
<a href="#">Michael Bergin. 2014. Daily Averages of Aerosol Properties in Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A2KM2D.</a>	1
<a href="#">Michael Bergin. 2013. Daily Averages of Aerosol Properties in Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A2Q949.</a>	1
<a href="#">Michael Bergin. 2015. Monthly Averages of Aerosol Properties in Summit, Greenland. NSF Arctic Data Center. urn:uuid:7db8d7a7-3e68-480b-b446-309d3e198750.</a>	1
<a href="#">Michael Bergin. 2011. Hourly Averages of Aerosol Properties in Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A2P940.</a>	0
<a href="#">Michael Bergin. 2011. Daily Averages of Aerosol Properties in Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A2ZT04.</a>	0
<a href="#">Detlev Helmig. 2014. Summit snowpack gases. NSF Arctic Data Center. doi:10.18739/A2NM08.</a>	meta only

<a href="#">Detlev Helmig. 2015. Atmospheric Hydrocarbons at GEOSummit, Greenland, as Tracers for Climate Change, Air Transport, and Oxidation Chemistry in the Arctic. NSF Arctic Data Center. doi:10.18739/A2V31B.</a>	meta only
<a href="#">Vladimir Romanovsky. 2009. Thermal State of Permafrost (TSP): The US Contribution to the International Permafrost Observatory Network. NSF Arctic Data Center. urn:uuid:15120906-ddeb-4d8d-be69-799147216f0b.</a>	meta only
<a href="#">Von Walden, Matthew Shupe, and Ralf Bennartz. 2010. Integrated Characterization of Energy, Clouds, Atmospheric State, and Precipitation at Summit (ICECAPS). NSF Arctic Data Center. urn:uuid:16726b27-2bf6-42c9-a30d-60f82d6271fc.</a>	meta only
<a href="#">Von Walden and Matthew Shupe. 2010. Radiosonde - temperature and humidity profiles. NSF Arctic Data Center. urn:uuid:1d944346-82f2-4081-9a63-bfd153319e7b.</a>	meta only
<a href="#">John Burkhart. 2013. Collaborative Research: Science Coordination Office for Summit Station and the Greenland Traverse. NSF Arctic Data Center. urn:uuid:21ec42d1-c45e-4f9b-b7e3-f919d26dfec4.</a>	meta only
<a href="#">Matthew Shupe. 2010. Ceilometer measurements. NSF Arctic Data Center. urn:uuid:294084c9-2490-49a3-92d0-edcc578a8cf0.</a>	meta only
<a href="#">Jeffrey Thayer. 2015. High Resolution, Active Remote Sensing of Cloud Microphysics at Summit, Greenland with Polarized Raman Lidar. NSF Arctic Data Center. urn:uuid:2c68c9eb-fe0e-486c-aeb1-755668f766ae.</a>	meta only
<a href="#">Matthew Shupe. 2010. Depolarization lidar measurements. NSF Arctic Data Center. urn:uuid:3eefc5ec-f255-43f1-b593-40a4e27a5a0e.</a>	meta only
<a href="#">Von Walden, Matthew Shupe, and Ralf Bennartz. 2010. Microwave Radiometer Measurements of Sky Brightness Temperature. NSF Arctic Data Center. urn:uuid:462f38a1-2769-4f95-a96a-363fceb1ba8d.</a>	meta only
<a href="#">Matthew Shupe. 2010. Millimeter Cloud Radar Measurements. NSF Arctic Data Center. urn:uuid:4fc72872-f2e4-455a-837b-4cd668b9f6aa.</a>	meta only
<a href="#">Detlev Helmig. 2015. Atmospheric Hydrocarbons at GEOSummit, Greenland, as Tracers for Climate Change, Air Pollution Transport, and Oxidation Chemistry in the Arctic. NSF Arctic Data Center. urn:uuid:5870816a-e9f6-4d2e-9582-80bd0d774269.</a>	meta only
<a href="#">Matthew Shupe. 2010. Micropulse lidar measurements. NSF Arctic Data Center. urn:uuid:6312cec9-6a76-4363-8f70-28607f8f8b51.</a>	meta only
<a href="#">Louisa Kramer. 2014. Long-term measurements of nitrogen oxides at the GEOSummit station, Greenland. NSF Arctic Data Center. urn:uuid:90c29228-135f-42b1-ab3e-60b806dd9d84.</a>	meta only

<a href="#">David Noone. 2014. Closing the Isotope Hydrology at Summit: Measurements of Source Regions, Precipitation and Post-deposition Processes. NSF Arctic Data Center. urn:uuid:9e2899f9-c157-457d-b5a4-b61a5e0b0be9.</a>	meta only
<a href="#">Peter Lavrentyev. 2013. Impacts of Climate Change and Ice Conditions on Microbial Food Web Dynamics in the Barents Sea. NSF Arctic Data Center. urn:uuid:b27c535c-eea3-48ea-a32b-122011a80496.</a>	meta only
<a href="#">Joseph McConnell. 2014. Continued Core Atmospheric and Snow Measurements at the Summit, Greenland Environmental Observatory. NSF Arctic Data Center. urn:uuid:bea82705-5ef8-47db-a38b-f11be53602d7.</a>	meta only
<a href="#">Matthew Shupe. 2010. Precipitation Occurrence Sensor System measurements. NSF Arctic Data Center. urn:uuid:d0966c69-c0cf-46ad-afda-856843be8433.</a>	meta only
<a href="#">Von Walden, Matthew Shupe, and Ralf Bennartz. 2010. Polar Atmospheric Emitted Radiance Interferometer measurements. NSF Arctic Data Center. urn:uuid:d199a10e-6024-4d60-9d63-3f76de17e054.</a>	meta only
<a href="#">Matthew Shupe. 2010. Sodar measurements. NSF Arctic Data Center. urn:uuid:d4e21a76-486d-4ca1-a299-8a2e9ecff688.</a>	meta only
<a href="#">Jihong Cole-Dai. 2013. Collaborative Research: An Isotope MIF Study of Volcanic Events in Greenland Ice Cores. NSF Arctic Data Center. urn:uuid:d7ca6f59-984a-49a7-839e-0f0b246d466f.</a>	meta only
<a href="#">Roger Bales. 2013. Core Measurements at Summit, Greenland Environmental Observatory. NSF Arctic Data Center. urn:uuid:d9aaac33-178f-4e49-a8e7-1c84137cdbe5.</a>	meta only
<a href="#">David Holland. 2015. Seal-Tag Hydrographic Observations in Ice-Ocean Fjords, Greenland. NSF Arctic Data Center. urn:uuid:e80cb387-679e-488c-ada2-6653710581ce.</a>	meta only
<a href="#">Roger Bales. 2009. Core Atmospheric Measurements at Summit, Greenland Environmental Observatory. NSF Arctic Data Center. urn:uuid:e9136a64-661f-470d-9b3a-72f31d54d066.</a>	meta only
<a href="#">Dennis Darby. 2013. Collaborative Research: Do Holocene Variations In Arctic Sea Ice And Greenland Icebergs Drifting Through Denmark Strait Reflect Natural Cycles. NSF Arctic Data Center. urn:uuid:fe8c2542-1e66-4354-bb73-16de17745102.</a>	meta only

## Appendix E - Atmospheric, Meteorological and other Measurements made at Summit in 2016

This Appendix list the measurements that were taken at Summit in 2016. **Table E.1** shows measurements use for surface energy budget calculations, **Table E.2** summarizes the measurements of aerosols, **Table E.3** summarizes the atmospheric measurements and **Table E.4** lists the instruments and measurements that the science technicians maintain.

**Table E.1**-Measurement commonly used for Surface Energy Budget

Variable	Instrument	SEB Component	Institute
2 m T	Logan RTD	Sensible Heat	NOAA
2 m dewpoint	Vaisala HMP155	Latent Heat	NOAA
10 m wind speed/dir	Lufft Ventus-UMB sonic anemometer	Flux Calculations	NOAA
Pressure	Setra and Honeywell pressure transducers		NOAA

**Table E.2-Measurements of Aerosols**

<b>Instrument</b>	<b>Measurement</b>	<b>Institution</b>
Three Wavelength Integrating Nephelometer	Aerosol light scattering and back-scattering at three wavelengths	NOAA
Continuous Light Absorption Photometer (CLAP)	Light absorption by particles at three wavelengths	NOAA
Aethalometer	Equivalent Black Carbon concentration/Light absorption by particles at 7 wavelengths	NOAA
Radionuclide Filter	Concentrations of Be-7 and Pb-210 on filter samples collected at nominal 2-day resolution.	UNH
Drum Sampler	Aerosols by size (8 modes, 10 to 0.09 $\mu\text{m}$ ), time (12hr data, continuous sampling), composition (32 elements) and optical absorption (8 wavelengths, 350 to 720 nm)	UC Davis

**Table E.3-** Measurements that are part of the NOAA observatory.

Measurement	Start date	Status	frequency	auto
<b>NOAA Meteorology</b>				
Wind Speed	6/25/08	Ongoing	minutes/hours	no
Wind Direction	6/25/08	Ongoing	minutes/hours	no
Temperature	6/26/08	Ongoing	minutes/hours	no
Ambient Pressure	6/25/08	Ongoing	minutes/hours	no
Relative Humidity	8/15/08	Ongoing	minutes/hours	no
<b>NOAA Carbon Cycle Surface Flasks</b>				
Carbon Dioxide	6/23/97	Ongoing	Weekly	no
Methane	6/23/97	Ongoing	Weekly	no
Carbon Monoxide	6/23/97	Ongoing	Weekly	no
Molecular Hydrogen	6/23/97	Ongoing	Weekly	no
Nitrous Oxide	6/23/97	Ongoing	Weekly	no
Sulfur Hexafluoride	6/23/97	Ongoing	Weekly	no
Carbon-13/Carbon-12 in Carbon Dioxide	6/23/97	Ongoing	Weekly	no
Oxygen-18/Oxygen-16 in Carbon Dioxide	6/23/97	Ongoing	Weekly	no
Carbon-13/Carbon-12 in Methane	4/27/10	Ongoing	Weekly	no
Methyl Chloride	10/18/04	Ongoing	Weekly	no
Benzene	7/17/06	Ongoing	Weekly	no
toluene	7/17/06	Ongoing	Weekly	no
ethane	10/18/04	Ongoing	Weekly	no
ethene	10/18/04	Ongoing	Weekly	no
propane	10/18/04	Ongoing	Weekly	no
propene	10/18/04	Ongoing	Weekly	no

i-butane	10/18/04	Ongoing	Weekly	no
n-butane	10/18/04	Ongoing	Weekly	no
i-pentane	10/18/04	Ongoing	Weekly	no
n-pentane	10/18/04	Ongoing	Weekly	no
n-hexane	10/18/04	Ongoing	Weekly	no
Wind Speed	6/23/97	Ongoing	Weekly	no
Wind Direction	6/23/97	Ongoing	Weekly	no
Temperature	5/10/04	Terminated - 2004-08-09	Weekly	no
isoprene	7/17/06	Ongoing	Weekly	no
Acetylene	8/18/10	Ongoing	Weekly	no
<b>NOAA HATS Flask Sampling</b>				
HFC-134a	6/20/04	Ongoing	Weekly	no
HCFC-22	6/20/04	Ongoing	Weekly	no
methyl chloride, benzene	6/20/04	Ongoing	Weekly	no
HCFC-142b	6/20/04	Ongoing	Weekly	no
Halon-1211	6/20/04	Ongoing	Weekly	no
methyl bromide, methyl iodide	6/20/04	Ongoing	Weekly	no
CFC-113, CFC-11, CFC-12	6/20/04	Ongoing	Weekly	no
Dichloromethane, chloroform	6/20/04	Ongoing	Weekly	no
tetrachloroethylene	3/10/09	Ongoing	Weekly	no
carbonyl sulfide	6/20/04	Ongoing	Weekly	no
HFC-152a	6/20/04	Ongoing	Weekly	no
Halon 2402	3/10/09	Ongoing	Weekly	no
HFC-227ea	5/8/11	Ongoing	Weekly	no
HFC-365mfc	6/8/09	Ongoing	Weekly	no
Methyl Chloroform, CCl4	6/20/04	Ongoing	Weekly	no
<b>NOAA HATS In Situ Observatory</b>				
Nitrous Oxide	7/16/07	Ongoing	hr/day/mo ave	no



Sulfur Hexafluoride	7/16/07	Ongoing	hr/day/mo ave	no
CFC-12	7/20/07	Ongoing	hr/day/mo ave	no
Halon-1211	11/22/07	Ongoing	hr/day/mo ave	no
CFC-113	7/20/07	Ongoing	hr/day/mo ave	no
carbon tetrachloride	7/20/07	Ongoing	hr/day/mo ave	no
Methyl Chloroform	7/20/07	Ongoing	hr/day/mo ave	no
CFC-11	7/20/07	Ongoing	hr/day/mo ave	no
<b>NOAA Aerosol Surface In-Situ</b>				
Light Scattering Coefficient	1/10/11	Ongoing	hourly	no
Light Absorption Coefficient	1/10/11	Ongoing	hourly	no
Particle Number Concentration	1/10/11	Ongoing	hourly	no
<b>NOAA Radiation In-Situ Observatory</b>				
Direct Beam	5/28/06	Ongoing	Minute ave.	no
Shortwave Global	5/28/06	Ongoing	Minute ave.	no
Diffuse	5/28/06	Ongoing	Minute ave.	no
Reflected Shortwave	5/28/06	Ongoing	Minute ave.	no
Downward Longwave	5/28/06	Ongoing	Minute ave.	no
Upward Longwave	5/28/06	Ongoing	Minute ave.	no
<b>NOAA Surface Ozone</b>	6/1/00	Ongoing	Minute ave	no
<b>NOAA Ozonesonde Profile</b>	2/12/05	Ongoing	Weekly	no

**Table E.4** - List of instruments Maintained by Science Technician at Summit and start date when known. Some of these are duplicates to those already listed in Table E.1-3.

<b>Instrument</b>	<b>Date</b>
BSI UV Spectroradiometer	8/2004
CU Gas Chromatograph	
Non-methane hydrocarbons	
Methane	
CU Steffen Solar Radiation Suite	
CU Steffen Tower Suite	
CU Steffen upGPR - Upward looking GPR for snow accumulation and densification measurements	5/2015
DTU Magnetometer - Full vector geomagnetic measurements as part of ground station network	7/2014
Howat - Cosmic Ray sensor for SWE and accumulation measurements	5/2016
ICECAPS Radiosondes - upper air meteorology	2010
ICECAPS CAPABL	2010

ICECAPS Ceilometer	2010
ICECAPS IceCAM	2010
ICECAPS IcePIC	2010
ICECAPS MMCR	2010
ICECAPS MPL	2010
ICECAPS MWR	2010
ICECAPS PAERI	2010
ICECAPS POSS	2010
ICECAPS SODAR	
ICECAPS TSI	
NASA Bamboo Forest - stake array accumulation measurements	8/2003
NASA ICESat - GPS and stake accumulation measurements	8/2006
NOAA Aethalometer	
NOAA CATS GC	

NOAA CC Flasks	
NOAA HATS Flasks	
NOAA Met	
NOAA NEPH/CLAP	
NOAA O3 Sonde	
NOAA Solar	
NOAA Surface O3	
Potsdam Seismometer	8/2003
UCD DRUM	
UChicago WVR	7/2016
UNH Radionuclide	

## Appendix F - Agenda for Summit Science Summit

### Summit Science Summit Agenda

*Agenda for March 28-29, 2017*

#### Overview and Purpose

The Summit Science Summit will bring together a multidisciplinary group of Arctic Scientists to review Summit measurements, define the leading research questions that are answered by Summit data and to make community-based recommendation on future science goals and measurements for Summit. This workshop will define the important science questions for Summit and define the measurements and accuracies needed for measurements to answer those questions. Please note that our discussions will focus on science topics and scientific data.

#### Location and logistics

Everyone in the room or online is here for a reason. Your scientific expertise matters, is important and unique. Everyone is expected to contribute at the meeting and there will be ample opportunity.

This meeting is intentionally set to be fast paced so you will be engaged. Feel free to bring any electronic device you want but if you are using it for anything besides the meeting you may not be able to keep up. This meeting will also have a strong remote-in presences. At the pre-meeting we will make sure everyone can use the video conferencing system and has access to the google drive and documents. The google drive will be updated routinely for remote participants to stay informed.

Please visit this page <https://www.nsf.gov/about/visit/> for more information on visiting NSF. Make sure you have RSVPed to Lora Koenig ([lora.koenig@colorado.edu](mailto:lora.koenig@colorado.edu)) for the meeting by March 10, 2017. If you requested travel assistant you will receive an email by March 10th with detailed information on travel logistics.

#### Objectives, Goals and Outcome

1. Articulate major science questions investigated at Summit
2. Elucidate the current state of Summit measurements
3. Illustrate the current uses of the data (ie. Atmospheric monitoring, glaciological monitoring, etc)
4. Define the utility of the data

5. Determine the temporal, seasonal variability of measurements and the accuracy to which they must be monitored for scientific analysis. Also quantify model sensitivity to Summit data where available.
6. Provide a detailed report on the current state and applications of Summit data that will include community-based recommendation on future science goals and measurements for Summit

## Google Drive Link

<https://drive.google.com/open?id=0BxbKi9U85PJIUWJFVWd6QkINaXc>

## Agenda

Tuesday March 28, 2017

9:00 am Welcome and Meeting Logistics

Lora Koenig/Jennifer Mercer

Quick technology primer-google slides and real-time question functions, google doc for final report and google form for questions at anytime. How to follow real-time notes and slides for remote attendees who will come and go.

### Setting the Stage- All the background you need to know

9:15 am Briefing from NSF

Jennifer Mercer/Will Ambrose/Kate Ruck

Information on proposals and charge for Summit Summit.

9:25 am Briefing from NOAA

Brian Vasel

9:45 am Briefing from SCO on Summit Science and Impact

SCO\*

Major Science Accomplishments. Publications, most cited publications, funded projects. Major Scientific questions.

### Our Focus- Summit Science

10:00 am Overview of Objectives and Science Questions

Bruce Vaughn/ Lora Koenig

10:15 am Break

### Current Data- What is it, what has it done, what can it do?

10:30 am The Data/Existing science.

Steering Committee

Data being collected at Summit and previously collected. What data is being collected now and at

what intervals? What is its variance?

10:40 am Open Discussion - The Data/Existing science                      Slides from Attendees

Who uses it? Science Discoveries? Unanswered Scientific questions? What data is needed? What precision/accuracy is needed to answer science questions?

11:00 am - Small Group Discussion

Continue into small group rotating discussions. Each group will have a steering committee member to take notes. The groups are different every time but the committee member will have a specific science topic. Out of each round the group has to have one top question and one secondary on data/measurements/models. They can also have a “we need more data on questions”, an unknown. One group will be the virtual group. It may or may not rotate but will have discussion during this time and will report back. Notes to be taken in google drive.

11:40 am - Wrap up of discussion and report back as large group

12:00-1:30 Lunch- On your own/ Take a Break and come back rejuvenated.

**Recommendation: What data do we need in the future to maintain and grow science discovery.**

(Please note that timing in this section will be more fluid as we want ample time to discuss topics properly. For on-line participants please watch the realtime notes to stay informed if you need to step away and rejoin. On-line participants will be strongly encouraged to participate through video, voice and chat, as appropriate. Lynn Montgomery ([lynn.montgomery@colorado.edu](mailto:lynn.montgomery@colorado.edu)) will be moderating on-line participation and will be assisting virtual attendees.)

1:30 - Measurements and Models

What are models capturing/not capturing? What are the errors on the models vs measurements?

2:30 - Frequency needed to answer science questions

How often do we need measurements/model input? What are the long-term measurements and impact of losing long term measurements?

3:30 - Break

3:45 - Future **Science** Recommendations

What we need? What can we live without? What can we automate? What do we need people to collect? What can satellites/drones/robots collect?

5:30 - Dismissal

## Wednesday March 29, 2017

9:00 am - Welcome and writing tasking

9:15 am - Small group writing - Break as appropriate for your group

10:45 am - To Do List and assignments

11:15 am - Thank you and good-byes

11:30 am - Dismissal for Attendees

1:00 pm - Steering Committee Meeting

\*The Summit Coordination Office (SCO) consists of Jack Dibb, John Burkhart, Zoe Courville and Bob Hawley.