Summit, Greenland Observatory

An Arctic Observatory Serving Scientific Research into the 21st century

An outline for an extended 5-year plan

March, 2010

The Summit Arctic Observatory is a cooperative effort of agencies and organizations in several countries. The U.S. National Science Foundation has been and remains the primary supporter of the station, guiding its development, ensuring operational support, and funding many of the research projects carried out at Summit. In cooperation with NSF, the National Oceanic and Atmospheric Administration has begun installing observational systems for understanding the long-term trends of climate-critical variables, taking advantage of the ideal location and the opportunity for a cooperative venture. Summit is on target for becoming one of six NOAA Global Atmospheric Baseline Observatories.

Relevant websites:

NSF Polar Programs – http://www.nsf.gov/dir/index.jsp?org=OPP

GEOSummit Website – http://www.geosummit.org/

NSF Summit Camp Website – http://www.summitcamp.org/

NOAA Summit Observatory Website – http://www.esrl.noaa.gov/gmd/obop/sum/

Disclaimer: This document is a white paper, written by scientists and intended to guide scientific efforts at Summit into the next decade. The views expressed herein are not necessarily those of NSF, NOAA, or any other agency mentioned.

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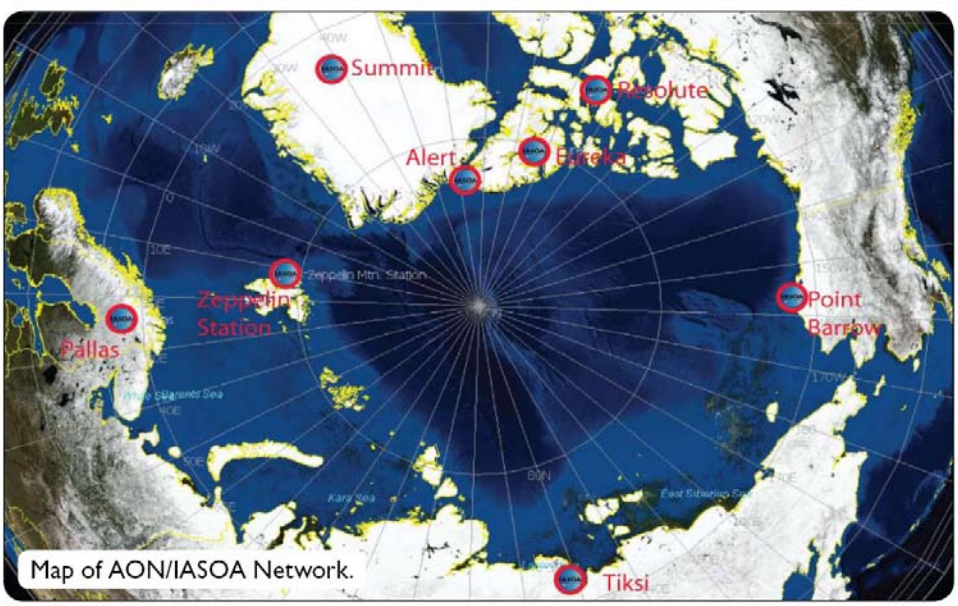
Summary

Summit is a unique observatory that will serve a critical role in understanding arctic and global climate change over the next several decades. ***As the only dedicated, staffed observatory operating year-round at high altitudes in the Arctic, Summit offers easy and immediate access to the free troposphere, is relatively free of local influences that could corrupt climatic records, traces averaged trends in the northern hemispheric troposphere, and captures rare phenomena that can represent climatic trends and help scientists understand the impacts of climate change.*** Summit is situated ideally for studies aimed at identifying and understanding long-range, intercontinental transport and its influences on air and snow chemistry and albedo. For radiation measurements, it is the only arctic site with a year-round dry snow and ice background.

While other research observatories in the Arctic such as those at Barrow, Alert, Ny-Alesund, Tiksi, and Chersky lie at sea level near coastal and continental influences, Summit will remain free of regional effects from increased shipping, melting ice, and thawing permafrost – changes that are likely to be observed in the near future. Summit records would not be corrupted by such influences unless they represent widespread Arctic trends or are sufficiently significant to have large-scale effects. Summit thus serves as a reference site, analogous to a white cell in a spectrometer, for arctic measurements of climate change. Process studies targeting aspects of the climate system (e,g,, atmospheric chemistry, air-snow exchange, boundary layer dynamics, energy balance, cloud physics/microphysics and radiative impact) conducted at Summit benefit from the suite of long-term, continuous measurements that can help in identifying questions and interpreting and understanding results, something that is not available at temporary or seasonal field sites.

Vision: *Summit station will be a pre-eminent polar research station in coming decades, integrated into an arctic network of observations and supporting cutting edge research in a variety of disciplines by teams from the US, Europe and Asia. Investigations into tropospheric chemistry, snow chemistry, air-snow exchange and climate change will remain prominent at the facility, but other geophysical fields (e.g., seismic, stratospheric, ionospheric, space weather) will also be represented. In addition, Summit will increasingly serve as a test bed for new sensors and technology designed for remote operation or autonomous exploration in isolated regions and harsh environments. Continued improvements in communications technology will allow for scientists and the general public to fully participate in experiments and events at Summit from their desks back home around the world.*

A Cornerstone of Arctic Research



I. Arctic Change as an Indicator and Feedback of Climate Change

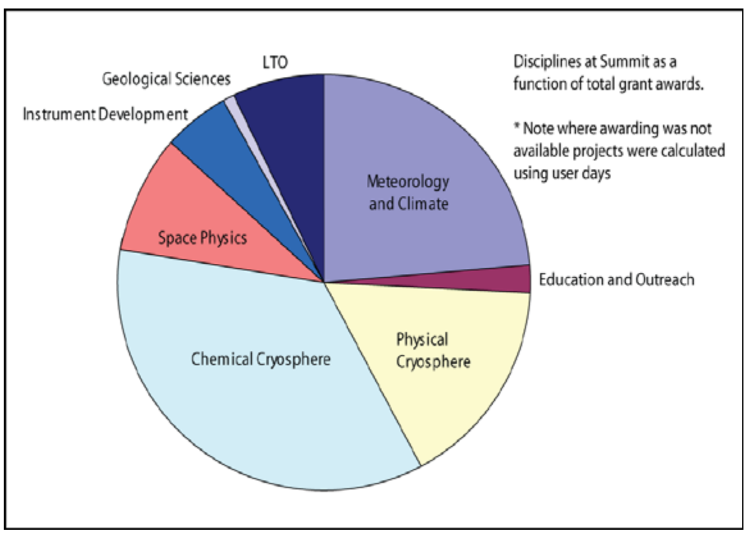
The Arctic region is currently undergoing profound atmospheric, terrestrial, and oceanic changes related to notable changes and variations in climate. In many cases, observed changes do not represent and frequently exceed model projections and predictions. The Arctic is not just an indicator of climate change, but also provides numerous feedbacks. These feedbacks are associated with unique Arctic characteristics, such as those associated with reductions in sea ice cover, increasing coastal water temperatures, pronounced continental warming, potential release of carbon and methane associated with permafrost thaw, and rising sea level. The changes are further complicated by social adjustments that accompany them – adjustments that may further modify the Arctic system such as expanded maritime and land transportation, fisheries, resource exploration and extraction. Environmental changes due to climate change and human responses to those changes in the Arctic already are having, and will continue to have, significant ramifications for marine and land ecosystems, indigenous human populations, societal human health and infrastructure, and international maritime water column and sea bed claims. Some projections suggest that Arctic system adjustments to global climate change may be modifying northern hemispheric mid-latitude weather patterns, or will soon be. Immense effort in the future will be aimed at studying these phenomena and understanding their effects and global impacts.

Amid these Arctic changes and efforts, Summit Station in coming decades will become a critical, perhaps the sole, background site in the northern hemisphere for studies of global climate change, as it will remain free of many of the local and regional influences for decades to come. Precisely because it is not located in a coastal area that is subject to nearby climate change events, Summit Station will become an increasingly important site for studies that need to be free of significant local effects. For those trying to separate local change from large-scale phenomena, whose studies simply require being free of regional effects, who might need to observe long term change in the free troposphere, who will be studying the exchange between the stratosphere and troposphere and its linkage to climate, or who wish to study extraterrestrial phenomena, Summit will be the increasingly favored site or at least a necessary component for their work.

II. Near Term Opportunities for Science to be Conducted at Summit

Summit supports a mixture of long-term observation programs that are building extended time series for detection and quantification of large scale changes in the Arctic system. In addition, Summit supports an ever changing set of short term "campaign-based" investigations that are expected to yield insight or resolution through intensive but short observational or experimental efforts. In recent years many campaigns have focused on air/snow exchange, both to more fully exploit the glaciochemical records recovered from the Summit ice cores and to elucidate the impact of snow photochemistry on the overlying atmosphere. Other teams have collected new shallow ice cores for targeted investigations responding to open questions raised by the deep ice cores, or because new analytical techniques have been developed that allow measurements not possible 15 years ago. Advances in methods to measure stable isotopes in very small samples have lead to several recent studies generating time series in snow and ice cores, and also using isotopic tools to understand air/snow exchange processes. Several teams have conducted deep firm air sampling from the new bore holes to further our understanding of recent changes in atmospheric composition and to refine understanding of the processes controlling the mixing of air within the firn and trapping of that air in ice, in order to make full use of existing and future measurements of trapped gases in deep glacial ice. Several campaigns have made measurements relevant to glacier dynamics (e.g., densification, vertical strain) using new techniques including satellite borne sensors; results from these studies add to knowledge about the history of the Greenland ice sheet and perhaps will inform simulations of the large scale impact of the recent dramatic increase in the discharge rates of several large outlet glaciers. Another important group of Summit users is made up of those testing new concepts and designs; in recent years these have included examples ranging from "green" infrastructure like the wind turbine and electric snow machines, ice core drills designed for deep coring in Antarctic and shallow coring on Europa and perhaps other bodies in the solar system, several different new ice penetrating radar systems, to autonomous rovers for exploration in remote regions of Greenland, Antarctica, and also other planets and moons.

The pie chart below summarizes the range of research conducted at Summit over the past 6 years and Appendix 1 lists funded projects at Summit since 2003. Similarly wide ranging studies are ongoing or have been proposed for the near future. The exact mix of users moving forward is impossible to predict since this will depend on funding decisions, and also new issues posed by the many currently active science communities as new discoveries are made at Summit and elsewhere. However, it is safe to state that interest in Greenland and Summit station will grow as climate change focuses ever more attention on the Arctic.



III. Operational and Scientific Advantages of the Summit Observatory

As the only high elevation year-round observatory north of the Arctic Circle, Summit has proven to be a valuable location for numerous multidisciplinary investigations including: sampling of globally transported atmospheric compounds, investigation of the snow-to-air transfer of atmospheric compounds, investigation of the complex photochemical cycling of reactive nitrogen and other short-lived species, detailed studies of the boundary layer and energy fluxes over the ice sheet, seismic measurements, magnetic measurements of the ionosphere, and also testing of remotely operated vehicles for glaciological and other autonomous measurements.

Providing the highest quality records available for the evaluation of climate change in the northern hemisphere is a core component of Summit as a research platform. Data sets produced from Summit provide a long term record of free tropospheric conditions in the northern hemisphere free of impact from local or regional pollution sources. The station will continue to contribute to established monitoring networks such as GAW, AMAP and IASOA. Formal incorporation into the National Oceanic and Atmospheric Administration (NOAA) baseline observatory network will occur in 2011. Support from NSF's Arctic Observing Network (AON) program will extend observations of UV radiation, long range transport and deposition of aerosol-associated compounds, and impacts of clouds on radiative budget at least through 2013. Summit is expected to be incorporated into the Baseline Surface Radiation Network, extending these 10+ year long climatically relevant data series into the future as well. Adding in-situ measurements of aerosol optical properties (planned by NOAA and also proposed for focused campaigns) will provide unparalleled observations of the agents forcing climate change in the Arctic.

Unique to Summit

High Elevation

- Surface measurements representative of Arctic free troposphere
- Low water vapor supports measurements of upper atmosphere

High Latitude

- Combined with high elevation yields extreme cold temps for monitoring ozone depletion
- Strong seasonal radiation cycle

Pristine/Remote

- Background levels of important atmospheric components can be characterized

Dry Snow/Accumulation Region

- Dry ice sheet location supports intercomparison studies with Antarctica (Dome C, WAIS)
- High snow accumulation provides high annual resolution for ice core interpretation

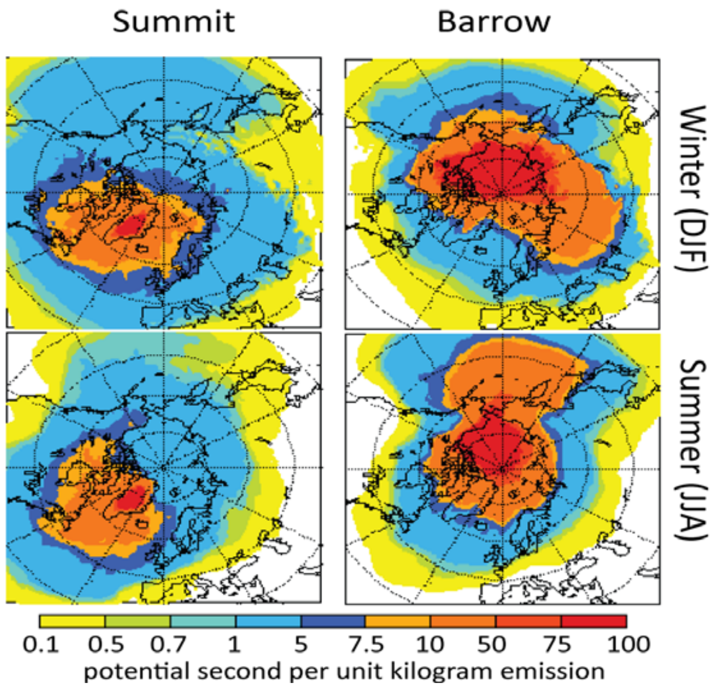
Year-round Science

- Access to seasonal data

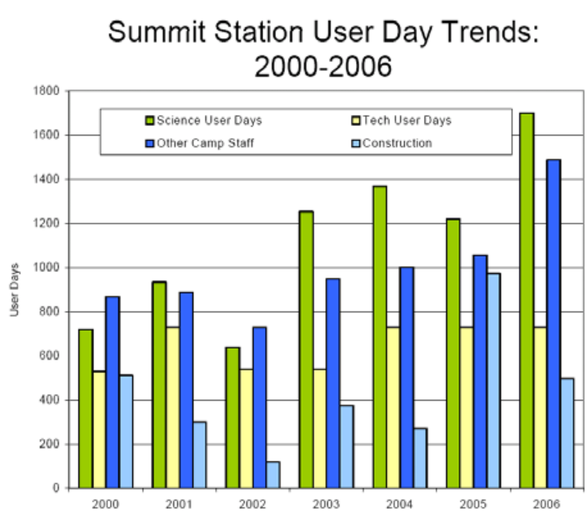
"Summit is the best place in the Northern Hemisphere for long-term solar observations given its clean air, high elevation and cold environment."
-Koni Steffen, Summit PI

A core value of the station is the availability of year-round baseline measurements of climate and chemical variables in the atmosphere. These measurements are used by numerous investigators working both on the station as well as incorporating the data into larger scale 'pan Arctic' and Arctic systems science analyses. However, in the remote environment of Summit, the slightest pollution can cause 'noise' in the signal creating a challenge to evaluate long term changes. As such, a critical requirement of the facility is to remain a 'clean air' station and to utilize best practice approaches to minimize the generation of pollution and to mitigate impacts when practical.

Greenland experiences various large scale atmospheric regime dynamics during the calendar year. These differing air masses can provide critical insight into the Arctic region and global climate change. Thus, year-round, continuous measurements of these different flow regimes are essential to furthering our understanding of the Arctic. Over seasonal time scales Summit is influenced by source regions that encompass much of the northern hemisphere. It is noteworthy that transport to Summit does not show pronounced seasonal changes in dominant upwind source regions, thereby integrating the influences of a large airshed throughout the year. In contrast, Barrow and other stations in the Arctic Basin experienced marked seasonal changes in the size and region of upwind influence. One consequence of this difference is that the low altitude stations are strongly impacted by the winter/spring phenomenon known as Arctic Haze (figure left). Also, as noted earlier, the Arctic basin stations are already being, and will increasingly be, strongly influenced by physical and cultural changes resulting from changing climate (less sea ice, melting permafrost, earlier snow melt) in the Arctic that will not be directly manifested at Summit for some time.



The goal of Summit Station is to become a 'flagship' Arctic observatory providing continuous year-round measurements of key climate variables while serving the needs of a diverse range of scientists. The primary objective of the facility is to provide the highest quality long term year-round measurements of the free troposphere. While this initial objective requires Summit to be a 'clean air' facility, it is not intended to be exclusive, and serving the needs of multidisciplinary science can still be accomplished through innovative solutions and renewable energy utilization. The global scientific community recognizes Summit as a valuable Arctic research site and recent station population numbers reflect this. The overall trend of Summit population has been +10% per year growth in user days since 2000. This increase in total user days includes both science user days and support staff user days (figure right).



IV. Contributions and Research Highlights

A review of publications from Summit, Greenland exemplifies the diverse nature of research at the facility and highlights the importance of the pristine environment. Research topics include firn microphysics, atmospheric chemistry, meteorological dynamics, climate change, and geophysical investigations. There have been more than a dozen articles published in Science and Nature magazine and over 25 in Geophysical Research Letters - all considered high impact journals. In 2007 alone there were 24 articles published. Overall since 1990 research at Summit has resulted in an average of 12 articles per year.

Results from some of these studies have required new paradigms in modeling atmospheric components of the atmosphere. The assumption of snow as a sink for compounds such as Ozone, HO_x, NO_x, and other reactive species has been shattered as numerous investigations have shown that this medium is highly reactive, offering periods of uptake and release at magnitudes that potentially impact the tropospheric budgets. It is not hyperbole to claim that a 1998 campaign at Summit launched the new field of snow photochemistry which now has dozens of researchers conducting field studies throughout the Arctic and Antarctic, and a similar cadre studying the nature of ice and its interaction with atmospheric species in laboratories around the world.

V. Observatory Background

Baseline and intensive measurement programs were initiated at the Greenland Ice Sheet summit during the 1980-1993 Greenland Ice Sheet Project 2 (GISP2) ice core collection program. The measurements were initially aimed at improving the interpretation of the ice core record, but the high quality and value of the datasets for understanding climate relevant processes were readily recognized. Being able to quantitatively record variations in atmospheric chemical processes from changes in ice composition using an explicit transfer function provides a powerful tool for examining the role of atmospherically based forcing in the climate system, as well as the response of the atmosphere to climate change. However, until 1997 all field experiments to develop and verify such models had been restricted to the summer months of May through August. A small team of researchers made similar measurements through the winter of 1997-1998 at the GISP2 camp, which began to address many of our current knowledge gaps regarding air-snow exchange processes at Summit throughout the year. Measurements at Summit have been continuous since 2003, when NOAA began to include measurements from Summit Station into its global network of climate monitoring stations.

NOAA recognizes Summit as a key component to the baseline observatory network. Strategically, Summit is ideally situated to complement the existing five observatories, especially Barrow, Alaska. Barrow is NOAA's other Arctic baseline observatory site; however it is located at sea level on the northern Alaskan coast. Barrow and the Arctic region have numerous long term threats to research conducted at sea level locations. These include increased/new shipping and flight operations and both onshore and offshore oil/gas explorations. In the Arctic region Summit is uniquely buffered from many of these influences because it is situated inland, at elevation and maintains snow cover year round. This is integral to understanding solar radiation dynamics in the Arctic region where there is a great potential for increased open water area and changing surface reflectivity dynamics. Currently there is intense interest in the hypothesis that increased deposition of absorbing aerosols, especially anthropogenic black carbon, may be reducing the albedo of snow enough to cause early snow melt throughout the northern hemisphere. Also, absorption of incoming radiation by black carbon while it is still in the atmosphere will warm the layer of air the aerosol is in, which may warm the surface and contribute to melting. The impacts of aerosols and clouds, acting separately but also through coupled interaction, on the radiative budget are not well understood in general and are largely unknown over the Greenland icesheet. Summit is an ideal location to establish the magnitude of these climate forcings due to the high albedo of dry snow, and the relative weakness of metamorphic processes that cause large and rapid decreases in the albedo of warmer snow packs (quantifying the effect of absorbing impurities on snow albedo is proving difficult, since the small changes can be masked by other processes).

VI. Operational Needs to Conduct These Studies & Intersection of Clean Energy with Science

Experiments in atmospheric chemistry have played a significant role in the development of Summit Station. A continuing objective of the facility is to provide a pristine sampling environment for measurement of trace gasses. Also, air-to-snow exchange of reactive compounds will likely continue to be investigated at Summit. Continued advances in analytical technology will create opportunities for more compounds to be measured both in the atmosphere and in ice cores at low concentrations. These new measurements may yield valuable proxies for climate reconstruction. Interpretation of the measurements will continue to rely on investigations of the preservation properties, and therefore, experimentation at Summit.

As with baseline observations, atmospheric measurements during many campaigns will rely on a sampling environment free of local sources of pollution. However, an additional challenge for air-to-snow exchange studies results from the ‘memory’ of the snow. That is, the snow surface is an integrative sampler of the local air. While observatory measurements may be flagged during pollution events, there is no such mechanism to prevent contamination from affecting the surface snow sample data. With more sensitive measurements, greater effort is required to reduce the impact from local pollutant sources – with the ultimate goal being a pollution-free infrastructure.

Pollution Impacts Science

» 15% down time in “clean air” measurements due to pollution from camp

A Clean Air Sector (CAS) was established and the prevailing winds at Summit are from the CAS more than 80% of the year. The CAS was established to preserve the unique atmospheric and terrestrial conditions found at the top of the Greenland ice sheet from Summit station influences. Except for special circumstances, access to the CAS is strictly prohibited. This includes foot and vehicle traffic. Aircraft activity is limited in the CAS, and guidelines for scientific or other activities have been established by the National Science Foundation (NSF) and CH2M-Hill Polar Services (CPS) in consultation with the Science Coordination Office (SCO). The pristine nature of the CAS is strictly preserved, not just for the current scientific activities, but also for future scientific interests at Summit. ***It is anticipated***

that the National Renewable Energy Laboratory (NREL) will continue to provide invaluable advice regarding the most cost effective ways to further reduce fossil fuel use at Summit and lead to a cleaner research environment for all science groups.

VII. Plan for Next Five Years (Science, Logistics and Interagency Support)

Summit station will be the pre-eminent polar research station in the world. It is likely that investigations into tropospheric chemistry, snow chemistry, air-snow exchange and climate change will remain prominent users of the facility, but other geophysical fields will also be well represented (e.g., seismic, stratospheric, ionospheric, space weather). In addition, Summit will also increasingly serve as a test bed for new sensors and technology designed for autonomous exploration on the moon, Mars and other objects in the solar system.

- **Science**

As noted earlier, projections about future science activities are difficult in general, since they require assumptions about Federal funding at several levels. In the case of researchers supported by NSF, the fact that proposals are generated by numerous individual investigators and are submitted to multiple programs within the foundation limits the informed planning horizon to two or three years at best.

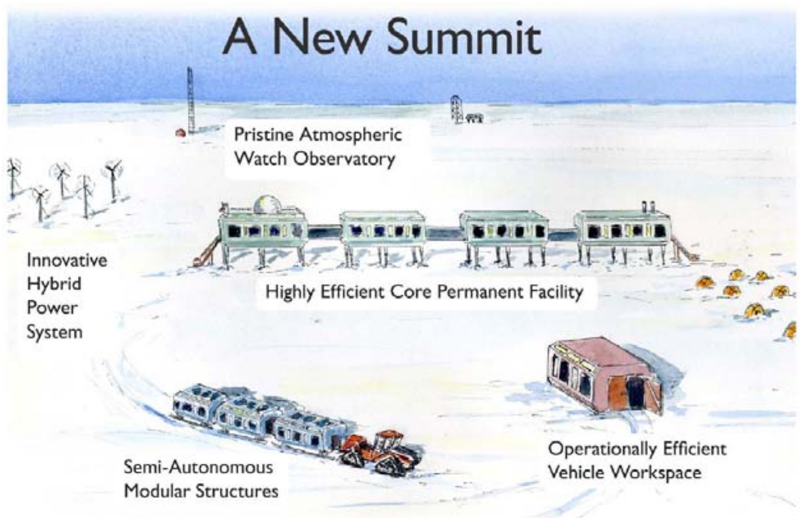
NOAA's near future plans are more specific, since they are formulated by a single group, but they are also uncertain due to the nature of the federal budget process. Growing societal concern about global change leads to optimism that NOAA will be supported at an increased level in the near future. The time line below is based on conservative estimates of NOAA budgets in the next few years, marked growth in the NOAA budget could compress the implementation (while reduced support could obviously extend the time line, or cause reassessment altogether).

- Year round staff (1) 2010.
- Year round staff (2) when Atmospheric Watch Observatory is completed and Summit officially joins NOAA's baseline observatory network in 2011.
- Aerosol measurements: absorption, scattering, total particles, and count (within the next two years as part of the NOAA climate system)
- Micro-pulse Lidar (cooperative with NASA/Goddard) to study aerosols, long-range transport, and polar stratospheric cloud (PSC) formation.

- **Logistics**

Increasing fuel costs and changed priorities of the New York Air National Guard (ANG) are likely to cause changes in operations at Summit. Initiating a surface traverse program for major resupply of the station will most likely require investigators to adopt much longer planning horizons. To ensure delivery on site via the traverse, longer timelines will be required in order to get scientific cargo into the cargo system well in advance of deployment of personnel to Summit. In some cases the lead time could be nearly a year, in particular heavy and/or bulky cargo that will need to be transported by vessel to the traverse depot in Thule. On the plus side, lengthening the supply chain in this manner will reduce emissions on station (currently the LC-130 operations account for nearly 25% of all diesel burned at Summit, and contribute an even larger fraction of emissions of many pollutants). Optimistically, this change in operations will also hasten the adoption of energy conservation measures and use of renewable sources of energy at Summit. In some sense these changes are just a rather large step in the evolution of the culture at Summit, which has already adopted a pedestrian culture and aggressive measures to reduce energy use on the station.

In general, it is clear that increasing the thermal efficiency of all structures should be a priority (retrofit or replacement). Creative means to reduce the need for snow removal around permanent structures will reduce the area impacted by emissions from heavy equipment, even if reductions of fuel used are small. This step could also reduce the operational workload for Summit staff, perhaps allowing smaller crew sizes. Proposed deployments of flexible work spaces mounted on sleds and including efficiency measures (high R values, passive solar heating, perhaps PV, day lighting) also appear likely to ease operational demands and reduce emissions. The cartoon (right) represents collective thoughts of SCO and CPS about the look of a future sustainable Summit station. Modularity should allow slow and steady progress toward this vision, with NREL pointing the way toward the most efficient elements that should be implemented first.



- **Interagency support (e.g., NOAA, DOE)**

Interagency support is critical to the success and establishment of Summit as a preeminent Arctic research site. Interagency collaboration is mutually beneficial to all parties involved. NOAA considers a major part of its role at Summit to be one of support to the NSF and other research projects. NOAA provides a continuous long-term back bone to climate monitoring that includes gases such as CO_2, Methane, CO, CFCs, HCFCs, Ozone, and measurements of solar radiation, aerosols, and meteorology. This data set (full measurement list in appendix 2) will enable other research groups to thrive and push the advancement of our understanding of the Arctic climate system. NOAA has a long history of expertise in providing baseline atmospheric observations in support of scientific research. The agency intends to continue to provide a similar service and product to all research groups at Summit.

In the past, NREL has advised the NSF on measures to help make Summit infrastructure and operations both cleaner (less fossil fuel use leads to lower emissions of many pollutants) and more sustainable (lower long-term operating costs, but also an example of moving toward a reduced fossil carbon future). Current discussions about a more active collaboration between NREL and NSF OPP could lead to reductions in financial and environmental impacts of OPP supported research throughout the Arctic and Antarctic. Formalizing this collaboration must be a priority.

Appendix 1.

All recent Summit Projects (*italics indicate support from agency other than NSF)*

Project title	Lead Institution
Continuing Operation of a Magnetometer Array on the Greenland Ice Cap (MAGIC) to Investigate Propagating Ionospheric Current Systems for Geospace Environment Modeling	Univ. Michigan
Sonic Logging of GISP2, GRIP and NGRIP Boreholes	Desert Research Inst.
ITR/SI+AP: A Mobile Sensor Web for Polar Ice Sheet Measurements	Univ. Kansas
Operation of the Magnetometer Array on the Greenland Ice Cap (MAGIC) and Interhemispheric Investigations of Multi-Scale Current Systems	Univ. Michigan
Radical Chemistry over Sunlit Snow at Summit, Greenland	Univ. New Hampshire
Preparation for a Deep Ice Coring Project in West Antarctica	Desert Research Inst.
A Unique Opportunity for In-Situ Measurement of Seasonally-Varying Firn Densification at Summit, Greenland	Univ. Washington
Core Measurements at Summit, Greenland Environmental Observatory	U. Cal. Merced
NOAA Summit Clean Air and Ozonesonde Program	*NOAA/ESRL/GMD*
Starting long-term stratospheric observations with RAMAS at Summit, Greenland	*Univ, Bremen*
BSRN-compatible irradiance measurements and the stable boundary layer (CHAntenna)	*Swiss ETH*
Astropoles	*Univ. Copenhagen*
SGER: Cool Robots: Scalable Mobile Robots for Instrument Network Deployment in Polar Climates	Dartmouth College
Transfer Functions of Hydrogen Peroxide and Formaldehyde	Desert Research Inst.
Photochemical Formation of Oxidants and Destruction of Organic Compounds in the Snowpack	U. Cal. Davis
Particulate Organic Carbon in the Air and Snow at Summit, Greenland	Georgia Inst. Tech.
Development of Multi-Axis Differential Optical Absorption Spectrometer for Measurements of Trace Gases in the Polar Troposphere	U. Cal. Los Angeles
Tumbleweed Polar Traverse Rover	*Jet Propulsion Lab*

Appendix 1. (cont.)

All recent Summit Projects (*italics indicate support from agency other than NSF)*

Project title	Lead Institution
Isotopic composition of HNO_3 and NO_x at Summit Greenland	Univ. Washington
Firn Structure, Interstitial Processes and the Composition of Firn Air	Dartmouth College
Hecht Mars Subsurface Ice Probe	*Jet Propulsion Lab*
Greenland Climate Network (GC-Net)	*Univ. Colorado*
Inter-comparison of organic pollutant deposition and transport	U. Cal. Merced
Mercury transfer processes between the lower atmosphere, snow, firn and ice of the last 150 000 years at Summit, Greenland	*LGGE*
Summit Radiation Experiment (IMAURad)	*Utrecht Univ.*
CEDAR: Inter-hemispheric High Latitude Ionospheric Electrodynamics Using a Coordinated Analysis of AMISR, Sondrestrom, SuperDARN and Other Data Sets	Univ. Michigan
POLAR-PALOOZA	Haines-Stiles Prod.
An Isotope MIF Study of Volcanic Events in Greenland Ice Cores	South Dakota St. U.
Dahl-Jensen Seismic Traverse (GEUS)	Univ. Copenhagen
Radical Chemistry over Sunlit Snow at Summit, Greenland	Univ. New Hampshire
BSRN-compatible irradiance measurements and the stable boundary layer (CHAntennaKS)	Univ. Colorado
IPY: PolarTREC Teachers and Researchers Exploring/Collaborating	ARCUS
A synthesis of existing and new observations of air-snowpack exchanges to assess the Arctic tropospheric ozone budget	Michigan Tech. U.
Continued Core Atmospheric and Snow Measurements at the Summit, Greenland Environmental Observatory	Desert Research Inst.
On-site isotope diffusion experiments conducted by Netherlands Arctic Program	*Univ. Groningen*
Polar Study using Aircraft, Remote Sensing, Surface Measurements and Models, of Climate, Chemistry,Aerosols, and Transport	*NILU*
Ultraviolet Radiation in the Arctic	Univ. Chicago

Appendix 1. (cont.)

All recent Summit Projects (*italics indicate support from agency other than NSF)*

Project title	Lead Institution
Spring and summertime diurnal surface ozone fluxes over the polar snow at Summit, Greenland	*Univ. Colorado*
Biomass-burning and anthropogenic impacts on arctic tropospheric chemistry	*Michigan Tech. U.*
GEOFON (GEOFOrschungsNetz **-** *Geo Research Network) (DESeismic)*	*Potsdam Univ.*
CryoSat Calibration / Validation (CRYOSAT)	*Univ. Cambridge*
Is There Cosmogenic Radiomethane in Polar Firn?	U. Cal. San Diego
VAUUAV	*NILU*
The Impact of Bromine Chemistry on the Isotopic Composition of Nitrate at Summit, Greenland	Brown Univ.
Understanding the Physical Properties of Northern Greenland Near-Surface Snow: A Spatial Variability Study	Dartmouth College
Validation of the Climate-SAF Inner Arctic Broadband Surface Albedo Product: Greenland and the Polar Ice Cap	*Finnish Met, Inst.*
Integrated Characterization of Energy, Clouds, Atmospheric State, and Precipitation at Summit (ICECAPS)	Univ. Idaho
IGERT: Polar Environmental Change	Dartmouth College

Appendix 2.

NOAA programs at Summit with data available to all research groups

Program/Measurement	Instrument	Sampling Frequency
Gases		
CO_2, CH_4, CO, H_2, N_2O, SF_6, $^{13}C/^{12}C$ of CH_4, $^{13}C/^{12}C$ and $^{18}O/^{16}O$ of CO_2,CH_3Cl, C_6H_6, C_7H_8, C_2H_6, C_2H_4, C_3H_8, C_3H_6, i-C_4H_{10}, n-C_4H_{10}, i-C_5H_{12}, n-C_5H_{12}, n-C_6H_{14}, C_5H_8	2.5-L glass flasks, MAKS or PSU *(Sampling began summer '97-98, again 00-02, then cont. since 2003)*	1 pair/week
Surface Ozone (O_3)	TEI surface ozone analyzer *(Sampling began 6/2004)*	Continuous
Ozone vertical profiles	Balloon borne ECC ozone sonde *(Sampling began 2/2005)*	~1 week, with additional by request in Spring when conditions warrant
Water-vapor vertical profiles	Balloon borne water vapor sonde *(Sampling began 2/2005)*	Only when conditions warrant
CFC-11, CFC-12, CFC-113, CS_2, H-2402, HCFC-22, HCFC-141b, HCFC-142b, HFC-134a, HFC-152a, H-1211, H-1301,CH_3Cl, CH_2Cl_2, $CHCl_3$, CCl_4, CH_3CCl_3, C_2Cl_4, CH_3Br, CH_2Br_2, $CHBr_3$, CH_3I, N_2O, SF_6, COS, C_6H_6	2.5-L, glass flasks (HATS) *(Sampling began 06/2004)*	2 pair/month (~8th & 23rd)
CFC-11, CFC-12, CFC-113, N_2O, SF_6, H-1211, CCl_4, CH_3CCl_3,	Automated CATS GC (HATS) *(Sampling began 07/2007)*	1 sample/hour
Aerosols		
Black Carbon	Aethalometer *(Sampling began 08/2008)*	Continuous
Meteorology		
Air temperature	(2 and 10-m heights) Vaisala Resistance probes & Logan RTDs	Continuous
Pressure	Honeywell pressure transducer Setra pressure transducer	Continuous
Wind (speed and direction at 10m height)	R.M. Young wind monitor	Continuous
Dew point temperature (2m)	Vaisala humidity probe *(All met instrument sampling began 08/2005)*	Continuous