Advancing Arctic Atmospheric Science through Developing Collaborative, Targets for Large, International Observatories

Sandy Starkweather[1], Von Walden[2], Taneil Uttal[3], James Drummond[4], Jeff Key[5], Jennifer Kay[6], Timo Vihma[7], Henrik Skov[8], John Burkhart[9]

On behalf of the International Arctic Systems for Observing the Atmosphere (IASOA)

[1]Cooperative Institute for Research in Environmental Science (CIRES), Boulder, USA
[2]University of Idaho, Moscow, Idaho, USA
[3]National Oceanic and Atmospheric Administration (NOAA), Boulder, USA
[4]Dalhousie University, Halifax, Canada
[5]Center for Satellite Applications and Research, NOAA/NESDIS, USA
[6]National Center for Atmospheric Research (NCAR), Boulder, USA
[7]Finnish Meteorological Institute (FMI), Helsinki, Finland
[8]Aarhus University, Aarhus, Denmark
[9]Norwegian Institute for Atmospheric Research (NILU), Oslo, Norway

Executive Summary and Background: This white paper focuses on issues of Arctic observing network design, coordination and sustainability for the large, independently-funded Arctic atmospheric observatories (often co-located with substantial cryospheric observations). The International Arctic Systems for Observing the Atmosphere (IASOA) was initiated as an International Polar Year (IPY) project (Darby et al. 2011) to address key atmospheric science questions through coordinating the considerable atmospheric observing assets at nine (now ten) pan-Arctic observatories (Figure 1); it has since been accepted as a Sustaining Arctic Observing Network (SAON) Task, been endorsed as an International Arctic Science Committee (IASC) Activity and been recognized as a contributor to the World Meteorological Organization (WMO) Global Cryosphere Watch (GCW) CryoNet implementation and the World Weather Research Program (WWRP) Polar Prediction Project (PPP).

The mission of IASOA is to advance cross-site research objectives from independent Arctic atmospheric observatories through *(1) strategically developing comprehensive observational capacity, (2) facilitating data access and usability through a single gateway, and (3) mobilizing contributions to synergistic science and socially-relevant services derived from IASOA assets and expertise*.

Many observing system design approaches have emphasized a top-down, model-driven geographically optimized design for Arctic observing (ADI, 2012); for IASOA observatories, such geographic optimization is impractical as there are already decades of observations at legacy locations. A complementary, bottom-up approach is more appropriate for long-term observatory design development. Thus IASOA network design initiatives focus on sustaining and enhancing observatory capacity and mobilizing science that best utilize the long-term, climate-relevant datasets and observing assets at the current locations (IASOA mission “arms” 1 and 3). This approach also considers how these observatories can serve as super-nodes for contextualizing

observations at distributed sites; support campaign and intensive efforts like the WMO's Year of Polar Prediction (YOPP) and Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC); and maximize the potential for interdisciplinary research at each site.

For IASOA, issues of design are closely linked to coordination, where independent funding agencies recognize the enhanced value of contributing to common targets for which the pan-Arctic perspective is essential (e.g. ozone match experiments). There are many viable targets to contribute to a pan-Arctic perspective on atmospheric chemistry, atmospheric physics and the interactions between the atmosphere and surface processes. This white paper presents the current important targets for IASOA initiatives, with a view towards improving network design and utilization at long-term observatories. These targets emerged as starting points due to a combination of data readiness and subject relevance; they are not an exhaustive list of the potential IASOA science contributions. Each emphasizes the value of entraining use perspectives in developing these targets.

Figure 1. The location of the ten observatories of the IASOA consortium. Station Nord, Greenland is the most recent addition to the consortium.

1.0 Bottom-up network design – Looking towards use to guide development

It is a vital time for the observational community to clearly connect the dots between the expense of sustaining long-term observational assets in the Arctic and the user communities who directly benefit from those assets. Understanding and improving how observations are used is vital for assuring broadly engaged and well-coordinated progress on the pressing interdisciplinary science questions posed by environmental change. Working as a consortium, IASOA can enhance the value of stand-alone efforts through developing pan-Arctic and interdisciplinary science targets and promoting participation in well-established international networks (e.g. Global Atmosphere Watch). These networks support the broad discovery and dissemination of quality assured observational datasets. IASOA also provides a forum for entraining the diversity of stakeholder use perspective into cross-site, atmospheric research. These perspectives provide a valuable reality check for new network investments and have the potential to broaden and deepen discovery research (Welp et al., 2006; Phillipson, 2012).

The IASOA steering committee recently adopted three guiding science objectives that are shared by the U.S. *Arctic Research Plan: FY 2013–2017* (NSTC, 2013) approach. These are:

1. Improve understanding of short-lived climate forcers (SLCFs) and their role in Arctic amplification.
2. Improve understanding of processes controlling formation, longevity, and physical properties of Arctic clouds, including the effects of—and sensitivities to—aerosols.
3. Develop an integrated understanding of Arctic atmospheric processes, their impact on the surface-energy budget, and their linkages with oceanic, terrestrial, and cryospheric systems.

The third "arm" of IASOA mission is to mobilize contributions towards these objectives from multiple sites to produce synergistic and socially relevant science. It is recognized that these efforts need to involve end-users in order to address the topic comprehensively and improve the applicability of results. Critiques of assessment and other forms of usable science (e.g. forecasts) have demonstrated that many climate assessment products (e.g. indices) are not put to use by the intended audience, often because the needs of that audience have not been sufficiently considered in the assessment framework (Cash, Borck and Patt 2006, Dilling and Lemos 2011). Cash et al. (2006) notably recognized the "loading dock" approach as one where scientists generate assessments under the flawed assumption that stakeholders will come along and pick them up off the "loading dock". In an extensive review of seasonal weather forecast users, Dilling and Lemos (2011) found that contextual (use) factors will influence the usability of science information and recommended that these factors are iteratively addressed with stakeholders. A review of environmental research projects in the UK (Phillipson, 2012) found that stakeholder participation at the early stages of research brought "significant benefits and creativity to the research."

There are multiple use contexts for information products derived from IASOA observatories including: basic research (e.g. model improvement), operations (e.g. weather forecasting), and decision making (e.g. air quality regulations). Each context presents unique considerations for usable information. Ultimately, the intersection between science and contextual factors that yields well-considered and highly usable science will be best served by an explicit focus on increasing it. We argue that this should be addressed in two ways: 1) developing methodologies within the physical science community to explicitly research and entrain user needs (even other scientific disciplinary or modal needs) into collaborative undertakings (Welp et al. 2006; Murray et al. 2012; Phillipson 2012); 2) developing the institutional spaces for linking observational expertise with these needs, such as the NOAA Regionally Integrated Sciences and Assessments (RISA). The following examples demonstrate three ways that the consortium can more explicitly involve observational stakeholders in the framing of IASOA science foci and also use stakeholder information preferences to improve observational capacity development, i.e. bottom-up network design.

1.1 From Instrument to Indices – A case study for black carbon

The phenomena of Arctic amplification is recognized as an inherent characteristic of the global climate system (Serreze and Barry 2011), that is also enhanced by anthropogenic influences principally from carbon dioxide, but also including heightened black carbon concentrations in the atmosphere. Black carbon (BC), a by-product of incomplete combustion, is an aerosol that absorbs solar radiation and warms the atmosphere. It falls in the category of short-lived climate forcers (SLCFs), which also includes ozone and methane. SLCFs are atmospheric constituents with relatively short residence times (days to years). They are thought to have an enhanced influence on Arctic radiative forcing relative to mid-latitudes (Quinn et al. 2008); in addition to increased atmospheric radiative forcing over high albedo surfaces, once deposited on the surface, BC can contribute to reduced albedo and enhanced melt (Hansen and Nazarenko 2004). The magnitude of these impacts is regionally distinct across the Arctic and at present poorly understood. The potential for a pan-Arctic network of intensive atmospheric observations to contribute to improved understanding and as well as on-going BC assessments is significant. Prior to assessing Arctic BC data from observational datasets (for which IASOA has 107 observatory-years of data for BC alone), the IASOA consortium initiated a survey of various end-users to better understand how they would ultimately use a black carbon assessment (Starkweather et al. 2012).

Three diverse groups were surveyed about the relative value they placed on different observational data from the IASOA observatories related to their BC studies: (1) the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP); (2) a U.S. multi-agency BC mitigation in study in the Russian Arctic (RU Mitigation); and (3) the International Maritime Organization BC Regulatory Initiative (IMO Regulatory). The survey results (Figure 2) revealed the diversity of user perspectives on the value of different types of observations. For example, an aerosol optical depth product might be quite appealing to modelers but considerably less valuable to shipping regulators. While for the mitigation study, speciation of black versus organic carbon and the meteorological transport patterns are of paramount importance. Currently, the observatories have limited capacity to characterize speciation. Such feedback informs future instrumentation priorities. The results of this limited survey have motivated the IASOA consortium to explicitly consider these preferences in an upcoming workshop whose goal is to frame an initial contribution on Arctic BC for the 2013 *Arctic Report Card*.

The qualitative responses from the survey further reveal important disconnects within the science community between observationalists and modelers. Respondents from the ACCMIP team all commented on the need for "readily available data" from websites, which they did not find. The comment below suggests what "readily available" might look like for this specific application:

"As a global aerosol modeler, I am generally looking for a long-term and monthly (or annual) average BC observation (as many as possible) for the model evaluation. [ ] However, I tend to avoid using it if the data is not available as monthly or annual average. I am not confident to do this conversion without deeply understanding this observation (e.g., instrument, site, and any unusual circumstances [ ] during the measurement period) unless it is clearly [sic] address how to do this conversion."

It is clear that observationalists and modelers must work more closely together in co-producing data products that can be readily used for model evaluation and development. The potential for the observational community to participate in these types of interdisciplinary dialogs is the subject of Section 1.2.

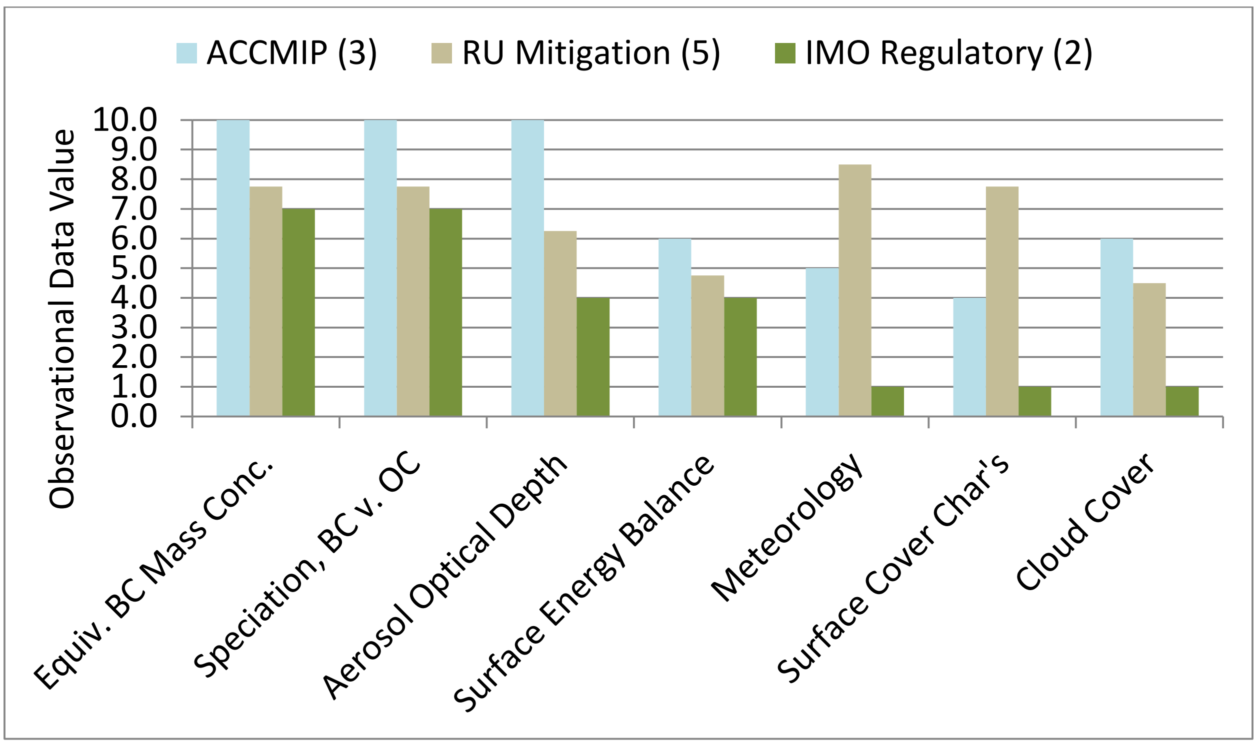

Figure 2. The relative value of different forms of observational data related to the climate forcing of black carbon in the Arctic as viewed by survey respondents from 3 case studies. Participant numbers are shown in parentheses after each case.

1.2 Improving observational outputs for the modeling community

A "call for input" effort was initiated last year from within the polar climate modeling community to more clearly articulate the ways in which observations are used to develop and evaluate climate models. The working document is titled: *On the observational needs for climate models in polar regions* (Kay et. al 2012). Because many observational efforts are motivated in part by the desire to be used in models, the working document outlines the ways in which observations are most commonly used and the most pressing observational needs for parameterization development and climate model evaluation.

One important issue identified was the need for a common language for concepts as basic as "what is a cloud?" and "what is the difference between process-scale and climate-scale?" Large differences in scale between observations and models particularly complicate matters, requiring those who work across the observational-modeling boundary to develop strategies for using observations made at one temporal-spatial scale to inform modeling efforts at multiple temporal-spatial scales.

A fairly obvious but still vital theme is the need for consistently gridded datasets with accompanying metadata in easy-to-read data formats (e.g., netcdf). The IASOA observatories represent many grid-points of climate-scale validation, yet even ten, well-distributed observatories yield a sparse comparison for the 1-2° grids used by global models. Many of the IASOA observatories present an added difficulty for the modeling community due to their coastal location. Resolving the utility of observations that are made in a mixed land-ocean grid cell for model evaluation is difficult, but essential.

The developments of this call for input and the resulting recommendations will be an important discussion for the IASOA consortium to follow. There are opportunities to provide both valuable climate-scale validation products from existing observations and to serve as a hub for process studies. One area where the IASOA consortium is already active is generating high-quality metadata for its observational datasets. The approach employed is elaborated upon in Section 2.0.

1.3 Improving observational outputs for the satellite community

The satellite and surface-based observing communities are inter-reliant users of each other's data products, because these observations complement each other in two ways. Surface-based observations are essential for assessing the validity of many satellite products. In turn, satellite products provide a spatial context for in situ point observations. The former is most important for IASOA design and implementation, as it benefits the satellite user community. The latter is most important for balancing the limitations of the fixed (and mostly coastal) locations of the IASOA observatories.

There are several observatory design considerations for the use of surface-based observations for satellite product validation. First, meteorological satellite sensors measure upwelling radiation, whether emitted or reflected, passive or active. Therefore, everything that affects the radiation between the satellite and the parameter of interest (e.g., clouds) would ideally be measured from the surface and fully characterized. Second, satellite sensors measure over an area. Surface measurements should be characteristic of that area, either by being made in a homogeneous area or by being distributed over an area representative of a satellite field-of-view (FOV). Figure 3 illustrates the heterogeneity of the surface near Barrow, Alaska, one of the IASOA sites, as seen from space. Of course, for a single satellite FOV near the Barrow site the surface is not as variable as the satellite image shows for the region, but over typical satellite "footprints" (375 m^2 to 100 km^2, depending on the sensor and product), homogeneity is an important consideration. The third design consideration is temporal sampling. However, this is generally not an issue as most surface measurements are made much more frequently than satellite overpasses.

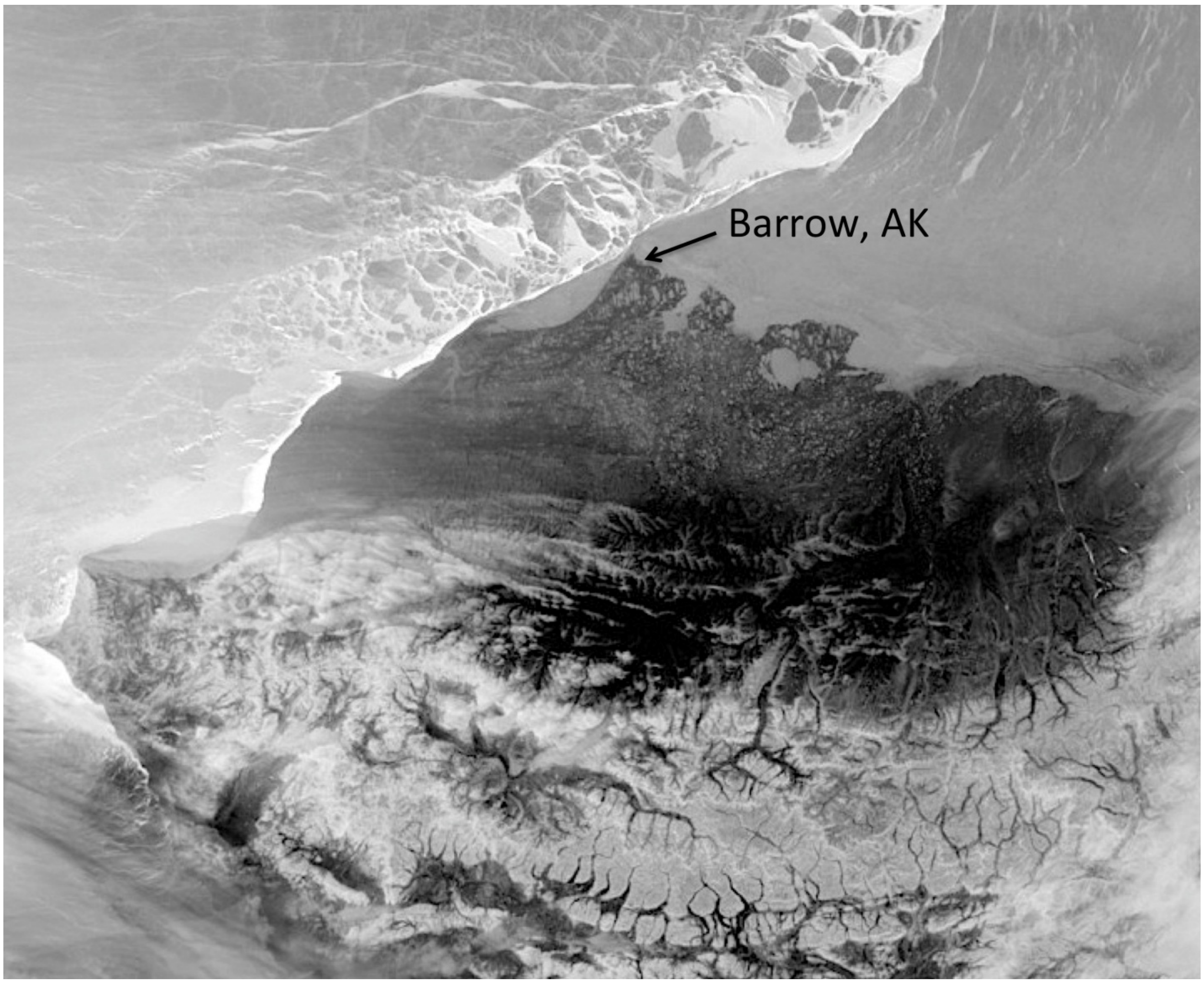

Figure 3. Infrared image of northern Alaska on 19 February 2013 from the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership (S-NPP) satellite. The image shows the spatial heterogeneity around Barrow, AK, one of the IASOA sites.

From a satellite perspective, the ideal observatory would measure the atmosphere (temperature, humidity, and winds at many vertical levels, cloud cover and cloud properties, aerosols, and some chemical species, surface radiation), cryosphere (snow cover, depth, and water equivalent, sea and lake ice cover and thickness, permafrost active layer and soil temperatures, glacier/ice sheet properties), and land (land cover, surface temperature). Prioritization of these measurements depends on the application. Geophysical parameters that are most difficult to estimate from space provide one perspective on user needs. These include, but are not limited to, low-level temperature inversion strength and depth, snow grain size and snow water equivalent, cloud optical depth and the frequency of mixed-phase clouds, ice thickness, snow depth on ice, and surface radiation. Point measurements of atmospheric properties are sufficient; surface properties would ideally be measured in multiple locations over an area.

The combined perspectives of the satellite community, the modeling community and diverse stakeholders interested in atmospheric indices all should inform the bottom-up design of the observing assets at the IASOA observatories and the way in which data products are developed from those assets. IASOA is developing the organizational potential to host and recommend experts to the forums in which these needs can be iteratively addressed.

2.0 Data Sharing

The second "arm" of the IASOA mission is to facilitate expedited access to and documentation of datasets collected at consortium observatories through a single data portal (Figure 4). Data access is complementary to network design and should not be considered an afterthought to network development. One of the significant constraints on developing cross-site and synthesis science is the difficulty of accessing well-documented datasets. Current consortium work, jointly funded by the U.S. National Science Foundation (NSF) and National Oceanic and Atmospheric Administration (NOAA) has supported progress on an IASOA data access portal to address this difficulty.

The portal search tool emphasizes providing a succinct, cross-site summary of measured variables. Search results lead users to standardized data documentation about the relevant datasets. Advanced data documentation covers file formatting, data processing, other data lineage issues, as well as extensive documentation about the measurements locations themselves. It is important to emphasize that the design process of this portal has been to maximize leveraging of existing data documentation from the constituent networks to which IASOA already contributes, such as WMO's Global Atmospheric Watch (GAW) and Baseline Surface Radiation Networks (BSRN). In general, IASOA promotes participation in and adherence to the standards of existing international observing networks. For those datasets that have no network or archive to submit to, the IASOA data management tools provide a metadata authoring interface and options for persistent archiving of data. Future work will include visualization services, the ability to assign Digital Object Identifier's (DOI)'s to datasets and faceted datasets search capabilities.

Category	Abisko	Alert	Barrow	Cherskii	Eureka	Ny-Aalesund	Pallas-Sodankyla	Station Nord	Summit	Tiksi
Aerosol	●		●		●	●	●			●
Physical, Optical	●		●		●	●	●			●
Atmospheric State					●				●	●
Surface Meteorology					●					●
Upper Air State									●	
Cloud Properties										●
Macrophysical										●
Cryosphere					●					●
Snow					●					●
Greenhouse Gas			●							
CO2			●							
HCFCs			●							
Ozone			●						●	●
Total Column Ozone			●							
Vertical Ozone Profile									●	
Surface Ozone										●
Radiometric		●			●		●			●
Longwave Broadband		●			●					●
Shortwave Broadband		●			●		●			●
Surface Properties					●					●
Surface Flux					●					●
Surface/Subsurface State					●					●

Figure 4. The new access portal is being incrementally populated with existing and soon-to-be authored metadata. This view shows the first twenty metadata records, which were created using the IASOA metadata authoring tool. Hundreds of compatible entries will be harvested automatically from source like GAW.

3.0 Sustainability

The first "arm" of the IASOA mission is to strategically develop long-term observational capacity to meet its stated science objectives. It has long been recognized that no one nation or observatory location can comprehensively characterize the diversity of the Arctic atmospheric climate; addressing these issues requires a system of strategically located and developed observatories. Yet it is also recognized that long-term, year-round measurements at Arctic facilities are costly to sustain. Logistics and energy costs often dwarf the other costs associated with procuring and operating instruments. Arctic research facilities must have well-articulated missions, efficiently utilize their observational capacity and sustainably operate their infrastructure. As part of a bottom-up "design" each observatory (or major project at an IASOA observatory) should be able to clearly articulate its unique role in the constellation of Arctic observing assets. What makes this observatory vital to the big picture? What types of science questions can only be addressed in the context of this unique (or representative) location? Sustaining observations is a challenging issue when long-term observatories are supported by revolving grants, such as at Eureka, Canada or Summit, Greenland; though even mission-based observatories like Barrow, AK have struggled with sustaining their funding. Below are some examples of successful bottom-up rationales for sustaining operations at the long-term observatories.

3.1 Eureka/PEARL

The Polar Environment Atmospheric Research Laboratory (PEARL) at Eureka, Nunavut (80.1N, 86.4W) is an observatory complex situated next to the Eureka Weather Station that operates year-round. Features of the sites include the capability of year-round operation, instrument maintenance and repair, internet communications, and a range of support capabilities. Access is by aircraft (no scheduled service) or by an annual sealift. The runway is sufficient to handle large aircraft. The weather station provides accommodations and other support for fairly large (<25) research teams.

PEARL began operations in 2005, taking over a series of ozone-related observations begun at the site in 1993. It operated during International Polar Year and continued beyond that. It is host to ~25 instruments both active (radar, lidar, etc.) and passive (all-sky cameras, CIMELs, etc.). One of the great advantages is the synergy between the instruments and the ability to combine datasets from similar times and the same location.

The uniqueness of PEARL is its ability to provide a significant clustering of instrumentation at 80N within the Canadian sector of the Arctic. It is also situated in a location with a significant probability of clear-sky conditions making it ideal for instruments using the sun, moon or stars as a radiation source for atmospheric measurements. In fact there have been recent studies of the site for a Polar telescope and the astronomical "seeing" has been found to be very good. Although the only access is by nonscheduled aircraft, the co-location of the weather station and the season military presence makes working at the site much more reasonable than its location might at first suggest. Costs are high but manageable and many of the housekeeping functions can be shared with, or purchased from, the weather station. The measurements made at PEARL provide a unique view of the Arctic from a non-marine site. Many of the instruments are qualified as part of international networks and PEARL often provides one of the most Northerly measurements of the network. By maintaining instruments qualified to participate in the networks, PEARL levers its information with the rest of the data provided to the network to provide a better picture of the globe.

Sustaining operations is a continual challenge. PEARL is supported by a series of limited-term grants and these must be frequently renewed as government interest in this part of the Arctic waxes and wanes. Over the time that the observatory has been operational, there has been a significant increase in instrument automation which has lowered the cost of acquiring the data, but put more stress on the communication links both for bandwidth and reliability. Lower staffing levels, a result of reduced funding, mean that if an instrument does fail, then it takes significant time to repair as there is only sporadic on-site support (operators).

3.2 Summit, Greenland

Summit, Greenland (72.6N 38.5W) is a unique observatory that will serve a critical role in understanding arctic and global climate change over the next several decades (SCO, 2010). It is the only staffed observatory operating year-round at high altitudes in the Arctic. By virtue of its high altitude (4210 m) 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-Ålesund, 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.

Summit Station currently maintains a suite of cloud instrumentation similar to those deployed at Barrow, Alaska and Eureka, Canada. Summit is complementary to these sea level sites by virtue of its altitude and location in central Greenland. Measurements made at Summit also have the potential to represent a large area of high elevation topography over the ice sheet.

The primary objective of the Integrated Characterization of Energy, Clouds, Atmospheric state, and Precipitation at Summit (ICECAPS) project is to acquire high-quality data to facilitate studies of Arctic cloud processes, aerosol-cloud-atmosphere interactions, and surface energy and mass budgets over the central Greenland Ice Sheet (GIS). The process-level observations being made by ICECAPS are vital to properly address current limitations of mesoscale, regional, and global climate models to simulate cloud properties.

Since 2008, long-range planning efforts at Summit, Greenland have focused on managing fuel use; both to realize cost savings (~$15/gallon) and to reduce the impact of local pollution on the sensitive atmospheric and snow chemistry measurements. In addition to addressing the energy efficiency of the permanent structures, the long-range planning efforts addressed the impact of skied aircraft-based logistics. Planning models revealed that considerable cost savings could be realized by diverting a stream of cargo towards a tractor-based Greenland Inland Traverse (GrIT). The skied aircraft were also responsible for a considerable portion of the air and snow contamination on station. Planning and design efforts at Summit can serve as a model for other Arctic observatories with similar environmental, climate and technological issues. An on-going emphasis on autonomous instrument development will also pave the wave for observatories to shift to un-manned status, further reducing the need for expensive housing structures.

3.3 Growth at Station Nord, Greenland

One of the primary factors limiting research in the High Arctic are the lack of access and the lack of well-equipped modern research infrastructure. Establishment of an advanced scientific station at Station Nord, Greenland (81.4N, 16.7W) will provide the scientific community with hitherto unavailable possibilities for pushing the frontiers of Arctic research and acquiring new knowledge that otherwise would be impossible to obtain. Modern research demands highly specialized equipment and facilities, which will be made available through the new infrastructure.

Atmospheric pollutants have been measured at Station Nord almost continuously since 1990. This makes the record from Station Nord one of the longest time series of air pollution measurements in the Arctic. The location was selected because it is the place where the largest anthropogenic signal is observed with a strong and clear seasonal variation. Furthermore, Station Nord is located on a peninsula and surrounded by perennial sea-ice. The sea north of North Greenland is extremely interesting because the multiyear ice is predicted to persist for the longest period. This makes Station Nord an ideal location for studying climate interaction involving Arctic haze, consisting of high levels of pollution that lead among other phenomena to reduced visibility and special processes occurring at the interface between the cryosphere and the atmosphere.

Station Nord is located in the world’s largest national park and provides access to a number of animal species that are hard to approach in other areas of Greenland. This offers a unique opportunity to conduct a wide range of ecological and eco-toxicological studies at the polynyas and open leads present in the perennial sea ice which serve as habitat for a series of large sea mammals. There are also large colonies of nesting polar birds in the vicinity of Station Nord which so far have only been studied superficially. Finally, several pristine lakes are located close to the station, where neither the food webs nor the sediments have been studied and which will provide important information of the connection between climate, pollution load and biodiversity, and changes in the ecosystem processes.

The infrastructure will consist of one stationary and two mobile sub-units. The sub-units may be operated together or independently. In the following they are called Base Station, Mobile Station and Air Station:

1. The stationary Base Station located at Station Nord will contain accommodation facilities, an atmospheric observatory, well-equipped laboratories for chemical, biological and geological analyses and plenty of storage room. The Base Station will have accommodation for 10 scientists at a time.

2. The Mobile Station will consist of mobile laboratories and living quarters consisting of tents and vehicles. The Mobile Station will make it possible to perform short-term in-situ investigations and campaigns at substantial distances away from the Base station.

3. The Air Station includes unmanned air vehicles (UAVs) and ground based remote sensors that will make it possible to study vertical profiles of the atmosphere to an altitude of a few kilometers, and to make aerial observations of snow, sea-ice and the landscape. The Air Station may be moved and operated at different places, e.g. as part of the Mobile Station.

The Mobile and Air stations will enable data collection at various locations combined with the excellent facilities at the Base Station for processing and analysis.

These examples demonstrate the unique contribution of three of the ten IASOA observatories. Articulating and promoting the unique role of each observatory is an important consortium effort and is being integrated into the new developments on the IASOA website; it is complementary to promoting the collective value of all the observatories. While the observatories constitute a backbone of vital infrastructure, emerging technologies have the potential to greatly expand the value of the long-term observations and reduce the human and energy input required to sustain them. These include autonomous platforms and systems that transcend the constraints of the fixed locations and surface-based instrumentation with the potential to close important geographic gaps in atmospheric observations. Promoting the development of these new technologies is the topic of the following section.

4.0 Observing technology for a new century – Developing innovative and autonomous platforms for atmospheric observations

To fully understand the rapid changes that are occurring in the Arctic, it is essential to measure the important components of the climate system with adequate spatial and temporal coverage. There is currently a lack of spatial coverage of atmospheric measurements over the Arctic Ocean, especially vertical profiles of the atmospheric state and cloud properties. Observational networks are capable of measuring the surface meteorology from ocean buoys and energy fluxes above clouds from satellite instruments. But there is a critical observational gap between the surface and the base of clouds over the Arctic Ocean. Due to the difficulty in making measurements in this harsh environment, new technologies are necessary to understand how atmospheric and cloud properties affect the surface energy budget, and specifically the growth and decay of sea ice. The Arctic atmosphere community should collaborate with oceanographers to identify new technologies, including a new-generation of surface-based instruments, including autonomous platforms. Such measurements will be essential for understanding atmospheric and cloud processes and for validating satellite observations in the Arctic.

Unmanned Aerial Systems (UAS) have a great potential for atmospheric observations in the Arctic. In particular, by providing information on horizontal variations of the atmosphere UASs can provide a lot of added value to the point measurements gathered at IASOA observatories. Various types of UAS are presently available. The smallest ones have a weight of less than 1 kg, and can measure vertical profiles of air temperature, humidity, and wind up to the height of about 1 km (Reuder et al, 2012). Such a small, low-priced UAS provides a cost-effective alternative for rawinsonde soundings. The maximum altitude reached is much lower, but many of the challenges in modeling of the Arctic atmosphere are related to the lowest kilometers. The largest scientific UAS applied in the Arctic, the Global Hawk, has a weight of approximately 5000 kg, an operation time of about 30 hours, and capability to reach an altitude of 20 km. As with manned research aircraft, most UAS can simultaneously make meteorological observations and remote sensing of ice and ocean properties, such as surface temperature and albedo, as well as ice concentration and freeboard. The most sophisticated UASs have various benefits compared to manned research aircraft: longer mission duration, possibility to fly in more dangerous conditions (storm, poor visibility), possibility for very low flight altitudes (e.g. measurements on atmosphere-ice-ocean interaction), and use of a variety of sites for take off and landing (ship decks, sea ice camps). Significant challenges in the use of UAS in the Arctic are related to aviation regulations. Different countries apply different rules for the use of UAVs, and so far only one UAS mission has crossed a border of two Flight Information Regions (between Svalbard and Greenland). The Arctic Monitoring and Assessment Program (AMAP) has an expert group working with the legal, technical, and scientific challenges of UAS operation in the Arctic. The international community is also interested in application of UAS in search and rescue duties in the Arctic. A UAS fleet available for regular atmospheric observations as well as search and rescue could provide potential for a synergy benefit.

IASOA observatories, with their excellent infrastructure, trained science technicians, range of environmental conditions and impressive array of atmospheric and cryospheric measurements have the potential to serve as valuable test beds for this new generation of technologies.

5.0 Summary

The large, independently-funded observatories of the IASOA consortium represents a considerable and sustained contribution to the International Network of Arctic Observing Systems (INAOS). Moving forward, this contribution will continue to evolve through dialog at forums like the Arctic Observing Summit and through developing collaborative, user-informed targets for international participation such as:

1. Hosting workshops and providing observational expertise to participate in science-based dialogs with modelers, the satellite community and non-science stakeholders;
2. Developing methodologies and institutional spaces for iteratively integrating the use context into data product development and observatory capacity;
3. Serving as coordinated super-nodes for intensive observing activities such as YOPP and MOSAiC;
4. Promoting interdisciplinary platform and instrumentation development workshops;
5. Serving as coordinated test-beds for new technology development;
6. Facilitating transnational access to long-term datasets and infrastructure.

In the case of IASOA, coordination has the potential to lead to capacity improvements and cross-site data product development. When the consortium is able to identify common targets of interest across the diverse observatories and demonstrate the value of broad participation, we see motion towards activity and investment, as was the case with the Tiksi Hydrometeorological Observatory (Uttal et al. 2013) and the creation of the initial IASOA data access portal. Creating common targets for implementation enables individual funding partners to independently invest in the context of their own priorities. Current coordination is sustained largely by funding from the U.S. National Science Foundation (NSF) and the U.S. National Oceanic and Atmospheric Administration (NOAA). These funds support an Implementation Scientist to investigate and advance the ideas brought forward by the voluntary IASOA Knowledge to Action Steering Committee (KASC). The International Arctic Science Committee – Atmospheric Working Group (IASC-AWG) has also provided workshop funds.

Below are some examples of the types of targets that IASOA is currently developing, organized by the 3-arms of the mission statement.

For coordinated capacity development:

Target	Status
Achieve Global GAW status for Tiksi Hydrometeorological Observatory (THO)	Planned, late-2013
Promote the inclusion of the Russian Arctic Drifting Observatory in the IASOA consortium	On-going
Continue to develop US-Russian bi-lateral agreement for the long-term operation of THO	On-going

For data sharing and inter-comparison:

Target	Status
Develop current inventories of available measurement	Complete, 2009 (on-going)
Develop an interoperable (WMO, SAON, ACADIS, CANDAC) implementation of the ISO 19115 metadata standard	Complete, 2013
Develop a single data access gateway for all IASOA data to expedite access to datasets and their related metadata	Prototype complete, April 2013
Provide a meta-data authoring tool accessible to IASOA data contributors to create discovery and use metadata	Prototype complete, April 2013
Host a workshop for IASOA data managers to convene and advance data sharing initiatives	Planned, late-2013
Promote the concept of an Arctic atmospheric data sharing treaty at the Arctic Council level	Raised, SAON board meeting, Oct-2012
Develop standards for Arctic Flux Net measurements	Planned, late-2013

For synergistic science and socially-relevant services:

Target	Status
Frame and develop an IASOA-wide baseline black carbon index for inclusion in the 2013 Arctic Report Card	Workshop planned, April 2013 (AOS)
Frame and develop an IASOA-wide baseline surface radiation assessment for inclusion in the 2013 Arctic Report Card	Workshop planned, April 2013 (AOS)
Conduct formal stakeholder researcher among Arctic black carbon stakeholders, particularly in the shipping industry	Proposed to NSF Arctic SEES, September 2012

References

AON Design and Implementation Task Forace. Designing, Optimizing, and Implementing an Arctic Observing Netowrk (AON): A Report byt the AON Design and Implementation (ADI) Task Force (2012). Study of Environmental Arctic Change (SEARCH), Fairbanks, AK. 64 pp.

Cash, D. W., J. C. Borck & A. G. Patt (2006) Countering the loading-dock approach to linking science and decision making. Comparative analysis of El Nino/Southern Oscillation (ENSO) Forecasting systems. . Science, Technology and Human Values, 31**,** 465-494.

Darby, L., T. Uttal, A. Makshtas & J. Drummond. 2011. International Arctic Systems for Observing the Atmosphere (IASOA). In Understanding Earth's Polar Challenges: International Polar Year 2007-2008 Summary by the IPY Joint Committee, eds. I. Krupnik, I. Allison, R. Bell, P. Cutler, D. Hik, J. López-Martínez, V. Rachold, E. Sarukhanian & C. Summerhayes, 391-396. Rovaniemi, Finland: University of the Arctic.

Dilling, L. & M. C. Lemos (2011) Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. Global Environmental Change, 21**,** 680-689.

Executive Office of the President - National Science and Technology Council (NSTC). (2013) Arctic Research Plan: FY 2013–2017. Washington, D.C. http://www.whitehouse.gov/sites/default/files/microsites/ostp/2013_arctic_research_plan.pdf

Hansen, J. & L. Nazarenko (2004) Soot climate forcing via snow and ice albedos. Proceedings of the National Academy of Sciences of the United States of America, 101**,** 423-8.

Kay, Jennifer, Gijs de Boer, Elizabeth Hunke (2012) On the observational needs for climate models in polar regions. http://www.cesm.ucar.edu/working_groups/Polar/PCWG_workingdoc_obs4models_July22012.docx.pdf

Murray, M. S., et al. (2012), Responding to Arctic Environmental Change:Translating Our Growing Understanding into a Research Agenda for Action, Stockholm/Fairbanks.

Phillipson, J., Philip Lowe, Amy Proctor, Eric Ruto (2012), Stakeholder engagement and knowledge exchange in environmental research, Journal of Environmental Management, volume 95, pp. 56-65.

Reuder, J.**,** and M. Jonassen (2012) First results of turbulence measurements in a wind park with the Small Unmanned Meteorological Observer SUMO.Energy Procedia, 24, 176-185.

Quinn, P. K., T. S. Bates, E. Baum, N. Boulderday, A. M. Fiore, M. Flanner, A. Fidlind, T. J. Carrett, D. Koch, S. Menon, D. Schindell, A. Stohl & S. G. Warren (2008) Short-lived pollutants in the Arctic: their climate impact and possible mitigation strategies. Atmospheric Chemistry and Physics, 8**,** 1723-1735.

Serreze, M. C. & R. G. Barry (2011) Processes and impacts of Arctic amplification: A research synthesis. Global and Planetary Change, 77**,** 85-96.

Starkweather, Sandra, Taneil Uttal, Kim Derry, Mark Serreze, John Ogren (2012) Developing Useable Black Carbon Information – Case Studies from the IASOA Network. Global Monitoring Annual Conference 2012. Boulder, Colorado May 15th - 17th.

Summit Science Coordination Office (SCO). (2010). Summit, Greenland Observatory - An Arctic Observatory Serving Scientific Research into the 21st century. In http://www.esrl.noaa.gov/gmd/obop/sum/Summit%20Science%20Outlook%20%28White%20Paper%29%20rev%20Mar2010_jhb-2.pdf.

Uttal, Taneil, Alexander Makshtas, Tuomas Laurila. (2013). The Tiksi International Hydrometeorological Observatory – An Arctic Members Partnership. Bulletin of the WMO, vol 62.

Welp, M., A. de la Vega-Leinert, S. Stoll-Kleemann, and C. C. Jaeger (2006), Science-based stakeholder dialogues: Theories and tools, *Global Environmental Change*, *16*(2), 170-181.