Contributions of animal-borne sensors to understanding broad-scale oceanographic-biological linkages

Olivia Lee

University of Alaska Fairbanks, 930 Koyukuk Dr, PO Box 757320, Fairbanks, AK 99775-7320. Email: oalee@alaska.edu.

Biologically relevant environmental observations

The wide-ranging animal migrations of many Arctic species make them ideal observing platforms for sampling environmental variables using globally-accepted standards for oceanographic data. Marine mammals in particular have contributed a significant number of oceanographic observations in the Antarctic (Figure 1) often providing observations in regions that would otherwise prove challenging for deploying observing instruments. Oceanographic sampling using marine mammals in the Arctic is significantly less common by comparison, with most contributions obtained using hooded seals (Fedak 2013). However the contributions from instrumented pinnipeds in the Arctic are expected to increase after the implementation of the MARES project begins collecting oceanographic data with instrumented bearded seals.

In addition to providing internationally-accepted standard oceanographic observations, animal-borne sensors (ABS) also provide information on biologically relevant oceanographic conditions. Unlike buoys that passively track currents, instrumented animals can sample water masses along preferred migratory routes and foraging locations. The use of ABS to monitor environmental variables and animal behavior provides an important link to understand how changes in the physical environment (that can also be monitored over broad scales using remote sensing technology) affects the biological components of Arctic ecosystems that is often harder to track. An improved understanding of the physical-biological linkages in polar waters is needed to explore more quantitative proxies for monitoring species change in the Arctic using remote sensing technology (Skidmore et al. 2015). In addition it provides an opportunity to test how migratory species affect the environment through transfer of energy or nutrients, thus acting as a biological conduit linking Arctic with non-Arctic ecosystems.

Challenges for sustainable observations

Coordination and data assimilation from disparate oceanographic sensors: Integration of oceanographic measurements from ABS to Arctic oceanographic observing programs can be particularly challenging if ABS oceanographic measurements are designed to maintain a tight coupling between environmental measurements and animal dive behavior, or habitat use. As an example of data integration challenges, international ocean observing systems, such as the International Arctic Buoy Program (IABP), often have established standards for collection of data. There may also be provisions for including additional data that are not required across the network of buoys. In contrast, ABS may only collect a sub-set of the required IABP measurements, and animal swimming behavior may violate data user needs to track sea ice and water masses that are typically recorded from drifting buoys. In the case of IABP there also are requirements for real-time data transmission and archiving. Programmed ABS sampling and data transmission rates based on animal dive depth thresholds or tradeoffs to improve battery longevity may make the format of ABS datasets unique and more challenging to incorporate into existing data processing frameworks that are used to serve real-time data.

Despite the challenges in integrating data across different sensor types, there are opportunities to improve coordination and build on existing data standards established for some ABS collected measurements. The level of precision and units of measurement could be informed by existing standards from global observing networks. Additional pre-processing and subsampling of ABS data may also provide more uniform observations that are not as heavily influenced by animal behavior. Establishment of data collection or processing standards to improve data interoperability will require commitment from a coordinating body that can represent the disciplinary interests of biologists and oceanographers.

The Integrated Ocean Observing System (IOOS) in the United States has established an Animal Telemetry Task Team to handle the unique ocean sampling regime of satellite tagged animals, and may provide a useful starting point for determining standards for oceanographic measurements from tagged animals (Moustahfid et al., 2014). The U.S. Arctic Marine Biodiversity Network (AMBON) may also be helpful partners in developing standards for ABS measurements in the Arctic that could account for the effects from different forms of sea ice that may be actively avoided or pursued by animals that are collecting oceanographic data. From a pan-Arctic perspective, the Marine Expert Network of the Circumpolar Biodiversity Monitoring Program (CBMP) may have the resources and coordination infrastructure in place to best lead an international effort to bridge the disciplinary divide that prevents active sharing of environmental data from ABS with the broader Arctic observing community. Establishing cooperative partnerships with existing funded entities with similar goals for integrating ABS data into ocean models should be a priority and would ensure that efforts are not duplicated.

Technological barriers: Long-term observations using animal-borne sensors will continue to prove challenging given the limitations in sensor technology, battery life, and attachment methods. Currently deployments are biased towards larger marine mammals capable of carrying satellite-linked instruments with minimal interference on behavior. Short battery-life limits the duration of data collection, and the annual molt of pinnipeds affects the duration that animals can carry instruments attached to fur. The high cost and effort involved in deploying instruments also limits sample size and may contribute to the difficulty in achieving sustainable funding for long-term ABS studies.

Supporting sustainable observations

In addition to technological advances that may improve the affordability and duration of observations from animal-borne sensors, a few implementation strategies are suggested for improving the sustainability of observations from animal-borne sensors:

1) *Coordination on data standards to maximize data interoperability:* Inclusion of ABS data on overlapping oceanographic variables should meet established data standards where applicable to improve data interoperability with the broader Arctic observing community. Such efforts to establish data standards should involve an international community of biologists and oceanographers. These efforts may build from some initial coordination support from the Marine Expert Network of the Circumpolar Biodiversity Monitoring Program, or national efforts that have complementary goals for integrating ABS data into ocean models or observing networks designed to detect environmental change.
2) *Rapid data access*: Oceanographic data with little or no embargo period are often most useful to the broader community, but animal tracking data are infrequently openly shared beyond derived mapped products. Commitment to providing a short QA/QC period prior to releasing oceanographic data through commonly-used ocean data access sites (e.g. sites where similar GEOSS observing data can be accessed) would increase the use and demand for ABS data. Currently support from national data archives (e.g., U.S. National Oceanographic Data Center,

ACADIS) provide a very flexible format for quality control and data archiving that do not always meet the need for rapid data access. Data sharing agreements and protocols for automation in the processing and serving of standardized data may need to be developed, and could begin by exploring ways to integrate data with existing operational Arctic observing networks (e.g., IABP) that have developed tools for data processing and rapid data access.

3) *Coordination with the modeling community*: Contributions from ABS towards validation of modeled oceanographic output may provide significant benefits. ABS data may help modelers gain additional insight into how species and ecosystems respond to environmental changes in the ocean. Such efforts would require conscientious coordination between modelers and biologists in order to develop, test, and validate hypotheses of physical-biological linkages in the Arctic.

Establishment of strong partnerships between the ocean-observing, and marine mammal research communities as well as a commitment to open data access are essential for promoting sustainable observations using ABS. However, the full value of using ABS on migratory species to improve understanding of oceanographic-biological linkages over broad scales has not yet been fully investigated in the Arctic.

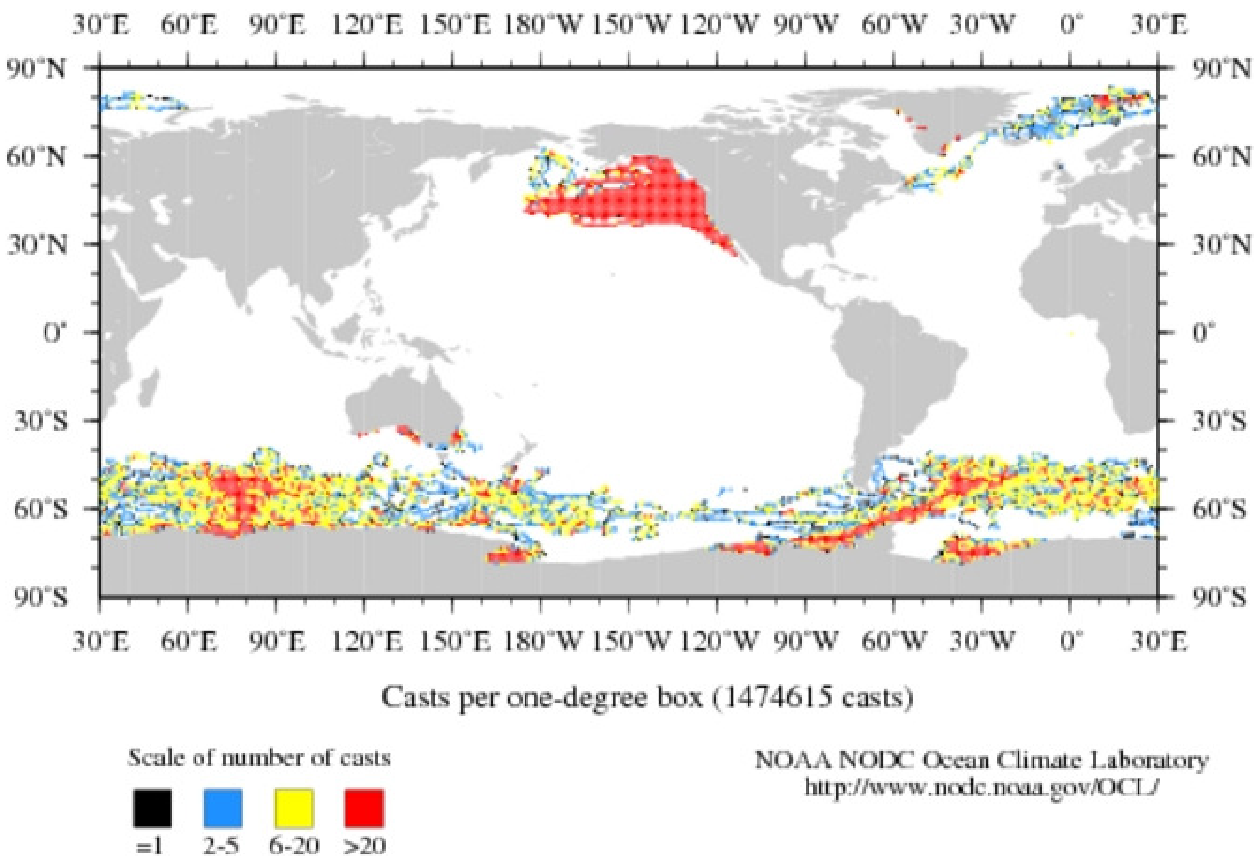

Figure 1. Distribution of CTD casts from animal-borne sensors. Source: National Oceanographic Data Center.

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Arctic observation initiatives of Korea Polar Research Institute for monitoring and understanding Arctic climate change

Seong-Joong Kim, Yoo Kyung Lee, Kyoung-Ho Cho, Joo-Hong Kim, Jinyoung Jung, Sung-Ho Kang, Baek-Min Kim, Mincheol Kim, So-Young Kim, Hyoung Sul La, Jisoo Park, Ki-Tae Park, Sang-Jong Park, and Eunjin Yang

Korea Polar Research Institute

Abstract

The Arctic is responding quite sensitively to the increase in atmosphere greenhouse gases. In particular, the Arctic sea ice is decreasing substantially and the permafrost is changing rapidly as well, influencing the local Arctic climate and resulting in a severe weather in mid-latitudes. Korea Polar Research Institute (KOPRI) has the Arctic research station (Dasan) at Ny Alesund and the icebreaker Araon launched in 2009. Utilizing these infrastructures, KOPRI has given a big effort in understanding the Arctic climate change mechanism through various monitoring and numerical simulations. We performed atmosphere environment monitoring at Ny Alesund and several Araon expeditions towards the Pacific sector of the Arctic. Through these activities, KOPRI was able to obtain past climate records and to understand ocean biogeochecmical cycles. Understanding the Arctic-midlatitude teleconnection is critical in predicting a severe weather in mid-latitudes. To deepen our understanding of the teleconnection mechanism, KOPRI plan to undertake the observation for the cloud over the Arctic.

1. Introduction

The Arctic environment is well known to be particularly sensitive to perturbations of the radiative budget. During the last century the temperature increase in the Arctic has been observed to be two times larger than the global average (IPCC, 2013). Climate feedback is important in the understanding of global warming because feedback processes may amplify or diminish the effect of each climate forcing, and so play an important part in determining the future climate status. Dimethyl sulfide (DMS) is a climatically important sulfur compound produced from oceanic biological activities. DMS in the atmosphere gives rise to the formation of aerosol which can act as cloud condensation nuclei (CCN), and has important consequences on the radiative budget of the earth. Therefore, increase in oceanic DMS emission into the atmosphere could diminish the effect of global warming. However, there remain crucial uncertainties in the pathway of atmospheric DMS and its contribution to aerosol-CCN population. Arctic Ocean is the hotspot for the emission of DMS due to its distinct biological properties and thus it is important to identify changes of DMS emission and key processes that influence DMS-aerosol-cloud formation in the Arctic environment.

The region including the Chukchi Borderland, northeastern East Siberian Sea, and Mendeleev Ridge is the hotspot for detecting sea ice retreat, hydrographic and biochemical responses to Arctic climate change. This region is characterized by the local complexity in topography and intersection of Pacific-origin waters from the south and Atlantic waters from the west. The Pacific water inflow through the Bering Strait is a key conveyor for heat, salt, nutrients, and biological material to the upper layer of the Pacific Arctic region. Recently, rapid decline of sea ice extent has been observed and its monthly average rate in September is -13.3% decade^{-1} compared to the 1981–2010 average (Perovich et al., 2015). The August sea surface temperature (SST) anomaly in the Chukchi Sea increases at a rate of about 0.5°C decade^{-1} compared to the 1982–2010 average (Timmermans and Proshutinsky, 2015). These can influence on the ocean environment change, such as circulation pattern, water mass, halocline formation, nutrients, primary production, and zooplankton ecosystem. The greatest increases in primary production during 1998‒2010 occurred in the East Siberian Sea (+112.7%), Laptev Sea (+54.6%), and Chukchi Sea (+57.2%) (Petrenko et al., 2013). Recent studies emphasize the importance of nutrient availability as a critical driver for primary production in Arctic Ocean environment. Increases in nutrient drawdown coincided with a deepening of the nitracline during 2003‒2011 in the southern Beaufort Sea (Bergeron and Tremblay, 2014; Frey et al., 2014). In recent years, 30‒50% of nutrients and approximately 40% of integrated chlorophyll-*a* concentration decreases have been observed in the northern Chukchi Sea (Lee et al., 2015). In addition, Arctic climate change leads to increase dissolved organic carbon (DOC) export to the Arctic Ocean due to increased river runoff and the thawing of permafrost. The transport and fate of DOC in the Arctic therefore is a potentially important carbon system component that could have a significant impact on the global carbon cycling. Besides, Arctic climate change has profoundly affected marine ecosystem, from plankton to predators. Understanding the mechanisms by which climate variability impacts mid-trophic level is critical for determining the Arctic marine ecosystem's response to climate change. In order to identify how rapidly ocean environmental parameters alter in response to Arctic climate change, it requires comprehensive *in-situ* field measurements of ocean and sea ice variables in high-resolution spatial and temporal scales.

2. Observation activities

(1) Arctic Aerosol Studies in Ny-Ålesund

Objectives:

The overall main research objective of KOPRI aerosol research team is to address the question: **will future changes of the Arctic climate induce positive or negative feedbacks with respect to DMS-aerosol-cloud interactions?** To improve knowledge gaps regarding these issues, KOPRI aerosol research team has been carrying out the analysis of physicochemical property of Arctic aerosol in collaboration with Pohang University of Science and Technology (POSTECH), Stockholm University, Norwegian Polar Research Institute (NPI) and Norwegian Institute for Air research (NILU):

Research Activities in Ny-Ålesund

The Zeppelin observatory is located in the Arctic on Zeppelin Mountain on the island archipelago of Svalbard (79^{o}N, 12^{o}E). The observatory is located in an undisturbed Arctic environment, away from major pollution sources. The unique location of the observatory makes it an ideal platform for the monitoring of global atmospheric change. Korea aerosol research team has been carrying out the aerosol research program since 2007. Currently, we are observing numerous aerosol parameters (e.g., CCN, DMS, number of nano-size particles, and size distribution of aerosol particles) at an observation site.

Figure 1. (a) CCN counter, (b) DMS analyzer installed in Zeppelin observatory, (c) high volume sampler installed on the roof of Gruvebadet laboratory

(2) 2015 6th RV ARAON Arctic Expedition (ARA06C) into Eastern-Siberian and Chukchi continental margin

Objectives

The 6th Arctic expedition of RV ARAON (ARA06C) started on August 25, 2015 in Barrow, Alaska and returned to Nome on September 09, 2015. The overall objective of the marine geology program during the ARA06C was to obtain records of undisturbed long glaciomarine sediments with JPC system to constrain, and thus better understand the timing and chronology of marine glaciations along the East-Siberian and Chukchi continental margins. The selection of sampling sites was based on hydroacoustic and sediment-core data obtained during previous RV ARAON cruises, ARA02 to ARA04 (2011 to 2013) as well as RV Polarstern cruise PS72 in 2008.

Methods and approaches

A total of 10 geological stations were chosen for the ARA06C cruise based on previously collected data for geophysical records, providing age control, and investigating paleoceanographic environments. The sub-bottom profiler (SBP) survey was carried out for detailing the position of coring sites. Cores were collected in water depths between 100 and 2,250 m using several coring devises (e.g. Box corer, multiple corer, gravity corer and jumbo piston corer). Once retrieved on deck, gravity cores and JPC cores were cut up in lengths of 1.5 m and labeled, transported to the laboratory for the MSCL logging.

Expected outcomes

The data collected will provide new insights into glacial history and sediment stratigraphy of the Chukchi-East Siberian region of the Arctic Ocean. A combination of MB bathymetry and SBP records, collected on this and earlier cruises, is expected to allow identification of glacial deposits and glacigenic seafloor features as well as depocenters of undisturbed marine/glacimarine sediments. Sediment cores taken from carefully selected locations will help ground-truth geophysical records and to add the age control and information on sedimentary environments.

Figure 2. About 14 m long glaciomarine sediment cores were taken with JPC system installed on RV Araon during 2015 Arctic Expedition.

(3) Strategic ocean observations in a rapidly changing environment in the Pacific Arctic region

Objectives

Our observation aims to improve our understanding of following specific issues:

Despite long-term decline of sea ice extent, its interannual variation has been observed. Then how much this variation is related with the release of substantial heat within the Pacific-origin water layer? What is the long-term trend of vertical distributions and lateral/temporal variations of heat and freshwater contents over the Chukchi Borderland?

The western Arctic Ocean is currently experiencing rapid environmental change due to natural and anthropogenic factors that include accelerated warming and decrease in sea ice cover extent. They may have a major impact on ecosystem functioning and biogeochemical cycling of the western Arctic Ocean. The second aim of this study is to characterize the biogeochemical consequences and ecosystem alterations directly related to loss of sea ice in rapidly warming the Chuckchi Sea.

Proposed strategy for observations

Study area

Since 2010, KOPRI has carried out ship-based campaigns aboard Korean ice-breaking research vessel ARAON during the summertime period of July to September. The ARAON has repeatedly visited the northern sites of the Pacific Arctic region including the Chukchi Borderland, the East Siberian Sea, and the Mendeleev Ridge. Thus KOPRI's oceanic observations will be continued to accumulate long-term data acquired in this region.

Parameters to be measured and observation methodology

The observation variables will be classified into hydrographic, biochemical, and meteorological categories and observation methodology will be proposed as integrated observation systems which consist of vessel-based, mooring-based, and ice-based observations as described below:

1) Vessel-based observation: Ship-borne oceanographic equipment allows us to measure various parameters: water temperature (T), salinity (S), pressure, ocean current, dissolved oxygen (DO), nutrients, dissolved and particulate organic matters, primary productivity, phytoplankton and zooplankton biomass with usage of the carousel water sampler equipped with a conductivity-temperature-depth (CTD) profiler, lowered acoustic Doppler current profiler (LADCP) and other sensors, acoustic instruments (i.e., EK60), plankton net samplers (i.e., Bongo Net), and expendable instruments (expendable CTD, expendable current profiler).

2) Mooring-based observation: Ocean mooring system sustains long-term observation on the properties of water column and sea ice, which include T, S, ocean current, ice bottom tracking motion, ice thickness, phytoplankton/zooplankton biomass with usage of ADCP, T-logger, MicroCAT CTP recorder, acoustic zooplankton fish profiler (AZFP), Ice Profiling Sonar (IPS), sediment trap, and PAR/fluorometer. The long-term mooring system is essential to monitor the fate of Pacific- and Atlantic-origin waters in terms of heat and mass balance in the upper ocean because sea ice retreat is partially influenced by warm water inflow from the Pacific and Atlantic Oceans.

3) Ice-based observation: Sea ice camps will provide us with various opportunities to carry out melt

pond studies, under-ice observations, and sea ice dynamics from the ice-tethered buoy deployment. A melt pond is the most distinctive feature of Arctic sea ice during July-September because it is formed by snow/ice meltdown driven by solar radiation on the sea ice surface. In the melt pond studies, we can understand potential physical, chemical, and biological processes in the different types of melt ponds. Those processes will involve physical evolution of the melt ponds, food-web interactions under environmental change, plankton's composition, diversity and physiology, and distinctive distribution of nutrients. Under-ice mooring systems can offer continuous record of temperature, salinity, ocean current, heat and freshwater fluxes in the surface mixed layer, vertical distribution of zooplankton, and under-ice primary production of phytoplankton and sea-ice algae. KOPRI has been collaborating with international research partners in deploying in-floe buoys during the sea ice camps. The buoys will be Ice-Tethered Profiler (ITP), wave buoy, autonomous ocean flux buoy (AOFB), Ice Mass Balance Buoy (IMB), high-precision GPS buoy (SATICE), upper layer temperature of the Polar Oceans (UpTempO) buoy, and Ice-Atmosphere-Arctic Ocean Observation System (IAOOS).

International collaborations

With KOPRI's major infrastructural supports we plan to collaborate with national and international research groups and institutions. The Pacific Arctic Group (PAG, pag.arcticportal.org) is proposing the Pacific Arctic Climate Ecosystem Observatory (PACEO) across the oceanic Beaufort Gyre to understand the shelf-basin exchange and the regional ocean-sea ice interaction over the Chukchi Borderland. The key collaborative partners will be Inha University, Incheon National University (INU), Tokyo University of Marine Science and Technology (TUMSAT), Ocean University of China (OUC), UK Scottish Association for Marine Science (SAMS), British Antarctic Surveys (BAS), Applied Physics Laboratory/University of Washington (APL/UW), UPMC (LOCEAN-LATMOS), ICM-CSIC/MIT, CRREL, and ONR-MIZ team.

(4) Climate manipulation experiment in the Arctic tundra

Objectives:

The Arctic ecosystem is undergoing dramatic changes due to climate change. Since 2012, through long-term monitoring of the Canadian Arctic tundra, changes in ecosystem structure and function have been examined. The study aims to observe the effects of climate warming and increased precipitation on the structure and functioning of plant and soil microbes.

Methods and approaches:

The study site is Cambridge Bay (69°07′48″N and 105°03′36″W) which is located on the southeast coast of Victoria Island, Nunavut, Canada. Average temperature is 4.2°C and -23.8°C in summer and winter, respectively. Precipitation is low with an average precipitation of 140 mm annually. This area is classified as prostrate dwarf-shrub, herb tundra (CAVM Team, 2003) with vegetation dominated by small prostrate shrubs (*Dryas* spp.) and sedges (*Carex* spp.). The climate manipulation experiment was conducted with summer warming and increased precipitation both separately and combined. Hexagonal 2 m-diameter open-top chambers (OTCs) were established to increase air temperature of 1-2°C and 2 L of water was added to sites every week to manipulate the increased precipitation of additional 4 mm per year. The manipulation experiment was conducted during summer season from late June to early October each year. Changes in plant and soil microbial community structure as well as soil ecosystem functioning such as microbial biomass, soil respiration and extracellular enzyme activity were monitored on a biennial basis.

(5) Atmosphere observation to enhance weather and climate prediction capabilities

Backgrounds and Objectives

One of KOPRI's research themes aims at contributing to the enhancement of Arctic–mid-latitude weather and climate prediction capabilities. Among many other things regarded as the high potential to improve the model predictability in the middle-to-high latitudes, Arctic clouds and boundary-layer processes are thought to deserve attention as the kernel of our problem not only because they are always involved in the high-impact weather events but also because they are central to many climate feedbacks resulting in amplified warming in the Arctic (Curry et al. 1996).

The importance of the radiative effects of Arctic clouds led to several intensive field experiments with the main object of understanding them and improving model parameterizations: the First ISCCP Regional Experiment Arctic Clouds Experiment (FIRE-ACE: April–July 1998; Curry et al. 2000), the Surface Heat Budget of the Arctic Ocean (SHEBA: October 1997–October 1998; Uttal et al. 2002), the Mixed-Phase Arctic Cloud Experiment (M-PACE: 27 September through 22 October 2004, Verlinde et al. 2007), and the Arctic Summer Cloud Ocean Study (ASCOS: 2 August–9 September 2008; Tjernstrom et al. 2014). For all that, numerical model simulations in Arctic cloud properties still show a large inter-model spread (Tjernström et al. 2008; Karlsson and Svensson 2013), which means that the Arctic clouds and surrounding processes are one of the least understood components in numerical models. The primary reason is because the widely-used physical parameterizations have been founded on the field observations carried out mostly over the midlatitude and Tropics. As the scarcity of polar observations hinder any further enhancement of understanding and predictability, the scientists are still anxious for abundant observation data in the polar region.

Strategies

<u>Integration of observation and modeling</u>

For the sake of enhancing our knowledge about the Arctic clouds, surrounding processes and also related radiative balance at the surface, our new project will integrate observation and modeling with detailed contents as follows:

Observation. Establish infrastructure for observing Arctic cloud and surrounding processes based on Ny-Alesund (land) and IBRV *Araon* (ocean)
- Addition and stable operation of Ny-Alesund-based equipment for clouds, boundary-layer and radiative processes observations
- Stable operation of *Araon*-based equipment for near-surface meteorology, cloud observation, and regular radiosonde launch for observing atmospheric profile

Modeling, Develop the Arctic–mid-latitude regional weather and global climate prediction system
- Develop an improved cloud microphysics scheme, equipped with the uniquely developed source code for the process
- Construction of sea ice/ocean/land initialization tools for the climate prediction system
- Construction of analysis fields for regional weather prediction with the data assimilation system including available observations from KOPRI infrastructure as well as existing network

Proposed and potential international collaborations

Observation part. Any research activities in Svalbard should be endorsed by the Svalbard Integrated Earth Observing System (SIOS). As South Korea is already the regular member of the SIOS, the planned establishment of new equipment (e.g., eddy-covariance system, Doppler wind lidar, and micro-pulse lidar, cloud particle/aerosol observing equipment on tethered balloon sonde, AWS, radiation sensors, etc.) in Ny-Alesund may not be restricted by the SIOS member countries. Practical issues need to be secured are the selection of optimal site for the observations of clouds, boundary-layer and radiative processes and the stable operation by the international collaboration with the experienced institutes such as AWI (Germany), NPI (Norway), and ISAC (Italy). We discussed our optimal site with the AWI atmospheric research team and received the AWI's current status and revised plan of atmospheric observation network including their proposal for the planned KOPRI's equipment (Figure 3). Since AWI has the most extensive atmospheric observation network in Ny-Alesund, the coordinated selection of our optimal site with AWI would create new synergistic effects

Figure 3. (Left) Overview of measurement AWI sites in Ny-Alesund. (Right) Proposed KOPRI optimal sites by the AWI atmospheric research team (Credit: Christoph Ritter, AWI)

KOPRI Icebreaker *Araon* regularly makes an Arctic expedition every boreal summer from late July through early September. Her voyage across the ice-free and ice-covered ocean enables us to carry out ocean-based observations of clouds and surrounding processes under a variety of surface conditions. ~~Although the full annual observation is not possible,~~ *Araon*-based oceanic observations of clouds and other atmospheric properties in late-summer and early-autumn are the good counterpart in the Pacific Arctic sector where the Ny-Alesund station cannot cover. *Araon*-based observation equipment will be enhanced by including the followings: the eddy-covariance system, cloud/aerosol lidar, all-sky camera, CCN counter, radiosonde, and surface-based meteorological and radiation sensors. Our enhancement of ship-based atmospheric observation mainly targets to prepare the 2017-2019 Year of Polar Prediction (YOPP; polarprediction.net) IOP activities in which KOPRI plans to participate and also contributes to the Pacific Arctic Climate Ecosystem Observatory (PACEO) proposed by the Pacific Arctic Group (PAG; pag.arcticportal.org).

Modeling part. Proposed development of the Arctic–mid-latitude regional weather and global climate prediction system would not be possible without national and international collaborations. KOPRI observed data and other data from the existing network (e.g., ARM Climate Research Facilities) will be applied to the scheme development. The improved scheme will be implemented in both weather and climate version of prediction system. For the regional weather prediction system, the Polar Weather Research and Forecasting (P-WRF) model developed by the Byrd Polar and Climate Research Center will be selected as a first step. The global climate prediction system is based on the NCAR Community Atmospheric Model (CAM) with a new convection scheme (Park 2015) and an improved microphysics scheme to be developed.

3. Conclusion

KOPRI's observing activities has been stronger recently in conjunction with the launch of ice breaker and expansion of pan-Arctic observation sites. With these infrastructures, the international cooperation has been more enhanced. The outcome of the Arctic observation helps understand the status of ongoing rapid Arctic climate change and predict the influence to mid-latitude weather, especially in winter. The continuing KOPRI's observing activities for the Arctic ocean and atmosphere will contribute to the Year of Polar Prediction (YOPP) themes by enhancing our existing activities more intensively during the YOPP period.

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Future development and challenges on Arctic Data archive System (ADS)

Hironori Yabuki[1,2] , Takeshi Sugimura[1], Takeshi Terui[1], Hiroyuki Enomoto[1]
1. National Institute of Polar Research(NIPR)
2. Japan Agency for Marine-Earth Science and Technology (JAMSTEC)
e-mail: yabuki.hironori@nipr.ac.jp

1. Introduction

The easy access use is made possible from the industrial and the social public using research results(thesis and research data, etc.) using a public research fund, and a concept as open science aiming at linking it to creation of innovation by opening the new way as well as promoting a scientific technical research effectively is showing a rapid expanse to creation of worldwide. And the principle opening to the research result and data by a public research fund by GRC (Global Research Council), OECD(Organization for Economic Cooperation and Development) and G8 in 2013 etc.

Under these background, even in Arctic research, open access of a variety of variation mechanism and scientific knowledge, such as future prediction result brought about by actual grasp their environment change has been demanded.

In order to clarify the environmental variation system of complex Arctic with a variation of the time-space scale that is different consisting of air- land- marine, and human sphere, through interdisciplinary research, through interdisciplinary research, a wide variety of observational data, simulation data, satellite data, and even there is a need for the creation of A New knowledge of using the big data that integrates the research results. Also those integrated with the big data, scientific knowledge by using these, it is necessary to continue to properly publish to society.

2. Development of Arctic Data archive System(ADS)

Arctic Data archive System(ADS: https//ads.nipr.ac.jp), through proceed with the visualization and the development of online analysis system of integrated big data, aiming for integrated analysis information platform, not only as a mutual distribution platform of data, we have developed a system that enables open access research data and scientific knowledge obtained in the Arctic research.

ADS has been doing the systems development of following up to now.

- Metadata Management System by own metadata schema.(KIWA: Fig.1)
  - Metadata exchange system by using OAI-PMH, GI-cat.
  - Currently, this service is carried out in cooperation with GCW in WMO. Also this service have done coordination with GEO-Portal.
  - A system for space-time search using GoogleEarth collected data
  - DOI (Digital Object Identifier) registration system
- Visualization and analyzed system for the satellite data and grid data by online(VISION: Fig1)
- System to Semi-real-time polar environ. obs. monitor and sea ice prediction in the Arctic, Antarctic by using the satellite data (AMSR2) that is delivered in near-real-time from JAXA.(VISHOP:Fig1)
- System for visualizing numerical data such as time-series data(VISION-Graph)
- System for distributing satellite data and the like to the research vessel, etc.(VENUS)

- This system has been carried out data delivery to icebreaker of Japan (Shirase), research observation vessels of Japan (Mirai, Umitaka-maru).

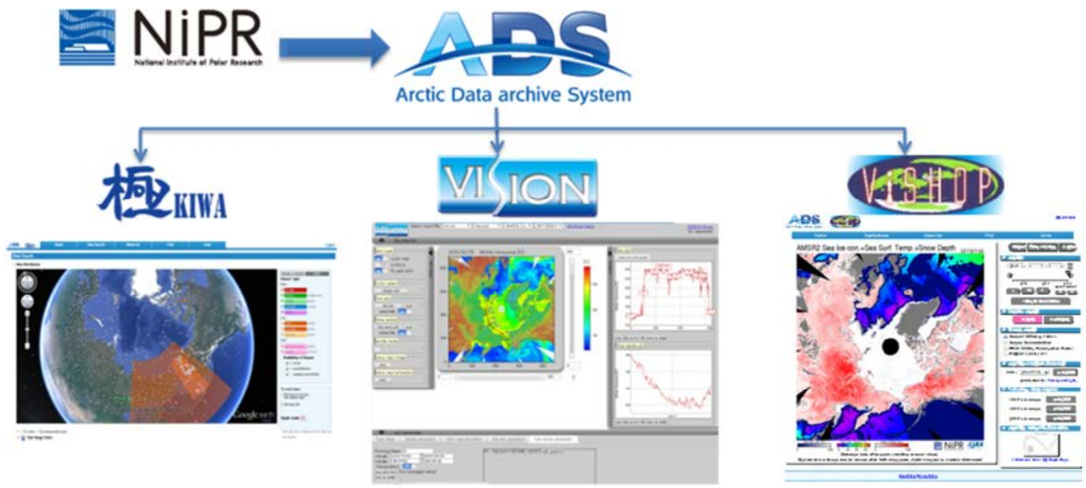

Fig.1 : Structure of ADS, Research data registration system and Metadata search service(KIWA), Online visualization application for Climate, Satellite and Simulation data(VISION) and Semi-real-time polar environ. obs. Monitor and Sea Ice prediction(VISHOP)

3. Future development and challenges

ADS is not only a system that provides the data to various data users and stakeholders, in order to promote joint research and international cooperation in the Arctic region, anyone that is aimed at developing integrated analysis platform through the available Web interface. Furthermore in ADS, to developing of the information providing service of push-type in accordance with the needs of stakeholders.

By widely publish the technology developed in ADS, to promote the technology transfer system construction, to help the same technical problem solved in other areas. In ADS future, to carry out research and development the following items.

- Advancement of data and meta-data registration and retrieval system
  Promotion of data registration and data usage
- Enhanced of international cooperation of data and metadata
- Advancement of visualization, basic data analysis and the like of software and Web applications in order to provide an integrated analysis platform
- System construction of the push-type information service
- Advancement of small and medium-sized data server linkage function by ADS grid
- System Technology publishing, which is research and development in the ADS and technology transfer promotion to other systems.

4. Conclusion

The share of research data and scientific knowledge in the Arctic and non-Arctic nations, there are need for coordination of data repository and data center in a various country.

Important to drive the open-science, it is important data published and data cited, it is necessary to promote these data published and data cited. We, through the development of ADS activity, believe that can contribute to the sharing of research data and scientific knowledge in the Arctic and non-Arctic nations.

Arctic Dust Observation Network

Bullard, J.E., Darlington, E.F.
Department of Geography, Loughborough University, Leicestershire, LE11 3TU UK.
J.E.Bullard@lboro.ac.uk

Introduction

Dust forms an important component of the earth-atmosphere system, yet is mainly associated with subtropical deserts. In contemporary climate conditions, dust is produced by a number of geophysical processes taking place in the high latitudes, including glacial and periglacial processes (Bullard, 2013). Arctic dust storms are frequent in Alaska (e.g. Crusius et al., 2011), Canada (e.g. Lewkowicz, 1998), Greenland (Bullard and Austin, 2011) and Iceland (e.g. Arnalds, 2010). Dust emissions from these events affect terrestrial, marine and atmospheric systems. Glacier albedo is decreasing owing to dust deposition, forging a positive feedback and enhancing glacier melt (Dumont et al., 2014). Transport of dust to the ocean provides a source of iron to the high latitude oceans (Prospero et al., 2012), which can potentially boost primary productivity and enhance CO_2 drawdown (Achterberg et al., 2013). Dust emissions can also lead to exceedences in air quality standards and health impacts in populated areas such as south central Alaska and south west Iceland (Department of Environmental Conservation, 2012; Thorsteinsson et al., 2011). Yet despite affecting both the environment and societies, the timing, frequency and magnitude of high latitude dust storm events remain poorly understood. Source areas for dust production may be on the rise, owing to the fast retreat of glaciers that are a producer of this sediment, leading to enhanced dust emissions. Or, surfaces could become armoured by the glacial sediment, decreasing future emissions. To address these unknowns, a coordinated monitoring effort is required in the high latitudes to improve understanding surrounding dust generation and emissions, and how these may change as cold climate environments start to warm.

Current effort & associated problems

At present, there is spatio-temporal scarcity of ground-based measurements to determine the magnitude of dust emissions as highlighted by an ongoing survey by the High Latitude and Cold Climate Dust Network (www.hlccd.org). There have been a handful of ground-based measurements in the Arctic, which use a variety of instruments to determine the volume of dust. These have been geographically sparse, and actively monitoring for only short time periods. Satellite images overcome spatial constraints, revealing the distances that dust storms travel (>500 km). However, cloud cover restricts the availability of suitable images, providing sporadic temporal coverage and is a particular limitation during spring and autumn which are the main dust storm seasons. An intense field campaign in Iceland during summer 2015 (Mockford et al., 2015) highlighted that ground-based measurements, spanning eight weeks, can reveal the timing, frequency and magnitude of storms. In addition, particle measurements indicate the source location of the dust. These measurements can be used to providing a better understanding of the characteristics of dust being removed from source areas and entering the ocean or being deposited in terrestrial systems to affect soil formation and lake biogeochemistry. Such a study provides a basis to expand dust monitoring, and has readily highlighted that existing monitoring programmes are not adequate to properly resolve dust emissions in the Arctic.

Proposed solution

Dust monitoring is established in the tropics, where hot arid deserts are known active dust sources. Focus on the high latitudes and cold environments has only recently gained momentum, owing to the key linkages with the climate system and human health. Forming an integrated dust observation network across the Arctic together with existing automatic weather station infrastructure would provide valuable data to assist in quantifying dust storm events. Recent technological advances have led to automated instrumentation to quantify dust and the ability to download data from remote areas via satellite, which are helping to overcome previous temporal sampling and access issues. By selecting strategic locations based upon dust source characteristics, an in depth knowledge of dust activity in the Arctic would be obtained. Collaboration with an automatic weather station network would provide complimentary data, enabling the climate thresholds (wind, temperature, precipitation and humidity) for active dust transport to be established. The proposed dust monitoring network would use the same instrumentation at each location, ensuring data consistency. In addition, a community dust monitoring and reporting network would be valuable in known dust source areas, to enhance data capture and overcome logistical issues with instrumentation and satellite data. Such programmes have been effective in Australia, which has similar data scarcity issues (DustWatch, 2015; Leys et al., 2008). Forming such a synergy would allow for better predictions of future dust emissions, which is an important part of the global climate system.

Benefits of the Dust network

Monitoring dust emissions and associated air quality in the Arctic is challenging due to the size of the area of interest and the relatively small and dispersed population. A single pan-Arctic network of specified instruments collecting data using an agreed set of protocols will allow comparison of observations across the region. Data from such a network will be invaluable to stakeholders with interests at a variety of scales. It will enable users to determine the magnitude, frequency and impact of local dust events for understanding their contribution to air quality, local soil nutrient redistribution and hazards such as reduced visibility. This will be of particular value to those concerned with public health, transportation networks and land management. At a regional to global scale, quantification of the spatial and temporal variations in the relative importance of natural dust events across the Arctic region will be invaluable to scientists including marine biologists, biogeochemists, atmospheric scientists and sedimentologists. A better understanding of dust emissions and dust redistribution from the Arctic would also contribute to improved global climate modelling and forecasting.

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Comparative long-term forest ecosystem study in circumpolar region.

Yojiro Matsuura[1], Akira Osawa[2], Takuya Kajimoto[1], Tomoaki Morishita[3], Kyotaro Noguchi[1], Kenji Ono[4], Jumpei Toriyama[5], Kazumichi Fujii[1], Naoki Makita[6]

[1]Forestry and Forest Products Research Institute (FFPRI) Japan, Tsukuba 305-8687
[2]Kyoto University, Graduate School, Kyoto 606-8502
[3]FFPRI, Shikoku Research Center, Kouchi 780-8077
[4]FFPRI, Tohoku Research Center, Morioka 020-0123
[5]FFPRI, Kyushu Research Center, Kumamoto 860-0862
[6]FFPRI, Kansai Research Center, Kyoto 612-0855

Contact person: Y. Matsurua, email to: orijoy@ffpri.affrc.go.jp

Our forest ecosystem research was conducted in the circumpolar region, including Eastern and Central Siberia, Interior Alaska, Northwest Territories, Canada, and Finland-Estonia region. The research area includes four types of permafrost conditions, i.e. continuous, discontinuous, sporadic permafrost, and permafrost-free soils. The dominant conifers among surveyed sites are region-specific. Evergreen conifers are dominant species, except in Eastern and Central Siberia. The deciduous conifer larch (genus *Larix*), is the only dominant in areas with continuous permafrost.

The permafrost larch forest ecosystem shows unique features in terms of forest biomass allocation and root system development (Osawa et al. 2010). Our long-term forest census and stand reconstruction results using tree ring analysis among several sites show specific growth patterns among sites. A root biomass and fine root dynamics study was also conducted in Siberia, Interior Alaska, NWT Canada, and Finland-Estonia sites. The ratio between above-ground and below-ground forest stand biomass was nearly 1 to 1 in the continuous permafrost region of Siberia (Matsuura et al. 2005, Kajimoto et al. 2006).

The moss-lichen complex organic layer that develops on the sparse coniferous forest floor plays a significant role in determining the depth of permafrost thaw (20 to 890 cm) during the growing season and patterns of biomass accumulation (Noguchi et al. 2012). Upland black spruce stands that develop on north-facing slopes with discontinuous permafrost following forest fires exhibit a critical relationship between permafrost thaw depth and biomass accumulation. In regenerated black spruce stands of the same age cohort, greater depth of thaw during the growing season results in greater biomass accumulation. Similar positive patterns of permafrost thaw depth and biomass accumulation were observed in Siberia and Interior Alaska (Matsurua unpublished data).

The relationship between biomass accumulation and the environmental conditions that regulate belowground process may be one of the key ecological factors impacted under changing climate conditions in the future. Our research covers greenhouse gas (GHG) fluxes in permafrost forest soils (Morishita et al.2014). Soil organic carbon (SOC) storage regime varies among circumpolar forest ecosystems. The nature and origin of the soil parent materials greatly affects soil carbon storage. Although most of the circumpolar region was glaciated during the Pleistocene era, eastern and central Siberia, and central Interior Alaska were not glaciated. Such differences in geological history lead to a variety of SOC accumulation regimes in circumpolar forest soils. Soils in regions that were not glaciated during the Pleistocene, such as soils of the continuous permafrost region in Siberia, have much greater SOC accumulation, while soils that developed following glacier retreat have less

SOC (see Figure). Another factor which affects the SOC regime and soil characteristics is the process of soil genesis in cold climate regions. There is a large difference in the carbon-to-nitrogen (C/N) ratio values between soils originating from fluvial parent material and soils that developed from the in situ weathering of rock fragments (see Figure, Matsurua unpublished data).

Our field survey results demonstrate that circumpolar forest ecosystems are not uniform. Each region has a unique geological history and process of ecosystem development. We propose an international research platform to enhance long-term and comparative research under a changing climate.

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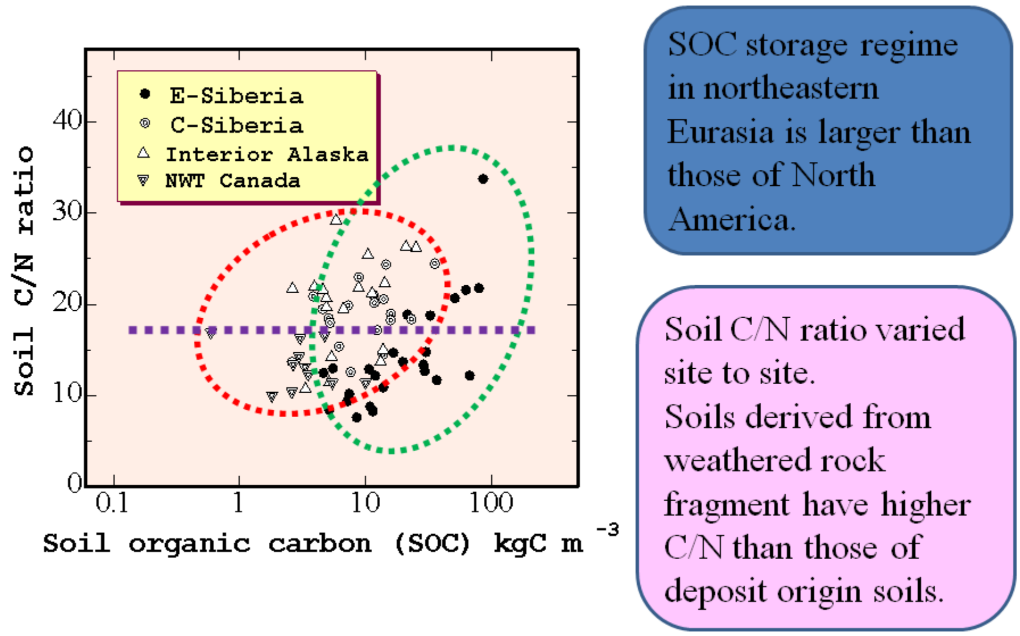

1) SOC storage regime in NE Eurasia was larger at one order of magnitude than that in North America. (Mann-Whitney U test, p=0.0000)
2) Soil C/N ratios in eastern Siberia were lower than those in central Siberia. (Mann-Whitney U test, p=0.0021)
3) Soil C/N ratios in NWT Canada were lower than those in Interior Alaska. (Mann-Whitney U test, p=0.0164)

Application of IASOA circumpolar observations in studies of atmospheric transports into and out of the Arctic for the Year of Polar Prediction

Timo Vihma[1], Taneil Uttal[2], Von Walden[3], Christopher Cox[4], Sandy Starkweather[4], Alexander Makshtas[5], Jeff Key[2]

[1]Finnish Meteorological Institute (email: timo.vihma@fmi.fi)
[2]National Oceanic and Atmospheric Administration
[3]Washington State University
[4]Cooperative Institute for Studies of the Environmental Sciences
[5]Arctic and Antarctic Research Institute

Executive Summary

The International Arctic Systems for Observing the Atmosphere (IASOA) is an International Polar Year legacy consortium that focuses on coordinating measurements of the Arctic atmosphere collected at ten observatories in the U.S., Canada, Russia, Norway, Finland, and Greenland. The IASOA data portal and collaboratory process support thematic expert groups that work towards common goals for utilizing interoperable data products across the observatories. In addition to detailed surface observations and upper-air radiosonde program, some of the IASOA observatories collect information on the vertical profiles of moisture, cloud boundaries, cloud water/ice contents, and aerosols using radars, lidars ceilometers and radiometers. Collectively the IASOA network provides a unique source of information that can be utilized in order to provide the best possible empirical estimates of the horizontal atmospheric transports of momentum, heat, moisture, cloud water, cloud ice, and aerosols into and out of the Arctic Ocean region. These can be used in turn to support the evaluation of atmospheric reanalyses, weather and climate models, and satellite remote sensing products, and subsequently studies on the interaction between the Arctic and lower latitudes including the role of mid- and low-latitude forcing on the Arctic amplification of climate warming and the effects of Arctic changes on mid-latitude weather and climate. In addition, the IASOA data are valuable for the evaluation of gridded products (reanalyses, models, and satellite data) with respect to Earth surface variables, such as snow depth, soil moisture, surface temperature, radiative fluxes, albedo, as well as turbulent fluxes of sensible heat, latent heat, CO_2, and CH_4. Evaluation of surface fluxes is a vital to complement the evaluation of horizontal transports. These together will yield a comprehensive assessment of the quality of available gridded products in representing atmospheric budgets of heat, moisture, greenhouse gases, and aerosols in the Arctic. The IASOA thematic study will be a unique approach as Arctic transport studies have so far been addressed without full utilization of direct observations; it is expected that this activity will directly support the objectives of global initiatives such as the WMO Year of Polar Prediction (YOPP).

1. Introduction

During recent decades, climate warming in the Arctic has been 2-4 times faster than the global mean. This phenomenon is called as the Arctic amplification. The air temperature increase has been both a reason for and a consequence of recent rapid changes in the Arctic sea ice and snow cover. Since the early 1980s, Arctic sea ice extent has decreased by roughly 50% in summer and autumn, and an equal relative decrease has been observed in winter sea ice thickness. In May and June, the rate of decrease in Northern Hemisphere terrestrial snow cover has been even faster. Arctic amplification is partly due to local processes in the Arctic, related to the surface albedo, clouds, water vapor, aerosols, the shape of the temperature profile, and the small heat capacity of the shallow atmospheric boundary layer (e.g., Vihma et al., 2014). In addition, heat transport in the ocean and heat and moisture transports in the atmosphere strongly contribute to Arctic amplification. The Arctic near-surface warming has been mostly driven by changes in local sea ice cover and sea surface temperatures (SST), but the majority of warming aloft is explained by SST changes at lower latitudes and related changes in the temperature of air-masses originating from the south (Screen et al., 2012). In addition, a few studies have suggested strong effects of the tropics on the Arctic (e.g., Ding et al., 2014). In addition to climate trends, weather events in the Arctic may be strongly affected by forcing from lower latitudes. During recent decades, extreme weather events have been common in the Arctic but, in general, little attention has been paid to the attribution of individual weather events in the Arctic.

Concurrent with Arctic amplification, changes have been observed in the occurrence, duration, and strength of extreme weather events at lower latitudes. High extremes in air temperature and precipitation have become increasingly common (Donat et al., 2013). Summer events have included heat waves and droughts in the USA and central/southern Europe and Russia, as well as rains and floods in central/northern Europe and East Asia. However, despite the average net global warming, the occurrence of cold winter months has increased in recent decades over land areas from 20° to 50°N (Cohen et al., 2014). Throughout mid-latitudes, recent weather extremes have often been associated with the persistence of particular circulation patterns (Hoskins and Woollings, 2015). An intriguing question is whether extreme weather events have been related to climate change in the Arctic (Vihma, 2014; Overland et al., 2015).

All the above calls for better quantitative understanding on the atmospheric transports of heat, momentum, potential energy, moisture, other greenhouse gases, clouds, and aerosols from lower latitudes to the Arctic and vice versa. As the possible Arctic effects on mid-latitudes may be regional, seasonal, and episodic (Overland et al., 2015), extensive, multi-decadal circumpolar observations are necessary to support meaningful analysis and particular attention is needed on the vertical profiles of the transports. For moisture transport it is not enough to estimate the latent heat transported to the Arctic but also the cloud formation and enhanced downward longwave radiation that the transport will produce in the Arctic. Seasonal aspects of the transports and the effects of the meridional structure of recent climate warming are particularly important. The decrease in the north-south temperature gradient within mid-latitudes has been strongest in summer (Coumou et al., 2015) but simultaneously a new frontal zone has appeared across the southern coasts of the Arctic Ocean, where in summer the continents have warmed much faster than the ocean (Crawford and Serreze, 2015). The effects of these changes on summer weather need to be investigated.

The prospects for better understanding and quantifying Arctic transports depend on optimized usage and further enhancement of atmospheric observations from the circumpolar Arctic land surfaces as well as the Arctic Ocean. Present observations available include basic variables (atmospheric pressure, air temperature, humidity as well as wind speed and direction) from standard weather stations but these only yield near-surface data. Vertical profiles of air temperature, moisture, and wind are available from about 40 circumpolar radiosonde sounding stations north of 65°N (e.g. Nygård et al., 2014), and more detailed observations are made at the ten observatories of the International Arctic Systems for Observing the Atmosphere (IASOA). When utilized together with near-surface, radiosonde, and satellite observations as well as atmospheric reanalyses, the IASOA observations have a potential to bring a significant added value for investigations of atmospheric transports in and out of the Arctic Ocean region by providing a picket fence of observations that are roughly distributed in the coastal regions that bound the Arctic Ocean.

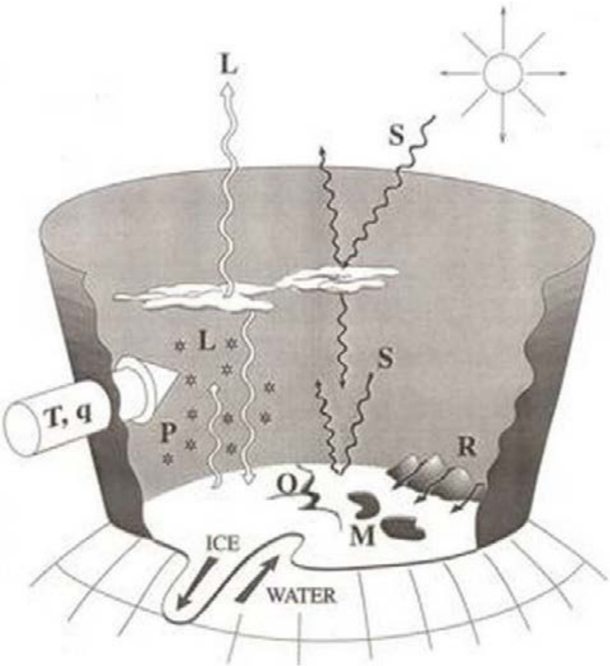

Figure 1. Schematic illustration of processes in the Arctic atmosphere. Figure by N. Untersteiner. First used in "SHEBA, a research program on the Surface Heat Budget of the Arctic Ocean", NSF Arctic System Science Report No. 3, August 1993.

R=Runoff (freshwater)
L=Longwave radiation
S=Shortwave radiation
O= Ocean heat
M = Melt (snow and ice)
P = Precipitation
T = Temperature (heat transfer)
q = moisture

2. The Circum-Arctic Atmospheric Observatories

Over the last decade the environmental agencies and research institutions involved with operating a number of atmospheric observatories that encircle the Arctic Ocean have voluntarily developed a consortium to promote comprehensive networked observing of the important components of the atmospheric system (Figure 2). To date the focus has been on developing cross-network inventories, filling observing gaps, providing data access, developing standardized observing practices and compiling climatologies of individual components of the atmospheric system. The IASOA consortium (Uttal et al., 2015) now enters its second decade with the intent to support a system science approach to global observing initiatives. In doing this the challenge will be to not only maintain and expand high-quality, long-term, observing programs, but also to develop products and protocols that will allow full usage and integration of the surface observational datasets. A critical component of this effort is maintenance of a data portal providing access to IASOA observations (http://www.esrl.noaa.gov/psd/iasoa/dataataglance).

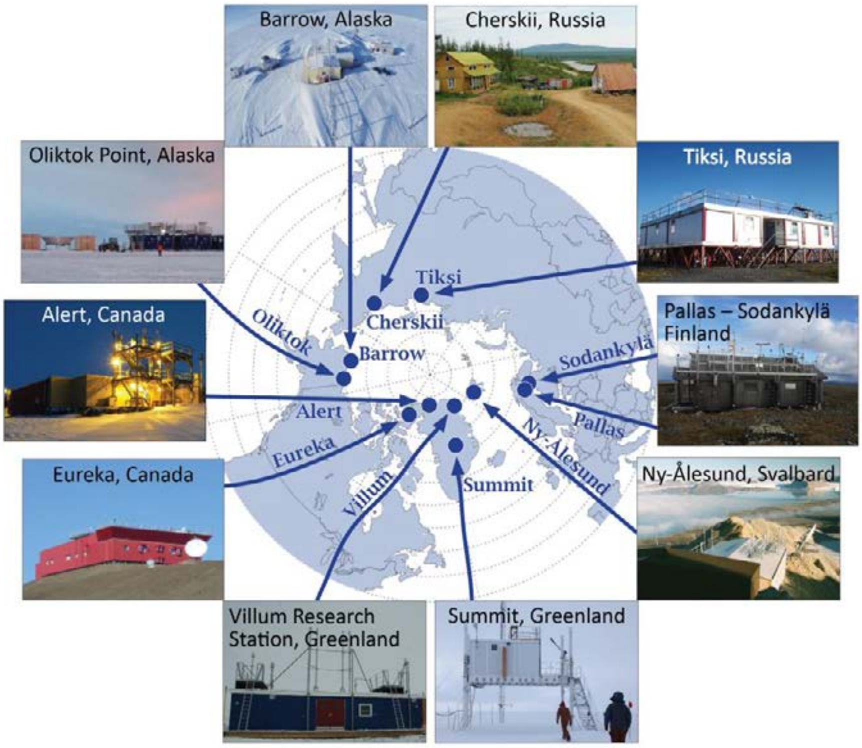

Figure 2: The member IASOA observatories as of November 2015. The red circle marks Cape Baranova, which is expected to soon become an official IASOA station.

The IASOA sites also provide valuable data for satellite validation. 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 feature 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). For a single satellite FOV (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.

From a satellite perspective, the ideal observatory would measure the atmosphere (temperature, humidity, and winds at many vertical levels, cloud properties, aerosols, 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, soil moisture). 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, sea and lake ice thickness, the depth of snow on ice, and surface radiation. Point measurements of atmospheric properties are generally sufficient; surface properties would ideally be measured in multiple locations over an area.

The current IASOA sites are all based on land, but many border the Arctic Ocean and are, therefore, influenced by open water and sea ice depending on the time of year. These sites already provide valuable data on the atmospheric state and cloud properties over the sites, but the detail of characterization depends on the particular instruments deployed at the site. In general, IASOA sites measure basic surface meteorology; some also launch routine radiosondes for vertical profiling. Many sites also measure broadband solar and infrared radiative fluxes, which is challenging in Arctic conditions (Matsui et al., 2012). Despite the difficulties, high-quality broadband measurements can yield valuable information regarding clouds (Long and Turner, 2008). A few of the IASOA sites are considered “super sites” (Barrow, Eureka, Summit) and deploy additional sophisticated instrumentation, including cloud radar, cloud lidar, microwave radiometers and spectral radiometers (in the visible, near-infrared, and infrared). These sites provide much more detailed information of boundary-layer processes and cloud macrophysical and microphysical properties, and, therefore, are an extremely valuable and under-utilized resource for satellite validation (e.g., Shupe et al., 2011; Shupe 2011; Cox et al., 2014a; Cox et al., 2014b).

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 has developed the organizational potential to host and recommend experts to the forums in which these needs can be iteratively addressed.

3. Developing Useable Observation-based Products and Analysis Tools

Observers and modelers have long struggled to build meaningful linkages through ingesting observations into reanalyses, observation-model validation/comparison exercises, developing model parameterizations based upon observational data, and through running model-based observing system simulations. In general, these efforts continue to be hampered by different “world views” manifested by large differences in observation versus time and space resolutions and differences in what is actually observed (e.g., radar reflectivities) and what is modeled (e.g., cloud hydrometeor sizes and composition). Another problem is presented by the requirement for “product” data sets such as derivations of quantities that require careful quality control, editing, calibration, interpolation, error flagging and retrieval of parameters from raw data sets, and often requires integration of data from multiple sensors. Consequently, a major challenge in the utilization of the IASOA data sets will be coordinating the development of standardized observing products across the network. Examples of possible products include separate components of the energy-surface flux balance, radar-lidar based cloud microphysical profiles, black carbon absorption coefficients from filter samples, and development of a net moisture and energy horizontal flux product from the IASOA network of upper air observations.

Another line of effort that has been initiated to address the challenges of time-space matching is the development of an IASOA tool set for extracting data from large gridded data in the vicinity of the IASOA observatories. At present, a test tool has been developed for extracting model output from archives at the NOAA Earth Systems Research Laboratory, including the NCEP/NCAR Reanalysis monthly means, the NCEP/DOE AMIP-II Reanalysis monthly means and the North American Regional Reanalysis (NARR) (http://www.esrl.noaa.gov/psd/data/timeseries/arctic/). Additionally, the National Snow Ice and Data Center has developed a utility to interactively subset MODIS satellite data for the IASOA Observatory sites for certain Version 5 (V005) MODIS products. The products available are: MOD09A1, MOD10A1, MOD11A2, MCD43A1, MCD43A2, and MCD43A4 (http://nsidc.org/cgi-bin/mist/mist_search.pl).

4. Usage and added value of IASOA observations in studies of atmospheric transports

High-resolution circumpolar estimates of atmospheric transports of momentum, heat, moisture, cloud water, cloud ice, and aerosols into and out of the Arctic require gridded products, such as atmospheric reanalyses, weather or climate model output, or satellite observations. All these products include errors and uncertainties. We expect that IASOA data will be particularly useful for validation of these gridded products, allowing quantification of the errors and uncertainties. In addition, direct calculations on atmospheric transports can be made for the observatory sites.

In the Arctic, atmospheric reanalyses and short-term numerical weather prediction results are reasonably accurate for synoptic-scale patterns of atmospheric pressure and, above the boundary layer, wind and air temperature, but large errors are present in all variables close to the Earth surface (Jakobson et al., 2012) and in moisture variables at all altitudes (Jakobson and Vihma, 2010). Both global and regional climate models include considerable uncertainties in basically all variables in the Arctic (e.g. Tjernström et al., 2008; Hawkins and Sutton, 2009). Satellite remote sensing in the Arctic is hampered by the darkness during the polar night, extensive cloud cover during summer, and challenges in distinguishing between signals originating from the atmosphere and snow/ice surface. The latter issue is a problem particularly for remote sensing of atmospheric moisture, cloud water, and cloud ice.

IASOA data provide possibilities to evaluate reanalyses, weather and climate models, and satellite remote sensing products with respect to the vertical profiles of air temperature, humidity, wind speed and direction, cloud water and ice content, and aerosols. Additionally, vertical profiles of transports of momentum, heat, moisture, cloud water, cloud ice, and aerosols can be evaluated at the locations of the IASOA observatories, yielding estimates of the biases and uncertainties of circumpolar transports calculated from the gridded products. The vertical profiles of wind, temperature, and humidity are also observed at radiosonde stations, but profiles of cloud water and ice content as well as aerosols are only observed at IASOA stations. Evaluation results will provide guidance for the selection of the best method of calculating the transports of various quantities.

This allows for an advance in studies on regional processes and interactions between the Arctic and lower latitudes. It is remarkable that the work carried out in the field has so far hardly utilized observations on transports. Observations have mostly been used as a source of information on the changes in the Arctic (e.g. sea ice, snow and air temperatures in the Arctic) and on the effects of Arctic changes on mid-latitudes (e.g. observations on precipitation and near-surface air temperature in mid-latitudes), but the estimates of the transports and teleconnections have been mostly based on reanalyses and model products (see Vihma (2014) and Cohen et al. (2014) for reviews). Due to the station locations (Figure 2), IASOA data are particularly suitable in investigating the effects of the new frontal zone that has appeared across the southern coasts of the Arctic Ocean (Section 1). In addition to exact comparison of gridded products and IASOA observations on the same variables, interesting comparisons between related variables can be made; an example is given in Figure 3.

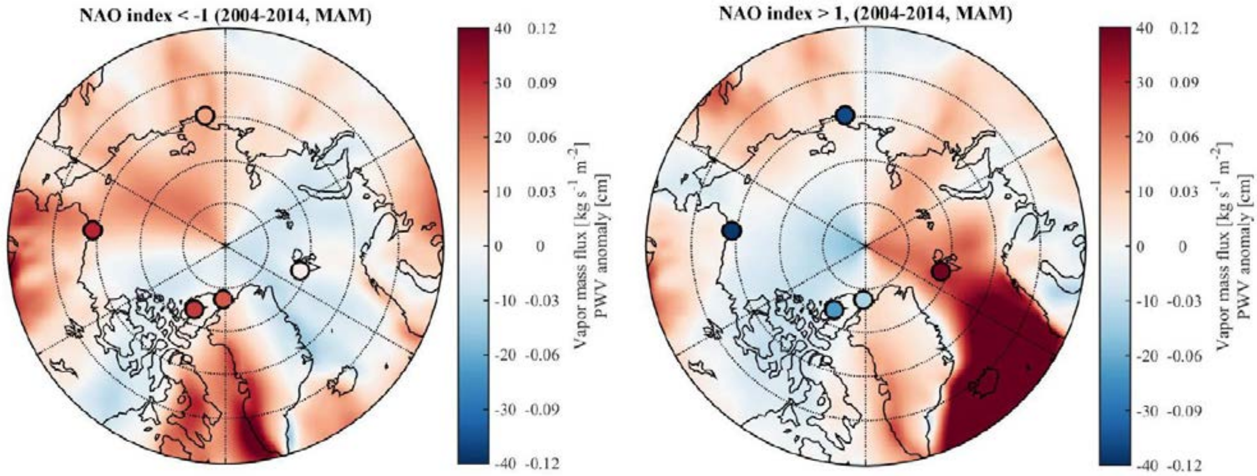

Figure 3. An example of comparison between reanalysis products and IASOA observations. The water vapor mass flux based from ERA-Interim (Dee et al., 2011) is plotted for circumpolar high-latitudes and the observed precipitable water vapor anomaly is plotted for the sites of five IASOA observatories. The fields differ between springs (MAM) of strongly negative (left) and positive (right) NAO index.

In addition to atmospheric transports, the IASOA data are valuable for evaluating reanalyses, models, and satellite products with respect to Earth surface variables, such as snow depth, soil moisture, surface temperature, shortwave and longwave radiative fluxes, albedo, as well as turbulent fluxes of sensible heat, latent heat, CO_2, and CH_4. Evaluation of surface fluxes is a vital activity complementing the evaluation of horizontal transports. These together will yield comprehensive understanding on the quality of available gridded products in representing budgets of heat, moisture, greenhouse gases, and aerosols in the Arctic.

The activities described above strongly contribute to the WMO Polar Prediction Project and its Year of Polar Prediction (YOPP). The preparatory and YOPP work will include (a) development of interoperable, error-corrected climatology of long-term meteorological observations and other key data (e.g. surface energy balance data products), (b) exploration of impact of Arctic observations on forecast models, (c) identification of specific regimes for forecast improvements (e.g. strong surface inversions) and most sensitive locations, and (d) coordinated experiments for enhanced observations across the IASOA network during YOPP (e.g. four daily radiosonde soundings). Much of the work will be carried out in the recently established IASOA Regional Processes Working Group.

5. Linkages between IASOA and other regional and global observing initiatives

The IASOA consortium serves as a key building block for an international Arctic network for atmospheric observations. In this capacity, it serves as a contributing task to the Sustaining Arctic Observing Networks (SAON) process. IASOA can be viewed as a regional network that draws together a host of global networks, including the Global Atmosphere Watch (GAW), the Baseline Surface Radiation Network (BSRN), the Global Cryosphere Watch (GCW), the Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN), the Total Carbon Column Observing Network (TCCON), the Aerosol Robotic Network (AERONET) and more. Each of these global networks has a specific topical focus and has made great strides towards establishing common observing practices for key parameters and developing global archives for data. IASOA studies on atmospheric transports will be strongly supported by similar observations from mid-latitudes. Further, IASOA builds upon the value of these existing global networks by providing the impetus to move from common observational practices to value-added, interoperable data products for the Arctic region. For some programs, notably GAW and GCW, IASOA will provide critical input on best practices for conducting these observations in the Arctic.

IASOA also provides an organizational nexus for coordinating with other regional efforts with overlapping interests. For example, IASOA has begun to network through Europe's International Network for Terrestrial Research and Monitoring in the Arctic (INTERACT) program to develop synergies between terrestrial and atmospheric observations of Arctic carbon. IASOA shares common objectives with the Pan Eurasian Experiment (PEEX) program through their common interest in observing atmospheric composition of importance to Arctic air pollution.

6. Future perspectives

Presently IASOA is a well-functioning consortium with a unique network of observatories around the Arctic Ocean and a value-added capacity to establish topical collaboratories to accelerate research in key areas. Analyses of the measurements have yielded advance in understanding the properties of Arctic clouds and aerosols, the atmosphere-surface exchanges of heat, energy, and gases, and the role of black carbon, ozone and methane, in the Arctic climate system. Further, a major role of IASOA observatories has been to provide ground-truth for satellite remote sensing. Broadening the focus of IASOA from local observations to regional processes, particularly to transports of heat, momentum, and atmospheric constituents in and out of the Arctic will be a major step forward. A large part of it is reachable with the present observations, but there are several paths to make further advance.

First is the continuation of filling measurement gaps at individual stations of high-resolution vertical profiles of wind, air temperature and humidity, cloud water and ice content, and aerosols. Using information from the three stations (Barrow, Eureka, Summit), which already have comprehensive suites of radars, lidars and spectral radiometers that provide profiles of cloud water/ice and aerosols, it will be assessed if it would substantially enhance the Arctic observing network to add this capacity to additional stations. Second, additional stations are needed to fill data gaps, which may be critical with respect to information on atmospheric transports into and out of the Arctic. For instance a recent significant advance is the development of Cape Baranova Station, which is expected to become an official IASOA station when data transfer protocols are established (Figure 2). Third, work is being initiated to increase the number of distributed measurements around stations to assess horizontal variability of the Arctic land surface, which may be significant. Finally, the IASOA observatories are sites where active utilization of recent advances in measurement technology, including Unmanned Aerial Systems (UAS), is being deployed.

To maximize the added value of IASOA observatories, the priority of actions in developing the network have to be considered taking into account the expected advances in (a) satellite remote sensing of the atmosphere and Earth surface, (b) other in-situ observations, such as standard weather stations and radiosonde sounding stations, and (c) numerical models and data assimilation systems. For example, if we expect a strong advance in satellite remote sensing of precipitation and soil moisture, the value of IASOS stations is maximized by investing more on observations on soil moisture, terrestrial ecosystems, snow cover, evapotranspiration, precipitation, air moisture, cloud water and ice contents, as well as the related atmospheric transports. This will yield better understanding in the level of the Arctic freshwater cycle (Prowse et al., 2015).

Finally, there is potential to better integrate IASOA observations with research on Arctic ecosystems. A lot of changes have been observed in Arctic biomes and ecosystem types, many of them being driven by changes in climate and hydrological conditions. Changes in biomes and ecosystems in turn affect fluxes of carbon/methane, heat and water (Wrona et al., 2016, submitted), which calls for integration of IASOA observations and terrestrial ecosystem research. In addition, there is potential for more inter-disciplinary science via analyzing the effects of the atmospheric transports on hydrology, glaciology, physical oceanography, as well as marine ecosystem research. This can be achieved via close integration with observation networks in the above-mentioned fields.

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The Global Cryosphere Watch Surface Network in the Arctic and Beyond

Wolfgang Schöner[1], Jeff Key[2], Charles Fierz[3], Barry Goodison[4], Øystein Godøy[5], Michele Citterio[6], Þorsteinn Þorsteinsson[7], Kari Luojus[8], Árni Snorrason[7], Miroslav Ondráš[9]

[1]Department of Geography and Regional Science, University of Graz, 8010 Graz, Heinrichstraße 36, Austria, email: wolfgang.schoener@uni-graz.at
[2]National Oceanic and Atmospheric Administration (NOAA), Madison, Wisconsin, USA
[3]WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland
[4]World Meteorological Organization (retired), Geneva, Switzerland
[5]Norwegian Meteorological Institute, Oslo, Norway
[6]Geological Survey of Denmark and Greenland, Copenhagen, Denmark
[7]Icelandic Meteorological Office, Reykjavík, Iceland
[8]Finnish Meteorological Institute, Helsinki, Finland
[9]World Meteorological Organization (WMO), Geneva, Switzerland

Summary

The cryosphere exists in various forms in about one hundred countries, at all latitudes and altitudes. It is one of the most useful indicators of climate change yet is significantly under-sampled. The World Meteorological Organization (WMO) Global Cryosphere Watch (GCW) is providing service-oriented information for informed decision-making and policy development related to climate, water and weather. It will ensure a comprehensive, coordinated and sustainable system of observations and information that will allow for a full understanding of the cryosphere and its changes.

One of the main objectives of GCW is the development of a surface-based cryosphere observing network with two components: a core component called, CryoNet, and contributing stations. Through the continuing implementation of CryoNet, GCW is leading the effort to establish best practices, guidelines and standards for cryospheric measurement, as well as refining observational requirements for the various elements of the cryosphere. To date, 36 stations distributed globally have been approved for inclusion in CryoNet, with many more to come. Ten of those stations are located in the Arctic; additional stations are needed to fill gaps.

To provide access to data from its surface network and from other sources, GCW is establishing interoperability between data management systems. The GCW Data Portal will make data and information available to users while providing the ability to exchange data and information among a distributed network of providers. Interoperability between the GCW Data Portal and a number of data centers worldwide has been established, though much remains to be done.

1. Introduction

The cryosphere is a component of the Earth System that, at the Earth's surface, includes snow cover, sea ice, lake and river ice, glaciers, ice caps, ice sheets, permafrost, seasonally frozen ground, and solid precipitation at the surface. The cryosphere is global, existing not just in the Arctic, Antarctic and mountain regions, but also in various forms at all latitudes and in approximately one hundred countries. The cryosphere provides some of the most useful indicators of climate variability and change, yet is one the most under-sampled domains of the Earth System. Improved cryospheric monitoring is essential to fully assess, predict, and adapt to variability and change in the Earth's weather, climate and water cycles.

The cryosphere, its changes, and its impacts have received increased attention in recent years. Today it receives constant coverage by the media, creating a demand for authoritative information on the state of the world's snow and ice resources. The World Meteorological Organization (WMO), with the cooperation of other national and international bodies and organizations, and using its global observing and telecommunication capability, is now providing an integrated, authoritative, continuing assessment of the cryosphere – a Global Cryosphere Watch (GCW).

GCW is an international mechanism for supporting all key cryospheric in-situ and remote sensing observations. GCW includes observation, monitoring, assessment, product development, and related research. It will have a positive impact on prediction, thus supporting assessments of the future state of the cryosphere and climate. GCW provides the framework for reliable, comprehensive, sustained observing of the cryosphere through a coordinated and integrated approach on national to global scales to deliver quality-assured global and regional products and services. GCW implementation encompasses:

- Requirements: Meet evolving cryospheric observing requirements of WMO Members, partners, and the scientific community, by contributing to the WMO Rolling Review of Requirements (RRR) process;
- Standardization: Enhance the quality of observational data by improving observing standards and best practices and guidelines for the measurement of essential cryospheric variables;
- Access: Improve exchange of, access to, and utilization of observations and products from WMO observing systems and those of its partners;
- Coordination: Foster research and development activities and coherent planning for future observing systems and global observing network optimization.

The observing network of GCW is a component of the WMO Integrated Global Observing System (WIGOS). Through WIGOS and the WMO Information System (WIS), GCW provides a fundamental contribution to the Global Earth Observation System of Systems (GEOSS). GCW will organize analyses and assessments of the cryosphere to support science, decision-making, environmental policy and services through, inter alia, its foundational support to the Global Framework for Climate Services (GFCS). Collaboration and cooperation with partners are essential to successfully conduct GCW activities at the international, regional, and national levels. Therefore WMO, through its Executive Council Panel of Experts on Polar and High Mountain Observations (EC-PHORS), facilitates engagement of organizations with polar interests in the development of GCW.

In this paper we focus on the GCW surface observing network. Its objectives, structure, and status are described and illustrated. GCW, mainly through its standardization activities and Data Portal, has an ambitious goal of filling the existing gaps in polar and high mountain observations, data compatibility, and data accessibility, thus supporting other Arctic observing initiatives.

2. GCW Surface Network

The GCW surface observing network is comprised of a core component, called **CryoNet**, and contributing stations that are not part of CryoNet. The GCW network builds on existing cryosphere observing programs and promotes the addition of standardized cryospheric observations to existing facilities in order to create more robust environmental observatories. The overall objective of CryoNet is to provide a comprehensive network of cryospheric in situ observations using standardized procedures, as well as to enable a framework of network services according to user needs. CryoNet aims to link different cryospheric observational networks to achieve its comprehensive potential through:

- Extensive monitoring of the cryosphere using harmonized measurements;
- Providing cryospheric data for improved process understanding and modeling;
- Providing calibration and validation data for satellite measurements;
- Linking cryospheric ground truth observations to cryospheric models;
- Training in cryospheric measurement;
- Standardizing practices for cryospheric observations;
- Promoting long-term, sustainable observing and monitoring.

Network Structure

The basic component of the GCW network, including *CryoNet*, is the *station*. A station measures one or more components of the cryosphere and one or more variables of each component, for example depth and snow water equivalent of the component snow. All types of GCW stations need to make their data, metadata, and observation procedures available in a timely manner, preferably to a data centre that is interoperable with the GCW portal. Observations are made and quality controlled according to CryoNet best practices.

A *CryoNet station* must meet the minimum set of requirements, which includes providing ancillary meteorological measurements. Potential attributes of CryoNet stations are given below. All stations will be either Primary or Reference, and may have additional attributes.

- *Primary* - Have a target (intent) of long-term operation and have at least a 4-year initial commitment.
- *Reference* - Have a long-term operational commitment and long-term (more than 10 years) data records.
- *Cal/val* - In addition, the station is being used for calibration and/or validation of satellite products and/or (earth system) models, or it has been used for such purposes in the past and it still provides the needed facilities.
- *Research* - In addition, the station has a broader research focus related to the cryosphere.

The minimum requirements of CryoNet station are:

1. **Meeting Core CryoNet Measurement Requirements -** The station shall measure at least one of the variables of one of the cryosphere components (i.e. snow, solid precipitation, lake and river ice, sea ice, glaciers and ice caps, ice sheets, frozen ground and permafrost). The station location is chosen such that cryospheric measurements are representative of the surrounding region, and such representativeness needs to be clearly described.
2. **Commitment of Operational Continuity -** The station must be active. The responsible agencies are committed, to the extent reasonable, to sustaining long-term observations of at least one cryosphere component. There must be a commitment to continue measurements for a minimum of four (4) years.
3. **Metadata Up to Date and Availability -** The station metadata, including all metadata describing the station characteristics and observational programme, are kept up-to-date and available in the GCW Portal as the interface to the WIGOS Information Resource (WIR).
4. **Compliance with Agreed Regulatory Practice -** The station observational procedures, the instruments and method of observations, quality control practices, etc., should follow GCW endorsed regulations, manuals, guides and, to the extent possible, the recommended best practices.
5. **Data and Ancillary Data Freely Available -** Data are made freely available, and whenever possible in near real-time. In situ ancillary meteorological observations, as required by CryoNet best practices, should also be available with documented quality.
6. **Competency of Staff -** Personnel must be trained in the operation and maintenance of the station.

A *CryoNet site* generally encompasses an area greater than a conventional observing station and is comprised of two or more active GCW stations with varying capabilities that are operated as a coordinated unit. At least one station has to be a CryoNet station. A site may encompass several micro-climatological regions or extend over larger altitudinal gradients. Thus, further ancillary meteorological stations are part of a site. Different partners may operate the stations, but they are coordinated through one agency or institute. Each CryoNet site has to provide a concept describing the research approach and the site management.

Typically, sites have a broader research focus related to the cryosphere compared to stations.

Whereas simple sites investigate the cryosphere only, integrated sites aim to provide a better understanding of the cryosphere and/or its linkages to other components of the earth system, for example, the atmosphere, the hydrosphere, the biosphere, the oceans, soil, vegetation, etc. Potential attributes of CryoNet sites are:

- *Basic* - Monitor single or multiple components of the cryosphere.
- *Integrated* - Monitor at least two components of cryosphere or at least one cryosphere component and one other component of the earth system. Integrated sites are particularly important for the study of feedbacks and complex interactions between these components.

Requirements for CryoNet sites are:

1. A site comprises at least one CryoNet station.
2. Integrated sites have technical supporting staff.
3. Integrated sites have training capability.
4. There is a long-term financial commitment.
5. Data are made freely available, and whenever possible in (near) real-time.

CryoNet station and site characteristics are summarized in Figure 1.

CryoNet STATIONS

- measures at least one variable of a cryosphere component (e.g. snow, permafrost, sea ice…)
- have to fulfill CryoNet minimum requirements
- must have ancillary meteorological measurements
- have the target of long-term operation(primary) or long-term operational commitment with 10+ years record (reference)

Potential attributes: primary, reference, cal/val, research

CryoNet SITES

- contain two or more coordinated stations (at least one is a CryoNet station) with varying capabilities that are coordinated as a local cluster
- must have a concept describing the research approach and the site management

Potential attributes: basic, integrated

Figure 1: Properties of CryoNet Stations and CryoNet Sites.

A *GCW contributing station* is required to measure at least one variable of at least one cryosphere component (e.g. snow, permafrost, sea ice, etc.). Contributing stations are those that provide useful measurements of the cryosphere but do not fulfill CryoNet minimum requirements, or in some other way do not provide the quality and/or consistency of data required by CryoNet stations; for example, where data records may be short or with large gaps. These stations may be in remote, hard to access regions where cryospheric observations are scarce or in regions where they complement other cryospheric measurements. Mobile platforms such as ships, drifting stations and buoys may also be contributing stations. Contributing stations may have this attribute:

- *Reference* - Have a long-term operational commitment and/or long-term (more than 10 years) data records.

Synoptic/climate stations of the NMHSs measuring cryospheric variables to WMO standards, and providing their metadata and data via WIS and WIGOS, could fulfill the necessary requirements in order to contribute to GCW and to be accepted as stations in the GCW surface network.

As encouraged by GCOS, GCW will facilitate the establishment of high-latitude stations with co-located measurements of key variables, especially permafrost and snow cover, thus enhancing GCOS/GTOS Networks for Permafrost (GTN-P), Glaciers (-G) and Hydrology (-H) and including the measurements of solid precipitation. In addition, aerosol contamination of surface snow (dust, black carbon, heavy metals, etc.) will also be monitored to link with existing atmospheric measurements from the GAW network. GAW stations and WCRP/Coordinated Energy and Water Cycle Observations Project (CEOP) reference sites in cold climates are potential candidates. Community monitoring also offers new network opportunities for GCW.

GCW will drive performance and provide motivation for high quality observations. Being a GCW station or CryoNet site means being part of an international, operational, global observing system and thus providing observations of known quality for research and knowledge beyond a site's local region.

GCW Surface Network Status

The 17th World Meteorological Congress (Cg-17, May-June 2015) decided that Polar and High Mountain Regions would be one of the seven WMO priorities for 2016-2019, including operationalizing GCW. Cg-17 recognized that an immediate priority for GCW is to establish CryoNet. Through extensive collaboration with partners, more than 100 sites have been proposed for CryoNet, of which 36 will be used for a pre-operational testing phase. Most of these sites were proposed as a result of CryoNet workshops in Asia (Beijing, December 2013) and South America (Santiago de Chile, October 2014). They are listed in Table 1 and their geographic locations are shown in Figure 2. The existing gaps will continue to be filled through engagements with partners, including workshops being organized or planned for cold regions in Asia/Eurasia, Latin America, North America and regions with tropical glaciers.

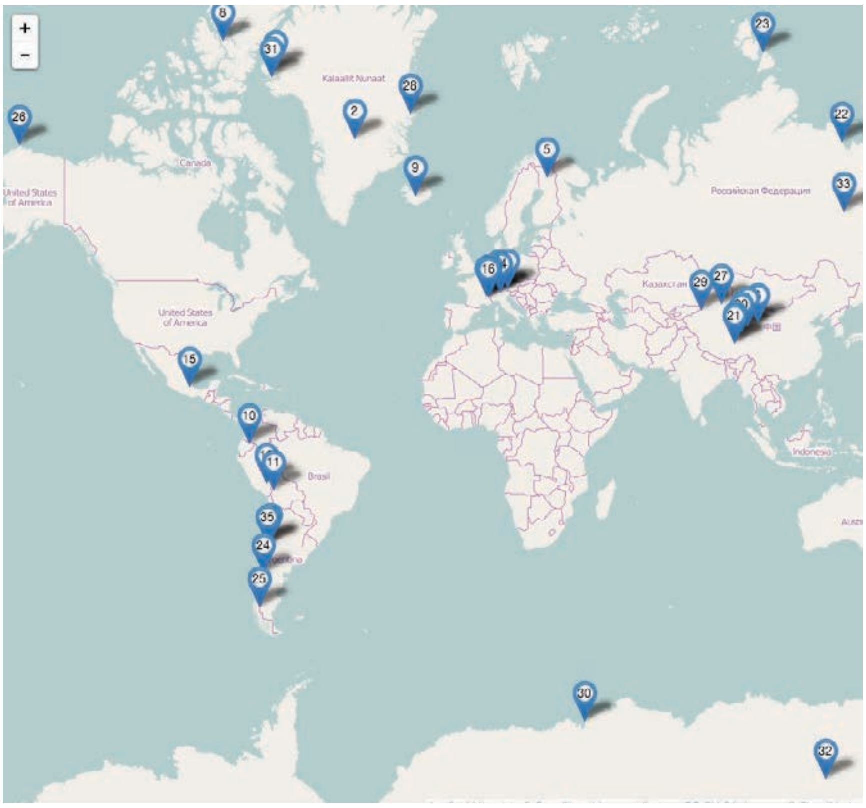


Figure 2: Locations of the 36 pre-operational phase CryoNet sites.

Table 1: The 36 sites approved for the CryoNet pre-operational testing phase.

	Station/Site	Operating Country	Location	Type
1	SIGMA-A	Japan	Greenland	Basic
2	PROMICE Greenland Ice Sheet Monitoring Network	Denmark	Greenland	Basic
3	Sonnblick	Austria	Austria	Integrated
4	Qilianshan Station of Glaciology and Ecologic Environment	China	China	Basic
5	Sodankylä-Pallas	Finland	Finland	Integrated
6	Qilian	China	China	Integrated
7	Tanggula Cryosphere and Environment Observation Station	China	China	Basic
8	Eureka	Canada	Canada	Basic
9	Hofsjökull	Iceland	Iceland	Basic
10	Antisana 15 alfa	Equador	Equador	Basic
11	Zongo Glacier	France	Bolivia	Integrated
12	Morenas Coloradas Rockglacier	Argentina	Argentina	Basic
13	Quelccaya Ice Cap	USA	Peru	Basic
14	Weissfluhjoch - Davos	Switzerland	Switzerland	Integrated
15	Glaciar Norte	Mexico	Mexico	Basic
16	Saint-Sorlin Glacier	France	France	Integrated
17	Argentiere Glacier	France	France	Integrated
18	Mer de Glace Glacier	France	France	Basic
19	Gebroulaz Glacier	France	France	Basic
20	Xidatan	China	China	Integrated
21	Tanggula	China	China	Integrated
22	Tiksi	Russia	Russia	Integrated
23	Ice Base Cape Baranova	Russia	Russia	Integrated
24	Vuriloches	Argentina	Argentina	Basic
25	Aonikenk	Argentina	Argentina	Basic
26	Barrow Baseline Observatory	USA	USA	Integrated
27	Tianshan	China	China	Basic
28	Zackenberg	Denmark	Greenland	Integrated
29	The Koxkar Glacier Camp (KGC)	China	China	Integrated
30	Syowa	Japan	Antarctica	Integrated
31	SIGMA-B	Japan	Greenland	Basic
32	Dome-C	France-Italy	Antarctica	Basic
33	Spasskaya Pad (Yakutsk)	Japan	Russia	Integrated
34	Forni Glacier	Italy	Italy (Europe)	Basic
35	Valle Nevado	Chile	Chile	Basic
36	Col de Porte	France	France	Integrated

3. Measurement Standards, Guidelines, and Best Practices

To ensure high quality and consistent observations, measurements at CryoNet sites will be made according to accepted guidelines, best practices and standards. Many of these have been compiled by WMO, though the compilations are not exhaustive for snow, ice, and permafrost measurements. Some existing cryosphere networks have implemented their own guidelines, best practices and standards. It will be a major effort for GCW to establish best practices that are in agreement with existing guidelines. Thus, CryoNet will draw on existing guidelines and best practices standards and add new ones, as necessary, to ultimately achieve the desired standards. They will be reviewed by the scientific community, modified as necessary, and maintained in the forthcoming *GCW Manual*.

As a first step towards a GCW measurement standard/guideline, GCW's CryoNet Team produced an inventory of existing measurement guidelines, best practices, and standards. Some details of that survey are given in Table 2. Existing manuals such as the WMO Manual on the Global Observing System and the WMO Guide to Meteorological Instruments and Methods of Observation (CIMO Guide) could serve as an important base for the *GCW Manual*. Establishing best practices, guidelines and standards for cryospheric measurements will include consideration of data homogeneity, interoperability, and compatibility of observations from all GCW observing and monitoring systems and derived cryospheric products.

Additionally, instrument intercomparison campaigns will be conducted in order to determine and intercompare performance characteristics of instruments under field or laboratory conditions. The current WMO Solid Precipitation Intercomparison Experiment (SPICE), which includes snowfall and snow depth, is of direct relevance to GCW and is considered as a contribution to GCW.

Table 2: List of existing cryospheric guidelines.

Organisation	Guideline (authors and title)	Year published	Cryospheric component
IACS, UNESCO	Fierz, C., Armstrong, R.L., Durand, Y., Etchevers, P., Greene, E., McClung, D.M., Nishimura, K., Satyawali, P.K. and Sokratov, S.A. 2009. The International Classification for Seasonal Snow on the Ground. IHP-VII Technical Documents in Hydrology No. 83, UNESCO-IHP, Paris. 90 pp.	2009	Snow
IACS, UNESCO	Cogley, J.G., Hock, R., Rasmussen, L.A., Arendt, A.A., Bauder, A., Braithwaite, R.J., Jansson, P., Kaser, G., Möller, M., Nicholson, L. and Zemp, M., 2010, Glossary of Glacier Mass Balance and Related Terms. IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris. 114 pp.	2010	Glaciers
UNESCO	Kaser, G., Fountain, A., and Jansson, P., 2003. A Manual For Monitoring the Mass Balance of Mountain Glaciers. IHP-VI Technical Documents in Hydrology No. 59, UNESCO-IHP, Paris.	2003	Glaciers
WMO	Goodison B.E., P.Y.T. Louie, D. Yang, 1998, WMO Solid Precipitation Measurement Intercomparison- Final Report, WMO/TD - No. 872	1998	Snow
WMO	Nitu R. and Wong K., 2010, CIMO Survey on National Summaries of Methods and Instruments for Solid Precipitation Measurements at Automatic Weather Stations	2010	Snow
WMO	World Meteorological Organization (WMO) 2008. Guide to meteorological instruments and methods of observation. WMO-8 8 1-681	2008	Snow
UNESCO, IAHS, ICSI, WMO	UNESCO, IASH, WMO, 1970. Seasonal snow cover, a guide for measurement compilation and assemblage of data. Technical papers in hydrology, a contribution to the International Hydrological Decade, published by the United Nations Educational, Scientific and Cultural Organisation, Place de Fontenoy, 75 Paris-7e, 37 pages.	1970	Snow
National Hydrology Research Institute Canada	Østrem G. and M. Brugmann, 1991, Glacier Mass Balance Measurements. A manual for field and office work. National Hydrology Research Institute (Canada), Science Report No. 4	1991	Glaciers
CEN	CEN/TR 15996:2010, Hydrometry - Measurement of snow water equivalent using snow mass registration devices	2010	Snow
UNESCO, ICSI, IAHS	UNESCO, IAHS, 1970, Combined Heat, Ice and Water Balances at Selected Glacier Basins. A Guide to Measurement and Data Compilation. Technical Papers in Hydrology No. 5,	1970	Glaciers

	UNESCO, Paris		
Environment Canada	Manual of Climatological Observations, 3rd Edition	1992	Precipitation, snowfall
Environment Canada	MANOBS, Manual of Surface Weather Observations, 7th Edition	1977, 2011	Precipitation, snow
WMO	WMO Sea ice Nomenclature, WMO-No.259. Volume I – Terminology, Volume II – Illustrated Glossary, Volume III – International system of sea ice symbols. Electronic version is available at http://www.aari.ru/gdsidb/XML/wmo_259.php	2004	Sea Ice
WMO	Sea ice Information Services in the World, WMO-No.574. "Sea Ice Information Services in the World" is intended to provide to mariners and other users the latest snapshot of the sea ice services available world-wide, effectively extending the WMO publication No. 9, Volume D - information for Shipping.	2010 edition	Sea Ice
WMO-IOC JCOMM	Electronic Chart Systems Ice Objects Catalogue, version 5.1	2012	Ice (sea, lake)
WMO	SIGRID-3: A vector archive format for sea ice charts, JCOMM-TR-23, WMO/TD-NO.1214	2010 edition	Ice (sea, lake and river)
WMO	Ice Chart Colour Code Standard, JCOMM-TR-23, WMO/TD-NO.1214	2004	Ice (sea, lake and river)
National Research Council Canada	Johnston, M.E, Timco, G. W. Understanding and Identifying Old Ice in Summer. National Research Council Canada, Canadian Hydraulics Centre, 2008	2008	Sea Ice
Arctic and Antarctic Research Institute Russia	Manual for ice experts – ice observers	2007	Sea ice
Meteorological Service of Canada	Manual of standard procedures for observing and reporting ice conditions	2005	Sea ice
Canadian Avalanche Association	Observation Guidelines and Recording Standards for Weather, Snowpack and Avalanches. Canadian Avalanche Association, Revelstoke, BC, Canada. Updated 2008.	2007	Snow, Weather, Avalanches
American Avalanche Association	Greene, E., Atkins, E.D., Birkeland, K., Elder, K., Landry, C., Lazar, B., McCammon, I., Moore, M., Sharaf, D., Sternenz, C., Tremper, B., and Williams, K., 2010. Snow, Weather, and Avalanches: Observational Guidelines for Avalanche Programs in the United States. American Avalanche Association, Pagosa Springs, CO.	2010	Snow, Weather, Avalanches
WGMS	General Guidelines for Data Submission and Notes on the Completion of Data Sheets. World Glacier Monitoring Service, Zurich, Switzerland:	2011	Glaciers
UNESCO, GTN-G	Perennial ice and snow masses – a guide for compilation and assemblage of data for the World Glacier Inventory. Technical Papers in Hydrology No. 1	1970	Glaciers
ESA	Guidelines for the compilation of glacier inventory data from digital sources, 23 pp. Online at: http://www.globglacier.ch/docs/guidelines_inventory.pdf	2010	Glaciers
GTOS	ECV T6 Glaciers and ice caps (GTOS Report), link:	2009	Glaciers
WMO	IGOS Cryosphere Theme Report, WMO TD-No. 1405, (http://igos-cryosphere.org/docs/cryos_theme_report.pdf)	2007	All
IPA	Global Terrestrial Network on Permafrost Strategy and Implementation Plan, 2012-2016	2012	Permafrost
International Ice Charting Working group	Ice Information Services: Socio-Economic Benefits and Earth Observation Requirements. Electronic version is available at: nsidc.org/noaa/iicwg/docs/IICWG_2007/IICWG_SE_2007_Update_Final_.pdf	2007	Ice (sea, lake and river)

4. Data Access and Interoperability

The main purposes of the GCW Data Portal (or “catalogue”; http://gcw.met.no) are to provide an overview of datasets relevant to GCW, to provide access to datasets wherever possible (e.g. real or near real-time data streams, archive access), and to connect GCW with the WMO Information System (WIS) and WMO Global Telecommunication System (GTS) when real time exchange of data is requested by the GCW community. The intention is to establish the GCW Data Portal as a WIS Data Collection and Production Centre (DCPC) and to rely on WIS and WIGOS efforts for standardizing the metadata that are submitted to WMO. GCW data management follows a metadata-driven approach where datasets are described through metadata that is exchanged between contributing data centers and the GCW catalogue.

GCW itself will produce few low-level datasets, but instead relies on distributed data management technologies and partners to establish the GCW catalogue, which will publish WIS-compliant descriptions of GCW data and products into WMO’s Global Information System Centres (GISCs) catalogues. This will create a unified interface to datasets in an otherwise fragmented terrain. No data will be kept in the GCW catalogue without an agreement with the data producer following a request from the user community. GCW will respect partnership, ownership, and data-sharing policies of its partners.

The ingested metadata will be harvested from project specific, national and international catalogues. In addition to harvesting existing catalogues, the data management part of the GCW Data Portal will facilitate forms for submission of metadata on datasets not handled by existing catalogues. Currently only a limited number of catalogues are integrated, but dialogues on integration have been established with a number of other catalogues (Figure 3). Quite frequently this involves some degree of adaptation of systems on either side.

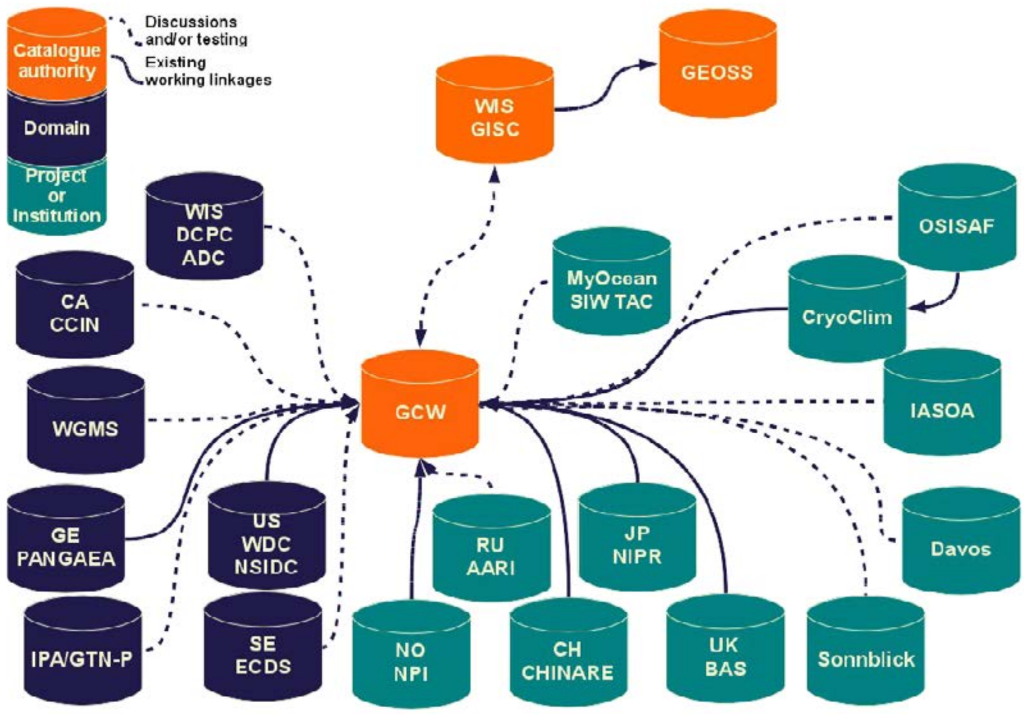


Figure 3: Data centers being addressed within GCW data management currently or in the short term. Solid lines indicate existing linkages; dashed lines indicate ongoing discussions and/or testing. All acronyms are defined at http://globalcryospherewatch.org/reference/acronyms.html.

There are technological considerations for catalogue interoperability, involving harvesting/exporting metadata using standard interoperability interfaces and documentation standards (e.g. Open Archives Initiative - Protocol for Metadata Harvesting (OAI-PMH), Open Geospatial Consortium (OGC) Catalogue Service for the Web (CSW), ISO23950, ISO19115, Global Change Master Directory (GCMD) Data Interchange Format (DIF)). OAI-PMH is the preferred solution for exposure of metadata due to its low cost of implementation. Implementations of OAI-PMH should support at least GCMD DIF or ISO19115 among which ISO19115 following the WMO profile is the preferred solution in the long term. To simplify data brokering, data streams established through Open-source Project for a Network Data Access Protocol (OPeNDAP) interfaces are the preferred solution as these map to the generic data model UNIDATA Common Data Model. There are relevant frameworks for catalogue interoperability including WMO Information System (WIS), ICSU World Data System (WDS), Group on Earth Observation (GEO).

The GCW Data Portal has been developed by the Norwegian Meteorological Institute (METNO), building on their web-based tool for searching data. This approach will facilitate seamless access with national meteorological and hydrological services (primarily utilizing WIS) and external data centers holding relevant cryospheric data and information at the national or global scale.

5. Recommendations

The Arctic observing initiatives and programmes are invited to consider participation in GCW implementation through:

1. Filling the gaps in the GCW Observing network and its core network, CryoNet, across the Arctic region, notably in North America, eastern Europe, western Russia, and over the Arctic Ocean;
2. Participation in the assessment, harmonization, and development of best practices to be applied to crysopheric observations in the Arctic;
3. Participation in the assessment, harmonization, and further development of vocabularies and definitions relevant to crysopheric observations in the Arctic;
4. Building interfaces with the GCW Data Portal; and
5. Community vetting of the observational requirements for crysopheric observations in the Arctic.

All of these aspects of implementation, particularly the first three, will enhance GCW's contribution to the Year of Polar Prediction (YOPP) scheduled to take place from mid-2017 to mid-2019.

More information on CryoNet and GCW is available online at http://globalcryospherewatch.org.

GCW
Global Cryosphere Watch

Introduction of "Long-term plan for Arctic Environmental Research"

Yuji Kodama[1], Hiroyuki Enomoto[1], Takashi Yamanouchi[1],
Tetsuo Ohata[1], Motoyoshi Ikeda[2], Yoshiyuki Fujii[1]
[1]National Institute of Polar Science
[2]Hokkaido University

Contact person: Y. Kodama, email to: kodama.yuji@nipr.ac.jp

1. Background

One of the main tasks of the Japan Consortium for Arctic Environmental Research (JCAR) is to develop a long–term Arctic research plan. This plan is organized around core subjects, and encourages forward progress towards common goals using a collaborative network of multidisciplinary researchers in JCAR. Although many researchers in JCAR have been conducting environmental research in the Arctic, some of the researches have not directly addressed the topics of global warming and biodiversity, and, we believe, those researches may also provide important new information on global warming and biodiversity and enhance the activities of JCAR as an academic community. Furthermore, this report includes guidelines to develop research infrastructure, construction of a research platform, and capacity building.

2. Brief summary

More than 140 JCAR members and scientists were involved in the development of this long-term Arctic research plan. The planning, writing, reviewing and publishing of this document took more than 1.5 years, and was completed in September 2014. The document describes the research important for next 10-20 years with four research focus areas identified by JCAR: 1) Elucidation of abrupt environmental change in the Arctic associated with on–going global warming; 2) Elucidation of environmental change in relation to biodiversity; 3) Broad and important subjects on the Arctic environment; 4) Development of methods enabling breakthroughs in environmental research. This report also describes the networks and infrastructures required to achieve the research goals and objectives. For each focus area a review of the current status of research is presented, along with several scientific questions and their justification.

3. Research topics.

The long-term plan for Arctic environmental research describes how the following research topics will be evaluated over the next 10-20 years:

- Atmospheric: Arctic warming by increase in longwave radiation and sensible-latent heat with sea ice reduction; Improvement in cloud modeling; Aerosols on cloud formation; Black carbon on snow and ice sheet; Arctic sea ice reduction on mid-latitude weather; Interaction between the Arctic and the equatorial region.
- Terrestrial snow and ice: Glacier calving-marine interaction; Northing of forest belt; Observation network and satellite observation; Biological effect on snow/ice albedo; Monitoring of early winter snow on permafrost in southern peripheral area; Increase in discharge of main Arctic rivers.
- Sea ice / Ocean: Prominent sea ice reduction at Siberian coast; Sea ice stability in Arctic Ocean due to warm water from the Pacific Ocean through Bering Strait; Monitoring of vertical mixing and reduction of sea ice in Barents Sea; Sea ice prediction in multiple time scales for Arctic Sea routes.
- Paleoclimate and solid geophysics: Proxy data from glacier and ocean bottom cores in the Artic; Watching hydrothermal mine and ocean bottom crustal change; Grounding line retrieval of calving glaciers with sea level rise; Melt water effect to glaciers and ice sheets.
- Upper Atmosphere: Monitoring of cooling in upper atmosphere; Continual monitoring in ozone depletion and global warming; Monitoring of solar activity; Monitoring of the geospace plasma for the safety in operating satellites.
- Terrestrial plant ecosystem: Fertilization in the feedback argument; Albedo reduction, evapotranspiration increase and reduction in soil moisture by northing of Forest belt; Biodiversity research in the Arctic.
- Terrestrial material cycle: Clarifying unknown part of carbon cycle in the Arctic; Amount of organic carbon in soil and permafrost for CO_2 andCH_4 release due to warming and forest fire; Nutrient and rare metal transferred by rivers and coastal erosion.
- Marine material cycle and ecosystem: Effect of sea ice reduction on productivity due to lower nutrient upwelling; Monitoring of change in biodiversity; Material transfer between continental shelf and ocean basin for the response of the

ecosystem; Changes in food chain and material cycle in other than summer.

- Social influence: Influence of opening of Arctic shipping routes; Earthquake and tsunami information transfer to residents; Influence to life style by changes in terrestrial ecosystem, increase in forest fire, changes in agricultural and fishing products; Information exchange, collaboration, mutual understandings on scientific research results.

4. Research infrastructure

The research efforts outlined in the long-term Arctic research plan will require the following infrastructure:

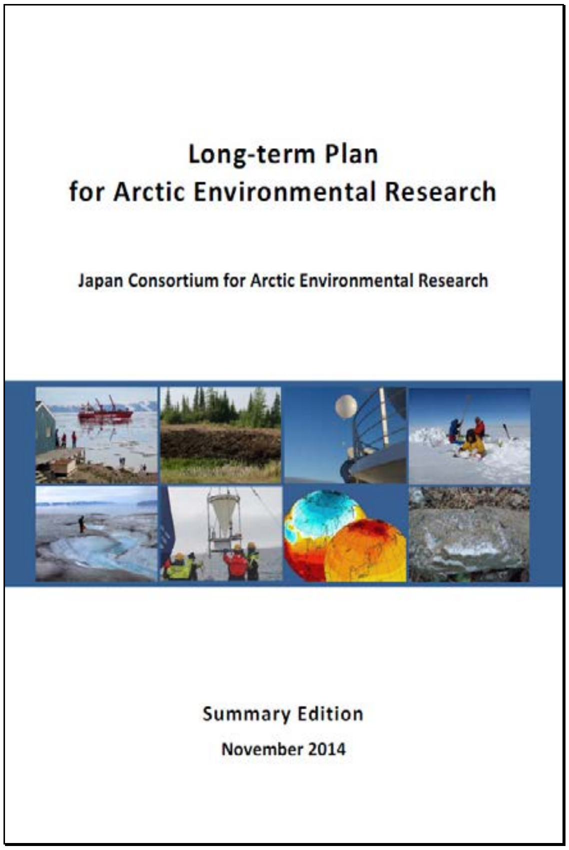
- Satellite remote sensing: Improve microwave sensors in order to better monitor sea ice distribution; Development of combined SAR, Lidar, radar altimeter for monitoring ice sheet, glacier, sea ice and snowpack; Development of gravitation sensor: Visual band sensors for terrestrial and marine ecosystem.
- National Researches: Matching of governmental and individual research; Taking use of non-Arctic states' perspective for international Arctic research.
- Research Vessels: Necessity of national research ice breaker for conducting independent and international research; Higher grade and better specification of the icebreaker than the ones existed.
- Data Archive: Establish a domestic data center; Retrieval and digitization of historical data; Putting DOI code to all Arctic data set; Collaboration with international data center.
- Observation network: Establishment of coordinated super site network for long-term monitoring and collecting the various parameters; By-lateral framework for cooperation in maintaining the observation site.

5. Practical use of this report

This report suggested the needs for Arctic environmental research without putting priorities, which could be done by whom needs them. It is a department store of research topics and purchased by stakeholders who need them.

Arctic research of non-Arctic states involves with Arctic states, therefore the research projects always have its international or by-lateral nature. Precondition of scientific activities in the Arctic is geopolitical stability in spite of rapid environmental and social change. It is important to educate young scientists in international circumstances.

Arctic environmental assessment must be done fairly. It is sometimes easily done by institutions in non-Arctic states rather than by domestic institutions due to no conflictions with local political organizations.



To see the whole text, visit http://www.jcar.org/english/longterm/

Sustainable seamless monitoring in the Arctic

Yuji Kodama, Hiroyuki Enomoto, Takashi Yamanouchi
National Institute of Polar Science

Contact person: Y. Kodama, email to: kodama.yuji@nipr.ac.jp

This report is extracted and modified from the "Long-term Plan for Arctic Environmental Research" published by the Japan Consortium for Arctic Environmental Research (JCAR).

Research monitoring of the Arctic environment has been carried out as two elements, remote sensing including the satellite and in situ observation. However, in situ field observations are hampered by the harsh environment of the Arctic, resulting in a sparseness of observing stations and large data gaps. Although recent progress in satellite monitoring has generated new information, there are still many factors that need to be observed in situ (e.g., ground truth measurement for microwave bands, snow density and temperature, soil moisture in surface soil). Accurate monitoring of the Arctic environment requires continuous, high density measurements that may only be achieved through international cooperation.

For convenience, the monitoring fields are divided into the ocean, cryosphere, atmosphere and land, followed by the priority long-term monitoring method. For the ocean, the monitoring of sea ice change in extent and thickness, marine ecosystem and material cycle throughout the year using an icebreaker and satellites are needed. In the cryosphere, determining the mass balance and related various quantities of the Greenland ice sheet and the mountain glaciers in the Arctic, the monitoring of coastal erosion, thermokarst associated with thawing, and management of boreholes to measure permafrost temperature in the permafrost region are essential. In the atmosphere, long-term precise measurement and understanding of the spatial variation of atmospheric minor constituents involved in changes of the climate, cloud and precipitation are important. For the monitoring over land, development and maintenance of comprehensive observing stations (super site) for the monitoring of vegetation change, terrestrial ecosystems and meteorological and hydrological elements, including heat, water and carbon fluxes at land surface are needed. The monitoring of all of the above elements will require both in situ observations and remote sensing.

For the monitoring of the above described elements, various organizations, systems, and facilities are required:

Research vessels

Japan does not possess an ice breaking research vessel, which could be operated in the Arctic Ocean. Japanese Arctic researchers are obliged to use foreign vessels for their research operations, and as a result developing a sound observation plan is challenging and the operations are limited. A new research ice breaker is a way to overcome this situation. The new vessel would allow us to immensely improve our observation ability of the Arctic Ocean. The equipment particularly needed includes: a moon pool, multi-purpose winch, automatic launcher for radio sonde, ROV (remotely operated vehicle), chemical-biological-geological laboratory (including cold rooms), long-time navigation capable and multi-sensor equipped AUV (autonomous underwater vehicle), sampling capable ROVF, long and large diameter piston corer, multi-beam bathymeter for ocean bottom survey, sub-bottom profiler for strata probing.

Satellite

It is necessary to improve the observation of sea ice distribution by using a micro-wave radiometer installed on satellite, which would double the present spatial resolution of AMSR2 (89GHz and 3～5km). An integrated observation system of Synthetic Aperture Radar (SAR) and Laser/Radar altimeter is also very effective for detecting the mass change of ice sheet/glacier, sea ice and snow cover. It also needs to develop a gravity measuring satellite, such like GRACE.

Japan now has plans to launch GCOM-C1/SGLI, which would cancel the dependency to US visible sensors in monitoring of the terrestrial and marine ecosystem.

Aircraft

Aircrafts are important platforms of observations between satellite and ground measurement. Especially it is needed to provide a platform for the electromagnetic induction probe (EM) in measuring the sea ice thickness and for direct measurement of atmospheric compositions and cloud particles. In the past, a commercial aircraft has been used for such Arctic observations, but it is effective to develop and possess an airplane with a new technology instruments. On the other hand, the usage of un-manned aircraft may also be a possibility.

Research and observation base in the Arctic

As a non-Arctic state, Japanese Arctic scientists need to have base stations in the Arctic. These stations must be long-term comprehensive measurement sites. The research goals, the measurement methods and their data are shared by the scientists of the host country under bi-lateral cooperation protocols. The priority of the measurements goes to the collection of various environmental parameters. Such a base is also important for early career scientists, especially those learning the operational skills in the harsh environment in the Arctic. There is also a need for an institute to maintain and manage the research base in the Arctic in cooperation with Arctic states, including the necessary domestic arrangements.

Data archive

The data archive system must be user friendly and flexible to differently formatted data. A Data Center is needed, where data rescue, digitization of data, and identification of dataset using DOI system can be operated. Cooperation with an international data center is essential to collect and use the various databases.

Instruments (Atmosphere, Upper-Atmosphere, Cryosphere, Land and Ocean)

There is a great need for instruments. One example is the development of a large radar network with EISCAT-3D, MU radar at Shigaraki, Japan, Equatorial Atmospheric radar in Indonesia, etc. for the distributed monitoring of the upper-atmosphere. Other examples are a high-resolution stable isotope analyzer for aerosols and gases, and a high resolution ice-core melt analyzer in the area of glaciology. For the terrestrial vegetation, a Hyper Spectral Camera, which will reveal the composition of the tree, is necessary. Development of an observation platform, such as ROV and AUV, is also important to be able to observe the sea ice from below.

Numerical model

In addition to hardware, such as massive calculation resources and large storage, there is a need to secure human resources to develop models and run the hardware. Furthermore, a system which will enable research technicians to prepare data and develop source codes is needed.

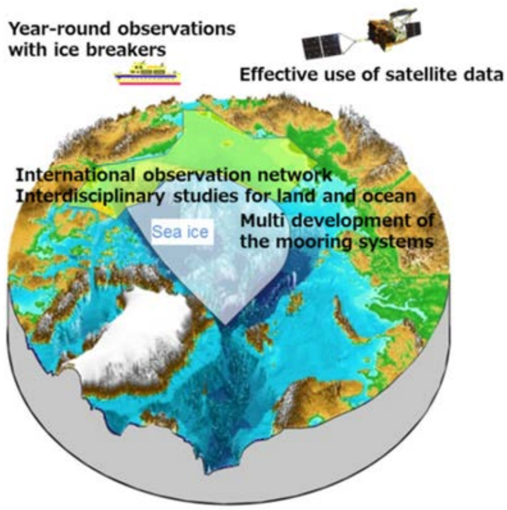


Figure 1: Elements necessary for the monitoring of marine ecology in the future (conceptual diagram). (References to the figure should be made in the body of the text)

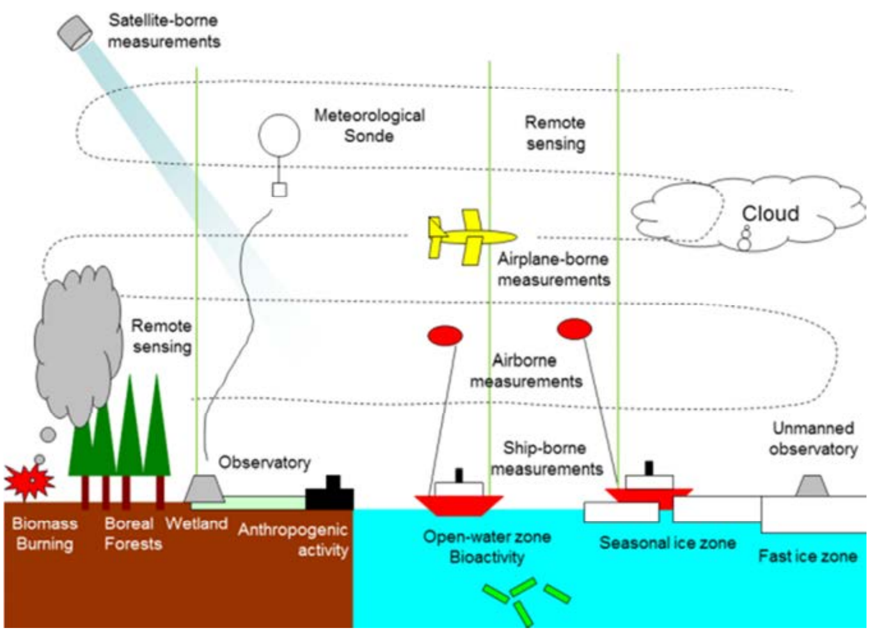


Figure 2: Elements necessary for the monitoring of atmospheric minor constituents in the future (conceptual diagram). [Theme A] (References to the figure should be made in the body of the text)