Arctic Observing Network (AON): 2009 Status Report and Key Recommendations

Results from the third AON PI Meeting; 30 November - 2 December 2009; Boulder, CO

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Results from the Third
NSF AON Principal Investigators (PI) Meeting
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Section I: Executive Summary

The third Arctic Observing Network (AON) PI meeting provided an opportunity to review observing system status and accomplishments at the close of the International Polar Year (IPY) 2007–2009 and to develop recommendations for refining, enhancing and sustaining the network in the years to come. Sponsored primarily by the National Science Foundation, with additional support from the National Oceanic and Atmospheric Administration and several other agencies, the AON included over 40 projects at the start of 2010. Meeting participants included AON investigators, agency representatives, international partners, and outside experts familiar with observing system implementation. Project status summaries in the Appendix of this report provide an overview of scientific accomplishments, linkages, and plans for the coming years.

Accomplishments

Overview presentations on the status of projects in the different thematic areas highlighted the following accomplishments:

1. **Atmosphere:** Building on strong international collaborative frameworks and synergies, atmospheric observations within the AON have wide geographic coverage throughout the Arctic as well as through the depth of the atmosphere. Key atmospheric chemistry measurements are integrated into this program thanks to significant methodological advances made under the AON.
2. **Ocean and sea ice:** Relying increasingly on autonomous, advanced measurement technologies, the ~15 ocean and sea ice programs collected Arctic-wide data helping to explain the causes underlying the record sea ice minimum of summer 2007 and track the response of the Arctic system to this extreme.
3. **Hydrology and cryosphere:** With three of the eight projects pan-Arctic in scope, through AON we now have baselines of hydrological and biogeochemical fluxes against which ongoing and future changes can be compared. Progress is good towards assessing the thermal state of the permafrost throughout the Arctic in a highly collaborative international program.
4. **Terrestrial ecosystems:** Through the development of several regionally distributed flagship sites that tie into past long-term research programs, baseline data are being collected to evaluate the impact of changing precipitation patterns and other climatic factors, as well as disturbances such as tundra fires, on land cover.
5. **Human dimensions:** The single funded human dimensions project evaluated the research value of existing data sets and developed community indicators to assess and inform environmental-change adaptation strategies.

Recommendations on Next Steps

Key recommendations for consolidation of the AON include:

1. An optimal balance needs to be found between flagship observatory sites and distributed observing networks within the AON.
2. Optimization of an AON capable of sustained, decadal-scale observing will require improved coordination between the agencies that support Arctic observations.
3. Ongoing AON design efforts need a community-based mechanism for identifying new observing priorities and reprioritizing existing activities should environmental change or advances in understanding render them unimportant.
4. Improved standardization and coordination of measurements.
5. Despite progress in developing robust, reliable

oceanographic instrumentation to measure biological and biogeochemical variables from moorings and mobile platforms, integration of biological, chemical, and physical measurements remains challenging and requires attention.

6. More rigorous efforts to integrate human dimensions into network design are both necessary and feasible given new statistical models that facilitate integration of data from different domains.
7. Participants recommended promoting and aiding the northward expansion of established, lower-latitude observing systems that offer the potential to meet some AON needs.

Participants highlighted the following needs that extend across all disciplines:

1. Creation of an international collaborative framework.
2. Better integration of remote sensing into the AON.
3. Collaborative workshops to address key questions that bridge disciplines and increase cohesion of the network.
4. Historical data rescue.
5. Establishment of a community-based Arctic regional climate model.

Participants also identified several near-term issues that must be addressed to foster the evolution of diverse AON components into a sustained, integrated international observing system:

1. System design efforts must be undertaken that (a) draw both from bottom-up approaches driven by individual projects and incremental refinement of measurement sites based on data, model results, and local expertise, and (b) top-down efforts driven by rigorous approaches to observing system design and optimization such as Observing System Simulation Experiments (OSSEs) and other modeling or synthesis efforts.
2. Implementation of a sustained, integrated observing network may prove challenging under existing support mechanisms. AON may need to look towards the methods that other large observing programs have successfully employed to build comprehensive, highly integrated networks. Approaches include reliance on steering committees for additional guidance, strong partnering with government agencies capable of supporting sustained measurements, and development of guidelines and practices that foster coordination.
3. AON must develop effective approaches for partnering with industry and a broad range of federal, state and local agencies to sustain long-term observing activities.
4. At the international level, AON should look to existing organizations, such as the World Climate Research Program's Climate and the Cryosphere (CliC) Program, to provide guidance for implementation and optimization.

Agency Coordination

Interagency coordination and collaboration will play a critical role in shaping an effective, sustainable AON. Although NSF currently supports the majority of AON activities, the network must evolve to serve the observational needs of a wider range of clients. Moreover, sustained observing over decadal timescales will require support from and transition of some AON components to organizations capable of hosting operational activities. This report includes summaries of science and measurement activities and priorities from organizations whose portfolios include Arctic interests.

International Collaboration and Coordination

Recommendations for fostering international coordination include:

1. An inventory of the growing web of international agreements could lead to multi-lateral science agreements, anchored within different agencies in the U.S.
2. AON researchers should contribute where appropriate to international topical data sets and archives.
3. Researchers should take advantage of existing agency programs dedicated to improving international collaboration.
4. A permanent international ice station could serve as a much-needed central Arctic platform for a wide range of observations and as a focal point for international collaboration.

Section II: Introduction and Overview

The Arctic Observing Network (AON) has been envisioned and is now being implemented as a system comprising atmospheric, land- and ocean-based environmental monitoring capabilities – from ocean buoys and community-based observations to satellites and terrestrial flagship observatories – that will help answer urgent questions posed by the scientific community, Arctic stakeholders and society at large. The AON serves the broader aims of the U.S. inter-agency Study of Environmental Arctic Change (SEARCH, www.arcus.org/search). Through a series of community workshops and other interactions, SEARCH identified overarching questions centered around improving understanding and informing responses to the complex, systemic change currently underway in the Arctic. The SEARCH Implementation Workshop Report (SIW, 2005) defined the AON as a key component of the broader SEARCH science strategy whose activities would be guided by modeling and synthesis efforts subsumed under the heading of "Understanding Change," and by input from scientists and a range of stakeholder groups concerned with "Responding to Change," i.e., studies of both observed changes in system behavior driven by change, as well as adaptation to and mitigation of such change.

The International Polar Year (IPY) 2007-2009 motivated increased observational efforts, funded in the U.S. through investments by the agencies that are part of SEARCH. The National Science Foundation (NSF) provided extensive support through the Office of Polar Programs' AON Program. The National Oceanic and Atmospheric Administration (NOAA) and several other agencies also contributed to these efforts, such that the AON included over 40 projects at the start of 2010.

Following implementation of the first dedicated AON projects in 2007, annual meetings have focused on coordinating and integrating observing activities. The first of these meetings, held in 2007 in Boulder, Colorado, established a foundation for effectively communicating plans and activities among AON investigators and provided guidance for the implementation of the Cooperative Arctic Data and Information System (CADIS, **www.aoncadis.org**), the designated portal for AON data dissemination and curation. The Second AON PI Meeting, held in Palisades, New York, was jointly organized by the European DAMOCLES Program (Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies) and SEARCH and sought strong international participation with the overarching goal of fostering broad network integration. This meeting included workshops designed to explore the potential role of autonomous and Lagrangian observation platforms and to synthesize the current state of knowledge and understanding of Arctic change. The resulting workshop report (Arctic Observation Integration Workshop Report, 2008) summarizes important outcomes and recommendations stemming from these meetings.

Building on past activities, and reflecting on needs identified during the first three years of the AON Program, the Third AON PI Meeting, held 30 November to 2 December 2009 in Boulder, Colorado, focused on: (1) producing a broad assessment of AON activities at the close of the IPY 2007-2009, (2) exploring the needs and contributions of a broad range of federal agencies, (3) placing U.S. AON efforts in an international context and (4) learning from the experiences of lower-latitude programs that successfully designed and implemented long-term observing systems. The meeting was attended by a total of 91 participants, with presentations by AON PIs, representatives of international programs (e.g., DAMOCLES, the Canadian ArcticNet Program and the International Study of Arctic Change, ISAC) and representatives of U.S. agencies engaged in SEARCH and AON-relevant activities.

This report summarizes the presentations and discussions of the third AON PI meeting, including key findings and recommendations for near- and medium-term activities. It also includes brief project summaries for individual AON projects. Thus, this document may also serve as a status report of the U.S. AON effort after the close of the IPY.

Section III: AON Accomplishments

Due to its inter-agency support, the total number of AON projects depends somewhat on how AON-related efforts are defined at the agency level; however, the core of the program currently includes over 40 projects, several of which have sub-projects led by different investigators. NSF-supported AON components are required to make their data available in a timely fashion through the CADIS portal and/or one of the other established facilities that offer data dissemination and curation (e.g., the National Ocean Data Center). The CADIS website thus provides an up-to-date overview of the current project roster, including further information on project scope, contributors and data access (**http://www.aoncadis.org/projects/**). A representative, though incomplete, chart of observation sites (Figure 1) provides a sense of the broad scope and geographic distribution of U.S. AON activities (see also project listing in Table 1, and the summary reports of AON projects that are part of this document). Both individual AON projects and the overall AON program are closely coordinated with a range of international observing system activities. Although the chart (Figure 1) does not reflect these ties, they are outlined in Section 4.

A brief review of the status of the AON themes follows below. These categories – atmosphere, ocean and sea ice, hydrology and cryosphere, terrestrial ecosystems and human dimensions – were defined in the Search Implementation Plan (SIW, 2005). The divisions reflect practical considerations, such as efficiencies achieved when networking projects with similar science foci and compatible methodologies and measurement approaches. The level of activity, evidenced by the number of projects supported, varies between these five themes. The factors driving this distribution include urgency associated with key questions (e.g., the mechanisms and impacts of recent, rapid summer sea ice retreat), limitations imposed by existing capabilities and complementarity with other observing programs not described here (such as those by agencies managing land use in Arctic Alaska, see Section 4 of this report). AON investigators agreed that distribution of effort should adapt in response to changing science priorities and societal needs, which could require significant realignment of resources.

Brief summaries of AON projects presented in Appendix 1 detail individual efforts, highlight commonalities and identify next steps at the project, theme and system level. This collection of short project reports captures AON accomplishments and characterizes the state of the network at the conclusion of the third IPY.

Atmosphere (based on summary presentation by T. Uttal at AON PI Meeting)

The present roster of up to ten atmospheric AON projects encompasses a range of research topics with coverage through the depth of the atmosphere, ranging from snow chemistry to the stratosphere-mesosphere. In contrast with the proliferation of automated ocean and sea ice sensor systems, atmospheric observations are significantly more reliant on instruments that require regular operator support for successful operations. Despite these challenges, and building on international collaborative frameworks, wide geographic coverage throughout the Arctic region has been achieved (see also Figure 1), including sites at Barrow, Cherskii, Summit, Eureka, Toolik, Atqasuk, Ny Alesund, Andøya, Chatanika, Kangarlussuaq and over the Arctic Ocean. The projects have identified several common themes. Logistical support is an on-going challenge, especially for programs that collect samples across international boundaries. The project investigators have noted a need for consistent data processing/formats and a desire to coordinate research activities with international collaborators. They also recommend the organization of topical workshops and development of mechanisms that allow for future site co-location and integration into global networks and programs.

Ocean and Sea Ice (based on summary presentation by M. Steele at AON PI Meeting)

A total of 15 NSF-supported AON projects focus on long-term characterization of sea ice thickness and extent, Arctic Ocean circulation, stratification, heat and freshwater content and biogeochemical properties, with the goal of quantifying, understanding and ultimately predicting change on seasonal to decadal timescales. Activities include measurements at two critical gateways (Bering Strait and Davis Strait, an integration point for the Canadian Arctic Archipelago), intensive systems in the Beaufort Gyre, Bering and Chukchi seas and North American shelf/slope system, a North Pole Observatory and arrays of drifting buoys that collect distributed, pan-Arctic measurements. Many of these systems exploit recent developments in autonomous ocean observing technologies to provide extensive, efficient, long-endurance measurements. Partly due to limitations imposed by sensor technologies, measurements currently favor basic physical parameters (e.g., temperature, salinity), with selected biogeochemical variables measured autonomously and a larger suite limited to annual (or longer time scale) hydrographic surveys. AON investigators identified accelerated implementation of biological and biogeochemical observing systems (ideally in conjunction with physical measurements) as a top priority. Such observations will be needed to address scientifically- and societally-driven tasks, such as documenting and understanding changes in Arctic ecosystems and investigating acidification of Arctic and sub-Arctic waters. Geographically, measurements focus largely on the North American Arctic, with greater emphasis on the open-basin than on the extensive shelf-slope system. AON investigators recommended greater engagement with, and participation in, international Arctic observing efforts irrespective of geographical proximity. Given that most human activity radiates from population centers and thus concentrates near the coasts, and that decreasing summer sea ice extent heightens the importance of the marginal ice zone, AON investigators also recommended increased attention to the shelf/slope system. Lastly, meeting participants noted that AON might benefit from ties with well-established lower-latitude ocean observing programs such as ARGO, CLIVAR and the Ocean Carbon Program by drawing on these programs' experience or, perhaps, by facilitating extensions into the Arctic.

Hydrology and Cryosphere (based on summary presentation by M. Holmes at AON PI Meeting)

To date, NSF AON has funded eight hydrology/cryosphere projects, three of which are part of the same over-arching effort (Thermal State of Permafrost, TSP). Three of the projects are pan-Arctic in scope [Arctic Great Rivers Observatory (Arctic-GRO), TSP and Circumpolar Active Layer Monitoring Network (CALM)]. While there is some uncertainty with regards to continuation of four projects that are at the end of their grant cycle (with potential options to submit proposal requests for renewal), substantial progress has been made to date. For example, the Arctic-GRO is now in a position to establish baselines in hydrological and biogeochemical fluxes against which future changes can be compared. The TSP and CALM work is progressing towards good pan-Arctic coverage of assessing the thermal state of permafrost. Recommendations by the Hydrology/Cryosphere investigators at the AON PI meeting were based on a review of how well SEARCH science questions have been addressed to date. While activities are underway to address most of the high-priority questions, these have not yet been integrated into a cohesive network with at least one dedicated flagship site.

Terrestrial Ecosystems (based on summary presentation by G. Shaver at AON PI Meeting)

The AON terrestrial group currently consists of four projects implemented over the past three years, with three projects part of international networks and/or presence at a number of circumpolar sites [International Tundra Experiment (ITEX) carbon, water and energy cycles in Arctic landscapes at flagship observatory sites and in a pan-Arctic network, and the Terrestrial Circum-Arctic Environmental Observatories Network (CEON)]. A fourth project examines the role of fire in the Arctic landscape. These projects form a well-structured, multi-scale monitoring system for plant and soil processes, vegetation community composition, and regulation of terrestrial carbon, water cycling and surface energy exchanges; however, neither aquatic ecosystems nor catchment-scale biogeochemistry are well-represented. In addition to regional and pan-Arctic scale monitoring, e.g., through remote sensing, the greatest need is for a clear system of priorities in selecting new projects that facilitate complementarity of new projects with ongoing AON research. This is being addressed in part through the AON Design and Implementation (ADI) effort but much remains to be done.

Human Dimensions (based on summary presentation by M. Murray at AON PI Meeting)

The AON includes only a single project focused on the human component of the Arctic System, "IPY Collaborative Research: Is the Arctic Human Environment Moving to a New State?" (PIs J. Kruse, University of Alaska Anchorage, Lawrence Hamilton, University of New Hampshire). Phase One of the project includes an assessment of whether existing data are adequate to meet arctic research needs and to support development of adaptive response strategies, with specific emphasis on commercial fisheries, tourism, harvest and consumption of local resources (especially marine mammals), oil, gas, and mineral development and marine transportation. The project also involves selection of community indicators, including modeling to support indicator selection and the development of an integrated GIS database accessible to arctic researchers and arctic organizations. To date the project has resulted in the creation of the Northern Places: Circumpolar Human-Dimensions Data Framework (**http://www.carseyinstitute.unh.edu/alaska-indicators-northern.html**).

This level of human component observing in the AON is inadequate. The AON can and should be envisioned as a program that encompasses a broad, well-defined set of relevant observations designed to improve understanding and projections and inform responding to change initiatives. This will require expanding the

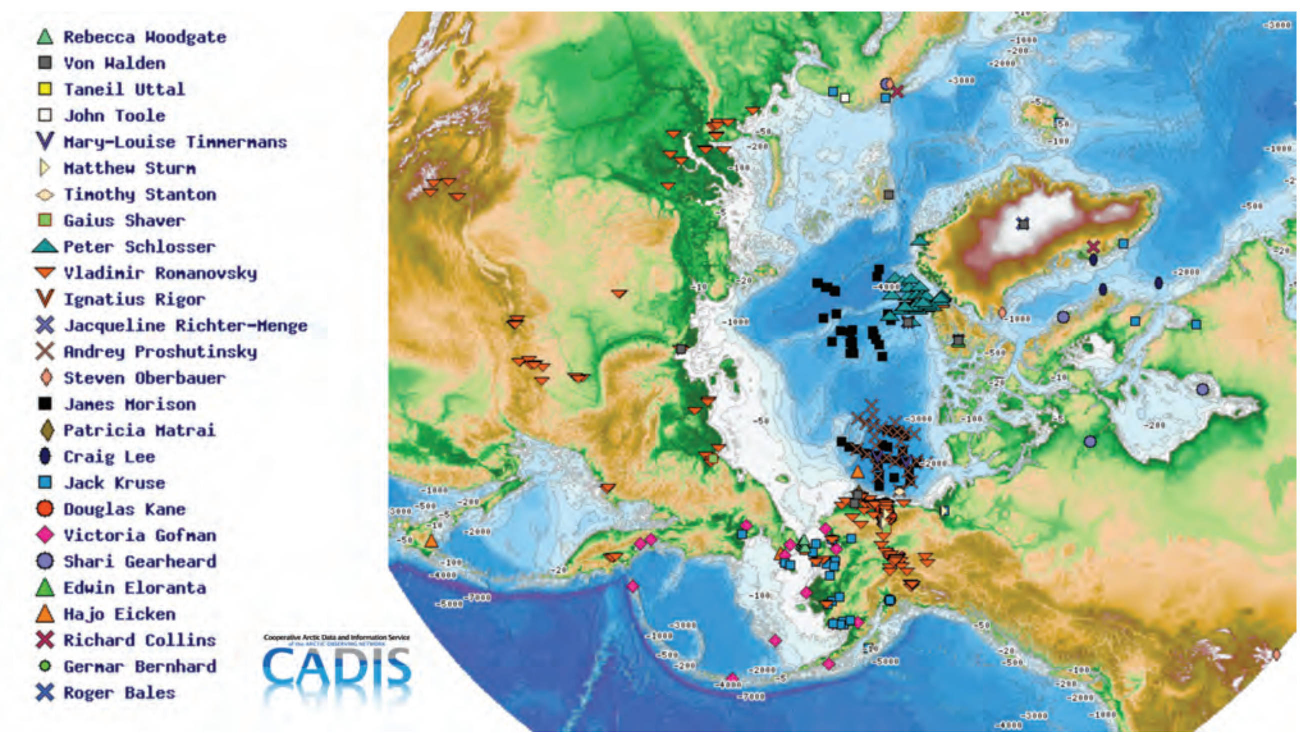

Figure 1. The AON Network measurement locations on a polar projection as of the end of 2009 (obtained from the CADIS GIS Mapserver tool). Observation sites, moorings, and the general region of drifting buoys are assigned a symbol unique to each investigator.

Table 1: List of NSF-AON Projects

(current and immediate past projects, as compiled on CADIS portal)

Please note: Only the lead PI is listed, even for collaborative projects which may have several co-PIs with leading roles at collaborating institutions

Lead PI		
Last Name	**First Name**	**Report Title**
Atmosphere		
Bales	Roger	Core Atmospheric Measurements at Summit, Greenland Environmental Observatory
Bales	Roger	Continued Core Atmospheric and Snow Measurements at the Summit, Greenland Environmental Observatory
*Bernhard	Germar	UV Monitoring Project
*Collins	Richard	Pan-Arctic Studies of the Coupled Tropospheric, Stratospheric and Mesospheric Circulation
Eloranta	Ed	Development of Data Products for the University of Wisconsin High Spectral Resolution Lidar
Eloranta	Ed	A Replacement Laser for the Arctic High Spectral Resolution Lidar
*Matrai	Patricia	The Collaborative O-Buoy Project: Deployment of a Network of Arctic Ocean Chemical Sensors for the IPY and Beyond
*Shepson	Paul	Halogen Chemistry and Ocean-Atmosphere-Sea Ice-Snowpack (OASIS) Chemical Exchange During IPY
*Walden	Von	Cloud Properties Across the Arctic Basin from Surface and Satellite Measurements - An Existing Arctic Observing Network
Walden	Von	Integrated Characterization of Energy, Clouds, Atmospheric State, and Precipitation at Summit (ICECAPS)
Ocean and Sea Ice		
*Eicken	Hajo	The State of the Arctic Sea Ice Cover: An Integrated Seasonal Ice Zone Observing Network (SIZONET)
Eicken	Hajo	Collaborative Research on the State of the Arctic Sea Ice Cover: Sustaining the Integrated Seasonal Ice Zone Observing Network (SIZONET)
Gofman	Victoria	Bering Sea Sub-Network: International Community-Based Observation Alliance for Arctic Observing Network (BSSN)
*Gofman	Victoria	Bering Sea Sub Network: A Distributed Human Sensor Array to Detect Arctic Environmental Change
*Lee	Craig	The Arctic Observing Network at Critical Gateways — A Sustained Observing System at Davis Strait
*Morison	James	North Pole Station: A Distributed Long-Term Environmental Observatory
Morison	James	Aerial Hydrographic Surveys for IPY and Beyond: Tracking Change and Understanding Seasonal Variability
*Pickart	Robert	An Interdisciplinary Monitoring Mooring in the Western Arctic Boundary Current: Climatic Forcing and Ecosystem Response
*Proshutinsky	Andrey	The Beaufort Gyre System: The Flywheel of the Arctic
Proshutinsky	Andrey	Continuing the Beaufort Gyre Observing System to Document and Enhance Understanding Environmental Change in the Arctic
*Richter-Menge	Jacqueline	Ice Mass Balance Buoy Network: Coordination with DAMOCLES
Richter-Menge	Jacqueline	Autonomous Ice Mass Balance Buoys for an Arctic Observing Network
*Rigor	Ignatius	Coordination, Data Management and Enhancement of the International Arctic Buoy Programme (IABP)
*Schlosser	Peter	A Modular Approach to Building an Arctic Observing System for the IPY and Beyond in the Switchyard Region of the Arctic Ocean
*Stanton	Tim	Ocean-Ice Interaction Measurements Using Autonomous Ocean Flux Buoys in the Arctic Observing System

Stanton	Tim	Toward Developing an Arctic Observing Network: An Array of Surface Buoys to Sample Turbulent Ocean Heat and Salt Fluxes During the IPY
*Steele	Mike	UpTempO: Measuring the Upper Layer Temperature of the Arctic Ocean
*Timmermans	Mary-Louise	Observing the Dynamics of the Deepest Waters in the Arctic Ocean
*Toole	John	Design and Initialization of an Ice-Tethered Array Contributing to the Arctic Observing Network
Toole	John	Towards an Arctic Observing Network: An Array of Ice-Tethered Profilers to Sample the Upper Ocean Water Properties during the International Polar Year
Toole	John	Continuation of the of Ice-Tethered Profiler Contribution to the Arctic Observing Network
Woodgate	Rebecca	Comparison of Water Properties and Flows in the U.S. and Russian Channels of the Bering Strait - 2005 to 2006
*Woodgate	Rebecca	The Pacific Gateway to the Arctic - Quantifying and Understanding Bering Strait Oceanic Fluxes
Woodgate	Rebecca	An Ocean Observing System for the Bering Strait, the Pacific Gateway to the Arctic - An Integral Part of the Arctic Observing Network
Hydrology/Cryosphere		
Kane	Douglas	Long-term Measurements and Observations for the International Arctic Research Community on the Kuparuk River Basin, Alaska
*Peterson	Bruce	Arctic Great Rivers Observatory (Arctic-GRO)
*Pfeffer	Tad	Dynamic Controls on Tidewater Glacier Retreat
Romanovsky	Vladimir	Thermal State of Permafrost (TSP): The U.S. Contribution to the International Permafrost Observatory Network
*Romanovsky	Vladimir	Development of a Network of Permafrost Observatories in North America and Russia: The U.S. Contribution to the International Polar Year
Romanovsky	Vladimir	Thermal State of Permafrost (TSP) in North America and Northern Eurasia: The U.S. Contribution to the International Network of Permafrost Observatories (INPO)
*Shiklomanov	Nikolay	The Circumpolar Active Layer Monitoring Network - CALM III (2009-2014): Long-term Observations on the Climate-Active Layer-Permafrost System
*Sturm	Matthew	A Prototype Network for Measureing Arctic Winter Precipitation and Snow Cover (Snow-Net)
Terrestrial Ecosystems		
*Oberbauer	Steve	Study of Arctic Ecosystem Changes in the IPY using the International Tundra Experiment
*Oberbauer	Steve	Sustaining and Amplifying the ITEX AON Through Automation and Increased Interdisciplinarity of Observations
Shaver	Gus	Carbon, Water, and Energy Balance of the Arctic Landscape at Flagship Observatories and in a PanArctic Network
*Shaver	Gus	Fire In the Arctic Landscape: Impacts, Interactions and Links to Global and Regional Environmental Change
Tweedie	Craig	Development and Implementation of the Terrestrial Circumarctic Environmental Observatories Network (CEON)
Human Dimensions		
*Kruse	Jack	Is the Arctic Human Environment Moving to a New State?
Data Management and Coordination		
*Gearheard	Shari	ELOKA: Exchange for Local Observations and Knowledge in the Arctic
*Moore	James	Cooperative Arctic Data and Information System (CADIS)

* *Projects for which a summary report of activities has been submitted for this publication.*

vision of human system observing beyond statistical data on health, demographics, and quality of life, moving outside the traditional community of Arctic investigators to bring in fresh perspectives, new ideas and the participation of new investigators. Willingness to take creative and scientific risks is required to facilitate progress. The AON ADI effort should drive some improvement in human component observing, but there also needs to be integration with ongoing understanding and responding to change activities if this element of the AON is to become operational.

Section IV: AON Investigator Perspectives on Network Design, Gaps and Urgent Needs

As the AON expands and implementation decisions become more complicated, issues of optimal system design and identification of critical shortcomings acquire new urgency. Meeting participants thus devoted time to assessing different design approaches, learning from examples taken from outside the Arctic (e.g., ARGO) and evaluating the mostly 'bottom-up' approach to network design and implementation followed by the AON to-date. This contrasts with efforts to examine network design from a systemic, model-driven perspective – such as the elements of the AON Design and Implementation effort currently underway. The value of reviewing bottom-up approaches rests in the vast store of specialized, sometimes region-specific, knowledge that typically lies behind these design decisions. The resulting systems are likely to be more cognizant of local- and regional-scale constraints on sensor deployment, effective at exploiting potential synergies derived from co-location, and more efficient when developing adaptive approaches that rely on data from the observing network for optimization.

Design efforts face the challenge of optimizing around a broad, sometimes competing, set of specifications defined by the need for observations that address needs ranging from climate research to informing the day-to-day activities of local stakeholders. The AON can be usefully considered in a nested framework of three overlapping domains that provide a range of design parameters (Table 2; Lee et al., 2010).

AON design efforts will face difficult challenges when optimizing across such broad sets of specifications. Although the AON can be envisioned as a network of networks, the constraints imposed by the layered applications clearly favor flexible technologies and approaches that can span multiple tasks and readily

Table 2: Observing system domains and design parameters

	Policy	Strategy	Tactics
Purpose	Science-driven network for climate research & long-term planning	Inform medium-term planning for government, industry and science	Narrowly-scoped networks defined by the needs of local stakeholder
Time scale	Decades, value placed on long records	Seasons to decades, long records valued	Rapid spin-up, spin-down; flexible design
Spatial scale	Distributed, far from population centers	Limited geographic scope, perhaps near population centers	Tightly focused on regions of human activity
Data	Long, consistent records; real-time data return not necessary; resource constraints govern implementation	Rapid data access (near real-time) may be required	Deliver useful products in real-time; data have little shelf life; ease of access is key

adapt to changes in the Arctic environment, stakeholder needs and advances in understanding that redefine observational priorities. Such a framework of applications can provide guidance as the AON faces difficult design choices. Moreover, the constraints posed by these different domains also call for strong coordination and development of synergy between different agencies with activities or mandates in the Arctic (see also Section 4). Several of the projects summarized in Appendix 1 of this report offer perspectives on how to implement observations that bridge two or all three of these domains (e.g., Circumpolar Active Layer Monitoring Program, International Arctic Buoy and Ice-Tethered Profiler Programs, or the SnowNet and Seasonal Ice Zone Observing Networks).

At the AON PI Meeting, the challenges and opportunities implicit in the categorization of different domains and requirements summarized in Table 1 were addressed two-fold. First, an interdisciplinary working group examined some of the overarching issues that need to be addressed in coming years to build a network of networks that is optimized to balance the demands of the policy, strategic and tactical domain in a sustainable fashion. A summary of these discussions is provided in the subsequent section. Second, at the disciplinary level, different working groups identified key gaps or urgent needs for additional resources or efforts. While AON PIs are aware of the broader constraints placed on Arctic research, these gaps were highlighted mostly as guidance to different government agencies and planning bodies (similar to the priorities listed by the North Slope Science Initiative in Section 4) to help synchronization and coordination of efforts meant to help build a more sustained observing effort that achieves a balance between the different types of demands placed on an observing system. A summary of such key gaps or urgent needs follows for the key disciplines represented in the AON at the end of this section.

Overarching, Cross-disciplinary Considerations in Observing Network Implementation

1. **Further work is needed to understand the optimal balance between flagship observatory sites and distributed observing networks within the AON.** While flagship sites foster co-location of diverse measurements and lead to improved understanding of processes driving change, they require substantial investments in infrastructure and may have only a limited sampling footprint. Distributed observatories composed of numerous, low-cost, autonomous sensor systems would likely provide better coverage for the detection of spatially complex signals of change. However, such systems would be restricted to quantifying a limited range of variables. Strong guidance from modeling and synthesis studies, analysis of historical data and remotely-sensed fields will be required to inform these design decisions.
2. **Optimization of an AON capable of sustained, decadal-scale observing will require improved coordination between the agencies that foster and support Arctic observing.** These concerns were examined both from the PI perspective and that of key agencies, with presentations provided by representatives of NSF, NOAA, NASA, Office of Naval Research, several Department of Interior agencies and the inter-agency North Slope Science Initiative. Section 4 presents summaries of agency science priorities and observing activities.
3. **Ongoing AON design efforts need a mechanism based in the science community to identify new observing priorities and reprioritize existing activities should environmental change or advances in understanding render them irrelevant or demonstrate them to be unimportant.** The SEARCH Panels (Observing Change, Understanding Change, Responding to Change) have a key role to play in this context.
4. **Several sub-groups identified a need for better standardization and coordination of measurements.** For example, coordinated atmospheric and cryospheric measurements were identified as necessary for improving the tracking of black carbon and other aerosols in the snow cover. Such standardiza-

tion would require early engagement of agencies charged with maintaining climate reference station networks and observations.

5. **Although significant progress has been made in developing robust, reliable oceanographic instrumentation to measure biological and biogeochemical variables from moorings and mobile platforms, integration of biological, chemical and physical measurements remains challenging.** Critical observing programs, such as NOAA-led efforts focused on marine mammals and fisheries, depend on such integration. Interdisciplinary concerns should become an integral component of network design considerations.
6. **More rigorous efforts to integrate human dimensions into network design are both necessary and feasible given new statistical models that facilitate integration of data from different domains (climate, economics, ecosystems)**. The lack of key Arctic human dimensions data, such as data lacking from the U.S. census, will challenge these investigations.
7. **Participants recommended promoting and aiding the northward expansion of established, lower-latitude observing systems that offer the potential to meet some AON needs.**

Gaps and Urgent Needs at the Level of Disciplinary Observations

At the AON PI Meeting, disciplinary working groups also identified infrastructure and support issues that currently limit development of a sustainable observing network and potentially stand in the way of the type of integration highlighted in the two preceding sections. These disciplinary summaries follow below and are meant to provide guidance to planning bodies in the evaluation of broader-scale needs and potential synergies with other observing programs.

Several key needs extended across the different disciplinary groups. These include calls for the following:

1. **Create an international collaborative framework.** There are large regional gaps in the existing in situ observation network, including areas that are known to be particularly dynamic; for instance, the Eurasian sector where dramatic retreats of the summer sea ice cover have been recorded by satellite and have impacted ocean, atmosphere and the coastal regions. International partnership agreements should be established to facilitate the access of observation teams and their equipment to important study regions in the Arctic.
2. **Integrate remote sensing into the AON.** Spatial coverage of Arctic observations is limited by politics and logistics. Combination of in situ measurements with remote sensing is the solution - complementary use of remote sensing (e.g., GRACE) and in situ measurements has already proven successful. This requires NSF and NASA support of a joint initiative for coordinated and integrated remote sensing and in situ observations in the Arctic, ideally in partnership with other countries.
3. **Structure collaborative workshops to address key questions.** The time is right for hosting a workshop series that brings together relevant investigators across social, biological, and physical sciences to devise projects that bridge the disciplines. This should include the strategic design of an observing system for the Arctic Ocean, using models to optimize its attributes. The workshops should be structured around key interdisciplinary questions, rather than the classic model of presenting current projects. For instance, a possible topic is the long-term outlook for sea ice.
4. **Develop historical data rescue methods.** Through the support of CADIS, SEARCH clearly values the development of a widely accessible central repository of data that are collated and stored for posterity. This effort should be extended to include data rescue and resurrection of in situ measurements collected in historical campaigns to optimize the contextual interpretation of new data.
5. **Establish a community-based Arctic regional climate model.** Predictive forecasts of arctic conditions, necessary for policy makers and community leaders to plan for the impacts of change, are dependent on regional climate models. They also facilitate the strategic development of the AON. A community-based Arctic Regional Coupled Climate Model,

modeled on WRF or CCSM to allow availability to all and input from many, would facilitate the further advancement of predictive capabilities. Attributes should include modularity, data assimilation and a nested grid system to optimize model component development, reanalysis studies, and tiered model resolution.

Atmosphere

There are many challenges in designing an optimal network of measurements of the Arctic atmosphere. In general, researchers strive to understand how the atmosphere interacts with other components of the Arctic system, including sea ice, oceans, permafrost, snow and ice, and the biosphere. As the climate continues to change in the Arctic, human adaptability and health are becoming more important issues. Therefore, it is important to improve our ability to quantify the atmospheric terms in equations describing the Arctic system.

Over the past decade, many groups have documented how researchers might improve knowledge of the Arctic atmosphere. These include the Study of Environmental Arctic Change (SEARCH) program, early documents from NSF's Arctic Observing System, the 10-year plan put forth recently by the Canadian Arctic Research Initiative, as well as others. Four key issues are: 1) inadequate measurements over the Arctic Ocean, 2) current observatories have a "coastal bias", 3) measurement technologies for remote locations are not fully developed (e.g., insufficient power), and 4) the inability to sustain long-term measurement networks with short-term grants. The particular gaps in atmospheric measurements are described below.

To design an effective observing network for the Arctic atmosphere, researchers must: 1) create a nested "network of networks," 2) collaborate with existing programs from different science disciplines (oceanography, sea ice, ...) and international efforts, 3) integrate observations within existing modeling frameworks (forecasting and simulation), and 4) effectively integrate measurement strategies with existing and future (planned) satellite observations. In particular, there is a great need to interface with the Arctic modeling community to more fully understand the limitations of simulating key Arctic atmospheric processes, including troposphere/stratosphere exchange, stable boundary-layer parameterizations, and clouds, aerosols, and precipitation. Increased interaction should elucidate which atmospheric measurements will have the greatest impact on improving model predictions of the Arctic system.

In light of these facts, the following key gaps or urgent issues have been identified:

1. **Increase the number of longer term surface-based measurements of atmospheric variables over the Arctic Ocean. This may include increased utilization of buoys, ships, UAVs, and ice stations. Improved buoy designs are needed for deploying new instrumentation over various sea ice types and open water.**
2. **Design and conduct a new multi-year field program that focuses on atmospheric measurements and their effect on other components of the Arctic system.**
3. **Deploy a new permanent ice station over the Arctic Ocean for long-term measurements of the Arctic atmosphere.**
4. **Deploy instrumentation at Tiksi, Russia on the Siberian coast to make this comparable site to Barrow, Eureka, and Summit, in terms of atmospheric and cloud measurements.**
5. **Develop long-term funding sources to support improved atmospheric measurements in the Arctic.**

Ocean

For the Arctic Ocean, key gaps or urgent observing needs are summarized below, with the first three activities recognized as top priority items in the 2005 Report of the SEARCH Implementation Workshop (SIW).

1. **Sustain repeat hydrographic and tracer sections across water mass fronts.** Fronts represent boundaries between physical, chemical, and biological regimes that are changing as summer sea ice retreats and the Arctic climate warms. Annual surveys can be in summer by icebreaker (e.g., Beaufort Gyre Observing System, BGOS), in spring by aircraft (NPEO,

Switchyard), and in the future by gliders or other autonomous sensors. Submarines are another useful platform capable of repeat trans-Arctic sections along the historical SCICEX line. Given the rapid changes observed in recent years, repeat surveys (hydrologic and tracer) on at least an annual time scale are required. Co-located late summer and late spring surveys are required to observe seasonal variation.

2. **Sustain flux measurements through connecting straits.** Water transports between the Arctic and the North Atlantic Ocean (e.g., via Fram and Davis straits) influence local ecosystems and the global ocean circulation. The Pacific inflow, via Bering Strait, is a key source of heat, freshwater and nutrients for the Arctic, with further field influence on the Arctic outflows and the Atlantic.

3. **Sustain time series at key sites that monitor boundary currents.** Changes to the Atlantic Water boundary current (AWBC) have been linked to climate trends and oscillations. Sustained monitoring of the AWBC needs to be established in the Canada Basin by long-term multiple mooring arrays, supported by annual surveys. NABOS needs to be continued to monitor the boundary current in the Eurasian basin.

4. **Support interdisciplinary measurements.** Coupled models predict that the Arctic Ocean will experience the earliest and largest pH changes on the planet. Limited recent observations lend credence to this prediction. Robust measurements of pH and the carbon system at key locations are required. In situ sensing systems need to be optimized for deployment in the Arctic environment. Appropriately calibrated in-situ chemical sensing systems are required to more effectively address aspects of circulation and biogeochemical change. Examples of sensors of proven utility include dissolved oxygen and optical nitrate.

5. **Sustain the observation programs that measure changes in Arctic Ocean circulation.** To elucidate phenomena that are of interannual to decadal time-scale, well chosen and productive surveys and programs that have some history (e.g., NPEO, Beaufort Gyre Observing System, Bering Strait observational program, Ice-Tethered Profiler, Ice-Mass Balance Buoy, Ocean flux and O-buoy programs and co-located Ice Based Observatories) should not be interrupted or stopped. Continuation of existing time series was also recommended in the SEARCH Implementation Workshop (SIW) Report (2005).

6. **Support development and broad deployment of distributed autonomous systems (floats, gliders, IBOs) within the AON.** These systems offer highly scalable, flexible measurement capabilities that could provide distributed, year-round measurements across the Arctic (ANCHOR Workshop Report, http://anchor.apl.washington.edu). Near-term priorities should include support for the development and testing of a low-frequency acoustic navigation source capable of basin-scale ranges and funding of a basin-scale pilot experiment that addresses high-priority science while also providing a proof-of-concept exercise for the envisioned network of floats, gliders and IBOs supported by long-range acoustic navigation and short range acoustic communications. The Arctic Observation Integration: Workshops Report (ARCUS, 2008) identifies the Beaufort Gyre as a logistically feasible and scientifically valuable target for this effort.

7. **Continue to monitor the evolving ocean/ice albedo feedbacks that are unfolding particularly in the Beaufort Sea.** This involves the following observational elements, which have largely been proven in IPY deployments: a) Improved satellite and in situ estimates of open water fraction (which result both from melting processes and divergence), b) Improved satellite-based and in situ measurements of ice divergence, c) Wide coverage of coincident upper ocean, ice and atmospheric heat flux measurements (including long term short and long-wave radiation), d) Continued coverage of at least the upper ocean temperature and salinity profile structure and preferably turbulent diffusivity to look at the regionally variable ocean contributions to ocean-ice fluxes at sites coincident with the coupled flux measurement sites.

8. **Develop an initiative for Makarov Basin observations.** The Atlantic-Pacific front and Transpolar Drift boundaries move through the Makarov Basin

(the southern portion of which is greatly under-sampled) shifting position at interannual and decadal timescales. An initiative (possibly U.S. and Russian) is required to monitor the southern half of the Makarov Basin through regular CTD surveys and a sustained mooring.

Sea Ice

The following activities, in loose priority order, are immediate needs for the sea ice observations component of the AON. Activities that correspond to the top priorities in the SIW Report (2005) are indicated.

1. **A coordinated comprehensive investigation to improve remote measurements of sea ice thickness and snow depth (SIW, pg. 15, Priorities 1 and 2).** Satellite-borne instruments designed to measure sea ice thickness and snow depth are key monitoring tools, providing extensive spatial and temporal coverage. New airborne and ice-based technologies are available to further improve the degree of certainty in these satellite assets and provide an important opportunity to help bridge the transition between ICESat, ICESat2 and CryoSat. A highly coordinated, interagency and international effort to collect and analyze a comprehensive set of observations from all relevant ice-based, airborne and satellite-borne assets would facilitate a significant state-of-the-art advancement.
2. **Sustained sea ice mass balance measurements (SIW, pg. 15, Priorities 1 and 2).** Changes in the extent, thickness and composition of the sea ice cover have a wide ranging impact, from environmental to socioeconomic to geopolitical. In coordination with ocean and atmosphere measurement, an observational network that includes strategic in situ measurements (e.g., ice mass balance buoys, moored upward looking sonar, GPS buoys), repeated submarine (e.g., SCICEX) and pan-Arctic airborne thickness surveys (e.g., Lidar, radar, electromagnetic induction), and satellite remote sensing (e.g., ICESat, CryoSat, QuikScat, Radarsat) should be continued, uninterrupted. The aim of this integrated, interdisciplinary approach is to reveal, monitor and attribute changes in the sea ice mass balance (including the overlying snow cover) on the interannual to decadal time scale, with adequate attention to both the seasonal and perennial sea ice zones. AON and SAON are in place to facilitate this observing network. The challenge is to assure the longevity of these programs.
3. **Development of a portable, air-deployable, "disposable" energy balance station (SIW, pg.15, Priority 3).** The inability to efficiently collect a suite of observations to define the energy balance of the atmosphere-ice-ocean system is a significant technology gap. Particular attention should be given to developing an autonomous ice drifting buoy that measures parameters at the surface and throughout the atmospheric boundary layer (approximately 500 m) to complement existing autonomous ocean (e.g., Ice-Tethered Profilers) and ice (e.g., Ice Mass Balance buoys) systems. These stations should be designed for deployment onto relatively thin first-year ice and should be able to maintain proper sensor configurations (e.g., free of rime ice). A key challenge would be adequate power supply in during winter.
4. **Sustained observations of the energy balance of the atmosphere - ice - ocean boundary layer system (SIW, pg.15, Priority 3).** Changes in the conditions of the sea ice cover are driven by the energy balance of the atmosphere-ice-ocean boundary layer system. These changes affect the physical, biological and chemical characteristics of the arctic region. Key measurements include the sea ice albedo, surface net radiation and shortwave energy partitioning, turbulent atmospheric and oceanic heat fluxes to the ice, and the heat and salt budget of ocean mixed layer and regional input by ice growth/melt. The routine and sustained collection of these observations as part of AON should be assured.

Hydrology and Cryosphere

Several of the existing AON hydrology and cryosphere projects are actually networks themselves. For example, both the TSP and CALM projects are networks of many sites making coordinated measurements on permafrost and the active layer, and the ARCTIC-GRO project is a network where water quality samples are being collected from the six largest Arctic rivers in Russia, Canada, and Alaska. Focused networks such as these tend to be more successful than loosely defined networks. It was also agreed that maintenance of river water discharge monitoring stations within the pan-arctic watershed is essential for linking the various hydrology and terrestrial cryosphere projects. Although government agencies in the U.S., Canada, and Russia are in charge of maintaining river discharge gauges, R-ArcticNet and Arctic-RIMS have been a very important resource facilitating data access and discovery. It was noted that no representatives from the discharge monitoring agencies or R-ArcticNet / Arctic-RIMS were at the meeting and that it would be good to involve these groups more formally in AON.

There was also a lot of discussion about the importance of co-location of the different components of AON, both within the hydrology and cryosphere domain as well as between hydro/cryo and the other components of AON. In spite of this recognition, the reality is that for a variety of reasons there is currently very little overlap in the spatial domains of the various hydrology and cryosphere projects. This stifles opportunities for synergisms that arise from co-location of complementary observations.

In general the group felt that future funding opportunities should not be over prescriptive, but that there might be better resources for new investigators to learn about the suite of existing AON projects. There was also some discussion as to whether requiring pre-proposals might help NSF and the AON community increase the likelihood that new efforts would compliment the existing AON. There was concern about the fate of AON proposals that were submitted to the annual ARO – would reviewers get enough guidance to evaluate the AON proposals given that their merit very much depends on how they fit with and add to the existing network? Similarly, with current funding for many of the AON hydrology and cryosphere projects approaching an end, what are (or should be) the requirements for renewal proposals?

To facilitate network design, the consensus was that there was no substitute for face-to-face meetings. The hydrology and cryosphere group lamented that we did not have more time to brainstorm about collaborations, priorities, and synergisms during this AON PI meeting.

In terms of most urgent priorities for the future, they really are the same ones that have been previously identified (Table 3). In fact, the three highest priority activities (all identified as Priority 1) could be combined into a single priority – we need a few flagship research

Table 3: SEARCH Hydrology/Cryosphere Observing Activity Priorities (SIW, 2005)

Activity	Priority
1. On land, initiate at least one intensive site for integrated time series measurements that include climate, surface energy balance, hydrology, glaciology, trace gases, permafrost/active layer, C/N/P budgets, species composition, vegetation structure, and contaminant compounds; apply new technology, numerical analyses, and remote sensing to extrapolate field measurements to high quality circumarctic gridded datasets	1
2. Determine water balance components in flagship research watersheds, key benchmark glaciers, and on the Greenland Ice Sheet through field measurements, remote sensing, and modeling	1
3. Determine spatial variation and temporal patterns of permafrost degradation, glacier ablation, and changing water resources	1
4. Characterize permafrost and hydrological controls on vegetation change and quantify the resultant impact of ecosystem change on freshwater fluxes and biogeochemistry	2
5. Integrate hydrology and glacier measurements with ecosystem dynamics	3
6. Integrate glacier and ice sheet mass balance measurements with observations of climate dynamics	2

watersheds where a broad, integrated, and complimentary suite of measurements are being made. These watersheds should be of sufficient size to facilitate scaling up, but not so large as to be intractable at the whole-watershed scale. These research watersheds should also be broadly dispersed in order to capture some of the spatial variability apparent at the pan-arctic scale. No one group (or proposal) should attempt to tackle all aspects of a particular watershed. Instead there should be an open call for investigators to propose focused studies that would contribute to the whole. Candidate watersheds might include the Kuparuk River and comparably sized sub-watersheds in the Yukon and Kolyma basins. Perhaps the Yukon basin site could be selected to include glacial coverage. Much like an oceanographic cruise benefits greatly from the synergisms that develop as a result of a group of scientists making their measurements at common sites, so too would the hydrology and cryosphere communities benefit from this level of coordination and co-location.

Terrestrial Ecology

The current group of terrestrial AON investigators identified the following high priority needs:

1. **Better access to satellite data obtained with a high level of resolution (~1 m) over the Arctic.** These data will enable investigators to assess land cover changes over a wide spatial area, to complement more intensive, process-based measurements made at the few sites where we are currently working. A number of satellite systems already exist with reasonable Arctic coverage; many of them, however, are commercial satellites and it is expensive to obtain the imagery. It would be very useful to establish a satellite data harvesting facility that would archive and make these data available to the community at low or no cost.
2. **An accessible and researcher-available airborne LiDAR and visible-IR spectrometry and photography system (with GPS) for all-season use.** The National Ecological Observatory Network (NEON) is developing such instrumentation as part of their Airborne Observation Package (AOP). The coupling of the visible-IR spectrometry with the LiDAR is still under development, but is expected to be completed soon, in which case a manufacturer (and better cost estimates) will presumably be available. The NEON AOP will not be based in the Arctic, though limited missions will be flown in the vicinity of their key sites.
3. **Airborne LiDAR shows great promise for a) determining snow depth and distribution over large areas, b) examining frost heaving in permafrost terrain, c) quantifying biomass changes over seasonal and longer periods, and d) developing digital elevation models for regional and local snow, weather, and ecosystem modeling.** An aircraft-mounted LiDAR system, with co-registered aerial photographic system mounted on a plane that resides in Alaska and is available for both winter and summer studies is needed. The instrumentation and control systems require approximately $500,000. The aircraft need not be a dedicated aircraft, but will potentially require modification for the instrumentation (est. $100,000). One possibility is to have the aircraft owned, operated and maintained by the Office of Aircraft Services (DOI), in which case funds to allow researchers not with DOI to access the aircraft and use it for field campaigns will need to be identified and made available. The aircraft should also be capable of being used as a platform for other instruments, including hyperspectral scanners.
4. **Mobile Field Camp & Laboratory**: The U.S. Arctic terrestrial research program currently relies on a few fixed stations (Toolik, Barrow, Inigok), with either daily helicopter access to more distant points, or rudimentary spike camps for more intense campaigns (a nylon tent and small stove). An intermediate facility is needed — essentially a mobile camp and laboratory system that can be placed where new and exciting terrestrial science arises, and where on-site research extending from weeks to months is expected. This modular system should be both air and over-snow deployable, should be able to house about 4 to 6 researchers, and should include modern power and communications modules that allow rapid dissemination of broad-band data from the site (via satellite) and can meet power demands typical of

both field and laboratory science. Development of this mobile camp and lab should take place in four phases.

5. **Mobile eddy covariance tower systems, with the capability to measure meteorological variables, energy balance, and fluxes of CO_2, methane, and water vapor.** These should be deployable at sites that are not on the road system. Data on energy balance and the fluxes of radiatively active gases such as CO_2, methane, and water vapor are essential for observing feedbacks from the terrestrial system to future climate in the Arctic. Mobile tower systems would complement the longer-term, continuous measurements that are being made continuously at flagship observatories, such as Toolik Lake, Alaska; Barrow, Alaska; North East Science Station, Cherskii, Russia; Zackenberg, Greenland; and Abisko, Sweden. Again, NEON provides a model for these mobile towers with their proposed relocatable tower systems, of which only one system is currently scheduled to be deployed in the Arctic. It might be possible to simply order a few more according to their design, but developing remote power systems will be a challenge.

Human Dimensions

To advance understanding of human dimensions in the changing Arctic system, we should follow through on the SEARCH implementation plan's recommendation for integrated research on the interactions between environmental, socioeconomic and cultural changes. Environmental changes and emerging issues that have substantial importance for Arctic residents were summarized recently by the North Slope Science Initiative:

- weather and climate
- increasing marine activity
- changing sea ice conditions
- contaminants affecting subsistence diets and species
- permafrost
- coastal and riverine erosion
- hydrology and lake drying
- coastal salinization
- fire regime
- vegetation change
- species of interest, such as fish, caribou, marine mammals, migratory birds
- increasing marine activity
- sea ice

For all of these emerging issues, environmental changes already are manifest and likely to increase. Human impacts could be expected across a range of economic activity, infrastructure, employment, migration, transportation, health and subsistence indicators. Observing systems exist in scattered form needing integration for some of these indicators (such as migration, transportation, fisheries, some aspects of health), but are very weak for others (particularly subsistence). With coordination of scattered existing data plus new observations, integrated, empirical studies are possible and needed. Such studies will contribute not only to better understanding of human impacts and feedbacks, but also to the prospects for adaptive steps and more sustainable Arctic communities.

In addition to integrated research on human-environment interactions, there is also a need often expressed by Arctic residents for improved, user-friendly access to scientific observations about Arctic environmental changes, such as daily information on sea ice, on medium-term changes affecting the health of key species, or on contaminants in country foods.

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Section V: Agency Summaries

Interagency coordination and collaboration will play a critical role in shaping an effective, sustainable AON (IARPC, 2007). Although NSF supports the majority of current AON activities, the network must evolve to serve the observational needs of a wider range of clients. Moreover, sustained observing over decadal timescales will require support from and, perhaps, transition of some AON components to organizations capable of hosting operational activities. In an effort to advance interagency coordination efforts within the AON, representatives from organizations whose portfolios include Arctic interests provided summaries of their science and measurement priorities along with overviews of current activities.

National Oceanic and Atmospheric Administration

The National Oceanic and Atmospheric Administration (NOAA) conducts both operational and research observations in the Arctic region. These are done to satisfy mission requirements identified in NOAA's Strategic Plan. In summary, NOAA's strategic priorities are weather, climate, marine and coastal resource management, and commerce and transportation. Most observing activities have a primary reason for being, but in fact support more than one strategic priority. The major observing activities are described below.

Atmospheric Observations

NOAA and its partners maintain a network of atmospheric observatories around the Arctic. Primary sites include Barrow, Alaska; Eureka/Alert, Canada; Greenland Summit; and Tiksi, Russia. The principal observables are solar radiation, surface energy budget, trace gases, aerosols, clouds and their properties, greenhouse gas fluxes, and standard meteorology. In Alaska, NOAA maintains a network of weather observing sites to obtain the real-time data to support weather forecasts for Alaska.

Hydrologic Observations

NOAA conducts observations of precipitation and river stage to provide timely and accurate river and flood forecasts in Alaska.

Ocean and Sea Ice Observations

NOAA is a partner with other organizations to maintain support for the International Arctic Buoy Program, whose on-ice buoys provide real-time surface air temperature, sea level pressure and ice drift to operational weather and ice forecast centers. Similarly, NOAA helps support a network of Ice Mass Balance Buoys and Ice Profiling Sonar moorings to obtain data on changes in sea ice thickness and help understand the causes for the observed changes.

The Alaska Ocean Observing System (AOOS) is another NOAA-supported activity focused on ocean observations in the near-shore regions of Arctic Alaska with an emphasis on public benefit. The AOOS also houses the Alaska Marine Information System.

NOAA and partners conduct the Russian-American Long-term Census of the Arctic (RUSALCA), whose long-term objective is to detect climate-related changes in the Arctic marine environment and the biological response to those changes. The project combines observation and modeling and emphasizes the geographic area of the Northern Bering and Chukchi Seas, including both the U.S. and Russian portions of this area.

NOAA conducts fishery stock assessment observations in the southeastern Bering Sea on an annual basis to provide the data required for fishery management. Data on target species and the general environment are obtained to aid with projection of future resource abundance. Initial marine fishery resource observations have been conducted in the Beaufort and Chukchi seas.

Additionally, marine mammal surveys are conducted in the Bering, Beaufort, and Chukchi seas to determine population levels and their trends for those species (whales, sea lions, and seals) under NOAA's protection and management.

NOAA maintains a number of automated marine observing systems around the Arctic region of Alaska. These include continuously operating water level stations, coastal meteorological and marine stations, and offshore meteorological and wave buoys. These systems report in real-time and the data are available to the public.

Future Priorities

Over the next few years, NOAA expects to reorient its Arctic activities to emphasize six new strategic objectives, as defined in a recent Arctic Vision and Strategy Report (www.arctic.noaa.gov). These new objectives may cause a realignment of observing locations, variables, and/or approaches over this time period.

Department of the Interior/U.S. Geological Survey

The U.S. Geological Survey (USGS) has historical records on the natural features of Alaska that date back to its earliest geologic expeditions in the 1800s. Today, the USGS Alaska Science Center (ASC), with its headquarters in Anchorage, Alaska, provides local scientific expertise and products to a wide variety of partners. Bureaus of the Department of the Interior (DOI) manage more than 200 million acres of trust lands in Alaska. These include the lands and waters of National Parks, National Wildlife Refuges, Bureau of Land Management units, and Federal offshore areas. The DOI science supports the management of Alaska's federal trust lands and waters, including mammals protected by the Marine Mammals Protection Act, migratory birds subject to federal laws and international treaties, anadromous fish, species protected under the Endangered Species Act, wildlife and fish of key importance to rural subsistence harvest, and sea otters and their habitats recovering from the Exxon Valdez Oil Spill. Science products include trends assessments from long-term inventory and monitoring data, digital elevation models, landcover and geological maps, and scientific studies that focus on wildlife-habitat interactions and the effects of climate change.

The USGS conducts studies on the mineral-resource potential of all public lands in Alaska to provide information on where mineral commodities are known and suspected to occur and the environmental consequences of the presence of those commodities. Studies focus on bedrock and surficial geologic mapping, rock and stream sediment geochemical surveys, airborne and ground geophysical investigations, and mineral resource assessments.

The USGS monitors streamflow at more than 170 locations to forecast flooding and streambed scour, predict the magnitude and frequency of extreme events, provide hydrological assessments for water resources development, describe the status and trends of water quality, and assure minimum instream flows for fisheries.

USGS conducts fisheries research on public lands and waters. Topics include tracking populations of fish and other aquatic species for subsistence, commercial, and sport harvest, environmental conditions that affect aquatic populations, habitat use in rivers, estuaries and coastal areas, changes in water temperature and sea ice extent, and coastline erosion.

The USGS provides science for forecasting and mitigating disasters. Monitoring programs that address natural and emerging hazards include volcano tracking through the Alaska Volcano Observatory, cooperative programs between the USGS, the Geophysical Institute at the University of Alaska in Fairbanks, and the Alaska Division of Geological and Geophysical Surveys, the USGS streamflow monitoring network for flood warning and mitigation, and studies of emerging wildlife diseases, such as Avian Influenza (Highly Pathogenic H5N1) in migratory birds.

Two new DOI initiatives are underway in response to the September 14th, 2009 Interior Secretarial Order 3289 defining DOI's Climate Change Response Strategy. The USGS is currently leading a collaboration of DOI Bureaus and the University of Alaska to establish the Alaska DOI Regional Climate Science Center (CSC) as the first of a network of eight regional Climate Science Centers that DOI Secretary Salazar called for in Order

3289. The goal of the Regional Centers is to build science collaborations to understand processes controlling climate change impacts on high priority resources, and to provide science information and tools that can help land, water, fish, wildlife, and cultural heritage resource managers develop strategies for responding to those impacts. The primary functions of the Regional Centers will be to link physical forcing factors through downscaled GCMs with biological, physical, ecological, and cultural resource response variables for assessing climate change impacts, develop regional response models and projections for priority ecosystems, species, habitats, and other natural and cultural resources within the region, develop response models and forecasts to support adaptation and adaptive management strategies, assess the outcomes of adaptation activities, and facilitate and fund research and decision support tools that supply regional-level information on the effects of climate change on land, water, fish and wildlife, and cultural heritage resources.

The Fish and Wildlife Service is establishing four Landscape Conservation Cooperatives (LCCs) in Alaska that will serve as local centers for encouraging communication and collaboration among resource managers and climate change scientists in order to solve local climate change issues. The LCC provides a geographical framework, based on Bird Conservation Units that are roughly equivalent to ecoregions, within which decision-support research and tool development can occur to support local conservation actions in a changing climate.

A new USGS "Changing Arctic Ecosystems" initiative will strive to understand both "what" is happening to wildlife and their supporting ecosystems and "why" it is happening in response to changes to the ice-dominated ecosystems [marine (sea ice) and terrestrial (permafrost)] of the Arctic. This research initiative focuses on three broad ecosystems, and is structured to understand the linkages between physical processes, ecosystems, and wildlife populations. The three ecosystems are: (1) the marine sea ice ecosystem of the Bering, Chukchi and Beaufort seas; (2) the continuous permafrost-coastal ecosystem of the Arctic Coastal Plain of far northern Alaska; and (3) the discontinuous permafrost-boreal forest ecosystem spanning the transition between the Interior and far northern regions of Alaska.

DOI bureaus have been providing scientific information on climate-related issues in Alaska for many years prior to the development of the CSC. The BLM is the current program coordinator for the North Slope Science Initiative, a multi-agency effort to describe and understand the ecosystems and resources of the North Slope of Alaska. The National Park Service has enhanced its Inventory and Monitoring Program and is collaborating with scientists within and outside of the government to track ecosystem health on Park lands. The Minerals Management Service plays an active role in Arctic coast and ocean science. The USGS has also been an active member of the Great Rivers project, an international team of scientists investigating changes in river carbon flux, and is helping initiate a new international boreal forest biogeochemistry assessment. DOI therefore brings significant resources to the challenge of developing a comprehensive, multi-scale strategy for linked research and monitoring in the Pan-Arctic region.

The USGS/DOI Climate Effects Network is linking research and long-term observations into a multi-scale, multi-program strategy for tracking the status and trends of climate impacts across the United States. This network will help link information and data across Climate Science Center and Landscape Conservation Cooperative (LCC) units, as well as other federal, state, and NGO programs, so that interdisciplinary assessments of climate impacts can be accomplished, and gradients of climate broader than those occurring in individual LCC units can be utilized to understand local to national-scale ecological responses.

National Aeronautics and Space Administration

NASA's Earth Science Division supports research activities that address the global integrated Earth system to characterize its properties on a broad range of spatial and temporal scales, to understand the naturally occurring and human-induced processes that drive them, and to improve our capability for predicting its future evolution. The focus of the Earth Science Division is the use of space-based measurements to provide information not available by other means. NASA's program is an end-to-end one that starts with the development of observational techniques and the instrument technology needed to implement them; tests them in the laboratory and from an appropriate set of surface-, balloon-, aircraft-, and/or space-based platforms; uses the results to increase basic process knowledge; incorporates results into complex computational models that can be used to more fully characterize the present state and future evolution of the Earth system; and develops partnerships with other national and international agencies that can use the generated information in environmental forecasting and in policy and resource management.

As a global research program, NASA supports a wide range of Arctic science activities. NASA funding sources for Arctic science are varied, although the Cryospheric Program is the main source, funding studies with ICESat and CryoSat 2. Other programs active in the Arctic include Physical Oceanography, Ocean Biology & Biogeochemistry, Atmospheric Composition, and Terrestrial Ecology. In addition, there is a range of interdisciplinary solicitations that offer opportunities to conduct Arctic research.

Nearly all NASA Earth Science Research and Analysis programs support Arctic work by funding researchers at NASA centers, other government laboratories and at academic institutions. Some resources used for Arctic work include satellite instruments (e.g., AMSR-E and MODIS), satellites (e.g., GRACE, and the now defunct ICESat and QuikScat), and a wide range of manned and unmanned aircraft. In addition to the current suite of satellite assets, there are two satellites in planning stages that are especially relevant to AON goals. ICESat-2 is a LIDAR mission planned for launch in 2015 that would measure ice mass change, sea ice freeboard, and terrestrial biomass, and would have abilities to study Arctic rivers. DESDynI will be a combined InSAR radar and LIDAR mission planned to launch in 2019 that would have the ability to discern ice motion, as well as terrestrial biomass.

NASA has a strong legacy of measurements in the Arctic such as Arctic sea ice coverage beginning in 1978 with Nimbus-7 and continuing with the A-Train result on the cause of the maximum summer melt of Arctic sea ice in 2007 September. Additional examples of NASA-supported Arctic research include the "rctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) program in 2008. The SEARISE - <u>Sea</u>-level <u>R</u>esponse to <u>I</u>ce <u>S</u>heet <u>E</u>volution – program and a suborbital mission entitled IceBridge that is designed to bridge the gap between the recently failed ICESat and next LIDAR (ICESat 2) mission. In addition to satellites and manned aircraft, NASA has a fleet of unmanned airborne vehicles (UAVs) for polar science. One example of their use was the 2009 "Characterization of Arctic Sea Ice Experiment" (CASIE) expedition. A current program is ICESCAPE - Impacts of Climate Change on the EcoSystems and Chemistry of the Arctic Pacific Environment – that will conduct field campaigns on the icebreaker *Healy* in 2010 and 2011 to improve understanding of carbon cycling in the Beaufort and Chukchi seas. In addition to these major campaigns, a wide range of research awards are regularly made to small groups of researchers with more narrow research questions.

NASA can support AON science in many ways since its assets already have been collecting data for the Arctic for many years and are expected to do so into the future. NASA supports the efforts of AON to develop in situ observational capacities that NASA can leverage with to enhance our validation and calibration efforts in the Arctic. Our modeling efforts also require improved observations that AON would support. NASA Earth Sciences are committed to working with AON and other efforts to improve understanding of the global integrated Earth system as the Arctic changes in coming decades.

Office of Naval Research

Given the observed and predicted changes in the Arctic environment, the Navy must consider these issues when developing future policy, strategy, and investments. To address the challenges of the changing Arctic, the Navy has established Task Force Climate Change (TFCC), which has developed an Arctic roadmap to lay out the Navy action items, objectives, and desired effects related to Arctic activities. Among these actions is a renewed charge to monitor, understand, and predict ongoing changes in the Arctic maritime environment. The Office of Naval Research (ONR) is charged with identifying and addressing the science and technology needs to enable the development of the required naval capability for operating in the Arctic.

ONR's planned activities in the Arctic will focus on research that will provide a comprehensive understanding of the present and future physical environment on tactical, operational, and strategic scales. The unifying goal for ONR will be the development of integrated (atmosphere, ocean, cryosphere and land surface) predictive models that can be used to forecast Arctic conditions on lead times ranging from days to decades. Short-term environmental forecasts will be the initial priority, and will require the assimilation of both in situ and remote sensing observations to provide the initial conditions. These observations are also essential to ONR's other scientific goals in the Arctic, which are a better understanding of the dynamics of the environmental processes and an ongoing monitoring of environmental change. The requirements of the predictive models will guide further scientific investment, such as the development and placement of new observational sensors and the need to better understand particular physical processes that impact changes in the Arctic environment.

The development of new models for predicting the Arctic environment, the development of new sensors, platforms, and techniques for observing the Arctic environment, and the formulation of scientific efforts to provide new understanding of the Arctic environment will all be done in close coordination with other U.S. and International agencies that fund Arctic research and operate in the Arctic. Activities and efforts under consideration by ONR include enhancements in the observation network in the Arctic, development of new platforms (e.g., UUVs) and methods (e.g., acoustics) for making observations, and a renewal and enhancement of scientific participation in the SCICEX and other Arctic field programs.

North Slope Science Initiative

Over the past two years, the North Slope Science Initiative (NSSI) has been engaged in identifying data and information resources that managers need to make better decisions over the next two decades (Table 3). Observational systems and platforms top the recommendations, along with targeted research. While the first 13-Emerging Issue Summaries (www.northslope.org) were presented to the senior agency managers in December 2009, it was clear that the collective identified needs were well beyond what any single agency or entity could implement. So the NSSI began the process of prioritizing subject areas where the greatest number of interested parties would benefit. At the top of the priorities is the need to bring together and synthesize weather and climate data across the North Slope and the marine environment and make this information available to both agency staff and researchers. In addition to the synthesis, there is a clear need to expand in an improved, well coordinated, and centrally managed system to collect and store weather and climate data across the North Slope. The NSSI is working in conjunction with the Minerals Management Service and the University of Alaska Fairbanks (UAF) to inventory and normalize meteorological stations and data collected over the past four decades. This will be the first step in identifying were gaps in the data exist and in planning for the placement of future stations.

A second priority is the clear need to develop a comprehensive, accurate and digital base map of the vegetation associations across the North Slope. Since the availability of Landsat Thematic Mapper imagery there have been approximately 55 different attempts to provide a base vegetation map for the North Slope. The majority of these have been to support the oil and gas industry in their monitoring programs and have focused on relatively small areas. A few have attempted to quantify vegetation at the landscape level but have focused on the administrative constraints imposed by their agency. Additional vegetation maps have been made available for the entire North Slope but have not been supported by field validation efforts and thus have questionable accuracy for monitoring change over time. The NSSI, in conjunction with the Alaska Natural Heritage Program, National Land Fire and Ducks Unlimited, Inc., have initiated a three-year field project that, when complete, will provide the first comprehensive, field validated, digital land cover map with high accuracy that can be used as a base for a number of user requirements including measuring change.

Other broad subject areas, such as permafrost, coastal and riverine erosion, sea ice and ocean condition, increasing marine activities, fire regime, contaminants and social and economic structure are also addressed in the Emerging Issue Summaries. These subject areas are currently being evaluated by the NSSI Science Technical Advisory Panel for inclusion in a strategic implementation plan. Beyond the emerging issues, the NSSI is aggressively implementing a comprehensive Project Tracking System (PTS) that currently has nearly 1200 records of planned, current and recently completed projects in the U.S. Arctic. In addition to the PTS, the NSSI, in conjunction with the UAF-housed Geographic Information Network of Alaska (GINA), is developing a data discovery and delivery system for arctic information that can be used by data and GIS managers and fed into CADIS.

References

Interagency Arctic Research Policy Committee (IARPC) (2007). Arctic Observing Network: Toward a U.S. contribution to Pan-Arctic observing, *Arctic Research*, **21**, 94 pp.

Table 4: Summary of "Emerging Issues" for North Slope Science Initiative *(www.northslope.org)*

Management-based General Issue	Examples of Specific Management Concerns	Science & Information Needs to Address Identified Issue/Concern
Permafrost	• Adequacy of measurement & monitoring • Infrastructure stability & seasonal travel • Impact on vegetation, hydrology, wildlife	• Expand monitoring, centralize data access • Active layer depth & compression will be key in the short-term, need to ID thresholds for change • Combined ground measures & remote sensing may hold promise for monitoring
Coastal and Riverine Erosion	• Location and rate of erosion • Risk to infrastructure, cultural sites • Links to permafrost, ocean condition	• Accessible current & historic shoreline data • Accurate maps of at-risk sites & resources • Models to generate change and risk maps • Need to instrument coast for wind and waves
Sea Ice & Ocean Condition	• Access to data and model projections • Effect on oil spill response • Effect on species/distributions/harvest	• Need historic shore-fast and pack ice records • Evaluate technology, scenarios, risk models • Downscale and generate impact models • Fate/effects of oil spill in various ice settings
Marine Activities	• Increasing transport & development • Impact on subsistence species & hunters • Added pollutants & invasive species	• Baselines (species, noise, water quality, ...) • 1- to 20-yr development & operational scenarios • Impact models, accessible data & formats
Species of Interest: Caribou	• Data comparability across N. Slope herds • Climate & development harvest impacts • Herd reaction to development activities	• Herd-to-herd variation in mgt is OK, but need consistent measures to detect wider changes • Historic variability, winter ecology studies

Management-based General Issue	Examples of Specific Management Concerns	Science & Information Needs to Address Identified Issue/Concern
Species of Interest: Marine Mammals	• Species shifts – northward & sea-to-land • Shipping, whale migration, hunter access • Effects of changing acoustic environment	• Integrative studies of marine ecosystems • TEK, telemetry, sea-to-land shift impact • Acoustic baseline, arctic-specific noise tests
Species of Interest: Migratory Birds	• Migratory bird habitat shifts, loss • Subsistence harvest effects • Ice loss and oil spill risks for seabirds	• Habitat use/selection studies & models • Better bird population trend, subsistence use data • Bioenergetics studies, oil spill prevention
Vegetation Change	• Baseline from which to detect change • Change effects on habitat, food sources • Change via fire, hydrology, invasion, …?	• Complete NSSI landcover map, store in GINA • Develop change detection plan, L-T monitoring • Prevent invasives, model with fire & hydrology
Hydrology & Lake Drying	• Energy development water requirements • Protection of water for species needs • Sufficiency of water availability info, peak and minimum flow estimates	• Studies of link to permafrost change • Water quality/quantity data and models • Gauging network and/or remote sensing alternative, real-time data access • Improved DEMs critical to status/modeling
Saltwater Intrusion	• Species composition & habitat changes • Water quality for winter ice roads/pads • Sea level rise and coastal inundation	• Clarify extent of existing salt marsh • Study/model plant community impacts • Avoid use of saline water for ice roads, develop mitigation techniques • Improved DEMs for sea level impact models
Changing Fire Regime	• Are fire regime & risks changing? • Species & subsistence use changes • Fire mgt. response & village safety	• Monitor Anaktuvuk fire impact & recovery • Complete landcover map, basis for fuel model • Support AK Wildland Fire Coordinating Group
Weather & Climate	• Adequacy of meteorological network • Timely access to accurate weather data • Effect on winter exploration, permafrost, erosion, hydrology, species survival/shifts	• Synthesize existing information on network • ID gaps, design network to meet user needs • Improve year round operation & reporting • Scale down for impact modeling
Contaminants	• Spill response/planning • Contaminant release via thawing/erosion • Differentiation of natural vs. industrial	• Map sensitive areas & contaminant sites, especially in high erosion risk areas • Spill response planning & capacity • Pre-development baselines (soil, water, biota)
Social & Economic Structure	• Impact study structure & comparability • Community burden of multiple studies • Efficacy of mitigation (prior/future) • Impact on subsistence, diets, networks • Economic & health impact & outlook	• Standardization of key social indicators • Coordination/clearinghouse for studies • Matching TEK and western science in study design, monitoring, and interpretation • Modeling economic, resource and social vulnerability and sustainability

Section VI: International Collaboration and Coordination

Recommendations for International Coordination

Arctic research benefits from a tradition of strong international collaboration driven by the clear benefits of shared logistics, cooperative measurement programs and free exchange of data and information. However, the lack of international implementing agreements and issues surrounding security, customs and visa regulations of individual countries, the U.S. included, hamper pan-Arctic science efforts. This affects (a) physical access to regions of scientific interest, (b) standardization and exchange of data and joint support of network science, and (c) development of international science collaborations. Based on these findings, a series of recommendations emerged from the meeting:

1. There is a growing web of bilateral memorandums of understanding and agreements between different countries and agencies. Although these documents generally do not provide authorization for actions such as transferring funds, clearing customs, acquiring data or granting permissions for physical access and data sharing, it would be useful to inventory these agreements. Building on past successes and emerging needs, NSF, NOAA and other agencies might consider drafting preliminary requirements for a multi-lateral Arctic science agreement that will facilitate international research collaboration, access and open data exchange. The requirements document could be submitted to the Sustained Arctic Observing Network (SAON) Steering Group to carry forward to the Arctic Council, and to the U.S. Arctic Research Commission (USARC) to carry forward to the U.S. Congress.
2. Where appropriate, NSF/AON should contribute (or maintain contributions) to existing data archives for topical data sets such as Baseline Surface Radiation Networks (BSRN), Global Atmosphere Watch (GAW), the Arctic Monitoring and Assessment Program (AMAP), the ARGO Float Program and the International Arctic Buoy Program (IABP).
3. AON researchers should take advantage of NSF Office of International Science and Engineering (OISE) programs, such as Partnership for International Research and Education (PIRE), that promote international research collaborations. NSF/AON program managers should study the OISE program "International Collaboration in Chemistry between U.S. Investigators and their Counterparts Abroad (ICC)" with an eye toward instigating a similar Arctic-centric program.
4. All disciplines repeatedly identified the need for additional mid-basin measurements in the Arctic Ocean and resolution of variability at seasonal and longer timescales. Ice stations of other platforms capable of collecting such observations would require international partnership and financial contributions. If established, it would provide a focus for developing research partnerships and collaborations across national boundaries and disciplines. The SHEBA and Russian drifting station programs should be reviewed as a proof-of-concept exercise. U.S. agencies should consider developing a partnership for a permanent ice station to define key components, implementation protocols and also identify foreign agencies that could provide long-term support.

Venues for Fostering International Coordination

Two efforts carry great potential to foster international coordination and collaboration:

The Sustaining Arctic Observing Networks (SAON) process aims to enhance Arctic-wide observing activities by facilitating partnerships and synergies among existing activities (such as AON), and promoting sharing and synthesis of data and information. Among its highest priorities, SAON will complete and periodically update inventories of Arctic observing activities conducted by various nations and work with the observing networks and sites identified in the inventories to improve access to existing data. SAON will promote international partnerships and integrated data analysis, including incorporation of traditional knowledge. The multi-agency U.S. AON represents one of the largest coordinated observing activities in the Arctic. Ensuring access, sharing, integration, and long-term survival of the AON data is a challenge similar to that faced by SAON in the international arena. Close collaboration in these areas between AON and SAON has obvious benefits. At the policy level, the U.S. is encouraging further development of SAON. At the practical level, the U.S. participants in the SAON Steering Group are preparing specific task statements for review and implementation starting in 2011. Funding agency support will be required for these tasks.

The International Study of Arctic Change (ISAC) is an IPY legacy that will provide an additional venue for international coordination of activities that will guide arctic observation efforts. Among other priorities, including the development of a Responding to Change initiative that provides feedback to observational programs, ISAC will make recommendations for optimization and addressing gaps in observing as related to ISAC goals. Observing arctic change for the purposes of understanding and real-world problem solving requires the development of a system that serves both science and society/stakeholders. An AON partnership with ISAC will facilitate coordination among existing and emerging observation programs and improve international exchange of information and joint planning and coordination of observation programs. ISAC, through its developing relationship with the International Arctic Science Committee, should be positioned to provide scientific guidance to the SAON initiative. In the build-up phase to the utilization of an Arctic Observing System sustained through SAON efforts, ISAC plans to link existing Arctic environmental change observations through efforts to develop a memorandum of understanding among the programs that control the presently deployed observing systems, including the AON. Recent efforts at the State of the Arctic conference brought together over 20 different initiatives in coordinated, collaborative, international Arctic research. Synthesis of these activities highlights the need for continued and improved coordinated observing activities across all components of the Arctic system and among many nations.

Section VII: Data Dissemination, Use and Archiving

The Arctic Observing Network's primary output is the multi-disciplinary data produced by the many projects that form the network. The AON program requires all AON projects to provide their data to the community in a timely fashion, without embargo periods. By providing rapid, open access to quality-controlled, fully-documented data AON hopes to promote broad, community-wide use of these valuable holdings. All AON investigators are required to adhere to the SEARCH Data Policy (**http://www.arcus.org/search/searchscience/data.php**), thereby maximizing community-wide data access, integration and, ultimately, long-term preservation. AON also strives for changes in the practice of science by emphasizing the need for both the community and data users to properly recognize and credit data providers.

The diverse, extensive outflow of AON data requires a management strategy and motivated the development and implementation of the Cooperative Arctic Data and Information Service (CADIS) (**http://www.aoncadis.org/**). CADIS aims to incorporate community standards, visualization tools, data archiving and curation expertise into AON support and data management activities. It creates a foundation for long-term access to data archives, discovery, delivery and analysis by the Arctic science community and other users. AON investigators had archived more than 160 data sets from 37 investigators and 12 nations in CADIS by the end of 2009 (Figure 1). CADIS reached a major milestone in fall 2009 with the release and implementation of the user interface for metadata and data upload via the CADIS Data Portal. Primary features include an advanced metadata authoring tool, web portal, data upload tool, semantic search, dataset download, interoperability with selected Arctic archives (e.g., NSIDC, NCAR/EOL, Norway, British Antarctic Survey) and visualization tools for browsing project overview information. User support is provided to assist AON investigators with all aspects of the CADIS applications.

After 3 years of system development and support to the AON community, the CADIS team used a questionnaire as part of the evaluation of the service. Positive comments suggest that CADIS has become a central location for accessing AON data and metadata. Reponses also noted that the support team has been very helpful in assisting data providers to organize and publish their data and metadata. A majority of AON investigators are willing to consider a structured ASCII data format for AON data, though it is also clear that flexibility in acceptable data formats is desired. Some areas of suggested improvement include how searches are handled, both within the archive itself and for queries originating from outside CADIS; increasing community awareness of CADIS and its capabilities; developing more effective support for AON social science data and information; organizing data format conversion capabilities and improving map based search and visualization utilities. The AON investigators also recommended that CADIS expand links to other related datasets that will be used when analyzing basin-wide phenomena.

Support for AON data management will continue to evolve as AON grows to produce a rich legacy of Arctic data. CADIS must continue to offer a systematic approach that supports the data providers while improving efficient access to these data. CADIS will have effective metadata and data entry tools, visualization techniques (map based, parameter based, project based) and improved search capabilities for the discovery and access to this diverse data archive. There will be increasing opportunity to link to and/or provide supplementary or supporting datasets that are relevant to AON. These data could include remote sensing data and products (e.g., imagery, ice concentration), integrated datasets produced by the AON PIs or other groups, operational data from state or federal agencies and model results from intercomparison projects, reanalysis or other special efforts. These datasets would typically be linked via existing web sites and not require CADIS to directly archive the data.

AON faces an upcoming challenge to define and implement a process for meeting stakeholder needs with useful products. In addition, discussions at the PI meeting suggest that there is a growing interest in distributing AON data products to local Arctic communities and other potential end users. The AON group proposed a small pilot study in which CADIS would provide near real time data for access by interested users. One possibility would be to provide local meteorological and sea ice state products to a community that might use this information to establish fishing and hunting schedules or time the shipping of goods in and out of their locale.

Section VIII: Summary and Outlook

Existing AON projects align with the scientific priorities and broad design criteria laid out in the SEARCH implementation documents (in particular SIW, 2005). AON investigators and the broader scientific community now face the challenge of integrating these diverse components into a broader network that is part of an overarching, international observing system. Discussions at the AON PI meeting identified four near-term issues that will have to be addressed to progress toward this goal:

1. Design and optimization efforts should draw from: (a) bottom-up approaches driven by individual projects and incremental refinement of measurement sites based on data, model results and local expertise, and (b) top-down efforts driven by rigorous approaches to observing system design and optimization such as Observing System Simulation Experiments (OSSEs) and other modeling or synthesis efforts, to tailor an integrated approach for the AON.
2. Implementation of an effective, sustained observing network that adheres to design and implementation principles defined by activities such as outlined in (1) may prove challenging for existing support mechanisms that rely solely on peer review of short-duration projects that focus on individual components of the system and reference the overarching science goals. Although this system is integral to much of NSF-supported science, AON may need to look towards the methods that other large observing programs have successfully employed to build comprehensive, highly integrated networks. Approaches include reliance on steering committees for additional guidance, strong partnering with government agencies capable of supporting sustained measurements and development of guidelines and practices that foster coordination.
3. Given the important role of agencies and other entities, such as Arctic communities and industry, in sustaining long-term observations, progress needs to be made in developing effective approaches to foster coordination, joint planning and partnered implementation of Arctic observing systems.
4. At the international level, existing efforts such as coordination through the World Climate Research Program's Climate and the Cryosphere (CliC) Program, or the International Arctic Systems for Observing the Atmosphere (IASOA) Project may provide important guidance and frameworks for the implementation and optimization of an observing network.

A major challenge, unique to AON in relation to other observing systems with a more disciplinary focus, is the broad, inherently inter-disciplinary nature of the driving questions. While SEARCH has been structured to meet this challenge, effective techniques for promoting inter-disciplinary synthesis and integration still need to be explored. Stakeholders and mission-oriented government agencies can provide some guidance, since many of the questions they face in the context of Arctic change cut across disciplines.

Coordination with agencies and stakeholders will also be crucial because of their important role in sustaining longer-term observations and their focus on questions of immediate societal relevance. Owing to the rapidity of Arctic change and the urgency of some of the challenges it presents, the AON is ideally positioned to generate information of potential value to those affected. However, improved communication and coordination among the scientific community, government agencies and stakeholder groups will be required to meet this challenge. A review of successful approaches for fostering communication and joint planning in other settings may help in building the required institutions and support structures for such an integrated system. At the more practical level, there is a need for a discussion to identify the products stakeholders and agencies expect from an AON and to scope the level of effort that will be required to deliver these products.

Similarly, effective channels and mechanisms for joint planning and coordination of observing system activities must be developed. This will involve discussion of overarching scientific questions and development of science plans, such as through the International Study of Arctic Change. Equally important are questions revolving around international agreements and other approaches that can help ensure data exchange, standardization and inter-comparability of measurements, coordination of logistics, improved access for deployment of observing system components and related questions.

Appendix A:
AON Project Reports – Atmosphere

UV Monitoring Project

ARC-0856268

Germar H. Bernhard[1] and John E. Frederick[2]

Project Summary

The main objective of the AON project "Ultraviolet Radiation in the Arctic" is to perform observations of solar UV radiation at Barrow, Alaska, and Summit, Greenland, over the period August 2009 to July 2012. These data will help to advance knowledge of the present and future solar radiation climate of the Arctic and of the factors that drive changes in UV radiation. The project ensures continuation of activities initiated by the "NSF UV Spectral Irradiance Monitoring Project" (UVSIMN), which was established in 1988 to observe solar UV irradiance at seven mostly high-latitude sites, including three locations in Antarctica. UVSIMN measurements at Barrow and Summit commenced in 1990 and 2004, respectively. To date, the UVSIMN network has produced one of the longest climate data records (CDR) of UV radiation in existence, and this AON project will add additional data to this CDR.

About 900 researchers have used UVSIMN data for investigating the effects of stratospheric ozone depletion, other climatic factors on UV radiation at the Earth's surface, and subsequent consequences on aquatic and terrestrial ecosystems and humans. We anticipate that data collected during the period of this AON project will form the basis of new studies on UV radiation and its effects.

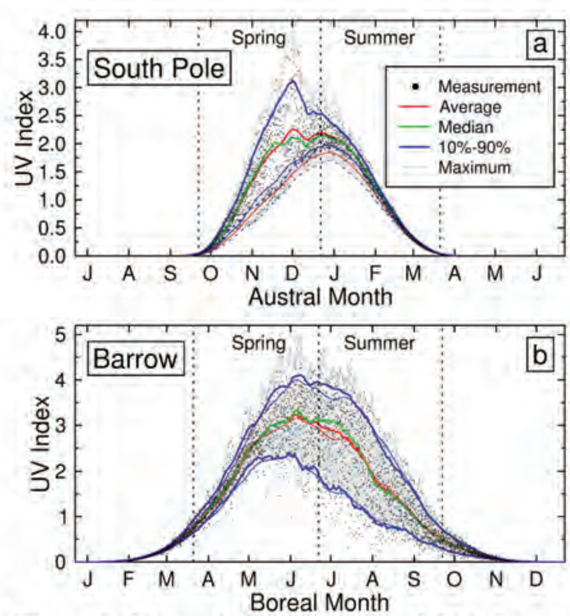

Figure 1. Climatology of noontime UV Index at South Pole and Barrow. Measurements of the noontime UV Index covering all years of network operation are indicated by black dots. Associated statistics (average, median, 10th and 90th percentile, overall maximum) are drawn with thick lines. Reconstructions of historical UV Indices are indicated by thin lines and gray-shading.

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Science and Technology Development Highlights

This AON project has commenced only three months ago and it is therefore too early to report on science highlights from this period. We therefore showcase results that are based on historical UVSIMN measurements performed at Barrow and Summit. These results can only give a glimpse of the breadth of knowledge gained from the network's observations.

We established a UV index climatology for all network sites [*Bernhard et al*., 2009a]. Examples for South Pole and Barrow are contrasted in Figure 1. At South Pole, there is a strong enhancement during the spring (October, November) due to the effect of the ozone hole. At Barrow, average UV indices are more symmetrical about the summer solstice (broken vertical line), but the variability is much larger in summer than spring. This is a consequence of the annual cycles of snow cover, sea ice extent, and cloudiness, which were discussed in great detail by *Bernhard et al.* (2007). Measured values from South Pole and Barrow were also compared with estimates of historical UV indices (1963-1980 for South Pole; 1973-1980 for Barrow), which were reconstructed from data of total ozone predating UVSIMN operations. These estimates are indicated in Figure 1 by gray shading. During October and November, the average UV Index measured at the South Pole between 1991 and 2006 was 55-85% larger than the estimate for the years 1963-1980. In contrast at Barrow, there was little change between the two periods; the gray shaded area in Figure 1 has a similar pattern to that of recent measurements. While this analysis provided valuable insight into the evolution of UV irradiance during the last 30 years, considerable uncertainties remain because of changes in factors other than ozone, which were not available from measurements. This fact emphasizes the importance of continued observations.

We also compared UV indices at South Pole and Summit (*Bernhard et al*., 2008). One important result was that UV indices measured during the austral spring at South Pole are 1.9-2.4 times larger than UV indices during the vernal spring at Summit despite the similar location on vast highly reflective and high altitude ice sheets.

In addition to analyzing data scientifically, we developed an extensive set of software tools for the quality control of spectral measurements of the UVSIMN. The data quality of network instruments was successfully assessed via several international intercomparison campaigns, leading to certification of UVSIMN data by the Network for the Detection of Atmospheric Composition Change (NDACC).

Lessons Learned

Operating sophisticated instrumentation over long periods of time at remote locations is challenging. High-quality CDRs required for achieving the objectives of an Arctic Observing Network, as defined by *SEARCH*, can only be obtained with good on-site support, which includes regular inspection of instrumentation and calibration. It is vital for the success of AON projects that the level of on-site support remains adequate beyond the IPY period, or is improved when necessary. Over the last year, we have contacted several PIs of other AON projects. We believe that direct PI-to-PI contact via e-mail, telephone, or the annual AON meetings is the most effective means to integrate with other AON projects.

Modification of Activities Through Interaction with Other Projects

First connections to researchers interested in UVSIMN data are usually established via the online registration form at http://www.biospherical.com/nsf/login/login.asp, which all users have to fill out to obtain data access. The form requests contact information as well as a short description of how network data will be used. This formal process of establishing a connection with other researchers is most effective in our opinion. Discussions with data users have resulted in modification of data products and the inclusion of new data products. For example, actinic flux and photolysis rate data were included as a result of a request from the group performing the NSF-sponsored Antarctic Tropospheric Chemistry Investigation (ANTCI) experiment at the South Pole. These data products have also been made available for Summit, following requests by Cort Anastasio and Karen Ram from the University of California.

Description of Data and Examples of Data Use

The primary data products of this AON project are spectra of solar irradiance measured between 280 and 600 nm. Secondary data products include photosynthetically active radiation (PAR); short-wave (0.3-3.0 μm) irradiance; time series of spectral irradiance at various wavelengths; integrals over several wavelength bands (e.g., UV-A, UV-B); biologically effective dose-rates (e.g., the UV index); total ozone; effective surface albedo; cloud optical depth at 450 nm; and actinic flux and photolysis rate data for the reactions $O_3 \rightarrow O(1D) + O_2$ and $NO_2 \rightarrow NO + O(3P)$. Furthermore, all measured spectra are complemented with two sets of spectra calculated with a radiative transfer model. One set is based on the assumption that the scene is free of clouds; the second set uses the measured cloud optical depth as an additional input parameter of the model. These model spectra are a valuable tool for interpreting the measurements. Preliminary data are typically available within one week after measurements have been performed. Final data, which have passed various steps of quality control, are published annually.

Based on download statistics, the project's data support the following fields: atmospheric research (14%); validation of satellite data, radiative transfer models, and measurements by other instrumentation (11%); UV effects on algae, bacteria, primary production, plants, soil, fish, shrimp, larvae, insects, land animals, and humans (18%); and material research, engineering, and photovoltaic (6%). 29% of data access is related to education. We are aware of 173 publications that have used UVSIMN data, of which 102 are peer-reviewed. These publications include work in atmospheric sciences (45%); effects research (30%); and validation of satellite, model, and instrument data (25%). UVSIMN data have been featured frequently in WMO/UNEP Scientific Assessments of Ozone Depletion.

In June 2009, UV data from Barrow were requested from Noah Ashley, University of Alaska, Anchorage, to study how changes in UV radiation may affect the circadian rhythms in Lapland Longspurs over the summer. This research is supported by NSF grant ANT- 0817635. In September 2009, albedo data from Barrow were requested by Chelsea Thompson, Purdue University, West Lafayette, and Sasha Madronich, National Center of Atmospheric Research, Boulder, to interpret ClO and BrO measurements at Barrow, Alaska, which were conducted as part of the AON project "Halogen Chemistry and Ocean-Atmosphere-Sea Ice-Snowpack (OASIS) Chemical Exchange During IPY."

List of Publications

A complete list of publications is available at the website http://www.biospherical.com/nsf/references.asp.

The publications below include selected papers based on data from Barrow and Summit only.

Bernhard, G., C. R. Booth, and J. C. Ehramjian. (2009a). Climatology of Ultraviolet Radiation at High Latitudes Derived from Measurements of the National Science Foundation's Ultraviolet Spectral Irradiance Monitoring Network, accepted for publication in: UV Radiation in Global Climate Change: Measurements, Modeling and Effects on Ecosystems, edited by W. Gao, D. L. Schmoldt, and J. R. Slusser, Springer-Verlag and Tsinghua University Press, ISBN: 978-3-642-03312-4, in press.

Bernhard G., C. R. Booth, J. C. Ehramjian, and V. V. Quang. (2009b). Dissemination of data from the National Science Foundation's UV monitoring network, in: Ultraviolet and Visible Ground- and Space-based Measurements, Trace Gases, Aerosols and Effects VI, edited by J. R. Herman, and W. Gao, Proc. SPIE, 7462, in press.

Bernhard, G., C. R. Booth, and J. C. Ehramjian. (2008). Comparison of UV irradiance measurements at Summit, Greenland; Barrow, Alaska; and South Pole, Antarctica, *Atmos. Chem. Phys.*, *8*, 4799–4810.

Bernhard, G., C. R. Booth, J. C. Ehramjian, R. Stone, and E. G. Dutton (2007). Ultraviolet and visible radiation at Barrow, Alaska: Climatology and influencing factors on the basis of version 2 National Science Foundation network data, *J. Geophys. Res.*, *112*, D09101, doi:10.1029/2006JD007865.

Bernhard G., C.R. Booth, J.C. Ehramjian, and S.E. Nichol. (2006). UV climatology at McMurdo Station, Antarctica, Based on Version 2 data of the National Science Foundation's Ultraviolet Radiation Monitoring Network, *J. Geophys. Res.*, *111*, D11201, doi:10.1029/2005JD005857.

Kancler, E., C. Gautier, P. Ricchiazzi, S. Yang, and P. Pilewskie. (2005). Spectral observations and modeling of the Arctic surface radiation environment, *J. Geophys. Res.*, *110*, D23203, doi:10.1029/2005JD005813.

Díaz, S., D. Nelson, Don, G. Deferrari, and C. Camilión. (2003). Estimated and measured DNA, plant-chromosphereand erythemal-weighted irradiance at Barrow and South Pole (1979-2000), *Agr. Forest. Meteorol.*, *120*, 69-82.

Gurney, K. R. (1998). Evidence for increasing ultraviolet irradiance at Point Barrow, Alaska, *Geophys. Res. Lett.*, *25*(6), 903-906.

Relation to Other International Arctic Observing Efforts

Over the period of operating the UVSIMN, we have maintained good working relationships with colleagues in Canada and Europe, who perform UV measurements in their respective countries. This has led to several joint publications. For example, we have participated in a intercomparison in Oslo, organized by the Norwegian Radiation Protection Authority that maintains a network of UV monitoring sites throughout Norway, including Svalbard. UVSIMN UV data have also been submitted to the World Ozone and UV Data Center (WOUDC, www.woudc.org), which is part of the WMO GAW program.

Pan-Arctic Studies of the Coupled Tropospheric, Stratospheric and Mesospheric Circulation

ARC-0632387

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Project Summary

This proposal sets forth a three-year plan to extend our understanding of the circulation of the Arctic atmosphere during the upcoming Fourth International Polar Year. Specifically, an observational study that combines satellite measurements, lidar measurements, and meteorological soundings and analyses to study the troposphere, stratosphere, and mesosphere will be conducted. The study is an international collaboration between investigators at six institutions in Canada, Germany, Japan and the United States. An international network of four Rayleigh lidars located in observatories at Andoya, Norway (69°N, 16°E), Chatanika, Alaska (65°N, 147°W), Eureka, Nunavut (80°N, 86°W), and Kangarlussuaq, Greenland (67°N, 51°W), provide a chain of high-resolution temperature measurements from the eastern Arctic to the western Arctic. The lidars will yield high-resolution measurements of the structure and circulation of the Arctic stratospheric vortex, the Aleutian anticyclone, the stratospheric surf-zone, planetary waves, tides, and gravity waves that are corroborated by the synoptic-scale satellite and meteorological observations.

Intellectual Merit: The proposed activity will address the following specific studies: the structure, evolution, and variability of polar vortices and anticyclones, coupling and feedbacks between waves and large-scale circulation, links between the middle and lower atmosphere, atmospheric tele-connections, and modes of variability. This study will provide data and analyses in support of studies of ozone depletion, stratospheric climate, climate oscillations in the Arctic, and long-range horizontal and vertical transport in the Arctic. We have three specific goals: 1) a study of the Arctic atmosphere that uses observations, modeling and theoretical interpretation to document 3-D structure and evolution of the Arctic vortex and anticyclones with emphasis on vortex-vortex interactions and stratospheric warming/mesospheric cooling events during IPY; 2) to determine our ability to forecast synoptic-scale weather events in the troposphere based on observations and analyses of the mesosphere and stratosphere, and 3) a study of the coupling between anomalous stratospheric weather and tropospheric annular modes during IPY.

Relevance to IPY: This study addresses all six IPY themes. Using the Arctic as a vantage point, the study will generate benchmark datasets and analyses that will reveal the current state of the polar environment, support studies of climate change, detect and analyze polar-global interactions, investigate new frontiers, and address environmental questions of importance to polar societies. The study is a part of the IPY Expression of Intent PASSMeC (#11) that is a component of two IPY proposals, IPY-SPARC (#196) and IASOA (#217). These proposals have both been endorsed by the IPY Joint Committee. The study will also be integrated into the IPY educational and outreach programs.

Broader Impacts: The proposed activity will support education and training of students in science and engineering. The activity will both draw on and contribute to research infrastructure in the Arctic, enhance international collaborations, and promote collaboration among observers, modelers and theorists. The observations, analyses and results of this activity will directly contribute to the CAWSES, CEDAR, SEARCH, SPARC and WACCM programs. The study will support Arctic environmental studies by extending our understanding of coupling between the middle and lower atmosphere. The possibility of improving tropospheric weather forecasts is of high value to the public.

Science and Technology Highlights

Stratospheric sudden warming (SSW) events occurred in both winters of the IPY and resulted in major disruptions of the stratospheric vortex and the circulation of the Arctic stratosphere and mesosphere. In 2007-2008 there were several warming events culminating in a major warming in late February with a splitting of the vortex. In 2008-2009 there was a more disruptive major warming with a splitting of the vortex in late January and formation of an elevated stratopause. The split vortex persisted through February 2009. These events provide us with a unique data set for the study of wave-mean-flow interactions at planetary scales, and assess how planetary waves and gravity waves interact with each other and the mean flow and influence the general circulation.

We have documented the evolution of the Arctic stratosphere and mesosphere with both high-resolution measurements and large-scale satellite observations and analyses during these two IPY winters. Using the Rayleigh lidars at our primary observatory (Chatanika, Alaska) and at the four secondary observatories (Andoya, Norway; Eureka, Canada; Kangarlussuaq, Greenland; and Kühlungsborn, Germany), we have acquired high-resolution measurements of the temperature and the relative density profiles. Using reanalysis data from the Meteorological Office (MetO) and the Goddard Earth Observing System (GEOS) and data from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument data aboard the Thermosphere Ionosphere Mesosphere Energetics Dynamics (TIMED) satellite we have documented the large-scale circulation.

We have conducted a long-term (over 40 years) comparison study between Whole Atmosphere Community Climate Model (WACCM) and ECMWF Reanalysis (ERA) investigating the characteristics of cold-air outbreaks in the model and the reanalysis. Having validated our efforts we are moving forward to look at linkages between the stratosphere and troposphere using a model-observation approach that allows us to understand the physical coupling that underlies observed correlations.

The measurements allow characterization of planetary wave activity, tidal activity, and gravity wave activity. We find systematic correlations between the wave activity and the daily winds that is consistent with nonlinear interactions. We find systematic differences in the gravity wave activity between different sites in the Arctic and interannual variability at the different sites that raises questions about our understanding of zonal-mean balance in the wave forcing of the circulation.

Lessons Learned

Investigator-investigator connections are critical for coordinating a network of research observations hosted by independent research groups operating under independent national programs. In Fall 2006, just after the submission of the proposal, Collins spent a Fulbright scholarship at the Leibniz-Institute of Atmospheric Physics (L-IAP) of the University of Rostock. During that scholarship period he worked with Drs. Michel Gerding and Gerald Baumgarten who coordinate the Rayleigh lidar programs at Andoya, Norway, and Kühlungsborn, Germany. These professional relationships were key to the L-IAP providing raw data to the UAF group allowing rigorously consistent processing of the gravity wave data.

Consistent data processing is absolutely critical for making inter-site comparisons. The analysis of wave perturbations that represent on order 1% relative density fluctuations can change by a factor of 2 based on subtle changes in the processing algorithms. While data processing techniques are enumerated in the peer-reviewed literature, intercomparison of published data values is not always significant. As part of the IPY work we compared various data processing techniques to allow comparison of the IPY data with historical measurements published in the early 1990s.

Our analysis of planetary wave activity, using a synoptic approach that identifies the polar vortex and Aleutian anticyclone, allows us to render movies of the seasonal evolution of the vortex and anticyclone and has appeared to capture the attention (and we hope imagination) of our colleagues at conferences and workshops. The dramatic dynamic activity during the IPY winters, where the vortex was disrupted, only served to strengthen the impact of the movies in providing physical insight into the complex processes of planetary wave activity and wave breaking. We have coupled this synoptic view with the traditional planetary wavenumber and wave flux analysis from satellite measurements to better understand the dynamics of the circulation as well as have researchers accept this synoptic view as an additional tool for understanding the middle atmosphere circulation. The movies attracted undergraduate students to develop a movie viewer that we incorporated into our website (see below).

We should have initiated direct model-observation comparison studies at the outset of our activities in spring 2007 before the observational phase of the activity began in the first IPY winter. We began working on those model-observation comparison studies as the data sets were acquired and are developing them in the third year of the proposal, but will request a no-cost extension to complete this phase of the study. This is a critical component of the project in maximizing the depth of physical discoveries that can garnered from the observations.

Modification of Activities

Based on coordination of International Polar Year (IPY: http://www.ipy.org) we partnered with the Stratospheric Processes And their Role in Climate (SPARC) program. As part of that collaboration we 1) framed the lidar observations in terms of the SPARC reference atlas and 2) incorporated the SPARC atlas into the data retrievals and 3) participated in the SPARC observational network.

The network was extended to include measurements from the Leibniz-Institute of Atmospheric Physics of the University of Rostock at Kühlungsborn, Germany (54°N, 12°E).

The temperature data from the lidar network also provide a reference data set for comparison with reanalyses (e.g., GEOS) and satellite assimilation and forecasting efforts (e.g., SPARC).

In spring 2009 we incorporated an undergraduate research team from the Department of Computer Science at the University of Alaska Fairbanks into the project. Collins served as an external mentor in "CS472: Senior Project." I worked with the instructor, Dr. Peter Knoke, and a student team, Matthew Jones, Brian Paden, Farrin Reid, and Ruth Rutter, to develop a visualization scheme for the Artic vortex during the IPY. We worked with the students to define the project and their software was included in our PASSMeC website for the IPY (http://research.iarc.uaf.edu/IPY-CTSM/teamvortex/index.php).

Examples of Data Use

Researchers at the National Center for Atmospheric Research (Drs. Han Li- Liu and Dan Marsh) have conducted model runs of the Whole Atmosphere Community Climate Model (WACCM, http://waccm.acd.ucar.edu/) and the Thermosphere Ionosphere Mesosphere Electrodynamic General Circulation Model (TIME-GCM, http://www.hao.ucar.edu/modeling/tgcm/) for the IPY. These runs allow benchmark comparisons with data sets for understanding the physical processes that underlie the evolution of the atmosphere during the IPY. These model-observation comparisons are a legacy of the IPY as the model runs can be retuned to explore the relative role of different physical processes (e.g., gravity-wave forcing of the mean flow).

Education and Outreach

This project has provided research and design opportunities for two graduate students and six undergraduate students. Dr. Brentha Thurairajah obtained her Ph.D. in Atmospheric Sciences at the University of Alaska Fairbanks (UAF) in 2009. Dr. Thurairajah won an NSF-CEDAR postdoctoral award and is now working at Virginia Tech as part of the Aeronomy of Ice in the Mesosphere (AIM) investigation. Mr. Donavan Wheeler is continuing his Ph.D. at the University of Colorado, Boulder. Ms. Brita Irving is working on her BS in Physics at UAF. Ms. Irving plans to graduate in 2010 with honors, and she is using this experience to support her honors project. Ms. Caroline Larsen worked on the project as an undergraduate reseacher in the summer of 2008. The project also provided four UAF undergraduates, (Matthew Jones, Brian Paden, Farrin Reid, Ruth Rutter) with a senior project in Spring 2009. These computer science students developed an application for the project website that allows visitors to the site to view the structure of the stratospheric vortex. The team carried out this project for class credit in CS472: "Senior Project and Professional Practice" in the spring semester of 2009. The class instructor was Dr. Peter J. Knoke.

This project has been presented in a variety of settings to visitors to the UAF campus, including K-12 school students, members of the public, fellow reseachers attending conferences, and the National Science Board. We have also presented the project to the general public through contributing to newletter and magazine articles at UAF, and to the wider scientific community by coauthoring an article in the SPARC (Stratospheric Processes And their Role in Climate) Newsletter.

List of Publications and/or Web Sites

Web Sites

Project: http://research.iarc.uaf.edu/IPY-CTSM/index.php

Lidar Research Laboratory at Poker Flat Research Range Chatanika Alaska: http://www.gi.alaska.edu/splidar/

Arctic Observing Network: http://www.eol.ucar.edu/projects/aon-cadis/projects/

Dissertations and Theses

Thurairajah, B, *Role of waves on the circulation of the Arctic middle atmosphere: Rayleigh lidar measurements and analysis*, PhD Dissertation, University of Alaska Fairbanks, 2009.

Peer-Reviewed Journal Articles

Thurairajah, B., R. L. Collins, and K Mizutani, Multi-year temperature measurements of the middle atmosphere at Chatanika, Alaska (65°N, 147°W), *Earth Planets Space, 61,* 755-764. 2009.

Thurairajah, B., R. L. Collins, V. L. Harvey, R. S. Lieberman , and K Mizutani, Rayleigh lidar observations of reduced gravity wave activity during the formation of an elevated stratopause in 2004 at Chatanika, Alaska (65°N, 147°W), *J. Geophs. Res.,* in press, 2010

Peer-Reviewed Conference Presentations

Thurairajah, B., R. L. Collins, V. L. Harvey, D.E. Atkinson, K. Mizutani, J. M. Livingston, C. J. Heinselman, M. A. McCready, W. Pan, Analysis of the wave-driven circulation in the Arctic middle atmosphere using Rayleigh lidar observations, *Twenty-Fourth International Laser Radar Conference,* Boulder, USA, 23-27 June, 777-780, 2008

Newsletters

Farahani, E., N. McFarlane, R. L. Batchelor, R. L. Collins, V. L. Harvey, N. J. Livesey, G. L. Manney, M. L., Santee, K. Strong, K. A. Walker, Features of the Arctic stratosphere during IPY, *SPARC Newsletter*, 33, 6-13, July, 2009.

Conference and Workshop Presentations

Harvey, V. L., R.L. Collins, D.E. Atkinson, B. Thurairajah, The stratospheric warming event in 2009, Canadian Network for the Detection of Atmospheric Change (CANDAC) workshop, Toronto, Canada, 16 October 2009. (Invited)

Collins, R. L., V.L. Harvey, B. Thurairajah, D.E. Atkinson, G. Baumgarten, M. Gerding, J. M. Livingston, F.-J. Lübken, K. Mizutani, R.J. Sica, Pan-Arctic Study of the Circulation of the Arctic Middle Atmosphere during the IPY, *MOCA-09: IAMAS-IAPSO-IACS Joint Assembly*, Montreal, Canada, 19-29 July, 2009.

Collins, R. L., B. Thurairajah, V. L. Harvey, R. S. Lieberman, Gravity Wave Activity in the Arctic Middle Atmosphere during the 2003-2004 Winter, *MOCA-09: IAMAS-IAPSO-IACS Joint Assembly*, Montreal, Canada, 19-29 July, 2009.

Harvey, V. L., R. L. Collins, D. E. Atkinson, B. Thurairajah, Vertical Coupling Between the Stratosphere and Mesosphere During IPY, *AGU Joint Assembly*, Toronto, Ontario, Canada, 24–27 May, 2009.

Collins, R. L., Middle atmosphere research and associated lidar activities at the University of Alaska, *European Space Agency Workshop on Space Lidar for Observation of the MLT Region*, Noordwijk, Netherlands, 27-28 April, 2009.

Collins, R. L., V. L. Harvey, B. Thurairajah, D. E. Atkinson, C. J. Larsen, G. Baumgarten, J. Fiedler, B. J. Firanski, M. Gerding, J. Höffner, J. M. Livingston, F.-J. Lübken, K. Mizutani, W. Pan, R. J. Sica, K. B. Strawbridge, Rayleigh Lidar Network Observations and Analysis of the Evolution of the Arctic Middle Atmosphere during the IPY Winter 2007-2008, *AGU Fall Meeting*, San Francisco, CA, 15-19 December, 2008.

Thurairajah, B., R. L. Collins, V. L. Harvey, R. S. Lieberman, D. E. Atkinson, J. M. Livingston, K. Mizutani, H.-L. Liu, (Invited) Coupling between the Arctic middle and upper atmosphere during the 2007-2008 IPY winter, *AGU Fall Meeting*, San Francisco, CA, 15-19 December, 2008.

Collins, R. L., V. L. Harvey, B. Thurairajah, D. E. Atkinson, C. J. Larsen, G. Baumgarten, J. Fiedler, B. J. Firanski, M. Gerding, J. Höffner, J. M. Livingston, F.-J. Lübken, K. Mizutani, W. Pan, R. J. Sica, K. B. Strawbridge, The Structure and Evolution of the Arctic Middle Atmosphere during the IPY Winter; Rayleigh Lidar Network Observations and Analysis, (Invited) *Annual European Meeting on Atmospheric Studies by Optical Methods,* Maynooth, Ireland, 24-29 August, 2008.

Collins, R. L., B. Thurairajah, D. E. Atkinson, V. L. Harvey, K. Mizutani, and R. S. Lieberman, Pan-Arctic study of the coupled tropospheric, stratospheric, and mesospheric circulation, *SPARC Data Assimilation and International Polar Year Workshop*, Toronto, Canada, 4-7 September, 2007.

The Collaborative O-Buoy Project: Deployment of a Network of Arctic Ocean Chemical Sensors for the IPY and Beyond

(ARC-0612331, 0611992, 0612047, and 0612457)

PIs: Patricia Matrai, Don Perovich, Paul Shepson and William Simpson, in full partnership with Jan Bottenheim (Environment Canada)

Project Summary

O-Buoy, a buoy-based instrument platform, was designed, constructed, and field-tested for year-round measurement of ozone, bromine monoxide, carbon dioxide, and meteorological variables over Arctic sea ice. The O-buoy operates in an autonomous manner with daily, bi-directional data transmissions using Iridium satellite communication. The O-buoy is equipped with three power sources: primary lithium ion battery packs, rechargeable lead acid packs, and solar panels that recharge the lead acid packs, and can fully power the O-buoy during summer operation. This system is designed to operate with minimal direct human interaction to aid in our understanding of the atmospheric chemistry that occurs in this remote region of the world. The current design requires approximately yearly maintenance limited by the lifetime of the primary power supply. The O-buoy system was field tested in Elson Lagoon, Barrow, Alaska (February to May 2009), and is now deployed in the Beaufort Sea (September 2009–2010). Three additional O-Buoys are being assembled: OB-2 will be deployed next year at Barrow (February–May) and the two funded by Canada IPY at 60°N, 90°W (OB-3; February–May 2010) and 80°N, 120°W (OB-4; March–May 2010).

It is known that surface chemistry involving sea salt results in depletion of ozone (O_3) and elementary mercury (Hg) at the surface during springtime in the Arctic. However, due to the logistics challenge of long-term measurements, there have been very few such measurements of O_3 or other chemical species in the atmosphere above the Arctic Ocean surface (except from satellites and aircraft). And, although it is believed that more open water will render the Arctic Ocean a larger CO_2 sink, there are no long term measurements of CO_2 from the Arctic Ocean itself (only around it). Because of new developments in instrumentation, power management, and instrumentation control, there is a new opportunity to meet these data acquisition challenges, with large payoff to the Arctic science communities, through development of robust, unattended, self-contained and autonomous buoys. Long-term, ocean-based atmospheric data sets are needed to quantify seasonal and interannual variability in a fast changing ice field that will vary in different regions of the Arctic Ocean.

Science and Technology Development Highlights

- On-ice BrO, CO_2 and O_3 data were compared to land-based values sampled in close proximity at Barrow by an UAF DOAS sensor and the NOAA ESRL, respectively, with excellent results. While the data agree well, it is not necessarily the case that they should, depending on the spatial heterogeneity of the ozone depletion and BrO chemistry, the elucidation of which is an objective of the O-buoy effort.
- During the Barrow test period, multiple ozone depletion events were sampled.
- O-Buoy's dual power sources (lithium and solar-charged lead-acid batteries) were reliably switching from one to the other as each exceeded or dropped below 10.5V through three different sampling schedules in the field: 1) minimum, during the dark period (Li power); 2) normal, as a function of day length and solar gained (phasing Li and sun-powered); and 3) full, sampling continuously for 24 h (sun-powered).
- Internal O-buoy housing temperature was close to seawater temperature and very constant, providing

optimal behavior of instruments.

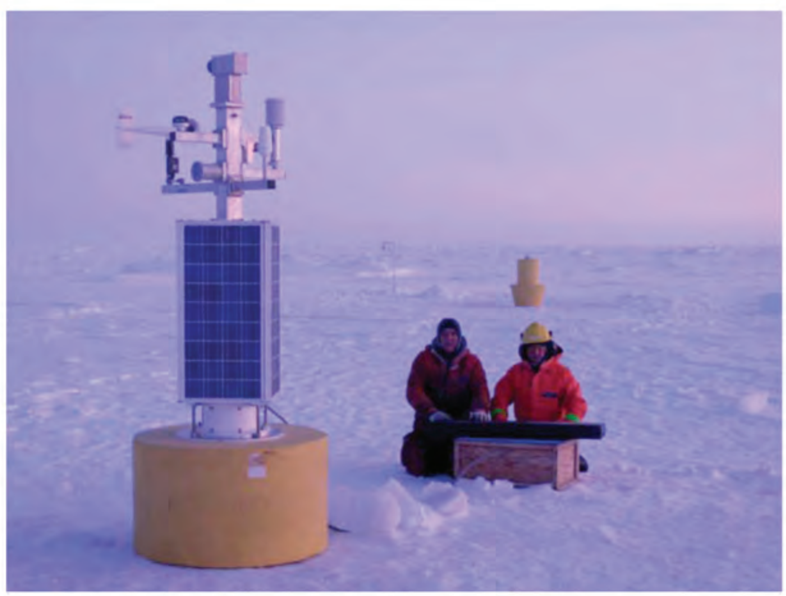
- Reliable prediction of power usage has led to an ongoing power re-design to maximize battery lifetime, extending unattended deployment to at least 2 years, effecting improved duty cycle and data acquisition. This will be implemented in O-Buoys 2-4 this month.
- Daily data transmission operated via Iridium, with the data stored on a ftp site, backed up daily at a SRI ftp://isr.sri.com/pub/vpr/obuoy/archive/buoy1 and at a Bigelow server. Daily or weekly submission protocols to AON CADIS are being established; the three concentration variables take longer to QA/QC carefully to final status.
- Monitored variables are displayed real time in http://transport.sri.com/obuoy/monitor, except concentrations that need significant post acquisition QA/QC.

Lessons Learned

- The images below show the 1st test deployment in Barrow with snowmobile and sleds (left top), the 1st deployment in the Beaufort by helicopter (left bottom) and the O-Buoy in the Beaufort Sea (with CRREL IMB and WHOI ITP in the background, on the same floe) (right).
- PVC wire insulation cracks in the cold; simplify field installation and any on site assembly even more.
- The coordination for ship time usage was possible through WHOI and personal contact. Other contacts have been established informally with the North Pole Observatory, NABOS, IABP, and Environment Canada. This needs to happen much earlier!
- Co-location of various on-ice sampling systems is highly beneficial, from logistics and science. Continued coordination will be very beneficial, especially if recovery is desirable for a "floe observation network."
- There will be benefit from sharing accumulated knowledge on instrument powering sources relevant to extreme cold conditions.

Interactions with Other Projects

Deployment to the Beaufort Sea was coordinated via Don Perovich (O-Buoy and IMB projects) with the WHOI Beaufort Gyre project, specifically Rick Krishfield, and in collaboration with Canadian colleagues, specifically Sarah Zimmermann, Institute of Ocean Sciences, Sidney, BC, Canada, who kindly agreed to add one more person on board the CCG *Louis St. Laurent* for the Sept 17 - Oct 15, 2009 cruise.



Future deployments are being explored and/or organized with the North Pole Observatory, NABOS, IABP, and Environment Canada for three O-Buoys in 2010.

Examples of Data Use

Nothing to report yet. Our first O-Buoy was deployed in the Beaufort Sea on October 7, 2009.

Publications and Web Sites

Knepp, T. N., J. Bottenheim, M. Carlsen, D. Carlson, D. Donohoue, G. Friederich, P. M. Matrai, S. Netcheva, D. K. Perovich, R. Santini, P. B. Shepson, W. Simpson, R. Stehle, T. Valentic, C. Williams, and P. J. Wyss. Development of an autonomous sea ice tethered buoy for the study of ocean-atmosphere-sea ice-snow pack interactions: the O-buoy. *Atmos. Meas. Tech. Discuss.*, 2, 2087–2121, 2009 http://www.atmos-meas-tech-discuss.net/2/2087/2009/amtd-2-2087-2009.pdf

Carlson, D., Donohoue, D., Platt, U., and Simpson, W. R.: A low power automated MAX-DOAS instrument for the Arctic and other remote unmanned locations, *Atmos. Meas. Tech. Discuss.*, 2, 2347-2375, 2009. http://www.atmos-meas-tech-discuss.net/2/2347/2009/amtd-2-2347-2009.pdf

O-Buoy web site: http://www.bigelow.org/index.php/research/facilities/srs_laboratories/paty_matrai_laboratory/research/o_buoy_/

O-Buoy data display: http://transport.sri.com/obuoy/monitor

Dispatch of the latest deployment: http://www.whoi.edu/beaufortgyre/dispatch2009/dispatch21.html

International Arctic Observing

As far as we know, O-Buoy is the only on-ice deployed system dedicated to the quantitative sampling of atmospheric compounds over the Arctic Ocean. When a network of such O-Buoys has been deployed, it will fulfill specific scientific objectives of the Canadian IPY program (Canadian OASIS) and broad goals of the U.S. SEARCH (section 4.1.1.) and EU DAMOCLES programs.

Outreach

Presentations have been made at AGU (2007, 2008, 2009), AON workshops (2007, 2008, 2009), Arctic Science Summit Week (2007), EGU (2007, 2009), and IABP (2009). Outreach has been made with a Science Schoolyard Presentation, 7 Feb 2009, Barrow, AK. One postdoctoral fellow (UAF), two graduate students (Purdue, UAF) and one summer undergraduate intern (UAF) have been involved, and the two technical papers submitted for publication and listed above have graduate students as lead authors.

The O-Buoy web site can be seen at http://www.bigelow.org/index.php/research/facilities/srs_laboratories/paty_matrai_laboratory/research/o_buoy_/. O-Buoy data are displayed at http://transport.sri.com/obuoy/monitor and have been (and are continuously) deposited at AON CADIS. The meteorological and GPS data will also be submitted daily to WMO via the IABP.

Halogen Chemistry and Ocean-Atmosphere-Sea Ice-Snowpack (OASIS) Chemical Exchange During IPY

(ARC-0732556)

PI: Paul B. Shepson, Purdue University

Project Summary

While it is known that average temperatures in the Arctic are increasing at about twice the global rate, and that that is impacting the rate of decline of sea ice extent, there are a variety of feedbacks between the changes at the Arctic Ocean surface and drivers of climate change. Among them is the relationship between the sea ice and cloud cover in the Arctic. We hypothesize that halogen atom chemistry derived from the salt associated with the surface of the sea ice has a very large impact on the oxidizing power of the Arctic atmospheric boundary layer, which in turn results in production of cloud condensation nuclei, which in turn influences cloud cover. In the absence of sea ice, the boundary layer is much better mixed, and because of that and the absence of salt at the surface, the halogen atom chemistry and CCN production in the near surface air will slow. However, we do not yet have the ability to directly measure halogen atom concentrations, so that this important chemistry (that results in rapid depletion of ozone and mercury during Arctic spring) can be monitored as sea ice cover changes in the coming decades.

The objective of this proposed three-year research effort is to develop a novel method for ultra-trace level determination of the halogen atom (Cl, Br, and I) and radical (ClO, BrO and IO) concentrations in the air above the Arctic Ocean. Our method involves sampling air into a quartz flowtube, in which the halogen atoms react rapidly with trifluoropropene to produce a halogenated ketone that can be detected with great sensitivity using chromatographic techniques. We propose to complete our ongoing development of this method, and associated field calibration techniques, so that we can then use the method for measurements in a variety of environments (to enable testing of our hypothesis), such as multi-year ice, first year ice with frost flowers, and open ocean, during the International Polar Year. This work has been coordinated with the IPY projects OASIS, CFL, SEARCH, and ASCOS. We conducted measurements in year 1 of the proposed three-year project from the Canadian icebreaker CCGS *Amundsen* (spring 2008) and as part of OASIS2009 at Barrow, AK, as part of a large international collaboration aimed at improving our overall understanding of air-cryosphere interactions. As part of this effort, we are developing a robust and portable sampling device that will facilitate long term measurements of halogen atom chemistry as ice cover in the Arctic changes, as part of the Arctic Observing Network.

Science and Technology Development Highlights

Thus far, this project has been highly successful. We proposed development of a new high sensitivity method for measurement of ClO_x and BrO_x, to quantify halogen chemistry in the Arctic. We successfully developed a new flow-tube-based method, which quantitatively converts the halogen radicals to stable halogenated ketone products that are then detected with ~1 ppt limits of detection via GC/ECD, with ~40 minute time resolution. In Figure 1 we show the flow tube on top of the KBRW tower in Barrow; this Figure also depicts the chemistry involved, and shows a schematic diagram of the flow tube method. Instrumental detection limits of about 1 ppt for both BrO and ClO have been achieved. We utilized this method in 2008 on board the CCGS *Amundsen* in the eastern Beaufort Sea to demonstrate the utility of this method for measurement of BrO, and produced an excellent data set, which has been compared to long path DOAS data from the U. Heidelberg group. In Figure 2 we present a plot of the BrO and O_3 data obtained from the *Amundsen*, showing the error bars for BrO

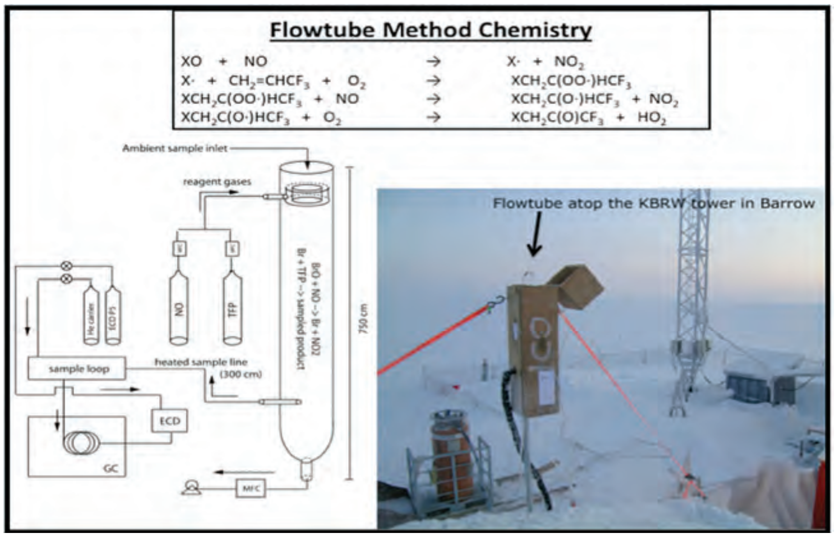


Figure 1. Flowtube method schematic and chemistry

and the remarkable inverse correlation between BrO and O_3. A manuscript was prepared (by PhD student Phil Tackett, now employed post-graduation at ICX Analytical Instruments) and is now in the revision stage ("Observations of Halogen Chemistry from the Arctic Ocean Surface Using a Flowtube Reaction Method for Determination of Halogen Free Radicals," Tackett et al., *JGR*). That paper was a collaboration between scientists at Purdue, Environment Canada, U. Heidelberg, and U. Bremen. We also co-authored a paper with collaborator Son Nghiem about the role of sea ice types and transport in bromine chemistry events in the Arctic; this paper ("Chemical Anomalies in the Arctic Troposphere from Sea Ice to Mountainsides") is being revised for resubmission to *Nature Geosciences.*

We then played a major role in the organization of the OASIS2009 campaign in Barrow, AK, designed to make significant leaps forward in our understanding of air-snow exchange and halogen chemistry related to Arctic haze and ozone and mercury depletion events in the Arctic, and how these processes may change with climate change. Research groups from Purdue, Environment Canada, NCAR, Georgia Tech., U. Heidelberg, CRREL, U.C. Davis, U. Toronto, LGGE-Grenoble, U. Villanova, CU, NOAA, and U. Fairbanks convened at Barrow and conducted an unprecedented array of measurements in the gas, snow, and aerosol phases from February through April 2009. The Shepson group made a unique set of ClO_x measurements using the new flow tube methodology, which, taken with the Georgia Tech. group's measurements of molecular halogens, point to a previously underestimated importance of chlorine atom chemistry in the Arctic boundary layer. During OASIS2009 in Barrow, we conducted measurements of ClO. In Figure 3, above right we show ClO data for a selected component of the campaign during which there was active chlorine chemistry. As shown, there are periods when O_3 is present but depleted during which chlorine chemistry is playing an active role in the depletion. This changes our perspective on the role of chlorine chemistry in Arctic ozone depletion events. In

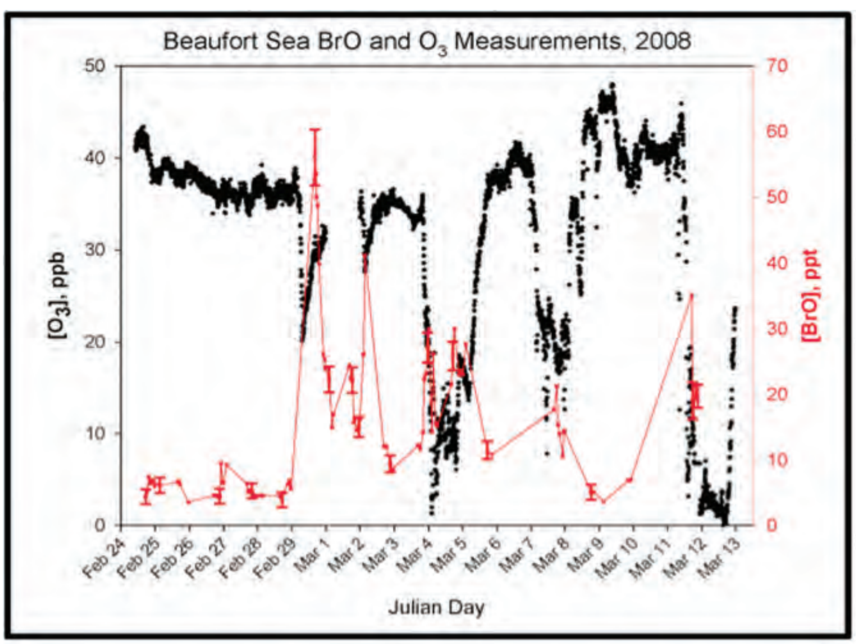
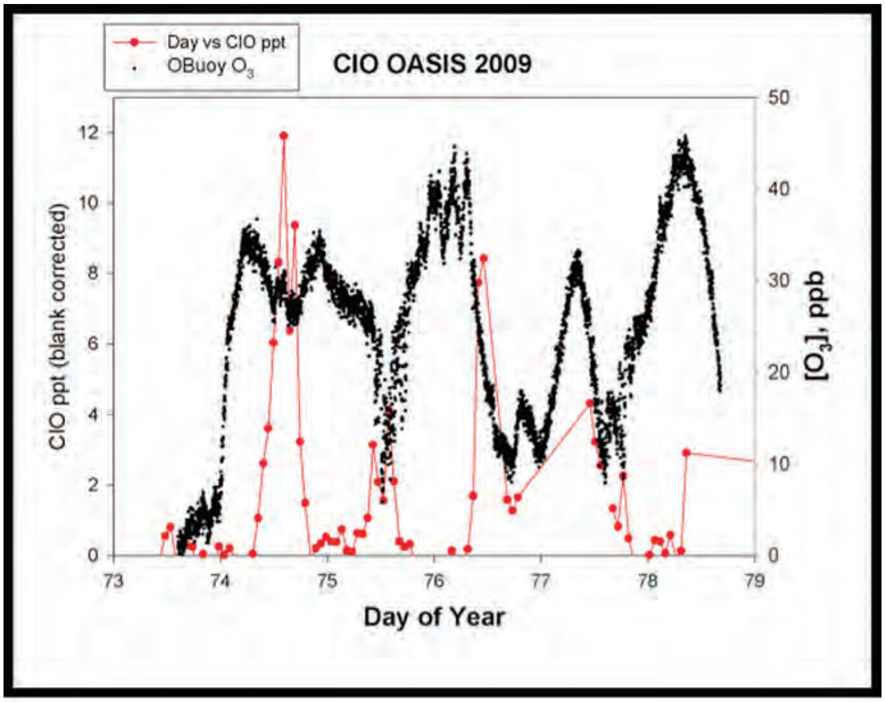


Figure 2. BrO measurement data from the Beaufort Sea.



December 2009 we organized a workshop at U.C. Davis, at which the results were discussed and analyzed, and at this workshop, we agreed to publish a special OASIS issue of *JGR-Atmospheres*; we identified 41 prospective papers with associated lead authors for this special issue. PI Shepson will be Guest Editor of that special issue. This campaign was extremely successful, and will produce an array of new insights regarding the interactions between the cryosphere and the atmosphere in a rapidly changing Arctic. We are still in the process of finalizing Level 1 data. Our final data will be made available publicly through the National Snow and Ice Data Center.

During the OASIS campaign, we developed a first version of a portable flow tube system, e.g., for measurements from a sled platform. A photograph of this flow tube is shown in Figure 4. We are currently working on the design and construction of a sled that would contain a fully functional portable version of this flow tube system.

As part of our group's work to better understand the chemistry on the surface of snow and ice, we completed two separate studies, one on snowflake surface chemistry and morphology (Knepp et al., "Measurement of Acidic Ions and Their Qualitative Effects on Snow Crystal Morphology and the Quasi-liquid Layer," *Atmospheric Chemistry and Physics, 9*, 7679-7690, 2009), and a paper involving molecular dynamics simulation of the nature of halide ions on the surface of water (Gladich et al., "Halide and Sodium Ion Parameters for Modeling Aqueous Solutions in TIP5P-Ew Water," in press with *Chem. Phys. Lett.*). We have also submitted a review article on laboratory studies of chemistry on the surface of snow and ice (Boxe et al., "Photochemistry Laboratory Studies of Organic and Inorganic Molecules on Ice and Snow Crystals Relevant to Polar Chemistry," *Chem. Rev.*, submitted).

Lessons Learned

We have learned that the flow tube technique is highly powerful and sensitive, but that it is difficult to work with in the ambient Arctic environment. For this reason, we are working on a high quality sled environment that will help us effectively and successfully incorporate this technology into the AON.

Figure 4. Photograph of portable flow tube system

Interactions with Other Projects

This project connects with the O-Buoy project, which has successfully designed, built and deployed a buoy, first into Elson Lagoon, and now in the Beaufort Sea. The O-Buoy project provides long-term measurements of BrO, CO_2 and O_3, which are part of our efforts to monitor connections between climate change, sea ice loss, and impacts and feedbacks with respect to atmospheric composition. Our work with this project and OASIS helps the community understand and interpret the long term record, and will enable improved predictive capability for the future. Information about the O-Buoy can be obtained from: http://www.bigelow.org/index.php/research/facilities/srs_laboratories/paty_matrai_laboratory/research/o_buoy_/ and ongoing data can be found at: http://transport.sri.com/obuoy/monitor.

Publications and Web sites

Gladich, I., M. Carignano, P. B. Shepson, and I. Szleifer, Halide and Sodium Ion Parameters for Modeling Aqueous Solutions in TIP5P-Ew Water, *Chem. Phys. Lett.*, in press, 2010.

Boxe, C., Guzman, M. I., A. Grannas, M. Hoffmann, P. B. Shepson, W. Simpson, R. Honrath, Richard, Photochemistry Laboratory Studies of Organic and Inorganic Molecules on Ice and Snow Crystals Relevant to Polar Chemistry, *Chem. Rev., submitted, 2009.*

S. V. Nghiem, I. G. Rigor, A. Richter, J. P. Burrows, P. B. Shepson, J. Bottenheim, D. G. Barber, A. Steffen, J. Latonas, F. Wang, G. Stern, P. Clemente-Colón, S. Martin, D. K. Hall, P. Tackett, G. Neumann, and M. Asplin, Chemical Anomalies in the Arctic Troposphere from Sea Ice to Mountainsides, submitted, *Nature Geosciences,* 2009.

Tackett, P. J., P. B. Shepson, J. W. Bottenheim, A. Steffen, U. Platt, and A. Richter, Observations of halogen chemistry from the Arctic Ocean surface using a flowtube reaction method for determination of halogen free radicals, *J. Geophys. Res.,* submitted, 2009.

Knepp, Travis N., Tennie L. Renkins, Paul B. Shepson, Measurement of Acidic Ions and Their Qualitative Effects on Snow Crystal Morphology and the Quasi-liquid Layer, *Atmospheric Chemistry and Physics., 9*, 7679-7690, 2009.

Outreach

To communicate with the public about the Arctic, our science, and how it connects to Arctic people and the impacts of climate change, we worked with adventure/nature writer Peter Lourie (www.peterlourie.com) and created a new web site that involves researchers, native Arctic people, and others working and living in the Arctic talking about their work, their lives, and their perspectives on a changing Arctic. This site has an array of excellent video interviews about sea ice, Arctic wildlife, climate change, atmospheric chemistry, and life in the Arctic. See: www.arcticstories.net. We plan to keep building this site, with high quality Arctic science stories.

Cloud Properties Across the Arctic Basin from Surface and Satellite Measurements - An Existing Arctic Observing Network

Matthew Shupe (U. of Colorado)
Von Walden (U. of Idaho)

Project Summary

The objective of this project is to create higher-order, value added cloud data products using observations from existing and past Arctic atmospheric observatories in order to characterize the macrophysical and microphysical properties of Arctic clouds. Observations used in this project are from Barrow and Atqasuk, Alaska (1998-present), SHEBA (1997-1998), Eureka, Canada (2005-present), Ny'Alesund, Norway (2002-present), and Summit, Greenland (2001-2002). Each observatory contains at least one ground-based instrument that is able to observe clouds, while some contain a comprehensive multi-instrument suite that offers a detailed perspective on many important cloud properties. At the simpler observatories, lidars provide information on cloud occurrence fraction and base height. At the more extensive observatories, coordinated measurements from radar, lidar, infrared spectrometer, microwave radiometer, and radiosondes are combined to characterize cloud occurrence fraction, vertical distribution, boundaries, phase, microphysical properties, and cloud radiative forcing. This project has capitalized on a number of existing observational techniques and has further refined methods for combining multiple cloud sensors to best derive cloud fraction and properties. The ultimate objectives in producing these data sets are to provide a means to characterize the current state of clouds in the Arctic and to provide legacy cloud data sets that can be used to understand cloud-atmosphere processes, evaluate model performance, and detect future changes.

Each Arctic atmospheric observatory has instrumentation capable of identifying the presence of clouds. On an annual basis, clouds occur 58-83% of the time at these observatories, with the highest frequency observed at Barrow and the lowest frequency observed at Summit. Annual cycles of monthly average cloud fraction (Fig. 1) suggest a typical late summer and fall maximum in cloudiness and a winter minimum. All observatories follow this general annual cycle except Eureka, which shows higher cloudiness in the winter and a minimum in the spring. The annual amplitude of monthly mean values (a measure of the annual variability of cloudiness on monthly scales) is typically about 30-40%, while being only 20% in Ny'Alesund and much larger at Summit. Interannual variability at specific sites is <12% for monthly averages, and typically <3% for annual cloud fractions. In some ways these comparative estimates of

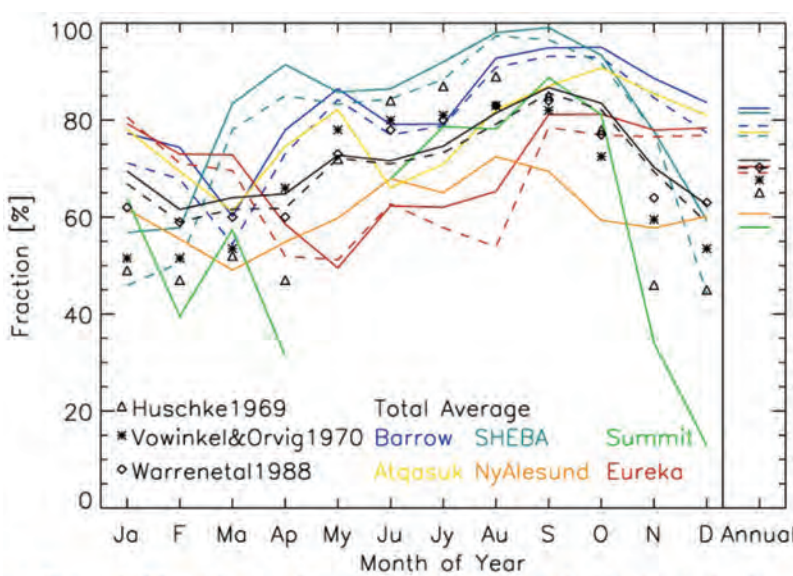


Figure 1: Monthly cloud occurrence fraction at Arctic atmospheric observatories. Solid lines are multi-sensor best estimates, dashed lines are for only laser-based instruments.

the cloudiness at each site are impacted by the distinct instrument suites used to identify the clouds. By capitalizing on the complementary strengths of each instrument, it is expected that the cloud fraction is well estimated at the multi-instrument sites (Barrow, Eureka, SHEBA). However, the comparative measurements at these sites suggest that the cloud fractions estimated for the sites where only lidar observations are available (Atqasuk, Ny'Alesund, Summit) might be underestimated in some months by as much as 10%.

For the multi-sensor observatories, a more extensive analysis is possible that examines the vertical cloud distribution and cloud phase composition (Fig. 2). Cloud liquid water, which is important for determining cloud radiative effects, is particularly prevalent in the western Arctic locations. Liquid water occurs ~56% of the time at Barrow and SHEBA, including 20-40% of the time in the cold and dark winter months. In contrast, cloud liquid water only occurs ~30% of the time in Eureka, where clouds are typically colder, contributing to a relatively lower cloud radiative effect at that site (e.g., Fig. 3). At all locations, liquid water occurs higher in the atmosphere within mixed-phase clouds. Clouds composed solely of liquid water rarely occur above 2 km, while those containing liquid in the presence of ice can occur as high as 6-8 km.

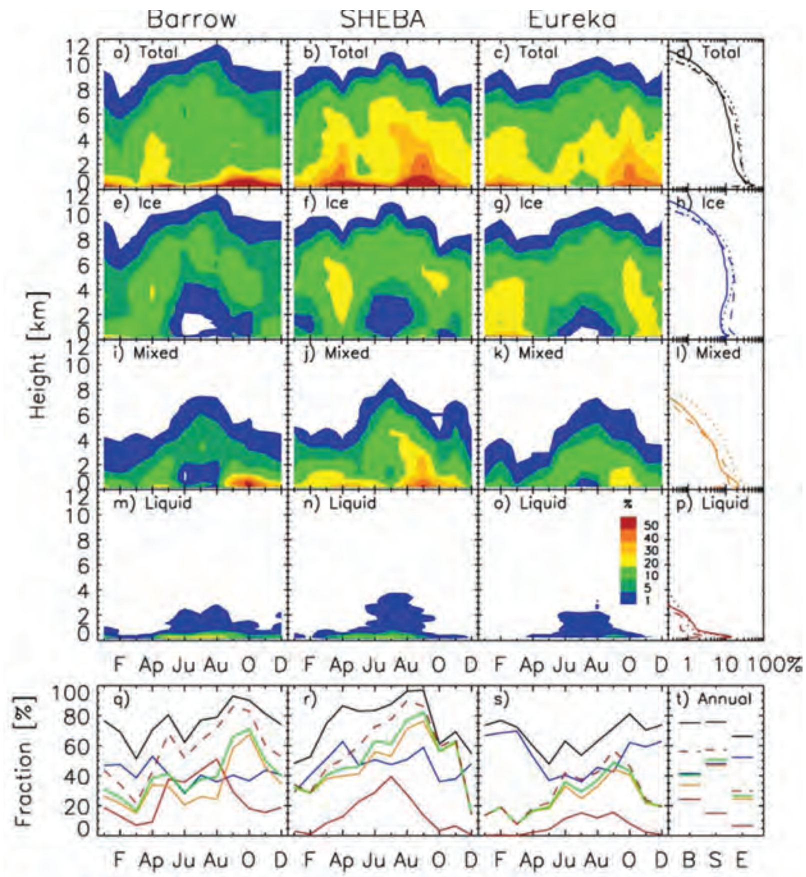


Figure 2: Cloud vertical distribution and phase. Contour maps show the mean occurrence fraction of all (top row), ice (second row), mixed-phase (third row), or liquid (fourth row) clouds as a function of month and height. The top four panels in the right column are the annual average profiles for Barrow (solid), SHEBA (dotted), and Eureka (dashed). The bottom row of curves are the total fraction of each cloud category irrespective of height, including: all clouds (black), ice clouds (blue), liquid clouds (red), mixed-phase cloud (orange), mixed column (green), and liquid water present in the column (red dashed). Annual mean values for each of these are given in panel t for Barrow (B), SHEBA (S), and Eureka (E).

At all observatories, the likelihood that clouds will contain liquid water tends to increase as temperature increases. While liquid water does not occur below -40 C, 5% of clouds contain liquid water in the -30 to -40 C temperature range. As temperature increases to the -10 to 0 C range, mixed-phase clouds are more common than either all-ice or all-liquid clouds. However, there are important distinctions between the sites. Generally, clouds are coldest, and therefore contain typically less liquid water, at Eureka, and warmest in Barrow. As a result of these differences, and the important role that cloud liquid water plays in determining cloud radiative effects, the overall cloud radiative forcing is stronger in Barrow relative to Eureka (Fig. 3), varying from a weak-warming effect in the winter to a strong warming effect in the summer and fall.

The temporal cloud occurrence fraction is strongly impacted by the persistence of clouds above a given site. Median cloud persistence (or the period over which clouds are continuously observed) for all observatories ranges from 3-5 hours. However, 5% of clouds at the far western Arctic sites last longer than 100 hours, strongly

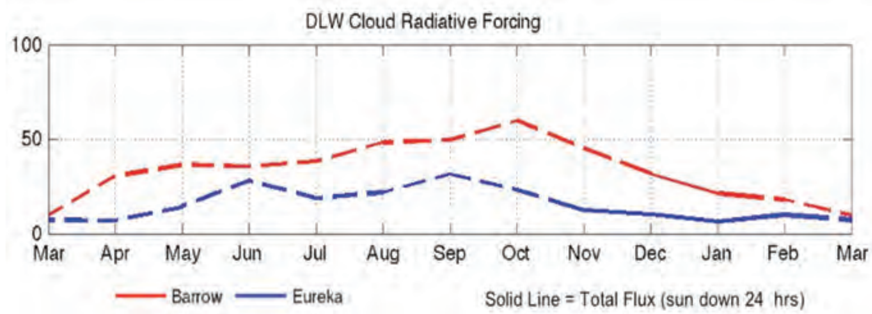


Figure 3: Downwelling LW cloud radiative forcing in W/m2 for 2006-2008

skewing the distribution of cloud persistence at those sites and contributing to the generally high cloud fractions observed there. Low-level clouds are the most persistent, with a gradual decrease in persistence time with an increase in height. There are unique differences among sites, where mid- and high-level clouds over Barrow are, on average shorter lived than at SHEBA and Eureka, while low-level clouds at Eureka are shorter lived than at the other two multi-instrument sites.

Lessons Learned

The ability to characterize cloud properties in the Arctic is hindered by a number of observational limitations. While some observations are better than no observations, datasets that are limited to one year or less (such as those from two of the sites used in this study) are very difficult to interpret within the context of temporal and spatial variability. To best characterize clouds at a given site, the observatory should be in operation for multiple annual cycles in order to include a wider, more representative collection of cloud events. In addition, to truly understand spatial variability in cloud properties, more observations are needed in undersampled regions, including most of the Eastern Arctic and over the Arctic Ocean. Lastly, the comparative, integrated studies outlined here have been complicated by the unique suites of instruments at each of the atmospheric observatories. In some cases, differences in observing capabilities among sites might inhibit or even prevent intercomparisons between sites. This type of study would be improved by more consistency in observational instruments among the existing and possible future Arctic observatories.

Data Use and Dissemination

Data sets characterizing cloud occurrence and macrophysical properties for most available years at all six Arctic observatories have been archived at the CADIS AON archive. By the end of 2009, cloud microphysical properties data sets for the multi-sensor cloud observatories will also be added to the CADIS archive. These data sets have been used in a number of studies both by the Principle Investigators and by collaborators. The PIs have submitted two manuscripts detailing cloud occurrence, macrophysical properties, and phase at the Arctic observatories. Collaborative projects have included model evaluations and basic characterization of Arctic cloud properties.

Coordination with Broader International Arctic Observing Efforts

This project fits into the broader international Arctic observing efforts in a number of ways. First, it has been designed and implemented to support the international IASOA effort, which integrates observations from Arctic atmospheric observatories. In addition, this project directly utilizes observations from a number of international sources (Japanese, Norwegian, Canadian, American) and agencies (DOE, NOAA, NSF). Cross-cutting projects of this nature help to integrate international efforts towards better observing and characterizing Arctic clouds.

Appendix B: AON Project Reports – Ocean and Sea Ice

The State of the Arctic Sea Ice Cover: An Integrated Seasonal Ice Zone Observing Network (SIZONet)

OPP-0632398

Hajo Eicken, GI-UAF (hajo.eicken@gi.alaska.edu)
Don Perovich, CRREL (donald.k.perovich@usace.army.mil)

Project Summary

This interdisciplinary project implements an integrated program for observing seasonal ice in the context of sweeping environmental, (geo)political and socio-economic change in the North. In addition to sampling of sea ice state variables, the observation-system design is guided by the concept of sea ice system services (SISS). By assessing the nature and extent of SISS, an integrated observation network can be built that will lead to prediction of key trends in a changing Arctic in a way that provides maximum benefit for the broadest range of affected interests. The project's overarching scientific goal is to track intertwined changes and selected important impacts in a rapidly evolving Seasonal Ice Zone (SIZ) in order to improve our understanding and predictions of the Arctic sea ice cover over the course of the century.

The project is working toward establishing a network of researchers, Arctic residents, industry and other stakeholders, all of whom have needs for sea-ice information. It builds infrastructure and an integrated sea-ice data set. The U.S. component of SIZONet is based on activities at observing sites in coastal Alaska (Barrow, Wales) and includes a springtime sampling and ice thickness survey campaign flown out of Barrow. Comparable measurements are carried out by partner sites in Norway, Japan and Canada. Joint field campaigns and deployment of sensors and an international field course (see book resulting out of this work in the publications list) aid with standardization and intercomparability of data sets. These activities tie into the efforts of an international CliC Working Group on Arctic Sea Ice coordinated by the SIZONet team.

Dialog and input by potential data and information users, in particular Alaska coastal communities, have helped define and optimize the observations. These efforts are complemented by ice observations carried out by indigenous experts at several coastal sites in Alaska and Russia.

Science and Technology Development Highlights

- Worked with Iñupiaq and Yupik sea ice experts to create ice observation routine and database for archival, analysis and eventual dissemination of local ice expertise.
- Developed an ice trail network mapping program related to ice use and hazard identification in collaboration with Barrow whaling captains and other North Slope ice users.

- Relied on concept of sea ice system services to guide observing system design and explore how to optimize information provided to key stakeholder groups.
- The contrasting impacts of ice retreat patterns and ice characteristics in the summers of 2007 and 2008 in the Alaskan Arctic demonstrated minimum ice extent in September is not always a good measure of impacts of ice retreat on subsistence hunting and other ice uses.
- Based on coastal ice observer records, feedback from stakeholders and analysis of ice albedo and melt data, we developed a coastal sea ice breakup forecast for the Barrow region that allows tracking of breakup in relation to key variables (downwelling shortwave flux/cloudiness, atmosphere/ocean dynamics).
- Ice thickness measurements and ice coring showed flushing of old (>5-7 years) ice out of the high Canadian Arctic into the Beaufort and Chukchi seas.
- Depth distribution of snow on sea ice plays a key role in controlling melt ponding and albedo patterns of spatial and temporal variability.
- Developed a seasonal ice buoy, allowing tracking of first year melting ice in the Chukchi Sea.

Lessons Learned

- Being responsive to both stakeholder information needs and collecting scientifically relevant data are not mutually exclusive but require thought and an overarching conceptual framework; this requires

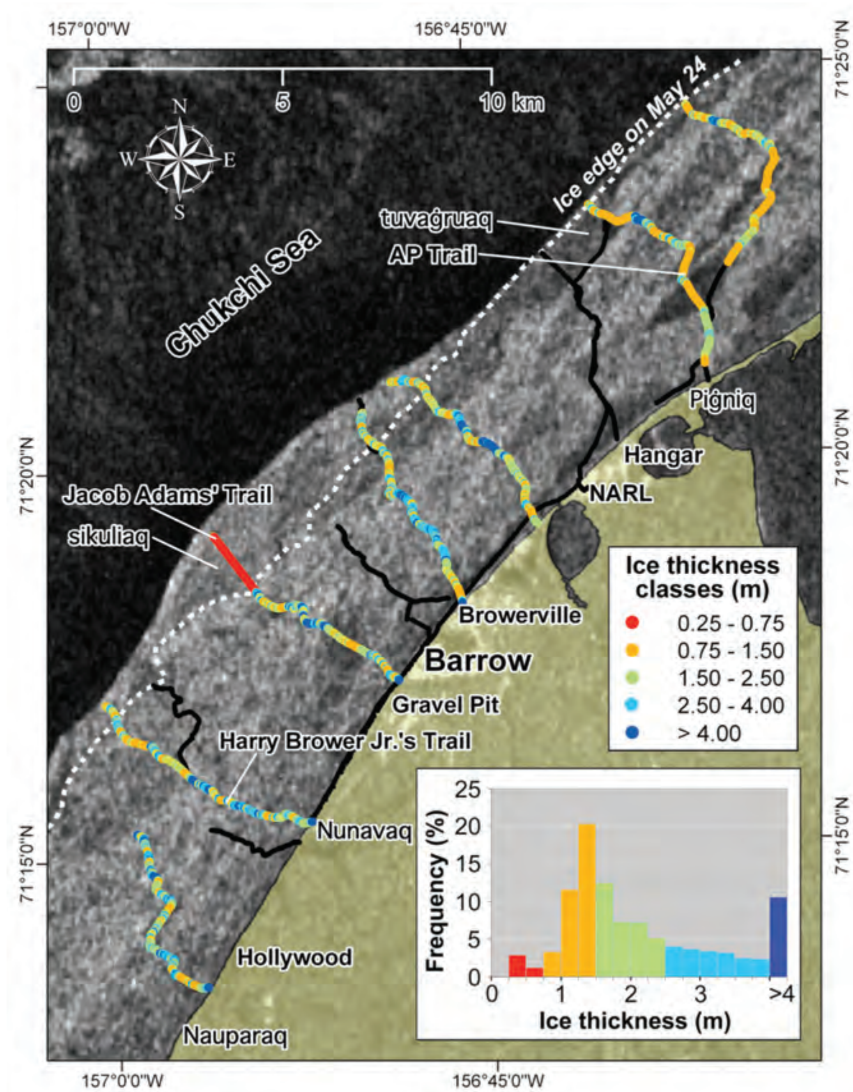


Figure 1: Map of the 2008 whaling trails on sea ice at Barrow. Trails are shown here with ice thickness data overlaid on select trails where measurements were made. The two trails south of Nunavaq were not fully mapped since they were incomplete at the time of mapping in early to mid-April. The trail off Barrow was abandoned before making it to the ice edge. The SAR image, acquired by the RADARSAT-1 satellite and provided by the Canadian Space Agency and C.E. Tweedie and A.G. Gaylord, is from April 5, 2008. Figure from Druckenmiller et al. (submitted): Assessing the shorefast ice: Iñupiat whaling trails off Barrow, Alaska, in: Krupnik, I. et al. (Editors) SIKU – Arctic Residents Document Sea Ice Use, Springer, Berlin.

more on-the-ground efforts (individual meetings, workshops, correspondence) than originally anticipated.

- Moving towards amphibious mass balance buoys is challenging and will require dedicated resources; outsourcing buoy production to a commercial vendor has proven challenging and on occasion reduced buoy reliability.
- There is great potential for progress in more coordinated observation programs through collegial international collaboration in the context of formally established working groups (in our case the CliC Sea Ice Working Group). The problem is finding resources to support these types of activities.

Adjustments Based on Interaction with Other Projects

Coordination with ELOKA early on helped clarify the approach to take in building of an ice observations database for coastal ice observers. There is significant promise that further coordination among the projects collecting community-based observations will help in identifying linkages and patterns between changes in different components of the Arctic system.

Data Use Examples

- Ice trail data and data derived from coastal ice observatories were used by a wider group of residents (in particular hunters, but also local government and search and rescue) in Barrow (and less so in Wales).
- Several modeling and remote sensing groups used data from the ice mass balance site at Barrow and ice-core data for development of large-scale sea ice models and validation of remote sensing data (M. Vancoppenolle, U. Louvain; Olivier Lecomte, U. Louvain; Chawn Harlow, UK Met Office). Data were also used by a NOAA contractor to validate and help plan deployment of tide gauges in the Barrow area.
- The coastal radar in Barrow is considered as navigation aid (Allan Ross, BP).
- Combination of web cam, radar and mass balance site is used by a number of research groups for planning purposes, as it provides information about the range of possible conditions as well as near-realtime updates. The web cam is also highly frequented by the broader public.

List of Publications and Web Sites

SIZONET: www.sizonet.org

Geophysical Institute, University of Alaska-Fairbanks: www.gi.alaska.edu/BRWICE

Alaskan Ocean Observing System Data Management: ak.aoos.org/SIZONet/

Druckenmiller, M. L., H. Eicken, M. A. Johnson, D. J. Pringle, and C. C. Willliams (2009) Towards an integrated coastal sea-ice observatory: System components and a case study at Barrow, Alaska. *Cold Reg. Sci. Technol.*, 56, 61-72

Druckenmiller, M. L., H. Eicken, J. C. George, L. Brower (in press) Assessing the shorefast ice: Iñupiat whaling trails off Barrow, Alaska. In: *SIKU – Arctic Residents Document Sea Ice and Climate Change*; edited by I. Krupnik, C. Aporta, S. Gearheard, L. Kielsen Holm, G.Laidler. Springer, Berlin.

Eicken, H. (in press) Indigenous knowledge and sea ice science: What can we learn from indigenous ice users? In: *SIKU – Arctic Residents Document Sea Ice and Climate Change*; edited by I. Krupnik, C. Aporta, S. Gearheard, L. Kielsen Holm, G.Laidler. Springer, Berlin.

Eicken, H., R. Gradinger, M. Salganek, K. Shirasawa, D. K. Perovich, M. Leppäranta (eds., 2009) Sea ice field research techniques. University of Alaska Press, Fairbanks, Alaska (with several chapters by SIZONet team partners), 566pp.

Eicken, H., and I. Krupnik (in press) Learning about sea ice and its use from the Kingikmiut. In: *Kingikmi Sigum Qanuq Ilitaavut - Wales Iñupiaq Sea-Ice Dictionary*, edited by I. Krupnik, H. Anungazuk and M. Druckenmiller, Arctic Studies Center, Smithsonian Institution, Washington, D.C.

Eicken, H., I. Krupnik, W. Weyapuk Jr., and M. L. Druckenmiller (in press), Ice seasons at Wales, 2006-2007. In: *Kingikmi Sigum Qanuq Ilitaavut - Wales Iñupiaq Sea-Ice Dictionary*, edited by I. Krupnik, H. Anungazuk and M. Druckenmiller, Arctic Studies Center, Smithsonian Institution, Washington, D.C.

Eicken, H., A. L. Lovecraft, and M. L. Druckenmiller (2009) Sea-ice system services: A framework to help identify and meet information needs relevant for Arctic observing networks. *Arctic*, 62(2), 119-136

Kapsch, M.-L., H. Eicken, M. Robards (in press) Sea ice distribution and ice use by indigenous walrus hunters on St. Lawrence Island, Alaska. In: *SIKU – Arctic Residents Document Sea Ice and Climate Change*; edited by I. Krupnik, C. Aporta, S. Gearheard, L. Kielsen Holm, G.Laidler. Springer, Berlin.

Perovich, D. K., J. A. Richter-Menge, K. F. Jones, and B. Light (2008) Sunlight, water, and ice: Extreme Arctic sea ice melt during the summer of 2007, *Geophys. Res. Lett.*, 35, L11501, doi:10.1029/2008GL034007

Perovich, D.K. and J.A. Richter-Menge (2009) Loss of sea ice in the Arctic, *Annual Review of Marine Science*, 1, 417 – 441

Perovich, D.K. and S. Gerland, Arctic sea ice observations: Integrated protocols and coordinated data acquisition, *EOS Trans. Amer. Geophys. Union*, 90, 12 May 2009.

Linkages to International Observing Efforts

- SIZONet partners initiated and help lead Climate and the Cryosphere (CliC) Arctic Sea Ice Working Group, working toward improved coordination and intercomparability of field-based sea ice measurements.
- Collaboration on buoy deployments (joint field campaigns, exchange and intercomparison of instruments, etc.) and aerial ice thickness surveys with other SIZONet partners in Norway, Japan, Germany and Canada.
- SIZONet partnered with the IPY Project Sea Ice Knowledge and Use (SIKU) and contributed three chapters to the SIKU book that is currently in preparation.

Bering Sea Sub Network: A Distributed Human Sensor Array to Detect Arctic Environmental Change

Lilian Alessa, Victoria Gofman, Andy Kliskey

Project Summary

The Bering Sea Sub Network (BSSN) (http://bssn.net) is a regional initiative of community-based organizations in Western Alaska and Northeast Russia. It operates as a distributed network that uses humans as individual, coordinated sensors for local environmental observations throughout the year.

This is required for local communities to become part of arctic observing networks required for a pan-arctic perspective on social-ecological change. The overall goal of BSSN is to improve knowledge of the environmental changes occurring in the Bering Sea region that enable scientists, arctic communities and governments to understand, anticipate and respond to these changes. Since BSSN was first conceived in 2005, it has emerged as an observing network that connects people bound by a common geographic area who share similar traditions, values, and ideals. A two-year pilot phase operated during the International Polar Year (2007-2009) involving six communities and has led to a full phase project commencing in 2009. The goals of BSSN are to:

1. Understand the variations in environmental and socio-economic conditions that have a meaningful impact on everyday life in indigenous communities in the Arctic

2. Understand the evolution of past and present consequences of change and potential strategies in order to enhance communities' capacity to adapt

3. Understand the interactions and feedbacks between the biophysical and social systems, so as to assess how changes in each impact one another

Science and Technology Development Highlights

As anthropogenic and environmental behaviors rapidly evolve many ecosystems and communities, managers of natural resources, scientists, and other stakeholders increasingly need tools that can rapidly alert them to emerging events that can affect social well-being. Data detailing such behaviors may derive from disparate sources, requiring an approach to merge multiple media sources to be analyzed in order to allow responses to events to be formulated at an appropriate time scale. In addition, applied methods need to provide both quantitative capacity for detailed analysis as well as qualitative functionality that can rapidly display emerging trends and potentially significant individual events. We are developing an information fusion approach for conducting text searches on the BSSN network derived

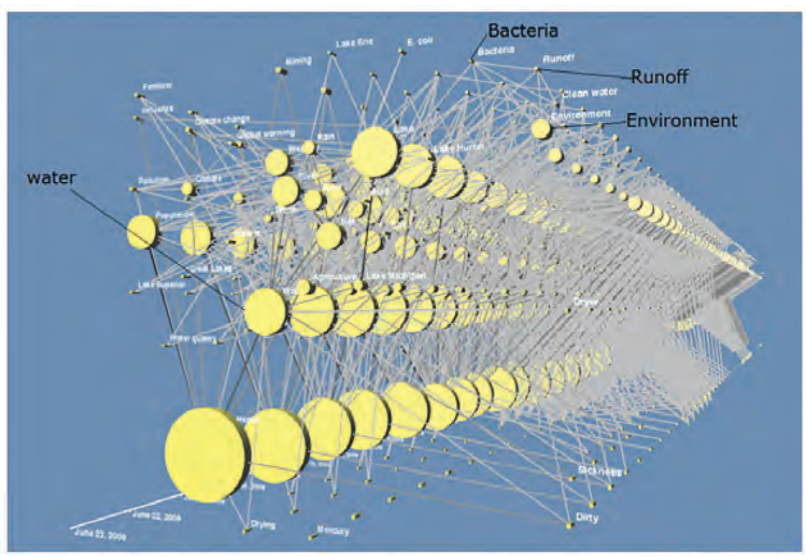


***Figure 1.** Output from the information fusion tool that is under development*

qualitative data in order to provide communities and scientists with rapid search capabilities that identify potentially significant social-ecological events. Along with general analytical utility, a network approach that links associated terms is used in assessments in order to show semantic relationships between terms, helping to identify potentially significant events.

Lessons Learned

Utilizing emerging communication tools is essential

Despite the distances between the PIs and member communities, extensive communications were possible due to the use of digital tools, such as Skype, to supplement scheduled teleconferences where possible. These tools allow real time audio and visual interactions on a daily basis and enable a distributed, coordinated network to function smoothly and acquire systematic data, reliably. The use of emergent communication and data acquisition tools will be further applied in BSSN to build on the growing momentum of community collaboration that we developed in the pilot phase.

Training and face-to-face meetings for community coordinators are essential

The training period for community coordinators needs to be extended from three to five days in order to better equip them to independently cope with the variability inherent in the respondents. On-site training in each community proved to be more efficient than training at a seminar in a central location, such as Anchorage. This could help minimize the amount of oversight and physical presence required by the PIs in the communities themselves. The development of a Manual for Community Coordinators (see Supplementary Documents,) designed and vetted during the pilot phase, will significantly improve both efficiency and precision in the future.

It is possible to reduce 'filtering' by respondents?

One of the significant accomplishments of the survey question design, which occurred through extensive discussions between the communities, Westat and the PIs, was in the reduction of "filtering" by respondents. This can be achieved by focusing on actual events and individual life experiences while extracting information on various physical and natural phenomena. Special attention was paid to avoiding "driving" respondents to any "well-known" facts or media-publicized conclusions. This approach will increase objectivity in respect to assessments based on the observations of local residents. Of equal importance is the improvement of data accuracy as questionnaire entries are entered in their original languages, English and Russian.

Examples of Activities Modified Through Interactions with Other Projects

There has been close interactions with other NSF-funded projects in the Arctic, including the Intersections of Humans, Hydrology and Climate Change (ARC 0328686, ARC 0327296), EPSCoR Resilience of the North (EPS 0701898), and IPY Municipal Water Systems and Hydrological Change (ARC 0755966) awarded to PI Alessa, that have contributed to the design and implementation of the BSSN network. There is ongoing liaison between BSSN project personnel and personnel on the North Pacific Research Board / NSF supported BEST (Bering Ecosystem Study) project.

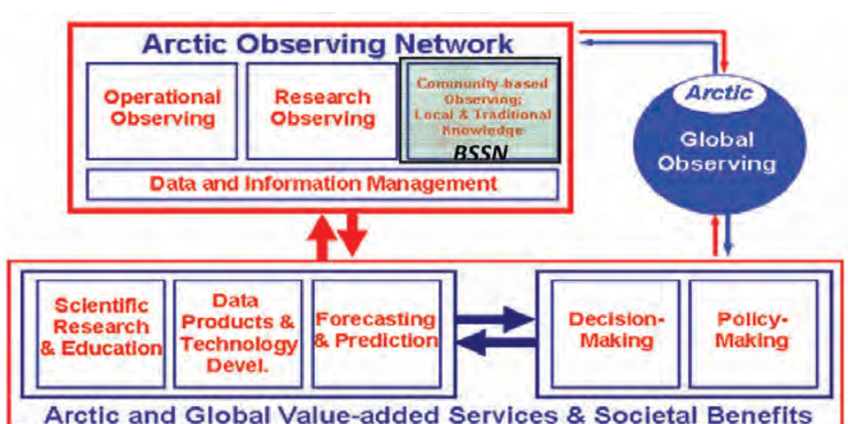


Figure 2. The role of BSSN in Arctic Observing Networks. Source: NRC 2006.

Brief Examples of Data Use for Science and Stakeholders

Preliminary pilot phase data from BSSN provide insight to the constraints on adaptation: individuals in Alaskan communities are far more mobile than those in Russian communities, through freedom and means (i.e., fuel) to move, leading to greater options to respond to change in the former – particularly those affecting local scales.

List of Publications, Web Sites

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Web site for BSSN: http://www.bssn.net

Web site for AIA: http://aleut-international.org

Web site for RAM Group: http://ram.uaa.alaska.edu

Fit with Broader Suite of International Arctic Observing Efforts

BSSN contributes to AON, which is an integral part of the SEARCH program to improve observational capabilities in the Arctic and leave a long-term legacy for the benefit of science and society. BSSN data will increase knowledge and understanding of the regional causes and consequences of rapid arctic change, provide insight into the consequences of change to local communities in the Bering Sea region, and assist in the development of adaptive responses to arctic change. BSSN is engaged in efforts to develop distributed, community-based monitoring networks including SAON (Sustaining Arctic Observing Networks), RAVON (Resilience and Vulnerability Observing Network), and is a U.S. contribution to the CBMP (Circumpolar Biodiversity Monitoring Program).

The Arctic Observing Network at Critical Gateways — A Sustained Observing System at Davis Strait

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Project Summary

The Davis Strait observing system, positioned at one of the three primary Arctic gateways, was designed to quantify exchange between the Arctic and subpolar North Atlantic on the western side of Greenland. Although observations and models point to increased Arctic freshwater discharge in the coming decades, the community lacks the long records of gateway fluxes and discharge characteristics needed to isolate secular change from cyclic variability, draw statistically meaningful relationships between flux variability and possible forcing mechanisms, constrain numerical models and, ultimately, develop efficient monitoring and predictive capabilities. The on-going Davis Strait program has produced a five-year time series that captures the variability and structure of the integrated Canadian Arctic Archipelago discharge after it has undergone pathway transformations and just prior to entering the subpolar North Atlantic. The Davis Strait observing network employs a complementary system of moorings, autonomous gliders and ship-based hydrographic surveys to quantify, with robust error estimates, watermass variability, volume, liquid freshwater, heat and ice fluxes, ambient noise and marine mammal presence at weekly to interannual timescales, with biennial assessment of biogeochemical properties that integrate large-scale change. The project also includes significant technology development, including autonomous gliders and acoustic navigation for extended (months to a year) operations in ice-covered waters and novel mooring designs.

Science Results and Technology Development

Davis Strait Seasonal and Interannual Variability

An observing system that includes moorings, autonomous, long-endurance Seagliders and annual hydrographic sections has characterized circulation, water mass structure and fluxes [volume, freshwater (liquid and ice) and heat] at Davis Strait since autumn 2004 (Fig. 1). These complementary platforms: (1) resolve deformation-scale O(10 km) motions across the 300 km wide strait, (2) quantify temperature and salinity variability near the critical but hazardous ice-ocean interface, (3) collect measurements over shallow shelves and (4) provide weekly resolution over multi-year timescales.

Sections of along-strait velocity, salinity and temperature derived from moored (Fig. 2) and glider-based measurements (Fig. 3) reveal the persistent structures and seasonal changes that govern flux variability. A sharp, persistent front separates south-going Arctic waters (to the west) from north-flowing waters composed of the upper-ocean West Greenland Current (Arctic waters that have exited Fram Strait and rounded Cape Farewell) and the deeper Irminger Current (warmer, more saline Atlantic water) that hugs the West Greenland slope. The cross-strait position of this important front varies seasonally and interannually, which strongly impacts flux calculations (Curry et al., 2010). Glider-based sections provide a well-resolved measure of frontal position and structure and quantify seasonal changes in the upper ocean, addressing two large sources of uncertainty. High-resolution sections across the deep Strait

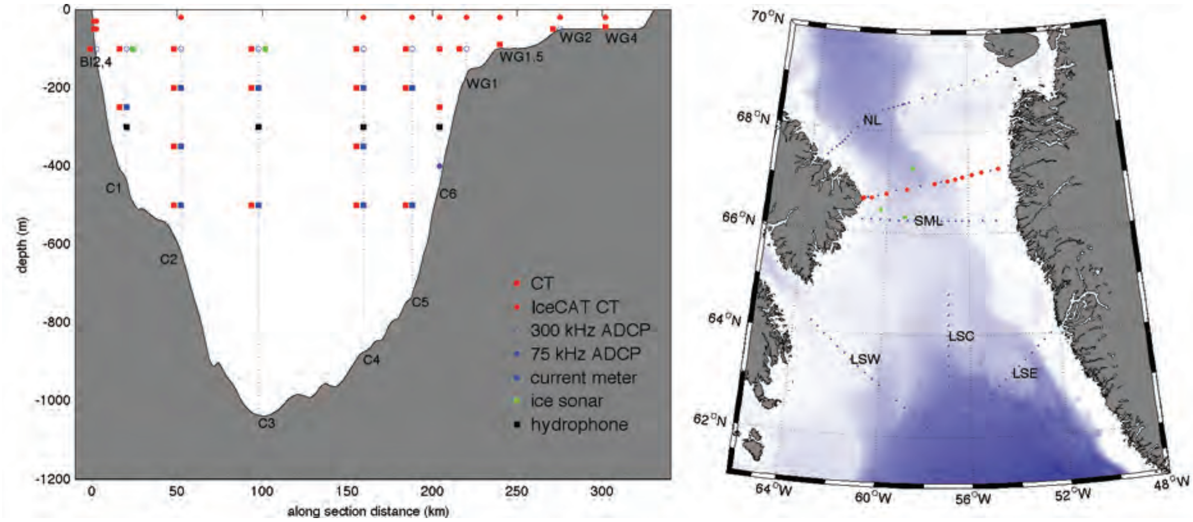

Fig. 1: Bathymetry and array geometry for the proposed 2010-2015 Davis Strait observing network. The 2004-2010 configuration is similar. On the chart (left) blue squares mark CTD stations, red circles array moorings, and green circles isolated sound sources. Upward-looking ADCPs (right, blue circles) provide velocity measurements that reach from instrument depth to the ice-ocean interface.

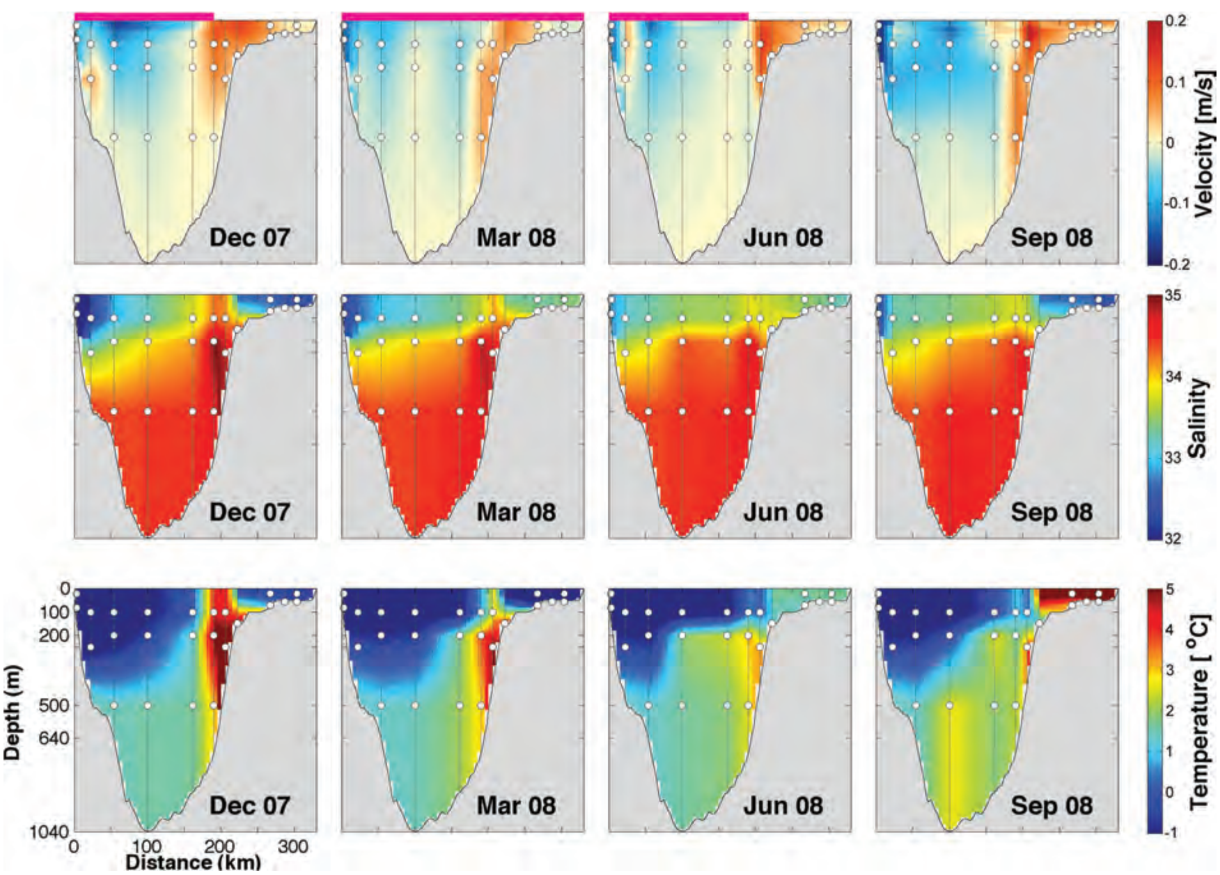

Fig. 2: Davis Strait monthly mean (Dec, Mar, Jun and Sep) velocity, salinity, and temperature sections, calculated using data from the 2007-2008 moored array. White dots mark discrete instrument locations. ADCPs provide measurements of velocity over the entire upper 100 m.

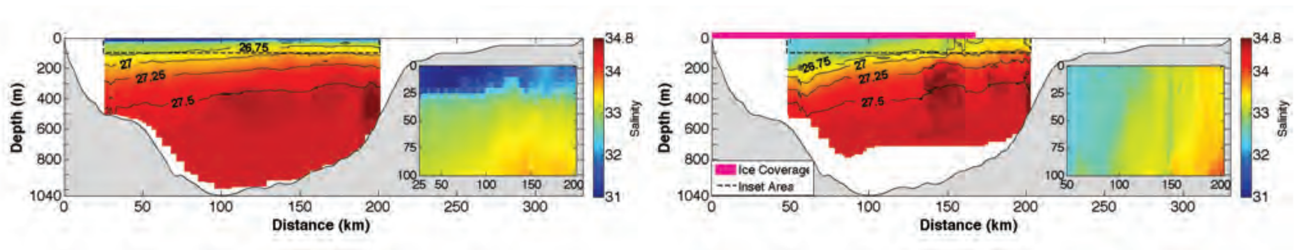

Fig. 3: Salinity (color) - potential density (contour) sections across Davis Strait in ice-free (September 2008, left) and ice-covered (December 2008, right) periods collected by Seaglider 108. The inset magnifies the upper ocean, depicting the upper 100 m across the entire section. Typical profile resolution is better than 4 km. Note the dramatic change in upper ocean structure and the presence of small-scale features in both salinity and density.

(Fig. 3) during ice-free (September) and ice-covered (December) periods show the mixed layer thickening and salinity increasing, perhaps due to brine rejection and convective overturning driven by sea ice formation, within the wedge of Arctic water flowing south under the ice. With successful wintertime operations, Seaglider now provides high-resolution under-ice sections that quantify seasonal and interannual changes in important flow structures that were previously impractical to sample.

Robust quantification of fluxes and uncertainties relies on understanding the inherent spatial and temporal scales and accounting for them in sampling and analysis. Davis Strait exhibits energetic tidal variability, which must be fully resolved and removed by low-pass filtering. Spatial decorrelation length scales estimated from the measurements range from 15-25 km, depending on parameter, season and depth. Flux estimates were calculated from the moored time series for 2004-2008 using linear interpolation between sites and simple extrapolations to the sea surface and bottom (Fig. 4, black). More refined, optimal flux estimates employ objective analysis on fields constructed using moored time series with hydrographic and historical data used to constrain interpolation and extrapolation to the surface and sea floor (Fig. 4, red; Curry et al., 2010). Analysis of subsequent years (2005+) is ongoing, and incorporates glider-based sections to reduce flux uncertainty by accurately characterizing both upper ocean and small-scale features, which are marginally resolved by the moored array.

Measurements collected by moored Upward-Looking Sonars (ULS) characterize the spatial and temporal variability of ice in the strait (Fig. 5). Mean thickness decreases eastward across the array, with virtually no ice at the easternmost site. The observations suggest that interannual variability in ice thickness may be largest in the western strait. Preliminary ice flux estimates (Curry et al., 2010) suggest a 15 mSv contribution to freshwater flux, consistent with expectations.

Volume and freshwater flux estimates for 2004-2008 reveal net southward flux year-round, with minima in autumn, maxima in winter (increased CAA export; Prinsenberg et al., 2009) and a hint of a secondary summer maximum (freshwater release from Baffin Bay ice melt). The 4-year record reveals striking interannual variability in both strength and phase; for example, timing of the freshwater flux maxima varies over a 3-month span (Dec-Feb), and the peak can be narrow (2006), broad (2007) or largely absent (2005). This suggests caution when drawing conclusions from fluxes based on annual hydrographic surveys.

Neither these time series nor those at Fram Strait (de Steur, 2010) show the anticipated increase in southward freshwater flux, though Davis Strait findings may change as the calculations are refined by incorporating more accurate measures of upper ocean salinity. The 2004-2005 estimates that include corrections for the upper ocean (Fig. 4, red line) produce larger southward freshwater fluxes (−123 ± 41 mSv vs. -93 mSv). Curry et al. (2010) find that the upper 150 m carries 54% of the net volume and 73% of the net freshwater flux, suggesting that the more refined 2005-2008 freshwater flux estimates will be larger than those depicted here. This clearly illustrates the importance of glider-, ADCP- and

IceCAT-based upper-ocean measurements. Baffin Bay volume and freshwater budgets (2004-2005), calculated using contemporaneous measurements at the major CAA passages to the north, close to within 29% (15%) of Davis Strait volume (freshwater) flux estimates (Curry et al., 2010). The multi-year record is now becoming long enough to begin investigating forcing mechanisms. Initial calculations show no clear relationship between Davis Strait fluxes and either the Arctic Oscillation, even accounting for the 1-year lag found by Jahn et al. (2009), or Arctic Dipole, perhaps due to a shift in dominant forcing patterns. Ongoing efforts focus on exploring connections with these and other measures of large-scale atmospheric forcing.

Additional studies explored connections between arctic outflows and subarctic climate. An analysis of the 2007-2008 return of Labrador Sea deep convection proposed a mechanism in which increased CAA freshwater discharge drives increased Labrador Sea deep convection by modifying sea ice extent and, thus, the location where maximum oceanic heat loss occurs (Vage et al., 2009). This provides another, somewhat counter-intuitive, process by which Arctic freshwater can impact the MOC. The Davis Strait observing system was also used

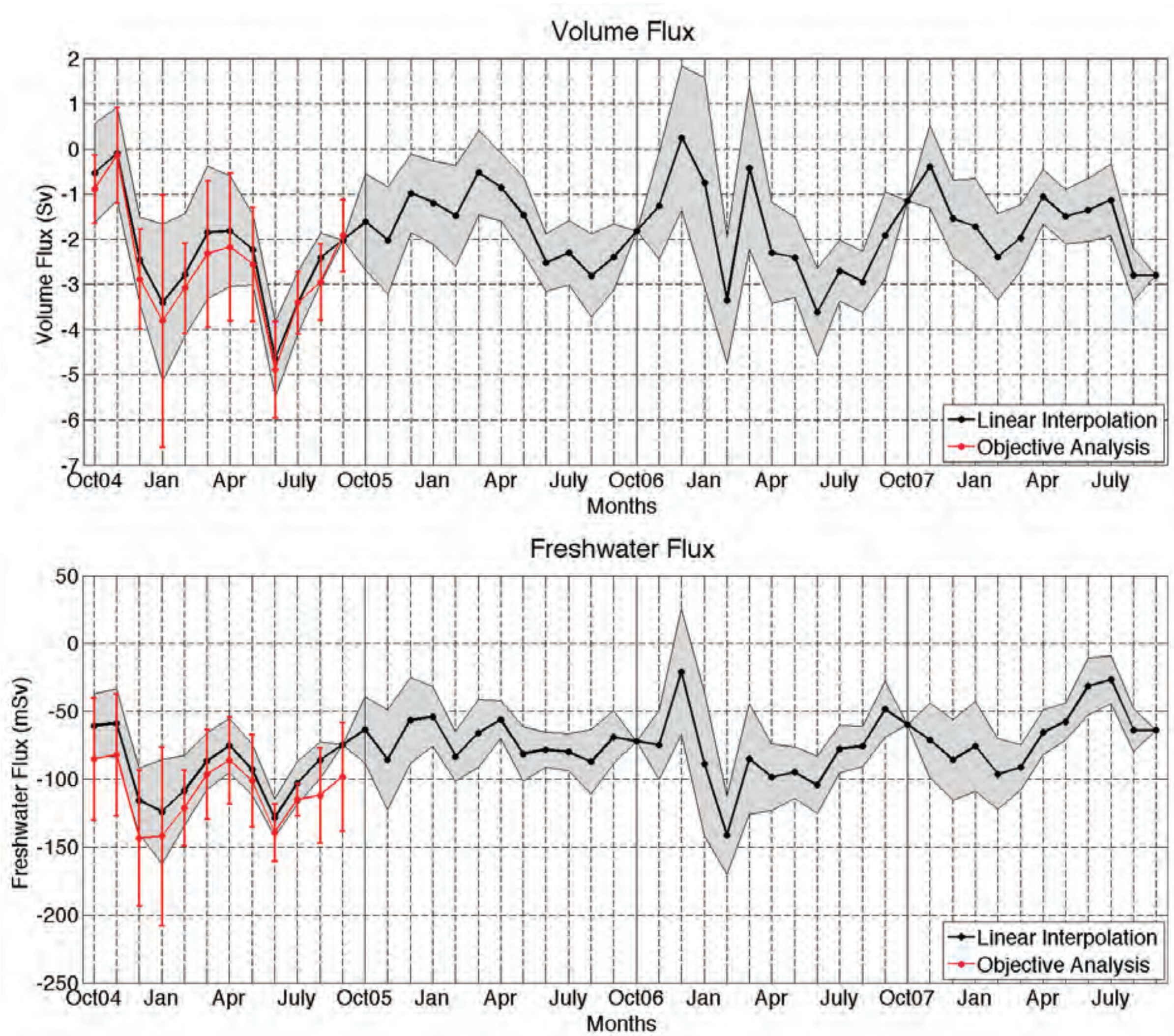

Fig. 4: Monthly average volume (top) and freshwater (relative to S=34.8, right) flux from Oct 2004 - Sep 2008. The black line marks flux estimates from linear interpolation of the moored measurements, with gray shading marking the standard deviation of the daily fluxes used in the monthly mean. Red lines mark estimates and uncertainties for 2004-2005, calculated by objective analysis of fields constructed using moored time series, CTD sections and archived data.

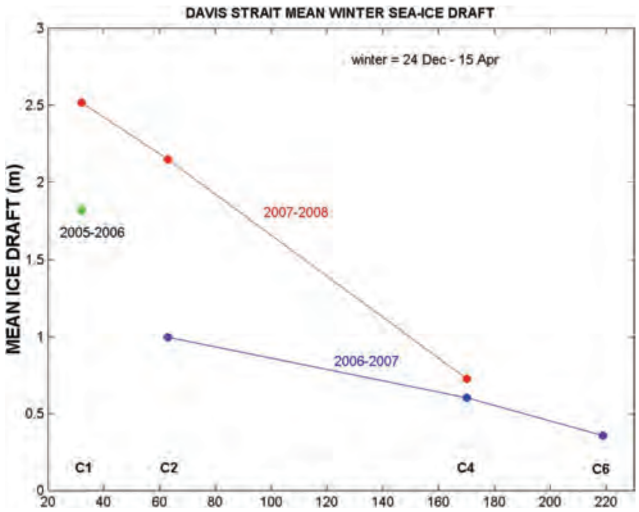

Fig. 5: Mean wintertime (24 Dec - 15 Apr) ice draft across Davis Strait. Colors denote different years, with values plotted west to east.

to study ocean acidification. The 5-year record of chemical measurements reveal corrosive Arctic outflow (low saturation state with respect to argonite) and provide a baseline for CAA outflow saturation state and downstream modification that will ground future assessments of Arctic Ocean acidification and its impacts (Azetsu-Scott et al., 2010).

Observing Technology

The Davis Strait program has produced significant technical achievements, foremost of which is the first-ever successful, extended operation of autonomous gliders under the ice. Seaglider 109's (SG109) December 2006 excursion was the first successful under-ice transit by any glider. From the ice edge on the eastern side of the strait the vehicle navigated to a waypoint under the ice 50 km to the west and back east again over the course of one week. In 2008–2009, SG108 completed the first wintertime mission with repeat crossings, operating for 6 months with a total of 333 dives, 51 days and 710 km of operations under the ice before recovery by a Greenlandic coast guard vessel (Fig. 6a & Fig. 3). The 2009–2010 deployment (SG143) sampled through the autumn and occupied one complete under-ice section before a problem with the roll mechanism (which the glider uses to steer) forced a January recovery using a Greenlandic fishing boat (Fig. 6b).

These successful missions demonstrate that under-ice autonomy and navigation, developed in Davis Strait for high-latitude glider operations, function well. Gliders determine the presence of overhead ice by consulting an on-board ice climatology, assessing the temperature

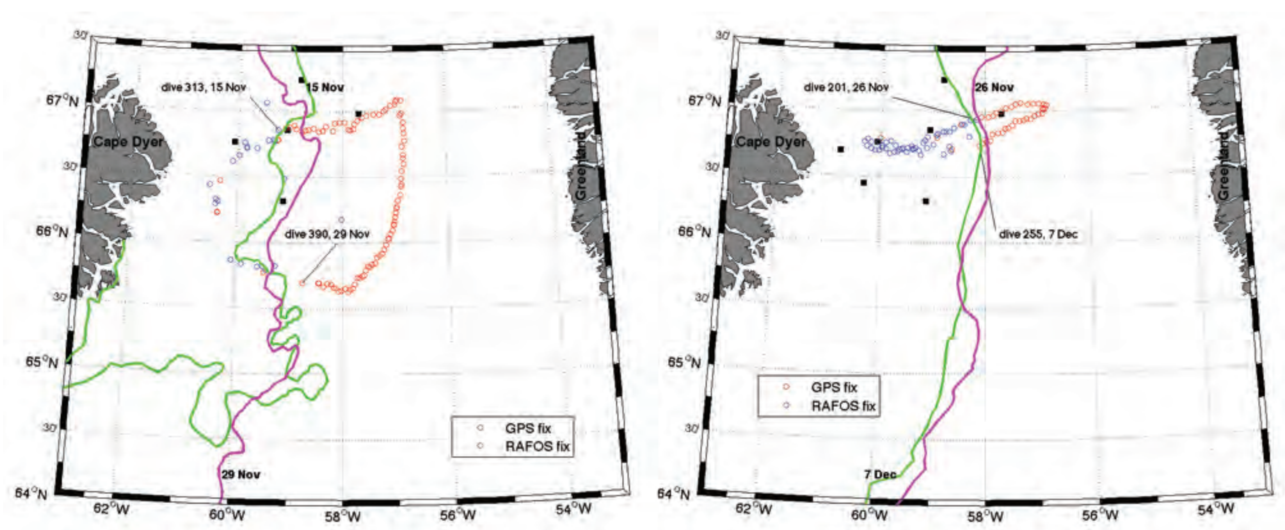

Fig. 6: Glider track plots from 2008 (SG108, left) and 2009 (SG143, right). Improved navigation in 2009 reflects better acoustic coverage (black squares) on the western side of the Strait and improvements to the navigation algorithm. RAFOS fixes (blue) mark dives when the glider was navigating acoustically due to ice cover. Colored lines mark ice edges extracted from Canadian Ice Service daily ice charts. Ice edge lines and selected glider positions are annotated with dates.

profile as the vehicle nears the surface and using an altimeter to sense overhead obstacles. The glider may try to surface even when ice is expected if a sufficient number of dives is queued for upload. Using this approach, SG108 was able to surface in 8 of 33 attempts. The glider never got stuck in ice during a surfacing attempt, though it did get stuck on the underside of the ice twice, for 90 and 60 minutes, during dives when it was not trying to surface. This reinforces the need for ice avoidance and careful behavior when operating anywhere near the ice. For the 2009–2010 mission, we adjusted altimeter use for ice avoidance and programmed the glider to turn a little further from the ice-ocean interface to provide a wider safety margin.

Glider navigation also performed well, though the 2008–2009 mission did reveal a problem with navigation reception near the heavily ice covered Baffin side of the strait. With poor navigation results, the glider was unable to detect that it had achieved its target and as a result continued moving west into shallow water and a strong southward current. Unable to stem the current, the glider was swept south before returning to the eastern end of the line (Fig. 6a). In 2009, we made adjustments to the quality filtering of navigation solutions and reorganized the source array to provide better acoustic coverage in the west. Consequently, the under-ice transit from 2009 follows a dramatically better track (Fig. 6b). Efforts to improve navigation and under-ice autonomy are ongoing.

Another significant technology development in Davis Strait has been the IceCAT system for near-surface sampling in ice/iceberg threatened environments. IceCATs use an inductively coupled CTD sensor near the surface connected via weaklink to a datalogger moored just above the anchor. Use of IceCATs has expanded from two shelf/slope sites in 2004 to five sites in 2009. IceCAT technology has been successfully transferred to other research groups, and the instruments are now seeing routine use in the Bering Strait and Bering Sea.

Marine Mammal Populations

In a joint effort between U.S. and Greenland scientists, three hydrophone packages that monitored from 0.1 to 1000 Hz were deployed from October 2006–October 2007 on Davis Strait array moorings. We aimed to study the seasonal occurrence of vocal marine mammals and the oceanographic processes that may influence the phenology of their migratory behavior. Automatic detection methods were used to determine the presence of baleen whale vocalizations. All three instruments were ice-covered from the beginning of December 2006 until late June 2007. Blue and sei whales were only heard in the late summer/early fall and showed no clear relation to ice cover. No feeding sounds were recorded from humpback whales, only song in November and December. Songs decreased as ice cover increased. Fin whales were the dominant bio-acoustic signal recorded in Davis Strait and were recorded year-round suggesting they may not be limited by the ice edge in 2006-2007. Bowhead song was primarily recorded in April and May when the instruments were covered by ice and in 2007 at least four distinct songs were recorded. Springtime ambient noise levels were high in Davis Strait due to ice noise and bearded seal song, which sometimes masked bowhead whale calls. Under a scenario where ambient noise levels increase due to anthropogenic input and/or less ice cover, acoustic masking could negatively impact bowhead whales' ability to hear each other. Further, if humpback whales spend more time in Davis Strait under decreased ice conditions, it may become difficult to distinguish between the two species (Stafford et al., 2010).

In a more detailed study of fin whale calls (Simon et al., 2010), it was demonstrated that fin whales are present in Davis Strait all year round. The contemporaneous peaks in song activity and estimated conception time suggest that Davis Strait is important not only for fin whales to refill energy stores during summer, but also is a likely mating ground for some fin whales during winter, making it likely that some fin whales do not perform large annual migrations. The singing activity of fin whales is strongly linked to sunlight hours, likely controlled by the vertical migrative behavior of the prey, further suggesting that fin whales might feed during the few daylight hours of the Arctic winter in Davis Strait. The difference in magnitude of fin whale signals between the three recorders showed that the distribution of fin whales in Davis Strait is restricted by the ice edge; changing ice conditions may change at least the winter distribution of fin whales in the future.

Lessons Learned

Analysis of five-year time series, along with the accompanying annual hydrographic sections and the historical record provides some useful lessons. Although the fluxes calculated from the autumn hydrographic sections suggest a general increase in southward volume and freshwater flux, annual means calculated from the moored time series show no significant trends. This provides a simple lesson in aliasing, illustrating the dangers of using fluxes estimated from annually occupied sections as proxies for the true annual mean. The observations have also yielded information on the dominant spatial and temporal scales and on the regions that account for the largest portions of flux variance. These findings are being exploited in our continued efforts to optimize observing system design.

The wintertime Davis Strait is a remote, difficult operating environment that, when combined with the normal trials of instrument development and extended autonomous operation, presents severe challenges. The fate of SG113 in 2008 illustrates some of the hazards. Due to pilot error and unfortunate timing, SG113 embarked on an under-ice section without all of the usual under-ice behaviors activated. The glider probed the ice at the top of every dive and, when it finally found a hole (on the western margin, after completing a section), froze in at the surface because it lingered too long trying to transmit the entire backlog of data. Though we were able to monitor its southward drift for a few days before it was crushed, weather, ice and its remote location precluded rescue. The loss of SG113, while painful, confirmed the wisdom of our normal under-ice behavior, which allows the glider only limited surface time when accessing though a hole in the ice. Reliability issues remain a problem for gliders operating everywhere in the world, and Davis Strait gliders have experienced failures unrelated to the harsh environment. Our group invests significant effort in general reliability engineering across all operations (Arctic and lower latitude), which has resulted in a gradual but steady decline in failures.

Interactions with Other Projects

Joint scientific analyses are ongoing with collaborators from the Bedford Institution of Oceanography, the National Oceanographic Center, Southampton, Alfred Wegner Institute and others. Measurements were collected at all of the major gateways during the IPY period, and the combined data holdings provide a unique opportunity to investigate Arctic mass, heat and freshwater budgets. These efforts thus primarily focus on developing an understanding of Arctic – Subarctic exchange, its variability and forcing mechanisms. Results from these efforts will be used to guide the shape of ongoing measurement efforts at the various gateways. The Data Dissemination section below provides some specifics.

Technological developments produced by the Davis Strait program are being introduced into the high-latitude observing community. In 2010, we will assist Dr. W. Smith (Virginia Institute of Marine Science) with the first Seaglider deployments in Antarctica, where under-ice operating behavior will be utilized to pass the glider under an ice bridge and into a large polynya. Scientists at Alfred Wegener Institute are using RAFOS equipped Seagliders for under ice operations in Fram Strait. T. Weingartner and K. Aagaard are using IceCATs in the Bering Sea as part of the Bering Sea Ecosystem Study. Weingartner plans to expand IceCAT deployments to the Chuckchi Sea in coming years. R. Woodgate is using IceCATs as part of efforts to monitor fluxes through Bering Strait.

The program also supports long-view efforts to introduce autonomous technologies into the Arctic observing toolbox. For example, Davis Strait provides a testbed for developing acoustic navigation and communication technologies to enable the application of autonomous platforms to Arctic ocean science. Acoustic data transfer, including gliders that shuttle data between moored sensors and data repositories, and development of improved acoustic signals for navigation, follow priorities defined by the ANCHOR workshop (http://anchor.apl.washington.edu, supported by ARC-0511163) and discussed in the Arctic Observation Integration Workshop Report (ARCUS, 2008). Developments surrounding data transfers between mobile platforms (Seagliders) and moored assets provide fundamental building blocks for larger Arctic observing networks that could exploit these capabilities to improve data return and, in some cases, provide delayed-mode access to data from sensors located beneath the ice.

Data Dissemination and Use

Davis Strait data are available for public access on the IOP web server, through CADIS AON portal and, soon, at NODC and NSIDC. The data are being used by modeling efforts that include: Drs. T. Tsubouchi, A.N. Garabato and S. Bacon (National Oceanography Centre, Southampton), who are constructing a pan-Arctic inverse model that will aid in the array optimization and interpretation of results, Dr. L. Axell (Swedish Meteorological and Hydrological Institute) for assimilation into two-way coupled ocean-ice-atmosphere reanalysis and Dr. Y. Aksenov (NOCS) for model evaluation. Davis Strait data have also been used in analysis conducted by numerous investigators within the Department of Fisheries and Oceanography (Canada), the Canadian Meteorological Service, the Danish Meteorological Institute, and IFREMER and LODYC (France).

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North Pole Station: A Distributed Long-Term Environmental Observatory

OPP-0352754
J. Morison, K. Aagaard, A. Heiberg, R. Moritz, M. Steele (Applied Physics Laboratory), and J. Overland (Pacific Marine Environmental Laboratory)
OPP-0352984 – Falkner; OPP-0352687 – McPhee ; and ARC-0634226 – IPY Aerial Surveys

Project Summary

The North Pole Environmental Observatory (NPEO) is a collaborative project established in 2000 with the aims of tracking and understanding ongoing changes in the Arctic environment, and providing central Arctic Ocean data and infrastructure for the polar science community. The original grant was renewed in 2004 and again in 2009.

We have carried out springtime deployments of the NPEO in 2000 through 2008. Operating from a base camp, we conduct hydrographic surveys, install automated drifting stations, and service the first long-term, deep water (4300 m) oceanographic mooring in the central Arctic Ocean. Our hydrographic survey stations include CTD and water sampling to about 900 m depth conducted with a ski-equipped Twin Otter airplane landing on the ice. The hydrographic stations have typically been made every degree of latitude down one of several lines of longitude, repeating the survey lines every 2-3 years. For IPY in 2008 this was expanded to five lines near the Pole and four lines in the Beaufort Sea. In addition to CTD casts, the hydro surveys collect water samples for chemical analysis. New developments have included oxygen and nutrient profiling with new instruments. The 2008 Beaufort Sea survey included the use of new Air eXpendable CTDs (AXCTD) to make CTD stations far from shore without landing on the ice. The automated drifting stations typically consist of meteorological, Ice Mass Balance (IMB), and oceanographic buoys. The ocean buoys have been provided by other projects, namely the Japan Agency for Marine Science and Technology (JAMSTEC, Takashi Kikuchi), and more recently Woods Hole Oceanographic Institution (WHOI, John Toole et al.). Similarly, an Autonomous Ocean Flux Buoy (AOFB) has been installed for a separate, NSF-supported, collaborating project at the Naval Postgraduate School (NPS, Tim Stanton). We commonly install small atmospheric pressure/temperature buoys for the International Arctic Buoy Program (IABP) during hydrographic survey flights. The mooring has typically included an APL-built Upward Looking Sonar (ULS) at 50 m depth to measure ice thickness, four CTDs to 600 m measuring water properties through the halocline and the Atlantic Water temperature core, and an additional three CTDs to 2500 m. Ice velocity and current profiles are measured with an up-looking Acoustic Doppler Current Profiler (ADCP) at 80 m, and seven current meters below that. A related project (Arctic Ocean Bottom Pressure, OPP 0326109) has developed and installed Arctic Bottom Pressure Recorders with acoustic modem data upload capability. These data are compared with ocean bottom pressure (OBP) observations of the Gravity Recovery and Climate Experiment (GRACE) to track circulation changes throughout the Arctic Ocean. In 2009, we were not funded for field work, but we were able to arrange for installation of an automated drifting station by our partners at JAMSTEC, NPS, PMEL and the IABP.

Science and Technology Highlights

The North Pole is a critical region for monitoring Arctic change because it is sensitive to variations in the Arctic Ocean circulation associated with anticyclonic (clockwise) and cyclonic (counterclockwise) shifts in the front between salty Atlantic-derived and less salty Pacific-derived upper ocean waters. These Atlantic-Pacific (AP) frontal shifts pass over the North Pole region roughly parallel to the Lomonosov Ridge in the anticyclonic mode and along the Alpha-Mendeleyev ridges in the cyclonic mode. Shifts to the cyclonic mode

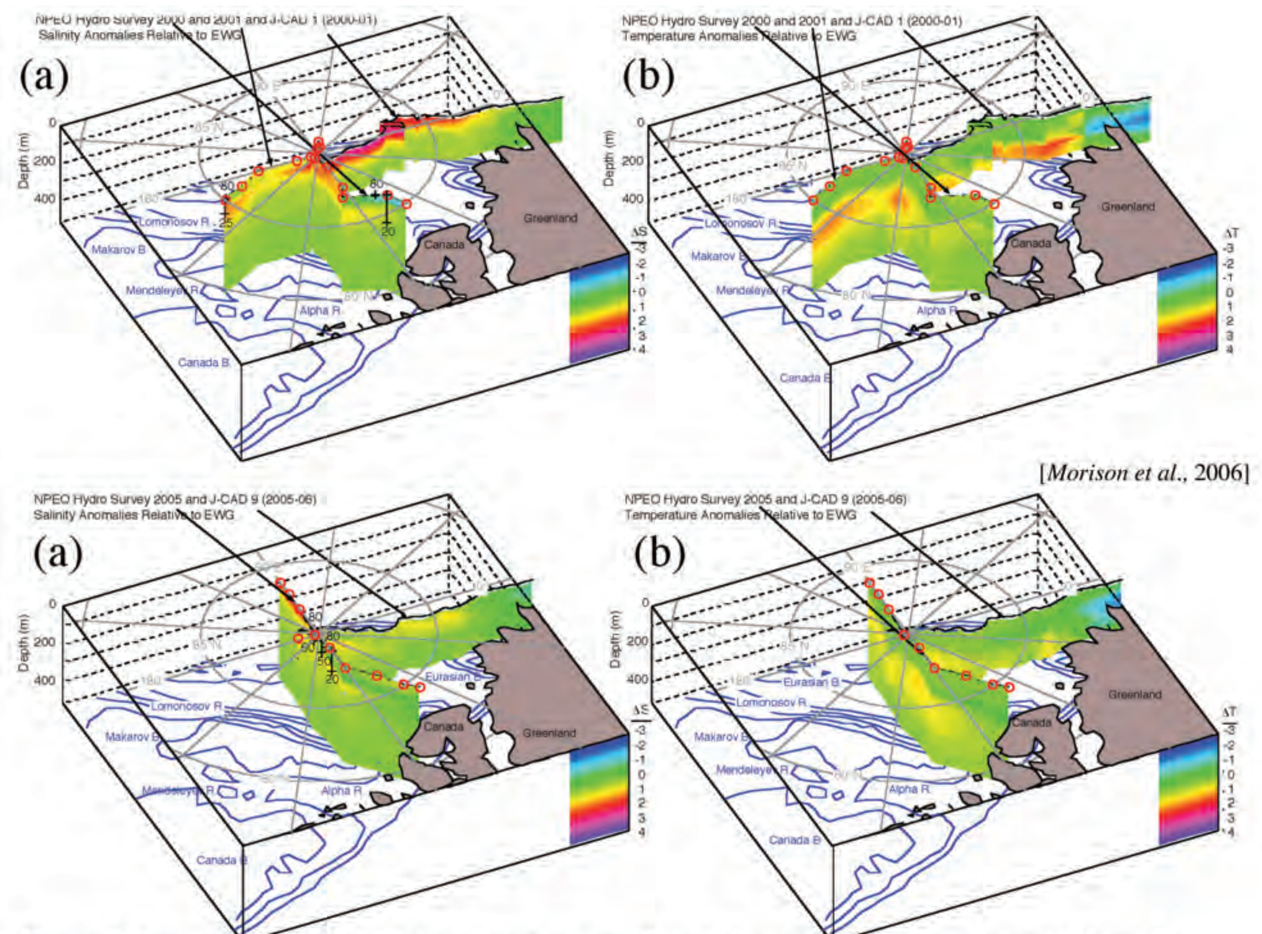

Figure 1. Anomalies of salinity (a) and temperature (b) relative to climatology measured along the NPEO and J-CAD sections for 2000-01 (top) and 2005-06 (bottom). Pacific Water % boundaries are indicated by + in (a).

bring saltier, and hence denser, Atlantic-derived water across the Makarov Basin between the Lomonosov Ridge and Alpha-Mendeleyev ridges on the Russian side of the Arctic Ocean. The orientation of the front is climatically important because, among other things, it influences the alignment of the the Transpolar Drift of sea ice across the Arctic Ocean and into the North Atlantic. In the clockwise mode, sea ice is pulled more rapidly from the Beaufort Gyre region off Canada and Alaska, tending to reduce the average age, thickness, and extent of Arctic sea ice. The counterclockwise orientation of the AP Front has been related to the wintertime strength of the Northern Hemisphere Polar Vortex, the counterclockwise circulation of the atmosphere quantified by the Arctic Oscillation (AO) index and due to low atmospheric pressure over the Arctic. Conversely, high pressure over the Beaufort Sea and a low AO index in summer have been associated with reduced ice extent at the end of summer because ice is pulled away from the coasts into a convergent gyre under a high-pressure system.

Our hydro surveys, oceanographic buoy, mooring, and bottom pressure observations have shown that the strongly cyclonic circulation pattern of the 1990s, with Atlantic-derived waters advanced farther into the basin, also characterized central Arctic Ocean conditions in 2000-2001 [Morison et al., 2006] (Fig. 1, top). Salinity in the upper 200 m near the Pole and in the northern Makarov Basin were elevated above the pre-1990 climatology. Temperatures in the Atlantic Water core along the Lomonosov Ridge were elevated 1-2°C. By 2005-2006 (Fig. 1, bottom) the 1990s shift in frontal structure had virtually disappeared. The upper-ocean salinity anomalies near the Pole decreased to near zero and were consistent with Pacific-derived salinities in the Canadian Basin. NPEO hydrochemistry indicated that Pacific-derived water advanced to the Pole [Alkire et al., 2007] and the Transpolar Drift shifted back from its alignment along the Alpha-Mendeleyev Ridge in 2000 to the Lomonosov Ridge by 2004. In situ measurements of OBP from the ABPRs near the Pole confirmed the accuracy of bottom pressure measurements by the GRACE satellite system [Morison et al., 2007]. These showed a declining trend in bottom pressure through 2005 accounted for by the steric mass change due to decreasing upper ocean salinities within 200 km of the Pole (Fig. 2). GRACE OBP trends indicated large-scale reversion from the cyclonic state between 2002 and early 2006.

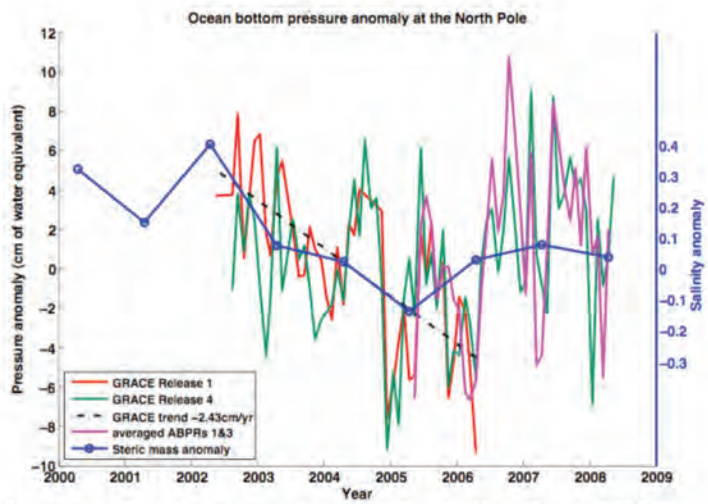

Figure 2. Bottom pressure at the North Pole from GRACE Releases 1 and 4. Also shown: ABPR in situ pressure and the steric mass anomaly (cm water equivalent) due to the average North Pole salinity anomaly above 200 m scaled at right. (Figure from Morison et al. [2007] extended beyond 2006)

Since 2005, the NPEO oceanographic data (Figs. 3 and 4) and GRACE observations (Fig. 2) analyzed under the Arctic Ocean Pressure grant and NASA grant NNX08AH62G, indicate that the salinity and temperature anomalies have reverted toward the cyclonic pattern, but superimposed on this was the anticyclonic spin up of the eastern Beaufort Sea especially in 2007-2008. By 2007 and 2008 surface salinities near the Pole (Fig. 3) increased to 1 psu above pre-1990s climatology, and Atlantic Water core temperature anomalies rose to 0.5°C. In 2008, hydro stations and our first AXCTD survey showed that the Beaufort Sea upper ocean was exceptionally fresh (Fig. 4) [McPhee et al., 2009], and surface freshening dominated the eastern portion of the Canadian Basin. Our water chemistry for the Spring '08 Beaufort Sea indicates that above 190 m depth, runoff dominated ice melt as a source of the fresh water. In spite of the spectacular melt of 2007, the melt contribution to springtime upper ocean freshwater content was mainly negative, consistent with net annual ice production and export. Bottom pressure measured by *in situ* gauges and GRACE near the Pole rose to near 2003 levels by 2007 due to increasing salinity (Fig. 2), and the newest release of GRACE data indicates this increase was mostly sustained in 2008-2009 with a basin-wide trend in 2006-2009 back toward the cyclonic pattern of bottom pressure.

Additionally, Kikuchi et al. [2004] use NPEO ocean buoy data to show the retreat in the early 2000s of the convectively formed Lower Halocline Waters from the Amundsen Basin. Kikuchi et al. [2005] show that Atlantic water temperature signals on the Makarov Basin side of the Lomonosov Ridge are delayed 7 years relative to the Amundsen Basin side due to the time required for the Atlantic water to circulate counterclockwise around the Makarov Basin. NPEO ocean data from the surveys and drifting buoys have been used to determine the interannual variability of ice-ocean heat fluxes [McPhee et al., 2003] and Pacific Water trajectories [Steele et al., 2004]. Falkner et al. [2005] use shelf-derived low-oxygen waters to trace patterns of halocline circulation. The mooring data show variability on relatively short time scales that reflects the heterogeneity of the Arctic Ocean, even within the upper deep water [cf., Kadko and Aagaard, 2009]. A significant part of the variability is associated with eddies drifting past the mooring, including one extremely large perturbation in 2002, which resulted from a large and deep-reaching anticyclone [Aagaard et al., 2008].

By measuring radiation, ice conditions, and basic atmospheric parameters over nine years, NPEO has begun to achieve statistically stable estimates of ice and surface meteorological conditions. At least from 2000-2006, the Arctic was in a new climate pattern without a dominant atmospheric circulation influence from either the Arctic Oscillation (first EOF of Northern Hemisphere atmospheric pressure) or North Pacific (second EOF) pattern. The "Arctic Warm" (third EOF) pattern resulted in warm air advection into the Arctic as occurred in the 1930s [Overland 2006, Turner et al. 2006]. Opposite to the 1930s, winds under the recent phase of the Arctic Warm pattern tend to blow ice toward Fram Strait and out of the Arctic Ocean, thereby further reducing the ice cover. Overland et al. [2008], by comparing the NPEO surface air temperature data for 2002-2007 with meteorological data from Russian North Pole (NP) drifting stations 1937-1990, show a shift toward earlier dates for spring melt in the central Arctic Ocean. From the NPEO radiation buoy measurements, Bond et al. [2008] have found a summer average year-to-year range sufficient to make the difference in whether or not first year sea ice lasts the summer. Inoue et al. [2005] find that the incident radiation drops significantly when melt ponds, seen in the NPEO Web cameras, form due to a reduction in multiple reflections between the surface and clouds. Perovich et al. [2008] compare NPEO and Beaufort Sea IMB data to show that the exceptional ice loss in the Beaufort Sea in summer 2007 was dominated by bottom melt.

Improvements

In the future, we would like to include:

1. Continuation of the North Pole mooring and automated radiation measurements, which were dropped from our 2009 renewal. These records are being discontinued just as they are becoming long enough to assess decadal variability.

2. Establishment of regular sections and/or an oceanographic mooring in the Makarov Basin where the largest cyclonic versus anticyclonic changes in upper ocean conditions occur.

3. Expansion of the airborne hydrographic surveys into the Beaufort Sea, "Canadian Data Hole" and Makarov Basin using long-range aircraft and our new AXCTD.

4. Installation of more ABPR to cross-calibrate with GRACE before the possible end-of-life of the GRACE satellites. These ABPR measurements could provide a GRACE proxy through the hiatus between the present GRACE system and the follow-on mission beginning c. 2020.

5. Installation of ABPR off the coast of Greenland and Svalbard to separate ocean and ice sheet mass balance signals in GRACE gravity observations. These would benefit both oceanography and ice sheet glaciology.

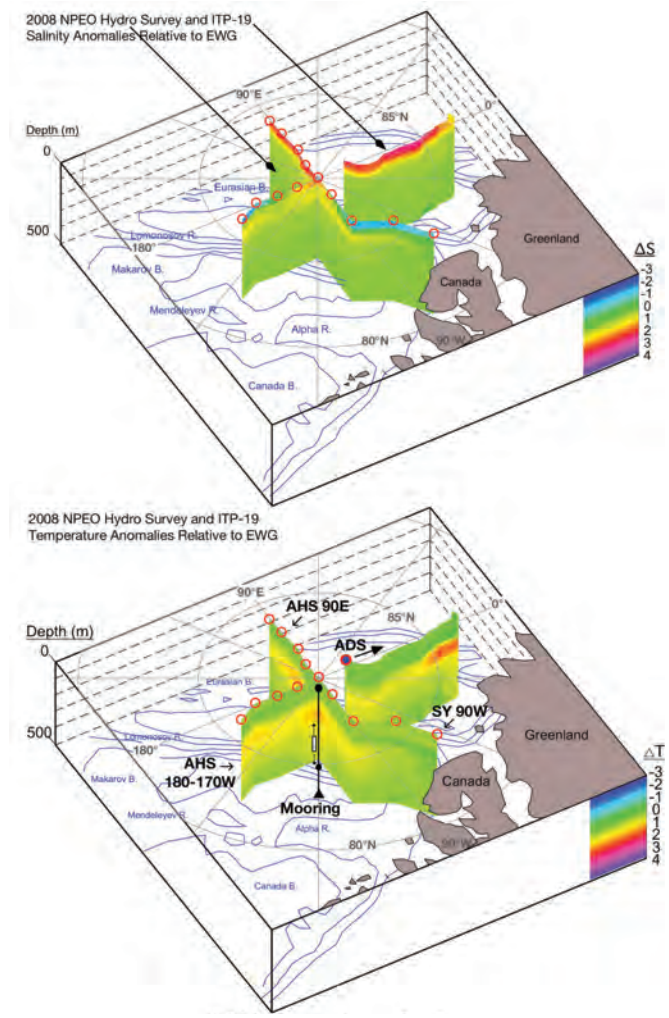

Figure 3. NPEO 2008 anomalies of salinity (top) and temperature (bottom) relative to climatology from the 90°W, 90°E, and 180°-170°W hydro surveys and the ITP19 drift along ~0°. The bottom plot also shows the proposed NPEO mooring, (not renewed at this time) and projected Airborne Hydro Surveys (AHS) and Automated Drifting Station (ADS).

Interaction with Other Projects on Science, Logistics, and Data

One of the aims of NPEO is to improve the scientific infrastructure for research in the central Arctic by providing scientific data, collaboration, and operational support. At least 21 programs have been proposed that depended on NPEO. Of these that we know about, nine science projects and two IPY outreach programs have been funded, a success rate that speaks to the advantages of maintaining a central Arctic Ocean platform where operational support and collaborative data are available. Examples of funded collaborating projects include:

Switchyard Project (AON grant of Schlosser et al.) – NPEO co-PI, Mike Steele, is also a co-PI on this project which took over NPEO hydrographic measurements in the Lincoln Sea and up 90°W to the Pole in 2002. Switchyard and NPEO share resources and data, and at times NPEO has done the northern stations on 90°W.

Beaufort Gyre Observational Program (BGOP) (AON grant of Proshutinsky et al.) – BGOP uses moorings, drifting buoys and summer ship cruises to track change in the Beaufort Sea. Our Spring 2008 hydro survey was done in collaboration with this group. NPEO airborne survey lines are coordinated with the predicted tracks of BGOP ITPs deployed upstream in the Transpolar Drift to help distinguish between temporal and spatial variability. Comparison of North Pole and BGOP Beaufort Sea bottom pressure records is important in resolving changes in the distribution of Arctic Ocean mass and circulation.

Nansen and Amundsen Basins Observatory System (NABOS, Polyakov et al.) – Comparison of NPEO data with this mooring and hydrographic effort on the Siberian continental slope tells us how ocean warming propagates along the Atlantic Water pathway [***Polyakov et al.*, 2005**].

Towards an Arctic Observing Network: An array of Ice-Tethered Profilers (ITP) to sample the upper ocean water properties during the International Polar Year (AON grant of Toole et al.) – Continuing a collaboration that has developed over the last few years, this project will install ITPs at NPEO automated drifting stations.

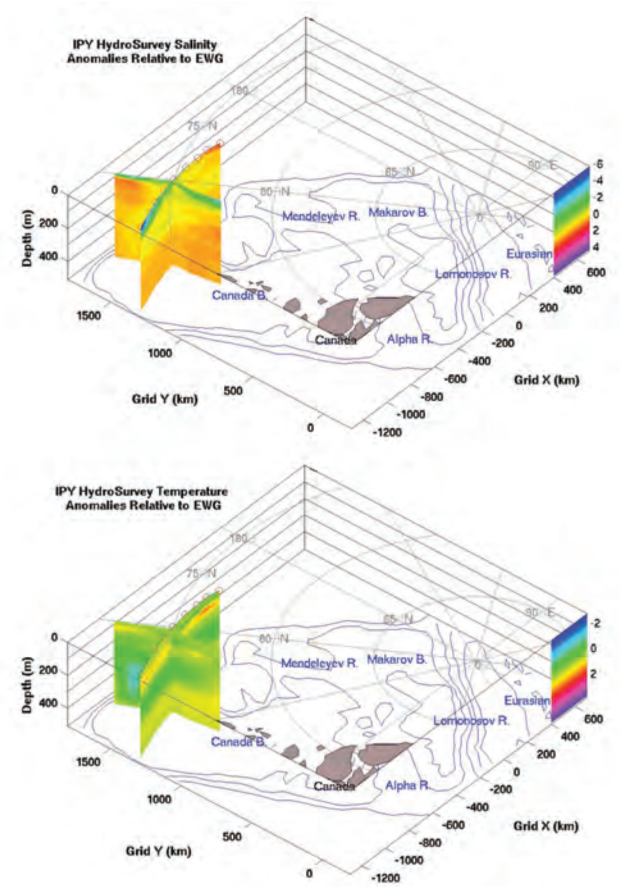

Figure 4. NPEO-IPY Airborne Hydro Survey 2008 anomalies of salinity (top) and temperature (bottom) relative to climatology in the Beaufort Sea from ice-landing stations and AXCTD drops.

Ice Mass Balance Buoy Network (AON grant of Perovich and Richter-Menge) – This project deploys IMB throughout the Arctic Ocean. It will continue to supply IMB for the NPEO automated drifting station.

Autonomous Ocean Flux Buoys for Polar Studies (AON grant of Stanton) – will install an AOFBs at the NPEO automated drifting stations.

International Arctic Buoy Program (Navy-NOAA funded Joint Ice Center and AON projects of Rigor) – NPEO will deploy at least two IABP buoys per year, IABP will begin covering Argos costs and process the data from the NPEO basic meteorological buoy.

Automated Nutrient Measurements (NSF-OPP grant of Christensen) – This project installed nutrient and optics sensors near the top of the NPEO mooring and conducted small-scale CTD and nutrient profiling in the North Pole region.

Soot Measurements in the Arctic (AON grant of Grenfell and Warren) – NPEO will continue to collect snow samples for determination of soot concentration, and in the future we will add short snow thickness surveys at the airborne hydro survey stations.

International Collaboration

JAMSTEC Ocean Buoy Program (Takashi Kikuchi, Japan) – JAMSTEC has been a key partner in NPEO since 2000 by supplying oceanographic drifting buoys for the automated drifting station. Under the auspices of our U.S.-Japan High Level Consultations on Climate Change Agreement, JAMSTEC will continue to participate in NPEO by contributing Polar Ocean Profiling System (POPS) data to the NPEO Web site for our joint comparison with the NPEO buoy, hydrographic survey, and mooring data. As POPS buoys are available, JAMSTEC will deploy them through NPEO.

University of Bergen Internal Waves and Mixing Study (Ilker Fer, Norway) – Fer will contribute velocity and microstructure measurements at the NPEO base camp and supply eXpendable Current Probes (XCP) for the NPEO hydro surveys. We will collaborate with Fer to derive internal wave and mixing estimates from the XCP and CTD data collected during the airborne hydrographic sections and from the mooring.

In addition to the partner in the NPEO mentioned above, we facilitate the IABP deployments and contribute data to the IABP. We also collaborate with Norwegian projects measuring mixing and turbulence, and ocean bottom pressure. NPEO is included in the integrated Arctic Ocean Observing System (iAOOS) plan.

Data

NPEO subscribes to the SEARCH open data policy and strives to make its data available to the public as quickly as possible. NPEO data are available at the NPEO web site: (http://psc.apl.washington.edu/northpole/). Individuals from at least 50 different institutions all over the world have taken data via ftp from our web site. For those automated drifting station buoys for which it is practical, we post data in real time. The hydrographic data and most of the other buoy data for which post-processing is required are posted within a few months after collection. The mooring data by virtue of its volume and complexity takes a year after recovery and post-recovery calibration to begin dissemination. NPEO data was originally archived with the NSIDC-ARCSS Data Coordination Center (http://nsidc.org/arcss/). This has now been transferred to the Arctic Observing Network (AON) Cooperative Arctic Data and Information Service (CADIS), http://www.aoncadis.org/. A direct link to the NPEO archive is: http://cdp.ucar.edu/browse/browse.htm?uri=http%3a%2f%2fdataportal.ucar.edu%2fmetadata%2fcadis%2fOcean_and_Sea_Ice%2fEnvironmental_Obs%2fEnvironmental_Obs.thredds.xml.

CADIS includes a link to the NPEO ftp site to allow public access to that archive. The data from the ITP oceanographic buoy deployed at the 2007 (ITP7) and 2008 (ITP19) NPEO automated drifting stations are available at the WHOI web site, http://www.whoi.edu/itp/. The ocean flux buoy data is available at the NPS web site, http://www.oc.nps.navy.mil/~stanton/fluxbuoy/.

Outreach

As outreach, the NPEO web site has been extremely successful, garnering an average of about 1,800 hits per day. We respond to numerous questions the site generates from the public, generating greater outreach opportunities. The NPEO PIs have given numerous media interviews resulting in various news articles and programs. A few highlights of these include:

2002 – We recorded a live interview from the Pole with Larry Bowen of CBS.

2003 – We took Andrew Revkin from the *New York Times* and Alexandra Witze from the *Dallas Morning News* to the Pole. They wrote news articles about NPEO operations and science. Revkin featured the experience in his book for young people, *The North Pole Was Here*.

2004 – We were accompanied by a CBS Television News team to the Pole. This resulted in five television segments, three of which were shown on the CBS evening news and two of which appeared on the CBS *Early Show*.

2005 – Footage of co-PI , Dr. Kelly Falkner was shot at the North Pole and appeared in a History Channel and in an NSF produced film (Dec 2006) and on PBS (Jan 2007).

2006 – co-PI Mike Steele was interviewed for Idea Network, for a special that was aired on Chukyo TV Network in summer 2006.

2007 – Morison was interviewed live by Hala Gorani on CNN International, Your World Today regarding the record minimum ice extent in 2007 [Gorani, 2007].

In addition, Morison has participated in two public radio talk shows dealing with the North Pole environment: NSF-sponsored Earth & Sky Radio Series of National Public Radio. In 2002, he was made an Advisor for the Earth & Sky Radio Series. He has regularly contributed information to Andy Revkin's *New York Times* articles and Dot Earth blog [e.g., Revkin, 2008a&b, 2010].

In 2003, we undertook a new form of outreach. We took UW graduate student Daniel Dyer to NPEO to shoot video and develop materials for his Masters in Communications. Dyer combined his video footage with that of Peter West (NSF) to produce an educational DVD about research and science in the North, aimed at students in grades 6-12. This effort was successful and he received his Masters degree in the summer of 2003. Dyer has worked with the NPEO PIs to polish the DVD and make it clearer and more entertaining. We provided this DVD to NSF and the material and other video material is now available through the NSF Public Affairs Web site, http://www.nsf.gov/od/lpa/news/03/ma0329.htm.

We also give public lectures whenever the opportunity arises. Soon after the NPEO 2004 deployment, the PI gave a one-hour presentation on Arctic change and the North Pole Environmental Observatory for the University of Washington Science Forum Series. The recording of this is run repeatedly on University of Washington Television (a local cable television channel). He also has given invited lectures for the general public on Arctic change and the NPEO at the Climate Change Forum, Marylhurst University in October 2005, and the "Byrne Lecture" at Oregon State University in March 2006. These venues are particularly good for informing educators and the general public with interests in science and climate. In fall 2008, we gave a talk at Bowdoin College celebration's of Peary's expeditions to the North Pole and at the Society for Advancement of Chicanos and Native Americans in Science (SACNAS) convention. At the SACNAS convention we also sponsored a booth aimed at promoting careers in environmental science for underrepresented minority students.

To make the science community aware of the opportunities at NPEO we hold townhall meetings at the various large ocean-related conferences each year. We describe the way NPEO is run and highlight the various measurements, and we provide information about how others can take advantage of NPEO either through access to the data or participation in the field. Townhall meetings include those at the 2004 through 2007 Fall AGU meetings in SanFrancisco, the 2005 International Glaciological Society Sea Ice Symposium in New Zealand, and the 2006 Ocean Sciences meeting.

The NPEO team at UW participates in various talks and demonstrations as part of the annual Polar Science Weekend at the Pacific Science Center that began in March 2006. This effort targets families and K-12 school classes during the week. We install a small ice camp display. Lectures and demonstrations by NPEO co-PI Mike Steele reprise material given in grade school visits. They include "Extreme Cold," which deals with the arctic vs. Antarctic, sea ice vs. freshwater ice, polar bears vs. penguins. Freezing various things with liquid nitrogen, including salty water balloons, demonstrates the effect of extreme cold on things containing water. Food coloring is used to show the brine channels in sea ice and a "salinity taste test" staffed by volunteers from Polar Science Center and Seattle elementary school students is very popular. Incidentally, we find that the human tongue can easily distinguish 0, 5, and 10 ppt salinity water samples, but has trouble with 30, 35, and 40. We point out where in the world one might find water with these salinities. In 2010,we plan on participating once again in the Journey North Mystery Class (http://www.learner.org/jnorth/mclass/) aimed at teaching young students fundamental geography.

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An Interdisciplinary Monitoring Mooring in the Western Arctic Boundary Current: Climatic Forcing and Ecosystem Response

Robert S. Pickart, Jeremy T. Mathis, Kathleen M. Stafford; Co-Principal Investigators

Project Summary

The modification and fate of the Pacific water that enters the Chukchi Sea through Bering Strait is of fundamental importance to the western Arctic ocean-atmosphere-ice system. Among other things, the Pacific water advects heat northward, which influences the pack-ice cover, supplies nutrients that help fuel primary production, and, via physical and biogeochemical transformation, impacts carbon cycling, zooplankton distribution, whale feeding, and halocline ventilation. The major conduit of Pacific water through the Arctic is the western Arctic boundary current, which forms from the outflow of Herald and Barrow canyons at the shelf edge of the Chukchi and Beaufort seas. The current flows eastward, advecting elevated concentrations of nutrients, chlorophyll, dissolved and particulate organic carbon, and zooplankton. Bowhead and beluga whales congregate near the current along the outer shelf and continental slope of the Beaufort Sea. Furthermore, due to wind-driven upwelling and hydrodynamic instability, the current fluxes a substantial fraction of its mass, heat, salt, and biogenic content offshore, impacting the interior water column, ice concentration, and ecosystem.

This project consists of a strategically placed mooring in the core of the western Arctic boundary current east of Barrow Canyon (Fig. 1) that measures both the alongstream and cross-stream fluxes of important physical, chemical, and biological quantities. The measurements will enhance our understanding of the western Arctic ocean-atmosphere-ice system, including crucial aspects of the ecosystem that are unattainable throughout most of the year due to ice cover. Using new generation moored profilers, the mooring will provide full-water column profiles (from the seafloor to the underside of the ice) of temperature, salinity, dissolved oxygen, pH, turbidity, chlorophyll fluorescence, nitrate, backscatter (proxy for zooplankton) and velocity. In addition, the mooring will provide timeseries of ice thickness and ice velocity, bottom pressure, and marine mammal calls.

From earlier projects, a 4-year timeseries already exists at the site. The AON program will double the length of the existing timeseries, providing an 8-year record. This will allow improved understanding of how different climate states (measured by the Arctic Oscillation, North Pacific Index, etc.) impact various aspects of the water column and ecosystem. The mooring has strong links to existing AON components studying the atmosphere, ice variability in the region, adjacent interior circulation, and the inflow and outflow of Pacific water. The information obtained from the mooring will help tie these measurements together and improve our understanding of the greater Arctic system.

Mooring Description

The mooring was deployed in summer 2009 and will remain in the water until summer 2013, with yearly turnaround cruises. The mooring contains two vertical profilers: a Coastal Moored Profiler and an ArcticWinch Profiler. The former is attached to the mooring wire and mechanically travels between the bottom and the mooring's top float at 40 m depth. The latter profiler is attached via a nylon line to a small winch located on the top float. The profiler rises to the underside of the ice and is programmed so that once its vertical motion stops, the winch pulls the package back down to the top float. At the conclusion of each round trip the data are transferred inductively to a data logger on the top float. Each profiler will measure pressure, temperature, conductivity (salinity), dissolved oxygen, pH, turbidity,

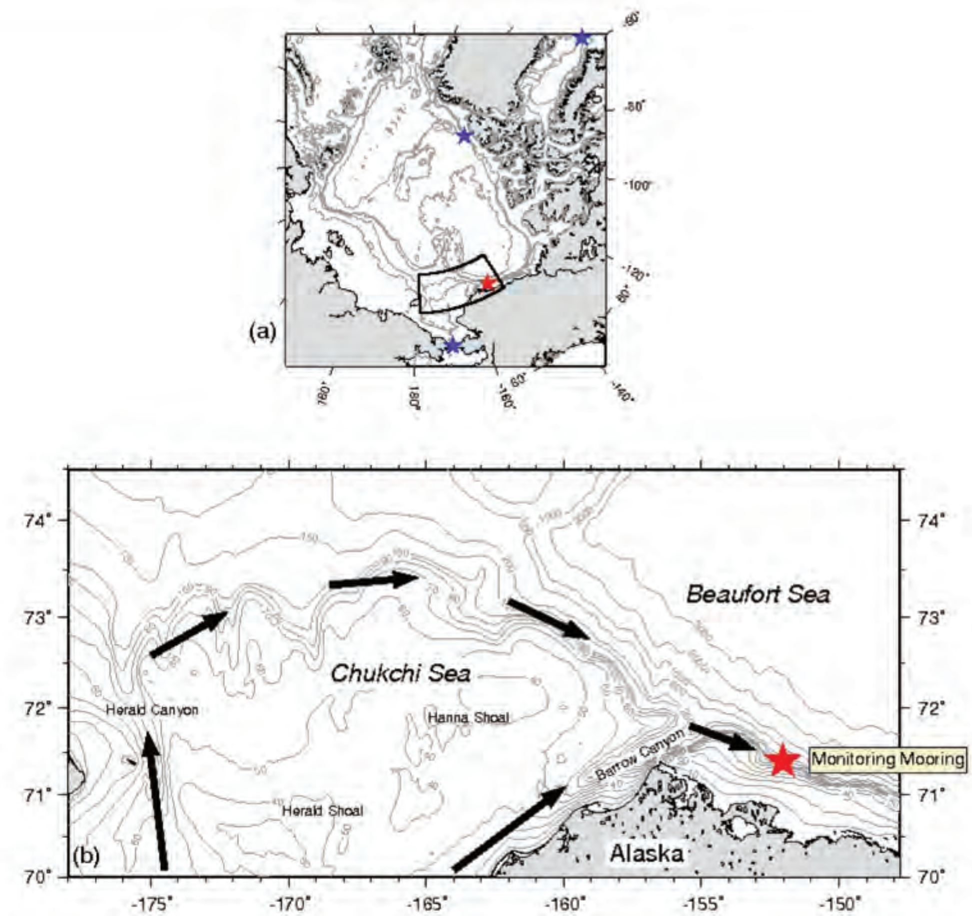

Figure 1: (a) Location of the AON western Arctic boundary current monitoring mooring (red star) in relation to the Bering Strait, Switchyards, and Davis Strait AON programs (blue stars). (b) Enlarged view of the region outlined in (a). The arrows represent the two main pathways of Pacific Water from Bering Strait into the western Arctic boundary current.

chlorophyll fluorescence, and nitrate (ISUS). This configuration will provide one complete profile a day from the seafloor to the underside of the ice, and a second profile from 40 m to the bottom (i.e., the lower profiler).

The ISUS sensor is being incorporated into the profilers for the first time, and this requires both hardware and software modifications. Hence the nitrate capability won't be functional until year two. A MicroCat will be attached to the top float and another positioned directly below the bottom-stop of the deep profiler. These will provide calibration information for the two profilers. The mooring will also contain an upward-facing long-ranging acoustic Doppler current profiler (ADCP) at the bottom of the mooring and a higher-frequency upward-facing ADCP on the top float. Together, these will provide a complete vertical profile of absolute velocity and backscatter (proxy for zooplankton), and a timeseries of ice velocity. An upward-looking sonar on the top float will provide ice thickness data, and a bottom pressure gauge will give information on the mass field of the water column. All of these variables will be measured hourly.

The mooring will, for the first time in the Arc-

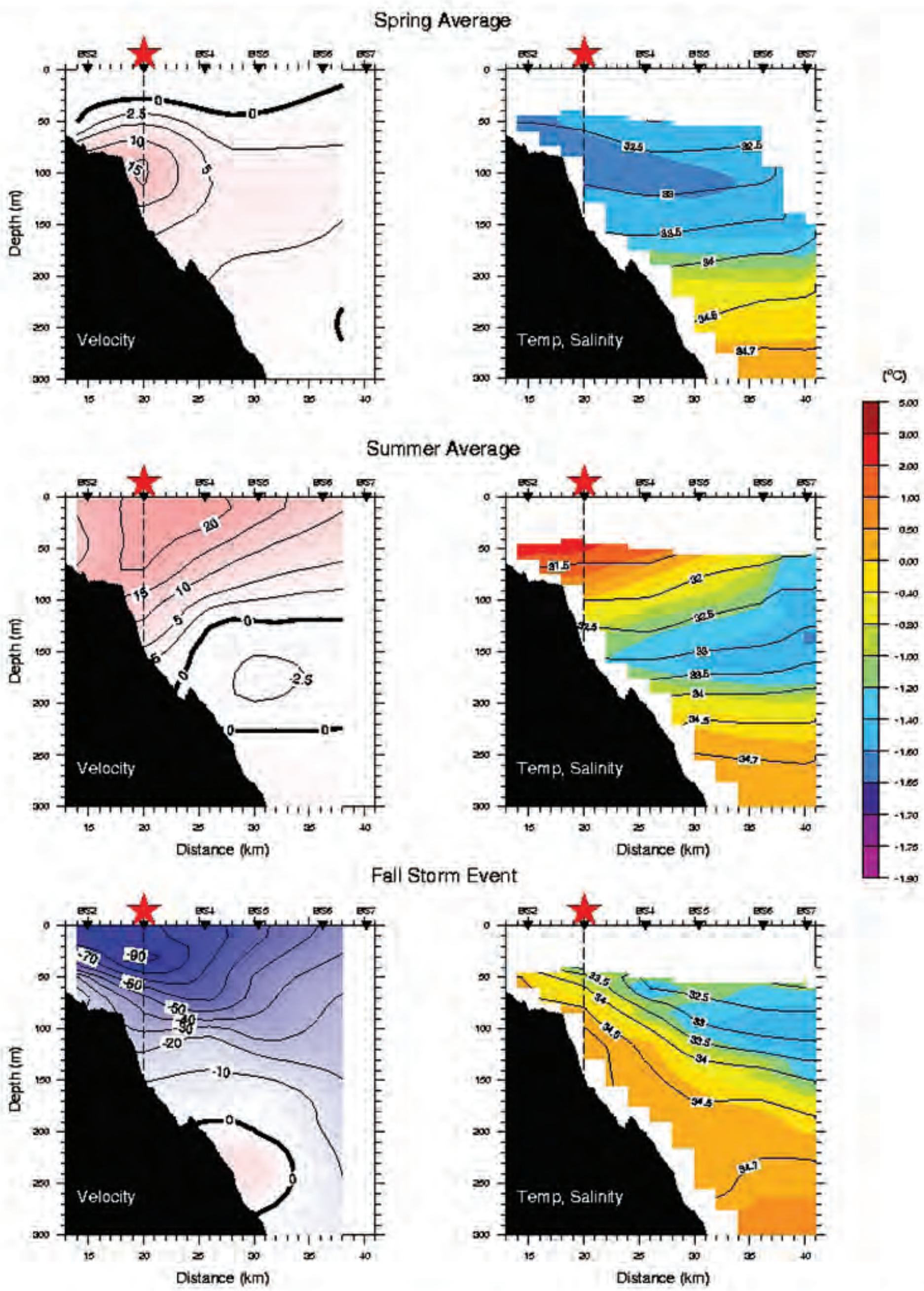

Figure 2: Different configurations of the western Arctic boundary current from a previous moored array. The AON monitoring mooring site, located at the center of the current, is denoted by the red star and corresponding dashed vertical line. The left hand column is alongstream velocity (red is eastward, blue is westward) and the right hand column is potential temperature (color) overlain by salinity (contours). Top Panel: Mean boundary current during spring (April-June); Middle Panel: Mean boundary current during summer (July-September); Bottom Panel: Snapshot of the boundary current during the height of an upwelling storm.

tic environment (and to our knowledge in the World Ocean), provide complete water column profiles of these biochemical and physical variables over a full seasonal cycle. To complete the mooring, a hydrophone will be situated on a separate bottom platform immediately adjacent to the tall mooring. The hydrophone will provide a timeseries of acoustic data to monitor ambient noise levels, including sounds produced by marine mammals as well as ice, wind, and anthropogenic noise sources.

Boundary Current Processes

The monitoring mooring is situated at the center of the western Arctic boundary current (Fig. 2). The current has different seasonal configurations, changing from a bottom-intensified current in winter and spring (Fig. 2, top panel), to a surface-intensified flow in summer and early fall (Fig. 2, middle panel).

Throughout the year the current is trapped to the shelfbreak, enabling accurate measurement of its transport from a single mooring. In addition, the current is subject to significant mesoscale variability leading to cross-slope exchange of mass, heat, salt, and biogenic material. The mooring measures these cross-stream fluxes as well. One of the dominant mechanisms of shelf-basin exchange is wind-driven upwelling. These events are frequent in fall and winter (although they occur in all seasons), whereby easterly winds reverse the boundary current and cause upwelling of warm and salty Atlantic Water onto the shelf (Fig. 2, bottom panel). The easterly winds usually result from Aleutian low storms, which are located far to the south in the Gulf of Alaska. As many as 30 upwelling events can occur in a single fall and winter (Fig 3). The impact of these storms on the shelf and basin, the modulation of the response due to ice, and the large-scale ramifications of upwelling and other physical processes (e.g., hydrodynamic instability of the current) for the Arctic system need further investigation. Finally, the boundary current varies significantly from year to year in its hydrographic structure, dynamics, and response to atmospheric forcing. A long-term record is needed to understand how the current responds to different climatic states, and how this in turn impacts other components of the Arctic system.

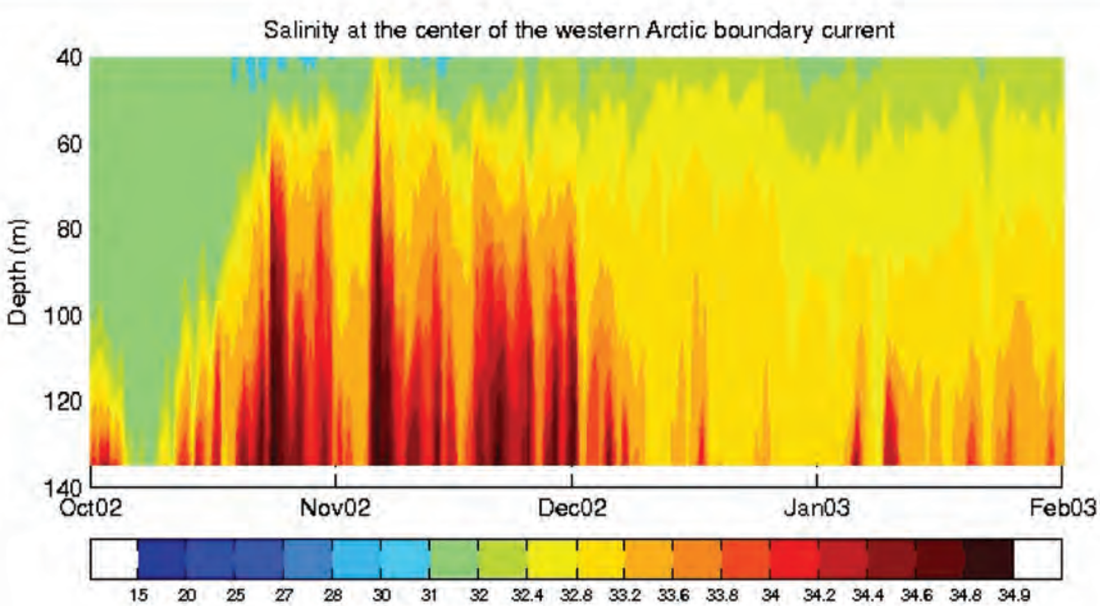

Figure 3: Timeseries of salinity vs. depth at the center of the western Arctic boundary current, from a previous mooring deployment at the AON site. The time period shown is October 2002 to February 2003. The spikes of high salinity indicate upwelling of warm and salty Atlantic water due to easterly wind events.

Links to Other AON Components

The monitoring mooring will provide information that will help the community better understand the linkages between various aspects of the Arctic system – from storms that are located thousands of kilometers away, to the pack-ice that modulates the ocean's response to the wind, to the manner in which the physical characteristics of the water column impact the ecosystem from nutrient dynamics up to the higher trophics. The mooring provides an important link between upstream monitoring (Bering Strait) and outflow measurements (the Canadian Archipelago, Davis Strait, Fram Strait), because the western Arctic boundary current connects these entry and exit points. The boundary current is also the interface between the shelf and basin, and will provide pertinent information for monitoring of the interior by moorings as well as drifters. The pronounced response of the boundary current to atmospheric forcing, and the importance of ice in modulating this response, will shed light on the ramifications of a changing atmosphere and cryosphere on the Arctic Ocean. Finally, by measuring the full suite of properties, the mooring provides a crucial link between the physics and biology of the western Arctic.

Publications

Because the mooring was only recently deployed (summer 2009) no data have been returned from the project. However, numerous studies have been carried out using previous mooring data collected at the site:

Spall, M., R. S. Pickart, P. Fratantoni, and A. Plueddemann, 2008. Western Arctic shelfbreak eddies: Formation and transport. *Journal of Physical Oceanography*, **38**, 1644-1668.

Pickart, R.S. and G. Stossmeister, 2008. Outflow of Pacific water from the Chukchi Sea to the Arctic Ocean. *Chinese Journal of Polar Oceanography*, **19**, No. 2, 135-148.

Nikolopoulos, A., R. S. Pickart, P. S. Fratantoni, K. Shimada, D. J. Torres, and E. P. Jones, 2009. Thewestern Arctic boundary current at 152°W: Structure, variability, and transport. *Deep Sea Research II*, **56**, 1164-1181.

Pickart, R. S., G. W. K. Moore, D.J. Torres, P.S. Fratantoni, R.A. Goldsmith, and J. Yang, 2009. Upwelling on the continental slope of the Alaskan Beaufort Sea: Storms, ice, and oceanographic response. *Journal of Geophysical Research*, **114**, C00A13, doi:10.1029/2208JC005009.

Llinás, L., R. S. Pickart, J. T. Mathis, and S. L. Smith, 2009. Zooplankton inside an Arctic Ocean coldcore eddy: Probable origin and fate. *Deep-Sea Research II*, **56**, 1290-1304.

The Beaufort Gyre System: The Flywheel of the Arctic

Andrey Proshutinsky[1], Richard Krishfield[1], John Toole[1] and Mary-Louise Timmermans[2]

Project Summary

This project continues the Beaufort Gyre Observational System (BGOS, Figure 1) measurement program initiated in 2003 that is documenting changes in sea ice and ocean parameters that are presently occurring in the Beaufort Gyre (BG) region. The project contributes water temperature, salinity, currents, geochemical tracers, sea ice draft, and sea level to the Arctic Observing Network (AON) using bottom-tethered moorings and shipboard measurements. In 2009-2014, three moorings will continue to acquire precise data on the variations of the vertical distribution of seawater properties, bottom pressures and sea ice draft at sites 75N and 150W, 78N and 150W, and 77N and 140W. Ship-based sampling covering the entire BG will be performed in collaboration with scientists from Canada and Japan with shared logistics expenses to augment the year-round mooring measurements. Temperature, salinity, oxygen, nutrients, barium and delta-^{18}O will be measured and analyzed at 30 standard locations in sections along 140W, 150W, ~ 75N and ~78N using shipboard CTD/rosette to extend the long-term time series started in 2003. Samples that provide information on longer time-scales, such as CFCs and carbon tetrachloride, alkalinity, total CO_2, dissolved inorganic carbon and tritium/^3He, will be collected less frequently. Between CTD/rosette casts, expendable CTDs that profile to 1100 m depth will be used to increase spatial resolution of the temperature and salinity fields. The project has been and will continue to be coordinated with the basic elements of AON to enhance effectiveness and interconnections of observational activities.

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Science and Technology Development Highlights

Scientifically, the major reason for the initiation of the BG Exploration Project in 2003 was to field an experiment designed to test the hypothesis of Proshutinsky et al. [2002, hereinafter referred to as P2002] on the origin of the salinity minimum in the center of the BG. Hydrographic climatology shows that because of this salinity minimum, which extends from the surface to ~400 m depth, the Canada Basin contains approximately 45,000 km^3 of fresh water. P2002 hypothesized that in winter, the wind (a dynamic factor) drives the ice and ocean in a clockwise (anticyclonic) sense so that the BG accumulates fresh water mechanically through a deformation of the salinity field (Ekman convergence and subsequent downwelling). In summer, winds are weaker (and may even reverse to be counterclockwise) and the summer resultant anomaly in Ekman convergence releases fresh water, thereby relaxing salinity gradients and reducing BG fresh water content (FWC). Theoretical studies and relatively simple numerical experiments [Proshutinsky et al., 2005; Dukhovskoy et al., 2004] have shown that in order to understand the important role of the BG in Arctic climate it is necessary to carry out a long-term observational program. The BGOS field program continued the data acquisition from 2005–2008, including the IPY period, and the study has recently been extended for 2009-2014. New technologies utilized in this project include: moored profiler instrumentation, satellite techniques allowing mapping of sea ice thickness and sea surface heights in the ice covered regions, and an easily-deployed Ice-Tethered Profiler (ITP – a separate AON project) that returns daily high vertical-resolution measurements of upper ocean temperature and salinity (results reported separately).

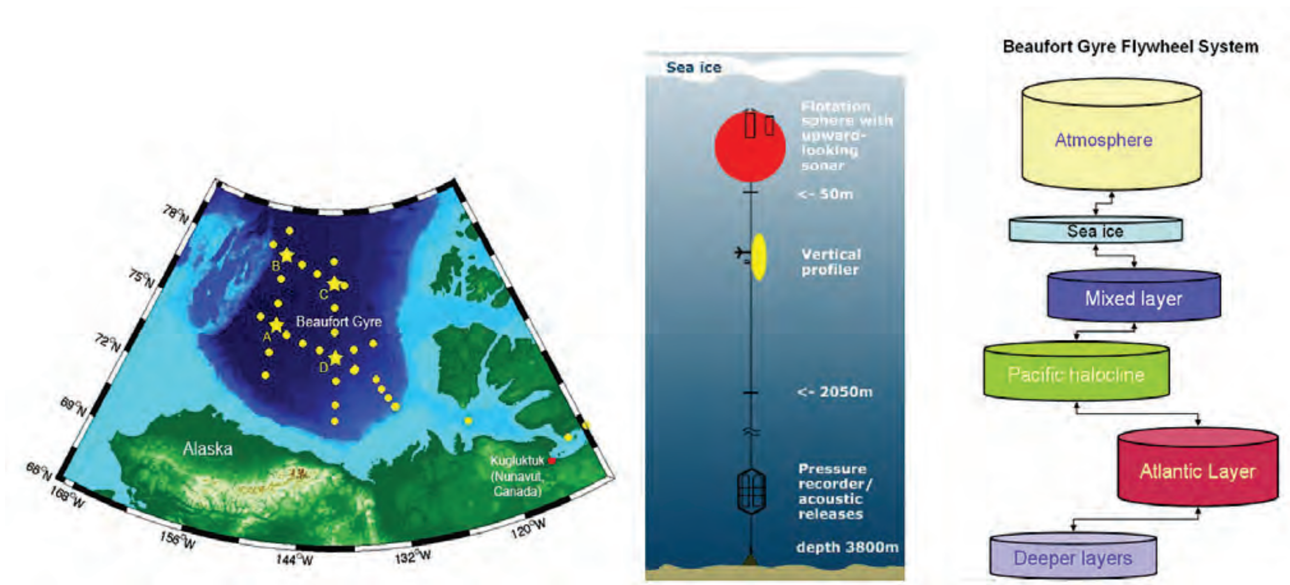

Figure 1. Left panel shows locations of BGOS moorings (stars) and standard sites for CTD and geochemistry observations. Middle panel shows standard mooring equipped with McLane Moored Profiler (MMP), Upward-Looking Sonar for measuring sea ice draft, and bottom pressure recorder to measure changes in sea level. Mooring D is also equipped with an ADCP. Others have had additional MMPs profiling at depths below 2000 m (A) and also sediment traps (A, B, C, and D). Right panel is a coupling diagram of the Beaufort Gyre system. Components (or "wheels") of this system store and exchange mass and energy with other components differently during different climate regimes. Quantifying and describing the state and variability of these wheels and their couplings is essential to understand the state and fate of the present day Arctic climate.

Lessons Learned

In order to enhance our understanding of the role of the BG in Arctic climate it is necessary to carry out multifaceted studies combining investigations of the BG system comprised from several elements depicted as "wheels" in Figure 1 (right panel). Quantifying and describing the state and variability of all these wheels and their couplings is essential to understand the state and fate of the present day Arctic climate. From this viewpoint it is important to enhance observational activities in the BG region to: (a) better cover processes in the atmosphere (that are significantly undersampled currently), (b) obtain additional knowledge about sea ice (sea ice thickness and deformation parameters to validate models and to understand horizontal scales of changes in different seasons) and (c) better describe and parameterize interactions among the atmosphere, sea ice and ocean.

Interactions with Collaborative Projects

BGOS collaborates with different AON projects both based on the scientific needs and interests and logistically to provide a platform for deployment of different instruments and measurements. Examples include: sediment traps and ITPs from WHOI; Ice Mass Balance Buoys from CRREL; Ocean Flux Buoys from NPS; University of Alaska sea ice and biological sampling; and many others.

Examples of Data Use

BGOS data are being used to support scientific investigations, education, operational modeling and public outreach. Peer reviewed scientific papers utilizing BGOS data are listed in the following section. In addition, BGOS data are being used by Arctic Ocean Modeling Intercomparison Project (AOMIP) investigators to evaluate model fields and assess model representations of physical processes. To date, students in the U.S., Canada, Norway, Russia and Sweden have used BGOS data in their dissertation work. Operational models operated by the U.S. Navy and groups in Norway and Russia are accessing BGOS data for initialization/ constraints and/or validation. BGOS operations together with the ITP program have been showcased by the "Live from the Poles" outreach activity as well as via teacher workshops and numerous presentations at schools and science museums.

List of Publications

The BGOS project web site is www.whoi.edu/beaufortgyre. Approximately 40 publications are presented at this site. The most recent ones are published as a special section of the *Journal of Geophysical Research Oceans* and they are:

Asplin, M. G., J. V. Lukovich, and D. G. Barber (2009), Atmospheric forcing of the Beaufort Sea ice gyre: Surface pressure climatology and sea ice motion *J. Geophys. Res.*, 114, C00A06, doi:10.1029/2008JC005127 92009.

Guay, C. K. H., F. McLaughlin, and M. Yamamoto-Kawai (2009), Differentiating fluvial components of upper Canada Basin waters on the basis of measurements of dissolved barium combined with other physical and chemical tracers *J. Geophys. Res.*, doi:10.1029/2008JC005099.

Lukovich, J. V., M. G. Asplin, and D. G. Barber (2009), Atmospheric forcing of the Beaufort Sea ice gyre: Surfacestratosphere coupling *J. Geophys. Res.*, 114, C00A03, doi:10.1029/2008JC004849.

McLaughlin, F., E. Carmack, W. J. Williams, S. Zimmermann, K. Shimada, and M. Itoh (2009), Joint effects of boundary currents and thermohaline intrusions on the warming of Atlantic water in the Canada Basin: 1993-2007 *J. Geophys. Res.*, doi:10.1029/2008JC005001.

Nishino, S., K. Shimada, M. Itoh, M. Yamamoto-Kawai, and S. Chiba (2008), East–west differences in water mass, nutrient, and chlorophyll a distributions in the sea ice reduction region of the western Arctic Ocean *J. Geophys. Res.*, 113, C00A01, doi:10.1029/2007JC004666.

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Perovich, D. K., T. C. Grenfell, B. Light, B. C. Elder, J. Harbeck, C. Polashenski, W. B. Tucker, and C. Stelmach (2009), Transpolar observations of the morphological properties of Arctic sea ice *J. Geophys. Res.*, 114, C00A04, doi:10.1029/2008JC004899.

Pickart, R. S., G.W.K Moore, D. J. Torres, P. S. Fratantoni, R. A. Goldsmith, and J. Yang (2009), Uwpelling on the continental slope of the Alaskan Beaufort Sea: Storms, ice, and oceanographic response *J. Geophys. Res.,* doi:10.1029/2008JC005009.

Proshutinsky, A., R. Krishfield, and D. Barber (2009), Preface to special section on Beaufort Gyre Climate System Exploration Studies: Documenting key parameters to understand environmental variability *J. Geophys. Res.*, 114, C00A08, doi:10.1029/2008JC005162.

Proshutinsky, A., R. Krishfield, M.-L. Timmermans, J. Toole, E. Carmack, F. McLaughlin, W. J. Williams, S. Zimmermann, M. Itoh, and K. Shimada (2009), Beaufort Gyre freshwater reservoir: State and variability from observations *J. Geophys. Res.*, doi:10.1029/2008JC005104.

Timmermans, M.-L., J. Toole, R. Krishfield, and P. Winsor (2008), Ice-Tethered Profiler observations of the double-diffusive staircase in the Canada Basin thermocline *J. Geophys. Res.*, 113, C00A02, doi:10.1029/2008JC004829 17 December 2008.

Yang, J. (2009), Seasonal and Interannual Variability of Downwelling in the Beaufort Sea *J. Geophys. Res.*, doi:10.1029/2008JC005084, in press.

Yamamoto-Kawai, M., F. A. McLaughlin, E. C. Carmack, S. Nishino, K. Shimada, and N. Kurita (2009), Surface freshening of the Canada Basin, 2003–2007: River runoff versus sea ice meltwater *J. Geophys. Res.*, 114, C00A05, doi:10.1029/2008JC005000.

Relationships to International Arctic Observing Efforts

Since August 2003, a team of Woods Hole Oceanographic Institution scientists has collaborated with researchers from the Institute of Ocean Sciences, Canada and the Japan Agency for Marine-Earth Science and Technology. The BGOS program is also coordinated with the U.K Arctic Synoptic Basin-wide Oceanography and the Scottish Association for Marine Science Ice Mass Balance Array (SIMBA) programs.

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Proshutinsky, A., J. Yang, R. Krishfield, R. Gerdes, M. Karcher, F. Kauker, C. Koeberle, S. Hakkinen, W. Hibler, D. Holland, M. Maqueda, G. Holloway, E. Hunke, W. Maslowski, M. Steele, and J. Zhang (2005), Arctic Ocean study: Synthesis of model results and observations *EOS*, 86 (40), 368-371.

Ice Mass Balance Buoy Network: Coordination with DAMOCLES

PIs: Jackie Richter-Menge and Don Perovich, ERDC-CRREL, Hanover, NH

Project Summary

This project contributes to the design and establishment of an effective Arctic Observing Network (AON) through the coordinated installation of ice mass balance (IMB) buoys. The IMB buoys have proven to be a critical and unique element of atmosphere-ice-ocean observing arrays. The autonomous, ice-based drifting buoys measure, delineate and, importantly, attribute thermodynamically-driven changes in the thickness of the ice cover. The IMBs are deployed strategically and in coordination with other elements of the AON to optimize the observation of changes and trends in sea ice throughout the Arctic Basin. Many of the deployments are facilitated through productive, long-term partnerships with the North Pole Environmental Observatory (NPEO), the Beaufort Gyre Environmental Observatory (BGEO), the International Buoy Programme (IABP), and Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies (DAMOCLES). Responding to the increasing amount of seasonal ice, we are working to advance the current IMB technology to enable operation in seasonal as well as perennial ice. The overarching goal of the project is to contribute to an integrated atmosphere-ice-ocean observing array by providing a comprehensive description of the response of the ice cover to atmospheric and oceanic forcing.

Science and Technology Development Highlights

There have been 48 IMBs deployed in the Arctic Ocean since 2000, with an average of 5 deployments per year. These deployments have been concentrated in the North Pole and Beaufort Sea regions (Figure 1). There are currently 5 active IMBs.

The average life expectancy of an IMB is about 1 year. The longest running IBM (2006C) operated for 3 years and 12 days, from 9 Sept 2006 to 21 Sept 2009.

The IMBs provide a means *to observe* changes in the sea ice mass balance. These observations can then be integrated with other data *to understand* the changes in sea ice. Take as an example data collected from 7 ice mass balance buoys that were operating during the summer of 2008. Figure 2 shows the approximate summer position of these buoys (white dot), the total amount of summer surface melt (red bar), and the total bottom melt (yellow bar) for the summer of 2008. All of the buoys were installed in undeformed multiyear ice, with

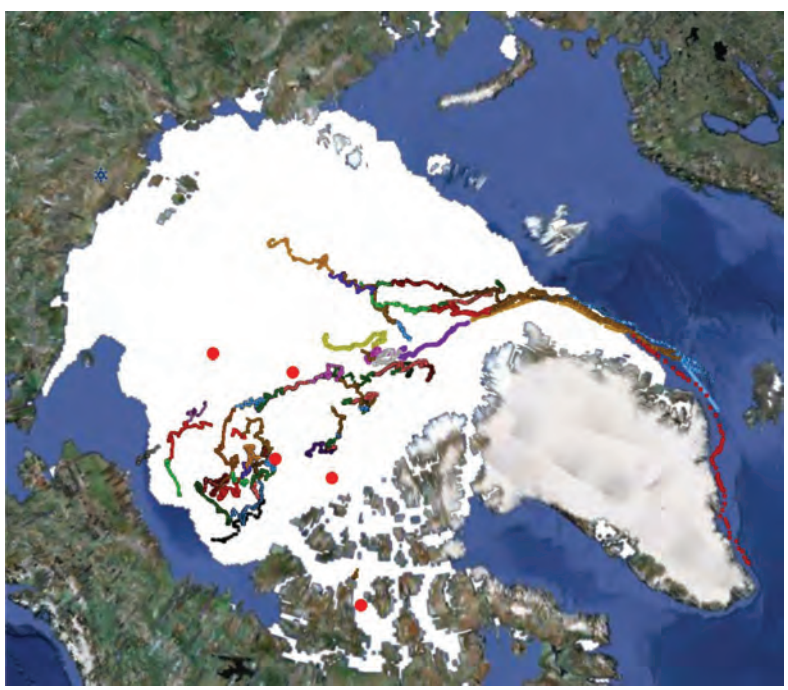

Figure 1. Example ice mass balance buoy drift tracks. Red dots indicate active IMB deployment sites on 4 November 2009.

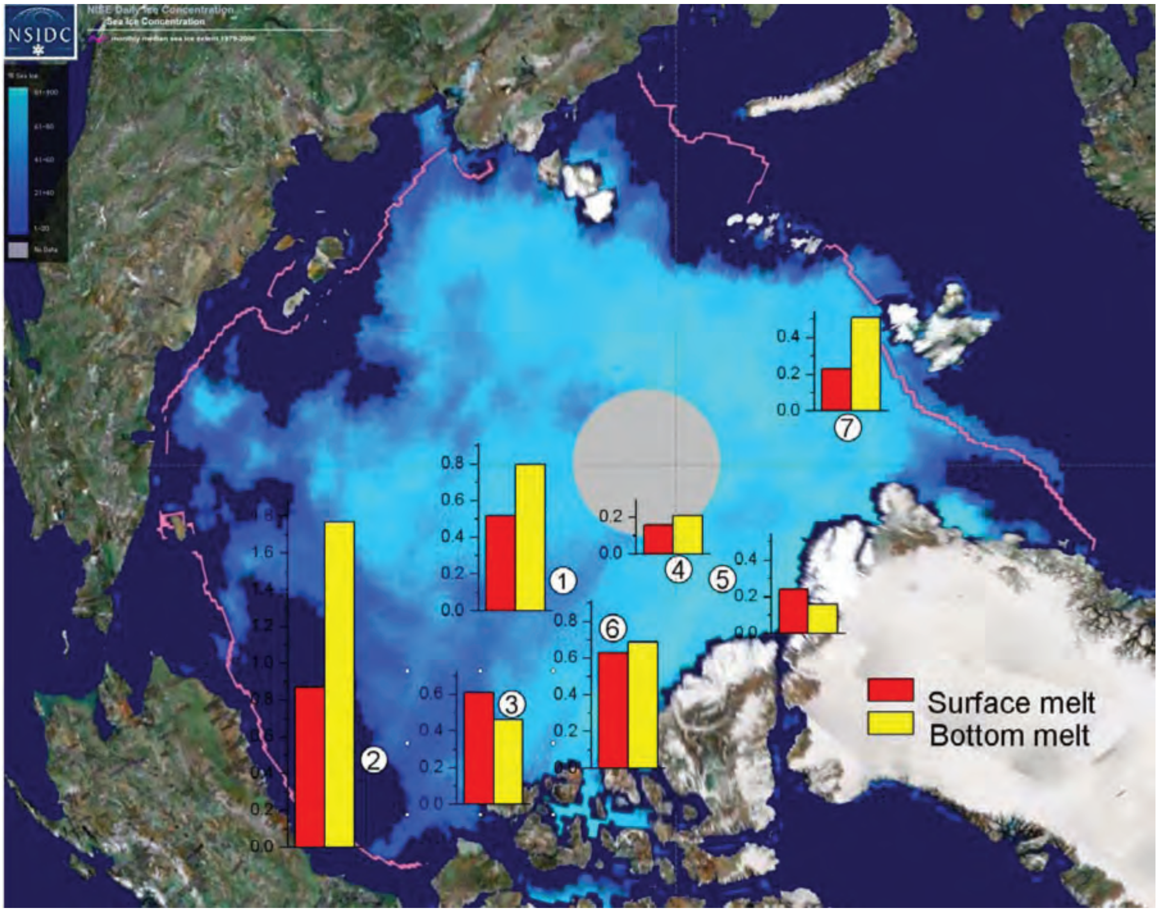

Figure 2. The total amount of surface (red) and bottom (yellow) melt during the summer of 2008 measured at seven ice mass balance buoys. The white dots denote an approximate position of the buoys during summer. The ice at buoy number 2 completely melted. Also displayed is a map of the ice concentration in September 2008 from the National Snow and Ice Data Center.

end of winter ice thicknesses ranging from 1.83 m to 3.17 m. One of the buoys was installed in 2006, another in 2007, and five in 2008. During summer 2008 there was considerable regional variability in the amount of surface, bottom, and total melting. The smallest amount of melting was at a location north of Greenland, where 0.3 m of surface melt and 0.1 m of bottom melt resulted in a total thinning of only 0.4 m. The maximum melting was in the Beaufort Sea, where 3.2-m-thick ice completely melted by 23 August 2008, with more than 0.85 m of surface melt and 1.77 m of bottom melt measured. On average there was 0.47 m of surface melting and 0.66 m of bottom melting.

The background map in Figure 2 displays ice extent and concentration in September 2008. A casual examination shows a tendency towards greater bottom ablation in regions of lower ice concentration. The largest observed bottom melting was at the ice edge site in the Beaufort Sea, while the smallest was north of Greenland where the ice concentration was large throughout the summer. There were also large amounts of bottom melting in the Beaufort Sea in the summer of 2007 due in part by enhanced solar heating of the upper ocean (Perovich et al., 2008).

Lessons Learned

Coordination, coordination, coordination. It is hard to have too much coordination. The success of the IMB project has been highly dependent on the strategic deployment of a limited number of drifting buoys in coordination with other projects. This approach has benefited the quality of the data (e.g., coincident atmosphere, sea ice, ocean measurements critical to interpreting results) and has kept the project cost relatively low through shared logistics.

Coordinated deployments have been done on a PI to PI basis. A recommended improvement to this approach is the establishment of an AON-level summary of upcoming deployments, which might reveal other opportunities for strategic deployments. This summary should include deployments supported by other agencies (e.g., NASA, NOAA, USCG, Navy) and international partners.

Project Coordination

Most coordination has been on a PI to PI basis, including coordination with international partners. For this project, this includes:

- North Pole Environmental Observatory (NPEO)
- Beaufort Gyre Environmental Observatory (BGEO)
- International Buoy Programme (IABP)
- Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies (DAMOCLES)
- Seasonal Ice Zone Network (SIZONET)
- Russian North Polar Drift Station
- GreenARC

This project has also benefited greatly by complementary support from NOAA Climate Program Office, Arctic Research Program.

Data Use

The IMB data are being used by the remote sensing community for the development and evaluation of algorithms and to interpret satellite observations. IMB ice temperature data have been used to evaluate and improve QuikSCAT retrievals of the onset of melt in spring and freezeup in fall (Nghiem et al., 2007). IMB snow depth and ice thickness observations have been used to demonstrate that ICESat freeboard retrievals are within 10 cm of IMB surface-based measurements (Kwok et al., 2007). IMB results can continue to give baseline data to support the development of sensors and algorithms to remotely sense snow depth, ice thickness, and the onset of melt and freezeup. The IMB results can also be used to understand remotely observed changes in ice thickness. For example, semiannual airborne and satellite surveys of ice thickness can measure seasonal and interannual changes in ice thickness. Surface based IMB observations can attribute those changes to ice growth, surface melt, or bottom melt (e.g., Haas, 2008; Giles et al., 2008). Data from Ice-Tethered Profiles (ITP) and IMBs have been combined to investigate changes in the Arctic Central Canada Basin mixed layer properties and the impact of these changes on sea ice growth and decay at the ice/ocean boundary (Toole et al., submitted).

Publications and Web Sites

Gascard, J.-C., et al. (2008) "Exploring Arctic transpolar drift during dramatic sea ice retreat," *Eos Trans. AGU*, p. 21, vol. 89(3).

Nghiem, S.V, I.G. Rigor, D.K. Perovich, P. Clemente-Colon, J.W. Weatherly and G. Neumann (2007) "Rapid reduction of Arctic perennial sea ice," *Geophys. Res. Lett.,* 34, L19504, doi:10.1029/2007GL031138.

Perovich, D. K., J. A. Richter-Menge, K. F. Jones, and B. Light (2008) "Sunlight, water, and ice: Extreme Arctic sea ice melt during the summer of 2007," *Geophys. Res. Lett.*, 35, L11501, doi:10.1029/2008GL034007.

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Toole, J.M., M.-L. Timmermans, D. K. Perovich, R. A. Krishfield, A. Proshutinsky and J.A. Richter-Menge (submitted) "Influences of the ocean surface mixed layer and thermohaline stratification on Arctic sea ice in the central Canada Basin," *J. Geophys. Res.*

We produce a pubic web site to archive and disseminate data from the ice mass balance buoy network: **http://imb.crrel.usace.army.mil/**

The position of our buoys can also be followed on the web site for the International Arctic Buoy Programme: **http://iabp.apl.washington.edu/index.html**

We have also uploaded our IMB data and metadata to CADIS.

International Contributions

The IPY project funded by NSF was specifically aimed at collaborating with the EU-sponsored project DAMOCLES. The objective was to incorporate IMBs as an integral part of the DAMOCLES atmosphere-ice-ocean observing network. Through this collaboration, we were able to extend the coverage of the IMB network. We continue to be in contact with members of the DAMOCLES program, discussing future opportunities for collaboration that include instrument deployments.

In spring 2009, we participated in the Danish-led field program GreenARC off the coast of Greenland. An IMB was deployed as part of that program.

Collaborating with A. Proshutinsky (WHOI) and colleagues at Russia's Arctic and Antarctic Research Institute (AARI), an IMB was recently (summer 2009) deployed at the Russian drift station. We are working to develop this collaboration, again focusing on extending the coverage of the IMB network in the Arctic Ocean.

Additional References

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Haas, C., A. Pfaffling, S. Hendricks, L. Rabenstein, J.-L. Etienne, and I. Rigor (2008) Reduced ice thickness in Arctic Transpolar Drift favors rapid ice retreat, *Geophys. Res. Lett.*, 35, L17501, doi:10.1029/2008GL034457.

Kwok, R., G. F. Cunningham, H. J. Zwally, and D. Yi (2007) Ice, Cloud, and land Elevation Satellite (ICESat) over Arctic sea ice: Retrieval of freeboard, *J. Geophys. Res.*, 112, C12013, doi:10.1029/2006JC003978.

Nghiem, S.V, I.G. Rigor, D.K. Perovich, P. Clemente-Colon, J.W. Weatherly and G. Neumann (2007) Rapid reduction of Arctic perennial sea ice, *Geophys. Res. Lett.*, 34, L19504, doi:10.1029/2007GL031138.

Coordination, Data Management and Enhancement of the International Arctic Buoy Programme (IABP)

Investigators: Ignatius Rigor, Pablo Clemente-Colón, Kyle Obrock, Mark Ortmeyer
http://iabp.apl.washington.edu

Project Summary

A network of automatic data buoys to monitor synoptic-scale fields of surface air pressure, air temperature, and ice motion throughout the Arctic Ocean was recommended by the National Academy of Sciences in 1974. Based on this recommendation, the Arctic Ocean Buoy Program was established by the Polar Science Center (PSC), Applied Physics Laboratory, University of Washington, in 1978 to support the Global Weather Experiment. Operations began in early 1979, and the program continued through 1990 under funding from various agencies. In 1991, the International Arctic Buoy Programme (IABP) succeeded the Arctic Ocean Buoy Program, but the basic objective remains – to maintain a network of drifting buoys on the Arctic Ocean to provide meteorological and oceanographic data for real-time operational requirements and research purposes including support to the World Climate Research Programme, the World Weather Watch Programme, and the Arctic Observing Network.

The IABP is composed of 28 different research and operational institutions from 8 different countries. The IABP is funded and managed by Participants of the program. Management of the IABP is the responsibility of the Executive Committee, and operation of the program was delegated to the Coordinator of the IABP, Ignatius Rigor.

The United States contribution to the IABP is coordinated through the United States Interagency Arctic Buoy Program (USIABP), which is managed by the National Ice Center (NIC) and the PSC. The USIABP is a collaborative program that draws operating funds and services from a number of U.S. government organizations and research programs, which include the International Arctic Research Center, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the National Science Foundation (NSF), the Naval Oceanographic Office, the NIC, the Office of Naval Research, and the U.S. Coast Guard. From these contributions the USIABP acquires and deploys buoys on the Arctic Ocean, and supports the Coordination and Data Management for the IABP by the PSC.

Broader Impacts

The observations from the IABP have been essential for: 1) Monitoring Arctic and global climate change (many of the changes in Arctic climate were first observed or explained using data from the IABP); 2) Forecasting weather and sea ice conditions; 3) Forcing, assimilation and validation of global weather and climate models; 4) Validation of satellite derived estimates of sea ice motion, surface temperature, sea ice thickness, etc.

Outreach

We work closely with undergraduate and graduate students at the University of Washington to provide research advise and career guidance. Our outreach work also emphasizes targeted presentations of our research and polar climate change in various public forums such as press releases through the UW, press conferences at AGU meetings, and presentations at broadly attended venues such as the Alaska Forum on the Environment. This work has resulted in dozens of press interviews and quotations, including news pieces on ABC, CBC (Canada), CBS, TF-1 (France), National Public Radio, New York Times, and Science. We make outreach presentations at the UW, K-12 schools, at other public venues in Seattle, and are also actively involved in larger-scale outreach programs such as our annual Polar Science Weekend at Seattle's Pacific Science Center, which is the most attended museum in Washington. And we have contributed buoys and other geophysical equipment to the Around the Americas cruise (http://www.aroundtheamericas.org/), which hopes to heighten the awareness of the public to our changing climate.

Intellectual Merit

Over 600 papers have been written using the observations and data sets produced by PSC for the IABP (http://iabp.apl.washington.edu/publications.html). These observations provide the longest continuing record for the Arctic, and have been one of the cornerstones for environmental forecasting and studies of climate and climate change. The IABP is also evolving to better support the operational and research requirements of the community by deploying buoys, which also monitor sea ice, and ocean conditions. These stations provide critical atmospheric, ice, and upper ocean hydrographic measurements that cannot be obtained by other means.

Data Management

The data from all IABP/USIABP buoys are released to the research and operational communities in near real-time through the WMO Global Telecommunications System. Research quality fields of ice motion, sea level pressure (SLP) and surface air temperature are also analyzed and produced by the APL-UW; these fields can be obtained from the IABP web server at http://iabp.apl.washington.edu/, and have been archived at various data centers. As of May 4, 2009 12-hourly interpolated time series from each buoy, and the optimally interpolated gridded fields of SLP and ice motion from 1979–2006 have been posted to the CADIS web site. The IABP/POLES gridded SAT analysis has been posted through 2004. (This data set will not be updated since we will be releasing a new ARCSS-SAT analysis shortly.) Given the increased volume of data during the IPY, we are still in the midst of processing the data sets for 2007 and 2008, but we have begun posting some of these data on CADIS, e.g., the 12-hourly interpolated data have been updated through 2008. We plan to post 3-hourly interpolated data by June 2009. We are working on collecting all the metadata for all the buoys going back to 1979, which will allow others to process the raw buoy data. We plan to provide the metadata, raw data, and netCDF versions of all these data by December 2009.

Deployment Plans

During the last few years the IABP has been deploying over 50 buoys/year and has been able to maintain a network of about 40 buoys reporting at any given time. During the IPY, the buoy network peaked at over 200 buoys, and has since settled to just under 100 buoys.

There were 88 buoys reporting in the IABP network on November 4, 2009.

- 70 of 88 have barometers and/or temperature sensors (i.e., all except NPS AOFB and WHOI ITP).
- 33 of 88 were purchased by the USIABP.
- 44 of 88 were deployed using logistics coordinated by the USIABP.

Our deployment plans for 2009 are shown in Fig. 1, during which time the participants of the IABP deployed 62 buoys. Our plans for 2010 will be similar, with the additional possibility of deploying buoys from the Korean icebreaker *Araon*, and the Chinese icebreaker *Xuelong*.

Challenges

- Developing buoys that can survive freeze/thaw cycles in increasing areas of seasonal ice.
- Deploying buoys in the Eurasian Arctic, especially in the Russian EEZ. The RMS difference between estimates of sea level pressure by the various reanalyses fields is over 2.5 hPa in areas where there are no buoy observations to constrain the reanalyses (Inoue et al. 2009, Fig. 2).
- Getting as much buoy data in near real-time onto WMO GTS so operational centers can use the data to forecast weather, sea ice, and assimilate the data into reanalyses data sets.

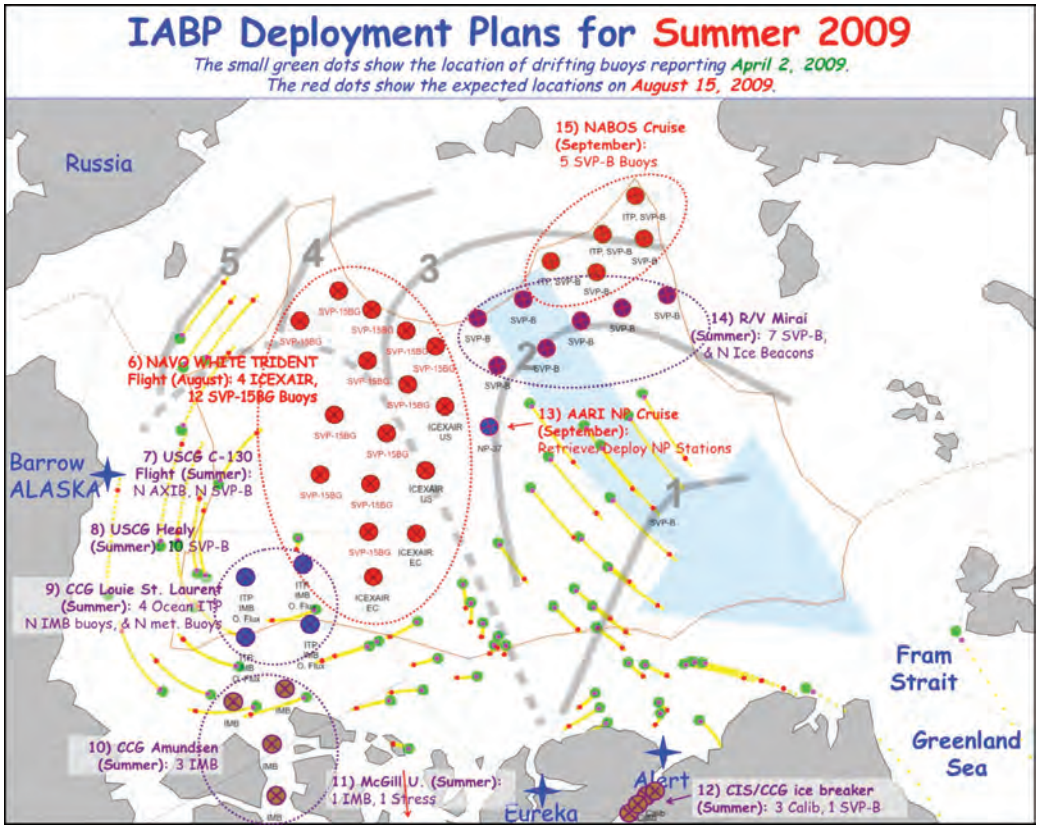

Figure 1. Deployment plans of the IABP during the summer of 2009. The grey lines show average residence times of sea ice (i.e., years until the ice will drift through Fram Strait; the orange lines are the Exclusive Economic Zones, the green dots show the current buoy positions, while the yellow line shows how these buoys will drift in the mean, and the small red dots are where the current buoys may be on August 15. Details can be found at http://iabp.apl.washington.edu/overview_deploymentplans.html

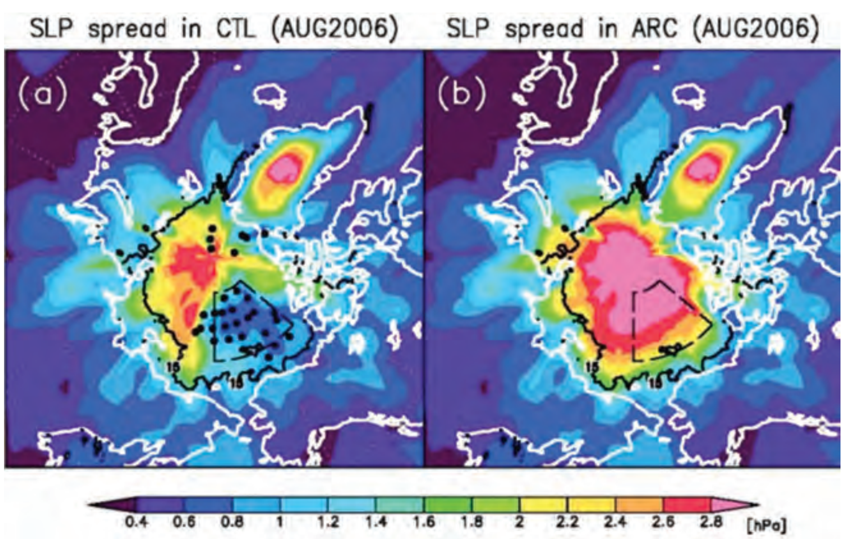

Figure 2. Analysis ensemble spread of SLP in August 2006 for (a) CTL (b) and ARC. Dots depict the positions of the Arctic drifting buoys. The thick line denotes ice concentration grater than 15%. From Inoue et al. 2009.

A Modular Approach to Building an Arctic Observing System for the IPY and Beyond in the Switchyard Region of the Arctic Ocean

(ARC-0633885)
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Hydrochemical section: Bill Smethie (bsmeth@ldeo.columbia.edu)
Hydrochemical survey: Mike Steele (mas@apl.washington.edu)
Mooring team: Craig Lee (craig@apl.washington.edu)
Sea ice remote sensing: Ron Kwok (ron.kwok@jpl.nasa.gov)

Project Summary

The Switchyard project samples the marine environment in the Lincoln Sea (just north of northern Ellesmere Island, Canada, and Greenland) north to the Pole. We call this the "Switchyard" region because like a train switching yard, different water masses and sea ice types converge into this region and are sent on their way, with some recirculating back into the Arctic Ocean's Beaufort Gyre and the rest into the North Atlantic Ocean on different "tracks" to the west of Greenland via Nares Strait and to the east of Greenland via Fram Strait. This is the water that influences the downstream deep water formation and thus global ocean circulation, and so it is crucial to document interannual changes in this region to achieve both understanding and a predictive capability.

The project consists of four main components:

1. **Hydrochemical section:** This is a section between the Lincoln Sea and the North Pole, consisting of 5-8 stations taken annually in early May. A Twin Otter aircraft lands on an ice floe, a hole is drilled, and a winch with conducting wire is used to lower a CTD-O (i.e., a suite of digital temperature, salinity, and dissolved oxygen sensors) and 1-3 specialized rosettes of 4 Niskin bottles (for measuring various chemical constituents) each to a depth of about 600 m. This section cuts across the Transpolar Drift Stream and several segments of the deeper Atlantic Water circulation.
2. **Hydrochemical survey:** This is a regional survey of the Lincoln Sea of maximum radius 500 km, consisting of 10-16 stations taken at the same time as the section, using another Twin Otter aircraft. A much lighter winch is used to lower a CTD-O to 500 m or 1000 m depth (depending on bathymetry), and a single ocean surface Niskin bottle sample is taken. This activity takes about half the time of a "section" station and thus we get about double the stations, for a complete sample of the regional hydrography.
3. **Shelf-slope mooring line:** This is a growing activity to observe the eastward-flowing waters along the continental shelf and slope of Northern Ellesmere Island, an extension of such boundary currents found elsewhere in the Arctic Ocean. At this point there are 3 moorings deployed, with 3 more planned for spring 2010. The moorings use an innovative acoustic data downlink, eliminating the need for expensive mooring recovery operations. Moorings are deployed by Twin Otter and data are downloaded by landing nearby, using a helicopter.
4. **Sea ice remote sensing studies:** This activity has focused on an analysis of sea ice fluxes through the Canadian straits, including Nares Strait, using remote sensing.

Technology Highlights

- ***Hydro section*:** We have developed a Modular Rosette System that includes: 1) a Seabird CTD (SBE 19+), 2) a Seabird dissolved oxygen sensor (SBE 43), and 3) a series of 1-3 new 4-bottle Niskin rosettes that can fit through a 12" diameter hole drilled through the sea ice. Development of this instrument took a few years of trial and error, but it is now working quite reliably with generally 90% or more successful tripping of bottles on each station.
- ***Hydro survey*:** Seabird electronics is no longer making a 1000 m pressure case for their CTDs, only 500 m and 5000 m. For our 1000 m casts with small winches, we require a new model. Thus we special-ordered a 1000 m Delrin plastic case that worked well in 2009, and plan to order another back-up unit in the future.
- ***Moorings*:** Our switchyard moorings represent a new philosophy, with acoustic downloading of all data that eliminates expensive recovery operations.

Science Highlights

- ***Oxygen minimum waters*:** Using dissolved oxygen data from the hydro section and survey, K. Falkner et al. (2005) described and explained the presence of water layers with low oxygen values relative to those immediately above and below. These layers originate on the Arctic shelves, circulating within the basin in complex ways dependent on the depth at which they inject into the interior flow.
- ***Ice flux through Nares Strait*:** Kwok (2005) showed that the annual total sea ice flux through Nares Strait is less than 10% of that through Fram Strait, with a strong seasonal amplitude. No particular interannual trend was found from the six years of RADARSAT data analyzed.
- ***Modification of waters within Nares Strait:*** Munchow et al. (2006) used hydro survey data to determine that waters within the strait are substantially modified, relative to that which enters the northern end of the strait in the Lincoln Sea.
- ***Hydrographic relaxation:*** Morison et al. (2006) used hydro section data to determine that central Arctic Ocean hydrographic conditions in the early-mid 2000s had relaxed back to a condition very similar to that in the 1980s, i.e., before the large shifts seen in the 1990s.
- ***Freshwater build-up in the Canadian Basin*:** McPhee et al. (2009) used hydro section and survey data to show how the freshwater content of the Canadian Basin was much higher in 2008 than in the historical climatology.
- ***Freshwater outflow from the Arctic Ocean*:** de Steur et al. (2009) used CTD data from both the hydro survey and hydro section to show that recent freshwater build-up in the Beaufort Gyre is "leaking" into the Lincoln Sea and thus may indicate a coming freshwater export into the North Atlantic Ocean (Figure 1).
- ***Black carbon*:** Hegg et al. (2009) show that black carbon found in snow on Arctic Ocean sea ice (including data from Switchyard) comes not from biomass burning, but rather from "pollution," the source of which was not determined in this analysis. A follow-up manuscript soon to be submitted stresses the relatively clean nature of the Arctic Ocean snow cover.
- ***General freshening of the Switchyard region*:** Survey data from 2008 and 2009 indicate that there has been a general freshening of all water types in the Switchyard region, including Eurasian water mass assemblies. The chemical signature indicates that these are meteoric waters, as opposed to sea ice melt.
- ***Seasonality of Lincoln Sea shelf waters*:** The first year of mooring data (spring 2008 – spring 2009) indicates substantial seasonal variations, which will be explored further using data from the three moorings deployed over the following year (to be downloaded in spring 2010).

Lessons Learned

- ***New technology takes time to develop and test.*** The Modular Rosette System used in the hydro section took a few years of field work to develop into the robust system it is today. This success might have been much more difficult if the project had been funded on a typical 3-year cycle, or within a broad program like ANS instead of a dedicated observational program like AON.

- ***We must be responsive to weather/marine conditions.*** The hydrochemical survey was originally conceived as an annual high-resolution survey across the continental slope, using a helicopter and our small winch. This worked well for the first few years of our program. However, in recent years an increase in low clouds and fog in our operating window (i.e., May) has severely limited the days on which a helo can fly. As a result, we shifted our focus to a large-scale hydro survey using the more weather-resistant Twin Otter aircraft. This has proved very successful. As the arctic climate changes, other AON projects may also need to modify their observational strategies to adapt.

Interactions with Other Projects

- ***NPEO*:** We have a strong collaboration with the North Pole Environmental Observatory, which consists in part of hydrochemical surveys similar to those conducted during Switchyard. One of our Twin Otters comes south from the Pole, saving staging costs. We also share some equipment and personnel. NPEO used to do our Lincoln Sea–North Pole section, but now we coordinate with them to create even longer sections that start in the Lincoln Sea and extend through the Pole and into the Canadian or Eurasian Basins.

- ***Black carbon surveys*:** For the past 3 years we have collected snow samples for an NSF project led by T. Grenfell and S. Warren to determine the distribution

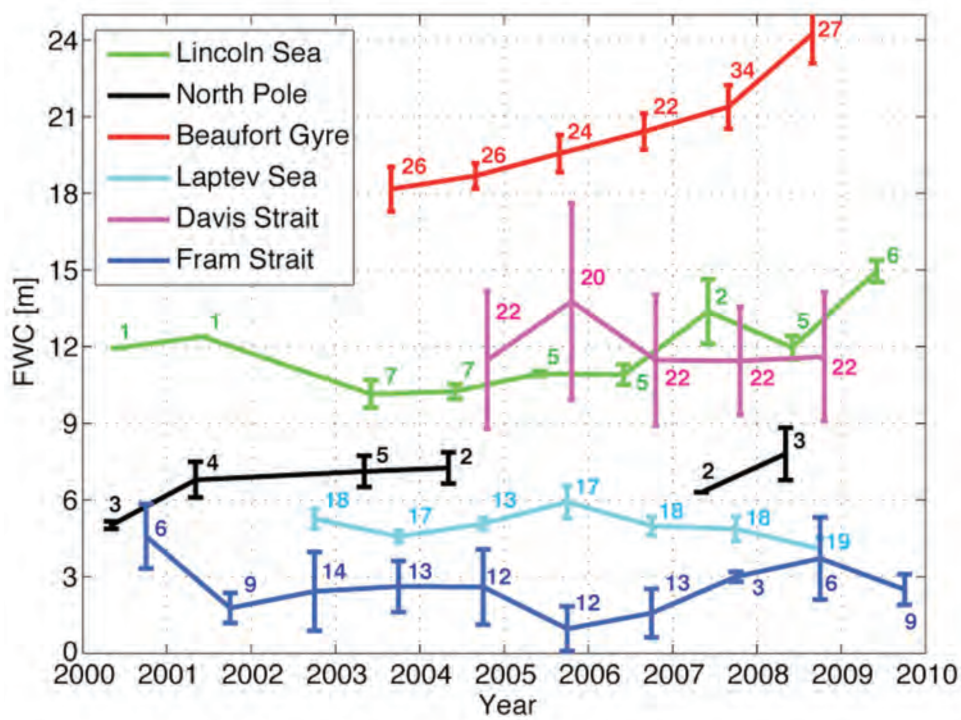

Figure 1. From de Steur et al. (2009): Freshwater Content (FWC) for six regions of the Arctic Ocean over the 21st century, using annual hydrographic survey data in each case. The large build-up in the Beaufort Gyre is obvious and has been the subject of very recent papers by Proshutinsky et al. (2009) and McPhee et al. (2009). Increasing FWC in the Lincoln Sea (as observed in the Switchyard project) indicates that this freshwater may be "leaking" toward the North Atlantic Ocean. Relatively flat trends in Fram and Davis straits indicate that this freshwater pulse has not yet reached these exit points. Vertical lines indicate +/- 1 standard deviation of FWC within one or more 150 km box, except for Davis and Fram straits, where the boxes are 50 km. Small numbers indicate the total number of hydrographic profiles used for each point on the graph.

of black carbon ("soot") across the arctic marine and terrestrial environments. Our data are some of the cleanest in the arctic, providing an important baseline point.

- ***IABP*:** We annually deploy ice-drifting buoys for the International Arctic Buoy Program, both from the section and survey flights. Our deployments are important for determining the characteristics of the bifurcation seen in the Switchyard region, i.e., where some sea ice recirculates back southwestward into the Beaufort Gyre, some finds its way through Nares Strait, and some heads southeastward into Fram Strait and then the East Greenland Current.

Data Use

- See Science Highlights and Interactions with Other Projects.

Publications

deSteur, L., M. Steele, J. Morison, I. G. Rigor, C. M. Lee, and E. Hansen, Recent changes in Arctic Ocean freshwater distribution, *Geophys. Res. Lett.*, submitted, 2009.

Falkner, K., M. Steele, R. Woodgate, J. Swift, K. Aagaard, and J. Morison, Dissolved oxygen extrema in the Arctic Ocean halocline from the North Pole to the Lincoln Sea, *Deep-Sea Res.* I, 52, 1138-1154, 2005.

Hegg, D. A., S. G. Warren, T. C. Grenfell, S. J. Doherty, T. V. Larson, and A. D. Clarke, Source attribution of black cargon in arctic snow, *Environ. Sci. Technol.,* 43, 4016-4021, 2009.

Kwok, R., Variability of Nares Strait ice flux, *Geophys. Res. Lett.*, 32, L24502, doi: 10.1029/2005GL024768, 2005.

McPhee, M., A. Proshutinsky, J. Morison, M. Steele, and M. Alkire, Rapid change in freshwater content of the Arctic Ocean, *Geophys. Res. Lett.*, 36, L10602, doi:10.1029/2009GL037525, 2009.

Morison, J., M. Steele, T. Kikuchi, K. Falkner, and W. Smethie, Relaxation of central Arctic Ocean hydrography to pre-1990s climatology, *Geophys. Res. Lett.,* 33, L17604, doi: 10.1029/2006GL026826, 2006.

Morison, J., M. Steele, T. Kikuchi, K. Falkner, and W. Smethie, Relaxation of central Arctic Ocean hydrography to pre-1990s climatology, *Geophys. Res. Lett.*, 33, L17604, doi: 10.1029/2006GL026826, 2006.

Munchow, A., H. Melling, and K. K. Falkner, An observational estimate of volume and freshwater flux leaving the Arctic Ocean through Nares Strait, *J. Phys. Oceanogr.*, 36, 2025-2041, 2006.

Web Site

http://psc.apl.washington.edu/switchyard

International Cooperation

- We operate out of Alert, Nunavut, Canada. Our operations are at the discretion of the Canadian military, which permits our access to facilities and even provides some personnel support. This could change at any time, for example if territorial tensions over the Canadian Archipelago were to escalate.
- We have plans to share data with a joint British-Danish hydrographic and sea ice experiment that operated in spring 2009 on the northern coast of Greenland.
- We have made inquiries with NOAA and NASA teams that occasionally fly a P3 aircraft over the Lincoln Sea for sea ice surveys, with a goal of deploying some expendable CTD probes into open water in the area.

Education/Outreach

- In our first year, we took Dan Dyer, a graduate student in videography, to the field. He used footage shot in that trip to make an educational DVD that also contained an interview with M. Steele.
- We will take a U.S. grade school teacher to the field in 2010, via the PolarTREC program.
- Our field scientist and data analyst Roger Andersen acted as "beta tester" for the fall 2009 update to the CADIS data portal web site.

Ocean-Ice Interaction Measurements Using Autonomous Ocean Flux Buoys in the Arctic Observing System

Tim Stanton and Bill Shaw
Naval Postgraduate School

Project Summary

Our project continues observations of turbulent fluxes, heat content, and current profiles in the ocean boundary layer below sea ice in the Beaufort Sea and Transpolar Drift regions of the Arctic Ocean. A series of three ice-deployed Autonomous Ocean Flux Buoys (AOFB) are being deployed each year to robustly measure heat, salt and momentum fluxes near the ocean-ice interface using direct, eddy-correlation techniques. Significant scientific and logistic leverage results from collaboratively deploying the AOFBs on the same ice floe as systems concurrently measuring the ocean T/S structure, the conductive fluxes through the ice cover, and at some stations, the bulk atmospheric and radiative fluxes, all of which are components of the Arctic Observing Network.

These observations are motivated by the need to resolve the role of competing processes that are contributing to the dramatic decrease in perennial ice cover extent and volume in the Arctic during the last few years. The ocean plays a critical role in the coupled ocean/ice/atmosphere system that supports perennial ice cover through a surprisingly delicate thermodynamic balance. Direct, long-term observations of the oceanic vertical fluxes allow the contributions of external forcing factors including atmospheric wind fields, solar irradiance, and changes in the upper ocean heat content and stratification to basal ice formation of melting to be evaluated. The AOFB flux and high-resolution, upper-ocean / ice temperature measurements at each observation site are also directed at understanding the details of the enhanced ice-albedo feedback mechanisms, including the formation of surface-trapped fresh warm layers, and the possibility that the forcing and feedback mechanisms will push the coupled ice/ocean system into an ice-free summer mode.

Observations from the repeated, multi-year-duration deployments of the AOFBs will lead to improved understanding of basic physical processes that are affecting the thermodynamic balance of the Arctic Ocean ice cover. It is this balance, considered throughout the basin, that will determine if the Arctic transitions to a state of greatly reduced or no perennial ice cover. The proposed collaborative ice floe observatories will generate canonical data sets, previously only attainable from manned ice stations. These observations will serve as invaluable audit points for the testing and evaluation of regional and global models by providing a suite of data comparable to the most intensive manned camps, but with greater temporal and spatial coverage.

Science and Technology Development Highlights

The successful field deployment of the buoy has required the following technical developments:

- Integrating a compact, 10 Hz response, 0.1 m°C resolution, thermistor-based temperature sensor and a commercial, inductive conductivity sensor to measure departure from freezing point and turbulent fluctuations of temperature and salinity for use in the eddy-correlation heat and salt flux measurements. The conductivity cell turn-on characteristics are determined for each cell to achieve the required accuracy for this application.
- Modifying a commercial, low-power, acoustic travel-time velocity sensor to measure three component mean and turbulent velocity components with mm/s resolution in a 10 cm^3 sample volume. This required a new housing design and algorithm development to reduce transducer selection switching transients in the velocity calculations.

- Designing a robust sensor package suspension system, buoy housing, and antenna "tophat" to support the flux package and acoustic Doppler profiler, to permit deployment in less than half a day, and to allow multi-year survival in the Arctic pack ice.
- Developing processing algorithms for in-situ, spectral flux calculations, current and shear profiling, remote buoy infrastructure control, and short-term data buffering.
- Developing robust, two-way data communications with the buoy based on the then newly revived Iridium cell-phone system. This was a challenging but critical component of the flux buoy design that allows remote control of sampling strategies and the transmission of raw data and spectral flux quantities far in excess of Argos satellite capacity. The data transmission protocol is robust to the frequent dropouts in the Iridium system and has been shared with several groups requiring moderate bandwidth communications in polar regions.
- Developing software to process, archive, and distribute the data in real time on a land-based Linux computer at NPS.
- Designing a power system consisting of banks of current-limited lithium primary batteries, supplemented by a wind generator. An automatic, adaptive sampling strategy increases sample rates during periods of strong winds (and hence larger turbulent fluxes) when the wind power is available. This greatly increases the lifetime of the primary lithium batteries, while increasing resolution of all the observations at times of greatest forcing.

The following developments are ongoing in response to the rapid decline in the perennial ice cover:

- Designing and integrating a 16-element thermistor string to resolve thermal structure in and below the ice to better than 2 m°C to document near-surface solar heating effects.

Lessons Learned

During the evolution of the flux buoy program, we have improved the temperature and conductivity sensors, recognized the need for increased sampling coverage of the upper water column to resolve summer radiative fluxes, and developed a very high resolution thermistor string to make this measurement. We are currently redesigning the ACM current sensor to remove thermal drift problems and improve the sensor noise floor.

Interactions with Other Projects

A very significant modification of our deployment program has occurred through a close collaboration with the WHOI ITP group who routinely deploy the ocean flux buoys, greatly reducing the AON logistic costs, and ensuring co-location and complimentary measurements at a maximum number of sites.

We are hopeful that interactions with two currently proposed projects will be fruitful. Proposed collaborations with J. Hutchings (IARC) and I. Rigor (PSC-UW) will build on our ongoing work relating ocean heat content and heat fluxes to ice divergence. Proposed collaborations with W. Maslowski (NPS) and Andrew Roberts (IARC) will investigate the boundary layer and air-sea-ice interaction formulations used in a regional Arctic Ocean model.

Brief Examples of Data Use

An example of the type of integration that is possible with the IBO concept is provided by the synthesis of Stanton et al. (2009, submitted) that describes the interannual variability of the ocean-to-ice heat flux and compares the ocean flux to estimates of the shortwave radiative flux entering the upper ocean through open water from the 2002-2008 NPEO drifts. The analysis relies on data from the AOFBs, PMEL radiometers, and open water estimates from both the passive microwave SSMI sensor and divergence calculations using the International Arctic Buoy Program drift tracks. Over the years 2002-2008 the summer-averaged, ocean-to-ice heat flux has varied between 9.7 and 4.6 W m^{-2}. The average fluxes were relatively large in 2002, 2003, and 2007, and relatively small from 2004-2006. For each year except 2002, we estimate that average incoming radiation was larger than the average ocean-to-ice heat flux, and thus that radiative flux was sufficient to completely support the ocean-to-ice heat flux, although there is substantial variability in the amount of radiative 'surplus'. The anomalously large ocean-to-ice heat transport in 2002 may be indicative of a nonlocal heat transport process. We also suspect that the summertime measurement of upper ocean heat content and surface radiation may provide a more accurate estimate of local open water concentration than is currently possible with the passive microwave sensors. We are also working with other groups in understanding inertial ice motions and momentum coupling using the flux buoy's high resolution GPS position and ice velocity data.

List of Publications and/or Web Sites

Shaw, W. J., T. P. Stanton, and M. G. McPhee (2008), Estimates of surface roughness length in heterogeneous under-ice boundary layers, *J. Geophys. Res.*, *113*, C08030, 10.1029/2007JC004550.

Stanton, T. P., W. J. Shaw, and J. Hutchings (2009), Variability of summertime ocean-to-ice heat flux in the Transpolar Drift: 2002-2007, *J. Geophys. Res.*, submitted.

Project website: www.oc.nps.edu/~stanton/fluxbuoy

Real-time data access: www.oc.nps.edu/~stanton/fluxbuoy/deploy/deploy.html

Archive data access: www.eol.ucar.edu/projects/aon-cadis/

How Project Fits Within the Broader Suite of International Arctic Observing Efforts

This project presents a unique opportunity to make long term, direct heat flux measurements at selected sites in the Arctic Ocean in the context of co-located water column structure and ice thermal structure observations. These direct flux observations provide important control points for the occupied grid points in coupled ocean/ice/atmosphere models of the region, allowing comparison with flux timeseries and net annualized fluxes calculated in the models. To date, our internaltional collaborators have included Takashi Kikuchi (JAMSTEC, Japan) and Ben Rabe (AWI, Germany).

Outreach Efforts

We are funded to develop an educational website to complement and explain our existing data-focused site. We have recently hired a half-time employee, Brian Baumgartner, who will be leading this effort for the next year.

UpTempO:
Measuring the Upper Layer Temperature of the Arctic Ocean

(ARC-0856177)

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Project Summary

The surface layer (0-60 m) of the Arctic Ocean has in recent years experienced unprecedented summertime warming. The causes are still under investigation, but are undoubtedly related to extreme summer sea ice retreat, which allows more atmospheric heating and northward advection of warm sub-arctic waters. Warming surface waters in turn melt more sea ice ("ice-albedo feedback") and delay fall ice growth. They also affect marine ecosystems, atmospheric boundary layer characteristics, and water mass formation. Presently, we can observe ocean surface temperatures by satellite, although these data need more validation and do not tell us about the vertically integrated heat content of the upper ocean. Hydrographic cruise data can measure sub-surface warming, but provide only a "snapshot" view of the warming at one time during summer. Ice-based buoys exist that can measure temperature profiles, but these are not optimized for observing the open sea.

This project is designed to fill this gap in the Arctic Observing Network measurement strategy, i.e., to measure the time history of summer warming and subsequent fall cooling of the seasonally open water areas of the Arctic Ocean. We are focusing on those areas with the greatest ice retreat, i.e., the northern Beaufort, Chukchi, East Siberian, and Laptev seas. We are doing this by building relatively inexpensive ocean thermistor string buoys, to be deployed in the seasonally ice-free regions of the Arctic Ocean.

Technology Highlights

The main idea is to build a buoy with a surface float that contains:

- ARGOS or Iridium antenna
- sea level pressure sensor
- batteries and electronics

Hanging down from this float is a string of thermistors with higher resolution near the surface (depths = 2.5 m, 5 m, 7.5 m, 10 m, 15 m, 20 m, 25 m, 30 m, 35 m, 40 m, 50 m, and 60 m) that measure temperature every two hours with 0.05°C accuracy. A few pressure sensors are also added, which with a cable model provides thermistor depths when the cable swings off the vertical owing to ocean current shear. In the longer term, we also plan to add a higher accuracy thermistor plus conductivity cell at 5 m depth for calibration purposes. Battery life is estimated at 2 years.

The buoys can be deployed in open water during summer, or possibly in a lead or simply left on the ice during spring. Deployment is by "ship/aircraft of opportunity." We will generally rely on the kindness of our colleagues to deploy these simple buoys, similar to the strategy employed by the International Arctic Buoy Program. We will pay for shipping and logistics costs to get the buoys to the deployment vessel.

We received funding at the start of summer 2009, which we used to build four buoys in a very short time. Two buoys had a traditional spherical hull, while the other two had a strengthened hull with a new inverted, tiered shape manufactured by LBI Corporation.
The buoys were manufactured by Clearwater Instrumentation in Watertown, MA. Three of the buoys

were deployed by icebreakers in August and September (two off the U.S. Coast Guard icebreaker *Healy* and one off the Canadian Coast Guard icebreaker *Louie St. Laurent)*. Unfortunately, all failed within a couple of days, eventually sending no signals at all. The fourth was not deployed when it was found to be malfunctioning while on board the Canadian Coast Guard icebreaker *Sir Wilfred Laurier*. Our best guess is that the antenna failed, as a new ARGOS3 antenna was used in these buoys.

We are now planning deployments for 2010. Clearwater will contribute 2-3 buoys, and we have placed a new order for 6 more with MetOcean Data Systems of Dartmouth, NS, Canada. These will be deployed by ships in the summer, and possibly by helicopter north of Alaska in the spring, if the manufacturing time line will allow this.

Science Highlights

None yet; however, we did obtain some temperature profiles from a buoy before it died this past summer, which looked "reasonable" compared to recent hydrographic profiles obtained via summer cruises.

Lessons Learned

From our experience this past summer, we are focused this year on providing ample time for testing of equipment before deployment. We had discussions with both Clearwater and a representative of the ARGOS company about the antenna, which it turns out is somewhat tricky to manufacture properly. ARGOS is interested in motivating the community to transition to their new ARGOS3 system, which like Iridium provides the ability for two-way communication. Thus, they may provide a buoy for us at no cost to deploy this summer that uses this new system.

The two buoys we manufactured this summer contained lithium batteries. We had to ship on a very tight schedule, and this presented some severe shipping problems since these batteries are "hazardous cargo." We are inclined now to use alkaline batteries in our buoys, which provide more shipping flexibility. This is important, given our "opportunistic" deployment strategy.

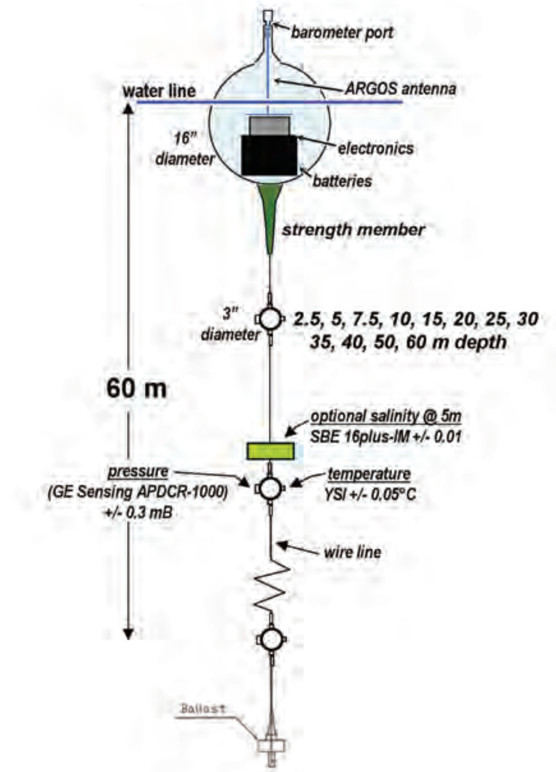


Figure 1. Schematic of the UpTempO buoy. The hull contains an antenna, electronics, batteries, and a barometer. Below the hull hangs a 60 m string of 12 thermistors. Some buoys will include a Seabird temperature/conductivity pair at 5 m depth for calibration of the other sensors.

Interactions with Other Projects

Given our "opportunistic" deployment strategy, we rely on a number of other projects.

- ***IABP*:** The UpTempO buoys will be part of the International Arctic Buoy Program; e.g., their data will be reported on the IABP web site (in addition to CADIS).
- ***BGOS*:** This past summer, a buoy was deployed via the *Louie St. Laurent*, whose mission also includes Andrey Proshutinsky's BGOS project. We hope to deploy again on this cruise in 2010, so that the "snapshot" temperature profiles taken in open water by the CTD survey can be extended through the rest of the summer and into the winter by looking at our buoy data.

- ***NABOS:*** We have contacted Igor Polyakov about the deployment of a buoy on this cruise, in the deep water to the north of the Laptev or East Siberian seas.
- ***SIZONet:*** We have contacted Hajo Eicken about a possible springtime deployment north of Alaska. The advantage of this opportunity, if it works, is that the buoy would measure the entire summer warming and then fall cooling in the first year of observation.
- ***IMBs:*** How much heat is in the upper ocean, and what effect does this have on ice melting? We can address this question by looking at data collected by our buoys and any nearby IMBs. CRREL is now developing a "seasonal" IMB that can float, which we hope can be deployed near our buoys in the near future.
- ***ITPs:*** These buoys obtain temperature profiles from about 7 m depth down to 800 m. WHOI is now manufacturing a version that can float. We anticipate a close collaboration in the future between these larger, more expensive buoys and our smaller, cheaper buoy.

Data Use

None yet.

Publications

None yet.

Web Site

Eventually, our data will be on the IABP web site: **http://iabp.apl.washington.edu/**

International Cooperation

We will be deploying our buoys on U.S., Canadian, and Russian icebreakers this summer.

Education/Outreach

We give many outreach talks to K-12 and college classes in the Seattle area. We include information about Arctic Ocean warming and the ways we are measuring it now and plan to in the future. We include a schematic of our UpTempO buoys (Figure 1) and how ocean temperature varies with depth. The most recent example was a 1.5-hour talk and demonstration at a "Science Night" at Roosevelt High School in Seattle on January 14, 2010.

Observing the Dynamics of the Deepest Waters in the Arctic Ocean

M.-L. Timmermans (Yale University) and L. Rainville (University of Washington)

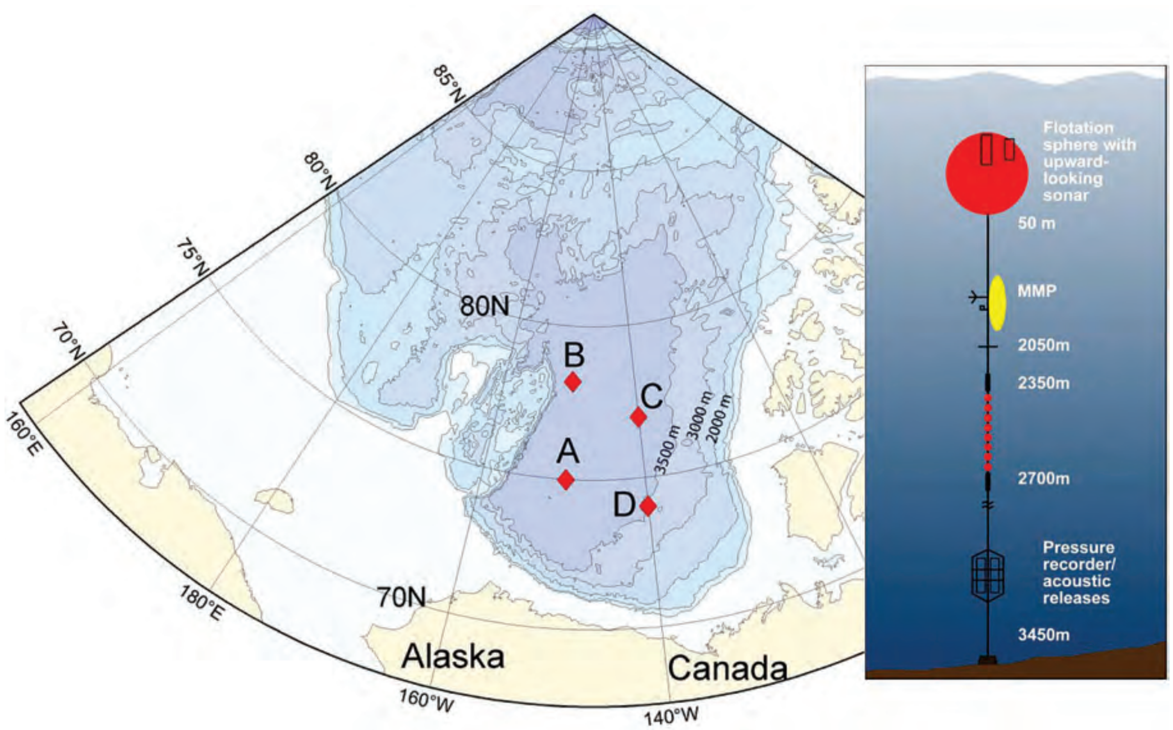
Project Summary

This study aims to understand the dynamics and properties of the deepest waters in the Arctic Ocean and how changes in the shallow and intermediate Arctic waters are manifest in the deep water. To this end, we were funded for one year (2007-2008) to add instruments to the deep section of two Beaufort Gyre Observing System (BGOS) moorings deployed in the Canada Basin. We were most fortunate to leverage internal Woods Hole Oceanographic Institution funds to re-deploy the deep instruments on mooring D (Figure 1) for an additional year (2008-2009). In 2009, deep observations were subsequently continued on moorings A and D under the BGOS, and will continue for the duration of the BGOS program. The moored observations reveal that the isolated deep Canada Basin is a dynamically active environment, not the quiet basin previously assumed.

Technology Development Highlights

While the moored measurements are moderately conventional, to our knowledge these are the first ever long time series measurements in the deep Canada Basin over the abyssal plain. The measurements are providing fascinating insight into the dynamics and evolution of the deep-basin waters.

Figure 1. Left: The Canada Basin in the Arctic Ocean. Beaufort Gyre Observing System (BGOS) mooring locations are marked by diamonds. This AON project funded the placement of instruments on the deep sections (deeper than 2000 m) of moorings A and D for IPY (2007-2008). The time-series of deep measurements has been subsequently extended under BGOS. Right: instrument configuration for mooring D.



Science Highlights

Measurements of temperature, salinity, and pressure show vertical excursions in the deep water column at tidal/inertial frequencies and larger motions, with amplitudes up to 100 m, at sub-inertial frequencies (periods of about 50 days). Investigation of the inertial motions, to understand the propagation and energetics of internal waves in the Canada Basin, is ongoing. Moored profiler measurements in the intermediate water column indicate that sub-inertial displacement amplitudes decrease above the sea floor. We have shown how the low-frequency excursions are consistent with a bottom-trapped topographic Rossby wave. Observations also show evidence for lateral intrusions of new water masses that are likely coherent over hundreds of kilometers.

Connection to the Beaufort Gyre Observing System and the Arctic Ocean Model Intercomparison Project

The initial collaboration with the BGOS was fruitful and cost-effective. It seemed a sensible continuation to make the deep measurements an integral part of the BGOS. Measurements on both upper and deep sections of moorings allow us to assess the relationship between motions at depth and those in the intermediate water column, necessary to understand the character of waves and propagation of energy, for example.

A further beneficial connection is to AOMIP, an international effort to examine and improve numerical models of the Arctic Ocean, and we have established collaborations with this effort. Our investigation of deep dynamics is limited by the spatial coverage of the measurements; modeling efforts will allow us to test our hypotheses on the origin and energetics of the observed deep motions.

Publications

Timmermans, M.-L., L. Rainville, L. Thomas and A. Proshutinsky, 2009: Moored observations of bottom-intensified motions in the deep Canada Basin, Arctic Ocean. Submitted to *J. Mar. Res.*

Timmermans, M.-L., H. Melling and L. Rainville, 2007: Dynamics in the deep Canada Basin, Arctic Ocean, inferred by thermistor-chain time series. *J. Phys. Oceanogr.*, 37, 1066-1076.

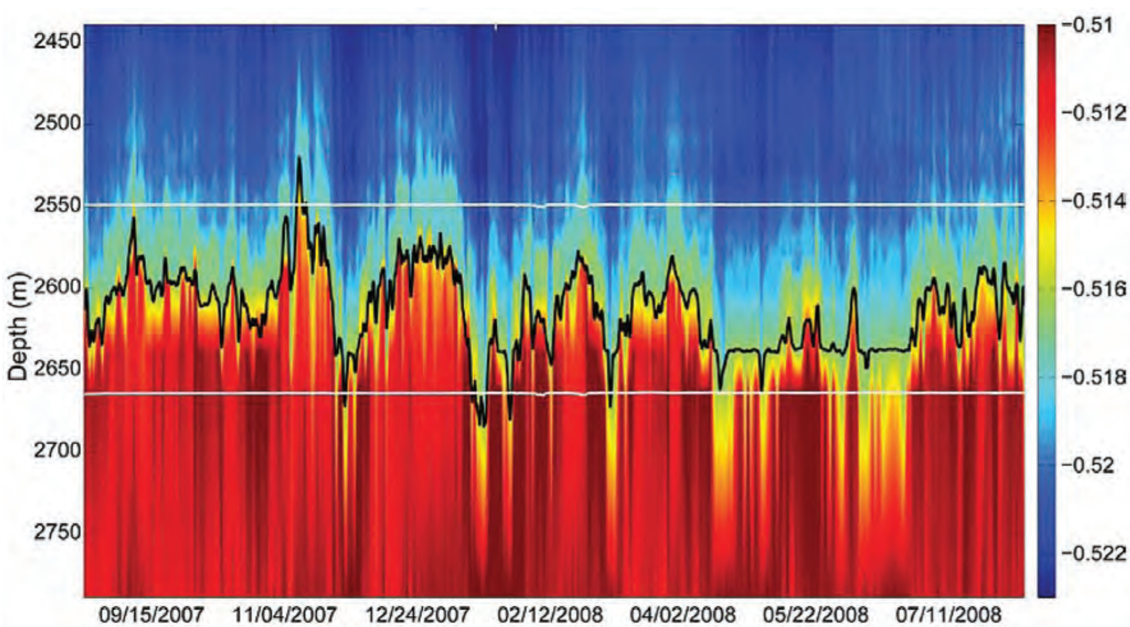


Figure 2. Depth-time section of temperature from the deep instruments on mooring D. Isopycnal displacement is shown by the black line. Depth-time series from pressure sensors are shown by the gray lines.

Design and Initialization of an Ice-Tethered Array Contributing to the Arctic Observing Network

J. Toole, R. Krishfield, M.-L. Timmermans, S. Laney, C. Ashjian, and A. Proshutinsky

Project Summary

Studies conducted over the last decade indicate that the Arctic may be both a sensitive indicator of climate change and an active driver of climate variability. As evidenced by the record minimum sea ice extent observed in August 2007, significant changes in the Arctic are underway now. The major goal of the Ice-Tethered Profiler (ITP) project is to conduct sustained sampling of the central Arctic Ocean water properties during all seasons in conjunction with companion instrument systems (funded separately) sampling meteorological, sea ice and ocean mixed layer parameters. The ITP program is returning upper-ocean observations during this time of rapid evolution to help quantify the physical changes that are occurring, to better understand their causes, and to assess their impacts on the Arctic Ocean ecosystem.

For the period 2004 through the International Polar Year, our group (in collaboration with fellow European investigators) constructed and deployed 30 ITP systems in the Arctic that to date have returned more than 20,000 temperature and salinity profiles down to ~750 m depth. These observations are contributing to diverse studies of Arctic Ocean physical and biological ocean processes on spatial scales ranging from basin width down to ~1 m and time scales from diurnal to interannual. Moreover, ITP data are facilitating numerical model initialization/validation, and stimulating general interest in Arctic science issues. Research and understanding that builds on these observations will lead to better appreciation of the Arctic's role in the earth's evolving climate system. In parallel with the science program, we are evolving the ITP instrument design and capability to both improve long-term functionality and to return additional oceanographic information. A current focus for the latter effort is adding sensors to observe optical parameters of seawater that relate to questions in phytoplankton ecology and marine biogeochemistry.

Science and Technology Development Highlights

The first prototype ITP system was fielded in August 2004. In the subsequent years, the instrumentation has been evolved in an effort to improve system performance and enhance capabilities. The instrument consists of three main components (Figure 1), a surface electronics package housed in a buoyant float (able to support

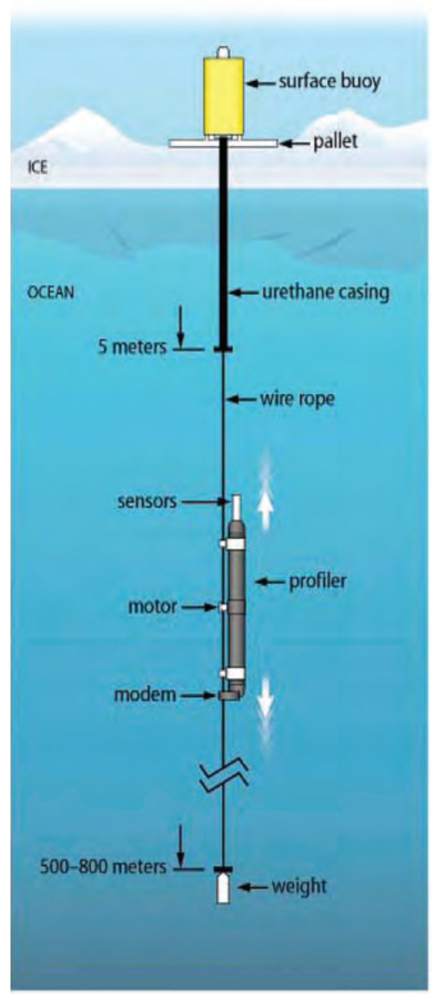


Figure 1. Schematic drawing of the ITP showing the major components.

the complete instrument in open water), a weighted, wire-rope tether extending down to 700-800 m, and a cylindrical profiling vehicle that moves up and down the tether carrying oceanographic sensors sampling the sea water properties. One-way profiles between the bottom of the tether and ~7 m depth are initiated on a pre-programmed schedule and the data from each profile are relayed to shore-side support computers in near-real time. Standard battery capacity is sufficient to occupy 1500-2000 vertical profiles. Given that all acquired data are telemetered to shore, the instrumentation may be considered expendable, but systems may be recovered if ship time is available. In the 2004-2008 period, a total of 30 ITP systems were deployed in the Arctic that collectively returned more than 20,000 temperature and salinity profiles (Figure 2). In addition, two ITP systems were recovered after 1 and 2 year deployments, respectively.

Recent developmental highlights include a redesign of the surface buoy to better survive thin ice and open water, and successful open water deployments of ITPs in the marginal ice zone. Dissolved oxygen data have been acquired from 5 ITP systems in addition to temperature and salinity observations. An initial effort to collect bio-optical sensor data from an ITP was not successful (ITP was crushed by sea ice before returning any profile data) but we are continuing to pursue collection of such data and implementing an innovative scheme for protecting the sensors from biofouling and acquiring reference data to track calibration drift. Most recently, we experimented with adding a current meter to the suite of sensors on the ITP.

In parallel to developing and refining the instrumentation, we created procedures to edit and calibrate the acquired data and make them widely available. Our various data products are described in detail on the project web site www.whoi.edu/itp. Final calibrated, edited data from the first set of ITP instruments has been released and submitted to the CADIS data archive; a second set of instrument data is nearly ready for formal distribution. Preliminary data are always available from the project web site in near-real time. To further facilitate data access (particularly by those running operational numerical models), we recently worked with NOAA personnel to have ITP data distributed on the GTS network

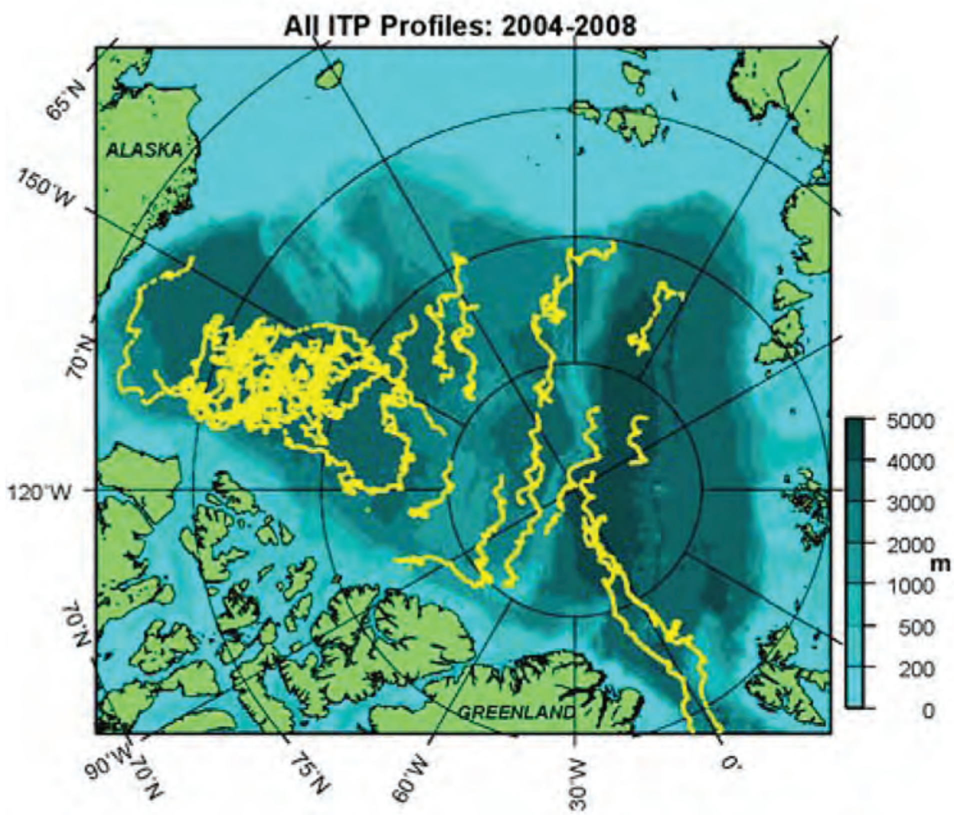


Figure 2: Location of temperature and salinity profiles acquired by ITPs in the period 2004-2008.Owing to the high spatial resolution of ITP observations, the dots marking each profile location appear as continuous lines.

and documented similar to how Argo float observations are cataloged.

Lessons Learned

Not to sound glib, but we believe the ITP project has been highly effective at coordinating with other AON projects in the U.S. as well as with observational programs based in Europe, Canada and Japan. Fully 1/3rd of the ITP systems fielded in the 2004-2008 period were funded by European collaborators. But regardless of funding source for the instrumentation, *all* ITP data route through our data servers and all of the observations are made available immediately. Deployments of ITP systems have occurred from Canadian, Russian and German ships as well as U.S./Russia ice camps. Instrument deployment sites have been coordinated with Japanese investigators who developed and are deploying a similar instrument system (the POPS – Polar Ocean Profiling System). Buoy locations are being tracked and displayed by the IABP (International Arctic Buoy Program) along with plans for future deployments.

Interactions with Collaborative Projects

Pursuant to the Ice-Based Observatory concept, several ITP systems have been deployed in conjunction with other buoy systems sampling the surface mixed layer, the sea ice and (less frequently) the surface meteorology and air chemistry. Specific examples include the Cold Regions Research and Engineering Laboratory Ice-Mass Balance (IMB) and the Scottish Association for Marine Science SIMBA buoy systems, the Naval Postgraduate School Autonomous Ocean Flux Buoy (AOFB) system, the National Oceanic and Atmospheric Administration drifting meteorological station as well as the University of Hamburg PAWS meteorological station, and the Optimare Ice-tethered Acoustic Current (ITAC) profiler with GPS mast. Data from clusters of these buoy systems provide data on the response of the upper ocean and sea ice to atmospheric forcing, key information for understanding the future evolution of the Arctic. The team leaders of each of these observational groups talk frequently and actively coordinate their respective deployments. These interactions developed organically without external direction.

Examples of Data Use

ITP data are being used to support scientific investigations, education, operational modeling and public outreach. Peer reviewed scientific papers utilizing ITP data are listed in the following section. In addition, ITP data are being used by AOMIP investigators (Arctic Ocean Modeling Intercomparison Project) to evaluate model fields and assess model representations of physical processes. To date, students in the U.S., Canada, Norway and Sweden have used ITP data in their dissertation work. Operational models operated by the U.S. Navy and groups in Norway and Russia are accessing ITP data for initialization/constraints and/or validation. ITP operations have been showcased by the "Live from the Poles" outreach activity as well as via numerous presentations at schools and science museums.

List of Publications

The ITP project web site is www.whoi.edu/itp. A partial bibliography of papers utilizing ITP data follows:

Jackson, J.M., E.C. Carmack, F.A. McLaughlin, S.E. Allen and R.G. Ingram. Identification, characterization and change of the near-surface temperature maximum in the Canada Basin, 1993-2008. *J. Geophys. Res.* In press, 2009.

Johnson, G.C., J.M. Toole and N.G. Larson, Sensor Corrections for Sea-Bird SBE-41CP and SBE-41 CTDs. *J. Atmos. and Ocean. Tech.,* 24, 1117-1130, 2007.

Krishfield, R., K. Doherty, D. Frye, T. Hammar, J. Kemp, D. Peters, A.Proshutinsky, J. Toole, and K. von der Heydt, Design and Operation of Automated Ice-Tethered Profilers for Real-time Seawater Observations in the Polar Oceans, WHOI-2006-11, 79 pp., 2006.

Krishfield, R., J. Toole, A. Proshutinsky & M.-L. Timmermans. Automated Ice-Tethered Profilers for seawater observations under pack ice in all seasons. *J. Atmos. Ocean. Tech*., 25, 2091-2095, 2008.

McPhee, M. *Air-Ice-Ocean Interaction: Turbulent ocean boundary layer exchangeprocesses,* Springer Science + Business Media B.V. ISBN 978-0-387-78334-5, 215 pp., 2008.

Newhall, R., R. Krishfield, D. Peters, and J. Kemp, Deployment Operation Procedures for the WHOI Ice-Tethered Profiler, WHOI-2007-05, 48 pp., 2007.

Simmons, V.T. Sokolov, M. Steele and J. Toole. Arctic Ocean warming contributes to reduced polar ice cap. Submitted to *J. Phys. Oceanogr.* 2009.

Proshutinsky, A., R. Krishfield, M. Timmermans, J. Toole, E. Carmack, F. McLaughlin, W. J. Williams, S. Zimmermann, M. Itoh, and K.Shimada. Beaufort Gyre freshwater reservoir: State and variability from observations, *J. Geophys. Res.*, 114, C00A10, doi:10.1029/2008JC005104, 2009.

Rabe, B., M. Karcher, J. Toole, U. Schauer, R. Krishfield, R. Gerdes, S. Pisarev, F. Kauker and T. Kikuchi. A first assessment of changes in the Arctic Ocean freshwater content from the 1990s to the IPY years. In preparation.

Smedsrud, L. H., A. Sorteberg, and K. Kloster. Recent and future changes of the Arctic sea-ice cover, *Geophys. Res. Lett.,* 35, L20503, doi:10.1029/2008GL034813, 2008.

Timmermans, M.-L., J. Toole, R. Krishfield, and P. Winsor. Ice-Tethered Profiler observations of the double-diffusive staircase in the Canada Basin thermocline, *J. Geophys. Res.,* 113, C00A02, doi:10.1029/2008JC004829, 2008.

Timmermans, M.-L., J. Toole, A. Proshutinsky, R. Krishfield, and A. Plueddemann, Eddies in the Canada Basin, Arctic Ocean, observed from Ice-Tethered Profilers, *Journal of Physical Oceanography,* 38(1), 133-145, 2008.

Toole, J., R. Krishfield, A. Proshutinsky, C. Ashjian, K. Doherty, D. Frye, T. Hammar, J. Kemp, D. Peters, M.-L. Timmermans, K. von der Heydt, G. Packard and T. Shanahan, Ice Tethered-Profilers Sample the Upper Arctic Ocean, *EOS*, Trans. AGU, 87(41) , 434, 438, 2006.

Toole, J.M., M.-L. Timmermans, D. K. Perovich, R. A. Krishfield, A. Proshutinsky, and J.A. Richter-Menge. Influences of the Ocean Surface Mixed Layer and Thermohaline Stratification on Arctic Sea Ice in the Central Canada Basin. Submitted to *J. Geophys. Res.*, 2009.

Relationships to International Arctic Observing Efforts

The ITP program has strong connections to the European Union DAMOCLES project, the UK Arctic Synoptic Basin-wide Oceanography and Scottish Association for Marine Science Ice Mass Balance Array (SIMBA) programs, and the Joint Western Arctic Climate Studies (a U.S./Canada/Japan activity) including the Beaufort Gyre investigation of freshwater anomalies.

The Pacific Gateway to the Arctic - Quantifying and Understanding Bering Strait Oceanic Fluxes

Funding from NSF-OPP and NOAA-RUSALCA

Rebecca Woodgate and Ron Lindsay (University of Washington, Seattle)

Tom Weingartner and Terry Whitledge (University of Alaska, Fairbanks)

Overview

Over recent years, various NSF and NOAA grants have supported the Bering Strait moorings.

Comparison of Water Properties and Flows in the U.S. and Russian Channels of the Bering Strait - 2005 to 2006, PI: Woodgate, ARC-0528632 - supported activities relating to mooring deployments in 2005 and recovery in 2006 and a comparison of water properties in the U.S. and Russian channels of the strait [*Woodgate et al.*, 2007]

IPY: COLLABORATIVE RESEARCH: The Pacific Gateway to the Arctic - Quantifying and Understanding Bering Strait Oceanic Fluxes, PIs: Woodgate, Weingartner, Whitledge and Lindsay, ARC-0632154 - supported activities relating to mooring deployments in 2007 and 2008 and recoveries in 2008 and 2009.

Collaborative Research: An Ocean Observing System for the Bering Strait, the Pacific Gateway to the Arctic - An Integral Part of the Arctic Observing Network, PIs: Woodgate, Weingartner, Whitledge and Lindsay, ARC-0855748 - is supporting activities related to upcoming mooring deployments in the strait (deployments in 2010, 2011, 2012 and recoveries in 2011, 2012 and 2013).

Since the first of these grants was complete in 2007, and the third of these grants is preparing for initial field work in 2010, we detail below results from the 2nd grant, the current IPY grant.

Project Summary

Extracts from Woodgate et al. [2008] NSF Annual Report

The Bering Strait, a narrow (~ 85 km wide), shallow (~ 50 m deep) strait at the northern end of the Pacific, is the only ocean gateway between the Pacific and the Arctic. Although the flow through the strait is small in volume (~ 0.8 Sv northward in the annual mean), due to its remarkable properties (high heat and freshwater content, low density, high nutrients) it has a startling strong influence, not only on the Chukchi Sea and the Arctic Ocean, but also on the North Atlantic overturning circulation and possibly world climate. Draining the Bering Sea shelf to the south, the Bering Strait throughflow is an integrated measure of Bering Sea change. The comparatively warm, fresh throughflow contributes ~ 1/3rd of the freshwater input and possibly ~ 1/5th of the oceanic heat input to the Arctic, and provides the most nutrient-rich waters entering the Arctic Ocean. Furthermore, the low density of these waters keeps them high in the Arctic water column, giving them a key role in upper ocean ecosystems and physical processes including ice-ocean interactions. At the time when dramatic change, especially the retreat of sea ice, is observed in the Bering and Chukchi seas and the Arctic, we measured significant increases of Bering Strait fluxes of volume, freshwater and heat, the heat flux in 2004 being the maximum recorded in the last 15 years up to 2004 [*Woodgate et al.*, 2006].

Yet, our understanding of what sets the properties and variability of the Bering Strait throughflow is still rudimentary. Indeed, our ability to measure these fluxes accurately has, in the past, been constrained by lack of data, both from the most nutrient-rich western half of the strait (which lies in Russian waters), and from the upper water column (due to potential ice-keel damage to instrumentation), where stratification and coastal boundary currents (especially the Alaskan Coastal Current in the eastern channel) contribute significantly to freshwater and heat fluxes.

This NSF project (teamed with ship-time and logistic support from the NOAA RUSALCA – Russian U.S. Long Term Census of the Arctic – project) addresses these deficiencies by providing (in collaboration with

Russian, Canadian and Japanese colleagues) an observationally focused study of the entire Bering Strait region, consisting of a high resolution mooring array, deployed from 2007-2009, covering the two channels of the strait and one "climate" site to the north of the strait, supported by annual CTD surveys and mooring servicing, satellite data, and theoretical and modeling results.

In August/September 2007, a joint U.S. (UW and UAF) and Russian mooring team deployed the first eight-mooring, high resolution array in the Bering Strait from the Russian vessel *Sever* [*Woodgate*, 2007]. Three moorings were deployed across the western (Russian) channel of the strait. Four moorings were deployed across the eastern (U.S.) channel of the strait. A final eighth mooring was deployed ~ 30 n mi north of the strait at a "climate site" occupied since 1990 and hypothesized to be a useful average of the flow through the strait. The eight sites are a combination of three sites established in the 1990s, three sites established since 2001/2004 and two new sites. Together they give the highest resolution to date in the Bering Strait. These moorings included six upward looking ADCP (Acoustic Doppler Current Profilers) to measure water velocity in ~ 2 m bins to the surface, and upper-layer temperature salinity sensors in ice-resistant housings (ISCATs). These are the first long-term moored upper-layer measurements made in the strait. Also, during the cruise, one high resolution CTD section was taken across both channels of the strait to give a spatial setting for the mooring data.

In October 2008, a joint U.S. (UW and UAF) and Russian mooring team recovered and redeployed these moorings from the Russian vessel *Lavrentiev* [*Woodgate*, 2008]. The mooring operations were successful, despite extreme biofouling, especially on the western mooring of the eastern channel. The lateness of the cruise (October rather than August) was dictated by changes in the ship schedule. We lost three days of ship time to bad weather, and returned to port early due to forecasts of extreme icing conditions. This reduction in operational time meant no high resolution CTD section was completed this year. Excitingly, this year's data returned the first year-round record of stratification in the Bering Strait. One ISCAT survived all year – the others recorded successfully until they were lost, presumably due to ice break up.

In August 2009, another joint U.S. (UW and UAF) and Russian mooring team, this time on the Russian vessel *Khromov*, recovered the final IPY mooring array, and replaced the same eight mooring with funding from NOAA-RUSALCA [*Woodgate*, 2009]. This year, three ISCATS (all in the eastern channel) returned a full year of data; the other two were again lost mid-winter. A further two high resolution CTD sections were completed on this cruise.

Science and Technical Highlights

2007 Bering Strait fluxes of volume and heat show record length highs

Extract of text and figure from Woodgate et al. [2010]

"Using year-round data from in situ moorings and satellite-sensed sea surface temperatures, we quantify oceanic fluxes of volume and heat from the Pacific to the Arctic via the Bering Strait between 1991 and 2007 with special focus on 1998 to 2007. We find heat flux increases almost monotonically from 2001 to 2007. Reflecting both high volume transports and high temperatures, the 2007 heat flux was the greatest recorded to date, 5-6 x 10^{20} J/yr (range reflecting uncertainty in depth of the summer surface layer). This is almost a doubling of the total 2001 heat flux and somewhat greater than the incoming solar energy into the Chukchi Sea. Moreover, the interannual variability in the Bering Strait heat flux is slightly larger than that of shortwave solar input to the Chukchi.

We suggest that PW flow (both in terms of the transport of ice and of far-field and locally gained heat) acts initially as a trigger for the onset of the seasonal melt back of ice, and subsequently may provide a year-round modest thinning of the western Arctic ice, as it feeds a subsurface temperature maximum under the ice pack in winter. Factors such as large interannual variability in heat flux, timing of the delivery of heat to the Arctic Ocean, and volume flux are also important. Overall, the Bering Strait's leverage on the Arctic system may be greater than its comparatively small volume may suggest.

The data suggest that change in volume flux, which drives about half of the change in heat flux, is due not just to varying winds but also to significant (> 0.2 Sv equivalent) variation in the large-scale pressure-head forcing between the Pacific and the Arctic. This suggests that estimating the flow from wind-data alone will underestimate flux variability. Similarly, sea-surface temperatures show more interannual variability than the temperatures of the bulk of the water column, suggesting that methods that are tightly coupled to SST may overestimate flux variability.

The oceanic heat that passes through the Bering Strait is solar in origin. Although in terms of delivery of heat to the high Arctic we must also consider solar input in the Chukchi, measuring the oceanic heat entering through the Bering Strait gives a useful boundary condition and is undoubtedly simpler and more accurate than assessing the heat budget over the Bering Sea to the south." (See Figures below.)

First ever year-round measure of stratification in the Bering Strait

Extract of text and figure from Woodgate et al., NSF Annual Report, 2008. Data recovered in 2009 yield three complete year-round records of stratification in the eastern channel of the Bering Strait but are not presented here.

"The figure shows preliminary results from the upper-layer ISCAT system on mooring A4 in the Alaskan Coastal current for the first 200 days of the deployment (Sept 2007 to ~ March 2008). Magenta indicates data from the ISCAT deployed at ~ 15 m. Black indicates data from the conventional Seabird temperature-salinity sensor at ~ 42 m depth. The top panel shows the depth of the instruments. Strong currents in early winter pull the ISCAT down to ~ 30 m. The bottom two panels show temperature and salinity data from both instruments. The upper layer is warmer and significantly fresher for some months in late summer – the difference in salinity is at times sizeable, about 4 psu. By January most of the stratification in the water column has gone. The next step is to quantify the contribution of this stratification to the estimates of fluxes for the entire strait.

Risk of damage from sea ice in the strait has prevented deployment of instruments in the upper layer in previous years. The ISCATs telemeter their data down to a logger at a safe depth, in case the temperature-salinity sensor is itself lost during the deployment. Of the six ISCATs deployed in the strait in 2007, only one ISCAT upper sensor survived the entire year, the other ISCAT upper sensors were lost at various times in early spring, likely relating to the break-up of ice. Yet, up to the time of loss, the telemeter system worked well and we have recovered the valuable data from the ISCATs up to the time of loss. For 2008, the ISCATs have been deployed uniformly ~ 2 m deeper, in an attempt to mitigate loss, but, the necessity of recording the upper layers means the instruments have to be placed in the ice-risk zone. Note that since the moorings are deployed in the summer, even if instruments are lost in the spring break-up of ice, before that loss they will record what is likely the time of greatest stratification in the strait, i.e., summer through to winter. The ADCP velocity data will also be used to assess stratification, by consideration of velocity shear. This information, combined with ISCAT data, will be used to quantify the importance and estimate the most cost-effective method of monitoring the upper layers."

AON Integration

As listed below, the Bering Strait mooring data is used by a variety of studies, both quantitatively and qualitatively. Often users are seeking monthly or weekly averages, and as these requests become common, we post files of this description on our website.

More formal collaborations exist within the NOAA-RUSALCA program, of which the moorings and CTD lines are an integral part. This is also an international collaboration with Russian partners. Through ASOF (Arctic Subarctic Ocean Fluxes) and other connections, we collaborate with studies in the Canadian Archipelago and the Fram Strait. A particularly exciting recent collaboration is with the AOMIP community, to compare observational results with modeling studies.

Examples of Data Use

Metadata for all the Bering Strait moorings have been deposited at CADIS (Cooperative Arctic Data and Information System). All calibrated mooring data have been archived at the National Ocean Data Center, are available via our website (http://psc.apl.washington.edu/BeringStrait.html) and are cross linked with CADIS. Bering Strait data have been used in various

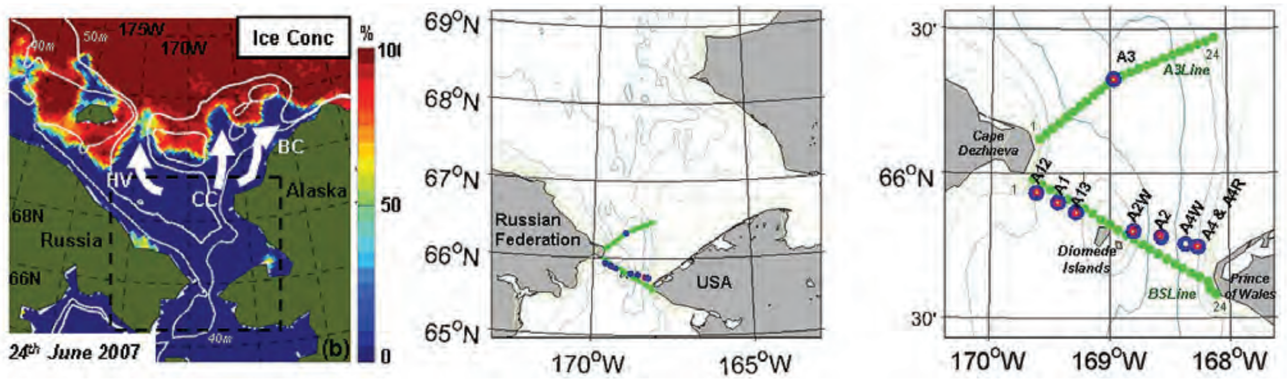


Figure 1: (Left) Chukchi Sea AMSR-E sea ice concentration, with schematic topography, showing how the ice edge is marked by the three main water pathways through the Chukchi (white arrows) via HV, Herald Valley; CC, Central Channel; and BC, Barrow Canyon. Figure from Woodgate et al. [2010].

(Middle and right) Map of the Bering Strait region and detail of the strait showing Khromov RUSALCA 2009 Leg 1 CTD sites (small green dots) and 2009 mooring locations. Blue dots with red center indicate a site of recovery and deployment. Blue dot indicates deployment only. Depth contours are every 10 m. Figure from Woodgate [2009].

research areas including non-physical oceanography and areas beyond oceanography, such as biological studies of seabirds and mammals. Voluntary registration at our data site (at times averaging 30-50 registrations a month) shows the data are in demand for work ranging from climate modeling to king crab fishing, including a wide variety of studies covering local, Arctic and global subjects (North Pacific, Gulf of Alaska, Bering Sea, Chukchi Sea, Arctic Ocean, Arctic Ocean outflows, North Atlantic), with topics including ocean circulation; multidisciplinary shelf-basin exchange; eddy processes; benthic-pelagic coupling; ocean sedimentation; hydrology; heat, freshwater and nitrogen budgets; biogeochemistry, including CDOM, POC, and PIC; modeling and observational studies of present-day, future and paleo conditions, including analysis of sediment cores; future climate predictions (including Arctic and Atlantic meridional overturning circulation investigations); present-day and paleo climate stability; recent studies of accelerated retreat of Arctic sea ice; changes in the fate of Pacific water in the Arctic; and ecosystems and ecosystem change, including effects on algae, plankton, euphasiids, seabirds, grey and bowhead whales.

The moorings also provide a potential logistics platform for other projects. In the past the moorings have carried water sampling devices and various bio-optics systems. In summer 2009 whale acoustic sensors were deployed on the moorings by Kate Stafford (UW) under separate funding. We are in discussions to include pCO_2 sensors on future versions of the moorings.

Broader Implications

By providing an improved evaluation of the Bering Strait fluxes, this project will contribute to local, Arctic and global studies.

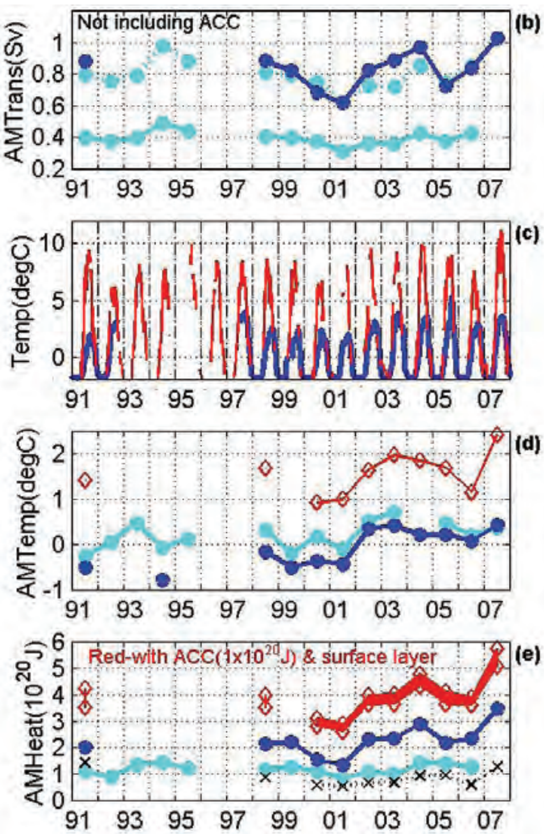
Most topically, with the startling retreat of the Arctic sea ice, quantifying the heat flux through the Bering Strait and the impacts of the Bering Strait throughflow on Arctic stratification become urgent issues in the quest to understand causes of Arctic sea ice retreat.

Within regional oceanography, the work provides vital information for physical, biological and biogeochemical studies within the Bering Strait and Chukchi Sea, since the physical oceanography of the Chukchi Sea is dominated by the properties of the Bering Strait throughflow. Since the Bering Strait is fed from the south, the Bering Strait throughflow is also some indicator of conditions on the Bering Sea shelf, an economically important zone for U.S. fisheries and the focus of the NSF BEST (Bering Ecosystem Study) Program.

The Bering Strait throughflow is also the Pacific input to the Arctic Ocean, which is important for maintaining the Arctic Ocean halocline and providing nutrients for Arctic ecosystems. The Pacific inflow also brings heat into the Arctic. The fate of Pacific waters in the Arctic (especially their ventilation depth) relates to their density which is, to a large extent, set by the time the waters traverse the Bering Strait.

Globally, the Bering Strait throughflow is an important part of the global freshwater budget. Models suggest that an increase in the Bering Strait freshwater flux may weaken the Atlantic meridional overturning circulation. Other modeling studies count the Bering Strait flow as critical for the stability of world climate.

Thus, a better observational estimate of the Bering Strait flow and its variability is critical for a wide range of studies.



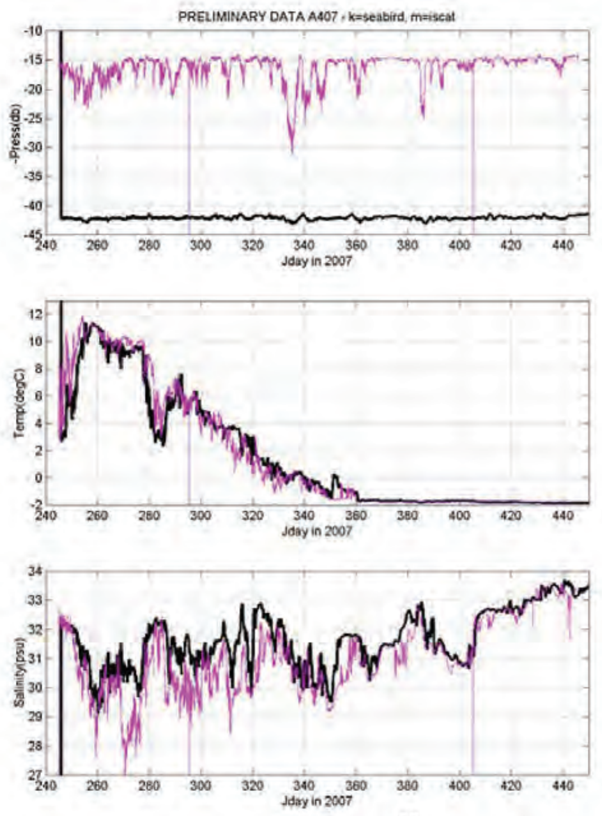


Figure 2 (Left): Bering Strait time-series from 1991-2007. Uncertainties are ~ 0.1 Sv, 0.8 x 10^{20} J/yr. (b) Annual mean (AM) transports (not including the Alaskan Coastal Current (ACC), ~ 0.1 Sv) – blue, total from A3; dashed cyan, total from A2; solid cyan, eastern channel transport only from A2. (c) Temperatures – blue, 30-day smoothed A3 near-bottom; red, 7-day average AVHRR-SST. (d) AM temperature– blue, A3 near-bottom; cyan, A2 near-bottom; red, SST near A3. (e) AM heat fluxes – cyan, from A2 for eastern channel only; blue, total from A3 data only; red area, total including ACC correction (~ 1 x 10^{20} J/yr) and a 10 m (lower bound) or 20 m (upper bound) surface layer. Black crosses, amount of heat added by a 20 m surface layer. Figure from Woodgate et al. [2010]

(Right) Preliminary results from the upper-layer ISCAT system on mooring A4 in the Alaskan Coastal current for the first 200 days of the deployment (Sept 2007 to ~ March 2008). Magenta indicates data from the ISCAT deployed at ~ 15 m. Black indicates data from the conventional Seabird temperature-salinity sensor at ~ 42 m depth. The top panel shows the depth of the instruments. Strong currents in early winter pull the ISCAT down to ~ 30 m. The bottom two panels show temperature and salinity data from both instruments. The upper layer is warmer and significantly fresher for some months in late summer – the difference in salinity is at times sizeable, about 4 psu. By January most of the stratification in the water column has gone. Figure from NSF annual report.

Publications and Web Site

- Our Bering Strait website is at: **http://psc.apl.washington.edu/BeringStrait.html**. This contains links to data, cruise reports, papers, and information for the general public, and a page dedicated to the Bering Strait IPY project at: **http://psc.apl.washington.edu/HLD/Bstrait/IPYbstrait.html**

Annual Cruise Reports, available via our web site

- 2005 cruise on the Canadian Vessel *Sir Wilfrid Laurier* [*Woodgate*, 2005]
- 2006 cruise on the Canadian Vessel *Sir Wilfrid Laurier* [*Woodgate*, 2006]
- 2007 cruise on the Russian Vessel *Sever* [*Woodgate*, 2007]
- 2008 cruise on the Russian Vessel *Lavrentiev* [*Woodgate*, 2008]
- 2009 cruise on the Russian Vessel *Khromov* [*Woodgate*, 2009]

Technical Reports

- 2007 report studying the use of A3 as a "climate station" for the Bering Strait [*Woodgate et al.*, 2007].
- Contributions to the NOAA State of the Arctic Annual Report.

Journal Articles

- On Bering Strait freshwater fluxes [*Woodgate and Aagaard*, 2005]
- On Bering Strait monthly climatology [*Woodgate et al.*, 2005]
- On Bering Strait interannual variability [*Woodgate et al.*, 2006]
- On the fresh and salt water balance for the Bering Strait [*Aagaard et al.*, 2006]
- On Bering Strait heat fluxes in 2007 [*Woodgate et al.*, 2010]
- Considering heat flux estimates from satellite data [*Mizobata et al.*, submitted]
- Considering model-data intercomparison for 2007 [*Zhang et al.*, submitted]
- Using Bering Strait and Chukchi data for variational data assimilation [*Panteleev et al.*, accepted]
- Numerous conference presentations/lectures, including presentations at: NOAA, DAMOCLES (Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies) meeting, the Gordon Research Conference, ASOF (Arctic Subarctic Ocean Fluxes) meetings, ESSAS (Ecosystem Studies of Sub-Arctic Seas), AON (Arctic Observing Network) meetings, RUSALCA meetings (Russian-American Long-Term Census of the Arctic), and at the AOMIP (Arctic Ocean Model Intercomparison Project) meeting.

In addition, Bering Strait results contributed to public outreach at the Polar Science Weekends at the Pacific Science Center in Seattle; Arctic Adventure, a UW evening lecture series; and UW classes taught by Woodgate on the Changing Arctic Ocean, and contributions to Careers in Oceanography (Ocean 500) and Technology for Oceanographic Research (EE 500G).

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Appendix C: AON Project Reports – Hydrology/Cryosphere

Arctic Great Rivers Observatory (Arctic-GRO)

PI: Bruce Peterson (Marine Biological Laboratory)

Co-PIs: Max Holmes (Woods Hole Research Ctr.), Jim McClelland (UT Austin), Peter Raymond (Yale), Rob Striegl (USGS)

Postdoc: Suzanne Tank (Marine Biological Laboratory)

Participants: Alexander Zhulidov (CPPI-S, Russia), Robin Staples (INAC, Canada)

Project Summary

The riverine linkage between land and the Arctic Ocean plays a central role in the rapidly evolving dynamics of the arctic system. The Arctic Great Rivers Observatory (Arctic-GRO) project measures the flux of water-borne constituents in six Great Arctic Rivers: the Ob', Yenisey, Lena, Kolyma, Yukon, and Mackenzie (Fig. 1). Together, these rivers deliver the majority of the continental fresh water to the Arctic Ocean, the most landlocked and freshwater dominated of the Earth's seas. Arctic-GRO measurements are conducted at downstream locations that capture the vast majority of runoff from the major arctic watersheds, in the same manner as Arctic-GRO's antecedent, PARTNERS, which was the first comprehensive study of riverine fluxes to the Arctic Ocean. Our observations are being used to test hypotheses about the magnitude, controls and ecological significance of riverine input to the Arctic Ocean, and will provide new information on inter-annual variability and trends in these fluxes.

Monitoring the Great Arctic Rivers is critical for understanding environmental change in the Arctic, a goal of SEARCH. Sampling large rivers near their mouth provides one of the most efficient ways to assess changes occurring across vast continental regions that may diagnose environmental change on land and forecast imminent changes in circulation and biogeochemical processes in the Arctic and North Atlantic Oceans. One example is the measured increasing trend in Siberian river discharge over the past several decades. While this almost certainly indicates recent changes in constituent fluxes, data are not yet adequate to assess trends in water chemistry. Additionally, land-ocean fluxes play an important role in the three major feedbacks from

Fig. 1: The six great Arctic rivers. Red circles indicate sampling locations.

the Arctic to the global climate system; affecting sea ice extent and albedo through inter-annual variability in discharge, trace gas feedbacks through transport of dissolved gases and organic carbon, and ocean circulation through trends in freshwater inputs to the Arctic and North Atlantic Oceans. Although models of the climate, hydrology and biogeochemistry of the Arctic atmosphere-land-ocean system must include land-ocean linkages, these data are currently sparse at best.

Arctic-GRO takes advantage of existing international collaborations and infrastructure that have been developed over the last decade, and is based upon strong scientific collaborations among U.S., Canadian and Russian scientists with experience in arctic hydrology, biogeochemistry, ecology and global change. The Arctic-GRO also represents a major component of the Arctic Circumpolar Coastal Observatory Network (ACCO-Net), an overarching IPY initiative designed to link key coastal erosion monitoring sites established as part of the International Arctic Coastal Dynamics project with major arctic river sampling sites established as part of the NSF Freshwater Integration study. All data collected will be freely available through the Cooperative Arctic Data and Information Service (CADIS).

Science Highlights

Samples from Arctic-GRO year 1 (2009) are still being collected, shipped and analyzed. The scientific value of Arctic-GRO can be illustrated in part by highlighting some results from the PARTNERS project. Select PARTNERS and Arctic-GRO publications are listed in Section 6.

- When considering a suite of 20 constituents, each of the Great Arctic Rivers has a **unique biogeochemical composition** that distinguishes it from the others (McClelland et al. 2008).
- Differences in constituent signatures between rivers can be used as **freshwater tracers** to elucidate hydrologic processes within watersheds and trace water from these rivers as it circulates through the Arctic Ocean. These include oxygen and hydrogen isotope ratios (Cooper et al. 2005, Cooper et al. 2008), uranium isotope ratios (Andersen et al. 2006, 2007), and the rare earth elements hafnium and neodymium (Zimmermann et al. 2009).
- The **radiocarbon ages** of dissolved organic carbon (DOC) vary among the large rivers and vary systematically over the annual cycle (Raymond et al. 2007).
- Fluxes of **DOC** are larger than published estimates because previous studies undersampled early season discharge. Early season DOC is more labile than DOC collected later in the season or under ice. A new paradigm for the land-ocean carbon cycle in the Arctic is emerging (Cooper et al. 2005, Raymond et al. 2007, Holmes et al. 2008).
- The rivers contain overlapping **microbial communities** that shift seasonally but recur every year. These persistent communities can be fingerprinted genetically and may provide an early indication of changes in catchments as well as possible genetic tracers of river water in ocean circulation and mixing (Crump et al., in press).
- Recent synthesis efforts have produced **new estimates of riverine nutrient fluxes** to the Arctic Ocean (Fig. 2, Holmes et al. in prep.) and are assessing the importance of these fluxes to the biological functioning of Arctic shelves and seas (Tank et al. in prep.)

Lessons Learned

It has proven difficult to work on aspects of the project in Russia because of the permissions and permits that must be obtained often a year or more in advance for sample collection and transport. Our field program in Russia has been successful in spite of these obstacles, but we are considering a future strategy that would minimize transport of samples back to the United States by using improved analytical capabilities at the Northeast Science Station in Cherskiy.

Linkages with Other Projects

As an intermediary between land and ocean, Arctic-GRO links naturally with catchment mass balance studies, coastal erosion studies, and coastal and open ocean budget and circulation studies. Much could be gained

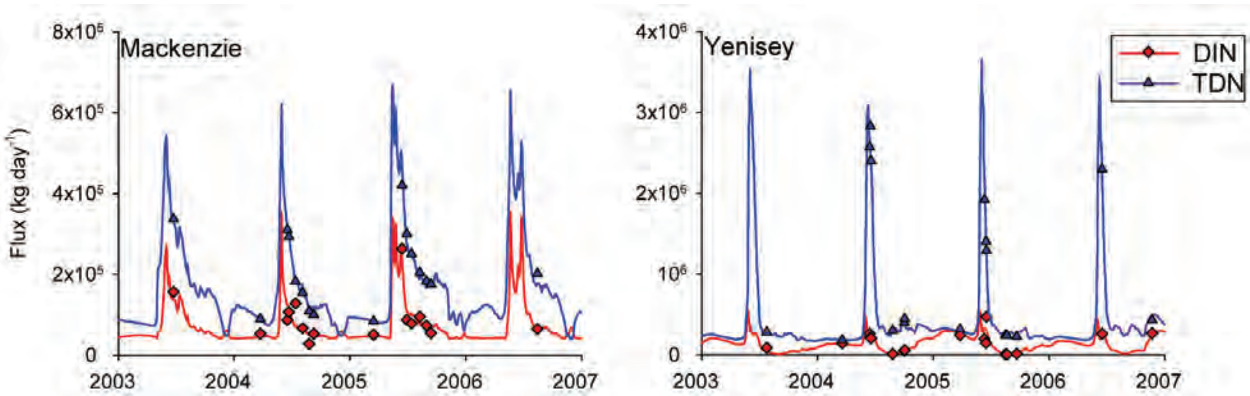

Fig. 2: Estimated fluxes of dissolved inorganic nitrogen (DIN) and total dissolved nitrogen (TDN) from two of the six Great Arctic Rivers, shown for the time span of the PARTNERS project. Fluxes are estimated using the USGS LoadEstimator program, using measured river discharge and constituent concentrations. Measured fluxes of DIN and TDN are shown as red diamonds and blue triangles, respectively. Estimated full-year fluxes are shown as red and blue lines for DIN and TDN, respectively.

from meetings with AON projects that focus on either watershed or ocean processes and could incorporate export or input biogeochemical fluxes into their work.

Activities and Connections: An Example

The PARTNERS data set is being used on an ARCSS Synthesis (SASS) project (McGuire-lead PI) to link continental water and carbon export with the Terrestrial Ecosystem Model (TEM) and the MIT ocean model to achieve closure in the Arctic/Subarctic atmosphere-continental-ocean carbon budget.

Project Data Use and Outreach

Project data use for science is illustrated in sections above. Arctic-GRO is one of only a handful of projects that involves multiple sampling trips to multiple sites in multiple arctic nations, and thus provides an extraordinary opportunity to develop a pan-arctic community of educators and learners. Arctic-GRO efforts focus on involving K-12 students, their teachers, and community leaders at the study sites, as well as students, teachers, and the general public outside of the Arctic in the excitement of northern research. These efforts build on community collaborations that were initiated during the PARTNERS Project and expanded in the IPY Student Partners Project. A great diversity of students have and will be involved in this work, both inside and outside of the Arctic.

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Relation to Other Observatories

Arctic-GRO is one of several arctic projects committed to making measurements at the Northeast Science Station in Cherskiy, which is located next to the Kolyma River ~130 km upstream from the East Siberian Sea. Tiksi, near the mouth of the Lena River, has also been selected as a core observatory site supporting activities of multiple projects through a partnership between the Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet), NOAA, and NSF. Tsiigehtchic, on the Mackenzie River, is the site of ongoing monitoring and research efforts through the Canadian IPY initiative.

Dynamic Controls on Tidewater Glacier Retreat

OPP 0732726
PIs: W.T. Pfeffer, S. O'Neel, I. Howat

Project Summary (adapted from NSF reports)

We are studying the ongoing and historical changes in dynamics at the ocean-terminating and rapidly retreating Columbia Glacier, in Prince William Sound, on the south-central Alaskan coast. Net mass loss from Alaskan glaciers is estimated to be ca. 80-130 GT/yr for ca. 2003-2008 [Figure 1; compare to the entire discharge of the Greenland Ice Sheet at ca. 267 GT/yr (Rignot, 2008)]. Columbia Glacier discharges ca. 4-7 GT/yr to the ocean, and is the only ocean-terminating glacier in Alaska with a long-term record of discharge, and one of the few glaciers in Alaska with any long-term measurement program of any kind. Ocean-terminating, or tidewater, glaciers (TWGs) also merit special attention because they are among the most strongly non-linear dynamic glacier systems in the world, and provide valuable information for understanding dynamic changes on ice sheet outlet glaciers.

Our work continues the acquisition of an unmatched 30-year record of photogrammetrically-determined surface topography and velocities (achieved with vertical photography and continuous ground-based time lapse observations). We are also conducting a variety of ground-based experiments, including seismic observations of calving, high-rate time lapse observations of calving, high-rate GPS and optical survey measurements of surface speed, laser scanning of the calving front, and meteorological observations. Finally, we are collecting and organizing the 30-year record of aerial photography and photogrammetry for archival at CADIS/NSIDC. Preparation for archival includes the collection of the original film and diapositive media in a single location (these were previously held in Boulder, Colorado, Tacoma, Washington, and Fairbanks, Alaska, with no comprehensive index), photogrammetric scanning of film and diapositive media, and reconstruction or recalculation of exterior orientation of the imagery for photogrammetric calculations. Collaborators in this work include Ed Josberger (USGS, Tacoma, WA), Yushin Ahn (Ohio State University), David Finnegan (CRREL, Hanover, NH) and Jacek Jania (University of Silesia, Poland).

Aerial Photogrammetry

An archive of vertical photography consisting of 129 flights covering the lower ~15 km of Columbia Glacier during the period 1977-2004 and housed at INSTAAR and the USGS office in Tacoma has been compiled and prioritized for scanning. (Eight additional flights since 2004 were scanned at the time of acquisition.) So far, over 200 air photos from 1977–1989 have been scanned photogrammetrically. Postdoctoral scholar Yushin Ahn (Ohio State University) has begun working on aerotriangulation and orthorectification of image models in preparation for digital elevation model (DEM) production and eventually velocity field derivation by autocorrelation feature tracking. To date all recent imagery (>2004) has been processed and historical imagery for which ground control data were available is also complete. Some control has been lost from the early imagery, and we are developing new methods to reprocess these images using known control from other time periods. This unanticipated problem has delayed results. Improvements to Matlab based feature tracking software are underway, including image enhancement and surface fitting for sub-pixel accuracy. Geospatial data from these efforts is being quality checked for consistency (especially in reference frames) and prepared for archival at CADIS/NSIDC. Modern margins have been extracted and a first order estimate of above sea-level volume change was estimated. Columbia Glacier has lost nearly 150 km^3 of ice since the retreat began in the early 1980s.

Terrestrial Photogrammetry

We have also developed new methods for reducing labor during oblique imagery photogrammetric processing. A more user-friendly data reduction process has been developed that includes cross-correlation image registration. Over 300 images of the terminus region of Columbia have been analyzed for short-term changes in geometry. Early results were presented at the Fall 08 AGU meeting. A PhD student, Ethan Welty, has begun at CU Boulder and his studies will focus on oblique time-lapse photogrammetric methods. In collaboration with Extreme Ice Survey (J. Balog), we have serviced three time-lapse cameras that have run quasi-continuously since 2007, and installed five additional cameras at different locations on the glacier in May and August 2009.

Meteorological Observations

A satellite-telemetered weather station was deployed at ca. 1000 m elevation in collaboration with David Finnegan (USACE-CRREL). This station is one of the only real-time weather stations in a mountain location in south-central Alaska.

Telemetered GPS

A lightweight, disposable GPS system was tested at the glacier in spring 2009. This successful experiment showed it is possible to telemeter GPS positions back to the margins and record motion in regions where instrument loss has prohibited GPS work in the past. Results show that the terminus region continues to exhibit rapid flow speeds on the order of 15 m/d.

Seismology

A single broadband seismometer was re-installed at a near-terminus site used in previous work for observations of iceberg calving using detection filters developed by us in 2004-2005. Optical surveys of terminus motion were made, which show that the terminus region has now gone afloat after retreating through the Kadin-Great Nunatak constriction. Patterns of seismicity have also changed radically, showing a 50% overall decrease in seismicity associated with calving, although the calving rate remains high. Time lapse photography is being used to constrain mechanical processes involved in iceberg calving by using rapid image acquisition with precise timing. Our efforts have documented several extremely large calving episodes where the entire floating portion of the glacier has calved off within the standard interval for routine timelapse imagery (0.3-0.5 hour). While the photographs have documented a substantial increase in characteristic calving event size, seismic energy release has decreased, suggesting either a change in mechanics or a change in coupling of the energy with the solid earth. Figure 1 shows that the distribution of event duration has shifted, with shorter, smaller events becoming the norm, even as the terminus retreat accelerates. Changes in seismicity are being addressed by post-doctoral scholar Fabian Walter (Scripps Institute of Oceanography) who is analyzing data from several glacier seismicity projects. An invited talk will be presented at Fall 09 AGU meeting and a paper on these results is in preparation.

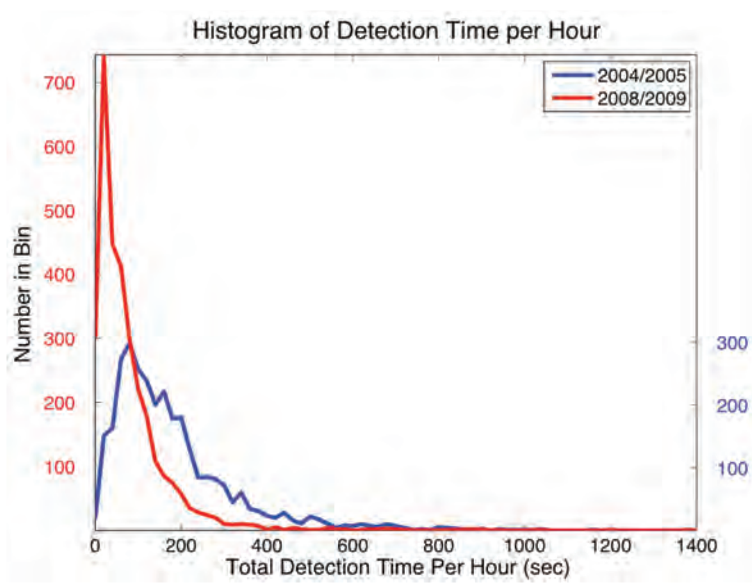

Figure 1. Calving detections per hour

Collaborative Modifications

- Salary support for CO-I O'Neel from USGS global change program
- Comparison of tidewater advance/retreat with seismic and image data via collaborations with NSF EAR 0810313 (AGU 09 presentation by O'Neel et al.)
- Weather station collaboration with CRREL Flood & Coastal Storm Damage Reduction, Emergency Management Technologies Research Program
- GPS collaboration (JPL)
- Postdoctoral efforts (Fabian Walter, supported by NSF 0739769)
- Time-lapse collaborations with Extreme Ice Survey

Presentations, Publications and Outreach

Several presentations have been given (AGU San Francisco 2008; Midwest Glaciology, 2008; Northwest Glaciology 2008; USGS Alaska Science Center, 2009; Geological Society of America, 2009; Northwest Glaciology, 2009, NASA Sea Level Workshop, Austin, Texas, 2009; University of Washington, January 2010; USFS Chugach Forest Leadership Team, February 2010). A recent paper titled "Kinematic constraints on 21st century sea level rise," was published in *Science* using some ideas from this project. One paper is in preparation at this time, and close to submission (Iceberg calving during transition from grounded to floating ice: Columbia Glacier, Alaska; Walter et al.)

Outreach projects have been supported by supplementary funds from NSF/DRL Informal Science Education ($75,000, NSF Grant #0741610) and NSF/EAR Geomorphology ($75,000, NSF Grant #0731541). These grants supported the construction of the first time lapse cameras for the Extreme Ice Survey (www.extremeicesurvey.org) and video processing for the NOVA television production "Extreme Ice" documenting glacier changes at Columbia Glacier and elsewhere. Further outreach has been coordinated with EIS to disseminate time-lapse imagery, and make public presentations (principally by EIS leader James Balog). Other presentations, contacts and collaborations have been made with the following organizations:

- The Climate Project
- World Wildlife Fund (WWF)
- National Ecological Observatory Network (NEON)
- Alaska Conservation Foundation
- American Chemical Society
- Norwegian Polar Institute
- Alliance for Climate Education
- Southwest Alaska Conservation Coalition
- NASA
- COP 15 Climate Congress, Denmark, 2009

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Science Crossover Activities

Geophysical Institute, University of Alaska, Fairbanks and USGS Alaska: Chris Larsen and Shad O'Neel. As part of a multi-discipline study in Icy Bay, Alaska, EIS provided three time-lapse camera systems and technical support to the research team. Chris Larsen and Shad O'Neel from USGS were the main collaborators and carried out all fieldwork on site.

Tuatara Systems: Corey Jaskolski. Continuing the development of the customized EIS Controller, used to trigger the time-lapse cameras, EIS and Tuatara worked closely together to put out improved units in the field in 2009.

U.S. Army Corp of Engineers, Cold Regions Research and Engineering Lab: David Finnegan. Working in Alaska, David Finnegan installed two EIS camera systems at Hubbard Glacier as part of an ongoing study of the advancement of the Hubbard terminus in relation to the village of Yakutat.

Massachusetts Institute of Technology, Computer Science and Artificial Intelligence Lab (CSAIL). EIS is currently developing a relationship with CSAIL to provide time-lapse imagery from Iceland as part of a research project aiming to investigate techniques for decomposing time-lapse videos into different motion frequencies, while trying to isolate those different kinds of motions in order to appropriately show the viewer events of different rates and timescales.

Luc Moreau, French Glaciologist. Continuing the EIS repeat photography work in the European Alps, Luc shot Trient Glacier in Switzerland in the summer of 2009. More information on Luc may be found at: http://moreauluc.site.free.fr/homepage_038.htm.

University of Washington Applied Physics Laboratory, Ian Joughin. EIS paired with Ian Joughin to continue his ongoing research of supra-glacial melt features and moulin formation on the Greenland Ice Sheet.

The City College of New York, Marco Tedesco. EIS teamed up with Marco Tedesco in the summer of 2009 for a research and photography trip to the Greenland Ice Sheet. EIS provided extensive experience and knowledge to carry out fieldwork on the ice sheet, along with deploying multiple short-term time-lapse camera systems during the trip.

CIRES, Konrad Steffen. EIS provided a time-lapse camera package and technical training to Liam Colgan and Dan McGrath, graduate students at CIRES at the University of Colorado. This team installed the camera on the Greenland Ice Sheet northeast of Ilulissat. The aim was to capture the formation of a supra-glacial melt channel and moulin system. This goal was attained in the summer of 2009, and the team is set to deploy the camera again in the summer of 2010.

Fit of Project into Broader Context of AON

Our work at Columbia Glacier is unusual in being the only project within AON involving glacier dynamics. Clear opportunities for collaboration and data sharing across projects exist through 1) freshwater discharge into Prince William Sound and the Gulf of Alaska, 2) contributions to the larger problem of land ice losses from Alaska (see Fig. 2), and 3) the use of Columbia Glacier data to inform glacier dynamics modeling of marine-terminating glaciers across the circumpolar Arctic, including Greenland.

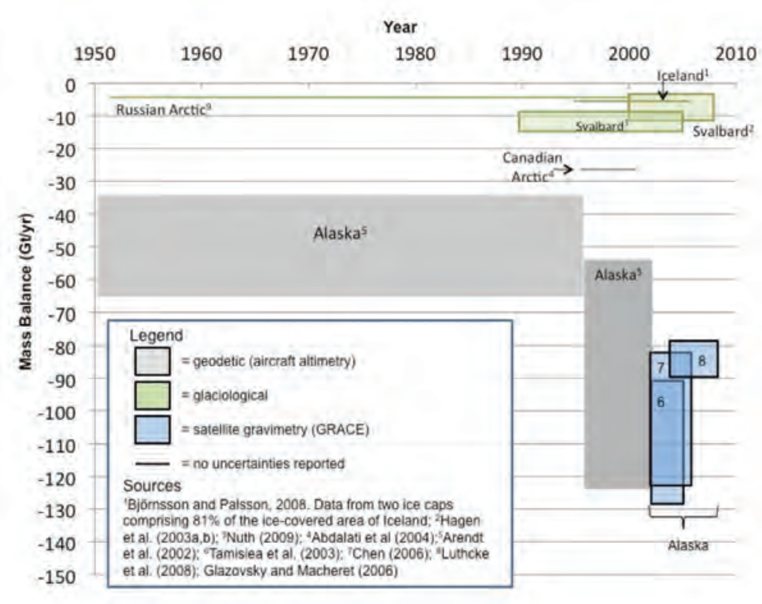

Figure 2. Mass loss rates for Arctic glaciers and caps, including Alaska, showing acceleration of losses ca. 1995–present.

Development of a Network of Permafrost Observatories in North America and Russia: The U.S. Contribution to the International Polar Year

PI: Vladimir E. Romanovsky
Geophysical Institute, University of Alaska Fairbanks

Project Summary

The thawing of permafrost that is already occurring at the southern limits of the permafrost zone can generate dramatic changes in ecosystems and in infrastructure performance. There exists no global database that defines the thermal state of permafrost within a specific time interval. This project provides the U.S. contribution to the International Polar Year *Thermal State of Permafrost (IPY/TSP)* project that measures temperatures in a large number of globally distributed boreholes in order to provide a "snapshot" of permafrost temperatures in both time and space. The Alaskan and Russian borehole temperature data sets will also provide the baseline to reconstruct past surface temperatures, to assess the future rates of change in near-surface permafrost temperatures and permafrost boundaries, and to provide spatial data for validation of climate scenario models and temperature reanalysis approaches.

Project Goals

The overarching goal of our research is to obtain a deeper understanding of the temporal (interannual and decadal time scales) and spatial (north to south and west to east) variability and trends in the permafrost temperatures in the North of Eurasia and Alaska to develop more reliable predictive capabilities for the projection of these changes into the 21st century.

To achieve this goal the following tasks were proposed:

1. Obtain standardized temperature measurements in permafrost regions of Alaska and Russia
2. Work towards establishing a sustainable network of boreholes for long-term temperature observation in Russia and Alaska
3. Develop a joint Alaska-Russian permafrost temperature database and report initial results at the Ninth International Conference on Permafrost (NICOP) (June 2008, Fairbanks)

Development of Borehole Network for Permafrost Temperature Observations

Objective 1:

Upgrade, maintain and acquire data from the Alaskan network of permafrost observatories.

During the time of the project, temperature has been measured in all Alaskan boreholes with the long-term continuous records that go back to the late 1970s. In addition, measurements were resumed in seven existing deep boreholes where observations were discontinued in the 1980s. Twelve new permafrost boreholes were added to the existing network during the IPY time frame.

Objective 2:
Develop a sustainable network of permafrost observatories in Russia and participate in the acquisition of a comparable set of data from regional observatories in Russia.

To achieve this objective the following work was performed:

a. Collaboration with partners in Russia. Memorandums of agreement were signed with 11 Russian partners' organizations representing the Russian Academy of Sciences, Russian universities and industrial organizations at the level of Directors of these organizations.

b. Protocol of geothermal measurements development. To standardize all investigation within the frame of the project, the "Manual for monitoring and reporting data permafrost borehole temperatures" was developed. It allows better permafrost data collection and interpretation. This protocol was discussed among all participants and the final version was produced.

c. Boreholes inventory and instrumentation. A large number of existing boreholes have been identified for possible measurements ("candidate sites"). Currently the observational network includes 194 boreholes situated in Alaska (63); European Russia (46); Western Siberia (35); Northern (13), Central (7) and Southern (12) Yakutia; Baikal region (10); Chukotka and Magadan region (3) and Kamchatka (5). Most of the boreholes (154) are less than 30 m deep (surface, shallow or intermediate according to GTN-P classification) and instrumented for continuous observations. Some of them (40) are 50 – 200 m deep and measured once or twice per year. Additionally, 155 shallow boreholes (less than 10 m deep) were instrumented near many schools in Alaska as a part of the Permafrost Outreach Program.

Results of measurements are available for download from the Cooperative Arctic Data and Information Service (CADIS) website: http://www.aoncadis.org/

Objective 3:
Encourage the development of a new generation of arctic researchers and permafrost specialists.

Several young scientists (postdoc, PhD and undergraduate students) are involved in our research both at the UAF and in Russian partners' organizations.

Conclusions

Based on the comparison of historical and recently obtained data the following conclusions can be made:

- Most of the permafrost observatories in Russia and Alaska show substantial warming of permafrost during the last 20 to 30 years (Figures 1 and 2). The magnitude of warming varied with location, but was typically from 0.5 to 2°C at the depth of zero annual amplitude.

This warming occurred predominantly between the 1970s and 1990s. There was no significant observed warming in permafrost temperatures in the 2000s in most of the research areas; some sites (especially in the Alaskan Interior) even show a slight cooling during the late-1990s and early-2000s and then in 2006-2009. Warming has resumed during the last one to two years at some locations, predominantly along the Arctic Ocean coasts both in Alaska and in Russia.

- Considerably less or no warming was observed during the same period in the north of East Siberia.

Permafrost is already thawing in specific landscape settings within the southern part of the permafrost domain in the European North, in northwest Siberia, and at some locations in interior Alaska. Formation of new closed taliks and an increase in depth of pre-existing taliks has been observed in this area during the last 20 to 30 years.

- Permafrost temperature reanalysis provides a valuable tool to study past changes in permafrost temperature, which helps to place recent changes into a long-term perspective.

An implemented spatially-distributed permafrost model shows that if warming in air temperatures continues to occur as predicted by most climate models, widespread thaw of late-Holocene permafrost may be in progress by the mid-21st century. If warming continues, some Late Pleistocene permafrost will begin to thaw by the end of the 21st century.

Education and Outreach Activities

This project provides the opportunity for development of the career of postdoc A. Kholodov and PhD student E. Jafarov. We also recruited one undergraduate student who is involved in this project. Our collaborators in Russia, Mongolia and Kazakhstan also provide for a broad participation of young researchers (under- and graduate students, postdocs). The Permafrost Monitoring outreach program established long-term permafrost and active layer monitoring sites adjacent to schools in Alaska and in the circumpolar permafrost region. Monitoring stations in Alaska are located in communities within the permafrost regions such as Kotzebue, Nome, Fairbanks, Eagle, Circle, Northway, Glennallen and others. Currently, there are 108 schools in Alaska involved in the project. The project has both scientific and outreach components. The data gathered from these stations are shared with other schools and made available to the public through our web site (http://www.uaf.edu/permafrost).Through this project, students in remote communities learn more about science in a way that is meaningful to their daily lives.

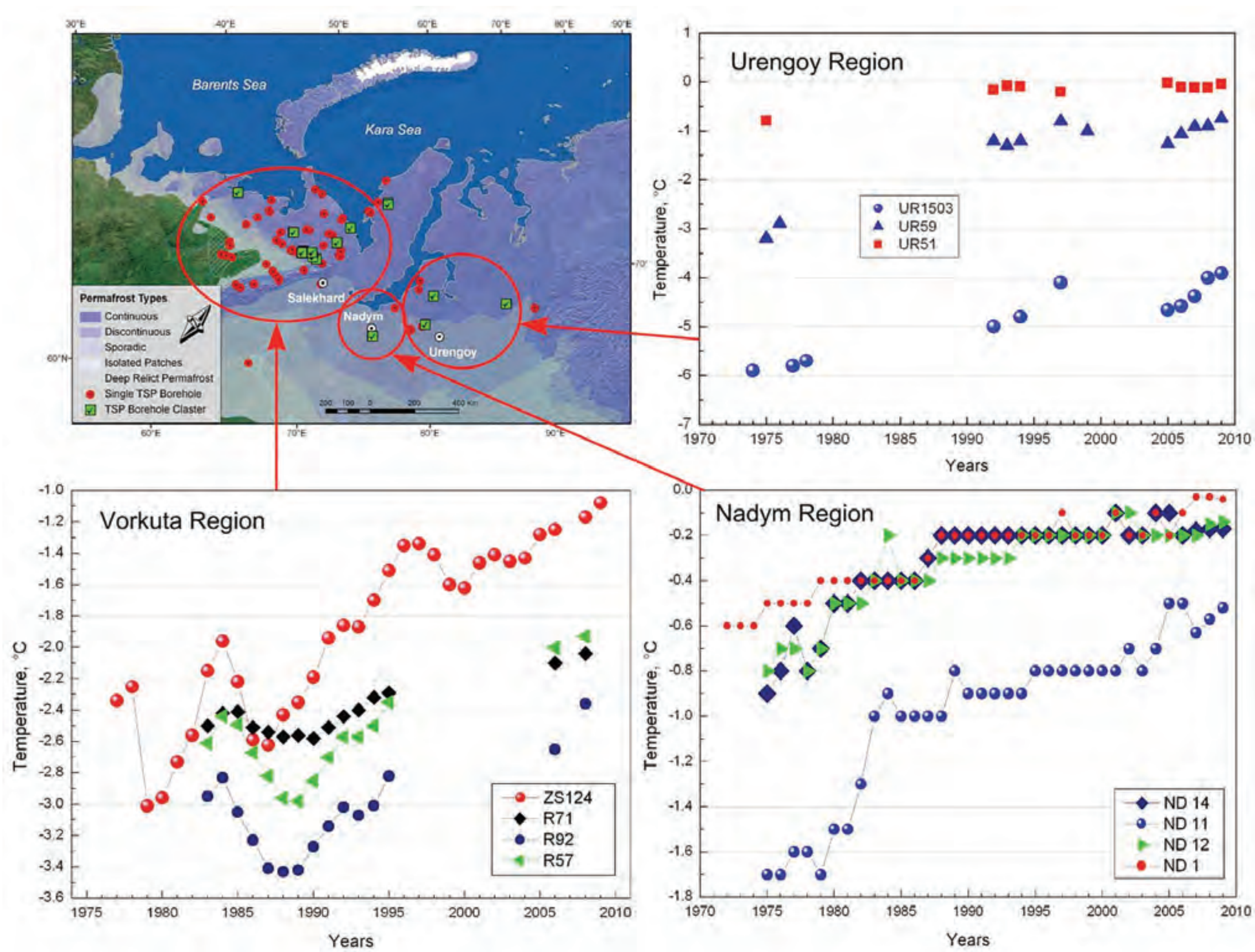

Figure 1. Permafrost temperature time series from U.S.-Russia TSP Permafrost Observatories in the Russian European North and in West Siberia.

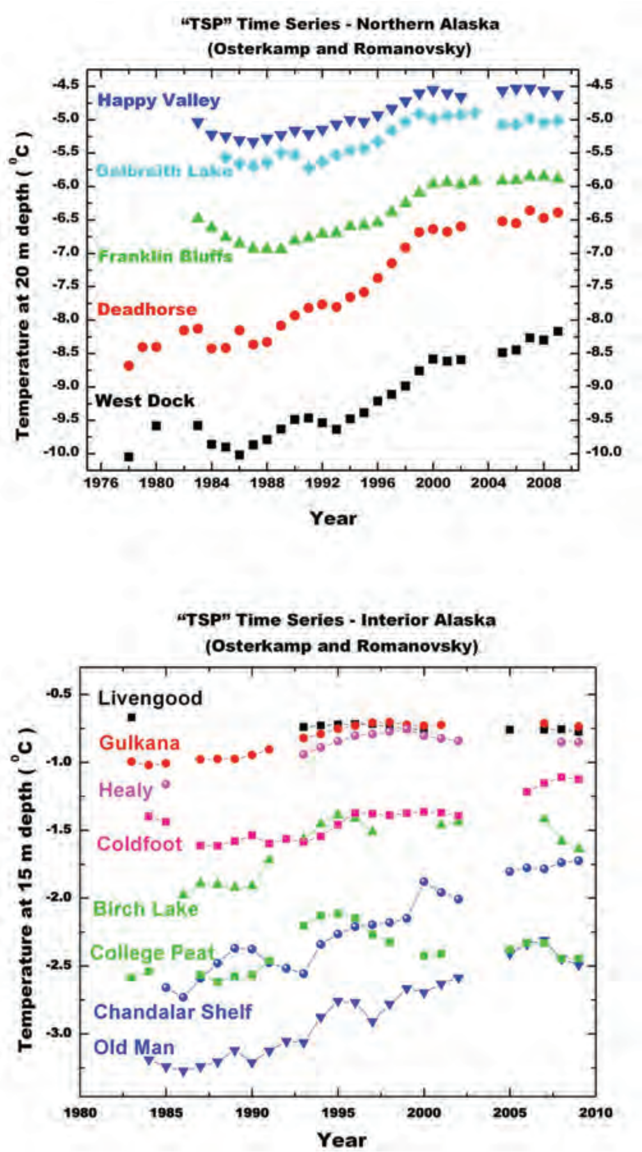

Figure 2. Permafrost temperature time series from Alaskan Permafrost Observatories.

Interactions with Other AON Projects

Close relations with the Circumarctic Active Layer Monitoring project (CALM) were established. Some key boreholes are associated with CALM sites.

Also, observations in the boreholes situated in the Tiksi area are incorporated into the Russian-U.S. project "Hydromeorological Observatory in Tiksi."

List of Publications

Web sites

CADIS: http://dataportal.ucar.edu/metadata/cadis/cadis.thredds.xml

Geophysical Institute Permafrost Laboratory: http://www.gi.alaska.edu/snowice/Permafrost-lab/projects/projects_active/proj_tsp.html

Permafrost Outreach Program: http://www.uaf.edu/permafrost/

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The Circumpolar Active Layer Monitoring Network—CALM III (2009-2014): Long-term Observations on the Climate-Active Layer-Permafrost System

N. Shiklomanov (George Washington University) and F.E. Nelson (University of Delaware)

Project Summary

The AON Circumpolar Active Layer Monitoring (CALM) program is concerned with observing the response of the active layer and near-surface permafrost to climate change at multi-decadal time scales. CALM and its companion borehole temperature program, *Thermal State of Permafrost*, are coordinated international observational networks devoted to permafrost (together, they comprise the Global Terrestrial Network-Permafrost, or GTN-P). The present active-layer network of 168 sites represents the only coordinated and standardized program designed to observe and detect decadal changes in the dynamics of seasonal thawing and freezing in high-latitude soils. Long-term observations of active-layer thickness and dynamics, obtained using standard measurement protocols, are the essential rationale behind the CALM network. Local site conditions and seasonal variations in climate create complex interactions that determine the magnitude of seasonal soil thaw and information about related biogeochemical processes. Long-term time series of thaw measurements at the same locations and across diverse terrain types and regions are required to identify scales of spatial variation, establish trends, and validate models. Measurement of thaw subsidence is an integral part of the observation program. The geographical focus of the network of CALM is on Arctic tundra environments, where the program has made substantial progress at building a consistent, long-term database that has been used effectively and extensively by the modeling community and has helped to shape recent ACIA and IPCC reports. Although AON CALM is concerned only with observing stations located in the Arctic region, it is important to note that CALM is a global network incorporating observatories outside the Arctic Circle, including a rapidly developing Antarctic component (“CALM-South”). About half of the sites in the CALM network are maintained and data reported on a voluntary basis. The circum-Arctic nature of CALM fosters extensive international collaboration between researchers and students involved in project activities. An outreach component of the project includes extensive involvement of a local, predominantly indigenous, population in an observational program at remote Arctic sites. CALM data are incorporated into our web-accessible database (http://www.udel.edu/Geography/calm). Although the CALM project was initiated in the mid 1990s it was incorporated into the NSF AON program in summer 2008. The current funding cycle began August 15th 2009.

Science and Technology Highlights

The initial CALM observational program of the early 1990s was based on a two-component conceptual model involving a seasonally frozen active layer and underlying perennial frozen materials (permafrost), leading to the hypothesis that the thickness of the active layer will increase in concert with climatic warming. Subsequent analysis of data obtained from some of the CALM sites indicated, however, that this simplified conceptualization is inadequate to explain the long-term behavior of the active-layer/permafrost system, particularly in ice-rich terrain. The effects of climatic change on the active layer and near-surface permafrost are complicated by the existence of selfregulating mechanisms associated with the ice-rich “transition layer” at the base of the activelayer, which imparts robustness to the upper permafrost with respect to external climatic forcing. The primary characteristic of the three-tier system is that the active layer, transitional zone, and long-term permafrost undergo freeze/thaw cycling over highly divergent timescales: the annual (active-layer), decadal (upper portion of transition layer), multi-century to millennial (lower portion of transition layer), and long-term (stable permafrost). Thaw penetration into the ice-rich transition layer is accompanied by loss of volume (thaw consolidation) and subsidence of the ground surface. The CALM program has developed a cost-effective methodology using Differential Global Positioning (DGPS) for periodic monitoring of the vertical position of the ground surface, and has tested it extensively. We consider results from the DGPS ground heave/subsidence measurements to be among the most significant features of CALM thus far. Beginning next year we will experiment with the use of ground-based LIDAR technology for ground surface monitoring to increase efficiency and the spatial extent of surface heave/subsidence observations.

Lessons Learned

CALM was the first international program devoted to the collection of geocryological data using standardized methods. Significant efforts were made to expand geographical coverage in the CALM II program, and this was reflected by substantial growth in the number of observational sites. The subsequent inception and funding of the Thermal State of Permafrost (TSP) under the stimulus of the International Polar Year (IPY) and the International Permafrost Association (IPA) in several countries provides a basis for more comprehensive assessment of permafrost conditions, from local to global scales. CALM and TSP are two companion permafrost monitoring programs, and their coexistence under AON provides a remarkable opportunity for designing an optimized permafrost monitoring network and for sharing logistical and intellectual resources, especially outside Alaska. The specific area where earlier collaboration could have produced significantly better results is Russia. The unexpected and exponential rise in cost of field operations in Russia over the last five years has presented significant changes to both projects, and requires creative solutions. Many logistical and methodological challenges could be avoided by developing closer collaborative activities with the partner observational program operating in the same area. The simultaneous funding of both the CALM and TSP projects by the NSF/AON program promotes a high level of collaboration, which is reflected in developing plans for joint operation of several sites across the circumpolar Arctic.

During the later stages of the CALM II project significant efforts were made to involve local, predominantly indigenous, people in the observation program. Local people involved in subsistence fishing and hunting in the vicinity of CALM sites were tutored in the performance of basic measurements, observation of unusual and/or catastrophic changes in the environment, and in the reporting of data. Involvement of the local population allowed us to reduce the size of CALM's field parties, significantly reducing annual logistical costs for operations at remote sites. Promoting the importance of environmental observations through local involvement also served as an effective measure against vandalism. However, the plans to involve local populations were developed relatively late, as a response to increases in field costs in Russia. Development of outreach plans during initial stages of the current project will help us to offset the numerous logistical constraints associated with maintaining remote sites.

Modification of Activities

Close collaboration between the AON TSP and AON ITEX programs was built into CALM III during the proposal-writing stage of the project. In collaboration with TSP we have indentified critical gaps in both observational programs and have developed a plan for comprehensive permafrost monitoring under joint CALM and TSP observational programs at 11 sites, nine of them in Russia and two in Alaska. Sites were selected by CALM and TSP PIs Shiklomanov and Romanovsky, in collaboration with CALM and TSP participants. Both scientific and logistical factors were considered during the process. Under the developed plan we will share logistical and intellectual resources, as well as instrumentation, to achieve the common goal of providing a more comprehensive assessment of permafrost conditions at the global scale. The field implementation of the joint observational program is scheduled to begin in summer 2010.

Within Alaska, we have made agreements with the ITEX program to complement one another's observations. In particular, CALM personnel will be actively involved in developing and implementing ITEX active-layer and permafrost observations, while ITEX will contribute significantly to landscape and vegetation characterization and mapping for the CALM sites. During summer 2009 we initialized extensive field collaboration between ITEX and CALM in areas around Barrow, Aquasuk, and Ivotuk. A joint publication analyzing both ITEX and CALM observations is currently in preparation. We are planning to continue to expand our collaborations with native communities in all geographical areas.

Data Use

One of CALM's primary objectives is to develop coherent datasets, incorporating long-term observations on the active layer and upper permafrost that are suitable for assessing changes in polar terrestrial ecosystems. CALM is the world's primary source of empirical information about the active layer, its spatial patterns, and temporal trends. Scientific results from the CALM II program have been published in 75 peer-reviewed publications and five books and edited volumes. Active-layer observations and auxiliary information from the CALM network provide a circumpolar database, which has been used extensively by the broader scientific community in biochemical, ecological, geomorphological, hydrological, and climatic research. Because CALM investigators adhere to a standardized observational protocol, data from the program are used extensively for validation of modeling efforts at a variety of geographic scales. CALM is, in the first instance, a global-change observational program. CALM data serve as a source of fundamental information for climate-change assessments, such as the Arctic Climate Impact Assessment (ACIA) and the Intergovernmental Panel on Climate Change (IPCC) reports. CALM was identified as a model program with respect to data harmonization in the recent U.S. National Research Council report *Toward an Integrated Arctic Observing Network.*

Web Site

One of CALM's primary objectives is to develop coherent datasets, incorporating long-term observations on the active layer and upper permafrost that are suitable for assessing changes in polar terrestrial ecosystems. At present, the CALM database consists of submissions from 168 sites, and includes active-layer thickness (ALT), soil temperature and moisture (where available), and heave/subsidence data (where available). The majority of available data are distributed through the CALM website maintained by the University of Delaware's Department of Geography (www.udel.edu/Geography/calm). The web-based summary table contains average ALT at all stations for all years, and is linked to metadata and individual data sets. CALM data are an integral part of the Circumpolar Active-layer and Permafrost System (CAPS) CDs produced by the National Snow and Ice Data Center for the 7th and 8th International Conferences on Permafrost.

International Collaborations

CALM has developed partnerships and collaborations with other international organizations and programs, including GCOS/GTOS, CEON, CliC, ITEX, ICARP, IASC. CALM has made significant contributions to *International Polar Year 2007-08* as a major component of the *Thermal State of Permafrost* IPY project. CALM currently operates in the territories of 53 nations and the ranks of its investigators include individuals from 14 countries.

A Prototype Network for Measuring Arctic Winter Precipitation and Snow Cover (SnowNet)

Project Leader: Dr. Matthew Sturm

Co-PIs: Dr. Glen Liston (CSU), Dr. Chris Hiemstra (CSU), Dr. Doug Kane (UAF), Dr. Sveta Berezovskaya (UAF), Dr. Daqing Yang (UAF)

Participants: Art Gelvin (CRREL), Stephanie Saari (CRREL), Tom Douglas (CRREL), Dave Finnegan (CRREL), Ken Irving (UAF), Simon Filhol (Grenoble), Chun-Mui Chiu (Purdue)

Project Summary

Formidable difficulties arise when monitoring solid precipitation in the Arctic. Wind-driven snow, sleet, grauple, hail, and rime can clog gauge orifices, stick to surfaces, and cause meteorological instruments to stop working. Moreover, precipitation is not the only climate metric of interest. Sublimation, snow depth (or water equivalent) on the ground, and wind transport of snow are also values that need to be monitored as the Arctic climate changes. The struggle to measure this suite of values has been long, frustrating, and fraught with difficulty (Goodison, 1978; Benson, 1982; Golubev, 1985; Yang et al., 1998; 2000 2005; Sugiura et al, 2003; Benning and Yang, 2005). Hopes for a technological "fix," a gadget that works reliably in the tough arctic environment and measures all the relevant variables, have yet to materialize, so the basic problem remains. Our project addresses this fundamental Arctic observing problem.

In two Alaskan (Barrow, Imnavait Creek) and one Canadian location (Trail Valley Creek) we have installed and operated a suite of instruments that record precipitation, weather, blowing snow, snow on the ground, sublimation (eddy correlation and gradient tower methods), and snow-drift volume. This suite is far more extensive than is typical for most observing networks. We conducted periodic intensive snow surveys (depth and density) on 100 to 1000-m transect lines located in and around each site yielding ~70,000 total snow depth and ~400 density observations. We also employed ground-based LiDAR to measure millions of snow depths at our Alaska sites. Measurements were taken during the winters of 2007-2008, 2008-2009 (Alaska sites), and are ongoing (all sites) this winter. We developed an extensive spatial dataset for our sites containing topography and high resolution (<0.50 cm) aerial photos and land cover maps.

The basis of our proposed method for improving measurement of the winter water balance components was the balance equation:

$$G(t, x, y, z) = P - S - T$$

where G is the snow depth on the ground, P is precipitation, S is sublimation, T is transported snow, t is time, and x, y, and z are location coordinates. Our initial hypothesis was that while no individual measurement in the equation might be made with complete accuracy, by combining the various measurements, in conjunction with available modeling tools, more robust and reliable values of each could be computed. As we discuss in *Lessons Learned*, some terms (T and G) in the equation can be measured with greater accuracy and ease than others (P and S). In fact, some of the more labor-intensive measurements (like S) are perhaps better estimated using data-assimilation models rather than using measurements alone. We maintain that a combined meaurement/modeling approach will be the best way to improve winter snow observations. Perfecting this approach within the NSF-AON system alone will not be enough. We need to work with agencies operating the larger observing networks, convincing them to take a renewed look at their current efforts and their sizeable shortcomings, identifying the cost-to-benefit ratio of these efforts, and developing a more reliable observational system.

Science and Technology Development Highlights

Under SnowNet we developed and/or tested several novel instruments for monitoring snow.

- *Solid-state snow water equivalent sensor*: This device was developed by CRREL for the NRCS but had not been installed or operated in the Arctic. The device weighs snow on the ground in a manner that avoids previous problems associated with snow pillows (bridging and poor performance during snow melt). We developed methods of installing the device in tundra and the sensors have performed well at all sites.
- *Rotating sonic sounder*: This is a new invention on which we (Gelvin and Sturm) have started a patent application. At thousands of locations in the Arctic and elsewhere in the U.S., snow depth is measured by a single sonic sounder built by Campbell Scientific, Judd, or other companies. These devices work well where the snow is level, but where snow drifting frequently occurs (much of the Arctic) a single point is rarely representative of most snow depths. The new device rotates a sounder on a 2-m arm using a stepper motor, thereby sweeping out a 12-m transect, providing not only a better snow depth average, but also a measure of the local change in surface drifting.
- *Sublimation by gradient tower*: Snow sublimation is typically estimated using the eddy correlation method. The instruments alone cost nearly $50,000, and the high-speed monitoring of water vapor using a Lyman-alpha device is subject to chronic failure by frost or riming in arctic environments. An attempted alternative method was to use a gradient tower (temperature, wind, and humidity at three heights) to calculate sublimation. In comparing the gradient tower and eddy correlation methods, we obtained identical accuracy. Our investigation indicates a two-height gradient tower is preferable to the more difficult to operate and expensive eddy correlation tower.
- *Drift flux*: Using pre-existing snow fences, and erecting our own, we have created drifts (***T***=total winter flux) whose volume we monitor real-time using multiple sonic sounders placed at and downwind from the fence. Drifts are also periodically monitored during field surveys. While the initial installation is labor-intensive, we found these set-ups provide an easy way to compute ***T***.
- *Repeat LiDAR Surveys*: To capture snow depth on the ground (***G***), we developed a method of using ground-based LiDAR during the winter, and again in summer when the ground is bare. While not strictly an operational method for monitoring (it is time-consuming and the equipment is expensive), the resulting maps are considerably more detailed (cm resolution snow maps) than any previous product we have been able to produce and can be used to relate the snow to the underlying tundra topography and land cover.

Lessons Learned

The problem of monitoring winter precipitation and snow remains difficult. There remains a code of silence about acknowledging the real difficulties in getting good snow measurements in the Arctic and elsewhere. What is needed is an honest assessment nationally of what works, where, and whether the effort to make it work is worthwhile. The way forward is to focus on this honest assessment by working with the agencies, and then build a consensus of how to get the best results for the money and time available. We should also capitalize on the things we can measure well, and standardize equipment and techniques required to make those measurements cost-effectively.

Modification Due to Interaction with Other Projects

SnowNet worked closely with SIZONet, sharing personnel and equipment (including the LiDAR), which led to better protocols and higher efficiency on both projects.

Data Use by Scientists and Stakeholders

SnowNet data are being used to address fundamental science issues involved in making snow distribution observations. Specifically, our Barrow site is part of the national NRCS Wyoming gauge network and key elements of that site will be transferred to NRCS at the conclusion of the project. We are advising the BLM, the largest land manager for the North Slope of Alaska, on snow and hydrologic issues through the North Slope Science Initiative (Sturm and Kane). We are consulting with the Alaska Department of Transportation on snow measurements related to tundra opening and closing for oil exploration and have recently provided them SnowNet data in a retrospective permitting analysis where considerable tundra damage occurred due to thin snow. As our data record lengthens and as more data become available, we expect our user group to grow substantially. In addition (see above) we believe our fundamental research in methods and instrumentation will inform and influence national agency strategies in snow monitoring.

Publications and Web Sites

Sturm, M. B. Taras, G.E. Liston, C. Derksen, T. Jonas, J. Lea. (Submitted) Converting snow depth to snow water equivalent using bulk density estimates and snow classes. *J. of Hydromet*.

Sturm, M. and A. Wagner. (In Prep) Using repeated spatial patterns of snow in snow distribution modeling. *Water Research*.

http://www.ipysnow.net/

http://www.facebook.com/pages/SnowNet-An-AON-IPY-Project/148111225125

International Arctic Observing Networks

Two SnowNet members (Sturm and Kane) are on the NRB Solid Precipitation Task Force. This pan-Arctic group (U.S., Canada, Greenland, Iceland, Sweden, Norway, Finland, Russia, and Denmark) is comprised of members who operate networks in which winter precipitation is a crucial input for run-off, hydropower, and climate models. We (Kane and Sturm) have managed to get the Secretariat to embrace a renewed look at this topic. The expected outcome is a) a document of best practices in making these measurements, b) a list of areas of research needed, and c) potentially a pan-Arctic testing period of new/novel approaches.

Appendix D: AON Project Reports – Terrestrial Ecosystems

Sustaining and Amplifying the ITEX AON through Automation and Increased Interdisciplinarity of Observations

Steven Oberbauer (Florida International University), Robert Hollister (Grand Valley State University), Craig Tweedie (University of Texas, El Paso), and Jeff Welker (University of Alaska, Anchorage)

Project Summary

The International Tundra Experiment (ITEX) Arctic Observing Network (AON) collects data on phenology, plant growth, community composition and ecosystem properties as part of a greater effort to study environmental change in the Arctic. The network, started in early 1990s, now provides tremendous value for detecting changes within long-term experimentally warmed and control plots across a range of sites and ecosystems that span the major vegetation types of the Arctic. While of great value, these manually collected measurements are labor intensive and time consuming, greatly restricting frequency and spatial extent of sampling. Recent advances in sensor technology hold the promise to allow sampling of surrogates of these manual measurements rapidly and over large areas. Here we will continue the ITEX AON observations and initiate a suite of related, non-intrusive structure, reflectance and thermal measurements using robotic sensor platforms (networked infomechanical systems, NIMS). These new measurements will allow us to scale our measurements to the regional level by linking to existing 1 km^2 sample vegetation grids and satellite imagery, providing urgently needed data critical to our understanding of the impacts of changing tundra vegetation on the interactions between the land and the atmosphere for the Arctic and the global system, including carbon and water fluxes and energy balance.

Significant Developments

The initial activities for this project were to be reconnaissance and site selection fieldwork during the Alaska 2009 field season. However, because of the timing of the start date on the project, that fieldwork was not possible. Consequently, a rearrangement of the future scheduling and logistics of the project has been required. Project collaborators have been in frequent contact and with CPS, the Arctic logistics provider, to redesign the fieldwork for 2010 rather than delay the project fieldwork for one full year. Again because of the timing, it is not possible that all the robotic sensor systems planned for year 2 can be ready for a first field season starting in 2010. A hybrid field season phasing in the robotic sensor systems over the 2010 and 2011 field seasons has been the chosen solution. Current activities have included equipment ordering, application for research permits for the study sites, working with the logistics provider on field power systems and site access issues, development of the robotic sensor system platforms, and recruitment of the postdoctoral fellow and summer research assistant. We have had conference calls and email exchanges with the Arctic logistic providers about the electrical power needs for our systems. We have ordered most of the sensors that we knew would be increasing in price at the end of the year to minimize sensor costs. We are currently ordering the majority of the remainder of the specific sensors for the robotic platforms. We have been working to obtain existing plans for the robotic units that will house the sensors, since the vendor who was originally planned to build these is no longer in business. We have spent considerable time investigating the best possible configuration of sensors. We have had two face to face meetings with most of the PIs of the project taking advantage of meetings at Santa Barbara in October (ITEX phenology synthesis meeting) and Boulder (AON PI-meeting, November, 2009); most will meet again at the State of the Arctic Meeting in Miami (March 2010).

Study of Arctic Ecosystem Changes in the IPY using the International Tundra Experiment

PI: Steven Oberbauer, with Tiffany Troxler and William Gould (USDA Forest Service)

Project Summary

This subproject of the ITEX AON has five components: 1) A quantitative resurvey of the vegetation of the North American ITEX warming plots at Toolik and ARCS 1 km^2 vegetation grids at Toolik and Imnavait Creek during the IPY. These point-quadrat measurements provide the most precise measurements available of vegetation structure and composition and how they may have changed in response long-term warming by open top chambers (OTCs) and to climate change since the mid 1990s. 2) Remeasurement of plant phenology during the IPY on North American ITEX plots for comparison with phenology in the mid 1990s. 3) A synthesis workshop on changes in vegetation structure and composition across the ITEX network in response to experimental warming and climate change based on early ITEX data and data collected during the IPY. 4) A synthesis workshop of trends in phenology across the ITEX network based on data collected in the mid 1990s and the IPY. 5) A study of indicators of ecosystem function to evaluate ecosystem changes in response to OTC warming from across the ITEX network.

Scientific Developments

Component 1. Response of vegetation structure and composition to experimental manipulation of snow and temperature. We used OTCs combined with large snow fences to artificially warm and modify winter snow regimes in moist tussock tundra and dry tundra plots established at Toolik Lake Field Station, Alaska. The study assesses the effects of these factors after 14 years of treatment:

a) Ordination suggest major changes in vegetation composition found at both the moist and dry sites after 14 years with snow depth being the most important factor

b) Warming is having a greater effect at the moist tundra site than the dry site

c) Snow depth is a significant factor in the dry site and both the snow and warming treatments are significant in the moist site

d) Shrubs, moss and lichen abundance were all significantly affected by the warming treatment, with shrub and litter abundance increasing and lichen abundance decreasing with warming

e) Species richness has not changed but diversity has decreased slightly as the dominant shrub and graminoid species have increased in abundance

Long-term monitoring of vegetation change in tundra ecosystems – Toolik Lake and Imnavait Creek 1 km^2 permanent plots. This study investigates the changes in the vegetation structure and composition of a very large number of permanent control plots in a tundra landscape from 1989 to 2008:

a) The extent and complexity of the canopy has been increasing over time with the amount of surface having both an understory (ground surface vegetation, typically bryophytes, lichens, and prostrate shrubs) and upper story (typically erect shrubs, graminoids, or forbs) increasing from about 60% to 80% (Figure 1a)

b) The height of the canopy has been increasing over time at both sites. The mean difference between lower and upper canopy hits increased from under 3 to 6 cm at Imnavait Creek (Figure 1b) and from just over 4 cm to nearly 12 cm at Toolik.

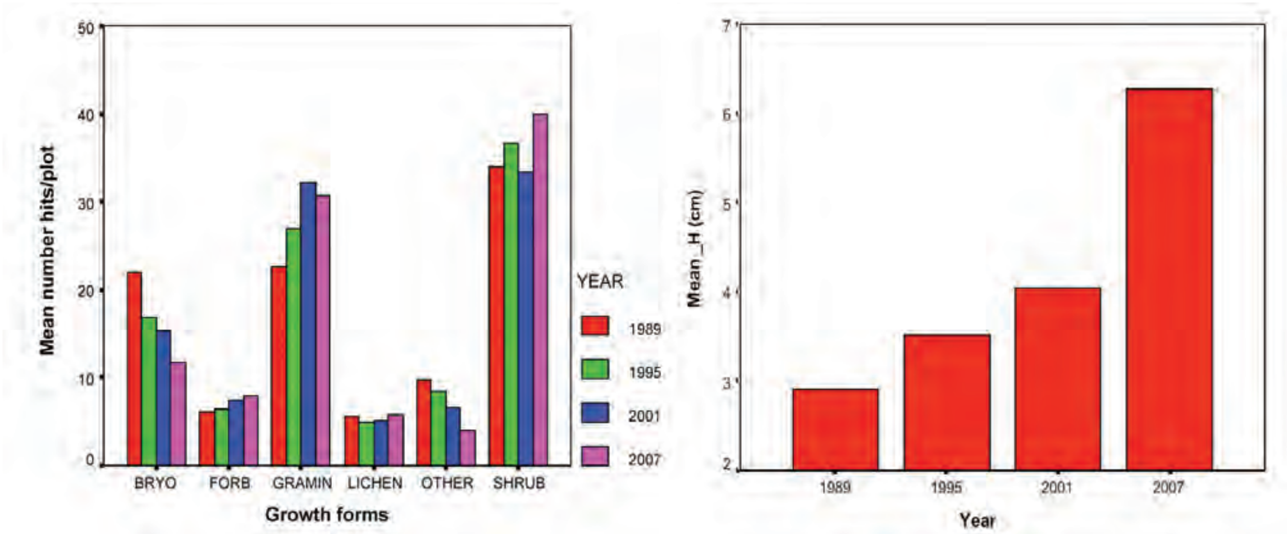


Figure 1. Point quadrat results over an 18-year period at Imnavait Creek (Gould, unpubl.)

Component 2. ITEX warming and control plots at Toolik were measured for phenology in both 2007 and 2008, as were control plots of the ITEX seasonal manipulation project (snow removal) and are being used in the phenology synthesis effort (Component 4).

Component 3. The vegetation synthesis originally scheduled for Spring 2009 was delayed for logistical reasons to Spring 2010 and will take place May 2010 in Vancouver, Canada. Many of the data sets in final form are already in hand. Most groups across the ITEX network who signed letters of support were able to conduct point-quadrat remeasurement of old plots during the IPY allowing assessment of both long differences between controls and warmed plots and background changes in control plots as well.

Component 4. We completed a very successful week-long synthesis working group meeting at the National Center for Ecological Analysis and Synthesis (NCEAS) in Santa Barbara, October 12-16.

Most groups across the ITEX network who signed letters of support were able to conduct remeasurement of phenology on long-term plots allowing assessment of both background changes in control plots as well as log difference between controls and warmed plots. The compiled data set includes more than 150 site years of data and more than 20,000 records on plot phenology. Climate data to accompany much of the phenology data have also been compiled. Many, but not all species, are showing earlier flowering (Figure 2) and earlier greenup than they did in the 1990s.

Component 5. We have obtained samples of soil respiratory CO_2 from many of the ITEX sites to test if old carbon is being lost from the sites in general and in response to the OTC warming. At least one site, Barrow Alaska, is showing evidence of loss of old carbon. We also have samples of litter from most sites for measurement of nutrients and secondary compounds. Processing of these samples is ongoing. We have been measuring peak season ecosystem components of CO_2 fluxes on Barrow and Atqasuk ITEX plots whenever possible since 2000. At the dry site warming (OTCs) causes the sites to be a CO_2 source even at peak season (negative values of NEE in Figure 3). **At the wet site, both warmed and control plots were CO_2 sources at peak season during the warm and dry years in 2007 and 2009**.

Lessons Learned

The ITEX network was established with specific guidelines formulated in a procedures manual. Even so, site and species differences and funding constraints have led to some divergence in data sets that makes synthetic efforts challenging and in the end data are often reduced to the simplest common parameter. That ITEX has

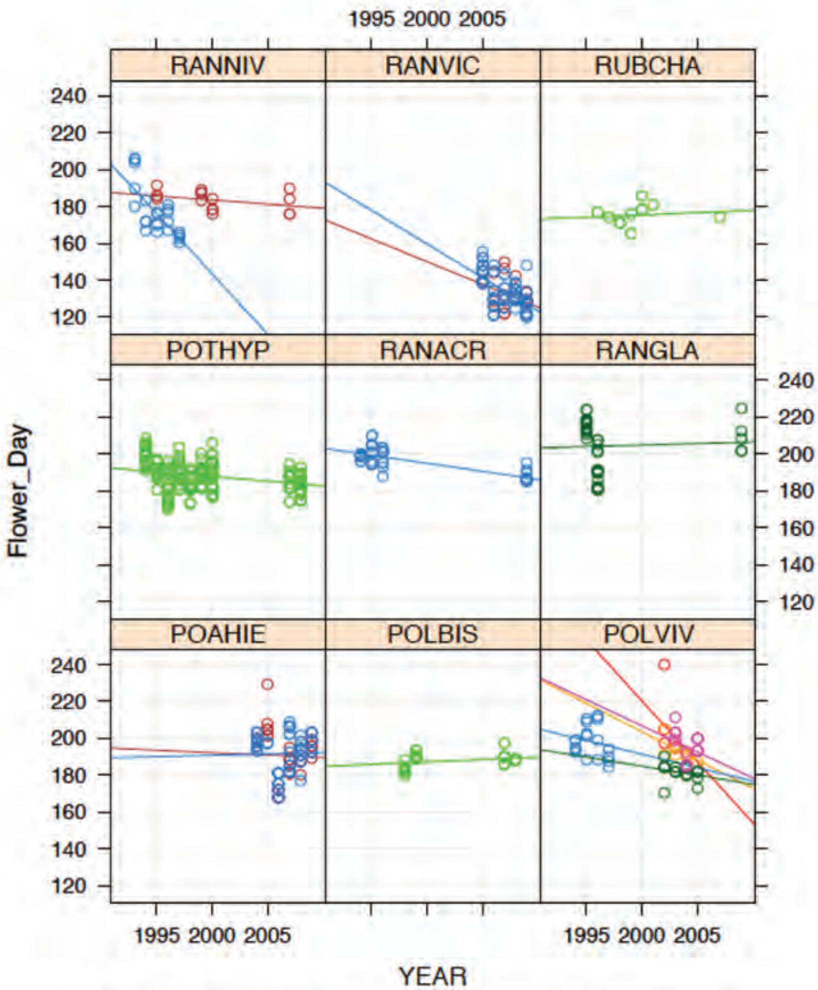


Figure 2. Flowering Day (day of year) vs. year for small subset of the species included in the ITEX phenology data set. Different colors are for different sites. Lines trending down to the right indicate a trend toward earlier flowering.

successfully persisted is in a large part as result of the simplicity and low cost of its passive treatment. Some of the key sites have been maintained in unfunded years through assistance by other groups/projects, assistance that was only feasible because of the design simplicity.

Modification and Connections

Because of the fundamental nature of the measurements (phenology, growth, and plot composition and structure), ITEX measurements have formed a core framework that is a strong basis for commonality with other groups doing terrestrial measurements. The need for corroborating remotely sensed data with on the ground measurements has led to wide adoption of handheld remote sensing measurements at the ITEX plots. Through common interests and core facilities at University of Florida, we have linked with Ted Schuur's group on the study of loss of old soil carbon. Through our synthesis activities we benefited from strengthened connections with the MBL IAB AON flux network; gap filling approaches developed in the Ameriflux network were recently applied en mass to our phenology site climate data. There really is nothing quite like participants together in the same room for a significant block of time devoted to the same goal. Because ITEX is a network, it is based on connections. Nevertheless, one of our most important linkages is that between our NSF-sponsored AON efforts and the Canadian IPY efforts spearheaded by ITEX president Greg Henry. We have combined our efforts for the upcoming ITEX vegetation change workshop to support a larger and more comprehensive look at recent vegetation change in the Arctic than what would have been possible otherwise.

This project was specifically designed with built-in synthesis activities to analyze the major research efforts on phenology and vegetation composition and structure. We already are using essentially all the existing ground-based phenology data within our NCEAS working group. The upcoming vegetation synthesis will use all of the existing ITEX vegetation data but will also include a large number of groups and sites outside of the ITEX network, especially linking with data from the Back to the Future and Greening of the Arctic efforts, with whom we have already established connections.

Web Sites

http://www.nceas.ucsb.edu/funded2009;

http://www.fiu.edu/~oberbaue/ITEX-IPY.htm,

http://www.geog.ubc.ca/itex/

Outreach Activities

Most of our outreach was done during the IPY. We have continued to work with our 2008 PolarTrec teacher Elizabeth Eubanks to incorporate research into the science classroom of her school in Lake Worth, FL. In November 2009 we installed an ITEX OTC and a wireless weather station at the school that transmits data directly to the classroom. We also installed dendrometers on nearly three dozen mangrove trees adjacent to the school so that students can track seasonality of tree growth (Figure 3).

Figure 4. Oberbauer demonstrating fabrication of stainless steel vernier dendrometers to 6th, 7th, and 8th graders for use in measuring monthly diameter increment of mangrove trees adjacent to St. Mark School in Lake Worth, FL.

Fire in the Arctic Landscape: Impacts, Interactions and Links to Global and Regional Environmental Change

NSF-OPP-0856853 (MBL, Woods Hole, MA)

G.R. Shaver, N.T. Boelman M.S. Bret-Harte, W.B. Bowden, L.A. Deegan, A.E. Giblin, C.R. Johnson, G.W. Kling, M.C. Mack, E.B. Rastetter, A.V. Rocha

Project Summary

The 2007 Anaktuvuk River (AR) fire created a unique opportunity to observe the response of a pristine tundra landscape to a major disturbance. The area burned is large enough (>1000 km^2) that its impacts can be measured directly at multiple scales, from small plots to large (3rd-order) catchments and to the atmospheric boundary layer above the entire burn. As the burned area recovers over time, observations of changes in key ecosystem processes and in terrestrial and aquatic communities will afford insights into controls and interactions among system components that would not be possible from long-term observation of an undisturbed or unmanipulated tundra landscape.

Observations, comparisons, and analysis will build upon work begun in 2008, the first summer following the fire, and will continue through 2009-2011. Key components of the research include measurement of (1) surface C, water, and energy exchanges, (2) terrestrial organic matter, C, and element stocks, (3) terrestrial vegetation composition and structure, (4) lake and stream chemistry and water flow, (5) lake and stream community composition, and (6) evaluation of spectral reflectance measures of production, biomass, community composition, and burn impacts for use in scaling up to larger areas and for comparison with satellite- and airplane-based measures of reflectance. Data will be made available via the Arctic LTER data base, which currently hosts a wide range of relevant, comparative data sets.

Science and Technology Development Highlights

We have set up and maintained three eddy co-variance/micromet towers in unburned, moderately-burned, and severely-burned sites through two complete summers (2008-2009). We have also maintained a network of five automated stream samplers in selected catchments through each summer. These instruments are all powered using solar panels and backup batteries. Instrument maintenance and data recovery are achieved on regular visits by helicopter from Toolik field station. Vegetation and soils have been described in sites of varying burn severity, and estimates of C and N loss and recovery are available. Aquatic communities (lake and stream) have been described as well as changes in lake and stream chemistry.

Lessons Learned

Although all of our original objectives have been met, the amount of data and samples we can collect is limited by (1) access to helicopters for transportation to the site, (2) instrument power requirements and power supplies, (3) lack of radio or satellite communications with instruments in the field, and (4) personnel available for sample handling and chemical analysis. The first and last of these limitations have been minimized through collaboration with the Arctic LTER project and the OPP “Thermokarst” project. Our power problems affect the choice of instruments we can use in the field (e.g., open-path vs. closed-path gas analyzers) but we are working with the AON “Carbon, Water, and Energy Flux” project to calibrate instruments against each other. We continue to explore wireless communications options.

Examples of Data Use

Recovery from the burn continued in 2009, as seen in satellite imagery, changes in surface energy balance, and in C balance (Figures 1-4). Dissolved N and P concentrations were higher in stream water in burned watersheds (Figure 5).

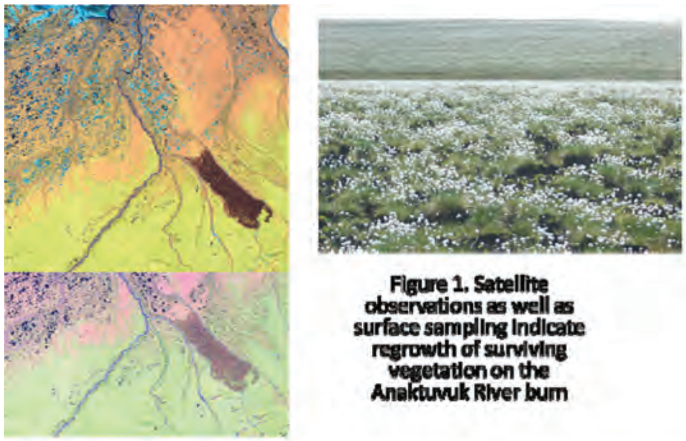
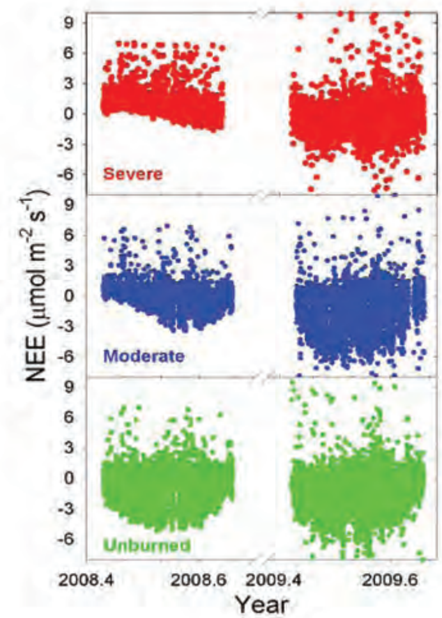


Figure 1. Satellite observations as well as surface sampling indicate regrowth of surviving vegetation on the Anaktuvuk River burn

Figure 2. Half-hourly observations of net ecosystem exchange (NEE) of CO2 in unburned, moderately-burned, and severely burned tundra at the Anaktuvuk River Fire sites. Data are from June-August 2008 and 2009; negative values indicate net CO2 removal from the atmosphere (i.e., during midday when photosynthesis exceeds respiration); positive values indicate net CO2 loss to the atmosphere (mostly at night when respiration exceeds photosynthesis)



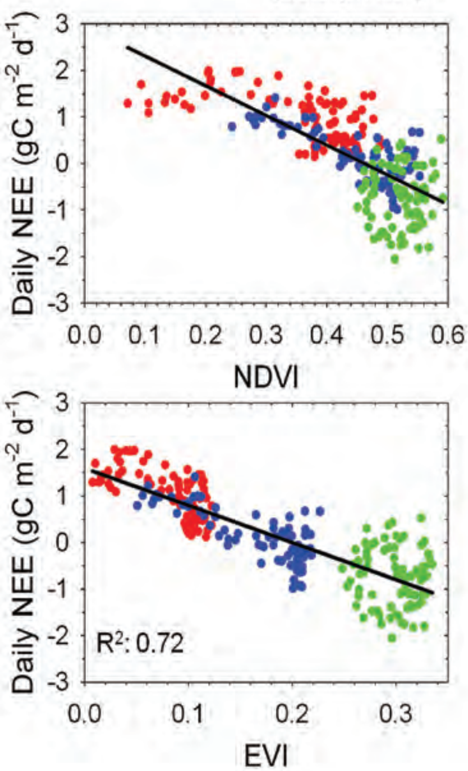
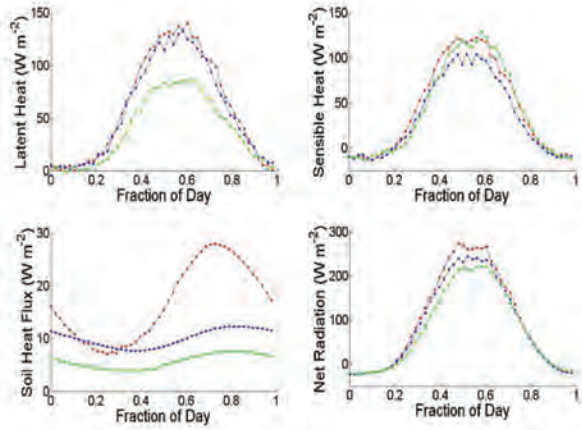


Figure 3. Daily NEE in unburned (green) and severely- (red) and moderately-burned (blue) sites is correlated with surface reflectance properties including commonly-used measures such as NDVI and EVI

Figure 4. Components of surface energy balance in unburned (green) and in moderately- and severely-burned (blue, red) tundra in 2008. Points are seasonal averages for each half hour through a day



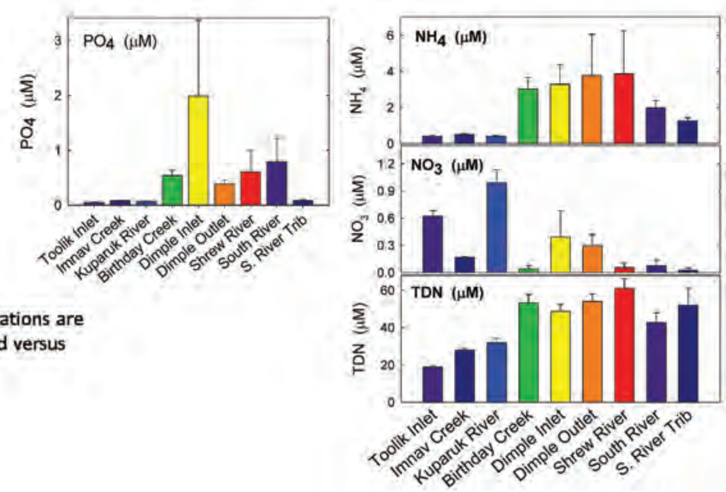


Figure 6. N and P concentrations are higher in streams of burned versus unburned watersheds

Interactions with Other AON and Local Projects

The fire that led to the organization of this project was an unexpected event. Immediately after the fire, Shaver led the effort to obtain SGER funds from both NSF-OPP and NSF-NEON. Preliminary work on the burn in 2008 was done by a coalition of ecologists working near Toolik Lake including investigators, students, and technical staff from the AON project on "Carbon, Water, and Energy Balance of the Arctic Landscape," and several projects related to the Arctic LTER. The proposal that supports this project was written as a follow up to the successful work done with NSF-SGER funds in 2008.

Interactions with the AON "Phenology" project (Oberbauer, PI) will be particularly important in the future as models relating carbon fluxes to plant phenology are developed. We have begun to talk more frequently with these long-time colleagues, starting with attendance by Rocha at the AON-ITEX phenology synthesis workshop at NCEAS in Santa Barbara, September 2009.

On the burn site, many of the variables being measured are of direct relevance to the "Hydrology and Permafrost" projects of AON (e.g., Figure 4). In 2008 we set up CALM grids for monitoring of active layer depth, and in 2009 we extended our observations of soil temperature profiles in collaboration with scientists from Vladimir Romanovsky's group.

We continue to work closely with the group of projects based at Toolik Lake, particularly the Arctic LTER project. The LTER project is now doing most of the chemical analysis of samples collected from the fire site. We also are working closely with the LTER data managers to ensure that our data are archived in the LTER data base using LTER Network protocols, including search and filtering capabilities that will allow comparison and synthesis with the national network of LTER sites. Finally, we are working closely with the NSF-OPP "Thermokarst" project to identify sites within the burned area where permafrost thaw is occurring, and with scientists from the Bureau of Land Management interested in developing burn severity models for tundra wildfires.

Relation to Broader Observing Efforts

Shaver is currently a member of the Steering Committee of the International Study of Arctic Change (ISAC), and is Co-Organizer of a symposium on arctic C balance to be held at the IPY Oslo Science Conference in June. Shaver and Rastetter participated in a special session on Arctic C fluxes at the Ecological Society of America meeting in August 2009. Bret-Harte attended the Sustained Arctic Observatory Network (SAON) organizing meetings in Stockholm, Edmonton, and Helsinki, and Rastetter and Shaver attended the Edmonton meeting.

AON research at Toolik Lake is already linked to the Arctic LTER program and the 26-site U.S. LTER Network. Within the next 5 years Toolik Lake will also become one of 20 National Environmental Observatory Network (NEON) sites. One important activity of this AON project is to ensure that data, methods, and research designs are compatible across all of these projects, especially as the NEON effort goes from planning to implementation.

Publications

(two published, three manuscripts in preparation)

Rocha, A.V., and Shaver, G.R. 2009. Advantages of a two band EVI calculated from solar and photosynthetically active radiation fluxes. *Agricultural and Forest Meteorology*, 149: 1560-1563. doi: 10/1016/j.agrformet.2009.03.016.

Rastetter, E.B., Williams, M, Griffin, K.L., Kwiatkowski, B.L., Tomasky, G., Potosnak, M.J., Stoy, P.C., Shaver, G.R., Stieglitz M., Kling G.W., Hobbie, J.E. 2009. Application of the ensemble Kalman filter to assimilate eddy covariance flux data into a model of Arctic carbon exchange. *Ecological Applications*, accepted.

Web Sites

AON flux project web site:
http://aon.iab.uaf.edu/index.html

Arctic LTER project web site:
http://ecosystems.mbl.edu/arc/

Appendix E: AON Project Reports – Human Dimensions

Is the Arctic Human Environment Moving to a New State?

Jack Kruse, University of Alaska

Project Summary

The Arctic Observation Network Social Indicators Project (OPP0638408) is intended to contribute to the development of the Arctic Observation Network and to the science goals of SEARCH in two ways: (1) develop and make available to the science community relevant datasets; and, (2) identify gaps in the existing observation system and recommend appropriate actions to fill those gaps.

The *SEARCH Implementation Plan* identified the following arenas of human activity likely to involve climate-human interactions: (1) subsistence hunting; (2) tourism; (3) resource development and marine transportation; and, (4) commercial fishing. This project seeks to develop and assess data sets in these four areas.

Again drawing from the *SEARCH Implementation Plan* priorities, the project also seeks to develop and assess data sets measuring social outcomes. In collaboration with the *Arctic Council's Arctic Social Indicators* working group, this builds on the recommendations of the *Arctic Human Development Report* by focusing on data sets in six areas: (1) material well-being; (2) cultural continuity; (3) education; (4) health and demography; (5) ties with nature; and, (6) fate control.

In anticipation of the long-term goal of integrated analysis of social, natural, and physical science data sets, we are working in collaboration with the *Arctic RIMS* project to structure data in a regional geography that is embedded in the ArcticRIMS GIS system. The Arctic, using the *Arctic Human Development Report* definition as a guide, consists of 75 regions. Recognizing that individual communities within the same region often differ in the climate-human interactions, the project is also compiling a limited set of place level databases. The target time period is 1980 to the present and the target time step is annual. All databases share a common record structure of location (region or place) and year.

Science and Technology Highlights

Subsistence Hunting

- Most comprehensive harvest surveys are community-specific. It is seldom possible to generate regional estimates. Since communities within the same region (e.g., coastal and inland) often differ in the composition of subsistence harvest, community-specific data is highly relevant to understanding arctic change.
- To understand climate-subsistence interactions it is necessary to take into account changes in the total resource harvest. Variations in the harvest of individual resources are large from year-to-year. Harvesters try to compensate for low harvests of one resource with harvests of other resources. Multi-year changes in harvest of an individual resource coupled with changes in the total resource harvest are of particular importance to social outcomes.
- The project's Alaska-Northern Canada database consists of 1,521 place/year records of which 631 records include estimates of harvest of all resources as well as harvests of specific resources. Separate harvest reports are available for 131 species and seven resource categories (e.g., large land mammals, salmon) as well

as total harvest. Harvests are expressed as kilograms of edible harvest per capita.

- From 2000 to 2006 103 comprehensive harvest surveys have been conducted compared with 110 in the 1990s. There are 50 instances where it is possible to compare harvest amounts in the 1990s and 2000s. Thirty of these observation sets are separated by four years or less.
- There is no existing network of comprehensive harvest studies in arctic North America.
- Analysis of 631 comprehensive community harvest surveys shows that measuring harvests of top 10 species in each community accounts for a mean of 90 percent of total harvest. This finding has major implications for the feasibility of conducting economical, targeted harvest surveys in communities participating in the AON network.
- The forthcoming *Arctic Social Indicators* report will identify subsistence harvest and consumption as one of a few primary arctic social indicators.
- We collaborated with other researchers directing regional projects involving communities in a proposal to test targeted harvest surveys. These researchers included: Shari Gearheard [IPY: Exchange for Local Observations and Knowledge of the Arctic (ELOKA) OPP0632345], Susan Crate (Assessing Knowledge, Resilience & Adaptation and Policy Needs in Northern Russian Villages Experiencing Unprecedented Climate Change OPP0710935), Gary Kofinas (Heterogeneity and Resilience of Human-Rangifer Systems: A Circumpolar Social-Ecological Synthesis, OPP0531200), Larissa Abryutina (Russian Association of Indigenous Peoples of the North, RAIPON), Kristina Lasko (Saami Council), Gerard Duhaime (Laval University), and Birger Poppel (University of Greenland).
- **Recommendation**: International pilot testing of targeted harvest surveys in collaboration with participating communities. Foster development of the approach as part of a community-based observation network.

Commercial Fishing

- Since climate-fishing interactions are likely to differ by resource, we are focusing on key resources in each region. Alaska: crab, halibut, herring, salmon, other groundfish, other shellfish. Norway: Atlantic Cod, Atlantic Mackerel, Blue Whiting, Capelin, Pollock, Haddock, Shrimp. Iceland: match with Norwegian species. Russia (Chukotka): Chum Salmon.
- Of particular relevance to social outcomes of fishing activity is where fish are landed and where fishers live. Measures include: (1) number of fishers; (2) number of licenses; (3) metric tons; (4) value. We are compiling landings data by region for Alaska, Iceland, and Norway.
- Of particular relevance to climate-fishing interactions is where fish are caught. We have been collaborating with the Norwegian College of Fisheries in Tromso, and through them, with the Ministry of Fisheries. They have been able to process landings and log book microdata into GIS format to track changes in harvest location. Additional work of this type is now being done in the *Fish Exchange Project* centered in Bergen. This work was reported at the recent S4D Workshop in Oslo.
- Understanding climate-fisheries interactions requires marine geospatial observations of catch locations and terrestrial geospatial observations on employment and income. This understanding also requires that the two types of observations be linked. A change in catch locations, for example, can be accompanied by a shift between resident coastal fishers and non-resident offshore fishers. Linkage of harvest and shoreside economic data constitutes the principal gap in fisheries observations.
- **Recommendation**: Starting with groundfish fisheries in Alaska and Norway, expand the approach of the Norwegian Fish Exchange Project in collaboration with the Alaska Fisheries Science Center and the Norwegian Fisheries Directorate to create a time series database at a 25 km resolution that includes landings

by harvest location and port, biomass survey data, and spatial fisheries regulations. Making this linkage will require reanalysis of microdata and re-aggregation separately for offshore processors and shorebased catcher boats.

Resource Development & Marine Transportation

- Climate-resource development interactions may produce changes in resource production, but existing production statistics vary by country and cannot be aggregated across resource types. Changes in value can be aggregated but value is affected by price as well as activity level. The ideal measure of resource development activity for the purpose of understanding social outcomes at the regional level is employment. Such data are not available by industry by region and are collected inconsistently across countries. Alaska and Norway petroleum data are readily available by field and thus can be aggregated by region. Russia petroleum data are not reported separately for the Arctic. Marine transportation data (i.e., numbers of vessels by industry traveling routes involving arctic waters) exist but are currently classified.
- We are creating indexes of resource activity by region based on the best proxy variables for each country.
- We collaborated with Hajo Eicken's team proposal ***AON Collaborative Research on the State of the Arctic Sea Ice Cover: Sustaining the Integrated Seasonal Ice Zone Observing Network*** (SIZONET) in a proposal to collect historical data on ore shipments and barge activity through the Bering Strait, and match this data with sea ice data. Together, these data would support analysis of the effects of changes in sea ice conditions on the economics of resource development and the cost of living in Northern communities.
- **Recommendation**: Seek funding and implement proposed integration of marine transportation and sea ice data.

Tourism

- Tourism activity does not uniquely account for employment in any reported industry sector. The Accommodation industry, for example, experiences demand by resident travelers (e.g., business and government personnel providing services) as well as non-resident travelers. To address this problem, the World Travel and Tourism Council has developed methods for reorganizing national accounts to identify the contribution of tourism to a state or national economy. This approach, called Satellite Accounting, has been implemented in Norway. The satellite accounting approach cannot be practically applied at the level of arctic regions, but could be extended to arctic states (i.e., at a more aggregated level than the 75 regions identified in this project).
- Given the uneven application of satellite accounting in arctic nations, we are focusing on two types of measures: (1) employment in sectors with significant tourism-driven demand; and, (2) number of visitors.
- At our project workshop of researchers and stakeholders, we together identified a major shortcoming of tourism data. In many instances, tourism-related jobs in the Arctic are held by transients. In addition, many tourism-related businesses are owned and managed by firms located outside the arctic. For both reasons, tourism statistics often are not accurate measures of local economic impacts.
- **Recommendation**: Include in the initial testing of the community-based observation network a measure of tourism local benefits that can be compared with standard tourism measures of activity.

Social Outcomes

- We have developed and released through CADIS a database containing 597 social outcome measures in the domains of employment, housing, mobility, education, language, and income for 27 regions of Alaska for the period 1970 to 2000. These measures are based on decennial census data.

- Larry Hamilton, in a collaborative AON project, is developing an annual, pan-Arctic population database that uses the same spatial and time structure.
- We have developed a place-level data base containing 703 social outcome measures in the same domains as the regional database for 408 places in Alaska, again for the time period 1970–2000.
- A member of the project team, Gerard Duhaime, and his colleagues created *ArcticStat* as a single portal for accessing social and economic data from arctic national statistical agencies. Duhaime's team was successful in negotiating collaborations with the national statistical agencies of Canada, Greenland, Norway, Sweden, Finland, Iceland, the Faroe Islands, the United States, and Russia. *Arcticstat* includes links to data at the regional level on vital statistics, education, employment, income, migration, health, housing, and national accounts.
- *ArcticStat* is a major step toward the development of a pan-Arctic social outcomes database. Its use also presents major challenges. We have downloaded over 3,400 tables using *ArcticStat*. We have successfully used special software to recognize complex table structures and to recreate original tables. We have learned in the process of testing our protocols that national statistical agencies vary widely in their choice of what data to publish. They often differ in how they group data. Their tables are intended to be printed, not used as a database and combined with data from other countries. Yet the development of recommendations for improving the comparability of arctic social and economic data depends on having first developed a variable-by-variable comparison. Creating readable electronic files of tabular data is a first step in this process. The second step is to convert the tables to databases sharing the same file structure and variable naming conventions. Only then will it be possible to make variable-by-variable comparisons.
- **Recommendation:** Compile *ArcticStat*-derived tables into a pan-Arctic regional database that will support a variable-by-variable comparison. Create comparable variables to the extent possible. Recommend country-specific tabulation changes that will significantly improve the comparability of data.

Lessons Learned

- The *SEARCH Implementation Plan* logically identified the compilation of existing data as a high priority task. We designed our project accordingly. Most sources of social science data are national agencies that operate under strict confidentiality regulations. This is true for both business and individual records. They in turn choose to aggregate and publish summaries of data within the context of their national mandates and interests. National differences in mandates and interests result in differences in what summaries are published. Published summaries are not intended as databases but rather as reports to be printed. These challenges cumulatively make the tasks of compiling existing data and collecting primary data of much greater complexity and effort than we ever imagined.

Interactions with Other Projects

We discussed many of these interactions in more detail above. This is a listing.

- ArcticRIMS (Richard Lammers et al.): Collaborated on common geospatial system
- Arctic Social Indicators (Joan Larsen et al.): Collaborated on common definition of social outcome domains and key measures including total harvest of subsistence resources; collaborated with ASI leadership on Phase 2 AON proposal
- Norwegian Fish Exchange Project (Geir Odd Johansen et al.): Collaborated on joint approach to compiling and linking Barents Sea and Bering Sea fisheries catch and landings data
- SIZONET (Hajo Eicken et al.): Collaborated on integrated proposal for linking marine transportation and sea ice data
- Shari Gearheard [IPY: Exchange for Local Observations and Knowledge of the Arctic (ELOKA) OPP0632345]: Collaborated on proposal for testing targeted harvest surveys as part of the development of a community based observation network
- Susan Crate (Assessing Knowledge, Resilience & Adaptation and Policy Needs in Northern Russian

Villages Experiencing Unprecedented Climate Change OPP0710935): Collaborated on proposal for testing targeted harvest surveys as part of the development of a community-based observation network

- Gary Kofinas (Heterogeneity and Resilience of Human-Rangifer Systems: A Circumpolar Social-Ecological Synthesis, OPP0531200): Collaborated on proposal for testing targeted harvest surveys as part of the development of a community-based observation network
- Larissa Abryutina (Russian Association of Indigenous Peoples of the North, RAIPON): Collaborated on proposal for testing targeted harvest surveys as part of the development of a community-based observation network
- Kristina Lasko (Saami Council): Collaborated on proposal for testing targeted harvest surveys as part of the development of a community-based observation network
- Gerard Duhaime (Laval University): Collaborated on proposal for testing targeted harvest surveys as part of the development of a community-based observation network
- Birger Poppel (University of Greenland): Collaborated on proposal for testing targeted harvest surveys as part of the development of a community-based observation network

Project Web Site

www.search-hd.net

Project Relationship with International Arctic Observing Efforts

Concurrent with the development of our original proposal in 2006, the Arctic Council initiated the Arctic Social Indicators project (ASI) as a follow-up to the Arctic Human Development Report (AHDR). The intent of ASI is to devise a limited set of indicators that reflect key aspects of human development in the Arctic, that are tractable in terms of measurement, and that can be monitored over time at a reasonable cost in terms of labor and material resources. Four members of our project team were invited to be ASI participants: Kruse, Hamilton, Duhaime, and Rasmussen. Over the past three years, we have collaborated with over 50 other scientists and indigenous people in ASI. Building on the recommendations of the AHDR, ASI identified six dimensions to describe human development: material well-being, education, demography and health, cultural integrity, contact with nature, and fate control. Within each of these dimensions, scientists and indigenous people involved in ASI identified an indicator, or index composed of several indicators. ASI leadership, including Hamilton, Rasmussen, and Kruse, presented ASI results to the membership of the International Society of Quality of Life Studies in San Diego in 2007 and to the membership of the International Arctic Social Science Association in Nuuk in 2008.

The work of the Arctic Observation Network Social Indicators Project and ASI has, by design, converged. We are both using the same six dimensions to describe social outcomes (or in ASI terminology, human development). It has become clear to both groups that there are critical gaps in the existing Arctic Observation Network. The most critical gap is the lack of current and ongoing observation of subsistence resource harvests, particularly in Alaska and Canada. It is equally clear that the gap in resource harvests can only be filled through primary data collection. Less clear is how best to measure the dimensions of fate control and cultural integrity. Testing of alternative measures, including those requiring primary data collection, is required. Even education and

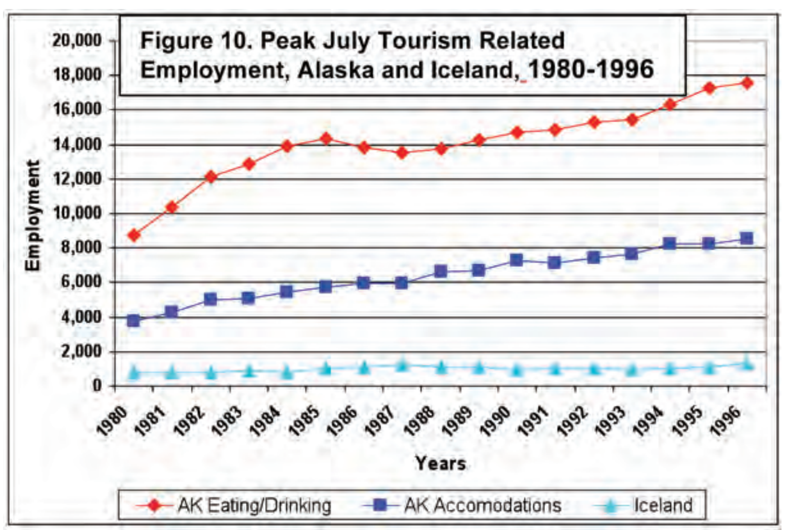
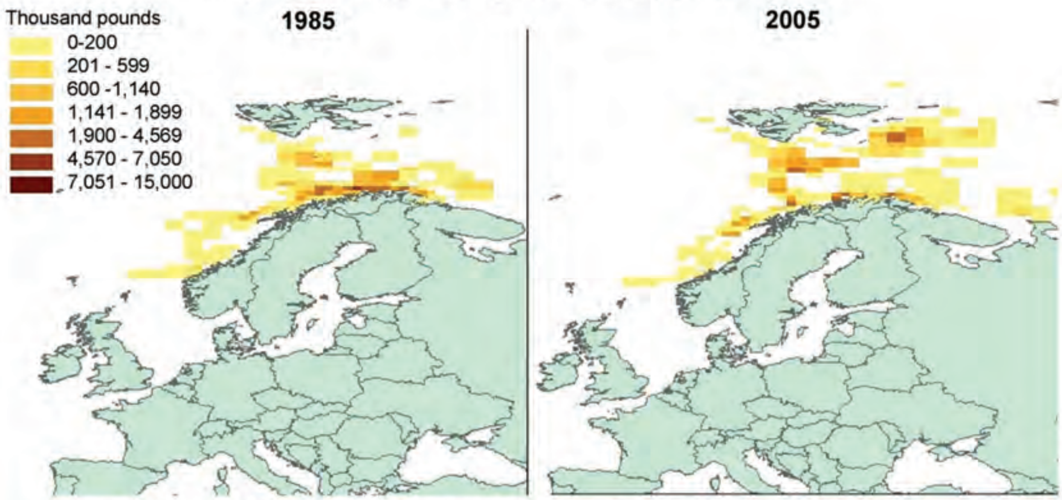


Figure 10. Peak July Tourism Related Employment, Alaska and Iceland, 1980-1996

Map 1. Location of Norwegian Cod Catches, 1985; 2005



Location of Cod catches shows shift to the north and east between 1985 and 2005.
Source: Norwegion Fisheries Directorate

Figure 6. Distribution of Change in Kilograms Per Capita Edible Resource Harvest Between Successive Harvest Surveys for 47 Communities, 1980s to 1990s

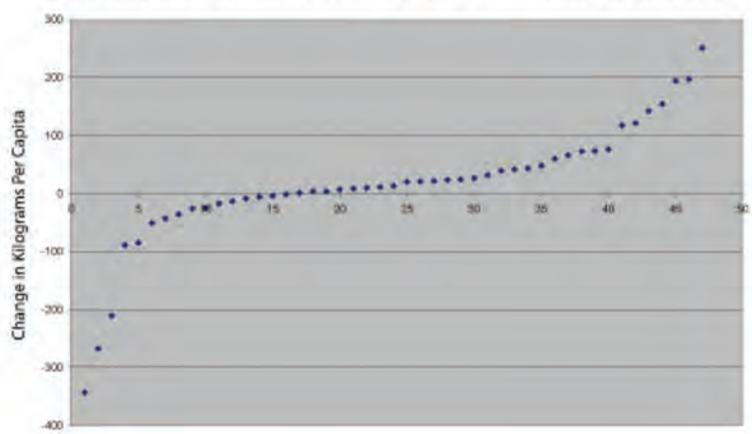
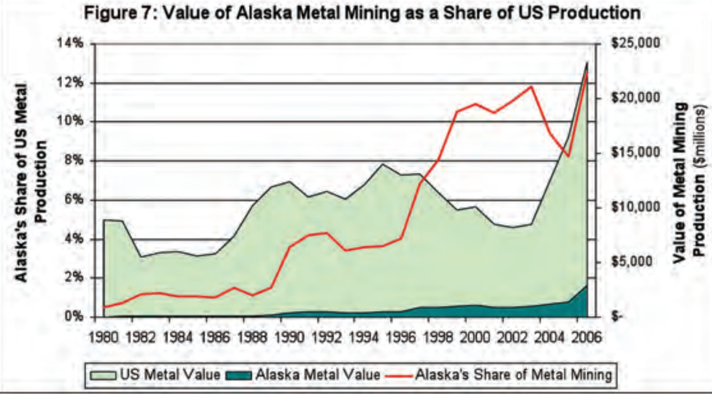


Figure 7: Value of Alaska Metal Mining as a Share of US Production



Appendix F: AON Project Reports – Data Management and Coordination

ELOKA: Exchange for Local Observations and Knowledge in the Arctic

Shari Gearheard

Project Summary

Local and traditional knowledge (LTK) provides rich information about the Arctic environment at spatial and temporal scales that scientific knowledge often does not have access to (e.g., localized observations of fine-scale ecological change, or local and regional sea ice conditions prior to 1950s ice charts and 1970s satellite records). Community-based research and monitoring programs allow for Arctic residents to share detailed knowledge, contribute 'frontline' observations and measurements, and develop local assessments and response strategies to the impacts of Arctic change. Thus, community-based research and monitoring are a key component of any Arctic Observing Network.

One of the greatest challenges of local and traditional knowledge (LTK) research and community-based monitoring to date has been effective and appropriate means of recording, storing, and managing data and information. It has been a challenge to find effective means for protecting sensitive information while also making community-based data and information available to Arctic residents and researchers, as well as other interested groups such as teachers, students, and decision makers. Without network and data management services to support LTK and community-based research, a number of problems have arisen such as: misplacement or loss of extremely precious data (e.g., knowledge from Elders who have passed away); lack of awareness of previous studies and repetition of research in the same regions and communities resulting in research fatigue and waste of resources; and a reluctance or inability to initiate or maintain community-based research or monitoring because no data management system is available.

There is an urgent need for effective and appropriate means of recording, preserving, and sharing data and information being collected in Arctic communities.

The **Exchange for Local Observations and Knowledge of the Arctic**, (**ELOKA**), is working to fill this gap. (eloka-arctic.org)

To date, ELOKA has established partnerships with several current community-based research projects to develop data management services and products appropriate to their goals and needs. This work has resulted in two community-based research data management case studies that will be posted to our website in late 2009 and early 2010 (see section 2). Through the case study process, we have helped our partners evaluate their own existing data and data management procedures for preservation and distribution, and assisted them in making data management plans for future data collection efforts. We are establishing data management requirements based on the unique characteristics and nature of LTK data, which will allow us to create a data system supporting this valuable information and ensuring that it remains discoverable and relevant to a broad range of users from scientists, to communities, to educators and decision makers. At the same time, we are working with our partners to ensure that data are appropriately protected and assigned different levels of access where needed. We have also created the ELOKA web portal, a communication and outreach tool working to foster greater community involvement and interaction. In our work to date, we have identified more functions and services that are needed to support the discovery and inclusion of LTK and community-based research in Arctic science and initiatives like "A Study of Environmental Arctic Change (SEARCH)" and the "Arctic Observing Network (AON)." We have also found a greater need for education and outreach concerning data management goals and procedures.

ELOKA's mission is to provide a **data management service and user support** to facilitate the collection, preservation, exchange, and use of **local observations and knowledge** of the Arctic.

Science and Technology Development Highlights

A *new website* for ELOKA was designed and released in 2009.

- Web enhancements are ongoing including development of an LTK project catalog (in collaboration with the SAON) and creating an LTK Resources page.
- New tools were developed for ELOKA users and are being worked into the website:
    a. Metadata Collection Tool: Allows contributors to characterize their data submissions on-line providing ELOKA staff consistent metadata and way to preview submissions.
    b. ELOKA Project Registry: Users will be able to search for and access information about other arctic LTK and CBM projects and researchers via this online directory application.
    c. Interactive Video/Transcript Viewer: ELOKA is continuing work on a video streaming application for the presentation of interviews and their translations (currently under development).

ELOKA has made significant progress in *data handling* over the last year, including our first two test case data sets and our metadata requirements and tools development.

Case Study Data Sets

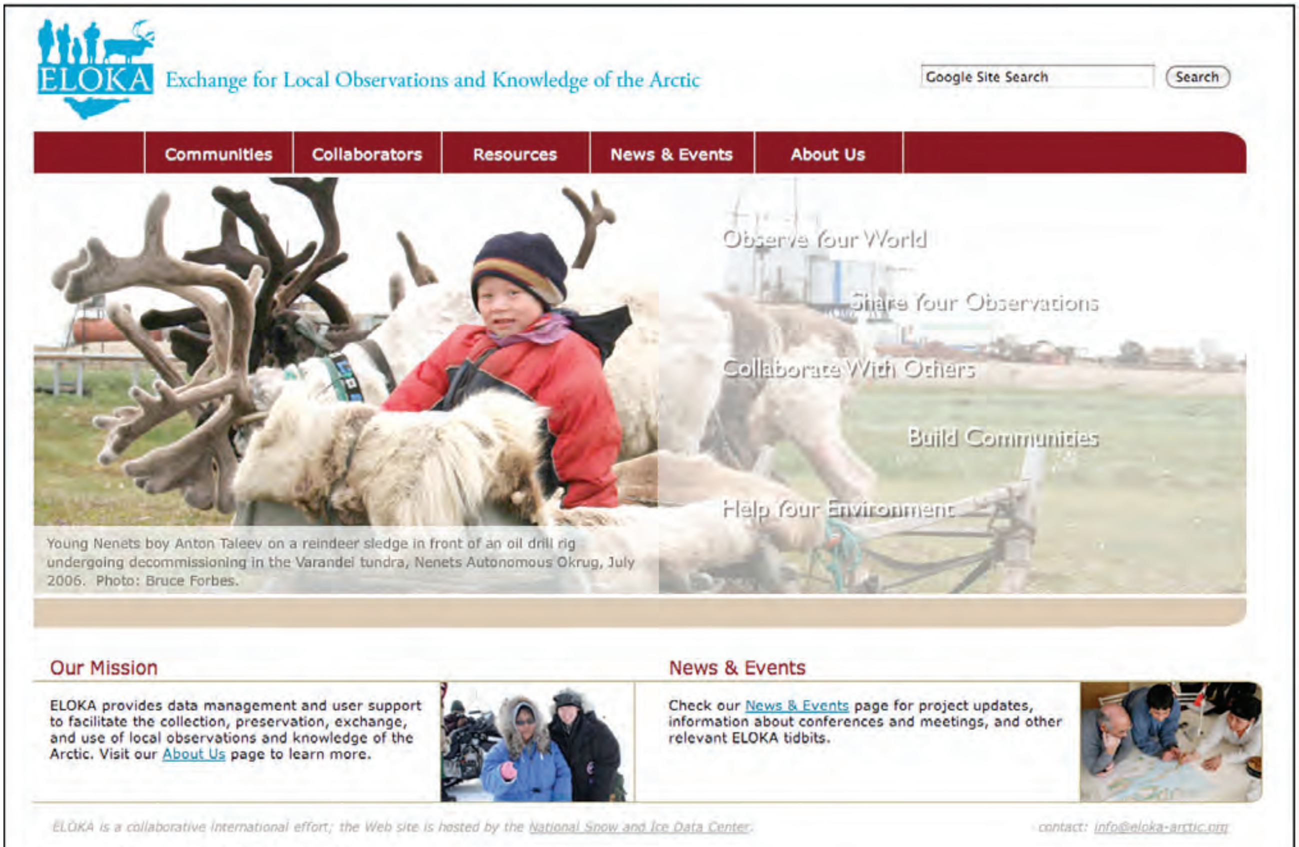
1. ***Partnership with Community of Sanikiluaq (Nunavut, Canada)***

   ELOKA and the Hamlet of Sanikiluaq are collaborating on the collection and distribution of information provided by local hunters as they describe changes in local sea ice conditions. The collection includes video, photos, and maps that characterize the sea ice changes and the adjustments the hunters are making to hunting practices and travel routes on the ice. A website devoted to the presentation of this collection is under development and will include background on the community and the surrounding Hudson Bay region, streaming video, photos, and maps detailing hunter observations. Release of the collection on the ELOKA website is expected by the end of 2009, conditional on approval by the community and hunters.

2. ***Partnership with Dr. Martin Nweeia, Harvard University Narwhal Tusk Project***

   ELOKA is also working with Dr. Nweeia and his collection of elder and hunter interviews gathered during his narwhal research into the function of their tusks. The data set includes interviews from Inuit elders and hunters from communities on Baffin Island and Greenland as they describe their observations of narwhal behavior and the whale's environment. Web-based presentation of these interviews is planned providing streaming videos and synchronized English translations with release expected in early 2010.

3. **ELOKA** is negotiating data management agreements with several other potential data contributors. If agreements can be reached work on these datasets could begin in early 2010. Collaborators include the Bering Sea Sub-Network (BSSN) and the SIKU (Sea Ice Knowledge and Use) projects.



Screenshot of ELOKA's homepage.

Metadata Development

Established metadata requirements necessary for online discovery and access, and linkage to other Earth science data systems, notably CADIS. We have also developed an online tool for collaborators to provide us with the detailed metadata necessary to develop rich products.

Other Developments

We are exploring the use of the Fedora Object Management System, which allows the management and tracking of complex e-science objects that may include multiple components (e.g., files, transcripts, videos, mylar overlays, digital maps, etc.). We are interested in how this system can help us manage ELOKA collections, but also how it might link to other data activities at NSIDC, including the NSF-funded Data Conservancy led by Johns Hopkins University.

Lessons Learned

We have learned a great deal about the unique challenges of managing LTK, however integrating LTK into other projects remains a challenge. As a first step we are developing a registry of projects, individuals, and organizations working with LTK in the Arctic. We have begun collaborating with SAON, who is constructing a similar list. We see this as a first step to simply identify what work is being done where so that researchers can be aware of the scope of information potentially available, to eliminate duplicative or redundant studies, and to help minimize "research fatigue" by some communities.

We have learned that data acquisition for LTK can be a lengthy and complex process involving much discussion and iteration around data description and presentation ideas. To help address this, we have begun developing an "ELOKA Handbook." This online resource will help answer many frequently asked questions and assist data providers in understanding more about the importance, details, and processes around data management. It will also guide users on the unique aspects of these data and their appropriate use.

We have also learned that data presentation approaches are often different than with traditional geospatial data. While the map remains a powerful and useful metaphor for data presentation, we have discovered that an approach highlighting individuals and cultures is essential to presenting the data in a way that is meaningful to the communities themselves as well as beyond. This will be evident in the two product sites.

Examples of Modified Activities Through Interactions with Other AON Projects

We have established contact with the Bering Sea Sub-Network (BSSN) and are discussing what data management services they might find useful. We have collaborated with the Cooperative Arctic Data and Information System (CADIS) to describe ELOKA data according to standard metadata formats and to make the data discoverable through CADIS.

Brief Examples of Data Use for Science and Stakeholder Needs

The first ELOKA data will be published in late 2009 and early 2010. We will be able to evaluate data use next year.

List of Publications, Web Sites

eloka-arctic.org

How ELOKA Fits with the Broader Suite of International Arctic Observing Efforts

- ELOKA is collaborating with the SAON to host an LTK project registry
- ELOKA services are being developed in collaboration with NSIDC and CADIS in order to link LTK and science data holdings and make these holdings discoverable together
- ELOKA has contributed to IPY Data management activities and is the leading LTK component of the IPY Data and Information Service
- ELOKA may be able to provide a model for effective management of LTK by other projects

Cooperative Arctic Data and Information System (CADIS)

James Moore and Don Middleton, National Center for Atmospheric Research (NCAR)
Florence Fetterer, National Snow and Ice Data Center (NSIDC)
Mohan Ramamurthy, University Cooperation for Atmospheric Research (UCAR)

Project Summary

The CADIS team is made up of two-dozen people from the supported organizations listed above. This team has been brought together in a collaborative project to develop a coordinated data management service to meet the needs of the Arctic Observing Network (AON). AON is a major contribution of the U.S. National Science Foundation (NSF) to the International Polar Year (IPY). CADIS is intended as a development project to bring community standards, visualization tools, data archival and stewardship expertise and vision to develop a data management support capability for AON. It creates a foundation for long-term access to data archives, discovery, delivery and analysis by the Arctic science community and other users. **AON Investigators had archived 161 data sets from 37 Investigators and 12 nations in CADIS by November 2009.**

Science and Technology Highlights

We develop and support the primary web pages for the AON Project data management activities. The site is: http://aoncadis.org/. This site contains detailed information about all of the AON projects, meeting summaries, and is the primary gateway to the AON data services including the CADIS system where PIs can publish metadata and data for their AON projects. The AON network as of November 2009 is shown in Fig. 2.

CADIS reached a major milestone in fall 2009 with the release and implementation of the user interface for metadata and data upload via CADIS Data Portal. NSIDC, NCAR and UCAR brought an unprecedented combination of experience and technical expertise together to develop, implement, test and refine the general user interface based on experience to date with AON investigator use of CADIS. Primary features include an advanced metadata authoring tool, web portal, data upload tool, semantic search, dataset download, interoperability with selected arctic archive sites (e.g., NSIDC, NCAR/EOL, Norway, British Antarctic Survey) and visualization tools for general project overview information. User support is provided to assist AON investigators with all aspects of the CADIS applications.

The development of new effective visualization capabilities is a key CADIS focus, and we made progress on several related fronts including:

- A GIS Mapserver capability for locating all AON measurement locations on a polar projection map (Fig. 2)
- A new map search interface for the NOAA/PMEL Live Access Server (LAS) will be developed to expose services for both point observation as well as gridded datasets
- Project level summary data using the Arctic Research Mapping Application (ARMAP) GIS interface that, among other things, shows AON observations in the context of other arctic observations
- Integration of the NSIDC JAZ Geographic User Interface into basic and advanced search functionality
- Develop data management tools for configuring Unidata's THREDDS Data Server (TDS) for potential real-time data access
- Began work on a mechanism for developing visualizations of datasets using the Unidata Integrated Data Viewer (IDV)

We have developed and tested the federation of metadata records between the CADIS gateway and partner national and international data centers based on using the Open Archive Initiative (OAI) Protocol for Metadata Harvesting (PMH) to share metadata records.

Lessoned Learned

There is a remarkable diversity of data types and formats, user expectations and implementation realities. Encompassing all of these things and providing a data management system that meets the needs of all potential users is the challenge being addressed by CADIS. It has been important to set achievable goals and remain flexible to changing requirements and new capabilities available to us.

The CADIS team used a questionnaire as part of the evaluation of CADIS after three years of system development and support to the AON community. Some key positive comments are that CADIS is the central location for accessing AON data and metadata. The support team has been very helpful in assisting data providers to organize and publish their data and metadata. A majority of AON investigators are willing to consider a structured ASCII data format for AON data, however it is also clear that remaining flexible regarding acceptable data formats was encouraged.

Some areas CADIS needs to work on include improving data searching within the archive itself as well as how researchers outside AON can find AON datasets in CADIS; increasing community awareness of CADIS and its capabilities; developing more effective support

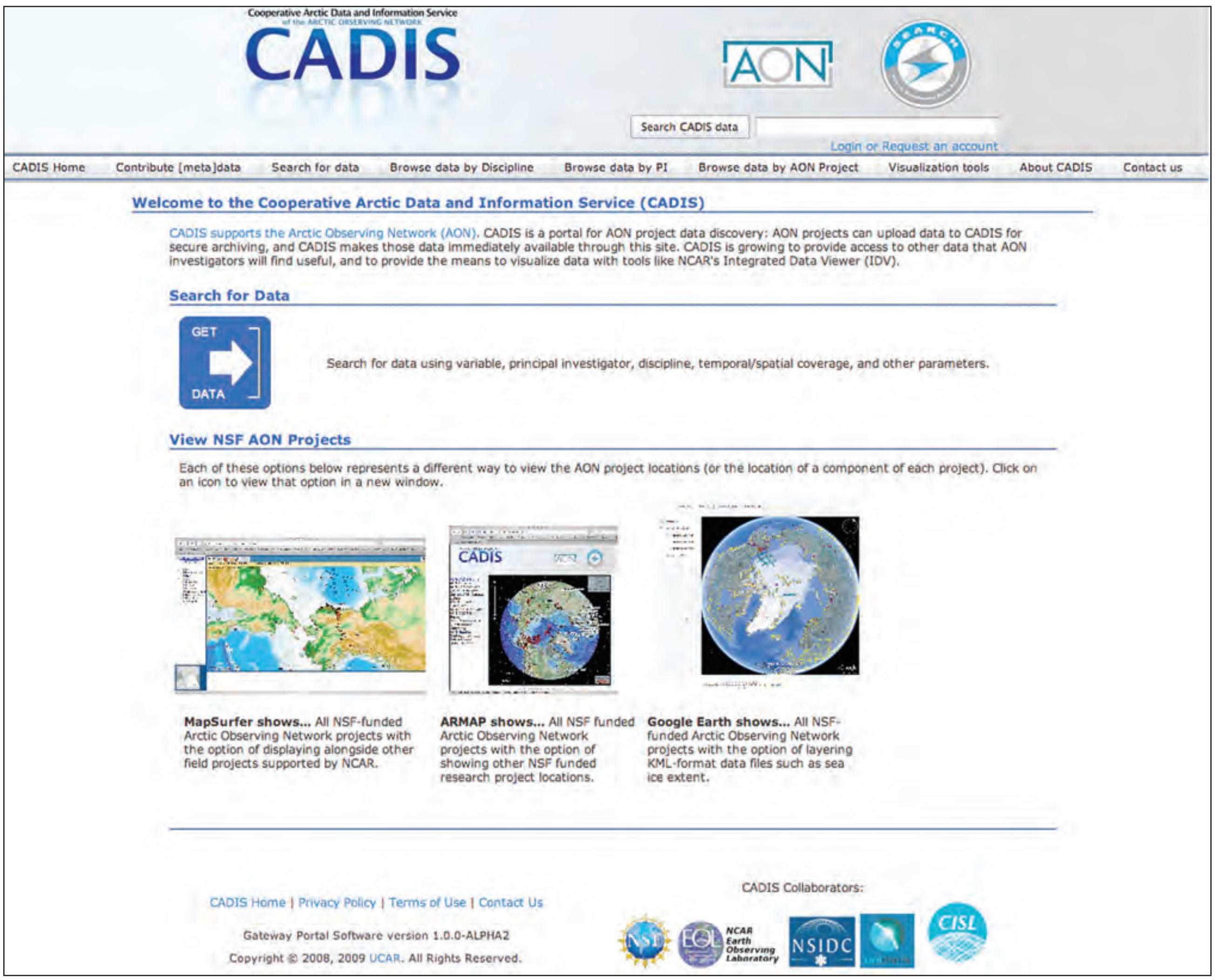


Figure 1. A Schematic of the AON CADIS Vision. CADIS will facilitate the exchange of data and information for AON data providers, the science community and stakeholders

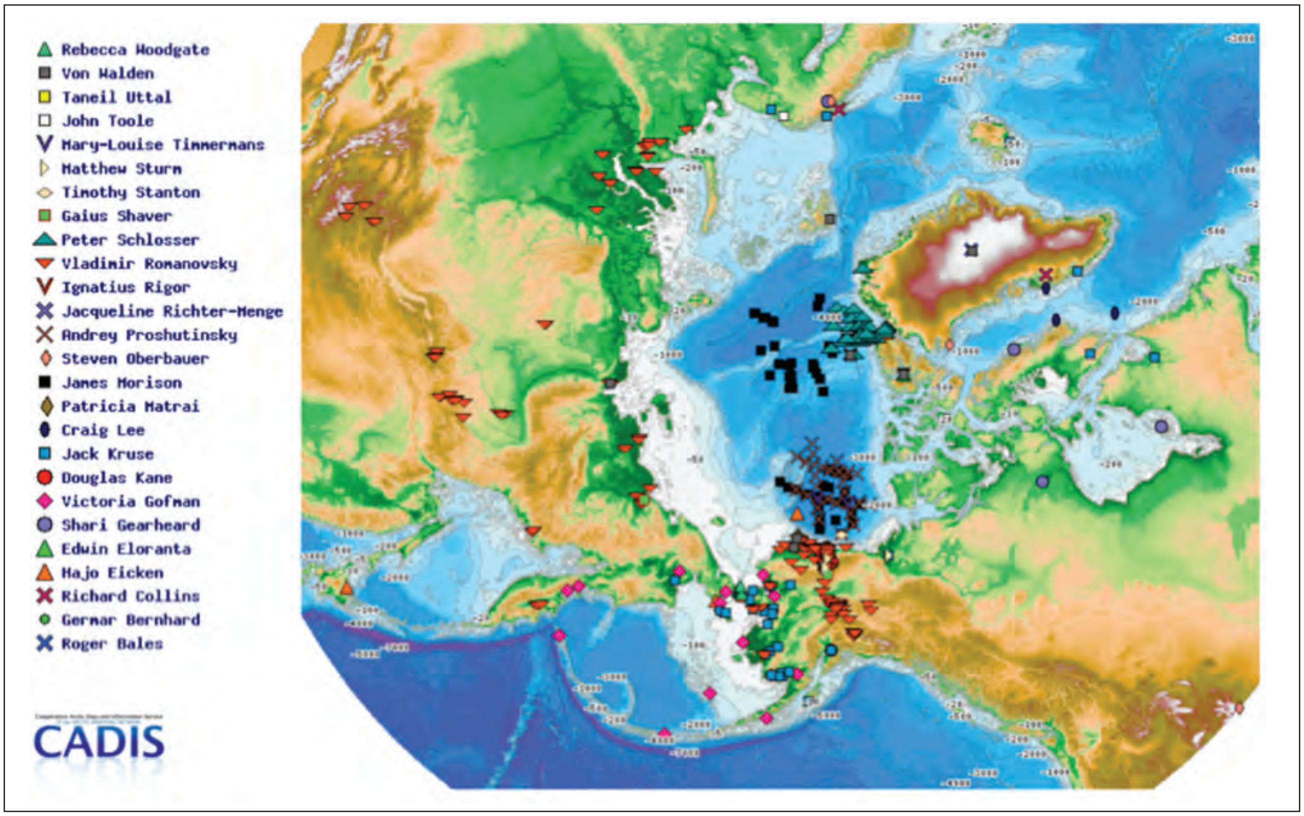


Figure 2. The AON Network geographic coverage as of November 2009. This plot was produced the CADIS GIS Mapserver tool. CADIS allows this information to be presented in Google Earth and LAS tools via the CADIS Portal. PIs listed by unique symbol and may have multiple observations sites.

for AON social science data and information; organizing data format conversion capabilities and improving map based search and visualization utilities. The AON investigators also recommended that CADIS expand links to other related datasets that will be used when analyzing basin-wide phenomena.

How Activities were Modified Through Interactions with Other Projects

The CADIS team distributed a data questionnaire to all AON investigators at the beginning of the network development in 2007. The information from this questionnaire was key in setting priorities and goals for the development of CADIS. We tried to tune the capabilities of CADIS to the needs of the AON PIs and balance this with the matching requirement to implement best practices in developing an effective and supportive data management system. We also met with PIs at several venues to seek out advice and perspective on our work to make sure we were developing a system to match the needs of the AON investigator team.

Examples of Data Use for Science and Stakeholders

The information contained in the AON archives on CADIS have been accessed and utilized by the NSF to summarize the work of AON in deploying the network across the pan-Arctic. The investigators are sharing the AON data for all manner of analysis. That said, CADIS still needs to improve so that the investigators refer others interested in AON data to CDIS as the access point.

List of Publications and Web Sites

http://aoncadis.org

Since CADIS was a development effort and in support of other AON investigators, our major 'publication' is the CADIS Portal for publishing, discovering, visualizing and downloading AON datasets.

All groups contribute to CADIS PI and management functions, engineering design and implementation, and general interfacing with various communities and projects. In addition, there were several presentations and discussions held on CADIS at meetings and other fora to inform the community of our activities and seek input from the community that would help focus CADIS capabilities. These included:

American Meteorological Society
January 2008 New Orleans, LA

Arctic Observation Integration Workshops
March 2008 Palisades, NY

Sustained Arctic Observing Networks Workshop
April 2008 Helsinki, Finland

GEWEX CEOP Meeting
September 2008 Geneva, Switzerland

Sustained Arctic Observing Networks Workshop
October 2008 Edmonton, Alberta, CA

American Geophysical Union
December 2007 & 2009 San Francisco, CA

Fit to International Arctic Observing Efforts

The CADIS team has significant experience in working with international data management groups. We have considered the applicability of international standards, especially for metadata, and have used several (e.g., IPY Metadata Standard, NASA GCMD, ISO) to guide the AON metadata profile.

Attention has been given to working with the International Arctic Systems for Observing the Atmosphere (IASOA) to develop pathways for bringing real time and post season datasets into the CADIS archive. These activities will be continued in the next year.

We have just confirmed the ability to exchange metadata and thereby develop important virtual links with international archives and data. Successful demonstrations have been completed with Norway, and further testing with the UK (British Antarctic Survey) and Canadian IPY archives are planned. This is an important step to providing seamless discovery and access to all Arctic data from all nations involved in this vital research.

CADIS Education and Outreach Efforts

Both the NSIDC and NCAR have strong education and outreach components in their organizational community support. CADIS has been advertised via links through both these centers but much more needs to be done. Obviously, the CADIS gateway itself must be considered as a major community outreach tool for AON. The CADIS team needs to focus on improvements to the gateway that will help the community to utilize the rich data contained in the AON archive. An outcome of the 2009 AON PI Workshop is to try to consolidate the diverse activities of the AON investigator community into an inventory of educational opportunities hosted in CADIS. Our hope is that the community will be able to discover these outreach activities via CADIS and then work with the investigators to access specific information of interest. In addition, we may consider the preparation of targeted educational materials in the future to help the larger community understand the focus and activities of AON.

Appendix G: Agenda

AON 2009 PI Meeting- Draft Agenda (11/29/09)

Objectives

(1) Review current (post-IPY) status of AON science achievements, network scope, lessons learned and future directions as IPY-support winds down.
(2) Broad look at the issues surrounding network design and optimization
    a. AON 'design' to-date (how we got to the SEARCH Implementation plan and beyond)
    b. Outside perspectives (ARGO, TOGA-TAO, OOI, etc)
(3) Integration with international efforts - placing US-AON in the broader frame of Arctic observing.
(4) Evaluate data dissemination/data flow, access and usage. Both for science and by stakeholders.

Outcomes and Products

Report that includes:

- Collection of short project progress reports, available on-line prior to meeting, also feeds plenary syntheses talks.
- Summary of lessons learned during the IPY.
- Assessment of key challenges impeding AON development.
- Recommendations for fostering international coordination and collaboration post IPY.
- Assessment of AON data usage by both science and stakeholders.
- Recommendations for encouraging/enabling more widespread data use.

Posters

Participants are encouraged to display posters detailing project achievements. Posters will be on display throughout the entire meeting. The Welcome Reception on Monday evening will provide an opportunity for poster viewing.

Monday, 30 Nov

0745-0815 Registration/Badge Pick-up- (Flagstaff Ballroom Foyer)

Poster room available for poster set up. (Canyon Room adjacent to Flagstaff)
Coffee will be available inside Canyon Room.
Those staying at the Millennium can get the breakfast included with lodging in the first floor Café. Coupons are provided at check in.

0815 Introductory Talks (Flagstaff)

- Meeting Logistics (10 min, local hosts)
- AON Status and Future Directions (15 min, Martin Jeffries)
- Arctic and climate following the IPY (20 min, Mark Serreze)

0900 - 1145 Disciplinary Overview Talks (Session Leader, Craig Lee)
Integrated progress reports for each discipline at the end of the IPY. Network status, science and technology highlights, lessons learned, system gaps, future objectives and activities, obstacles and challenges. Drawn from the short Project Reports, personal communication with PIs and personal perspective.

- Ice-ocean (30 min, Mike Steele)
- Atmosphere (30 min, Taneil Uttal)
- Hydrology (30 min, Max Holmes)

1030 - 1045 Coffee Break *(Canyon Room adjacent to Flagstaff)*

- Terrestrial Ecology (30 min, Gus Shaver)
- Human Dimensions (30 min, Maribeth Murray)

1145 - 1200 General Discussion

1200 - 1315 Group Lunch – no charge *(Canyon Room adjacent to Flagstaff)*

1315 - 1415 Agency Overview Talks (Session Leader, Taneil Uttal)
Summarize AON contributions from outside NSF.

- NOAA (15 min, John Calder)
- NASA (15 min, Fred Lipschultz)
- DOI (15 min, Pete Murdoch)
- ONR (15 min, Scott Harper)

1415 - 1600 Network Design Talks (Session Leader, Hajo Eicken)

- ADI Task Force Overview (15 min, Hajo Eicken)
- IABP as an early example of AON design (15 min, Ignatius Rigor)
- ARGO (15 min, Breck Owens)

1515 - 1530 Coffee Break

- Permafrost Network (15 min, Vladamir Romanovsky)
- IASOA (15 min, Darby/Uttal)

1600 - 1730 Breakout Groups - Network Design and Optimization

Group 1-Suite 231: facilitator- Max Holmes, rapporteur- Syndonia Bret-Harte

Group 2- Suite 331: facilitator- Mary Louise Timmermans, rapporteur- Larry Hamilton

Group 3-Suite 431: facilitator- Taneil Uttal, rapporteur- Jim Moore

Group 4-Boulder Creek Living Room: facilitator- Von Walden, rapporteur- Lisa Darby

Parallel groups: all groups address the following questions:

- What lessons can be taken from the design of other observing networks? Are there other examples that the AON community should consider?
- What can be done now by individual AON projects to prepare ground for design and optimization studies; what are the types of design/optimization activities currently employed?
- What level of specificity should design activities aim to provide? For example, should design efforts recommend variables to monitor, general locations and levels of uncertainty, or should they specify exact instrument locations and sampling schemes?
- What tools and approaches hold promise for design exercises and how can they best leverage existing AON projects?

1730 - 1900 Welcome reception/poster session with heavy hors d'oeuvres and cash beer and wine bar**.** (Canyon Room adjacent to Flagstaff)

Tuesday, 1 Dec

Coffee will be available inside Canyon Room adjacent to Flagstaff.
Those staying at the Millennium can get the breakfast included with lodging in the first floor Café. Coupons are provided at check in.

0815 - 0915 Network Design and Optimization Plenary Summaries and Discussion (4 groups 10 min+ 5 min for discussion, Moderator, Hajo Eicken)

- Each group summarizes discussions.
- Plenary discussion to integrate into a single set of answers.

0915 - 1015 Integrating Activity Talks (Session Chair: Mary-Louise Timmermans)

- Sea Ice Outlook (15 min, Walt Meier)
- AOMIP (15 min, Andrey Proshutinsky)
- Remote sensing (15 min, Walt Meier)
- North Slope Science Initiative (15 min, Denny Lassuy)

1015 - 1030 Coffee Break

1030 - 1145 Data Dissemination and Usage Talks (Session Chair: Jim Moore)

- Status of SEARCH Data Advisory Group activities and planning as relevant to AON data and dissemination efforts (15 min, Steve Oberbauer)
- Example(s) of data delivery to stakeholders and subsequent usage (15 min, Hajo Eicken)
- CADIS overview and Q & A including results from the questionnaire (30 min, Jim Moore)

1145- 1315 Lunch ***This will be a special 90 minute lunch to allow AON PIs and meeting participants the opportunity to work with CADIS team members to use and evaluate the CADIS user interface. This can include usability testing and user help for entering AON data and metadata. CADIS Lunch will take place in the main meeting room.***

1315 - 1500 International Coordination Talks (Session Chair: Mairbeth Murray)

- S4D Summary (15 min, Peter Schlosser)
- ISAC Overview (15 min, Michael Tjernström)
- SAON (15 min, David Hik)
- DAMOCLES/ACOBAR (15 min, Jean-Claude Gascard)
- Norwegian Polar Institute Ice Center (15 min, Edmond Hansen)
- ArcticROOS (15 min, Georg Heygster)

1500 - 1515 Coffee Break

1515 - 1715 Breakout Groups- Challenges to AON Development
As in previous breakout, use OCP members as facilitators and rapporteurs.
Assign each group one task.

- Identify gaps in scientific understanding, technology development, logistical capacity and/or political concerns pose challenges to AON design & implementation.

Facilitator: Mary Louise Timmermans, Rapporteur: Max Holmes

- Develop recommendations for promoting international coordination and collaboration. How do we build connections both within the Arctic community and with the lower latitude communities?

Facilitators: Taneil Uttal, Rapporteur: Von Walden

- Develop recommendations for enhancing accessibility & utility of AON data., including CADIS and other data access systems. Both science and stakeholder uses.

Facilitators: Syndonia Bret-Harte, Rapporteur: Jim Moore

Wednesday, 2 Dec

Coffee will be available inside Canyon Room.

Those staying at the Millennium can get the breakfast included with lodging in the first floor Café. Coupons are provided at check in.

0800 - 1000 Plenary Summaries and Discussion (Moderator: Craig Lee)

- Each group summarizes discussions.
- Plenary discussion to refine breakout findings.

1000 - 1015 Coffee Break

1015 - 1030

- Baseline Surface Radiation Network (15 min) Ellsworth Dutton

1030 - 1200

Action Items and Meeting Report
Project summaries on the web site
Other issues

1200 Meeting Adjourn

Appendix H: Participants

Attendee List
Arctic Observing Network PI Meeting
November 30, 2009 – Boulder, CO
Participants: 89

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