SEARCH WORKSHOP ON LARGE-SCALE ATMOSPHERE–CRYOSPHERE OBSERVATIONS

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A multivariate, multidisciplinary Arctic observing system is key to the resolution of climate change issues.

The Arctic has undergone significant temperature swings over the last 100 years. In the past three decades, there have been demonstrable Pan-Arctic environmental changes. The areal coverage of sea ice has diminished and sea level pressures in the central Arctic have decreased, resulting in a shift of wind and heat flux patterns. Warmer surface temperatures are observed in northern Europe during winter and in Alaska and northwest Canada during spring, there is an increase in the frequency of years with cold temperature anomalies in the lower stratosphere over high latitudes, and permafrost temperatures have risen in Siberia and Alaska, with increased erosion. Satellite estimates of "greening" have increased over both the Eastern and Western Hemispheres, with longer growing seasons and changes in the character of the tundra. The influence of warm Atlantic water in the Arctic Ocean is becoming more widespread and intense, with implications for the stability of the upper-water column (Serreze et al. 2000). These changes are robust, and many other biological and physical changes are suggested—increases in cod in the Barents Sea and shrimp off of southern Greenland, increases in calf survival for some caribou populations in North America, and declines and redistributions of marine mammal populations, although the causes for these changes are less certain. It is important to recognize that these events have already occurred or are under way, and that it is desirable to anticipate their future course or at least assess their potential range. These observed changes have made it more difficult for those who live or work in the north to predict what the future may bring.

The interagency Study of Environmental Arctic Change (SEARCH) program is based on the principle

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that these atmospheric, oceanic, and terrestrial changes are interrelated, with consequences for ecosystems and society, and with impacts on midlatitudes (more information available online at http://psc.apl.washington.edu/search). A hypothesis of SEARCH is that the changes are related to a rising trend in the Arctic Oscillation (AO), a mode of atmospheric variability that is potentially active over a broad range of timescales (Thompson and Wallace 1998). Here the AO phenomenon is used to broadly describe the strengthening and increased zonality of the polar vortex as shown by the AO and related teleconnection indices. A major task for SEARCH is to determine how existing observation systems can be best used and enhanced to understand and anticipate the course of the ongoing changes in the Arctic. A workshop was held in Seattle, Washington, during 27–29 November 2001 to review existing land, sea ice, and atmospheric observations, and the prospect for an Arctic System Reanalysis to provide a comprehensive depiction of these changes. The workshop review was based on white papers, invited speakers, panels, and input from the 68 scientists who participated. A full report is available online at the workshop Web site (www.epic.noaa.gov/SEARCH/obs/workshop). Assessment of the equally important areas of paleoenvironmental, biological, ocean, and human observations was beyond the scope of the initial effort and is the focus of future summaries.

AN ARCTIC CHANGE DETECTION SYSTEM.

A major workshop conclusion is that *present datasets are vastly underutilized in understanding Arctic change.* Barriers include lack of conceptual models for conducting interdisciplinary analyses, data accessibility, various data formats, spatial inhomogeneity, and lack of easily applied tools for visualization and analysis of multidisciplinary data. SEARCH can provide solutions by harnessing existing methodologies and technologies.

A goal of SEARCH is to understand and project the future course of the recent and ongoing interrelated, multivariate changes in the Arctic. A recommendation at the workshop was that SEARCH would be well served by *developing a protocol for detection of Arctic change.* Such an operational definition would help refine SEARCH hypotheses, aid in prioritizing an observational system, and improve communication of SEARCH results. By utilizing different lines of evidence for Arctic change, SEARCH can provide a comparative, interdisciplinary approach.

As used by SEARCH, "detection" has a broader context than is generally used by the climate change community. The climate change community often uses detection in the narrow sense that some indicator, such as global surface temperature, exceeds the range of background noise of natural climate variability (Barnett et al. 1999), for example, due to anthropogenic and other external factors. For the many ecosystem and societal applications of SEARCH, it is important to understand the ongoing changes in the Arctic, whether they are natural or external.

Three candidates for the development of a protocol for detection are 1) comparison of conceptual models of Arctic variability, 2) the use of multiple lines of evidence, and 3) selection of robust indicators for the impact of Arctic change on midlatitude climates.

A comparison of conceptual models will sharpen the focus for the detection problem. The mean annual surface temperatures for the Northern Hemisphere in the twentieth century increased until about 1940, slightly decreased until the early 1970s, and increased through 2000. Changes in the Arctic mirrored the Northern Hemisphere with, perhaps, a greater relative increase in the 1930s. These temperature changes are reflected in other variables such as the strength of the polar vortex and ice extent. Extrapolation models for the atmosphere (Polyakov and Johnson 2000) and for sea ice (Venegas and Mysak 2000) suggest constructive interference in the 1990s of a 60–80-yr low-frequency oscillation, and decadal-scale variability associated with the AO. These authors imply that a forward projection would suggest a major reversal of previous trends in 2000–30. An alternative model comes from the Global Climate Model hindcast for the twentieth century completed for the Intergovernmental Panel on Climate Change (IPCC; Stott et al. 2001). Results attribute the temperature maximum in the 1940s to a weak solar influence plus natural variability in the four ensemble runs. However, the models could not reproduce the temperature increases of the 1990s without including increased CO_2 forcing. Thus, the IPCC conceptual model would project increased warming in 2000–30 after a brief minimum associated with the decadal change of the AO. At present, neither the evidence nor the understanding of polar processes is available to unequivocally distinguish between these scenarios.

SEARCH can provide a more formal compilation of information to address multivariate aspects of change. One can attempt to reduce the dimensionality of the system by selecting relatively independent lines of evidence instead of subsets that covary in time or have similar spatial patterns. The process can be transparent and several approaches can be taken for detection. For example, the time series can be combined into a single attribution, with greater confidence than for any individual variable. Alternatively, each series can be tested separately, and detection can be based on categories, such as "most" of the evidence, the "balance" of the evidence, or "some" of the evidence depending on the number of series that pass a given detection criteria. (A beginning of a SEARCH data collection is available online at www.unaami.noaa.gov.)

At the workshop, M. Wallace showed an example of research driven by a potential application. Thompson et al. (2002) noted the number of days during winter when 14 cities had extreme cold temperatures, colder than 1.5 of the standard deviation from the mean value. The number of cold days associated with a weak polar vortex (negative AO) was about double the number associated with the strong vortex (positive AO). They further showed that the magnitude of the temperature change associated with the AO was about 3°C over northern midlatitudes, about the same magnitude as the influence of a shift from El Niño to La Niña. Thus, by focusing on extreme events rather than mean values, these authors demonstrated a practical midlatitude influence of the AO.

AN ARCTIC OBSERVING SYSTEM. A second workshop conclusion is that *there is inadequate cohesion among various Arctic disciplines and data types to form a complete observation set of Arctic change.* This situation results from several factors. Many routine observations were not designed specifically for climate studies. Many research studies are of limited duration at diverse and uncoordinated locations. Temporal intercalibration is lacking between datasets due to changes in instrumentation or satellites. In short, there has been no program like SEARCH to promote and support basinwide, continuous, long-term, multidisciplinary datasets in the Arctic.

A distributed observing system for the Arctic must accommodate a wide range of spatial patterns of variability. A hypothesis of SEARCH is that many Arctic processes, both biological and physical, show Arcticwide covariability, both for individual variables and between variables. However, even for parameters such as surface temperature, there is not one fixed mode of variability, and patterns shift on seasonal and decadal scales. This leads to the following criteria for a distributed multivariate observation set:

- Observations should be Pan-Arctic.
- Observations should resolve variability on a scale of 500 km, which is typical of meteorological or different ecosystems length scales.
- Observations should emphasize both regions of large decadal variability and long-term trends; priority is given to locations with long records.
- Observations must be multivariate. Detection, diagnosis, and prediction is improved by using multiple indicators.
- Data from observations must be accessible. This includes future observations and retrospective datasets.

Atmospheric observations and recommendations. A goal for SEARCH is to provide an Arctic component to the global change community by providing a focus for Arctic observations and parameterization of Arctic processes in climate models. Thus, the recommendation for atmospheric observations in SEARCH is primarily to augment current atmospheric observing systems and for quality control of operational data.

Forming the backbone of an observing system are the World Meteorological Organization (WMO) sites (2455 sites north of 50°N) and current and future environmental satellites. Arctic scientists share the difficulties of the larger climate community in using the data for decadal timescales, for example, issues of accuracy, length, and continuity of the records, urbanization, and changes in location and instrumentation type. *Although the current set of WMO surface observation stations is adequate for many SEARCH purposes, we advocate continuation of quality measurements, intercomparison of measurements, and easily accessible, current archives of value-added datasets.* It is unfortunate that the Arctic stations included in the Global Climate Observing System (GCOS) Surface Network (GSN; 244 sites north of 50°N)—selected for quality, continuity, and longevity—are too sparse to adequately monitor potential spatial variability of Arctic change.

Coverage in the central Arctic is available through the International Arctic Buoy Program (IABP), which has maintained sea level pressure observations in the Arctic since 1979. SEARCH can support IABP by providing improved logistics to keep a uniform grid of observations in place and enhancing the sites with additional sensors.

The number of northern upper-air profiling stations from WMO is just 10% (238) of the number of surface stations. The number is particularly low over the high Arctic land areas and nonexistent over the Arctic Ocean Basin. SEARCH has the opportunity to improve the situation by converting the 22-yr historical Television Infrared Observational Satellite (TIROS) Operational Vertical Sounder (TOVS) data to a climate quality dataset by minimizing the biases in the radiances for the Arctic region. SEARCH sees great utility for value-added, gridded, Pan-Arctic datasets from satellite data, such as cloud, vegetation, and radiation fields. Direct measurements for calibration and validation are a particularly important element for a climate change observing system. A review of satellite and data center issues is provided by the National Research Center's (NRC's) report (Walsh et al. 2001).

In addition to distributed and satellite-based observing systems we will need a small number of strategically placed long-term, intensive ground-based atmospheric observing stations on land with an option for making similar measurements on ice breakers, ice camps, and field experiments. Such sites provide baseline information and allow calibration and validation of remote sensing applications for the distributed observing system. Intensive measurements would include spectral and broadband radiation fluxes, surface albedo, clouds, aerosols, CO_2, and greenhouse gases. Currently, and historically, sites are operated at Barrow, Alaska, and Kiruna, Sweden, with some observations in northeast Canada and Svalbard. Given the spatial dependence of several environmental parameters in the Arctic, augmenting observations in northeast Canada is a priority.

Terrestrial observations and recommendations. There are a large number of terrestrial parameters that can track change in the Arctic. For land cover there are tree and shrub lines, growing season, and snow extent and depth. For soil thermal regime there are permafrost temperatures and extents, and freeze–thaw duration. For hydrology there are precipitation, river flow, areal extent of lakes, and mass balance of glaciers. A particular advantage of these measurements is that they are usually integrated measurements, often providing a natural smoothing to intraseasonal meteorological variability. *SEARCH should advocate continued quality-controlled terrestrial data from land cover, permafrost boreholes, glacier and lake monitoring sites, and coordinated runoff measurement activities.*

The Normalized Difference Vegetation Index (NDVI), based on the Advanced Very High Resolution Radiometer (AVHRR) satellite sensors provides an index of "greenness," which has increased 12% for Eurasia and 8% for North America since 1982 for April–October averages (Zhou et al. 2001), and is consistent with local measurements of expanding growing seasons, greater growth of trees, and expansion of shrub tundra. For the previous decade the International Tundra Experiment (ITEX) has monitored growth of shrubs at 27 Arctic sites. SEARCH should make the best use of calibrated satellite sensing of vegetation changes supported by continuing selected ITEX sites and IGBP transects. IGBP transects provide detailed information along six north–south lines that track in situ changes around the Arctic Basin.

A north–south network of boreholes in Alaska, in operation since 1983, has documented that permafrost temperatures at 20-m depth have increased. Boreholes already exist along four other transects in western and eastern Canada and western and eastern Siberia. The International Permafrost Association is implementing a Global Terrestrial Network for Permafrost (GTN-P) as part of GCOS.

The National Aeronautics and Space Administration (NASA) airborne laser measurements have identified changes in the Greenland ice sheet in the 1990s. The proposed Ice, Cloud, and Land Elevation Satellite (ICESat) mission has the potential to provide systematic coverage of the Greenland ice sheet. Elsewhere across the Arctic the smaller glaciers exhibit a mixed response, but are generally shrinking in recent decades, except in Scandinavia due to winter precipitation increases.

Although there are many conventional datasets in precipitation, they do not provide adequate coverage of polar regions. Biases are a large problem due to the use of different gauges, undercatch of snowfall, and sensitivity to wind speed. While corrections can be made, large errors remain. Data on snow extent since 1972 are available at 25-km spatial resolution and weekly temporal resolution, but volume and snow–water equivalent amounts are difficult to estimate. Serreze et al. (2000) note about a 10% decrease in snow cover over this period for the Northern Hemisphere. River discharge is typically obtained from gauging stations. While it is disconcerting that the number of monitoring stations has been dropping in recent decades, only 12 gauges are sufficient to capture 57% of the runoff from major rivers flowing into the Arctic (Shiklomanov et al. 2002). The National Science Foundation (NSF) is beginning a program focused on Arctic hydrology as part of SEARCH, called the Community-wide Hydrological Analysis and Monitoring Program (CHAMP).

Sea ice observations and recommendations. Sea ice cover is a critical component of the Arctic environment, largely controlling the energy exchange between the atmosphere and ocean. Sea ice also appears to be a sensitive indicator of changes in the global circulation system; ice motions based on satellite data, and drifting buoys since 1978 show a relation to the North Atlantic Oscillation (NAO; Kwok 2000). Kwok's results and the modeling results of Proshutinsky and Johnson (1997) suggest that during a positive NAO both the Beaufort gyre anticyclonic motion and the transpolar drift stream weaken and shift toward the Canadian basin. Tucker et al. (2001) suggest that the rapid apparent thinning of the sea ice in the central Arctic Basin (Rothrock et al. 1999) in the late 1980s was consistent with the shift toward a positive AO.

Monitoring sea ice extent is successfully achieved using microwave sensors on satellites. Data on ice extent exists from the mid-1970s and will continue to be collected and archived for the foreseeable future.

The workshop recommends that efforts to accurately track sea ice thickness be given high priority. Although this is a difficult task, it is most important for climate change as a thinner ice cover would dramatically change the Arctic heat balance. Specifically, current generation sea ice models and existing direct measurements should be used to develop an observational strategy employing submarine transects, moored upward-looking sonar, and instrumented drifting buoys to monitor changes in thickness over time. Preliminary estimates based on a 48-yr model hindcast have been made by R. Lindsay and J. Zhang to demonstrate the feasibility of this approach. Locations near the North Pole are more suitable for tracking the change in mean ice thickness averaged over the basin, while locations in the East Siberian Sea and near the Canadian Archipelago are more suited for tracking decadal shifts. More retrospective investigations are necessary, however, as the long-term behavior of sea ice in various Arctic regions is a controversial issue.

AN ARCTIC SYSTEM REANALYSIS. An objective of the SEARCH workshop was an assessment of the desirability and viability of an Arctic system reanalysis, which would merge historical atmospheric, oceanic, terrestrial, and sea ice data with models of the evolving Arctic system. *The workshop concluded that a compelling case can be made for an Arctic system reanalysis.* First, the reanalysis would produce long time series of temporally consistent fields (subject to changes in observing system input) of Arctic upper-air and surface winds, humidities, and temperatures for studies of circulation variability (e.g., the AO, NAO, and their Arctic manifestations), for budget studies, and for the driving of sea ice, ocean, and terrestrial models. Second, the reanalysis would provide a context for evaluations of ongoing and future changes in the Arctic, enabling a key goal of SEARCH to be addressed. Third, the reanalysis would provide fields for which direct observations are sparse or problematic (e.g., precipitation, evapotranspiration, radiation, and clouds). The fields would be at relatively high resolution (e.g., 30 km), which is especially valuable in topographically and coastally complex areas. Fourth, the system-oriented approach required for a reanalysis would provide a community focus, involving at least the Arctic terrestrial, sea ice, and atmospheric communities. Fifth, the reanalysis would leverage upon, and provide a synthesis of, recent Arctic field programs [the Surface Heat Budget of the Arctic (SHEBA), the Land–Atmosphere–Ice Interactions/Arctic Transitions in the Land–Atmosphere System (LAII/ATLAS) study, and the Atmospheric Radiation Measurement (ARM) Program] capitalizing upon prior investments by bringing field results to bear upon the parameterizations used in large-scale models. Finally, the groundwork for an Arctic regional reanalysis is now being laid by the improvements inherent in the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) and by the National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR). The coincidence of this groundwork and the beginning of SEARCH provides a unique opportunity for an Arctic system reanalysis.

In summary, the workshop showed the feasibility of combining climate observations, modeling, and ongoing research to establish an Arctic Change Detection System. Understanding of the Arctic can improve change detection due to the roles of vegetation type, sea ice and other feedbacks in providing a multiyear memory for the climate system. Future activities in SEARCH will further develop this concept from the perspectives of biological, oceanographic, human, and paleoenvironmental investigators, and strengthen international coordination through the Cryosphere and Climate Project (CLIC) and a joint SEARCH–CLIVAR working group. We wish to thank the workshop attendees and those who contributed materials to the workshop report.

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