SEARCH Workshop on Large-Scale Atmosphere/Cryosphere Observations

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1.   Executive Summary

The Arctic environment has undergone significant temperature swings over the last 100 years. Over the last 30 years trends show surface temperature warming, melting permafrost, reduced sea-ice, longer growing seasons, and changes in the character of tundra. These changes are robust, and many other biological and physical changes are suggested—redistribution of marine populations, unusually cold stratospheric temperatures, changes in Icelandic and Aleutian midlatitude storm tracks, and shifts in ocean circulation. The Study of Environmental Arctic Change (SEARCH) is based on the principle that this complex suite of atmospheric, oceanic, and terrestrial changes are interrelated, with impacts on ecosystems and society.[1] 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.

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. The purpose of the workshop held in Seattle during 27–29 November 2001 was to review existing land, sea ice, and atmospheric observations and the prospect for an Arctic System Reanalysis, through white papers, invited speakers, and panels.[2] Assessment of the equally important areas of paleo-environmental, biological, ocean, and human observations were beyond the scope of this effort and are the focus of a future summary. Sixty-eight scientists participated (Appendix B), and reviews of the areas addressed form the major chapters of this report. Future efforts across a broad spectrum of disciplines will be accomplished through the SEARCH Panel on Detection/Observations.

The primary workshop conclusion is that *there is no 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 data sets due to changes

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[1]Serreze *et al.*, 2000; SEARCH Science Plan, 2001, `http://psc.apl.washington.edu/search`; Unaami website: `http://www.unaami.noaa.gov`

[2]Agenda—Appendix A, website `http://www.epic.noaa.gov/SEARCH/obs/workshop`

in instrumentation or satellites. In short, there has been no program like SEARCH to promote and support basin-wide, continuous long-term, multi-disciplinary data sets in the Arctic.

A second workshop conclusion is that *present data sets are vastly under-utilized 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 vi-sualization and analysis of multi-disciplinary data. SEARCH can provide solutions by harnessing existing methodologies and technologies.

A third conclusion is that *a distributed observing system must accommo-date a wide range of spatial patterns of variability.* A hypothesis of SEARCH is that many Arctic processes, both biological and physical, show Arctic-wide covariability, both for individual variables and between variables. Research has indicated that even for parameters such as surface temperature, there is not one fixed mode of variability and that patterns shift on seasonal and decadal scales. This conclusion leads to the following criteria:

- Observations should be pan-Arctic.
- Observations should resolve variability on a scale of 500 km, which is typical of meteorological length scales, or different ecosystems.
- Observations should be located in regions of large decadal variability and long-term trends; priority should be given to locations with long historical records.
- Observations must be multi-variate. Detection and prediction is im-proved by using multiple indicators.
- Data from observations must be accessible. This includes future ob-servations and making available retrospective data sets.

The following bullets provide examples of activities that would address the first SEARCH workshop conclusion *"There is no cohesion among various disciplines and data types to form a complete observation set of Arctic change"*:

- Advocate for continued quality-controlled data from surface-based and satellite weather sensors, permafrost boreholes, glacier and lake moni-toring sites, and coordinated runoff measurement activities.
- Make the best use of satellite sensing of vegetation changes supported by continuing selected International Tundra Experiment (ITEX) sites and IGBP transects.
- Develop a climate quality, four-dimensional temperature data set over the Arctic by upgrading the TOVS soundings by bias removal.
- Enhance logistics and sensor suite for the International Arctic Buoy Program (IABP).
- Continue to monitor sea ice extent with microwave sensors from satel-lite, and use current generation sea ice models and data to design a system for direct observations to track changes in ice thickness.

Sfc. temperature trend 1950–96 (C/decade)   AO surface temperature anomalies (C) 1950–96
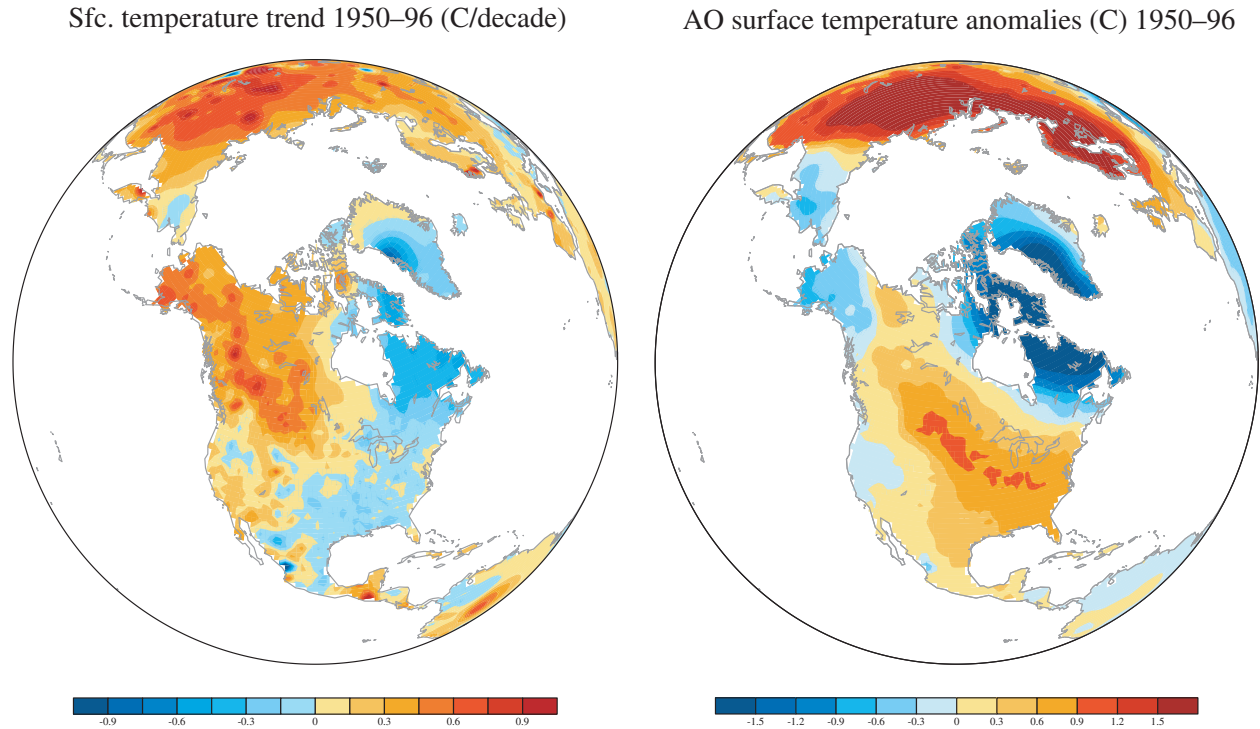
Figure 1.1: A map of 50-year trends of Northern Hemisphere winter temperatures; (right) the regression of local temperatures on to the wintertime AO index (JISAO website).

- Support the utility of long-term intensive measurement sites, especially radiation and chemistry, at Barrow, Alaska, Kiruna, Sweden, and Svalbard, with enhanced measurements in northeast Canada and Siberia.
- Initiate summaries of biological, oceanographic, and human observations. Note the existing Paleoenvironmental Arctic Sciences (PARCS) data archive at `http://www.ngdc.noaa.gov/paleo/parcs`.
- Strengthen international coordination.

The following bullets provide examples of activities that would address the second workshop conclusion, *"Present data are vastly underutilized in understanding Arctic change"*:

- Initiate a high-resolution Arctic System Reanalysis.
- Develop a protocol for detection of Arctic change.
- Develop multiple lines of evidence for change and make evidence available at a single website location.
- Support gridding and time intercalibration of satellite products for the Arctic.
- Support standards for data sets and metadata to readily permit timely sharing of information and enhance multidisciplinary analyses.

As an example of the third workshop conclusion, that *"A distributed observing system must accommodate a wide range of spatial patterns of variability,"* Fig. 1.1 (left) shows the map of wintertime temperature trends for the Northern hemisphere for the previous 50 years. There is large-scale spatial covariability, with warming trends over eastern Siberia and northwestern North America, and cooling over NE Canada and, to some degree, west of Bering Strait. To the right is shown the regression of temperatures at each location onto the Arctic Oscillation (AO), an index of northern hemisphere atmospheric circulation. The temperature pattern for the AO is similar to the 50-year trend in NE Canada and eastern Siberia, but there are differences: the AO has a stronger response in Scandinavia, and the cold region near Bering Strait now extends over Alaska. Eastern and midwest North America now shows warming. Even for surface temperatures there is not one fixed mode of variability; indeed these patterns shift on seasonal and decadal scales (Overland *et al.*, 2002).

1.1   References

Overland, J.E., M. Wang, and N.A. Bond (2002): On the recent temperature changes in the western Arctic during spring. *J. Climate, 15*, in press.

SEARCH Science Plan (2001): available at `http://psc.apl.washington.edu/search/`

Serreze, M.C., and coauthors (2000): Observational evidence of recent change in the northern high latitude environment. *Clim. Change, 46,* 159–207.

2. Detection of Arctic Change

One of the goals of SEARCH is to project the future course of the recent and ongoing decadal (e.g., 3–50 year), pan-Arctic complex of interrelated changes in the Arctic. A major suggestion at the workshop was that SEARCH would be well served by further developing the definition of detection of Arctic change. Change in the Arctic is multivariate and understanding the interrelation of the parts is a goal of SEARCH. Nevertheless, developing an operational definition would:

1. Help refine SEARCH hypotheses,

2. Aid in prioritizing an observational system, and

3. Improve communication of SEARCH results.

Therefore, a recommendation of the workshop is:

- *Develop a protocol for detection of Arctic change.*

In review of the literature (Klein, 1990; Risbey *et al.*, 2000) on multidisciplinary projects of large scope, credibility of the process is a major feature and is enhanced through quality control of the components, reproducibility of the analyses, stating uncertainties, clarity and transparency, without sacrificing the recognition of the underlying complexity of the system. Such procedures are promoted through formal methods, which develop alternate quantifiable metrics for specifying historical change and future detection. Because of the existence of different lines of evidence for Arctic change over the last 30 years, SEARCH is a candidate for a comparative approach to interdisciplinary studies.

"Detection" as used by SEARCH has a broader context than is used by the climate change community. For climate change, detection is often used in a narrow sense that some indicator, such as global surface temperature, exceeds the range of background noise of natural climate variability (Barnett *et al.*, 1999), i.e., due to anthropogenic and other external factors. For many ecosystem and societal applications of SEARCH, it is important to understand the ongoing changes in the Arctic, whether they are natural or external. Several authors have argued that external change will amplify or change the frequency of occurrence of natural large-scale patterns of variability (Palmer, 1999); this remains to be shown in the Arctic.

In this section, we do not develop a protocol. This should be an early activity of the SEARCH panel on detection/observations. We provide three examples which more fully develop detection concepts: (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.

2.1 Comparisons of Conceptual Models

The mean annual surface temperatures for the northern hemisphere in the 20th century increased until about 1940, slightly decreased until the early
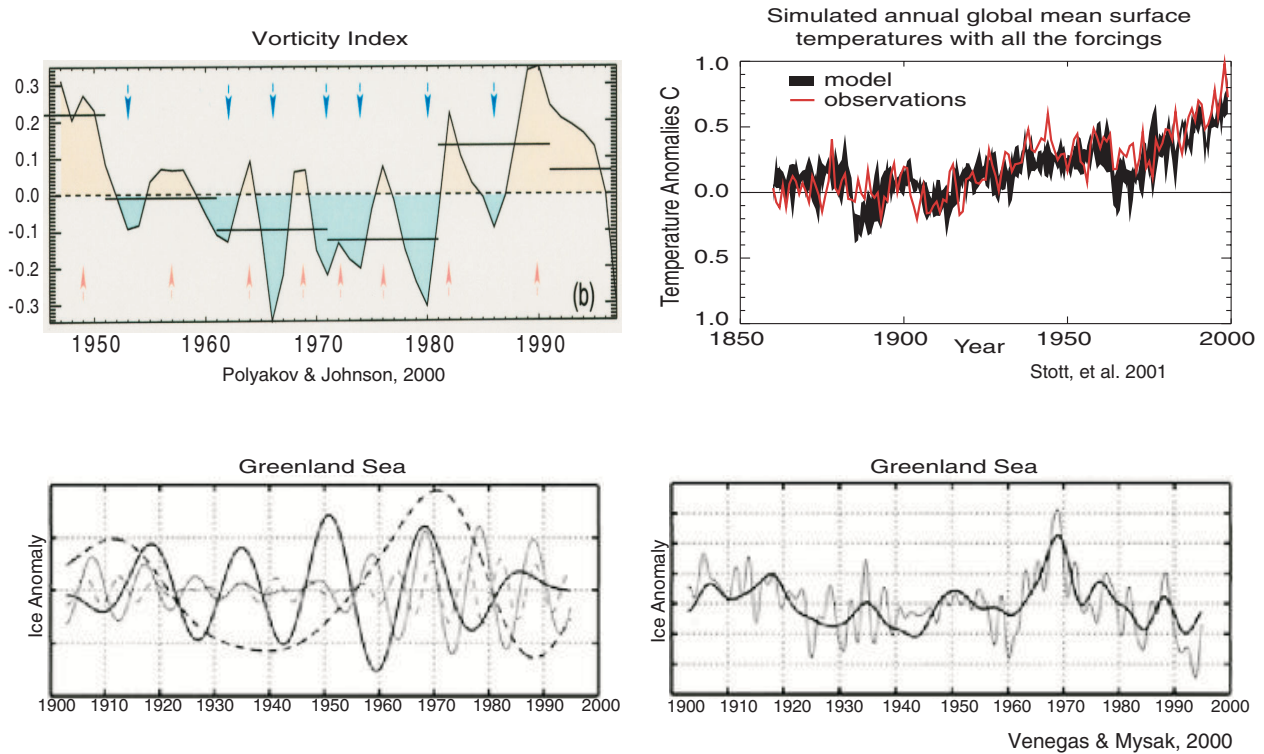
Figure 2.1: Recent trends of Arctic data. The upper left panel shows shifts in an Arctic atmospheric circulation index, based on vorticity. The lower panel shows changes in Greenland Sea ice anomalies (right) broken down into four different frequency components (left). The upper right panel shows modeled and observed global temperature changes over the last century.

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. The upper left panel in Fig. 2.1 from Polyakov and Johnson (2000) shows both a decadal scale variability associated with the Arctic Oscillation (AO) and a 60–80-year Low Frequency Oscillation (LFO). Because the LFO and AO both have a positive phase in the 1990s, these authors suggest that a forward projection of these two oscillations would predict a major temperature reversal in 2000–2020; we can call this the extrapolation model. The Greenland Sea ice record (Fig. 2.1, bottom right) was decomposed by Venegas and Mysak (2000) into four frequency bands (Fig. 2.1, bottom left). The sum of their low frequency and decadal oscillations also show a minimum ice area in the 1990s, with a projection for increases after this minimum.

An alternative model comes from the Global Climate Model (GCM) hindcast for the 20th century completed for Intergovernmental Panel on Climate Change (IPCC) (Scott, 2001). The temperature observational record and an ensemble average of four model runs is shown in Fig. 2.1 (upper right). These results show the temperature maximum in the late 1940s; the model attributes this warming to a weak solar radiation influence plus natural

variability in two of the four ensemble runs. However, the models could not reproduce the dramatic temperature increase in the 1990s without including increased CO_2 forcing in their model. Thus, the IPCC conceptual model would project increased warming in 2000–2020, after a brief minimum associated with the decadal change of the AO. One formal approach to detection is through the comparison of models. In the two examples we have major differences in these projections for the next 20 years. What is the evidence for each approach?

A third default model may also be considered. The previous examples project an ordered systems response. We can also hypothesize a stochastic or chaos-like system (Rind 1999; Overland, 2000). There is some suggestion that the northern hemisphere atmosphere system has several alternate states (Corti *et al.*, 1999). These states can have preferred residence times and long-memory behavior (Percival *et al.*, 2001), but also suggest that the system can have regime transitions or shock-like behavior. The large interannual variability of the AO during the previous 4 years (1999–2002) could suggest that the atmosphere is in a transition between more stable states. While prediction of a system with this type of climate noise is impossible, understanding the nature of the low frequency variability would help with the detection of rapid transitions.

2.2 Multiple Lines of Evidence

SEARCH is based on several recent observed changes in the Arctic which are robust: declines in sea level pressure, increased surface air temperatures, cold stratospheric temperatures, decreased sea ice cover, permafrost temperature increases, longer growing seasons, and changes in the character of tundra. There are many other less robust physical and ecosystem changes that have occurred over the previous 30 years in the Arctic.

SEARCH can benefit from a more formal compilation of this information to address the multivariate aspects of Arctic change. An excellent example is provided by Hare and Mantua (2000) for the North Pacific. In comparing 100 time series, they show that biological time series were the better indicators of regime-like behavior in 1976 and 1989 than physical data alone. Physical data has large interannual and multi-scale variability, while the biological data acted as a filter on the physical system.

The formal approach examines different lines of evidence. One can investigate the sources, quality, and quantity of available data. Uncertainties can be estimated and the signal/noise issue can be addressed individually. One can reduce the dimension of the system by the selection of relatively independent lines of evidence versus those subsets which 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 which pass a given detection criteria.
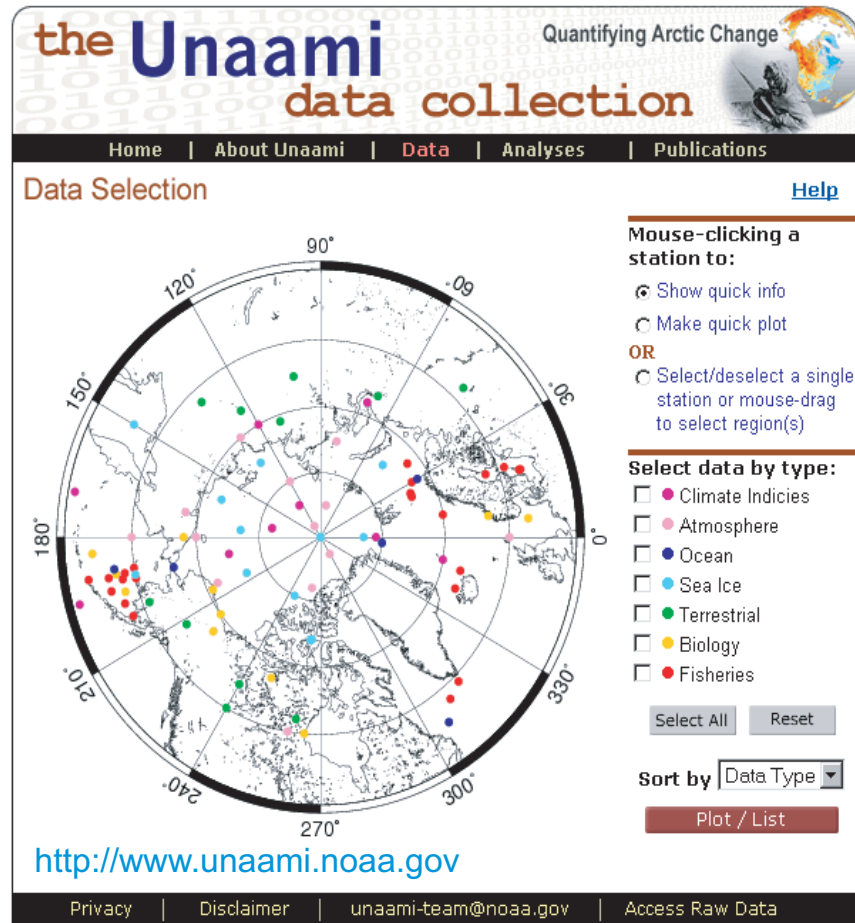
Figure 2.2: A sample from a data collection web site for 85 Arctic time series sorted by location and data type.

Figure 2.2 shows a data collection for the Arctic of 85 time series divided into seven categories: fisheries, biology, terrestrial, sea ice, ocean, atmosphere, and climate indices (`http://www.unaami.noaa.gov`). These data were chosen to span the years 1975–1995. The number of long time series drops off significantly before this time. Longer time series of a century or more are available; sea ice extents and air temperatures are an example as discussed by R. Colony at the workshop. Such expanded data collections should form the basis of understanding the covariability and independence of Arctic change.

2.3   Impact of Arctic Change on Midlatitude Climate

At the workshop, Mike Wallace (Thompson *et al.*, 2001) made a presentation which shows an example of research driven by a potential application. Thompson *et al.* 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 (Table 2.1). They sorted this data into those days after

Table 2.1: Number of days of cold temperatures which follow a weak vortex (negative AO) versus a strong vortex (positive AO).

−1.5 std. temperature threshold	Total	Weak vortex: days +1–60	Strong vortex: days +1–60
$< -17°$C in Juneau, AK	334	104	66
$< -18°$C in Chicago, IL	411	149	67
$< -6°$C in Atlanta, GA	416	149	73
$< -10°$C in Washington, D.C.	392	153	77
$< -9°$C in New York, NY	403	164	99
$< -1°$C in London, UK	442	157	77
$< -3°$C in Paris, France	446	148	68
$< -9°$C in Stockholm, Sweden	348	154	54
$< -9°$C in Berlin, Germany	450	142	77
$< -22°$C in St. Petersburg, Russia	381	137	46
$< -20°$C in Moscow, Russia	472	152	80
$< -29°$C in Novosibirsk, Russia	480	155	69
$< -4°$C in Shanghai, China	471	170	84
$< -1°$C in Tokyo, Japan	328	130	60

Thompson *et al.*, 2002

the atmosphere shifted to a weak vortex (negative AO) and a strong vortex (positive AO). The negative phase of the AO has a more north-south wave-like character compared to the positive AO with a more west-east (zonal) character. The number of cold days associated with a weak vortex were about double the number associated with the strong vortex. They further showed that the magnitude of the change was about 3 degrees 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.

2.4 References

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3. Atmospheric Observations

Compiled by James Overland with contributions from Roger Colony, Jennifer Francis, Barry Goodison, Roy Jenne, Jeff Key, Lawrence Mysak, Steven Pawson, Ignatius Rigor, Bob Stone, Patrick Sheridan, Russ Schnell, Mike Wallace, Betsy Weatherhead, Taneil Uttal, and Bernie Zak.

A goal of SEARCH is the development of a distributed observing system to track Arctic change. This observing system includes both biological and physical data. The backbone is the World Meteorological Organization (WMO) sites, which collect routine weather data, and current and future environmental satellites. This information net is primarily designed for operational, short-term weather forecasting, rather than long-term climate studies. The operational focus creates potential problems in using the WMO data to detect changes over decadal time scales. Issues include data accuracy, ability to detect small changes, the length and continuity of the record, site changes and urbanization, and changes in instrumentation type and automation. Arctic scientists share the issue of using WMO and satellite data for climate purposes with the larger climate community. Such issues are addressed by the Global Climate Observing System (GCOS) at `http://www.wmo.ch/web/gcos/`.

As noted in the Introduction, there are changes in the Arctic that show large-scale (500 km+) covariability, but there is no one particular spatial pattern of variability. Thus, to explore and potentially project such changes, a uniform distribution of sites is necessary (300–500 km) which track a variety of processes. SEARCH provides an Arctic component to the overall global climate program by providing a focus for Arctic observations and parameterization of Arctic processes in climate models. Thus, the recommendations for atmospheric observations in SEARCH are primarily to augment routine atmospheric observing systems and for quality control of operational data.

Recommendations

- Although the current set of WMO surface observation stations is adequate for SEARCH purposes, *we advocate for continuation of quality measurements, intercomparison of measurements, and support of easily accessible, current, and archives of value-added data sets.* The subset of GCOS surface network (GSN) stations is not adequate to monitor the potential spatial variability of Arctic change.

- The number of WMO upper air locations is only about 10% of the number of surface stations; there is no coverage over the central Arctic. This provides a major data void for SEARCH research. *SEARCH has an opportunity to improve this situation by converting the 22-year historical TOVS atmospheric temperature sounder data set to climate quality by bias removal for the Arctic portion of the entire data set.*

- The International Arctic Buoy Program (IABP) has maintained sea level pressure observations in the central Arctic since 1979. *SEARCH*

> *can support IABP by providing logistics to keep a uniform grid of ob-*
> *servations, and enhancing the sites with additional sensors such as*
> *quality temperatures, radiation, ice thickness, and ocean properties.*

- *SEARCH sees great utility for value-added gridded data sets from satel-*
  lite data, such as cloud, vegetation, and radiation fields.

- Intensive observing sites are located at Barrow and Northern Europe.
  Because of the large-scale spatial variability of changes in the Arctic,
  it is important to maintain observations at a site in NE Canada with
  the same range of observational measurements. Future consideration
  should be made for a Siberian site.

- *Work is required to prioritize integrated data sets for change detection.*

3.1   The Synoptic Observational Network in the Arctic

At the workshop, Barry Goodison and Roy Jenne reviewed the meteoro-
logical observation network in the Arctic. The number of surface stations
north of 50°N as of 29 October 2001 was 2477 and are shown in Fig. 3.1.
The source of this metadata is WMO Publication No. 9, Volume A, which
contains a complete list of the active surface and upper air weather observ-
ing stations at `http://www.wmo.ch/web/ddbs/publicat.html`. The pub-
lication is updated every 2–3 months. A second source of data is from
the Global Climate Observing System (GGOS) Surface Network (GSN),
`http://www.wmo.ch/web/gcos/gcoshome.html`. The GSN is a subset of
989 sites for the globe (244 sites north of 50°N) selected for quality, conti-
nuity, and longevity, with a coverage every 500 km. Polyakov *et al.* (2002)
make use of 49 Arctic stations with data time series longer than 65 years.

   Given the large regions of covariability for many variables of Arctic
change as suggested in Fig. 1.1, the WMO Station coverage for tempera-
ture and pressure, and the present archiving by the National Climate Data
Center (NCDC), appear adequate for the requirements of SEARCH histor-
ical analyses and future detection activities. We can make this statement
even with the loss of some stations in the Russian Arctic. It should be
recognized, however, that good spatial coverage of observation sites are an
essential underpinning of research to improve understanding of the climate
system. SEARCH should be concerned about further loss of observation
sites, especially those with long historical time series, and the continuity
and intercalibration within the records.

   The large void over the central Arctic ice pack in Fig. 3.1 is covered
through the International Arctic Buoy Program (IABP). Further details will
be provided in Section 3.3. Another source of weather information is the Arc-
tic Climate System Study (ACSYS), Precipitation Data Archive (APDA),
`http://dwd.de/research/gpcc/acsys`. As of December 1999, they list
Arctic synoptic weather stations as well as a subset of stations sorted by
river catchment areas. They also link to 30 other snow and precipitation
data sources.

WMO Publication No. 9 Volume A

2477

All active Synoptic Stations north of 50 N as of 29 Oct 2001
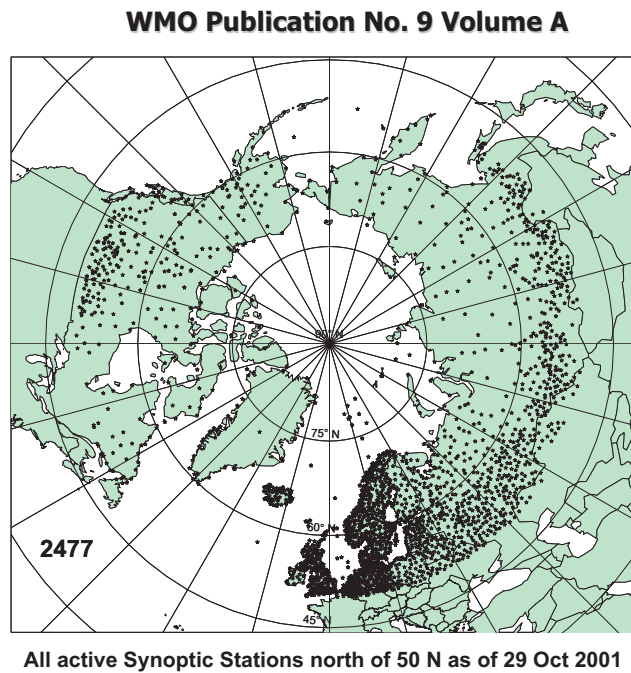
Figure 3.1: Location of WMO surface observation stations.

The coverage of upper air profiling stations from the WMO web site is shown in Fig. 3.2. The number of stations is just 10% (238) of the number of surface stations. The number of stations is particularly low over the high Arctic (land area) and non-existent over the Arctic Ocean basin. This lack of coverage is a major problem. One opportunity for upper air data in the Arctic is through the use of satellite sounder data available since 1980. This was an operational weather product and needs to be recalibrated as a climate product. Additional discussion is in Section 3.5.

A method to make the best use of this limited information is through Reanalysis Projects, such as that undertaken by the NCAR Data Support Section and the Model Development Group at the National Center for Environmental Prediction (NCEP). The NCAR group has developed an extensive data set with major quality control, duplicate removal, and systematic error removal. The 110 upper air stations north of 60°N and their period of coverage during the period 1940–1999 are listed on the workshop web site: `http://www.epic.noaa.gov/SEARCH/obs/workshop/reports.shtml` under Roy Jenne. This upper air station data, along with surface reports, aircraft reports, and some satellite wind and temperature data after 1973, are used in a 6-hour analysis/forecast cycle using a state-of-the-art weather forecast model to extrapolate the observations in space and time. The extrapolation is good when there is adequate data coverage upwind of the region of interest. Lack of coverage remains a problem for the central Arctic. The NCAR/NCEP reanalysis has a nominal resolution of 208 km. The

WMO Publication No. 9 Volume A

All active Upper Air Stations north of 50 N as of 29 Oct 2001
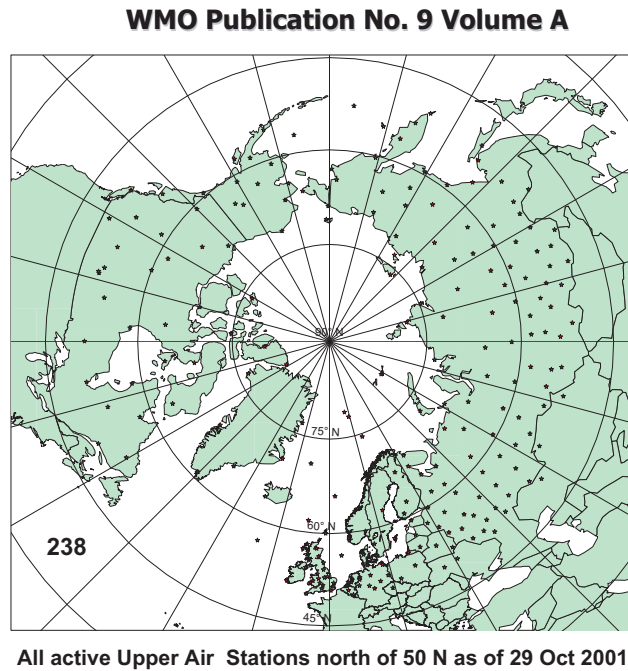
Figure 3.2: Location of WMO upper air observation stations.

model also computes secondary variables which are not measured directly, such as radiation and moisture fields. Reanalysis fields are available at `http://wesley.wwb.noaa.gov/ncep_data/index.html`. Thirty-one variables are available on different atmospheric pressure levels and 62 additional variables at a single pressure level. Further information on the NCAR processed data set is at `http://dss.ucar.edu`.

3.2   Satellite Data

Satellites provide a spatial and temporal basis for following Arctic change. A review of satellite and data center issues is provided in a National Research Council (NRC) Report, *Enhancing NASA's Contributions to Polar Science* (J. Walsh and coauthors, 2001). Certainly the Polar Operational Environmental Satellites with twice daily coverage of visual and IR images and temperature soundings are basic. MODIS (MODerate resolution Imaging Spectroradiometer) flying on TERRA and to fly on AQUA provides imaging in 36 spectra bands every 2 days. The future ICESat mission will provide cloud property information not otherwise available from passive sensors, especially the high ice clouds common over polar areas. It will have an altimeter to provide information on ice sheets. The Total Ozone Mapping Spectrometer (TOMS) has provided measurements for most of the period 1978–present.

Key recommendations from the NRC report are:

- *Foster consistency within and among different satellite products.*

- *Develop spatially and temporally coherent geophysical data sets.*

- *Provide emphasis to sensor optimization for polar applications, which is not now a priority. Clear examples are precipitation estimation and cloud properties.*

- *Data centers should work toward improvement of tools for analyzing combined data sets. This includes documentation, temporal consistency, gridding, and format conversions.*

3.3   International Arctic Buoy Programme

Ignatius Rigor reported that the International Arctic Buoy Programme (IABP) has maintained a network of buoys in the Arctic Basin since 1979. These buoys measure sea level pressure (SLP), surface air temperature (SAT), and other geophysical quantities. The data are transmitted and collected through the Argos satellite system. The IABP strives to maintain a network of at least 25 buoys evenly distributed across the Arctic Ocean. These buoys have expected life spans of 1 to 2 years, and more than 5000 buoy-months of data from over 500 buoys have been collected.

The IABP data are used for both operations and research, e.g., forecasting weather and ice conditions, validation and forcing of climate models, validation of satellite data, and for studies of climate change. For operations, the data are made available to the forecasting community through the Global Telecommunications System. For research, the data are analyzed at the Polar Science Center of the University of Washington, which also coordinates the IABP. The data and more information on the IABP can be obtained from `http://IABP.apl.washington.edu/`, or from the World Data Center for Glaciology at the National Snow and Ice Data Center in Colorado.

The success of the IABP depends on maintenance of the buoy network. The buoys have finite life spans, and a tremendous amount of resources are required to purchase and deploy buoys. In the past the program was able to seed the buoy network in the Beaufort Sea and the large gyre circulation would carry buoys out to cover the Arctic Ocean. However, given the recent predominance of high AO conditions reducing the Beaufort Gyre, maintaining the buoy array in the east Arctic has been more difficult. *Therefore, an opportunity for SEARCH is to provide increased support for logistics and continued development of methods for seeding the eastern Arctic.* For example, Fig. 3.3 shows a recent location of the buoy array, with a particularly large data void in the central/eastern Arctic.

Given the complex nature of Arctic climate, another SEARCH opportunity is to develop and deploy buoys with more sensors, e.g., CTDs, anemometers, radiometers, and thermistor strings. The cost to attach additional sensors to a buoy is small in comparison to the cost of the logistics to deploy a buoy, but the benefits to the operational and research communities can be significant. These additional data are useful in their own right and are essential for calibrating radiation and GCM models.
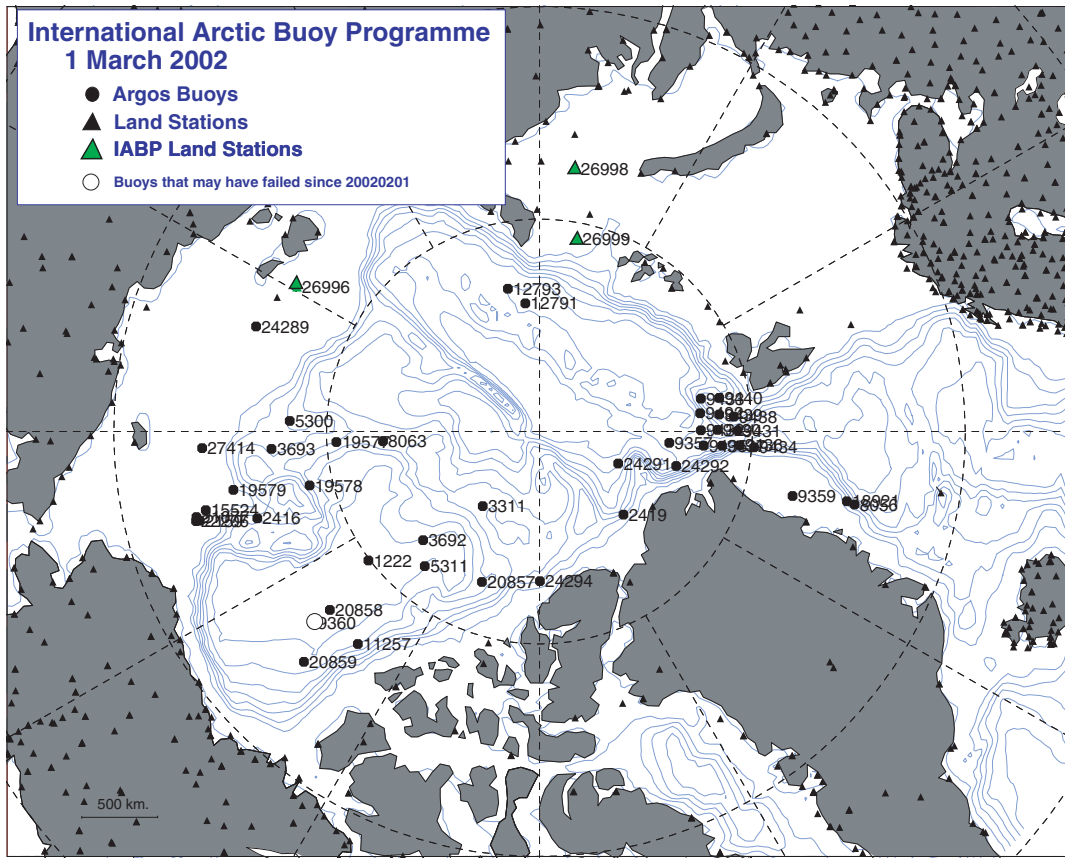
Figure 3.3: Locations of buoys as part of the International Arctic Buoy Program (IABP). Note the data void in the central Arctic.

3.4 Cloud and Radiation Data Sets

Jeff Key reported that both in situ and satellite-derived cloud and radiation data sets are available for Arctic climate studies. The following list includes those that can potentially be used for the detection climate change. It does not include data sets collected during field experiments or data that do not constitute a time series. The temporal scales range from hourly to monthly averages, covering periods up to four decades.

3.4.1 Existing data sets

Baseline Surface Radiation Network (in situ): The Baseline Surface Radiation Network (BSRN) is a project of the World Climate Research Programme with a goal of detecting changes in the earth's radiation field over long time scales. BSRN stations in the Arctic are at Barrow, Alaska, and Spitsbergen, Norway. The Antarctic BSRN stations are Neumayer, Syowa, and South Pole. All stations measure global, direct, diffuse, and longwave downward radiation. All but Syowa also measure shortwave and longwave upward radiation and have 3-hourly synoptic observations. Spitsbergen and
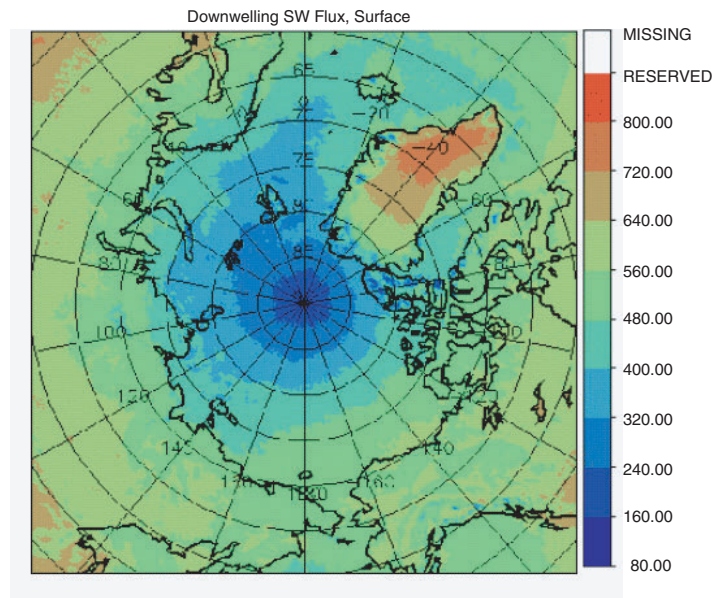
Figure 3.4: Downwelling shortwave flux at the surface for the month of June, averaged over the period 1985–1993, calculated from the AVHRR Polar Pathfinder data set.

Neumayer have instrument-measured cloud base height. The stations began measurements as part of the BSRN in 1992 and 1994. On the Web: `http://bsrn.ethz.ch`.

Arctic Global Radiation Data Set (in situ): The Arctic Global Radiation (AGR) data set was compiled from Arctic land stations, ocean drifting stations, and empirically derived long-term climatological estimates from earlier Russian studies (Fig. 3.4). The AGR is a two-part data set, the first being a time series of monthly fluxes covering the region north of 60 degrees latitude. While many of the station time series are short, some exceed 40 years in length. The second part of the AGR is a long-term monthly mean gridded climatology for the region north of 65°N. On the Web: `http://nsidc.org/data/arcss066.html`.

Edited Synoptic Cloud Reports Over the Globe (in situ): Surface synoptic weather reports over the globe for the 10-year period from December 1981 through November 1991 were processed by C. Hahn, S. Warren, and others to provide a data set designed for use in cloud analyses. The information in these reports relating to clouds, including the present weather information, was extracted and put through a series of quality control checks. With this data set a user can develop a climatology for any particular cloud type or group of types, for any geographical region and any spatial and temporal resolution desired. On the Web: `http://cdiac.esd.ornl.gov/epubs/ndp/ndp026b/ndp026b.htm`.

AVHRR Polar Pathfinder (satellite): The AVHRR Polar Pathfinder composites are a collection of products for both poles, consisting of twice-
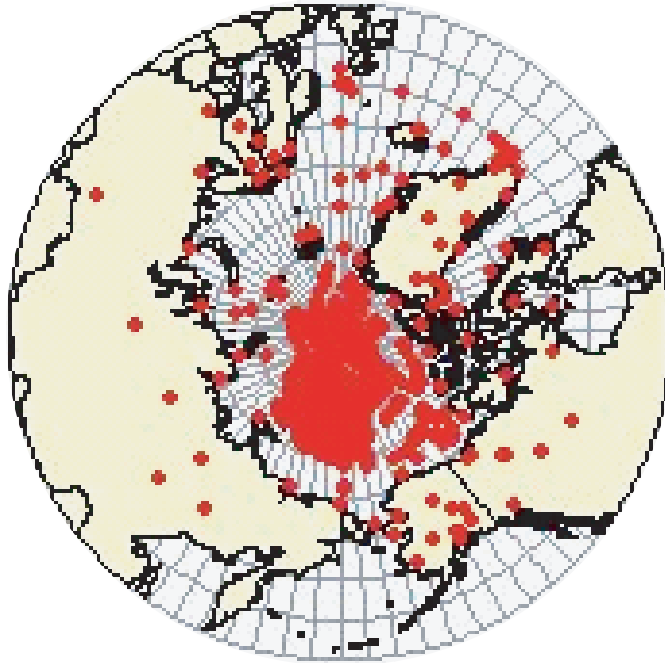
Figure 3.5: Locations of data sources in the AGR data set.

daily gridded and calibrated satellite channel data and derived parameters at
a 5 km spatial resolution. Data include five Advanced Very High Resolution
Radiometer (AVHRR) channels, clear sky surface broadband albedo and skin
temperature, viewing and illumination geometries, surface type mask, cloud
mask, and time of acquisition. Data are composited onto two grids per day
based on common local solar times and scan angle. The data set currently
covers the period 1981–1998. The APP data set has been extended to include
cloud properties, surface radiation, and top-of-atmosphere radiation. At
present the years 1982–1993 have been processed. An example is shown
in Fig. 3.5. On the Web: `http://nsidc.org/data/nsidc-0066.html` and
`http://stratus.ssec.wisc.edu/projects/app`.

   TOVS Path-P (satellite): The TIROS-N Operational Vertical Sound-
er (TOVS) Polar Pathfinder (Path-P) data set consists of gridded daily
Arctic fields of atmospheric temperature, water vapor, skin surface tem-
perature, total effective cloud fraction, cloud top pressure and temperature,
solar zenith elevation, surface pressure, turning angle between geostrophic
wind and surface stress over ice, emissivity, boundary layer stratification,
and the geostrophic drag coefficient. Data are available for the period 1979–
1998 at a resolution of 100 km. An example is shown in Fig. 3.6. On the
Web: `http://nsidc.org/data/nsidc-0027.html`.

   International Satellite Cloud Climatology Project (satellite):
ISCCP was established as part of the World Climate Research Programme
to collect and analyze satellite radiance measurements to infer the global
distribution of clouds, their properties, and their diurnal, seasonal, and in-
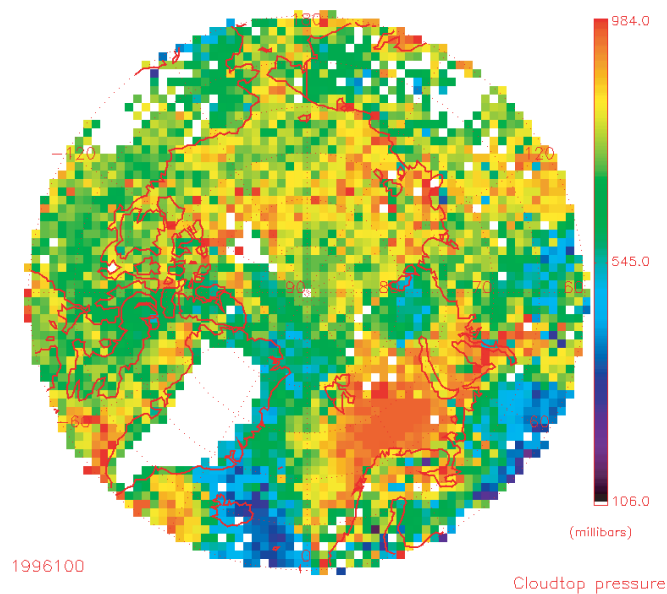
Figure 3.6: Cloud pressure over the Arctic for 10 April 1996 from the TOVS Path-P data set.

terannual variations. Variables include cloud amount, cloud optical depth (daytime), cloud temperature and pressure, cloud phase, surface clear sky temperature, and visible reflectance. Data are currently available for 1983–1998 and will ultimately continue through mid-2002. The spatial resolution of the "D1" (3-hourly) and "D2" (monthly) data sets is 280 km, though a 30 km data set is also available. This is a global product. On the Web: `http://isccp.giss.nasa.gov/products/onlineData.html`.

Wisconsin HIRS Cloud Climatology (satellite): The High resolution Infrared Sounder (HIRS), part of the TOVS sensor suite, is also being used to generate a global cloud product at the University of Wisconsin. Variables include cloud amount, cloud emissivity and transmissivity, cloud height, and cloud temperature. The data set currently covers a 12-year period from 1989 to the present. The spatial resolution is 2° latitude by 3° longitude. An example is shown in Fig. 3.7. On the Web: `http://www.ssec.wisc.edu/∼donw`.

3.4.2 Outlook: The next 5 years

Some of the data sets described above will be extended to include additional years. The BSRN network will continue to collect data, the ISCCP data set will be processed through 2002, the extended APP data set will cover the years 1994–1998, and the Wisconsin HIRS cloud climatology will continue indefinitely (a related project will generate a 22-year climatology by mid-2002). Additionally, there is a possibility that the TOVS Path-P data set will be used to generate surface shortwave and longwave fluxes, providing another source of radiation information over a 20-year period. A comparison
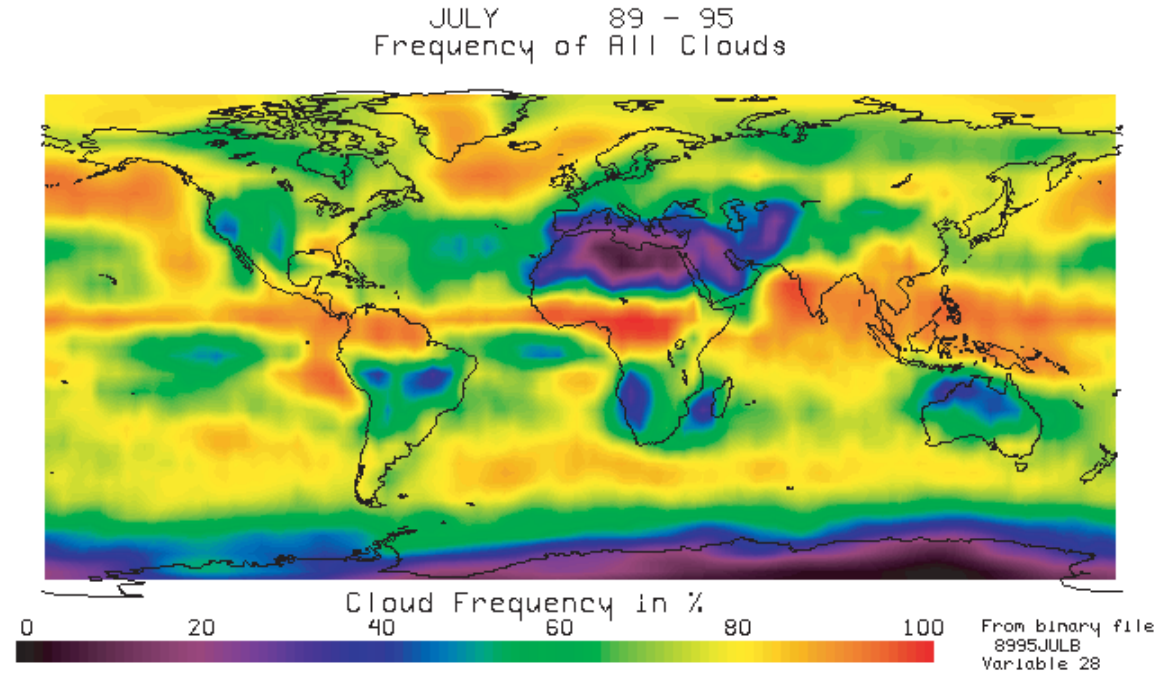
Figure 3.7: Global cloud amount for July over the period 1989–1995 from the Wisconsin HIRS Cloud Climatology project.

of the TOVS-derived surface radiative fluxes to measurements made during SHEBA is given in Fig. 3.8 (A. Schweiger, personal communication).

3.5   Satellite Temperature Sounding Data

Jennifer Francis reported that the Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) instrument has flown on NOAA polar-orbiting satellites since 1979 and has collected one of the longest and most complete satellite data records in existence. It was originally designed to serve the weather forecasting community by providing temperature and moisture profiles in regions of the Earth that had few conventional meteorological stations. An example of lower stratospheric temperature anomalies for April months in the 1990s are shown in Fig. 3.9. Further details are available in several reports by J. Francis at the workshop website. Data from this sensor have shown potential for a wide range of climate applications. A problem arises in this context, however, as the radiances were not adequately calibrated for long-term accuracy, hence substantial biases exist in data from the various platforms. These biases have several sources, e.g., different sensor characteristics on each platform, instrument degradation, orbital changes, and systematic errors in forward radiative transfer models. Absolute and relative errors in the radiances reduce the potential value of TOVS observations for monitoring and understanding climate change.

An opportunity for SEARCH is to address these errors for the Arctic. Many of the known errors should be regionally and seasonally independent,
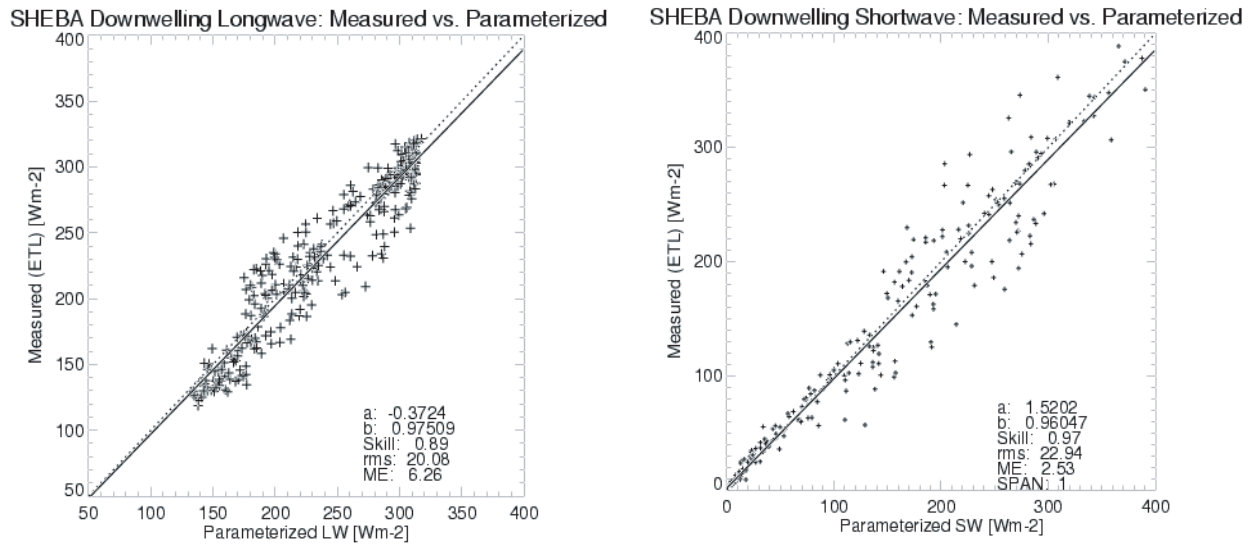
Figure 3.8: Downwelling longwave (left) and shortwave (right) fluxes computed from the TOVS Path-P data set ("Parameterized") and measured at the surface over the SHEBA year.

but we suspect some may be peculiar to or exacerbated in Arctic conditions. *Thus, efforts should be primarily directed to the Arctic to produce a data set of TOVS radiances with biases minimized.* Once this has been completed, the data should be of value both for geophysical retrievals with sufficient accuracy to identify changes since 1979, and future changes, as well as for direct assimilation by numerical atmospheric models for reanalyses.

One would begin by assessing techniques used by other experienced groups—such as those who produce the NCEP and ECMWF reanalysis data sets and long-term, global TOVS retrievals—to learn of the successes and failures of their methods and/or data sets of corrections. A large number of suitable, high-quality radiosonde profiles would need to be assembled and matched with satellite observations coincident in space and time. This effort would involve data rescue, sorting, and evaluating the quality of available radiosonde data. Large numbers of data are needed so that random errors, such as in radiosonde measurements and from satellite noise, can be removed by averaging. By employing one or perhaps two well-characterized (in terms of their biases in varying atmospheric conditions) forward radiative transfer models, we could calculate from the radiosonde/satellite match-ups the corrections to TOVS radiances.

Another avenue of effort is to take advantage of periods when two satellites flew simultaneously. Radiances measured in close space and time proximity, as well as the retrievals from these radiances, can be compared to determine relative biases. This method may be particularly effective in polar regions, as orbits converge in high latitudes, resulting in frequent overpasses of the same area.

This effort would be an intensive multi-step process that would need to be performed collaboratively at NOAA/NESDIS, NCEP and other institutions

Satellite−Derived 200 hPa Temp. Anomalies in March for the 1990s from TOVS
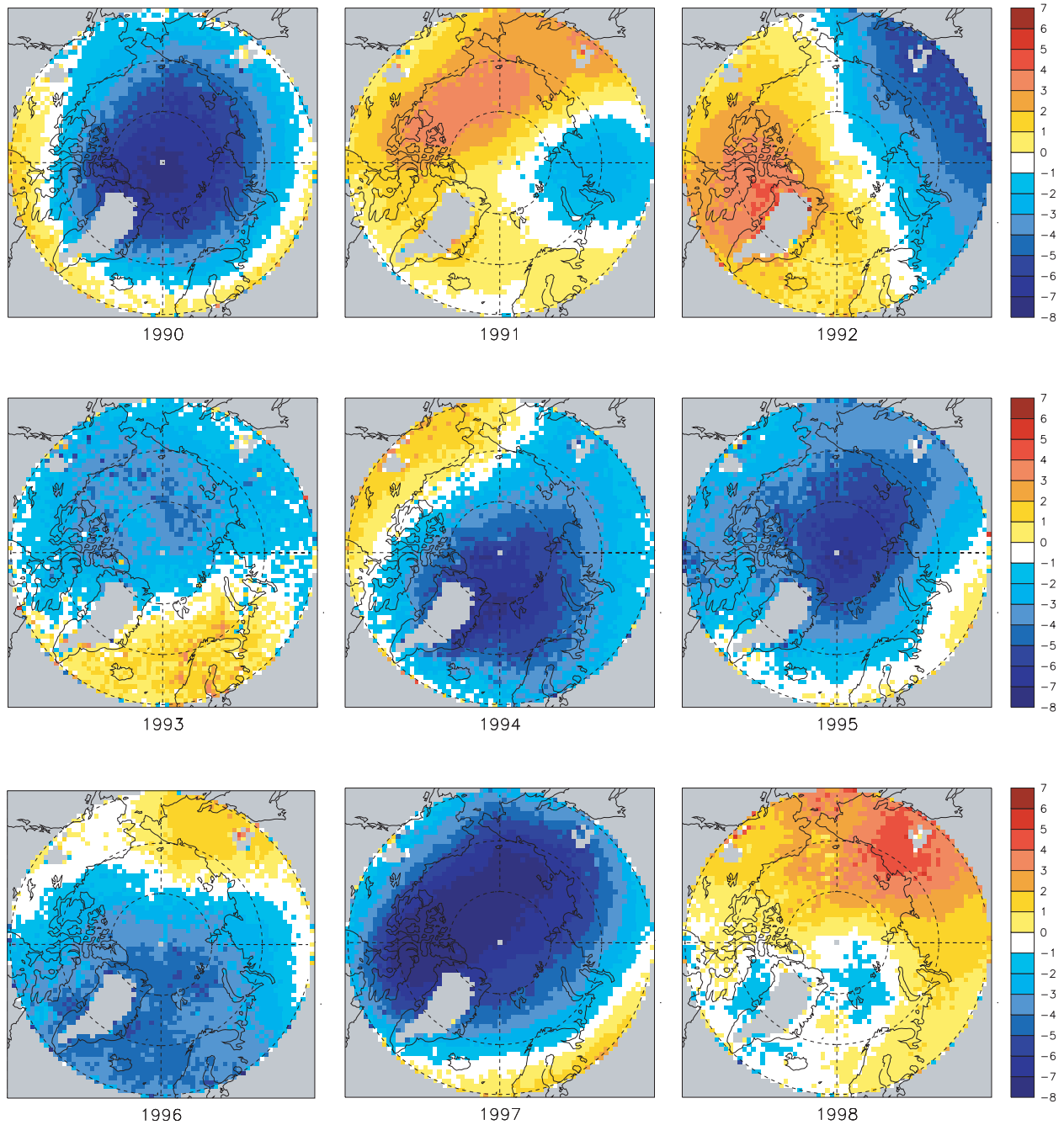
Figure 3.9: An example of temperature anomalies in March for different years based on satellite temperature profiling data.

with TOVS expertise. A related but preliminary project is already underway at NOAA/NESDIS, which involves rescuing a data set of radiosondes (so-called DSD5). Additional soundings will be needed from later periods and for airmass types that are not well represented in the archived data set. Converting TOVS retrievals from an operational data set to a climate quality data over the data sparse Arctic areas will be a major tool for direct study of atmospheric changes and for use in reanalysis projects, especially a recommended Arctic system reanalysis as part of SEARCH.

3.6 Long-Term Intensive Atmospheric Observing Stations

3.6.1 Rationale

In addition to the distributed and satellite-based observing systems discussed so far in this section, it is necessary to operate a small number of strategically placed, long-term, intensive ground-based, atmospheric observing stations on land with an option for making similar measurement sets on icebreakers, at ice camps, and at field experiments. The primary purpose of such sites would be to:

- Make detailed measurements of key parameters over sufficient periods to monitor climate change and assess seasonal and decadal climate variability

- Support interpretation and validation of satellite data

- Provide measurement suitable for developing new model parameterizations

- Provide measurements sufficiently detailed to conduct process studies to advance fundamental understanding of Arctic atmospheric processes

Taneil Uttal and Bernie Zak commented on this approach.

3.6.2 Strategy

In developing a plan for intensive sites it is necessary to isolate the type, frequency, and accuracy of measurements required, to review existing facilities and capabilities, and to determine optimum site selection within the logistic constraints that are likely to be imposed by the Arctic environment.

Intensive sites would make continuous, long-term measurements of parameters such as spectral and broadband surface radiation fluxes, surface albedo, clouds (fraction, vertical distribution, microphysics and optical properties), aerosols (chemical composition, optical depth, concentration, spatial distributions), Arctic haze, surface sensible heat and latent heat fluxes, ozone, carbon dioxide greenhouse gases (CO_2, O_3, water vapor, NO_2, CH_4), precipitation, and high quality, standard meteorological observations (pressure, temperature, winds, humidity).

Currently, and historically, sites are operated at Barrow, Alaska and Kiruna, Sweden, with some observations in NE Canada and Svalbard. Figure 1.1 (left) shows a map of wintertime temperature trends for the Northern
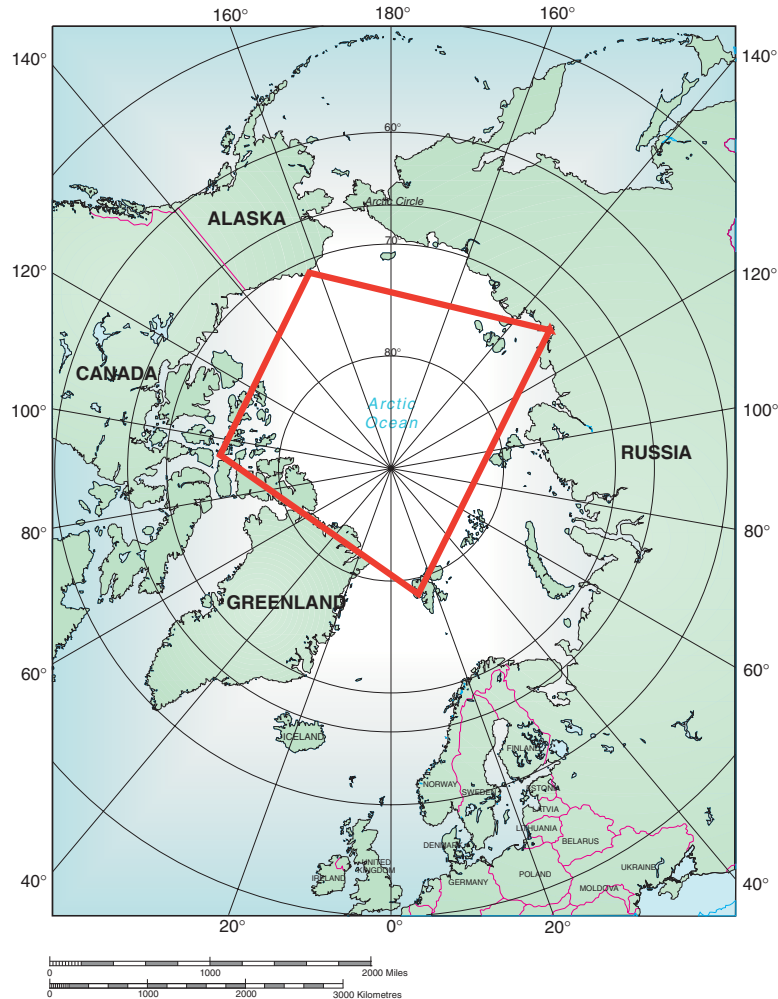
Figure 3.10: Barrow is the present site of extensive atmospheric measurements. The present concept would enhance measurements at existing stations, two possibilities being Alert and Svalbard, with eventual development at a third station in Russia such as Tiksi. Red lines on the figure indicate a flight track for proposed aircraft sorties which would monitor horizonal variability between stations.

hemisphere for the previous 50 years. There is large-scale spatial covariability, with warming trends over eastern Siberia and northwestern North America, and cooling over NE Canada and, to some degree, west of Bering Strait. *Inspection of Fig. 1.1 supports a priority recommendation of the importance to augment intensive observations in NE Canada.* This has been a region of cooling, which is out of phase with the Barrow and Kiruna. To complete the array, a location in Russia should be a future consideration.

The observing strategy envisioned is to develop widely distributed, largely autonomous observing networks in conjunction with embedded, high intensity, manned observing stations at key locations. These observations would optimally be supplemented with a program of annual aircraft sorties and ship cruises that are performed on a regular basis from year to year to provide a measurement of large-scale horizontal variability (Fig. 3.10). The

Figure 3.11: Fish eye lens view of the NOAA/CMDL Barrow Observatory.

aircraft and ship would provide a critical link with ocean/ice, satellite and autonomous network observing programs. Finally, it is recommended that a portable suite of instruments be developed that could be episodically deployed at ice stations, on ice breakers, and in land-based field campaigns to complement fixed sites. The Barrow, Alaska site is discussed in some detail in the following section.

3.6.3   The Barrow, Alaska site

The atmospheric measurements being made at the NOAA Climate Monitoring and Diagnostics Laboratory (CMDL) Baseline Observatory and the Department of Energy Cloud Atmospheric Radiation Measurement Program in Barrow, Alaska represent some of the most technologically advanced and comprehensive measurements of the clouds, radiation, chemistry, and other aspects of the physical atmosphere. The Barrow location and its unusually strong complement of atmospheric sensors is unique not only in the Arctic but also with respect to comparable stations throughout the world.

The CMDL observatory has the primary goal of monitoring the atmospheric constituents that are capable of forcing climate change and those that may cause depletion of the global ozone layer. Measurements such as meteorology, surface ozone, carbon dioxide, aerosols, and radiation began in 1972–1974 and are some of the longest continuous atmospheric records in the Arctic. Today, over 200 different measurements are conducted at the Barrow Observatory through 35 cooperative programs (Fig. 3.11).

The DOE ARM North Slope of Alaska (NSA) facility adjacent to the NOAA site commenced measurements of key radiation and cloud measurements in February 1998. The radiation measurements are made by a number
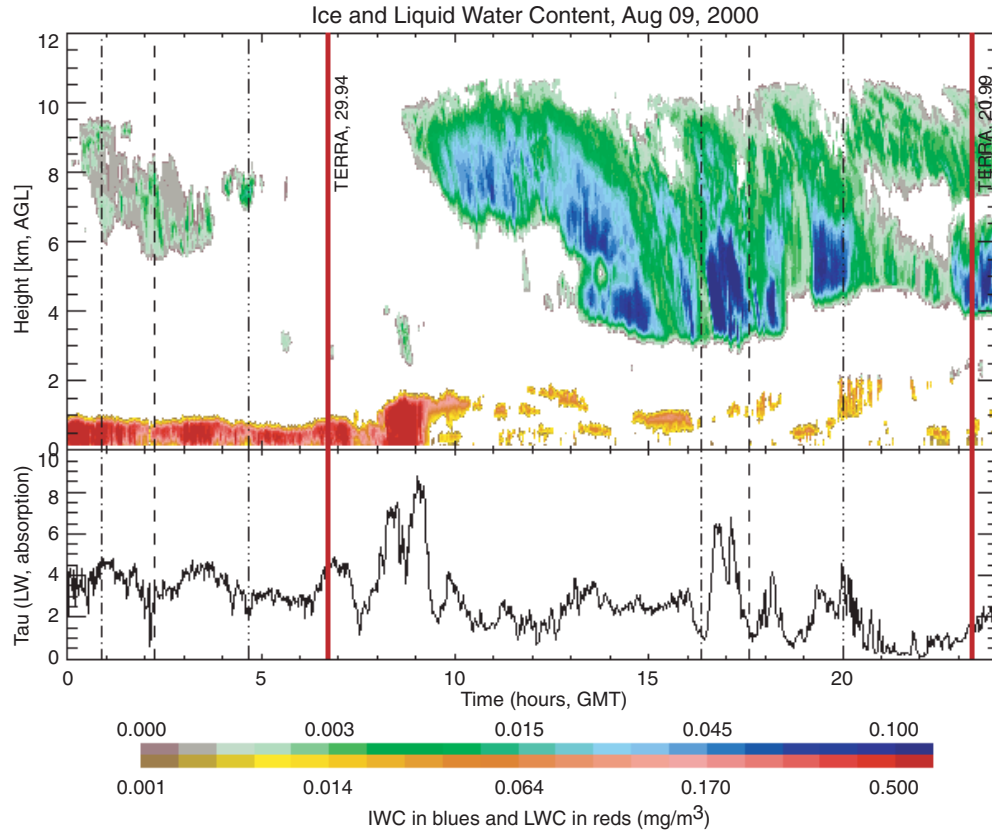
Figure 3.12: Time-height (24 hours, 0–12 km AGL) cross section of radar and radiometer cloud water content retrievals for a low level all liquid boundary layer cloud at the surface and an all-ice liquid cloud in the upper atmosphere. TERRA satellite overpass times are indicated in red, NOAA satellite overpasses are indicated with dashed lines.

of broad-band and spectral sensors, which are complemented by state-of-the-art cloud measurements from millimeter cloud radar, and micropulse lidar. By combining measurements from these passive and active sensors, time-height records of detailed cloud properties can be derived which are important in assessing cloud effects on atmospheric heating profiles and atmosphere-surface heat and exchanges (Fig. 3.12).

The Barrow station, including a strong history of community support, serves as a prototype for enhanced atmospheric measurements that would be highly desirable at other key locations in the circumArctic.

3.7   Data Archives

Florence Fetterer has summarized 24 Arctic data sets in a report at the workshop web site, `http://www.epic.noaa.gov/SEARCH/obs/workshop/reports.shtml`. These data are available at NCDC, National Snow and Ice Data Center (NSIDC), and other centers.

SEARCH needs to move beyond logging data sets, which is being handled well by various data centers, including satellite data at various Distributed Active Archive Centers (DAACs).

Taking a cue from the previous chapter on developing a detection strategy, these data should be developed into multiple lines of evidence for Arctic change, and referenced at one web site, a SEARCH virtual observation and detection location. Information at this site should be updated frequently, at least quarterly, and include biological and physical data. Value-added studies could be posted at this site.

Arctic-wide data sets of quality controlled data with at least a 30-year record length are necessary for addressing the detection problem. Data sets from Eurasia for precipitation (liquid and solid), radiation, river discharge, snow depth (water equivalent), sea ice, and soil temperature that are available to SEARCH researchers are incomplete. While the scope of the work needed varies for each parameter, the tasks that must be performed are:

- *Catalogue data sources:* How complete is the existing record, and where do data that can fill gaps reside? Can additional data be acquired, how soon, and at what cost? This information must be compiled before the scope of the data rescue effort can be determined.

- *Assess data quality:* How were the data digitized and documented? Were quality control routines preformed on the data? Are they needed?

- *Update the record:* Former Soviet Union snow data, monthly precipitation and evaporation data, meteorological data from Russian coastal stations, and Russian river ice thickness and duration data sets are available to researchers but are current only through the early 1990s. We need to update these data sets through 2001 where possible.

- *Extend the record back in time and fill spatial and temporal gaps:* For example, soil temperature data from China and Mongolia (87 stations) and Russia (140 stations) are available and require resources for quality control and publication. These data help cover a data sparse area. Meteorological data from Russian stations that are internationally exchanged represent about 10% of the national station network. Most of these station records date back at least to the early 1950s and in some cases the 1930s.

Once the complete data record is obtained, data sets need to be prepared so that they can be used directly to address detection problems. This will usually involve (a) statistical characterization of the data set with additional quality control routines, (b) providing a browse capability, (c) providing documentation, metadata and cataloguing the data, and (d) gridding the data set for easy visualization, computation of modes of variability, and cross correlation with other data sets.

Two examples illustrate the type of work that needs to be done to complete the historical record (for Russian radiation data) and to re-establish near-real-time data broadcasting (for Arctic hydrology).

3.7.1   Russian radiation data

The Global Energy Balance Archive (GEBA) database is the primary source for digital radiation data, but it contains little data from the former Soviet

Union. Mean monthly or monthly totals of solar radiation parameters from the Russian North Pole (NP) drifting station program were published in "Handbook of the Radiation Regime of the Arctic Basin (Results from the Drift Stations)" by Marshunova and Mishin, edited by Radionov and Colony. To complete the historical record of Russian Arctic radiation measurements, the Arctic and Antarctic Research Institute (AARI) in St. Petersburg should be contracted to prepare synoptic (4 times daily) radiation data from the NP stations. These data date from the 1950s through 1991. In addition, AARI should be funded to prepare any available radiation data from land stations (AARI has proposed digitizing global radiation and cloud type from 12 stations back to 1936).

3.7.2   Arctic hydrology network

Due to a reduction in the number of river discharge gauges, the Arctic drainage basin area monitored has decreased by 67% from 1986 through 1999, at a rate of 79% in Russia and 59% in North America. The reduction is due primarily to budget cuts, compounded in Russia by the loss of qualified personnel to staff remote stations (Shiklomanov *et al.*, 2001). It is a critical problem because data from smaller sub-basins are needed to measure the spatial variability of runoff, but gauges from smaller rivers have been eliminated preferentially. A prototype project, the Arctic Rapid Integrating Monitoring System (Arctic-RIMS), has begun to organize a continuous operational river discharge monitoring system by compiling near-real-time daily discharge data for a selection of 56 gauges. It is a collaborative project between U.S. researchers and the Arctic and Antarctic Research Institute, St. Petersburg. SEARCH has a unique opportunity to leverage the work being done under Arctic-RIMS by supporting the reestablishment and maintenance of gauge stations in Russia that will help characterize the hydrologic cycle beyond the freshwater flux to the Arctic Ocean (which is the emphasis of Arctic-RIMS). Much of the time-consuming process of making contacts in Russia and identifying the most important gauge stations has already been done. SEARCH should begin planning to strengthen and expand the Arctic-RIMS network so that near-real-time delivery of data continue after the completion of Arctic-RIMS in 2005.

3.8   References

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4. Terrestrial Observations

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4.1 Introduction

Evidence continues to mount that warming experienced in the Northern Hemisphere during the past few decades has been affecting terrestrial ecosystems in high latitude regions (Oechel *et al.*, 1993, 2000; Kurz and Apps, 1999; Osterkamp and Romanovsky, 1999; Barber *et al.*, 2000; Serreze *et al.*, 2000; Stocks *et al.*, 2000; Sturm *et al.*, 2001; Silapaswan *et al.*, 2001). These changes are affecting the function and structure of upland and freshwater aquatic ecosystems, and it is important to understand the nature of these changes as they have implications for human livelihoods in high latitude regions and elsewhere through effects on subsistence resources, commercial fisheries resources, infrastructure, and industrial activity (e.g., oil and gas development). As climate changes in high latitudes are expected to be amplified in comparison to temperate and tropical latitudes, it is also important to understand how spatial and temporal variability in climate is affecting spatial and temporal variability in high latitude terrestrial ecosystems, as this understanding will provide insight that is relevant to understanding responses to climate change in other terrestrial regions. Changes in high latitudes may also have consequences for the functioning of the Arctic System that are associated with (a) water and energy exchange with the atmosphere, (b) the delivery of fresh water to the Arctic Ocean, and (c) the exchange of radiatively active gases with the atmosphere (Chapin *et al.*, 2000; Forman *et al.*, 2000). It is important to understand terrestrial changes that have consequences for the Arctic System because these responses may affect the rate and magnitude of changes that occur in high latitudes and elsewhere.

Four important points emerged from the workshop on the nature of terrestrial observation networks. First, observation networks need to be designed so that they provide information on how spatial and temporal variability in climate is affecting spatial and temporal variability in high latitude terrestrial ecosystems. This insight is relevant to understanding responses to climate change that have implications for human livelihoods in high latitude regions and elsewhere. *Second, the spatial domain of terrestrial ecosystems that has potential to influence the Arctic System extends far beyond the boundaries of "tundra" and should include the land mass that contributes fresh water inputs to the Arctic Ocean (see Fig. 4.1), i.e., north of 40° N. Third, changes in terrestrial ecosystems that may have consequences for the Arctic System or that may indicate large-scale impacts of changes in the Arctic System include changes in (a) land cover, (b) snow cover, (c) soil thermal regime, (d) terrestrial glaciers, (e) lakes and wetlands, (f) hydrology, and (g) trace gas exchanges. Finally, changes in these features of terrestrial ecosystems may simultaneously influence the different climatic feedbacks relevant to the Arc-*

tic System. For example, changes in land cover or in permafrost dynamics simultaneously influence water and energy exchange, hydrology, and the exchange of radiatively active gases. Observation systems should be designed so that the systems can contribute to sorting out the net effect of the various feedbacks to the Arctic System (e.g., see Betts, 2000).

Presentations and discussions at the SEARCH Observations Workshop provided information on terrestrial feedbacks to the Arctic System, on the existing observation networks, and on the studies that have identified changes in various features of high latitude terrestrial ecosystems. Of particular relevance are the network of the International Geosphere Biosphere Program (IGBP) high latitude transects, the Land Atmosphere Ice Interactions (LAII) research efforts of the Arctic System Science Program (ARCSS), and the two Long Term Ecological Research (LTER) sites in Alaska located at Toolik Lake and Bonanza Creek (see Fig. 4.2). Below we provide a limited set of key recommendations for SEARCH to consider as priority in its efforts to establish networks for high latitude terrestrial observations. Then we present a summary of the opportunities for continuing and enhancing observations for the various features of high latitude terrestrial ecosystems that emerged from the workshop. Finally, we provide a comprehensive summary of the information on terrestrial observations presented at the workshop to document the rationale that led to the opportunities that we identify and recommendations that we make. A partial summary of potential terrestrial observations is presented in Table 4.1

4.2 Key Recommendations for Continuing/Enhancing High Latitude Terrestrial Observations

Below we provide a set of recommendations for the SEARCH effort to continue and enhance high latitude terrestrial observations. These recommendations are based on our judgment that implementation of these recommendations will provide important information on how spatial and temporal variability in climate is affecting spatial and temporal variability in high-latitude terrestrial ecosystems. We also feel that the implementation of these recommendations will provide some information relevant to how high-latitude terrestrial ecosystems influence the climate of the Arctic System through water/energy exchange, freshwater flux to the Arctic Ocean, and the exchange of trace gases with the atmosphere. Our recommendations are also based on our perspective that SEARCH efforts should build on LAII research (e.g., ITEX, FLUX, ATLAS), on LTER Research (Toolik and Bonanza Creek LTERs), and should build on international efforts (IGBP, EU, Japanese, and Canadian). The recommendations represent a limited set of the opportunities identified above with the perspective that initial resources committed by SEARCH should be devoted to these issues, and other issues should receive attention as additional resources for SEARCH become available. The terrestrial observations supported by SEARCH will be most valuable to advancing scientific understanding of terrestrial responses and variability if they are integrated with process and modeling studies. Also, it is important that information from observation networks and process and

Figure 4.1: The pan-Arctic drainage basin. Figure from Forman *et al.* (2000).
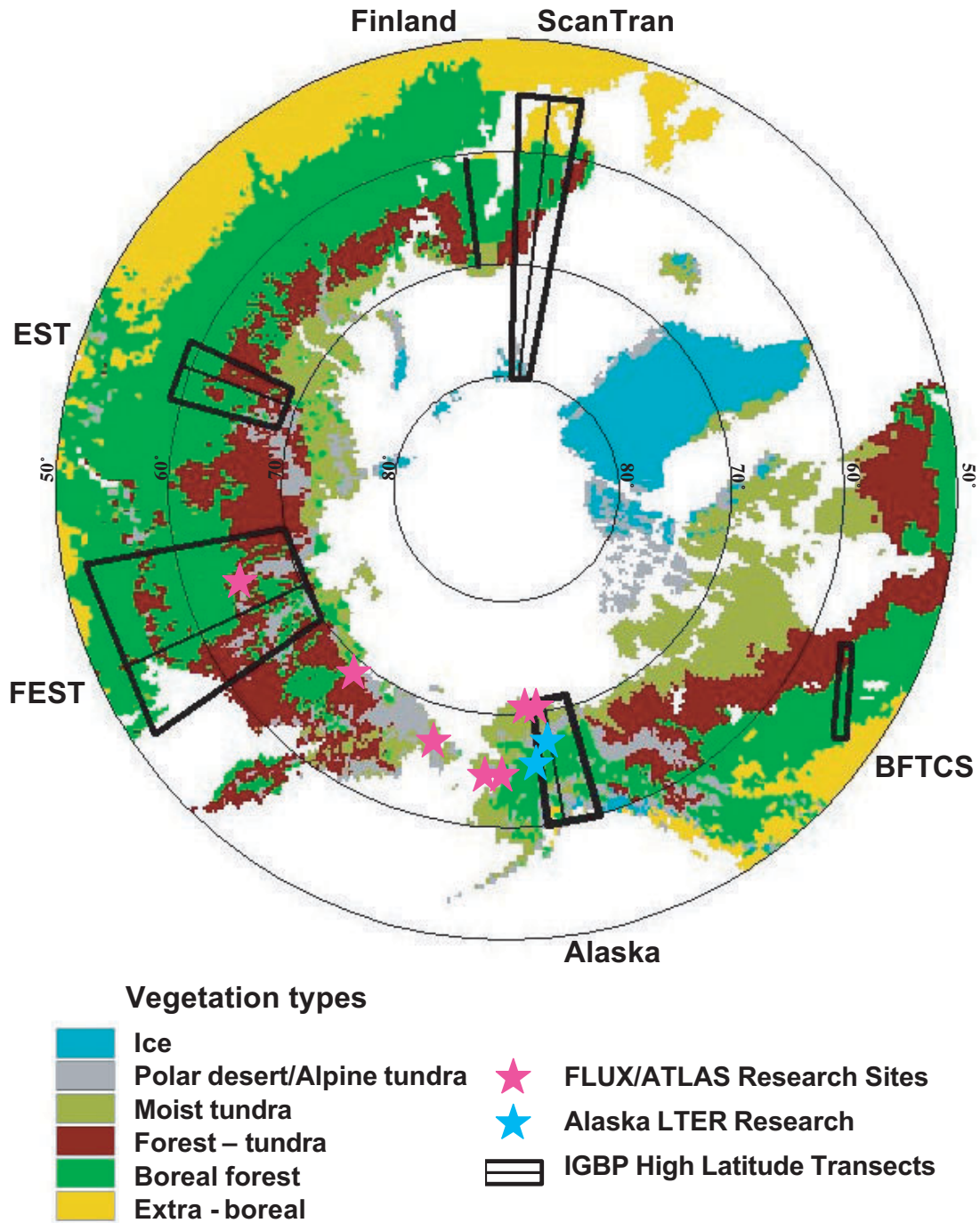
Figure 4.2: Polar projection vegetation map indicating the location of high latitude transects. Also shown are the locations of ARCSS-LAII research sites from the FLUX and ATLAS efforts and the locations of the Toolik and Bonanza Creek Long Term Ecological Research Sites in Alaska. Figure is based on figure from McGuire *et al.* (2002).

Table 4-1: A partial listing of existing observation networks for parameters that are changing features of terrestrial ecosystems. In the "Feedbacks" column, R is for radiative forcing, H represents hydrology, and C is for carbon and methane.

Parameter	Primary existing observation program, network, and/or data set	Observation method	Spatial coverage and resolution	Temporal coverage and frequency	Comments	Other relevant programs, information sources	Feedbacks
Land Cover							
Treeline	Individual researchers	Tree rings ("forest demographics")	Individual sites, but pan-Arctic. Resolution varies	Change has a 100-year time scale. Need observations every 5 years to capture change relevant to AO	Remote sensing a possibility, but only on long (50-year) time scale. Need for periodic obs. campaigns	ATLAS	R, H, C
Shrubs	ITEX	Passive warming experiment	Individual sites (of several m-sq plots), but pan-Arctic	11-year time series	Remote sensing (and photography) possible with TM & ETM at sub-decadal intervals	ATLAS	R, H, C
Growing Season	AVHRR studies	Remote sensing (well developed application)	N. hemisphere, 1 km and 8 km	Sub-monthly, 1981–present	Can use growing degree days for proxy	[Boston University site]	R, H, C
Disturbance (e.g., fire)— extent and severity	AK (BLM) and Canada (CFS) large fire scar data base	Fire records, plus remote sensing	AK, Canada, at about 1 km	AK: 1950–present Canada: 1960–present	Need fire data base for northern Eurasia and other disturbance data bases for pan-Arctic (e.g., logging, insect defoliation)	Alaska fire service URL	R, H, C
Snow Cover							
Extent	NOAA operational snow product	Optical remote sensing, with passive microwave beginning in 1999	N. hemisphere, 25 km	Gridded 25 km weekly product from NSIDC incorporating NOAA analysis: 1971–1995. Daily operational product from NOAA/NESDIS: 1997–present	Possible discontinuity in NOAA product in 1999. 500 m gridded product from MODIS instrument: 2000–present	NOAA/NESDIS Climate Prediction Center, NOAA/NESDIS Satellite Services Division	R, H
Depth	National (U.S., Russia, Canada) obs. networks, a standard obs. at synoptic and climate stations	Manual. Remote sensing of depth is immature application	Point measurements, limited number of transects	Daily beginning in 1950s, earlier for some stations	Closure of stations, and change to automatic methods impacting consistency and coverage	Global Climate Observing System	H, C
SWE	National (U.S., Russia, Canada) networks	Snow course, some automated sensors. Remote sensing of depth is an emerging application.	Point measurements, limited number of transects. Satellite-derived Canada product	Varies, daily to 10-day. Daily (if satellite derived)	Decline in number of snow course measurements	NASA Cold Lands Processes (CLP) experiment for rmt sensing validation. Canadian CRYSYS program	H
Soil Thermal Regime							
Permafrost/seasonally frozen ground extent	Int. Permafrost Asso. map (CAPS CD-ROM)	Developed based on expert opinion, not observations	Northern hemisphere. Gridded version (12.5 km) available	Static	Need pan-Arctic map of better spatial resolution, based on observations	IARC/WDC Frozen Ground Data Center	R, H, C
Active Layer Depth	CALM network	Individual stations	Pan-Arctic	Measured annually	Network record not long enough yet to evaluate for monitoring trends. Need to re-establish and maintain borehole transect network		R, H, C
Temperature, freeze/thaw duration	Existing borehole sites, e.g., IGBP trans-Alaskan boreholes (incorporation of these and others in GTMP network proposed)	Boreholes	Pan-Arctic, point measurements, limited number of sites with multiple boreholes	Varies by borehole, generally longer than 20 years. Weekly to monthly needed in uppermost 20 m, annually to every 10 years at greater depths [from GTOS requirement]	Timing of freezing, thawing, may be detectable with remote sensing. NASA CLP program is investigating	GTMP network. GCOS–Global Terrestrial Network for Permafrost	R, H, C

Table 4-1: (continued).

Parameter	Primary existing observation program, network, and/or data set	Observation method	Spatial coverage and resolution	Temporal coverage and frequency	Comments	Other relevant programs, information sources	Feedbacks
Terrestrial Glaciers							
Mass Balance	World Glacier Monitoring Service	In situ (stake) measurements. Airborne laser campaigns	Pan-Arctic	Needed annually	Large glaciers not well documented. Reduction in the number of glaciers monitored since 1980s	GCOS-Global Terrestrial Network for Glaciers. USGS, University of Alaska programs for U.S. glaciers	H
Parameter (e.g., length, elevations, area)	World Glacier Monitoring Service	In situ measurements, remote sensing measurements soon to come	Pan-Arctic	Length: needed annually to every 10 years. Inventory parameters: every 30–50 years		GLIMS project for glacier parameters from space	R
Lakes and Wetlands							
Ice cover duration	LIAG Global Lake and River Ice Phenology Database	In situ observations, with remote sensing an emerging application	About 270 northern hemisphere lakes in LIAG data base	Annual ice on, ice off dates		Canada Ice Service programs. Lake Ice Analysis Group (LIAG)	R, H
Areal extent of lakes and wetlands					There is a need to monitor a selection of lakes, with change detection studies		R, H, C
Hydrology						CHAMP, RIMS (Monitoring network)	
Precipitation	National networks				Intercomparison studies show serious differences in obs. from different nations		H
Runoff	National networks	Gauging stations	Pan-Arctic stations	1930–present (Russia), 1970–present for AK and Canada	The number of operational gauge stations has decreased	Arctic-RIMS active archive, underway since 2001	H
Soil moisture					There is a need for this product. Remote sensing validation issue?		H, C, R
Water constituents	Russian network				ARCSS project to evaluate data quality	USGS starting 5-year program in Yukon	C
Trace Gas Exchange (CO$_2$/Methane)	Loose pan-Arctic network of investigators	Chambers, eddy covariance towers	Individual pan Arctic sites, 1 m to 1 km	1970's–present, duration depends on investigator. Most focus on growing season. (Need winter as well)		ATLAS, CONGAS, BERMS, BOREAS, Northern wetland studies, LAII flux study [access data through distributed data bases, e.g., JOSS]	C, H, R
	Siberian tall tower	One 600 m eddy covariance tower	Central Siberia, about 1000 km × 1000 km area covered	Under construction	Max Plank Institute involved		
	Aircraft campaigns	Aircraft gas sampling	Siberia, continental spatial scope	Monthly, for 1 year, in 2001 or 2002	Max Plank Institute involved		

modeling studies ultimately be incorporated into coupled models of the Arctic System at the pan-Arctic scale. From the set of opportunities in the following Section 4.3, we highlight the following five recommendations:

- *SEARCH should provide resources for maintaining the operation of U.S. ITEX sites,* as the International ITEX data set now has information on changes in vegetation communities over the last decade. This should be combined with extensive calibration and use satellite-based vegetation indices over the Arctic basin.

- *SEARCH should provide resources to ensure the maintenance and, where possible, the re-establishment of long-term monitoring of permafrost and glacier mass balance.* Resources are needed for upgrading equipment and for providing maintenance of Russian borehole sites and the sites along the Alaskan IGBP transect already in existence and for the re-occupation of abandoned USGS borehole sites in Alaska. Similarly, for glaciers, resources are needed to maintain current monitoring efforts and re-establish programs on glaciers in critical regions.

- *SEARCH should provide resources for monitoring a key selection of lakes throughout the pan-Arctic for break-up dates, freeze-up dates, and changes in lake size.*

- *SEARCH should coordinate with ARCTIC-CHAMP to determine how it can best provide operational assistance to that effort.*

- *SEARCH should provide some support for the operation of key sites that are comprehensively monitoring how climatic variability influences variability in water, energy, and trace gas exchange (e.g., eddy covariance sites);* priority for support should go to sites that are currently providing long-term records of observations and for sites that have a history of long-term studies of processes.

4.3 Opportunities for Continuing and Enhancing High Latitude Terrestrial Observations

4.3.1 Land Cover

Key observational opportunities for detecting changes in land cover in SEARCH are to (1) maintain continuity of the ITEX measurements, (2) conduct analyses of AVHRR and MODIS imagery that are more relevant to the high latitudes than the global analyses that have been conducted in the past, (3) conduct change-detection studies of Landsat and other fine-scale imagery to determine the extent of shrub expansion throughout the pan-Arctic, (4) conduct periodic campaigns for determining the extent of tree-line expansion throughout the pan-Arctic, and (5) assist in the development of an operational capability for monitoring the extent of fire disturbance in Russia and insect infestations in North America.

4.3.2   Snow Cover

Existing operational snow extent estimates from NOAA are probably adequate for evaluating changes in snow extent. NOAA's Office of Research and Applications is currently compiling these products on a CD-ROM of snow and land cover from 1981-present. There are difficulties for water content.

4.3.3   Soil Thermal Regime

The maintenance of a high latitude network of five borehole transects (one in Alaska, two in Canada, and two in Siberia) would provide the capability to monitor permafrost temperature with depth, active layer depth, soil moisture, and changes in freeze-thaw dynamics in a manner that is relevant to the Arctic System. The network could become operational with a modest investment in equipment and maintenance for the Russian borehole sites and for the re-occupation of abandoned USGS sites in Alaska. Network data management is an issue that needs to be resolved.

4.3.4   Glaciers and Ice Sheets

While satellite remote sensing of glacier mass balance is improving as resolution increases, there are still a number of issues that need to be resolved before it is fully operational. Fieldwork is generally expensive, but a stake network for Arctic glaciers might be effective as ablation and accumulation rates are small. Aircraft airborne laser campaigns represent the best means of currently assessing volumetric changes for glaciers and ice sheets. New observational programs should, where feasible, be undertaken on glaciers that have been the subject of mass balance studies in the past.

4.3.5   Lakes and Wetlands

There is an opportunity for SEARCH to monitor a selection of lakes throughout the pan-Arctic for break-up and freeze-up dates using in situ methods. The selection of lakes may usefully be stratified by drainage basins, ecoregions, and lake size (large vs. small). Currently, satellite remote sensing of break-up and freeze-up dates is a research and development activity rather than an operational activity. There is also the opportunity to conduct change-detection studies of Landsat and other fine-scale imagery to determine whether changes in lake area represent interannual variability or represent longer term trends.

4.3.6   Hydrology

There are opportunities for SEARCH (1) to initiate a monitoring network for soil moisture, (2) to assist with occupying and maintaining key discharge stations that are at risk or have ceased operation, and (3) to assist in the effort to rescue Russian data into pan-Arctic and global archives. Remote sensing research and development should be focused toward ultimately providing the capability to provide an operational soil moisture product. SEARCH should

coordinate with ARCTIC-CHAMP to determine how it can best provide operational assistance to that effort.

4.3.7 Trace Gas Exchanges

There are opportunities for SEARCH to support the continued operation of currently operating eddy covariance sites along with the expansion of eddy covariance sites for key sites. Higher priority for support should go to sites that are providing longer records of observations and for sites that have a history of long-term studies of processes (e.g., the two LTER sites in Alaska). If intensive sites for ground-based monitoring of atmospheric processes (e.g., the DOE ARM/NOAA CMDL site at Barrow) are installed around the pan-Arctic by SEARCH, then eddy covariance sites should be established along with associated process studies as the exchanges of trace gases are coupled with exchanges of water vapor and energy with the atmosphere. SEARCH should also consider how it can augment and enhance the tall tower and aircraft campaigns that are just being initiated in Siberia. SEARCH should also consider to what extent it can assess the quality of extant data on DOC and other river constituents that have been archived and to rescue data that have not been archived into an operational pan-Arctic data base of DOC and other constituents.

4.4 Review of Information Presented on High Latitude Terrestrial Observations—Background on Terrestrial Feedbacks Relevant to the Arctic System

Responses of high latitude ecosystems to global change have the potential to influence water and energy exchange with the atmosphere in several ways. Expansions of shrub tundra into regions now occupied by sedge tundra and of boreal forest into regions now occupied by tundra have the potential to reduce growing season albedo and increase spring energy absorption to enhance atmospheric warming (Bonan *et al.*, 1992; Thomas and Rowntree, 1992; Foley *et al.*, 1994; Chapin *et al.*, 2000; Beringer *et al.*, 2002). Other effects that may enhance atmospheric warming through decreased albedo include extension of the snow-free and ice-free periods on terrestrial and lake surfaces. Also, reduction in the area occupied by glaciers and continental ice sheets in high latitudes may reduce albedo; similarly, changes in the area of lakes or in the area occupied by open water in wetlands may affect albedo. Disturbance may also affect energy exchange with the atmosphere. For example, while fire disturbance often reduces albedo to approximately 0.05 shortly after the fire, fire disturbance provides the opportunity for deciduous forests to develop, which generally have higher albedo in comparison to conifer forests. Thus, disturbance regimes (e.g., fire) that increase the proportion of non-forested lands and deciduous forests have the potential to reduce energy absorption and work against atmospheric warming (Chapin *et al.*, 2000).

The delivery of freshwater from the continental land mass is of special importance to the Arctic Ocean since it contains only about 1% of the world's

ocean water, yet receives about 11% of world river runoff (Shiklomanov *et al.*, 2000; Forman *et al.*, 2000); the Arctic Ocean receives fresh water inputs from four of the fourteen largest river systems on earth (Forman *et al.*, 2000). Additionally, the Arctic Ocean is the most river-influenced and land-locked of all oceans and is the only ocean with a contributing land area greater than its surface area (Ivanov, 1976; Vörösmarty *et al.*, 2000a). Freshwater inflow contributes as much as 10% to the upper 100 meters of the water column for the entire Arctic Ocean (Barry and Serreze, 2000). Changes in fresh-water inputs to the Arctic Ocean have the potential to alter salinity and sea ice formation, which may have consequences for the global climate system by affecting the strength of the North Atlantic Deep Water Formation (Aagaard and Carmack, 1989; WMO/WCRP, 1994; Broecker, 1997). Modeling studies suggest that maintenance of the thermohaline circulation is sensitive to fresh-water inputs to the North Atlantic (Manabe and Stouffer, 1995). Also, freshwater on the Arctic continental shelf more readily forms sea ice in comparison to more saline water (Forman *et al.*, 2000). The responses of freshwater inputs to the Arctic Ocean depend on changes in the amount and timing of precipitation, and the responses of permafrost dynamics, vegetation dynamics, and disturbance regimes to global change. For example, changes in evapotranspiration associated with permafrost and vegetation dynamics have consequences for river runoff that depend additionally on changes in precipitation inputs to terrestrial ecosystems.

Increases in the atmospheric concentrations of radiatively active gases have the potential to influence the climate through altering the earth's near-surface energy balance (IPCC, 2001). Responses of high latitude ecosystems have the potential to influence the atmospheric concentrations of the radiatively active gases carbon dioxide and methane in several ways (Smith and Shugart, 1993; McGuire and Hobbie, 1997; McGuire *et al.*, 2000a, 2000b; Chapin *et al.*, 2000). High latitude ecosystems contain approximately 40% of the world's soil carbon inventory that is potentially reactive in the context of near-term climate change (McGuire *et al.*, 1995; Melillo *et al.*, 1995; McGuire and Hobbie, 1997). Regions affected by permafrost are especially vulnerable to climate change because of altered drainage. Thermokarst activity that leads to the expansion of lakes and wetlands may cause increased releases of methane from high latitude ecosystems (Reeburgh and Whalen, 1992; Zimov *et al.*, 1997). Reductions in the water table of tundra ecosystems substantially enhances the release of carbon from high latitude soils (Oechel *et al.*, 1995; Christensen *et al.*, 1998). The replacement of tundra with boreal forest might initially decrease but eventually increase carbon storage in high latitudes (Smith and Shugart, 1993), with time lags and rates of change that are sensitive to the rate and variability of climate change (Chapin and Starfield, 1997). Disturbance in the boreal forest region may substantially influence regional carbon exchange with the atmosphere (Kurz and Apps, 1999; Dargaville *et al.*, 2002). The responses of carbon storage in high latitude ecosystems have important implications for the rate of CO_2 accumulation in the atmosphere and international efforts to stabilize the atmospheric concentration of CO_2 (Smith and Shugart, 1993; McGuire and Hobbie, 1997; McGuire *et al.*, 2000b; Betts, 2000). In particular, it is impor-

tant to understand how the global energy balance implications of changes in trace gas exchanges of high latitude terrestrial ecosystems trade off against or contribute to responses of regional energy balance associated with changes that influence water and energy exchange in high latitudes (Betts, 2000).

Changes in terrestrial ecosystems that may have consequences for the Arctic System or that may indicate large-scale impacts of changes in the Arctic System include changes in (a) land cover, (b) snow cover, (c) soil thermal regime, (d) terrestrial glaciers, (e) lakes and wetlands, (f) hydrology, and (g) trace gas exchanges. Observation networks that monitor changes that affect these aspects of high latitude terrestrial ecosystems have the potential to provide information on how spatial and temporal variability in climate is affecting spatial and temporal variability in high-latitude terrestrial ecosystems. This insight is relevant to understanding responses to climate change that have implications for human livelihoods in high-latitude regions and elsewhere. Below, we review information provided at the workshop on these aspects of high latitude terrestrial ecosystems.

4.4.1 Land Cover

Key issues of land cover change in high latitude regions relevant to the Arctic System include expansion of treeline at the expense of tundra, expansion of shrub tundra at the expense of sedge tundra, changes in vegetation leaf area and growing season length, and changes in disturbance extent and severity.

The importance of improving the representation of the effects of land cover in climate re-analyses was highlighted by the fact that incorporation of improved information on albedo from the Boreal Ecosystem Atmosphere Study (BOREAS) in the recent ECMWF re-analysis (Viterbo and Betts, 1999). This resulted in a 2°C January warm bias for northern hemisphere in comparison with a 13°C January cold bias that was present in the prior ECMWF re-analysis. Information presented on land cover changes include documented expansion of treeline on the Seward Peninsula in Alaska and elsewhere (Lloyd *et al.*, 2002), documented expansion of shrub tundra on the Seward Peninsula and North Slope in Alaska (Silapaswan *et al.*, 2001; Sturm *et al.*, 2001), documented changes in growing season length in Alaska (Keyser *et al.*, 2000), and a doubling of annual area burned in the boreal forest of North America during the last 20 years in comparison with earlier decades (Stocks *et al.*, 2000). Analyses of northern hemisphere NDVI over the last two decades are consistent with expanding growing seasons, greater growth of trees, and expansion of shrub tundra (Fig. 4.3; Myneni *et al.*, 1997, 2001; Zhou *et al.*, 2001). The International Tundra Experiment (ITEX) is a pan-Arctic network of sites (Fig. 4.4a) using a common passive temperature manipulation (see Fig. 4.4b) to examine variability in species responses across climatic and geographic gradients of tundra ecosystems over the last decade (Henry and Molau, 1997; Arft *et al.*, 1999). Results indicate that leaf bud burst and flowering are occurring earlier on warmed plots, but that there has been little effect on the termination of growth at the end of the growing season (Arft *et al.*, 1999). ITEX measurements have also docu-
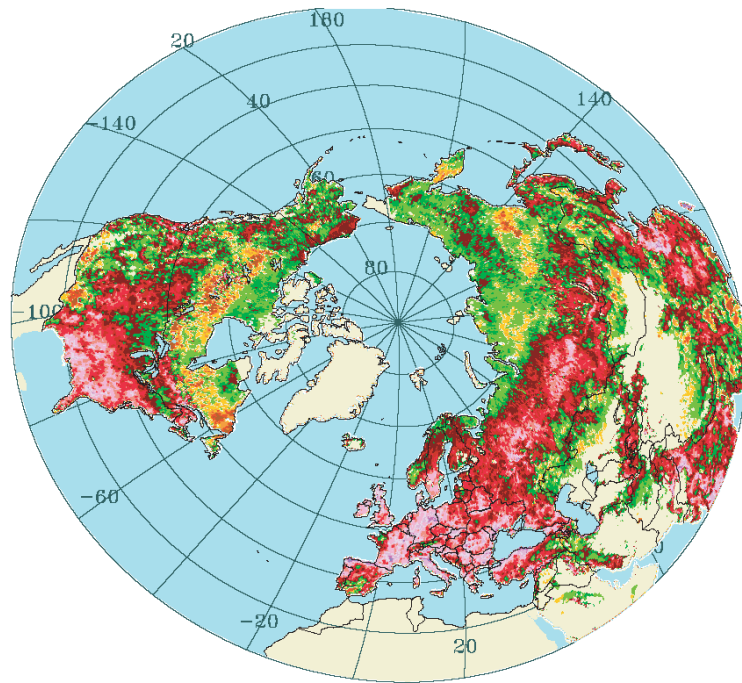
Figure 4.3: Changes in May to September NDVI from 1982–86 to 1995–99 across the northern hemisphere. Based on data from Zhou *et al.* (2001) and Myneni *et al.* (2001).

mented greater growth of shrubs in both control and passive warming plots (Fig. 4.4c).

While treeline expansion on the Seward Peninsula is detectable with ground-based tree-ring studies (Lloyd *et al.*, 2002), it does not appear to be detectable over the last two decades with Landsat imagery (Silapaswan *et al.*, 2001). The expansion of shrub tundra in Alaska is detectable with comparisons between historical (circa 1940s) and contemporary photographic imagery (Sturm *et al.*, 2001) and Landsat imagery (Silapaswan *et al.*, 2001). Silapaswan *et al.* (2001) demonstrated that the expansion of shrub tundra is detectable with Landsat imagery at decadal and sub-decadal resolution. Changes in vegetative leaf area and growing season length appear to be detectable via analyses of AVHRR imagery (Myneni *et al.*, 1997), and other satellite technologies (e.g., microwave; see Running *et al.*, 1999a) show some promise for monitoring changes in growing season length. In comparison with analyses of AVHRR imagery, it is anticipated that analyses of MODIS imagery will provide better information on changes in vegetative leaf area and growing season length. ITEX currently provides a pan-Arctic network of sites that is measuring changes in vegetation phenology, growth, and reproduction throughout the Arctic. The capability for monitoring the extent of fire disturbance is already operational in Alaska and Canada (Murphy *et al.*, 2000; Stocks *et al.*, 2000), but information on the extent of fire disturbance in Russia is currently not reliable.
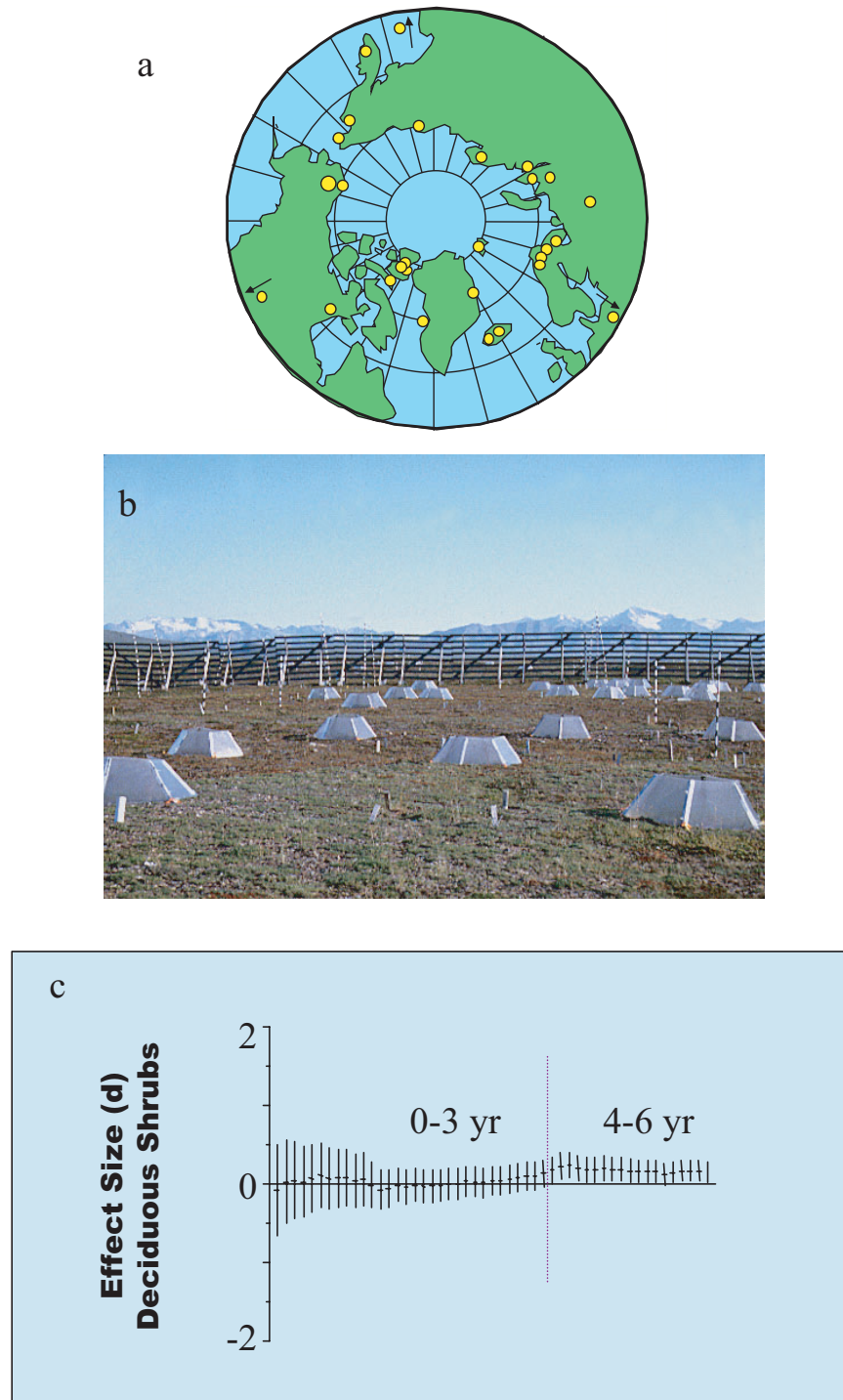
Figure 4.4: (a) Location of the International Tundra Experiment (ITEX) research sites across the pan-Arctic. (b) Contol and passive warming plots at the Toolik Lake ITEX site in Alaska. (c) Effect size of passive warming on shrub cover. Figure provided by M. Walker, University of Alaska Fairbanks.

4.4.2   Snow Cover

Key parameters of snow cover include snow extent, snow water equivalent, and snow depth.

Beginning in 1972, snow extent was operationally derived by NOAA from AVHRR/GOES imagery for the northern hemisphere at 25 km spatial resolution and weekly temporal resolution. Since 1999, the snow extent product has produced daily from a variety of satellite sources including passive microwave imagery. A 4 km product will be available this year. NOAA is moving toward fully automated processing, and expects to produce a twice daily product at 1 km resolution by 2004. A daily 500 m gridded snow cover product from the MODIS instrument has been available since September 2000. NCAR has some gridded snow cover from 1966 on. Serreze *et al.* (2000) summarize analyses of NOAA and other snow data sets and find that Northern Hemisphere snow cover has decreased by about 10% since 1972, due primarily to less snow in spring and summer.

4.4.3   Soil Thermal Regime

Key parameters of the soil thermal regime in high latitude terrestrial regions include permafrost temperature, active layer depth, seasonal freeze-thaw dynamics, and permafrost extent.

The permafrost thermal regime with depth is a natural low-pass filter that is capable of recording climatic variability on decade-to-century time scales. A north-south network of boreholes in Alaska that has been operational since 1983 has documented that permafrost temperatures at 20 m depth have been increasing over the past two decades. The Alaska borehole network identifies the value of measuring the permafrost thermal regime along transects, which is more valuable than randomly placed individual boreholes. Boreholes already exist along four other possible transects: (a) in Western Canada, (b) in Eastern Canada, (c) in western Siberia, and (d) in eastern Siberia (see Fig. 4.5a). The Canadian Geological Survey is making measurements for the borehole transect in Western Canada, while Laval University in Quebec is making measurements for the borehole transect in Eastern Canada. There are quality control problems with the borehole data being collected in Russia, primarily because of poor equipment. The Russian borehole sites could be made operational for a modest investment in equipment and maintenance. Re-occupation of some boreholes previously maintained by USGS in Alaska would also provide some valuable data as there are several decades of data available for these sites prior to the 1990s. Important issues to resolve in establishing a global network of five transects is to determine what obstacles exist to making data available in timely fashion and what is required to overcome those obstacles.

Active layer depth is being monitored across the pan-Arctic by the Circumpolar Active Layer Monitoring Network (CALM; Hinkel *et al.*, 2002). Interannual variability in active layer depth at a particular site is primarily related to interannual variability in summer air temperature. Longer-term variability in active layer depth requires measurements of permafrost tem-
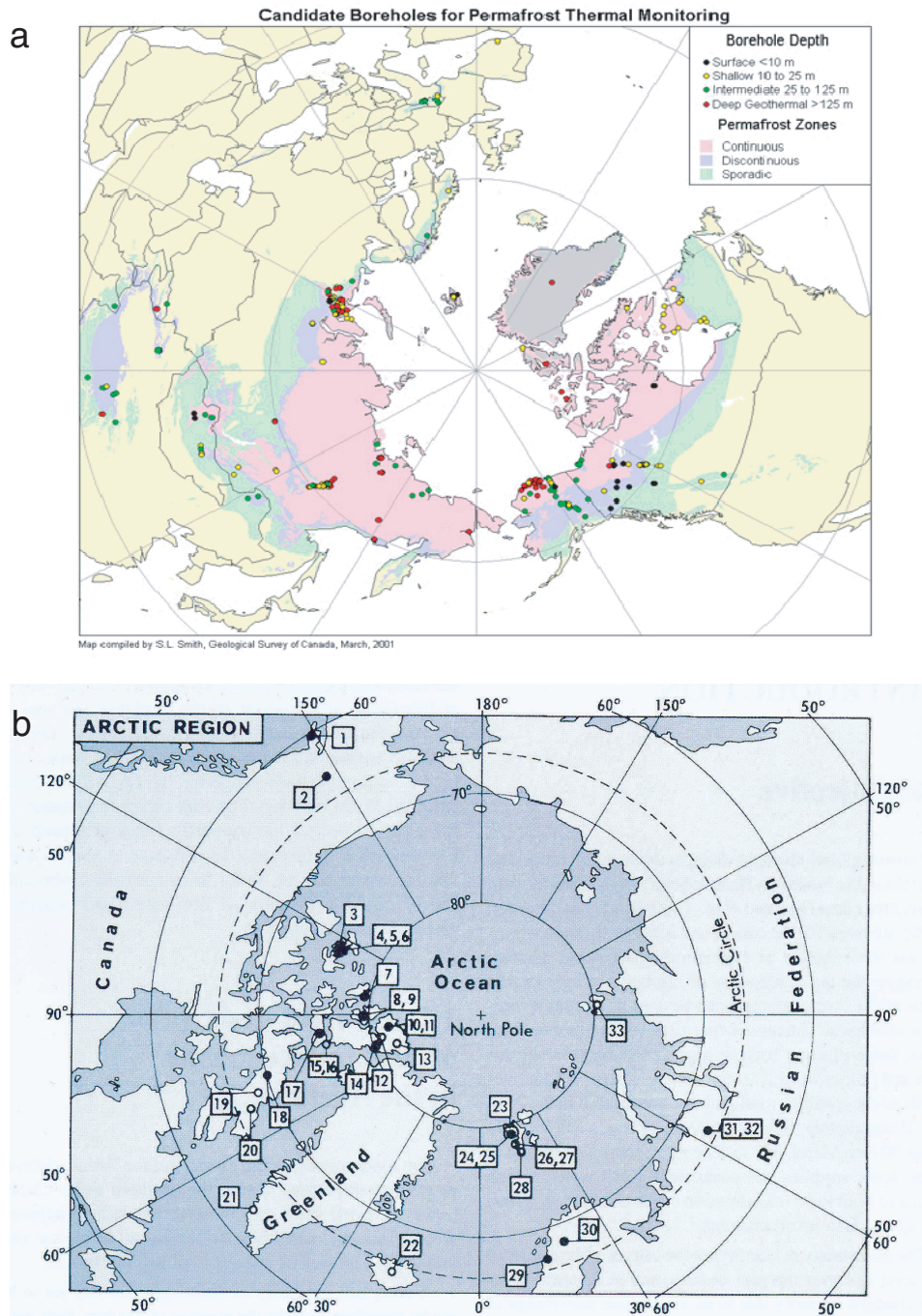
Figure 4.5: (a) Candidate boreholes for permafrost thermal monitoring (provided by V. Romanovsky, University of Alaska Fairbanks) and (b) Glacier mass balance locations in the Arctic (from Jania and Hagen, 1996). Black circles indicate glaciers with more than 20 years of observations, and empty circles indicate glaciers with between 5 and 20 years of observations. 1–Wolverine Glacier, 2–Gulkana Glacier, 3–Melville S. Ice Cap, 4–Melville W. Ice Cap, 5–Melville E. Ice Cap, 6–Leopold Glacier, 7–Meighen Ice Cap, 8–White Glacier, 9–Baby Glacier, 10–Ward Hunt Ice Shelf, 11–Ward hunt Ice Rise, 12–Per Ardua Glacier, 13–Gilman Glacier, 14–Agassiz Glacier, 15–Laika Glacier, 16–Laika Ice Cap, 17–Devon Ice Cap, 18–Barnes Ice Cap, 19–Decade Glacier, 20–Boas Glacier, 21–Satujokull, 22–Qamanarssup sermina, 23–Konsvegen, 24–Austre Brogerbreen, 25–Midre Lovenbreen, 26–Voringbreen, 27–Bertilbreen, 28–Hansbreen, 29–Storglaciaren, 30–Engabreen, 31–IGAN Glacier, 32–Obruchev Glacier, 33–Vavilov Glacier.

peratures for interpretation. Measurements of active layer at the borehole sites may provide the capability to observe and interpret long-term changes in active layer depth. The International Permafrost Association is implementing the Global Terrestrial Network for Permafrost (GTN-P) for the WMO/ICSU Global Climate Observing System (GCOS) and Global Terrestrial Observing System (GTOS). Northern hemisphere CALM sites (80 in number, `http://www.geography.uc.edu/%7Ekenhinke/CALM/map.html`) and nine European permafrost boreholes from the Permafrost and Climate in Europe program (`http://www.cf.ac.uk/earth/pace/fieldsites/index.html`) are currently part of GTN-P.

Freeze-thaw dynamics in high latitude regions are intimately tied to changes in growing season length, and have substantial implications for the exchange of water, energy, and trace gases with the atmosphere and influences hydrology. NSIDC currently provides a land-based freezing/thawing degree-day product based on climatology station records, but it does not provide adequate resolution or coverage of the polar regions, particularly in mountainous terrain. Also, it is not clear whether this product has been adequately validated for regions of continuous and discontinuous permafrost. Analyses based on data from NASA scatterometers (NSCAT, SeaWinds) show some promise for monitoring the freeze-thaw status of the land mass (Rignot and Way, 1994; Running *et al.*, 1999a; Frolking *et al.*, 1999), but the algorithms and technology need further evaluation and development as the scatterometers are not formally optimized for land-based cryospheric applications. It may also be possible to detect onset of surface melt from changes in surface microwave emissivity, which would go from relatively high emissivities when the surface is frozen to low values when the surface has standing water. A cold-processes satellite mission that has been proposed to NASA is focused on measuring changes in freeze-thaw dynamics and may provide the ability to monitor changes in freeze dynamics across high latitudes if the mission becomes a reality. The suggested borehole network would provide the capability to monitor systematic changes in freeze-thaw dynamics that could be valuable in validating climatological and remote sensing algorithms of freeze-thaw dynamics.

While the International Permafrost Association has put together a map of permafrost extent (International Permafrost Association's circumarctic map, published 1997, `http://www.grida.no/prog/polar/ipa/`), the map is primarily of interpretive value as the resolution is coarse and it is not useful for assessing changes in permafrost extent. *The mapping of permafrost in a spatially explicit fashion is a major challenge to the scientific community that requires new approaches.* There are several remote sensing technologies that might be brought to bear on monitoring thermokarst topography, which would aid in understanding changes in permafrost extent. In particular, the cold-processes satellite mission that has been proposed to NASA may provide some improved technical capabilities to map permafrost extent.

4.4.4 Glaciers and Ice Sheets

A key issue of high-latitude glaciers and ice sheets relevant to the Arctic System is whether ice mass is changing. Below we first discuss the monitoring of ice mass changes in the Greenland Ice Sheet and then discuss changes of ice mass in glaciers.

In spite of their poor temporal coverage, existing data sets from radar altimetry (Seasat, Geosat, ERS) provide a picture of change in the high interior of the Greenland Ice Sheet over the last few decades; this data stream continues but is not of use near the ice margins, where the most rapid variations occur. NASA airborne laser measurements have identified significant changes in the Greenland Ice Sheet over the last half of the 1990s, a result that has provided the first definitive measurement of one ice sheet's contributions to the present rate of sea level rise. The proposed ICESat NASA mission has the potential to provide systematic coverage of the Greenland Ice Sheet and, based on the aircraft results, would allow the first comprehensive assessment of the present contribution of the ice sheet to sea level rise. Note that extended time series of these measurements are necessary to understand the background variability of the processes which determine surface elevation, and provide the opportunity to assess the causes of change, which is required to develop a predictive understanding of ice sheet variations. Also required are data on accumulation rates and variations, melt rates, and changes in ice flow.

Elsewhere across the Arctic, the smaller glaciers have exhibited a mixed response to recent climate fluctuations. Syntheses of available data by Jania and Hagen (1996) and Dowdswell *et al.* (1997) indicate that ice mass of Arctic glaciers has been generally decreasing in recent decades, except in Scandinavia, where ice mass is increasing as a result of shifting atmospheric circulation patterns that have produced greater winter precipitation. There are numerous glaciers across the Arctic which have been part of long-term mass balance measurement programs (Fig. 4.5b). For example, the USGS has measured the seasonal mass balance of two glaciers in Alaska for more than 40 years. However, the number of glaciers under scrutiny has drastically declined as a result of declining interest by their respective funding sources. Haberli (2001) summarizes the global mass balance observations, and a comparison with the observations described in Jacek (1996) clearly shows the dramatic reduction in observations.

It is unlikely that interest in glacier mass balance measurements will increase to yield re-establishment of abandoned programs. Furthermore, these programs were man-power intensive and provided information from only a relative handful of glaciers. New capabilities in remote sensing, both satellite and aircraft, can observe Arctic glaciers on a routine basis and provide glacier fluctuation information, as is being carried out over Greenland. The USGS led GLIMS project is developing techniques to provide glacier information from ASTER observations. Other satellite data sources include LANDSAT 7, and the approximately 1 m resolution imagery from IKONOS and Quickbird. While imagery from the later two sensors is expensive, they are the harbingers of future hi-resolution imagery, and efforts should be undertaken

to develop techniques that take full advantage of these capabilities. Future Arctic glacier observations should, where possible, be made on glaciers that have an existing record of mass balance observations.

The World Glacier Monitoring Service is implementing the Global Terrestrial Network for Glaciers (GTN-G) for the WMO-ICSU Global Climate System (GCOS) and Global Terrestrial Observing System (GTOS). It consists of 60 glaciers from all of the world's major mountain ranges that are Tier 2 (with intensive research and observation activities) and Tier 3 (with annual mass balance studies) sites.

4.4.5   Lakes and Wetlands

Key issues of lakes and wetlands include changes in lake temperature, lake chemistry, break-up/freeze-up dates, ice thickness, lake area, and wetland expansion/
contraction.

Data presented from long-term monitoring of Toolik Lake in Alaska indicates that the lake has warmed substantially over the past 25 years and that the lake chemistry has become more alkaline.

Break-up and freeze-up dates of lakes are a good proxy for climate change and can be estimated via in situ and remote sensing observations. There are currently substantial limitations to using remote sensing. For example, while ERS 1/2 is quite useful for detecting frozen vs. thawed lakes, the temporal frequency is not good enough to precisely determine break-up and freeze-up dates. Products with daily temporal frequency, e.g., the AVHRR 1.25 km and 5 km resolution path finder (since 1982) and OLS on DMSP have the potential to be used to produce a record of break and freeze up over medium to large lakes. Thus, satellite remote sensing of break-up and freeze-up dates is currently a research and development activity rather than an operational activity.

Analyses of in situ observations suggest that lakes in North America are generally breaking up earlier (Magnusson *et al.*, 2000), although there are regional differences in trends. For example, in Canada the length of the ice-free season has increased in some areas and decreased in others. NSIDC maintains the LIAG database, which contains information for 270 lakes above 55°N, 155 of which are from Canada. Only about 20 of the lakes in the database have records that are older than 20 years. For some lakes, ice thickness is also measured. There is a need to rescue Russian data that has been collected on the timing of break-up and freeze-up. There is some limited evidence from historical photographs and Landsat imagery that low elevation lakes in Alaska and Yukon, specifically on the Seward Peninsula, in the Copper River Valley, and in Old Crow Flats are shrinking in size while lakes at higher elevation are not changing in area. It is not entirely clear if these observations represent interannual variability or represent longer-term trends. Remote sensing studies are currently being conducted to determine if this is a regional phenomenon that may be caused by greater drainage associated with permafrost degradation. There is also evidence of substantial

thermokarst development in the Tanana Flats near Fairbanks that may be leading to more open water in those wetlands (Osterkamp *et al.*, 2000).

4.4.6 Hydrology

Key parameters relevant to terrestrial hydrology include precipitation, evapotranspiration, soil moisture, and river discharge.

Although there are many conventional data sets for precipitation, they do not provide adequate coverage of high latitude and polar regions. Global precipitation data sets combining satellite and ground-based data are currently available from other agencies such as the WMO Global Precipitation Climatology Center and the Global Precipitation Climatology Project (GPCP). For Arctic applications, NSIDC maintains historical archives of land-station precipitation from the former Soviet Union and Canada. The observations in these data sets are available with corrections for gauge biases, the most severe of which is associated with the undercatch of snowfall. As different countries use different gauges, and the bias in the gauges depend on a lot of factors (e.g., wind speed), the correction for biases present in large-scale precipitation data sets is a difficult problem, and while corrections can be made, large errors remain.

Evapotranspiration fields currently must be estimated with a model. The simplest, so-called reference surface techniques require but mean daily temperature while more physically based functions, typically employed in soil-vegetation-atmosphere-transfer schemes and process-based studies, can require skin temperature, humidity, net radiation, aerodynamic roughness, albedo, leaf area index, and wind speed. While several, but not all, of these required input variables or parameters are measured routinely by satellites, there are very few sites where most of these variables are simultaneously measured on the ground. Vegetative properties such as leaf area index and land cover are also essential. Variables such as wind speed, temperature, humidity, and pressure data over polar land areas are obtained from rawinsonde observational networks and are archived at NSIDC. Coarse-resolution data sets for evapotranspiration are currently available from the National Center for Environmental Prediction (NCEP) and European Center for Medium-range Weather Forecasting (ECMWF) operational and re-analysis activities. Validation over grid-cell areas is needed in order to provide a basis for improved parameterizations of evapotranspiration in future reanalyses.

Passive microwave radiometers have been used to detect soil moisture. Systems such as SSM/I or AMSR have the advantage of acquiring this information on a routine basis (few days re-visit time) from space with a resolution on the order of 50 km or larger. However, interference from vegetation limits to what can usefully be obtained from these sensors at this time. The Global Soil Wetness Project uses AVHRR-derived vegetation information and modeling to produce global soil moisture fields, but these fields have not been adequately evaluated for high-latitude regions. A proposed NASA post-2002 mission to monitor soil moisture at 10 km resolution is currently

under consideration. Higher resolution SAR data has also been shown to provide some information about soil moisture.

River discharge must typically be obtained from ground-based station data available through several archives. Major subsets of these holdings have been organized into a pan-Arctic data collection, and the NSF-ARCSS funded Arctic-RIMS project is operationally monitoring near-real time river discharge information for river systems in the pan-Arctic drainage basin. Analyses of available data by Serreze *et al.* (2002), Yang *et al.* (2002) and Peterson and Holmes (personal communication) indicate that (1) annual water discharge is increasing for major rivers of the Eurasian plate (Yenisey, Lena, and Ob), but not for major rivers of the North American plate (Mackenzie, Yukon, Kolyma), (2) cold season discharge is increasing in the Yenisey and Lena drainages, (3) and that the discharge of the Yenisey has increased in the spring and decreased in the summer. These changes in the Yenisey appear to be related to higher air temperature, increased winter precipitation, and summer drying and may be additionally linked to changes in active layer thickness and to the thawing of permafrost. At a time when the analyses of historical data on river discharge are starting to yield substantial insights as to the effects of changes in the Arctic System, it is disconcerting that the number of monitoring stations has been dropping in recent decades (Shiklomanov and Vörösmarty, 2002). Major needs are to retard or reverse the degradation of the network of monitoring stations and to rescue Russian data that is not currently available in pan-Arctic and global archives.

While river discharge is the integrated response of a river catchment, the processes affecting discharge are so many and so complex that it may be difficult to invert information on variability and trends in river discharge to infer the changes in hydrologic processes that are responsible for dynamics of river discharge. Although additional gauging stations are needed to understand regional and global water balance, monitoring discharge alone will not enable attribution of changes in the hydrologic cycle to their causes. Thus, river discharge data will be of greatest value when accompanied by complementary meteorological data that permits complete water and energy balance analyses. A coordinated set of research basins, all monitoring snow distribution, snow melt, energy balance, soil moisture dynamics, runoff, evaporation, transpiration and sublimation with complementary techniques is needed to adequately characterize pan-Arctic changes in water and energy cycles. Such complete data sets are not collected operationally by any agency, but are currently being assembled in a very small number of research watersheds in the Arctic. These comprehensive research sites are characteristically of short duration with little or no long-term stability. Also, winter measurements frequently suffer because of harsh conditions combined with remote access, but can be improved with real-time telemetry monitoring. These stations should be supported and the technology improved to provide reliable year-round operation.

4.4.7 Trace Gas Exchanges

Key terrestrial parameters related to trace gas exchanges of high latitude terrestrial ecosystems with the atmosphere include carbon dioxide flux, methane flux, and the lateral transport, processing, and delivery of dissolved organic carbon (DOC) to surface hydrologic networks and the oceans.

There are two general modeling methods for assessing changes in the exchange of carbon dioxide between high-latitude terrestrial ecosystems and the atmosphere: (1) inverse modeling and (2) forward modeling. Inverse modeling is generally based on methodologies that use atmospheric CO_2 concentrations that have been observed at stations as part of the global CO_2 monitoring network; many of these stations are maintained by NOAA CMDL. In contrast, forward modeling uses process-based models that have been developed in the context of observations and process studies to simulate the exchange of carbon dioxide for large regions. Analyses based on inverse modeling suggest that during the 1980s northern high latitude ecosystems have released carbon while southern high latitude ecosystems have stored carbon (Kaminski *et al.*, 1999). The release of carbon by northern high latitude ecosystems appears to have been strongest in the late 1980s (Kaminski *et al.*, 1999), which is consistent with a synthesis of carbon studies for northern Alaska over the last two decades (Oechel *et al.*, 2000). Studies that have examined the confidence of inversion estimates in northern Europe, northern Asia, and northern North America have identified substantial interannual variability in the exchange of carbon dioxide for all regions (Dargaville *et al.*, 2002). There are large uncertainties in the inversion estimates because the methodology is not fully constrained and assumptions must be made to provide constraints that lead to a solution. Examination of the uncertainties associated with the assumptions than need to be made indicate that inversion estimates are much better constrained for northern North America than for northern Europe and northern Asia (Dargaville *et al.*, 2002). One forward modeling analysis for northern North America over the last two decades (McGuire *et al.*, unpublished) shows similar interannual variability in the net flux as the inversion analysis of Dargaville *et al.* (2002). The forward modeling analysis also identified that fire was the key issue responsible for the match of inter-annual variability between the forward and inverse estimates. Other studies indicate that regional changes in the fire regime, i.e., whether fire becomes more frequent or less frequent, primarily determine whether the region is a source or sink for carbon over the last several decades (McGuire *et al.*, unpublished). The nature of the fire regime also appears to play a role in patterns of vegetation carbon turnover between northern North America and northern Asia as ground fires in northern Asia lead to longer turnover in comparison to crown fires in North America (McGuire *et al.*, 2002). With respect to long-term changes in soil carbon storage in high latitude ecosystems, a key uncertainty appears to be associated with limited understanding about the turnover of soil carbon in high latitude ecosystems (Clein *et al.*, 2000, 2002; McGuire *et al.*, 2002).

In comparison to carbon dioxide, both inverse and forward modeling of methane for high-latitude regions is substantially lagging primarily because

the availability of data for developing these models is much more limited in comparison to carbon dioxide. With respect to inverse modeling, the atmospheric chemistry of methane, which is more complex than the atmospheric chemistry of carbon dioxide, must also be considered.

Limitations on the understanding of patterns and controls over carbon dioxide and methane exchange with the atmosphere in high-latitude regions is primarily associated with limited data availability on variability in these fluxes and on controls over that variability. New technologies that rely on measuring the vertical structure of trace gases in the atmosphere are currently being deployed to document the spatial and temporal variability of trace gas fluxes. Tall eddy covariance towers and continental scale aircraft campaigns, both of which are now being initiated in Siberia with support from the European Union and the Max Planck Institute for Biogeochemistry, are designed to improve the spatial resolution of flux estimates in comparison to extant inversion techniques. SEARCH should consider to what extent it can augment and enhance these campaigns. At finer spatial scales (hectare to km^2), networks of eddy covariance sites are just beginning to provide insight concerning the spatial and temporal variability of trace gas, water, and energy fluxes (Baldocchi *et al.*, 2001; Running *et al.*, 1999b). For tundra in northern Alaska, eddy covariance sites have provided essential information during the 1990s for evaluating decadal-scale trends in summer carbon exchange with the atmosphere (Oechel *et al.*, 2000). A network of these sites now exists around the pan-Arctic which provides the capability to compare observations with estimates based on remote sensing (Fig. 4.6a) and process modeling (Fig. 4.6b). However, the collection of data at individual sites in this network is not operationally supported by any agency, but is maintained by research grant to a small number of investigators throughout the Arctic. Because these research sites have little or no long-term stability, they are vulnerable to the vagaries of funding. Also, similar to hydrologic measurements, winter measurements at eddy covariance sites frequently suffer because of harsh conditions combined with remote access. SEARCH should consider to what extent it can support operation of some of these sites along with associated process studies to better understand controls, particularly as these sites provide simultaneous information on the exchanges of trace gases, water vapor, and energy with the atmosphere.

The lateral transport and processing of DOC in freshwater systems to the oceans is important because it represents terrestrial carbon that may influence the exchange of trace gases between the atmosphere and aquatic ecosystems, both in freshwater and in the coastal zone (Kling *et al.*, 1991; Schlesinger *et al.*, 1991; Stallard *et al.*, 1998). This may be especially important in the Arctic because of the organic rich soils that are the source of DOC to aquatic ecosystems, which may be sources of CO_2 and methane to the atmosphere (Reeburgh *et al.*, 1998). While DOC has been measured at the mouth of some of the major river systems, different methods of measuring DOC make comparisons difficult. Also, lateral transport and processing of DOC in rivers of the pan-Arctic Drainage Basin are incompletely understood. The USGS is just initiating a 5-year program to document the lateral transport of DOC and other constituents in the Yukon River. The transport
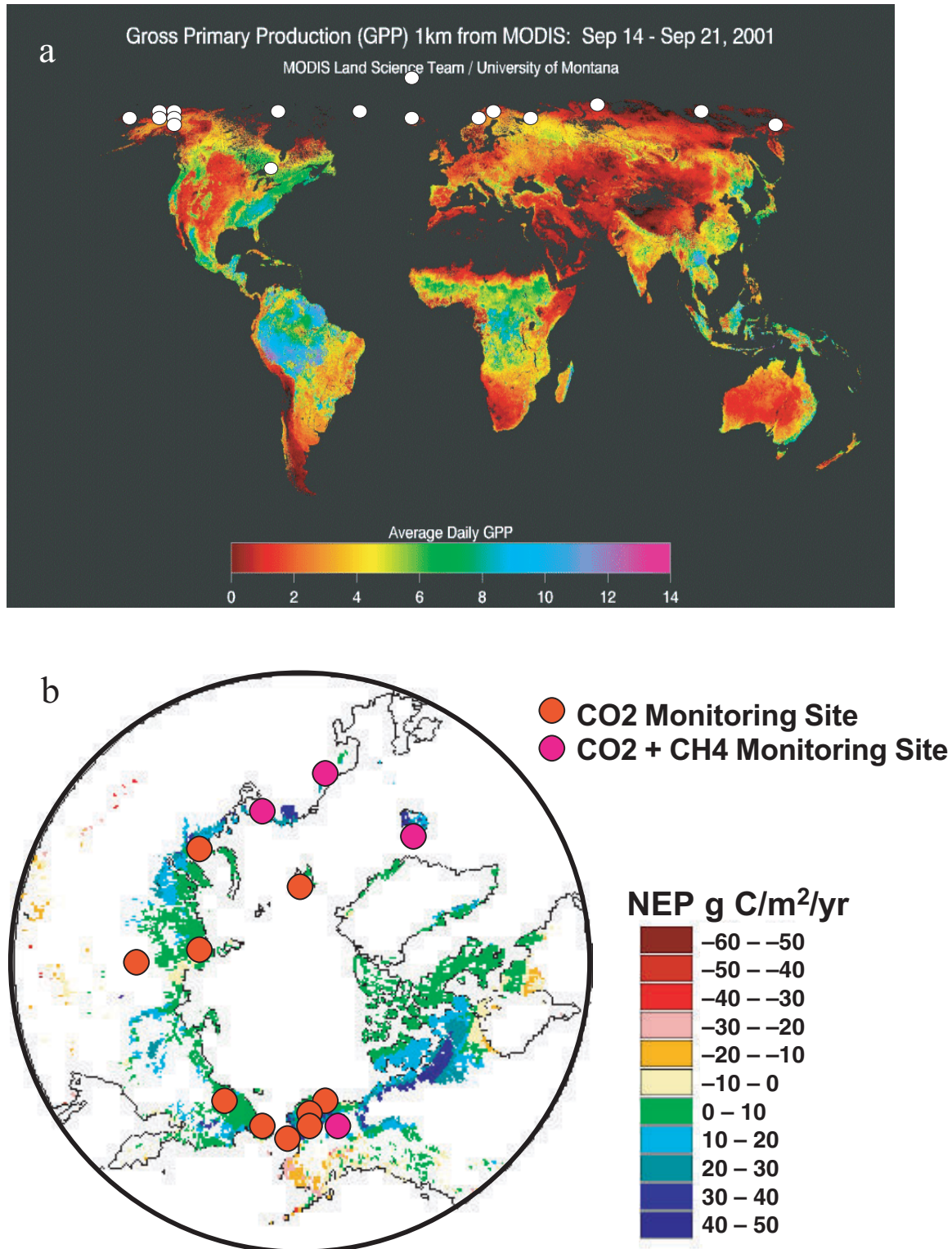
Figure 4.6: Locations of sites monitoring exchanges of carbon dioxide and methane between high latitude terrestrial ecosystems and the atmosphere (compilation of sites provided by W. Oechel of San Diego State University and T. Christensen, University of Lund). Fluxes measured at these sites have the potential to be compared with estimates based on (a) remote sensing (estimates courtesy of Steve Running, University of Montana) and (b) process modeling (NEP estimates for 1985–1994 from McGuire *et al.* 2000b).

and processing of DOC near the Siberian coast of the Arctic Ocean is also a focus of several RAISE studies funded by NSF ARCSS. There is a need to assess the quality of extant data that have been archived and to rescue data that have not been archived into an operational pan-Arctic data base of DOC and other constituents.

4.5   References

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5. Sea Ice Observations

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5.1 Introduction

During this session of the workshop, participants were asked to focus on issues associated with the design of a large-scale observing system to monitor variations in the sea ice cover that can be used as indicators of environmental change. Selecting this particular focus was not meant to diminish the importance of conducting investigations to improve the fundamental understanding of climate change. In fact, workshop participants acknowledged that studies designed to better understand dynamic and thermodynamic processes that govern energy exchange are critical for the development of predictive capabilities.

Focusing on the development of a large-scale observing system did allow participants to make considerable headway toward meeting the objectives of the workshop. The session began with brief presentations by each panel member, describing their perspective on important issues associated with relevant sea ice observations. A summary of these presentations can be found in the workshop notes, included on the workshop's web page. With this foundation, the floor was opened for discussion. The first part of the discussion was spent identifying key measurement parameters. Participants, then, qualitatively established a relative sense of the current level of confidence in measuring these parameters and discussed the available methods. Recognizing the particular importance of monitoring the sea ice thickness and the particularly high degree of difficulty in doing so, a significant amount of time was devoted to this specific topic. Based on the discussion, recommendations are made for immediate efforts that should be undertaken to more effectively exploit the sea ice cover as a tool for monitoring the environmental change in the Arctic.

5.2 Recommendations

It is important that efforts be made to continue to develop our capabilities to accurately measure the components that contribute to the distributed mass balance of the sea ice cover. These components include the sea ice extent, the dynamic and thermodynamically driven redistribution of the sea ice cover, the export of sea ice from the Arctic Basin, and the thickness of the sea ice cover, including the overlying snow cover. However, it is recommended that *efforts to accurately measure the thickness of the sea ice cover, including overlying snow cover, be given the highest research priority.* This recognizes the significant importance of measuring the thickness of the sea ice cover and the associated lack of confidence in the ability to do so at an accuracy and scale appropriate for a large-scale observing system. Specifically, we need to continue, improve, and expand current measurement techniques:

- Submarine transects should be continued, repeating measurements along identified transects to provide a historical record.

- Moored upward-looking sonar (ULS) should be deployed in a more systematic fashion to provide information on decadal and interannual variability.

- Previously obtained data from moored ULS should be made available to the scientific community, using a coordinated archival system.

- Instruments to measure ice thickness and snow depth (e.g., thermistor strings and acoustic range finders) should be added to surface-deployed drifting buoy stations.

- Sea ice models, coupled with recorded direct observations, should be used to optimize a deployment strategy for moored ULS and instrument-enhanced drifting buoys.

- A regional study should be conducted to develop and validate aircraft and satellite-derived snow and ice thickness measurements.

5.3   Background

As pointed out in the SEARCH Science Plan (SEARCH SSC, 2001), the sea ice cover is a critical component of the Arctic environment, largely controlling the energy exchange between the atmosphere and ocean. It is further emphasized in the SEARCH Science Plan that understanding the state of the sea ice cover is critical to all of the objectives of SEARCH. In addition to playing a key role in the surface energy balance, the sea ice cover appears to be a sensitive indicator of changes in the global circulation system. Both the extent and the thickness distribution of the sea ice cover respond quite dramatically to changes in the heat and momentum of the atmosphere and ocean. The thickness distribution in a given region is controlled by thermodynamic growth and decay, ice motion (advection), and mechanical redistribution. The state of the sea ice cover represents the integrated effects of atmospheric and oceanic forcing.

The sensitivity of the sea ice cover to changes in the global circulation system is well demonstrated in a recent paper by Kwok (2000). Kwok uses satellite data and measurements from drifting buoys to establish a new ice motion dataset of the Arctic Ocean for the winters from 1978 through 1996. Using this dataset, it is shown that patterns of variability in the sea ice cover can be directly linked to the North Atlantic Oscillation (NAO). It is specifically demonstrated that changes in the dominant mode of the NAO affect the ice motion, ice flux, and ice extent. Kwok's results are consistent with the modeling results of Proshutinsky and Johnson (1997), who report two dominant regimes of wind-forced circulation, affecting the ice motion over the 48-year study period, from 1946–1993. As Kwok suggests, it appears that the circulation patterns in the positive NAO (NAO+) and negative NAO (NAO–) regimes are respectively similar to the cyclonic and anticyclonic regimes identified by Proshutinsky and Johnson. During periods of
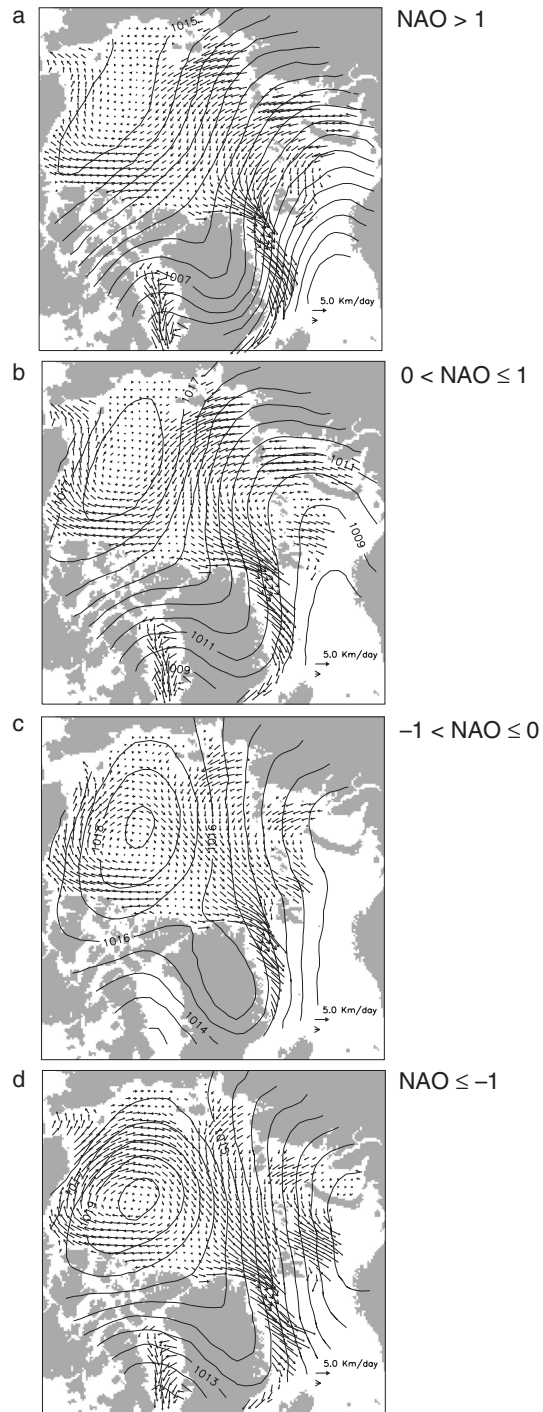
Figure 5.1: Composite patterns of monthly (October through May) sea-level pressure and ice motion fields between 1978 and 1996 partitioned based on the monthly NAO index. (a) NAO >1. (b) 0 < NAO ≤ 1. (c) −1 < NAO ≤ 0. (d) NAO ≤ −1. The contour increment is 1 hPa (from Kwok, 2000).

NAO+ or cyclonic circulation, both the Beaufort Gyre and the Transpolar Drift Stream weaken and the Transpolar Drift Stream shifts westward towards the Canada Basin (Fig. 5.1). Further consistent evidence of the sensitivity of the sea ice cover to changes in the global circulation system is provided by Tucker *et al.* (2001), who present an 8-year time series of sea ice thickness, derived from submarine-based upward looking sonar. This work shows that rapid thinning of the ice in the Canada Basin occurred in the late 1980s, coincident with a shift in the Arctic Oscillation (AO), which is closely related to the NAO, to AO+, and increased advection from the Arctic Basin. The fact that variations in the ice circulation pattern and, hence, state of the ice cover is strongly linked to changes in atmospheric forcing comes as no surprise. It has been well established by Thorndike and Colony (1982) that, away from coastal boundaries, the geostrophic wind explains more than 70% of the variance of daily ice motion in both winter and summer.

5.4   Key Parameters and Current Measurement Techniques

Given the sensitivity of the sea ice cover to variations in the global circulation system, the focus of this workshop session was to consider how to best exploit the sea ice cover for monitoring environmental change in the Arctic region. Participants unanimously agreed that the key parameter to monitor, to detect change in the climate system, is the distributed mass balance of the sea ice cover. The task of determining the distributed mass balance can be broken into four main components, listed below. The current relative level of confidence in quantitatively determining each of these parameters is represented by the order of this list, with the measurement of ice extent having the highest level of confidence:

- Measuring the extent of the ice cover,

- Establishing the redistribution of the ice cover, resulting from thermodynamic and dynamic processes,

- Measuring the export of ice from the Arctic Basin, and

- Determining the snow and ice thickness, including open water and thin ice fractions.

5.4.1   Ice extent

The level of confidence in measuring ice extent significantly exceeds that of the other three components. This is due, in large part, to the ability to effectively apply satellite imagery, specifically passive microwave data, to distinguish the boundary between the ice-covered and open ocean regions, throughout the year (e.g., Parkinson *et al.*, 1999). The satellite platform has the distinct advantage of providing a bird's eye view of the entire sea ice cover. It was suggested that particular regions of the Arctic ice cover could be selected for monitoring changes in the sea ice extent, as a function of environmental forcing conditions. These regions would be selected based on their demonstrated sensitivity to environmental change and the existence

of a relatively long historical record. A good example of a region that meets these criteria is the Sea of Okhotsk (Cavalieri and Parkinson, 2001).

5.4.2   Redistribution

Redistribution means the changes in the thickness distribution of the sea ice cover that occur due to both dynamic (advection, lead formation, ridge formation) and thermodynamic (ice growth and melt) processes. Currently, sea ice dynamic-thermodynamic models are a primary tool used to establish the redistribution of the ice cover (e.g., Zhang and Rothrock, 2001). There are a variety of sea ice models available for this analysis, each with a distinguishing set of assumptions and governing equations. Typically, the accuracy of a model is established by comparing model results of ice motion to the movement of drifting buoys, installed in the sea ice cover. Recent overviews provide a detailed perspective on the status of sea-ice models and model development (e.g., Randall *et al.*, 1998; Steele and Flato, 2000).

Ideally, direct measurements of the redistribution at appropriate spatial and temporal scales should be used in tandem with the models. Making such direct measurements has proven to be a very difficult challenge. However, recent examples of the application of data from the RADARSAT Geophysical Processor System (RGPS), derived from SAR imagery, show the potential in applying satellite imagery to this issue (e.g., Kwok, 1998; Stern *et al.*, 1995).

5.4.3   Export

Estimates of the volume of ice exported from the Arctic Basin, which primarily occurs through the Fram Strait, can be made with moored upward looking sonar (ULS) (Vinje *et al.*, 1998). Submarine-based ULS have also been used for this purpose (Wadhams, 1983). Satellite passive microwave data can be used to estimate the area of ice exported through the Fram Strait during the winter (Kwok and Rothrock, 1999). This is accomplished by tracking the displacement of common features in sequential images, to determine ice motion.

5.4.4   Ice thickness and snow depth

The most difficult parameter to measure represents the most important parameter to monitor: the thickness of the sea ice cover. Throughout this section, when the thickness of the sea ice cover is mentioned, it is intended that, whenever possible, any overlying snow cover also be measured. As explained in a background summary "Sea Ice Thickness: The Great Integrator", prepared for this workshop and available on the workshop's web page (`http://www.epic.noaa.gov/SEARCH/obs/workshop/reports.shtml`), there are a variety of techniques used to measure or derive the ice thickness:

- Moored upward looking sonar (ULS) (e.g., Melling *et al.*, 1995)

- Submarine-based ULS (e.g., Tucker *et al.*, 2001; Rothrock *et al.*, 1999; Wadhams and Davis, 2000)

- Aircraft-based altimeters (e.g., Wadhams *et al.*, 1992)

- RGPS (e.g., Kwok *et al.*, 1999)

- Buoys with thermistor strings (e.g., Perovich *et al.*, 1997)

Of these techniques, buoys with thermistor strings can also be used as an autonomous means of monitoring snow depth. Satellite microwave radiometers have been used in the Antarctic to derive the snow depth on sea ice (e.g., Markus and Cavalieri, 1998).

To date, the only technique that has provided the scientific community with a historical perspective, adequate to investigate the relationship between the ice thickness and environmental conditions, is the submarine-based upward looking sonar. Specifically, considerable data have been made available in the western, central, and eastern Arctic. Concerns have been raised regarding the impact of the limited regional sampling of the submarine data on the conclusions drawn from this data source. This limitation is due to the lack of submarine visits to all locations within the Arctic Basin and restrictions associated with data release.

To make more effective use of moored-upward looking sonar and instrument-enhanced drifting buoys, it was suggested that sea ice models, combined with recorded observations, be used to design a deployment strategy. Analyses can be done to identify locations of dominant modes of variation, related to environmental change, or good locations for measuring the annual variation in mean ice thickness. Associated studies can be conducted to determine the optimal location and number of instrumented sites within these regions.

Since the conclusion of the workshop, Ron Lindsay, at the University of Washington Applied Physics Laboratory, has applied the sea ice model described in Zhang and Rothrock (2001) to provide an example of how such an exercise could be carried out (Fig. 5.2). First, the sea ice model was used to create a 48-year time series of the basin-wide, annual mean ice thickness (Fig. 5.2a). Next, each model grid point was correlated with the basin-wide, annual mean ice thickness, to establish the optimal location for measuring the mean thickness of the sea ice cover. The results of this analysis are presented in Fig. 5.2b, where contours of R^2 are plotted. These results suggest that if, for instance, a moored ULS was located at a point between Canada and the North Pole it would explain 79% of the variance of the mean ice thickness, described by a linear fit to the thickness in this region. Fig. 5.2c illustrates the additional explained variance of the mean ice thickness gained by establishing two measurement sites, one at the North Pole and a second in the Chukchi Sea. With data from these combined sites, the explained variance in the mean ice thickness increases to 86%. An autocorrelation of the ice thickness at the North Pole (Fig. 5.2d) determines the fraction of the variance at each grid point explained by the time series of the ice thickness at the North Pole. This result suggests that the regional variability of the ice thickness is not well predicted by just one measurement site point between Canada and the North Pole.
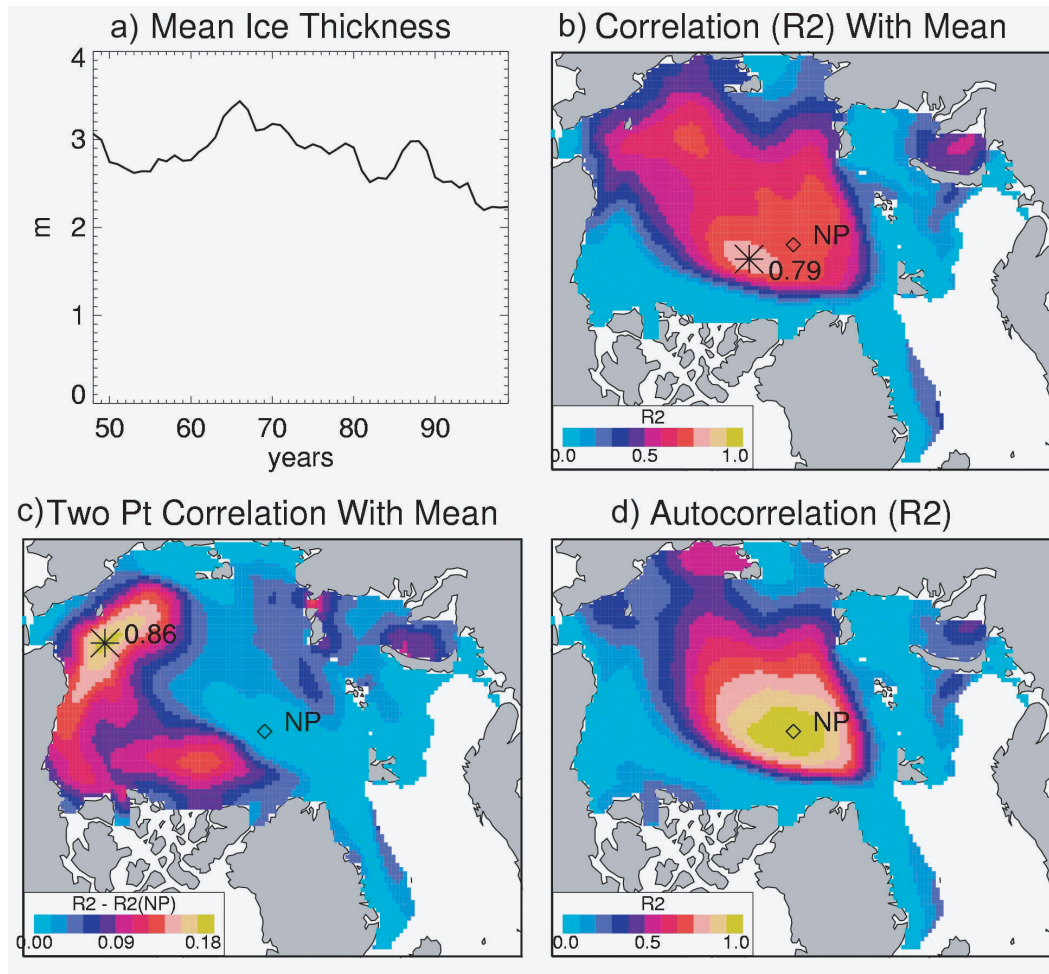
Figure 5.2: Example of the application of a sea ice model in the design of a large-scale observing system for the sea ice cover. Here, correlation analyses are used to determine the optimum location of moored upward-looking sonars (provided by Ron Lindsay).

Lindsay provides another example of the application of model results, to assist in the design of a large-scale sea ice observing system (Fig. 5.3). Here, the model described in Zhang and Rothrock (2001) is used to determine the difference in the mean ice thickness distribution between two dominant forcing regimes. In Fig. 5.3a, these two regimes are defined according to the work of Proshutinsky and Johnson (1997), who separated the years from 1946 to 1993 into one of two dominant wind-driven regimes; cyclonic or anticyclonic. In Fig. 5.3b, the same years are separated into categories using the positive and negative AO index, as defined by David Thompson at http://www.atmos.colostate.edu/ao/Data/ao_index.html. In each approach, the number of years in the two categories was nearly equal, although they were not necessarily the same years. While there are subtle differences between these two results, the agreement is more remarkable. Both confirm that the North Pole is a location of low variability in mean ice thickness. This result is consistent with conclusions drawn from submarine-upward looking
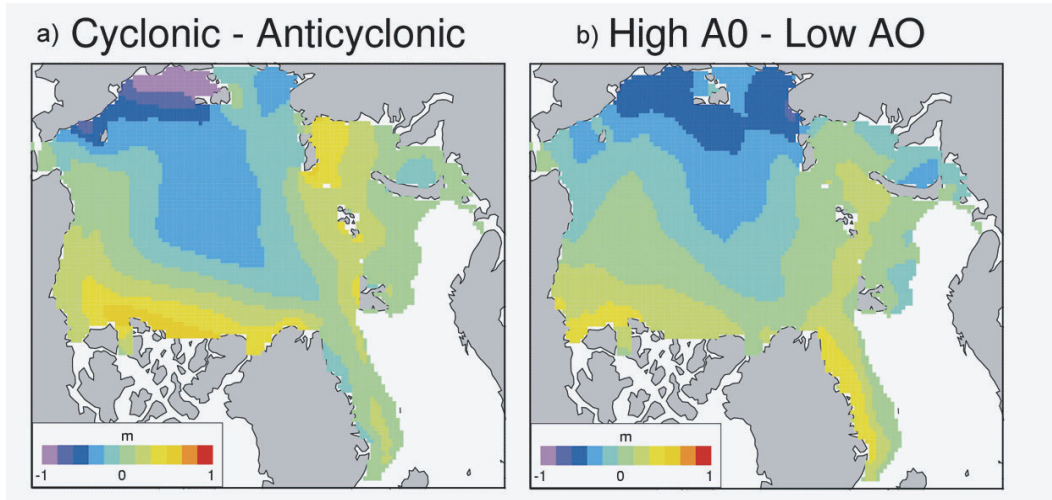
Figure 5.3: Example of the application of a sea ice model in the design of a large-scale observing system for the sea ice cover. Here, the level of variability in the mean ice thickness is established by comparing model results between two dominant types of atmospheric forcing (provided by Ron Lindsay).

sonar data, as reported in McLaren *et al.* (1994), Shy and Walsh (1999), and Tucker *et al.* (2001). Tucker *et al.* speculate that the location of the North Pole in a strongly advective region for both atmospheric forcing regimes is responsible for the low temporal variability in the ice thickness at the North Pole. The Canadian sector of the Beaufort Sea and the East Siberian and Laptev Seas are regions of high interannual variability in mean ice thickness.

The results from Lindsay's work are presented as an example of how the scientific community can apply established sea ice models to assist in the design of a large-scale sea ice observing system. If it was determined that such a course of action would benefit the objectives of SEARCH, it should be recognized that different sea ice models are likely to give different results. This is a consequence of the variety of fundamental assumptions made in the development of individual models. Given this expected variability, it is suggested that results from a number of selected models should be used in the design phase of the observing system. These results should be compared to determine the deployment locations most consistently indicated by the models. Direct observations and measurements of the characteristics of the sea ice cover should be coupled with the combined model results to provide an even greater degree of confidence in the design strategy.

All of the measurement techniques currently available to monitor the ice thickness are inherently limited, since they offer observations from specific locations within the Arctic Basin. Many also pose significant logistical challenges. Given the current capabilities of various satellite systems, developing these platforms into a tool that provides reliable information on snow and ice thickness would require investigations to develop and validate satellite-derived data (Walsh *et al.*, 2001). This can be done by a regional study, where currently available measurement systems are used in a hierarchical fashion. For instance, an array of moored upward-looking sonars

and drifting buoys, instrumented with thermistor strings, could be deployed in a selected test region, to provide Eulerian and Lagrangian time series of ice thickness, respectively. Surface-based transects to measure the snow and ice thickness and important physical properties could be conducted in the same region at critical times. Aircraft equipped with altimeters, and submarines equipped with upward-looking sonar, could also survey the region. This suite of measurements of snow and ice thickness would be compared to the results obtained from satellites, imaging the defined study region.

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6.   An Arctic System Reanalysis

Compiled by John Walsh with contributions from Greg Flato, Jennifer Francis, Roy Jenne, Fedor Mesinger, Mark Serreze, and Pedro Viterbo.

6.1   Summary and Recommendations

A reanalysis may be regarded as a reconstruction of historical states of climate system components (e.g., the atmosphere, the ocean) or of the more complete climate system. The general strategy is to use a model, based on the physical and dynamical laws governing the system component(s), and simulate variations over time while constraining the simulation to fit the available observational data. A reanalysis can incorporate all observational data deemed appropriate for an accurate reconstruction of the historical state. It dynamically interpolates these observations in space and time while imposing consistency with the physical and dynamical laws governing the medium. In the case of the atmosphere or ocean, the output includes sets of time-varying three-dimensional fields of variables such as temperature, pressure, wind (or ocean currents). In addition, the output of a reanalysis can include model-estimated values of quantities that are generally not widely available from observations, e.g., radiative fluxes, evaporation and precipitation, ocean salinity, sea ice thickness, etc.

A key objective of the SEARCH workshop of 27–29 November was an assessment of the desirability and viability of an Arctic reanalysis. The workshop presentations and discussion provided various reasons why a compelling case can be made for an Arctic regional 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 and ocean models. Second, the reanalysis would provide a context for evaluations of ongoing and future changes in the Arctic, enabling a key objective 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., 32 km in NARR), 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, Arctic field programs (SHEBA, LAII/ATLAS, ARM,...), 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 ERA-40 and by NCEP's North American Regional Reanalysis (NARR). The coincidence of this groundwork and the spin-up of SEARCH provides a unique window of opportunity for an Arctic reanalysis. Accordingly, the

panel recommends that SEARCH give priority to a reanalysis of the Arctic system.

While the argument for an Arctic reanalysis is compelling, some cautions emerged from the workshop. (1) A reanalysis of the Arctic atmosphere and ocean should be run separately, making use of observed surface conditions, SST, snow cover, winds, etc. The inclusion of a fully coupled atmosphere/ocean appears to be premature in view of the current status of Arctic Ocean models and data streams, so the inclusion of oceanic information in a system reanalysis will require a carefully conceived strategy. (2) A major challenge lies in the effective utilization of TOVS and other satellite data for the Arctic, especially since a major reprocessing of the TOVS radiances will be required. Even the conventional data to be assimilated will require significant effort in extraction and quality control. In addition, major technical issues such as the choice of 4D-Var or 3D-Var data assimilation procedures need to be addressed. (3) As implied by (2), the required commitment of resources, both human and financial, is substantial if an Arctic reanalysis is to be successful. *The commitment appears to be most easily achievable if an Arctic regional reanalysis is a follow-on to the North American regional reanalysis at NCEP.* Since the latter has only about 2 years until planned completion, this strategy requires immediate involvement, by a core of Arctic investigators, in planning activities with NCEP. In addition to the entrainment of potential sponsors, there must also be coordination with the TOVS reprocessing, with diagnostic evaluations of the Arctic output from ERA-40 and the NARR, and with the preparation of input data streams. While the window of opportunity is short and the required commitment is substantial, an Arctic regional reanalysis has the potential to be a flagship activity in SEARCH. It would provide SEARCH with an effective synthesis of efforts in Arctic data analysis, polar remote sensing, Arctic field programs, and large-scale modeling.

Recommended activities for the short term include the establishment of an active liaison with the North American Regional Reanalysis project at NCEP, the evaluation of the Arctic and subarctic output from the North American reanalysis, the establishment of a process by which the needs of the arctic community (and SEARCH in particular) are incorporated into the NCEP regional reanalysis system, the extraction and preparation of Arctic data that have not been used in reanalyses to date, and the preparation of a version of the TOVS data suitable for inclusion in an Arctic regional reanalysis. Longer-term activities include the recasting of component models of sea ice, the ocean, and the arctic terrestrial system into forms suitable for 3-D or 4-D variational assimilation, the meshing of these models with the established atmospheric reanalysis system, and the preparation of the data streams to be ingested into the non-atmospheric components of an Arctic system reanalysis.

6.2   Presentation and Discussion Issues

A prominent topic of discussion at the SEARCH Workshop was the possibility of an Arctic reanalysis. The panel discussion and presentations on

NCEP ETA 32 km/45-layer Model Topography
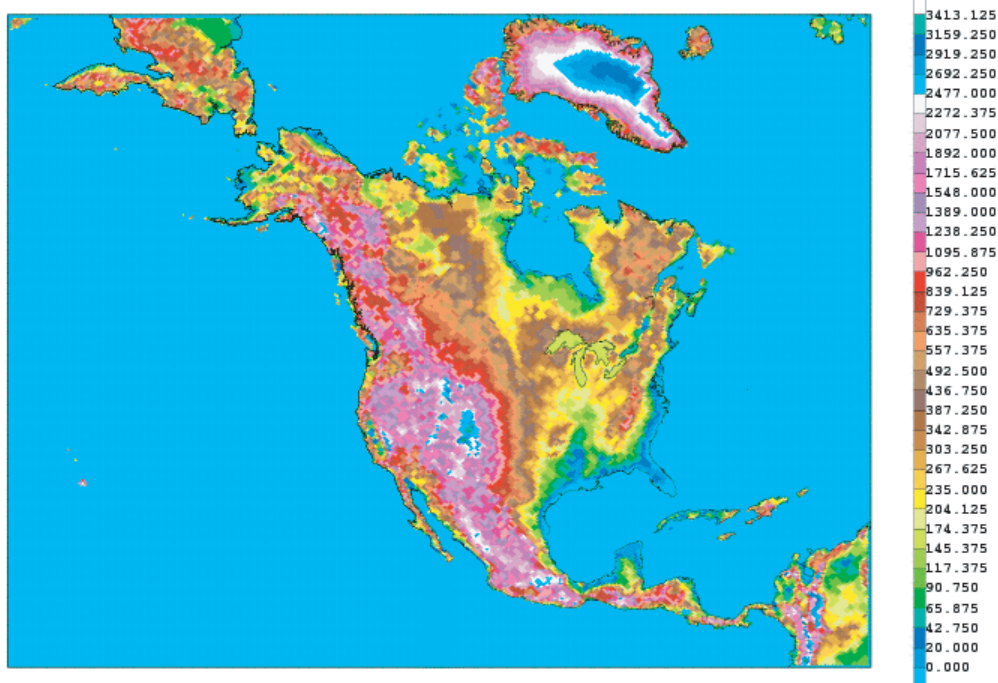
Figure 6.1: North American Regional Reanalysis (NARR) domain and topography.

reanalysis included input from representatives of the major centers involved in ongoing reanalysis efforts (Pedro Viterbo of ECMWF, Fedor Mesinger of NCEP, Roy Jenne of NCAR) as well as from Arctic scientists (Mark Serreze, David Bromwich, Greg Flato, Jennifer Francis) who have been active in the evaluation of model output, observational datasets, and remote sensing products of direct relevance to a possible Arctic regional reanalysis. The consensus of the participants was that an Arctic reanalysis is an increasingly attractive and viable possibility because of the conjunction of (a) ongoing reanalysis efforts at ECMWF and NCEP, (b) the recent involvement of Arctic scientists in broader reanalysis efforts, (c) the recent production and evaluation of remote sensing products for the Arctic, e.g., TOVS, and (d) the imminence of SEARCH, which can provide a scientific and organizational framework in which an Arctic reanalysis would be a core activity. We summarize here the Arctic regional reanalysis issues addressed in the individual presentations and in the general discussion sessions at the workshop. Since the Arctic was considered by the group to extend to the southern boundaries of the northward-flowing rivers, it is implicit in this discussion that the domain of an Arctic reanalysis must include some areas not traditionally regarded as the Arctic.

The NCEP/NCAR global reanalysis has been completed for the period back to 1948, and is being continued through the present. The major new reanalysis activity at NCEP for the next 2 years is the North American Re-

gional Reanalysis. Preliminary results from NARR test years (1987, 1998), shown by Fedor Mesinger, indicate that the regional reanalysis produces a striking improvement in precipitation relative to the global reanalysis, and that temperatures and winds from the surface to 200 mb are also improved relative to the global reanalysis. With regard to particular model formulations, Mesinger pointed out that the land-surface model upgrades made to the Eta model in July 2001 (and included in the current NARR system) contain several important cold-season processes: patchy snow cover, frozen soil (new state variable), variable snowpack density (new state variable), soil heat flux below a snowpack, and a maximum snow albedo dependent on major vegetation ecosystems. The planned period of coverage of this reanalysis is 1982–2003, and the domain includes much of the Arctic (Fig. 6.1). In this respect the NARR offers a promising testbed for a possible follow-on regional reanalysis for the Arctic. For example, both regional reanalyses would need to be driven by a global reanalysis. During the 2-year production period for the North American reanalysis, active diagnostic involvement by the Arctic community could pave the way for a logical and timely transition to an Arctic focus. As yet, the Arctic community's input concerning Arctic-specific reanalysis issues has been less extensive with NCEP than with ECMWF.

Pedro Viterbo reviewed reanalysis efforts at ECMWF. While ECMWF has no immediate plans for a regional reanalysis, it is in the midst of a 40^+-year (1958–2001) global reanalysis known as ERA-40. This effort has benefitted from (and will benefit in return) the Arctic research community, largely through interaction with the ACSYS working group on reanalysis. In the 6 years since the previous ECMWF reanalysis, ERA-15, two-thirds of the modifications to surface and boundary-layer formulations at ECMWF were motivated by high-latitude meteorology. The improvements are related to processes such as soil freezing, infiltration of frozen soils, surface snow cover, forest albedo in the presence of snow, and sea ice parameterizations. These modifications have led to marked improvements in the simulations of weather and climate in high latitudes. For example, surface air temperatures over southern Canada and eastern Asia have improved by 5–15°C, and the spring runoff peak in high latitudes is captured much more realistically by ERA-40 than by ERA-15. Such improvements represent the fruits of significant collaboration between a major modeling center and the Arctic community. The ECMWF-Arctic experience to date points to several necessary ingredients for a polar regional reanalysis: (1) inclusion of model physics that realistically represents phenomena specific to high latitudes (snow cover is an especially important consideration), (2) accurate specifications of lake temperatures, which can contribute significantly to the surface energy budget and the seasonality of near-surface air temperatures. As an example of (1), Fig. 6.2 illustrates the effect of a more realistic formulation of albedo in areas where vegetation has a significant masking effect on snow. Other "lessons" to be noted from the ECMWF experience in reanalysis are that an extensive testing phase (~25 years of data assimilation in the case of ERA-40) is necessary prior to the production run, and that a critical mass of personnel are required (five dedicated scientists, plus support from other departments at ECMWF, for ERA-40). The testing phase requires evaluations
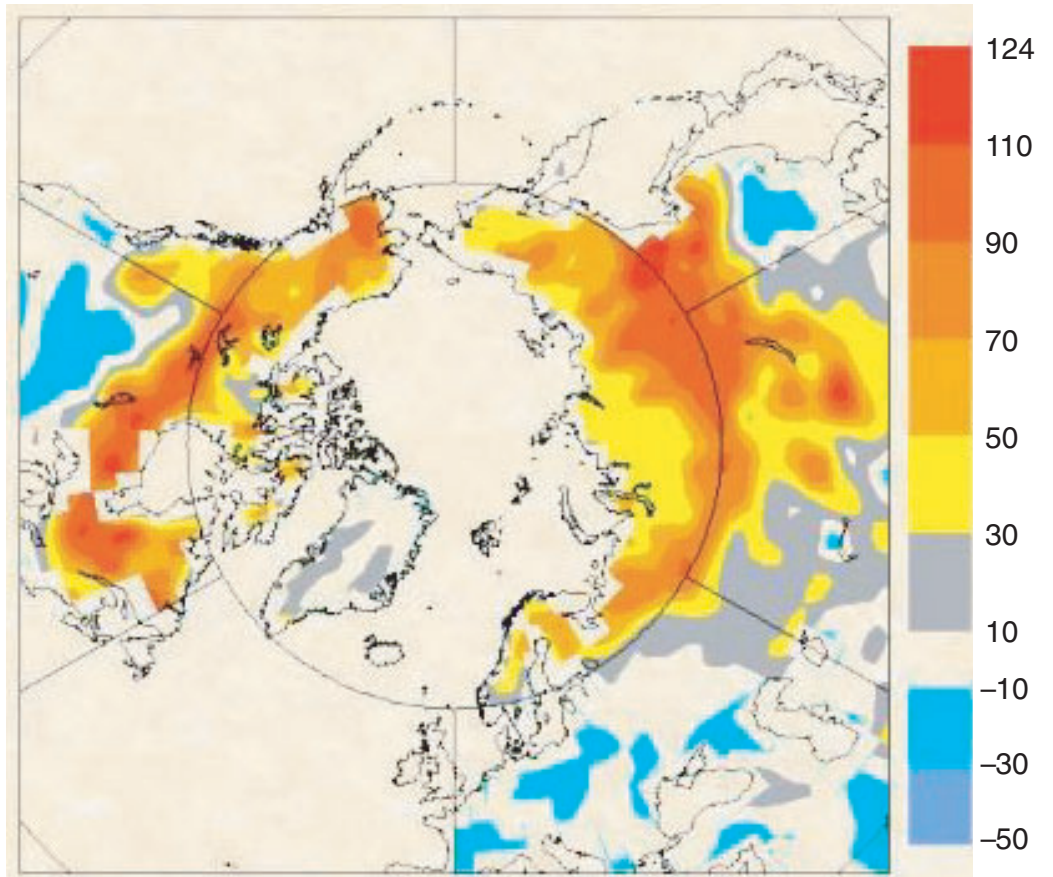
Figure 6.2: Difference in net shortwave radiation at the surface between the ERA40 system and the ERA15 system, averaged for April 1992. The figure shows a large increase in snow covered areas.

of various measures of accuracy of the reanalysis, not only on a large-scale (e.g., Arctic-wide) basis but also for specific regions within the Arctic. For example, the ACSYS working group on reanalysis has already uncovered a problem with the assimilation of TOVS data into ERA-40 over the central Arctic. This problem is apparent in the geopotential height fields, and it highlights the continuing need for proper handling of TOVS data over the data-sparse central Arctic.

Data inputs for any Arctic reanalysis will require a substantial effort prior to the actual assimilation activity. Roy Jenne of NCAR pointed out that key needs are (1) the addition to the database for reanalysis input of previously unused (or under-used) conventional data, including Canadian rawinsonde reports prior to July 1955, additional Canadian pressure and temperature reports from the 1948–1966 period, and the routine upper-air measurements from drifting ice stations (e.g., T-3 and the Russian NP series); (2) optimum uses of the VTPR and TOVS information, which together provide satellite inputs back to 1972. It is noteworthy that, in some respects, there is potentially better observational coverage for the upper-air in the earlier (pre-1980) decades when there were more permanent ocean weather ships (and ice sta-

tions), more rawinsonde sites, more frequent reconnaissance flights over the Arctic, and more dropsondes over the Arctic Ocean. In order to realize the full benefits of this information, however, it will be necessary to perform considerable data archeology in the Former Soviet Union to uncover and extract the wide variety of atmospheric, land surface, and probably oceanic data that most likely exist. Jenne also stressed the advantages of the so-called "4D-Var" data assimilation scheme, which fits the analysis to observations over an entire 6–12 hour window, relative to the more traditional "3D-Var" procedure and its "snapshot" approach to fitting the observations.

Among the "lessons learned" from the NCAR experience in providing data for assimilation into the NCEP and ECMWF reanalyses are that the data collection, error-checking, and quality-control tasks are substantial. Consequently, the Arctic community would be well-advised to initiate soon any data synthesis efforts that will be needed for an Arctic regional reanalysis. Roy Jenne and Roger Colony also noted that many Arctic datasets extend back well beyond the 50-year time frame of present reanalyses, offering the possibility of more limited data analyses (i.e., not a full-blown reanalysis) for longer periods in order to provide more specific benchmarks for change detection. (Much of the atmospheric data extending back to the 1800s resides in the NCDC library in Asheville.)

While the NP and other observations from the central Arctic represent potentially valuable inputs and can provide opportunities for calibration and validation, they do not provide the space-time coverage needed over the Arctic Ocean and the surrounding seas. Remotely sensed data, particularly from TOVS, must assume a particularly important role in an Arctic regional reanalysis. However, as noted by Jennifer Francis, the present status of the calibration of radiances falls short of the requirements for climate applications. Several recommendations concerning TOVS were made at the workshop: (1) NOAA/NESDIS, as caretaker of the TOVS data, should assume the task of correcting biases in global radiance data in order to optimize their usage in reanalyses; (2) a focus on radiance bias corrections for polar conditions needs to be provided by a designated group composed of representatives from the polar user community, reanalysis centers, retrieval algorithm developers, and NESDIS; (3) residual uncertainties should be quantified to aid in trend assessments and other uses of the products. With regard to (1) and (2), an effort is now underway to assemble a team, to include university and NOAA scientists as well as reanalysis experts, in order to make the bias corrections for the Arctic. The reprocessing will be directed at the assimilation of the radiances into reanalyses. For reanalysis purposes, there is a need to extend the retrieval-based dataset using the bias-corrected radiances; specific tasks with regard to Path-P include modification of the algorithms for use over high terrain, improvement of cloudy retrievals, extension temporally to the present, and extension spatially to 45°N or to a latitude that dovetails with the corresponding global dataset of retrievals. The retrieval of upper-level winds also requires attention in the context of reanalysis. Validation against rawinsonde reports offers one means for assessing the assimilated radiances and winds.

As indicated by the summary above, much of the discussion focused on

atmospheric models and the utilization of atmospheric data. A key issue in Arctic reanalysis is the interdisciplinary scope of the activity. Greg Flato noted that global atmospheric reanalyses show increasing (albeit coarse-resolution) success in the Arctic, although cloud/radiative interaction and the simulation of surface pressure (wind) patterns appear to merit increased attention. The viability of including other climate system components (ocean, sea ice, terrestrial) is a function of the readiness of the models and, perhaps more importantly, the availability of data for assimilation and validation. Flato suggested that sea ice is a good candidate for inclusion, since a variety of ice models are well established and the observational databases of ice coverage (concentration) and ice motion are substantial. A sea ice model contains sufficient "physical" information that it should indeed be beneficial to a reanalysis effort, since the model information would offset to some degree the (poorly characterized) errors in the ice observations. The potential to obtain ice thickness as a derived product makes a sea ice model an especially attractive candidate for inclusion in an Arctic reanalysis. The ice thickness information, in turn, can improve the estimates of the surface fluxes over sea ice. However, Arctic ocean models and ocean data streams do not appear to have reached this stage of readiness, making it difficult to establish credibility through validation. One may also argue that it will even take a significant research effort to recast a typical ocean–sea ice model into a form suitable for 3-D or 4-D variational assimilation, and even more effort to merge the recast model with an established atmospheric reanalysis system.

Recent results from terrestrial packages, such as the TESSEL module used by ECMWF, indicate that the inclusion of the terrestrial component may be viable, although underlying issues of validation and feedbacks to the atmosphere need more thorough consideration. Land surface data assimilation is already performed through the inclusion of snow information from surface stations, some (but not all) of which are included in ERA-40. The ERA-40 results highlight the importance of the accurate representation of snow cover extent. There remains the challenge of incorporating remotely sensed information on the terrestrial component, particularly snow water equivalent and vegetative characteristics. The seasonal and spatial variations of the latter represent a prime opportunity for entrainment of the terrestrial community into the reanalysis effort.

Finally, Flato addressed the underlying "hypothesis" that the highest-quality reanalysis results, in principle, from a system ingesting all available data (subject to caveats that the error variances must be known, etc.). This hypothesis requires a degree of "faith" on the part of the user of the assimilated data, whereas demonstrable quality (and quantitative measures of that quality) derive from comparisons to independent data with suitable sampling and other characteristics. Data from field campaigns provide one source of such comparison data, but the sampling issues can introduce difficulties into the evaluation. One can argue that a more systematic, ongoing "quality assurance" system would be beneficial, even during the production phase of a reanalysis. While this type of activity has, to varying degrees,

been part of past reanalyses, it may be especially important in a reanalysis for a relatively data-sparse region such as the Arctic.

7. International Coordination

SEARCH involves large-scale covariability of Arctic change and thus there is clear need for improved planning for international coordination. Howard Cattle from the Met Office, Bracknell, UK, provided a review of the WCRP Arctic Climate System Study (ACSYS) and Cryosphere and Climate Project (CliC). Barry Goodison reviewed the current situation in Canada. European planning for Arctic monitoring is underway (Johannessen *et al.*, 1997).

The ACSYS was a 10-year program with a sunset date at the end of 2003. Progress with ACSYS includes:

- Increased range and accessibility of sea ice data sets on CD-ROM

- Establishment of the in situ ice thickness database

- Work to assess and improve polar aspects of atmospheric reanalysis

- Continue development of Arctic runoff and precipitation archives

- Ice-ocean interaction modeling studies and hydrological model inter-comparisons

- Development of the Arctic data and information service

The goals of CliC are

- Improve understanding of the physical processes and feedbacks between the cryosphere and climate system

- Improve cryosphere representation in climate models

- Assess impacts of past and future climate variability of the cryosphere

- Enhance observation and monitoring

Potential areas of joint SEARCH-ACSYS/CliC collaboration are

- *Establishing and maintaining long-term observations in the Arctic to detect and track environmental climate change*

- *Collaborating in the promotion of modeling efforts to synthesize observations, the representation of climate processes in models, and the simulation and prediction of Arctic change*

- *Promoting appropriate process studies to understand potentially important feedbacks*

- *Promoting the application of knowledge of Arctic climate change to provision of scenarios for appropriate impact studies*

- *Exchange of up-to-date information with regard to data management systems being used within SEARCH and ACSYS/CliC and coordinate if possible*

- *Cross SSG/SSC representation to build links*

- *Joint sponsorship of meetings, workshops, and conferences where appropriate*

It should also be noted that there is a joint SEARCH-CLIVAR (Climate Variability) working group to coordinate research on physical climate change in the Arctic and Arctic/lower latitude interactions. Coordination with Russia is an important issue; there are promising developing activities in hydrology.

7.1   Reference

Johannessen, O.M., E. Bjørgo, and M. Miles (1997): Operational Climate Monitoring Program for Arctic Ice Cover. In: *Operational Oceanography: The Challenge for European Cooperation,* J.H. Steel *et al.* (eds.), Elsevier, 361–367.

8.   Acknowledgments

Appendix A: Agenda

SEARCH Workshop on Large-Scale Atmosphere/Cryosphere Observation

27 November 2001—Background Talks

"Setting the Stage"

8:15 a.m.	James Morison	Introduction to SEARCH
8:30 a.m.	Jim Overland	Introduction to Workshop
8:45 a.m.	Lawrence Mysak	The Changing Arctic
9:15 a.m.	Mike Wallace	Annular Modes

9:45–10:15 a.m.   *Break*

10:15 a.m.	Steven Pawson	Stratospheric Change
10:45 a.m.	David McGuire	Monitoring the Biosphere
11:15 a.m.	Don Perovich	Sea Ice—Spanning the Scales
11:45 a.m.	Roger Colony	Retrospective—Temperature and Sea Ice

12:15–1:20 p.m.   *Lunch*

"Observations—Preview"

1:30 p.m.	Drew Rothrock	In Situ and Derived Sea Ice Thickness Observations
2:00 p.m.	Barry Goodison	Surface Observation Network
2:30 p.m.	Larry Hinzman	Hydrology and CHAMP
3:00 p.m.	Taneil Uttal	Intensive Sites

3:30–3:45 p.m.   *Break*

"Data Assimilation and Modeling"

3:45 p.m.	David Bromwich	Plan for an Arctic Reanalysis
4:15 p.m.	Pedro Viterbo	Experience at ECMWF
4:45 p.m.	John Walsh	Fully Coupled Models

5:30 p.m.   *Reception*

28 November 2001

8:30–8:45	**Introduction to Panels—Jim Overland**

8:45–11:45 a.m.   **Sea Ice Observations—Discussion**

Panel: Don Cavalieri
Greg Holloway
Ron Lindsay
Ola Persson
Ignatious Rigor
Jackie Richter-Menge, Chair

11:45–1:00 p.m.   *Lunch*

1:15–4:15 p.m.   **Atmospheric Observations—Discussion**

Panel: Roy Jenne
Jeff Key
Steven Pawson
Bob Stone
Mike Wallace
Jennifer Francis
Jim Overland, Chair

4:15–4:45 p.m.   **International Connections—Howard Cattle**

29 November 2001

8:30–11:30 a.m.   **Land Observations—Discussion**

Panel: Claude Duguay
Barry Goodison
Ed Josberger
David McGuire
Vladimir Romanovsky
Bernie Zak
Roger Barry, Chair

11:30–12:50 p.m.   *Lunch*

1:00–4:00 p.m.   **Arctic Reanalysis—Discussion**

Panel: Greg Flato
Bob Grumbine
Roy Jenne
Amanda Lynch
Mark Serreze
John Walsh, Chair

4:00–5:00 p.m.   **Summary Reports**

Sea Ice	Richter-Menge
Atmosphere	Overland
Land	Barry
Reanalysis	Walsh

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