Hydroclimate Observations in Arctic Alaska: Analysis of Past Networks and Recommendations for the Future

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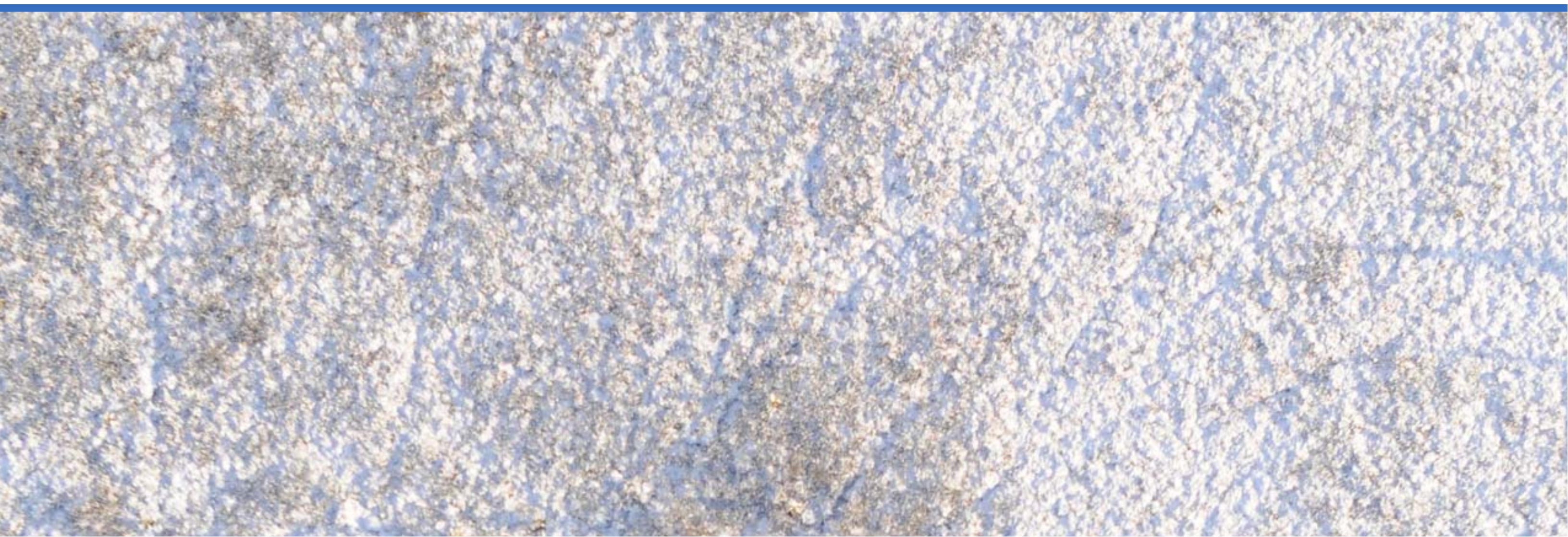

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The report cover photo is an airborne image of snow on tussocks, by J. Cherry, 2010.

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Executive Summary

The Arctic Landscape Conservation Cooperative (LCC) and the North Slope Science Initiative have both identified the importance of synthesizing and disseminating existing climate and hydrology data as well as improving the design of climate and hydrologic monitoring networks to meet management and research needs. We have partnered with the Arctic LCC to address this issue. During this project we designed a geodatabase called *Imiq*, inventoried hydrologic, climate, and related datasets, and populated the *Imiq* database with both data and metadata. Finally, we analyzed some of the spatial characteristics of the existing hydroclimate data and the observational network structure, in an effort to inform the development of an improved climate and hydrologic monitoring network. After analyzing the assembled data, several watersheds, communities, and other locations emerge as obvious candidates for enhanced monitoring infrastructure.

Site selection was further refined by discussions with several expert working groups organized by the Arctic LCC, including those on the related topics of climate, hydrology, permafrost, and coastal processes. Because most of the existing sites that were inventoried lack consistent support for long-term physical measurements, site recommendations that emerged from our analysis were based on the following factors:

1. The sites or areas have existing long-term or historical measurements of hydrologic and climate (referred to here as hydroclimatic) variables.

2. The sites or areas have some kind of existing physical infrastructure nearby (transportation, communication, a source of electrical power, or shelter).

3. The sites have intrinsic value because of their physical properties or relevance to socio-economic needs. For example, they are either highly representative of a particular physiographic region or their physical properties are distinctive enough that they challenge the existing knowledge of the arctic region. Other sites are logical because they are near a community or resource and the information would be valuable for decision-making. This 'intrinsic value' category is generally derived from expert opinion rather than emerging from the statistical analyses performed as part of this project.

In this report, we describe some of the anticipated physical changes in arctic Alaska as a motivation for enhanced monitoring, we inventory the current and historical network of observations, we discuss the impacts of the historical network on our state of knowledge about arctic Alaska's hydroclimate--including the role of observations in numerical modeling--and we present recommendations regarding the station network design and future management of data from the network.

The recommendations detailed in this report suggest cooperative, interagency support for the following:

A. The designation of research watersheds or concept areas (areas representing a hydro-physiographic region) with either new instrumentation or support for existing instrumentation. Some of these could be joint ventures with other LCCs.

B. Enhanced observing programs in communities, including both villages and work camps. Logical partners include agencies already operating community-

based observational programs such as the National Weather Service, the Federal Aviation Administration, the Alaska Department of Transportation and Public Facilities, and the Alaska Native Tribal Health Consortium.

C. Special attention to preservation and expansion of hydrologic gauging. Many of the past recommendations for enhanced gauging in the Arctic have never been realized, because of funding constraints. Existing gauges are threatened to be shut down for the same reason. Long-term river discharge measurements are a critical component to a hydroclimate observational network, particularly because they integrate many of the changes occurring upstream in the watersheds.

D. Expanded observation of the most sparsely measured variables, including evapotranspiration (ET), soil temperature and moisture, lake water levels, solar and long-wave radiation, relative humidity, snow depth, and snow water equivalent. Where the few existing measurements of these variables are made now, they are typically supported by a single research group and sites are vulnerable to the annual funding decisions of a small number of program managers.

E. Implementation of new instruments and techniques for hydroclimate observations, particularly for variables for which conventional measurements work poorly (i.e. snow) or are very costly (i.e. river gauging, ET fluxes). Arctic LCC support for instrumentation research and development may be most appropriate for technologies with relatively advanced readiness levels, according to the Technology Readiness Level (TRL) system used by the U.S. Government.

F. Ongoing improvements to data management practices such that various types of hydroclimate observations made by many different investigators can be integrated, analyzed, ingested into models, and used to improve our overall understanding of the arctic system.

The *Imiq* database that resulted from the project described in this report makes a unique contribution to the ongoing data integration efforts in the geosciences. It is the only database containing all of the historical data from major hydroclimate networks in northern Alaska. The goal of the authors is to continue to update *Imiq* and to make it a valuable community resource.

Introduction

The motivation behind the science planning of the Arctic Landscape Conservation Cooperative and the North Slope Science Initiative, with respect to enhanced monitoring, is to help plan and coordinate support for new and existing observational networks on a long-term, consistent basis. In the past, climatological and hydrological observation networks in arctic Alaska have largely been planned, built, and maintained on an *ad hoc* basis. That is, the measurements were driven by a site-specific scientific study or application, for a limited duration. The consensus is that this *ad hoc* approach may not be sufficient for the detection of the sort of wide-scale climate changes that are anticipated in the Arctic (Martin et al., 2009; NSSI, 2010, Streever et al., 2011).

Motivation: Anticipated Climate Change in Northern Alaska

There are many changes anticipated in the Arctic as the climate warms, sea ice patterns shift, and the region experiences normal and accelerated patterns of climate variability. These physical changes, such as the amount of snow and the timing of its arrival, have critical impacts on human and other biological systems and are important to detect. Many of these changes have already been detected. Others are sufficiently variable, and our observations sufficiently sparse, so that patterns are difficult to discern. These observed and projected changes have been described at length in publications such as the Arctic Monitoring and Assessment Program (2011), Hinzman et al. (2005), IPCC (2007), Rawlins et al. (2011), and White et al. (2007). Only a brief summary will be provided here as motivation for the inventory and network analysis.

A number of first-order changes to the arctic climate are highly likely in a warming world, including warmer air temperatures. These increases have been strongest in winter since the mid-Twentieth Century (Shulski and Wendler, 2007) although recent work has shown how cold winters can also be consistent with global warming, through a pattern of hydroclimate feedbacks (Cohen et al., 2012a,b). Because of the increased northward transport of warm, moist air, increased precipitation and increased cloudiness are both anticipated, particularly in the cold season (i.e. more snowfall). Unfortunately, snowfall is one of the most difficult measurements to obtain, because the automated technology for measuring small, dry particles in remote conditions is insufficient (Cherry et al., 2005, 2007). This makes detection of arctic precipitation trends with conventional gauges very challenging: the historical variability and instrument error are much greater than observed trends (Cherry et al., 2012).

Other changes are more uncertain because of the complexity of feedbacks and the response of the climate system over time. Because of increased air temperatures, soil active layer depth and soil temperatures are likely to increase, although in places where the onset of snow cover is delayed, soil may have more time to cool before being capped with insulating snow. The length of the growing season is generally expected to increase, although if snow depth increases significantly, it may take longer to melt, resulting in a later green-up date.

Arctic Hydroclimate Network Analysis

The surface water balance is changing in the Arctic, but these changes are not uniform. Much of the North Slope, because it is underlain by continuous permafrost, may experience an increase in lake surface area due to increased precipitation and, in some places, development of thermokarsts (hollows produced by thawing ground). However, as soil temperatures reach thawing points and active layers deepen, a larger portion of the surface water may transition to subsurface storage. The balance between available surface water and the evaporative potential of the atmosphere will impact whether or not evaporation increases. The mechanism of summer precipitation in arctic Alaska, away from the direct influence of the coast, is largely a function of moisture recycling between the land surface and the atmosphere. Thus, the amount of summer precipitation is also tied closely to the availability of surface water and the evaporative potential of the atmosphere. Unfortunately, direct measurements of evaporation in arctic Alaska are actually so sparse that they have not even been included in the inventory or analyses presented here.

Changes in runoff relate closely to surface water balance, but also to changes in subsurface storage and connectivity. Subsurface storage and connectivity link closely to permafrost distributions and the evolution of ground temperature on seasonal to multidecadal timescales. For some rivers that originate on the North Slope of the Brooks Range, changes in glaciers also have a significant impact on runoff. The mass balance of the glaciers depends on the relative impacts of changes in solid and liquid precipitation, temperature, and albedo (the fraction of incoming light that is reflected as opposed to absorbed).

Finally, the impacts of changes in the physical system upon the biological systems create additional feedbacks. One example of this is changing vegetation and the feedbacks to the climate system via albedo change, enhanced interception of snow by larger shrubs, and the resulting changes in the surface energy balance. It is challenging to measure the impact of physical climate change on biological systems (and *vice versa*) from individual stations. Although the purpose of this report is to inventory and analyze current and historical *in situ* observations, we recognize that use of remote sensing and model interpolation and downscaling techniques are also critical tools for the monitoring of arctic climate change and its impacts on human and other biological systems. These topics will be discussed further in the sections below.

Methods for Inventory, Data Acquisition, and Data Integration

The authors initiated the data integration effort by making a list of known data sources and their points of contact. Individuals with known datasets were contacted with a letter describing our efforts and asking them to help us identify and obtain hydroclimate data from arctic Alaska. These individuals included those at the Arctic LCC Hydrology meeting held in 2009 and those representing agencies on the Interagency Hydrology Committee for Alaska, as well as individuals who are known to be long-term researchers in arctic Alaska. Project personnel also searched online data archives such as the National Snow and Ice Data Center (NSIDC) and the USGS Water Catalog for the region of interest. Project workflow is represented in Figure 1. Data and Metadata were acquired and input into a SQL Server geodatabase. The database was named '*Imiq*', which is the Inupiat Eskimo word for 'potable water' (Webster and Zibell, 1970) and similar to the Yupik word '*Emeq*', which means the same. To input some datasets, digitization or other time-intensive processing was required. Capacity was included for access-restricted datasets, as necessary. A provisional website was built with a simple interface to the *Imiq* geodatabase metadata (http://ine.uaf.edu/werc/projects/lccdatalibrary/index.html).

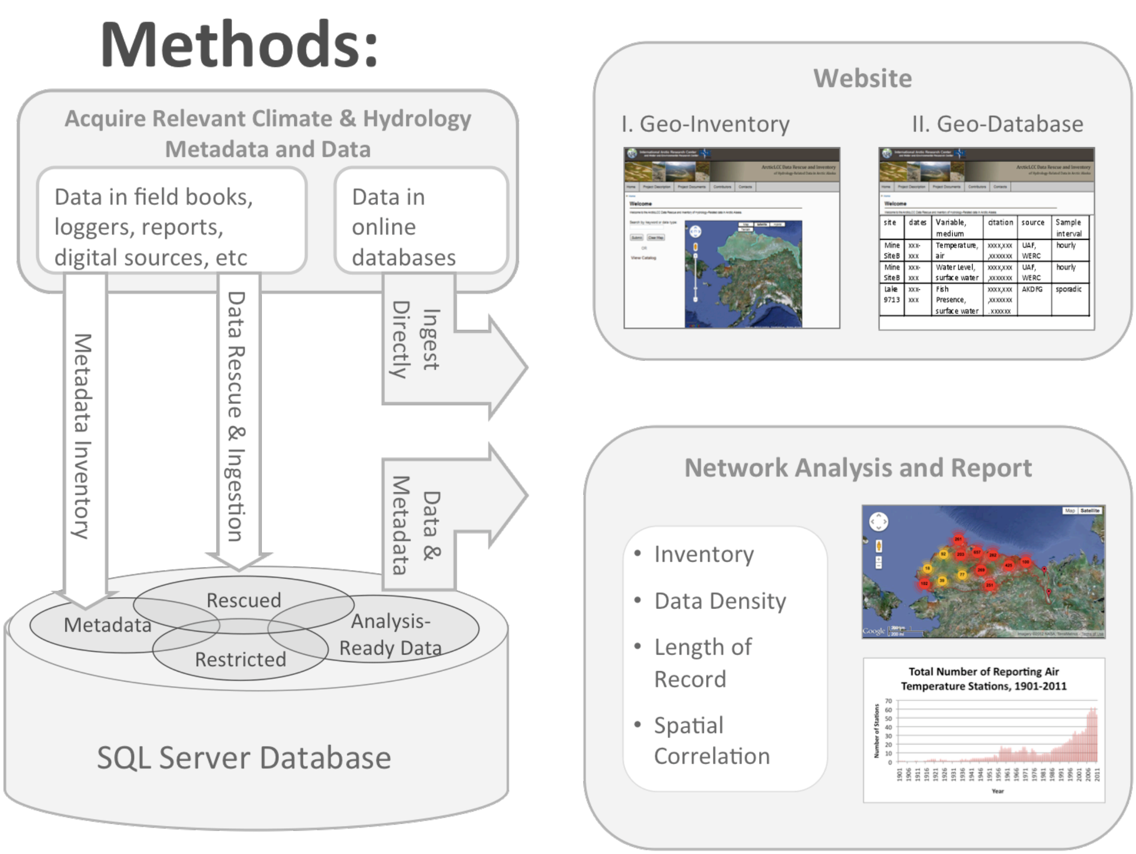

Figure 1: Project workflow.

Arctic Hydroclimate Network Analysis

Selected results of the inventory and network analysis will be shown and discussed directly below; expanded results are shown in Appendix A. Appendix B is a list of sources and sites currently in the *Imiq* database. Appendix C is a list of known data sources that were not included in this first version, but should be included in subsequent versions when more personnel time is available to reformat and input datasets. Additional documentation about the *Imiq* geodatabase is included in Appendix D and is also available from the authors.

Finally, the project team was aware of several other data integration programs, either on the North Slope of Alaska or the larger region and avoided duplication. These included the Arctic System Reanalysis, described in Bromwich et al. (2010), which makes use of historical data at first order stations and generates a model-data fusion climate product. The North Slope Decision Support System (http://www.nsdss.net/) is a web-based tool to help primarily in the planning and construction of ice roads for the oil and gas industry. This information system uses a geodatabase with meteorological information and some hydrologic information. We chose a compatible database structure so that some of the data could be shared between the two databases.

A state-wide program, the Alaska Ocean Observing System, also uses some of the same data sources, particularly for meteorology, but the emphasis in this system for land-based assets is real time monitoring; it does not function as a historical data archive for land-based meteorology at this time (http://www.aoos.org). Another project, the Beaufort/Chukchi Seas Mesoscale Meteorology Modeling Study, funded by the Bureau of Ocean Energy Management (BOEM), assembled meteorological data from some of the same sites used in our study, but for a limited time period (1979-2009) and they focused primarily on air temperature and wind. More information is available at http://mms-meso.gi.alaska.edu/obs.html.

The North Slope Science Catalog (http://catalog.northslope.org/) is an NSSI-led/Geographic Information Network for Alaska (GINA)-implemented effort to inventory North Slope research, but it does not, at the time of writing, actually host hydroclimate datasets. Another portal, the Barrow Area Information Database (BAID at http://www.baid.utep.edu/) hosts a number of relevant datasets and also points users to other datasets hosted remotely. Any future maintenance and expansion of the Arctic LCC *Imiq* Hydroclimate Geodatabase could include some of the datasets hosted or cataloged by BAID, the North Slope Science Catalog, NSIDC, the Arctic Research Mapping Application (ARMAP at http://www.armap.org/), the National Center for Atmospheric Research's Earth Observing Laboratory's Data Library (NCAR-EOL at http://data.eol.ucar.edu/), the Arctic Long Term Ecological Research program at Toolik Lake, the Arctic Observation Network's ACADIS portal, the Alaska Geospatial Data Clearinghouse (http://www.agdc.usgs.gov), and the National Hydrographic Database; this will be discussed further in the recommendations.

Despite these related efforts, the *Imiq* geodatabase fills a unique niche for data integration as a comprehensive, multi-agency repository for hydroclimatological and water-related historical data from northern Alaska.

Results of the Data Inventory and Observed Climate in Northern Alaska

After it was determined that sufficient data were contained in the *Imiq* hydroclimate geodatabase to do a meaningful network analysis, an inventory was performed. Expanded results are shown in Appendix A. Parameters inventoried and analyzed included air temperature, precipitation, relative humidity, snow depth, snow water equivalent, and river discharge. Many other parameters exist in the geodatabase, including those listed at the end of Appendix D, the Database Documentation.

As part of the inventory, spatial queries were performed including the number of years a station was operating (for each parameter), the start and end dates of each station (for each parameter), as well as time-series of the number of stations reporting each parameter. Basic spatial climatologies were calculated and plotted for each parameter and for each season over every station's period of record. Station density was calculated and mapped for each parameter and various seasons. Gridded maps of variables were generated using the Inverse Distance Weighting technique. Finally, scatter plots and histograms were used to look at patterns of variability with elevation. These plots are all shown in Appendix A.

Several clear patterns emerge in the network coverage. The oldest stations are at the perimeter of the Arctic LCC domain, including Barrow, which dates back to 1901. Most of these long-term sites are in the coastal communities. The two long-term sites at the southern edge of the domain are also community based, while the longest, consistently operating, inland site is at Umiat, with a weather record dating back to the World War II era. Long-term snow depth measurements exist in a few of these communities, but nearly all snow water equivalent measurements, and most snow depth records, are from the past decade. Many of these were commissioned as part of infrastructure engineering and design projects and are unlikely to evolve into long-term records without additional support. Of the variables analyzed, discharge is the sparsest measurement, and many measurements were short-lived.

The spatial patterns in Figures A1-A11 and A36-A39 (in Appendix A) show that most measurements are either concentrated on the coast or along the road corridor. The mountainous or near-mountainous stations only include the McCall Glacier area (and not all data that exists here were obtained for the database), the passes (Atigun and Anaktuvuk), and the intermittent observations for engineering projects. Figures A45-A47 plot station parameters against elevation, showing that not only are most observations at low elevations, but that the known relationship between elevation and climate hinges on the presence of just two or three high elevation sites. Unfortunately, these plots obscure the distinction between distance from the coast and elevation; the statistical relationship between elevation and climate parameters is not as strong as it would be if these two effects were separated.

When the spatial analyses are divided by season, it is clear that some parameters, such as air temperature, have consistent station densities throughout the year. Others, such as precipitation, are far more difficult to maintain through the winter, so there is a seasonal asymmetry to the station densities.

The apparent decline in sites since 2009 (Figures A12-A17) is the result of two separate effects: a delay in the availability of station data and an actual decline in the number of sites, particularly those managed by UAF near the road corridor, because of the end of project funding. River discharge measurements tend to be short-lived, because once the resource permit applicant or management agency has the minimum amount of data required for permitting, the site tends to be discontinued. Other river discharge measurements have been discontinued because of budget cuts to the USGS and the high cost of gauging in remote areas.

Figures A40-A43 show gridded maps of Annual Air Temperature for different periods and portions of the network, which were generated with the Inverse Distance Weighting method. Figure A40 is an average for the whole period of record for all stations and A41 is for the period from 1940-1969, for all stations. The patterns look much cooler in the later figure, in part because the early record (1920-1940) had some warm anomalies relative to 1950-1970. The most recent period (1970 onward) shown in Figure A42 is another relatively warm period, but seemingly very similar to the century-long climatology in A40. Figure A43 shows the later period (1970 onward) but only for stations that existed before that period (generally longer term sites). This pattern looks different than if all stations are included: both the East-West and North-South temperature gradients are stronger if only long-term stations are included. Figure A44 shows the same period again, but only for new stations that appeared in this time. Comparing Figures A42-A45 provides some sense of the sensitivity of gridded products to changes in station density. This will be discussed further in the section on gridded products and model output below.

On the maps shown in Appendix A, several watersheds and other regions are highlighted. These are areas where either measurements are relatively dense (Kuparuk), relatively long-lived (Barrow area), a large number of parameters are measured (Harrison Bay), or they are representative of a particular subsystem of the region of interest (Camden Bay watershed with the Hulahula and Jago Rivers draining off of the Brooks Range glaciers). These will be proposed concept areas for additional monitoring and will be discussed further in the “Recommendations” section below. ‘Concept areas’ are envisioned as areas representing a particular hydro-physiographic region that are the location of intensive research activities.

It is also clear from the spatial analysis that the longest term, most consistent, highest quality data have been collected in communities, including the city of Barrow, and the villages and work camps. There are tremendous advantages to collecting data in places with existing infrastructure, near places where people routinely live or work. These data are typically useful for observing present weather and river conditions as well as for long-term planning. There are also more opportunities for individuals to perform routine and urgent maintenance on observational equipment in these locations, helping keep these records consistent and of good quality. For these reasons, enhanced community-based monitoring emerges as another clear recommendation from the network analysis.

Figure 2 shows a map of the resulting research watersheds, concept areas, and communities that meet one or more of the following criteria:

1. The sites or areas have existing long-term or historical measurements of hydroclimatic variables.

2. The sites or areas have some kind of existing physical infrastructure nearby (transportation, communication, a source of electrical power, or shelter).

3. The sites have intrinsic value because of their physical properties or relevance to socio-economic needs. For example, they are either highly representative of a particular physiographic region or their physical properties are distinctive enough that they challenge the existing knowledge of the arctic region. Other sites are logical because they are near a community or resource and the information would be valuable for decision-making. This 'intrinsic value' category is generally derived from expert opinion rather than emerging from the statistical analyses performed as part of this project. Identification of these sites were the results of the working group process established by the Arctic LCC on the topics of climate, hydrology, permafrost, and coastal processes. This will be discussed further in the recommendations section.

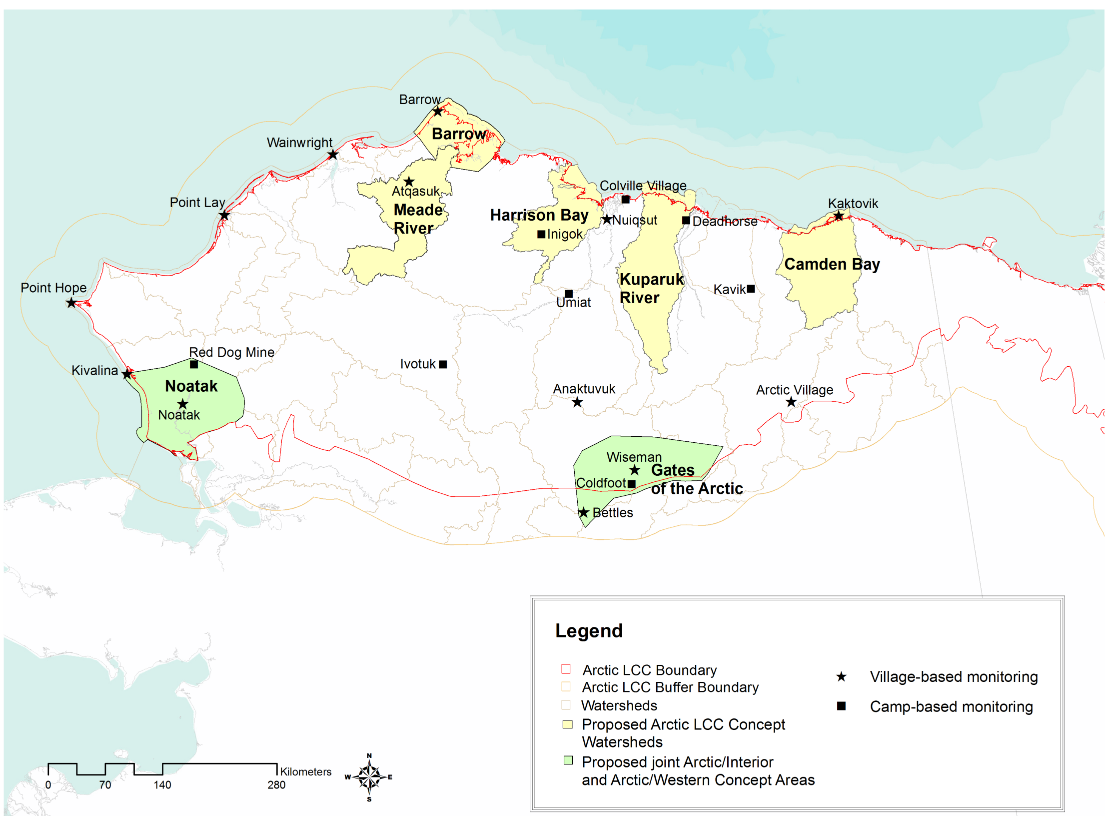

Figure 2: Proposed Watersheds and Concept Areas for the Arctic LCC and neighboring LCCs.

Arctic Hydroclimate Network Analysis

Because an extensive network analysis for streamflow monitoring was done several years ago by USGS (Brabets, 1996), this effort was not repeated here. Appendix I shows excerpts from this report, including a list of recommended gauging stations for Alaska's arctic region. Figure 3 shows current river observing stations in the domain, from NOAA's NWS Alaska-Pacific River Forecast Center data portal. In the Arctic LCC domain, only the Colville Village station is managed by the NWS through a community-based observer. The other sites are supported and managed through agencies such as USGS, BLM, UAF, USFWS, and the Arctic LCC. All of these sites are vulnerable to budget cuts. Long-term security for the existing sites is an obvious priority, followed by the establishment of new sites, such as those recommended in the Brabets (1996) report.

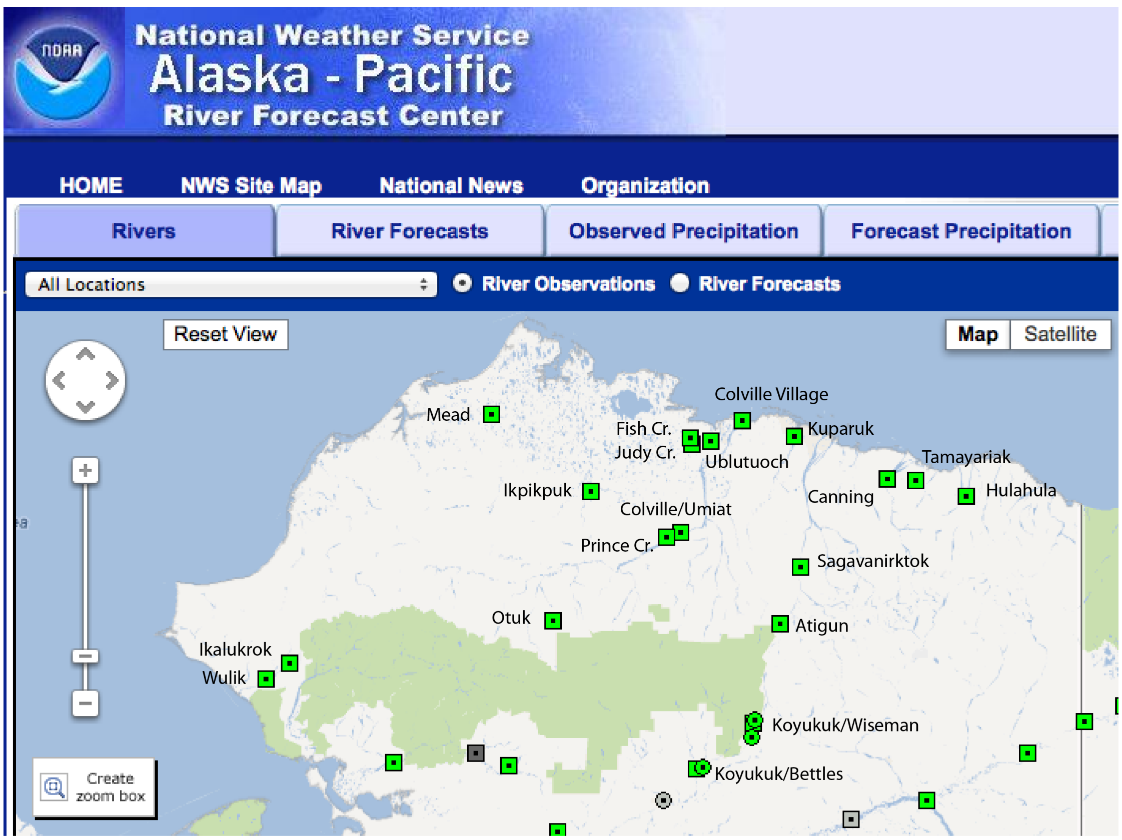

Figure 3: Current river observing stations operating as of August 2012 that report in near real time. The Canning River station will be discontinued on September 30, 2012. The Arctic LCC is helping sustain observations at several of these rivers through partnerships with USGS, USFWS, UAF, and NSSI. The only one of these northern Alaska river sites maintained through the NWS is the Colville site at Colville Village where there is a community-based observer (Ben Balk, pers. comm.).

Impacts of Historical Network Coverage on Our State of Knowledge

Our knowledge about the climate and hydrology of northern Alaska has evolved since one of the earliest studies, published in 1960 by Conover. He wrote about the climatology using only a few data points collected by the Army and the Weather Bureau. In 1975, Weller and Bowling edited a volume on Climate of the Arctic with an entire chapter devoted to Hydrology. By then new data had been collected as part of additional oil and gas exploration and the construction of the Trans-Alaska Pipeline System and the Dalton Highway. In 1996, Zhang et al. provided a review of the northern Alaska Climate studies done up until that time, as well as their own analysis. More recently, Shulski and Wendler (2007) updated some of these analyses. Finally, just this year (2012) Perica et al. published a new precipitation frequency atlas for Alaska, which includes the Arctic. Our own analysis and that of these authors suggest there are at least four effects of the passage of time on our understanding of Alaska's arctic climate. The number of observations has changed, the places where observations are made have changed, the technology used to take and communicate hydroclimate data has changed, and of course the climate itself has changed.

Changes in the Number and Location of Observations Over Time

Figures 4 and 5 show an example, using different portions of the network, of the temperature and precipitation record over time. These sites were chosen because they have the longest and most complete records from the database, but also because they represent several gradients of known variability, such as latitude and elevation. Figure 6 shows site locations relative to the regional topography. Figure 4 is the annual mean air temperature for both coastal and inland stations. These annual means were calculated from daily values, where at least ten days were required to be present to calculate a monthly value, and monthly values from all twelve months were required to calculate an annual mean (or in the case of precipitation in Figure 5, sum).

The Barrow temperature record effectively begins in 1901, but fails the missing data criteria for the following two decades; thereafter it is relatively complete until the present and is the only such record in northern Alaska. Barrow's precipitation record becomes relatively consistent in the 1920s and runs through the present. A consistent meteorological record begins in the inland community of Wiseman in 1936 (temperature) and 1939 (precipitation), runs for a couple of decades, then reappears in the 1990s. Chandlar and Umiat, also inland sites, have a similar appear/disappear/reappear pattern, although at different times. The largest number of long-term stations runs from the early 1950s through the 1980s, although this period is dominated primarily by coastal sites.

In addition to the stations' annual temperature and precipitation records, Figures 4 and 5 also show trends. The red lines show linear least-squares regression trends for the Barrow station only, and the three red lines show the trends over various periods. The black lines show an all-station mean over those same three periods. The trends, changes over the various periods, and statistical significance of the p-values at the 95% confidence level from a Student's T-test are shown in Table 1.

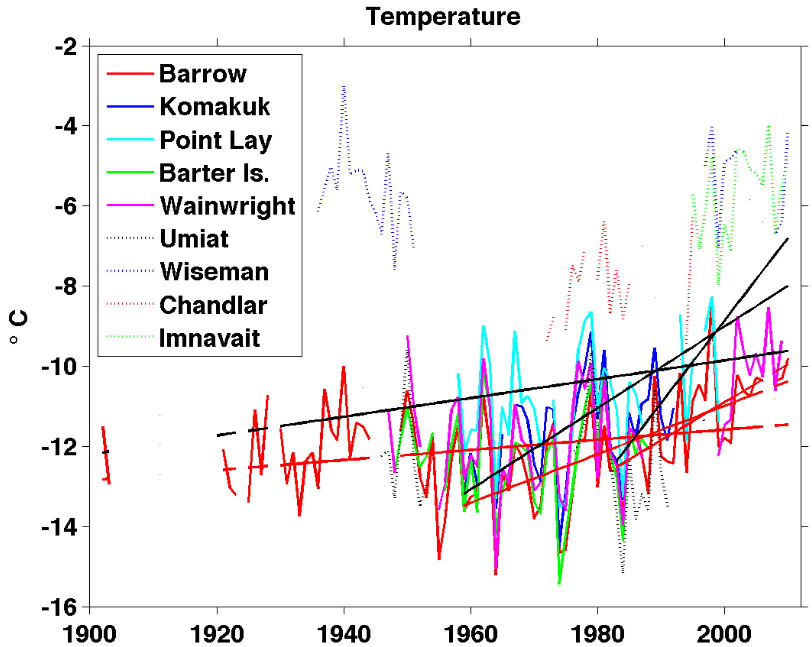

Figure 4: Temperature (°C) records and linear trends for select stations. Trends were calculated for the three time periods (1901-2011, 1958-2011, and 1980-2011). Straight red trend lines are for Barrow only, straight black trend lines are for the all-station mean.

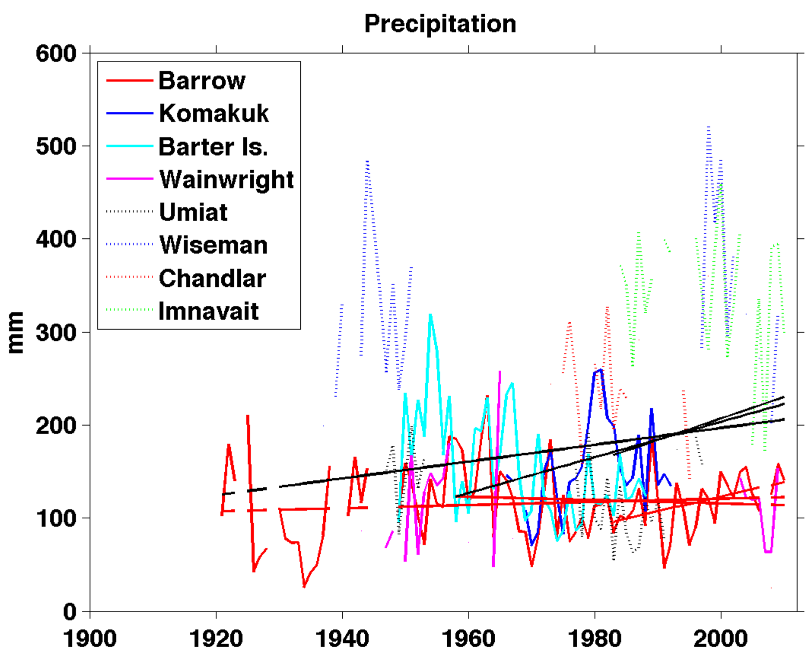

Figure 5: Precipitation (mm) records and linear trends for select stations. Trends were calculated for the three time periods (1920-2011, 1958-2011, and 1983-2011). Straight red trend lines are for Barrow only, straight black trend lines are for the all-station mean.

Variable (Annual)	Period	Trend	Change over period	Statistically Significant at 95% CL
Barrow Temperature	1901-2011	0.01 °C/yr	1.40 °C	N
Barrow Temperature	1958-2011	0.06 °C/yr	3.27 °C	Y
Barrow Temperature	1983-2011	0.10 °C/yr	2.77 °C	Y
All Stations' Temperature	1901-2011	0.02 °C/yr	2.60 °C	Y
All Stations' Temperature	1958-2011	0.10 °C/yr	5.49 °C	Y
All Stations' Temperature	1983-2011	0.21 °C/yr	5.98 °C	Y
Barrow Precipitation	1920-2011	0.2 mm/yr	15.7 mm	N
Barrow Precipitation	1958-2011	-0.2 mm/yr	-9.7 mm	Y
Barrow Precipitation	1983-2011	1.6 mm/yr	45.7 mm	N
All Stations' Precipitation	1901-2011	0.9 mm/yr	100.3 mm	Y
All Stations' Precipitation	1958-2011	1.9 mm/yr	103.3 mm	Y
All Stations' Precipitation	1983-2011	2.3 mm/yr	66.9 mm	N

Table 1: Annual mean temperature and precipitation trends at select northern hydrometeorology stations. Positive trends indicating increasing temperatures or precipitation amounts.

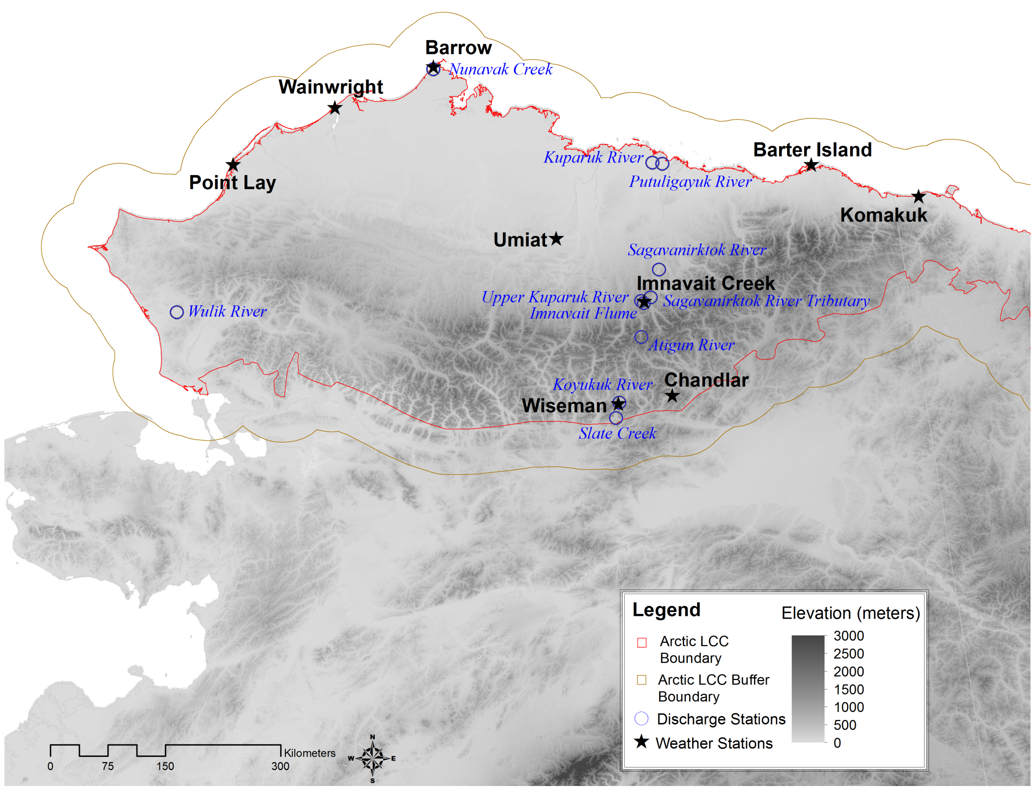

Figure 6: Locations of selected weather and river discharge stations in northern Alaska and Canada. Also shown are the Arctic LCC Boundaries and the regional topography.

Arctic Hydroclimate Network Analysis

The long-term temperature trend at Barrow is modest, showing an increase of only 1.4 °C since 1901. Temperatures have increased much more rapidly since 1958 and 1983, reflecting a relatively warm period at the start of the Twentieth Century, followed by a mid-century cooling, followed by a late-century-to-present warming. Precipitation in Barrow shows a modest long-term increase of 15.7 mm. It was relatively dry in the 1970s and 1980s, followed by a more recent increase in precipitation, according to this analysis (Table 1).

The trends of all stations averaged together look considerably different (Table 1). During the early part of the record, of course Barrow is the only station. With the exceptions of Wiseman and the early years of Umiat, the mid-century record is entirely dominated by coastal sites: Barrow, Wainwright, Barter Island, and later Point Lay and Komakuk (Canada). The other inland sites (Chandlar, Imnavait and the restablishment of the Wiseman and Umiat records) do not appear until the 1970s or later. While Umiat, on the Colville River, shares a climate similar to that of the coastal sites, the other inland sites (which are near mountains) are considerably warmer and wetter. The effect on the all-station averages of the appearance of the inland stations is an artificial warming with increased precipitation, and one that is exaggerated in the two later periods (1958-present and 1983-present).

A common technique for analyzing multiple climate stations with different periods of record is to calculate the station anomalies by subtracting each station's long-term mean from its own record. Figures 7 and 8 show the difference in the trends calculated from the raw data and those calculated from the average anomaly across all stations. Here the all-station mean is shown in black and the anomalies are shown in blue. Table 2 shows the trends and changes over period for the anomalies. There are very large differences between the trends in the raw data and the trends in the anomalies. While both temperature and precipitation anomalies are still increasing over the longest time period, they are doing so at a more moderate rate, compared to the raw trends. The more recent periods show even stronger differences, with temperature anomaly increases similar to those of the longest period and precipitation anomaly decreases, which is very different than the raw precipitation trends.

Variable (Annual)	Period	Trend	Change over period	Statistically Significant at 95% CL
All-Station Temperature Anomaly	1901-2011	0.01 °C/yr	1.11 °C	Y
All-Station Temperature Anomaly	1958-2011	0.04 °C/yr	1.95 °C	Y
All-Station Temperature Anomaly	1983-2011	0.06 °C/yr	1.80 °C	Y
All-Station Precipitation Anomaly	1901-2011	0.1 mm/yr	9.6 mm	Y
All-Station Precipitation Anomaly	1958-2011	-0.2 mm/yr	-12.3 mm	Y
All-Station Precipitation Anomaly	1983-2011	-0.2 mm/yr	-7.4 mm	N

Table 2: Trends in annual average temperature and precipitation anomalies for all-station means of the select northern hydroclimate stations shown in Figures 4 and 5.

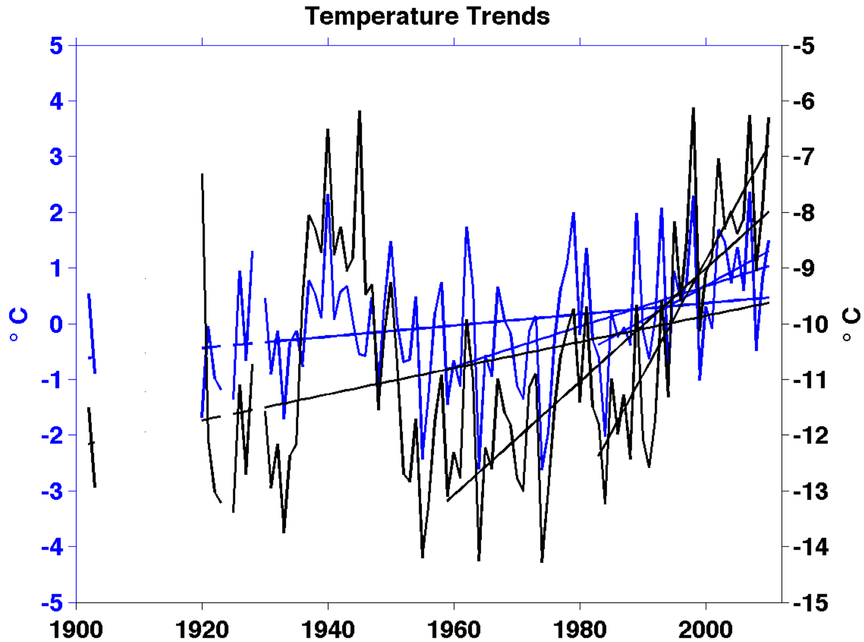

Figure 7: The all-station average of mean annual air temperature and the linear trends over the periods 1901-2011, 1958-2011, and 1983-2011 are shown in black. The mean of station anomalies and the corresponding trends are shown in blue. The difference highlights the errors introduced in trend analysis when the station network is inhomogeneous in time.

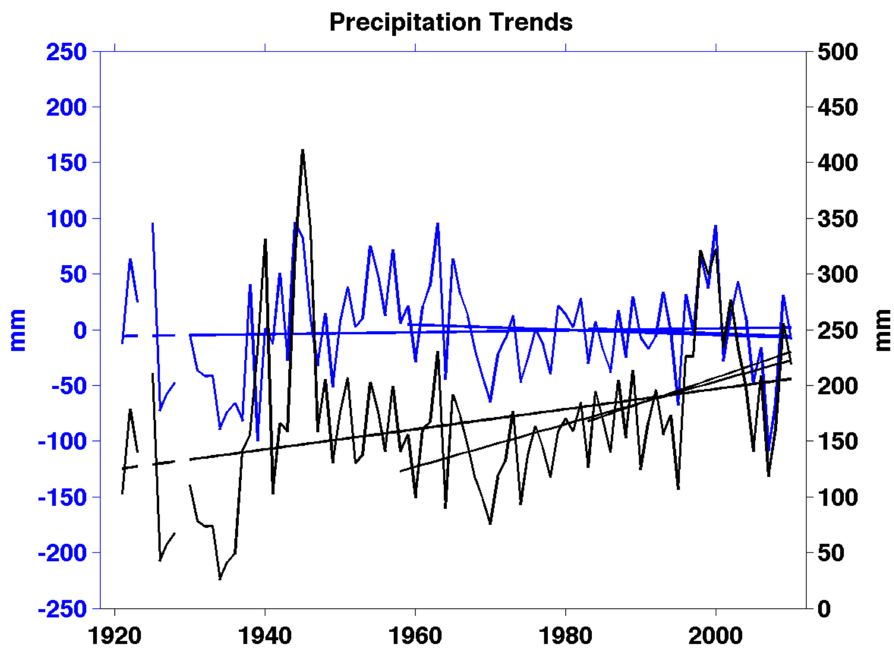

Figure 8: The all-station average of total annual precipitation and the linear trends over the periods 1901-2011, 1958-2011, and 1983-2011 are shown in black. The mean of station anomalies and the corresponding trends are shown in blue. The difference highlights the errors introduced in trend analysis when the station network is inhomogeneous in time. For precipitation, the sign of the more recent trends even changes from increasing to decreasing when the anomalies are used.

Arctic Hydroclimate Network Analysis

Many of the times series described above fail the statistical significance test. The Student's T-test is perhaps the most basic test for a linear trend, and the underlying distributions of these data may not be ideal for this test. For more robust results, further analysis should take non-stationarity (i.e. mean and variance change over time) and other likely properties of the data into account.

The results of this simple analysis, however, give us some insight on the relative roles of actual climate trends and trends that are an artifact of the change in station densities, although considerable uncertainty results from having only a single long-term station. It is useful to average trends over several stations, to detect robust signals of change. However, because the underlying climate varies so much on scales more local than the distance between stations, a comparison of the record at a single long-term site to a spatial average is difficult to interpret. The situation is more dramatic for precipitation (Figures 5,8), which is more spatially variable than temperature. These statistical effects are a strong argument for sustaining long-term measurements over a spatially consistent and representative area.

Changes in the Technology of Observing

The above analysis ignores the role of technological changes in temperature and precipitation sensors. Impacts on the climate record of changes in technology are difficult to analyze because often there is little or no instrument documentation in the archives. For example, Vaisala brand temperature/humidity sensors were used at climate research stations throughout the Kuparuk river basin. Older models of the sensor had a minimum temperature of -40 °C, below which the sensor would not record a temperature. Use of these sensors was eventually discontinued and some were replaced with sensors that could record lower temperatures. The result of this change in the sensor technology would be a perceived decrease in average temperatures, because more low temperature events (i.e., < -40°C) would be recorded in recent years. Technological advancements are typically a positive change, but better documentation would help detect the impact of these changes on climate records.

Nearly every parameter measured has some kind of bias and it is difficult to determine which sensor was in use at any given time, so it is not possible to estimate this network uncertainty, except qualitatively. Another important issue is whether the sensor biases are low enough to detect actual trends, given natural variability. This is considered a 'signal to noise' detection problem. The general consensus is that temperature trends are much easier to detect than precipitation trends because the sensors work more accurately and temperature is less variable in space and time than is precipitation.

Changes in the Large-Scale Climate Variability

Another underlying factor that challenges our understanding of climate change is the role of large-scale modes of variability in the ocean-atmosphere system. The Arctic Oscillation and the Pacific Decadal Oscillation are both natural modes of variability that evolve on approximately decadal timescales and are a known influence on Alaskan Climate (Shulski and Wendler, 2007), particularly in winter. Figures 9 and 10 show plots of the all-station winter temperature and precipitation anomalies alongside the Arctic Oscillation and Pacific Decadal Oscillation Indices. The inter-annual correlations between these time series are low, but they all have similar patterns at the decadal time scale. Because of the strong memory in the climate system on these time scales, it is particularly important to monitor environmental variables over the long term. While the source of the decadal to multi-decadal memory of the climate system is not well understood, it likely involves portions of the climate system that vary on long-time scales such as the ocean.

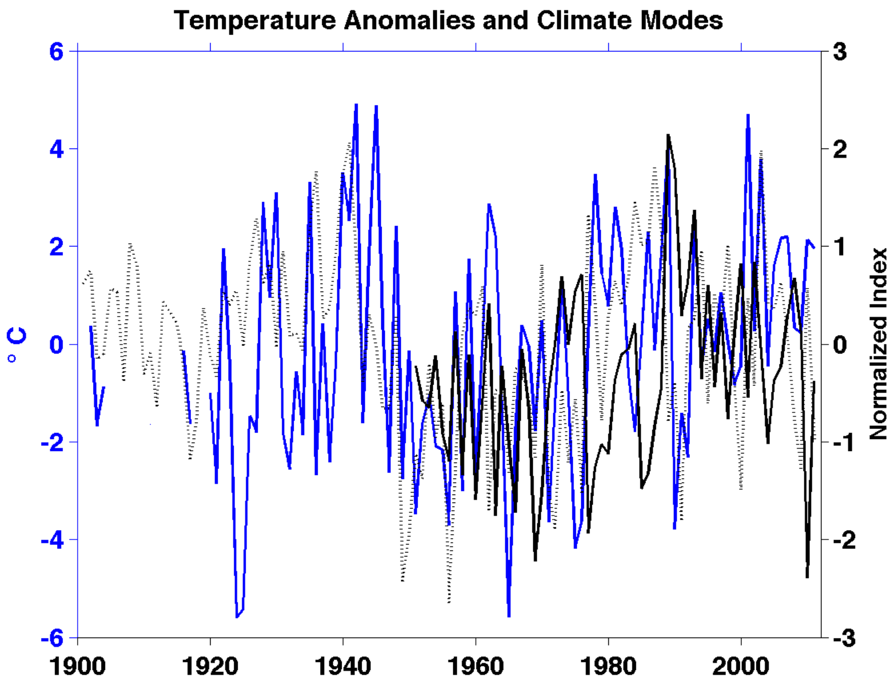

Figure 9: All-station average winter (Dec-Feb) mean temperature anomalies (blue) are plotted against the Arctic Oscillation (solid black line) and Pacific Decadal Oscillation (dotted black line) indices. While inter-annual correlations are low, all three time series show similar decadal patterns. AO and PDO indices are from (http://jisao.washington.edu/pdo/ and http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml).

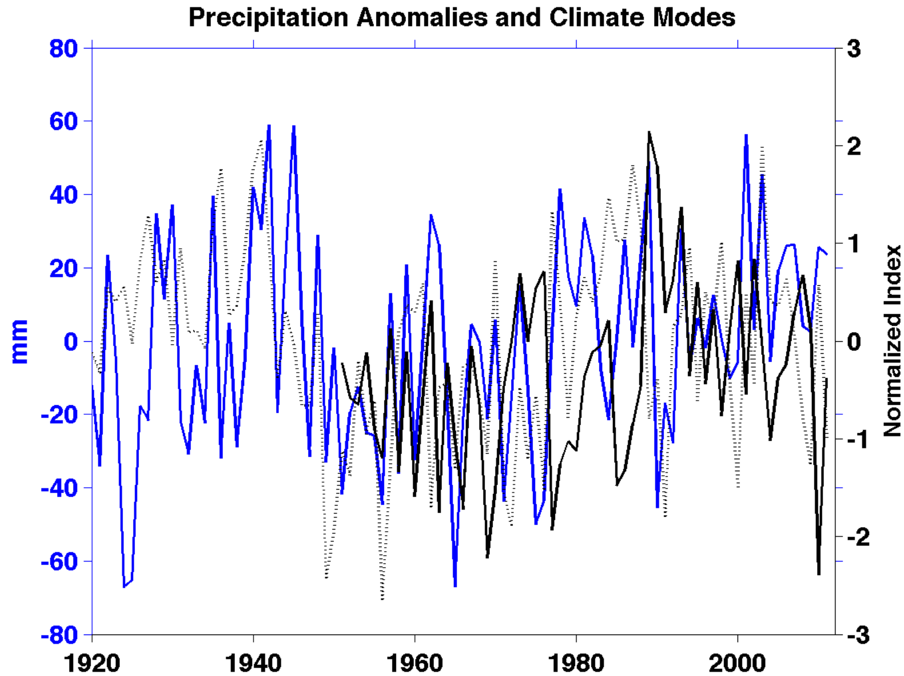

Figure 10: All-station average winter (Dec-Feb) mean precipitation anomalies (blue) are plotted against the Arctic Oscillation (solid black line) and Pacific Decadal Oscillation (dotted black line) indices. While inter-annual correlations are low, all three time series show similar decadal patterns.

Sparsely Measured Variables

River discharge measuring stations are considerably more sparse in space than are climate stations, although river gauges typically integrate drainage over a larger area then a climate station represents. River gauges are also more sparse in time: consistent monitoring only started on a few rivers in the 1970s, making it more difficult to assess the role of stations coming and going on our state of knowledge. Figure 11 shows normalized discharge (each station's record minus its mean and divided by its standard deviation) during peak snowmelt runoff in May/June. The process of normalization, whereby discharge values are divided by the station's long-term mean and subsequently divided by its standard deviation, makes it possible to compare trends over different sized rivers.

Trends are shown for the all-station mean (in black) and the Kuparuk River near Deadhorse (in green). The all-station trend is just slightly positive, while the trend in the Kuparuk is downward and the trend in the Nunavak (near Barrow) is upward. Figure 12 shows the time series for the average summer discharge, which has similar temporal patterns. Table 3 shows the trends numerically in their original units, for the Kuparuk and Nunavak Rivers. Figures 11 and 12 both show generally dry conditions in the most recent decade throughout the Arctic. While the trends in the Kuparuk seem large, they fail the Student's T-test for statistical significance. The Nunavak is a much smaller river, but the small upward trends are statistically significant (Table 3). The runoff trends for the Nunavak are consistent with increased precipitation in Barrow.

The importance of these trends for network design considerations is that interannual variability is large and long-term variability is driven by large-scale modes of climate such as the PDO and AO. Detection of long-term changes, outside of normal variability, requires long-term, consistent measurements with enough spatial coverage that one can separate localized responses from regional change.

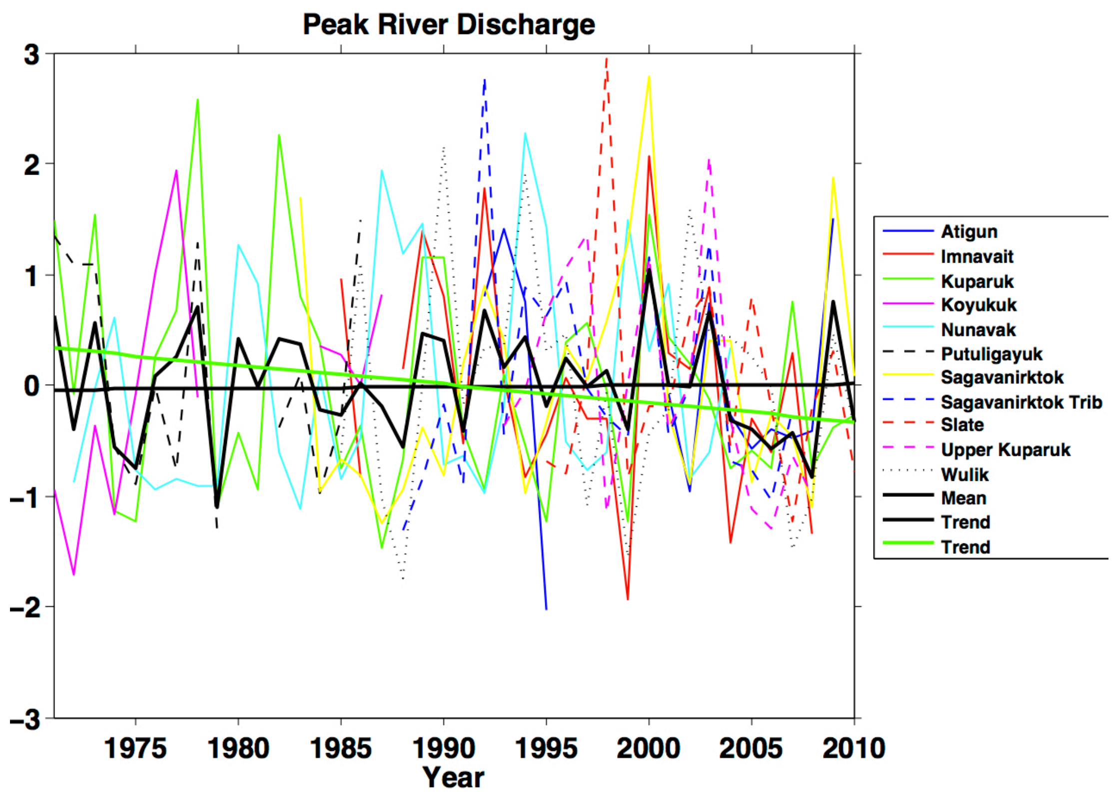

Figure 11: Peak (May-June) discharge anomaly time series and trends for several rivers in northern Alaska. The units are normalized discharge. The black time series is the all-station mean. The green lines are the Kuparuk River gauge near Prudhoe and its linear trend line. The Kuparuk record is the longest in the database that is also nearly continuous to the present.

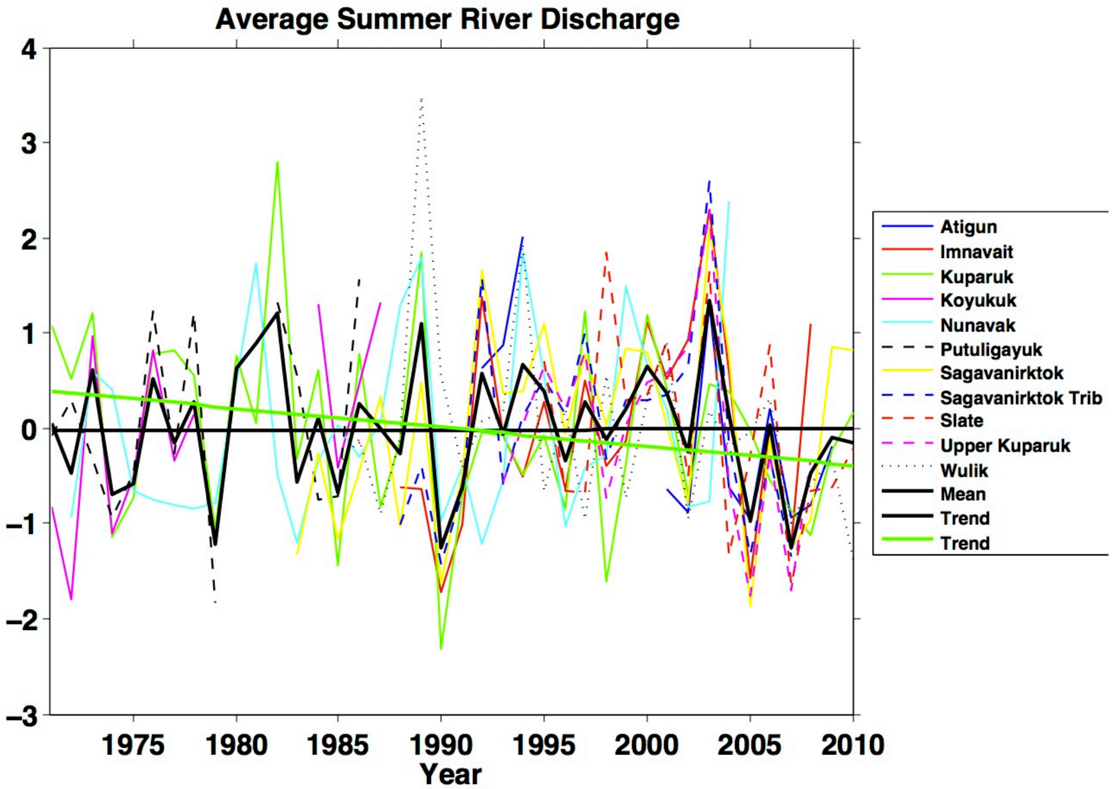

Figure 12: Average summer (June-August) discharge anomaly time series and trends for several rivers in northern Alaska. The units are normalized discharge. The black time series is the all-station mean. The green lines are the Kuparuk River gauge near Prudhoe and its linear trend line. The Kuparuk record is the longest in the database that is also nearly continuous to the present.

Variable and Discharge Station	Period	Trend	Change over period	Statistically Significant at 95% CL
Snowmelt Peak Kuparuk near Deadhorse	1971-2010	-10.10 cms^{-1}/yr	-403.82 cms^{-1}	N
Summer Avg Kuparuk near Deadhorse	1971-2010	-2.89 cms^{-1}/yr	-115.54 cms^{-1}	N
Snowmelt Peak Nunavak near Barrow	1972-2004	0.018 cms^{-1}/yr	0.59 cms^{-1}	Y
Summer Avg Nunavak near Barrow	1972-2004	0.005 cms^{-1}/yr	0.16 cms^{-1}	Y

Table 3: Trends in snowmelt peak (May-June) and summer (June-August) discharge at two long-term stations near Deadhorse/Prudhoe Bay and Barrow. For summer trends, the per yr actually refers to ‘per summer’ . Flows on the Kuparuk are typically 3-4 orders of magnitude larger than those on the Nunavak.

Arctic Hydroclimate Network Analysis

There are many more types of measurements in the *Imiq* database that are critical components of a hydroclimate monitoring network, including evapotranspiration, soil temperature and moisture, lake level and volume, radiation, relative humidity, etc. In the interest of time, not all could be analyzed here. Evapotranspiration (ET) is a particularly important variable in hydroclimate research, but only a handful of historical and active sites exist in northern Alaska, such as Toolik Lake, Barrow, and Atqasuk. Like with river discharge, one of the biggest challenges of building a site that uses eddy covariance techniques to estimate ET is its high cost, power requirements, and maintenance, compared to a typical weather station. However, ET measurements are incredibly valuable for studies on water balance and ecosystem-hydrologic interactions.

Snow is another component that has only been given cursory treatment here. The biggest challenge for detecting changes in frozen precipitation is that conventional gauges work poorly for snow and snow redistribution is a common (and largely unmeasured) occurrence in northern Alaska. The shortcomings of the observational network for some of these components (river discharge, snow water equivalent, lake levels, etc) could merit investment in new instrument research and development, especially if technologies exist which have already passed through initial testing. There are natural partners in the commercial sector, particularly in oil and gas exploration, who would benefit considerably from improved monitoring technologies and may be willing to contribute to research, development, and data collection.

Recommended Network Design and Plan implementation

The quantitative network analysis above was used to inform recommended site selection, as was input from experts. Appendix E is a draft report from the Arctic LCC Climate Technical Working Group that describes a number of efforts by agencies to design optimal weather or climate station networks with coverage in the Arctic. This is followed by the recommendations by Karl et al. (1996) for ‘Ten Principles of Climate Monitoring’ in Appendix F. Brabets (1996) completed a lengthy network analysis for river discharge measurements that is excerpted in Appendix I. The Arctic Observing Network program produced a survey on the optimal observing network (Appendix H). Nolan et al. (2006) also wrote about an optimal station design for the Alaska National Parks that is too lengthy to include here. Many of these ideal designs have been met by the realities of insufficient funding, insufficient personnel, or are simply very slow to be implemented.

The National Science Foundation (NSF) has sponsored several workshops with the goal of setting priorities for the Arctic Observation Network (AON), most recently in the spring of 2012. Although the NSF would like AON to grow into an interagency effort, it has few examples in Alaska of terrestrial AON projects co-funded with other agencies thus far. NSF also supports an archive called ACADIS (http://www.aoncadis.org) including a geodatabase of metadata associated with the projects it funds as part of the AON program. A screenshot of the geodatabase is shown in Figure 13. Most of the data shown here is also in

Imiq, although the ACADIS metadata geodatabase has not been updated since 2009 for the Alaskan Arctic. NSSI has a more recent update to its metadata geodatabase for current AON projects. NSF's AON program is a logical partner for the Arctic LCC program to help sustain networks, although the agency's support for long-term monitoring must compete with its support for hypothesis-driven science. The consequences of this competitive process have resulted in the loss of funding for at least one major hydroclimate network in arctic Alaska, built by investigators at the University of Alaska Fairbanks. These stations represent approximately two thirds of those shown here (Figure 13).

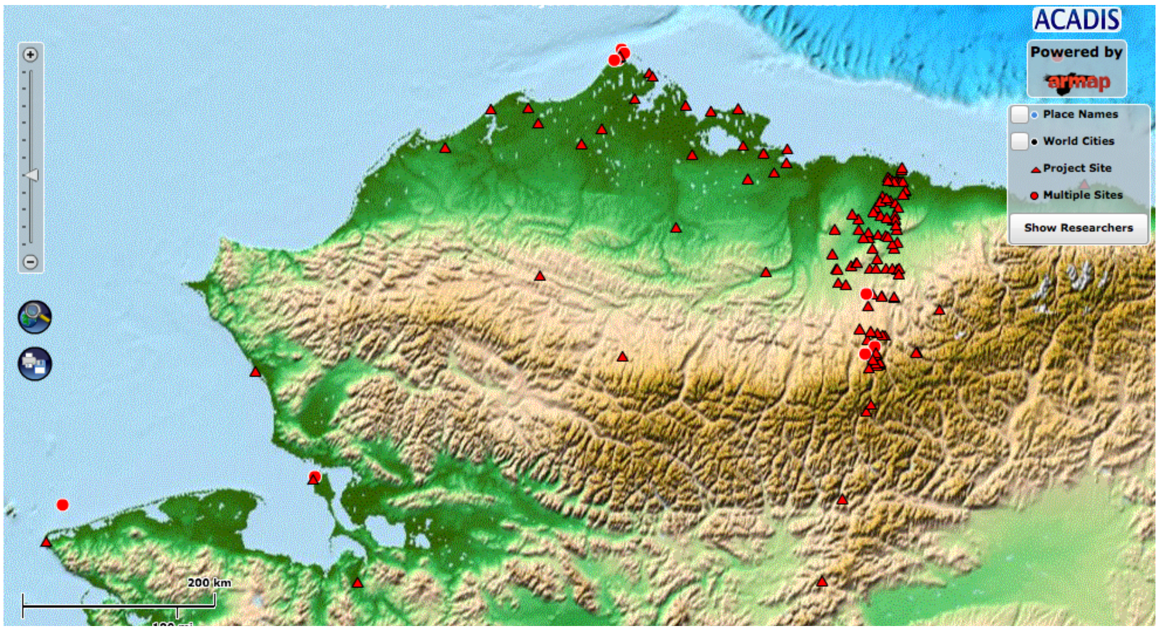

Figure 13: Screenshot of the ACADIS metadata geodatabase for NSF AON projects http://www.aoncadis.org) . Not all of the sites shown here are currently supported by the AON program. Many, particularly in the Kuparuk River Basin, lost NSF funding in 2009.

At this point it would be impractical to redesign the arctic Alaska hydroclimate observational network from scratch. What does seem achievable is to build a consortium of supporters to help maintain key existing measurements and where practical, fill in critical missing information. The details of these station designs will be described in a separate report to the Arctic LCC, (Crosby, in prep) but the network analysis helped support the choice of proposed concept study areas and community-based monitoring, shown in Figure 2. Each of these areas has its own assets. Barrow is an obvious choice because although Barrow has been an active research area for several decades, many of the research measurements there last only a few years. Support there might help transient measurements become long-term environmental data records. The Meade River watershed is included with the Barrow area because many researchers based in Barrow have also taken hydroclimate measurements in Atqasuk or at the Meade River.

Harrison Bay and Kuparuk are chosen because of the large number of existing observations and instrumentation in those areas. The Camden Bay area is downstream from McCall Glacier, where there are a number of historical weather and glaciological observations. However, few river discharge measurements exist here and this is a region where a significant data gap could be filled.

The Noatak and the Bettles areas have relatively dense observations and could provide an opportunity to partner with both the Western Alaska and Northwestern Interior Forest LCC's. These sites have multiple agencies managing observational networks and also nearby communities that could contribute to the network through community-based monitoring and 'citizen science'.

The Alaska Native Tribal Heath Consortium (ANTHC) has recognized the paucity of data in Northwest Alaska and other regions and that they could play a role in helping the communities they support to collect data for climate and engineering applications. Their program is called the Local Environmental Observer (LEO) program (http://www.anthc.org/chs/ces/climate/leo/). The National Weather Service has made use of community-based observers for many years through their Coop Station program. Other researchers have developed programs to encourage citizen scientists to measure parameters like lake ice and permafrost temperatures. This might become a significant source of data at some point in the future, particularly with the popularity of GPS-enabled smart phones that can be used in geotagging. Without institutionalization or (typically) compensation, it is unclear how long individuals might carry on such programs, although members of communities shown in Figure 2 would be good candidates.

In addition to villages and towns, camps at remote locations such as Umiat, Ivotuk, Red Dog Mine, Inigok, Colville Village, and Kavik make good observational sites because of their long-term record (Umiat) or the relatively large number of hydroclimate research observations there (Ivotuk, Inigok) or their transportation and communication infrastructure (Kavik, Red Dog, Colville Village). NOAA's Climate Reference Network is a likely partner here (see Figure 1 in Appendix E).

When sustainable funding is established for the relatively low-cost, easy-access sites, it then makes sense to begin filling in the voids between these sites. Until then, remote sensing and interpolation models may help fill gaps and will be discussed further below.

Other Relevant Datasets: Remote Sensing, Gridded Products, and Model Output

While the focus of this report has been on *in situ* hydroclimate observations, one could similarly assess the availability of various remote sensing instruments, programs, and products. Fortunately, most of the relevant satellite remote sensing products exist in online databases, if not in the regionally focused archives such as the Alaska Satellite Facility (ASF), GINA or the Alaska Geospatial Data Clearinghouse. The historical airborne remote sensing data is in need of considerably more attention. Much of this is housed at the ASF's Geodata center, but it is in need of digitization, orthorectification, mosaicking, and error analysis. This includes historical color, color infrared and pan-chromatic photographs of the North Slope that show snapshots of lakes, rivers, and other features related to hydroclimatology. Remote sensing data share many of the same issues as *in situ* data with slight variations; for example changes in network coverage issues might come from cloud cover instead of stations coming and going. There are still problems with variation in accuracy, precision, and sensitivity among sensors and biased sampling of particular conditions over time (i.e. cloud-free).

We recommend that with the future maintenance and expansion of the *Imiq* hydroclimate database, remote sensing data also be included. While Arctic LCC support for new satellite missions may be out of reach, airborne remote sensing is well within its reach, and the costs of obtaining high-resolution, high quality data is dropping. Rescuing older remote sensing datasets can also provide high value and be extremely useful sources for change detection.

Finally, the research areas of climate modeling, interpolation, and downscaling are currently evolving quickly. One of the drivers of this research area is the need to provide information about anticipated climate change on the small spatial and temporal scales that are meaningful for decision-making. However, the techniques may be just as useful for estimating spatial variations of current climate in sparsely monitored regions like the Arctic. These datasets could also be included in the *Imiq* geodatabase to provide access to both gridded model datasets and station observations. One example of a data library that has done this successfully is the International Research Institute for Climate and Society's Data Library at Columbia University (http://iridl.ldeo.columbia.edu).

The utility of observations for driving and verifying models cannot be emphasized enough. Simpson et al. (2005) wrote a paper in which they compared maps of air temperature and precipitation for Alaska using two different methods of spatial interpolation/downscaling with different underlying observational datasets. Table 4 is excerpted from this paper and lists the different climate station networks that were used to construct the maps using the two different approaches ('ANUSPLIN' and 'PRISM'). The PRISM approach has been more widely adopted, particularly by the Scenarios Network for Alaska and Arctic Planning at UAF, for the dissemination of downscaled climate products. Because this method uses more observational data, the results of the PRISM approach are more certain than those from the ANUSPLIN method. Figure 14 is also excerpted from this paper and shows the station locations for the data used to construct the maps, which are shown in Figures 15 and 16. These maps show distinctly different results for Alaska's North Slope climate because of the differences in the number of observations used and the corresponding methods for using them.

The purpose of discussing this example is to show that models (conceptual, statistical, and physically-based) need observations and that our knowledge of the climate is very sensitive to the spatial and temporal coverage of these observations. The other point to note is that even the PRISM product (which is distributed widely in Alaska) lacks most of the hydroclimate observations from northern Alaska. This is simply because of the historical difficulty in obtaining these observations from the researchers who made them (C. Daly, pers. comm). A searchable database like *Imiq* will make possible improved access to these data for investigators such as those who developed PRISM.

Data	ANUSPLIN	PRISM
Precipitation:		
54 GHCN precipitation records	Yes	Yes[1]
283 NWS COOP observing stations	No	Yes
44 USDA/NCRS Snotel stations	No	Yes
128 USDA snow course stations	No	Yes
41 precipitation stations from Yukon and BC (from Environment Canada)	No	Yes
48 snow course stations from the Yukon and BC (from Environment Canada)	No	Yes
Digital Elevation Model	Yes	Yes
Temperature:		
74 GHCN station records	Yes	Yes
278 NWS COOP station records	No	Yes
10 Snotel station records	No	Yes
28 BLM/Forest Service RAWS station records	No	Yes
500 mb reanalysis temperature data	No	Yes
Radiosonde data	No	Yes
Digital Elevation Model	Yes	Yes

Table 4: Excerpted from Simpson et al. 2005. This table shows data used by two different interpolation/downscaling techniques for the Alaska domain.

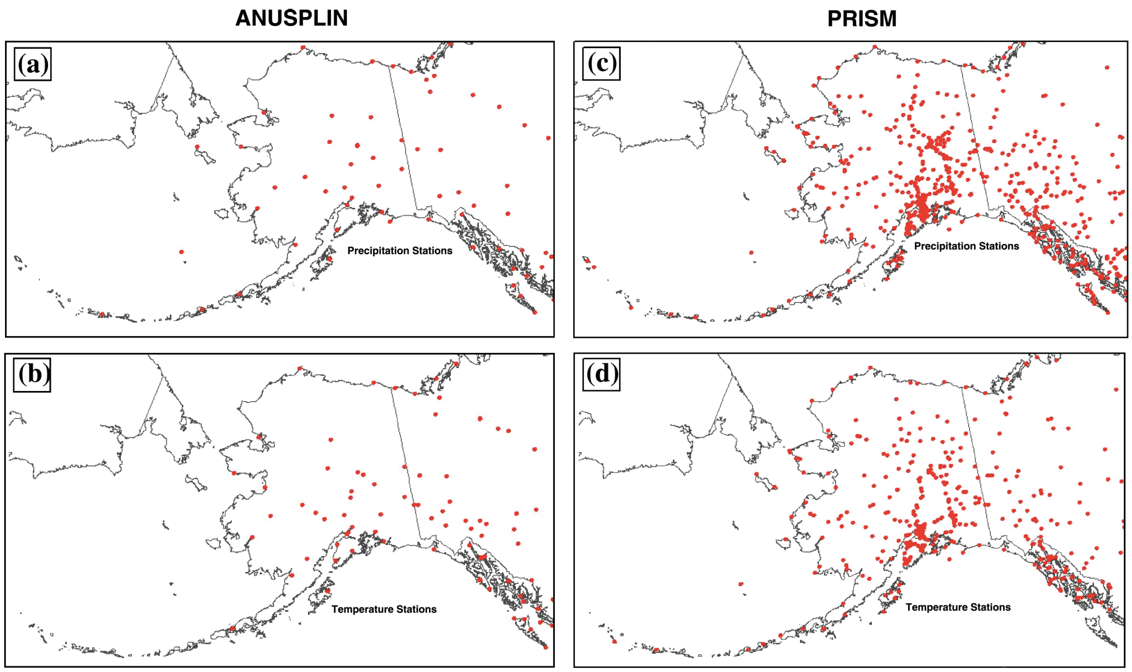

Figure 14: Location of precipitation (top panel) and temperature (bottom panel) measurements used in statistical downscaling for the ANUSPLIN (left) and PRISM (right) climate maps. The lower panels show the temperature stations used to generate the PRISM downscaled output. Figure excerpted and modified from Simpson et al 2005.

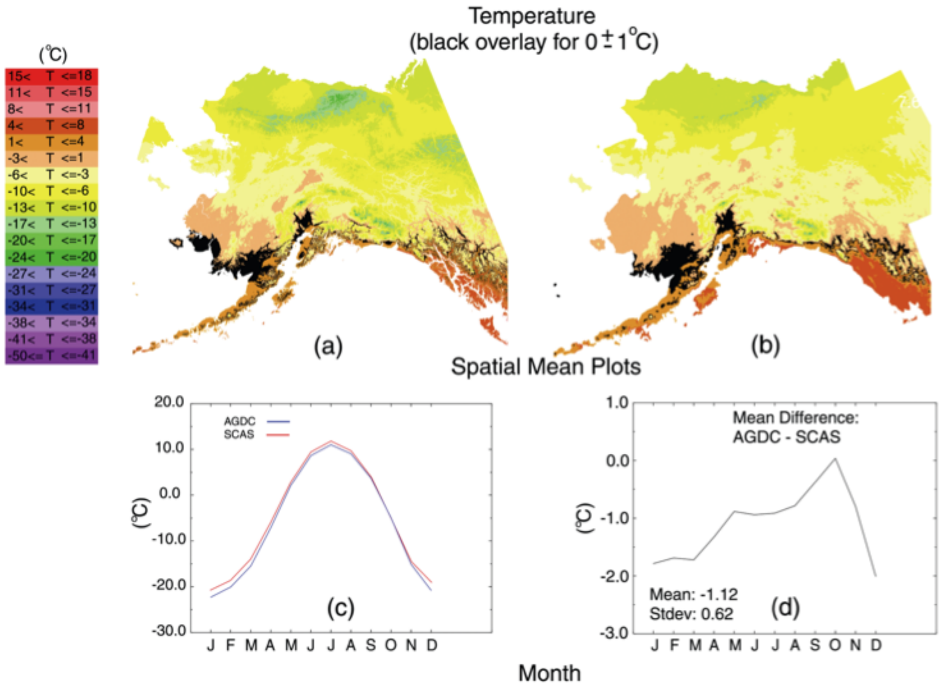

Figure 15: Maps and plots of mean annual surface air temperature (°C) produced by using ANUSPLIN/AGDC (a) and PRISM/SCAS (b) techniques. Panel (d) shows the difference in the output generated by the two techniques. Figure excerpted from Simpson et al. 2005.

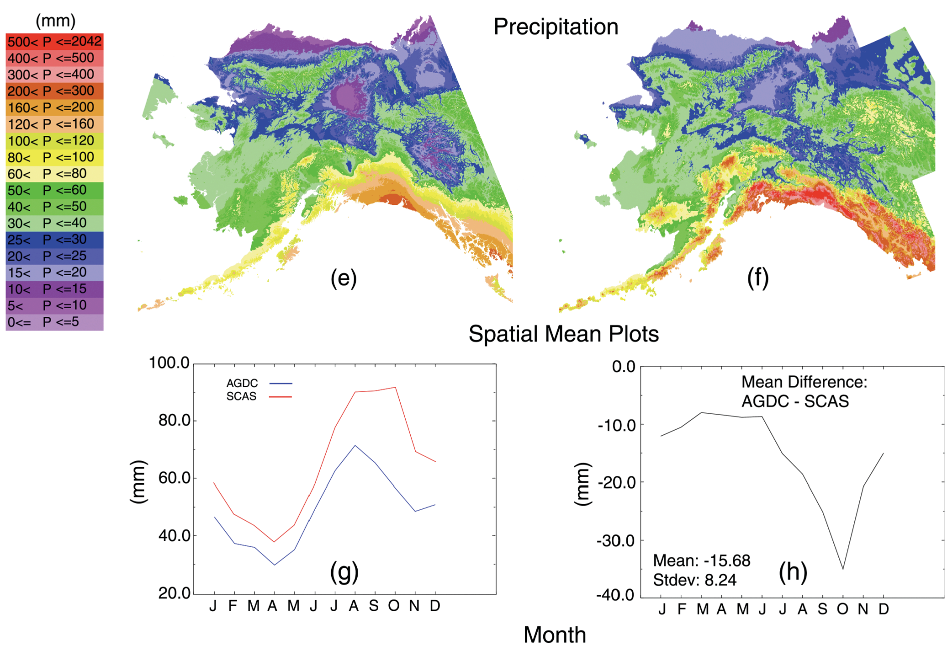

Figure 16: Maps and plots of mean annual total precipitation (mm) produced by using ANUSPLIN/AGDC (e) and PRISM/SCAS (f) techniques. Panel (h) shows the difference in the output generated by the two techniques. Figure excerpted from Simpson et al. 2005

Data Management

Discussions are ongoing about the future of the existing *Imiq* hydroclimate database that was constructed in the course of this project. There were many datasets that were not input into the database because of the limitations of time. Some of these are listed in Appendix C. Several of these datasets were missing metadata in their current form, or required additional quality assurance and control before being ingested. Others were not included because the project authors might not be aware of the data's existence.

The hope is that a data library such as GINA or another appropriate entity, will take over long-term maintenance and expansion of the database. One of the lessons learned throughout this project is that many observationalists at government agencies, private companies, and universities are unfamiliar with or otherwise unable to use searchable databases to archive their data and therefore considerable effort is required to get their data into the necessary formats. In the course of this project, this often required working with the observer to find metadata that was not originally published with the dataset. Continued maintenance and expansion of the *Imiq* database will require the efforts of both a data manager and a subject specialist to help configure data and contact observers. Use of web-based data submission forms for standard data types (i.e. snow surveys, discharge measurements, etc.) might help in this regard.

For the arctic region, it could make sense to coordinate this data integration effort with other regionally specific efforts such as the North Slope Science Catalog, which is also managed by GINA. If the database is to be expanded throughout the state, then other regionally specific and statewide data integration efforts exist and the data management plan should be coordinated with these other efforts, including the Alaska Ocean Observing System. However, currently, there are no other living (i.e. continually updated) databases that contain all of the data for the networks analyzed here.

Acknowledgments

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Tidwell, John Trawicki, Frank Urban, John Walsh, Kathleen Wedemeyer, Matthew Whitman, Emily Youcha, personnel at NOAA, USDA-NRCS, WRCC, and others. Many people went to considerable effort to collect the data in this *Imiq* database and that which we have yet to input. Some of their work is described in Appendix G, the Selected Bibliography.

References

Arctic Monitoring and Assessment Program (AMAP), 2011. Snow, Water, Ice, and Permafrost in the Arctic (SWIPA) Report.

Brabets, T.P., 1996. Evaluation of the Streamflow-Gaging Network of Alaska in Providing Regional Streamflow Information. U.S. Geological Survey Report 96-4001.

Bromwich, D., Y.-H. Kuo, M. Serreze, J. Walsh, L.-S. Bai, M. Barlage, K. Hines, and A. Slater, 2010. Arctic System Reanalysis: Call for Community Involvement, *Eos Trans. AGU*, 91(2), 13, doi:10.1029/2010EO020001.

Cherry, J.E., B. Tremblay, S. Déry, M. Stieglitz, 2005. Solid precipitation reconstruction using snow depth measurements and a land surface hydrology model, *Water Resour. Res,* Vol. 41, No. 9, W09401, 10.1029/2005WR003965.

Cherry, J.E., L.-B. Tremblay, M. Stieglitz, G. Gong, S. Déry, 2007. Development of the Pan-Arctic Snowfall Reconstruction: new land-based solid precipitation estimates for 1940-1999. *Journal of Hydrometeorology* , Vol. 8, No. 6, 1243–1263.

Cherry, J.E., S. Déry, Y. Chen, M. Stieglitz, “Climate and Hydrometeorology of the Toolik Lake Region and Kuparuk River Basin: Past, present and future” in *Toolik Lake Long Term Ecological Research Station,* ed. J. Hobbie, *in press* at Oxford University Press.

Cohen, J.L., J.C. Furtado, M.A. Barlow, V.A. Alexeev, and J.E. Cherry, 2012, Asymmetrical Seasonal Temperature Trends, Geophys. Res. Lett. 39 (2012) L04705, doi:10.1029/2011GL050582.

Cohen, J.L., J.C. Furtado, M.A. Barlow, V.A. Alexeev, and J.E. Cherry, 2012. Arctic warming, increasing snow cover and widespread boreal winter cooling, Environ. Res. Lett. 7 (2012) 014007.

Conover, J. H., 1960. Macro- and Microclimatology of the Arctic Slope of Alaska. U.S. Army, Environmental Protection Research Division, Technical Report EP-139.

Davey, C. A., K. T. Redmond, and D.B. Simeral. 2006. Weather and Climate Inventory, National Park Service, Arctic Network. Natural Resources Technical Report NPS/ARCN/NRTR – 2006/005.

Hinzman, L.D. et al. 2005. Evidence and Implications of Recent Climate Change in Northern Alaska and Other Arctic Regions, Climatic Change, Volume 72, Issue 3, Pages 251 – 298

IPCC, 2007: Climate Change 2007, The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S.D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Karl, T. R., V. E. Derr, D. R. Easterling, C. K. Folland, D. J. Hoffman, S. Levitus, N. Nicholls, D. E. Parker, and G. W. Withee. 1996. Critical issues for long-term climate monitoring. Pages 55-92 *in* T. R. Karl, editor. Long Term Climate Monitoring by the Global Climate Observing System, Kluwer Publishing.

Martin, Philip D., Jennifer L. Jenkins, F. Jeffrey Adams, M. Torre Jorgenson, Angela C. Matz, David C. Payer, Patricia E. Reynolds, Amy C. Tidwell, and James R. Zelenak. 2009. *Wildlife Response to Environmental Arctic Change: Predicting Future Habitats of Arctic Alaska*. Report of the Wildlife Response to Environmental Arctic Change (WildREACH): Predicting Future Habitats of Arctic Alaska Workshop, 17-18 November 2008. Fairbanks, Alaska: U.S. Fish and Wildlife Service. 138 pages.

Nolan, M. et al., 2006. Scoping Document for Monitoring Climate and Weather in the Arctic National Parklands, National Park Service Report.

North Slope Science Initiative (NSSI), 2009. Emerging Issue Summary: Weather and Climate. Retrieved on February 15, 2011 from http://www.northslope.org.

North Slope Science Initiative (NSSI), 2009. Emerging Issue Summary: Hydrology and Lake Drying. Retrieved on February 15, 2011 from http://www.northslope.org.

Perica, S. et al. 2012, NOAA Atlas 14; Precipitation-Frequency Atlas of the United States. Volume 7 Version 2.0: Alaska, 127p.

Rawlins, M.A., M. Steele, M. Holland, J.C. Adam, J.E. Cherry, J.A. Francis, P. Groisman, L.D. Hinzman, T.G. Huntington, D.L. Kane, J.S. Kimball, R. Kwok, R.B. Lammers, D.P. Lettenmaier, K.C. McDonald, E. Podest, J.W. Pundsack, B.Rudels, M.C. Serreze, A. Shiklomanov, O. Skagseth, T.J. Troy, C.J. Vorosmarty, M. Wensnahan, E.R. Wood, R. Woodgate, D. Yang, K. Zhang, T.

Zhang, 2011, “Analysis of the Arctic System Freshwater Cycle Intensification: Observations and Expectations,” *Journal of Climate*, Vol. 23:5715-5737.

Sanzone, D. M., S. D. Miller, and S. B. Young. 2005. Monitoring ecological change in the Arctic parklands. Vitals Signs Monitoring Plan for the Arctic Network: Phase I Report. Inventory and Monitoring Program, National Park Service: Fairbanks, Alaska.

Simpson, J.J., G.L. Huffford, C. Daly, J.S. Berg, and M.D. Fleming, 2005: Comparing Maps of Mean Monthly Surface Temperature and Precipitation for Alaska and Adjacent Areas of Canada Produced by Two Different Methods. ARCTIC, Vol. 58, No. 2, 137-161.

Streever, B., R. Suydam, J.F. Payne, R. Shuchman, R.P. Angliss, G. Balogh, J. Brown, J. Grunblatt, S. Guyer, D.L. Kane, J.J. Kelley, G. Kofinas, D.R. Lassuy, W. Loya, P. Martin, S.E. Moore, W.S. Pegau, C. Rea, D.J. Reed, T. Sformo, M. Sturm, J.J. Taylor, T. Viavant, D. Williams and D. Yokel, 2011. Environmental Change and Potential Impacts: Applied Research Priorities for Alaska’s North Slope. Arctic 64(3)390:397.

Thomas, W.O., 1993. An overview of selected techniques for analyzing surface-water data networks: World Meteorological Organization Operational Hydrology Report WMO/No. 806, 103p.

U.S. Climate Reference Network (USCRN), 2010. USCRN Overview. Information retrieved on February 17, 2010 from http://www.ncdc.noaa.gov/crn

Shulski, M. and G. Wendler, 2007. The Climate of Alaska. University of Alaska Press, 208p.

Webster, D.H. and W. Zibell, 1970. Iñupiat Eskimo Dictionary, Illustrated by Thelma A. Webster, Summer Institute of Linguistics, Inc., Fairbanks, Alaska.

Weller, Gunter and Sue Ann Bowling, 1975. Climate of the Arctic, Geophysical Institute, University of Alaska Fairbanks, 436p.

White, D., Hinzman, L., Alessa, L., Cassano, J., Chambers, M., Falkner, K., Francis, J., Gutowski, W., Holland, M., Holmes, M., Huntington, H., Kane, D., Kliskey, A., Lee, C., McClelland, J.,Peterson, B., Steele, M., Straneo, F., Woodgate, R., Yang, D., Yoshikawa, K., and Zhang, T., 2007. Changes and impacts in the arctic freshwater cycle, *JGR Biogeosciences*, Vol 122, G04S54, doi: 10.1029/2006JG000353.

Zhang, T., Osterkamp, T.E., And Stammes, K., 1996. Some characteristics of the climate in northern Alaska, U.S.A. *Arctic and Alpine Research* 28: 509–518.

Appendix A: Expanded Results from the Arctic LCC IMIQ Hydroclimate Database Network Analysis

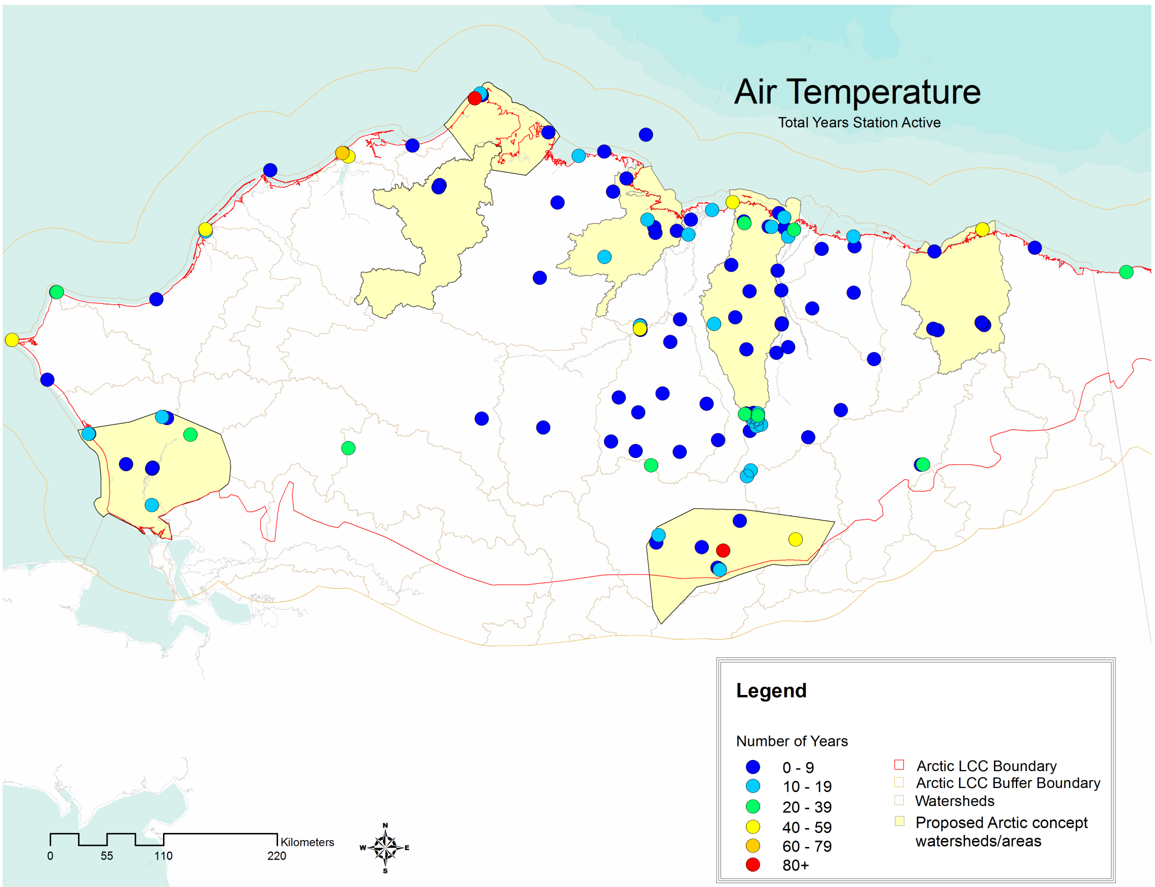

Figure A1: total number of years a station was reporting air temperature. The bin '0-9' refers to stations with more than zero and less than ten years of reporting and so on.

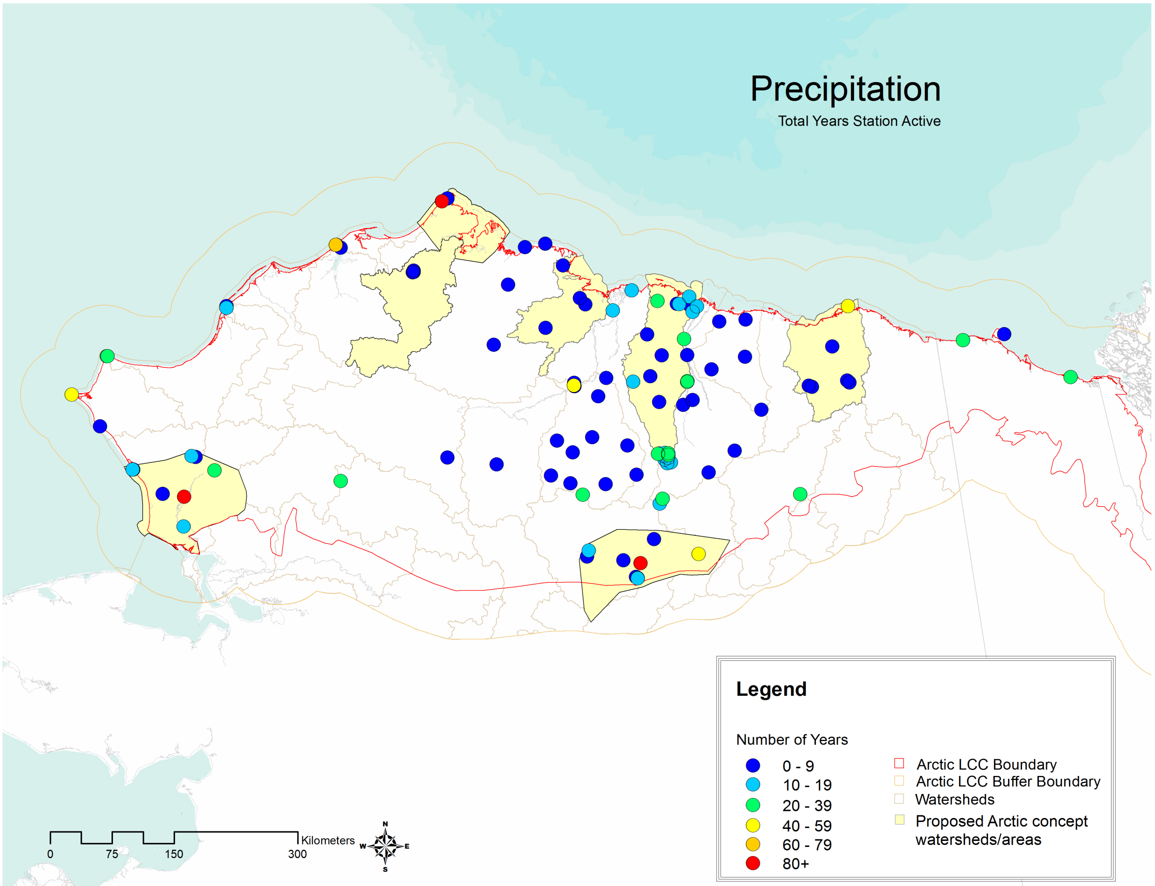

Figure A2: total number of years a station was reporting at least summer precipitation. The bin '0-9' refers to stations with more than zero and less than ten years of reporting and so on.

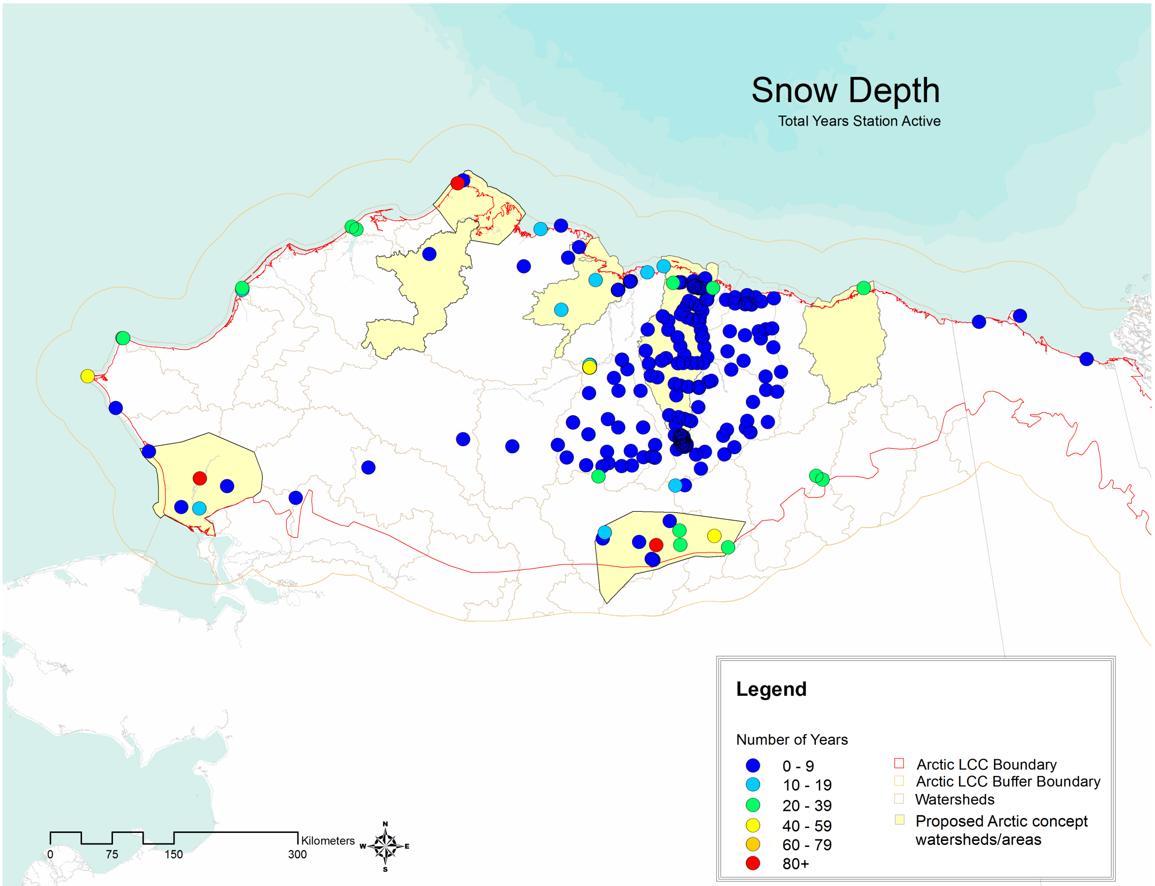

Figure A3: total number of years a station had snow depth measurements. The bin '0-9' refers to stations with more than zero and less than ten years of reporting and so on.

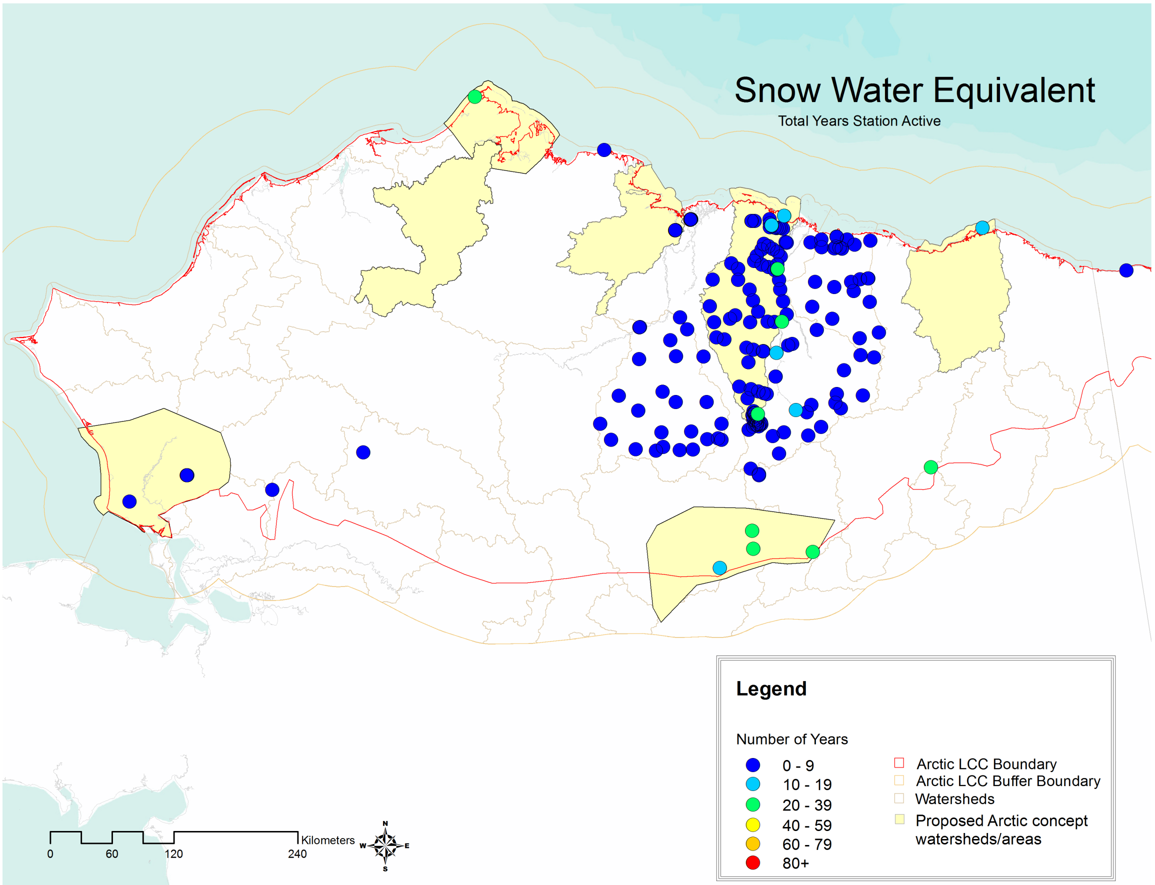

Figure A4: total number of years a station had snow water equivalent measurements. The bin '0-9' refers to stations with more than zero and less than ten years of reporting and so on.

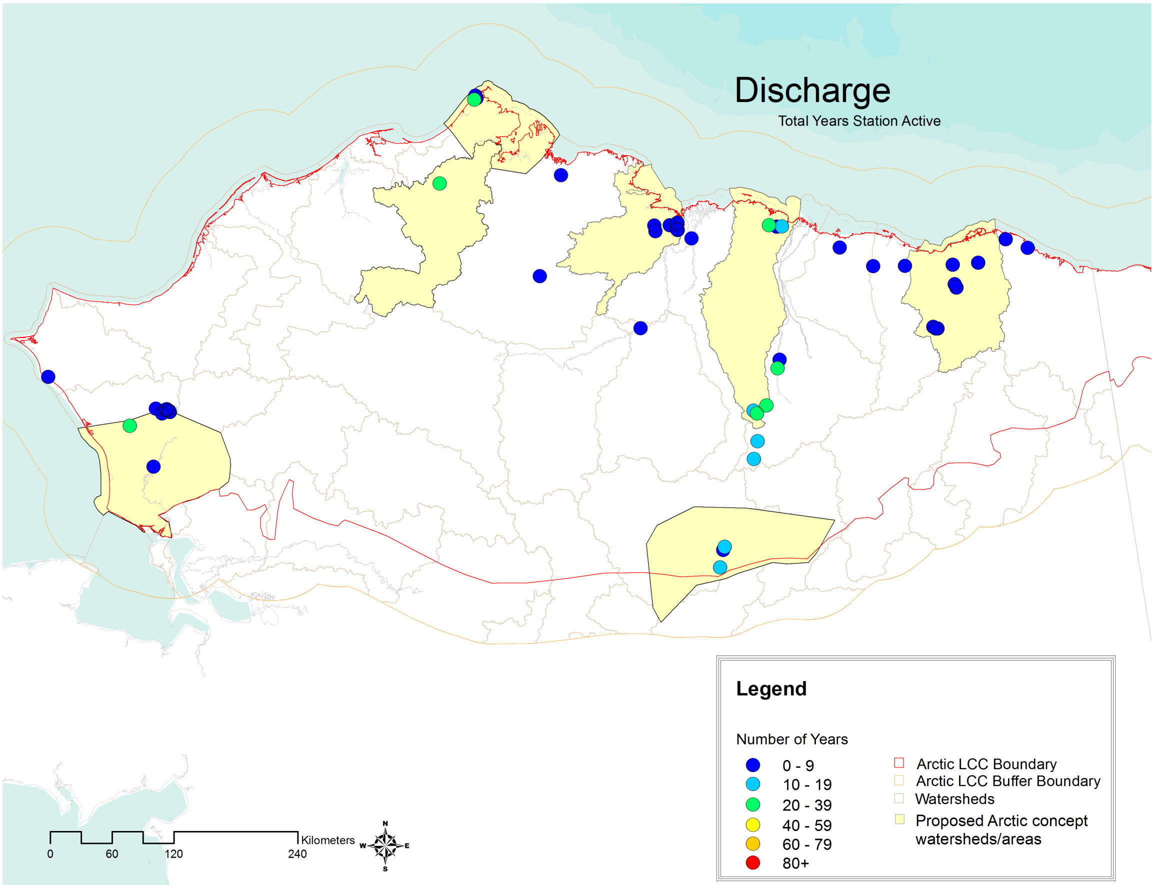

Figure A5: total number of years a station had river discharge measurements. The bin '0-9' refers to stations with more than zero and less than ten years of reporting and so on.

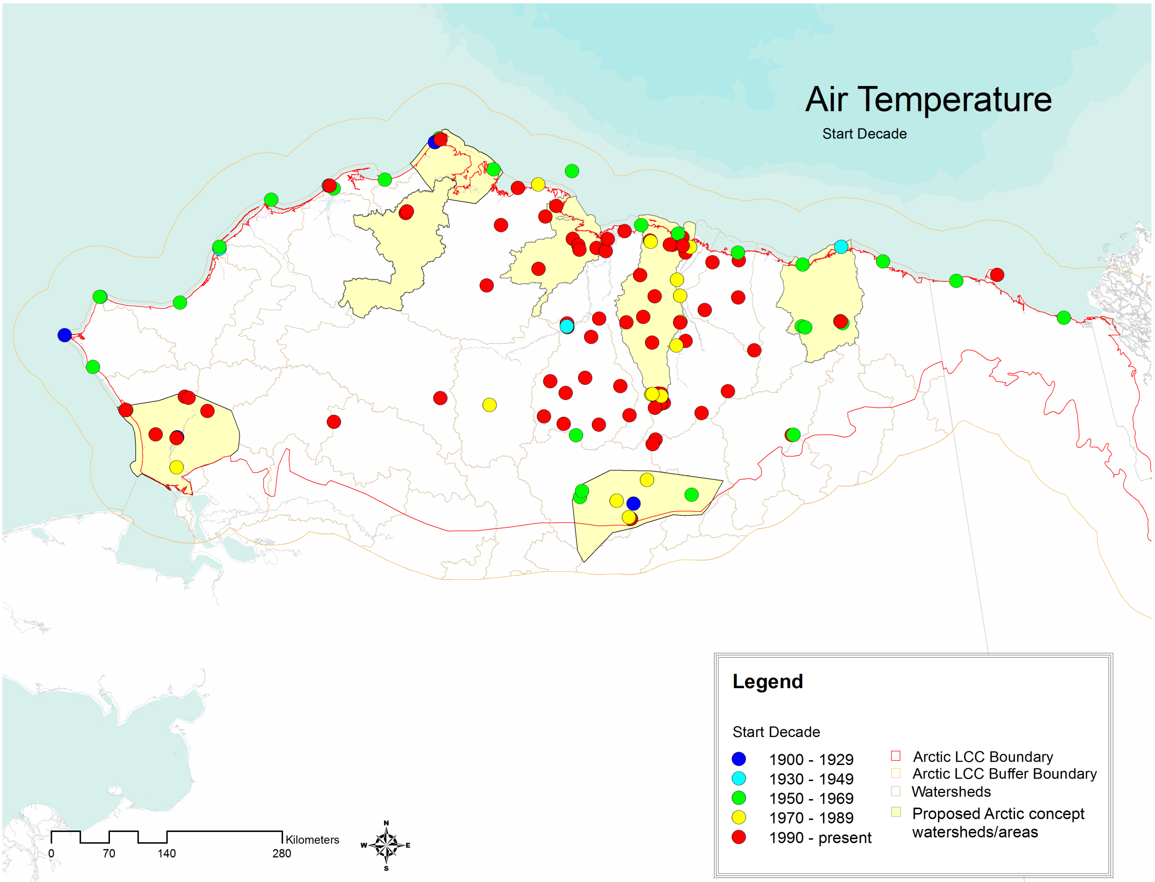

Figure A6: start era for air temperature measurements.

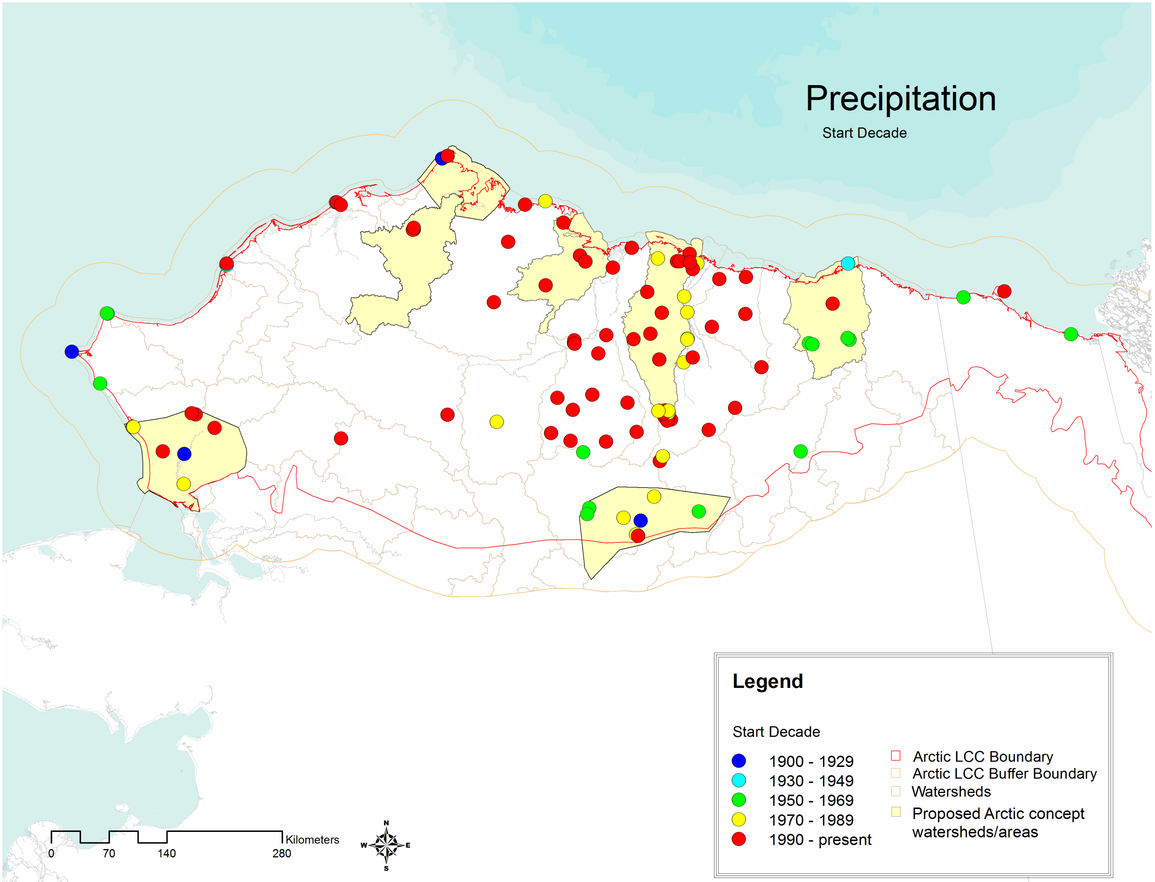

Figure A7: start era for precipitation measurements (many are summer only).

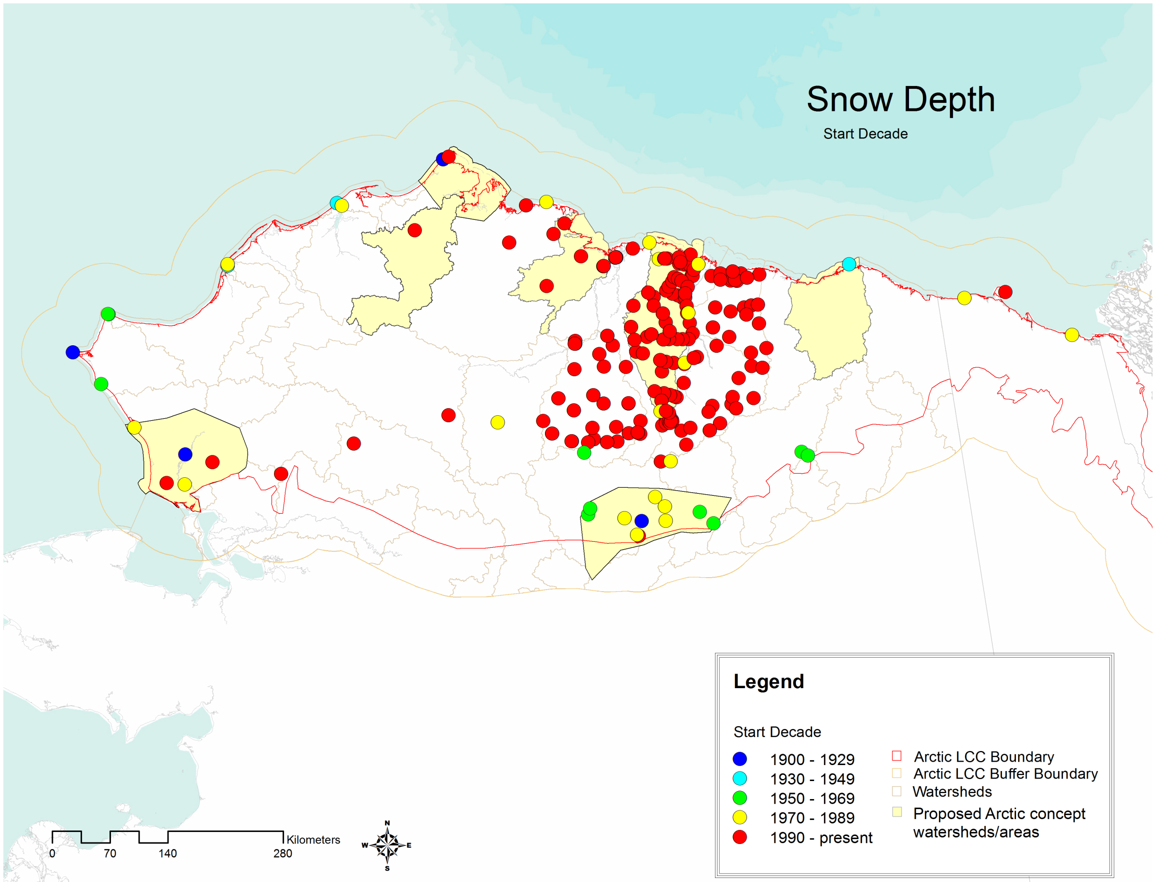

Figure A8: start era for snow depth measurements.

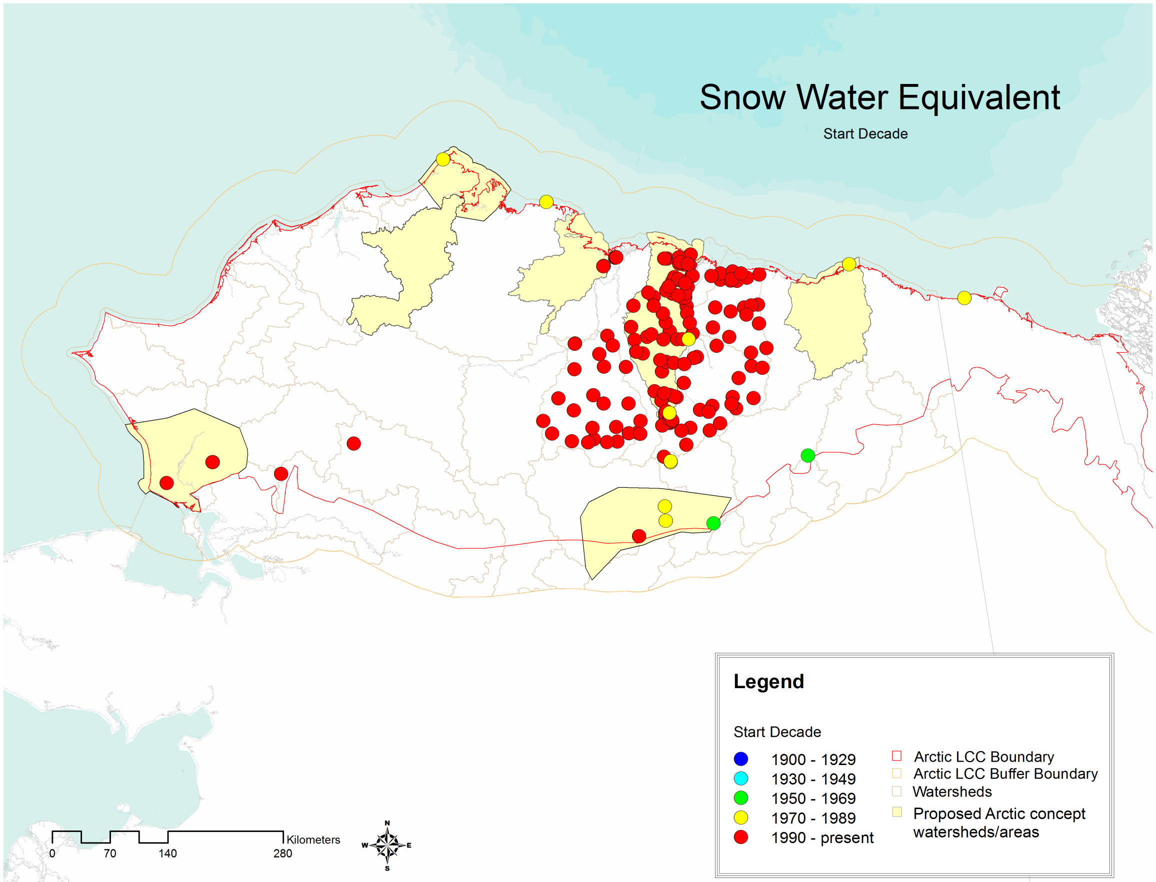

Figure A9: start era for snow water equivalent measurements.

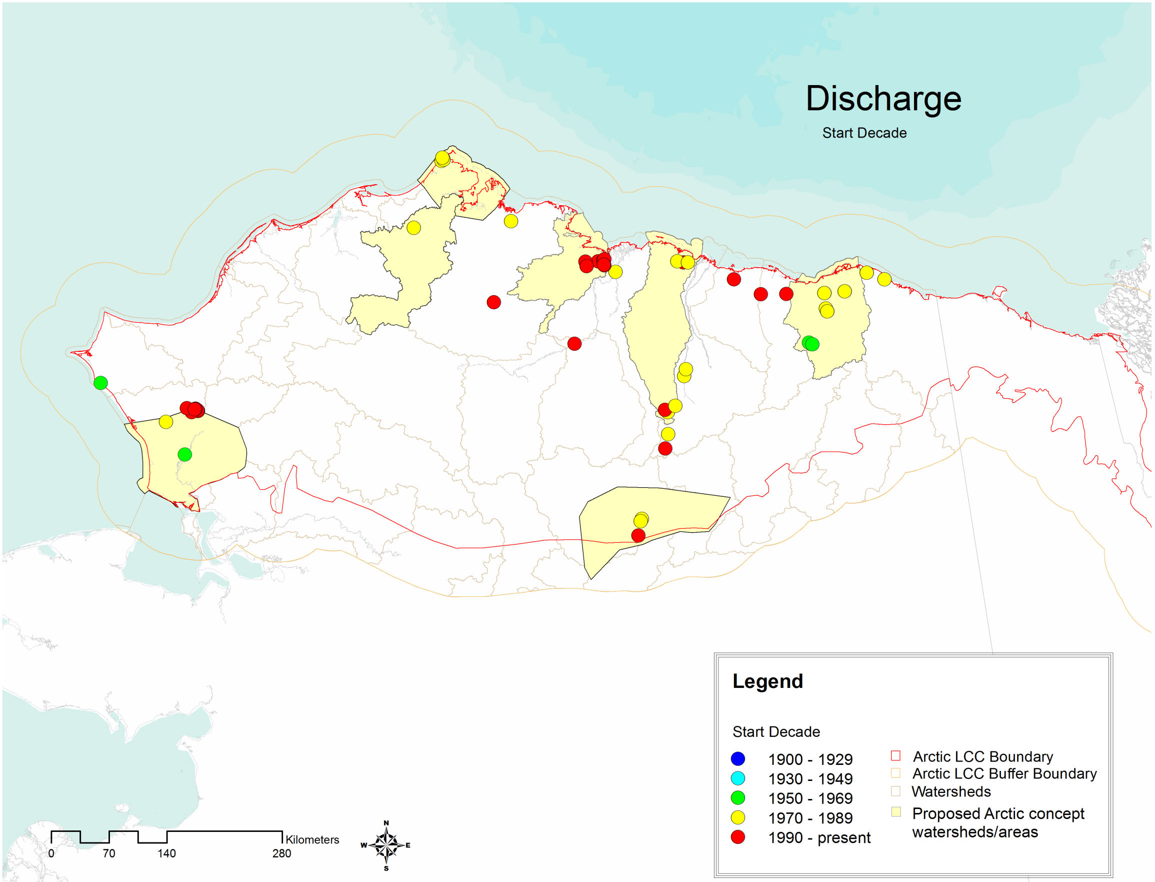

Figure A10: start era for river discharge measurements.

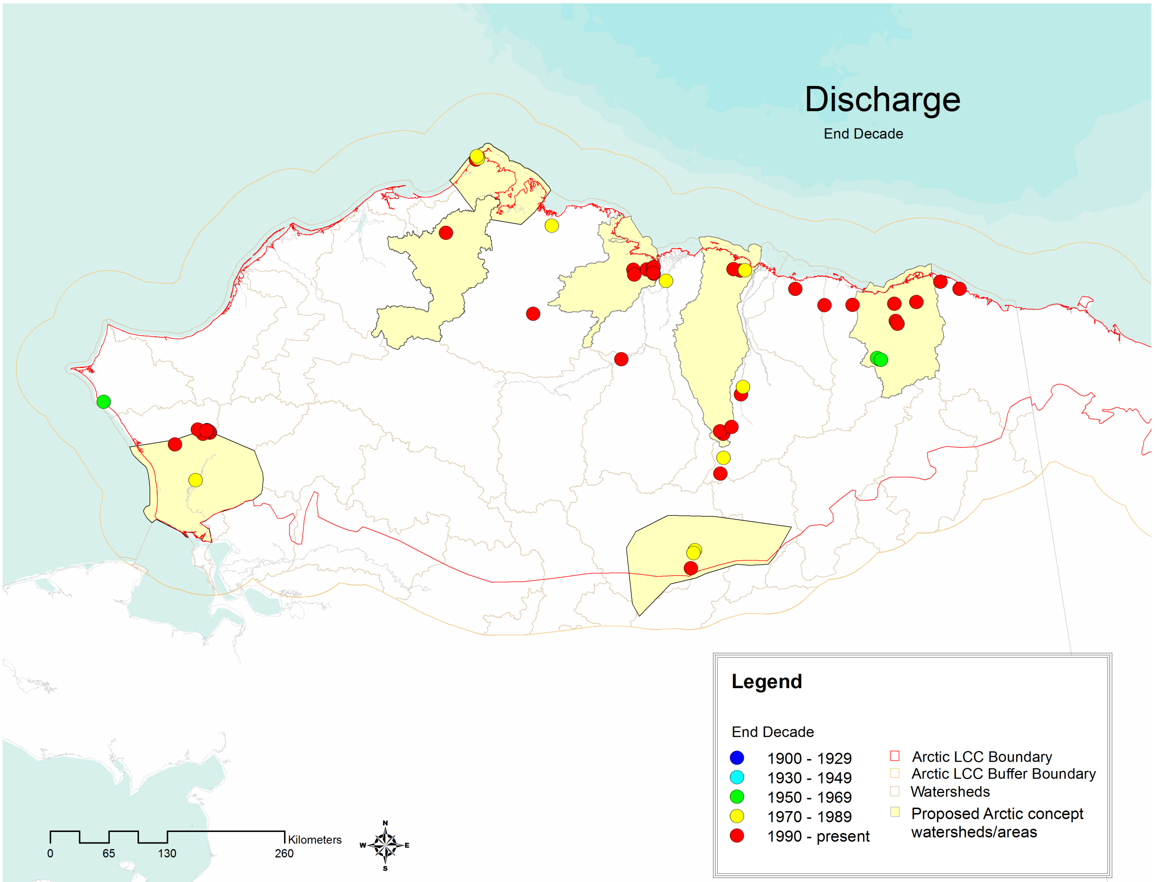

Figure A11: ending era for river discharge measurements.

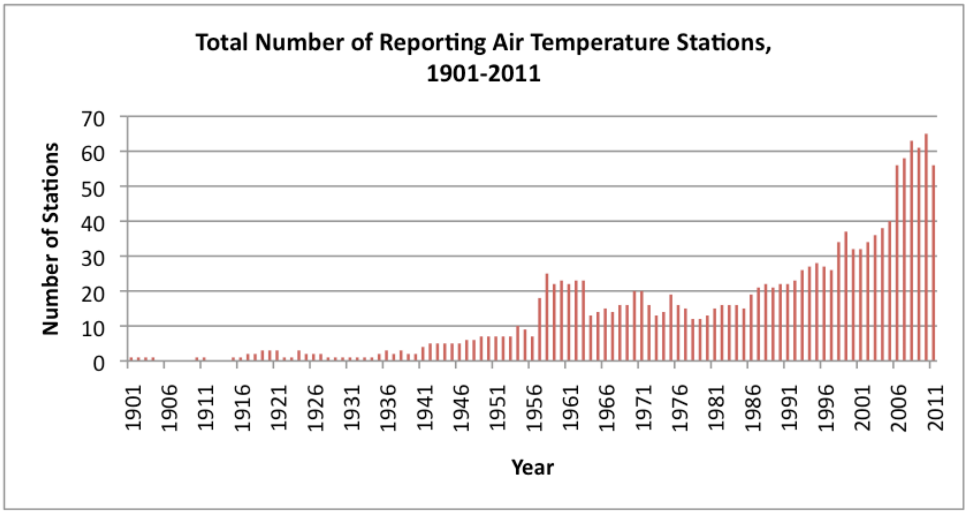

Figure A12: time series of station density for air temperature.

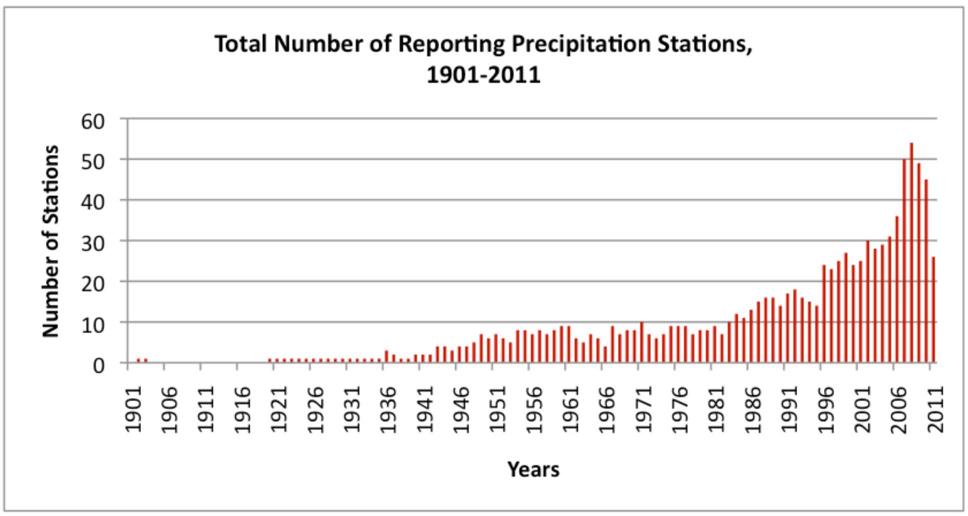

Figure A13: time series of station density for summer (June-August) precipitation.

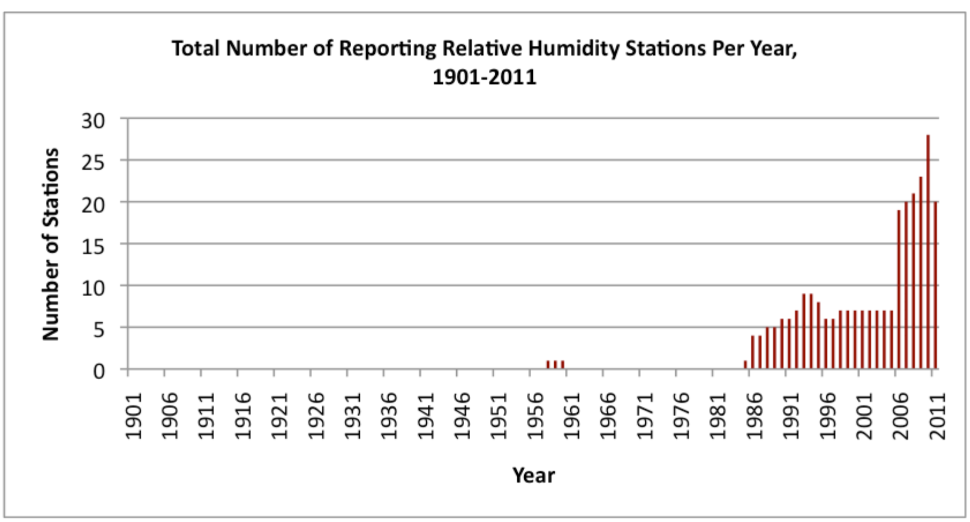

Figure A14: time series of station density for relative humidity.

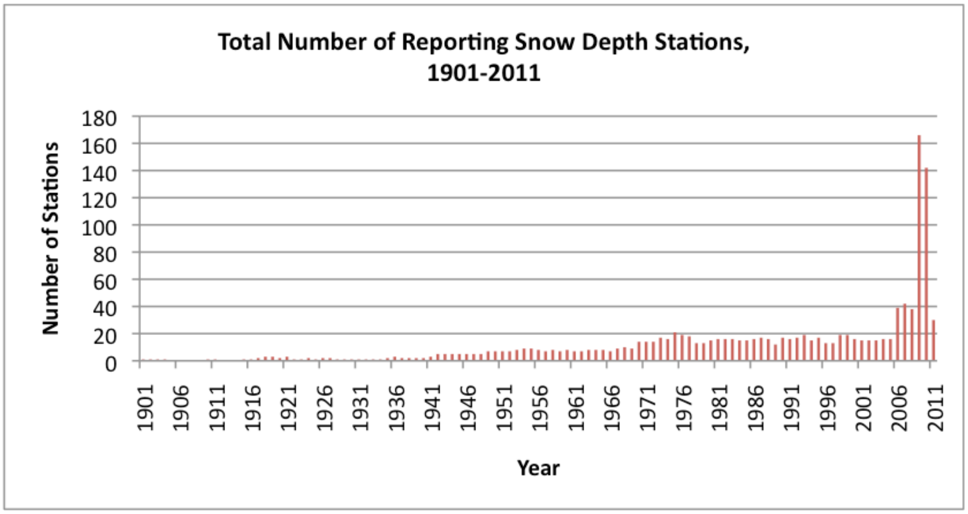

Figure A15: time series of station density for snow depth.

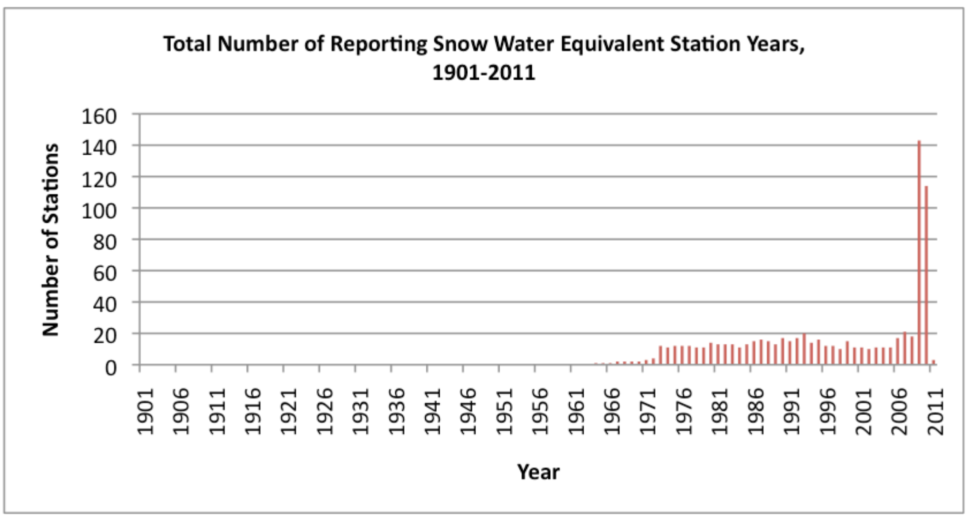

Figure A16: time series of station density for snow water equivalent.

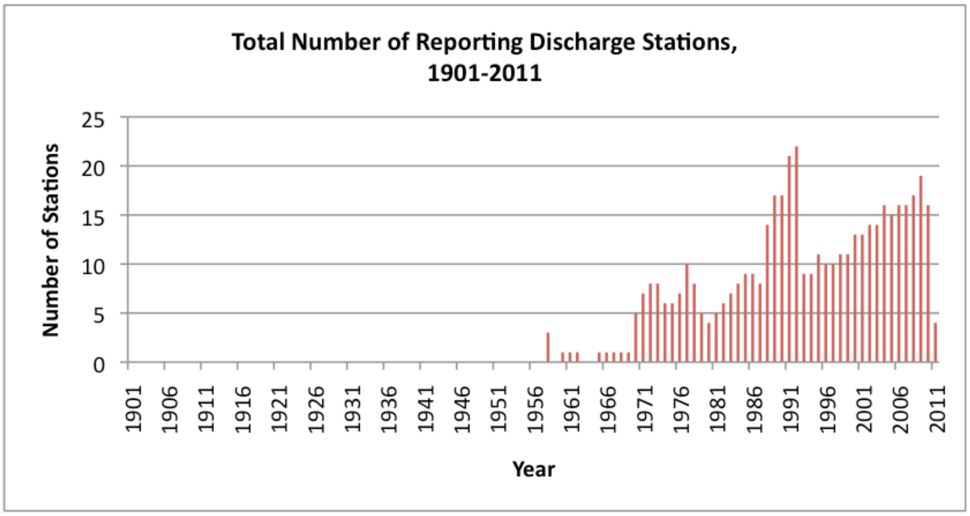

Figure A17: time series of station density for river discharge.

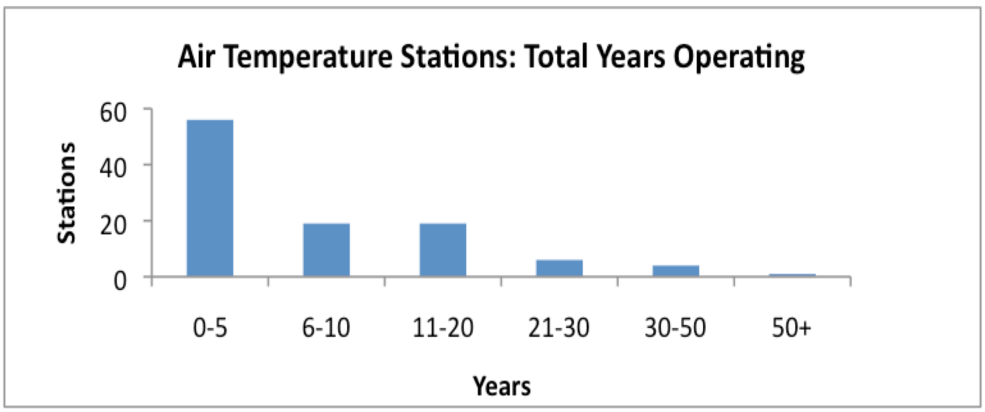

Figure A18: duration of individual stations in selected bins for the air temperature parameter.

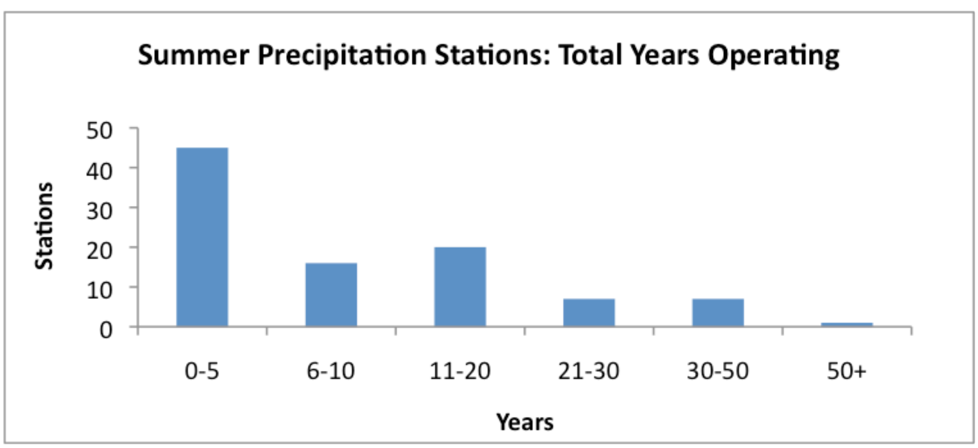

Figure A19: duration of individual stations in selected bins for the summer (June-August) precipitation parameter.

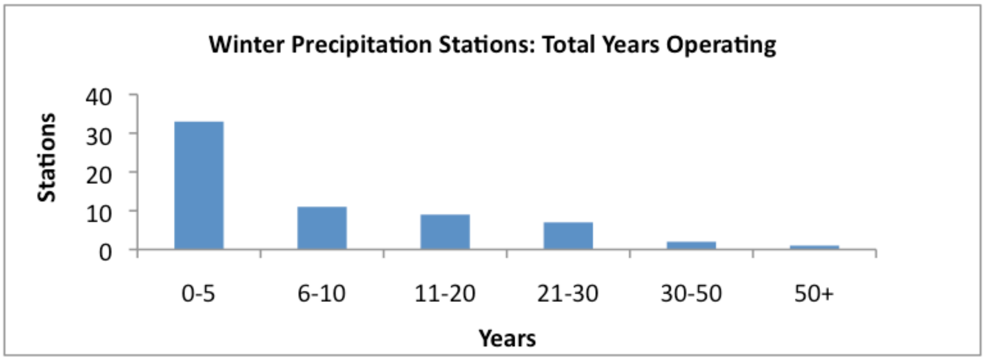

Figure A20: duration of individual stations in selected bins for the winter (December-February) precipitation parameter.

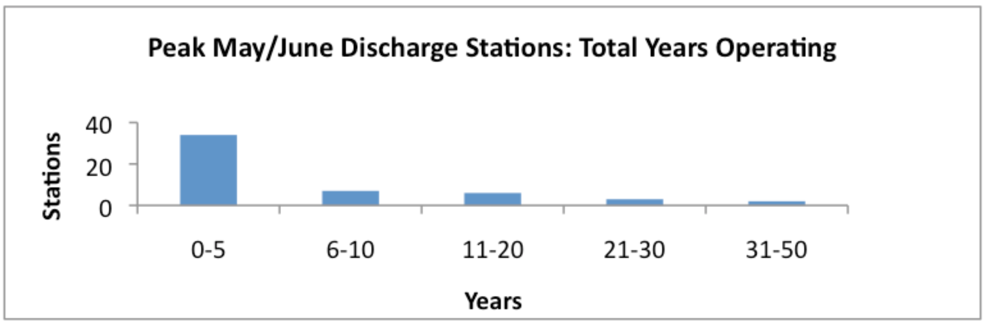

Figure A21: duration of individual stations in selected bins for the peak discharge parameter.

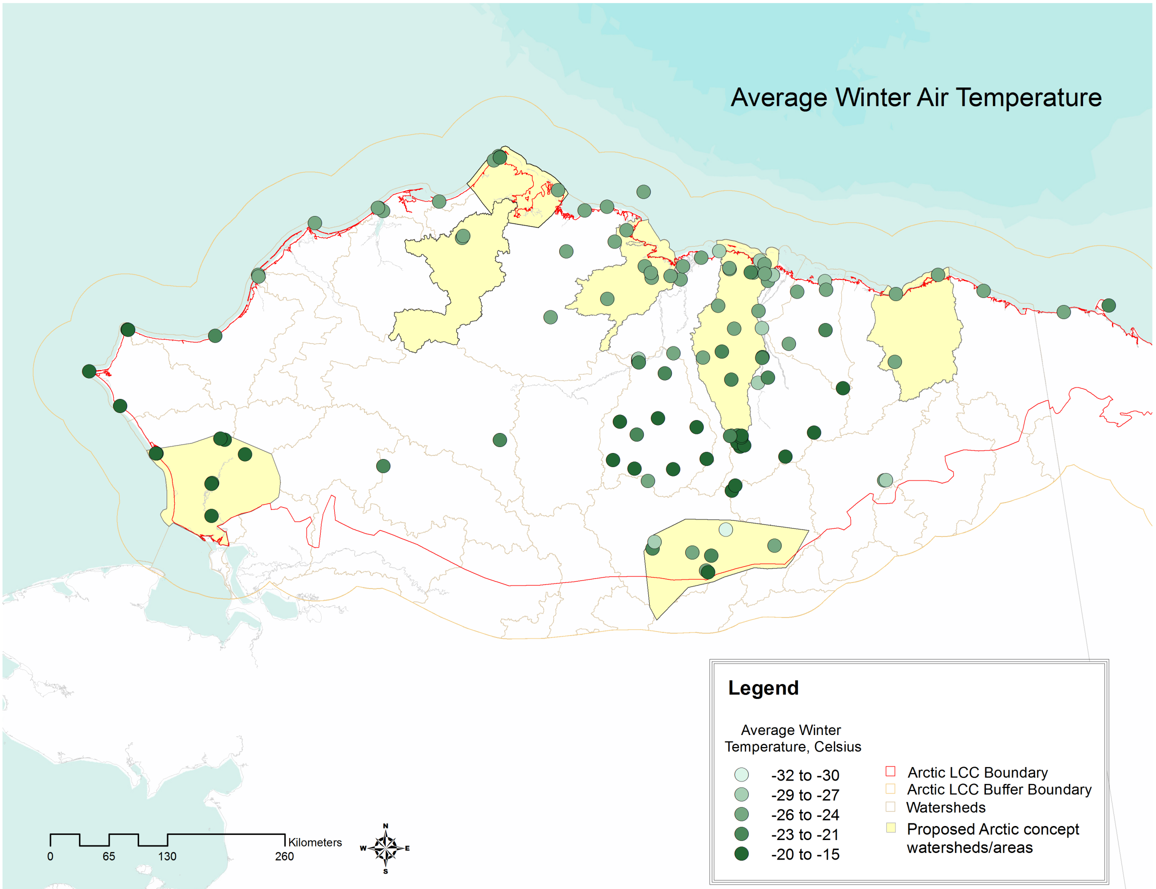

Figure A22: Average winter (December-February) air temperature observed by Arctic Networks over their period of record, which varies by site.

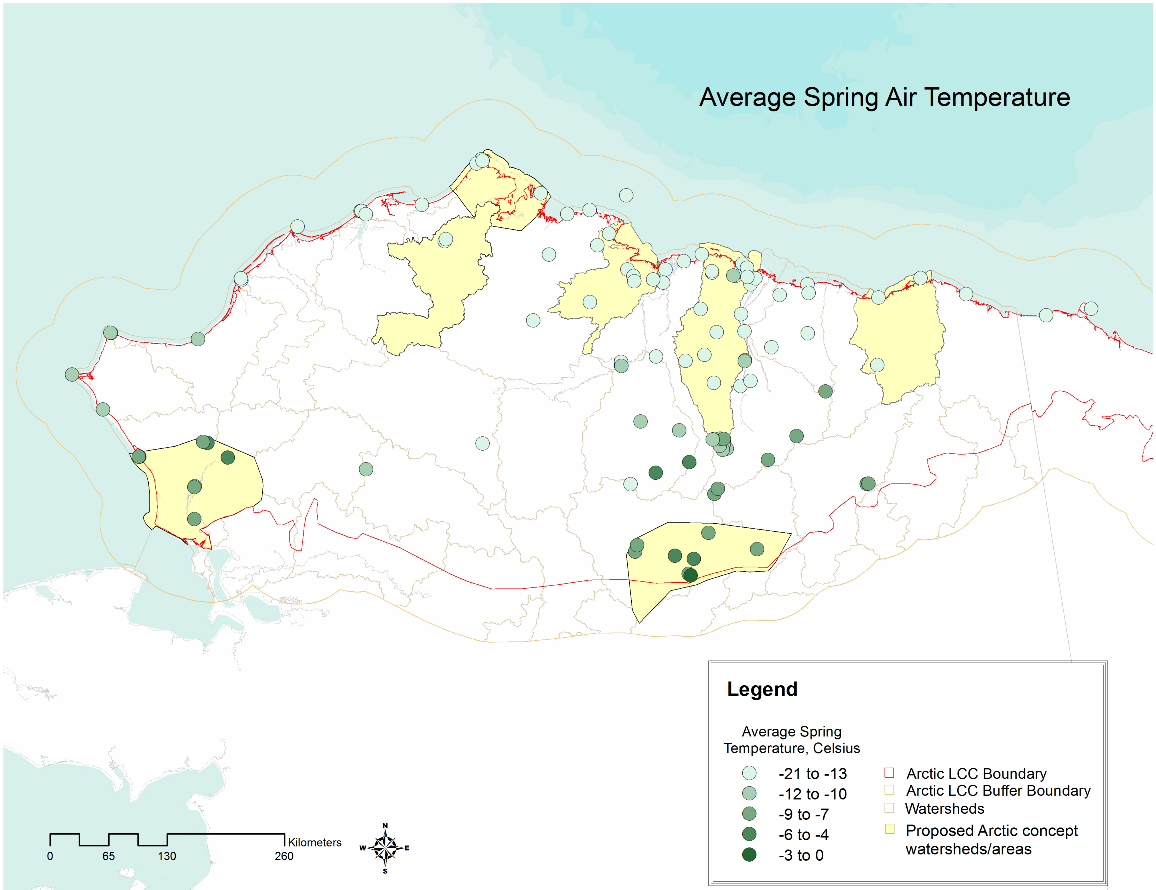

Figure A23: Average spring (March-May) air temperature observed by Arctic Networks over their period of record, which varies by site.

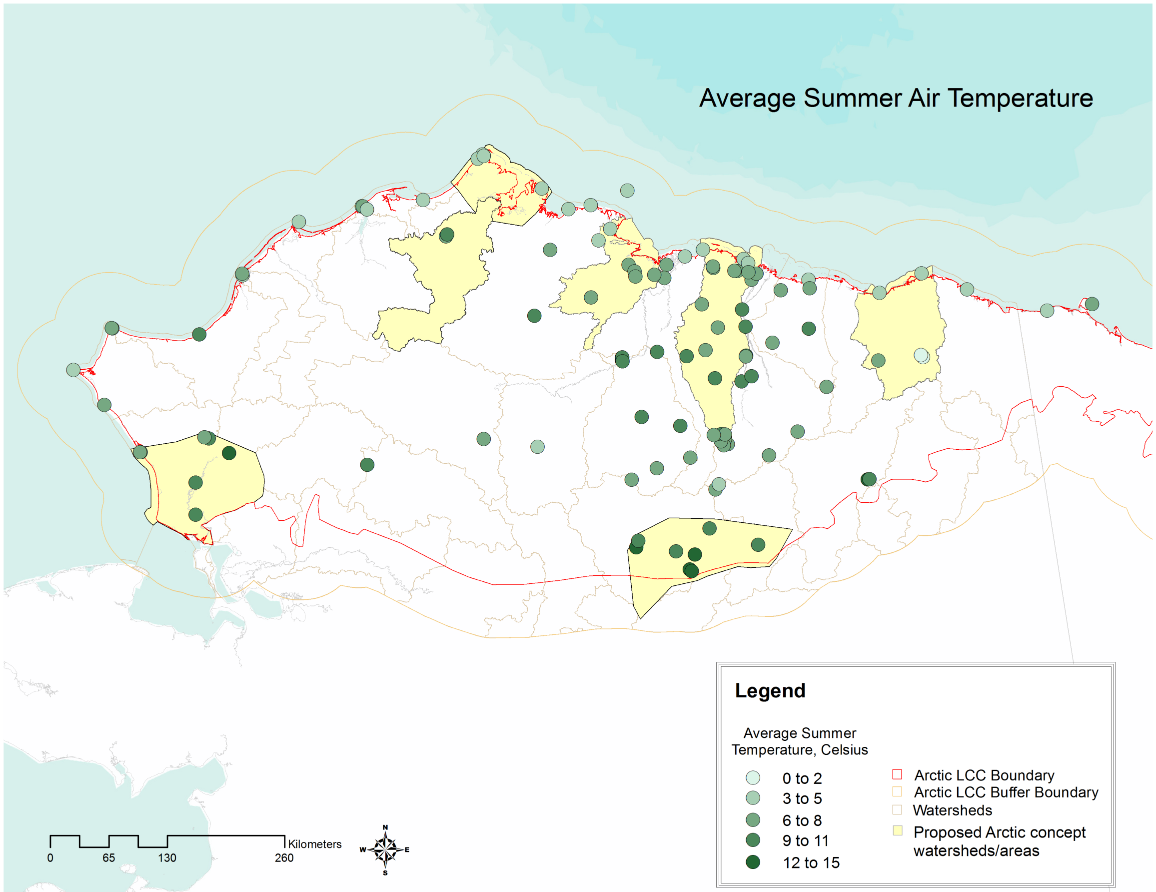

Figure A24: Average summer (June-August) air temperature observed by Arctic Networks over their period of record, which varies by site.

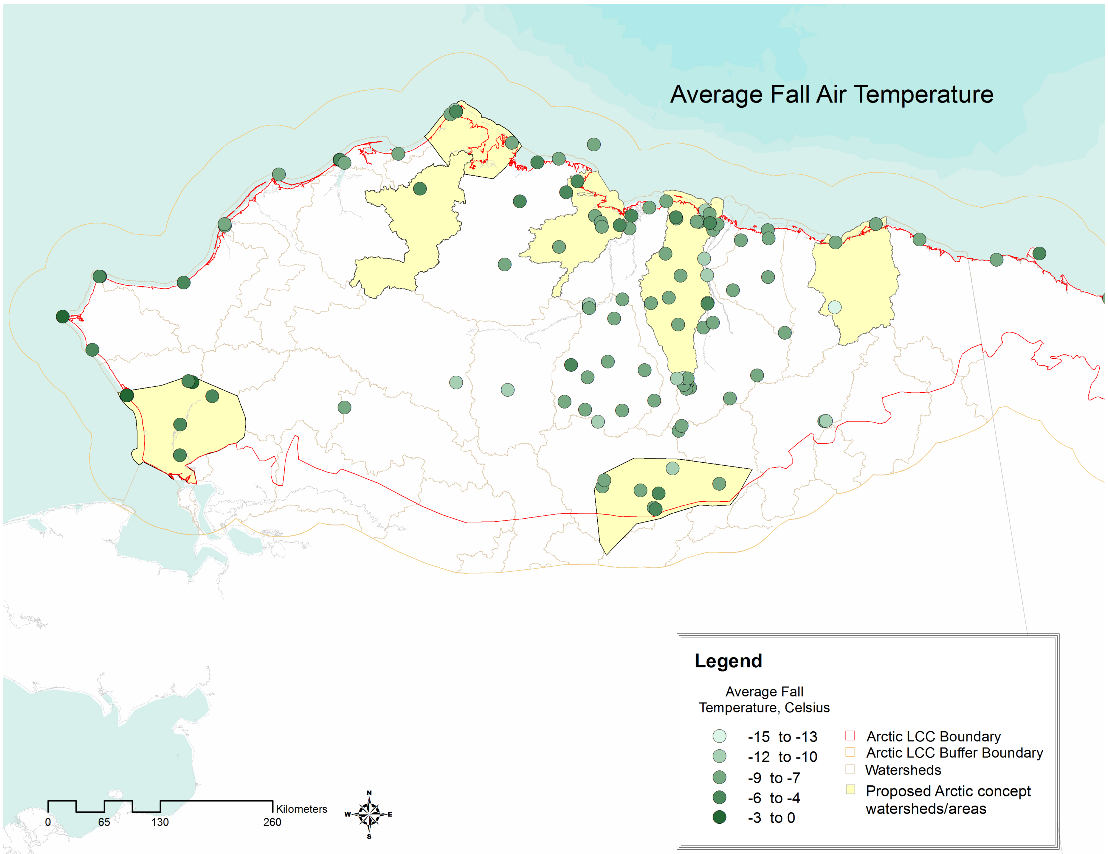

Figure A25: Average fall (September-November) air temperature observed by Arctic Networks over their period of record, which varies by site.

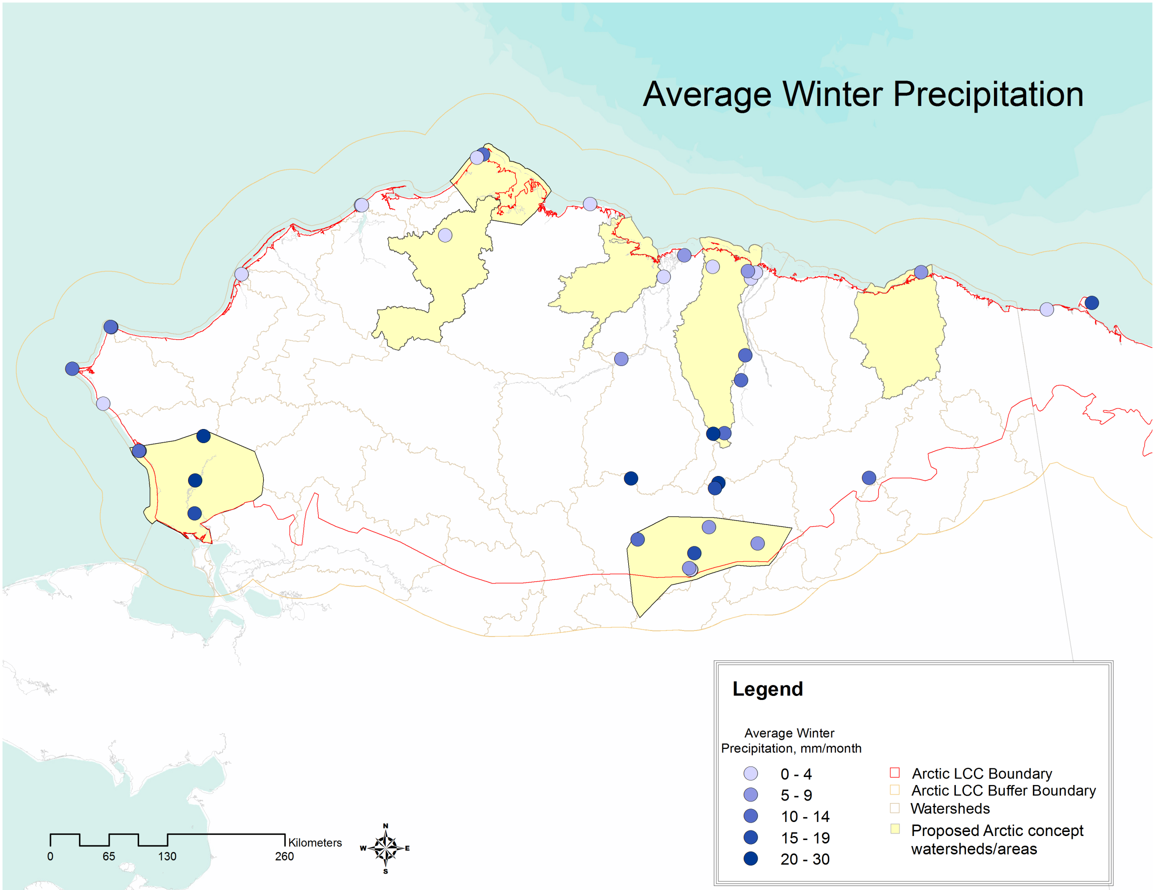

Figure A26: Average winter (December-February) precipitation observed by Arctic Networks over their period of record, which varies by site.

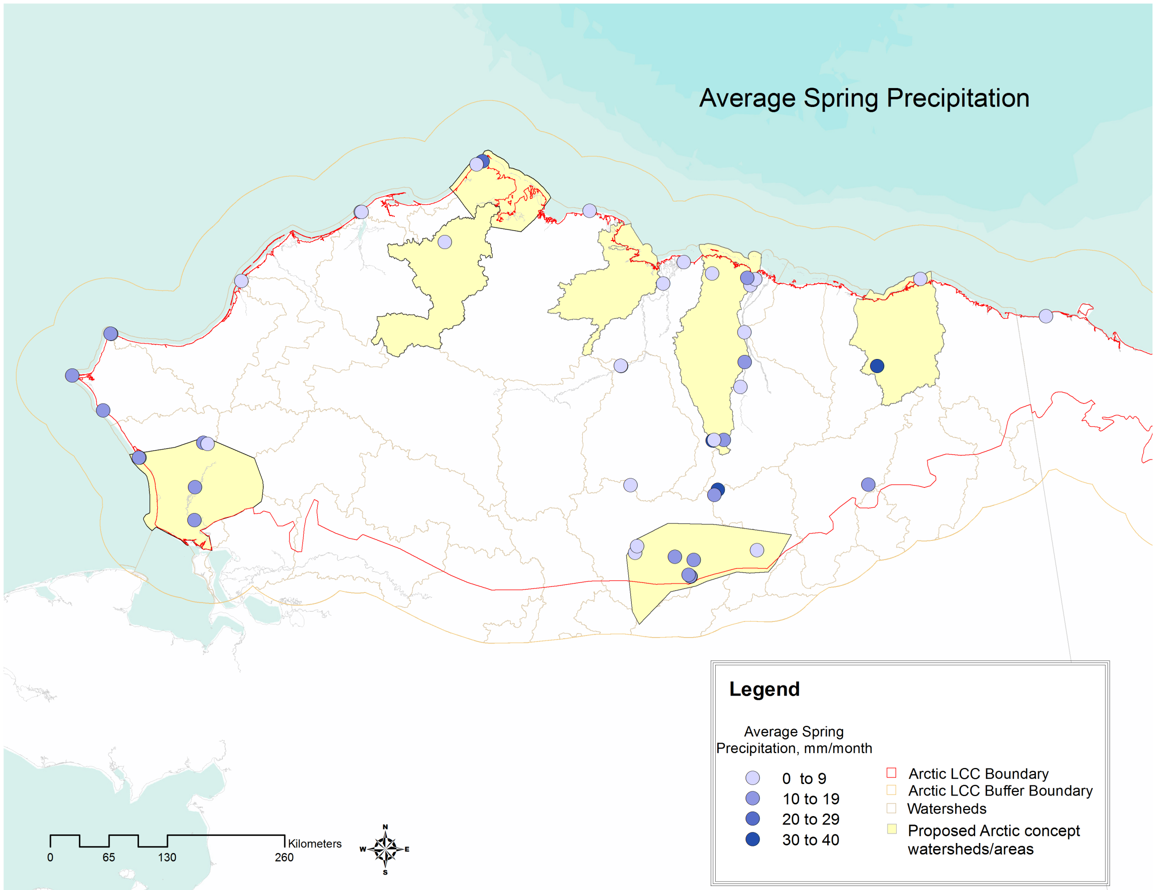

Figure A27: Average spring (March-May) precipitation observed by Arctic Networks over their period of record, which varies by site.

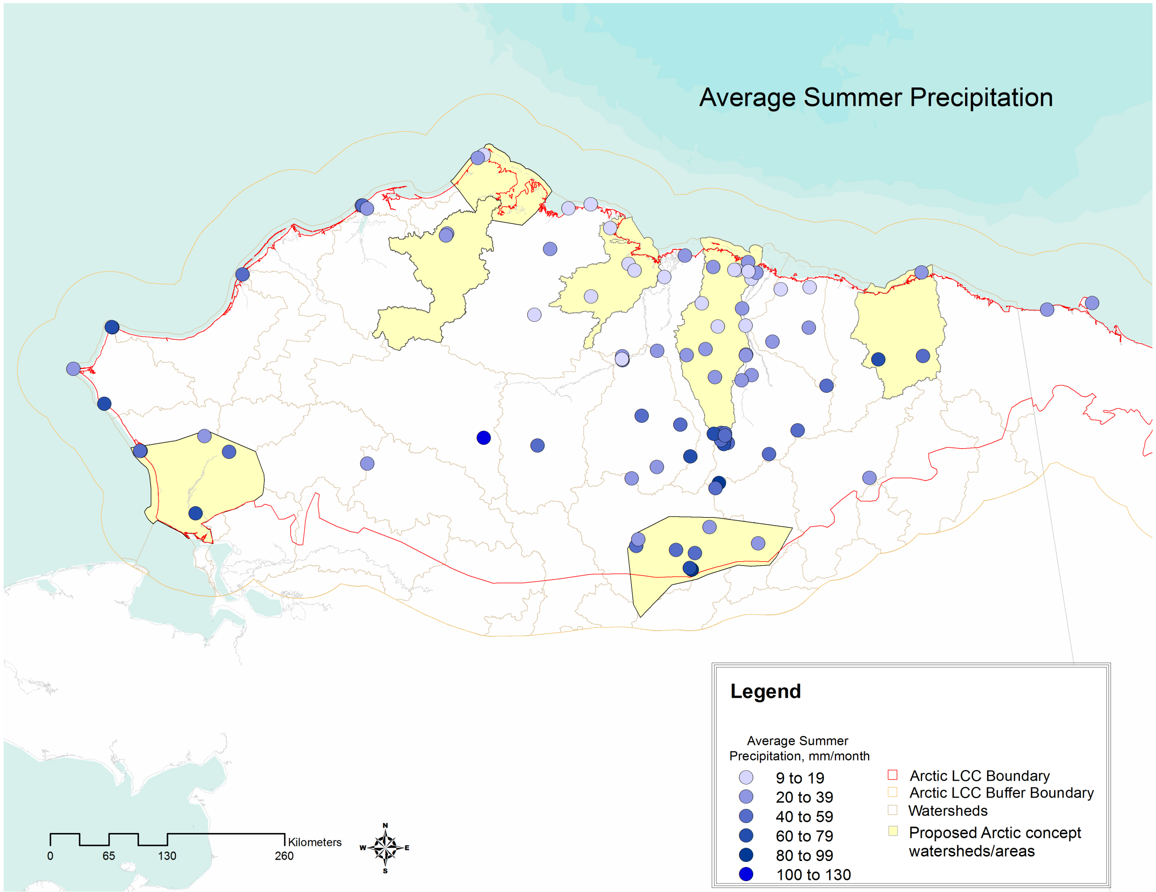

Figure A28: Average summer (June-August) precipitation observed by Arctic Networks over their period of record, which varies by site.

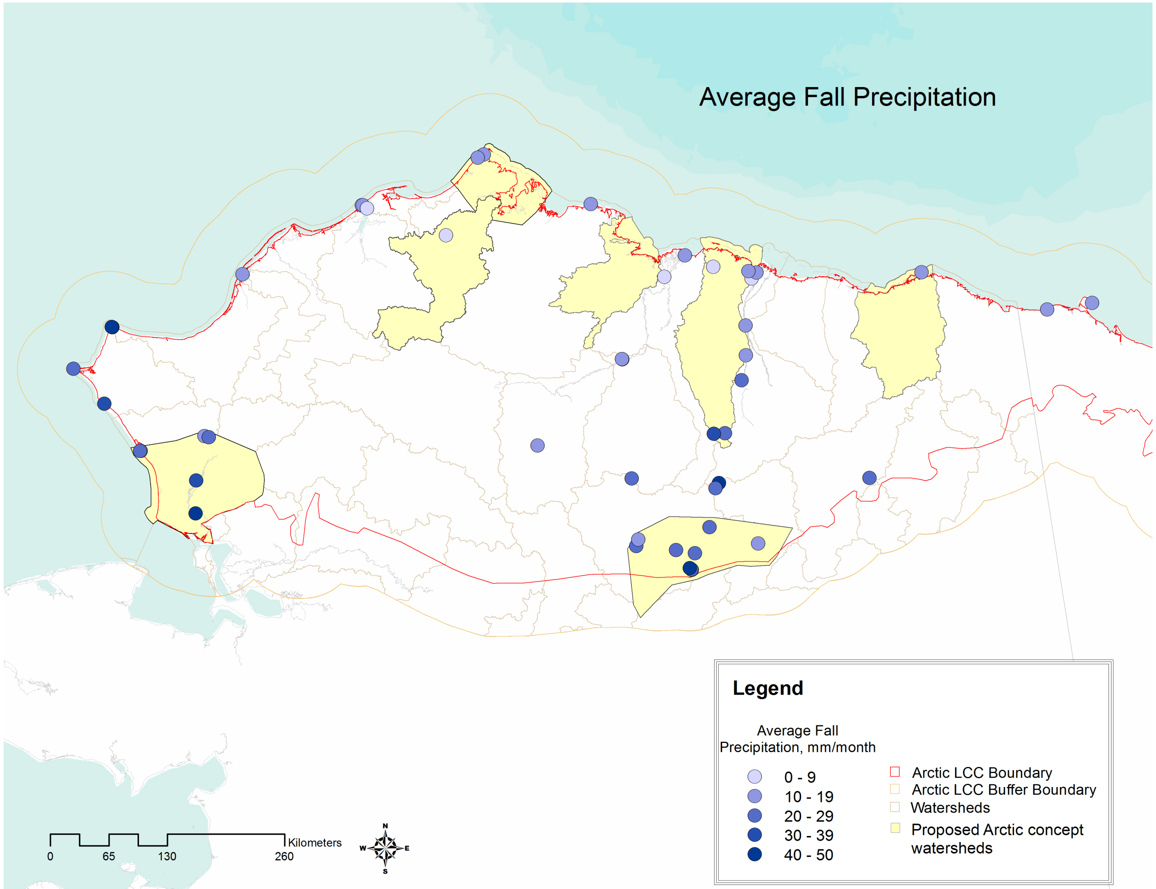

Figure A29: Average fall (September-November) precipitation observed by Arctic Networks over their period of record, which varies by site.

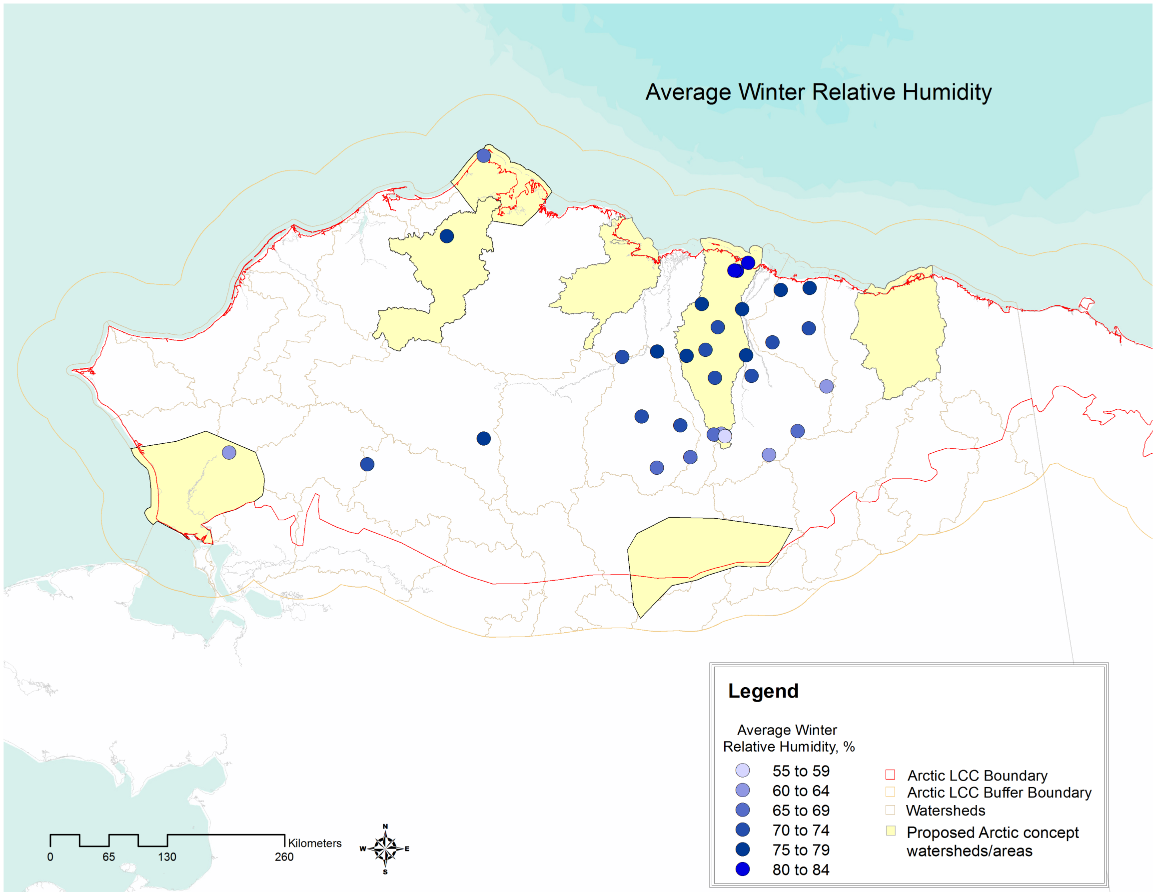

Figure A30: Average winter (December-February) relative humidity observed by Arctic Networks over their period of record, which varies by site.

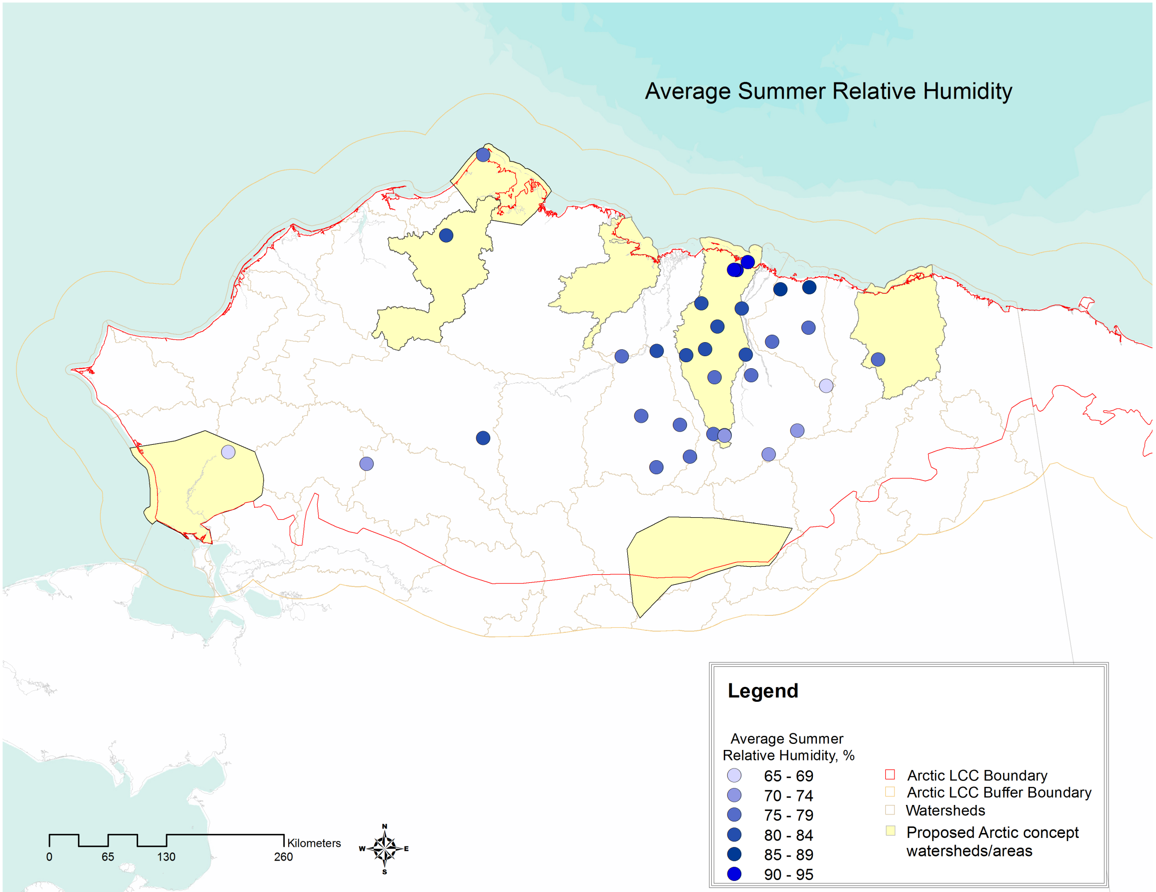

Figure A31: Average summer (June-August) relative humidity observed by Arctic Networks over their period of record, which varies by site.

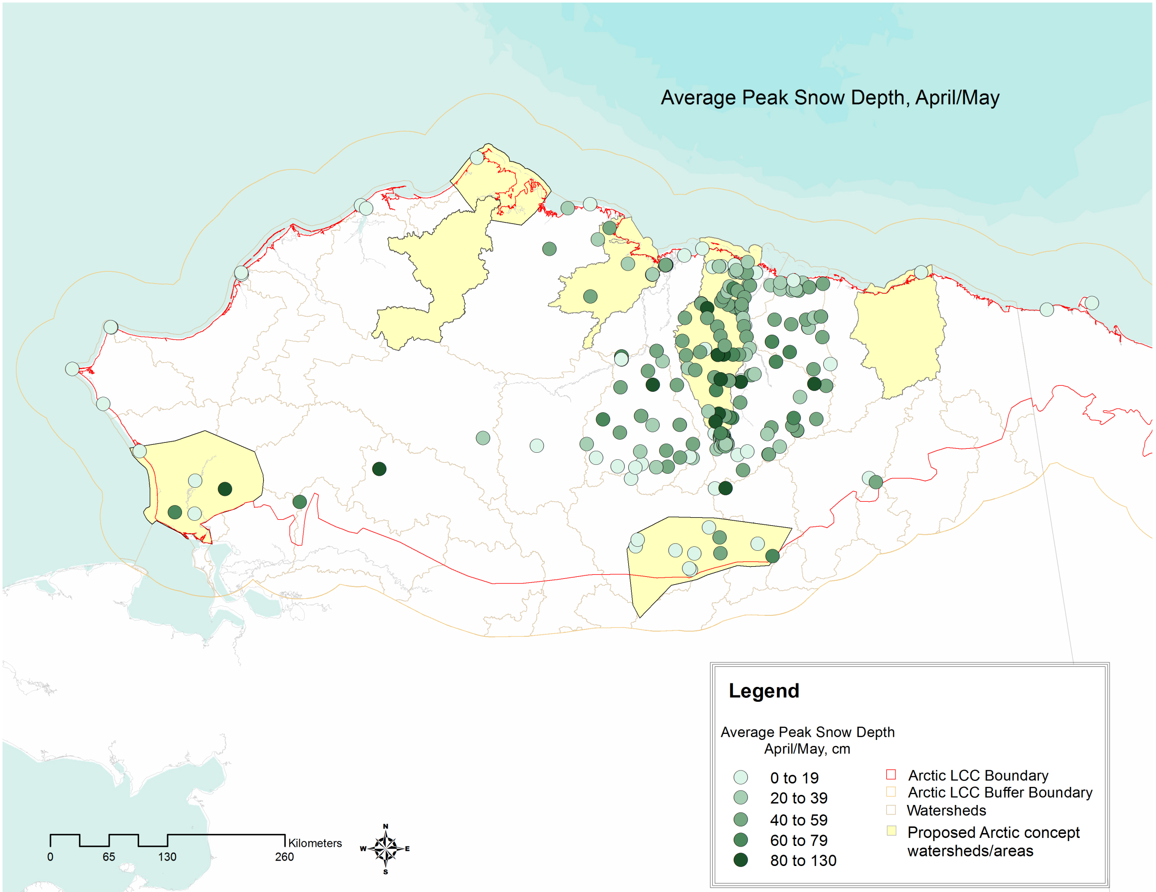

Figure A32: Average peak snow depth in spring (March-May) observed by Arctic Networks over their period of record, which varies by site.

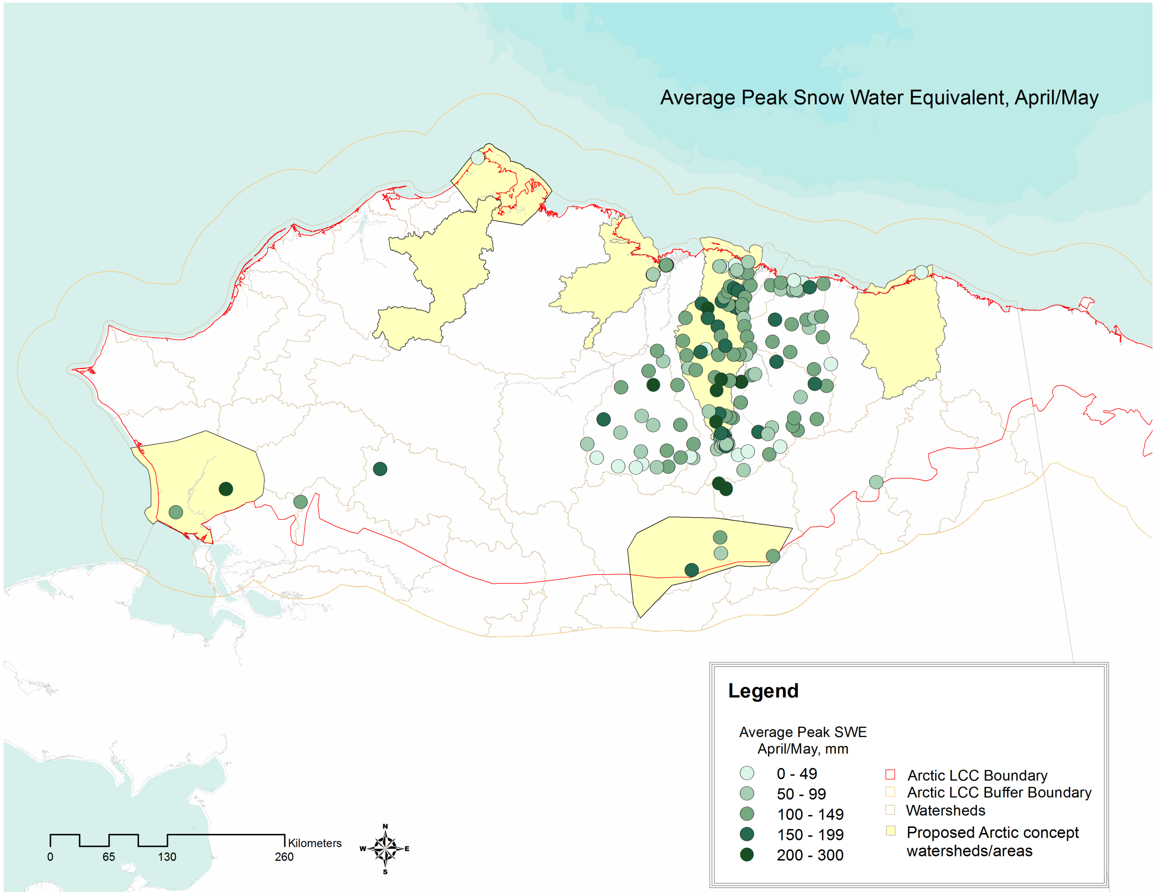

Figure A33: Average peak snow water equivalent in spring (March-May) observed by Arctic Networks over their period of record, which varies by site.

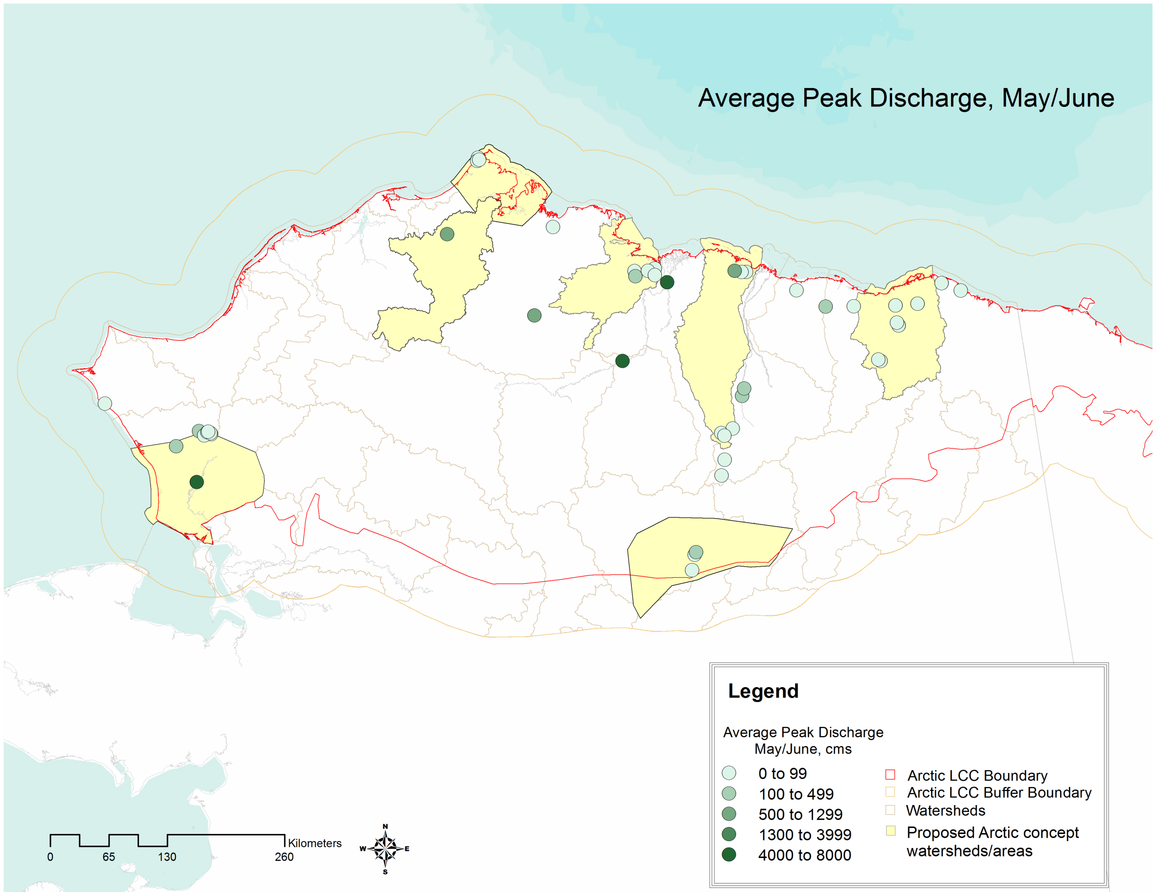

Figure A34: Average peak river discharge in May-June observed by Arctic Networks over their period of record, which varies by site.

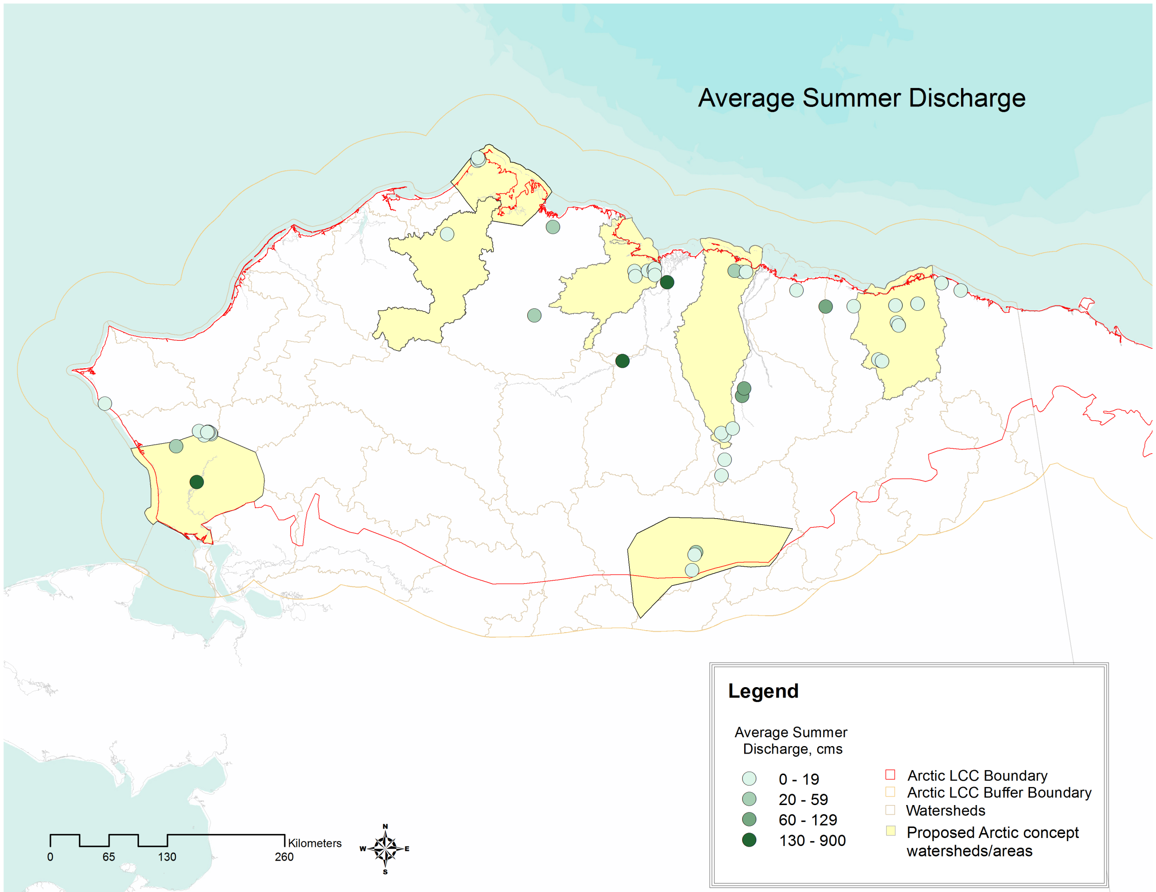

Figure A35: Average river discharge in summer (June-August) observed by Arctic Networks over their period of record, which varies by site.

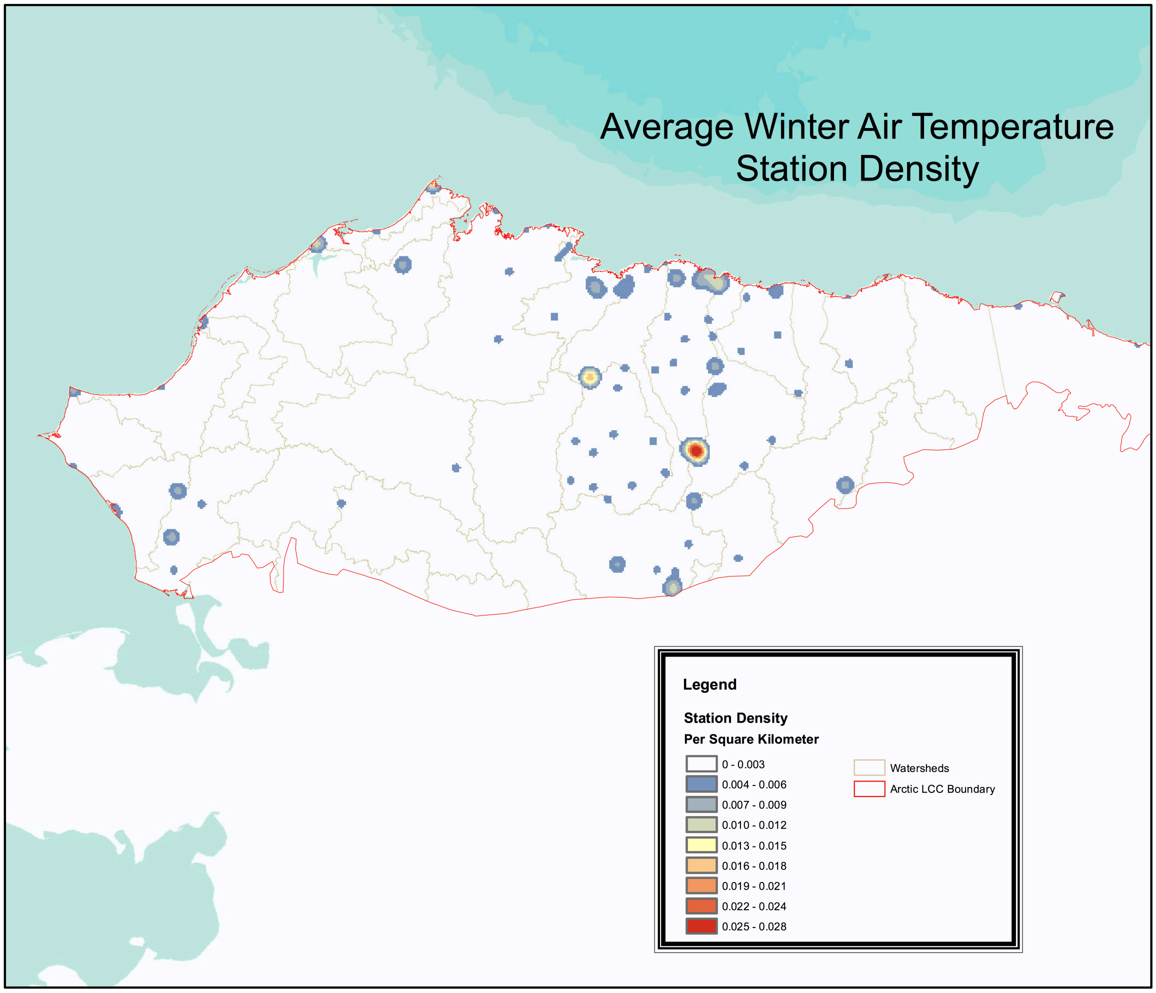

Figure A36: a quantitative analysis of winter (December-February) air temperature station density.

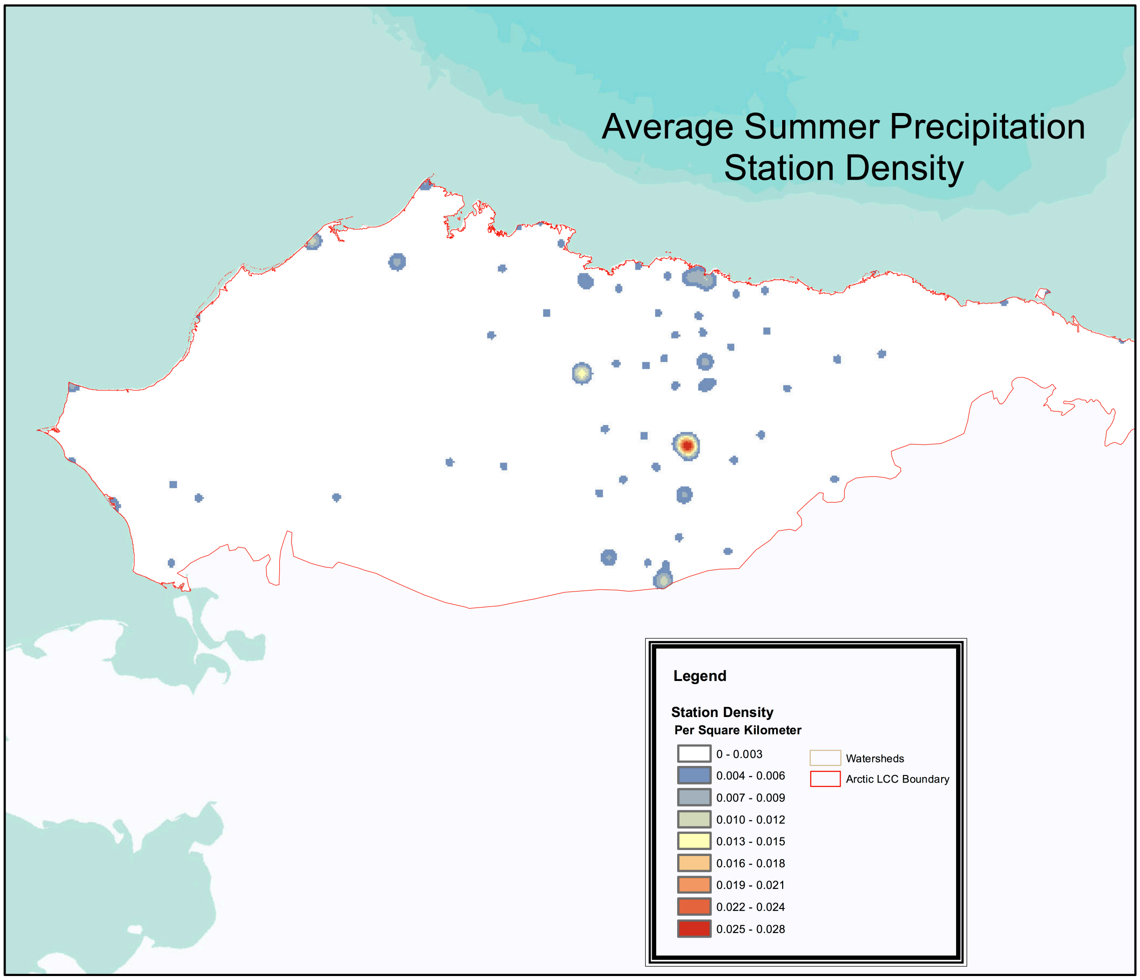

Figure A37: a quantitative analysis of summer (June-August) precipitation station density.

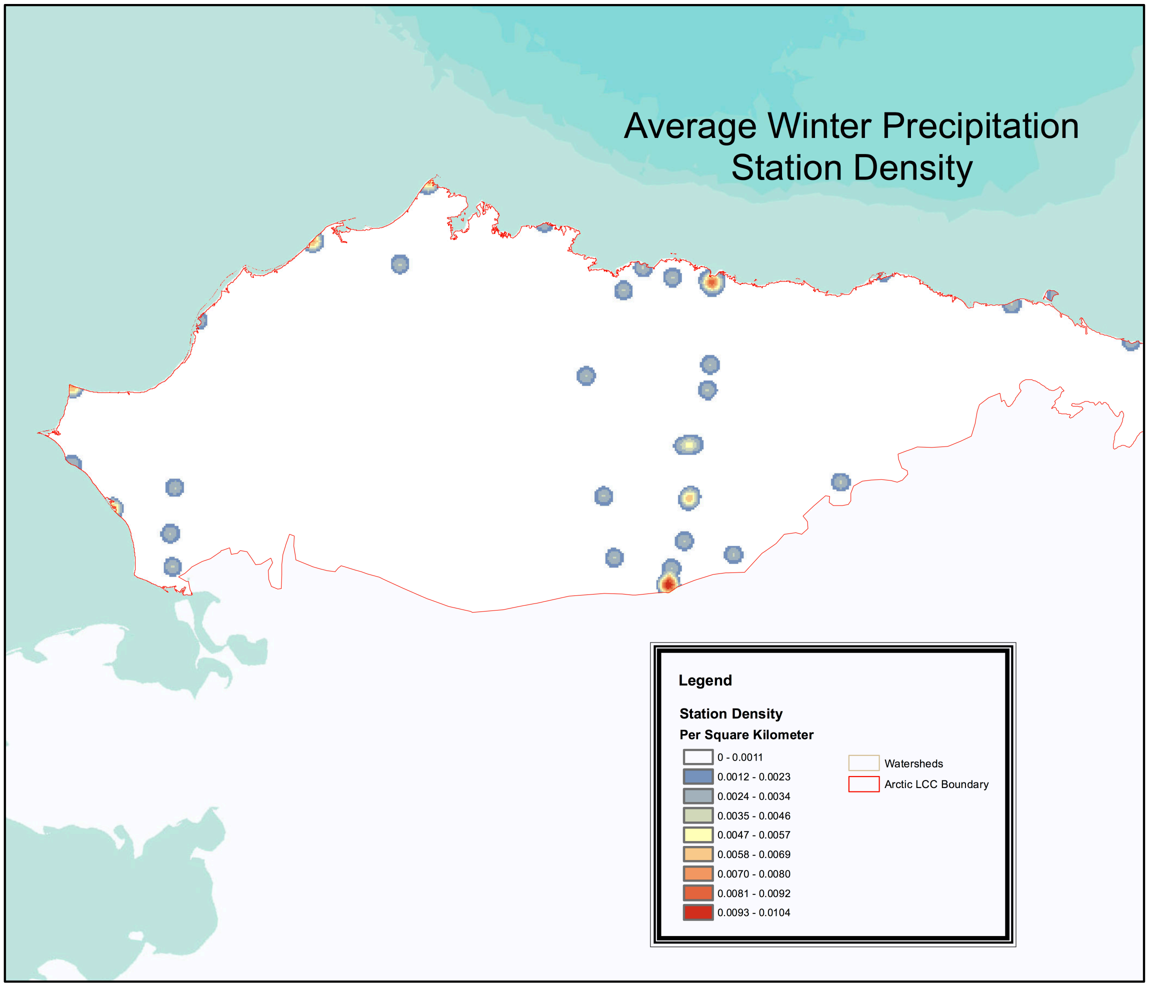

Figure A38: a quantitative analysis of winter (December-February) precipitation station density.

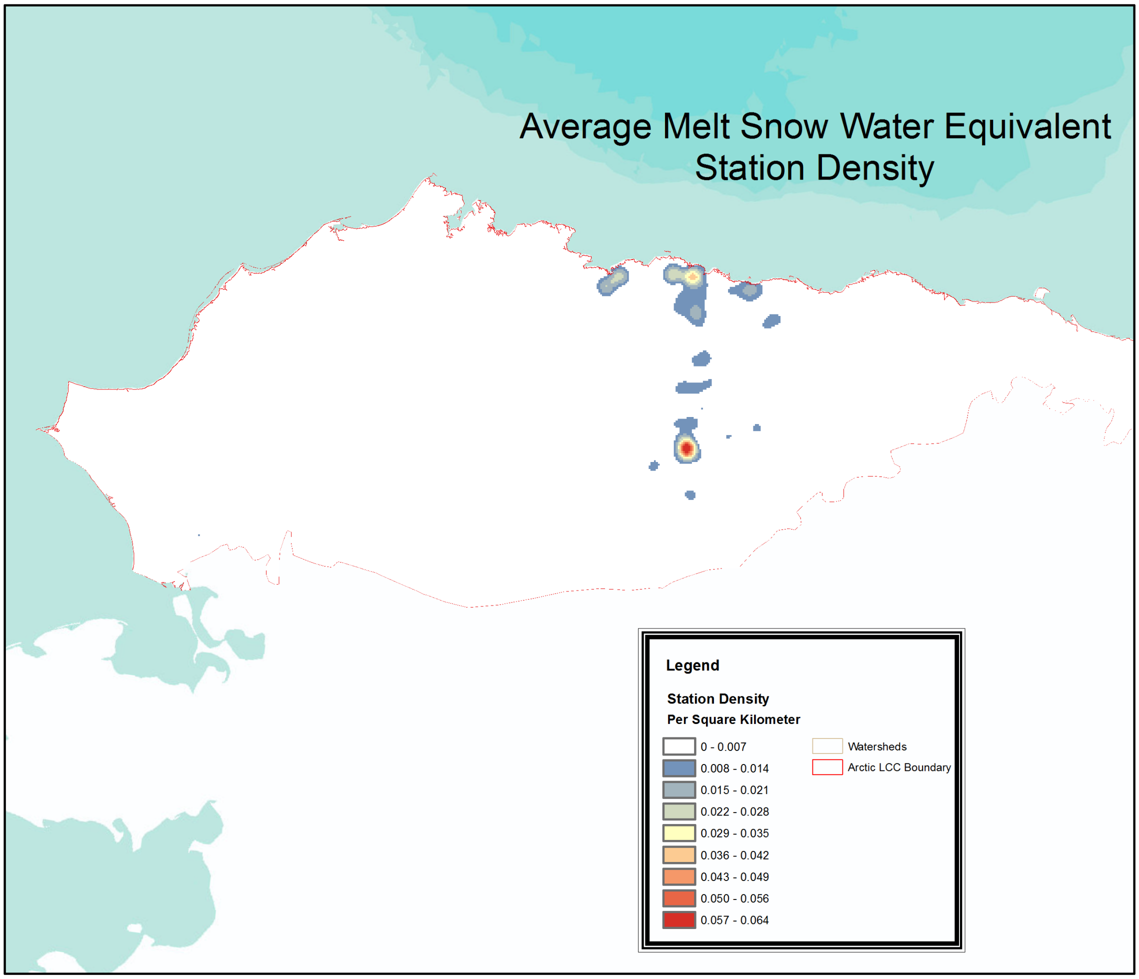

Figure A39: a quantitative analysis of SWE station density.

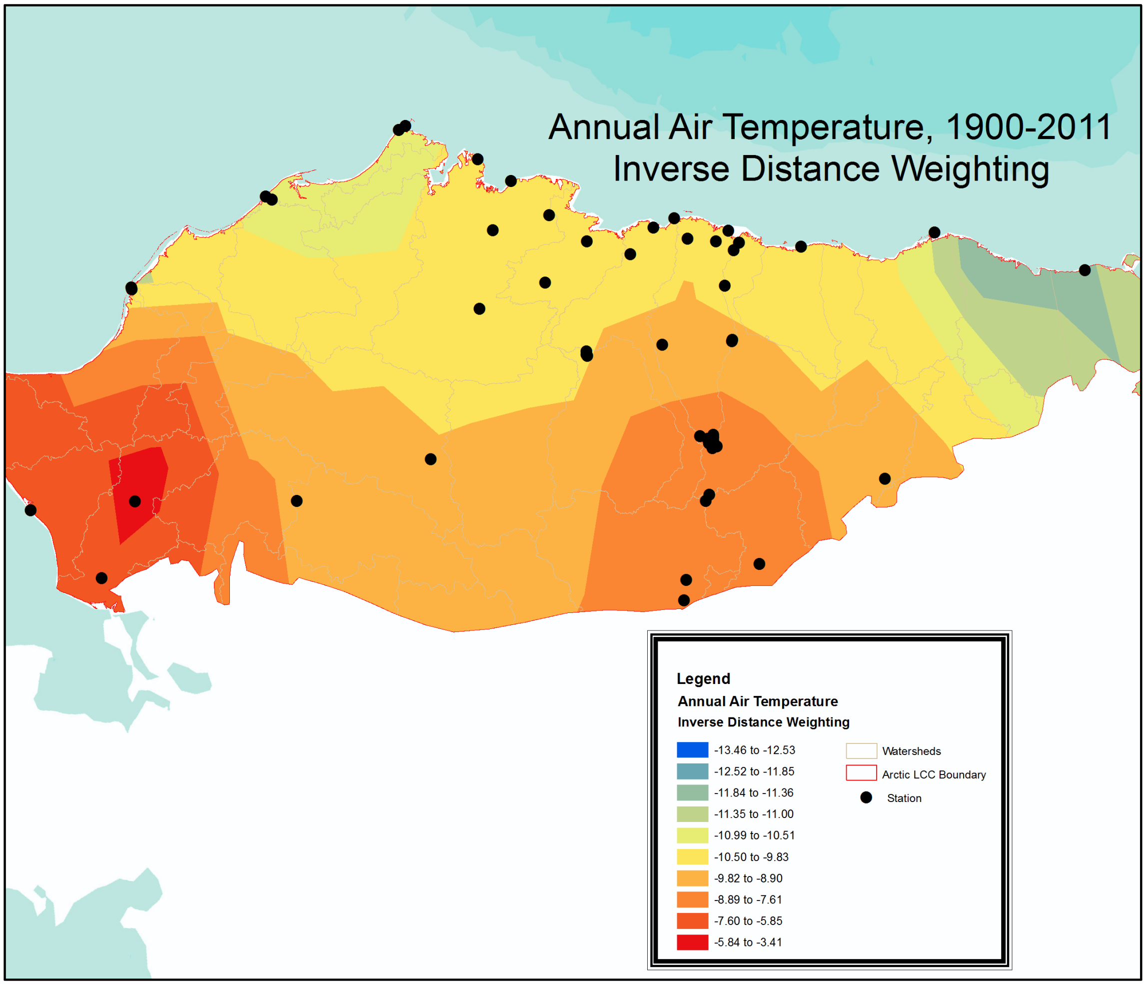

Figure A40: A spatially interpolated dataset for annual mean air temperature for the whole period of record. Black dots show locations of stations used in the interpolation.

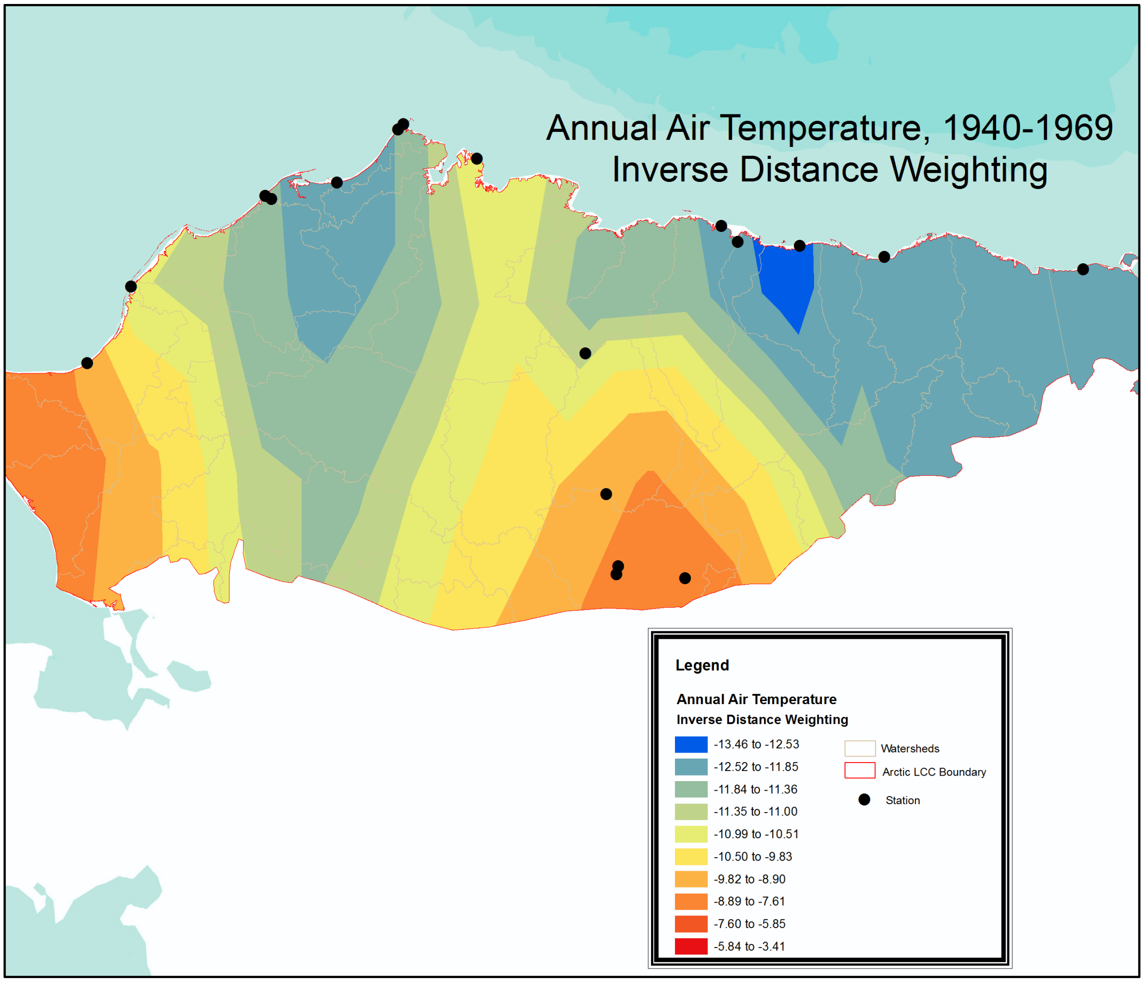

Figure A41: A spatially interpolated dataset for annual mean air temperature for the mid-century period of record. Black dots show locations of stations used in the interpolation.

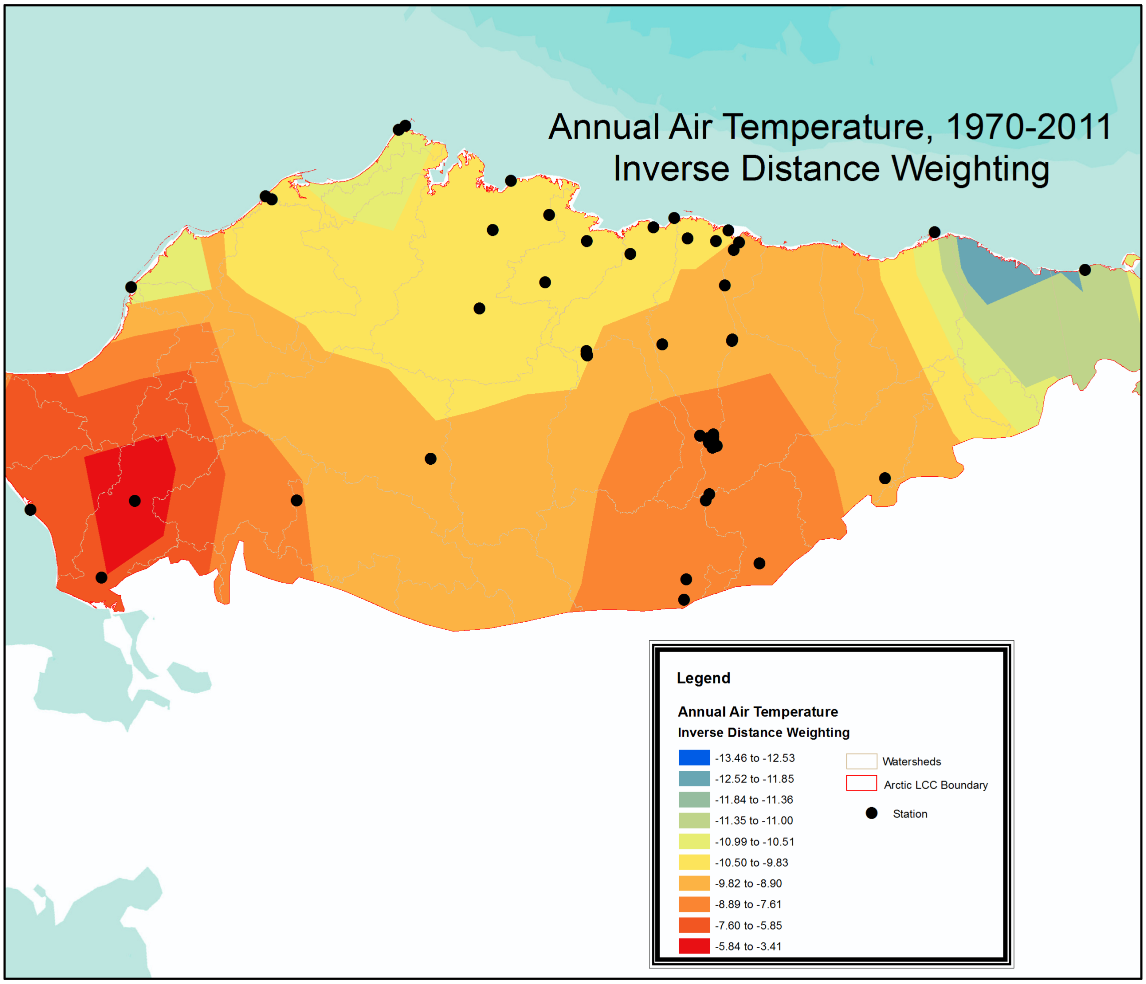

Figure A42: A spatially interpolated dataset for annual mean air temperature for the later period of record. Black dots show locations of stations used in the interpolation.

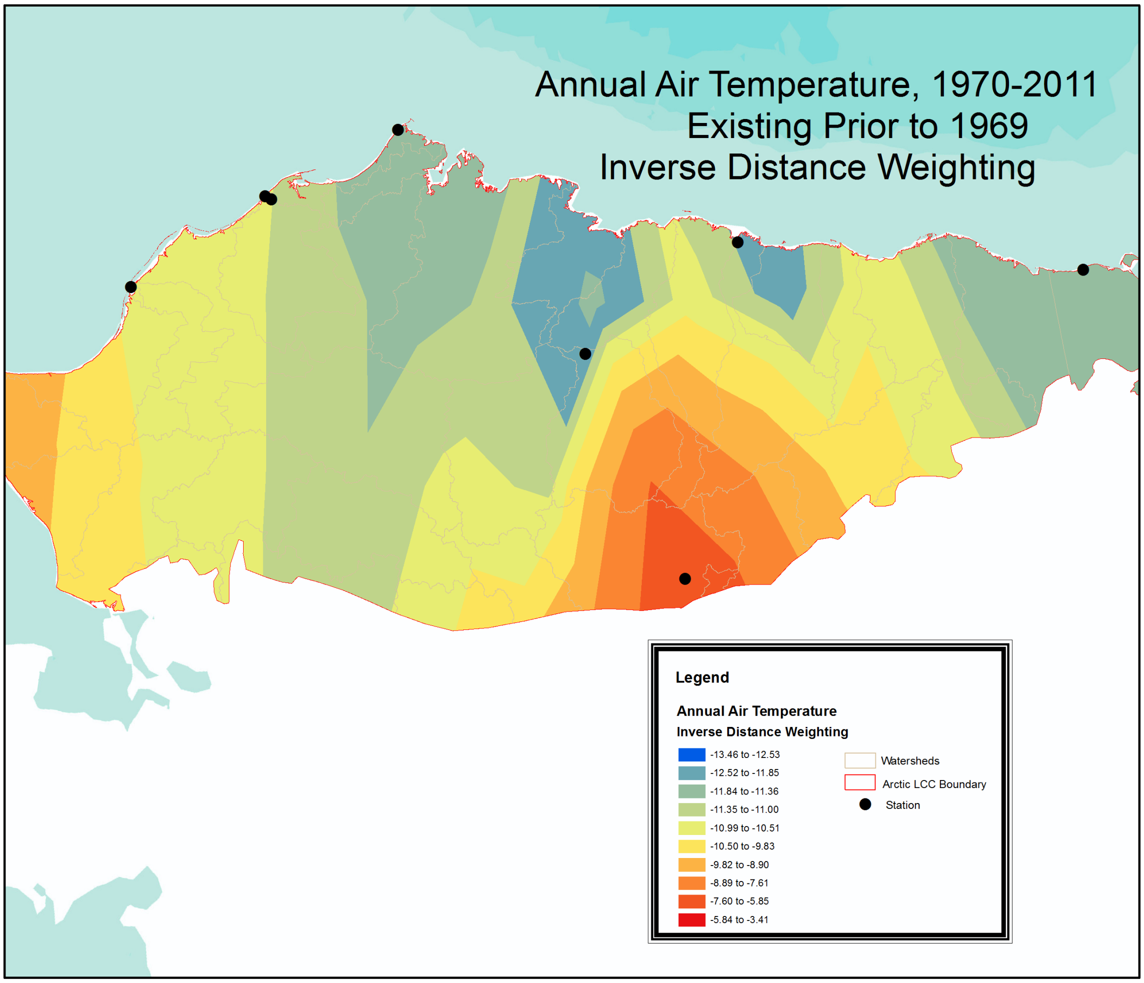

Figure A43: A spatially interpolated dataset for annual mean air temperature for the later period of record, using only stations that existed prior to that era (relatively long-term stations) that also ran during the period 1970-2011. Black dots show locations of stations used in the interpolation.

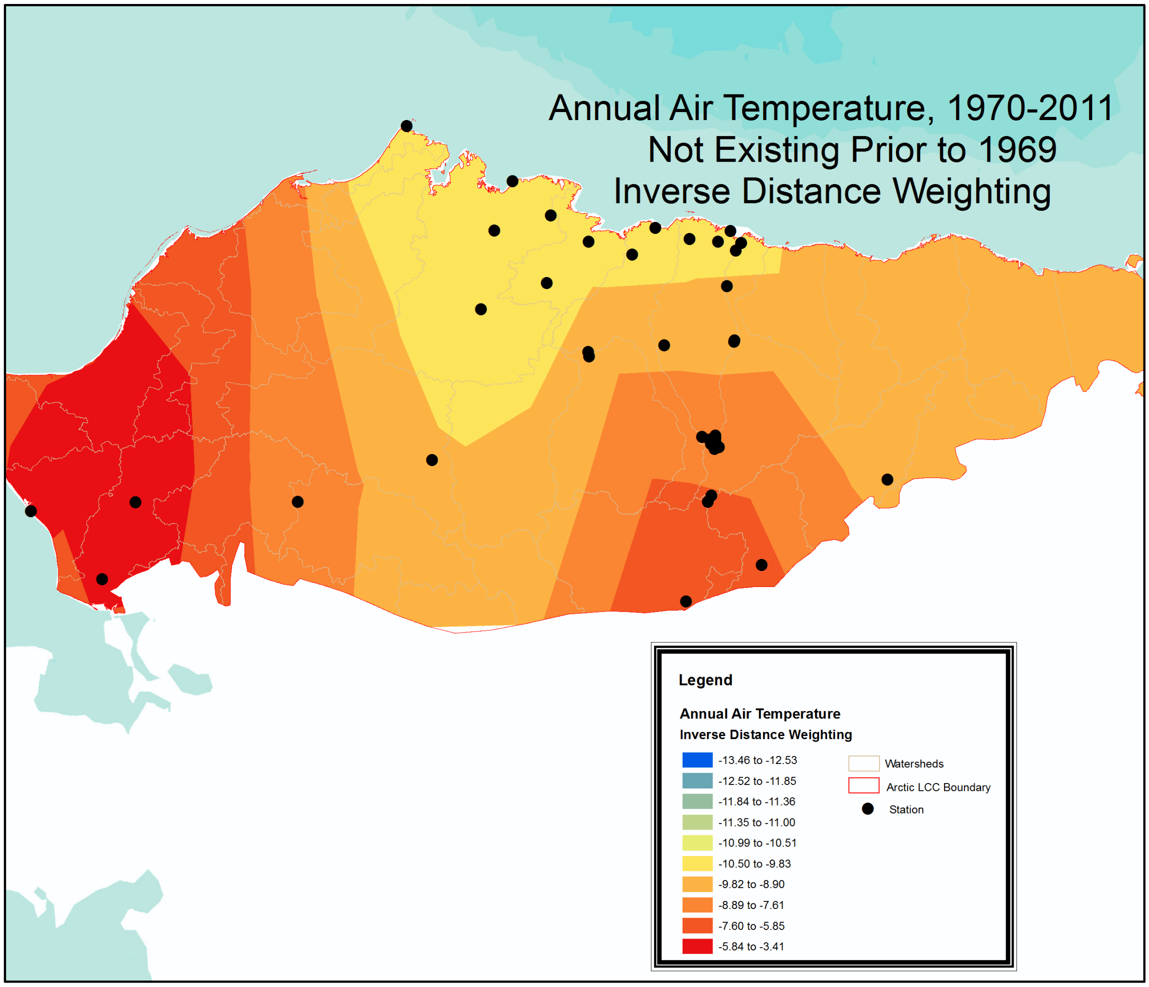

Figure A44: A spatially interpolated dataset for annual mean air temperature for the later period of record, using only stations that existed after the start of that era (relatively short-term stations). Black dots show locations of stations used in the interpolation.

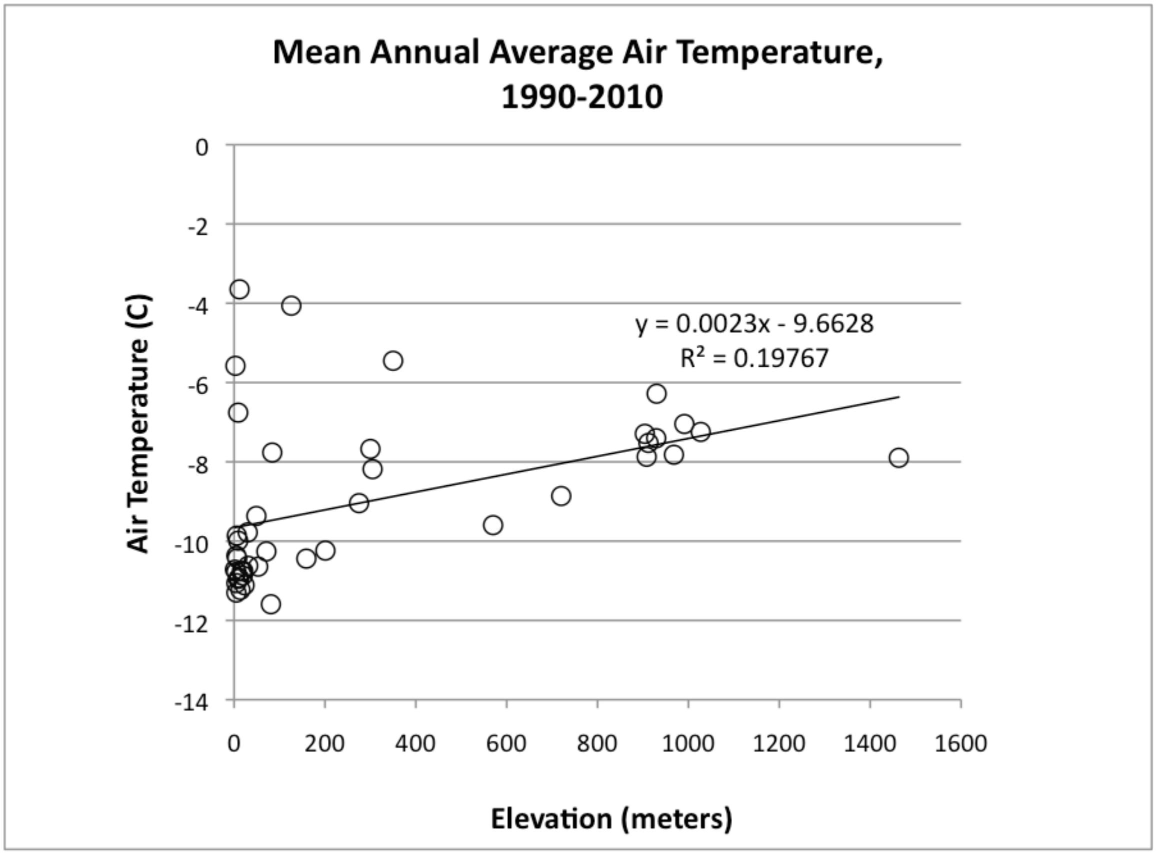

Figure A45: a scatter plot showing the relationship between mean annual air temperature by elevation. The period 1990-2010 was chosen because it had the highest number of sites with a diversity of elevations.

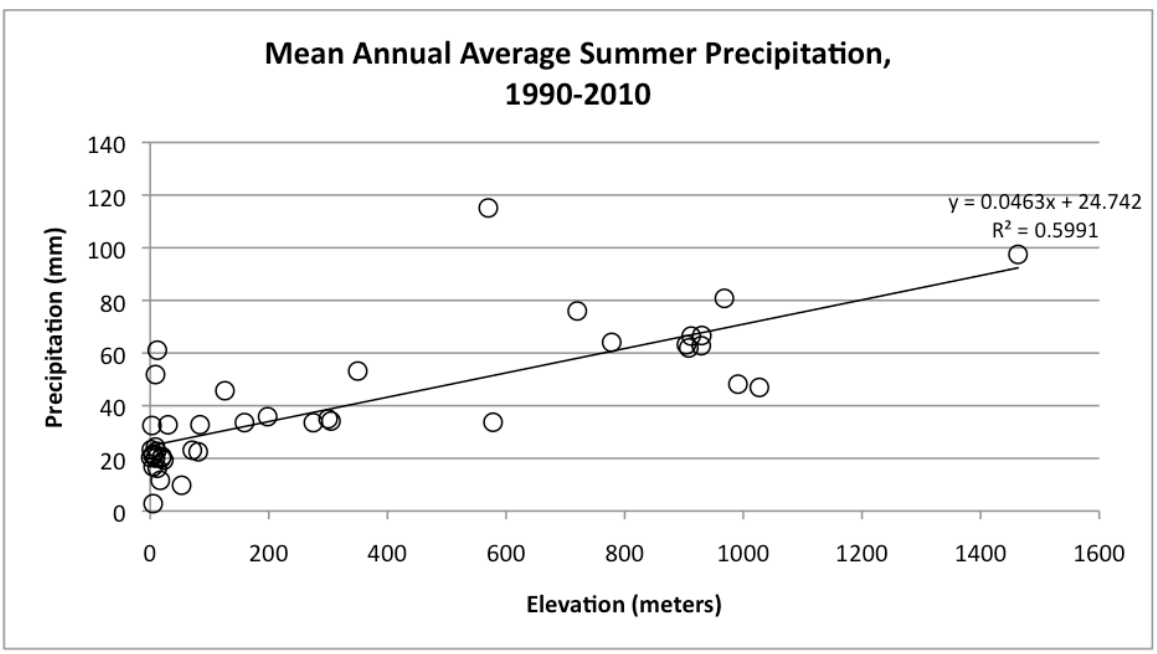

Figure A46: a scatter plot showing the relationship between mean summer precipitation by elevation. The period 1990-2010 was chosen because it had the highest number of sites with a diversity of elevations.

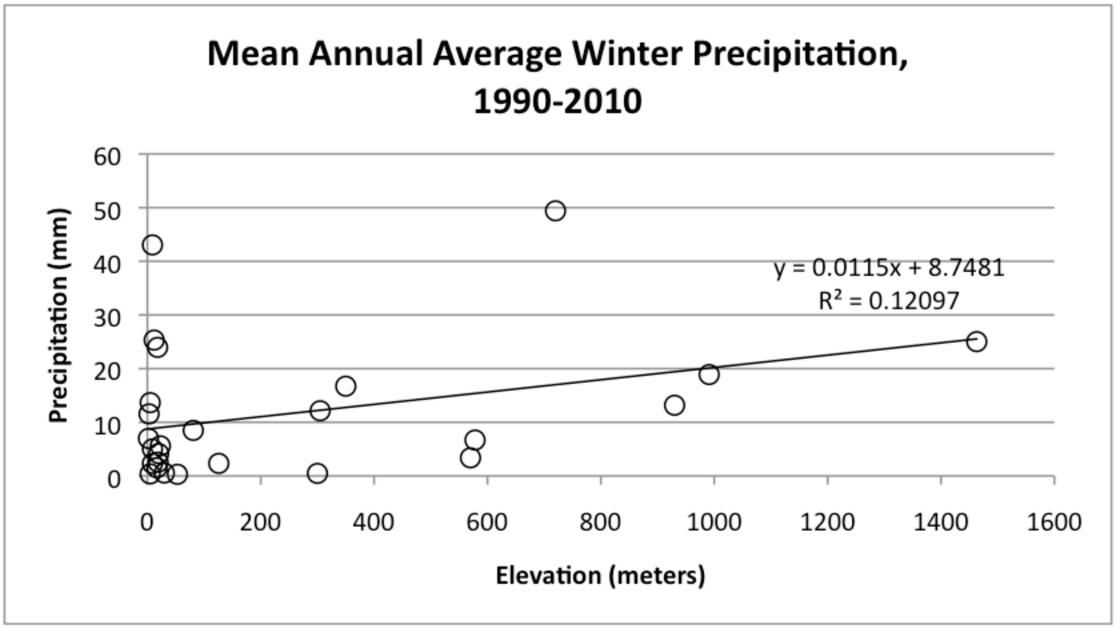

Figure A47: a scatter plot showing the relationship between mean winter precipitation by elevation. The period 1990-2010 was chosen because it had the highest number of sites with a diversity of elevations.

Appendix B: List of Sources for Data in the Network Analysis

The following sources of data were used, although not every site from each source has been loaded into the database. Typically sites on this list were not loaded because they were missing too much metadata to do so or had not undergone QA/QC.

Source ID	Organization	Source Description	Sites Loaded	Sites Not Loaded
1	International Arctic Research Center and Water and Environmental Research Center, Institue of Northern Engineering, Univeristy of Alaska Fairbanks	Meteorological data collected for the Total Precipitation Network	1	2
3	University of Alaska Fairbanks, Water and Environmental Research Center	Snow survey data collected by Water and Environmental Research Center, University of Alaska Fairbanks	157	31
4	National Oceanic and Atmospheric Administration	Archived weather data for multiple stations	51	129
29	University of Alaska Fairbanks, Water and Environmental Research Center	Climate and hydrology data collected on the North Slope (Umiat corridor) of Alaska listed on UAF INE WERC website	14	9
30	University of Alaska Fairbanks, Water and Environmental Research Center	INE WERC website	11	4
31	University of Alaska Fairbanks, Water and Environmental Research Center and International Arctic Research Center	Climate and hydrology data collected on the North Slope (Coastal PLain) of Alaska listed on UAF INE WERC website	18	9
34	University of Alaska-Fairbanks, International Arctic Research Center	UAF-Arctic Transitions in the Land Atmosphere System (ATLAS) weather station data posted on UAF INE WERC website (Seward Peninsula and North Slope)	1	6
35	National Oceanic and Atmospheric Administration	National Oceanic and Atmospheric Administration, Oceanic and Atmospheric Research, Earth System Research laboratory, Global Monitoring Division	1	0
39	U.S. GEOLOGICAL SURVEY	U.S. GEOLOGICAL SURVEY GTN-P Active-Layer Monitoring Site, Alaska, NPRA. Metadata found on project website	7	30
48	U.S. Fish and Wildlife Services, Water Resources Branch	Inventory information is from John Trawicki and agency report (see citation and source link fields)	119	0
114	National Park Service	Remote Automated Weather Station Network (RAWS) data for Northern Alaska	3	4
116	Bureau of Land Management	Remote Automated Weather Station Network (RAWS) data for Northern Alaska	1	4
124	Natural Resources Conservation Service	Snowfall Telemetry Network data for Northern Alaska SNOTEL	6	5

139	U.S. Geological Survey	USGS NWIS Web Services. Additional info: http://waterdata.usgs.gov/nwis/help/?provisional	30	24
145	Toolik Field Station, Environmental Data Center	Data from 1988 to 2008 can be queried and downloaded from http://toolik.alaska.edu/edc/weather/data_query.php. For more recent data contact EDC.	1	0
151	Circumpolar Active Layer Monitoring Network	Circumpolar Active Layer Monitoring Network (CALM). To access CALM data, go to http://www.udel.edu/Geography/calm/data/north.html and click on site code	41	1
154	U.S. Fish and Wildlife Service, Water Resource Branch	Data is available in pdf/report. John Trawicki sent data in electronic format (xls).	10	
164	Bureau of Land Management and University of Alaska Fairbanks	Matthew Whitman is data contact	4	1
169	University of Alaska-Fairbanks, Water and Environmental Research Center	Anna Liljedahl's Barrow Data	1	0
178	Arctic Institute of North America	Meteorological data collected for the McCall Glacier project IGY 1957-58	1	1
179	University of Alaska Fairbanks, Geophysical Institute	Meteorological data collected from the McCall Glacier by Bernhard Rabus, UAF GI	1	0
180	University of Alaska Fairbanks, Geophysical Institute	Meteorological data collected from the McCall Glacier by Gerd Wendler in 1969, UAF GI	1	0
182	Terrestrial Sciences Laboratory, Geophysics Research Directorate, Air Force Cambridge Research Center	Meteorological data collected from the Chamberlin Glacier for the Lake Peters IGY project 1958	1	0
183	Terrestrial Sciences Laboratory, Geophysics Research Directorate, Air Force Cambridge Research Center	Meteorological data collected from Lake Peters for the Lake Peters IGY project 1958-61	1	0
193	University of Alaska Fairbanks, Water and Environmental Research Center	Most data is available in North Slope Lakes Reports. Some data has to be entered from lab reports.	48	19
199	Bureau of Land Management and U.S. Geological Survey	USGS NWIS Web Services. Additional info: http://waterdata.usgs.gov/nwis/help/?provisional	6	1
200	Natural Resources Conservation Service	Snow Course	11	10
202	Department of Energy	Atmospheric Radiation Measurement Meteorological Station in Atqasuk Alaska was funded by Department of Energy.	1	0
203	Department of Energy, University of Alaska, Fairbanks	Atmospheric Radiation Measurement Total Precipitation Sensor in Barrow Alaska is funded by Department of Energy and managed by Jessica Cherry of University of Alaska Fairbanks, Water and Environmental Research Center, International Arctic Research Center	1	0

Appendix C: List of Sources for Data Not Yet Archived

The project team was aware of the following datasets in the region of interest, but because of the limitation of time, we were not able to enter these in the database or use them in the network analysis. These datasets should be included as the database is maintained and expanded, as they are valuable sources of information in a data sparse region. If the reader is aware of other appropriate datasets, not on this list, please send a note to Jessica Cherry at jcherry@iarc.uaf.edu with a description of the dataset and the point of contact.

Source ID	Organization	Source Description	Sites Not Loaded
132	Alaska Department of Fish and Game, Division of Sport Fish	Anadromous Cataloging and Fish Inventory in the Upper Koyukuk and Chandalar River Basins received from Joe Buckwalter -- data available online or from Joe.	88
175	Alaska Divsion of Fish and Game, Sport Fish Division	contact Joe Buckwalter at Fish and Game	87
191	Bureau of Land Management	BLM report OFR96: http://www.blm.gov/pgdata/etc/medialib/blm/ak/aktest/ofr.Par.54384.File.dat/ofr96.pdf	23
152	Bureau of Land Management	BLM report (Kostohrys 2000): OFR80: http://www.blm.gov/pgdata/etc/medialib/blm/ak/aktest/ofr.Par.54384.File.dat/ofr80.pdf	43
157	Bureau of Land Management	Metadata from Richard Kemnitz	14
159	Bureau of Land Management	Metadata from Richard Kemnitz	1
158	Bureau of Land Management and GeoWatersheds Scientific	Metadata from Richard Kemnitz	1
163	Bureau of Land Management and University of Alaska Fairbanks	Matthew Whitman is data contact	86
156	Global Change Research Group, SanDiego State University	Eddy flux data collected at towers and using aerial surveys-- Global Change Research Group, SanDiego State University, Walter Oechel	10
168	Global Change Research Group, San Diego State University	Walter Oechel	1
184	Global Change Research Group, San Diego State University	This data set contains eddy correlation data including CO2, H20, and Heat Flux at the Happy Valley Site in Alaska,1994.	2
117	Global Terrestrial Network for Permafrost and U.S. Geological Survey	GTN-P borehole data -- see GTNP.org	13
121	Global Terrestrial Network for Permafrost and University of Alaska-Fairbanks, Geophysical Institute	GTNP borehole measurements. See GTNP.org	9
118	Global Terrestrial Network for Permafrost and University of Alaska-Fairbanks, Water and Environmental Research Center	GTNP borehole measurements see NSIDC and GTNP.org	6

119	Global Terrestrial Network for Permafrost and University of Alaska-Fairbanks, Water and Environmental Research Center	GTNP borehole measurements	4
115	Global Terrestrial Network for Permafrost and University of Texas at El Paso	Borehole data (see GTNP.org)	5
148	MJM Consulting LLC	MJM Research, LLC (2007 report by Moulton et al.)	55
149	MJM Consulting LLC	MJM Research, LLC (2009 report by Moulton)	6
150	MJM Consulting LLC	MJM Research, LLC (2008 report by Moulton)	17
108	National Oceanic and Atmospheric Administration	NCDC Snow Stations	13
136	National Park Service	Proposed climate stations to be installed in 2011/2012	12
125	Natural Resources Conservation Service and NPS	Snowfall Telemetry Network data for Northern Alaska SNOTEL	1
170	Natural Resources Conservation Service and University of Alaska-Fairbanks	data files can be downloaded from http://soils.usda/survey/scan/alaska	1
42	Natural Resources Conservation Service and University of Cincinnati, Department of Geography	Soil Climate Research Stations -- metadata obtained from USDA web site (see link). Limited datasest are available	2
41	Natural Resources Conservation Service and University of Nebraska, Department of Geography	Soil Climate Research Stations -- metadata obtained from USDA web site (see link). Limited datasest are available	1
43	Natural Resources Conservation Service; University of Nebraska, Department of Geography; and University of Cincinnati, Department of Geography	Soil Climate Research Stations -- metadata obtained from USDA web site (see link). Limited datasest are available	6
44	The Bureau of Ocean Energy Management, Regulation and Enforcement	Wellsites identified on MMS inventory website	1
104	The Bureau of Ocean Energy Management, Regulation and Enforcement	MesoscaleMetStudy	2
143	Toolik Lake Long Term Ecological Research Station and Marine Biological Laboratory, Ecosystems Center	Yearly downloads available on LTER site	2
144	Toolik Lake Long Term Ecological Research Station and Marine Biological Laboratory, Ecosystems Center	Yearly downloads available on LTER site	3

140	Toolik Lake Long Term Ecological Research Station and University of Michigan	Data from 1998 to 2006 can be downloaded from Arctic LTER. More recent data can probably obtained from George Kling. Go to the following link for 2006 data for the Toolik Lake Climate Station: http://metacat.lternet.edu/knb/dataAccessServlet?docid=knb-lter-arc.1623&urlTail=landwater/lake_climate/data/2006_Toolik_Lake_Climate_Kling.dat . Data for the E5 climate station from 2000-2006 can be obtained by clicking on the links to yearly files found at: http://ecosystems.mbl.edu/arc/landwater/lake_climate/index.shtml	2
141	Toolik Lake Long Term Ecological Research Station and University of Michigan	Yearly downloads available on LTER site	2
142	Toolik Lake Long Term Ecological Research Station and University of Michigan	Yearly downloads available on LTER site	1
2	U.S. Fish and Wildlife Service	Fish presence, species composition, abundance, water quality, hydrology, and bathymetry data collected in the Arctic National Wildlife Refuge and the BLM National Petroleum Reserve-Alaska.	899
50	U.S. Fish and Wildlife Service, Arctic National Wildlife Refuge	Weather station data was sent by Steve Kendall, USFWS. Data files were in Excel format.	1
51	U.S. Fish and Wildlife Services, Arctic National Wildlife Refuge	Weather station data collected at camps during post-breeding bird surveys. Data were collected by Steve Kendall, USFWS. Data files were in Excel format.	1
190	U.S. Geological Survey	USGS_instantaneous irregular values	584
194	U.S. Geological Survey, Fort Collins Science Center		1
201	University of Alaska Fairbanks, Water and Environmental Research Center	McCall glacier measurements taken by Matt Nolan: met data and field campaigns to collect mass balance and survey data.	4
32	University of Alaska Fairbanks, Water and Environmental Research Center	Climate and hydrology data collected on the North Slope of Alaska listed on UAF INE WERC website	3
165	University of Alaska-Fairbanks	ET estimates using eddy covar technique	1
146	University of Alaska-Fairbanks, Institute of Arctic Biology and Marine Biological Laboratory, Ecosystems Center	Data can be downloaded from http://aon.iab.uaf.edu/AON_Results.html	4
176	University of Alaska-Fairbanks, Water and Environmental Research Center and U.S. Geological Survey	Chris Arp and Ben Jones	14
147	University of California-Santa Barbara	Sally McInytre, University of California-SantaBarbara supplied metadata and has data	6
	U.S. Army Cold Regions Research Laboratory	Snow Observations, Matthew Sturm, point of contact	

Appendix D: Database Documentation

The IMIQ hydroclimate database is designed to document all known datasets that are present in the Arctic LCC. Hydrological and climate data are being gathered by state, federal and private sectors and stored in various media forms, with varying levels of metadata. Due to this variability, the design of IMIQ is focused on standardizing the metadata for all datasets before loading the data values into the database. The steps that need to be followed to achieve this are data discovery, data acquisition and data processing.

Data Discovery

There are many forms that data can take, such as reports, spreadsheets, images and other database formats. It is possible that metadata for a dataset can be entered in long before the actual data values are loaded into the IMIQ database. During data discovery there are certain tables that can be populated without entering in the actual data values.

Table	Use
Sources	Contact and citation information for the dataset
Sites	Site information about where the data value was collected.

Optional tables that may be populated at this time are:

Table	Use
ISOMetadata	Project level metadata
Organizations	Organizations that a Source is related to
Processing	Data restrictions, priority of data entry, processing needs and QA/QC comments.

Populating the Sources and Sites tables will enable the IMIQ database to perform spatial queries. Spatial references can vary in SQL Server 2008 R2, so it is important that all spatial references be in WGS84 to enable these spatial queries to work across all sites, boundaries, watersheds and concept areas.

Data Acquisition

An acquired dataset will allow more of the metadata tables to be populated in IMIQ. The following are required tables in IMIQ:

Table	Use
Variables	Description of the measured variables
Devices	Description of devices used to collect data
Methods	Methods used to collect the data
Datastreams	Relevant information about a datastream, that ties together a Site and a Variable

These required tables will allow the data value to be associated with a specific Site and Variable. It will also define the processing method that was used and allow a way to incorporate any known parameters that will help with quality control of the datastream. Examples of these parameters are a range minimum and maximum threshold of a sensor or variable.

The following tables may be populated if the information is known or if the data value has a specific characteristic, such as data type of Category or a known sensor height.

Table	Use
Categories	Non-numeric data values definitions
QualityControlLevels	Level of quality control for the data
OffsetTypes	Data measurement offsets, both horizontal and vertical.
Datastreams	Relevant information about a datastream, that ties together a Site and a Variable
Qualifiers	Additional information concerning the conditions of the weather, instrumentation, etc, that a data value was collected

IMIQ addresses non-numeric data by using Categories. The Categories table will define the values that a non-numeric data value may have. Some categorical examples of this are a data value with an assigned data flag/code, sky condition observations, and cloud genus codes.

Data Processing

IMIQ has datastreams for each variable in a dataset. Ideally, the metadata that is stored in the Datastreams table, would be stored in the DataValues table to ensure that all metadata is directly related to a specific data value. However, since the IMIQ database is also performing data inventory, it may be the case that it is not possible to enter the data values immediately. All data values must be entered into one of the three tables:

Table	Use
DataValues	Actual data values and data value specific metadata
DataValuesRaw	Actual data values and data value specific metadata, that are not available to the public.
RasterDataValues	Non-point data values, such as raster and transects.

Additional tables that may be populated are:

Table	Use
DerivedFrom	Two data value IDs, one for the derived data value and one for the data value it was derived from.
Groups	Group data values that are related to each other.
Incidents	Natural or anthropogenic incidents that may have affected a data value.

During the design of the data model for IMIQ, all possible data types were considered. One table that has not been used and tested is the RasterDataValues table. The RasterDataValue table should be considered a concept and not a working table.

Quality Control and Quality Assurance

QA/QC of IMIQ has been cogitated, but not thoroughly implemented. A preliminary list of guidelines:

1. More than one person should perform quality control and quality assurance.
2. Metadata information should be reviewed for each datastream.
3. Check to see if the data values seem reasonable for a variable.
4. Retrieve data values that do not meet range minimum and maximum thresholds for variables and determine outliers.

Data

At the time of writing, IMIQ contains 3,358 datastreams that are related to Sites in the Arctic LCC region. The following table lists the variables and the counts for data values in the Arctic LCC region.

Variable Name	Sample Medium	Total Data Values
Altimeter setting rate	Air	2422083
Barometric pressure	Air	6461765
Ceiling height	Air	9468237
Radiation, global	Air	190257
Radiation, incoming longwave	Air	917203
Radiation, incoming PAR	Air	145160
Radiation, incoming shortwave	Air	1876247
Radiation, Net	Air	1955967
Radiation, net longwave	Air	35064
Radiation, outgoing longwave	Air	919963
Radiation, outgoing shortwave	Air	1497533
Radiation, PAR	Air	380514
Radiation, total incoming	Air	3969
Radiation, total outgoing	Air	3969
Relative humidity	Air	8001042
Sea level pressure	Air	3156079

Sky Cover	Air	26611286
Temperature	Air	42310487
Temperature, dew point	Air	3157385
Vapor Pressure	Air	380626
Visibility	Air	122949
Wind direction	Air	18238270
Wind sector	Air	190257
Wind Speed	Air	39605430
Wind vector magnitude	Air	380514
Ice thickness	Ice, waterbody	197
Precipitation	Precipitation	55435578
Snowfall	Precipitation	58
Ablation	Snow	60
Density	Snow	260
Snow depth	Snow	2366105
Snow Water Equivalent	Snow	150186
Snowfall	Snow	163491
Temperature	Snow	266508
Albedo	Soil	3969
Frost Free Day	Soil	7685
Temperature	Soil	16912012
Thaw Depth	Soil	902
Volumetric water content	Soil	531835
Water Content	Soil	1219594
Barometric Pressure	Surface Water	1619
Discharge	Surface Water	1385111
Electrical conductivity	Surface Water	1643
Evaporation	Surface Water	59200
Fish Detected	Surface Water	119
Free Board	Surface Water	197
Gage height	Surface Water	1902913
Ice	Surface Water	307
Luminescent dissolved oxygen	Surface Water	172
Oxygen, dissolved	Surface Water	1619
PH	Surface Water	1619
Radiation, PAR	Surface Water	190257
Reduction potential	Surface Water	1387
Runoff	Surface water	3260
Snow depth	Surface Water	197
Temperature	Surface Water	166654
Turbidity	Surface Water	1457
Volume	Surface Water	119
Water depth	Surface Water	62436
Water level	Surface Water	4900
Water pressure	Surface Water	1512
Time, z-time HHMM format	N/A	165988

Appendix E: Arctic Landscape Conservation Cooperative (LCC) Climate Technical Working Group

Overview Document – Core Objectives

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Jessica Cherry, University of Alaska Fairbanks
Greta Burkart, U.S. Fish and Wildlife Service
Amy Jacobs, University of Alaska Fairbanks

Background – Science and Management Needs

Weather and climate are key drivers in ecosystem structure and function. Global and regional scale climate variations will have tremendous impact on Arctic ecosystems (ACIA, 2004; Chapin et al., 1996; Hinzman et al., 2005). Long-term patterns in temperature and precipitation impose first-order constraints on potential ecosystem structure and function. Intensity and duration of weather events, seasonality, and interannual climatic variability provide secondary constraints on the fundamental properties of ecologic systems, such as soil–water relationships, plant–soil processes, nutrient cycling, and disturbance rates and intensity. These properties, in turn, influence the life-history strategies supported by a climatic regime (Neilson, 1987; Sanzone et al., 2005). Thus many of the future changes in fish and wildlife populations and their habitats will likely be directly related to changes in climate. It is imperative that a holistic effort geared toward an Arctic-wide climate network is established in order to improve downscaled climate models and the ability of land managers to make informed decisions about climate-related issues (NSSI, 2009).

The Arctic climate is characterized by a distinctive complexity due to numerous nonlinear interactions between and within the atmosphere, cryosphere, ocean, land and ecosystems. Sea ice plays a crucial role in the arctic climate, particularly through its albedo. Reduction of ice extent leads to warming due to increased absorption of solar radiation at the surface. Natural atmospheric patterns of variability on annual and decadal time scales also play an important role in the arctic climate. Such patterns include the North Atlantic Oscillation, the Pacific-North American pattern and the Pacific Decadal Oscillation, which are associated with prominent arctic regional precipitation and temperature anomalies (IPCC, 2007).

Climate variations are responsible for short- and long-term changes in ecosystem fluxes of energy and matter and have profound effects on underlying geomorphic and biogeochemical processes. Changes in climate that have already taken place are manifested in the decrease in extent and thickness of Arctic sea ice, permafrost thawing, coastal erosion, changes in ice sheets and ice shelves, and altered distribution of species (IPCC, 2001). With mean annual temperatures in the Arctic below freezing and the ground covered by snow more than 6 months per year, any increases in temperature and or changes in precipitation could have great impact on ecosystem structure and dynamics as well as major impacts on the land surface through changes in glaciers and permafrost. Without climate data, it is impossible to understand the causes of a variety of ecosystem changes now underway. Strategic deployment of climate stations across the Arctic will provide the necessary surface data that can be used to identify patterns and trends. The data generated by these stations will also contribute significantly to the understanding of Alaska's climate and high latitude manifestations of climate change.

During the last century, average air temperatures in the Arctic increased at a rate almost twice that of the global average. In Arctic Alaska most of this warming occurred during winter and spring and may be linked to wide-scale changes in terrestrial and aquatic ecosystems across the Arctic landscape (Martin et al 2009). Most global climate models predict that the Arctic will continue to warm at a rate higher than the global average and will be most pronounced in the winter. Annual Arctic precipitation is also very likely to increase (IPCC, 2007).

The North Slope Science Initiative (NSSI, 2009), United States Fish and Wildlife Service (Martin et al 2009), Alaska's Climate Change Sub-Cabinet (2009), and the Alaska Climate Change Executive Round Table (ACCER) have developed a list of priority questions and management needs for understanding impacts of climate change on a variety of resources, including fish, wildlife, habitat, and subsistence resources in Arctic Alaska. The North Slope Science Initiative's Emerging Issues Papers (2009) indicated that "weather and climate play a role in many short-term and virtually every long-term management decision on the North Slope".

The Arctic LCC Climate Technical Working Group has been formed to assist the Arctic Landscape Conservation Cooperative (LCC) Steering Committee with setting science priorities for issues related to weather and climate that address the conservation goals of the cooperative. The overarching focus of this Climate Technical Working Group is to improve our understanding of the physical aspects of climate change and the potential impacts of these changes on ecosystems.

The purpose of this report is to:

1) identify priority science and management needs related to the Arctic climate

2) define guidelines for development and maintenance of a long-term climate monitoring network in the Arctic LCC
3) briefly describe extant climate monitoring and research programs and to evaluate the sufficiency of these existing programs for meeting long-term needs
4) describe potential efforts and formulate order-of-magnitude cost estimates for developing and maintaining a climate monitoring network that meets science and management needs
5) describe the climate products that would be delivered for each element

General Guidelines for a Long-Term Climate Monitoring Network

It is important to distinguish whether the primary use of a given station is for weather purposes or for climate purposes. Weather station networks are intended for near-real-time usage, where the precise circumstances of a set of measurements are typically less important. In these cases, changes in exposure or other attributes over time are not as critical. Climate networks, however, are intended for long-term tracking of atmospheric conditions. Siting and exposure are critical factors for climate networks, and it is vitally important that the observational circumstances remain essentially unchanged over the duration of the station record. Some of the weather networks in the Arctic provide the only record of climate variables, however and care must be taken to evaluate the data record before a station is dismissed.

Throughout the planning and development process of a climate monitoring plan, there are various factors that require consideration in evaluating weather and climate measurements. Many of these factors have been summarized by Dr. Tom Karl, director of the NOAA National Climatic Data Center (NCDC), and widely distributed as the “Ten Principles for Climate Monitoring” (Karl et al. 1996; NRC 2001). These principals are used as guidelines for this working group. There are multiple independent stations and networks recording the weather in the Arctic, some are part of formal networks and others are project based or research driven (NSSI, 2009). Although numerous monitoring efforts are currently underway, a lack of coordination and integration has resulted in limited links between monitoring and science needs that respond to management issues (CBMP, 2007).

Priority Science Needs related to the Arctic Climate:

1. What are the long-term trends and variations in climate across the Arctic?
2. Is the synoptic climatology of this region changing?
3. What are the frequencies and patterns of extreme climatic conditions for common weather parameters, including air temperature, soil temperature, precipitation, wind speed and direction, and snow depth.
4. Do seasonal trends differ from annual trends?

5. What are the dominant climate gradients in the region?
6. Are spatial patterns of snow thickness, timing, and extent changing over time?
7. How can climate data from existing networks and projects be used to improve the quality of downscaled climate models?

Core Objectives of a Holistic Climate Program:

1. Understand the natural variation in weather and climate patterns across the Arctic using past and current data.
2. Analyze current trends in climate and weather patterns.
3. Predict future trends in climate and weather patterns in ARCN.
4. Understand the natural variability in depth, phenology and distribution of snow and ice in the Arctic.
5. Determine how the extent, duration and timing of snow and ice cover are changing in the Arctic.
6. Provide additional climate data from new stations in order to improve the current downscaled climate models for the region

Basic Approach

1. Inventory all stations and assess data record (in progress).
2. Analyze existing coverage and gaps to determine where new stations may be most useful.
3. Identify robust, consistent programs that could potentially provide the information, such as NOAA-CRN, SNOTEL, RAWS, UAF research projects, etc. (in progress).
4. Evaluate standardization of climate data measurements, dissemination, format, and archiving.
5. Ensure that all relevant climate data is being used in an effective, efficient, and consistent manner to better inform conservation managers.

Monitoring Programs and Projects Related to Climate Monitoring in the Arctic

There are a number of networks that are currently monitoring weather or climate in the Arctic. A compilation of existing data sources shows a wide range of climate monitoring efforts, including efforts related to weather forecasting (National Weather Service first order stations); specific research or science needs (RAWS –fire weather indices, UAF – numerous projects); other monitoring or research components (river gages, permafrost, vegetation, etc.); federal or statewide initiatives (SNOTEL – snow water equivalent, RWIS, State of Alaska Department of Transportation, ADF&G); and commercial resources (Red Dog Mine, Oil and Gas Companies). Davey et al. (2006) completed a comprehensive inventory of climate and weather stations in and around the boundaries of the National Park units in the Arctic; those descriptions are included below.

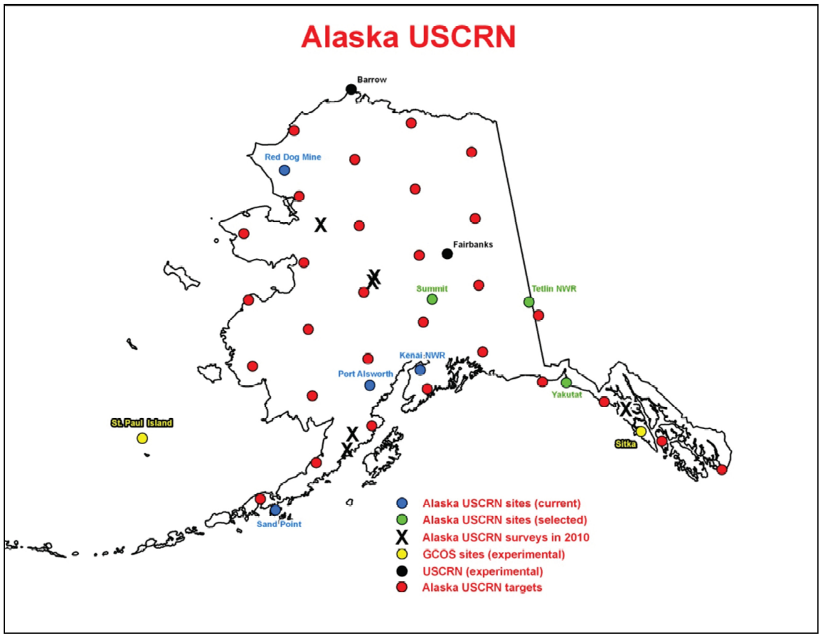
Acronym	**Name**
COOP	NWS Cooperative Observer Program
CRN	NOAA Climate reference Network
NADP	National Atmospheric Deposition Program
RAWS	Remote Automated Weather Station network
SAO	NWS/FAA Surface Airways Observation network
SNOTEL	USDA/NRCS Snowfall Telemetry network
USGS	Real-time permafrost and climate monitoring network
UAF WERC	Water and Environmental Research Center – University of Alaska Fairbanks
UAF IARC	International Arctic Research Center – University of Alaska Fairbanks
UAF IAB	Institute of Arctic Biology – University of Alaska Fairbanks
ARM	Atmospheric Radiation Measurement (DOE)
BLM	Bureau of Land Management
GWS	Geo-Watersheds Scientific
SDSU	San Diego State University (Eddy Covariance Towers + Met)
NPS	National Park Service (proposed monitoring stations)
NOAA	National Oceanic and Atmospheric Administration
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
TFS/LTER	Toolik Field Station/Long Term Ecological Research
FWS	US Fish and Wildlife Service

NWS Cooperative Observer Program (COOP)

The COOP network has been a foundation of the U.S. climate monitoring program for decades and continues to play an important role. These stations are operated by various agencies ranging from the National Weather Service, the Federal Aviation Administration, the National Park Service, and many individual volunteers. Manual measurements are made daily and consist of daily maximum and minimum temperatures, observation-time temperature, daily precipitation, daily snowfall, and snow depth. The quality of data from COOP sites ranges from excellent to modest. These are the only sites in the state that have long-term snow and year-round precipitation data. However, in 1999 many of these sites transitioned to fully automated real time weather sites (located near airports and villages), as a result, snowfall and winter precipitation measurements that were once manually recorded, are no longer being measured.

U.S. Climate reference Network (USCRN)

The USCRN consists of 114 stations developed, deployed, managed, and maintained by NOAA for the express purpose of detecting the national signal of climate change. The vision is to maintain a high quality climate network so that in 50 years we can determine, with confidence, how the climate of the nation has changed. There are currently 8 sites in Alaska with an additional 23 sites planned. All USCRN sites are equipped with a standard set of core sensors attached to a 10-foot 93 meter) mast. The core parameters measured are: air temperature, precipitation, solar radiation, and wind speed. There is a site at Barrow and at Red Dog Mine with potentially 4 more planned for the Arctic area (see map).



National Atmospheric Deposition Program (NADP)
The purpose of the NADP network is to monitor primarily wet deposition at selected sites around the U.S. and its territories. The network is a collaborative effort among several agencies including federal, state, tribal, and local governmental agencies. This network includes stations from the Mercury Deposition Network (MDN). Most NADP sites measure basic climate parameters. There are sites at Barrow and Bettles, AK.

Remote Automated Weather Station Network (RAWS)
The RAWS network of near-real-time weather stations is administered through many land management agencies, particularly the BLM and the Forest Service. Hourly observations include temperature, wind, humidity, solar radiation, barometric pressure, fuel temperature, and precipitation (when temperatures are above freezing). The fire community is the primary client for RAWS data. These sites are remote and data typically are transmitted via GOES (Geostationary Operational Environmental Satellite). Some sites operate all winter. Most data records for RAWS sites began during or after the mid-1980s. There are 3 active RAWS sites in the Arctic (Kelly, Noatak, and Umiat).

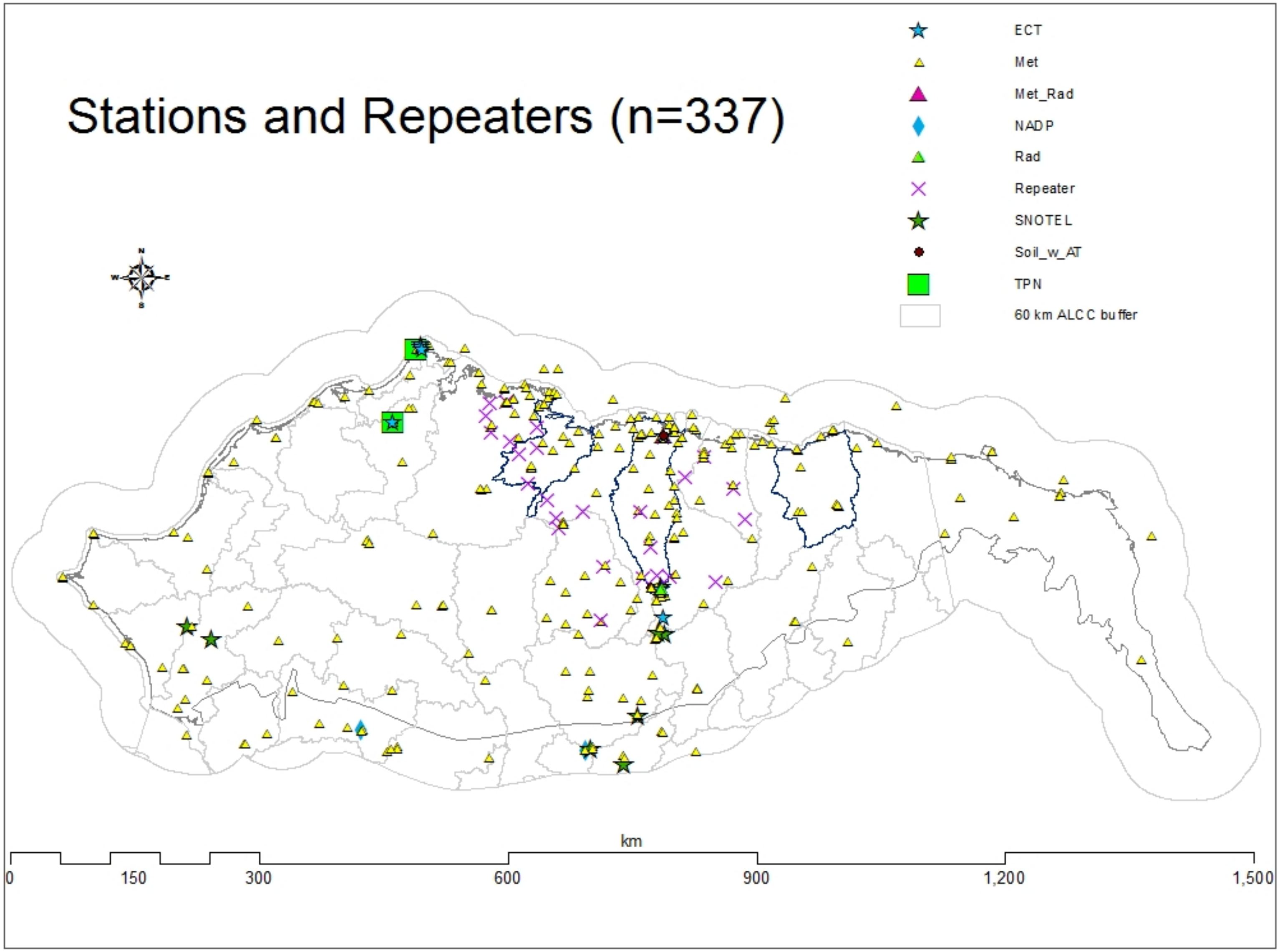
NWS/FAA Surface Airways Observation Network (SAO)
These stations are located usually at major airports and military bases. The Federal Aviation Administration, the National Weather Service and private parties manage the

Automated Surface Observing System (ASOS) and Automated Weather Observing System (AWOS). ASOS and AWOS is a suite of sensors, which measures, collects and broadcasts weather data to help meteorologists, pilots and flight dispatchers prepare and monitor weather forecasts, plan flight routes, and provide necessary information for correct takeoffs and landings. The system provides continuous data on conditions at the runway touchdown level.

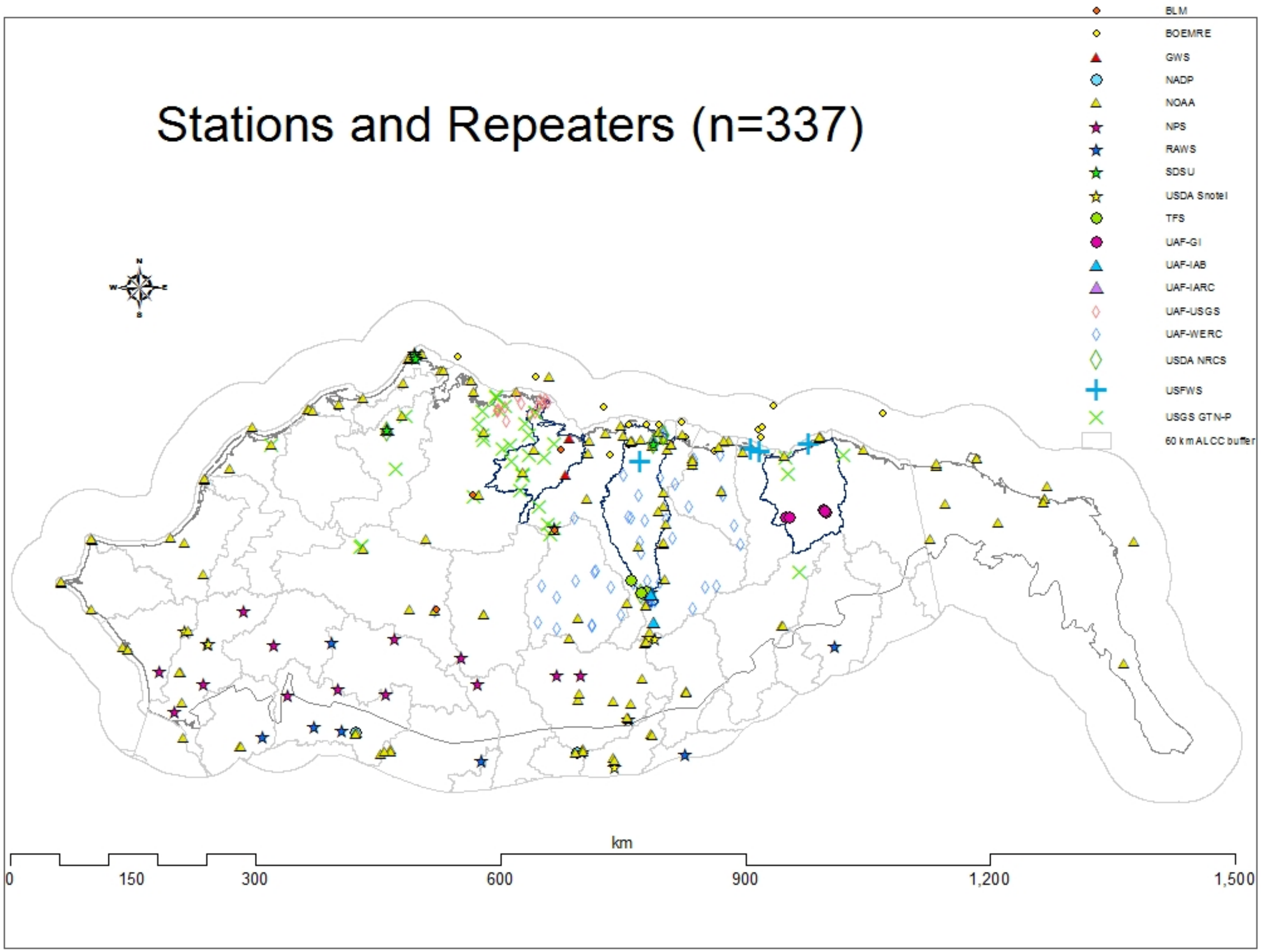
USDA/NRCS Snowfall Telemetry (SNOTEL) Network
The USDA/NRCS maintains a network of automated snow-monitoring stations known as SNOTEL. The network was implemented originally to measure daily precipitation and snow water content. Many modern SNOTEL sites now record hourly data, with some sites now recording temperature and snow depth. Most data records began during or after the mid-1970s.

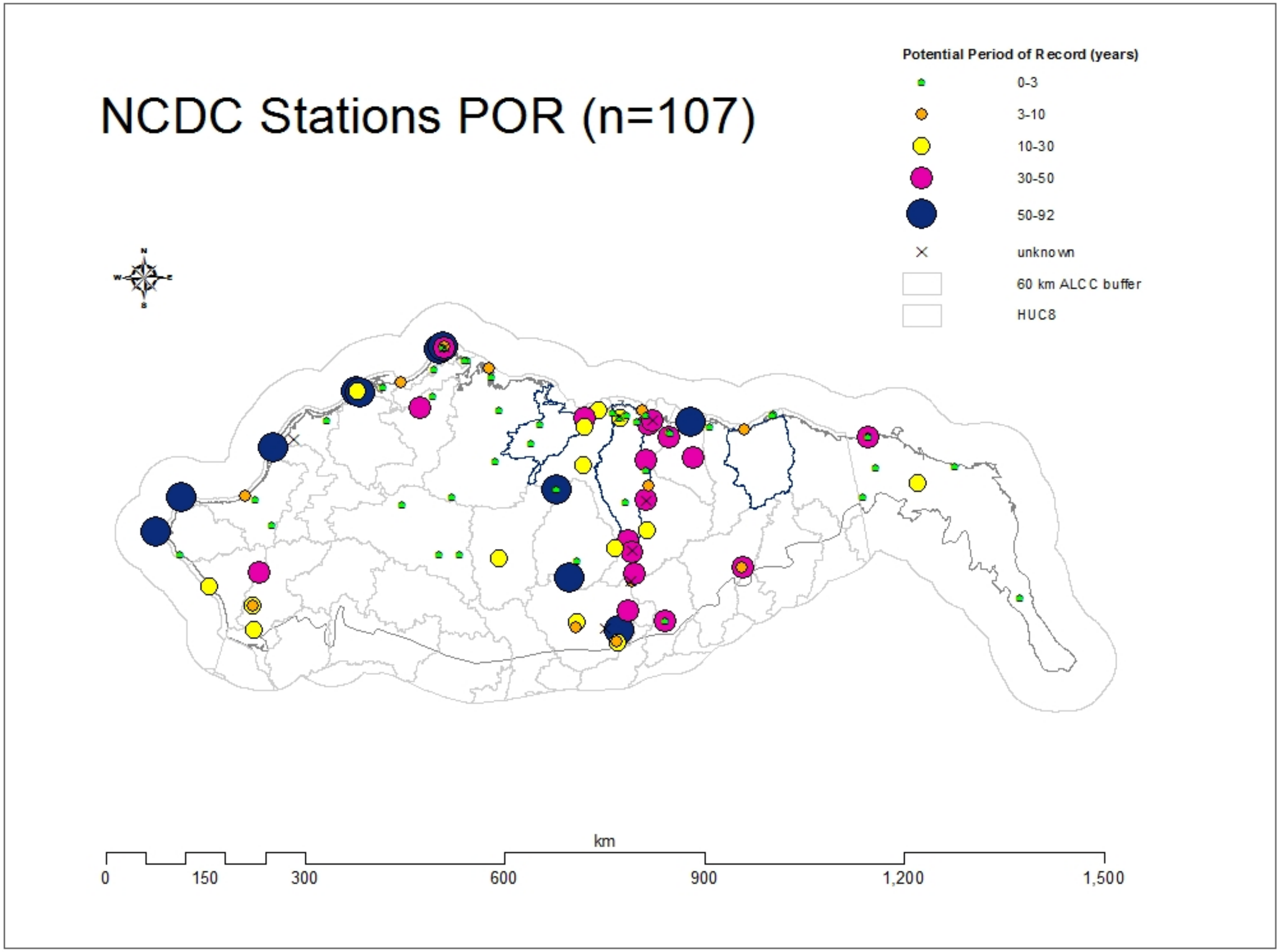
USGS Permafrost Network
The Department of Interior's (DOI) permafrost network in Alaska is part of a global network of permafrost monitoring stations (GTN-P) designed to monitor change in the solid earth component of the earth's cryosphere. This network covers federal lands in and around the National Petroleum Reserve Alaska (NPRA) and the Arctic National Wildlife Refuge (ANWR). The stations measure soil temperatures, active-layer thaw depth, and air temperature.

Water and Environmental Research Center (WERC) – multiple Arctic projects
NPR-A Hydrology: BLM and UAF personnel are performing detailed hydrologic fieldwork in the NPR-A. Field efforts involve stream gauging, water quality measurements, and basic weather variables. Umiat Corridor Project Summary: Project funded by the Alaska Department of Transportation and Public Facilities that will help characterize the major rivers and streams in the watersheds in the Umiat Road Corridor. This project is a continuation of many years of research conducted in the central North Slope. Weather stations are integral to the data collection efforts at these sites.



Stations and Repeaters (n=337)
ECT
Met
Met_Rad
NADP
Rad
Repeater
SNOTEL
Soil_w_AT
TPN
60 km ALCC buffer
km
0
150
300
600
900
1,200
1,500


Stations and Repeaters (n=337)
BLM
BOEMRE
GWS
NADP
NOAA
NPS
RAWS
SDSU
USDA Snotel
TFS
UAF-GI
UAF-IAB
UAF-IARC
UAF-USGS
UAF-WERC
USDA NRCS
USFWS
USGS GTN-P
60 km ALCC buffer
N
W
E
S
km
0
150
300
600
900
1,200
1,500


NCDC Stations POR (n=107)
Potential Period of Record (years)
0-3
3-10
10-30
30-50
50-92
unknown
60 km ALCC buffer
HUC8
N
W
E
S
km
0
150
300
600
900
1,200
1,500

Partnership with other Climate Agencies

The overall quality of Arctic climate data is dependent on outside agencies and contractors. Understanding how the data flow through the various steps of the process is integral to making any new effort run smoothly and efficiently. The success of any new climate monitoring effort will depend on these partnerships and how they are managed. Table 1 provides the list of partners critical to the success of this effort and the current contacts.

Table 1. Partnerships necessary for successful climate monitoring

Partner/Agency	Role	Contact
Western Regional Climate Center	Data archive, dissemination	Dr. Kelly Redmond – Deputy Regional Climatologist Dave Simeral – Assistant Meteorologist
National Interagency Fire Center	Data retrieval, QA/QC and dissemination	Bill Yohn – NPS – NIFC Contact
National Atmospheric and Oceanic Administration (NOAA)National Weather Service (NWS)- Anchorage (RFC) - Anchorage	Regional data dissemination, regional networking	James Partain – Regional Climate Services Director Gary Hufford –Physical Scientist Angel Corona - Chief Data Acquisition
National Weather Service (NWS) Fairbanks	Regional data dissemination, regional QA/QC, networking	Rick Thoman – Lead forecaster Eric Stevens – Meteorologist
National Climatic Data Center	Data archive	Climate Services Branch
Toolik Field Station		Gaius Shaver and Sydonia Brett-Hart
Alaska Fire Service	Coordination and collaboration for RAWS network	Kent Gale – Program Manager
USGS - GTNP		Gary Clow
University of Alaska Fairbanks and Partners	Data collection, analysis and interpretation; management of long-term datasets	Doug Kane – WERC Jessica Cherry – IARC/WERC Vladimir Romanovsky - GI

Projects Supporting Climate Monitoring/Downscaled Climate Science Needs

Updated PRISM Maps

In order to understand climate patterns and variation in Alaska parks the National Park Service Alaska Region Inventory and Monitoring Program collaborated with Oregon State University's PRISM Climate Group to generate spatially gridded average monthly and annual precipitation and temperature data set for the 1971 – 2000 normal period. The PRISM (Parameter-elevation Regressions on Independent Slopes Model) climate mapping system was used to generate these products http://www.prism.oregonstate.edu/. This mapping system integrates existing climate station data with scientific understanding of general climate processes and local climate features. These climate maps feature a 30-arc second (approximately 800 meter) grid size resolution for the state of Alaska (http://nrinfo.nps.gov/Home.mvc/showWelcomePage).

Scenario Network for Alaska Planning (SNAP)

The SNAP mission is to provide timely access to management-relevant scenarios of future conditions in Alaska. They are a collaborative organization linking the University of Alaska, state, federal, and local agencies, and non-governmental organizations. SNAP has been instrumental in providing datasets and maps projecting future conditions of temperature and precipitation state-wide (http://www.snap.uaf.edu/home). PRISM offers data at a fine scale, but does not offer climate projections. John Walsh and Bill Chapman et al (2008?) linked PRISM to GCM outputs in order to make the global climate models (GCM) useful at local scales.

Programs and entities related to climate monitoring

There are several entities, outside of the major federal and state agencies that deal with conservation issues that are key to a holistic view of climate vision for the Arctic.

Alaska Climate Research Center – group based out of the Geophysical Institute at the University of Alaska Fairbanks that conducts research focusing on Alaska and Polar Regions climatology. They also archive climatological data for Alaska.

Alaska Center for Climate Assessment and Policy (ACCAP) – the mission of ACCAP is to assess the socio-economic and biophysical impacts of climate variability in Alaska and make the information available to local and regional decision makers and improve the ability of Alaskans to adapt to a changing climate.

Atmospheric System Research Program (ASR) formerly called the Radiation Measurement Program (ARM), US Dept of Energy – this global program has an ongoing intensive observation site at Barrow. Atqasuk was another long-term facility, but Atqasuk is being decommissioned while a new site at Oliktok Point is being built. The goal of the ASR/ARM program is to collect atmospheric data in such a way that it can be used to verify specific models. The program also supports the development of these models, so that monitoring and modeling are highly integrated.

Does the current monitoring/research meet the science needs?

The sites that do exist provide the only record of Arctic climate available and are extremely valuable. One important objective for Arctic climate science will be to ensure that these existing sites keep operating. Sites include National Weather Service Cooperative Observer sites, automated airport weather stations, and the Remote Automated Weather Stations (RAWS). Most of these existing sites are located at relatively low elevations, along major rivers, and in towns and villages.

Several groups working on this same issue have documented that the current array of weather and climate measurements in the Arctic and Alaska in general is not adequate. The North Slope Science Initiative, Weather and Climate Emerging Issues Summary highlights many of the issues that this group will attempt to address. The NSSI recommendations will be utilized as they outline many of the same concerns and issues regarding climate science needs in the Arctic. The National Park Service (NPS) has also invested substantial time and effort to develop an effective and robust climate monitoring program that will answer critical questions about how the trends in temperature and precipitation are changing in Alaska national parks. Numerous workshops and meetings involving climate experts from around the state and country were held to discuss the development of the program and potential siting of new stations in Alaska parks. Several reports and recommendations are available for review (Sousanes, 2004; Redmond and Simeral 2004; Nolan, 2007; Davey et al., 2007). New climate stations were installed within parks by going through a series of steps, including: initial conversations with park staff and climate experts regarding data gaps, the use of a site criteria checklist to find candidate sites, reconnaissance and site evaluation, ranking and rating by a panel of climate/weather experts, and finally by putting potential new sites through the requisite permitting and compliance systems.

By developing the Arctic climate database we will be able to identify critical data gaps and identify potential new station locations. An alternative to the expert review/expert judgment analysis would be to employ the method used by Brabets (1996) for the evaluation of stream flow gauges in Alaska. Following a gap analysis, and the identification of potential new sites, the work group could then leverage existing networks for support for additional stations through formal interagency or cooperative agreements that provided additional funding or logistic support. Like the NSSI the Arctic LCC climate work group has the benefit of being an overarching organization that is not driven by a specific agency or university mandate.

The basic approach for a holistic climate science plan that will enable us to adequately address the science needs and questions related to climate changes in the Arctic will be to: 1) ensure that all existing long-term climate and weather stations in and around the Arctic, especially those that measure precipitation and snow, continue to operate and produce high quality data; 2) add new climate stations in areas that are not currently represented that measure and record air temperature, soil temperature, wind speed and direction, snow depth, relative humidity, solar radiation, and year-round precipitation (rain, snow and mixed precipitation); 3) ensure that the maintenance and calibration of the stations and sensors is a priority; 4) engage in partnerships and collaborations that foster efficiency and robust methods; 5) ensure that the data produced by the new stations are available to all interested parties including the National Weather Service, federal and state agencies, university staff, and the public via the internet, 6) analyze and summarize the data in useful formats to show means, totals, trends, and extremes; and 7) archive the digital data with the Western Regional Climate Center, or in the future with the new Alaska Regional Climate Center.

Cost Estimates

The costs associated with enhancing climate monitoring efforts in the Arctic can be broken down into four separate components, including: 1) new climate stations and associated costs, 2) long-term maintenance costs including travel to the sites, calibration, and sensor/hardware replacement and upgrade, 3) costs associated with data archiving and web based data tools, and 4) costs associated with data analysis and modeling efforts.

The number of new sites will determine the fixed costs for the overall program. The density of stations proposed for the Arctic can be scaled to meet the needs of other work groups and the funding available. The commitment to fund a new station would benefit from the assumption that maintenance and upgrades would be funded well into the future. The funding limitations might determine what a feasible density of new stations may be, rather than what would be desired to truly capture climate gradients across the Arctic.

The up-front investment in new climate stations includes the cost of the towers/tripods, dataloggers, sensors, power supplies, and enclosures. The long-term maintenance requires at least an annual site visit to replace sensors, download stored site data, troubleshoot problems, etc. The costs for maintenance include flights, travel, calibrations, and hardware upgrades (if any). The data archiving and web-based dissemination of incoming data may require a cooperative agreement with the Western or Alaska Regional Climate Center, or another appropriate source. Basic elements of archiving and dissemination would occur with little costs, but tailoring the data tools to the needs of the users may require additional funding. The costs of analysis and modeling will vary depending on the product that is desired. These would be short-term end product costs for a specific task and would not be recurring (Table 2).

Table 2. Example design and operational costs of climate monitoring program.

Estimated Costs	Initial Start-up cost	Operational Cost per year
Equipment: Complete climate station (one station)	$15,000-$30,000	$500-$30,000
Logistics: Flights and travel to a climate station (one station)	$200-$5,000	$200-$5,000
Cooperative Agreement with Archive	$0-$30,000	$0-$5,000
Data Analysis/Modeling	Will vary ($20,000-$400,000)	-

Data Access and Archiving

Management and stewardship are some of the most important activities to be undertaken in climate monitoring to ensure that high-quality climate data records are collected, retained and are accessible for analysis and/or re-analysis by current and future generations of scientists, resource managers, and the general public. The preservation of the data for future use requires facilities and infrastructure to ensure the long-term storage of the data. Another key component of data management includes adequate monitoring of the data stream. This includes timely quality control of the observations and notification to observing system operators and managers of both random and systematic errors, so that corrective action can occur. A central data portal is critical and should be used to gather, integrate, and analyze the data in a coherent and consistent format.

The disparate data sets and methods for accessing and archiving climate data make it a challenge to integrate all data sources into a single format available for all users. There are several data portals that serve climate data, including the Western Regional Climate Center, which is one of six regional climate centers that are currently operating in the U.S. They are responsible for disseminating climate data and information pertaining to the western United States including Alaska. The regional climate center program is administered by the National Oceanic and Atmospheric Administration and specific oversight is provided by the National Climatic Data Center (NCDC) of the National Environmental Satellite, Data, and Information Service (NESDIS). A new regional climate center for Alaska is in the development and planning stage**.**

One of the most useful data portals for Alaska at this time is the experimental data portal being developed through the Alaska Ocean Observing System (AOOS) available at http://data.aoos.org/maps/sensors.php. The web based interface displays current climate and oceanographic data from the major networks for the entire state. Stations can be filtered by climate parameter (temperature, snow depth, soil temperature) or by source (NWS, SNOTEL, COOP). This type of data dissemination system is a useful for consolidating multiple networks and data formats into one system that can serve a wide variety of users.

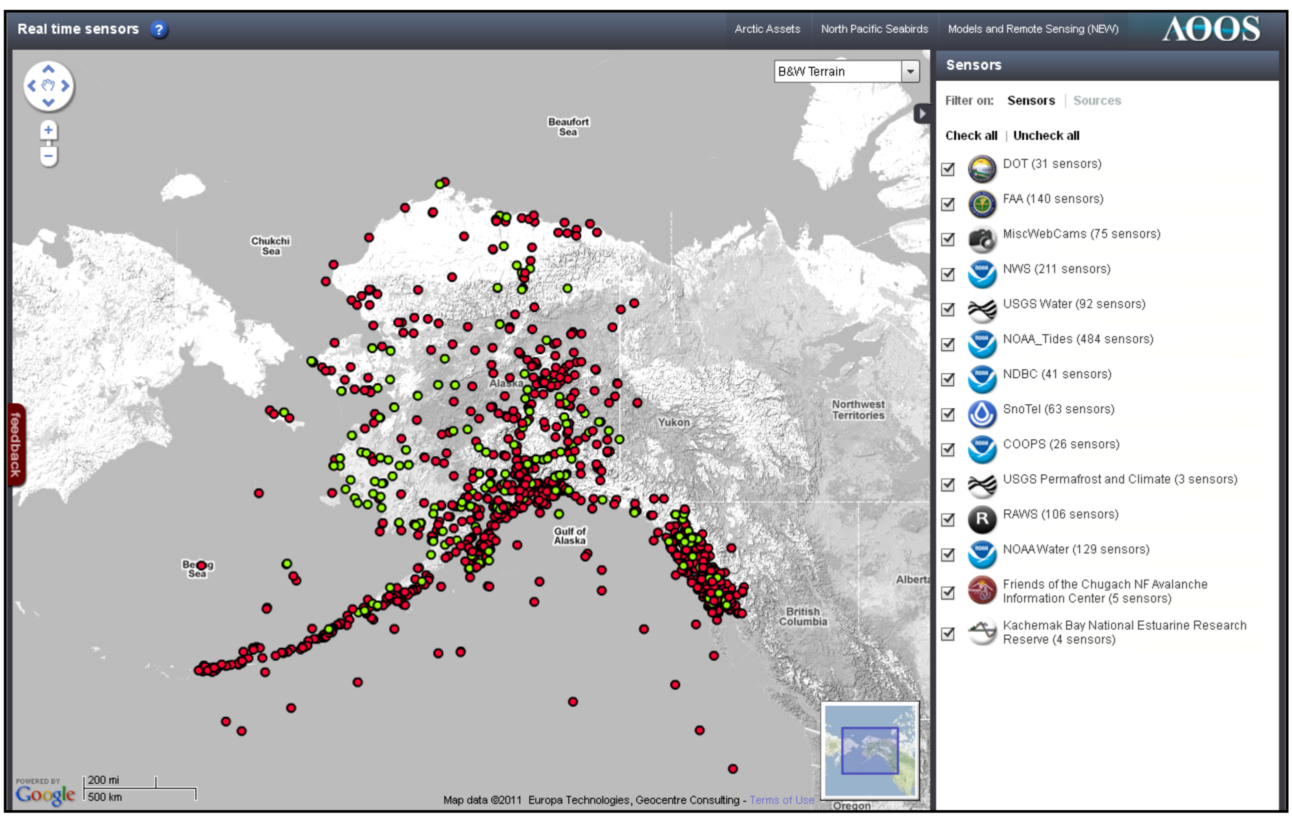
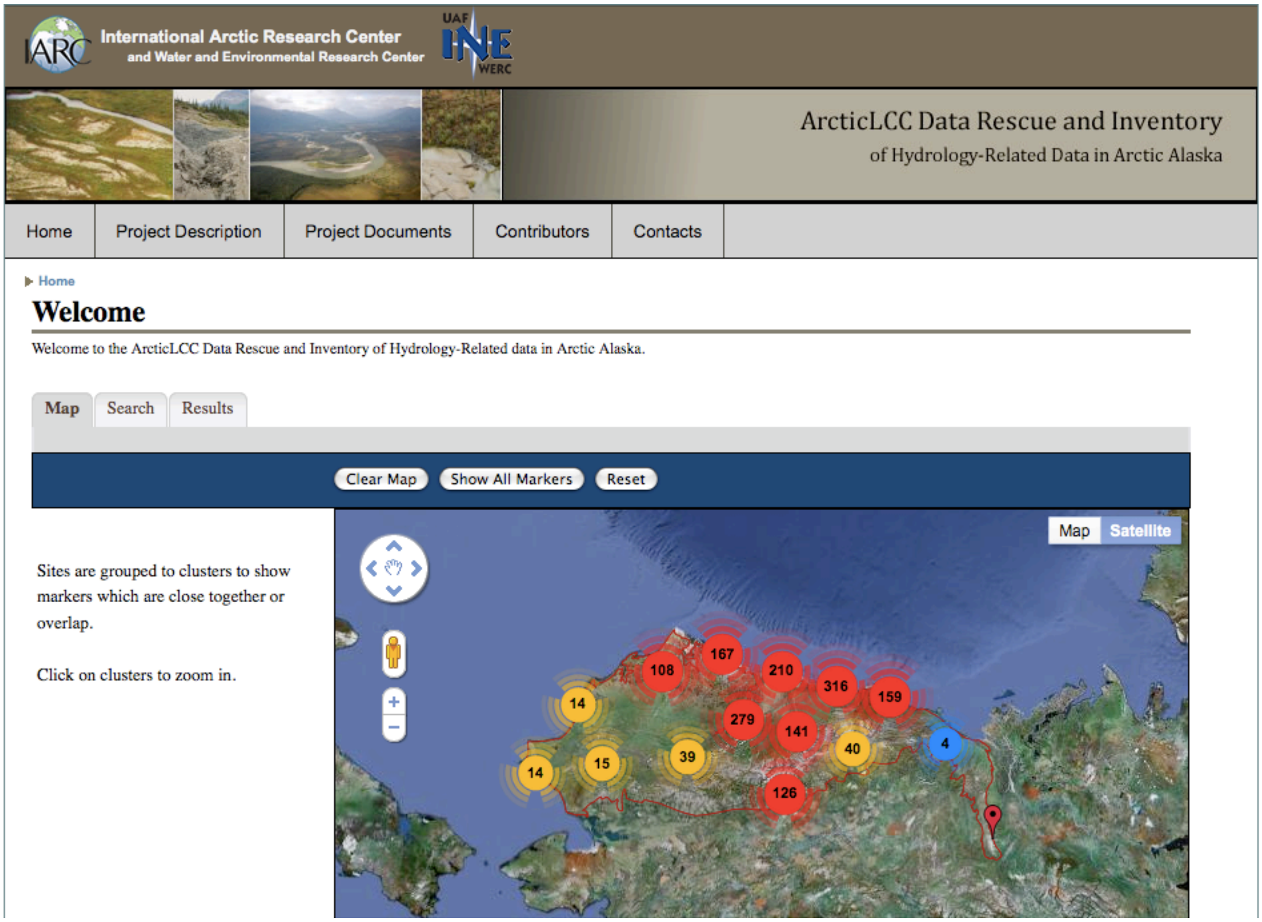


Figure 1. The Alaska Ocean Observing System real-time data sensor map. Retrieved on February 17, 2011 from http://data.aoos.org/maps/sensors.php.

Another portal under development at this time is the Arctic LCC hydroclimate database, available at:
http://ine.uaf.edu/werc/projects/lccdatalibrary/index.html



Data products

The products available to answer the science needs will include, publicly accessible data and data analysis tools, climate summary maps, and reports summarizing annual climate factors and long-term trends. Products such as refined downscaled climate models and specific analyses are examples of products that will stem from enhanced data set. Developing these products will likely be the work of researchers at all of the entities described herein for several years to come.

References:

Alaska Ocean Observing System (AOOS). 2011. Transitional Data Portal: Real Time Sensors. http://data.aoos.org/maps/sensors.php

Arctic Climate Impact Assessment. 2004. Available from http://www.acia.uaf.edu (accessed 26 November 2004).

Chapin, F. S., et al. 2005. Role of Land-Surface Changes in Arctic Summer Warming *Science* 310: 657-660.

Circumpolar Biodiversity Monitoring Program (CBMP), 2007. Circumpolar Biodiversity Monitoring Program Five Year Implementation Plan Overview Document. Retrieved on February 22, 2011 from http://arctic-council.org/filearchive/CPMP_Imp_Plan-Overview_Final-1.pdf

Davey, C. A., K. T. Redmond, and D.B. Simeral. 2006. Weather and Climate Inventory, National Park Service, Arctic Network. Natural Resources Technical Report NPS/ARCN/NRTR – 2006/005.

Hartmann, B., and G. Wendler, 2005. *The significance of the 1976 Pacific shift in the climatology of Alaska.* J. Climate, 18, 4824-4839.

Hinzman, L.D. et al. 2005. Evidence and Implications of Recent Climate Change in Northern Alaska and Other Arctic Regions, Climatic Change, Volume 72, Issue 3, Pages 251 – 298

IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S.D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Karl, T. R., V. E. Derr, D. R. Easterling, C. K. Folland, D. J. Hoffman, S. Levitus, N. Nicholls, D. E. Parker, and G. W. Withee. 1996. Critical issues for long-term climate monitoring. Pages 55-92 *in* T. R. Karl, editor. Long Term Climate Monitoring by the Global Climate Observing System, Kluwer Publishing.

Neilson, R. P. 1987. Biotic regionalization and climatic controls in western North America. Vegetation 70:135-147.

Nolan, M. 2006. Scoping Document for Monitoring Climate and Weather in the Arctic National Parklands, National Park Service report.

North Slope Science Initiative (NSSI), 2009. Emerging Issue Summary: Weather and Climate. Retrieved on February 15, 2011 from http://www.northslope.org.

Sanzone, D. M., S. D. Miller, and S. B. Young. 2005. Monitoring ecological change in the Arctic parklands. Vitals Signs Monitoring Plan for the Arctic Network: Phase I Report. Inventory and Monitoring Program, National Park Service: Fairbanks, Alaska.

Wendler, G. and M. Shulski. 2009**.** *A Century of Climate Change for Fairbanks, Alaska.* Arctic. Vol. 62(3): 295-300.

U.S. Climate Reference Network (USCRN), 2010. USCRN Overview. Information retrieved on February 17, 2010 from http://www.ncdc.noaa.gov/crn

Appendix F: Ten Climate Monitoring Principles

Suggested as guiding principles by the National Research Council and adapted from Karl, T.R., V. Derr, D. Hofmann, D.R. Easterling, C. Folland, S. Levitus, N. Nicholls, D. Parker, and G.W. Withee, 1995: Critical Issues for Long-term Climate Monitoring. Climatic Change, 31, 185-221.

1. Management of Network Change: Assess how and the extent to which a proposed change could influence the existing and future climatology obtainable from the system, particularly with respect to climate variability and change. Changes in observing times will adversely affect time series. Without adequate transfer functions, spatial changes and spatially dependent changes will adversely affect the mapping of climate elements.

2. Parallel Testing: Operate the old system simultaneously with the replacement system over a sufficiently long time period to observe the behavior of the two systems over the full range of variation of the climate variable observed. This testing should allow the derivation of a transfer function to convert between climatic data taken before and after the change. When the observing system is of sufficient scope and importance, the results of parallel testing should be documented in peer-reviewed literature.

3. Metadata: Fully document each observing system and its operating procedures. This is particularly important immediately prior to and following any contemplated change. Relevant information includes: instruments, instrument sampling time, calibration, validation, station location, exposure, local environmental conditions, and other platform specifics that could influence the data history. The recording should be a mandatory part of the observing routine and should be archived with the original data. Algorithms used to process observations need proper documentation. Documentation of changes and improvements in the algorithms should be carried along with the data throughout the archiving process.

4. Data Quality and Continuity: Assess data quality and homogeneity as a part of routine operating procedures. This assessment should focus on the requirements for measuring climate variability and change, including routine evaluation of the long-term, high-resolution data capable of revealing and documenting important extreme weather events.

5. Integrated Environmental Assessment: Anticipate the use of the data in the development of environmental assessments, particularly those pertaining to climate variability and change, as part of a climate observing system's strategic plan. National climate assessments and international assessments (e.g., international ozone or IPCC) are critical to evaluating and maintaining overall consistency of climate data sets. A system's participation in an integrated environmental monitoring program can also be quite beneficial for maintaining climate relevancy. Time series of data achieve value only with regular scientific analysis.

6. Historical Significance: Maintain operation of observing systems that have provided homogeneous data sets over a period of many decades to a century or more. A list of protected sites within each major observing system should be developed, based on their prioritized contribution to documenting the long-term record.

7. Complementary Data: Give the highest priority in the design and implementation of new sites or instruments within an observing system to data-poor regions, poorly observed variables, regions sensitive to change, and key measurements with inadequate temporal resolution. Data sets archived in non-electronic format should be converted for efficient electronic access.

8. Climate Requirements: Give network designers, operators, and instrument engineers climate monitoring requirements, at the outset of network design. Instruments must have adequate accuracy with biases sufficiently small to resolve climate variations and changes of primary interest. Modeling and theoretical studies must identify spatial and temporal resolution requirements.

9. Continuity of Purpose: Maintain a stable, long-term commitment to these observations, and develop a clear transition plan from serving research needs to serving operational purposes.

10. Data and Metadata Access: Develop data management systems that facilitate access, use, and interpretation of the data and data products by users. Freedom of access, low cost mechanisms that facilitate use (directories, catalogs, browse capabilities, availability of metadata on station histories, algorithm accessibility and documentation, etc.), and quality control should be an integral part of data management. International cooperation is critical for successful data management.

Appendix G: Selected Bibliography of Hydroclimate Research in Arctic Alaska

Arp, C.D., Jones, B.M., Schmutz, J.A., Urban, F.E., Jorgenson, M.T. in press. Two mechanisms of aquatic and terrestrial habitat change along an Alaska Arctic coastline. Polar Biology, doi:10.1007/s00300-1010-0800-5.

Arp, C.D., B.M. Jones, F.E. Urban, and G. Grosse. 2011, Hydrogeomorphic processes of thermokarst lakes with grounded-ice and floating-ice regimes on the Arctic Coastal Plain, Alaska. Hydrological Processes.Hydrological Processes 25(15):2422-2438.

Arp, C. D., B. M. Jones, M. Whitman, A. Larsen, and F. E. Urban. 2010. Lake temperature and ice cover regimes in the Alaskan Subarctic and Arctic: Integrated monitoring, remote sensing, and modeling. Journal of the American Water Resources Association, 46:777-791.

Atkinson, D.E., Hinzman L. 2008. Impact of the August 2000 storm on the soil thermal regime, Alaska North Slope. Conference Proceedings, Published Collection: Proceedings of the 9th International Conference on Permafrost, Fairbanks, Alaska, 29 June -3 July 2008: 65-70.

Balascio, N.L., Kaufman, D.S., and Manley, W.F., 2005. Equilibrium-line altitudes during the last glacial maximum across the Brooks Range, Alaska: Journal of Quaternary Science, v. 20, p. 821-838.

Balascio, N.L., Kaufman, D.S., Briner, J.P., and Manley, W.F., 2005. Late Pleistocene glacial geology of the of the Okpilak-Kongakut Rivers region, northeastern Brooks Range, Alaska: Arctic, Antarctic, and Alpine Research, v. 37, p. 416-424.

Beck, R.A., Rettig, A.J., Ivenso, C., Eisner, W.R., Hinkel, K.M., Jones, B.M., Arp, C.D., Grosse, G., Whiteman, D. 2010. Sikuliqiruq: Ice dynamics of the Meade River - Arctic Alaska, from Freezeup to Breakup from time-series ground imagery. Polar Geography 33:115-137.

Benning, J; Yang, D. 2007. Adjustment of Daily Precipitation Data at Barrow and Nome Alaska for 1995-2001. Arctic, Antarctic and Alpine Research. 37(3): 267-283.

Berezovskaya S.L., 2009. Uncertainty in snow depth measurements. 17th International Northern Research Basins Symposium and Workshop Iqaluit-Pangnirtung-Kuujjuaq, Canada, August 12 to 18, 2009

Berezovskaya S.L., G.E. Liston and D.L. Kane, 2009. Upper Kuparuk River Snow Distributions for hydrological analysis in Arctic Alaska. AWRA 2009 spring specialty conference, Anchorage, Alaska, 4-6 May 2009

Berezovskaya S. and D.L.Kane, 2007. Representativeness of snow water equivalent measurements for hydrological applications on Alaska's Arctic Slope. Proceedings of 7th International Conference on Global Change: Connections to the Arctic, 19-20 February 2007, Fairbanks, Alaska, USA

Berezovskaya S. and D.L.Kane, 2007. Measuring snow water equivalent for hydrological applications: part 1, accuracy of observations. 16th International Northern Research Basins Symposium and Workshop Petrozavodsk, Russia, 27 Aug. – 2 Sept. 2007

Berezovskaya, S., Hilton, K., Derry, J., Youcha, E., Kane, D., Gieck, R., Homan, J., and Lilly, M., 2010. Snow Survey Data for the Central North Slope Watersheds: Spring 2010. University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 10.01, Fairbanks, Alaska, 50 pp.

Berezovskaya, S., Derry, J., Kane, D., Gieck, R., and Lilly, M., 2010. Snow Survey Data for the Central north Slope Watersheds: Spring 2009. University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 09.01, Fairbanks, Alaska, 21 pp.

Berezovskaya, S.L., Derry, J.E., Kane, D.L., Lilly, M.R., and White, D.M., 2008. Snow Survey Data for the Sagavanirktok River Bullen Point Hydrology Study: Spring 2008. June 2008, University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 08.15, Fairbanks, Alaska, 30 pp. [Amended Figures 3 & 4 Aug. 26, 2008]

Berezovskaya, S.L., Derry, J.E., Kane, D.L., Geick, R.E., Lilly, M.R., and White, D.M., 2008. Snow Survey Data for the Kuparuk Foothills Hydrology Study: Spring 2008. June 2008, University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 08.14, Fairbanks, Alaska, 40 pp. [Amended Figures 3 & 4 Aug. 26, 2008]

Berezovskaya, S.L., Derry, J.E., Kane, D.L., Geick, R.E., Lilly, M.R., and White, D.M., 2007. Snow Survey Data for the Sagavanirktok River Bullen Point Hydrology Study: Spring 2007. July 2007, University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 07.18, Fairbanks, Alaska, 17 pp.

Berezovskaya, S.L., Derry, J.E., Kane, D.L., Geick, R.E., Lilly, M.R., and White, D.M., 2007. Snow Survey Data for the Kuparuk Foothills Hydrology Study: Spring 2007. July 2007, University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 07.17, Fairbanks, Alaska, 21 pp.

Bockheim, J.G., & Hinkel, K.M. (2005). Characteristics and significance of the transition zone in drained thaw-lake basins of the Arctic Coastal Plain, Alaska. Arctic, 58(4), 406, 417.

Boike, J., Hinzman, L. D., Overduin, P. P., Romanovsky, V. E., Ippisch, O., and K. Roth, A comparison of snow melt at three circumpolar sites: Spitsbergen, Siberia, Alaska. In: Permafrost, Phillips, M., Springman, S. and L. U. Arenson (eds), Swets & Zeitlinger, Lisse, pp. 79-84, 2003.

Bowden, W. B. , M. Gooseff, , A. Balser, L. Rogan, A. Green, B.J. Peterson and J. Bradford
2008. Sediment and nurtrient delivery from thermokarst features in the foothills of the North Slope, Alaska: Potential impacts on headwater stream ecosystems. J. Geophys. Res. 113, G02026, doi: 10.1029/2007JG000470.

Bowling, L.C., D.L. Kane, R.E. Gieck, L.D. Hinzman and D.P. Lettenmaier. 2003. The Role of Surface Storage in a Low-Gradient Arctic Watershed. Water Resources Research, 39(4): 1087, doi:10.1029/2002WR001466.

Bradford, J.H., J.P. McNamara, W.B. Bowden, and M.N. Gooseff. 2005. Measuring thaw depth beneath arctic streams using ground-penetrating radar. Hydrological Processes. 19: 2689–2699.

Brosten, T, JH Bradford, JP McNamara, JP Zarnetske, MN Gooseff, WB Bowden. 2006. Temporal thaw depth beneath two arctic stream types using ground-penetrating radar. Permafrost and Periglacial Processes. 17: 341–355. (DOI: 10.1002/ppp.566)

Byam, S.J., J. Cherry, N. Mölders, 2009. Coupled Atmosphere-Snow Modeling in the Arctic, Proceedings of the 17th Northern Research Basins Symposium.

Chapin, F.S., III, M. Sturm, M.C. Serreze, J.P. McFadden, J.R. Key, A.H. Lloyd, A.D. McGuire, T.S. Rupp, A.H. Lynch, J.P. Schimel, J. Beringer, H.E. Epstein, L.D. Hinzman, G. Jia, C.-L. Ping, K. Tape, W.L. Chapman, E. Euskirchen, C.D. Thompson, D.A. Walker, and J.M. Welker. 2005. Role of Land-Surface Changes in Arctic Summer Warming. Science 310:657-660.

Cherry, J.E., S. Déry, Y. Chen, M. Stieglitz, Climate and Hydrometeorology of the Toolik Lake Region and Kuparuk River Basin: Past, present and future, in *Toolik Lake Long Term Ecological Research Station,* ed. J. Hobbie, *in press* at Oxford University Press.

Cherry, J.E., L.-B. Tremblay, M. Stieglitz, G. Gong, S. Déry, Development of the Pan-Arctic Snowfall Reconstruction: new land-based solid precipitation estimates for 1940-1999. Journal of Hydrometeorology, Vol. 8, No. 6, 1243–1263.

Conover, J. H., 1960. Macro- and Microclimatology of the Arctic Slope of Alaska. U.S. Army, Environmental Protection Research Division, Technical Report EP-139.

Cooper, L.W, C. Solis, D.L. Kane, and L.D. Hinzman. 1993. Application of Oxygen-18 Tracer Technique to Arctic Hydrologic Processes. Arctic and Alpine Research, 25:3, 247-255.

Delcourt, Charlotte, Frank Pattyn, Matt Nolan, 2008. Modelling historical and recent mass loss of McCall Glacier, Alaska, USA. The Cryosphere 2:23-31.

DeMarco, J., Mack, M.C. and M.S. Bret-Harte, 2011. The effects of snow, soil microenvironment, and soil organic matter quality on N availability in three Alaskan Arctic plant communities. Ecosystems 14: 804-817, DOI: 10.1007/s10021-011-9447-5.

Edwardson, K.J., W.B. Bowden, C. Dahm, J. Morrice. 2003. The hydraulic characteristics and geochemistry of hyporheic and parafluvial zones in Arctic tundra streams, North Slope, Alaska. Advances in Water Resources 26:907-923.

Eisner, Wendy R., Bockheim, James G., Frohn, Robert C., Hinkel, Kenneth M., Peterson, Kim M., & Wolfe, Elizabeth S., 2003. Verification of the thaw-lake cycle using radiocarbon dating, north slope, Alaska. Proceedings of the Arctic System Science Program all-hands workshop 2002 101.

Euskirchen, S.E., Bret-Harte, M.S., Scott, G.J., Edgar, C. and G.R. Shaver, 2011. Seasonal patterns of carbon dioxide and water fluxes in three representative tundra ecosystems in the northern foothills of the Brooks Range, Alaska. Ecosphere, in press

Euskirchen, E.S., A.D. McGuire, T.S. Rupp, F.S. Chapin III, and J.E. Walsh. 2009. Projected changes in atmospheric heating due to changes in fire disturbance and the snow season in the western Arctic, 2003 – 2100. Journal of Geophysical Research – Biogeosciences 114, G04022, 15 pages, doi:10.1029/2009JG001095.

Euskirchen, E.S., A.D. McGuire, and F.S. Chapin III. 2007. Energy feedbacks of northern high-latitude ecosystems to the climate system due to reduced snow cover during 20th Century warming. Global Change Biology 13:2425-2438.

Everett, K.R., D.L. Kane and L.D. Hinzman. 1996. Surface Water Chemistry and Hydrology of a Small Arctic Drainage Basin. In: J. Reynolds and J. Tenhunen (eds) Landscape Function: Implications for Ecosystem Response to Disturbance. A Case Study in Arctic Tundra. Springer-Verlag, Ecologic Studies Series 120, pp. 185-201.

Fichefet, T., C. Dick, G. Flato, D. Kane and J. Moore. 2004. Progress in Understanding the Arctic Climate System. EOS, 85(16):159.

Francis, J. A., D. M. White, J. J. Cassano, W. J. Gutowski, L. D. Hinzman, M. M. Holland, M. A. Steele, and C. J. Vorosmarty (2009), An Arctic Hydrologic System in Transition: Feedbacks and Impacts on Terrestrial, Marine, and Human Life, J. Geophys. Res., doi:10.1029/2008JG000902.

Frohn, Robert C., Eisner, Wendy R., & Hinkel, Kenneth M., 2005. Satellite remote sensing classification of thaw lakes and drained thaw lake basins on the north slope of Alaska. Remote Sensing of Environment, 97(1), 116.

Gomersall, Claire E., & Hinkel, Kenneth M. (2001). Estimating the variability of active-layer thaw depth in two physiographic regions of northern Alaska. Geographical Analysis, 33(2), 141, 155.

Gooseff, M.N, A. Balser, W.B. Bowden, and J.B. Jones. 2009. Effects of Hillslope Thermokarst in Northern Alaska. Eos 90(4): 29-36. (27 January 2009)

Greenwald, M. J., W. B. Bowden, M. N. Gooseff, J. P. Zarnetske, J. P. McNamara, J. H. Bradford, and T. R. Brosten. 2008. Hyporheic exchange and water chemistry of two arctic tundra streams of contrasting geomorphology. J. Geophysical Research (Biogeosciences). doi:10.1029/2007JG000549.

Hall, D.K., Sturm, M., Benson, C.S., Chang, A.T.C., Foster, J.L., Garbeil, H. Chacho, E. 1991. Passive Microwave Remote and In Situ Measurements of Arctic and Sub-Arctic Snow Covers in Alaska. Remote Sensing of the Environment, 38(3): 161-172.

Hilton, K., Myerchin G., Van Breukelen, C., Schnabel W., and Lilly, M., 2010. Survey data for selected North Slope lakes and reservoirs from the Kuparuk River to Bullen Point: 2009. University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 09.05, Fairbanks, Alaska, 21 pp.

Hinkel, K. M., B. M. Jones, W. R. Eisner, C. J. Cuomo, R. A. Beck, and R. C. Frohn. 2007. Methods to assess natural and anthropogenic thaw lake drainage on the Western Arctic Coastal Plain of northern Alaska, J. Geophys. Res., 112, F02S16, DOI:10.1029/2006JF000584.

Hinkel, Kenneth M., & Hurd, John K., Jr. (2006). Permafrost destabilization and thermokarst following snow fence installation, Barrow, Alaska, U.S.A. Arctic, Antarctic, and Alpine Research, 38(4), 530, 539.

Hinkel, Kenneth M., Beck, R.A., Eisner, W.R., Frohn, R.C., & Nelson, F.E. (2005). Morphometric and spatial analysis of thaw lakes and drained thaw lake basins in the western Arctic Coastal Plain, Alaska. Permafrost and Periglacial Processes, 16(4), 327, 341.

Hinkel, K.M., & Nelson, F.E. (2003). Spatial and temporal patterns of active layer thickness at Circumpolar Active Layer Monitoring (CALM) sites in northern Alaska, 1995-2000. Journal of Geophysical Research, D, Atmospheres, 108(2), 13.

Hinkel, K.M., Klene, A.E., & Nelson, F.E. (2002). Letneye temperaturnoye pole vozdukha v rayone barrou (alyaska); predvaritel'nyye resul'taty--the summer air temperature field near Barrow, Alaska; Preliminary results. Extreme phenomena in cryosphere; basic and applied aspects; International conference abstracts--Ekstremal 139, 140, 294-295.

Hinkel, K.M., Bockheim, J.G., Doolittle, J.A., Kimble, J.M., Nelson, F.E., Paetzold, R., & Travis, R. (2001). Detection of subsurface permafrost features with ground-penetrating radar, Barrow, Alaska. Permafrost and Periglacial Processes, 12(2), 179, 190.

Hinkel, Kenneth M., Eisner, Wendy R., Miller, Laura L., Nelson, Frederick E., Outcalt, Samuel I., Peterson, Kim M., & Turner, Katie M. (1996). Formation of injection frost mounds over winter 1995-1996 at Barrow, Alaska. Polar Geography (1995), 20(4), 235, 248.

Hinkel, K.M., Brown, Jerry, Everett, Kaye R., Nelson, F.E., & Shur, Y. (1996). Temporal changes in moisture content of the active layer and near-surface permafrost at Barrow, Alaska, U.S.A.; 1962-1994. Arctic and Alpine Research, 28(3), 300, 310.

Hinkel, K.M., Nelson, F.E., & Outcalt, S.I. (1990). Temperature variation and apparent thermal diffusivity in the refreezing active layer, Toolik Lake, Alaska. Permafrost and Periglacial Processes, 1(3), 265, 274.

Hinkel, K.M., Jones, B.M., Eisner, W.R., Cuomo, C.J., Beck, R.A. & Frohn, R. (2007). Methods to assess natural and anthropogenic thaw lake drainage on the western Arctic Coastal Plain of northern Alaska. Journal of Geophysical Research-Earth Surface, 112, F02S16, doi:10.1029/2006JF000584

Hinzman, L.D. N.D. Bettez, W. R. Bolton, F. S. Chapin, M. B. Dyurgerov, C. L. Fastie, B. Griffith, R. D. Hollister, A. Hope, H. P. Huntington, A. M. Jensen, G. J. Jia, T. Jorgenson, D. L. Kane, D. R. Klein, G. Kofinas, A. H. Lynch, A. H. Lloyd, A. D. McGuire, F. E. Nelson, M. Nolan, W. C. Oechel, T. E. Osterkamp, C. H. Racine, V. E. Romanovsky, R. S. Stone, D. A. Stow, M. Sturm, C. E. Tweedie, G. L. Vourlitis, M. D. Walker, D. A. Walker, P. J. Webber, J. Welker, K. S. Winker, K. Yoshikawa. 2005. Evidence and Implications of Recent Climate Change in Northern Alaska and Other Arctic Regions. Climatic Change. 72(3):251-298.

Hinzman, L.D., D.L. Kane, K. Yoshikawa, A. Carr, W.R. Bolton and M. Fraver. 2003. Hydrological Variations Among Watersheds with Varying Degrees of Permafrost. Proceedings of the 8th International Conference on Permafrost, Zurich, Switzerland, 21-25 July 2003, Phillips, M., et al.(eds), A.A. Balkema Publishers, pp. 407-411.

Hinzman, L.D., D.L. Kane, and K. Yoshikawa. 2003. Soil Moisture Response to a changing climate in arctic regions. Tôhoku Geophysical Journal. 36(4):369-373.

Hinzman, L, Wegner M, Lilly MR. 2000. Hydrologic Investigations of Ground-water and Surface-water Interactions in Subarctic Alaska. Nordic Hydrology. 4:339-356.

Hinzman, L.D., D.J. Goering and D.L. Kane. 1998. A Distributed Thermal Model for Calculating Temperature Profiles and Depth of Thaw in Permafrost Regions. Journal of Geophysical Research–Atmospheres, 103(D22):28,975-28,991

Hinzman, L.D., D.J. Goering, S. Li and T.C. Kinney. 1997. Numeric Simulation of Thermokarst Formation During Disturbance. Crawford, R. M. M. Ed., Disturbance and recovery in Arctic lands: an ecological perspective Kluwer Academic Publishers, pp. 621. Dordrecht, the Netherlands. ISBN : 0-7923-4418-9 NATO Advanced Science Institutes Series: (NATO ASI) Partnership Sub-Series: 2 Environment Volume No. 25.

Hinzman, L.D., D.L. Kane, C.S. Benson and K.R. Everett. 1996. Thermal and Hydrologic Processes in the Imnavait Creek Watershed. In: J. Reynolds and J. Tenhunen (eds), Landscape Function: Implications for Ecosystem Response to Disturbance. A Case Study in Arctic Tundra. Springer-Verlag, Ecologic Studies Series 120, pp. 131-154.

Hinzman, L.D. and D.L. Kane. 1992. Potential Response of an Arctic Watershed during a Period of Global Warming. Journal of Geophysical Research, 97(03):2811-2820.

Hinzman, L.D., and D.L. Kane. 1991. Snow Hydrology of a Headwater Arctic Basin. 2. Conceptual Analysis and Computer Modeling. Water Resources Research, 27(6):1111-1121.

Hinzman, L.D., D.L. Kane, C.S. Benson, and K.R. Everett. 1991. Hydrologic and Thermal Properties of the Active Layer in the Alaskan Arctic. Cold Regions Science and Technology, 19(2):95-110.

Hinzman, L., Toniolo, H., Yoshikawa, K. and Jones, J. Thermokarst development in a changing climate. ACIA International Symposium on Climate Change in the Arctic . Reykjavik , Iceland . 2004

Hinzman, L.D. M.A. Nolan, D.L. Kane, C.S. Benson, M. Sturm, G.E. Liston, J.P. McNamara, A.T. Carr and D. Yang. 2000. Estimating Snowpack Distribution over a Large Arctic Watershed. In D.L. Kane (ed) Water Resources in Extreme Environments. American Water Resources Association Proceedings. 1-3 May 2000. Anchorage, AK p. 13-18.

Hinzman, L.D. and D.L. Kane. 1992. Climatic Change Impacts on Water Resources in Arctic Alaska. Northern Research Basins Conference. Whitehorse, YT Canada.

Hinzman, L.D., G. Wendler, R.E. Gieck, and D.L. Kane. 1992. Snowmelt at a small Alaskan arctic watershed 1. energy related processes. Northern Research Basins Conference. Whitehorse, YT Canada.

Hinzman, L.D., D.L. Kane and R.E. Gieck. 1991. Regional snow ablation in the Alaskan Arctic. in Northern Hydrology, Selected Perspectives, NHRI Symposium No. 6, eds. T.D. Prowse and C.S.H. Ommanney. Pub. by National Hydrology Research Institute. Saskatoon, Saskatchewan. p. 121-140.

Hinzman, L.D., Lilly, M.R., Kane, D.L., Miller, D.D., Galloway, B.K., Hilton, K.M., and White, D.M. 2006. Physical and chemical implications of Mid-Winter Pumping of Tundra Lakes - North Slope, Alaska. December 2006, University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 06.15, Fairbanks, Alaska, 152 pp. plus appendices.

Hobbie, J. E., B. J. Peterson, N. Bettez, L. A. Deegan, W. J. O'Brien, G. W. Kling, and G.W. Kipphut. 1999. Impact of global change on biogeochemistry and ecosystems of arctic freshwaters. Polar Research. 18:207-214.

Hobbie, J.E., L. A. Deegan, B. J. Peterson, E. B. Rastetter, G. R. Shaver, G. W. Kling, W. J. O'Brien, F. S. Chapin, M. C. Miller, G. W. Kipphut, W. B. Bowden, A. E. Hershey and M.E. McDonald. 1995. Long-term measurements at the Arctic LTER site, pp. 391-409. In: T. M. Powell and J. H. Steele (eds.). Ecological Times Series. Chapman and Hall, New York.

Hobbie, J. E., B. J. Peterson, G. R. Shaver and W. J. O'Brien. 1991. The Toolik Lake Project: Terrestrial and freshwater research on change in the Arctic. Proceedings of a University of Alaska Conference, "International Conference on the Role of the Polar Regions in Global Change", June 1990, Volume II: 378-383.

Holland, K., Reichardt, D., Cormack, C., Derry, J., Myerchin, G., Toniolo, H., and Lilly, M.R. 2008. Snowmelt and Lake Recharge Monitoring for Selected North Slope, Alaska, Lakes: May/June 2008.. University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 08.13, Fairbanks, Alaska, 15 pp.

Holland, K.M., Lilly, M.R., Schnabel, W., Toniolo, H., and Prokein, P., 2010. An Overview of Available Research Results Related to Lakes Located within the Arctic Coastal Plain and North Slope Foothills Region, 2009. University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 09.04, Fairbanks, Alaska, 27 pp.

Holland, K.M., Reichardt, D., Cormack, C., Derry, J., Myerchin, G., Toniolo, H., and Lilly, M.R. 2008. Snowmelt and lake recharge monitoring for selected North Slope, Alaska, lakes: May/June 2007. University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 07.21, Fairbanks, Alaska, 11 pp.

Jonas, Tobias, C. Rixen, M. Sturm, V. Stoeckli. 2008. How alpine plant growth is linked to snow cover and climate variability. J. of Geophysical Research, 113, G03013, doi 10.1029/2007JG000680.

Jones, B. M., C. D. Arp, K. M. Hinkel, R. A. Beck, J. A. Schmutz, and B. Winston. 2009. Arctic lake physical processes and regimes and implications on winter water availability and management in the National Petroleum Reserve Alaska. Environmental Management 43(6):1071-1084, DOI 10.1007/s00267-008-92410-0.

Jones, B.M., Arp, C.D., Beck, R.A., Grosse, G., Webster, J., and Urban, F.E. 2009. Erosional history of Cape Halkett and contemporary monitoring of bluff retreat, Beaufort Sea coast, Alaska. Polar Geography, 32:129-142.

Jones, B.M., Arp, C.D., Jorgenson, M.T., Hinkel, K.M., Schmutz, J.A., and Flint, P.L. 2009. Increase in the rate and uniformity of coastline erosion in Arctic Alaska. Geophysical Research Letters 36: 1-5.

Jones, B.M., K.M. Hinkel, C.D. Arp, W.R. Eisner. 2008. Modern erosion rates and loss of coastal features and sites, Beaufort Sea coastline, Alaska. Arctic, 61(4):361-372.

Jorgenson M.T., V.E. Romanovsky, J.W. Harden, Y. Shur, J.A. O'Donnell, E.A.G. Schuur, M.Z. Kanevskiy. 2010. Resilience and vulnerability of permafrost to climate change. Canadian Journal of Forest Research 40: 1219-1236, doi: 10.1139/X10-060.

Jorgenson, T and Y. Shur. 2007. Evolution of lakes and basins in northern Alaska and discussion of the thaw lake cycle. Geophysical Research Letters. 112. DOI: 10.1029/2006JF000531.

Kane, D.L., R.E. Gieck and L.D. Hinzman. 2008. Water Balance for a Low-Gradient Watershed in Northern Alaska. In: Proceedings of Ninth International Conference on Permafrost, D.L. Kane and K.M. Hinkel (Eds.), University of Alaska, Institute of Northern Engineering, pp. 883-888.

Kane, D.L., L.D. Hinzman, R.E. Gieck, J.P. McNamara, E. Youcha and J.A. Oatley. 2008. Contrasting Extreme Runoff Events in Areas of Continuous Permafrost, Arctic Alaska. Hydrology Research, 38(4):287-298.

Kane, D. L., and D. Yang. 2004. Overview for Water Balance Determinations for High Latitude Watersheds. Int. Assoc. of Hydrological Sciences Publication 290. pp. 1-12.

Kane, D. L. R. E. Gieck, D. C. Kitover, L. D. Hinzman, J. P. McNamara and D. Yang. 2004. Hydrologic Cycle on the North Slope of Alaska. Int. Association of Hydrological Sciences Publication 290, pp. 224-236.

Kane, D. L. and L. D. Hinzman. 2004. Monitoring Extreme Environments: Arctic Hydrology in Transition. Water Resources Impact, 6(1):24-27.

Kane, D.L., J.P. McNamara, D. Yang, P.Q. Olsson and R.E. Gieck. 2003. An Extreme Rainfall/Runoff Event in Arctic Alaska. Journal of Hydrometeorology, 4(6):1220-1228.

Kane, D.L., L.D. Hinzman, J.P. McNamara, Z. Zhang and C.S. Benson. 2000. An Overview of a Nested Watershed Study in Arctic Alaska. Nordic Hydrology, 4/5:245-266.

Kane, D. L. 1997. The Impact of Arctic Hydrologic Perturbations on Arctic Ecosystems Induced by Climate Change. In: Oechel, W. C., Global Change and Arctic Terrestrial Ecosystems, Springer-Verlag, Ecological Studies 124, pp. 63-81.

Kane, D.L., Gieck, R.E., and Hinzman, L.D. (1997) Snowmelt Modeling at a Small Alaskan Arctic Watershed Journal of Hydrologic Engineering, Vol. 2(4), pp. 204-210.

Kane, D.L., L.D. Hinzman, H. Yu and D.J. Goering. 1996. The Use of SAR Satellite Imagery to Measure Active Layer Moisture Contents in Arctic Alaska. Nordic Hydrology, 27:25-38. Remote Sensing

Kane, D.L., L.D. Hinzman, M.K. Woo, and K.R. Everett. 1992. Arctic Hydrology and Climate Change. In Arctic Ecosystems in a Changing Climate: An Ecophysiological Perspective. F. Chapin, R. Jeffries, J. Reynolds, G. Shaver, and J. Svoboda (eds). Academic Press, Inc. pp. 35-57.

Kane, D.L., L.D. Hinzman and J.P. Zarling. 1991. Thermal Response of the Active Layer in a Permafrost Environment to Climatic Warming. Cold Regions Science and Technology, 19:111-122.

Kane, D.L., L.D. Hinzman, C.S. Benson and G. E. Liston. 1991. Snow Hydrology of a Headwater Arctic Basin 1, Physical Measurements and Process Studies. Water Resources Research, 27(6):1099-1109.

Kane, D.L., R.E. Gieck, and L.D. Hinzman. 1990. Evapotranspiration from a Small Alaskan Arctic Watershed. Nordic Hydrology, 21:253-272.

Kane, D.L., and E.F. Chacho. 1990. Frozen Ground Effects on Infiltration and Runoff. In: Cold Regions Hydrology and Hydraulics, W.L. Ryan and R.D. Crissman (eds). American Society of Civil Engineers, New York, New York. pp. 259-300. Scale?

Kane, D.L., L.D. Hinzman, C.S. Benson, and K.R. Everett. 1989. Hydrology of Imnavait Creek, an arctic watershed. Holarctic Ecology, 12:262-269.

Kane, D.L., and J. Stein. 1984. Plot measurements of snowmelt runoff for varying soil conditions. Geophysica. 20(2):123-136.

Kane, D.L., and J. Stein. 1983. Water movement into seasonally frozen soils. Water Resources Research. 19(6):1547-1557.

Kane, D.L. 1980. Snowmelt infiltration into seasonally frozen soils. Cold Regions Science and Technology. Vol. 3, pp. 153-161.

Kane D.L. and S. Berezovskaya, 2007. Strategies for measuring snow water equivalent for hydrological application: part 2, spatial distribution at the watershed scale. 16th

International Northern Research Basins Symposium and Workshop, 27 Aug. – 2 Sept. 2007, Petrozavodsk, Russia

Kane, D.L., R.E. Gieck and L.C. Bowling. 2003. Impacts of Surficial Permafrost Landforms on Surface Hydrology. Proceedings of the 8th International Conference on Permafrost, Zurich, Switzerland, 21-25 July 2003, Phillips, M., et al.(eds), A.A. Balkema Publishers, pp. 507-512.

Kane, D.L., L.D. Hinzman, and E.K. Lilly. 1993. Use of Spatially Distributed Data to Model Arctic Hydrologic Processes. Sixth International Conference on Permafrost, Beijing, China. pp.326-331.

Kane, D.L. L.D. Hinzman, H. Yu and D.J. Goering. 1994. The Use of SAR satellite imagery to measure active layer moisture contents in Arctic Alaska. Tenth International Northern Research Basins Symposium and Workshop. Spitsbergen, Norway. August 28- September 3, 1994.

Kane, D., White, D., Lilly, M., Toniolo, H., Berezovskya, S., Schnabel, W., Youcha, E., Derry, J., Gieck, R., Paetzold, R., Trochim, E., Remillard, M., Busey, R., and Holland, K., 2009. Meteorological and Hydrological Data and Analysis Report for Bullen Point and Foothills Projects: 2006–2008. University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 08.18, Fairbanks, Alaska, 180 pp.

Kane, D.L., Berezovskaya, S., Irving, K., Busey, R., Chambers, M., Blackburn, A.J., and Lilly, M.R., 2006. Snow survey data for the Sagavanirktok River / Bullen Point Hydrology Study: Spring 2006. July 2006, University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 06-03, Fairbanks, Alaska, 10 pp.

Kane, D.L., Berezovskaya, S., Irving, K., Busey, R., Chambers, M., Blackburn, A.J., and Lilly, M.R., 2006. Snow survey data for the Kuparuk Foothills Hydrology Study: Spring 2006. July 2006, University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 06-06, Fairbanks, Alaska, 12 pp.

Klok, Lisette, Matt Nolan, and Michiel van den Broeke, 2006. Analysis of meteorological data and the surface energy balance of McCall Glacier, Alaska. Journal of Glaciology, 51 (174): 451-461.

Klene, Anna E., Hinkel, Kenneth M., Nelson, Frederick E., & Shiklomanov, Nikolay I. (2001). The n-factor in natural landscapes; variability of air and soil-surface temperatures, Kuparuk river basin, Alaska, U.S.A. Arctic, Antarctic, and Alpine Research, 33(2), 140, 148.

Knudson, J.A., and L.D. Hinzman. 2000. Prediction of streamflow in an Alaskan watershed underlain by permafrost. In D.L. Kane (ed) Water Resources in Extreme Environments. American Water Resources Association Proceedings. 1-3 May 2000. Anchorage, AK p. 309-313.

Kriet, K., B. J. Peterson and T. L. Corliss. 1992. Water and sediment export of the upper Kuparuk River drainage of the North Slope of Alaska. Hydrobiologia 240: 71-81.

Lammers, R. B., A. I. Shiklomanov, C. J. Vorosmarty, B. M. Fekete, and B. J. Peterson. 2001, Assessment of contemporary Arctic river runoff based on observational discharge records. J. Geophys. Res. 106:3321-3334.

Lilly, E.K., D.L. Kane, R.E. Gieck and L.D. Hinzman. Annual Water Balance for Three Nested Watersheds on the North Slope of Alaska. Seventh International Conference on Permafrost. Yellowknife, Canada. June 1998.

Lilly, M. R., Reichardt, D., and Derry, J., 2007. Mine Site B (6 Mile Lake) Water-Level and Use Observations, October 2005 through March 2007. North Slope Lake Project Hydrologic Notes, May 3. Water and Environmental Research Center, University of Alaska Fairbanks, 3 p.

Lilly, M. R., Reichardt, D., and Derry, J., 2007. Kuparuk Deadarm Reservoirs, Cells 1-3 Water-Level Observations. North Slope Lakes Project Hydrologic Notes, February 15. Water and Environmental Research Center, University of Alaska Fairbanks, 1 p.

Lilly, M. R., and Reichardt, D. A., 2007. Lake L9312 Water Levels, Monthly Water-Use and Cumulative Annual Permit Accounting. North Slope Lakes Project Hydrologic Notes, January 13. Water and Environmental Research Center, University of Alaska Fairbanks, 2 p.

Lilly, M.R., Reichardt, D., Derry, J., and White, D.M., 2006. Measurements of Hydrologic Gradients and Watershed Boundaries in Low-Relief Tundra Plain Lake Watersheds. North Slope Lakes Project Hydrologic Notes, September 19, Water and Environmental Research Center, University of Alaska Fairbanks, 3 p.

Lilly, M.R., 2006. Mine Site B (6 Mile Lake) Water-Level Observations. North Slope Lakes Project Hydrologic Notes, May 23, Water and Environmental Research Center, University of Alaska Fairbanks, 1 p.

Lilly, M.R., 2006. Kuparuk Deadarm Reservoirs, Cells 1-3 Water-Level Observations. North Slope Lakes Project Hydrologic Notes, April 16, Water and Environmental Research Center, University of Alaska Fairbanks, 1 p.

Liljedahl A., Hinzman L., Marchenko S., and S. Berezovskaya, 2008. The Effect of Spatially Distributed Snow Cover on Soil Temperatures: A Field and Modeling Study. Ninth International Conference on Permafrost, Fairbanks, Alaska, June 29 – July 3, 2008

Liljedahl A.K., Hinzman L.D., Harazono Y., Zona D., Tweedie C.E.,Hollister R.D., Engstrom R., Oechel W.C., Nonlinear controls on evapotranspiration in Arctic coastal wetlands, Biogeosciences, 8, 6307-6344, 2011

Liston, G. E., and M. Sturm, 2004: The role of winter sublimation in the Arctic moisture budget. Nordic Hydrology, 35(4), 325-334.

Liston, G. E. and M. Sturm. 2002. Winter precipitation patterns in arctic Alaska determined from a blowing snow model and snow depth observations. J. of HydroMeteorology, 3(5), 646-659.

Liston, G. E., J. P. McFadden, M. Sturm, and R. A. Pielke, Sr., 2002: Modeled changes in arctic tundra snow, energy, and moisture fluxes due to increased shrubs. Global Change Biology, 8, 17-32.

Lynch, A. H., F. S. Chapin III, L.D. Hinzman, W. Wu, E. Lilly, G. Vourlitis, E. Kim. 1998. Surface Energy Balance on the Arctic Tundra: Measurements and Models. Journal of Climate. 12(8):2585-2606. (relevance)

Martin, Philip D., Jennifer L. Jenkins, F. Jeffrey Adams, M. Torre Jorgenson, Angela C. Matz, David C. Payer, Patricia E. Reynolds, Amy C. Tidwell, and James R. Zelenak. 2009. *Wildlife Response to Environmental Arctic Change: Predicting Future Habitats of Arctic Alaska*. Report of the Wildlife Response to Environmental Arctic Change (WildREACH): Predicting Future Habitats of Arctic Alaska Workshop, 17-18 November 2008. Fairbanks, Alaska: U.S. Fish and Wildlife Service. 138 pages.

McFadden, J. P., G. E. Liston, M. Sturm, R. A. Pielke, Sr., F. S. Chapin, III, 2001: Interactions of shrubs and snow in arctic tundra: measurements and models. In: Soil, Vegetation, Atmosphere Transfer Schemes and Large-Scale Hydrological Models, IAHS, Publication No. 270, 317-325.

McGuire, A.D., M. Apps, J. Beringer, J. Clein, H. Epstein, D.W. Kicklighter, C. Wirth, J. Bhatti, F.S. Chapin III, B. de Groot, D. Efremov, W. Eugster, M. Fukuda, T. Gower, L. Hinzman, B. Huntley, G.J. Jia, E. Kasischke, J. Melillo, V. Romanovsky, A. Shvidenko, E. Vaganov, and D. Walker. Environmental variation, vegetation distribution, carbon dynamics, and water/energy exchange in high latitudes, Journal of Vegetation Science, Vol. 13: 301-314, 2002. (relevance)

McNamara, J.P. and D.L. Kane, 2009. The Impact of Shrinking Cryosphere on the Form of Arctic Alluvial Channels. Hydrological Processes, 23:159-168.

McNamara, J.P., J.A. Oatley, L.D. Hinzman and D.L. Kane. 2008. Case Study of a Large Summer Flood on the North Slope of Alaska: Bedload Transport. Hydrology Research, 38(4):299-308.

McNamara, J.P., D.L. Kane and L.D. Hinzman. 1999. An Analysis of an Arctic Channel Network Using a Digital Elevation Model. Geomorphology, 29:339-353. Remote Sensing

McNamara, J. P., D. L. Kane, and L. D. Hinzman. 1998. Hydrograph separations in an Arctic watershed using mixing model and graphical techniques. Water Resources Research, 33(7): 1707-1719. (relevance)

McNamara, J. P., D. L. Kane and L. D. Hinzman. 1998. An Analysis of Stream Flow Hydrology in the Kuparuk River Basin, Arctic Alaska: A Nested Watershed Approach. Journal of Hydrology, 206:39-57.

McNamara, J. P., D. L. Kane and L. D. Hinzman. 1997. Storm Flow Dynamics in a Nested Arctic Watershed. Water Resources Research, 33(7):1707-1719.

Mendez, J., L.D. Hinzman, D.L. Kane. 1998. Evapotranspiration from a Wetland Complex on the Arctic Coastal Plain of Alaska. Nordic Hydrology, 29(4/5):303-330.

Meyer, H., L. Schirrmeister, K. Yoshikawa, T. Opel, S. Wetterich, Hans-W. Hubberten, and J. Brown (2010), Permafrost evidence for severe winter cooling during the Younger Dryas in northern Alaska, Geophys. Res. Lett., 37, L03501, doi:10.1029/2009GL041013.

Miller, GH, Brigham-Grette J, Anderson L, Bauch D, Douglas MA, Edwards ME, Elias S, Finney BP, Funder S, Herbert T et al.. 2009. Temperature and Precipitation History of the Arctic. Past Climate Variability and Change in the Arctic and at High Latitudes. A report by the Climate, Change, U.S. Program and Subcommittee on Global Change, Research. Geological, Survey, U.S., Reston.

Miller, L.L., Allard, Michel, editor, Hinkel, K.M., Nelson, F.E., Outcalt, S.I., & Paetzold, R.F. (1998). Spatial and temporal patterns of soil moisture and thaw depth at Barrow, Alaska, U.S.A. Collection Nordicana, 57, 731, 737.

Mölders, N. and V.E. Romanovsky, Long-term evaluation of HTSVS' frozen ground/permafrost component using observations at Barrow, Alaska. J. Geophys. Res., 111: doi:10.1029/2005JD005957, 2006.

Morton, D., Z. Zhang, L.D. Hinzman and S. O'Conner. 1998. The Parallelization of a Physically Based, Spatially Distributed Hydrologic Code for Arctic Regions. Proceedings of the Symposium on Applied Computing. Atlanta, GA. 27 February - 1 March, 1998. Pp 684-689.

Munroe, J.S., J.A. Doolittle, M.Z. Kanevskiy, K.M. Hinkel, B.M. Jones, Y. Shur, F.E. Nelson, and J. M. Kimble. 2007. Application of Ground-Penetrating Radar Imagery for the Three-Dimensional Visualization of Near-Surface Structures in Ice-Rich Permafrost, Barrow, Alaska. Permafrost and Periglacial Processes 18(4):309-321.

Nelson, F.E., Allard, Michel, editor, Brown, J., Hinkel, K.M., Outcalt, S.I., & Shiklomanov, N.I. (1998). Spatial and temporal attributes of the active-layer thickness record, Barrow, Alaska, U.S.A. Collection Nordicana, 57, 797, 802.

Nelson, F.E., Bockheim, J.G., Hinkel, K.M., Mueller, G.R., Shiklomanov, N.I., & Walker, D.A. (1997). Estimating active-layer thickness over a large region; Kuparuk river basin, Alaska, U.S.A. Arctic, Antarctic, and Alpine Research, 29(4), 367, 378.

Nelson, F.E., N. I. Shiklomanov, and D. A. Streletskiy, V. E. Romanovsky and K. Yoshikawa, K. M. Hinkel, and J. Brown, 2008, A Permafrost Observatory at Barrow, Alaska: Long-term Observations of Active-Layer Thickness and Permafrost Temperature, . Kane, D.L. & Hinkel, K.M. (eds). 2008. Ninth International Conference on Permafrost. Institute of Northern Engineering, University of Alaska Fairbanks (2 Vols.), 2140 pp. p1267-1272.

Nolan, Matt, Anthony Arendt, Bernhard Rabus, and Larry Hinzman, 2005. Volume change of McCall Glacier, Arctic Alaska, from 1956 to 2003. Annals of Glaciology, 42: 409-416.

Nolan, Matt, 2003. The Galloping Glacier Trots: Decadal-scale speed oscillations in the quiescent phase. Annals of Glaciology, 36, p7-13.

Nolan, Matt, and Peter Prokein, 2003. Evaluation of a new DEM of the Putuligayuk Watershed for Arctic hydrological applications. 8th International Permafrost Conference, Zurich, Switzerland, July 2003.

Oechel, W.C., G.L. Vourilitis, S.J. Hastings, R.M. Zulueta, L.D. Hinzman and D.L. Kane. 2000. Acclimation of Ecosystem CO2 Exchange in the Alaskan Arctic in Response to Decadal Climatic Warming. Nature, 406(Aug. 31):978-981.

Olsson, P., Sturm, M., Racine, C., Romanovsky, V., and G. Liston, Five Physically-defined Stages of the Alaskan Arctic Cold Season and some Ecosystem Implications, Arctic, Antarctic and Alpine Research, Vol 35, No. 1, 74-81, 2003.

Osterkamp, T. E., Romanovsky, V. E., Zhang, T. and Gruol, V., Permafrost in Alaska: Warming, Thawing and Impacts, EOS, Trans. AGU, 82 (47), Fall Meet. Suppl., Abstract, F546, 2001.

Osterkamp, T. E., Romanovsky, V. E., Zhang, T., Gruol, V., Peterson, J. K., Matava, T., and Baker G. C., A History of Continuous Permafrost Conditions in Northern Alaska, EOS, Trans. AGU, 79(45), F833, 1998.

Osterkamp, T.E., and V.E. Romanovsky, Freezing of the active layer on the Coastal Plain of the Alaskan Arctic, Permafrost and Periglacial Processes, 8(1), 23-44,1997.

Osterkamp, T.E. and V.E. Romanovsky, Characteristics of changing permafrost temperatures in the Alaskan Arctic, Arctic and Alpine Res. 28(3), 267-273, 1996.

Osterkamp, T.E., T. Zhang, and V.E. Romanovsky, Evidence for a cyclic variation of permafrost temperatures in northern Alaska, Permafrost and Periglacial Processes, 5, 137-144, 1994.

Outcalt, Samuel I., Hinkel, Kenneth M., & Nelson, Frederick E. (1992). Spectral signature of coupled flow in the refreezing active layer, northern Alaska. Physical Geography, 13(3), 273, 284.

Pattyn, F., Matt Nolan, and Bernhard Rabus, 2005. Localized basal motion of a polythermal Arctic glacier: McCall Glacier, Alaska, U.S.A. Annals of Glaciology, 40: 47-51.

Paetzold, R. F., Hinkel, K. M., Nelson, F. E., Osterkamp, T. E., Ping, C. L., and V. E. Romanovsky, Temperature and Thermal Properties of Alaskan Soils, in Advances in Soil Science: Global climate change and cold regions ecosystems/ edited by R. Lal, J. M. Kimble, B. A. Stewart, Lewis Publishers, pp. 223-245, 2000.

Ravens, T. M., B. M. Jones, J. Zhang, C. D. Arp, J. A. Schmutz. 2011. Process based coastal erosion modeling for Drew Point (North Slope, Alaska), Journal of Waterway, Port, Coastal, and Ocean Engineering, Online First, DOI:10.1061/(ASCE)WW.1943-5460.0000106.

Rawlins, MA, Steele M, Holland M, Adam JC, Cherry JE, Francis JA, Groisman P, Hinzman L, Huntington TG, Kane DL et al.. 2010. Analysis of the Arctic System for Freshwater Cycle Intensification: Observations and Expectations. Journal of Climate. 23:5715-5737.

Romanovsky, V.E., and T.E. Osterkamp, Thawing of the active layer on the coastal plain of the Alaskan Arctic, Permafrost and Periglacial Processes, 8(1), 1-22, 1997.

Romanovsky, V. E. and Osterkamp, T. E., Interannual variations of the thermal regime of the active layer and near-surface permafrost in Northern Alaska. Permafrost and Periglacial Processes, 6(4), 313-335, 1995.

Romanovsky, V.E. and T.E. Osterkamp, Numerical modeling of active layer thicknesses and permafrost temperature dynamics in Barrow, Alaska: 1949-1996, EOS, Trans. AGU, 77(46) F188, 1996.

Romanovsky, V. E. and Osterkamp, T. E., Modeling of the permafrost temperature dynamics and active layer thawing and freezing at Prudhoe Bay, Alaska. EOS, Transactions, American Geophysical Union, 76(46), 237-238, 1995.

Romanovsky, V. E. and Osterkamp, T. E., Temporal and spatial behavior of the active layer in the Northern Alaska: 1986-1993. EOS, Transactions, American Geophysical Union, 75(44), p. 86, 1994.

Rovansek, R. J., L. D. Hinzman and D. L. Kane. 1996. Hydrology of a Tundra Wetland Complex on the Alaskan Arctic Coastal Plain. Arctic and Alpine Research, 28(3):311-317.

Rovansek, R.J., D.L. Kane and L.D. Hinzman. 1993. Improving Estimates of Snowpack Water Equivalent Using Double Sampling. Proceedings: Fiftieth Annual Eastern Snow Conference, Quebec City, Quebec. pp.157-164.

Rowland, J., Jones, C., Altmann, G., Bryan, R., Crosby, B., Geernaert, G, Hinzman, L, Kane, D., Lawrence, D., Mancino, A., Marsh, P., McNamara, J., Romanosky, V., Toniolo, H., Travis, B., Trochim, E, and Wilson, C. Arctic landscapes in transition: Responses to thawing permafrost. EOS, Vol. 91, No 26, (2010) 229 - 230.

Schramm, I, Boike J, Bolton WR, Hinzman L. 2007. Application of TopoFlow, a spatially distributed hydrological model, to the Imnavait Creek watershed, Alaska. Journal of Geophysical Research (Biogeosciences). 112:G04S46.

Shiklomanov, N. I., D.A. Streletskiy, F. E. Nelson, R.D. Hollister, V.E. Romanovsky, C.E. Tweedie, J.G. Bockheim, and J. Brown, Decadal variations of active-layer thickness in moisture-controlled landscapes, Barrow, Alaska, Journal of Geophysical Research, Biogeosciences, VOL. 115, G00I04, doi:10.1029/2009JG001248, 2010.

Shiklomanov, I. A., A. I. Shiklomanov, R. B. Lammers, B. J. Peterson, and C. J. Vorosmarty. 1999. The dynamics of river water inflow to the Arctic Ocean, in: The Freshwater Budget of the Arctic Ocean. Kluwer Academic Publishers, Netherlands.

Sibley, P.K, White, D.M., and Lilly, M.R. 2008. Introduction to Water Use from Arctic Lakes: Identification, Impacts, and Decision Support. Journal of the American Water Resources Association (JAWRA) 44(2): 273-275.

Sikorski, J.J., Kaufman, D.S., Manley, W.F., and Nolan, M., 2009. Glacial-geologic evidence for
decreased precipitation during the Little Ice Age in the Brooks Range, Alaska: Arctic, Antarctic, and Alpine Research, v. 41, p. 138-150.

Shi, X., M. Sturm, D. P. Lettenmaier, and G. E. Liston, 2007: Spatial and temporal variability of snow stratigraphy in Northwestern Alaska. Journal of Hydrometeorology, in review.

Stein, J., and D.L. Kane. 1983. Monitoring the unfrozen water content of soil and snow using time domain reflectometry. Water Resources Research. 19(6):1573-1584.

Stieglitz, M., Déry, S. J., Romanovsky, V. E., and T.E. Osterkamp, The Role of Snow Cover in the Warming of Arctic Permafrost, Geophysical Research Letters, VOL. 30, NO. 13, 1721, doi:10.1029/2003GL017337, 2003.

Streever, B., R. Suydam, J.F. Payne, R. Shuchman, R.P. Angliss, G. Balogh, J. Brown, J. Grunblatt, S. Guyer, D.L. Kane, J.J. Kelley, G. Kofinas, D.R. Lassuy, W. Loya, P. Martin, S.E. Moore, W.S. Pegau, C. Rea, D.J. Reed, T. Sformo, M. Sturm, J.J. Taylor, T. Viavant, D. Williams and D. Yokel, 2011. Environmental Change and Potential Impacts: Applied Research Priorities for Alaska's North Slope. Arctic 64(3)390:397.

Stuefer, S.L., Youcha, E.K, Homan J.W., Kane, D.L. and Gieck, R.E. 2011. Snow Survey Data for the Central North Slope Watersheds: Spring 2011. University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 11.02, Fairbanks, Alaska, 47 pp.

Sturm, M, B. Taras, C. Derksen, T. Jonas and J. Lea (In Press). Estimating Local to Global Snow Water Resources Using Snow Depth Data and Snow Climate Classes, Journal of Hydrometeorology.

Sturm, M., Schimel, J., Michelson, G., Welker, J., Oberbauer, S. F., Liston, G. E., Fahnestock, J., and V. E. Romanovsky, Are winter biological processes important in converting arctic tundra to shrubland?, BioScience, Vol. 55, No. 1: 17 – 26, 2005.

Sturm, M. and C. S. Benson. 2004. Scales of spatial heterogeneity for perennial and seasonal snow layers. Annals of Glaciology 38, 253-260.

Sturm, M. and G. E. Liston. 2003. The snow cover on lakes of the Arctic Coastal Plain of Alaska. J. of Glaciology, 49 (166), 370-380.

Sturm, M., D. K. Perovich, J. Holmgren. 2002. Thermal conductivity and heat transfer through the snow and ice of the Beaufort Sea. Journal of Geophysical Research-Oceans, 107(C21), 8043, doi:10.1029/2000JC000409

Sturm, M., J. Holmgren, and D. K. Perovich. 2002. The winter snow cover of the sea ice of the Arctic Ocean at SHEBA: Temporal evolution and spatial variability. Journal of Geophysical Research-Oceans, 107(C10), 8047,doi:10.1029/2000JC0004000.

Sturm, M., J. P. McFadden, G. E. Liston, F. S. Chapin, III, C. H. Racine, and J. Holmgren, 2001. Snow-shrub interactions in Arctic tundra: a hypothesis with climatic implications. J. of Climate, 14, 336-344.

Sturm, M., G. E. Liston, C. S. Benson, and J. Holmgren, 2001: Characteristics and growth of a snowdrift in arctic Alaska. Arctic, Antarctic and Alpine Research, 33(3), 319-32.

Sugiura, K., D. Yang, and T. Ohata, 2003: Systematic error aspects of gauge-measured solid precipitation in the Arctic, Barrow, Alaska, Geophysical Research Letters, 3(4), 1192, doi: 10.1029/2002GL015547.

Sugiura, K., T. Ohato, and D. Yang. 2006. Catch Characteristics of Precipitation Gauges in High-Latitude Regions with High Winds. Journal of Hydrometeorology. 7(5): 984-994.

Tape K.D., D Verbyla, J Welker. 2011. Twentieth century erosion in Arctic Alaska: the influence of shrubs, runoff, and permafrost. Journal of Geophysical Research, Biogeosciences

Taras, B., M. Sturm, and G. E. Liston. 2002. Snow-ground interface temperatures in the Kuparuk River Basin, Arctic Alaska, U.S.A.: Measurements and Model. . J. of HydroMeteorology.3(4), 377-394.

Toniolo, H., Derry, J., Irving, K. and Schnabel, W. Hydraulic and sedimentological characterization of a reach on the Anaktuvuk river, Alaska. Journal of Hydraulic Engineering ASCE (2010) - November

Toniolo, H., Kodial, P., Hinzman, L.D. and Yoshikawa, K. 2009 Spatio-temporal evolution of a thermokarst in Interior Alaska, Cold Regions Science and Technology, 56 (1), p.39-49.

Toniolo, H., Lilly, M.R., Derry, J., Reichardt, D., Holland, K., and McHugh, A., 2008. Beaufort Coastal Stations Summary and Data Review. University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 08.01, Fairbanks, Alaska, 34 pp.

Trochim, E. D.; Mumm, J. P.; Farnham, N. E.; Kane, D. L.; Prakash, A. Variations in Vegetation & Hydrology: Linkages to Evapotranspiration in the Alaskan Arctic. American Geophysical Union, Fall Meeting 2010, abstract #H41B-1087.

Trochim, E., Anupma Prakash and Douglas L. Kane. Investigating Water Tracks In The Foothills of the Alaskan Arctic. 9th ACUNS International Studen Conference on Northern Studies and Polar Region. Whitehorse, Yukon, Canada.

Tweedie, C.E., R.D. Hollister, P.J. Webber. (2003). Decadal changes in permafrost, land form and land cover near Barrow, Alaska. In: 8th International Conference on Permafrost, Zurich, Switzerland. 20-25 July, 2003.

Vörösmarty, C., Hinzman, L., Peterson, B., Bromwich, D., Hamilton, L., Morison, J., Romanovsky, V., Sturm, M., and R. Webb, Arctic Hydrology and Its Role in Understanding Global Change: A Call for Synthesis, EOS, AGU Transactions, V. 83, No. 22, 241-249, 2002.

Vörösmarty, C.J., L. Hinzman, B.J. Peterson, D.L. Bromwich, L. Hamilton, J. Morison, V. Romanovsky, M. Sturm, R. Webb, The Hydrologic Cycle and its Role in Arctic and Global Environmental Change: A Rationale and Strategy for Synthesis Study. ARCUS, Fairbanks AK. 84 pp, 2001.

Walsh, J., Anisimov, O., Hagen, J.O., Jakobsson, T., Oerelemans, J., Prowse, T., Romanovsky, V., Savelieva, N., Serreze, M., Shiklomanov, A., Shiklomanov, I.and Solomon, S. 2005. The Crysophere and Hydrologic Variability. Chapter 5 in Arctic Climate Impact Assessment (ACIA), Cambridge University Press, London, pp. 181-242, 2005.

Weller, Gunter and Sue Ann Bowling, 1975. Climate of the Arctic, Geophysical Institute, University of Alaska Fairbanks, 436p.

Weller, Gunter, Matt Nolan, Gerd Wendler, Carl Benson, Keith Echelmeyer and Norbert Untersteiner, 2007. Fifty years of McCall Glacier research: from the International Geophysical Year, 1957-58 to the International Polar Year, 2007-08. Arctic 60 (1).

White, D.M., Prokein, P., Chambers, M., Lilly, M., (2008), Assessment of water resources from Teshekpuk Lake to the Canning River, Journal of the American Water Resources Association, Vol. 44 Issue 2 Page 276-284.

White D., L. Hinzman, L. Alessa, J. Cassano, M. Chambers, K. Falkner, J. Francis, W. Gutowski Jr., M. Holland, M. Holmes, H. Huntington, D. Kane, A. Kliskey, C. Lee, J. McClelland, B. Peterson, S. Rupp, F. Straneo, M. Steele, R. Woodgate, D. Yang, K. Yoshikawa, T. Zhang (2007), The arctic freshwater system: Changes and impacts, J. Geophys. Res., 112, G04S54, doi:10.1029/2006JG000353.

Yang, D., D. L. Kane, Z. Zhang, D. Legates and B. Goodison. 2005. Bias Correction of Long-Term (1973-2004) Daily Precipitation Data over Northern Regions. Geophysical Research Letters, 32:L19501, doi:10.1029/2005GL024057.

Yang, D., D.L. Kane, L.D. Hinzman, R.E. Gieck, J.P. McNamara. 2000. Hydrologic response of a nest of watersheds to an extreme rainfall event in Northern Alaska. In D.L. Kane (ed) Water Resources in Extreme Environments. American Water Resources Association Proceedings. 1-3 May 2000. Anchorage, AK p. 25-30.

Yang, D., D.L. Kane, L.D. Hinzman, B.E. Goodison, J.R. Metcalfe, P.Y.T. Louie, G.H. Leavesley, D.G. Emerson, C.L. Hanson, 2000: An evaluation of the Wyoming gauge system for snowfall measurement. Water Resources Research, 2665-2678.

Yang, D, 1999: An improved precipitation climatology for the Arctic Ocean. Geophysical Research Letters, Vol.26, No.11, 1625-1628.

Yoshikawa K., L. D. Hinzman, D. L. Kane (2007), Spring and aufeis (icing) hydrology in Brooks Range, Alaska, J. Geophys. Res., 112, G04S43, doi:10.1029/2006JG000294.

Yoshikawa, K., C. Leuschen, A. Ikeda, K. Harada, P. Gogineni, P. Hoekstra, L. Hinzman, Y. Sawada, and N. Matsuoka, 2006, Comparison of geophysical investigations for detection of massive ground ice (pingo ice), J. Geophys. Res., 111, E06S19, doi:10.1029/2005JE002573.

Yoshikawa, K. and Overduin, P.P., 2005. Comparing unfrozen water content measurements of frozen soil using recently developed commercial sensors. Cold Regions Science and Technology. Volume 42, Issue 3, November 2005, Pages 250-256, doi:10.1016/j.coldregions.2005.03.001

Yoshikawa , K. and Hinzman, LD. 2003. Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska. Permafrost Periglac. Process 14: 151-160. DOI:10.1002/ppp.451

Youcha, E., Toniolo, H., and Kane, D., 2011. Spring and Summer Runoff Observations 2009-2010, Umiat Corridor Hydrology Project. University of Alaska Fairbanks, Water and Environmental Research Center, Report INE/WERC 11.01, Fairbanks, Alaska, 55 pp.

Zarnetske, J.P., M.N. Gooseff, T.R. Brosten, J.H. Bradford, J. P. McNamara, and W.B. Bowden. 2007. Transient storage as a function of geomorphology, discharge, and permafrost active layer conditions in Arctic tundra streams. Water Resour. Res., 43, doi:10.1029/2005 WR004816.

Zhang, T., T. Scambos, T. Haran, L.D. Hinzman, R.G. Barry and D.L. Kane. 2003. Ground Based and Satellite Derived Measurements of Surface Albedo on the North Slope of Alaska. Journal of Hydrometeorology, 4:77-91.

Zhang, T., Osterkamp, T.E., And Stammes, K., 1996. Some characteristics of the climate in northern Alaska, U.S.A. *Arctic and Alpine Research* 28: 509–518.

Zhang, Z., D.L. Kane and L.D. Hinzman, 2000. Development and Application of a Spatially Distributed Arctic Hydrologic and Thermal Process Model (ARHYTHM). Journal of Hydrological Processes. 14(6):1017-1044.

Arctic Observing Network Design & Implementation Community Survey

SurveyMonkey

1. What is your primary research field?

	Response Percent	Response Count
Atmosphere	18.1%	19
Ocean and Sea Ice	**38.1%**	**40**
Terrestrial Ecosystems	12.4%	13
Hydrology and Cryosphere	23.8%	25
Human Dimensions	7.6%	8
Other (please specify)		24
	answered question	**105**
	skipped question	**16**

2. What is your sub-discipline within this field (e.g., biological oceanography, boundary-layer meteorology, etc.)

	Response Count
	107
answered question	**107**
skipped question	**14**

3. In your research, do you primarily conduct (select one):

	Response Percent	Response Count
Modeling studies	6.7%	7
Observations - surface based	**66.3%**	**69**
Observations - airborne, in-situ upper-air, or satellite remote sensing	12.5%	13
Analysis or synthesis of data sets collected by others	14.4%	15
	Other (please specify)	21
	answered question	**104**
	skipped question	**17**

4. If possible, please provide a bibliographic reference(s) that you deem most relevant for design and optimization of the Arctic Observing Network (at a minimum name of first author, year of publication, title of publication, title of journal or book). Please indicate briefly as to why this publication is especially relevant.

	Response Count
	50
answered question	**50**
skipped question	**71**

5. How many scientific publications are you aware of that describe or discuss observing system design approaches (in the Arctic or elsewhere) relevant in your field?

	Response Percent	Response Count
None	25.5%	28
1-3	**36.4%**	**40**
3-10	23.6%	26
>10	14.5%	16
	answered question	**110**
	skipped question	**11**

6. In thinking about designing and implementing an Arctic Observing Network, please state whether addressing the following challenges are critical, important, somewhat important, or not important.

	Critical	Important	Somewhat important	Not important	Response Count
Achieving a balance of observations across different disciplines	36.5% (42)	**46.1% (53)**	13.0% (15)	4.3% (5)	115
Achieving a balance of observations across different regions	**51.3% (59)**	43.5% (50)	4.3% (5)	0.9% (1)	115
Balancing the needs and goals of all stakeholders	15.9% (18)	**45.1% (51)**	36.3% (41)	2.7% (3)	113
Prioritizing the type of observations made	36.6% (41)	**45.5% (51)**	17.9% (20)	0.0% (0)	112
Sustaining observations in the long-term	**80.0% (92)**	19.1% (22)	0.9% (1)	0.0% (0)	115
Coordinating observations between different programs or projects at the international level	36.8% (42)	**47.4% (54)**	15.8% (18)	0.0% (0)	114
Coordinating observations between different programs or projects at the national level	**47.4% (54)**	37.7% (43)	14.0% (16)	0.9% (1)	114
Optimizing observations across AON scientific priorities	20.7% (23)	**52.3% (58)**	24.3% (27)	2.7% (3)	111
Applying rigorous approaches to observing system design	36.0% (41)	**44.7% (51)**	17.5% (20)	1.8% (2)	114
				Other (please specify)	22
				answered question	**115**
				skipped question	**6**

7. In your opinion, how can the key challenges you identified in the previous question (Question 6) best be overcome

	Response Count
	82
answered question	**82**
skipped question	**39**

8. Please indicate if you agree or disagree with the following statements.

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Response Count
An Arctic Observing System has to meet information needs of key stakeholders outside of the scientific community; it is not sufficient for the observing system to address only fundamental science questions.	29.8% (34)	**36.8% (42)**	21.9% (25)	5.3% (6)	6.1% (7)	114
In my research field, design of an observing system is best done by those carrying out the observations.	21.2% (24)	**44.2% (50)**	23.9% (27)	8.8% (10)	1.8% (2)	113
In my research field, design of an observing system is best done through the use of modeling studies, e.g., observing system simulation experiments, or other methods based on the theory of observing system design.	6.2% (7)	28.3% (32)	**34.5% (39)**	24.8% (28)	6.2% (7)	113
In my research field, rigorous methods exist to guide design of an observing system.	12.4% (14)	29.2% (33)	**36.3% (41)**	17.7% (20)	4.4% (5)	113
Observing system design needs to include input from those using data or information products derived from the observing system; the observing system cannot be designed solely based on criteria developed by the scientific community.	27.8% (32)	**40.9% (47)**	18.3% (21)	11.3% (13)	1.7% (2)	115
Prioritization of the different types of observations that are part of an AON needs to be based on urgency and/or importance of the science question the observations help answer.	19.5% (22)	**58.4% (66)**	15.0% (17)	6.2% (7)	0.9% (1)	113
Design and implementation of an Arctic Observing System should primarily be driven and supported by government agencies (such as						

the National Oceanic and Atmospheric Administration or the Fish and Wildlife Service) rather than investigators supported through the National Science Foundation.	12.4% (14)	22.1% (25)	25.7% (29)	**28.3% (32)**	11.5% (13)	113
Prioritization of the different types of observations that are part of an AON should be based on stakeholder needs.	7.0% (8)	32.5% (37)	**40.4% (46)**	18.4% (21)	1.8% (2)	114
					Other (please specify)	25
					answered question	**115**
					skipped question	**6**

9. Are you aware of an observing system effort either within or outside of the Arctic that holds important lessons for the design and implementation of an Arctic Observing Network?

		Response Percent	Response Count
Yes		**63.2%**	**67**
No		36.8%	39
		Other (please specify)	11
		answered question	**106**
		skipped question	**15**

10. If you answered yes, what is the name of that observing system or program? (if possible please provide a relevant weblink or reference). If possible, please also indicate what the most important lesson from that observing system is for the AON.

	Response Count
	68
answered question	**68**
skipped question	**53**

11. If you currently generate observational data or have in the past, please indicate whether you provide public access to these data

	Response Percent	Response Count
Yes	**84.3%**	**91**
No	5.6%	6
N/A	11.1%	12
Other (please specify)		15
answered question		**108**
skipped question		**13**

12. Do you generate observational data that are being disseminated by a data center or portal?

	Response Percent	Response Count
Yes	**74.5%**	**82**
No	18.2%	20
N/A	7.3%	8
	Other (please specify)	9
	answered question	**110**
	skipped question	**11**

13. If you answered yes to the previous question, do you track the use of your data by others?

	Response Percent	Response Count
Yes	35.7%	35
No	**54.1%**	**53**
N/A	14.3%	14
	If applicable, please list the data center/portal you use to disseminate your data	29
	answered question	**98**
	skipped question	**23**

14. If you answered yes to the previous question, how do you track the use of your data?

	Response Percent	Response Count
Number of hits or downloads on relevant web page	**70.0%**	**28**
Data users have to register	27.5%	11
Informal feedback from data users	57.5%	23
Request to data users to send publications resulting from data use	35.0%	14
Bibliographic research tracking publications referencing the dataset	25.0%	10
Other (please specify)		12
answered question		**40**
skipped question		**81**

15. What do you consider the most effective way of tracking the use of data provided by an observing system?

	Response Count
	64
answered question	**64**
skipped question	**57**

16. Do you have any further comments or guidance for the AON Design and Implementation Task Force?

	Response Count
	31
answered question	**31**
skipped question	**90**

17. Contact information (Note: this information is not required, but is appreciated and will also qualify you to enter a drawing to win an umbrella detailed with a map of the Arctic)

	Response Percent	Response Count
First Name	**100.0%**	**59**
Last Name	98.3%	58
email address	98.3%	58
mailing address (optional)	37.3%	22
answered question		**59**
skipped question		**62**

EVALUATION OF THE STREAMFLOW GAGING NETWORK

Arctic Alaska

Arctic Alaska encompasses an area of 79,000 mi^2. The streams and rivers in Arctic Alaska flow generally northward from the Brooks Range into the Arctic Ocean (fig. 6). The largest river in the Arctic, the Colville River, flows eastward for 200 mi before turning to the north: its basin covers 30 percent of the subregion (23,200 mi^2). The area is underlain by continuous permafrost. More than half of the flat, western part of the coastal plain is covered by shallow lakes. Reconnaissance studies by Childers and others (1977, 1979) have shown that many of the rivers probably have no-flow periods during the winter.

Knowledge of the water resources in this area is important, whether it be for resource development or management of ecosystems. The largest oilfield in North America, Prudhoe Bay, is located in Arctic Alaska. Considerable interest exists for future petroleum development in the Arctic. Some of the more prominent areas mentioned include the Arctic National Wildlife Refuge (ANWR), the Colville River Delta, and the National Petroleum Reserve of Alaska (NPRA) (fig. 6). If future petroleum development does occur, infrastructure such as pipelines and roads will be constructed. Development of an adequate water supply will also be essential.

Streamflow information is also needed for management of ecosystems. Some of the largest caribou herds—the Porcupine and the Western Arctic—graze over large areas of this region. The arctic wetlands support large populations of ducks, geese, and shorebirds. Many of the streams and rivers support various species of fish.

Hydrologic data for the Arctic are sparse. Only nine streamflow-gaging stations have sufficient data for peak-flow analysis and only seven have sufficient data for average and low-flow analysis (table 3). In addition, with the exception of Nunavak Creek near Barrow, most of the sites are located along the Dalton Highway (fig. 6). Given the size of Arctic Alaska, the lack of data, and the spatial distribution of the existing data, no attempts were made to use GLS or network analysis procedures. Instead, cluster and spatial analysis techniques were utilized.

To design a proposed network for Arctic Alaska, the following procedure was used. First, potential sites were selected, using the hydrologic unit map (U.S. Geological Survey, 1987) as a guide. It was assumed that drainage area would be a significant variable for any statistical analysis and thus potential sites in each hydrologic unit were chosen to ensure that a wide distribution of this variable was obtained.

Using GIS procedures, a cluster analysis was done using the precipitation, physiography, and permafrost coverages of the Arctic region. Results of the cluster analysis indicated three distinct classification areas. The potential sites were then overlaid on the cluster map (fig. 7), to ensure that sites would represent the different classification areas. Potential sites were also overlaid on the precipitation, physiographic, and hydrologic unit boundary maps (fig. 8-10) for visual analysis to ensure spatial distribution. Sites were added or removed to adjust the distribution. Finally, a boxplot and a probability plot of the variable drainage area were developed (fig. 11-12) which indicate a good symmetrical distribution and a good normal distribution.

The proposed streamflow-gaging network for Arctic Alaska consists of 57 sites (table 4, fig. 10). Of these sites, the Meade (No. 14 on fig. 10), Colville (35), Kuparuk (38), and Jago (52) Rivers, and Nunavak Creek (13) would be index stations. These stations would provide a good spatial distribution across the Arctic, as well as good distribution of drainage areas. In addition, continuing data collection on the Kuparuk River and Nunavak Creek would provide long-term data necessary to detect trends in streamflow.

If the proposed network can not be implemented in its entirety, several alternative approaches are suggested. One approach would be to establish the index stations; another approach would be a reconnaissance of the 57 sites. After the reconnaissance was completed, a value for each of the proposed sites could be obtained using the crisp expert system. Sites with the highest value would then be selected. Another alternative would be to select a subregion within Arctic Alaska, such as eastern Arctic, and and operate those stations within the subregion.

Table 3. Streamflow data available for Arctic Alaska

Station No.	Station name	Flow data available			Remarks
		Peak	Average	Low	
15798700	Nunavak Creek near Barrow	X	X	X	Active gaging station
15896000	Kuparuk River near Deadhorse	X	X	X	Active gaging station
15896700	Putuligayuk River near Deadhorse	X	X	X	Discontinued gaging station
15904900	Atigun River tributary near Pump Station 4	X	X	X	Discontinued gaging station
15906000	Sagavanirktok River tributary near Pump Station 3	X	X	X	Active gaging station
15908000	Sagavanirktok River near Pump Station 3	X	X	X	Active gaging station
1591000	Sagavanirktok River near Sagwon	X	X	X	Discontinued gaging station
15910200	Happy Creek at Happy Valley Camp near Sagwon	X			Active crest-stage gage
15918200	Sagavanirktok River tributary near Deadhorse	X			Active crest-stage gage
TOTAL		9	7	7	

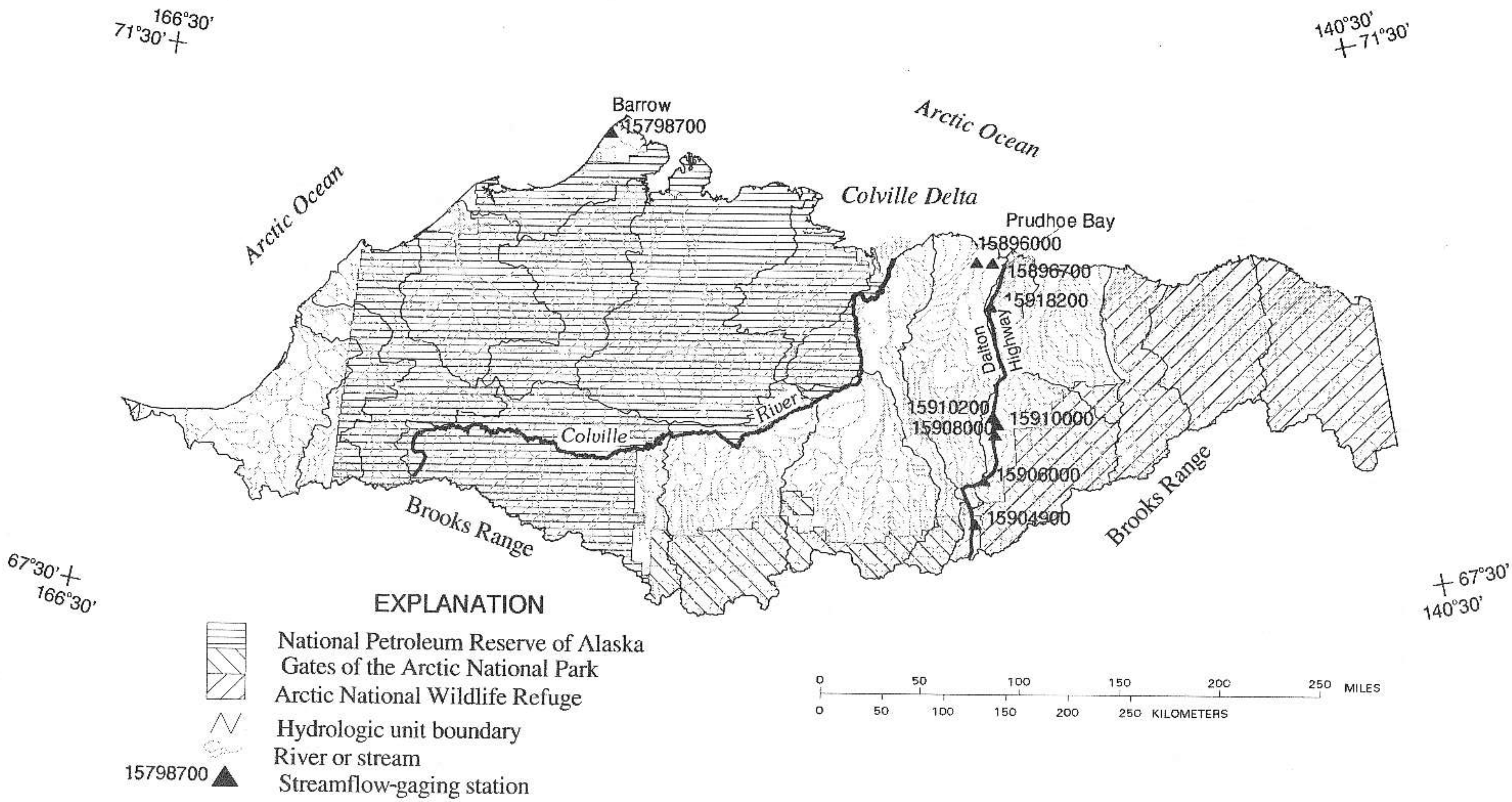


Figure 6. Land uses of Arctic Alaska and locations of past and current streamflow-gaging stations.

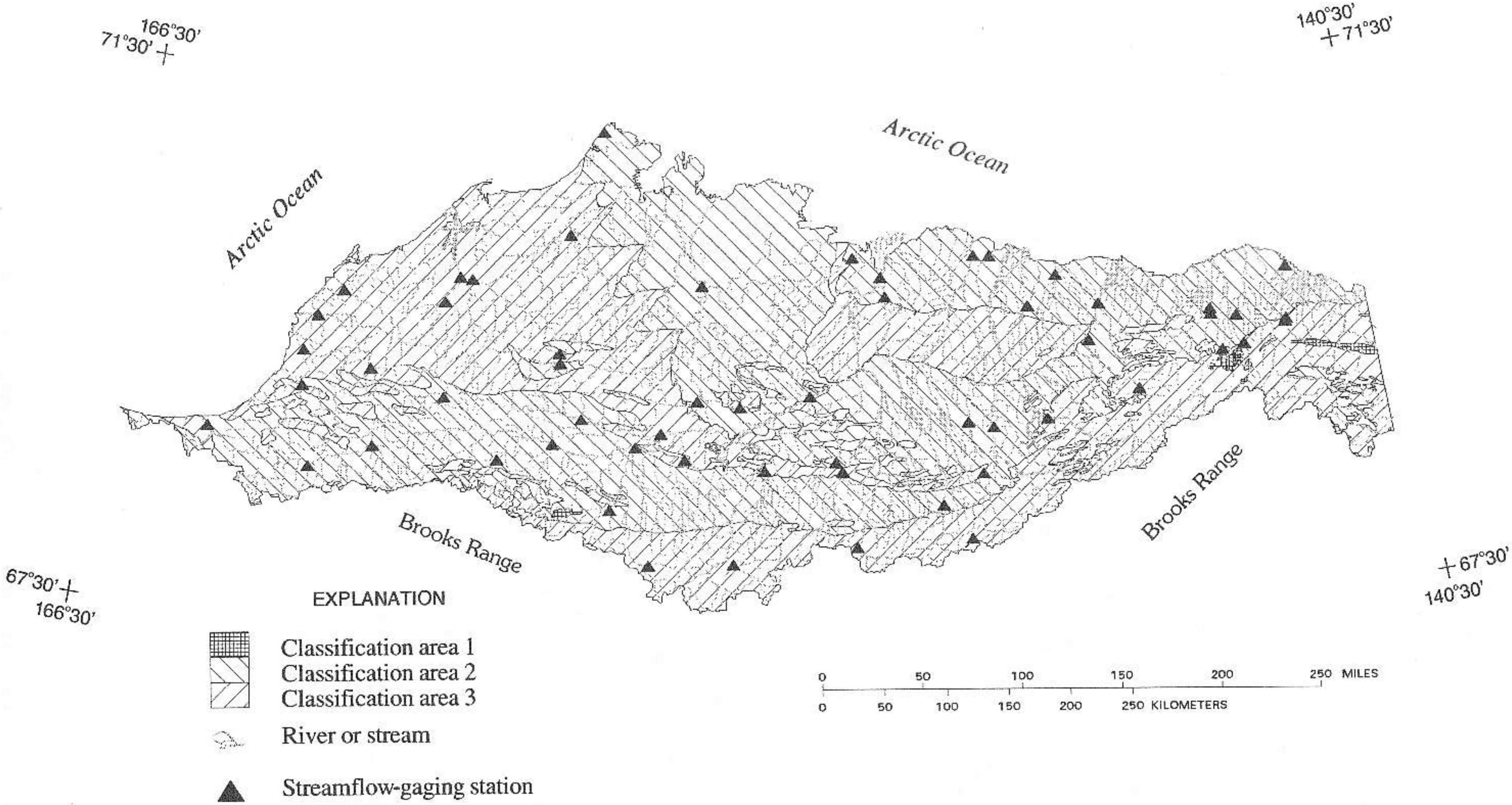


Figure 7. Proposed streamflow-gaging network and classification areas for Arctic Alaska.

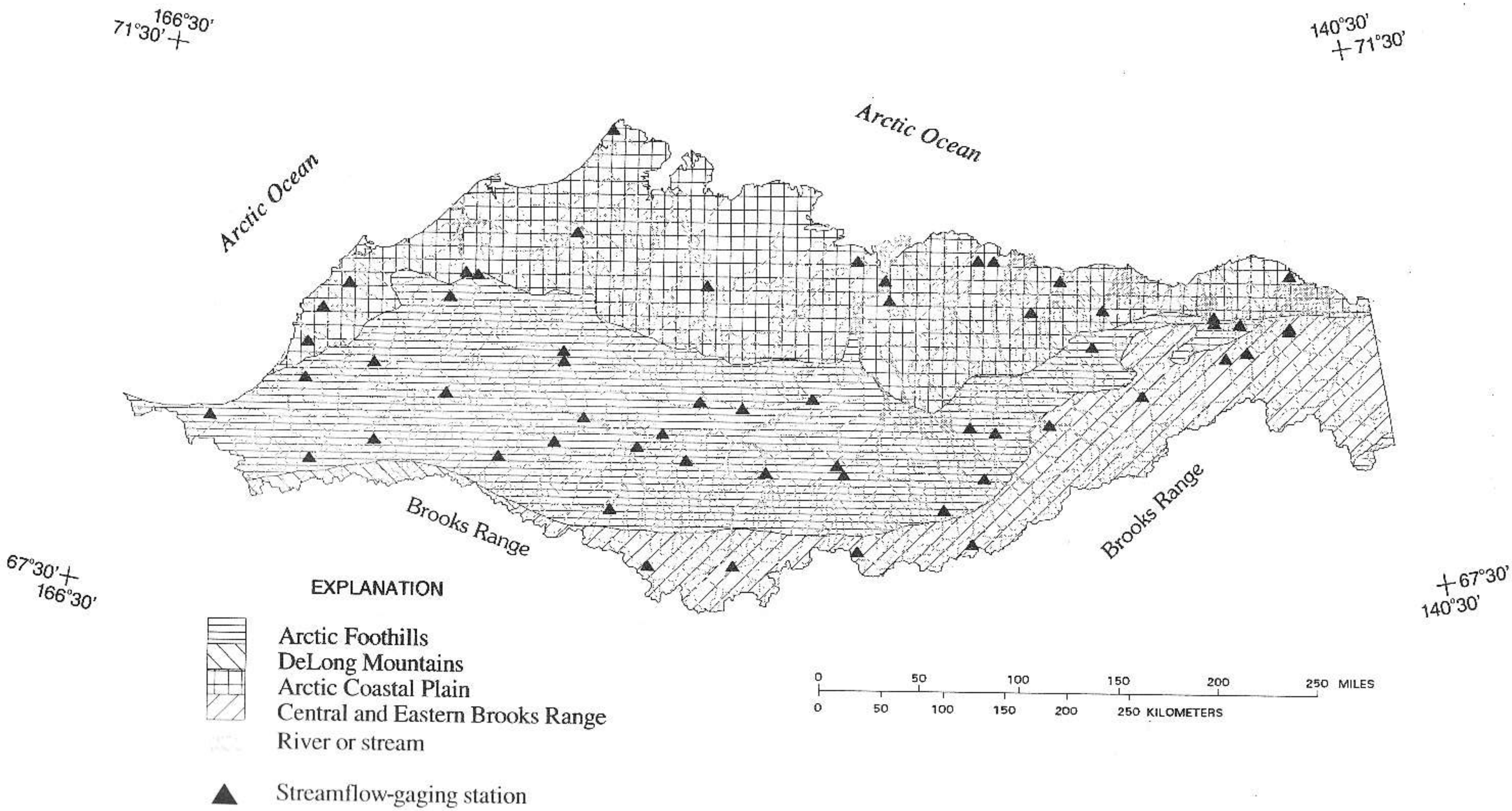


Figure 8. Proposed streamflow-gaging network and physiographic regions for Arctic Alaska (from Wahrhaftig, 1965).

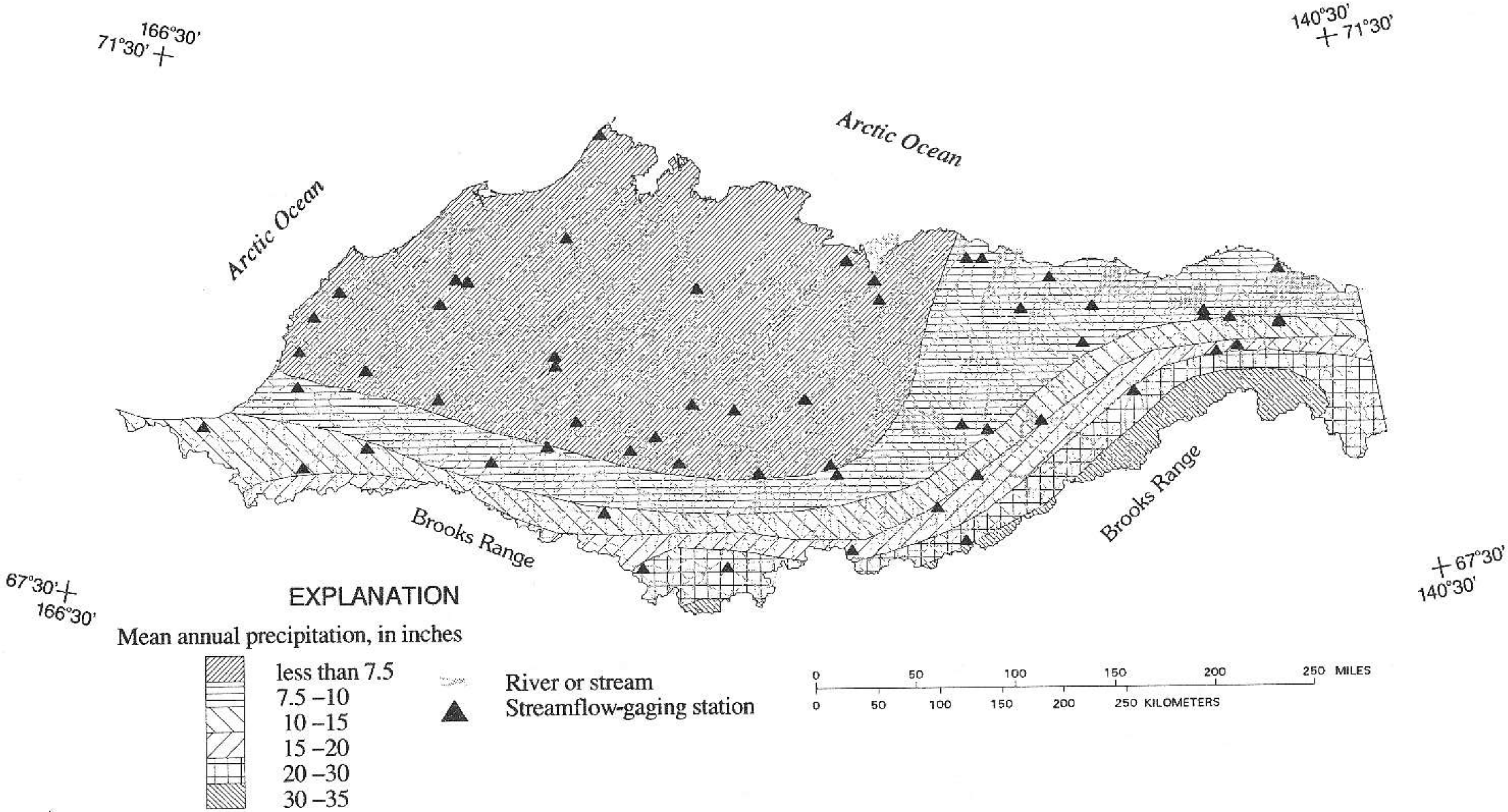


Figure 9. Proposed streamflow-gaging network and precipitation areas for Arctic Alaska (from Jones and Fahl, 1994).

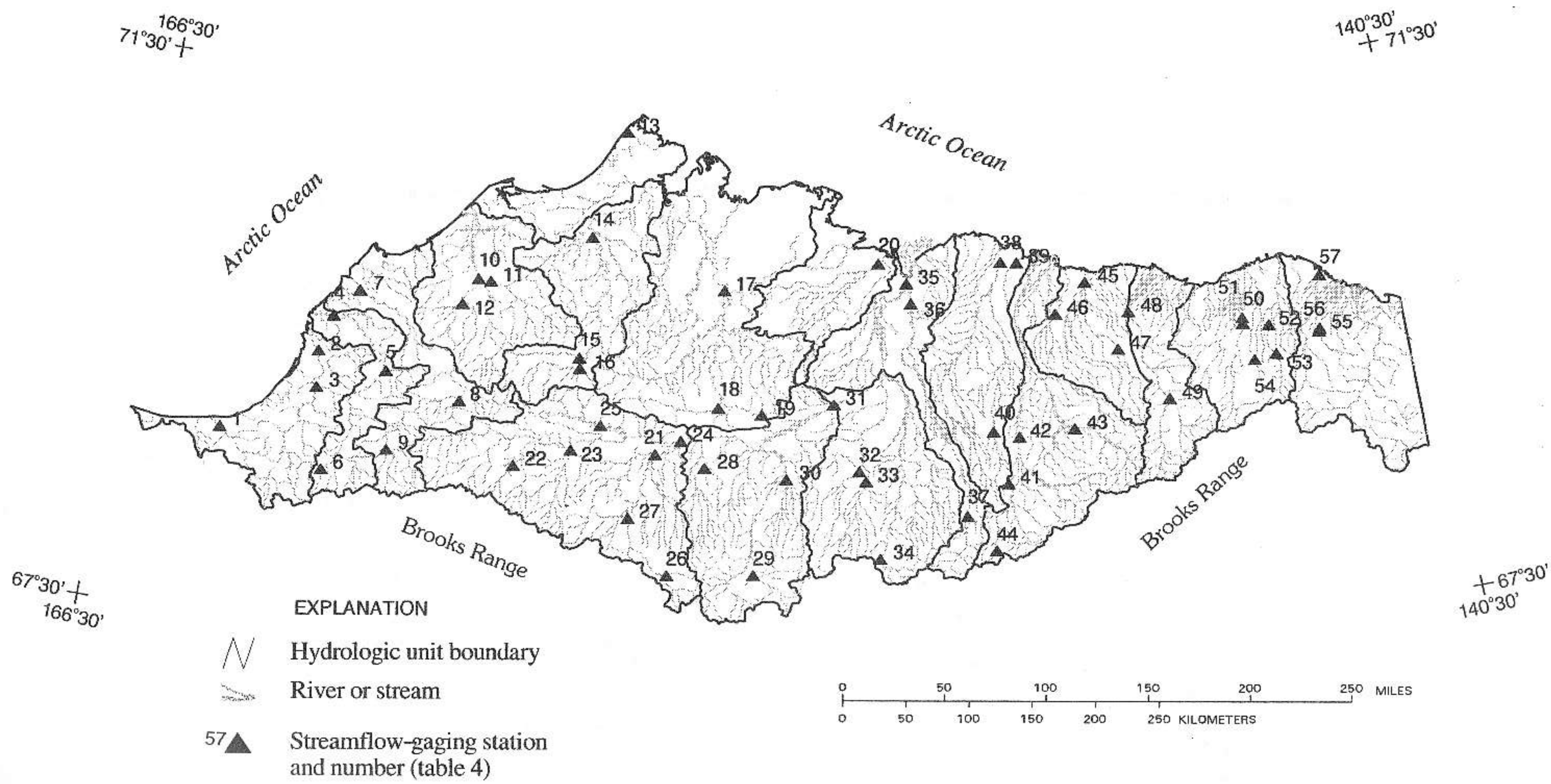


Figure 10. Proposed streamflow-gaging network and hydrologic unit boundaries for Arctic Alaska.

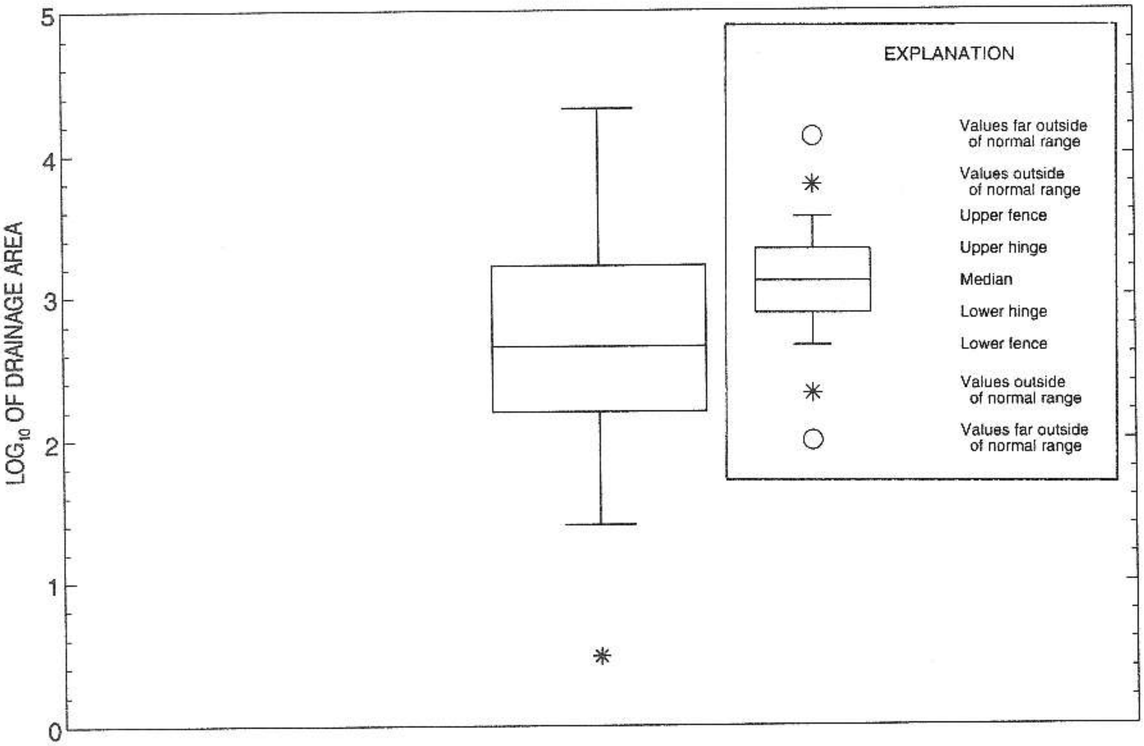


Figure 11. Boxplot of drainage areas of proposed streamflow-gaging stations for Arctic Alaska.

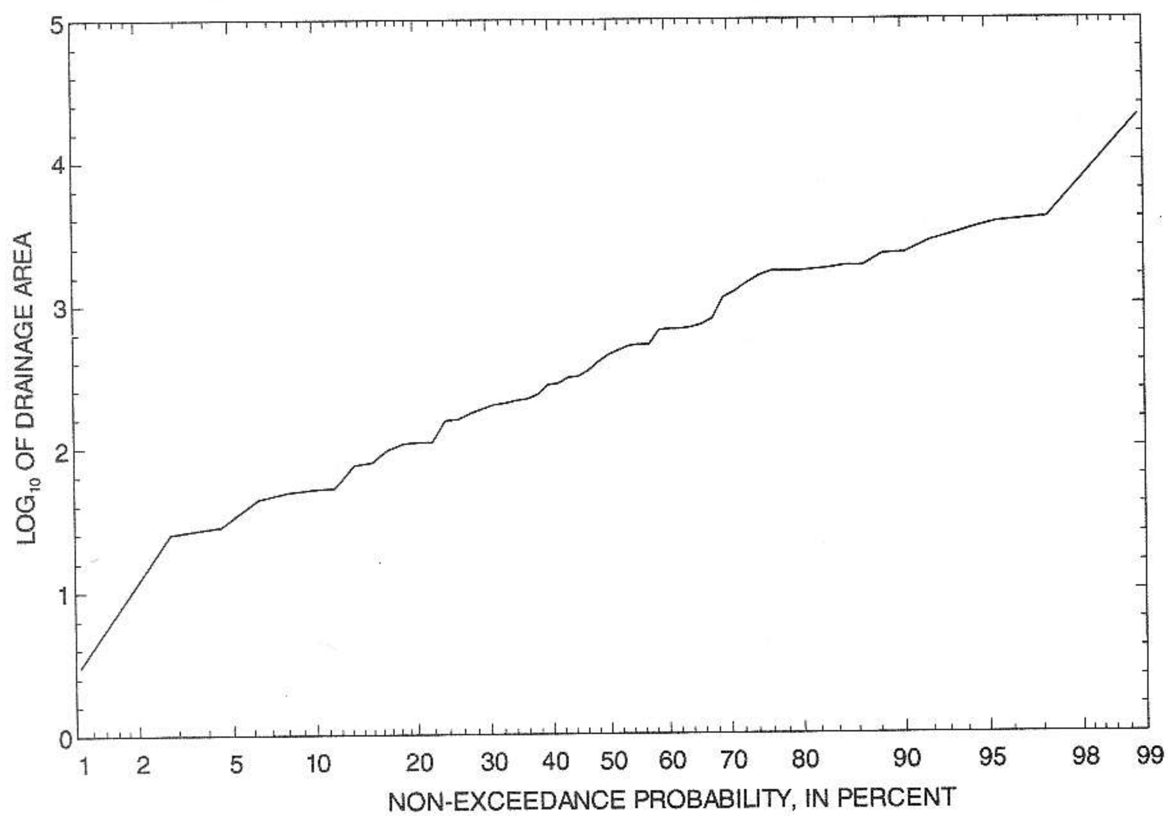


Figure 12. Probability plot of drainage areas of proposed streamflow-gaging stations for Arctic Alaska.

Table 4. Proposed streamflow-gaging network, Arctic Alaska
[HUC, Hydrologic unit code; mi^2, square mile; USGS station number indicated after site name]

Map No. (fig.10)	HUC	HUC area (mi^2)	Site name	Latitude/Longitude	Drainage area (mi^2)
1	19060101	3,560	Pitmegea River	68°51'15"164°25'36"	480
2			Kukpowruk River	69°29'50"162°43'30"	1,690
3			Deadfall Creek	69°14'03"162°40'20"	107
4	19060102	2,360	Kokolik River	69°45'39"162°31'00"	2,270
5			Avingak Creek	69°24'41"161°20'56"	284
6			Tingmerkpuk River	68°39'06"162°22'16"	52.0
7	19060103	3,830	Utukok River	69°57'48"162°03'12"	2,760
8			Disappointment Creek	69°14'43"159°50'21"	200
9			Adventure Creek	68°50'46"161°10'00"	50.7
10	19060201	4,230	Kuk River	70°08'06"159°40'42"	3,690
11			Avalik River	70°07'30"159°25'12"	1,130
12			Kaolak River	69°56'49"159°57'16"	309
13	19060202	2,120	Nunavak Creek (15798700)[1]	71°15'35"156°46'57"	2.79
14	19060203	4,160	Meade River[1]	70°29'20"157°24'40"	1,800
15			Shaningarok Creek	69°37'01"157°32'16"	353
16			Pahron Creek	69°32'31"157°30'55"	110
17	19060204	9,190	Ikpikpuk River	70°08'12"154°38'30"	3,980
18			Kigalik River	69°17'16"154°43'41"	532
19			Anak Creek	69°14'33"153°51'53"	43.5
20	19060205	2,630	Fish Creek	70°19'00"151°28'36"	1,700
21	19060301	7,920	Etivluk River	68°56'42"155°57'42"	2,260
22			Jubilee Creek	68°48'57"158°40'51"	154
23			Kuna River	68°57'04"157°36'18"	730
24			Awuna River	69°02'47"155°27'18"	1,420
25			Quartzite Creek	69°08'25"157°02'41"	97.2
26			Itilyiargiok Creek	68°04'49"155°39'45"	110
27			Nigu River	68°28'55"156°26'29"	511
28	19060302	5,850	Heather Creek	68°51'18"154°58'40"	187
29			Easter Creek	68°05'27"154°01'24"	394
30			Okokmilaga River	68°46'39"153°23'22"	789
31			Prince Creek	69°18'42"152°26'38"	217
32	19060303	5,540	Chandler River	68°49'33"151°58'31"	1,750
33			Siksikpuk River	68°45'09"151°50'59"	681
34			Anaktuvuk River	68°11'37"151°37'13"	206

Table 4. Proposed streamflow-gaging network, Arctic Alaska--Continued

[HUC, Hydrologic unit code; mi^2, square mile; USGS station number indicated after site name]

Map No. (fig.10)	HUC	HUC area (mi^2)	Site name	Latitude/Longitude	Drainage area (mi^2)
35	19060304	3,930	Colville River near Nuiqsut[1]	70°09'56"150°55'00"	20,700
36			Itkillik River	70°01'21"150°50'34"	1,720
37			Itikmalak River	68°28'18"149°55'01"	80.0
38	19060401	4,300	Kuparuk River (15896000)[1]	70°16'54"148°57'35"	3,130
39			Putuligayuk River (15896700)	70°16'03"148°37'41"	176
40			Toolik River	69°03'51"149°19'05"	233
41	19060402	5,280	Sagavanirktok River Tributary (15906000)	68°41'13"149°05'42"	28.4
42			Sagavanirktok River near Pump Station #3 (15908000)	69°00'54"148°49'02"	1,860
43			Ivishak River	69°02'34"147°43'48"	660
44			Atigun River (15904800)	68°12'54"149°24'13"	48.7
45	19060403	2,790	Shaviovik River	70°05'07"147°16'30"	1,580
46			Kadleroshilik River	69°52'39"147°55'11"	454
47			Kavik River	69°35'02"146°44'12"	279
48	19060501	2,670	Canning River	69°50'38"146°27'10"	1,870
49			Marsh Fork	69°11'19"145°49'55"	700
50	19060502	3,610	Sadlerochit River	69°39'13"144°12'10"	529
51			Hulahula River	69°41'47"144°12'10"	681
52			Jago River[1]	69°37'02"143°41'06"	321
53			McCall Creek	69°24'17"143°36'57"	24.7
54			Okpilak River	69°23'06"144°04'04"	159
55	19060503	4,590	Egaksrak River	69°32'05"142°41'05"	215
56			Kongakut River	69°30'54"142°42'34"	1,240
57			Sikrelurak River	69°54'43"142°30'52"	74.7

[1]Index station