Climate Monitoring for Southwest Alaska National Parks: Network Design and Site Selection

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Executive Summary

Climate and its behavior constitute a major environmental driver and in addition have myriad practical and management consequences and implications for National Park Service (NPS) units. These are especially important in Alaska, where there is also evidence of possible significant longer-term change under way. There is much to watch and yet resources permit continuous monitoring at only a limited number of places. Network design for climate monitoring has many dimensions, and this report attempts to address the main factors. A large number of these factors are found elsewhere: in Alaska, in other cold or mountainous regions, and in the remaining NPS units in the United States. Other factors are more specific to this region. There are also many other federal agencies and activities outside of NPS that are struggling with just these same issues. It is hoped that these comments can be of value for those purposes as well.

We cannot monitor everything everywhere for all time, desirable as that might be. The main goal of climate monitoring is tracking through time. Ideally we would like time histories of climate at every point. That is, we wish to know how spatial *fields* of inter-related elements vary through time. In actuality this has to be accomplished by using information from a small set of well-selected points. These points should be representative of desired spatial scales, of particular physical or biological settings (forests, coasts, glaciers, meadows, wetlands, canyons, ridges, etc), or of areas of cultural, educational, or interpretive interest. There are significant issues of scale, in both space and time, when we consider the representativeness of measurements.

Almost by definition, climate unfolds slowly. However, it does so with a mixture of nearly imperceptible steady change and a continuing parade of events of various magnitude, some of which act as disturbances that alter the trajectory of the state variables that describe living systems. Thus, long-term vision and commitment are essential. As well, implementation of such visions requires equal devotion to consistency of methodology and avoidance of artificial (non-climatic) influences that extend beyond the careers and lifetimes of the individuals who participate in making this happen

The climate backdrop is explored first. This encompasses annual means, conditions during the most extreme seasons, and the full annual cycle of means and totals, for the two main elements, temperature and precipitation. These are shown both at points and as spatial patterns. In terms of spatial patterns, the main distinctions addressed are coastal versus interior climate behavior, and low versus high elevations. Methods of obtaining spatial fields in topographically diverse terrain at scales of several kilometers are addressed. In this report we have relied mostly on PRISM estimates, largely based on extensive previous evaluation in mountainous locations in the contiguous states of the western U.S. This choice does not greatly affect the network design strategy. Temporal variability is also discussed. Of special interest, this area is well known for being subject to variability on the half-century time scale.

Monitoring needs to aim for a judicious blend of station uniqueness and redundancy against data loss and sensor failure. As much as possible and practical, monitoring efforts should leverage each other, though with sufficient assurance of continuity into the future for each contributing network. Existing monitoring networks are discussed and presented. Selected stations are used to understand co-variability and correlation patterns.

A more extended discussion of the considerations associated with new sites is presented. Such an analysis needs to be end-to-end, driven by gaps in knowledge as much as possible, but with full recognition of logistical and practical issues, which are immense, especially in this region. In the end, rich prior experience has shown that maintenance always proves to be the most important ingredient in a successful monitoring program.

Equipment and exposure issues are discussed, and these are further broken down by element type. The best exposures for some elements (like temperature) are not necessarily the best exposures for other elements (like precipitation). Attention is given to considerations associated with different physical settings. The accurate measurement of frozen precipitation is a much bigger challenge than for liquid precipitation. Remoteness and lack of electrical power pose added challenges. Heavy snow and frequent moisture (from the sky or in the soil), extreme cold, and long darkness, are among the many issues that make this area such a severe test for instrumentation and communications. The requirement for involvement of skilled and experienced personnel is stressed.

The report concludes with a set of recommendations and associated discussions for each of the main parks: Kenai Fjords, Lake Clark, Katmai, and Aniakchak, with maps of locations to examine more closely. "Virtual visits" from the office, utilizing maps, charts, tables, and graphs can be very helpful and cost effective, but ultimately an actual physical reconnaissance is needed.

An appendix gives related comments on potential sites in Wrangell – St. Elias, Yukon-Charley, and Denali National Parks. Many of the general comments given there also apply to the parks in the Southwest Alaska Inventory and Monitoring Network of NPS.

1. Introduction

As part of their overall mission, most national parks observe weather and climate elements. The lands under the stewardship of the National Park Service (NPS) provide many locations that would be excellent sites for the monitoring of climate. A number of national parks have been doing this for decades, and others are just getting started. As primary environmental drivers, weather and climate are also a prominent part of the Vital Signs inventory and monitoring program, and are emphasized in nearly every park unit. Some smaller units, or units without sites that have good exposure, may benefit more from using nearby measurements made by some other group for their own purposes.

The purpose of this document is to assist with improvements in the ability to monitor weather and climate in the Southwest Alaska Inventory and Monitoring Network (SWAN). This includes the following NPS units: Aniakchak National Monument and Preserve, Katmai National Park and Preserve, Kenai Fjords National Park, Lake Clark National Park and Preserve, and associated Wild and Scenic Rivers.

In preparing this report we have drawn freely from a second document under preparation for Channel Islands National Park (Redmond and McCurdy, 2005). Channel Islands National Park ("CHIS" in NPS terminology) is also a prototype park for NPS, and that report has raised many of the general issues relating to climate monitoring faced throughout the national park system.

A primary focus of the present report is on methods to select additional locations for long term monitoring sites. For this we have incorporated background knowledge and existing climate products, including station-based point information, spatially distributed information about temperature and precipitation, temporal correlations, and other information as available.

2. The climate background

2.1 Spatial patterns

Accompanying are a variety of maps of long term mean (30 years) temperature and precipitation, for the state of Alaska as a whole, and for southwest Alaska in particular. These include mean annual precipitation and mean annual temperature, mean monthly maximum and minimum temperatures in the most extreme months (January and July), and mean monthly precipitation in the most extreme wet and dry months. The driest portion of the year differs from site to site, but March is generally among the driest months, and September is among the wettest months at most of the locations in this part of the state.

Precipitation. Kenai Fjords is the wettest of the parks, and is wet throughout the park, especially on the coast and at higher elevations (**Figure 1**). The three remaining SWAN parks have wet coastal areas and drier interior areas, even

Aniakchak. Of these three SWAN parks, Lake Clark has the wettest areas, largely by virtue of having high terrain close to the ocean. Cook Inlet offers a more restricted access to moisture than the open ocean, but nonetheless it remains ice free most of the time and does contribute local moisture through evaporation. Annual precipitation decreases from 1-2 meters to 0.5 meter across these coastal mountains (Aleutian Range).

The spatial pattern of the annual cycle of mean monthly precipitation is shown in **Figure 2**. The dry portion of the year is from winter into late spring at most stations and locations in the SWAN network. Conversely, the wettest portion of the year is generally between August and October. In the interior, the high sun months are generally the wettest. We have chosen March and September to represent the climatologically driest and wettest times of the year for most of the SWAN region. **Figure 3** and **Figure 4** show the March and September precipitation patterns, respectively, for the state as a whole.

In **Figure 5** the annual precipitation for southwest Alaska is highlighted. Contrasting March to September for this portion of the state (**Figure 6** and **Figure 7**), in both months the coastal strip is much wetter than elsewhere. March is especially dry inland; the gradient of relative precipitation (normalized to the coast) is less in late summer, when nearly every location is somewhat wet, than it is in spring. **Figure 8** shows the same annual precipitation as **Figure 5**, but plotted with a different scale to highlight different features.

<u>Temperature.</u> **Figures 9-13** show statewide temperature patterns. These show the mean annual temperature, as well as the mean monthly maximum and minimum temperatures in the extreme coldest and warmest months, to encompass the range of typical extremes. They show that the interior is (much) colder than the coast in winter, but warmer than the coast in summer, as expected. With the high sun in summer, there is relatively little spatial variation in minimum temperature from the coast to the interior in summer, except for the effects of elevation. All of these effects are readily explainable on physical grounds and are expected.

Figure 14 shows that the SWAN area is close to freezing on an annual basis. This has important implications for this heavily glaciated terrain. Given the sensitive dependence of glaciers on temperature, much of the ice in this area seems vulnerable to even slight warming (assuming no major changes in precipitation amount or seasonality). In many places only a small shift in temperatures will change the climatic regime from one that is near to below freezing to one that is near to above freezing. All the areas in yellow on this figure are at annual temperatures between 0 and 2 degrees C below freezing, and a modest climate warming of +2 degrees C would change all these to above freezing, with obvious consequences. It is readily apparent that there are large areas in this circumstance. Locations with long term temperatures near the freezing mark, or just a degree or two below freezing, are thus good candidate locations for monitoring. Some of this ice is flowing downward from cooler source regions, but those regions are only a few degrees cooler. So it appears

that the national parks of the southwest coast are in a generally sensitive area for temperature. This argues that there perhaps should eventually be several stations throughout the area, partly to act as checks on each other and to provide some degree of reinforcement and to fill data gaps.

Figure 15 and **Figure 16** show that the maritime influence extends inland in winter and does not give way across the coastal divide to full Arctic conditions, particularly in the Kenai Fjords area. Across the Aleutian Range in the Lake Clark / Katmai / Aniakchak parks, there is a transition to somewhat more severe Arctic conditions, but in relative terms this transition is increasingly more modest in moving from Lake Clark to Katmai to Aniakchak along Cook Inlet and then southwest along the ocean shore. There is a greater winter contrast in temperature from Cook Inlet to the interior through Lake Clark NPP. **Figure 17** and **Figure 18** show the analogous summer situation. Generally, summer temperatures are warmer on the inland or interior side than along the south coast. Also, as expected, the highlands and mountains have lower maximums and somewhat lower minimums. The high sun and long days in mid-summer results in smaller spatial gradients and in rather small temporal variability. This is seen in the correlation analysis below as well. Cloudiness variations help control the amount of summer solar radiation absorbed.

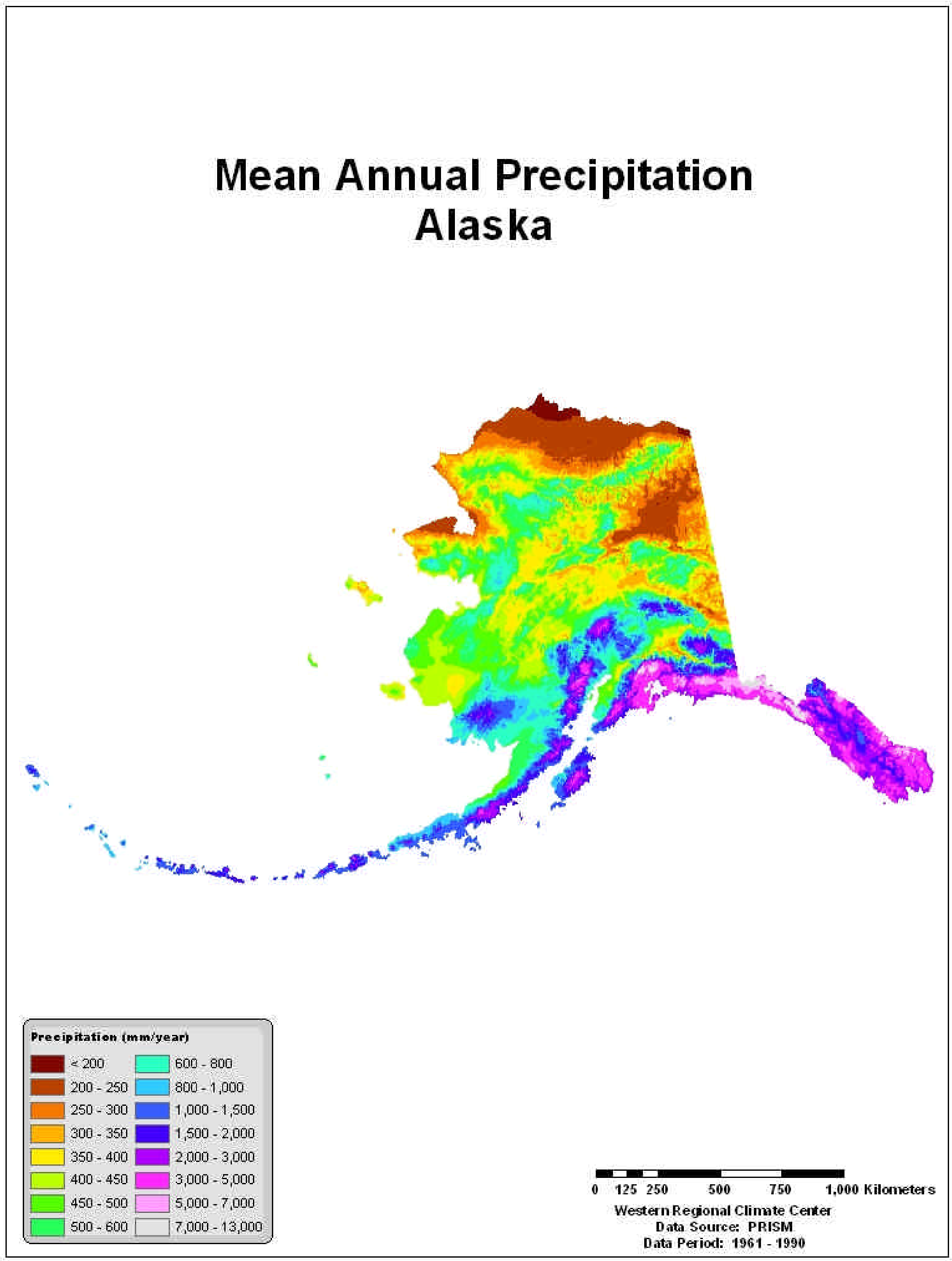


Figure 1. Mean annual precipitation for Alaska, 1961-1990.

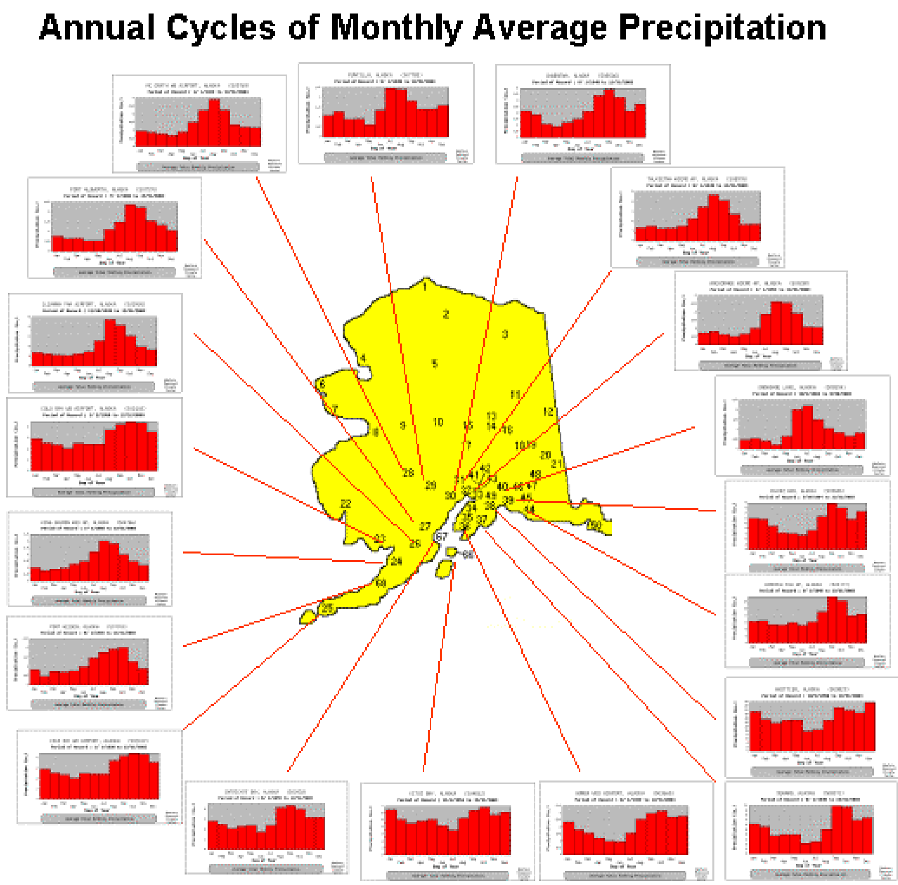


Figure 2 Annual cycles of average precipitation, by month, in Southwest coastal Alaska. Differing scales. The intent of this figure is to show the shapes of the annual cycle rather than the amounts. Varying periods of record. Taken from WRCC web pages at www.wrcc.dri.edu/summary/climsmak.html.

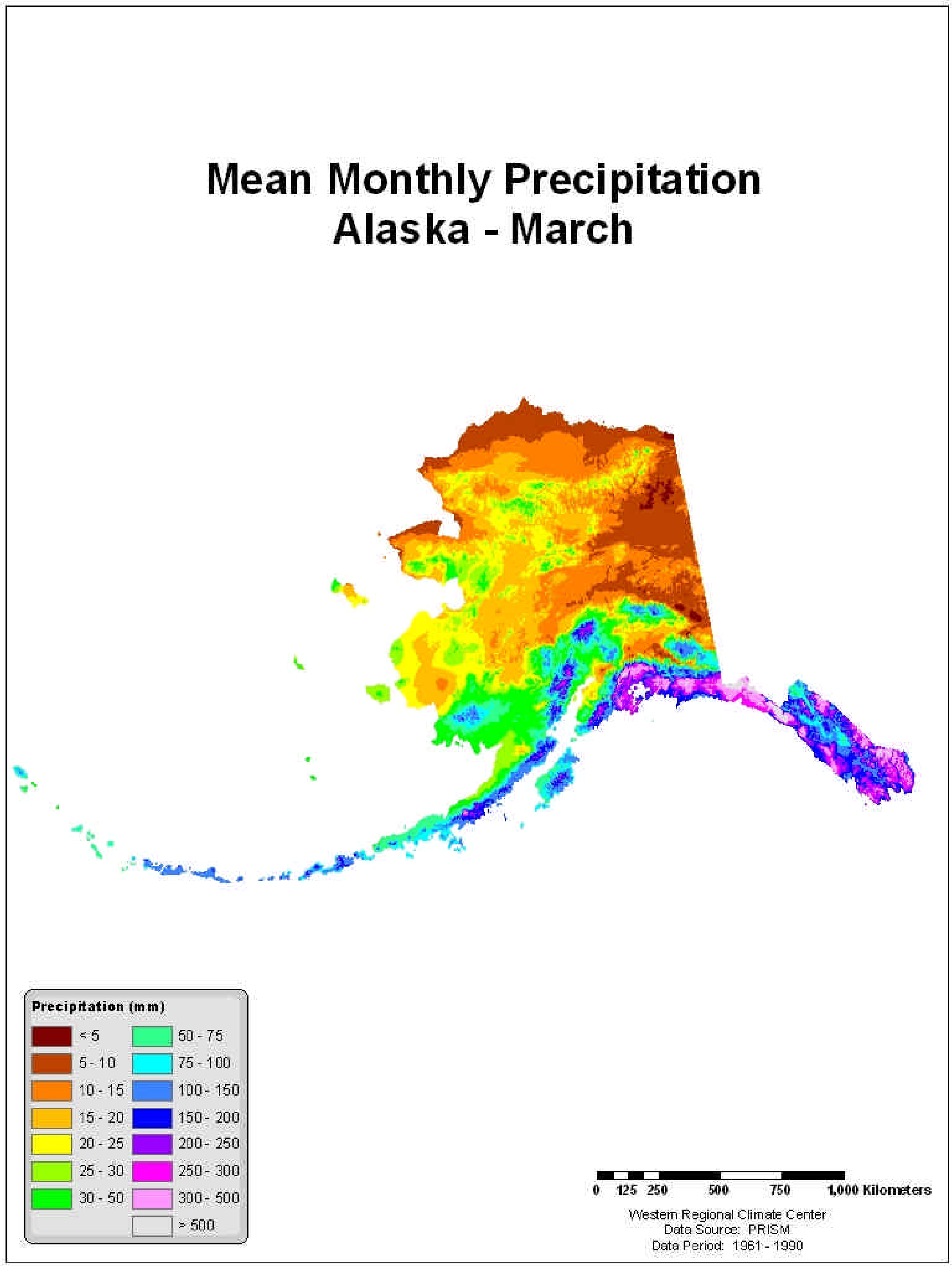


Figure 3. Mean precipitation for March for Alaska, 1961-1990.

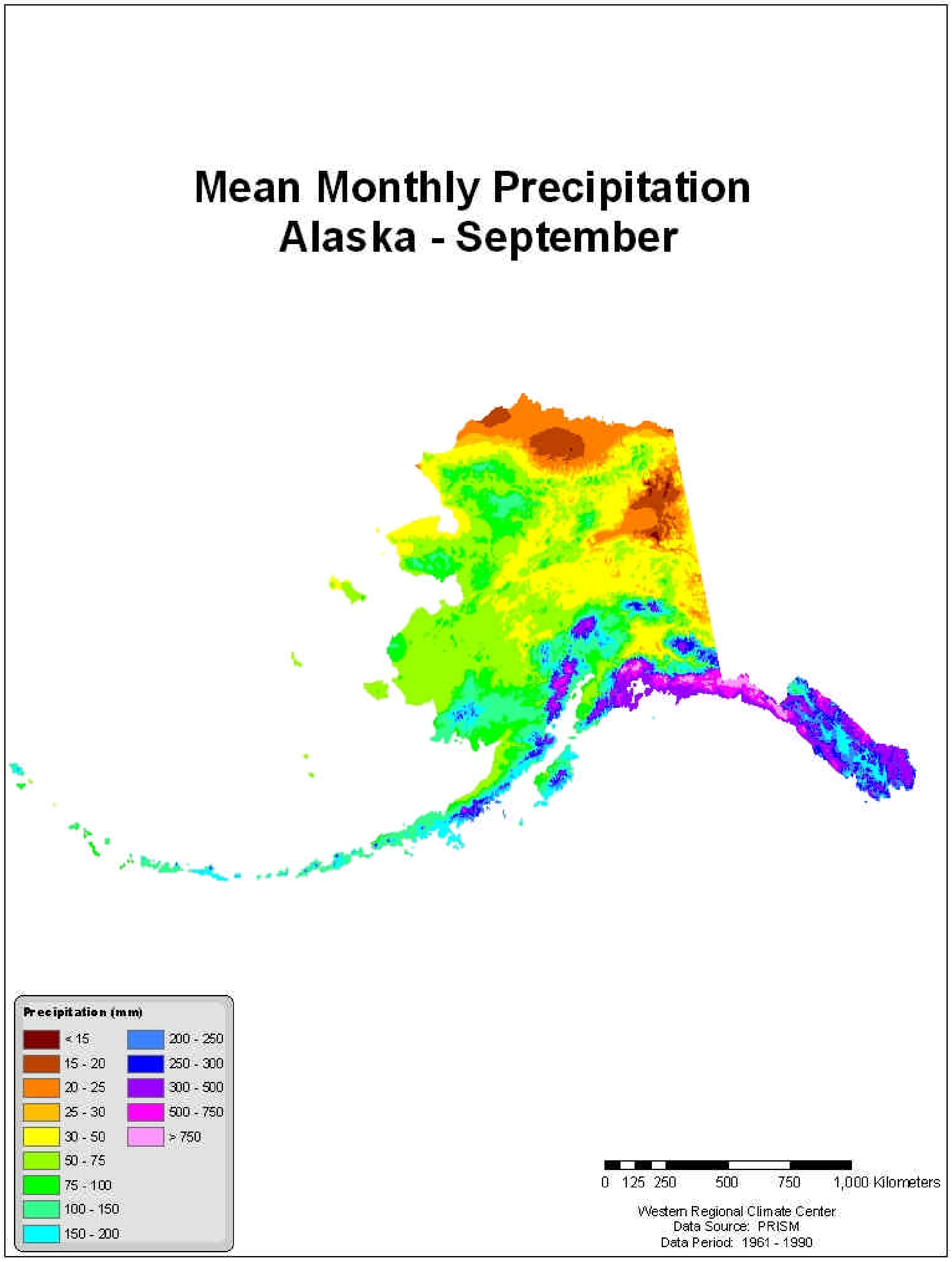


Figure 4. Mean precipitation for September for Alaska, 1961-1990.

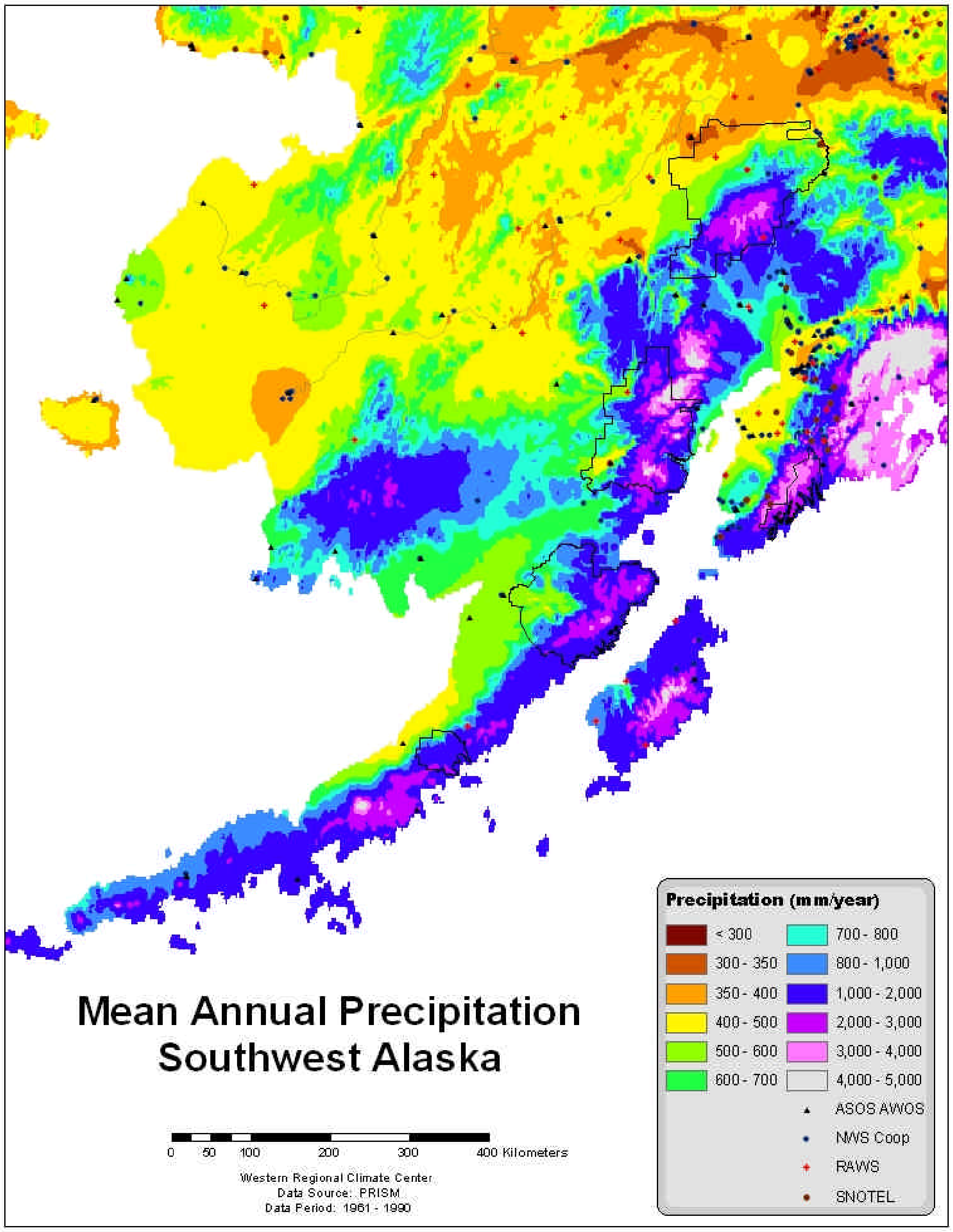


Figure 5. Mean annual precipitation, 1961-1990, for southwest Alaska, showing station distribution of several networks.

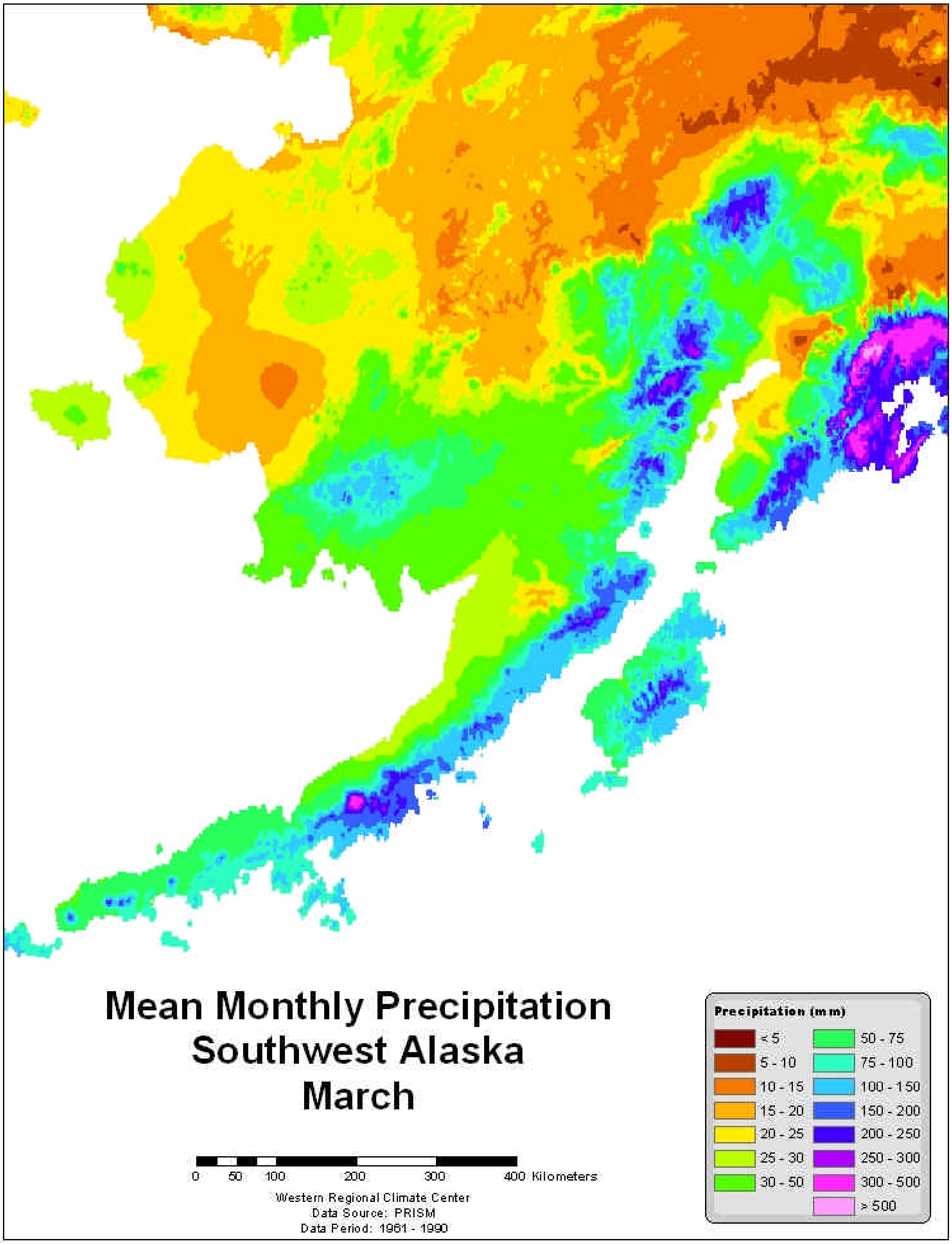


Figure 6. Mean monthly precipitation for March for Southwest Alaska, 1961-1990.

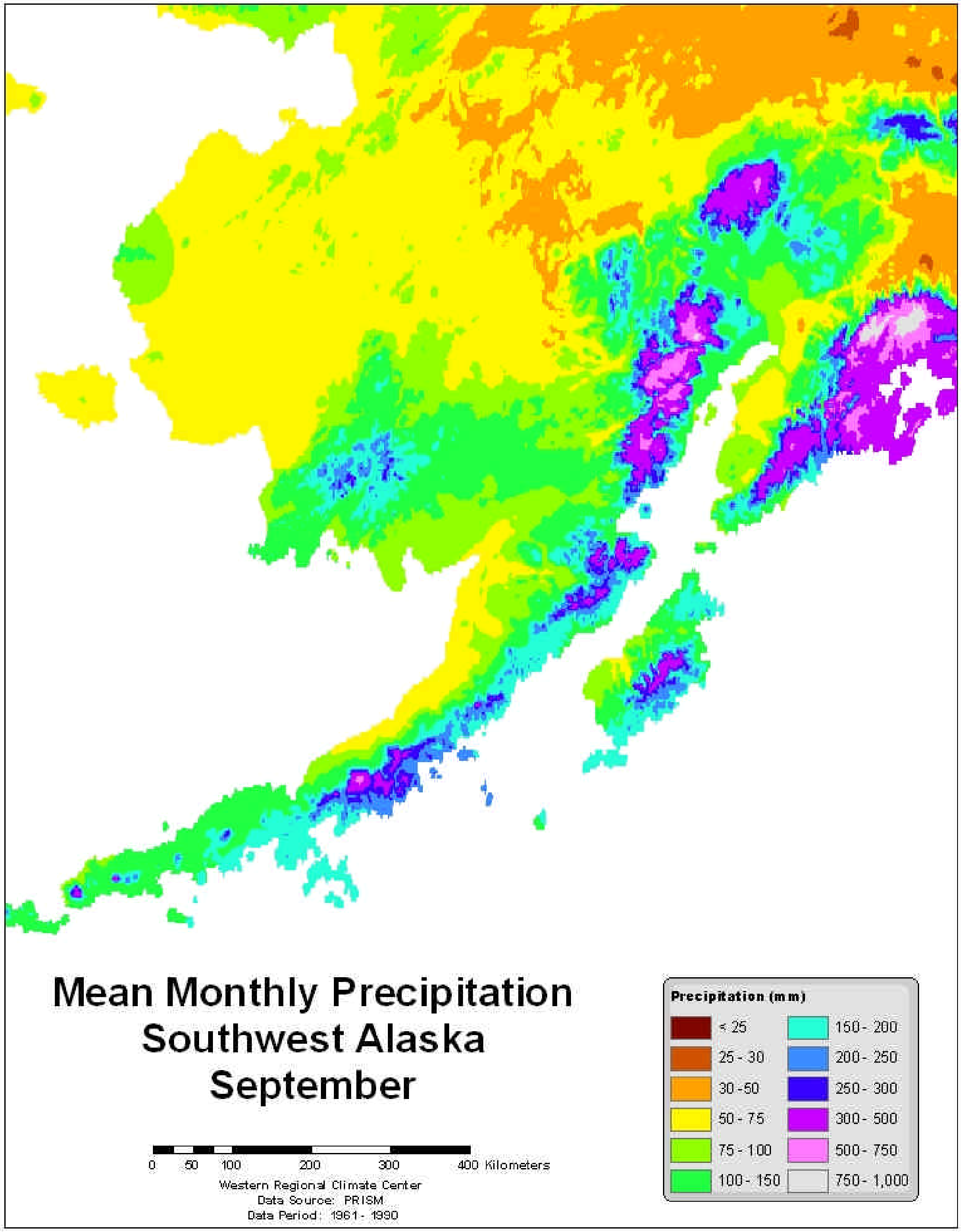


Figure 7. Mean monthly precipitation for September for Southwest Alaska, 1961-1990.

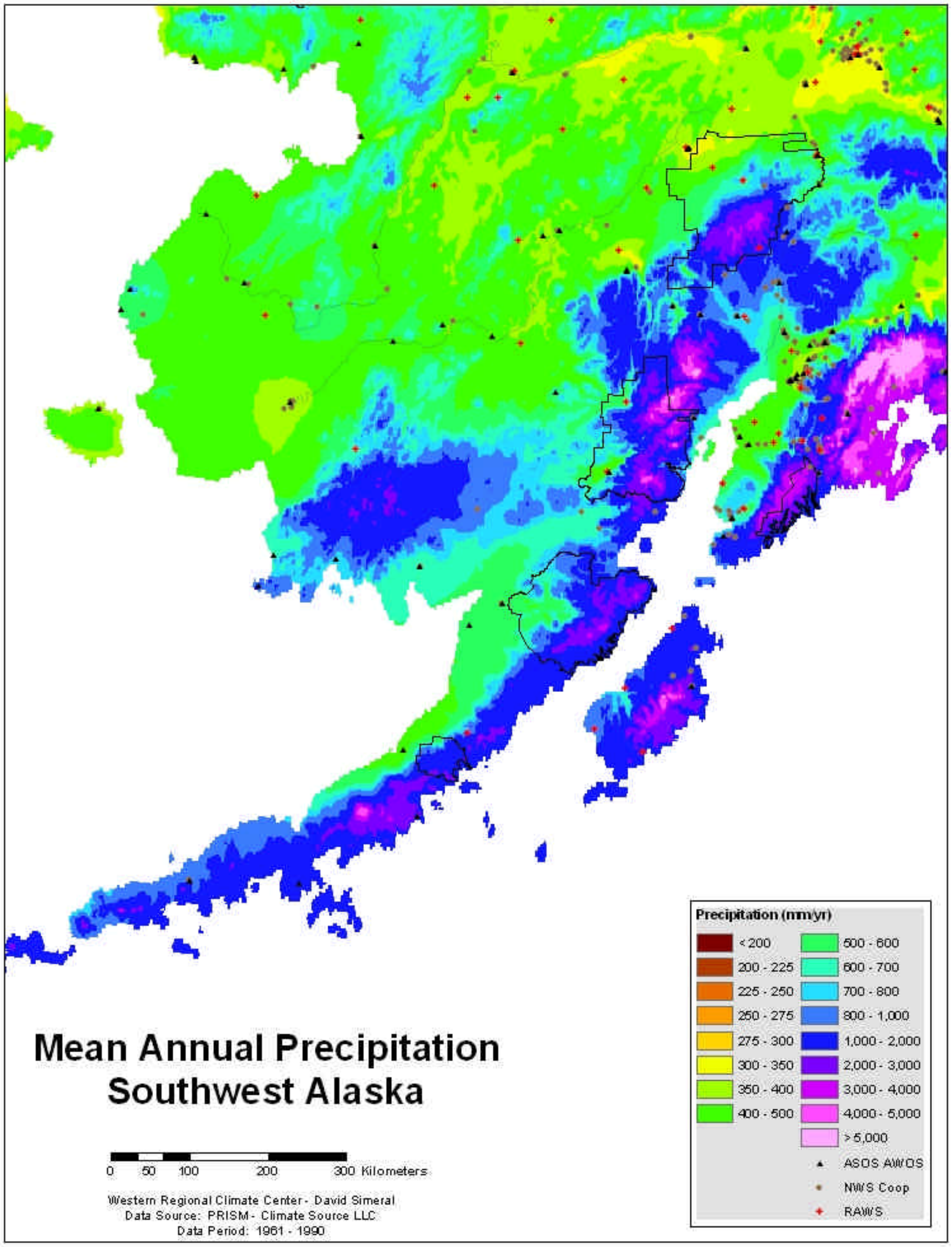


Figure 8. Mean annual precipitation for Southwest Alaska, 1961-1990, showing station distribution in several networks. Same map as Figure 5, different scale.

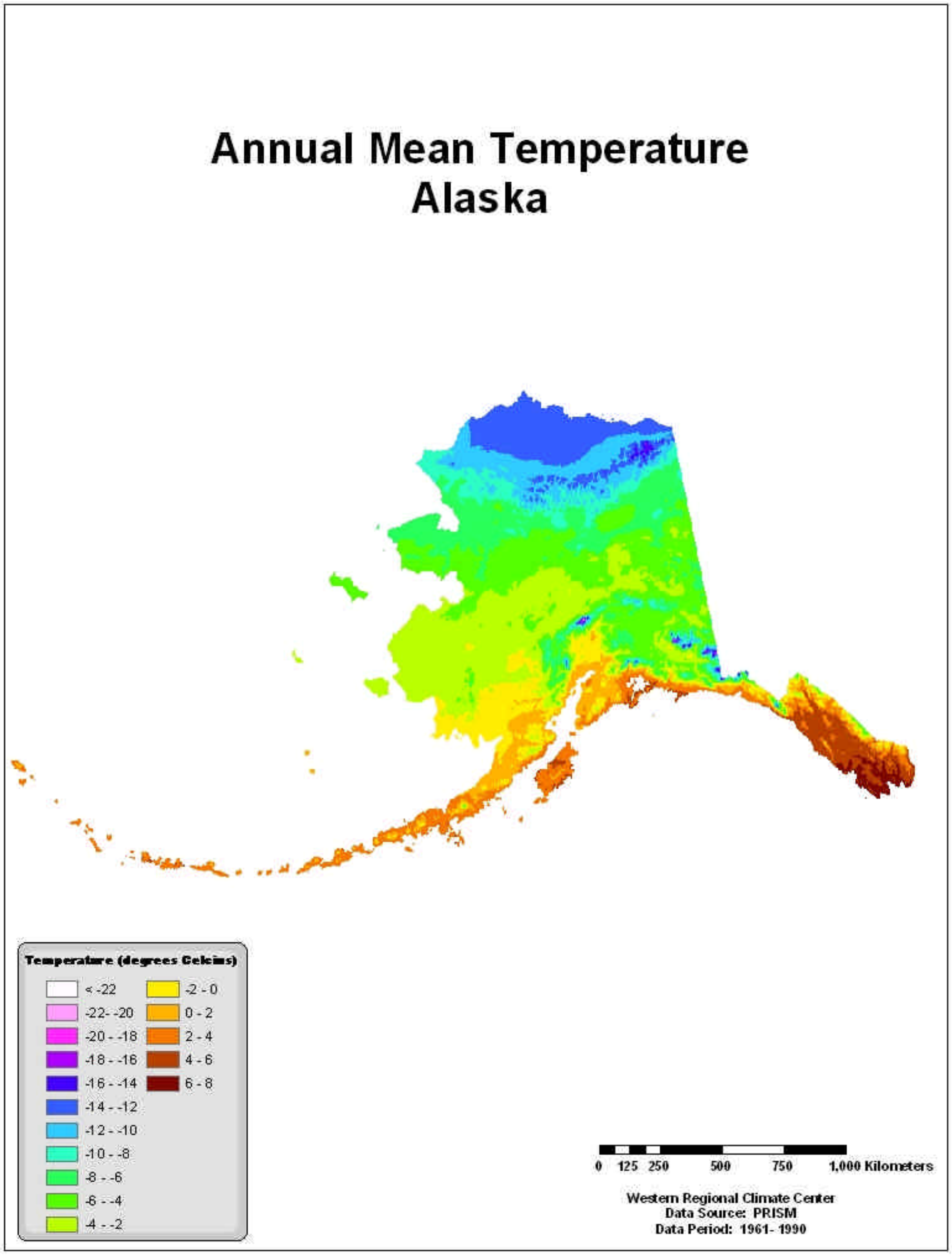


Figure 9. Mean annual temperature for Alaska, 1961-1990. Revised Jan 2006 to correct color scale.

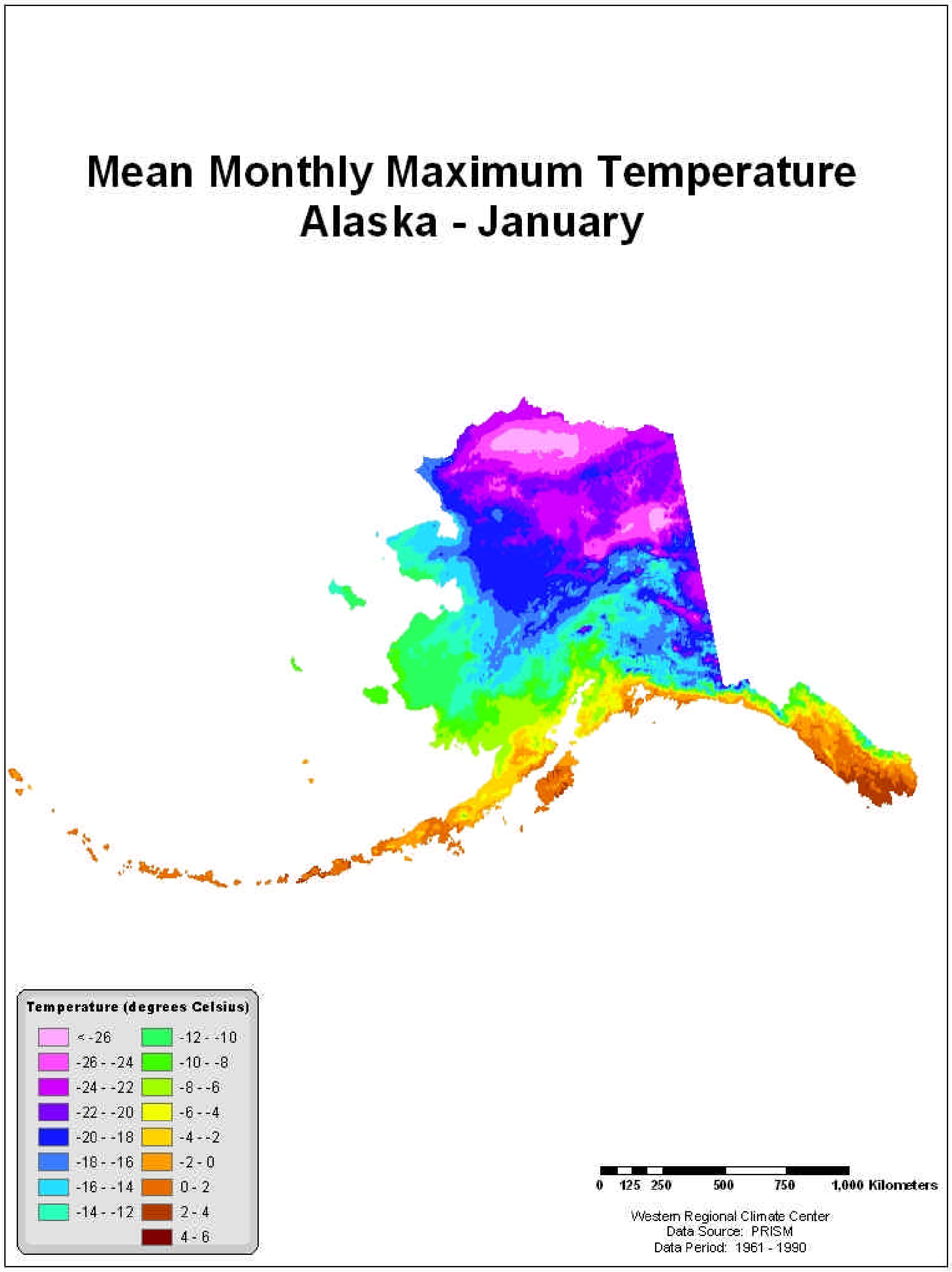


Figure 10. Mean monthly maximum temperature for January for Alaska, 1961-1990.

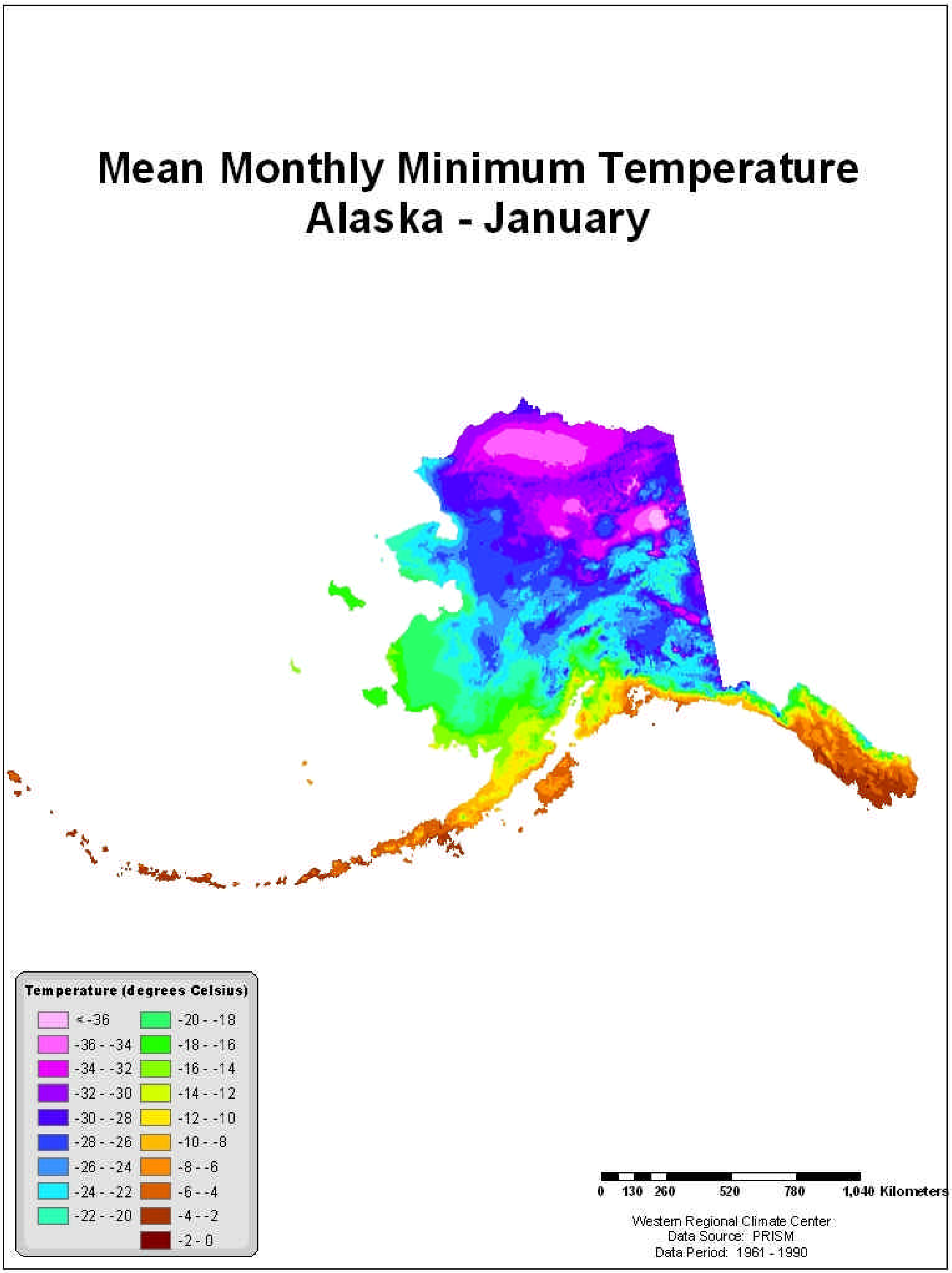


Figure 11. Mean monthly minimum temperature for January for Alaska, 1961-1990.

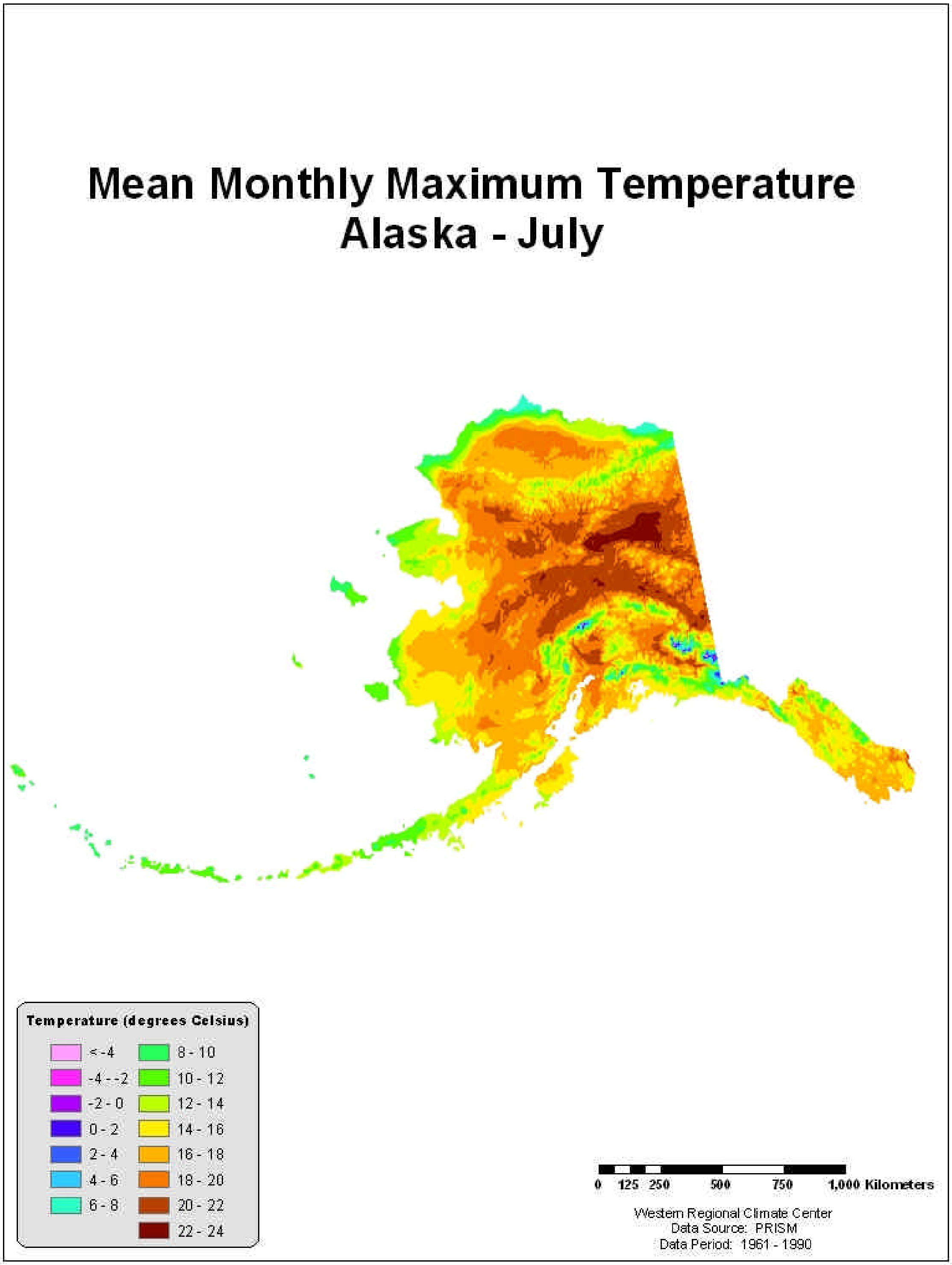


Figure 12. Mean monthly maximum temperature for July for Alaska, 1961-1990.

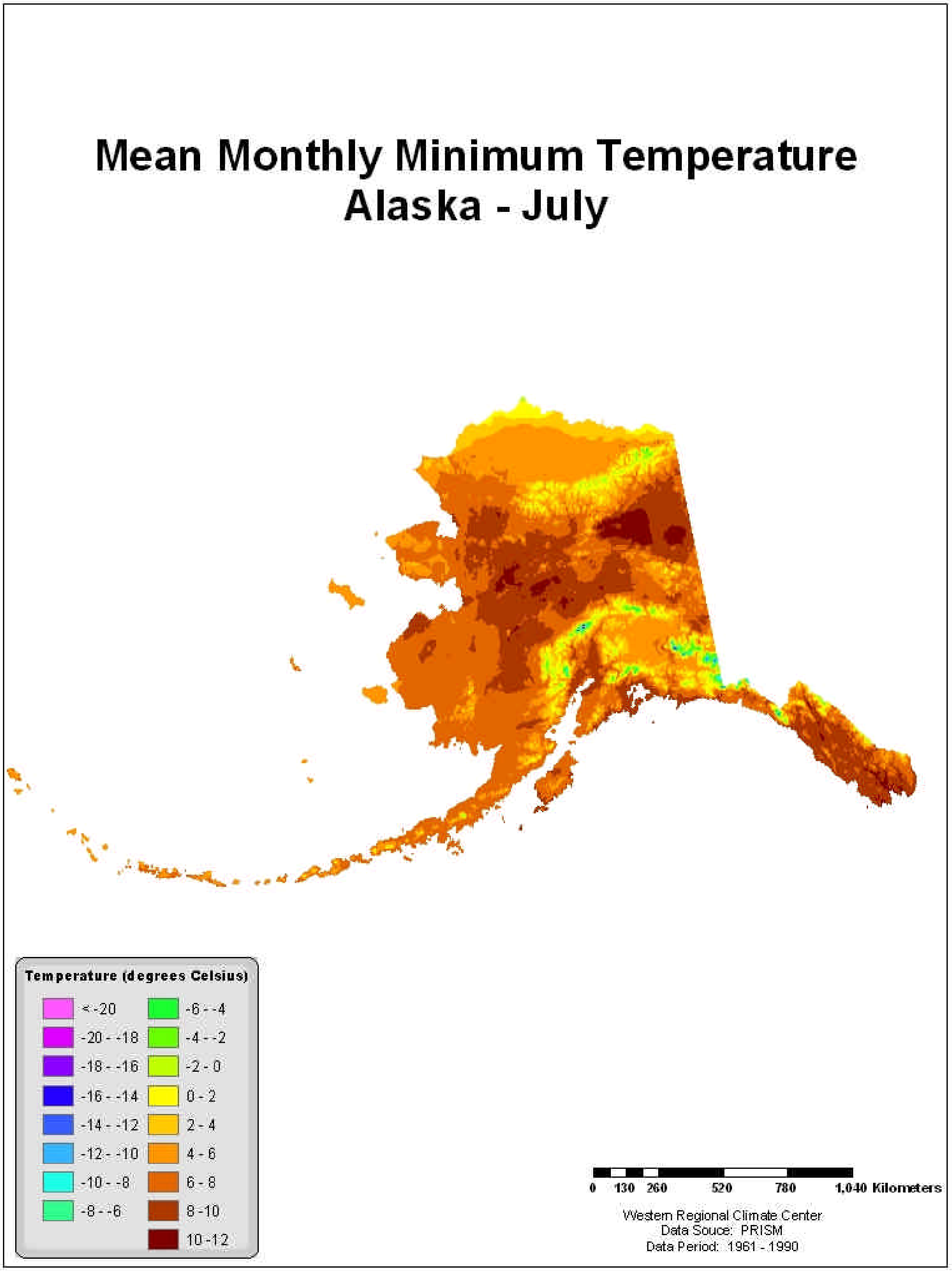


Figure 13. Mean monthly minimum temperature for July for Alaska, 1961-1990.

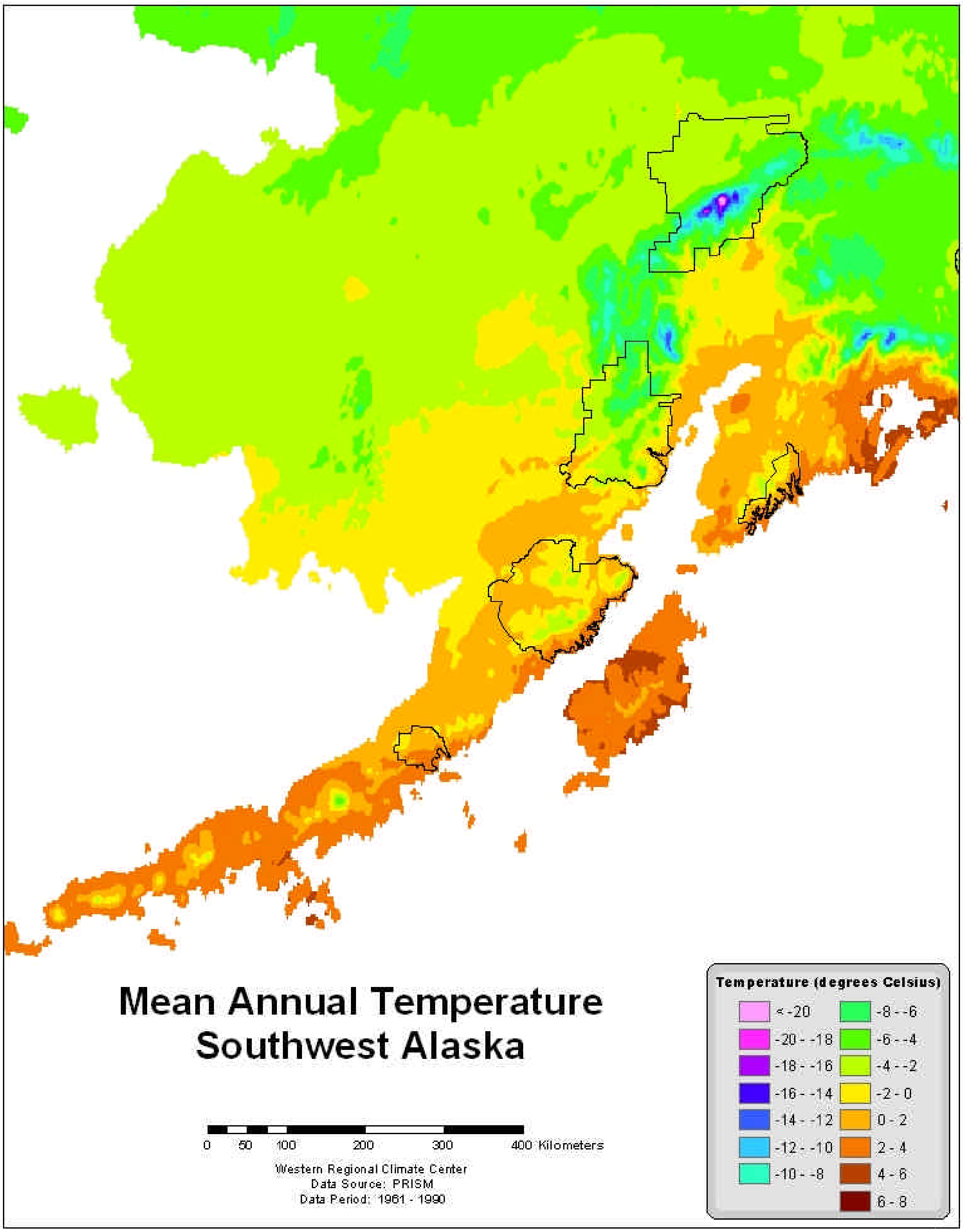


Figure 14. Mean annual temperature for southwest Alaska, 1961-1990.

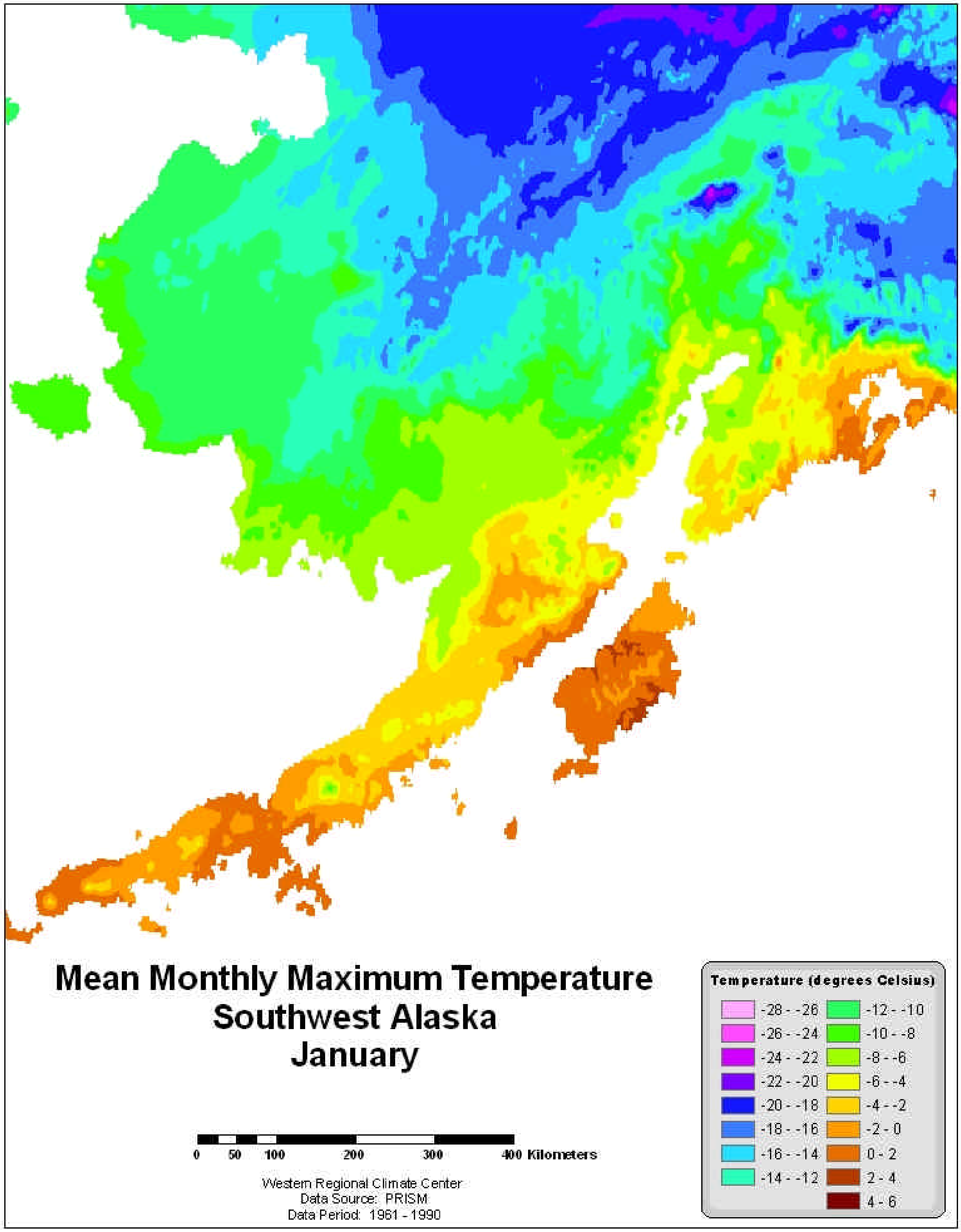


Figure 15. Mean monthly maximum temperature for January, for southwest Alaska, 1961-1990.

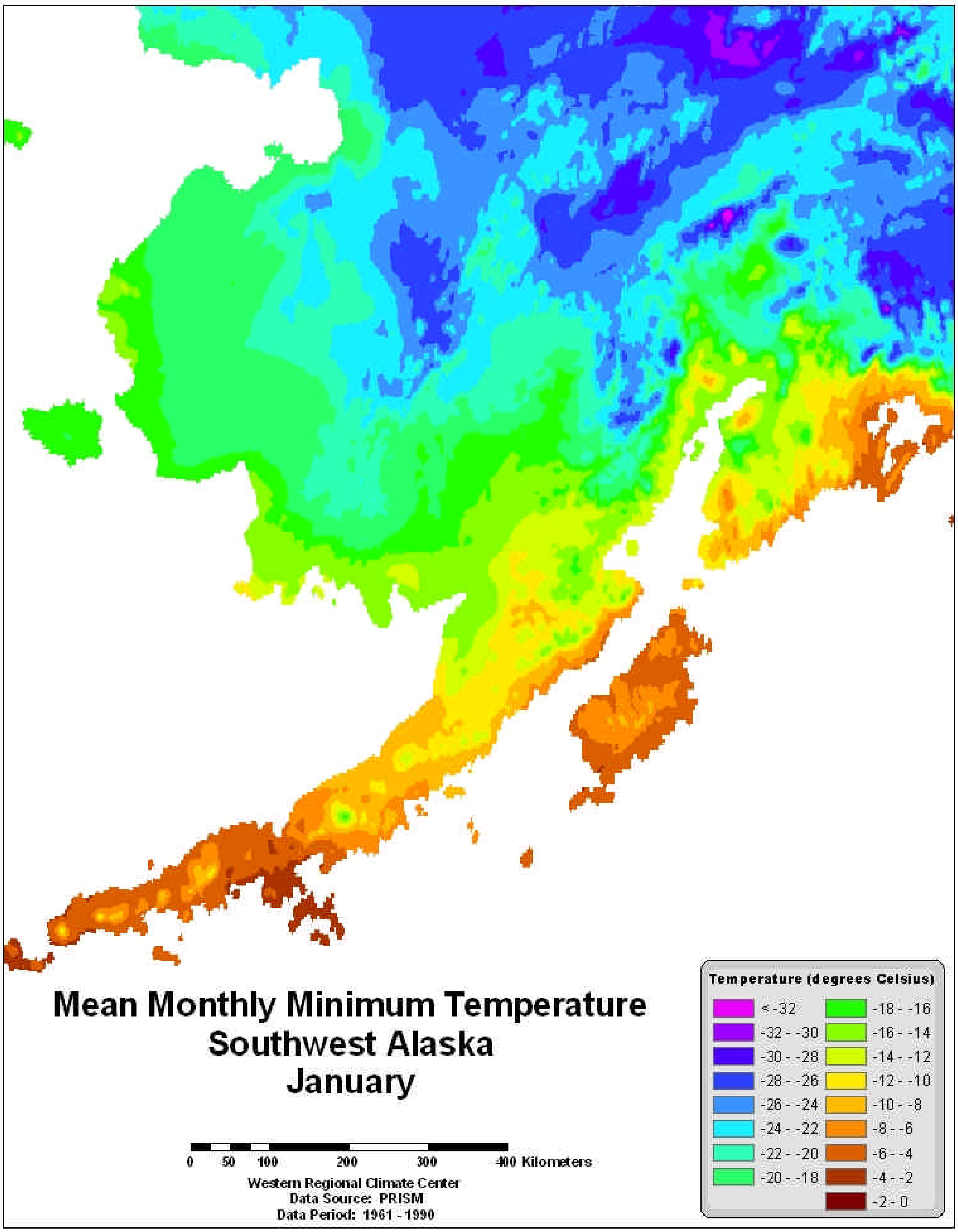


Figure 16. Mean monthly minimum temperature for January, for southwest Alaska, 1961-1990.

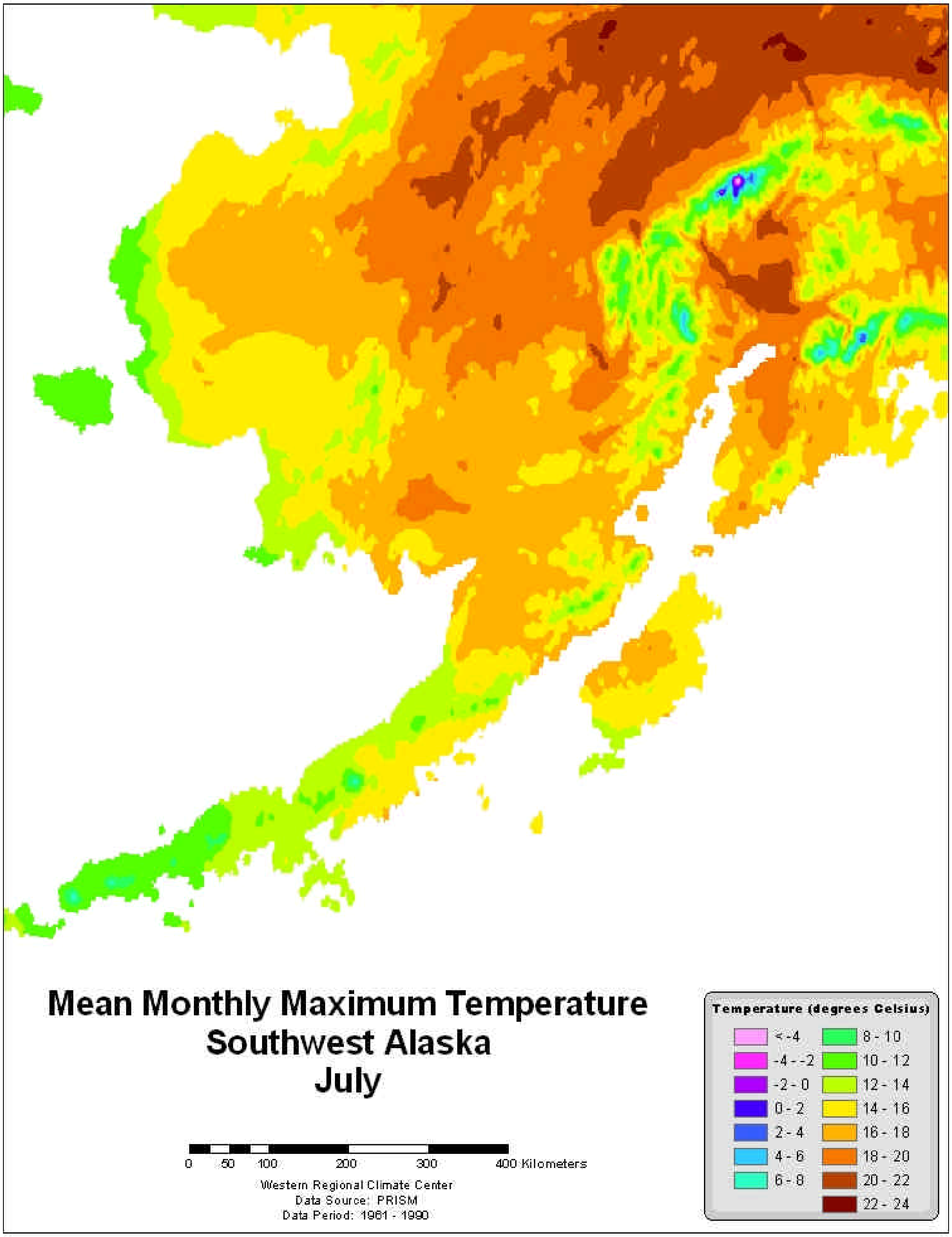


Figure 17. Mean monthly maximum temperature for July for southwest Alaska, 1961-1990.

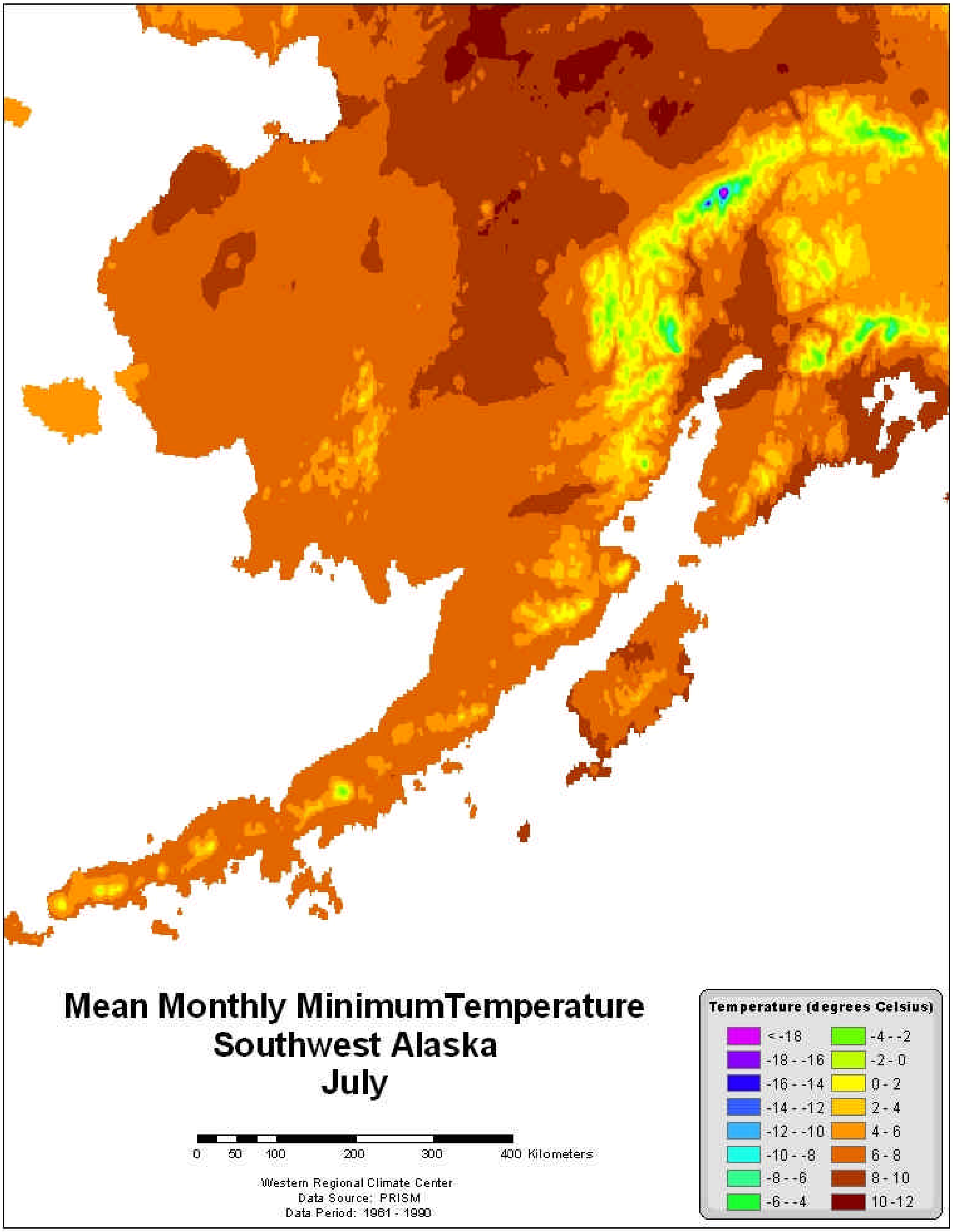


Figure 18. Mean monthly minimum temperature for July, for southwest Alaska, 1961-1990.

2.2 Temporal variability

Climate constantly fluctuates, on a variety of temporal scales. This area is not different from other places in this regard. However, in addition to the "typical" variations in climate seen at all locations, Alaska, and this part of Alaska, experience two additional sources of variability.

The first of these involves variations in the atmosphere and ocean in the North Pacific Ocean south of the southern Alaska coastline, that take 50-60 years to undergo a full "oscillation" from one phase and then back again (we are not sure if this a true oscillation at this point, having witnessed only a portion of two cycles). These variations affect the coast and coast ranges of the state. These were described and explored most fully by Mantua et al. (1997) and have come to be known as the Pacific Decadal Oscillation (PDO). The south coast of Alaska exhibits the greatest continental expression of this effect. The cause of variability on this time scale is a subject of active research, and is thought to relate to El Nino, La Nina, and the Southern Oscillation, seen in the tropical Pacific, thousands of kilometers to the south. These variations, experienced during the winter half of the year, have major effects on the regional climate, the ocean circulation, and on biological organisms and populations, such as salmon (Mantua et al., 1997).

Secondly, in recent years, much of Alaska has experienced unusually mild winters, and temperatures during the 1990s rose substantially beyond those in previous decades. In many quarters, these are being taken as the harbinger of large scale planetary warming of the surface of the earth. The Arctic has long been expected to be the place where the signal would be seen soonest and most clearly, and many are interpreting the recent unusual warmth in that context (Arctic Assessment, 2004). Though the area of greatest interest is primarily north of much of the coastal SWAN area, the entire region is affected.

Thus, there are compelling reasons for much better knowledge of the variations of climate in this area.

3. Existing Site Information

3.1 Types of networks

Most station data will be from locations that are part of one network or another, although there are also occasional special stations unaffiliated with a larger systematic monitoring program.

3.1.1. NOAA and FAA Hourly Surface Airways Stations

These stations are generally at airports, though not always. They record hourly or instantaneous values of the main meteorological elements: air temperature, a humidity element (dewpoint or relative humidity), wind speed and direction and gusts, barometric pressure, and sometimes hourly or accumulated precipitation. These networks are managed by NOAA National Weather Service, and by the FAA. Often, the FAA stations do not record precipitation, or provide precipitation records of reduced quality. Automated stations are typically ASOS (Automated Surface Observing System) for the National Weather Service (NWS) or AWOS (Automated Weather Observation System for FAA. Some of these sites only report episodically, with observers that are paid per observation.

3.1.2 NOAA National Weather Service Cooperative Stations

This is the main climate observation network in the United States, and is often referred to as SOD (Summary-of-the-Day). Measurements consist of once-daily readings of maximum and minimum temperature and instantaneous observation-time temperature, daily precipitation, daily snowfall, depth of snow on the ground, and occasionally pan evaporation. Readings are usually made by volunteers. NWS and FAA sites are often considered to be part of the cooperative network as well, if they take the above-mentioned types of summary observations. Typical observation days are from morning to morning, evening to evening, or midnight tot midnight. By convention, observations are ascribed to the date of instrument reset at the end of the period. For this reason, midnight observations represent the end of a day.

3.1.3 Interagency RAWS Stations

The Remote Automatic Weather Station (RAWS) network is used by many land management agencies, such as the Bureau of Land Management (BLM), National Park Service (NPS), Fish and Wildlife Service (FWS), Bureau of Indian Affairs (BIA), Forest Service (USFS), and other agencies. These sites record once an hour the temperature, relative humidity, wind speed and direction and gust speed, fuel stick temperature, and accumulated precipitation. Some sites also record solar radiation (some instantaneous, some time-integrated). Most gages do not have heaters, so hydrologic measurements are of little value when temperatures are below freezing or upon rising up to freezing after snow. These report hourly values by satellite, for hours that end on an assigned minute (not usually minute 00 or 30). There are approximately 1100 realtime sites in this network, and about 1800 historically (some are decommissioned or moved). The sites can transmit data all winter, but may be in deep snow in some locations. The Western Regional Climate Center is the archive for this network, and receives the station data and metadata through a special connection to the National Interagency Fire Center in Boise.

3.1.4 USDA Snotel Stations

The United States Department of Agriculture (USDA) maintains a set of snow monitoring stations within the National Resources Conservation Service (NRCS), known as Snotel (Snowfall Telemetry). These are specially designed for cold and snowy locations, and record accumulated precipitation (since October 1), water content of snow on the ground (Snow Water Equivalent, or SWE), and temperature. Most units now also record snow depth. Precipitation is intended for hydrological applications and water supply forecasting, so light amounts (0.00” to 0.09”) are not specifically recorded, but are rather lumped into 0.10” increment reports. That is, hydrological elements (precipitation and snow water equivalent) are tracked to 0.1 inch precision. Snow depth is tracked to the nearest inch. These stations function year round, in daily or hourly modes.

3.1.5 Other special networks

In addition to the major networks mentioned above, there are a variety of stations run for specific purposes by specific organizations, government agencies, or scientific research projects (e.g., USGS, NSF, university, tribal, community, air quality, etc). Sometimes these are readily accessible, and other times the data are very difficult to obtain, either in near-real-time or in delayed-access mode.

Collectively, information from all of these networks may be suitable for obtaining a better picture of the weather at any one time. However, this may have little relationship to their ability to serve as useful climate stations. The main needs for climate stations are consistency in time of station exposure, observational methodology, and instrument type and configuration. In practice, these can be very difficult to achieve.

3.2 Tables of sites and metadata

Lists of stations have been compiled showing the various stations and sites in each of several main networks. A station does not have to be within the boundaries to provide useful data and information regarding the park unit in question. Some might be physically *within* the administrative or political boundaries, whereas others might be just outside, or even some distance away, but would be *nearby* in behavior and representativeness. In the SWAN area, the number of the former is relatively small, and the number of nearby stations is higher, though usually still not fully sufficient for all purposes. What constitutes “useful” and “representative” are also significant questions, whose answers can vary according to application, type of element, period of record, procedural or methodological observation conventions, and the like.

Thus, we have chosen to make these files available in digital form.

These listings include name and site identification number, in one of several systems for tracking stations (typically agency-dependent or application-dependent), positional information; start and end of the entry if available, and other information as available and appropriate.

3.3 Maps of sites

By any measure, southwest Alaska does not enjoy a surfeit of stations. This can be seen from **Figure 19**.

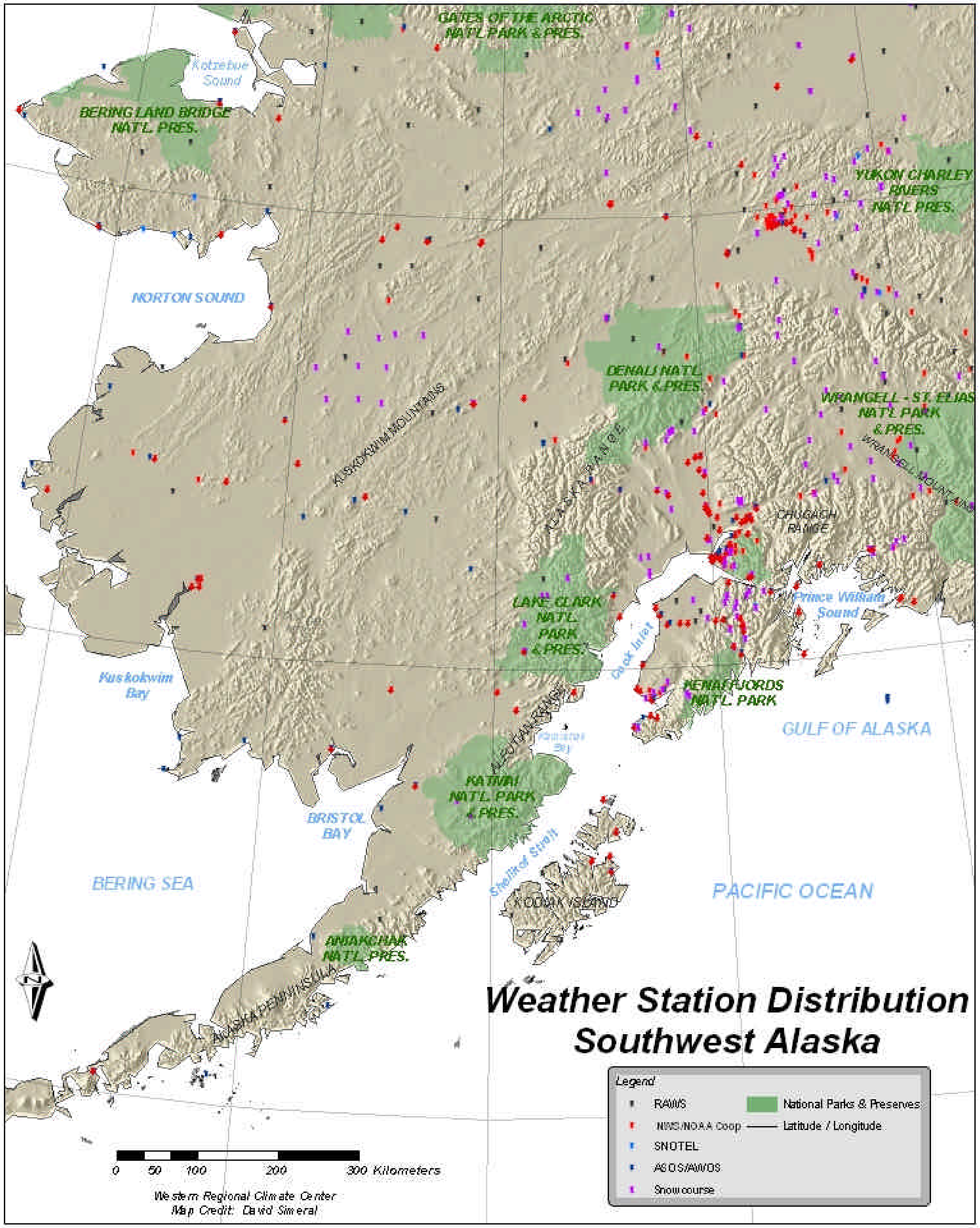


Figure 19. Station and network distributions in southwest Alaska.

4. Identification of potential new observations sites

4.1 Considerations

There are several criteria we would like to utilize in deciding where to deploy new stations:

- Where are the existing stations?
- Where have data been gathered in the past (discontinued locations)?
- Where would a new station fill a gap about the basic long-term climatic averages for an area of interest?
- Where would a new station fill a gap in how climate behaves in time?
- As a special case of behavior in time, what locations might be expected to show a more sensitive response to climate change?
- How do the answers to the above questions depend on the climate element? Are the answers the same for precipitation, temperature, wind, snowfall, humidity, etc.?
- What unique information is provided? “Redundancy is bad.”
- Because observing systems always have gaps and lose data, what nearby info is available to estimate for missing observations? “Redundancy is good.”
- How would logistics and maintenance affect these choices?

Two main purposes for climate observations are to establish the long-term averages for given locations, and to track the variations in climate. Broadly speaking, these address topics of absolute and relative climate behavior. Once the former have been “established” (a job that is never really finished, because the long-term averages continue to vary in time), the temporal variability quickly becomes the item of most interest.

In popular usage, we often encounter the notion that a site is “representative” of another site if it receives the same annual precipitation, or has the same annual temperature, or if some other element-specific long-term average has a similar value. This notion of what is “representative” of another place does have a certain limited validity, but there are other aspects of “representativeness” that need to be considered.

A good monitoring site can also be said to be “representative” if the climate records from that site show sufficiently strong temporal correlation measures, such as the Pearson correlation coefficient, r, with a large number of locations over a sufficiently large area. If station A receives 20 cm a year, and station B receives 200 cm a year, these are obviously quite different precipitation climates. However, if their monthly, seasonal, or annual correlations are high (say, 0.80 or higher for a particular time scale) one can be used as a surrogate to estimate the values at the other if a particular month, season, or year is missing. That is, a wet or dry month at one site is also a wet or dry month (relative to its own mean) at the comparison station. Note that high correlations on one time scale do not automatically imply good correlations on other time scales.

Likewise, two stations with similar mean climates (for example, similar annual precipitation) might not co-vary in close synchrony (for example, coastal versus interior.) This might be looked at as a matter of climate “affiliation” of a particular location.

Thus, the “representativeness” of a site can refer either to the basic climatic averages for a given duration (or time window within the annual cycle), or to the extent to which it co-varies in time with respect to all surrounding locations. One site can be representative of another in the first sense but not the second, or vice versa, or neither, or both – all combinations are possible.

If two sites are perfectly correlated (r = 1.00) then in a sense they are redundant. However, redundancy has value, because all sites will experience missing data, especially with automated equipment in rugged environments and harsh climates, where outages and other problems can be nearly guaranteed. In many cases those outages are caused by the weather, particularly by unusual weather, the very conditions we most wish to learn about. Methods to fill in those values will need nearby proxy information from this or other networks. Thus, redundancy is a virtue rather than a vice.

4.1.1 Temporal behavior

It is also possible that correlations between station pairs are good during certain portions of the year (i.e., January) but poor during other portions (e.g. September or October). The relative contributions of these seasons to the annual total (for precipitation) or average (for temperature), and the correlations for each month, are both factors in the correlation of a longer duration aggregated time window that encompasses those seasons (e.g., one of the year definitions, such as Calendar Year or Water Year). For this reason, we have picked a number of station pairs and show the annual correlation cycles for monthly mean temperature and monthly total precipitation. Note that it is also possible and is frequently observed, that temperatures can be well correlated but precipitation is not, or vice versa, and these relations can change by time of year. If two stations are well correlated for all climate elements for all portions of the year, then they can be considered redundant. With scarce resources, the initial strategy should be to try to identify locations that do not correlate particularly well, so that each new site measures something new, that cannot be easily guessed from the behavior of surrounding sites. (An important caveat here is that lack of such correlation be a result of physical climate behavior, and not a result of faults with the measurement process itself, i.e., by unrepresentative, or simply bad, data. Unfortunately, we seldom have perfect climate data.) As additional sites are added, we usually wish for some combination of unique and redundant sites to meet what amounts to essentially orthogonal constraints: new information, and more reliably furnished information.

A common consideration is whether to observe on a ridge in a valley, given the resources to place a single station in a particular few square kilometers. Ridge and valley stations will correlate very well for temperature when lapse conditions prevail, particularly summer daytime. In summer at night, or winter daylight, the picture is more mixed and correlations will be lower. In winter at night, when inversions are common and even the rule, correlations may be zero, or even negative, perhaps very negative, as the two sites are on opposite sides of the inversion. If one had the luxury of stations everywhere, one would find that ridgetops generally correlate very well with other ridgetops and valleys with other valleys, but ridgetops with valleys only under certain circumstances. Beyond this, valleys and ridges with similar orientations will usually correlate better with each other than those with perpendicular orientations, depending on their orientation with respect to large scale wind flow and solar angles.

Unfortunately, we do not have stations everywhere, so we are forced to use the few comparisons that we have, and include a large dose of intelligent guessing, using what we have observed elsewhere.

To assess the temporal representativeness, we have performed a correlation analysis, using stations in and near the SWAN parks, for monthly, seasonal, and annual temperature and precipitation (**Figure 20**).

In general, the cooperative stations managed by the National Weather Service have much longer records than automated stations like RAWS or the few Snotel stations around. RAWS often also have problems with precipitation, especially in winter, or with missing data, so that low correlations may be data problems rather than climate dissimilarity. The RAWS records are much shorter, so correlations should be digested with care, but these stations are more likely to be in places of interest to SWAN. We have included pairs of coop stations, pairs of a few RAWS stations, and Coop-RAWS pairs. For example, at Port Alsworth, the coop and RAWS stations are within a half mile of each other (if metadata are correct), and temperatures are well correlated, but precipitation is not, over the relatively short period of record. There are physical climatic reasons and observational reasons why stations within a short distance (even a few tens or hundreds of meters) may not correlate well.

Overall results of the correlation analysis (**Figure 21**) thus far show that temperature has much larger scale correlation structure than does precipitation, and that temperatures are correlated better than precipitation totals. This is not surprising. This can be taken as a measure of the role of the Aleutian Low and how pervasively it controls the large scale flow into southern Alaska.

To help interpret such correlations, aspects of the background climatology relating to flow and dynamics is shown is shown in several figures. The reference period here, 1968-1996, is an arbitrary 29-year period used by the NOAA Climate Diagnostics Center, with whose help these figures were developed. **Figure 22** shows the annual cycle of surface pressure patterns (reduced to sea level) for each month, starting in January and proceeding through December. The Aleutian Low forms in winter, decreases in strength toward summer, and shifts position during the year. **Figure 23** shows the upper air climatology from 1968-1996 of geopotential height at 700 mb (about 10,000 ft), for those same four months (Jan, Apr, Jul, Oct). Winds generally follow approximately these contours, with speed proportional to contour spacing, keeping low pressure on the left in the Northern Hemisphere. The vector mean monthly winds themselves are shown with arrows (for direction) in **Figure 24** and with contours (for speed). In calculating these vector speeds and directions, note that a north wind will cancel out a south wind of equal speed blowing for the same duration; vector mean speeds are always less than scalar mean speeds.

Information on the frequency of speeds and directions along the southern coast is difficult to find. Wind roses (joint direction and speed information) are shown in **Figure 25** for the open ocean location nearest to Kenai Fjords, the Pilot Rock Light about 25 miles south of Seward. For the approximate 5-year period used there, this site had 41,054 hourly observations on 1929 days. The high frequency of winds from the north in the winter months is caused by air coming south from Resurrection Bay and from topographic steering by the spine of the Aialik Peninsula a short distance to the west. Annual mean wind speeds here average 15.1 mph and calm conditions occur about 2 percent of the time. In the Katmai / Lake Clark area there are no convenient buoys. Instead, **Figure 26** shows wind conditions at the Kodiak Airport, for the period 1980-2000, a period after the last major shift in the Pacific Decadal Oscillation, and the position of the Aleutian Low, in 1976. For this period there are 174,755 observations on 7671 days. This is not an open ocean location and therefore speeds are lower, with an annual mean of 11.7 mph and calm conditions 2-3 percent of the time. Northwest winds tend to dominate at Kodiak during winter, giving way in May and especially June and July to more frequent easterly winds, then back to northwest as late summer and autumn approaches.

Figure 27 shows temporal behavior, in the form of time series from the NCEP Reanalysis of temperature in a latitude-longitude grid box at 850 mb (about 5000 ft above sea level) centered near the SWAN parks (57-61 N, 149-158 W), for the four main 3-month seasons, and for winter centered (July-June) and calendar definitions (Jan-Dec) of the year.   These show the year-to-year variability, some degree of long term trend, and the abrupt shift in 1976.

During the winter months, when the Aleutian Low exerts its greatest influence, pairwise correlations of mean monthly temperature are generally around $r = 0.90$. These very high values arise largely because the main flow is southerly, from the ocean toward land. In summer, temperature correlations are generally lower, for two reasons. One is that local effects are more influential. The second is that the variances are quite low; at a given location there is not as much variation from year to year between various Julys or Augusts, for example, as there is between Januarys or Februarys, so that small absolute anomaly differences can readily lower correlations. For the temperature correlations presented here, we have not differentiated between max temp and min temp, and rather have simply utilized mean monthly temperature. Maximum and minimum temperatures usually show different behavior from each other, depending on season and on elevation difference. In general maximum temperatures correlate better with each other than do minimum temperatures, since maximum temperatures are more frequently controlled by larger scale factors. Minimum temperatures are typically much more subject to more local influences. The best minimum temperature correlations are usually found between adjoining ridges.

For precipitation, correlations are generally lower, sometimes much lower, than for temperature. If the data are taken at face value this indicates a greater need for more precipitation stations than for more temperature stations. Unfortunately, we cannot take the data at face value because of issues with bad data, unmeasured snow, etc, that relate to how faithfully the gage data record the actual climate. But experience from many other settings has shown that we usually need more precipitation gages than temperature sites.

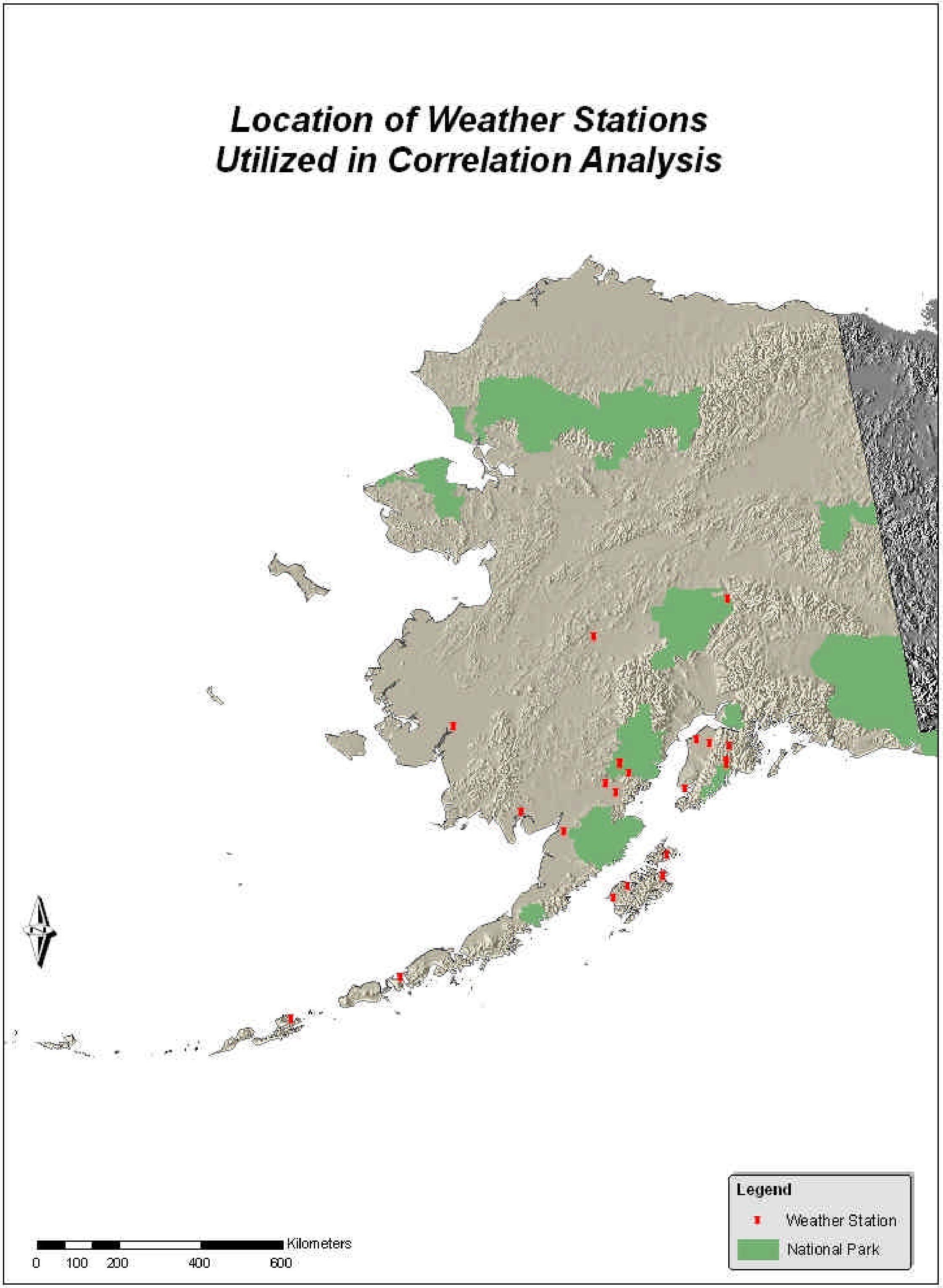


Figure 20. Locations of stations used in correlation analysis.

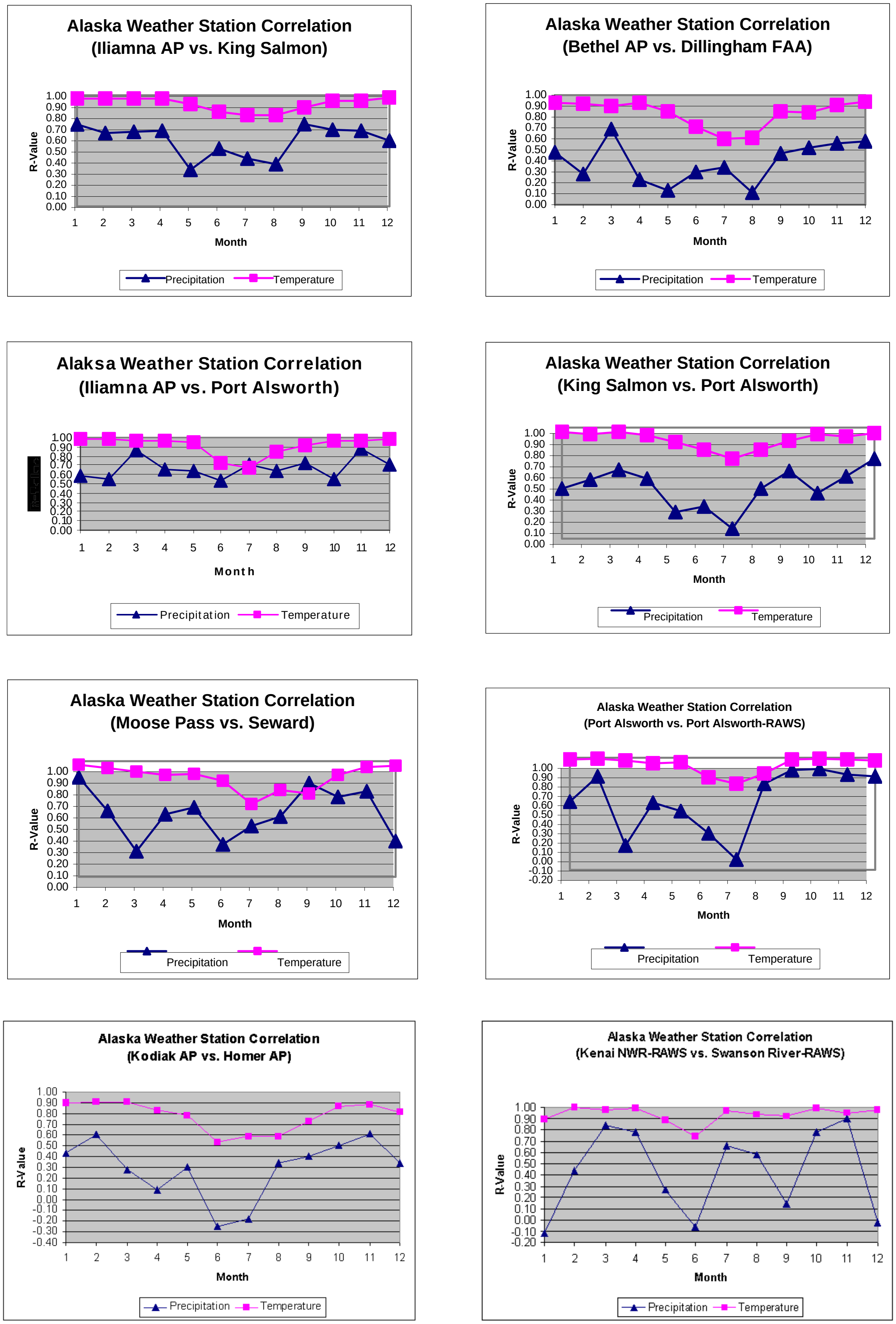
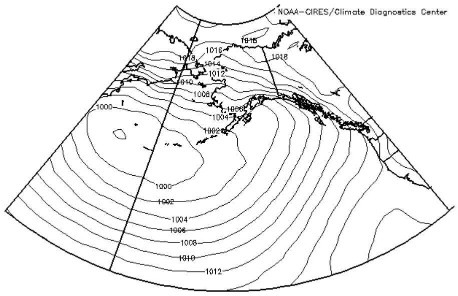


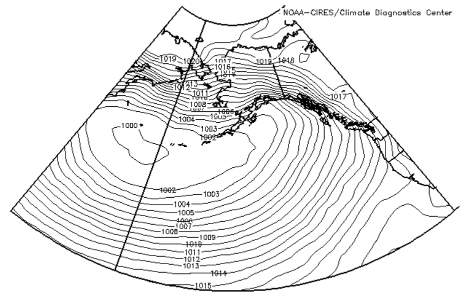
Figure 21. Correlations (period of record) between selected station pairs. See table of spreadsheet values for details on sample sizes.

NCEP/NCAR Reanalysis
Sea Level Pressure (mb) Climatology 1968–1996



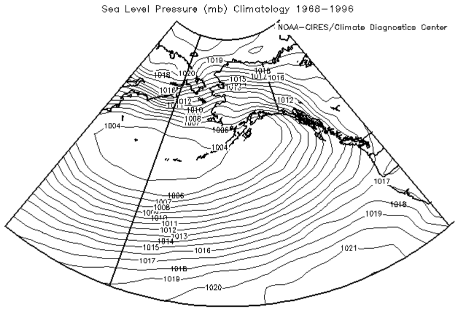
Jan

NCEP/NCAR Reanalysis
Sea Level Pressure (mb) Climatology 1968–1996



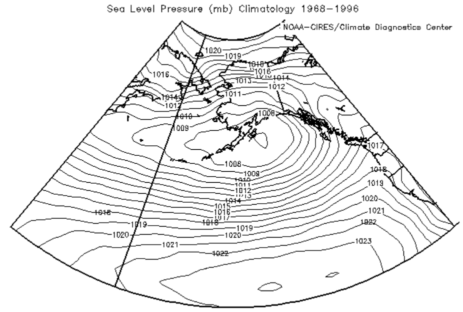
Feb

NCEP/NCAR Reanalysis
Sea Level Pressure (mb) Climatology 1968–1996



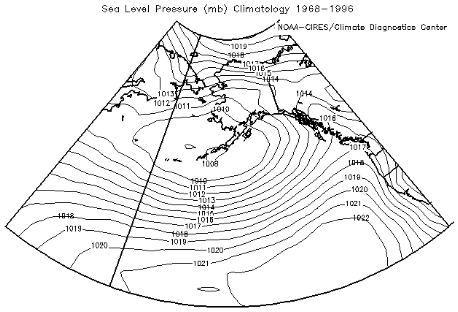
Mar

NCEP/NCAR Reanalysis
Sea Level Pressure (mb) Climatology 1968–1996



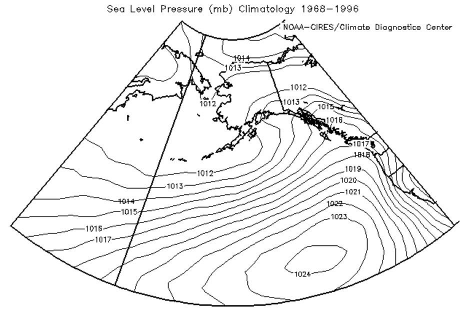
Apr

NCEP/NCAR Reanalysis
Sea Level Pressure (mb) Climatology 1968–1996



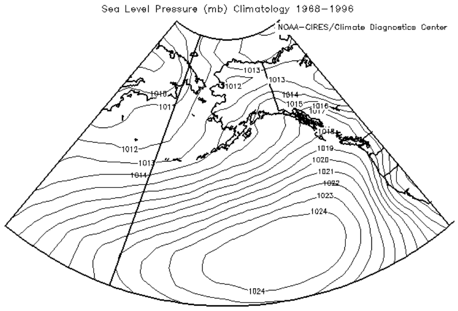
May

NCEP/NCAR Reanalysis
Sea Level Pressure (mb) Climatology 1968–1996



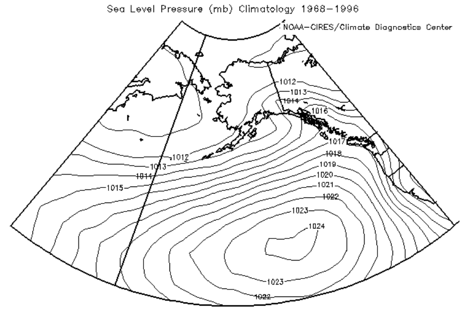
Jun

NCEP/NCAR Reanalysis
Sea Level Pressure (mb) Climatology 1968–1996



Jul

NCEP/NCAR Reanalysis
Sea Level Pressure (mb) Climatology 1968–1996



Aug

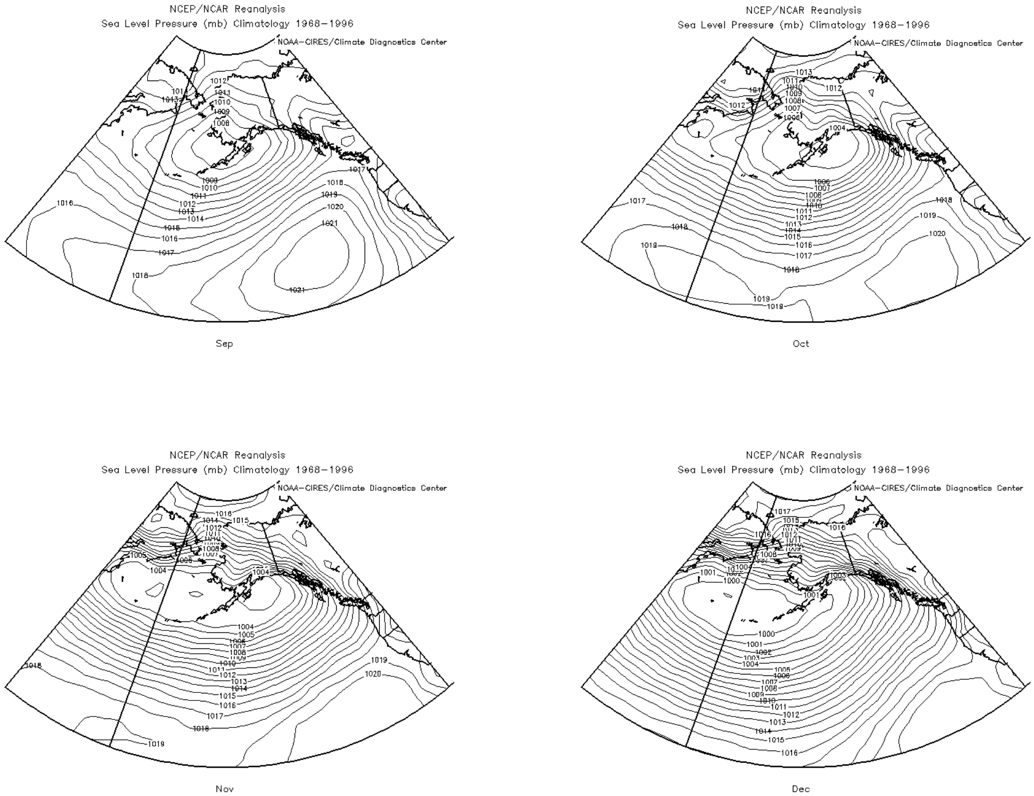


Figure 22 Mean sea level pressure (1968-1996) for each month in the annual cycle, January through December, arranged from top to bottom: Jan-Feb, Mar-Apr, May-Jun, Jul-Aug, Sep-Oct, and Nov-Dec. Units: millibars. Contour interval 1 mb. Analysis courtesy of NOAA Climate Diagnostics Center.

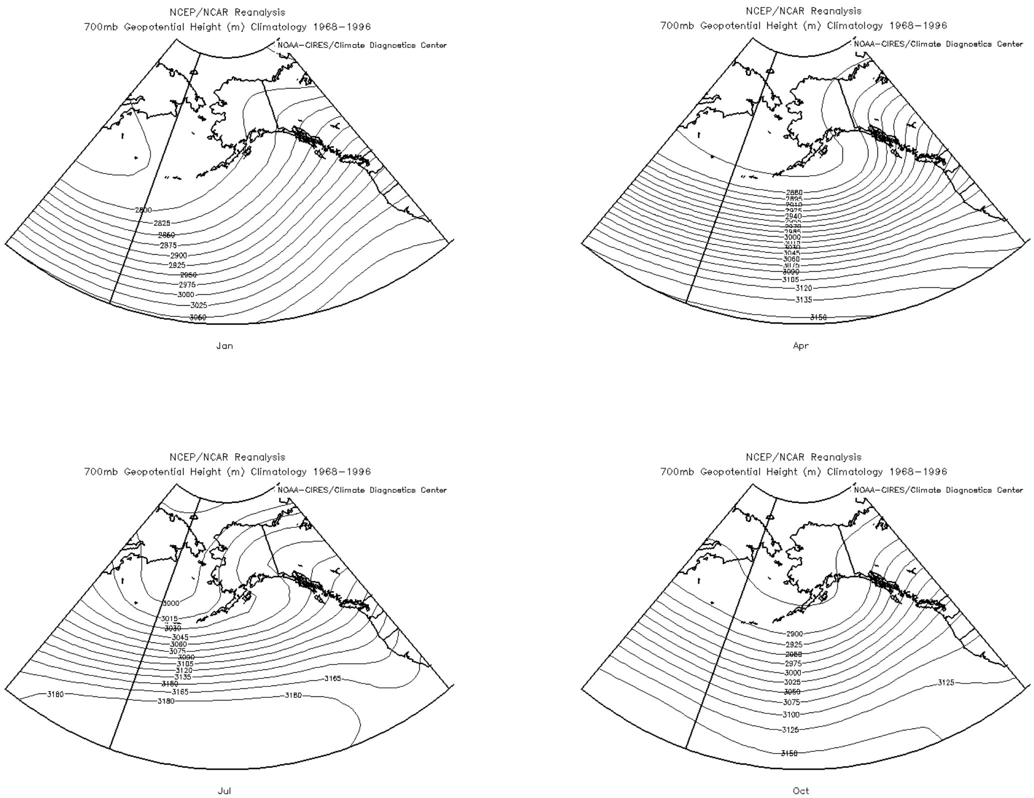


Figure 23. Mean monthly 700 mb patterns (approx 10,000 ft) for January, April, July and October, for the period 1968-1996. Winds tend to blow approximately along the height contours (with low pressure to the left, referenced to the direction toward which the air is moving), and at speeds inversely proportional to the contour spacing (closer spacing, higher speeds). Analyses courtesy NOAA Climate Diagnostics Center.

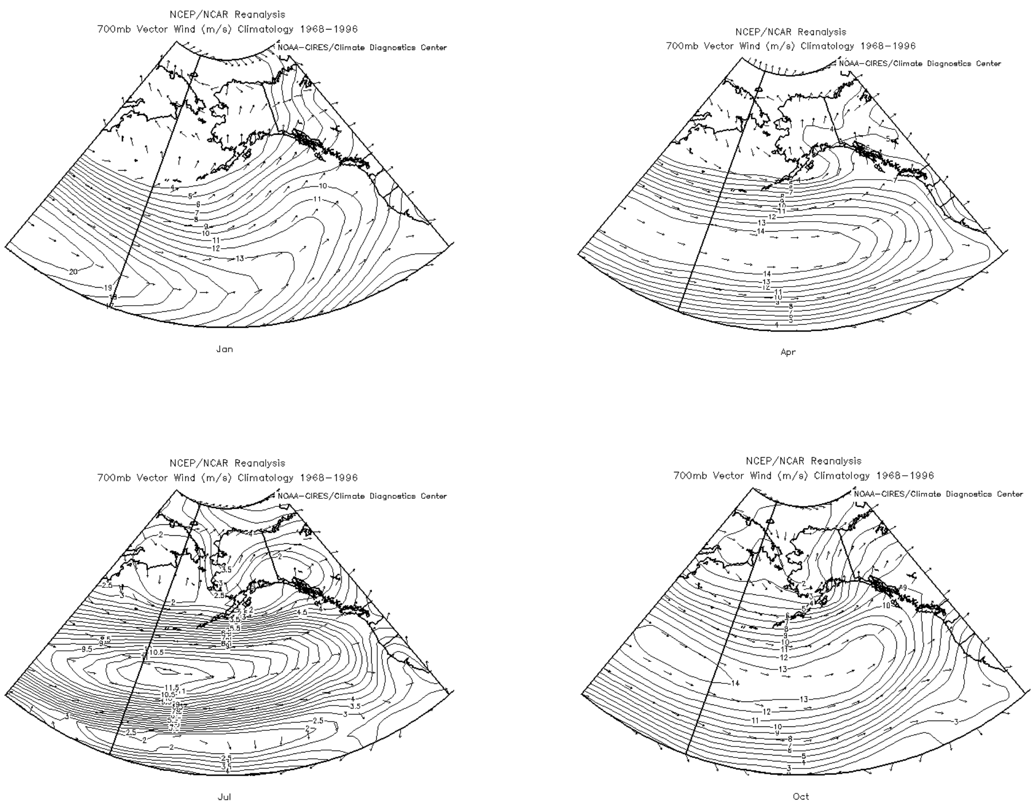


Figure 24. Mean monthly 700 mb wind patterns (approx 10,000 ft) for January, April, July and October. Arrows represent monthly vector mean ("resultant") wind directions, and contours represent monthly vector mean speeds ("isotachs"), in units of m/s. 1 m/s = 2.237 mph. Period 1968-1996. Analyses courtesy NOAA Climate Diagnostics Center.

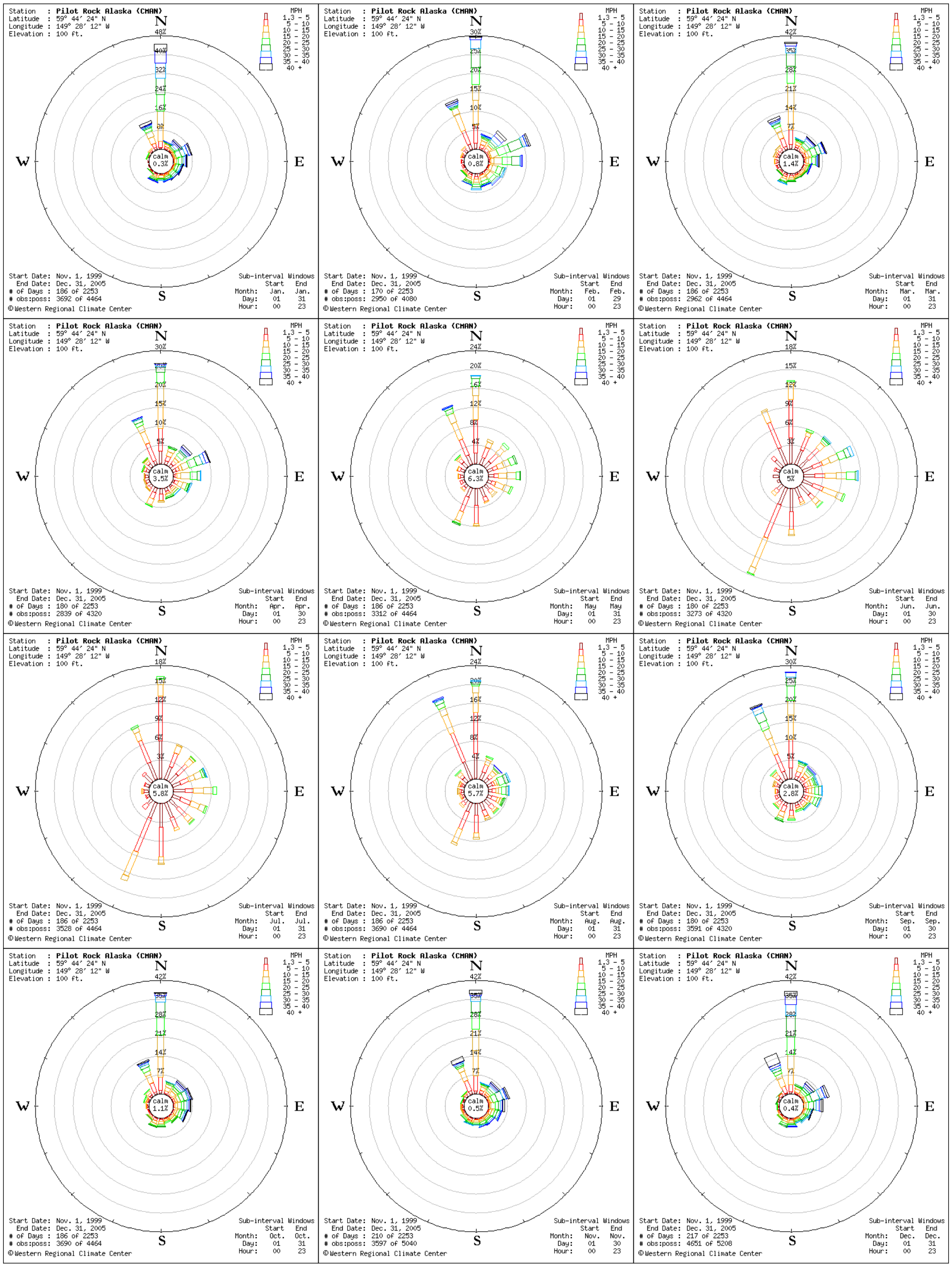


Figure 25. Wind roses by month. Pilot Rock, east of south end of Aialik Peninsula, 25 miles south-southwest of Seward, 59^{o} 44' 30" N, 149^{o} 28'12" W, anemometer elevation 100' above sea level. 3597 observations. January through December, taken from overall period November 1999 through January 2005. Units: mph. Increments: 5 mph. Calm: 1.3 mph. Frequency scales vary. Source: Western Regional Climate Center.

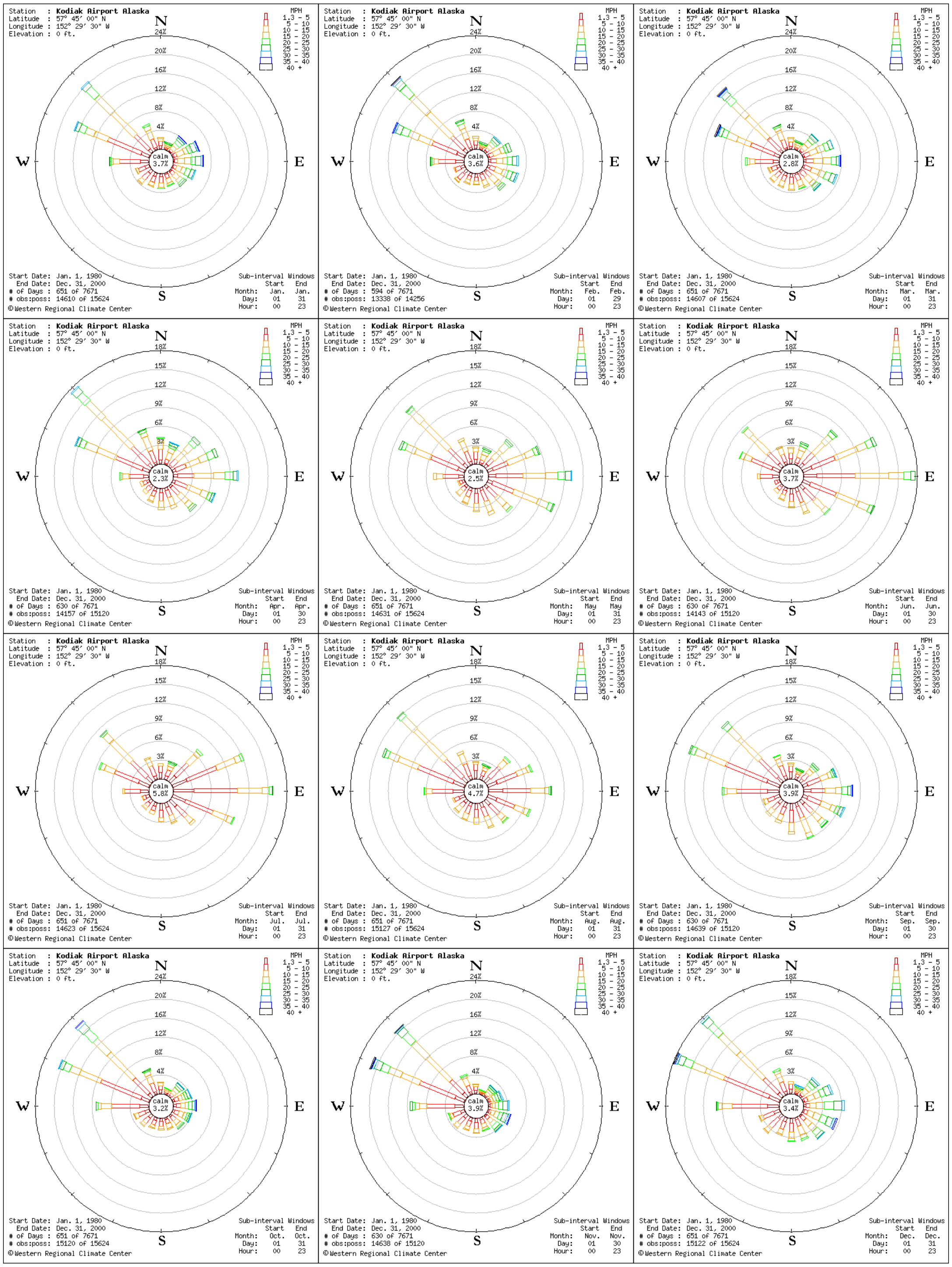


Figure 26. Wind roses by month. Kodiak Airport, Kodiak Island. 57^{o} 45' 00" N, 152^{o} 29' 30" W, elevation sea level. January through December, from overall period January 1980 through December 2000. 15122 observations. Units: mph. Increments: 5 mph. Calm: 1.3 mph. Frequency scales vary. Source: Western Regional Climate Center.

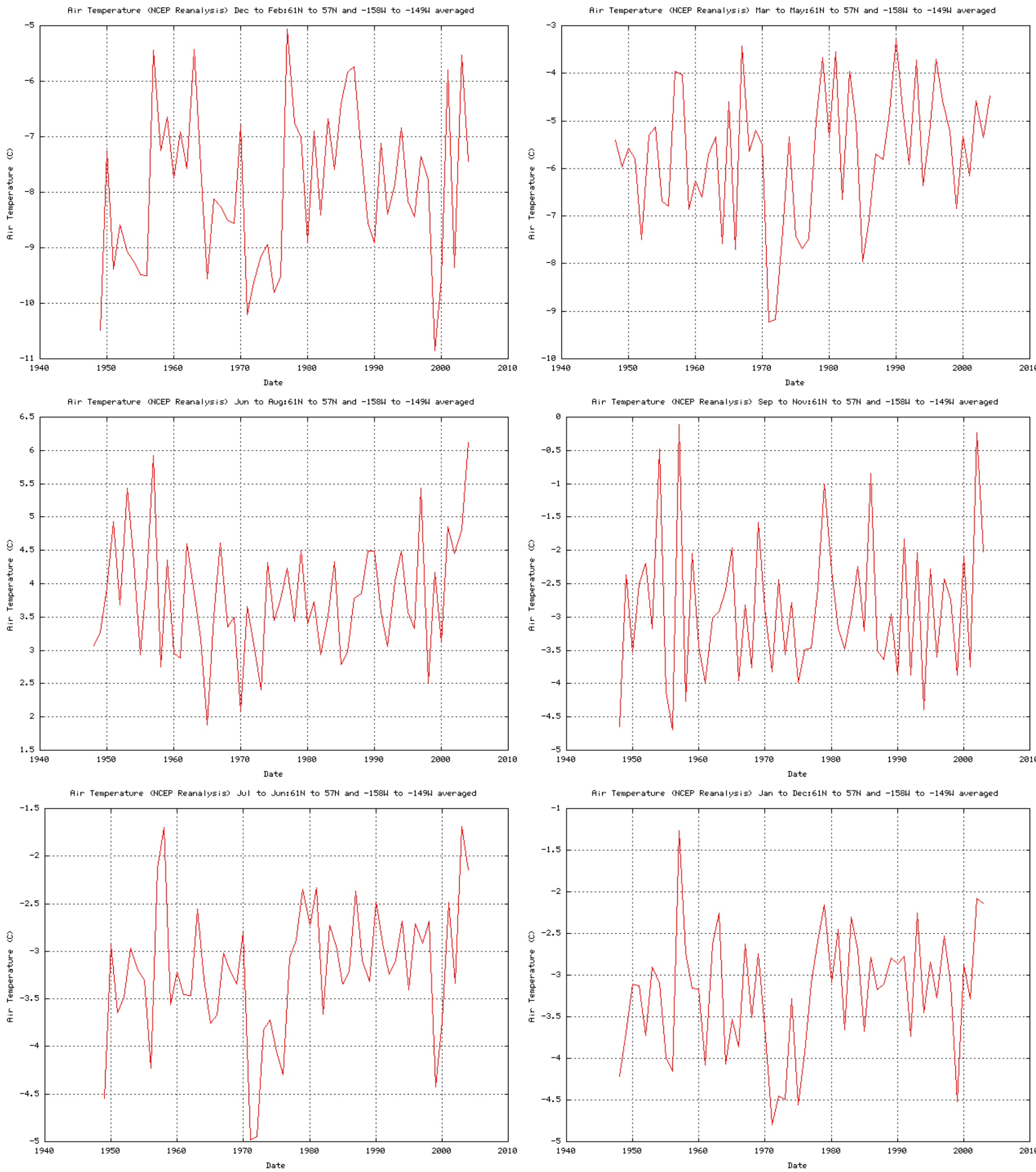


Figure 27. Area weighted temperature time series from NCEP Reanalysis at 850 mb (5000 ft) for area 57-61 degrees North latitude x 149-158 degrees West longitude. Top left: Dec-Jan-Feb. Top right: Mar-Apr-May. Middle left: Jun-Jul-Aug. Middle right: Sep-Oct-Nov. Bottom left: July-thru-June annual. Bottom right: Jan-thru-Dec annual. Data from 1948 through October 2004. Analyses courtesy NOAA Climate Diagnostics Center.

4.1.2 Spatial variations

A number of techniques exist to interpolate from isolated point values to a spatial domain. For example, a common technique is simple inverse distance weighting. Critical to the success of the simplest of such techniques is that some other property of the spatial domain, one that is influential for the mapped element, does not vary significantly. Topography greatly influences precipitation, temperature, wind, humidity, and most other meteorological elements. Thus, this criterion is clearly not met in this region of extreme topographic diversity. Simple Cartesian distance may have little to do with how rapidly correlation deteriorates from one site to the next, and in fact, the correlations can readily decrease from a mountain to a valley and then increase again on the next mountain. Such structure in the fields of spatial correlation is not seen in the relatively (statistically) well-behaved flat areas like those in the eastern United States.

To account for the dominating effects of topography and inland-coastal differences that are found in Alaska, some kind of additional knowledge must be brought to bear to produce meaningful, physically plausible, and observationally-based interpolations. Historically, this has proven to be an extremely difficult problem, especially to perform objective and repeatable analyses.

The National Park Service in Alaska has experimented with two different methods for distributing temperature and precipitation across spatial fields, ANUSPLIN and PRISM.

ANUSPLIN (Australian National University thin-plate smoothing spline surface fitting) was invented to interpolate in climate regimes that have much less spatial structure. A reference used here to assess some of its properties is the Version 4.1 User Guide, by M.F. Hutchinson, last revised February 2000, and available at <www.criacc.qc.ca/climat/anusplin/usesplin.html>. This document goes into considerable detail on the mechanics of using the technique. Its initial applications were in Australia, but the technique has been applied elsewhere. It is relevant to this discussion that the spatial climate gradients in Australia are far smaller than the climatic gradients that exist in North America, and that Australia does not have the extreme topography found in North America, especially in Alaska, and especially in this part of Alaska.

PRISM (Parameter Regression on Independent Slopes Method) was developed specifically to address the extreme spatial and elevational gradients exhibited by western United States climate (Daly et al., 1994; Daly et al., 2002; Gibson et al., 2002; Doggett et al., 2004). Its original motivation was a need for climate information at scales that matched available vegetation maps to assist with ecological modeling, essentially as a set of GIS climate layers. Elevation provides the predominant first order correction to the basic field; these corrections are further stratified by orientation (aspect). The purpose of this is to address “rain shadows” that are prevalent in mountains. The technique also recognizes that the values of time-integrated climate elements are affected by spatial scale, and that different elements can “feel” their physical forcing mechanisms differently at different spatial scales. Over the years the PRISM developers have added enhancements to address features that are of the type found in Alaska: inversions, coastal-interior transition zones, elevations of maximum precipitation, and of late, small scale trapping basins (scales of 1 km or less). In practice PRISM produces monthly maps, to allow for the annual cycle in elevational lapse rate of climatic values. Seasonal and annual maps are then derived from the monthly maps. For precipitation, for example, in many locations there is a considerable change in the magnitude of the seasonal cycle as elevation increases. In effect, this constitutes a seasonal cycle of precipitation “lapse rate,” to borrow from temperature terminology. In general, winter contributes more precipitation to the annual total the higher the elevation (up to a certain not-well-understood level). For continental western U.S. climate mapping it is very important to include this behavior. In Alaska, which lies north of the main belt of westerly winds in winter, this situation is much more complicated and the winter-centrism of higher elevations does not appear so prominently.

Both ANUSPLIN and PRISM are data driven; they can only be as good as their input data. It is particularly important to have high elevation data. Snotel has proved critical for this with PRISM. Also, radiosonde (balloon) data (for temperature and humidity) have been employed extensively to provide a match to free air conditions at the 700-500 mb levels (10,000 to 18,000 ft; 3000 to 5500 m). RAWS stations can be used for temperature, and all year if they remain unburied by snow. For precipitation, RAWS can be used in summer, or whenever temperatures are above freezing, but for winter precipitation these unheated gages are of little use. In Alaska as in the remainder of the West, the Snotel stations tend to be higher than other networks, but they are still relatively low (generally below 2000 ft / 600 m). Nevertheless, observation density is a difficult challenge for any data-driven technique in Alaska.

Precipitation mapping activities at the Western Regional Climate Center (WRCC) have in general utilized PRISM because the maps it produces have undergone a rigorous scrutiny in a subset of western states (OR/ID/UT/NV) where annual totals of precipitation were examined by state climate experts on a “pixel by pixel” basis, and compared with existing maps prepared by traditional hand methods and with other knowledge (vegetation, research projects, on-the-ground experience). This project was denoted by its participants, the PRISM Evaluation Group (PEG), which met several times in the late 1990s. In some cases, during the PEG process the map values produced by PRISM suggested considerations that the map reviewers previously had not thought of. The critiques arising from the PEG process formed the basis for additional rounds of improvement (see Daly et al., 2002). We have not been able to find evidence that other competing methods for producing precipitation maps have been subjected to this high degree of scrutiny.

In general during the PEG process it was difficult to obtain access to the estimated climate fields at the spatial scale, needed to make the comparisons, and furthermore with a common projection and with correct registration. An error of just one pixel-width can cause significant loss of skill in mountainous terrain. Performing these comparisons is very intensive and time consuming work for skilled experts, and the general consensus of the PEG process was that the PRISM maps were at least as good as the traditional hand-drawn versions. This process was taken very seriously by the PEG participants; state precipitation maps have significant economic repercussions to a number of sectors.

Note that PRISM does not try to replicate point values, but rather the “pixel-average” of the climate quantity at the pixel-average elevation, in the grid area (typically 10x10, 4x4, 2x2 or 1x1 km) surrounding the contained point. Also note that the mapped quantity is measured precipitation, not actual precipitation. As far as we know, this is true for all data-driven precipitation mapping. No corrections are made for exposure or undercatch, which can be severe (30-80 percent of actual precipitation lands in the gage) in snowy climates when gages are not shielded (see, for example, Yang et al., 1998, Yang et al., 2001).

Fleming et al. (2000) examined the properties of ANUSPLIN in an Alaskan setting, and found that this approach encountered significant difficulty in portraying the intense temperature inversions that predominate in winter. They note that interpolation techniques have substantial difficulty with inversions, precipitation “shadowing,” and cold air drainage. This paper characterizes precipitation shadows as primarily a large scale effect of major mountain chains, but there is much evidence that it exists on very small scales as well, on the order of a kilometer or less, in settings reminiscent of coastal Alaska (see, for example, Ralph et al., 2003), and physical reasoning suggests this ought to be the case. PRISM has the ability to address inversions, although it requires the basic data at sufficient elevational resolution to tell it about their strength. This information comes primarily from higher elevation (though still not very high) Snotel data, and from radiosonde (balloon) information.

Stillman et al. (1996) found comparable results for three techniques (ANUSPLIN, MT-CLIM, and PRISM). Zimmerman and Roberts (2001) compared Daymet (an outgrowth of MT-CLIM) and PRISM and found that the two techniques were comparable for precipitation, and after including other logistical and practical considerations, that for temperature Daymet had some properties that were better suited for their use. PRISM uses areally averaged (pixel-sized) values of elevation, currently at about 0.8 km resolution. Their rationale was that precipitation processes respond primarily to features generally of a kilometer or greater (though sometimes at somewhat smaller scales than this as well), but temperature can be affected by topographic influences on the scale of a few meters, so the actual elevation is of interest for certain applications.

A perpetual dilemma in comparing different interpolation methods is that the quality of the climatological fields is a function of both the quality of the method and the quality of the data / metadata, and it is very difficult to disentangle these two influences. For this project we did not have access to fine scale ANUSPLIN interpolations to particular data points, which in most cases are only known to the nearest rounded minute of latitude (approximately 1 mile), and this can make a significant difference in extreme topography. It is a considerable chore to set up the infrastructure and data needed to perform a fair comparison.

Because they are readily available, and because there is considerable experience in working with them, and relative comfort with the approach and values, the PRISM maps were employed to examine issues where monthly or annual amount is the item of interest. Furthermore, the spatial information provided by interpolation techniques is just one factor in deciding where to locate stations, and in our experience is not as important a factor as is the temporal behavior.

4.1.3 Climate change detection

Although general purpose climate stations should be situated to address all aspects of climate variability, it is desirable that they also be in locations that are more sensitive to climate change, from natural or anthropogenic influences, should it begin to occur. The question here is how well we know such sensitivities. The polar regions, and especially the North Pole, are generally regarded as being more sensitive to changes in radiative forcing of climate, because of positive feedbacks. The climate change issue is quite complex, because it encompasses more than just greenhouse gasses.

In this regard, the role of aerosols has recently begun to receive great attention from the research community, and in North America the cross-Pacific transport of particulates from population centers of eastern Asia has risen into prominence. These effects can locally significantly counteract, and even far exceed, those of the greenhouse gasses. What constitutes “local” has grown steadily larger in scale with increased industrialization and worldwide population growth (e.g., UNEP, 2004), and now has reached regional scales (i.e., the size of Alaska). Another surprising realization of recent years is that, because of this aerosol load, the amount of sunlight reaching the earth’s surface has decreased considerably, a problem referred to as “solar dimming” (Liepert, 2002). One way in which these tiny particles can do this is by acting as additional nuclei for cloud droplets. The larger numbers of smaller droplets reflect more energy from the earth system, and in addition may not be as effective in producing precipitation for the same size cloud.

The consequences of any or all of these effects to the Alaska Range and the adjoining coastlines are not clear. Atmospheric warming would be expected to have an effect on the extensive ice cover in the SWAN region (see the discussion of temperature in Section 2 and in particular **Figure 14**). In particular, mean temperatures are not far from freezing in many important zones, and small changes that move temperature from below to above freezing have significant potential to affect ice balance, and the character of storms if the ratio of rain to snow increases. The elevation of the rain/snow line, the manner of accumulation during the winter, the timing of the spring snowmelt runoff pulse, and the summer loss of ice, would all be affected by changes in temperature. Indeed, changes in the date of the beginning of spring snowmelt have already been noted into Alaska (Stewart et al., 2004). It is not certain that these effects would be the same at all elevations. The Pacific Ocean is a tremendous flywheel for stored energy, and changes in temperature next to the ocean may differ from changes in the interior across the Alaska Range. Furthermore, if changes occur, they will likely not be the same for each month. In mountainous and icy terrain, temperature should be considered a hydrologic element.

As for precipitation, there is some agreement that the worldwide hydrological cycle might be accelerated by the greenhouse component of climate change, but this would certainly not be uniform in space or time. There is much less agreement about precipitation changes among the various models than there is for temperature on whether the annual values would increase, decrease, or stay the same, and on which seasons would be affected, and in what way. At the regional scale (the size of Alaska) this situation seems destined to be the case for a very long time. We just don't know.

As noted earlier, this area in particular is affected by the Pacific Decadal Oscillation (Mantua et al., 1997), and some contribution to recent trends, on time scales of 20-50 years, may result from natural long-term variations in the North Pacific. Whether this "oscillation" will reverse or continue to be a factor, and what is driving it, is a subject of much speculation and active research.

Based on climate change considerations alone, a recommended strategy would entail station placement in the pure coastal zone, in the pure interior zone, at higher elevations closer to the location of what is now quasi-permanent ice, and in transition regions such as drainage divides. The idea of transects spanning transitions from marine to interior climates has great merit.

4.1.4 Element differences

The various climate elements (temperature, precipitation, cloudiness, snowfall, humidity, wind speed and direction, solar radiation) do not vary through time in the same sequence or manner, nor should they necessarily be expected to. The spatial patterns of variability should not be expected to be the same for all elements. These patterns should also not be expected to be similar for all months or seasons. The suitability of individual sites for measurement also varies from one element to another. A site that has good exposure for temperature, or for wind, may not be very well suited for the measurement of precipitation or of snowfall. A site that has good air movement may be situated in a topographic channel, such as a river valley or a pass, which restricts the range of directions and affects the distribution of speed-direction categories, and the appearance of "wind roses."

4.1.5 Logistics and practical factors

Even with the most advanced scientific rationale, sites may not be suitable because of the difficulty of servicing and maintenance. The types of climates in southwest Alaska are notoriously unkind to instrumentation. The lack of AC power precludes heating for precipitation and anemometers. Sites are remote, communications are difficult to maintain, human access is expensive and often affected by weather events, animals of all sizes can interact with stations in myriad ways, sites can be buried in snow, visits to sites can seldom be impromptu, automated equipment and electronics can be subjected to severe conditions at or beyond design criteria, station communications are often only one-way, and excessive wind, cold, snow, or precipitation can easily take a severe toll on instrumentation. For climate purposes, station exposure and the local environment should be maintained in their original state (vegetation especially), so that changes seen are the result of regional climate variations and not of trees growing up, bushes crowding a site, or surface albedo changing, clearing by fire, and so forth.

A number of recommendations pertinent to the SWAN area were provided by Redmond and Simeral (2004) in a discussion of potential sites at three national parks in the NPS Central Alaska Network (attached).

In the end, it is almost always logistics, maintenance and other practical factors that determine the success of weather and climate monitoring activities.

4.1.6. Personnel considerations

A large number of past experiences (almost exclusively bad) strongly support the necessity to place primary responsibility for station deployment and maintenance in the hands of seasoned, highly qualified, trained, and meticulously careful personnel, the more experienced the better. Over the course of time, even in “benign” climates, but especially in the harsh conditions found in Alaska, every conceivable problem will occur and should be anticipated: weather, animals, plants, salt, sensor and communication failure, windblown debris, corrosion, power failures, vibrations, avalanches, snow loading and creep, data logger program corruption, and many other exotic and cleverly maniacal gremlins that will visit the station. An ability to anticipate and forestall such problems, a knack for innovation and improvisation, the ability to think on one’s feet, “street smarts,” knowledge of electronics, practical and organizational skills, and the presence of mind to remember to bring all the myriad small but vital parts and spares and tools and diagnostic troubleshooting equipment and not lose them in the moss, are all qualities to be highly valued. Especially when logistics are so expensive, a premium should be placed on using experienced personnel, since the slightest and seemingly most minor mistake can render a station useless, or even worse, uncertain. Exclusive reliance on individuals without this background can be very costly and will almost always eventually result in unnecessary loss of data. Skilled labor, and an apprentice system to develop new skilled labor, will greatly reduce (but not eliminate) the types of problems that can occur in running a climate network.

5. Suggested locations

5.1 Factors to consider in site selection

In addition to issues raised earlier, a variety of factors need to be considered in selecting sites for new or augmented instrumentation.

5.1.1 Equipment and exposure factors

A. The measurement suite. All sites should measure temperature, humidity, wind, solar radiation, and snow depth. Precipitation is much more difficult, but probably should be attempted, with the understanding that in winter the measurements may be of limited or no value unless an all-weather gage has been installed. Even if an all-weather gage has been installed, it is a good idea to have a second gage present that operates on a different principle. For example, a fluid-based system like the one that Snotel uses, in concert with a higher resolution tipping bucket gage for summertime. Without heating, a tipping bucket gage is usually of use only when temperature is above freezing, and further, when temperature has not been below freezing for some time, so that accumulated ice and snow is not melting and being recorded as present precipitation. Gage undercatch is a significant issue in snowy climates, so shielding should be considered for all gages designed to work over the winter months. It is very important to note the presence or absence of shielding, and the type of shielding, and the dates of installation or removal.

B. Overall exposure. The ideal general all-purpose site has gentle slopes, is open to the sun and the wind, has a natural vegetative cover (whatever pertains to the area in consideration), avoids strong local (5-200 meter) influences, and represents a reasonable compromise among all climate elements. The best temperature sites are not the best precipitation sites, and the same is true for other elements. Steep topography in the immediate vicinity should be avoided, unless settings where precipitation is affected by steep topography are being deliberately sought, or a mountaintop or ridge line is the desired location. The potential for disturbance should be considered: fire and flood risk, earth movement, wind borne debris, volcanic deposits or lahars, vandalism, animal tampering, and general human encroachment are all factors.

C. Elevation. Mountain climates do not vary in time in exactly the same manner as adjoining valley climates do. This is more true the greater the degree to which temperature inversions are present, and to which winds during precipitation rise up the slopes at the same angle. In the maritime zones, precipitation variability will be moderately correlated among elevations, but in more interior settings this will be somewhat less true. There is considerable concern that mountain climates will be (or already are) changing, and perhaps changing differently than lowland climates. This has direct and indirect consequences for plant and animal life in the more extreme zones. In addition, glaciers and ice have a significant presence in Alaska, and seemingly small shifts in climate can greatly affect mass balances, and thus the growth or shrinkage of glaciers, snow fields, and ice fields. Glacier behavior is an important indicator of climate variability, but glaciers can be quite sensitive to subtle and small shifts in climate. For these reasons, each park with significant mountain and frozen water presence should try to have one or two stations at higher elevations. At this latitude "higher elevations" could be loosely translated as 3000-6000 ft (900-1800 m) or higher, and better if 5000 ft (1500 m) or more. This is about the level where the tops of some of the main ice fields are found. Elevations of special significance are those that are near the mean rain/snow line for winter, near the tree line, and near the mean annual freezing level (these may not all be quite the same). Because the lapse rate in heavy precipitation climates during their main precipitation seasons will often be near moist adiabatic, measurements at one elevation may be extrapolated to nearby elevations. In drier climates, and in the low-sun seasons, temperature and to a lesser extent wind, will show a variety of elevation profiles.

<u>D. Transects.</u> The concept of observing transects that span climatic gradients is a good one. This is not always straightforward in such topographically uneven terrain, but these could still be arranged by setting up station(s) along the coast, in or near passes atop the main coastal-interior drainage divide, and inland at one, two or three distances into the interior lowlands. Transects need not, and by dint of topographic constraints probably cannot, be straight lines, but the closer that a line can be approximated the better. The main point is to systematically sample the key points of a behavioral transition without deviating too radically from linearity.

<u>E. Glacial outwash areas.</u> Several of these are suggested. These are generally flat, near sea level, sometimes well exposed to the ocean, warmer and less likely to experience excessive snow than higher elevations, and are usually accessible via boat or other transportation. From an access standpoint they are often also below cloud level. Assuming that the general retreat of glaciers will continue, supportive measurements of the attendant climatic behavior that is helping them disappear make a lot of sense. However, sites need to be stable and on firm ground. These areas can be subject to major events such as large floods as water is released in quantity from lakes within the ice, or broken ice dams. The outwash channels are heavily braided, good evidence that they are subject to rapid change, so higher and non-erodable prominences, and rock outcroppings, should be favored. Sites that are 50-100 feet above a set of river channels have much less risk of flooding. A flood frequency of once (maybe twice) per century at the station site might be deemed an acceptable risk.

<u>F. Marine climates.</u> Salt is very corrosive and hastens the demise of instruments, electrical connections, moving parts, and just about anything metallic of value. Stations in marine locations would be best sited away from spray zones, and better yet, a kilometer or two inland, or up a bit, to minimize this influence. On the other hand, if islands are considered, they generally have good meteorological exposure at their high points, and are still worth considering, though they will take more maintenance. The swap-out rate for parts will be much higher than in non-corrosive environments.

G. Other topographic considerations. There are a variety of considerations with respect to local topography, and many of these are covered in other parts of this report. Local topography can influence wind (channeling, glacier winds, upslope/downslope, etc), precipitation (orographic enhancement, downslope evaporation, catch efficiency, etc), and temperature (frost pockets, hilltops, aspect, mixing or decoupling from the overlying atmosphere, bowls, radiative effects, etc), to different degrees at different scales. In general, for measurements to be areally representative, it is better to avoid these local effects, to the extent that they can be identified before station deployment (once deployed, it's a good idea not to move a station). The primary purpose of a climate monitoring network should be to serve as an infrastructure in the form of a set of benchmark stations, to which other stations can be compared. Sometimes, however, it is just these very local phenomena that we want to capture. Living organisms, especially plants, are affected by their immediate environment, whether it is representative of some larger setting or not. Specific measurements of limited scope and duration made for these purposes can then be tied to the main benchmarks. This experience is useful also in guiding how complex the benchmark monitoring needs to be, in order to capture which phenomena at which space and time scales.

Sites that drain (cold air) well are generally better than sites that allow cold air to pool. Slightly sloped (1 degree is fine) planes or small benches, from tens to hundreds of feet above streams, are often good locations. Furthermore these often tend to be out of the path of hazards (like floods), and to have rocky outcroppings where vegetation management will not be a major concern. Benches or wide spots on the rise between two forks of a river system are often the only flat areas, and sometimes jut out to give good exposure for winds from more azimuths.

5.1.2 Element-specific factors

A. Temperature. An open exposure with good air movement is much preferred. The most common measurement is about eye height, 1.5 to 2.0 meters. In snowy locations sensors should be 3-4 feet higher than the deepest expected snowpack in the next 50 years, or perhaps 2-3 times the depth of the average maximum annual depth. Sensors should be shielded from solar radiation, from above, from below (bouncing off snow), from sunrise/sunset horizontal input, and from vertical rock faces. They should be clamped tightly so as not to swivel away from level stacks of radiation plates. Nearby vegetation should be kept away from the sensors (several meters). Growing vegetation should be cut to original conditions. Small hollows and swales can cool tremendously at night and are best avoided. Side slopes, not on the very bottom of a valley, of perhaps a degree or two of angle, facilitate air movement and drainage, and in effect sample a large area during nighttime hours. Temperature can change substantially from moves of only a few feet. We have encountered many situations where flat and seemingly uniform conditions (like airport runways) appear to have different climate behaviors over distances of a few hundreds to tens of feet (differences of 10-20 degrees F). When snow is on the ground, these microclimatic differences can be much stronger, and differences of 5-10 degrees F can occur in the short distance between the thermometer and the snow surface on quiet evenings.

B. Precipitation (liquid). Quiet locations with vegetative or artificial shielding are preferred. Wind is bad; the less the better. Wind effects on precipitation are much less for rain than for snow. Devices that "save" precipitation have advantages, but most gages are built to dump precipitation as it falls, or must be periodically emptied. Automated gages give both the amount and the timing. Simple backups that record only the total since the last visit have a certain attraction (for example, storage gages, or lengths of PVC pipe, perhaps with bladders on the bottom): does the total from an automated gage add up to the measured total in a simple bucket (with evaporation prevention, such as with mineral oil)? Overhanging foliage and drip from trees can augment precipitation totals.

C. Precipitation (frozen). Quiet locations, or shielding, are a must. Undercatch is only about 5 percent for rain, but with winds of only 5-10 mph gages may catch only 30-70 percent of the actual snow falling, depending on density of the flakes. To achieve 100 percent catch of snow, the standard configuration is the one employed by the Climate Reference Network: the DFIR shield (Double Fence Intercomparison Reference), with 8 foot high vertical wooden slatted fences in two concentric octagons with diameters of 26 feet and 13 feet, and an inner Alter shield (flapping vanes). Numerous tests have shown this is the only way to achieve complete catch of snowfall (e.g., Yang et al., 1998; Yang et al., 2001). The DFIR is big and bulky; it is recommended that all precipitation gages have at least Alter shields on them. Near the coast, much snow is heavy and falls more vertically. In colder locations or storms, light flakes will frequently fly in and then out of a gage. Clearings in forests are usually good sites. Snow blowing from trees that are too close can augment actual precipitation totals. Artificial shielding (vanes, etc) around gages in snowy locales should always be used if accurate totals are desired. Moving parts tend to freeze up. Capping of gages during heavy snowfall events is a common occurrence. When the cap becomes pointed, snow falls off onto the ground and is not recorded. Caps and plugs often will not fall into the tube until hours, days, or even weeks have passed, typically when an extended period of freezing temperature or above, or sunlight, finally occurs. Liquid based measurements (e.g., Snotel "rocket" gages) do not have the resolution (usually 0.1 inch rather than 0.01 inch) that tipping bucket and other gages do, but are known to be reasonably accurate in very snowy climates. Light events might not be recorded until enough of them add up to the next reporting increment. More expensive gages like Geonors can be considered, and could do quite well in many Alaskan settings; however they need to be emptied every 15 inches or so (20-inch capacity) until the new 36-inch capacity gage is offered for sale. Recently the National Weather Service has been trying out the new (and very expensive) Ott all-weather gage. Riming can be an issue in windy foggy environments below freezing. Rime, dew, and other forms of atmospheric condensation are not real precipitation, since they are caused by the gage itself.

D. Snow depth. Windswept areas tend to be blown clear. Conversely, certain vegetation can act as a snow fence and cause artificial drifts. Some amount of vegetation in the vicinity can help generally slow down the wind. The two most common types are Judd and Campbell Scientific. Opinions vary on which is better. These use ultrasound, and look downward in a cone about 22 degrees in diameter. The ground should be maintained in such a manner that the zero point on the calibration scale does not change, and should be relatively clear of vegetation.

E. Snow water equivalent. This is determined by the weight of snow on fluid-filled pads, about the size of a desk top, sometimes in groups of four, or in larger hexagons 6-8 feet in diameter. These require flat ground, some distance from nearby sources of windblown snow, and shielding which is "just right:" not too close to shielding to act as a kind of snow fence, and not too far from shielding that blowing and drifting are a factor. Generally these require fluids with anti-freeze properties, and handling and replacement protocols.

F. Wind. Open exposure is needed. Small prominences or benches without blockage from certain sectors are preferred. A typical rule for trees is to stay back 10 tree-heights from all tree obstructions. Sites in long narrow valleys can obviously only exhibit two main wind directions. Gently rounded eminences are more favored. Any kind of topographic steering should be avoided to the extent possible. Staying away from major mountain chains, or single individual isolated mountains or ridges, is usually a good idea, if there is a choice. Sustained speeds and highest gusts (1 second) should be recorded. Averaging methodologies for both sustained winds and gusts can affect climate trends and should be recorded as metadata, and all such changes noted. Vegetation growth affects the vertical wind profile, and growth over a few years can lead to changes in mean wind speed even if the "real" wind does not change, so vegetation near the site (perhaps out to 50 meters) should be maintained in a quasi-permanent status (same height and spatial distribution). Wind devices can rime up and freeze, or spin out of balance. In severely rimed or windy climates, rugged anemometers such as those by Taylor are worth considering. These are expensive, but durable and can take substantial abuse. In exposed locations, plan for 100-150 mph winds, and be able to measure these. At a minimum, anemometers should be rated to 120-150 mph.

G. Humidity. This is a relatively straightforward element. Close proximity to lakes or spray can affect readings, but in soggy locations bogs are like lakes draped over the landscape. Humidity readings are typically less accurate near 100 percent, and at low humidities in cold weather.

H. Solar radiation. An unobstructed horizon is obviously best. This generally implies a flat plateau or summit. At these northern latitudes, the sun can be found at low angles in summer in the northern part of the sky, so more of the horizon should be clear than in southern latitudes. For example, on 2004 June 21, in Anchorage (61 N latitude) the sun rises just 33 degrees east of north, and crosses the eastern azimuth at a height of 27 degrees, reaches a maximum elevation angle of 52 degrees above the southern horizon, crosses west at 27 degrees and drops below the horizon 33 degrees west of north. Six months later, the sun rises 55 degrees south of east, crosses the meridian only 6 degrees above the horizon, and sets 55 degrees south of west. Only a pyranometer in a fairly flat location without nearby mountain peaks will record the direct beam contribution every day of the year. In most locations, trees or mountains will block part of the day.

I. Soil temperature. If there is soil at the site, this is a good idea. If a single depth is recorded, 10 cm is the most preferred. Other common depths are 25 cm, 50 cm, 2 cm, and 100 cm. Biological activity in the soil will be proportional to temperature, with important threshold effects near freezing.

J. Soil moisture. These are much more finicky and temperamental measurements, and take a degree of care to install. The soil should be characterized by a soil expert during installation. The readings can take some experience to interpret correctly. If accurate they are very useful.

K. Distributed observations. One can readily see that compromises must be struck among the above considerations, because some of them are mutually exclusive. How big can a “site” be? Generally we like to keep the equipment footprint as small as practical, with all the components next to each other (less than 10-20 meters or so). Readings from one instrument are frequently used to help interpret readings from the remaining instruments, and collectively these constitute a package deal. What is a tolerable degree of separation? Some consideration can be given to locating a precipitation gage or snow pillow among protective vegetation, while the associated temperature, wind and humidity readings might be in a more open and exposed nearby location 20-50 meters away. Ideally, we would like to know the wind *right at* the precipitation gage, but a compromise involving a short split, and in effect a “distributed observation,” could be entertained. There is no hard and fast rule, but we would suggest that the footprint of a site be kept to within about 50 meters. There are also constraints imposed by engineering and electrical factors that affect cable lengths, signal strength, and line noise; the shorter the better. Practical issues involve whether to trench to outlying instruments, or allow lines atop the ground, and associated problems with animals, people, weathering, and the like. Separating a precipitation gage by up to 100 meters or so from an instrument mast may be an acceptable compromise if other factors are not limiting.

K. Swap-out schedules. Instruments slowly degrade and a plan for swapping them out with new or refurbished or recalibrated instruments should be in place. After about 5 years, a systematic swapping procedure should result in replacement of most of the sensors in a network. Certain parts, such as solar radiation sensors, are candidates for annual calibration or swap-out. Anemometers tend to degrade as bearings erode or electrical contacts become uneven. Noisy bearings are a tip-off, and a stethoscope might aid in hearing such rumbles. Increased internal friction affects the threshold starting speed; once spinning they tend to work. Increases in starting threshold speeds can create more zero winds, and thus reduce the reported mean wind speed, with no real change in the wind properties. A field calibration kit should be developed and taken along on all visits, routine or otherwise, to a site. Rain gages can be tested with drip testers during field visits. Protective conduit and tight water seals can prevent abrasion and moisture problems, although seals can keep moisture in as well as out. Bulletproof casings are sometimes employed in remote settings. A supply of spare parts, at least one of each, and more for less expensive or more delicate sensors, should be maintained. These also permit swapping out during field visits so that instruments can be calibrated in the relative luxury of the operational home. The larger the network, the more the need for a parts depot.

5.1.3 Long-term comparability and consistency

A. Consistency: Hold the biases constant. Every site has biases, problems and idiosyncracies of one sort or another. A good rule of thumb is to simply try to keep these biases constant through time. Since the goal is to track climate through time, keeping sensors, methodologies, and exposure constant will insure that the only measured change is truly in the climate system. This means leaving the site as it originally was, or performing maintenance to keep it that way. Once a site is installed, the goal should be to never move the site, even by a few feet, or allow any significant changes within 100-300 feet, for the next several decades.

Sites in or near rock outcroppings will likely have less vegetation disturbance or growth through the years, and will not have their feet wet all the time, something that could speed corrosion.

Sites that will remain locally similar for some time are also preferable. For example, a site in the immediate vicinity of a glacier may become locally much more "balmy" and change rapidly as the ice withdraws, even if the ice is responding to regional climate over the last decade or two. In this case, a lightly vegetated prominence away from the direct influence of the ice (as thru reflected solar radiation, or glacially induced winds), and at about the middle elevation of the ice, would be more appropriate.

B. Metadata. Since the climate of every site is affected by features in the immediate vicinity, it is vital to record this information for all time, and to repeatedly update through time with each service visit. Distances, angles, heights of vegetation, fine scale topography, condition of instruments, shielding discoloration, and other factors from within a meter to several kilometers should be noted. Systematic photography should be undertaken, and updated at least once every year or two

For the photographic methodology used to document Climate Reference Stations, see Redmond (2004): Photographic Documentation of Long-Term Climate Stations, a .pdf version of a Powerpoint presentation dated 15 August 2004, and found on the WRCC web site at www.wrcc.dri.edu/nps/doc.

The main purpose for climate stations is *tracking through time*. Anything that affects the interpretation of records through time needs to be noted and recorded for posterity. The important factors should be clear to a person who has never visited the site, or was not alive when the site was installed.

5.2 Specific geographic recommendations

The intent here is to pick generalized locations for further reconnaissance by aerial or other means. We have extensively utilized various topographic display and visualization alternatives, to identify both general and specific possibilities. Photos found on the web were often quite helpful in visualizing particular locations. Comments from Park Service personnel and others who frequent these areas have been quite useful as well. Once candidate areas are picked, further scouting is needed. The method used by the NPS Inventory and Monitoring Central Alaska Network in Denali, Wrangell-St Elias, and Yukon Charlie parks, involving helicopter landings, photographs, and field notes, seemed to work quite well. Considering the size and expense of the commitment about to be made, there is no substitute for a visit and photo documentation.

5.2.1 Kenai Fjords

There are three main climate regimes to cover: the inland portion along the Resurrection, Skilak, and Tustamena drainages; the Harding Ice Field itself, and the maritime climate of the coast. See locator maps (**Figure 28** through **Figure 31**).

The inland area already has some information from existing RAWS sites (such as at Exit Glacier) and from Kenai National Wildlife Refuge to the northwest and west. To the extent that the main coast differs from the inland peninsula and from Cook Inlet, the existing stations can provide useful information. Some of these stations have operated for a while, too. For this reason, we have not suggested any new sites in this area.

The Harding Ice Field is a difficult observing challenge, so the initial focus should probably be at one of the more “benign” areas (if such a condition exists anywhere in this vicinity). However, the ice field is a key feature of the park, and is obviously heavily affected by climate and thus serves as an important climate indicator. Consequently, this area should be monitored for climate. This will likely be one of the hardest locations to keep equipment functioning and communicating continuously and accurately. The type of equipment needed must be very robust and durable. The best opportunities here involve leveraging with USGS and possibly others. The quantities to be measured should be those that affect the water balance of a glacier, generally standard meteorological quantities, but with an emphasis on the difficult issue of snow. Glaciers are in widescale retreat, and we should be monitoring them and their surroundings closely. This is an issue for all Alaska parks. Throughout this area, ice is encountered at fairly low elevations, so it is difficult to install any kind of station at more than 1000 to 2000 ft / 300-600 m, and the general suggestion is to keep most of them at or below this altitude. Another strategy is to just ignore precipitation or measure warm-weather precipitation, and concentrate on the other measurements. During this study, a new site was installed on the Harding Ice Field (see cover photo) at about 4200 feet, to the west of the Exit Glacier and of Seward and toward the north side of the ice field. This site does have a precipitation gage. At this writing we are awaiting the results of its first winter. For the time being, this site may be deemed sufficient to cover the whole ice field, so no additional site is suggested here.

The coast is quite under-represented by existing measurements, so this is the suggested starting place. If two new sites were put in, they should be placed to offer the maximum differentiation of signal between them, and in this case, for precipitation. Hence, sites along the northeast and southwest ends of the coast are suggested. One thought on the coastal locations is to try to locate in a fairly heavy precipitation area. Fortunately, at lower elevations, much of the annual precipitation will be in the warm season as liquid. Records are sparse, but established climate stations indicate that sea level snowfall will be generally 60-120 inches along this coast, more in protected bays and inlets next to large mountains. However, deep snows will occur on occasion, and modest snow cover is often present, at sea level, for much of winter.

On the northeast, the Alalik Peninsula seems to offer the first opportunity away from Seward. We had considered the outwash plain below Bear Glacier, which has reasonable exposure to the sea, with some blockage from the southwest by the peninsula itself. However it may be too icy and not suitable so we did not highlight it on the maps. (And, note general comments above, about glacial outwash areas.) Farther south along the Alalik Peninsula, a small promontory identified as Bear Glacier Point rises to only about 600-700 ft / 200 m above sea level, and could be considered. This stands out from the spine of the peninsula to be better exposed to southwest winds. Farther south a couple of other promontories are noted to the northeast and south of Bear Cove, along the peninsula, that have relatively good exposure from north around through east and south to west, with slight shadowing from the northwest. Another possible site is a flat spot east of Cliff Bay. Note that these are being judged from available topographic maps, not from photos or other information, and these sites may in actuality be totally unsuitable.

In the McCarty Fjord area, the topography is steep or ice covered over the northern half. Farther south, the outwash below Delight Lake has somewhat better exposure to several quadrants, with potential blockage from the ridge line extending to the southeast. An unnamed lake about 3 miles north of Delight Lake is similarly open though not quite as exposed to the ocean. It looks flat, but we cannot judge the nature of the surface. Across the fjord from here, a small peninsula jutting down on the east side of James Lagoon might offer a good sea level possibility. This will be favored for winds from the south and east, where orographic enhancement is stronger, and somewhat blocked for winds from the southwest. Winds with an eastward component are common in this area. One other site is suggested south southwest of here, toward the end of this peninsula, south of Surprise Bay and north of Harrington Point (? partly illegible).

This area is north of the Aleutian Low during the cool half of the year, with mean regional winds having an easterly component (**Figure 25**, **Figure 26**). During other parts of the year, at this latitude the wind often blows from the east during the sequence of directions that occur during the passage of a typical slow moving storm. In these circumstances, orographic effects will be noted on east facing steep slopes, especially on the west side of fjords and peninsulas, where the mountains rise directly and steeply from the sea.

A couple more sites are suggested along the northwest side of Nuka Passage. One is the outwash area below the Yalik Glacier and the other is about 10 km to the southwest, in the outwash area south of the lake at the foot of Petrof Glacier. Another potential area in the vicinity is the knoll attached to Nuka Point on Nuka Island, or the little low spot just about a km to its north, east of the small bay. This site is away from the mainland some, but is very well exposed in nearly every direction. The temperature would be dominated by nearby water temperatures. The wind and temperature and humidity field might be available from nearby NOAA data buoys, or C-MAN stations (Coastal Marine Automated Network); however, they do not record precipitation. Some degree of vegetative protection for precipitation would be helpful, as winds would be strong. Precipitation would be a principal reason for making measurements at this location.

We are not sure of whether an island presents logistic or other difficulties in servicing. Of all the sites in the Ailik Peninsula / McCarty Fjord area, the Nuka Island site has the best exposure (i.e., from the most directions) to storms from the open ocean. Another area discussed with NPS staff was the area around northern Ragged Island and bays to the north across McArthur Pass. On Ragged Island, the spit extending northeastward on the southeast side of Morning Cove was suggested. There is also what appears to be a small island at the end of this spit. As long as this is not too close to sea level (concern over coastal storm surges or tsunami run-up) this site does appear to have quite good exposure in nearly all directions, and to have potential safe harbor in Morning Cove for servicing visits. Another potentially suitable area is found between a small unnamed lake and the ocean, apparently high enough above the sea, and about a third of a mile north and slightly east of Steep Point, north of McArthur Pass.

With respect to elevated sites in Kenai Fjords, the most prominent feature is the Harding Ice Field, mentioned above, so this area is the obvious candidate. The source region (accumulation zone) for the Harding is above 5000 ft / 1500 m at its higher points, so if a precipitation measurement is attempted, a location somewhere above 4000 ft / 1200 m would be desirable. In this case, precipitation is extremely important to the ice balance, so there is a strong case to try to measure precipitation. The effort already under way with USGS appears to be looking for a rock island in the sea of ice. The only advice to offer here is to try to find a measurement site that will remain usable and representative of the ice field for several decades, should the ice field decide to diminish rapidly in extent or depth. Unless conditions directly on the ice itself are more desired (a perhaps better subject for a research project network), a site on terra firma but not far from the ice would likely be best.

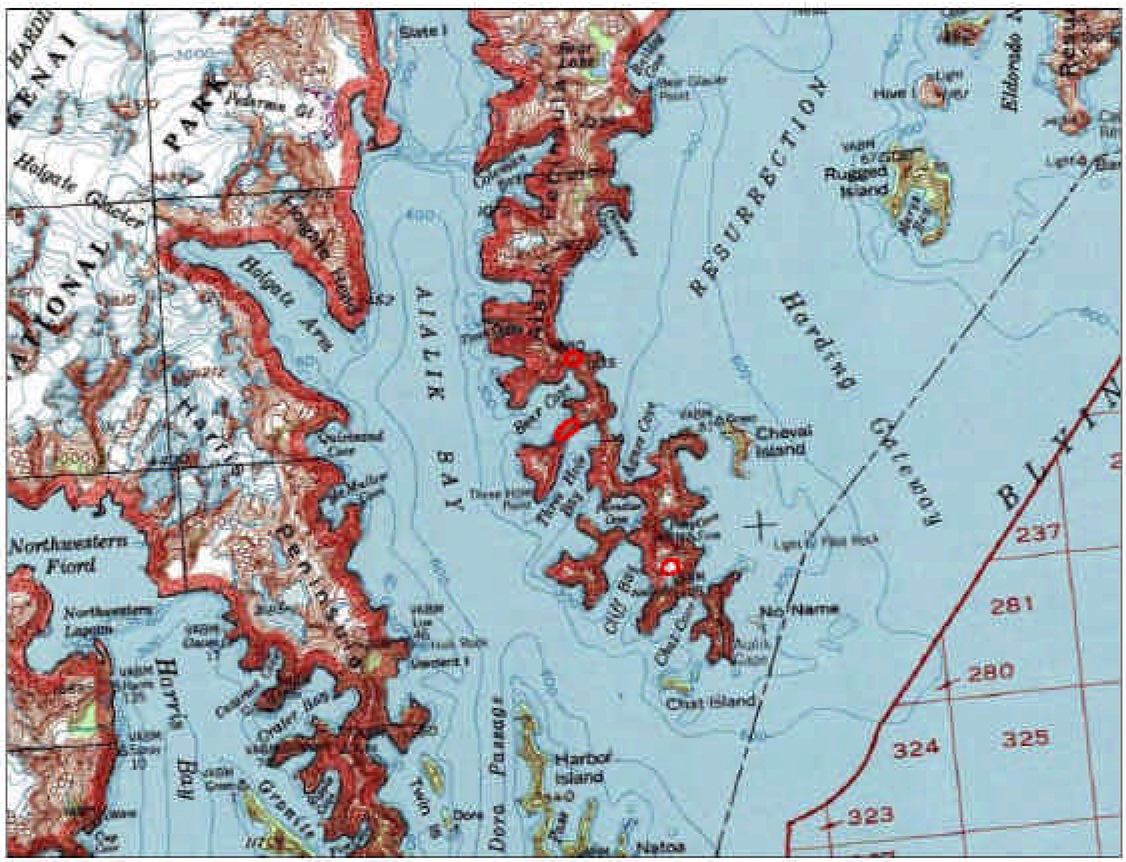


Figure 28. Kenai Fjords, Aialik Peninsula, 3 suggested locations, two near Bear Cove, one near Cliff Bay.

Figure 29. Kenai Fjords, 6 sites: Delight Lake, James Lagoon, Harrington Point, Yalik Glacier, Petrof Glacier, Nuka Island.

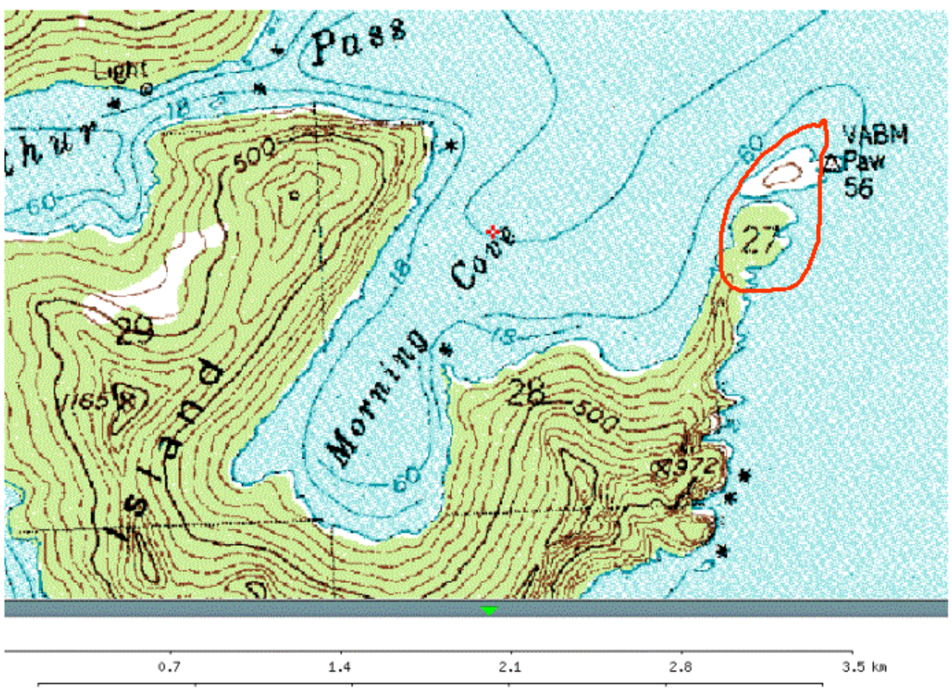


Figure 30. Morning Cove area on the northwest side of Ragged Island, east of southern end of McCarty Fjord.

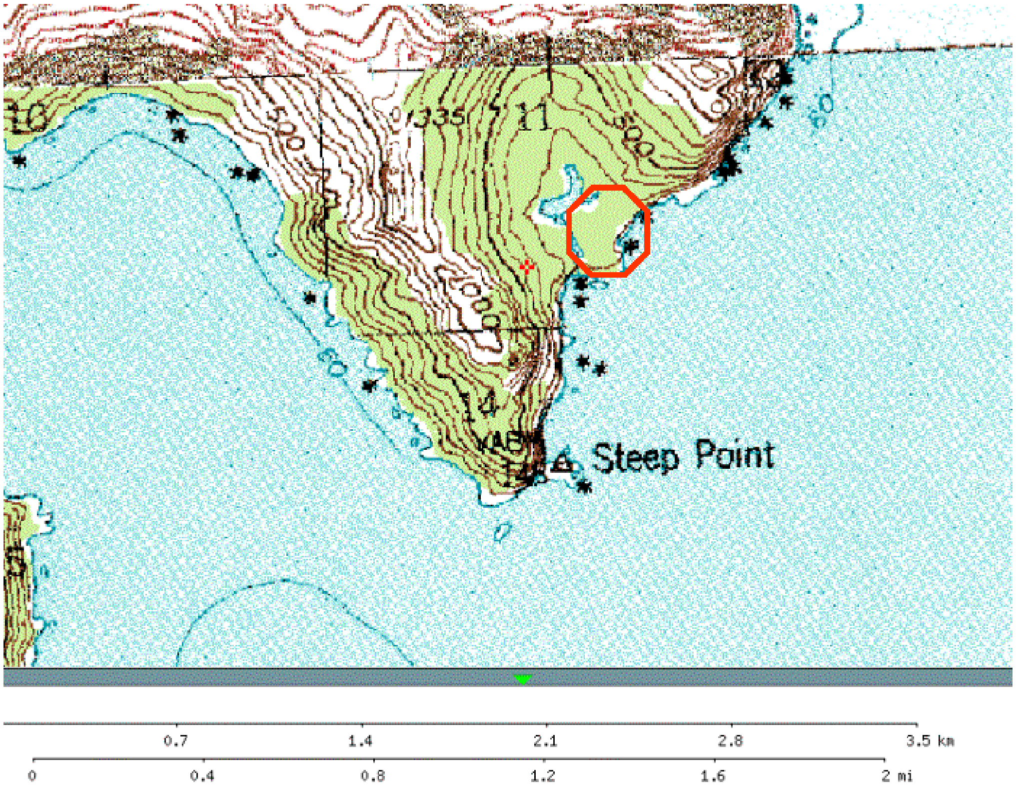


Figure 31. Small lake and shelf above ocean north of Morning Cove and near Steep Point, east of McArthur Pass.

5.2.2 Lake Clark

Lake Clark offers probably the best opportunity of the SWAN parks for a transect analogous to the one planned for Wrangell St Elias. This could be envisioned as extending from the area around Iliamna Volcano northwest or north northwest toward the Stony River and points farther interior. In temperature, Port Alsworth correlates reasonably well to both the interior and to the coastal locations. This correlation would be expected to be smaller if performed across the entire coast-to-inland distance. In precipitation, Port Alsworth correlates only mildly with points inland and points coastal. This may reflect a real lack of regional signal, or contamination by bad data. The climate changes from maritime to nearly full arctic in the winter across this span. See locator maps in **Figure 32** through **Figure 39**.

The area around Hickerson Lake, north of Chinitna Bay, looks like a good location. It has good exposure from the west, south and east, is close to sea level, can be set back from the ocean a km or two, a little bit above sea level, and can give good representation to regional air flow. This area is relatively close (a couple miles) to the large ice mass on Mount Illiamna. We did not factor in the likelihood that an eruption of this volcano would send debris down this pathway, but the main glaciers appear to follow other drainages. Between this area and Lake Clark, there are not a lot of ideal or easily accessible sites that are at very low elevations. The volcano is "in the way" over much of this area, but there may be some sites in narrow valleys or on ridges. Such a site might be a candidate for a non-precipitation station.

National Park Service personnel suggested the area near Silver Salmon Lakes, south of the Johnson River and between and south of Triangle Peak and August Hill. Land appears to be relatively flat and well exposed to the ocean, though with a somewhat narrower bench between ocean and mountains than at Hickerson. There are cabins and a human presence in this area, and an airstrip, and a potential willingness of some of the residents to help keep an eye on a station, but not too many people to disturb the measurements. Just a little farther southward down the coast, perhaps 2 miles, topographic maps show a sawmill, which may or may not still be present. Sawmills tend to be built on flat, open, and stable ground, and have generally been extensively cleared, so this may also be a good location for a station.

Another coastal location is north of Tuxedni Bay, in the coastal plain near the outflow of the Crescent River. The area has good ocean exposure to the northeast, east and south, and then begins to see some blockage from the southwest from topography several miles away. This area does not appear very difficult to reach. This site is not situated quite as nicely as Hickerson Lake. Given a choice, and all other things equal, from a climatic standpoint we'd elect for Hickerson or the Silver Salmon Lakes areas.

At pass level, Jack Barber of Alaska Air Taxi noted that it is possible to land a plane near Lake Clark Pass, and we have outlined several sites to the north of the upper end of the Tlikakila River, east northeast of Lake Clark. This is the coastal drainage divide. There is also a large glacier that enters from the north at this point, off the Neacola Mountains. We'd try to stay clear of floods and disruption that might come from this glacier if the climate were to warm. The locations we marked were north of Summit Lake, and a small unnamed lake just east of, and above, Glacier Fork where it empties into the Tlikakila River.

Another site suggested by the National Park Service (though not spotlighted in the figures) is near an FAA web camera, about halfway between Summit Lake and Blockade Lake, near where the North Fork of Big River makes a major jog to the right (to the southeast, referenced to river right). The position of this camera is given as 60 51'11" N, 125 37' 05" W, where the approximate elevation would appear to be about 600 feet, and with views toward Lake Clark Pass to the southwest and downriver to the southeast. The web site is accessible through http://akweathercams.faa.gov/viewsite.php. From the clear-day pictures at this site, there appears to be sufficiently good exposure in several directions.

Another set of sites is suggested about an equal distance downstream of Chakachamna Lake, along the southeastern extension of Mt Spurr. One set of sites is elevated, about 1000-3000 feet, and can be reached by plane (Jack Barber, personnal communication, Alaska Air Taxi) and another is along Straight Creek, which has road access. Jack also mentioned the McArthur River, though we did not suggest a site because of the apparent low and boggy nature of the area. These sites are not on the ocean but are in or near the coastal plain. The more elevated site would experience orographic lifting along the broad ridge that parallels Capps Glacier to its north, and thus likely be wetter than the valley bottom. A couple more spots of interest are southeast of Mt Spurr, along the Chakachatna River and the McArthur River, in the lowlands. As with all sites in this area, avoiding the hydrologic debris zones of volcanic eruptions would give long records even if the mountains did lose their temper in some future year, and furnish a good before-and-after possibility for examining disturbances and their local climate effects, or interpretations thereof. This site is the closest to Anchorage of all the sites considered in the SWAN area. A site in this area, one at Lake Clark Pass, and the set of sites near Telaquana, Turquoise, and Twin Lakes could serve as a transect.

The next location is near the inlet of the Tlikakila River as it enters Lake Clark and Little Lake Clark. There could be some potential spots 1-3 km upstream from the lake. This site could probably be reached by boat, from Little Lake Clark. It would be nice to stay away from the lake shore itself, since this large lake likely influences local temperatures. (A side point here: Since the Park is centered on the Lake, there is a rationale to have a special station that is intended to measure the climate where it is most affected by the lake … like on a small island, and perhaps with water temperature information.) Another couple possible locations are about 7-9 miles north of the mouth of the Tlikakila River, southwest from Portage Lake along the low divide, and between Portage Lake and Lachbuna Lake along and mostly north of the Kijik River. These sites should have better exposure to interior continental influences than a site at the mouth of the Tlikakila River.

We next consider Telaquana, Turquoise, and Twin Lakes. There are many good open locations in this area. Two locations shown are downstream of Twin Lakes, one on the north side of the Chilikadrotna River in the low and wide open divide between the Chilikadrotna River and the Mulchatna River to the north, and another a little farther west, and elevated and perhaps not so heavily vegetated or boggy. By staying in the river bottom, the winter inversion will be well sampled; by remaining a little higher, the coldest temperatures may not be experienced, and the surface may be a little less boggy, especially in summer. A third site is suggested north of Turquoise Lake on an extended low divide between it and Telaquana Lake. This site would probably sit above the Arctic interior inversion a little more often than the lower sites downstream of Twin Lake, on those days when the inversion is shallow. Another potential location is near the corner where the Mulchatna turns and flows northwestward, an area containing a series of small lakes northeast of the river. This area is between 2000 and 3000 ft / 600-900 m elevation. In winter there will be strong inversion effects from the river on up to the local hills and highlands. Finally the next candidate in this little series is near Telaquana Lake, perhaps near the old village, or along the long, low divide between the Telaquana River where it turns north and the Mulchatna, a stretch of 15-20 miles. Something along Stony River or Swift River, though getting away from the park proper, would be well into the Arctic climate regime in winter and could thus help provide useful background climate information about low spots in the northwest side of Lake Clark Park and Preserve.

We considered Merrill Pass, but this area appears too rugged and difficult to reach with a plane. A site not far from that, though still on the ocean side of the divide, is a flat area on the drainage divide between the Igitna River where it turns south after flowing east, and the Chilligan River to its north. This area is above the valley bottoms and a little less affected by channeling of air flow.

High elevation stations. Lake Clark has three large volcanoes over 10,000 ft / 3000 m in or near the park (Spurr, Redoubt, and Iliamna). Of these Spurr and Redoubt have erupted since 1990 and are considered active. Thus, stations in the vicinity of these peaks are likely to be disrupted, or enjoy a free ride to the stratosphere, or an unplanned float trip, so the immediate environments of these specific peaks, or known flow paths, should be avoided to obtain a long term climate record. Iliamna appears to be less active. There is considerable ice in the region around these peaks, which might be affected by climate warming. Locations on the marine-interior divide at 5000-6000 ft / 1500-1800 m that lie on or near this divide would be good locations to observe in Lake Clark. In conversation, Jack Barber (Alaska Air Taxi) thought that the area just west of Lake Clark Pass had places where a plane could land. The main choice for high elevation sites in Lake Clark would be between sites on the coastal-interior divide

(Chigmit Mountains) and sites that are one range removed from direct coastal influence. The former seem preferable to obtain wind flow patterns off the water, whereas the latter might give better insights into climate warming or flow pattern changes affecting glacier runoff into interior rivers that drain southwest toward Bristol Bay. Perhaps a high ridge on Double Peak could be identified (not shown on maps). These are in high precipitation and cloudiness regimes, and visitation and maintenance might be unusually difficult.

Another possibility might be on the ridge between the Tlikakila River and Little Lake Clark (the northeast end of Lake Clark), at about the 4000 foot / 1200 m level, even though this is a little low for a “high elevation” site. (This discussion is general, so we are not showing specific sites.) A site here could serve as part of a high-low pair. If two or more high elevation sites are contemplated, at least one of them should be part of such a high-low pair (two sites at much different elevations, horizontally within 10-20 km of each other, better if 2-10 km). The next two ridges to the north northwest of this location are also good candidates for a 5000 ft / 1500 m high elevation site (between the Tlikakila and Kijik, and between the Kijik and Chilikadrotna Rivers). These mountains are more toward the interior than the coast, and might be soonest or clearest to show climate change in the mountains.   Another location could be in the Revelation Mountains north of the Swift River. These mountains might be too rugged, though. Another site, already discussed above, is the one between the Igitna and Chilligan, which is at about 5000 ft / 1500 m and thus can qualify as “high elevation.” An eruption of Mt Spurr in 1953 raised the level of Chakachamna Lake by 10 ft / 3 m (a lahar blocking the lake exit), but this is east of and well below this location. The same eruption deposited several mm of ash on Anchorage.

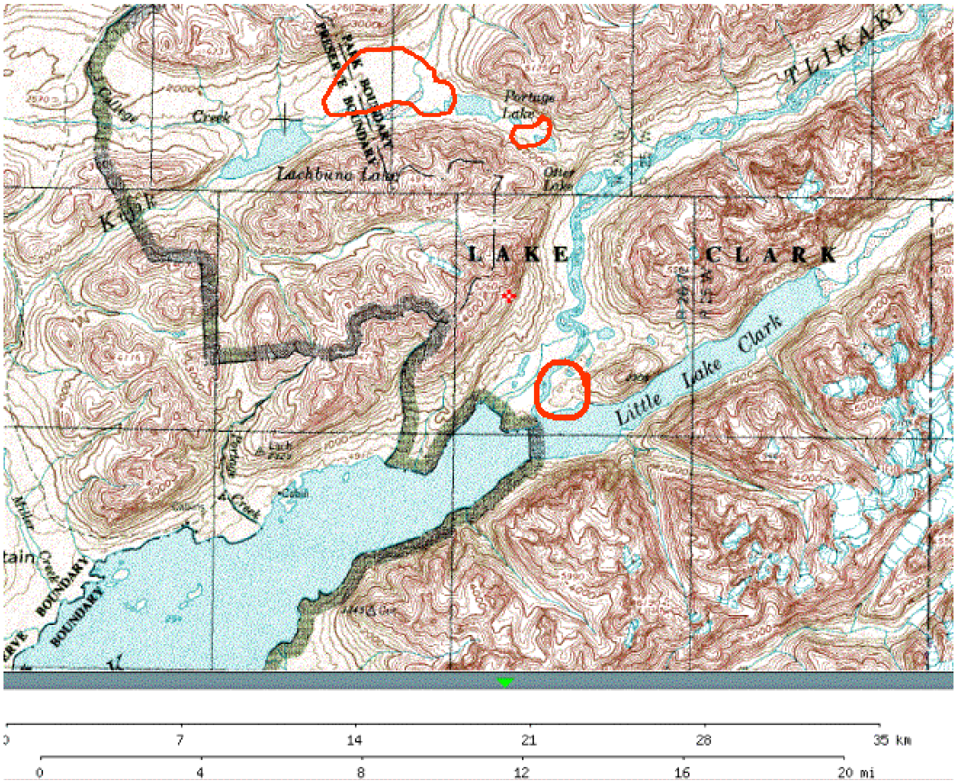


Figure 32. Mouth of Tlikakila River, and 3 suggested locations.

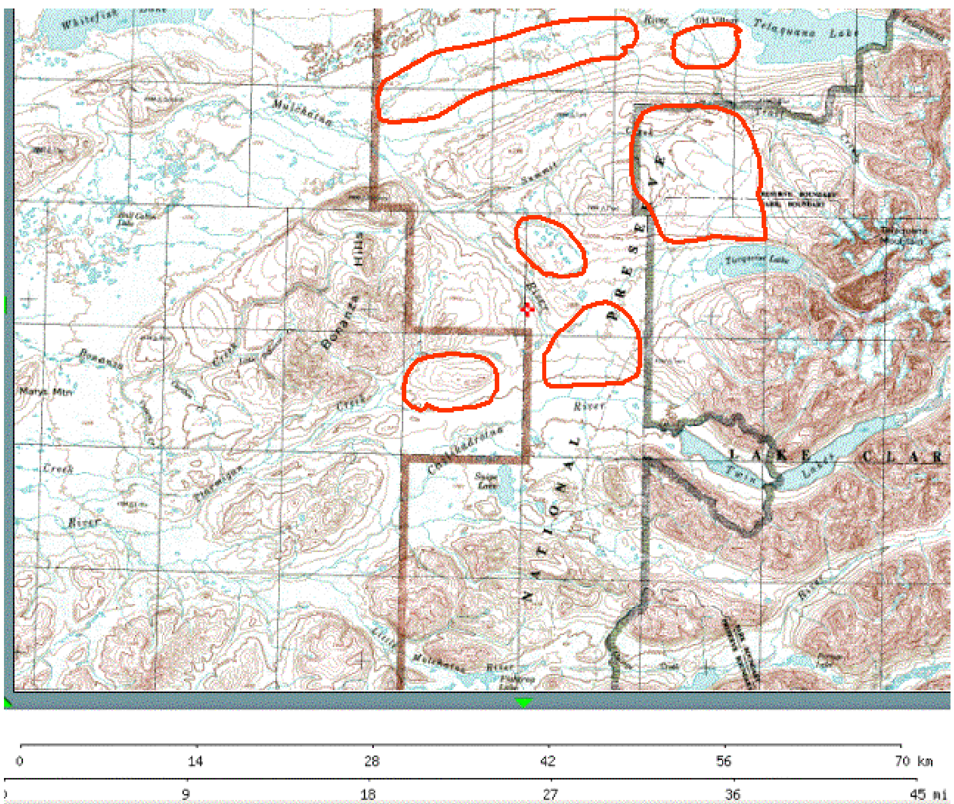


Figure 33. Suggested sites near Twin, Turquoise and Telaquana Lakes.

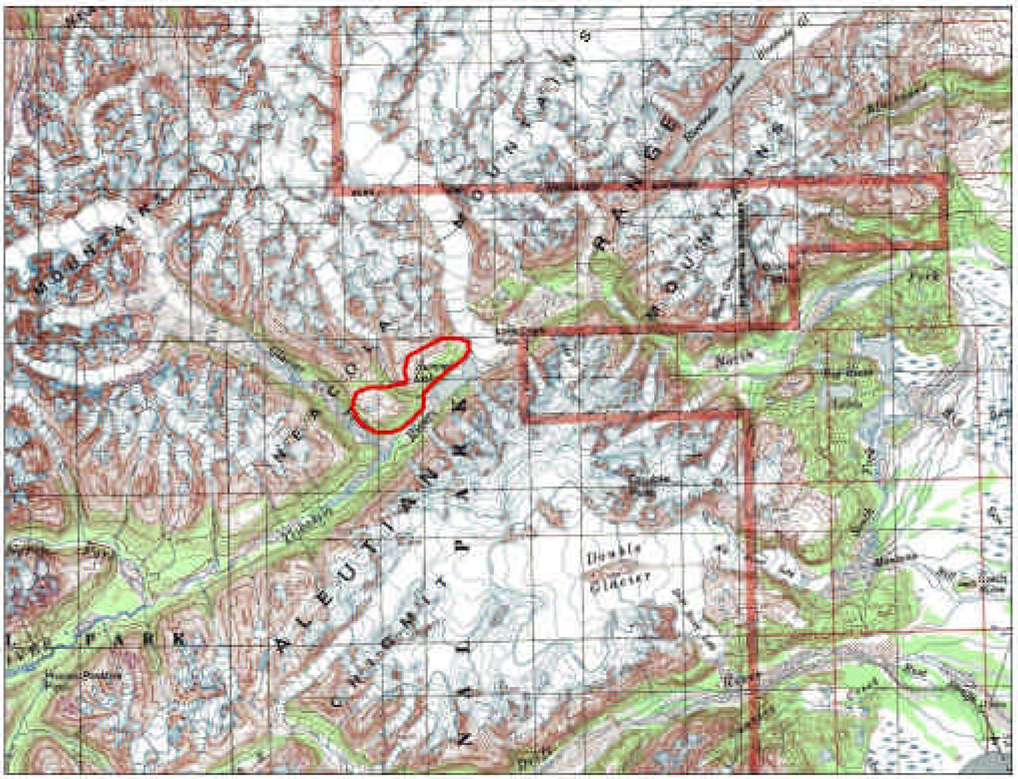


Figure 34. Lake Clark Pass, 1 suggested area.

Figure 35. Igitna – Chilligan River Divide. One suggested site.

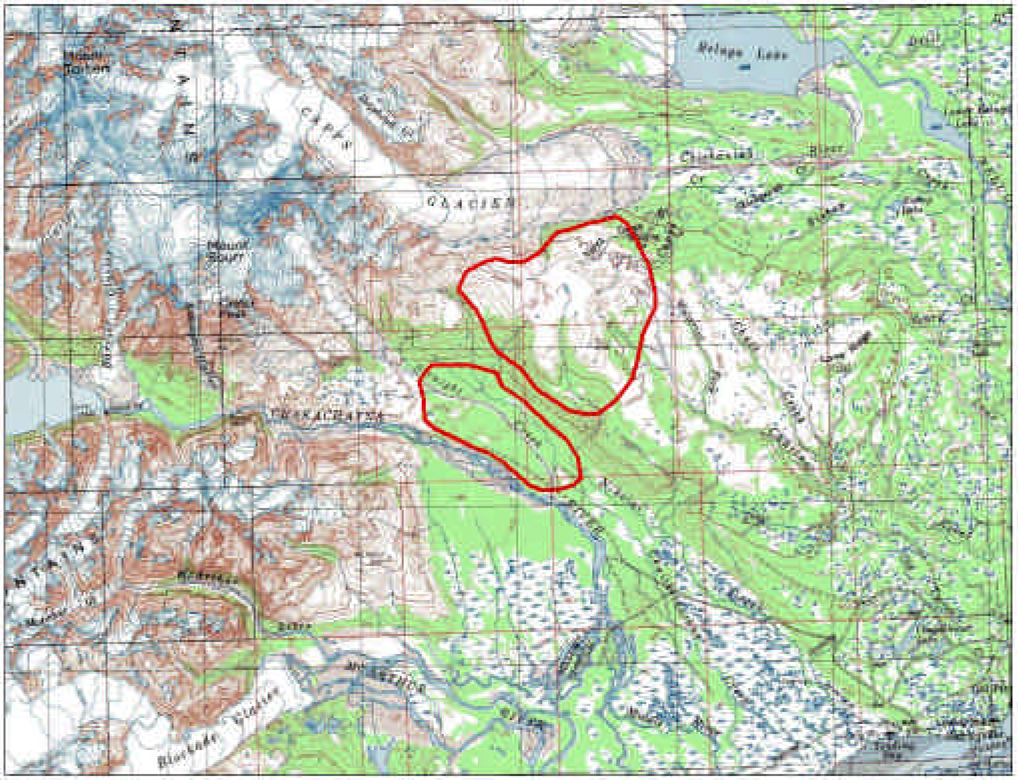


Figure 36. Mount Spurr, southeast flank. 2 suggested areas.

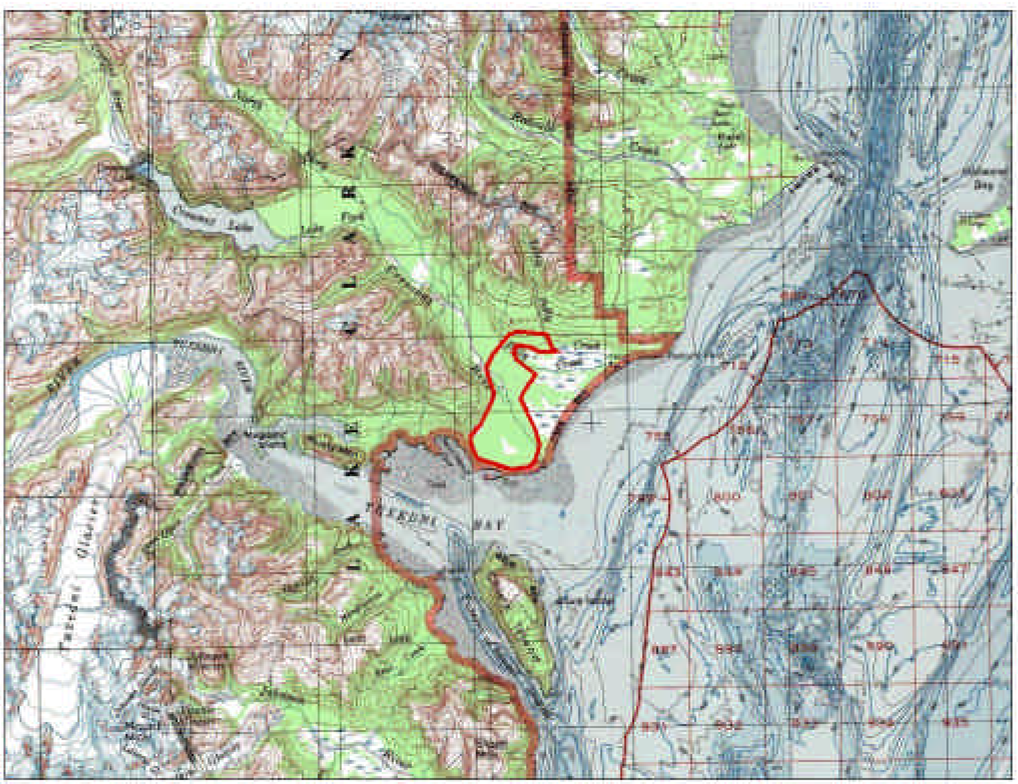


Figure 37. Crescent River, Tuxedni Bay. One suggested area.

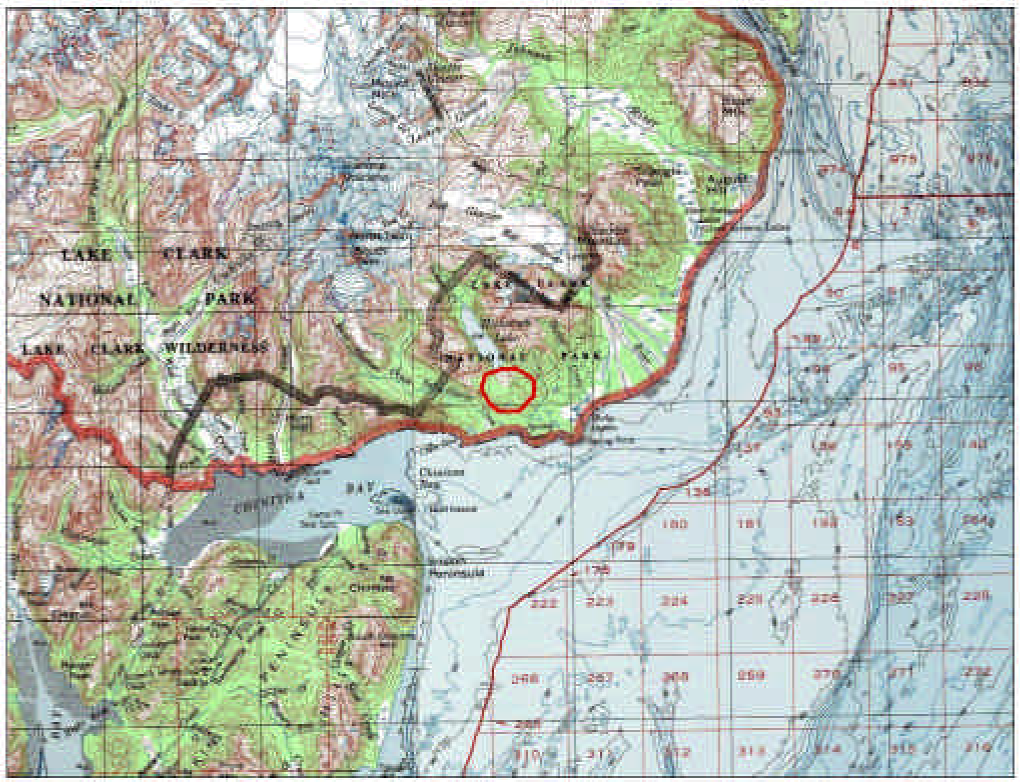


Figure 38. Chititna Bay, Hickerson Lake, one suggested site.

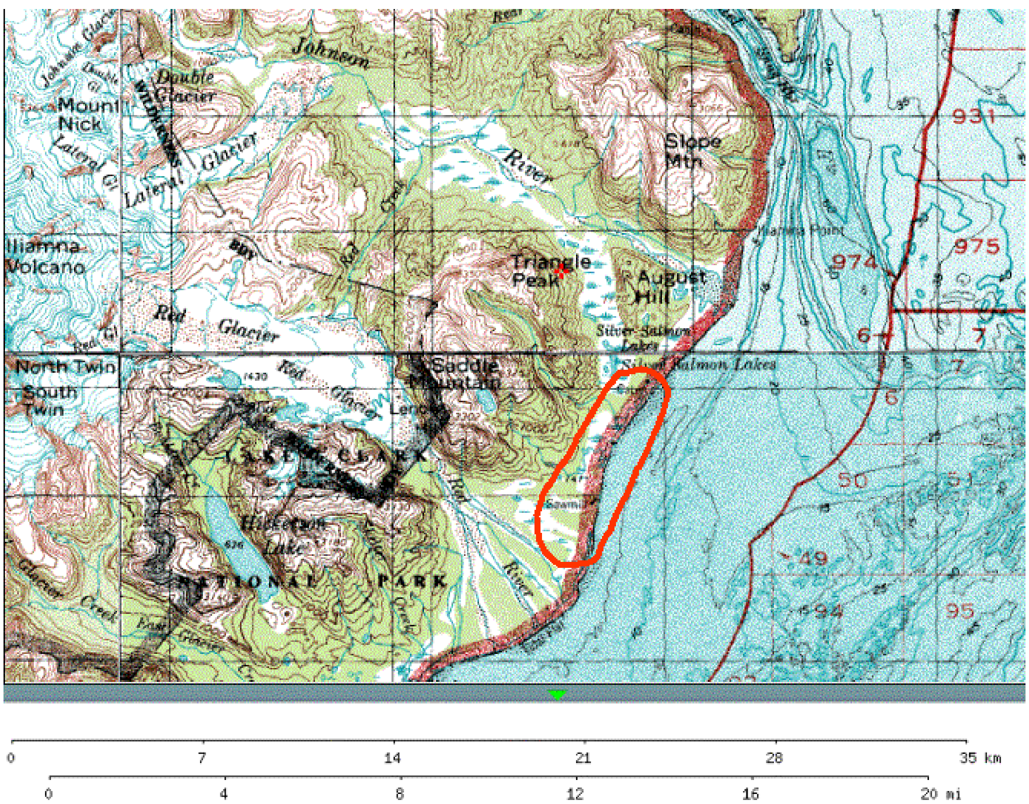


Figure 39. Silver Salmon Lakes area, north of Chilitna Bay.

5.2.3 Katmai

Katmai offers a transect possibility, too, although the maritime climate on the south side transits to a less severe climate than would a transect across Lake Clark Park and Preserve because of the influence of Bristol Bay. The guess from our corner is that Katmai Volcano (or Novarupta, actually) has expended itself for a while, and that it is thus safe to place meteorological equipment in the paths followed by debris during its heyday a century ago. See locator maps in **Figure 40** through **Figure 46**.

This park offers a big chunk of unmeasured territory. We begin with a suggestion for a location above the west end of Kulik Lake and above Kulik Lodge, along an elevated rim north of an unnamed like about a half mile south of the Lodge. The country here appears to be rolling and not unduly steep, and locations could probably be picked with good wind and temperature exposure, and flat locations suitable for a precipitation gage and snow measurements.

King Salmon, with its longstanding first order station, already holds down the need for an additional station on the west end of Naknek Lake. Brooks Camp also looks like a good spot for a climate station, or the area just to the south. South of Iliuk Arm near Brooks Camp, there appear to be possible sites along Merrill Creek, with possible road or trail access from the traverse to Windy Point. Any site between here and Katmai Pass could provide useful real-time information to this popular visitation area. Another site is suggested for the Valley of Ten Thousand Smokes. We picked a couple sites to the east and west of this valley to check out. Jack Barber of Alaska Air Taxi mentioned that he frequently lands here; we were not sure where exactly. The Windy Creek Overlook shown on topo maps looks like it has quite good exposure, and might be a very good site, even if precipitation were not emphasized. The guess is that this area gets a lot of people traffic from Brooks Camp, and this destination is a mere 18 mile hike in. The site appears to be about 1300 ft / 400 m above sea level. Of all the sites in the area, based solely on map information, the Windy Creek Overlook appears to be the best in the stretch from Brooks Camp to Katmai Pass.

Around Katmai volcano itself, elevation may be too high, unless precipitation is foregone or the station is well winterized. But there is a rationale for a higher elevation monitoring site that is closer to the level where the ice is found. If visual impact could be avoided, Katmai Pass could be a good location, and we suggested a site there. We cannot tell from topo maps whether there are adequate exposures here, but it looks that way.

One or two coastal locations somewhere in Katmai would be very good to have, since there is a complete lack of data from this area. One site is suggested just south of Atmo Mountain, given its name seemingly a fated place for a weather station. The site has good exposure to maritime conditions and good orographic conditions just to the north (topographic control of precipitation). A second site north of Atmo Mountain is also suggested, along the north bank of the stream that drains along the south edge of Topographers Peak. This site is blocked a bit by Atmo Mountain, though. Around the corner to the north, slightly inland, along the interfluve between the Katmai River and Soluka Creek, is another possible site. The area offers good exposure to the south, and significant orographic effects in three directions, including from the aptly named Barrier Range just to the north. A fourth coastal site on the peninsula that juts south just east of Katmai Bay looks like it would have very good ocean exposure, and orographic uplift just to the north, for potential heavy precipitation.

Further north along the coast, four sites were suggested. One is along the north side of Hallo Bay, a location with good open ocean exposure to the south and east, and good orographic uplift immediately to the north along the ridge line. A second site is north of here about a mile and a half, along the Big River near Kaguyak Crater. This site is a nice open coastal plain, though we cannot assess the vegetation situation from the map alone. Another small area was spotted and suggested about a mile and a half south southeast of Fourpeaked Mountain, right on the shore. The last site in this vicinity is up the coast toward the northeast about two miles, south of Fourpeaked Glacier.

The last sites along the coast of Katmai are further to the northeast, along the McNeil River. One site is north of the townsite of Kamishak, on isolated bumps that appear to rise from the lower plain, at McNeil Head just south of here, and along a low divide east northeast of McNeil Lake, suggested because it is a little higher and might be more rocky and less boggy than sites at lower elevations near here.

In the interior a site at Nonvianuk Lake (like Hammersly Camp) or at Kukaklek Lake would help tie down the conditions at the north end of Katmai Park and Preserve. There is a private landing strip at Big Mountain that might be a good site (logistics reasons); this location is about 3-4 km away from (south of) Lake Iliamna. Large Lake Iliamna itself should be avoided because of lake influence. Grosvenor Camp on Lake Grosvenor might make another good site. We have identified one area to its immediate north, and a second across the lake neck and on a low ridge to the south. What would be nice in this part of Katmai is a location not right on a large body of water, but not too far away, to track the interior lowland part of the Park’s climate, which could be decidedly different from the south ocean side, and may even be different from what is measured at King Salmon.

High elevation stations. As noted elsewhere, the coastal mountains in Katmai National Park separate maritime from somewhat less continental conditions than are found northwest of the mountains in Lake Clark Park and Preserve. There is not quite such a large difference across the coast range (Aleutian Range, in Katmai). The main ridge line in Katmai is only about 15 mi / 25 km from the coast, with summits in the 5000-7000 ft / 1500-2100 m range. This is a good elevation to monitor warming for ice melting. The east end of this drainage divide is more heavily glaciated, and may be more “at risk” of loss from warming. Ridge locations in this area would more readily reflect regional and open ocean patterns than would those near Lake Clark NPP because of this relative proximity to the ocean. Because of the attraction and visitor interest in the Katmai volcano vicinity, site of the most powerful eruption of the 20th Century, and the relatively lighter glaciation in its vicinity, this area might perhaps be a better candidate for a higher elevation site than others in the Park. Katmai Caldera itself is quite steep; perhaps sites could be found near the 6000 ft / 1800 m level to the west near Novarupta. It appears that all the ash of 1912 left large areas of relatively gently sloping landscape, and some of these could be suitable for a climate station location. The suggestion would be to look in the vicinity of Katmai Pass and the Mt Cerberus area, at or above 4000 ft / 1200 m, and more or less on the drainage divide. This would make a good candidate for an all weather precipitation gage.

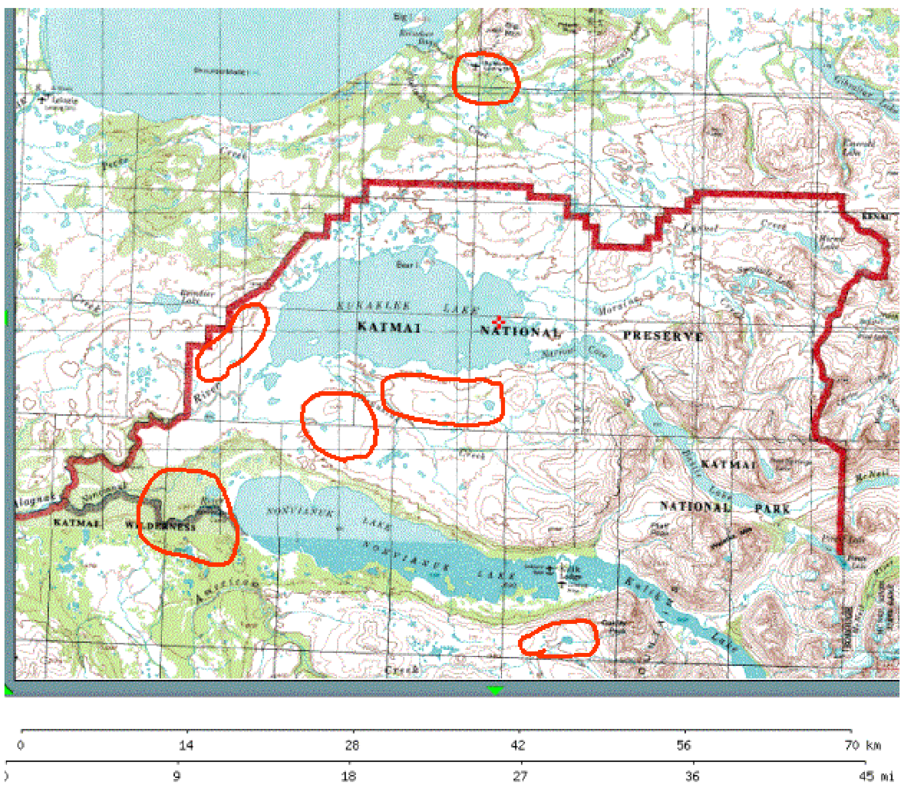


Figure 40. Potential sites at or near the north end of Katmai Park and Preserve.

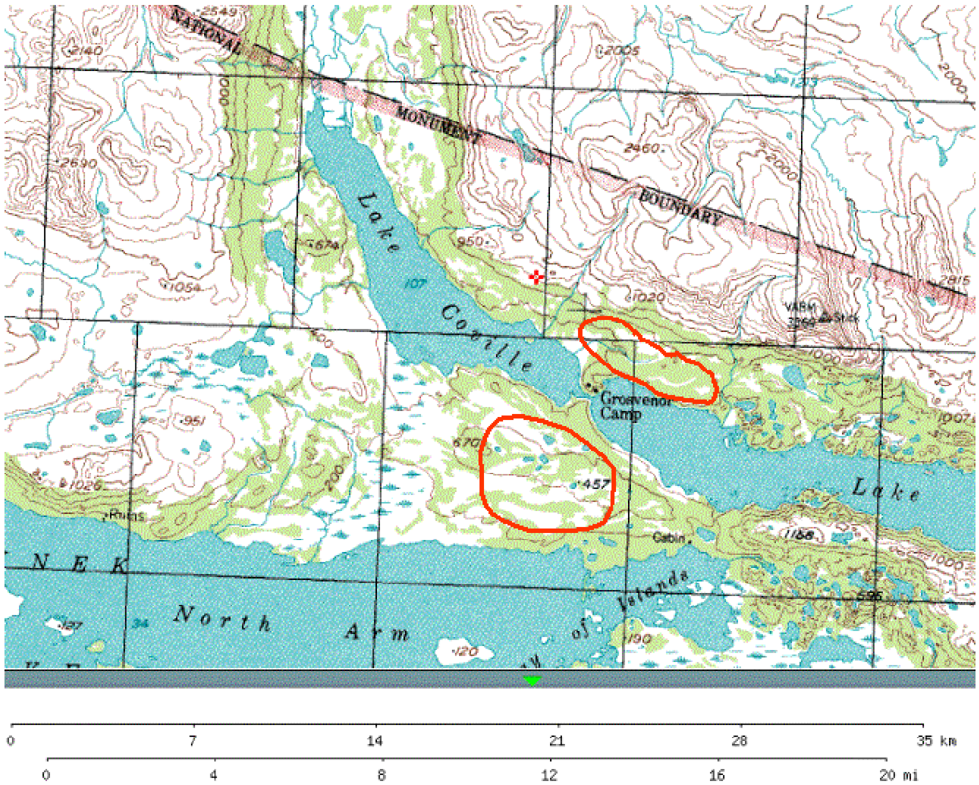


Figure 41. Two possible sites near Grosvenor Camp.

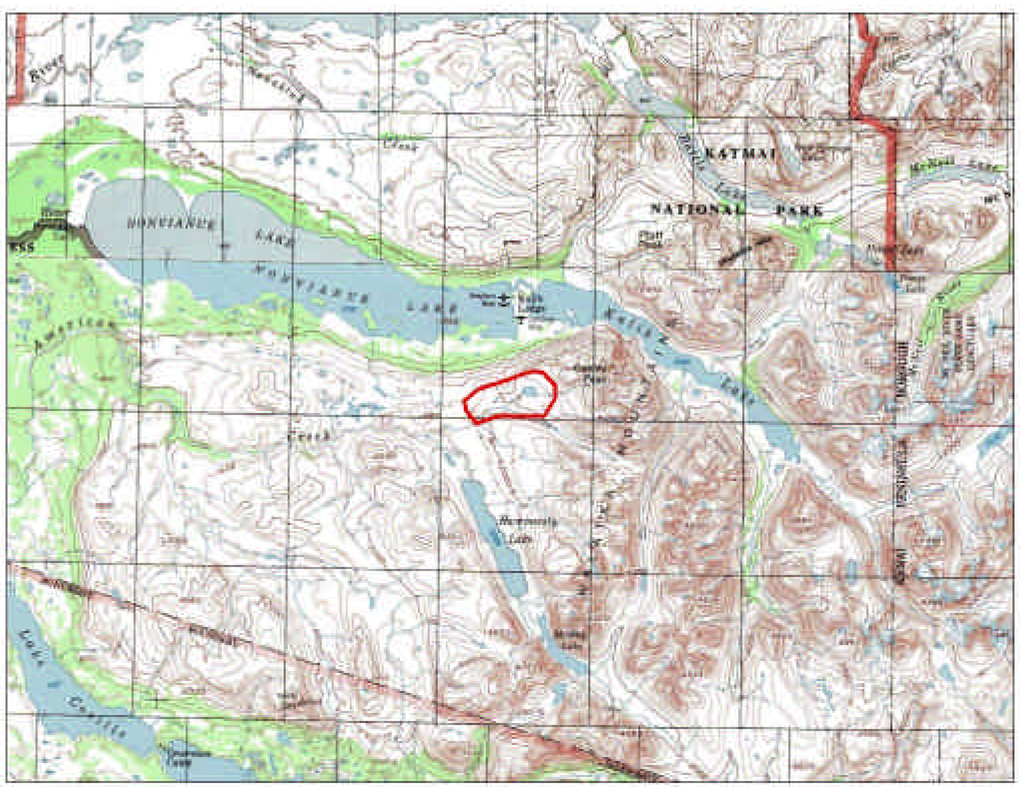


Figure 42. Katmai National Park. One suggested area, near Kulik Lake Lodge.

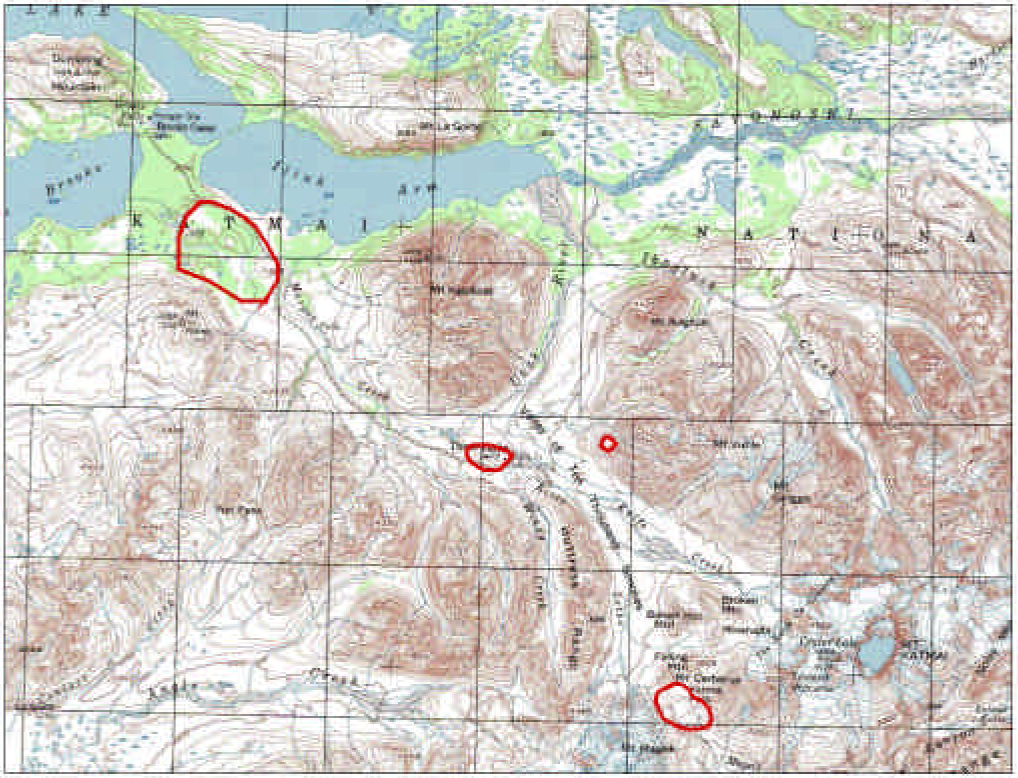


Figure 43. Katmai National Park. 4 sites near Brooks Camp, Valley of the Ten Thousand Smokes. and Katmai Pass.

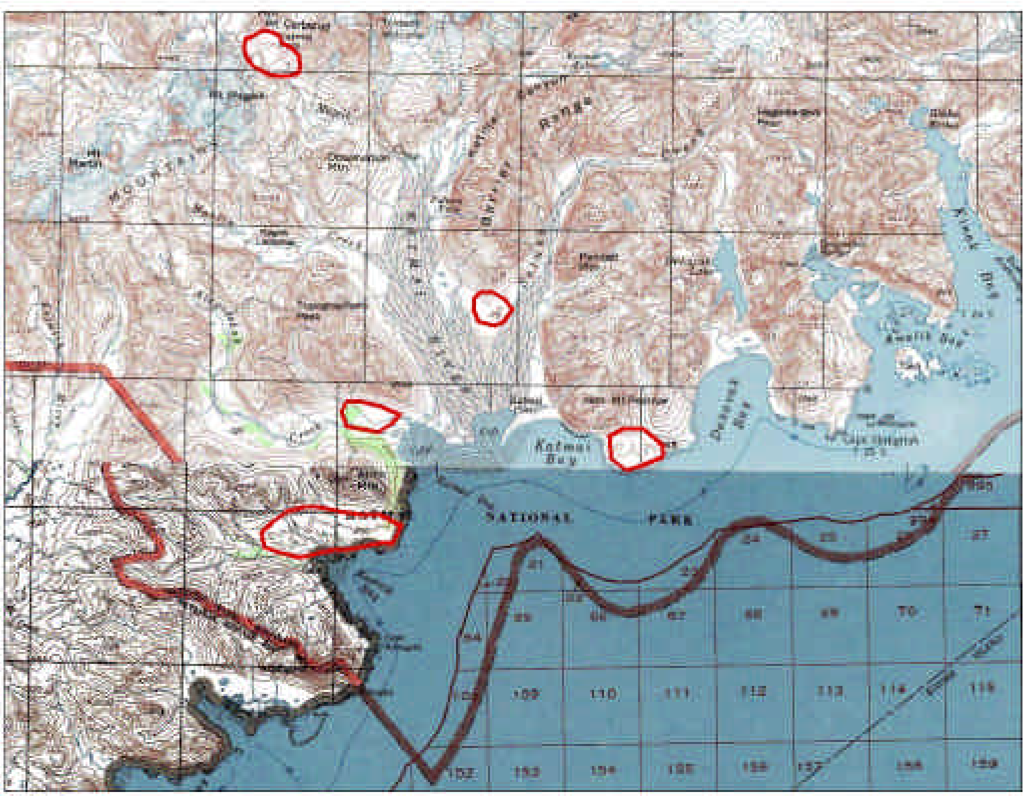


Figure 44. Katmai National Park. Four sites near Katmai Bay, and Katmai Pass.

Figure 45. Hallo Bay northeastward, 4 suggested areas

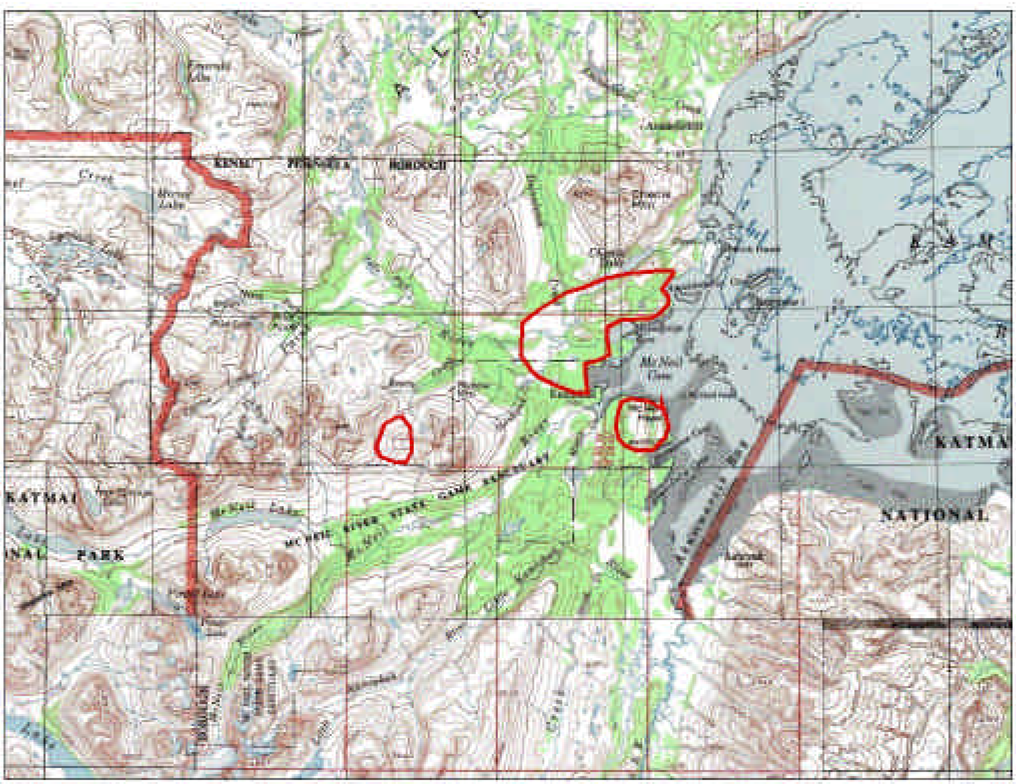


Figure 46. McNeill River.   3 suggested areas.

5.2.4 Aniakchak

This location seems to have two basic choices: one site on the south side and thus likely often more exposed to precipitation effects, and the other on the north side, to gather whatever "continental" influence might be present. See locator maps in **Figure 47** and **Figure 48**. The entire Monument is rather small and would probably show less climate variability than the other large units in the SWAN area. There is a nearby climate station in Port Heiden and it would be better to avoid areas already sampled.

Accordingly, two sites were identified inside the caldera itself. One of these is upstream (west of) Surprise Lake. We cannot tell what type of surface this is, whether boggy or marshy, or harder rock. The area is open and flat, and in the transition zone from south coastal to north coastal, and more to less precipitation. Another site just south and southwest of here is also inside the caldera, and closer to Vent Mountain. This site probably would be a little better, but might be subject to tephra or worse should the vent go off again (last display was in 1931, only 70 years ago). A third site is suggested on the south flank of the caldera rise, on a slight leveling of the slope and on a kind of plateau above two canyons or scalloped incisions to the west and the east. This site was suggested because it has good exposure to south winds rising from the Gulf of Alaska, and would likely take a good pounding and be well exposed in all directions. A fourth site near the crater is to the northeast, a little ways into the "rain shadow" of the Aleutian Range, if there is such a thing. From the PRISM maps, it appears that precipitation drops "precipitously" and thus this area might show different behavior from the caldera sites.

Another site is suggested southeast of the caldera, for the low drainage divide between the Aniakchak River and the North Fork (north fork of what is not specified, because if flows right into the Pacific Ocean). This site is a little farther from the caldera, but has very good direct exposure to the whole Pacific Ocean from here to Tahiti. The area looks like it could be serviced more easily as well. This site also appears to have rocky outcroppings and thus might not be heavily vegetated.

As for high elevation stations, this park is not very high, with a summit of 4400 ft / 1341 m. The north side appears to have smoother slopes leading to the higher elevations, and if a higher site is desired, this seems like as good a place as any to locate such a site. However, it appears that there are relatively few flat spots along the rim.

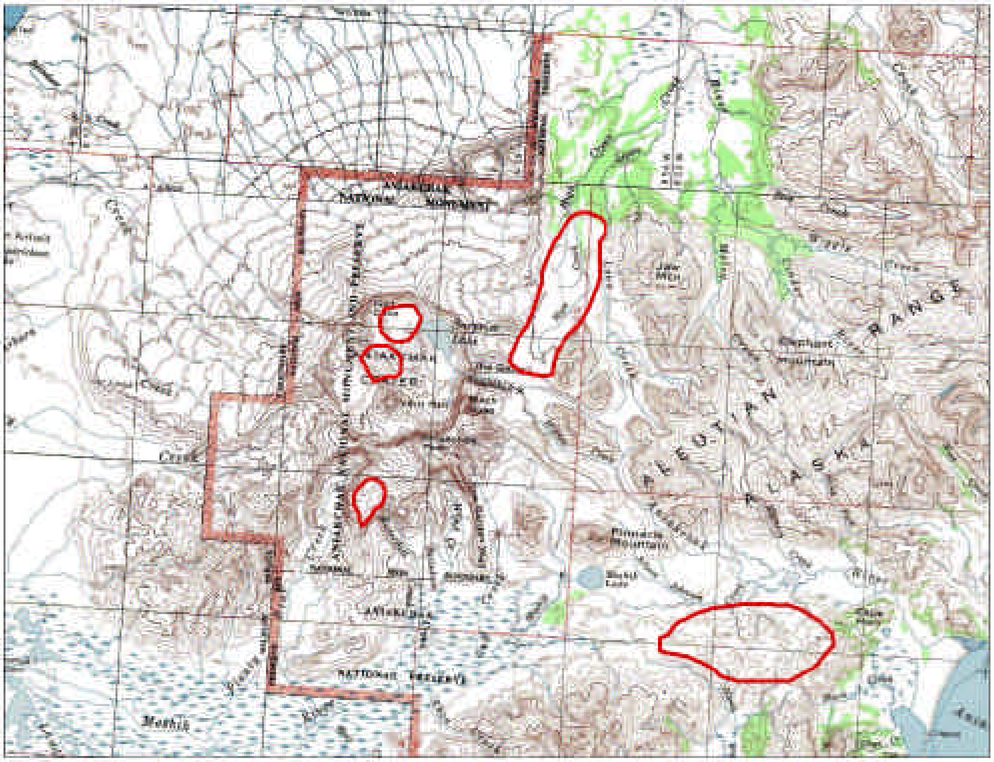


Figure 47. Aniakchak National Park. Two sites in crater, one site on south flank, one site to east, and one site along Aniakchak-North Fork Divide.

Figure 48. Aniakchak National Park. Aniakchak-North Fork drainage divide.

5.3 Discussion of priority

The sites discussed in the previous sections are summarized in **Figure 49**. This figure shows only proposed locations and areas and does not include existing sites.

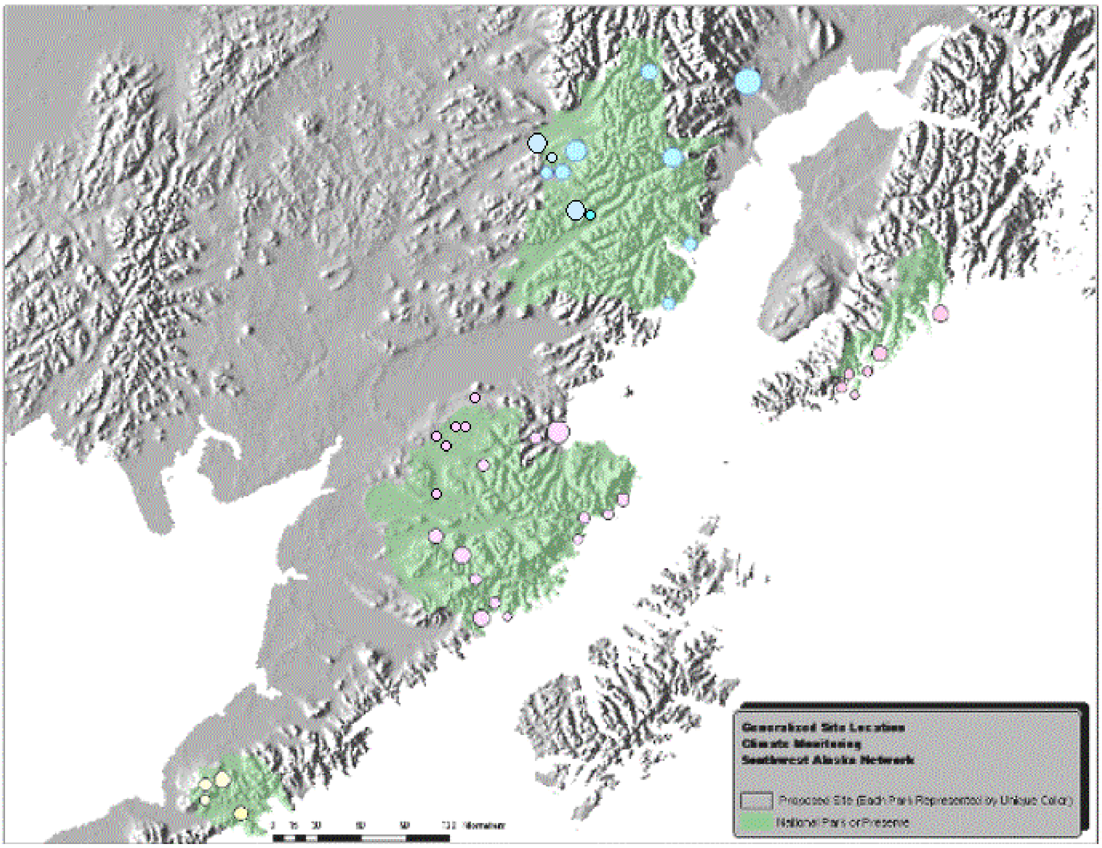


Figure 49. Generalized summary of suggested sites.

Each park unit should have at least 1 or 2 (Aniakchak) or 2 or 3 (Katmai, Lake Clark, Kenai Fjords) observing sites. The entire area has sparse data, and the coastal zone is the most undersampled area, and needs at least 2-3 sites. There should be at least a couple higher elevation sites. As discussed earlier, many of the ice covered areas are not too far from a mean annual temperature of freezing, and a site or two in the elevation zone between 2500 and 5000 feet would be helpful. If in severe locations, such sites might be candidates to forgo precipitation and measure the other main meteorological quantities.

At least one transect should be attempted. The Lake Clark area, with its more direct proximity to the interior seems more logical than does Katmai. However, it was harder to find suitable sites, given the rugged topography. The existing Lake Alsworth coop and RAWS sites (not shown) could form part of a transect to the interior from Tuxedni or Chitina areas. A “bent” line that includes the Lake Clark Pass area might also qualify as a transect. A transect readily suggests itself in

Katmai, from Katmai Bay to Katmai Pass to the Valley of Ten Thousand Smokes. The interior climate in this case is a little warmer in winter than in the Lake Clark area, because there is better access to the ocean in northern Katmai than northern Lake Clark. Another transect across the Aleutian Range is possible at Aniakchak, especially if Port Heiden is included. Transects should include 3-5 stations, with two endpoints and 1-3 mid points situated at key locations along the transition.

6. Web access to information

Web pages have been developed to provide access to SWAN parks, and can be found at www.wrcc.dri.edu/nps. The intent is to link this to a national map, and to an Alaska map.

We have been steadily developing software to summarize the data from these hourly sites. This has been under the aegis of the RAWS program, and a growing list of product generators, ranging from daily and monthly listers to wind roses and hourly frequency distributions and others are now available. All park data are available to park personnel via an access code (needed only for data listings) that can be acquired through request. The WRCC RAWS page is at www.wrcc.dri.edu/wraws.

Additional access to more standard climatological information is accessible though the above pages, as well as through WRCC's main Alaska pages at

www.wrcc.dri.edu/summary/climsmak.html

These summaries are generally for National Weather Service cooperative stations.

For site surveys for the Climate Reference Network, and for other networks, Kelly Redmond prepared a document giving advice on how to thoroughly photograph a prospective site. This can also be found at <www.wrcc.dri.edu/nps/docs>.

7. Acknowledgments

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9. Supplements and attachments

Data files will be posted to ftp.wrcc.dri.edu/npsak/swan2004 and likely remain there at least a year.

This report will be available at http://www.wrcc.dri.edu/nps/docs.

10. Contact information

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<u>Dataset Contents:</u>

- **Alaska PRISM Grids (sub-directory name in parentheses)**
  - Annual Mean Temperature (ann_mean)
  - Annual Mean Precipitation (ann_prec)
  - Annual Minimum Temperature (ann_min)
  - Annual Maximum Temperature (ann_max)
  - January Mean Monthly Minimum Temperature (jan_min)
  - January Mean Monthly Maximum Temperature (jan_max)
  - July Mean Monthly Minimum Temperature (jul_min)
  - July Mean Monthly Maximum Temperature (jul_max)
  - March Mean Monthly Precipitation (mar_prec)
  - September Mean Monthly Precipitation (sept_prec)

- **PRISM Maps**
  - **Alaska (files names in paretheses)**
    - Annual Mean Temperature (ann_mean_temp.pdf, ann_mean_temp.jpg)
    - Annual Mean Precipitation (ann_prec.pdf, ann_prec.jpg)
    - January Mean Monthly Minimum Temperature (jan_min.pdf,jan_min.jpg)
    - January Mean Monthly Maximum Temperature (jan_max.pdf, jan_max.jpg)
    - July Mean Monthly Minimum Temperature (july_min.pdf, july_max.jpg)
    - July Mean Monthly Maximum Temperature (july_max.pdf, july_max.jpg)
    - March Mean Monthly Precipitation (march_prec.pdf, march_prec.jpg)
    - September Mean Monthly Precipitation (spet_prec.pdf, sept_prec.jpg)
  - **Southwest Alaska (file names in parentheses)**
    - Annual Mean Temperature (swann_mean_temp.pdf, swann_mean_temp.jpg)
    - Annual Mean Precipitation (swann_prec.pdf, swann_prec.jpg)
    - January Mean Monthly Minimum Temperature (swjan_min.pdf, swjan_min.jpg)
    - January Mean Monthly Maximum Temperature (swjan_max.pdf, swjan_max.jpg)
    - July Mean Monthly Minimum Temperature (swjuly_min.pdf, swjuly_min.jpg)
    - July Mean Monthly Maximum Temperature (swjuly_max.pdf, swjuly_max.jpg)
    - March Mean Monthly Precipitation (swmar_prec.pdf, swmar_prec.jpg)
    - September Mean Monthly Precipitation (swsept_prec.pdf, swsept_prec.jpg)

- **Other Maps (file name in parentheses)**
  - Southwest Alaska Weather Station Distribution (sw_station_distribution.pdf, sw_station_inv.jpg)
  - Stations Utilized in Correlation Analysis (sw_corr_inv.pdf, sw_corr_inv.jpg)

  PRISM Metadata (file names in parentheses)
  - TMIN (meta_tmin_ak.txt)
  - TMAX (meta_tmax_ak.txt
  - TMEAN (meta_tmean_ak.txt)
  - PREC (meta_pre_ak.txt)

- **Charts, Tables, &Graphs (file names in parentheses)**
  - Alaska Weather Station Inventory by Network (ak_network_inventory.xls)
  - Weather Stations Utilized in Correlation Analysis (corr_station_invent.txt)

Appendix

Memorandum of 2004 April 6
Climate Monitoring Comments
Central Alaska Network Inventory and Monitoring Program

From: **Kelly Redmond**, Regional Climatologist, Western Regional Climate Center, Desert Research Institute, Reno NV
Dave Simeral, Field Meteorologist, Western Regional Climate Center, Desert Research Institute, Reno NV
Date: April 6, 2004

Overall Process

We felt that the process followed by the CAKN group was well matched to the circumstances within which they operate. In light of the logistical and maintenance difficulties, the sparsity of existing observations, the extreme demands imposed by the climate itself, the importance of the information to a host of users, and the demands on time and resources, the approach taken was logical and well thought out, and we'd recommend it continue to be followed.

The report "Climate Monitoring Site Evaluation 2004" was well written, easy to follow, logical in its sequencing, and covered the necessary bases. This documentation was also very helpful in making further assessments of the various potential sites, and we especially would encourage this precedent be followed elsewhere in Alaska.

Station Design

It is quite obvious that climate conditions in Alaska are extreme, and frequently tax the survivability of both living organisms and of instruments set out to record those conditions. Equipment must be designed to not just survive but also to record the worst conditions it is expected to encounter. The most frequent cause of weather data failure is the weather we wish to record, and it is often the extremes that are of the greatest interest to save for posterity. Therefore, as much care as possible should be taken that the instruments can function during whatever conditions the climate system will produce.

Further, to record climate, the observational circumstances need to remain fixed: local artificial (hopefully none) and natural influences on the measured climate elements, methodological procedures, instrument characteristics, and in fact most aspects of the site, to ensure that the resulting record faithfully tracks environmental variations through time.

It is also well worth remembering that the best quality control consists of not producing bad data to begin with. A corollary to this is that acquisition and deployment costs are a small fraction of the lifetime costs that include maintenance, quality control and data handling. All automated systems require human oversight and continued attention.

With sufficient attention to maintenance, the suite of instrumentation acquired for the proposed climate monitoring network is adequate to meet the objectives of conducting long-term monitoring in the extreme climates characteristic of Alaska. Given the high price of travel and maintenance and of missed data, equipment with known track records and proven reliability in hostile environments should be given priority. Reliance on vendors who subject instrumentation to extreme conditions prior to shipping gives added confidence that the instruments will function properly in the field. The selected data loggers and measurement systems did meet these criteria.

It is also worth noting that the accurate determination of precipitation occurring in frozen form still remains the most difficult and important measurement problem, even after decades of effort. Heated systems require considerable electrical power, more than can be generated by renewable local resources. All precipitation gages under-catch, especially in snow, and this problem is greatly compounded in windy locations. The Snotel precipitation gages used by the Natural Resources Conservation Service, though slightly less resolution, are a good compromise, and have about 15,000 station-years of experience to make such an assessment. In some cases, dual systems may be worth considering: the more coarse (0.10 inch) but accurate Snotel fluid-based systems in winter, and the higher resolution (0.01") rain gages for liquid precipitation in the summer.

The best sites for one element many not be the best sites for others. Temperature is best measured away from local influences, such as nearby trees and vertical rock walls, but wind shielding of trees and shrubs, at appropriate distances (close enough to slow the wind, far enough to not act as snow fences), is friendly to better precipitation measurements. Wind is the biggest enemy to accurate precipitation measurements, and especially as snow, when undercatch can easily exceed 50 percent. Open sites are good for temperature and wind; closed sites are better for precipitation.

Recommendations

The severity of conditions that must be endured can vary greatly in short distances, and thus need to be evaluated individually for each site. Especially in regions of high topographic relief, but even in seemingly simpler situations, it is often better to think of stations as providing "index" values, rather than values of the "true" climate, which vary continuously and on fine scales, even to a few meters. The question of what a "representative" site actually represents seldom has a simple and straightforward answer. Since these sites are multi-purpose, with many applications not yet known, they should strive to constitute good compromises between competing influences. In deciding on the sensor complement, it is worthwhile to remember that salary and transportation costs can greatly exceed incremental equipment costs.

Some specific recommendations and considerations, not exhaustive, include the following:
- a spare deep cycle battery at each remote station;
- suitable anchoring systems for the meteorological tower or tripod;
- fencing around stations when appropriate and practical;
- utilization of specially constructed anemometers for mountain sites that have high wind speed and icing potential;
- heated precipitation gauges when practical;
- heated anemometers when icing is frequent;
- deployment of taller towers at locations with high snowfall potential;
- camouflaging towers and instrumentation (except temperature: always white) to minimize visual impact and vandalism potential (humans and animals);
- addition of sonic snow depth sensors at selected sites;
- sufficient data storage to hold at least one year, 4 megabyte modules on dataloggers.
- self diagnostic capabilities, such as battery ranges, solar panel charging rates, internal temperatures, and the like, are cheap and easy and very useful

Site Selection

According to the ***Climate Monitoring Site Evaluation 2004***, the main criteria in locating sites was 1) to get the best possible spatial coverage in the park, 2) to sample different ecoregions within each park, and 3) to get a good elevational gradient between sites. Furthermore, the issue of accessibility and routine maintenance was addressed.

Climate measurements must meet a higher standard than "weather" measurements. The most demanding of these is consistency through long periods of time. A time frame of 50-100 years should be envisioned, and a few decades at minimum. The process of choosing appropriate sites for long-term climate monitoring should take into account a variety of considerations: representativeness, accessibility, security, budgetary demands (personnel & maintenance), communications, stability of exposure characteristics, local hazards (flooding, avalanches, riming, etc). In some cases, successional processes may be at work, and the site supervisor is confronted with choices: an open site may become a closed site as a forest regrows, or as the climate changes and new vegetative forms replace old, or as a burn or disease opens up closed vegetation.

A system that seems to make sense is one of benchmark, reference stations, in locations relatively immune to local change, coupled with satellite stations, located in these more changeable environments, where those local departures from regional conditions are the main item of interest. These local departures may also be very long term: a cold pocket (frost hollow) a few tens of meters in diameter can remain so for centuries.

Especially in cold climates, and especially with snow on the ground, localized spatial temperature variations can be extreme. A movement of just a few meters can change the measured climate. Temperature inversions are a common occurrence (the rule, in most cases), particularly when the wind is blocked or disrupted, and especially when dark.

No site will be without local influences of some sort: on wind, on precipitation, on temperature, on humidity, on solar radiation, or on any other climate element. The best and only recourse is to thoroughly document the site, and to re-document periodically as the site changes with time. It is impossible to over-document. The rule of thumb is to preserve whatever information will be needed to properly interpret the each of the separate element records a generation or two hence, when today's site supervisor is no longer accessible or even in existence.

Comments on the specific sites

As a general comment, the series of specific sites were nicely described. And given that only two pictures are generally shown, those pictures conveyed quite a bit of useful information.

Wrangell St-Elias Park and Preserve

Clustering and transects

The idea of small clusters, which are themselves grouped in transects or other geometrical arrangements, such as that proposed for Wrangell-St Elias, seems like a very good one. It implicitly incorporates the notion that climate varies on a variety of spatial scales simultaneously, and that there are always local departures, sometimes very great, from the general regional climate properties. Furthermore, particular regions (boxes) highlighted seemed well chosen.

Another comment: with wind blasting, some sites might be considered for everything BUT precipitation. In other words, precipitation is sacrificed for the sake of other elements. Also, the kind of precip shields that might be needed at many of these sites would be more like the DFIR (double fenced intercomparison reference), which in effect have a 26 foot diameter (octagonal) vertical slat wooden fence, a 13 foot diameter similar fence, and regular Alter shield (vanes) surrounding the gage itself. Otherwise, there will be severe undercatch. These are work to put up, can be painted, and might represent weight for the helicopter (might weigh several hundred pounds).

McCarthy Area

Gates Peninsula. Good comments.
Kennicott Glacier. Good comments. The third picture here is the same as the third Gate Glacier picture.
Jumbo Trail. Good comments. One says in a semi-protected bowl, another says on a slight slope. Are these compatible statements? For the Climate Reference Network, we've given a small preference to slightly sloped terrain

above drainage bottoms. The air is likely not to pond up during quiet or nighttime conditions. Slight slopes favor small movement all night via gravity drainage, so that effectively the sampled area increases.

Fireweed Mountain. Good comments. The note about glacier winds here and elsewhere is good. To the extent that glaciers partly *define* Wrangell St Elias, measurements that are biased by their presence are actually representative. If they recede, from climate change, the site climate might change for both large scale (regional climate change) and small scale (glacier packed up and left) reasons. These are both legitimate changes. One strategy is allow one site to be subject to both large scale and local influences, and another to be more insulated from local (glacier) influences.

Nikolai Mine. Good comments.

Nikolai Pass. Good comments.

Sourdough Ridge. Good comments.

Chititu. Good comments. Seemed like a pretty good site.

Summary of McCarthy area

We liked a Jumbo – Chititu combination. Not far behind, a Fireweed-Sourdough combination. Nicolai Pass is not that bad either. Chititu offers a nice south aspect for the big Aleutian storm winds. For glacial influence, Gates is probably a little better, but we thought that representing the whole area probably comes ahead of representing the glaciers. But among all the areas, it might be good to represent at least one glacier, hence we suggested a glacier site in the Tana River area.

Tana River Area

Iceberg Lake. Good comments. Rocky ground would mean warmer when sunny.

Iceberg Bench. Good comments.

Tana Glacier Seismic. Good comments. Possibly just forgo precip.

Ross Green Bench. Good comments. Nice site. With one-meter brush, this is halfway up to the thermometer. If cut back, would have to maintain this way indefinitely, probably cut 1-2 times a year.

Twelvemile Creek. Good comments.

West Fork Tana Knob. Good comments. Mtns in one direction, but seems open enough in all other directions. “At treeline”: a nice sensitive elevation. If climate changes treeline would also probably change. Good to be right at that special elevation.

Tana River Airstrip. Good comments. Take heed of the flood comments. We’ve paid close attention to this at all CRN sites, where major river rechannelization could change valley microclimates. A warmer climate could also change the flood regime.

Summary of Tana River area

We liked Tana River Airstrip paired with Tana Glacier Seismic (low versus high, protected versus open; vegetated versus glacial). Also, seismic locale gives more than one reason to visit. Another pair we liked was West Fork Tana Knob paired with Ross Green Bench. Twelvemile Creek also looked good as a Ross Green substitute. Iceberg Lake and Bench we were a little less enthused about, being kind of rocky, not too sure of their precip characteristics.

Chisana area

Euchre Mountain. Good comments. Hobos: ok for local studies, but wouldn't consider them for one moment for a long term climate record.
Chicken Airstrip. Good comments.
Gold Hill. Good comments. Nice location. A bit high, but as pointed out, could pair well.
California Creek. Good comments. What a great spot.
Beaver Lake. Good comments. Also nice exposure.
Chisana area summary

The Chicken Airstrip seemed like a decent site, and it's an airstrip, nearly certain to get visitors and attention, mostly of the good kind. This could be paired with California
Creek (slight preference for this) or with Gold Hill.
Nothing that wrong with Beaver Creek, however, either.
Euchre Mountain, of all these sites, seemed a little high, and maybe just a bit too much exposure.

Upper Chitna Glacier

Chitina Glacier Seismic. Good comments. Nice site. Maybe consider no precip gage.
Notch Airstrip. Good comments. Flooding potential there, but was downplayed.
Huberts Cabin. Good comments. A lot of trees of varied size close by. As long as they were cleared, ok.
Bernard Glacier. Good comments. Bison??? They like to scratch themselves. Might put up a sturdy rail fence.

Upper Chitna Glacier area summary

For a lower site, slight preference for Barnard Glacier location, then not far behind, Notch Airstrip.

For a higher site, Chitna Seismic seemed like a good choice. Of all the upper Chitna sites, this had slightly better vibrations. Plus, seismic sites have more than one reason to be visited and to receive attention, and most geologists can probably be trusted to identify obvious weather station problems if they glance that direction.

Tebay area.

Tebay Falls Creek. Good comments. Lovely spot.
Tebay Cabin. Good comments. Nice spot for precip, a little less so for temp.

Tebay area summary

Some preference for Tebay Falls Creek site.

Cheshnina area

Cheshnina. Good comments. Agree about precip.
Long Glacier. Good comments. Same issues as other near-glacier settings. Nice exposure for everything but precip.

Cheshnina area summary

We both agreed on the Long Glacier site as being just a little more preferable.
Box Score:

Among the three alternate boxes, we favored the upper Chitna area. Reason was this box is farthest from existing or planned data sources, the most data sparse area, appeared to be nothing in Kluane. There are existing data sources within 10-20 miles of the Cooper River. As for the other two boxes, we decided that the Cheshnina area was more unlike the other five boxes (likely closest to Chisana) and was more of a "dry interior" type than the other sites. The Tebay box would be a good spot for a precip measurement, and the Coast range is not that well sampled and could always use more, but the Tana sites are also somewhat coastal. So we decided Chitna, Cheshnina, Tebay. The French judge gave the high score to the Canadian ice itself, and the Ukrainian judge liked the blueberries.

Yukon Charley Rivers National Preserve

Three Fingers. Good comments. Aufeis? Hunters (1 per hundred) like to practice on weather stations.
Crescent Creek. Good comments.
Gelvins Airstrip. Good comments. This site is down in the bottom, would have some locally variable effects, heavily treed, with openings, could burn. Suggest leave this site, let somebody else put up a cheap weather station for the floaters, and place more consideration on the other two sites.
Beverly Bench. Good comments. Like the exposure. Not much comment on how magic 144 degrees is. Not sure what is meant by a "good hobo datalogger site". For reference stations, I'd use high quality stuff exclusively. Hobos are ok as temporary supplements.
Coal Creek. Good comments. Kelly was not too enthused. Not a natural site. Cold pocket. Flooding could be an issue, historic district issues might

necessitate relocation at a future date, need to keep well away from all artificial influences, probably best kept off cobble. This area could become popular at some point, though not quite Gatlinburg. Dave and Greg, on the other hand, liked the big open area, thought that the frequent visitation would help keep the station maintained, suggested a site off to the side of the open area, and thought this would be a good choice. The site could make a good contrast to the nearby RAWS site that is 1000 ft higher, during inversions.

Yukon Charley area summary

We seemed to like Beverly Bench a little more than the others. Nice spot, as well as not much other data around. Then, Three Fingers and/or close choice Crescent Creek. Then Coal Creek Airstrip. We all thought the Gelvins airstrip was not as good as the others, with local influences more of a possibility, flooding, wondering why those open patches were open, more susceptible to burning.

Denali Park and Preserve

West Fork Yentna. Good comments. No other stations in this area. Yes, it'd be more expensive. Needs a blueberry-cam.
Tokositna Valley. Good comments. High enough above floods. Year round snotel precip makes this attractive.
Eielson Visitor Center. Good comments. "Design includes climate monitoring station": does that mean a separate station from this one? If so, might put it elsewhere. The visitor center here deserves a really good high quality station. Lots of interest in this site. Keep well away from any possible expansion over the next 50 years, new parking lots, buildings, etc. For this one, I'd consider redundancy, especially in precip measurements. Really do not want <u>any</u> gaps in a visitor station record.
Kantishna. Good comments. Snow course upgrade to year round Snotel is attractive. Except for precip, any redundancy with the RAWS site at Wonder Lake? Most RAWS sites in cold climates are worthless for precipitation, except in summer when consistently above freezing. Redundancy can be good: quality control, backup data, etc. Good mixed exposure. Would not want to accidentally promote the relocation of Wonder Lake RAWS either (because "too close").

<u>Denali area summary</u>

No clear preferences, and we thought the Denali people probably already had ideas about what locations were important and what they might like to get from them, and figured they'd like to see them all funded. Just from a dot-on-a-map sense, the West Fork Yentna area seemed in greatest need of a data point.

Practical issue

No station installer has yet died from mosquitoes at a wind-blasted location.