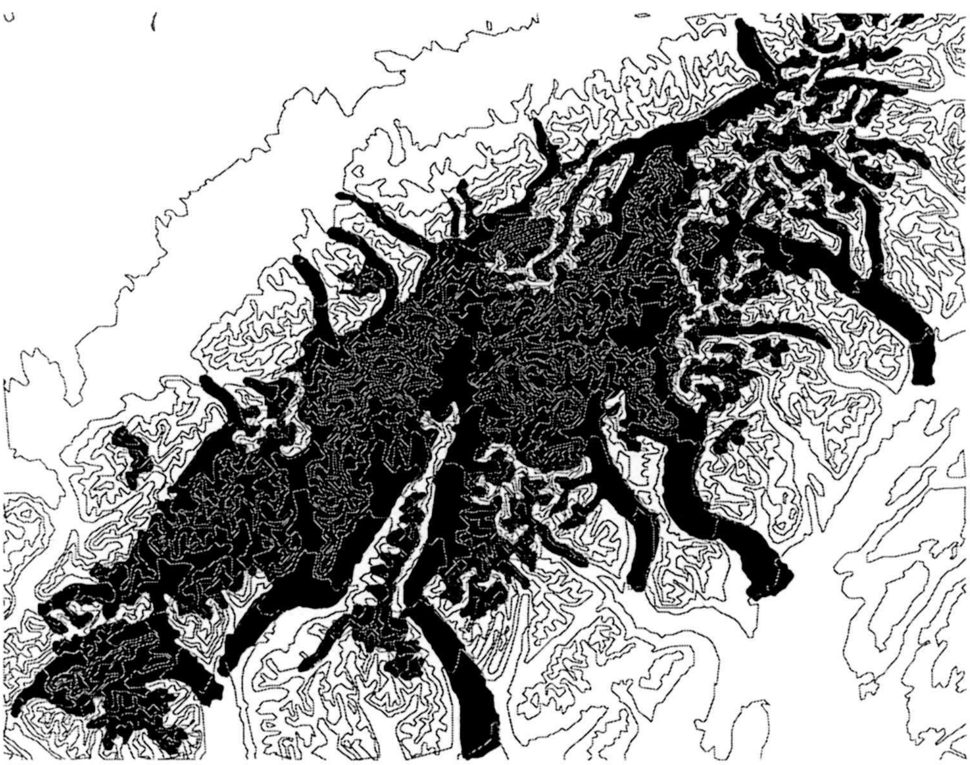
GLACIER MONITORING PROTOCOL HANDBOOK



DENALI NATIONAL PARK AND PRESERVE

NATIONAL PARK SERVICE
DEPARTMENT OF THE INTERIOR

GLACIER MONITORING PROTOCOL HANDBOOK

DENALI NATIONAL PARK AND PRESERVE ALASKA

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CONTENTS

INTRODUCTION

The objective of glacier monitoring in Denali National Park and Preserve is the characterization of glacier fluctuations in the past, present, and future. That knowledge will be compared to known climatic conditions both in order to gauge current climatic trends and also to understand how glaciers will respond to predicted climate changes.

Glaciers can be viewed as simple machines which are constantly adjusting to variable inputs and outputs, or changing climatic conditions. A steady-state glacier, or one that does not fluctuate due to a perfect balance of mass input and output, is a theoretical concept. No such glacier exists. Because climate changes from year to year, and century to century, glaciers are also always changing. Glacier response to changing climate can be viewed as a measure of that change.

Glacier fluctuations in Denali are being determined for the past, monitored in the present, and compared with records of climate to assess how glaciers respond to climate change. The nature and extent of glaciation in Denali during the Pleistocene epoch (the last 100,000 years) has been recorded in the surficial deposits and landforms left behind by the retreat of past glaciations and are there to be studied and related to our knowledge of past climates. The glaciers which exist today are being monitored to determine their real-time response to changing climatic variables, occurring first in glacier mass balance and in turn driving changes in glacier size and behavior. Knowledge and understanding of past and present glacial responses to climate will allow us to use glaciers as a meter of changing conditions, and perhaps enable a prediction of how glaciers will respond to predicted global climate variations.

Denali National Park and Preserve is a unique laboratory for this research because it is extensively glaciated. Fully 17% of Denali's six million acres are covered with glacier ice. These glaciers exist in at least two distinct climatic regimes. To the south, the maritime influences of the Gulf Alaska reach to Denali's south slope and undoubtedly bring in larger amounts of precipitation than in the north. On the north side of the Alaska range there exists a much dryer continental climate. Not only do we have the opportunity to study how glaciers are responding to climate in general, but we can also study how different climatic regimes are responding to the same global climatic variations. For these reasons it is necessary study, and attempt to understand, glaciation in Denali National Park and Preserve on a regional or park-wide scale. Such an understanding could then be related to known climatic variables and it may be possible to predict how glaciers will react to predicted global climate changes.

MONITORING DESIGN AND CONSIDERATIONS

The objective of glacier research in Denali is an understanding of glacier fluctuations at all times; past, present, and future. The prediction of future glacial extent, however, will be based on the results of our study of past and present glaciations. Therefore, the monitoring design for Denali's glacier research program focuses on present, or "active" glaciation, and on glacial histories as seen in the geologic record.

The monitoring design for active glacier research in Denali is intended to address the problem of characterizing current regional glacier conditions in three stages. The project begins with a "wide angle" view of glaciation in Denali by employing satellite remote sensing and other reconnaissance methods to obtain an initial understanding of glacier conditions on a regional scale. That baseline information is used to identify specific glaciers which are representative of other glaciers in their area or climatic regime, and which are practical for field study with conventional techniques in stage two. A "narrow focus" view is, therefore, taken in stage two which produces a detailed knowledge of conditions for a few specific index glaciers.

The results of field study in stage two then serve as groundtruth data for a more detailed analysis of the remote sensing imagery in stage three. The remote sensing data is calibrated with the groundtruth data by re-examining the imagery in relation to our knowledge of conditions at the index glaciers. This enables a return to the "wide angle" view, with the added capability of assessing glacier conditions park-wide by comparison to the index glaciers. In this way it is possible to obtain a regional understanding of glacier conditions and fluctuations while engaging in a minimum of costly and often impractical field research.

The reconnaissance techniques to be employed are satellite synthetic aperture radar (SAR) image analysis, and annual aerial observation of snow line character and positions at the end of summer. These methods will give us a good first look at glacier conditions on a regional basis and the results will be used to select index glacier candidates.
Conventional glacier survey techniques will be used to study the mass balance and flow characteristics of the index glaciers after they have been selected. This will be a traditional field exercise involving mass balance stake networks, longitudinal profiling, weather monitoring for average conditions and annual precipitation, and stream gauging of meltwater discharge. The methods to be employed are standard and well documented.

The detailed satellite image analysis to be carried out in stage three will employ a range of image processing and analysis techniques. Glaciers will be classified based on the appearance of the index glaciers in the SAR imagery. Once a regional characterization of conditions is accomplished, the continued acquisition and analysis of satellite imagery will constitute the major portion of a long term monitoring effort.

The study of glacial histories in Denali will depend primarily upon a field mapping effort. It will be necessary to spend significant amounts of time conducting field study of glacial landforms and deposits in order to assemble a history of glacial events. A large time frame should be allowed for this work given the size of Denali National Park and Preserve and the extent of past glaciations. It would not be unreasonable to expect that such a project would require 10 to 15 years for completion.

ACTIVE GLACIER MONITORING

Remote Sensing

Remote sensing refers to research methods which utilize satellite imagery, aerial photography, or other forms of data acquired at some distance from the glacier by sensors which receive varying wavelengths of natural or reflected radiation. For Denali this will mainly involve the use of satellite synthetic aperture radar (SAR) imagery both in the initial stages to perform reconnaissance, and in the final stages to make regional assessments of glacier conditions for long term monitoring.

Satellite remote sensing and image analysis are becoming increasingly important in glacier research. The most common type of data used is satellite SAR imagery. SAR is an active microwave imaging sensor that is particularly useful for the study of temperate latitude glaciers, like those in Denali, because it emits its own microwave signal and collects the return signal scattered from the earth's surface. In this way, SAR overcomes the problems of cloud cover and darkness which frequently obscure the mountain regions of Alaska and limit the use of passive sensors such as LANDSAT or aerial photography. With SAR it is possible to collect a continuous high resolution sequence of images which can be used to study glaciers in several ways.

Satellite SAR imagery can be used both to assess the current state of glaciers, and to monitor short or long term changes. Glacier surface areas, equilibrium line positions (from snow lines), and terminus positions can be determined from geometrically corrected and controlled SAR imagery. These data can then be used to monitor glacier fluctuations and long term changes.

Because of the frequency of coverage (typically every 30 days or less), SAR imagery can also be used to monitor and study short term glacier flow events such as surges. This is particularly important because continuous acquisition of SAR data would allow study of a surge even if the event was not recognized until after its conclusion. In this way, surges would not be "missed" due to the difficulty of field monitoring all of the surge-type glaciers in Denali. SAR imagery may also be used to roughly determine the timing of jökuhlaups (glacial outburst floods) which also might not be directly observed when they occur.

A further application of SAR data is the relatively new and promising technique of interferometric analysis. SAR interferometry is similar in principle to stereo-photo analysis and conventional aerial photo mapping. It involves the comparison of two images of the same area on the earth's surface, acquired from two distinctly different orbital positions between which the separation is precisely known. Depending on the distance between the positions of the satellite (the baseline), this method can produce either a topographic representation of the target area, or a representation of earth surface changes (e.g. glacier flow) in the time interval between the images. This method is gaining increasing acceptance as an important tool in glacier study. There is a solid foundation for its use, and a growing community of researchers proficient in its application. Regular observations of glacier surface topography would allow detailed mass balance determinations. Observations of flow would enable monitoring of glacier response to mass balance changes, or study of surge-type events. Interferometric processing is, at present, a highly technical field and cooperative arrangements for this work will be sought with qualified individuals or institutions.

A program of regular glacier observations using satellite SAR imagery will be established by Denali NP&P. An account will be setup with the Alaska SAR Facility (ASF) of the University of Alaska Fairbanks Geophysical Institute. ASF is a NASA funded ground station for the receiving and processing of SAR data from several satellites which collect imagery within an approximate 2000 km radius of Fairbanks. Once an account for data acquisition has been established, image processing facilities and skilled personnel will be available to assist Denali in the processing and analysis of SAR imagery. The cost of data acquisition and processing is low in comparison to all of the other methods outlined in this protocol. The most significant need will be to identify a source of funding to pay for the imagery, a cost which will likely range from $2000-$5000. It may also be necessary to establish an account with the Arctic Region Supercomputing Center in order to perform some image processing on their Cray supercomputers. There may be a cost associated with this which is unknown at this time, but would likely be similar to the cost of acquiring the SAR data. After initial processing and geometric correction, or interferometric processing, it should be possible to carry out image analysis with the UNIX workstation on which Denali currently runs its GIS software.

Regional Equilibrium Line Mapping

The equilibrium line on glaciers in temperate regions coincides roughly with the position of the snow line at the end of the summer (Paterson, 1994). Knowing the location of the equilibrium line allows the calculation of an *accumulation area ratio* (AAR; the area of accumulation at the end of summer, divided by the area of the entire glacier) (Paterson, 1994). In general, an AAR of 0.7 indicates a net balance of zero (Glen, 1963).

It is also useful to know the elevation of the equilibrium line for comparison to other glaciers in the same region. Regional trends in the equilibrium line altitude (ELA) may indicate mass balance trends which correlate with climatic factors.

Mapping of snow lines at the end of the summer (typically the last week of August) will be carried out on glaciers in Denali NP&P. This technique is considered a reconnaissance method in glacier mass balance study and it can be carried out in a number of ways. The most practical and useful methods for Denali NP&P are aerial reconnaissance, and satellite image analysis.

Reconnaissance flights should be made over as many glaciers as possible during the last week of August. During these flights the observed position of the snow line should be hand drawn on to 1:63,360 USGS topographic maps. The snow lines should also be photographed, and the character of the snow line recorded in a notebook used to document the flight. Photographs should be numbered and referenced in the notes so that images can be properly interpreted later. There are varying snow line morphologies which are indicative of positive or negative mass balance and the photographs will be used to classify the character of the observed snow lines according to Paterson (1994).

The first year's observations will allow a rough estimation of the mass balance states of the selected glaciers. Multiple years of observations will be compared in order to determine any trend in ELA and mass balance, which might then be correlated with contemporaneous climate records.

Similar observations of late-summer snow line positions should be made in terrain corrected SAR imagery. This will allow for an assessment of the accuracy of the aerial reconnaissance (and vice versa), and will enable a wider range of coverage than may otherwise be possible. See *Section 8* for details.

References:

Paterson, W.S.B., 1994, *The Physics of Glaciers*, 3rd ed., Elsevier, New York.

Glen, J.W., 1963, *Int. Assoc. Sci. Hydrol. Bull.*, **8**, 2, 68. (Contribution to discussion). [36]

Index Glacier Surveys

Index glacier surveys will encompass all field study carried out on glaciers in Denali. The term "index" is loosely applied and is used in reference to the remote sensing image analysis that is also an ongoing part of the glacier monitoring program. It does not imply that field study is merely a support function for remote sensing analysis, but does mean that any field work which is practical and can be accomplished will provide a site specific knowledge of glacier conditions. Because the overall goal of glacier monitoring is a regional understanding, field measurements should be viewed as reference points for a regional characterization.

Mass Balance - For glacier monitoring, the most important field data that can be collected pertain to glacier budget or mass balance. Mass balance is simply a way of describing how ice mass, in terms of an equivalent volume of water, is transferred through a glacier and how rates of accumulation balance rates of loss. In the simplest terms mass balance is a measure of whether a glacier is growing or shrinking, gaining or loosing mass. In a given year, usually defined as a balance year, a glacier will gain a certain amount of mass from precipitation and other sources, which is referred to as annual accumulation. Conversely, a glacier will also lose a certain amount of mass due mainly to melting, and this is referred to as annual ablation. Mass balance is nothing more than the arithmetic sum of these two parameters. If a glacier gains more mass than it loses in a year then it is said to have a positive net mass balance and vice versa for a negative net mass balance. The preferred way to express net mass balance is in terms of m^3 of water equivalent gained or lost.

Mass balance is of primary interest because it is directly controlled by climate. Climatic conditions control annual average temperature and precipitation, which determine the amount of ablation and accumulation. The simplest case would be that of warmer climate in which glaciers retreat as a result of increased melting and ablation. Consider, however, that a warmer climate might also lead to increased precipitation and therefore greater accumulation, giving a glacier a positive balance and causing it to grow despite the increased melting. Although the link between climate trends and changes in glacier mass balance is not always what one might expect, it is direct. The case of a glacier which grows in a warmer but wetter climate simply shows that the relationships can be complicated, and illustrates the need for monitoring of many different parameters in order to understand the causes and effects.

Denali National Park and Preserve presents a unique opportunity for study of the relationship between glacier mass balance and climate because it is heavily glaciated in distinctly different climatic regimes. At the very least there exists a sharp boundary between a maritime climate on the south side of the Alaska Range, and a dryer continental climate to the north. It is reasonable to assume that glaciers on either side of this significant weather barrier will receive differing amounts of precipitation and are influenced by different ranges of temperature. Further study may reveal the existence of localized climate regimes within the northerly and southerly zones, especially in proximity to Mt. McKinley which is known to have a strong effect on local weather.

Determination of glacier mass balance conditions and trends throughout Denali will allow us to examine the relationship between glaciers and climate. Once more knowledge of that relationship is established it may be possible to monitor glacier fluctuations as indications of climate variation. While the research efforts in remote sensing and equilibrium mapping will form the basis of regional mass balance assessments, detailed field study at a few specific sites will be critical for calibration of regional observations. For mass balance measurement this work will consist of standard glaciological field study techniques.

These standard techniques fall in two general categories: 1) measurement of accumulation and ablation referenced to a network of mass balance stakes, and 2) hydrological methods concerned with annual precipitation and runoff. Together these techniques will yield detailed knowledge of mass balance at index glaciers which are selected because they are readily observable with remotely sensed imagery, and because they are representative of glaciers in their area and climatic regime.

Glacier Morphology - Glacier morphology concerns the geometry of a glacier and its spatial position within its basin. Glacier morphology ***is*** in a state of constant change as a general function of the glacier mass balance. Glacier morphological responses are linked to changes in mass balance by ice movement and can range from thickening or thinning of portions of the ice body, and advance or retreat of the terminus. Glacier morphology can also be radically, and rapidly, altered by anomalous ice movements such as surges. We need to monitor glacier morphology because it is an indicator mass balance change, and thereby provides valuable checks on other observations, and because it is directly effected by poorly understood phenomena such as glacier surging.

Denali National Park and Preserve provides ample opportunity for monitoring glacier morphology. Not only is the park bisected into two climatic regimes by the Alaska Range, which create differing morphologies through mass balance, but there are also numerous surging as well as steady flow glaciers, affording the opportunity to compare types of motion. This provides a good comparative field laboratory for correlating general glacier morphology and movement with regional climate conditions. Monitoring changes in glacier morphology on a few key glaciers (surging or non-surging) can greatly refine the knowledge of south central and north central regional glacier/climate conditions in Alaska.

Terminus position changes have long been monitored in Europe and elsewhere to record degrees of glacial advance or recession over time. More recently, these records have served as indicators of local, regional and/or global climate change, and the addition of long-term records of such change in central Alaska would be a significant contribution to this growing body of knowledge on world glacier conditions.

Monitoring general glacier morphology is often accomplished by photo-documentation that is periodically repeated from known, or monumented, photo point locations. Precision monitoring of glacial morphology is accomplished by periodic topographical surveys of glacier surface elevations and terminus positions. Additionally, glacial landforms (erosional or depositional features, including lateral or recessional moraines, kettles, trim lines, etc.) can be topographicaly surveyed for information regarding historical glacier behavior, which can lead to more refined predictions on future glacier behavior. These surveys may be accomplished by conventional survey methods, by GPS, or by airborne methods such as radar.

GLACIER MORPHOLOGY - GLACIER SITE SELECTION - Area selection criteria for collecting glacier morphology data include the following:

❍ Glaciers where other data collections exist, are planned, or are ongoing.

❍ Glaciers where operation logistics are reasonable and feasible, and where personal safety is not compromised in the collection of data.

❍ Glaciers which are currently surging or which demonstrate surge history or surge potential.

❍ Glaciers of significant public interest or of particular interpretive value.

Figure 1 shows the current selected glaciers for intensive study. ************ more *******......

GLACIAL HISTORIES

A understanding of how glaciers are fluctuating in response to current climate trends will give us only a partial understanding of how glaciers may behave in the future. It is also necessary to know how glaciers have responded to past climate variations. That information is recorded in the glacial landscapes and surficial geology of Denali.

A large scale mapping effort is required to establish a glacial history for Denali. Previous mapping efforts have developed a glacial history for the northeast portion of the park, however, little information exists elsewhere. If a comprehensive glacial history can be developed for the park, comparisons to known past climate variations may shed some light on how glaciers will behave in the future. At the very least it is desirable to understand the current nature and extent of glaciation in the context of past conditions. We would like to determine such things as whether current glaciation is significantly different from the past and where we may be in the long term cycle of glacial advance and retreat.

PROGRAM COMPATIBILITY

An important consideration in the design of any glacier monitoring program is that of compatibility with other glacier study efforts in the region and the world. An increasing interest in global processes of climate change has created a need to standardize the types of glacier data collection so that results from widely separated regions may be compared.

Denali's glacier monitoring program is similar in design and methodology with the U.S. Geological Survey's monitoring strategy for glaciers in North America. Mass balance data collection methods have also been approved by the World Glacier Monitoring Service (WGMS) in Zurich, Switzerland. WGMS is central repository for glacier monitoring information operated by the International Commission on Snow and Ice (ICSI), part of the International Association of Hydrological Sciences (IAHS). Glacier monitoring data collected in Denali will be submitted to the WGMS, as well as published in appropriate professional journals. Only in this way will it be possible to make linkages to glacier/climate trends being studied in Alaska and the world. Such linkages are important for understanding global climate trends and their relation to changes in Denali.

MONITORING PROTOCOL

ACTIVE GLACIER MONITORING

Remote Sensing

The first step in building a program of remote sensing research for glacier monitoring is the establishment of an account for data acquisition with the Alaska SAR Facility (ASF) at the Geophysical Institute of the University of Alaska Fairbanks. A brief project proposal, or outline, is required, as is a source of funding to cover the cost of image processing and the production of digital images, which are typically shipped to the user on 8 mm magnetic tapes. Once an account is established and data are acquired (in the form of digital SAR images), image processing facilities at ASF will become available for the park's use.

Techniques in digital image processing and remote sensing image analysis are constantly changing. An important consideration should be the recognition that technologies and methodologies <u>will</u> change during the course of this research project. It will be necessary to remain current with the latest innovations in remote sensing and to try to adapt to and take advantage of the changes.

There are, however, some basic techniques, which should remain constant for some time, which will be implemented in this project. At the moment, SAR imagery is widely recognized to be the most useful form of digital remote sensing data for the study of glaciers. Therefore, SAR is the technology that will be utilized first for glacier study in Denali.

As outlined in Section I., remote sensing will be used both for the initial reconnaissance of glaciers in Denali and for the later, more detailed, long term monitoring. For both stages, a number of image processing steps will be necessary. The theory and mechanics which underlie these steps are complex. For specific information users of this protocol are referred to the following: 1) Roush, James J., 1996. *The 1993-'94 Surge of Bering Glacier, Alaska Observed With Satellite Synthetic Aperture Radar*, Masters thesis, University of Alaska Fairbanks, Fairbanks, Alaska, and 2) Curlander, J. and R. McDonough, 1992. *Synthetic Aperture Radar: Systems and Signal Processing.* John Wiley and Sons, New York.

In general, SAR image processing will involve the following steps: 1) *Radiometric Calibration*, a process which eliminates image brightness variations resulting from artificial effects such as signal attenuation and processor gain adjustments, 2) *Geocoding*, which reorients the imagery to conform to a user defined map projection and datum, 3) *Geometric Rectification*, which coregisters the imagery with a digital elevation model (DEM) in order to correct for pixel warping and location errors related to terrain height and target range. It may also be desirable to employ the technique of *SAR interferometry* to either generate elevation maps of glacier surfaces or to measure glacier motion. Processing techniques for interferometry involve the comparison of two nearly identical images separated either by time or distance. Should this method be used, information regarding specific image processing steps can be obtained from skilled individuals at the ASF.

Following image processing, image analysis will take place. Once the previously mentioned corrections have been applied to the raw SAR images, we will be able to map features which are visible in the imagery. This is possible because the corrected images contain three dimensional coordinates for every pixel (picture element) in the image. It is, therefore, possible to map the earth surface location of any feature of interest. This technique will be applied to the location of late summer snow lines on glaciers, mapping of glacier termini, calculation of total glacier surface areas, monitoring of glacier motion, and any other aspects of glacier dynamics which may be evident in the SAR. For the early reconnaissance stage of the project, these techniques will be used to make an initial assessment of glacier conditions and to identify ice bodies which may be suitable for field study as index glaciers. In the later stages of the project the same techniques will be applied to determine how the observations made at the index glaciers relate to glaciers on a regional scale in order characterize glacial activity park wide.

In general, both the image processing and image analysis techniques are carried out on UNIX workstation computers. Initial image processing as well as image analysis can be done on UNIX based systems at the ASF in Fairbanks. Further image analysis may also possible on the Sun Sparc 5

UNIX workstation which runs Denali's GIS applications. This may be done either with existing GIS software, or with the installation of other software packages.

Regional Equilibrium Line Mapping

Reconnaissance flights should be made over as many glaciers as possible each year during the last week of August. During these flights the observed position of the snow line should be hand drawn on to 1:63,360 USGS topographic maps. The snow lines should also be photographed, and the character of the snow line recorded in a notebook used to document the flight. Photographs should be numbered and referenced in the notes so that images can be properly interpreted later. Yearly collection of this information may also reveal trends in the location of the equilibrium line which may be indicative of mass balance changes. There are varying snow line morphologies which are indicative of positive or negative mass balance and the photographs will be used to classify the character of the observed snow lines, and thus the relative net mass balance.

According to Paterson, "...A low snow line with a sharply defined boundary with bare ice indicates that the net balance is probably positive. If the boundary is sharp but the snow line high, there has been increased accumulation after several years of negative net balance. A snow line separated from bare ice by areas of old firn indicates that the net balance is more negative than in the preceding few years (1994)."

If the total surface area of the glacier is known, and the area of accumulation (total glacier surface area above the snow line) can be determined, then a accumulation area ratio, or AAR, will be calculated. The AAR is equal to the accumulation area divided by the area of the whole glacier. Glen (1963), established the "rule of thumb" that an AAR of 0.7 roughly corresponds to a net balance of zero for many glaciers. In this way, a rough estimation of the net balance of a given glacier may be determined. Determination of AAR's for Denali glaciers should be determined wherever possible. Repeating this work on an annual basis should then reveal any trends in net mass balance.

References:

Paterson, W.S.B., 1994, *The Physics of Glaciers*, 3rd ed., Elsevier, New York.

Glen, J.W., 1963, *Int. Assoc. Sci. Hydrol. Bull.*, **8**, 2, 68. (Contribution to discussion). [36]

Index Glacier Monitoring

Mass Balance - In general there are three traditional methods for determination of glacier mass balance (Paterson, 1994). The first is a general category, called "reconnaissance," into which we place the remote sensing and snow line mapping efforts outlined under *Monitoring Design and Considerations*. The other two methods are field exercises which involve the direct measurement of accumulation and ablation over a network of mass balance stakes on the glacier (conventional surveys), and the measurement of annual precipitation and runoff in order to deduce mass balance in terms of accumulation from precipitation and ablation from melting (hydrological method). All three methods will give slightly different results and it is the combination of techniques which gives a reliable mass balance determination. The following is an explanation of how field study with conventional surveys and hydrological methods should be used in the study of index glaciers.

Direct Measurement - Once an index glacier has been selected, which is clearly visible in SAR imagery and is relatively easy to access and travel on, a network of mass balance stakes should be established across the glacier's surface. Measurements of accumulation and ablation will be referenced to these stakes. Ideally stakes should be distributed across the glacier surface ~~is~~ in a uniform pattern with an equally dense network at all locations. This may not always be possible so at a minimum a long line of stakes should be place up the glacier's center line and the further distribution should be as uniform as possible, preferably in lines intersecting the central line of stakes, but also allowing for eas~~y~~e of access.

Stakes should be of sturdy construction, preferably aluminum or steel in lengths of 4 to 6 m assembled from sections of 1 to 2 m. As stated, stakes should at least be placed along the glacier's center line, and further sites should located so as to give a uniform coverage of the surface. A logical numbering system should be used for the stakes. Stakes should be installed vertically to a depth of at least 1 m below the previous summer surface with the hot point steam drill recently purchased by Denali for the glacier monitoring program.

Total annual accumulation and ablation will be measured at each stake site. Accumulation will be measured at the end of the accumulation season in the spring by measuring snow depth, and snow density to determine a water equivalent volume. These measurements will be made either with snow depth probes (graduated rods) and snow corers, or by digging snow pits and weighing snow samples at incremental depths. The position of the mass balance stake will be surveyed with reference to fixed monuments adjacent to the index glacier.

Total annual ablation will be measured at the end of the ablation season in late summer. At this time the summer surface will be marked with colored dye so that it may identified during the following year's measurements, allowing a more accurate determination of annual accumulation. Ablation will be determined primarily by measuring the length of the stake which is visible above the surface. This is relatively simple in the ablation zone where the ice surface is bare. In the accumulation zone the length of visible stake <u>and</u> the snow depth and density must be measured.

The total annual accumulation and ablation measurements will allow a direct determination of glacier mass balance in term of an equivalent volume of water gained or lost from the glacier's surface.

Hydrological Monitoring - While direct measurements of mass balance on stake networks allow the calculation of mass change in terms of water volume, the actual amount of meltwater runoff and accumulation from precipitation can be measured. Essentially this involves gauging all of the runoff from a glacier basin, recording all of the precipitation, and taking any difference between the two as a measure of positive or negative mass balance. In reality, however, this is not quite so simple.

This method requires that most if not all of the meltwater runoff be channeled into one master stream which can be gauged, and this is an important criterion in the selection of an index glacier. Also, recording total annual precipitation is a complicated task due to the difficulty of accurately recording winter snow fall.

For a chosen index glacier a stage gauge should be installed on the master stream and discharge data should be logged continuously throughout the ablation season. This should be done with an automatic gauge connected to a datalogger and data storage module.

An automated weather station should be installed at location in the index glacier basin which is effected by weather that is representative of conditions throughout the basin. The most important parameters to be logged are precipitation and temperature. Precipitation is the key parameter for hydrological mass balance measurement, and temperature will ultimately be used for correlation with mass balance changes. Other parameters that would be of use for correlation with glacier fluctuations are solar radiation, relative humidity, and wind speed and direction although these have a less direct connection with ablation and are, therefore, considerably less important. During the ablation season a tipping bucket-type rain gauge should be used to measure liquid precipitation. Winter accumulation in the form of snow is difficult to measure with precipitation gauges and we should consider the use of an acoustic snow depth sounder, a snow pillow, or both.

Glacier Morphology

Glacier morphology data collection procedures can be broken down into five types; 1) Longitudinal Profiles, 2) Cross-Sections, 3) Feature Delineations, 4) Surface Flow Rates, and 5) Terminus Positions. All five types of data are acquired using the same basic topographic survey procedures. These procedures, along with systematic photo-documentation, are described below.

GPS Topographical Survey Method - GPS surveys of positions (x,y,& z coordinates) can be used for all types of glacial morphological data collections. Survey-grade GPS units in differential leveling applications, using only two units can provide **[*******************************see Echelmeyer precision/accuracy figures taking data every ***]**. Although higher orders of accuracy and precision can be obtained with more GPS units reading simultaneously at higher reading frequencies, the cost and general logistics are prohibitive, and generally only the two unit method has been employed intermittently at Denali.

The GPS method of position data collection may only be suitable for gross changes in ice surfaces or other feature locations, and not for intensive monitoring of glacier morphology. As technology and cost changes occur, GPS survey methods will most likely replace conventional survey methods. Only three longitudinal surveys using GPS methods have been performed on glaciers within Denali NP&P. As a reconnaissance tool, no repeat surveys or other replications of GPS surveys are intended. See **appendix IIIA-1** for a listing of study glaciers where GPS survey work has been accomplished.

In GPS surveys using two GPS units, one is left running at a base station (a monumented fixed point of known elevation, preferably 1st order) and the other used for obtaining the station elevations or feature positions. The equipment requirements and example field notes are displayed in **appendix IIIA-2** Time, temperature, and elevation (from station altimeter other than GPS) should be recorded in the field notes for each station. Initial and final readings should be taken back at the base station, to `close' the loop.

<u>Conventional Survey Method</u> - Topographical surveys of glaciers can also be accomplished using theodolites or electronic total stations with built-in distance measuring. For conventional survey methods, an instrument is set up at a fixed monument adjacent to the subject glacier, preferably with maximum site distance along the centerline or other area of interest of the subject glacier. At least one other monument should be in view for a backsight. Both monuments should be of high order geodetic or state plane control, or be tied to monuments of such quality (see **Appendix IIIA-3** for control monument listing).

Precision requirements......more........

Equipment and supply requirements for all conventional topographical survey field efforts are found listed in **Appendix IIIA-4**. Basic procedures after the instrument is set-up and backsight zeroed, is generally to make foresight shots to hand-held rangepole prisms on or near the glacier. **Appendix IIIA-5** shows typical conventional survey notes. Both polar and xyz coordinates are recorded. All five types of survey data are frequently collected in appropriate mixes at each set-up. The following guidelines are provided for each type of data collection:

1) Longitudinal Surveys: The longitudinal survey proceeds by making helicopter landings (or walking to random shot locations) at appropriate intervals (5km to 500 foot intervals) along the centerline of the glacier. Shots can begin from terminus to the ELA, or in a specific area of interest along the glacier. Typical field note recording is displayed in **Appendix IIIA-5. Figures 2 through 5** shows the typical shot configuration and results for longitudinal elevations of the Muldrow Glacier in several sections. Longitudinal surveys are performed annually, if possible, or however often as deemed necessary depending upon the surface elevation change expected on a given glacier. See **Appendix IIIA-6** for survey task schedule.

2) Cross-Sections: Topographic surveys across the ice body, perpendicular to flow, may also be employed to evaluate ice thickness or other morphologic changes. Shot intervals might be made tighter (50-500 feet) for these surveys. Fixed monuments off the glacier on each end of the cross-section might be useful for future re-survey, and for "giving line" to the prism holder. Field notes are similar to the **Appendix IIIA-5** example, with the addition of notations regarding end-point monument locations, and noting the direction of the survey perpendicular to the ice flow direction. It can be useful to perform the cross-section directly away from the instrument station (instrument set-up at one of the end-points) for insuring a precision line with maximum precision repeatability.

Like longitudinal surveys, cross-sections can be repeated annually or at whatever frequency depending upon the rate of ice elevation or position change that is expected on the study glacier. Cross-section surveys have not yet been accomplished on any glaciers in Denali NP&P to date.

3) Feature Delineations: The spatial location of glacial landforms may be important for both current or future glacial morphological conditions, and for glacial histories. Moraine positions and/or trimline relationships to existing ice levels may be documented by survey methods. Since most of these features are linear shaped resulting from ice flow erosion or deposition, they can be established as a series of linear shots which are labeled accordingly in the field notes. **Appendix IIIA-5** shows lateral moraine positions recorded in such field notes and **figure 2.** shows the graphic representation of those features.

4) Surface Flow Rates: These are survey shots made periodically to "targets" on the glacier to determine surface flow rates. A target is a metal or wooden structure, generally constructed to hold or receive the rangepole for the purposes of re-surveying the target location. **Figures 2,3 & 4** show the location of three flow rate targets and associated monuments on the Muldrow Glacier. Surface flow rate surveys can be done in any unit of time, (usually annually) however, more frequent shots (for instance, hourly) can and have been taken to better refine the daily or seasonal flow rate. Existing surface targets, and recommended survey frequencies are listed on **Appendix IIIA-6**

6) Terminus Positions: Surveys of glacier termini can include terminal ice limits, meltwater outflow positions, englacial features, firnl ine positions, longitudinal elevations, and other elevations and features that may help delineate terminus morphology conditions. It is often useful to establish instrument and backsight monuments on each side of the terminus area from which all the above features can then be shot. It is understood that these monuments may not have local geodetic control, and thus may "float" until such time that control can be brought in.

Field notation should look very similar to the example given in **Appendix A-4.** Shots of specific features should be labeled understandably with efforts to provide descriptive information in case the notes are transcribed by someone other than the field party. Frequency of re-survey of terminus position and features is again based on the rate of expected change on the given glacier, however, in most cases, terminus re-surveys are not expected to be necessary for at least three to five years following the last survey. **Appendix IIIA-6** shows the termini surveyed and the next recommended survey year. Figures ******** show mapped termini and associated features and monuments....

Photo Documentation - Whenever possible, systematic photo documentation should be made of any and all glacier visits in the air or on the ground. Glacier features of interest for photo documentation include any or all glacial and morphological features described in the above sections, with particular emphasis on documenting terminus positions, present ice levels (valley wall and/or central ice body) and indicators of past ice occupation (trim lines, moraines, and other lateral or englacial features. Photo stations should be well monumented and documented by field notes and photography.

35mm or bigger format photos of the glacier terminus should be taken centered over the two monuments. Put in the notes the size (focal length) of camera, the height of the camera from the rebar (HI, if you will), cardinal direction(s), elevation, date, time, type of film, no of shots, weather, field participants, and any other information that may enhance or clarify.

"Bracketing," or taking of several pictures of the terminus at different speeds or f stops is preferred. The pictures should show the limit of the ice as clearly as possible. The firn limit should also be photographed from the monument point if possible. All information above should be noted for all pictures taken.

GLACIAL HISTORIES

A field mapping effort to control the age and extent of glaciation in Denali should be carried out according to the standards for Quaternary geological field work. The methods used will include identification and mapping of glacial landforms, study and interpretation of glacial sedimentary exposures, and radiometric dating of glacial materials, or organics associated with glacial deposits, to determine age control for glacial advances. The final product of this effort will be a comprehensive written glacial history for Denali and a map showing the ages and extents of past glaciations. Cooperation with outside investigators (USGS or academic) would bring the necessary expertise to Denali. NPS personnel working on this project should have some background in geology or Quaternary geology, or be able to work with and learn from knowledgeable individuals.

A good reference for basic Quaternary geology techniques is:

Lowe, J.J., & M.C. Walker, 1984, *Reconstructing Quaternary Environments*, Longman Scientific & Technical, Essex, (in USA: John Wiley & Sons, New York).