Susitna-Watana Hydroelectric Project
(FERC No. 14241)

Glacier and Runoff Changes Study
Study Plan Section 7.7

Initial Study Report – Literature Review
Part A: Sections 1-11

Prepared for

Alaska Energy Authority

SUSITNA-WATANA HYDRO

Clean, reliable energy for the next 100 years.

Prepared by

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LIST OF ACRONYMS, ABBREVIATIONS, AND DEFINITIONS

Abbreviation	Definition
ablation	All processes that reduce the mass of the glacier. Glacier mass reduction occurs through the loss of snow and ice by melting, sublimation and calving.
albedo	A measure of the reflectivity of a surface, expressed as the fraction of the incoming solar radiation reflected by the surface.
aufeis	Sheet-like masses of layered ice that forms from successive flows of groundwater issuing at the surface during freezing temperatures.
evapotranspiration	The water loss from the surface to the atmosphere via evaporation and transpiration. The sum of evaporation and transpiration.
firn	The compacted snow on a glacier that remains after at least one year's ablation season, but has not yet metamorphosed into glacier ice.
frost blister	A seasonal frost mound produced through doming of seasonally frozen ground by a subsurface accumulation of water under elevated hydraulic potential during progressive freezing of the active layer.
jökulhlaup	A sudden outburst flood of water orginating from a glacier melted during a volcanic eruption. Also used when water filling an ice-dammed lake bursts out of the damned portion of the lake resulting in flooding.
lithalsa	A frost-induced raised land form in permafrost areas with mineral-rich soils, where a perennial ice lens has developed within the soil.
moulin	A deep pothole or shaft that allows supraglacial meltwater to enter a glacier.
nunatak	An island of bedrock which projects above the glacier, icefield or icesheet's surface and is completely surrounded by the ice.
palsa	A peaty permafrost mound containing a core of alternating layers of segregated ice and peat or mineral soil material.
periglacial	Describes cold, non-glacial landforms, climates, geomorphic processes or environments.
permafrost	Ground that has remained continuously below 0°C for at least two consecutive years.
pingos	A low hill or mound containing a core of massive perennial ice covered with soil and occasionally vegetation.
talik	An unfrozen section of ground found above, below, or within a layer of discontinuous permafrost or beneath a body of water in continuous permafrost due to a local anomaly in the thermal, hydrological, hydrogeological or hydrochemical conditions.
AEA	Alaska Energy Authority
FERC	Federal Energy Regulatory Commission
ISR	Initial Study Report
RSP	Revised Study Plan
SPD	Study Plan Determination
WaSiM	Water Balance Simulation Model
NMFS	National Marine Fisheries Service
ILP	Initial Study Report
GRACE	Gravity Recovery and Climate Experiment
km	Kilometer
mm	Millimeter

Abbreviation	Definition
Gt	Gigaton
GCM	General Circulation Model
RCP	Representative Concentration Pathways
UBC	University of British Columbia
V-A	Volume-Area
V-L	Volume-Length
w.e.q	Water equivalent
US	United States
LIA	Little Ice Age
W	Watt
m	Meter
K	Kelvin
PDO	Pacific Decadal Oscillation
ET	Evapotranspiration
PET	Potential Evapotranspiration
AET	Actual Evapotranspiration
D	Dimensional
C	Celcius
NOAA	National Oceanic and Atmospheric Administration
NCDC	National Climatic Data Center
SNOTEL	Snow Telemetry
NCEP	National Centers for Environmental Prediction
NCAR	National Center for Atmospheric Research
SNAP	Scenarios Network for Alaska and Arctic Planning
IPCC	Intergovernmental Panel on Climate Change
ECHAM5, GFDL21, MIROC, HAD and CCCMA	General Circulation Models
CORDEX	Coordinated Regional Climate Downscaling Experiment
NARCCAP	North American Regional Climate Change Assessment Program
A2, A1B and B2	Emission Scenarios
CMIP	Coupled Model Intercomparison Project

1. INTRODUCTION

On December 14 2012, Alaska Energy Authority (AEA) filed with the Federal Energy Regulatory Commission (FERC or Commission) its Revised Study Plan (RSP), which included 58 individual study plans (AEA 2012). Included within the RSP was the Glacier and Runoff Changes Study, Section 7.7. RSP Section 7.7 focuses on understanding how changes to the Upper Susitna basin hydrology due to glacial retreat and climate change can affect Project operations and environmental resources.

On February 1 2013, FERC staff issued its study plan determination (February 1 SPD) for 44 of the 58 studies, approving 31 studies as filed and 13 with modifications. RSP Section 7.7 was one of the 13 approved with modifications. In the February 1 SPD, FERC recognized the following:

AEA proposes to analyze the potential effects of climate change on glacier wastage and retreat and the corresponding effects on streamflow entering the proposed reservoir, and evaluate the effects of glacial surges on sediment delivery to the reservoir.
Specifically, AEA proposes to:

1. *review existing literature relevant to glacier retreat in southcentral Alaska and the upper Susitna watershed and summarize the current understanding of potential future changes in runoff associated with glacier wastage and retreat;*
2. *develop a hydrologic modeling framework that utilizes a glacier melt and runoff model (Hock 1999) and a Water Balance Simulation Model (WaSiM) to predict changes in glacier wastage and retreat on runoff in the Susitna basin;*
3. *simulate the inflow of water to the proposed reservoir and predict changes to available inflow using downscaled climate projections up to the year 2100; and*
4. *analyze the potential changes to sediment delivery from the upper Susitna watershed into the reservoir from glacial surges.*

FERC staff recommended the following in the February 1 SPD.

- *We find that the analysis of the potential changes to sediment delivery from the upper Susitna watershed into the reservoir from glacial surges as proposed by AEA is necessary, and therefore, are recommending approval of this portion of AEA's proposed study (item 4 as described above in the applicant's proposed study).*
- *We are not recommending approval of the remainder of AEA's proposed study (items 1-3 as described above in the applicant's proposed study). We have no objection to AEA conducting this portion of the study.*
- *We do not recommend extending the geographic range of the climate change assessment or adding an analysis of the natural resource impacts, as recommended by the NMFS and others.*

On February 21 2013, the National Marine Fisheries Service (NMFS) filed a notice of study dispute pursuant to section 5.14(a) of the Commission's regulations regarding FERC's failure to require AEA to implement the three study components related to glacier runoff and climate change that AEA proposed in the RSP (item 1). A Dispute Resolution Panel Meeting and Technical Conference was held on April 3 2013 to discuss NMFS' modification requests. On

April 26 2013 FERC provided its Study Dispute Determination, requiring the following modification;

We recommend that AEA review existing literature relevant to glacial retreat and summarize the understanding of potential future changes in runoff associated with glacier wastage and retreat, as described in RSP section 7.7.4.1.

On May 28 2013, NMFS and the Center for Water Advocacy (Center) filed requests for rehearing of the formal study dispute determination issued on April 26 2013. NMFS and the Center sought rehearing of the Director's finding that studies proposed by the potential applicant, AEA, and NMFS related to global climate change are unnecessary to conduct the Commission's environmental analysis and therefore will not be required to be conducted by AEA. On July 18 2013, FERC rejected the Center's request for rehearing and denied NMFS' request for rehearing.

AEA has adopted the RSP as the Final Study Plan with no modifications. This is the final report of the results of the literature review thus completing the FERC-approved study. The results of the literature review are presented below in Sections 4–7.

2. STUDY OBJECTIVES

The primary goal of this study is to analyze the potential impacts of glacier wastage and retreat on the Susitna-Watana Hydroelectric Project (Project). Specifically, how will glacier wastage and retreat, along with associated changes to the climate, affect the flow of water into the proposed reservoir? Currently several glaciers flow down the southern flanks of the Alaska Range near 13,832-foot Mount Hayes to form the three forks of the Upper Susitna River (Figure 2-1).

Glaciers in this area provide a significant portion of the total runoff within the Upper Susitna drainage, and it is well documented that these glaciers are currently retreating (Molnia 2008). Given this trend, changes to the runoff represented by glacial melting may occur in the future and may affect the Project. Therefore, it is important to understand how changes to the upper basin hydrology, due to glacier wastage and retreat and climate change can affect Project operations and environmental resources.

Specific objectives of the study are as follows:

- Review existing literature relevant to glacier retreat in south-central Alaska and the Upper Susitna watershed. This review will summarize the current understanding of potential future changes in runoff associated with glacier wastage and retreat.

Other objectives of the study that AEA is proceeding with are not part of the formal study for the ILP, but will be reported on in future years based on the work outlined in RSP Section 7.7.4.

3. STUDY AREA

The proposed study area is the Susitna River basin upstream of the proposed Watana Dam site.

4. GLACIERS

Glaciers are significant contributors to seasonal river discharge in many parts of the world, serving as frozen reservoirs of water that supplement runoff during warm and dry periods in which there is low flow. Glaciers in northern high-latitude regions have been experiencing increasingly negative cumulative mass balances since the early 1990s (Wolken et al. 2013). This trend is anticipated to continue as a consequence of global climate warming, as predicted unambiguously by all current climate models, and is expected to cause accelerated glacier wastage and retreat, thus reducing the storage capacity of snow and ice. As a result, river discharge volumes and timing in seasonal river runoff will change, and glaciers' ability to buffer this flow against seasonal precipitation extremes will be reduced or lost.

4.1. Glacier Changes in Alaska

Glaciers in Alaska (including northwest Canada) cover ~86,700 km^2 corresponding to 12% of all glacierized areas in the world outside the vast Greenland and Antarctic ice sheets (Pfeffer et al. in press). Roughly 14% of the area is drained through 50 tidewater glaciers. The mass balance of a glacier is a measure of the glacier's health and is defined as the change in the mass of a glacier over a stated period of time (Cogley et al. 2011). Alaskan glaciers have shown a coherent signal in glacier mass loss during the last several decades with acceleration of mass loss during the last two decades. Alaskan glaciers currently exhibit the highest glacier wastage rates on Earth (Gardner et al. 2013). Current annual thinning rates reach several meters per year for some glaciers that terminate near sea level (Van Looy et al. 2006; Larsen et al. 2007). During 1995 to 2001, annual volume loss from Alaskan glaciers equaled 0.27±0.1 mm/yr sea-level equivalent (Arendt et al. 2002) and added ~100 km^3 yr-1 to the freshwater discharge budget for the Gulf of Alaska watershed (Arendt et al. 2002). This runoff volume corresponds to about 50% of the annual discharge of the Yukon River (Raymond et al. 2007).

A revised estimate using US Geological Survey maps and satellite derived digital elevation models indicate mass losses of 42±9 Gt/yr during 1962 to 2006 (Berthier et al. 2010). Gardner et al. (2013) estimates a mass budget of -50± 17 Gt yr^{-1} for the period 2003-2009 based on evaluation of several published estimates from the Gravity Recovery and Climate Experiment (GRACE). However, GRACE estimates of mass loss vary widely in Alaska due to a combination of factors (i.e. different spatial and temporal resolutions; Table 4.1-1); more research is needed to resolve the discrepancies.

Average thinning rates vary widely across Alaska, but a pattern of recent acceleration is found uniformly. The mass changes are consistent with global atmospheric warming trends. Low-elevation climate station data in Alaska and northwestern Canada indicate that, during the period 1950 – 2002, winter and summer temperatures increased by about 2.08 ± 0.88 and 1.08 ± 0.48 °C, respectively, and precipitation may have increased in most parts (Arendt et al. 2009). However, climate-glacier interactions are complex and the precise causes of the observed glacier changes need further investigation.

Alaskan glaciers are expected to continue losing mass in the future (Radic and Hock 2011). 100-year projections of the Alaskan's glacier contribution to sea level rise indicate that Alaska is one of the largest regional contributors with multi-model volume losses varying from 18% to 45% by

2100 in response to temperature and precipitation projections of 14 general circulation models (GCMs) and the Representative Concentration Pathways (RCP) 4.5 and RCP8.5 emission scenarios (Radic et al. 2013; Figure 4.1-1).

4.2. Runoff from Glaciers

4.2.1. Characteristics of Glacier Discharge

Glaciers significantly modify streamflow both in quantity and timing, even with low percentages of catchment ice cover (e.g., Meier and Tangborn 1961; Fountain and Tangborn 1985; Chen and Ohmura 1990; Hopkinson and Young 1998; see Hock et al. 2005 for review). Glaciers are stores of water, amassing and releasing water on a wide range of time scales, thus, modulating basin hydrology through distinct characteristics of glacier runoff. Distinct characteristics of glacier runoff include (Röthlisberger and Lang 1987; Hock et al. 2005):

- *Annual runoff*: Annual runoff from glacierized basins is modulated by the glaciers' mass balances, i.e. the changes in glacier mass over time. Runoff is reduced in years of positive mass balance, as water is withdrawn from the hydrological cycle and put in temporary storage. In contrast, runoff is enhancedduring years of negative glacier mass balance since water kept in storage is released, producing more total runoff than in years of positive balance under otherwise similar conditions (Figure 4.2.2-1);
- *Diurnal cycles*: Glacier runoff is characterized by pronounced melt-induced diurnal cyclicity. Daily peak flows may increase by several hundred percent of daily minimum flows during days without rainfall;
- *Seasonal variations*: Glacier runoff shows distinct seasonal variations with very low winter runoff and a pronounced and seasonally delayed summer peak compared to non-glacierized basins (Escher-Vetter and Reinwarth 1994). While runoff from the glacier is minimal during the winter season of snow accumulation, runoff is large during the melt season, when melt of winter snow, firn and ice enhance down-glacier river flows;
- *Interannual variability*: Glacier cover dampens year-to-year variability in streamflow; a minimum is reached at 10-40% of glacierization with increasing variability with both lower and higher degrees of ice cover (Lang 1986). This so-called 'glacier compensation' effect occurs because in hot and dry years, glacier melt offsets reduced precipitation inputs;
- *Runoff correlation*: Runoff from highly glacierized basins often correlates with air temperature, while glacier-free basins tend to show positive correlations between runoff and precipitation;
- *Outburst floods*: Glaciers may also cause sudden floods, often referred to as jökulhlaups, posing a potential hazard for downstream populations and infrastructure. These outburst floods may be due to subglacial volcanic eruptions or sudden drainage of sub-glacial, moraine and ice-dammed lakes (e.g., Lliboutry et al. 1977; Bjornsson 2003).

In addition to contributing directly to runoff through ice wastage, glacier cover within a drainage basin decreases direct evaporation and plant transpiration, the combination of which can result in considerably higher water yields for basins with glaciers compared to unglacierized watersheds (Hood and Scott 2008). Furthermore, the proportion of streamflow derived from glacier runoff has pronounced effects on physical (Kyle and Brabets 2001), biogeochemical (Hodson et al. 2008; Hood and Berner 2009; Bhatia et al. 2013) and biological (Milner et al. 2000; Robinson et al. 2001) properties of streams. Consequently, changes in watershed glacier cover also have the potential to alter riverine material fluxes. For example, area-weighted watershed fluxes of soluble-reactive phosphorus decrease sharply with declining ice cover (Hood and Scott 2008). Recent studies also suggest that dissolved organic material contained in glacial runoff has a microbial source and is highly labile to marine heterotrophs (Hodson et al. 2008; Hood et al. 2009).

4.2.2. Effects of atmospheric warming on glacier runoff

The response of glacier runoff to climate changes is complex and will depend on the time-scale considered. Although the mass change response is immediate, some runoff response-variables will change sign at a later stage when enhanced melt rates have caused glacier volume to decrease significantly (Hock et al. 2005).

As climate changes and causes glacier mass balances to become progressively more negative, total glacier runoff will initially increase due to enhanced glacier melt rates (Jansson et al. 2003; Figure 4.2.2-2). In highly glacierized catchments runoff due to glacier mass loss may contribute a substantial fraction of annual water yields. Enhanced melt rates are caused primarily by atmospheric warming but are further accelerated by positive feedback mechanisms. For example, enlargement of bare ice areas due to faster removal of winter snow or loss of firn area will cause reduced albedo, thus increasing the amount of absorbed shortwave radiation and melt (Figure 4.2.2-3).

The glacier will respond to prolonged glacier net mass loss by dynamically adjusting its size and shape generally through retreat and thinning. While the mass loss in response to climate forcing is immediate, the geometric adjustment is delayed by the glacier's characteristic response time (Johannesson et al. 1989). The initial increase in runoff will be followed by a reduction in runoff as the glacier dwindles and eventually disappears (Figure 4.2.2-2). Hence, the ability of the glacier to augment streamflow in periods of otherwise low flow will be diminished and eventually lost. With high percentage of ice cover, the initial increase in runoff can be substantial and result in a higher frequency of flood events that might not be triggered by rainfall events. The timing of the turning point between runoff increase and decrease will depend on the competing effects of increased glacier thinning rates due to increased melt and decreased total melt water due to depletion of the glacier storage, which in turn is governed by both glacier and climate change characteristics. Anticipating the timing of the peak in runoff and the rate of decline in runoff following that peak are key questions in long-term water resource planning (e.g. hydropower development). The replacement of ice by coastal temperate forest and alpine vegetation may lead to further reduced water yields and a major change in catchment-wide nutrient cycling (Wolken et al. 2011).

Warming air temperatures prolong the melt season by causing earlier melt onset and later freeze-up (Sharp and Wolken 2011), thus modifying the timing of the seasonal glacier runoff peak. In addition, the pronounced daily cyclicity typical of glacier discharge will, at least in an initial phase, be amplified due to increased daily melt water production and feedback mechanisms. This increases the risk for floods substantially, especially when strong melt-induced flows coincide with heavy rain events. Feedbacks include more efficient water transport through the glacier as snow and firn layers that typically have large water retention capacity are removed more quickly, and melt waters are evacuated via efficient tunnel systems through the glacier ice (Figure 4.2.2-3; Braun et al. 2000; Willis et al. 2002).

4.2.3. Modeling Glacier Runoff

Glacier runoff has been modeled using stochastic, conceptual and physically based models (see Hock et al. 2005 for review). Stochastic models were widely used in the 1960s and 1970s for seasonal and short-term runoff forecasts often tailored to the needs to hydropower facilities. The models compute runoff directly as a function of meteorological variables based on multiple regression techniques (Lang 1968; Jensen and Lang 1973; Ostrem 1973). In contrast, conceptual and physical-based models attempt to compute the individual processes leading to glacier runoff.

Here, the modelling of glacier runoff and its response to climate change involves three principal steps (Hock et al. 2005): modelling of (a) glacier mass balance, i.e. the changes in the glacier's mass over the hydrological year; (b) the geometric adjustments of the glacier in response to glacier mass changes; and (c) the routing of melt and rain water through the glacier, i.e. transformation of water inputs into a discharge hydrograph down glacier. Glaciers are often only crudely represented in hydrological models. While many existing watershed models include routines for snow and ice melt, the geometric adjustments and glacier specific discharge routing are often ignored entirely or treated in very rudimentary ways, inhibiting accurate modeling of the modulating effects of glaciers on watershed runoff.

4.2.3.1. Glacier Mass Balance

Mass balance models generally fall into two categories: (a) temperature-index models based on air temperature as the primary index of melt energy (Hock 2003); and (b) physically based energy balance models computing all relevant components of the energy balance (Hock 2005a). Although the latter more adequately describe the physics of the processes involved, considerably larger data requirements often inhibit their use. Nevertheless, despite their simplicity temperature-index models have been shown to perform surprisingly well in hydrological modeling on catchment scales. However, they are less suitable to model the diurnal cyclicity of glacier runoff or the accurate representation of the spatial variation in melt rates across a basin.

To improve the physical representation of processes while retaining low data requirements, a complete hierarchy of melt models have been developed with a gradual transition from simple degree-day approaches to energy-balance-type expressions by increasing the number of input variables into model formulations. For example, the UBC-runoff-model (Quick and Pipes 1977) and the HYMET-runoff-model (Tangborn 1984) employ the daily temperature range in addition to air temperature as climatic input for their melt routines, a measure of cloud-cover and, hence solar radiation. Hock (1999) varied the degree-day factor as a function of potential direct solar radiation, thus significantly improving the modeling of both the spatial melt variations and the diurnal melt and glacier discharge amplitudes. This model is also included in WaSIM. Pellicciotti et al. (2005) elaborated on this approach by including parameterized shortwave radiation fluxes. Temperature-index models are widely used, promoted by ease of application and low data input requirements. However model parameters are often not transferable between catchments (MacDougall et al. 2011), and it remains unclear how model parameters will change under a different climate, a limitation that needs further research.

4.2.3.2. Geometric Adjustments

Glacier retreats to higher altitudes exert a negative, i.e. stabilizing, feedback on glacier mass change because loss of area at predominantly lower elevations will make the average thinning less pronounced than it would have been without retreat under the same climate conditions. Glacier thinning, in contrast, exerts a positive, i.e. self-amplifying, feedback; with decreasing surface elevation, the glacier is exposed to higher air temperatures, resulting in more negative mass balances. The net effect of these two opposing feedbacks will depend on a number of factors related to climate, glacier geometry and characteristics such as debris coverage (Bodvardsson 1955; Harrison et al. 2001; Huss et al. 2012). It is crucial to model the geometry changes resulting from climate change to be able to account for the mass-balance feedback and to model the turning point beyond which glacier runoff decreases (Figure 4.2.2-2).

Ideally the dynamical adjustment is calculated using physically-based numerical ice flow models. Such models solve a momentum balance equation, either the Stokes equations or an approximation thereof, however, detailed data requirement restrict their use in hydrological modeling. The most common approach to account for the glacier's dynamical adjustments as its mass changes is volume-area (V-A) or volume-length (V-L) scaling (Bahr et al. 1997). The annual volume change computed from the mass-balance model is subtracted from total glacier volume, and scaling is applied to derive a new area from the updated glacier volume. In case of volume loss, elevation bands or grid cells at lower elevations are then removed from the glacier domain.

Huss et al. (2010) suggested an approach of intermediate complexity, distributing the annual volume loss across the glacier surface based on observed typical elevation change patterns, which indicate generally low thinning rates at high elevations and strongly accelerated thinning rates at low elevations. An empirical function relating glacier surface elevation change to normalized elevation range is applied each year to adjust the elevation of each glacier grid cell. Each grid cell with a modeled elevation drop exceeding the current ice thickness is removed from the glacier, thereby also modeling glacier retreat. This approach has successfully been tested on smaller retreating glaciers, but does not provide a mechanism for glacier advance.

4.2.3.3. Discharge Routing

Detailed modeling of the physical processes involved in the transfer of water through a glacier is highly complex. Such models need to account for the time-transgressive growth and decay of conduits and passages through and under the deformable ice, and account for occurrence of crevasses, moulins and other entry points where water can enter the glacier system. Only few such glacier models exist (e.g. Arnold et al. 1998; Flowers and Clarke 2002), and generally are used as research tools rather than for routing water through glaciers in watershed models.

Instead, most hydrological models (if they include specific water routing through glaciers at all) adopt the widely used concept in hydrological internal flow routing of linear reservoirs (Chow et al. 1988). The glacier is divided into one or several parallel or serial reservoirs, each of which can be thought of a container of water where outflow is proportional to the stored water volume, which in turn depends on input from melt and rain water. Each reservoir is assigned a unique storage constant that represents the time shift between the centroid of the inflow and that of the outflow thus delaying the reservoir's outflow. A number of variants of this approach have been suggested (Figure 4.2.3.3-1), often assigning different storage constants based on the surface types of the glacier. For example, higher storage coefficients are applied for the snow and firn zones than for bare ice, reflecting their profoundly higher water retention capacity. Storage constant are often treated as model parameters obtained from model calibration. Despite its simplicity and pronounced changes in a glacier's internal drainage system throughout the melt season, the approach performs remarkably well (Hock and Noetzli 1997; Escher-Vetter 2000).

4.2.4. Previous Glacier Runoff Studies

A large number of studies around the world have highlighted the role of glaciers in the hydrological cycle and indicated significant hydrological changes in response to climate change, including changes in total water amounts and seasonality as described above (e.g., Braun et al. 2000; Casassa et al. 2009; Rees and Collins 2006; Hagg et al. 2006; Horton et al. 2006; Yao et al. 2007; Huss et al. 2008; Immerzeel et al. 2008; Koboltschnik et al. 2008; Stahl et al. 2010; Kobierska et al. 2013). Results vary with regard to the importance of glacier runoff relative to total runoff in glacierized catchments (Weber et al. 2010; Huss 2011). This can at least partially be explained by varying physical factors such as climate regimes, catchment size, degree of glacierization or glacier mass change rates. However, some of these differences are due to the different ways to define glacier runoff. Definitions of glacier runoff fall into two principal categories (Radic and Hock 2013): (1) those that only consider the net mass loss component of a glacier due to glacier wastage, i.e. runoff is zero if the glacier is in balance or gains mass; and (2) those that consider all meltwater originating from a glacier no matter the magnitude or sign of the mass budget. Glacier runoff generally is much larger if the latter definition is adopted than the former. Hence, the relative importance of glacier runoff to total runoff will differ between these two approaches.

Observations from gauge records in glacierized basins show both increases in runoff, for example, along the coast in southern Alaska (Neal et al. 2002), northwestern British Columbia (Fleming and Clarke 2003) or on the Tibetean Plateau (Yao et al. 2007), and negative trends in summer streamflow, for example in the southern Canadian Cordillera (Stahl and Moore 2006). The long-term effect of runoff reduction, resulting from a decrease in glacierized area, was also detected by Chen and Ohmura (1990), who analyzed multi-decadal discharge records in the Swiss Alps. Comeau et al. (2009) analyzed annual runoff in a large catchment in western Canada and found that reductions in glacier volume, due to receding glaciers, contributed 3% to total runoff during 1975-1998.

Various studies have modeled the impacts of future climate change on runoff in glacierized basins. To provide information in connection with a hydropower scheme, Adalgeirsdottir et al. (2006) modeled an increase in annual glacier runoff from ice caps in Iceland of up to 60% until about 2100, followed by a rapid reduction in runoff thereafter. Rees and Collins (2006) applied a hydro-glaciological model to hypothetical catchments with varying fractional ice area in the Himalayas and predicted gradual runoff increase over the next ~50 years, followed by a more abrupt runoff decline to lower than contemporary values over the next few decades. Stahl et al.

(2008) investigated the sensitivity of streamflow in response to changes in climate and glacier cover for the Bridge River basin in British Columbia, coupling a hydrological model with a glacier response model. Under the assumption of current climate, the model projected decreases in glacier area by 20% over the next 50 to 100 years causing a similar percentage decrease in summer streamflow.

Recent investigations in the monsoon-effected regions High Asian Mountains indicate that glacier melt may be of lesser importance than previously assumed since monsoon rains and glacier melt will continue to sustain the increasing water demands expected in these areas (Kaser et al. 2010; Immerzeel et al. 2013). In contrast a number of studies have investigated the hydrological consequences of continued glacier wastage in the tropical Andes in response to climate change in individual watersheds where glacier melt often is the only source of water during the dry season. Juen et al. (2007) and Vuille et al. (2008) used historical hydrological records and found a decrease in glacier runoff as glaciers shrank and strongly enhanced seasonality. Baraer et al. (2012) found that annual discharge in the investigated watersheds in Peru's Cordillera Blanca will be lower than present by 2-30%, with considerably more pronounced effects during the dry season. Several recent studies have highlighted the potential of glacier retreat in modulating runoff regimes, and indicated serious adverse effects on water availability if glacier recession continued (e.g. Pouyaud et al. 2005, Juen et al. 2007; Mark and Seltzer 2003; Mark and McKenzie 2007; Suarez et al. 2008; Kaser et al. 2010).

Even in non-arid regions the glacier contribution to river runoff can be substantial. Huss (2011) assessed the contribution of glaciers to runoff from large-scale drainage basins in Europe with areas up to 800,000 km^2 over the period 1908-2008 based on modeled monthly mass budget estimates for all glaciers in the European Alps. The glacier runoff defined as the water due to glacier net mass change was computed for each month and compared to monthly river runoff measured at gauges along the entire river lengths. Although ice cover of the investigated basins did not exceed 1% of the total area, the maximum monthly glacier contributions during summer ranged from 4% to 25% between catchments, emphasizing that seasonal glacier contributions can be significant even in basins with little ice cover.

4.2.4.1. Alaska

Few studies have quantified the effect of glaciers on Alaskan rivers. Neal et al. (2002) note an increase in runoff in some gauge records for glacier streams along the coast in southern Alaska. Several studies documented the impact of glacier water on the biogeochemical properties of Alaska streams (e.g. Hood and Scott 2008; Hood and Berner 2009). Neal et al. (2010) adopted a water balance approach to estimate the contribution of glacier runoff to freshwater discharge into the Gulf of Alaska; a 420,230 km^2 watershed covered 18% by glaciers. Glacier runoff (defined as all water including melt and rain water from the glacier area) contributed 47% of the total runoff (870 km3 a^{-1}), while 10% came from glacier net mass loss alone.

4.2.4.2. Upper Susitna Basin

Between 1981 and 1983, a joint effort between the University of Alaska Fairbanks and R&M Consultants, Inc. on behalf of the Alaska Power Authority (now Alaska Energy Authority) was made to analyze the runoff contributions produced from glaciers in the Susitna River Basin. The project goal was to determine the timing and amount of glacier runoff in order to aid development of water forecast models for the proposed Susitna hydroelectric dam. This study focused on the four major glaciers located on the southern side of the Eastern Alaska Range at the Susitna River and Maclaren River headwaters. These glaciers are: West Fork Glacier, Susitna Glacier and its Northwest and Turkey Tributaries, East Fork Glacier and Maclaren Glacier. The glaciers in the Talkeetna Mountains or Eureka Glacier were not included in this study.

The mass balance of the glaciers was determined by the glaciological method, i.e. measuring accumulation and ablation at stakes and in snow pits. The amount of snow and ice that had accumulated and melted was measured at each stake at specific times in the hydrologic year. This method is used to monitor the change in the glacier surface relative to a datum registered to the stake drilled into the glacier. During this study, three stakes were placed on each of the major glaciers at different elevations by mountaineers who used topographic maps to determine site elevations. One mass balance stake was placed in the ablation zone near 1000 m, one stake was placed at the equilibrium line of the glaciers near 1500 m, and another stake was set in the accumulation zone near 2000 m. Since the mass balance stake distribution was one stake per 50 km^2, the mass balance monitoring efforts were considered to be at the reconnaissance level (Clarke et al. 1985). The stakes were typically measured during the spring in April or May, during the summer in late August or early September. The sparse stake measurements of snow depth were supplemented by probing to the late-summer surface.

Mean snow density was used to convert the mass balance stake measurements to water equivalent balances. The mean snow density was calculated by measuring snow density as a function of depth from samples taken in snow pits dug near representative stakes and from cores of the entire snowpack. In May 1981, the winter snowpack and balance (1980 to 1981) was estimated from snow stratigraphy by identifying the late-summer surface while probing snow depth and from the snow pit measurements (Clarke et al. 1985). Snow temperatures versus depth were assessed in snow pits; by May, the snow was isothermal at 0°C (Harrison et al. 1983). The mean snow density used in spring and late-summer mass balance calculations was 400 kg/m^3, 500 kg/m^3 for mid-summer calculations, and 200 kg/m^3 for fall calculations. Over the three-year observation period, the annual balances are 0.1 ± 0.6 m w.eq./yr. The winter and summer balances, and the annual balances for each glacier are summarized in Table 4.2.4.2-1.

Glacier runoff was compared to stream gauges in the Susitna River at Gold Creek, Susitna River at the Denali Highway, and at the Maclaren River on the Denali Highway gauge (Figure 4.2.4.2-1). Approximately 34% of the runoff measured north of the Denali Highway (using Susitna River at Denali and Maclaren River at Denali stream gauges) was attributed to the glacierized area. The average runoff from the melting of snow, firn and ice was 1.3 m/yr, nearly 1.4 times greater than the runoff contribution from the non-glacierized area above the Denali Highway (0.95 m/yr). The glacier runoff component was approximately 2.5 times greater (13% of total runoff) than the volume contribution from the non-glacierized basin upstream of the Gold Creek stream gauge (Clarke et al. 1985). The primary glacier melt season during the period of study was during July and August, when 75% of the glacier meltwater was generated. The remainder was produced during the late spring in May and June, and in the fall before the winter freeze-up in November (Clarke et al. 1985).

Runoff from liquid precipitation was calculated from the high elevation Susitna Glacier climate station monitored by R&M Consultants, Inc (Figure 4.2.4.2-1). This station was located at 1433 m on a nunatak between Susitna Glacier and its Northwest Tributary. Several assumptions used in calculating rainfall over the glacierized basin are described in more detail in Clarke et al. (1985). From this rain gauge, a lower-limit on the precipitation runoff is 0.25 m/yr.

5. PERMAFROST

Permafrost is defined as any parent material that remains below 0˚C for more than two consecutive years. About 85% of Alaska is within permafrost zones, while glaciers cover ~5% of the state. There are four permafrost distribution classes that are typically used: continuous, where >90% of the land surface is underlain by permafrost; discontinuous, between 50 and 90%; sporadic, between 10 and 50%; and isolated, between 0 and 10% (Figure 5-1; Jorgenson et al. 2008). The majority of the upper Susitna basin is estimated to be underlain by discontinuous and continuous permafrost.

Permafrost has been a topic of discussion in the US and mainly Alaska, since the discovery of gold in Fairbanks. The main focus has been on permafrost engineering, e.g. the construction of mine shafts, rail and road systems. Many questions remain about the dynamic nature of permafrost, not only in applications of modern day infrastructure design and resilience, but also in other scientific disciplines, including biology, ecology, hydrology and atmospheric sciences. A lot has been learned over the last century, and the last few decades, when the attention of climate change has brought a wider audience to permafrost science.

5.1. Trends in Permafrost

During past glacial periods, air and permafrost temperatures were much lower than today. The last event that cooled the ground significantly was the Little Ice Age (LIA; ca. 1600-1800). Most shallow permafrost (<100 m) that exists in Interior Alaska were formed during the LIA (Romanovsky et al. 2010). Evidence suggests that permafrost warming and degradation in Interior Alaska began about 250 yrs ago (mid-1700s) and was associated with periods of relatively warm climate during the mid-late 1700s and 1900s (Jorgenson et al. 2001). Measurements and model simulations of the 19th and 20th centuries show periods of warming and stagnation of permafrost temperatures in Interior Alaska. Numerical model simulations suggest that permafrost warmed in the late 1960s and early 1970s in response to warmer air temperature and an increase in snow cover, but were nearly stable in the 1980s (Osterkamp and Romanovsky 1999). Measurements show permafrost warming since the late 1980s in Interior Alaska throughout the Tanana River region, in the region south of the Alaska Range from Tok westward to Gulkana (in the Copper River Valley) and beyond to the Talkeetna Mountains (Osterkamp 2005). Near Healy, this permafrost warming (since the late 1980s) also resulted in thawing from the top of the permafrost of about 10 cm/yr (Osterkamp 2005), which was almost entirely attributed to increased snow cover (Osterkamp 2007). In Gulkana, however, permafrost has been thawing from the bottom at a rate of 4 cm/yr since the 1980s and has accelerated to 9 cm/yr after 2000 (Osterkamp 2005). Interior Alaska permafrost has also experience degradation from both the top and bottom. Although initiated in the 1700s, permafrost degradation (from the top) has increased rapidly in the recent decades (Jorgenson et al. 2001). Continued thawing of permafrost will significantly alter the soil moisture, and the biogeochemical and hydrological cycles in Interior and south-central Alaska (Wolken et al. 2011).

5.2. Controls on Permafrost

The permafrost distribution and conditions are forced by upper (air) and lower (geothermal) boundary conditions, which are modified by snow, vegetation, and soil properties as described below:

Air temperature - The permafrost thermal regime is mainly a result of mean annual air temperature as it is the driving force to ground cooling or warming. Given enough time (decades to centuries), the ground temperature will become approximately the same as the air temperature on a mean annual basis. Accordingly, large-scale climate patterns control the thermal regime of permafrost;

Geothermal heat flux - Permafrost is warmed from below by geothermal heat flow. The geothermal heat flow varies across Alaska (and the planet) due to the thickness of the earth's crust. This can lead to various permafrost thicknesses in areas with the same vegetation, soil and mean annual air temperature (Jafarov et al. 2012);

Snow - Snow distribution has a major warming effect on permafrost temperatures as snow is an effective insulator during the cold season. The thermal effects of snow on ground temperatures depend upon the timing, duration, accumulation history, and characteristics of snow (Goodrich 1982). Snowpack heterogeneity across the landscape makes it challenging to accurately predict permafrost temperatures at fine geographical scales. Snow accumulation can be highly variable across local (~meters) to regional (km's) scales due to surface roughness (topography, vegetation) and atmospheric circulation (Liston and Sturm, 2002). Redistribution of snow through wind can create major snow drifts or snow-free areas due to repeated wind scouring. Redistribution of snow is often accompanied with sublimation when the moisture deficit in the air is high;

Vegetation - Vegetation is a major modifier on ground thermal regime as permafrost in the discontinuous permafrost zone can be present or absent in areas with identical climate, demonstrating the importance of biophysical factors (Shur and Jorgenson 2007). Especially mosses have a major impact on soil temperatures (Kade et al. 2006) due to their large porosity and therefore, large seasonal variation in moisture content. The overall thermal effect of mosses is ground cooling, which favors permafrost. The distribution of discontinuous permafrost is also controlled by aspect, which likewise plays a large role in the distribution of vegetation in Interior Alaska;

Soils - Soils controls soil temperatures mainly through pore size distribution, composition and amount of organic material. The soil's modifying prosperities on heat flow results in a thermal offset, which is defined as the difference between the mean annual surface temperature and the mean annual top of permafrost temperature. This difference is caused by the thermal conductivity of thawed versus frozen soils. In summer the pores are filled with liquid water that has a thermal conductivity of 0.6 $W/(m^2*K)$, and in winter, the water is frozen and has a thermal conductivity of 2 $W/(m^2*K)$. Based on the soil type and its porosity, the bulk thermal conductivity can range from 0.4 W/(m^2*K) in thawed peat to 3.5 W/(m^2*K) in pure granite. Porous soils, such as peat, leads to a greater difference in thawed versus frozen thermal conductivity, favoring cooling of the ground. Liquid water in soils also has a major impact on the heat capacity and latent heat released during freezing. Both these factors play a major role in the development of the active layer during the summer (higher ice content delays thaw) and it can prevent refreezing of the soil during the next winter resulting in a talik (multiyear unfrozen layer surrounded by permafrost). Taliks can have a major impact on the surface and groundwater hydrology of permafrost regions.

5.3. Periglacial Landforms

Periglacial landforms can alert the observer to the presence of permafrost. Most periglacial features are the result of soil movement related to repeated freezing and thawing, which is associated with expanding and shrinking of soil due to the presence of water. A common feature that forms due to shrinking of the ground during extremely cold conditions are ice wedges. The ice wedges form polygonal pattern that can be visible on the ground surface. During past cold periods, e.g. the Pleistocene, ice wedges formed in regions that are currently too warm for ice wedge growth. Inactive ice wedges can be found today in all of the permafrost zones in Alaska as massive ground ice features. Active layer processes that are also part of the periglacial landscape include nonsorted circles, sorted circles, solifluction lobes, gelifluction lobes, frozen debris lobes, rock glaciers and sorted strips. Many of these features are driven by temperature changes over time (seasonal to centennial) and they affect the formation of massive ground ice, which, unlike temperature, cannot be easily described or measured in permafrost. Artesian groundwater flow to the surface can lead to the development of aufeis (a surface ice deposit), frost blister (an ice deposit below the vegetation that looks like a blister), frost mound (small ice-cored mound), palsa (ice-cored peat mound), lithalsa (ice-cored mineral mound), or pingos (large ice-cored mounds).

5.4. Permafrost Modeling

Basic permafrost models include only two variables to simulate the soil thermal regime, the mean annual air temperature and the geothermal temperature gradient. From these two variables, permafrost temperatures can be estimated for any place where the mean annual air temperature is below freezing. This approach ignores most of the aspects of what controls permafrost distribution (see the modifiers described above), but could be used when no other data are available. Ultimately, knowledge is required about the geothermal heat flux, soil, surface properties, snow depth and density (Jafarov et al. 2012). Over the last few decades, the amount of data available to develop such datasets has increased dramatically due to the use of remote sensing techniques.

Surface and groundwater movement and storage is controlled by permafrost distribution. Current theory on the behavior of thermo-hydrological coupled models is advancing, but insufficient computational capability still represents a major challenge to creating simulations of large regions at a fine enough resolution to fully couple the two processes. Daanen et al. (2008) modeled the water movement in the active layer with a fully coupled three dimensional model during freezing in order the better understand the behavior of non-sorted circles at the decimeter scale. A coarser approach was taken to simulate the Alaska and circumpolar permafrost domain to develop an understanding of the water balance in the active layer (Rawlins et al. 2013). However, the coarser approach leaves many aspects of the dynamic surface conditions unanswered, which can have important feedbacks on the long- and short term state of permafrost.

6. HYDROLOGY

The hydrology of Interior and south-central Alaska is strongly influenced by seasonal to centennial variations in cryospheric components (i.e., snow, ice and permafrost). Permafrost and frozen ground are relatively impermeable layers (if ice rich) that restrict recharge, discharge, infiltration and movement of groundwater, by acting as a confining layer (Williams 1970). Glaciers are frozen reservoirs of water that can modify the streamflow from seasonal to centennial time scales (Fountain and Tangborn 1985). Both glaciers and permafrost are abundant in the Susitna basin and are expected to modify its hydrologic cycle as they continue to respond to climate change.

6.1. Runoff

Permafrost strongly affects summer runoff response to storm events. The presence of permafrost leads to a reduced basin storage, which in turn, increases surface runoff (Dingman et al. 1971; Haugen et al. 1982; Slaughter et al. 1983). Flood hydrographs for catchments underlain by permafrost tend to be flashier and more responsive than those from permafrost-free catchments (Slaughter and Kane 1979) due to the limited storage capacity of the active layer.

Like other major river systems in Interior Alaska, the streamflow in the Susitna River is characterized by a high rate of discharge from May through September and by low flows from October through April. About 86% of the total annual flow of the upper Susitna occurs from May through September (Alaska District, Corps of Engineers 1975). Winter snowpack in the Alaska Range determines the magnitude of early spring discharge; summer temperatures and precipitation determine the magnitude and duration of summer flow, and precipitation during the late summer/early autumn promotes any elevated magnitude or duration of late-season discharge (Ford and Bedford 1987). In large rivers that have their headwaters in mountainous, glacierized regions, e.g. the Susitna River, the timing of peak flows is not restricted to the spring snowmelt as heavy rainfall in summer and early fall add to high-elevation glacial wastage and snowmelt contributions (MacKay et al. 1973). Variations in the timing of river break-up, freeze-up and magnitude of snowmelt peaks in the Susitna River have been linked to shifts in the PDO (Pacific Decadal Oscillation) (Curran 2012).

Although glaciers cover only ~5 % of the Susitna basin, together with the adjacent mountain terrain, they contribute a disproportionate fraction of the average annual streamflow (see Glacier section). Roughly 38% of the streamflow at Gold Creek originates above the gauging stations on the Maclaren River near Paxson and on the Susitna River near Denali, although these gauging sites cover only 20% of the basin area (R&M Consultants and Harrison 1981). The Susitna glaciers alone (snow, firn and ice) are estimated to contribute about 13% of the annual runoff measured at the Devils Canyon (Figure 4.2.4.2-1; Bowling 1982 and Table 7.3; Clarke et al. 1985).

6.2. Surface Water and Wetlands

Surface water, groundwater and permafrost play a major role in nourishing wetlands in the Susitna basin. The presence of permafrost supports extensive wetlands in areas that are otherwise considered semi-arid as water is retained near the ground surface due to the limited subsurface storage capacity of the active layer (Callegary et al. 2013). In discontinuous permafrost regions, aspect can determine the presence or absence of permafrost, which in turn influences the distribution of wetlands (Dingman and Koutz 1974).

Artesian discharge of subpermafrost groundwater is known to occur in several regions and to be related to both lake and wetland formation in Interior Alaska (Cederstrom 1963; Kane and Slaughter 1973; Racine and Walters 1994). If permafrost degrades, surface water may either increase or decrease depending on the pressure of the underlying groundwater. In many cases, subpermafrost groundwater is artesian, which results in lake-levels rising. If the hydraulic gradient is downwards, the lake-levels will drop and permafrost can aggrade (re-grow).

6.3. Groundwater and Infiltration

Groundwater in permafrost zones occurs above (suprapermafrost), below (subpermafrost), and locally within (talik) permafrost. Groundwater recharge, whether it is to an aquifer above (within the active layer) or below the permafrost, is controlled by the amount of surface water that is available for infiltration and by the hydraulic conductivity of the soils. Frozen soils with high ice content have substantially lower infiltration rates than thawed soils and frozen soils with low pore ice content and (Kane and Stein 1983a; 1983b). Accordingly, soils that have ice-saturated pores are nearly impermeable. Ice saturated soils typically occur at the top of the permafrost or in near-surface soils that experience a snowmelt that is preceded by a wet fall season. However, frozen silts with low moisture content can readily accept snowmelt at rates greater than the snow can melt (Kane and Stein 1983b). The partitioning of the snowmelt water into groundwater recharge or surface runoff is, therefore, partly controlled by the moisture status of the frozen soils.

Recharge and discharge of water to and from the larger regional aquifers located below the permafrost are limited to the unfrozen zones that perforate the permafrost such as beneath streams, snowbanks, lakes, glaciers and south-facing slopes. The Tanana River, north of the Alaska Range, has a permafrost-free zone beneath it (Williams 1970), due to the local thermal anomaly caused by the river. Susitna River is most likely experiencing a similar phenomenon, which would allow the surface water in the river to connect with the underlying aquifer. Headwaters draining the north facing slopes of the Alaska Range, such as the Delta River and Jarvis Creek, are elevated above the regional aquifer with wells having static water levels as much as 61 m below the streambeds (Dingman et al. 1971; Wilcox 1980). Both Delta River and Jarvis Creek are influent, e.g. they lose water to the aquifer, once the rivers enter more permeable sediments (Wilcox 1980). It is possible that a similar hydrologic system is encountered in the upper Susitna basin.

In Interior Alaska, heat from groundwater may contribute to permafrost degradation because the groundwater is relatively warm (2–4 °C) year-round (Jorgenson et al. 2001). Similar to the lowlands of the Tanana River basin, groundwater springs surface in numerous places in the upper Susitna basin and are easily identifiable in the winter due to localized melt.

6.4. Evapotranspiration

Evapotranspiration (ET) represents the water loss from the surface to the atmosphere via evaporation and transpiration. Refined ET assessments are difficult to obtain due to the expensive techniques (eddy covariance) used in directly measuring ET (Aubinet et al. 2012), and to the rough assumptions that are built into simpler techniques, which are typically used in estimating ET. The most widely used approaches calculate the potential evapotranspiration (PET), e.g. the upper limit for water losses to the atmosphere. PET should not be confused with actual evapotranspiration (AET), which can be dramatically lower than PET. The loss of water from the surface to the atmosphere is driven by available energy and vapor gradients, but modified by a series of complex processes such as leaf stomata, soil moisture, etc. The most commonly used equations for calculating ET include: (1) Thornthwaite's potential evapotranspiration as it only relies on air temperature; (2) Hamon, which in addition to air temperature requires day length; and (3) closing the water balance equation with ET, which builds in the assumption of no storage change and integrates all errors associated with precipitation, runoff and storage change into the estimated ET. Iwata et al. (2012) measured the ET of a black spruce forest near Fairbanks, Alaska using the eddy covariance technique and found cumulative ET (snow-free period) ranging from 195 mm to 234 mm (average of 211 mm) with a typical maximum of 2.5 mm day^{-1} in July (year 2003-2009). In comparison, PET estimates of the upper Susitna basin ranges between 300 to 450 mm yr^{-1} (Patrick and Black 1968; http://www.snap.uaf.edu/data.php). The range in total precipitation is documented to be much larger than both measured evapotranspiration and estimated potential evapotranspiration in Interior Alaska (Iwata et al. 2012), suggesting an annual 1D water balance (precipitation minus potential evapotranspiration) to range between 25 and 300 mm in the upper Susitna basin (Ford and Bedford 1987).

7. CLIMATE

7.1. Observed Changes in Climate

Mean annual surface air temperature over northern high-latitude land areas (>60 °N) has increased by ~2.0 °C since the mid-1960s (Overland et al. 2012). In Alaska, weather station observations from 1949-2012 show a mean annual surface air temperature increase of 1.6 °C, a warming that appears to be unprecedented in at least the last 400 years (Overpeck et al. 1997; Kaufman et al. 2009). Mean annual air temperature has increased by ~1.3 °C during the past 50 years in Interior Alaska and by ~2.0 °C in inland south-central Alaska, with the greatest warming occurring in winter (Hartmann and Wendler 2005; Shulski and Wendler 2007). By the end of the 21st century, air temperature in this region of Alaska is projected to increase by 3 to 7 °C (Walsh et al. 2008). Projected increases in winter precipitation during this same time period could be offset by less summer precipitation (Karl et al. 2009; ACIA 2005).

7.2. Existing Meteorological and Climatological Data

The meteorological and climatological knowledge of inter-mountain south-central Alaska, including the upper Susitna basin, is generally poor due largely to the sparse and poorly distributed (mostly low elevation) data and the lack of consistent, long-term measurements. Available meteorological measurements (historic and current) and gridded climate products applicable to the Susitna basin are summarized below.

7.2.1. Station Observations

Daily time series for precipitation and minimum and maximum air temperature are available for 32 climate stations in or in proximity of the Upper Susitna Basin from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC; Figure 7.2.1-1). Additional daily meteorological data is available from a National Water and Climate Center SNOTEL station (Monahan Flat). Seven climate stations (Monahan Flat, Gracious House, Alpine Creek Lodge, Maclaren River, Tyone Lake, Lake Susitna and Lake Louise) are located within the upper Susitna basin, but show intermittent measurements throughout the period of record (Figure 7.2.1-2). Meteorological observations within the Susitna River basin are available from 1980-1984 (described below).

Precipitation is an important influence on the basin hydrology of northern high-latitude watersheds. However, biases towards systematic underestimation of precipitation are well known and due to the documented undercatch of precipitation gauges, and is especially the case for solid precipitation (Black 1954; Hare and Hay 1971; Benson 1982). Since snow is such a significant part of the annual meteorologic input of water (Dingman et al. 1971), these errors strongly affect the uncertainty of water balance calculations. Further, despite the knowledge of orographic forcing of precipitation, most precipitation gauges (and especially long-term installations), are located in valley bottoms due to logistical constraints. Accordingly, it is challenging to construct total precipitation for a watershed that is dominated by complex topography (e.g. the Susitna River basin).

7.2.2. Historical Observations in the Susitna Basin

As part of the early 1980s Susitna hydropower studies (as described above), many agencies participated in gathering field data to meet the FERC licensing requirements. These data were used to assess the hydrologic resources and aid the stream flow forecasting for future dam operations. In order to supplement climate data provided by NOAA, R&M Consultants, Inc. constructed six climate stations within the Susitna River Basin that recorded meteorological parameters in hourly time steps from 1980 to 1984 (Figure 4.2.4.2-1). One high-elevation climate station was installed in the Eastern Alaska Range near the confluence of the four major glaciers that contribute runoff to the Susitna River, two climate stations were installed in the Upper Susitna River Basin, one station was placed at the proposed Watana dam site, and two stations were installed downstream of the dam site (Table 7.2.2-1). At each climate station, meteorological observations of air temperature, wind speed and direction, relative humidity, precipitation, and solar energy were recorded. Air temperature at the six climate stations monitored from 1980 to 1984 is shown in Figure 7.2.2-1. Except for the climate data gathered between 1981- 1982, meteorological data were published in separate annual reports for each station (Table 7.2.2-2).

In addition to meteorological data, the Susitna hydropower studies also measured mass balance on glaciers in the upper basin (see section in Glaciers) and recorded a total of 165 snow depth measurements from 16 locations (on and off glacier) in the upper basin during 1981 and 1982 (Figure 7.2.2-2; R&M Consultants Inc. 1982).

The historic data from the 1980s Susitna hydropower studies are important for calibrating the hydrological model for the current Glacier and Runoff Changes study.

7.2.3. Gridded Datasets

Weather and climate data can also be represented spatially in the form of continuous grids of pixels. These datasets typically describe basic statistics of meteorological variables over a daily or monthly time step, and are generated by combining observations of meteorological variables at ground- and ocean-based stations. Gridded datasets are particularly useful in Alaska, where few ground observations exist. Table 7.2.3-1 lists some of the most commonly used gridded datasets for Alaska.

7.3. Projections of Future Climate

General circulation models (GCMs) are the most widely used tools to help understand and assess climate variability and change. However, the enormous mathematical complexity and limited computational resources generally prevent GCMs from resolving processes at a high spatial resolution.

The coarse resolution (100s of km) of the GCMs hinders their capability to capture detailed mesoscale weather systems and finer scale meteorological conditions. A comparison (Figure 7.3-1) of the annual mean precipitation resolved by the National Centers for Environmental Prediction - National Center for Atmospheric Research (NCEP-NCAR) global reanalysis (Kalnay et al. 1996) and mesoscale model downscaling at different resolutions over Alaska (Zhang et al 2007a,b) further demonstrates that the finer scale structures associated with terrain effects can only be captured in the high-resolution simulations. This discrepancy caused by the coarse resolution of GCMs limits their application and suitability for understanding and assessing regional and local scale climate variability and changes.

Downscaling methodologies (e.g., statistical or dynamical) are used to quantitatively obtain regional and local scale climate change information from coarse resolution GCM outputs. Statistical downscaling techniques such as those used in Scenarios Network for Alaska and Arctic Planning (SNAP) climate dataset. The SNAP dataset include years 1980-2099 and are downscaled to 2 km grid cells. Future projections from SNAP are derived from a composition of the five best-ranked GCMs (out of 15 used by the Intergovernmental Panel on Climate Change; IPCC) models for Alaska. Based on how closely the model outputs matched climate station data for temperature, precipitation, and sea level pressure for the recent past, their individual ranking order for overall accuracy in Alaska and the far north was as follows: 1) ECHAM5 2) GFDL21, 3) MIROC, 4) HAD, and 5) CCCMA. The five-model composite uses mean values from the outputs of these models. Results from three emission scenarios (A2, A1B and B2) are available from the SNAP website (http://www.snap.uaf.edu/home). Dynamical regional climate downscaling technique is commonly applied to better represent and understand the local weather systems and associated impacts (Bengtsson et al. 1996, Lynch et al. 1998, Zhang et al. 2007a, b). The Coordinated Regional Climate Downscaling Experiment (CORDEX, http://wcrp.ipsl.jussieu.fr/cordex/about.html) and the North American Regional Climate Change Assessment Program (NARCCAP, http://www.narcacap.ucar.edu) are such efforts. The downscaled domains included in CORDEX are mainly for the continental regions around the world and the NARCCAP covers most of North America. Unfortunately, a complete Alaska downscaling is not included in either CORDEX or NARCCAP efforts, further downscaling of the most recent CMIP5 simulations (fifth phase of the Coupled Model Intercomparison Project), an important resource for the IPCC fifth assessment report, is not planned in NARCCAP, thus necessitating further downscaling activity focused on the CMIP5 simulations for Alaska.

8. DISCUSSION

The FERC-required portion of this study is complete and the results of the larger study will be used to help in the assessment of project effects on the hydroelectric reservoir and operational planning.

9. LITERATURE CITED

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10. TABLES

Table 4.1-1. Reported studies of regional-scale glacier mass changes in Alaska (including the adjacent glaciers in northwestern Canada).

Assuming, where necessary, an ice/firn/snow density of 900 kg m-3 and rounding to whole years.

Reference	Original unit	Mass change (Gt yr^{-1})	Specific mass change (m w.e. yr^{-1})	Domain (area, km^2)	Period	Method
Alaska and NW Canada						
Arendt et al. 2002	–52±15 $km^3 yr^{-1}$ w.e.	–52±15	-0.57	Alaska (90,000)	1955-5/1995	Laser altimetry/maps
Arendt et al. 2002	–96±35 $km^3 yr^{-1}$ w.e.	–96±35	-1.07	Alaska (90,000)	5/1995-5/2000	Laser altimetry
Tamisiea et al. 2005	-110±30 $km^3 yr^{-1}$ w.e.	-110±30	-1.26	Alaska (87,000)	4/2002-6/2004	GRACE
Chen et al. 2006	-101±22 $km^3 yr^{-1}$ w.e.	-101±22	-1.11	Alaska (90,957)	4/2002-11/2005	GRACE
Luthcke et al. 2008	-84±5 Gt yr^{-1}	-84±5	-1.02	Gulf of Alaska (82,505)*	4/2003-9/2007	GRACE
Berthier et al. 2010	-41.9±8.6 $km^3 yr^{-1}$ w.e.	-41.9±8.6	-0.48	Alaska (87,860)	1962-2006	geodetic
Wu et al. 2010	-101±23 Gt yr^{-1}	-101±23		Alaska **	4/2002-12/2008	GRACE
Luthcke et al. 2013	-68.8±11 Gt yr^{-1}	-68.8±11	-0.91	Alaska (76,000)	12/2003-12/2010	GRACE
Gardner et al. 2013	-50±17 Gt yr^{-1}	-50±17	-0.57	Alaska (87,100)	2003-2009	GRACE
Arendt et al. 2013	-65±11 Gt yr^{-1}	-65±11	-0.79	Gulf of Alaska (82,505)	12/2003-12/2010	GRACE
Arendt et al. 2013	-61±11 Gt yr^{-1}	-61±11	-0.74	Gulf of Alaska (82,505)	10/2003-10/2009	GRACE
Arendt et al. 2013	-65±12 Gt yr^{-1}	-65±12	-0.79	Gulf of Alaska (82,505)	10/2003-10/2009	ICESat
Subregions in Alaska						
Adalgeirsdottir 1998	-34 km^3 ice	-0.71	-0.39	Harding Icefield (1,800)	1950/52-1994/96	Laser altimetry/map
Arendt et al. 2002	-5.3 $km^3 yr^{-1}$ w.e.	-5.3		Alaska Range **	1955-5/1995	Laser altimetry/maps
Arendt et al. 2002	-1.0 $km^3 yr^{-1}$ w.e.	-1.0		Brooks Range **	1955-5/1995	Laser altimetry/maps
Arendt et al. 2002	-5.4 $km^3 yr^{-1}$ w.e.	-5.4		Coast Range **	1955-5/1995	Laser altimetry/maps
Arendt et al. 2002	-2.7 $km^3 yr^{-1}$ w.e.	-2.7		Kenai Mountains **	1955-5/1995	Laser altimetry/maps
Arendt et al. 2002	-25.7 $km^3 yr^{-1}$ w.e.	-25.7		St. Elias Mountains **	1955-5/1995	Laser altimetry/maps
Arendt et al. 2002	-6.8 $km^3 yr^{-1}$ w.e.	-6.8		Western Chugach Mountains **	1955-5/1995	Laser altimetry/maps
Arendt et al. 2002	-1.3 $km^3 yr^{-1}$ w.e.	-1.3		Wrangell Mountains **	1955-5/1995	Laser altimetry/maps
Arendt et al. 2002	-4.2 $km^3 yr^{-1}$ w.e.	-4.2		Tidewater glaciers **	1955-5/1995	Laser altimetry/maps
Arendt et al. 2006	-7.4 ± 1.1 $km^3 yr^{-1}$ weq	-7.4 ± 1.1	-0.80	Western Chugach Mts (9,300)	1955-5/1995	Laser altimetry/maps
Larsen et al. 2007	-16.7 ± 4.4 km^3 ice yr^{-1}	-15.0±4.0	-1.03	Southeast Alaska (14,580)	8/1948-2/2000	geodetic
Arendt et al. 2008	-0.43±0.12 m w.e. yr^{-1}	-21.2±3.8	-0.64	St Elias Mtns (32,900)	9/2003-8/2007	Laser altimetry
Arendt et al. 2008	-0.63±0.09 m w.e. yr^{-1}	-20.6±3.0	-0.63	St Elias Mtns (32,900)	9/2003-8/2007	GRACE
Johnson et al. 2013	3.93±0.89 Gt yr^{-1}	3.93±0.89	-0.61	Glacier Bay (6,428)	1995-2011	Laser altimetry
Das et al. in press	-0.07±0.19 m w.e. yr^{-1}	-0.34±0.93	-0.07	Wrangell Mountains (4,900)	1957-2000	Laser altimetry/DEM
Das et al. in press	-0.24±0.16 m w.e. yr^{-1}	-1.18±0.78	-0.24	Wrangell Mountains (4,900)	2000-2007	Laser altimetry/DEM

* "32,900km^2, about 40% of the area" yields 82,250. So here we assume the area is equal to Arendt et al. 2013.

** Area not defined in the reference.

Table 4.2.4.2-1. Summer, winter and annual mass balances in meters water equivalent for the four major glaciers in the Susitna River Basin.

*Assumed annual balance at East Fork Glacier was -0.3 m in 1981. Data provided from Clarke et al. (1985).

Glacier Name	Mass Balance Measurements for Susitna River Basin Glaciers (m w.eq.)								
	Summer Balance b_s May 15 to September 30			Winter Balance b_w October 1 to May 14			Annual Balance b_a October 1 to September 30		
	1981	1982	1983	1981	1982	1983	1981	1982	1983
West Fork	-0.87	-1.02	-0.81	0.86	0.78	0.93	-0.01	-0.24	0.12
Susitna	-1.03	-0.87	-0.38	0.76	0.65	0.78	-0.3	-0.22	0.4
East Fork	--	-0.97	-0.69	--	0.77	0.78	--*	-0.2	0.09
Maclaren	-0.52	-1	-0.7	0.83	1.44	1.07	0.3	0.14	0.37
Average	-0.85	-0.96	-0.63	0.8	0.81	0.89	0.05	-0.15	0.26

Table 7.3. Total runoff measured at several stream gauges and the estimated runoff contributions from the glacierized area in the Susitna River Basin.

All data and averages are for the period 1981 to 1983 and are taken from Clarke et al. (1985). [a]The total flow above the Denali Highway is compiled from the Maclaren River and Susitna River at Denali Highway stream gauges. [b]The total glacier runoff contribution does not include runoff from glaciers in the Talkeetna Mountains at the Susitna River at Gold Creek stream gauge. [c]The glacierized area is not known accurately because the meltwater contribution from Eureka Glacier changes from the Delta River to the Susitna River at unknown intervals (R&M Consultants, Inc. 1981).

Stream Gauge Name	Runoff in Susitna River Basin					
	Average Total Runoff at Stream Gauge (m/yr)	Total Glacier Runoff (m/yr) (snow, firn, ice, rain)			Glacier Runoff Component % of Total Runoff[c]	Glacierized Area (km^2)[c]
	1981 - 1983	1981	1982	1983	1981 - 1983	1981 - 1983
Maclaren River at Denali Hwy	1.22	1.3	1.4	1.2	24%	160[c]
Susitna River at Denali Hwy	1.07	1.7	1.7	1.4	38%	628
Total flow above Denali Hwy[a]	1.1	--	--	--	34%	790[c]
Susitna River at Gold Creek[b]	0.59	1.6	1.6	1.4	13%	790[c]

Table 7.2.2-1. Meteorological stations used to record climatic data from 1980 to 1984 in the Susitna River Basin by R&M Consultants, Inc.

Climate Station Name	General Region	Land Cover Classification	Elevation (m)	Coordinates	Period of Record
Denali	Upper Susitna Basin	Shrubland	828	63° 05' 24" N 147° 28' 12" W	July 1980 - Dec 1984
Kosina Creek	Upper Susitna Basin	Shrubland	792	62° 41' 24" N 147° 58' 12" W	Aug 1980 - Dec 1984
Susinta Glacier	Alaska Range Mountains	Barren Land	1433	63° 31' 48" N 146° 53' 24" W	July 1980 - Dec 1984
Watana	At Proposed Dam Site	Shrubland	701	62° 50' 24" N 148° 30' 36" W	Apr 1980 - Dec 1984
Devil Canyon	Downstream of Dam Site	Coniferous Forest	457	62° 48' 50" N 149° 18' 50" W	Apr 1980 - Dec 1984
Sherman	Downstream of Dam Site	Mixed Forest	183	62° 42' 10" N 149° 49' 52" W	Oct 1981 - Dec 1984

Table 7.2.2-2. Individual sources for recovered climate data from the Susitna basin during the period 1980-1984.

Denali Station	Source
Year 1980 – 1981	R&M Consultants, Inc. (1982), Susitna Hydroelectric Project, Processed Climatic Data, Volume 2, Denali Station. Prepared for Acres American Inc. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol2/hydropower/APA_DOC_no._200.pdf.
Year 1981 – 1982	R&M Consultants, Inc. (1982), Susitna Hydroelectric Project 1982 Field Data, Collection and Processing, Supplement 1. Prepared for Acres American Inc. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/2/APA211.pdf.
Year 1982 – 1983	R&M Consultants, Inc. (1984), Processed Climatic Data October 1982 - September 1983, Vol. 2, Denali Station. Final Report, Document No. 1089. Under Contract to Hazra-Ebasco Sustina Joint Venture. Prepared for Alaska Power Authority. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/10/APA1089.pdf.
Year 1983 – 1984	R&M Consultants, Inc. (1985), Processed Climatic Data October 1983 - December 1984, Vol. 2, Denali Station. Final Report, Document No. 2768. Under Contracted to Hazra-Ebasco Sustina Joint Venture. Prepared for Alaska Power Authority. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/27/APA2768.pdf.

Devil Canyon Station	Source
Year 1980 – 1981	R&M Consultants, Inc. (1982), Susitna Hydroelectric Project, Processed Climatic Data, Volume 6, Devil Canyon Station. Prepared for Acres American Inc. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol2/hydropower/APA_DOC_no._208.pdf

Year 1981 – 1982	R&M Consultants, Inc. (1982), Susitna Hydroelectric Project 1982 Field Data, Collection and Processing, Supplement 1. Prepared for Acres American Inc. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/2/APA211.pdf.
Year 1982 – 1983	R&M Consultants, Inc. (1984), Processed Climatic Data October 1982 - September 1983, Vol. V, Devil Canyon Station. Final Report, Document No. 1092. Under Contract to Hazra-Ebasco Sustina Joint Venture. Prepared for Alaska Power Authority. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/10/APA1092.pdf.
Year 1983 – 1984	R&M Consultants, Inc. (1985), Processed Climatic Data October 1983 - December 1984, Vol. 5, Devil Canyon Station. Final Report, Document No. 2771. Under Contracted to Hazra-Ebasco Sustina Joint Venture. Prepared for Alaska Power Authority. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/27/APA2771.pdf.

Kosina Creek Station	Source
Year 1980 – 1981	R&M Consultants, Inc. (1982), Susitna Hydroelectric Project 1982 Field Data, Collection and Processing, Supplement 1. Prepared for Acres American Inc. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol2/hydropower/APA_DOC_no._204.pdf.
Year 1981 – 1982	R&M Consultants, Inc. (1982), Susitna Hydroelectric Project 1982 Field Data, Collection and Processing, Supplement 1. Prepared for Acres American Inc. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/2/APA211.pdf.
Year 1982 – 1983	R&M Consultants, Inc. (1984), Processed Climatic Data October 1982 - September 1983, Vol. 3, Kosina Creek Station. Final Report, Document No. 1090. Under Contract to Hazra-Ebasco Sustina Joint Venture. Prepared for Alaska Power Authority. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/10/APA1090.pdf.
Year 1983 – 1984	R&M Consultants, Inc. (1985), Processed Climatic Data October 1983 - December 1984, Vol. 3, Kosina Creek Station. Final Report, Document No. 2769. Under Contract to Hazra-Ebasco Sustina Joint Venture. Prepared for Alaska Power Authority. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/27/APA2769.pdf.

Sherman Station	Source
Year 1981 – 1982	R&M Consultants, Inc. (1982), Susitna Hydroelectric Project 1982 Field Data, Collection and Processing, Supplement 1. Prepared for Acres American Inc. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/2/APA211.pdf.
Year 1982 – 1983	R&M Consultants, Inc. (1984), Processed Climatic Data October 1982 - September 1983, Vol. 6, Sherman Station. Final Report, Document No. 1093. Under Contract to Hazra-Ebasco Sustina Joint Venture. Prepared for Alaska Power Authority. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/10/APA1093.pdf.
Year 1983 – 1984	R&M Consultants, Inc. (1985), Processed Climatic Data October 1983 - December 1984, Vol. 6, Sherman Station. Final Report, Document No. 2772. Under Contract to Hazra-Ebasco Sustina Joint Venture. Prepared for Alaska Power Authority. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/27/APA2772.pdf.

Susitna Glacier Station	Source
Year 1980 – 1981	R&M Consultants, Inc. (1982), Susitna Hydroelectric Project, Processed Climatic Data Volume 5 Susitna Glacier Station. Prepared for Acres American Inc. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol2/hydropower/APA_DOC_no._198.pdf.
Year 1981 – 1982	R&M Consultants, Inc. (1982), Susitna Hydroelectric Project 1982 Field Data, Collection and Processing, Supplement 1. Prepared for Acres American Inc. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/2/APA211.pdf.
Year 1982 – 1983	R&M Consultants, Inc. (1984), Processed Climatic Data October 1982 - September 1983, Vol. 1, Susitna Glacier Station. Final Report, Document No. 1088. Under Contract to Hazra-Ebasco Sustina Joint Venture. Prepared for Alaska Power Authority. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/10/APA1088.pdf.
Year 1983 – 1984	R&M Consultants, Inc. (1985), Processed Climatic Data October 1983 - December 1984, Vol. 1, Susitna Glacier Station. Final Report, Document No. 2767. Under Contract to Hazra-Ebasco Sustina Joint Venture. Prepared for Alaska Power Authority. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/27/APA2767.pdf.

Watana Station	Source
Year 1980 – 1981	R&M Consultants, Inc. (1982), Susitna Hydroelectric Project, Processed Climatic Data, Volume 5, Watana Station. Prepared for Acres American Inc. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol2/hydropower/APA_DOC_no._206.pdf.
Year 1981 – 1982	R&M Consultants, Inc. (1982), Susitna Hydroelectric Project 1982 Field Data, Collection and Processing, Supplement 1. Prepared for Acres American Inc. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/2/APA211.pdf.
Year 1982 – 1983	R&M Consultants, Inc. (1984), Processed Climatic Data October 1982 - September 1983, Vol. 4, Watana Station. Final Report, Document No. 1091. Under Contract to Hazra-Ebasco Sustina Joint Venture. Prepared for Alaska Power Authority. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/10/APA1091.pdf.
Year 1983 – 1984	R&M Consultants, Inc. (1985), Processed Climatic Data October 1983 - December 1984, Vol. 4, Watana Station. Final Report, Document No. 2770. Under Contract to Hazra-Ebasco Sustina Joint Venture. Prepared for Alaska Power Authority. Susitna Hydroelectirc Project, Federal Energy Regulatory Commission, Project No. 7114. Available at: http://www.arlis.org/docs/vol1/Susitna/27/APA2770.pdf.

Table 7.2.3-1. Overview of gridded Climate Products for Alaska.

Gridded Products	Spatial Resolution	Temporal Resolution / Period covered

OSU's David Hill's Monthly Temperature and Precipitation grids for Alaska, British Columbia, and Yukon	2 km	Monthly / 1961 - 2009
University of British Columbia NARR downscaled Temperature, Precipitation, and Solar grids (SE AK and BC at present)	< 2 km	Daily
SNAP Temperature and Precipitation historical (CRU TS 3.1 1901-2009)	771 m / 2 km	Monthly / 1901 - 2009
OSU's PRISM (1971-2000)	800 m / 4 km	Monthly / 1971 - 2000
NCEP Climate Forecast System Reanalysis (CFSR) (1979-2010)	38 km – 2.5 deg	Hourly, 6-hourly, monthly 1979 - 2010
ECMEF ERA 40 Temperature and Precipitation (1958-2002)	0.5 deg	1958 - 2002
ECMEF ERA Interim	0.5 deg	1979 – Present
NCEP and NCAR	2.5 deg	1948 – Present
NARR	32 km	1979 – Present

11. FIGURES

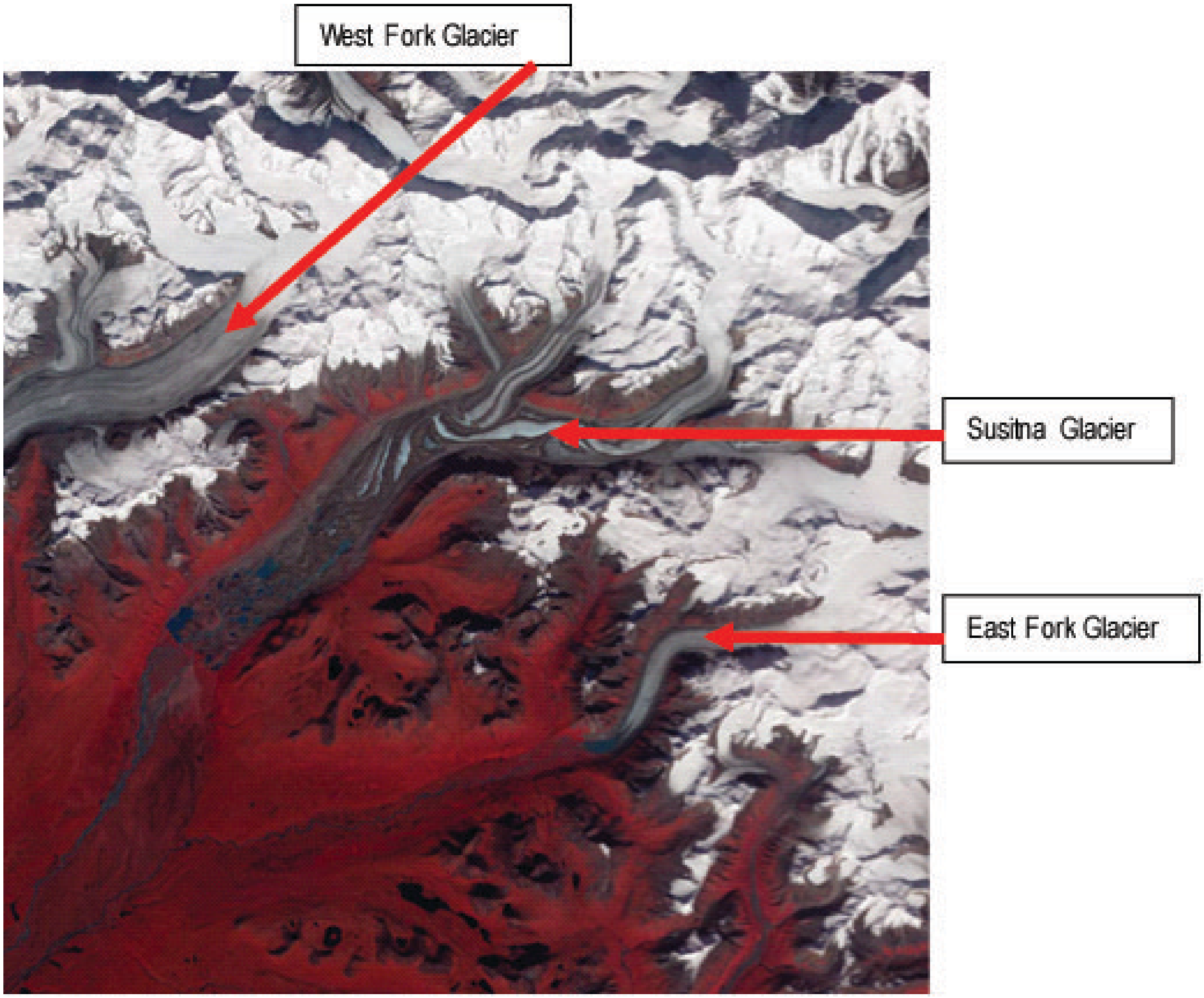

Figure 2.1. Susitna Glacier and other unnamed glaciers contributing to Upper Susitna River drainage.

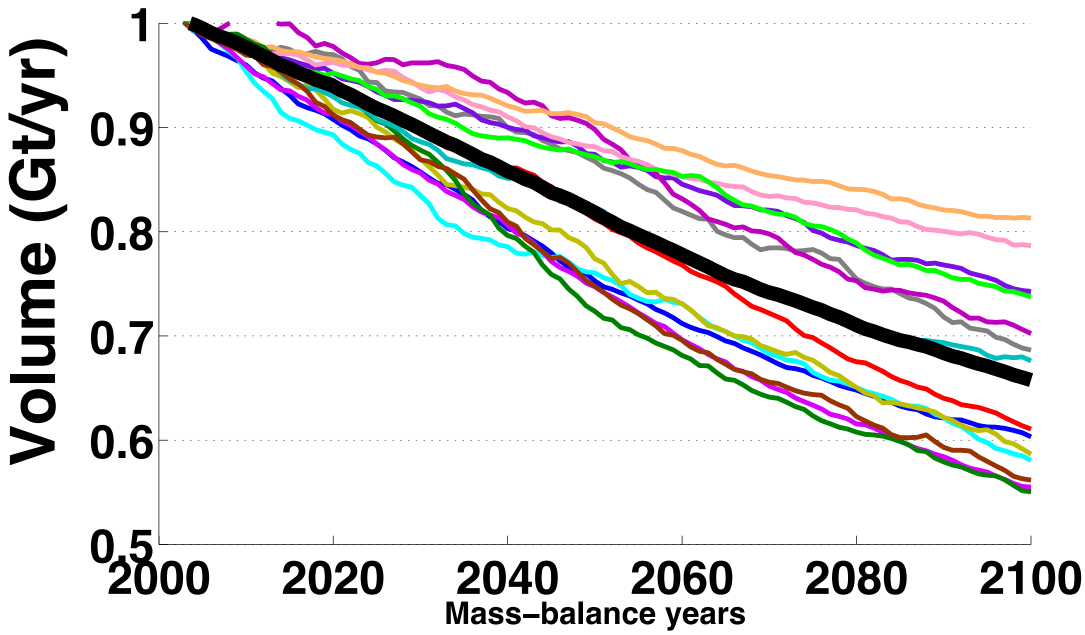

Figure 4.1-1. 100-year projections of glacier volume in Alaska using 14 Global Climate Models forced by the RCP4.5 emission scenario.
Glaciers in Alaska are expected to lose 18-45% (multi-model mean 32%) of their initial volume (2003) by the end of the century (Radic et al. 2013).

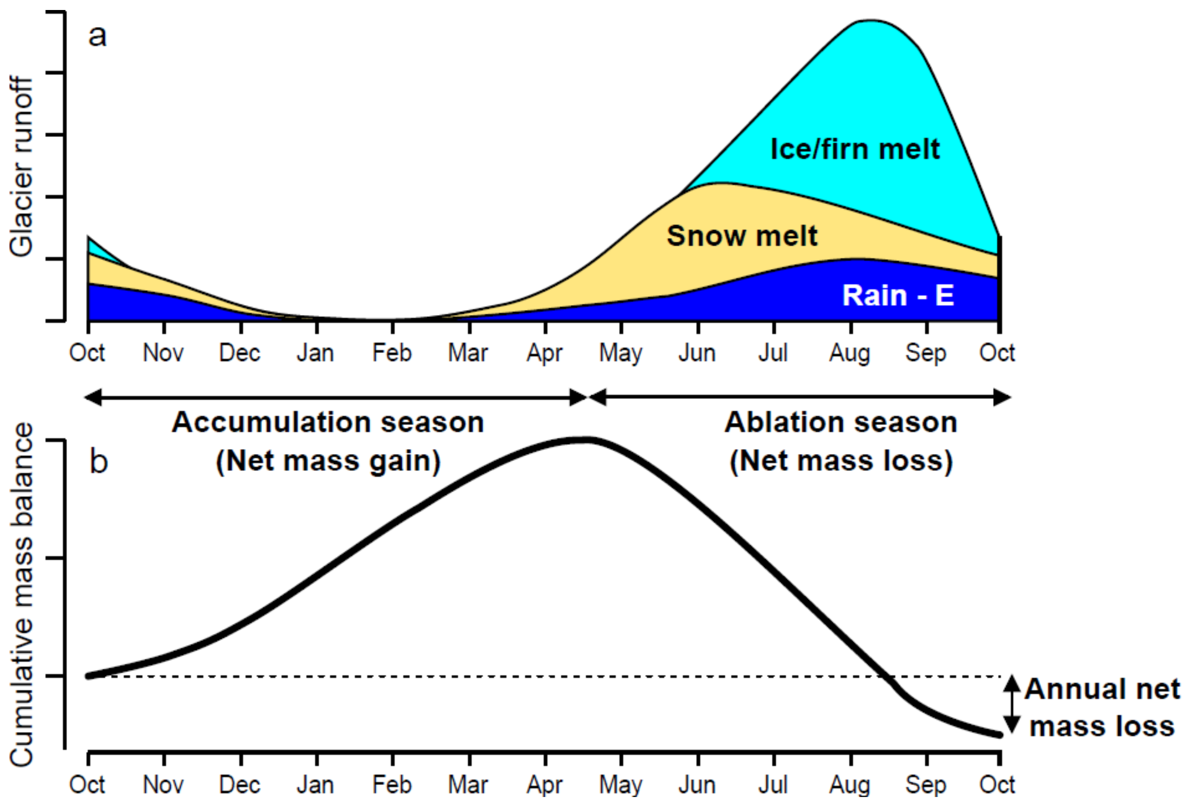

Figure 4.2.2-1. Variations in glacier runoff and mass balance.
(a) Schematic seasonal variation of total glacier runoff, defined as all water exiting a glacier, and its components, E is evaporation; (b) cumulative glacier mass balance in specific units (m w.e. year-1) showing a year with negative annual balance (Radic and Hock in press).

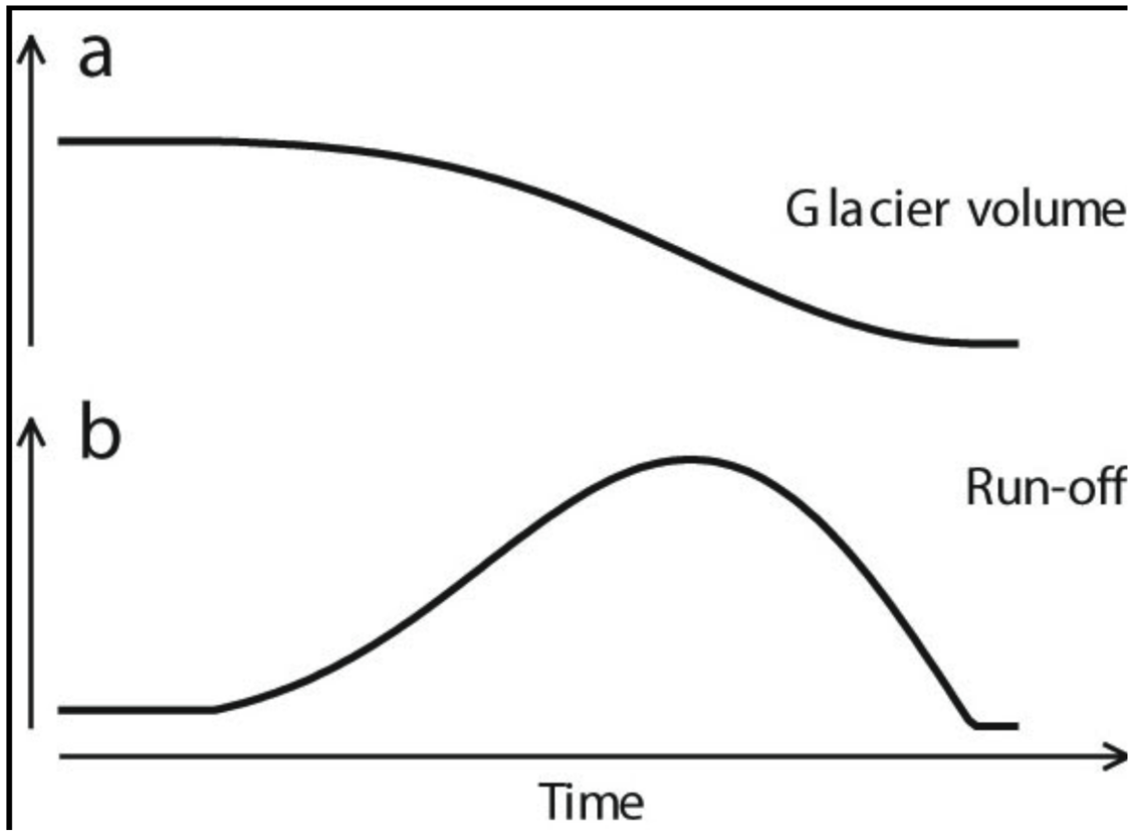

Figure 4.2.2-2. Schematic representation of the long-term effects glacier mass loss on: a) glacier volume; and b) glacier runoff.

Note that runoff initially increases as melt is enhanced but then reaches a 'turning point' beyond which runoff decreases as the glacier shrinks thus reducing the excess runoff from glacier storage (modified from Jansson et al. 2003).

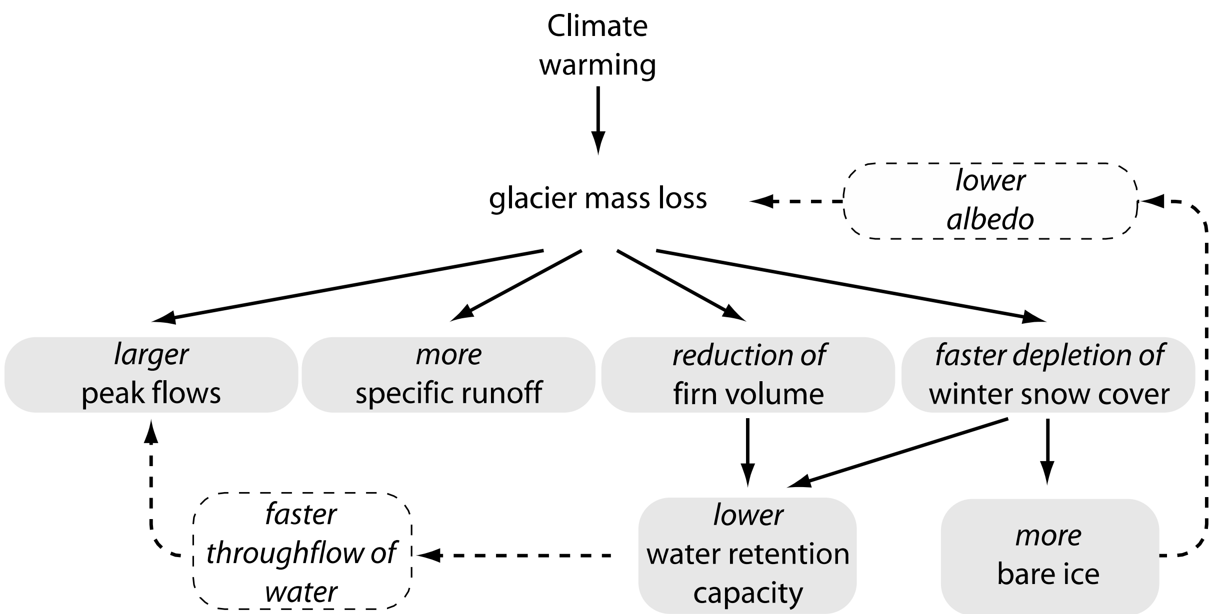

Figure 4.2.2-3. Initial effects of atmospheric warming on glacier runoff including feedback mechanisms leading to further enhanced runoff totals and peak flows (Hock et al. 2005).

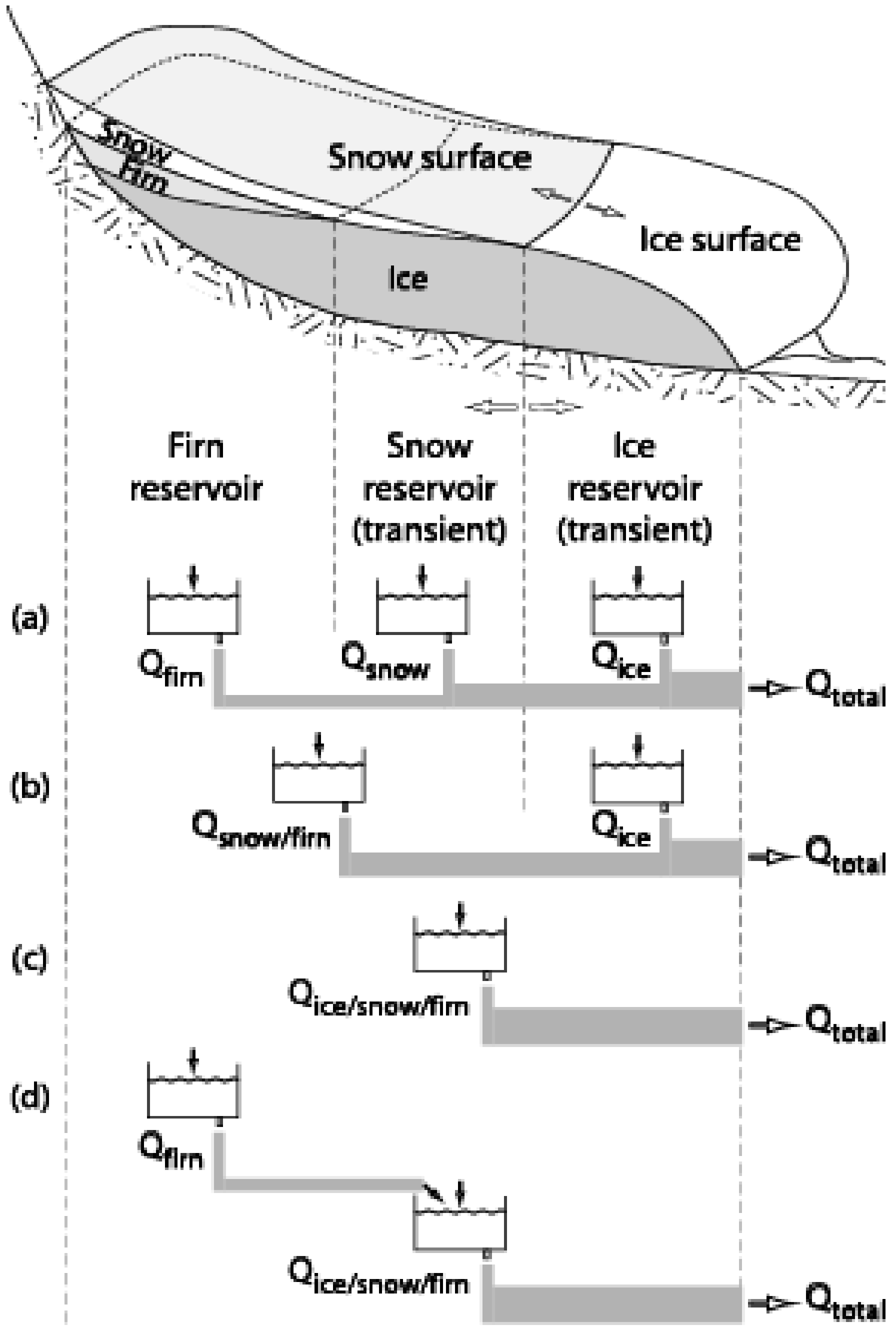

Figure 4.2.3.3-1. Concept of linear reservoirs as applied to glaciers using one to three (c-a) different linear reservoirs.

Reservoirs are coupled in parallel in (a-b), and in series in (d). Exact delineation of reservoirs varies between studies. Q is outflow from the reservoirs (Hock et al. 2005b).

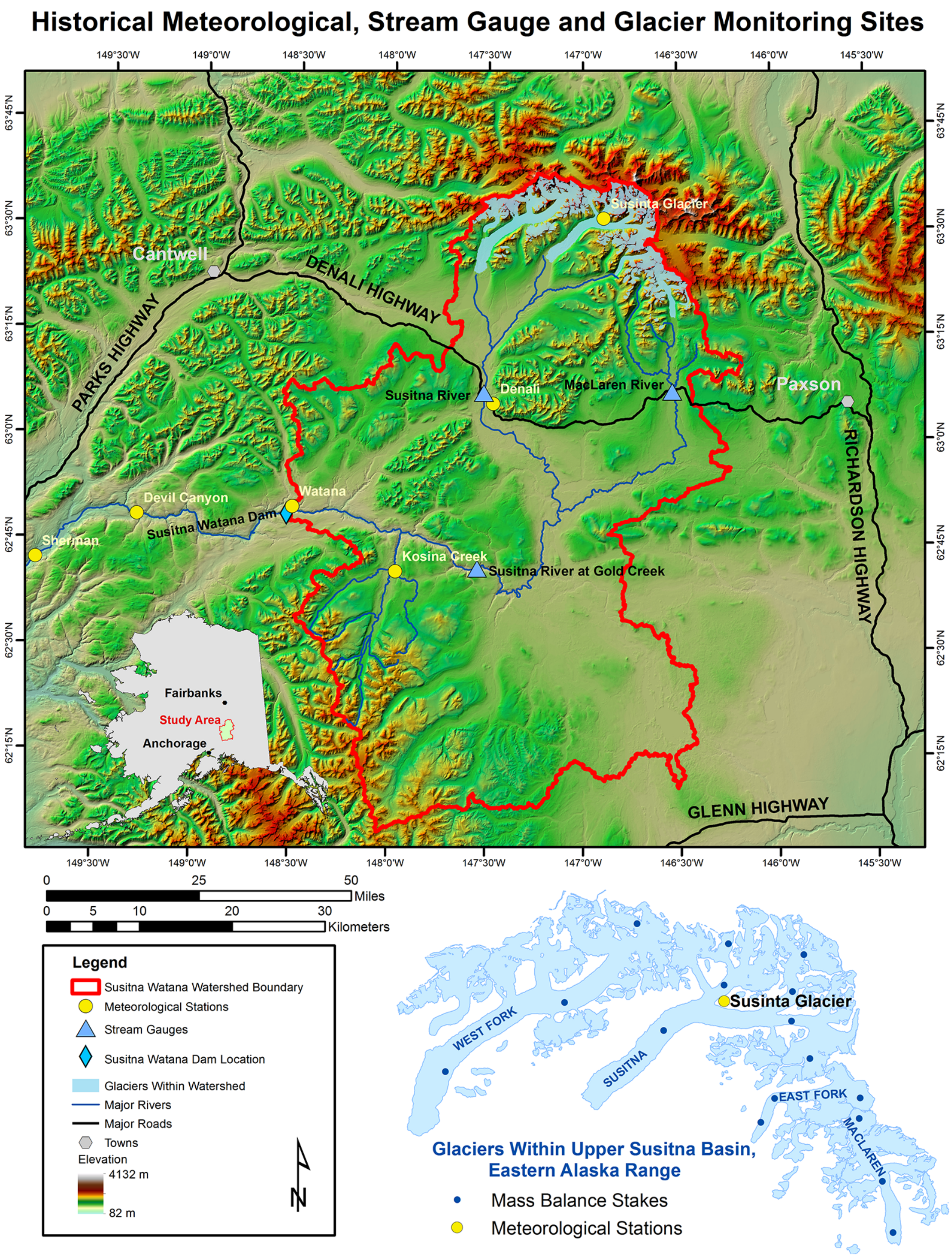

Figure 4.2.4.2-1 Map of the upper Susitna basin, including the locations of historical meteorological, stream gauge and glacier monitoring stations.

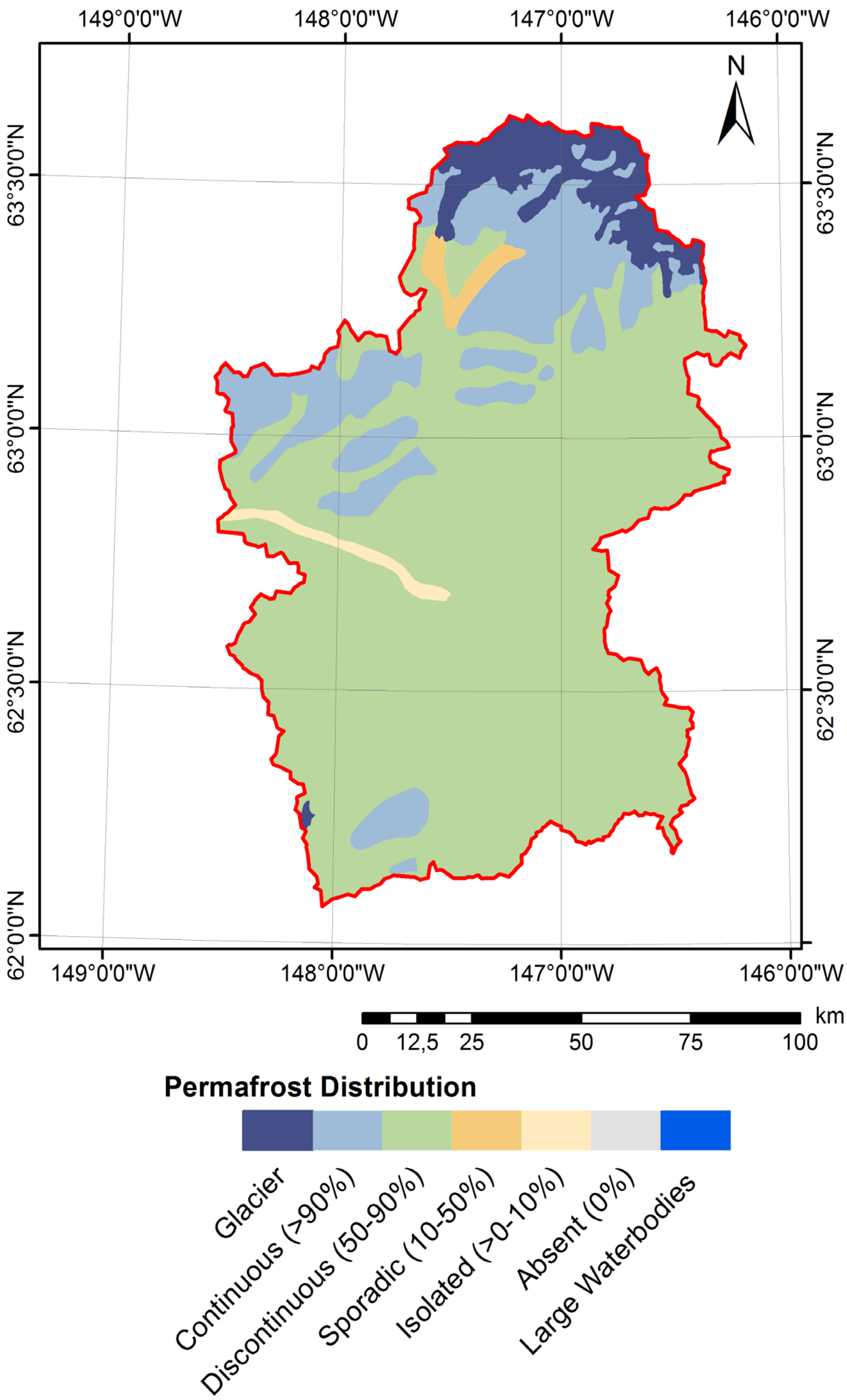

Figure 5-1. Permafrost distribution in the upper Susitna basin.
A majority of the area draining into the proposed dam is estimated to be underlain by discontinuous and continuous permafrost (modified after Jorgenson et al. 2008). Maximum depth to the base of permafrost in the Maclaren River junction with the Susitna River is about 200 m (Alaska District, Corps of Engineers 1975), while it is 40 m at Gulkana, which is just outside the basin to the southeast (Geophysical Institute permafrost lab).

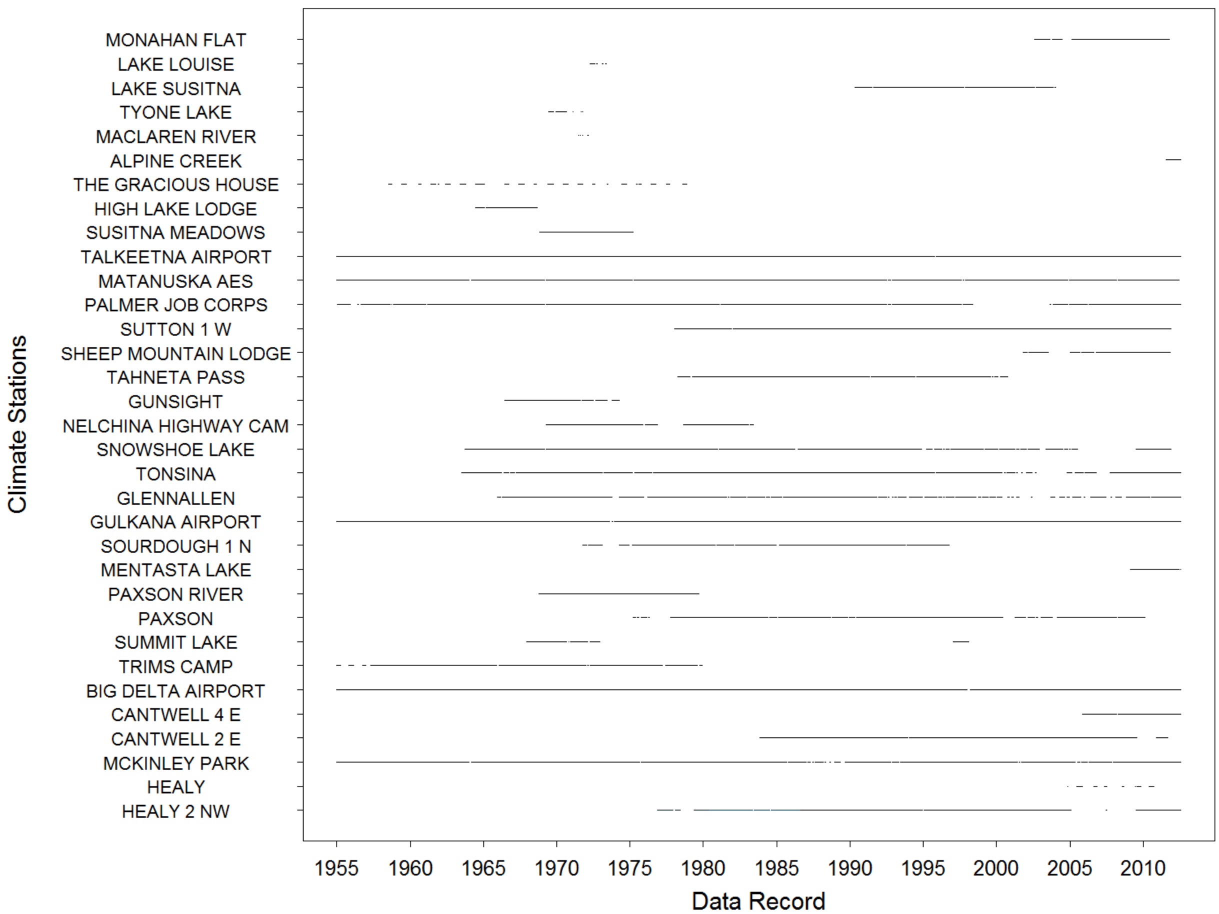

Figure 7.2.1-1. Coverage of temperature and precipitation data at 33 Climate Stations in and in proximity of the Upper Susitna Basin.
A black bar indicates that coverage exists.

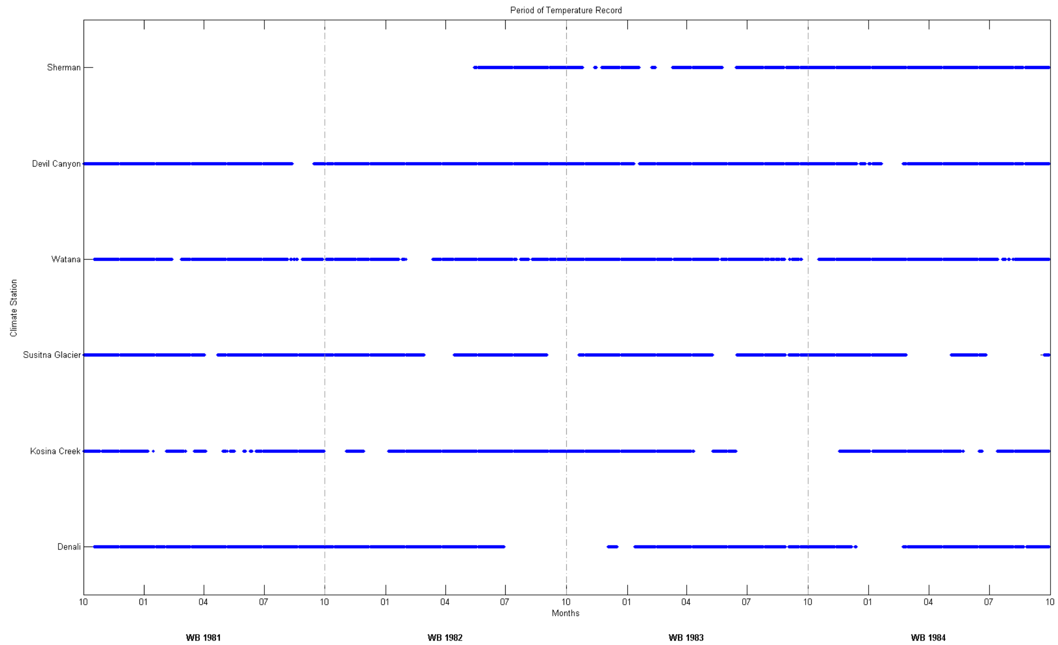

Figure 7.2.1-2. Period of record for temperature measurements collected during the 1980s in the Susitna basin.

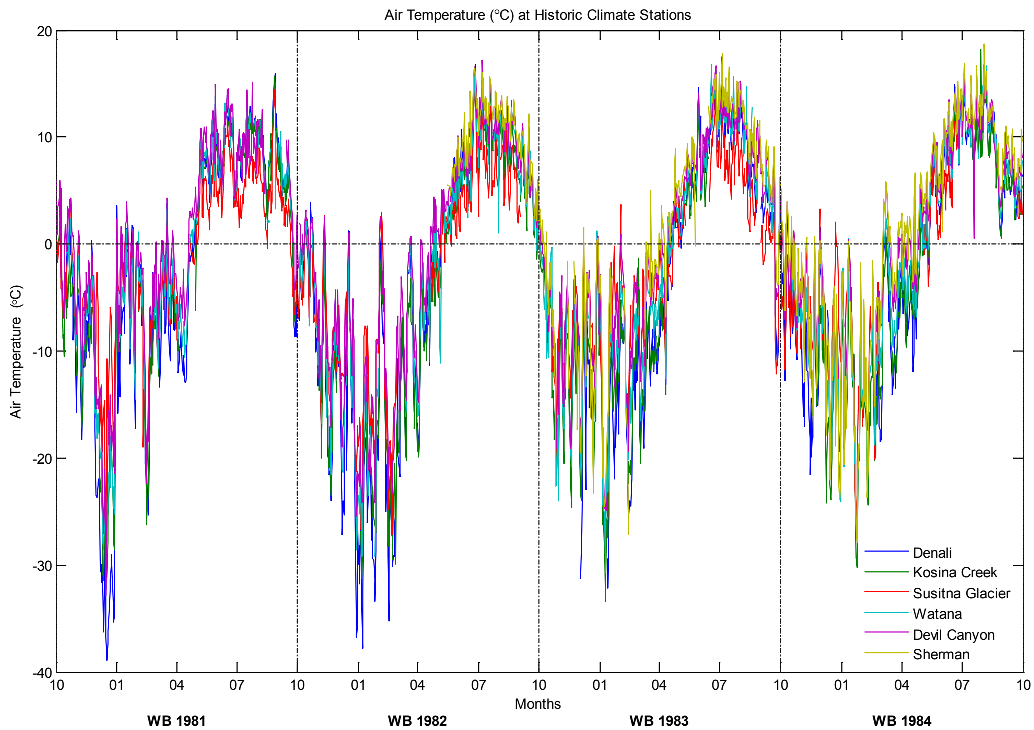

Figure 7.2.2-1. Air temperature in degrees Celsius at the six climate stations monitored from 1980 to 1984. The hydrologic year is indicated by the dashed black vertical lines. The hydrologic year runs from September 30th to October 1st of the following year.

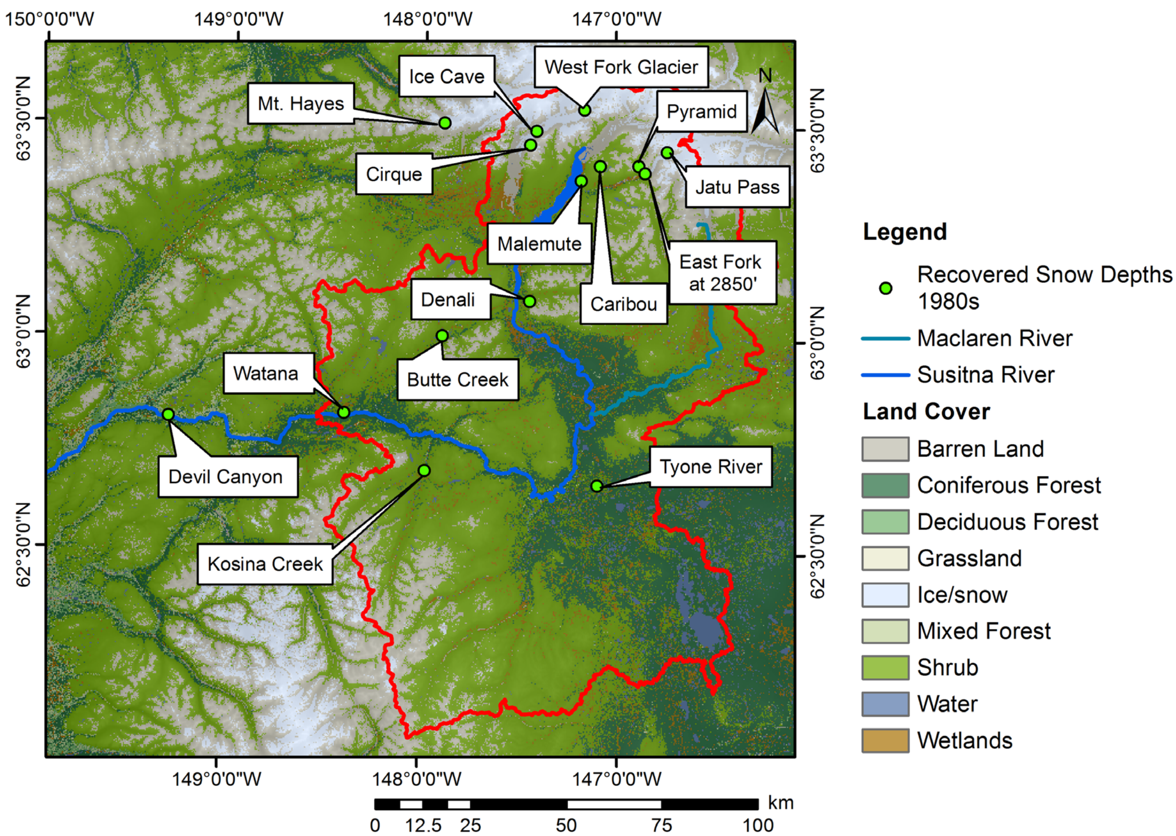

Figure 7.2.2-2. Recovered Snow Depth Measurements (1981 and 1982; source: R&M Consultants, Inc. 1982).

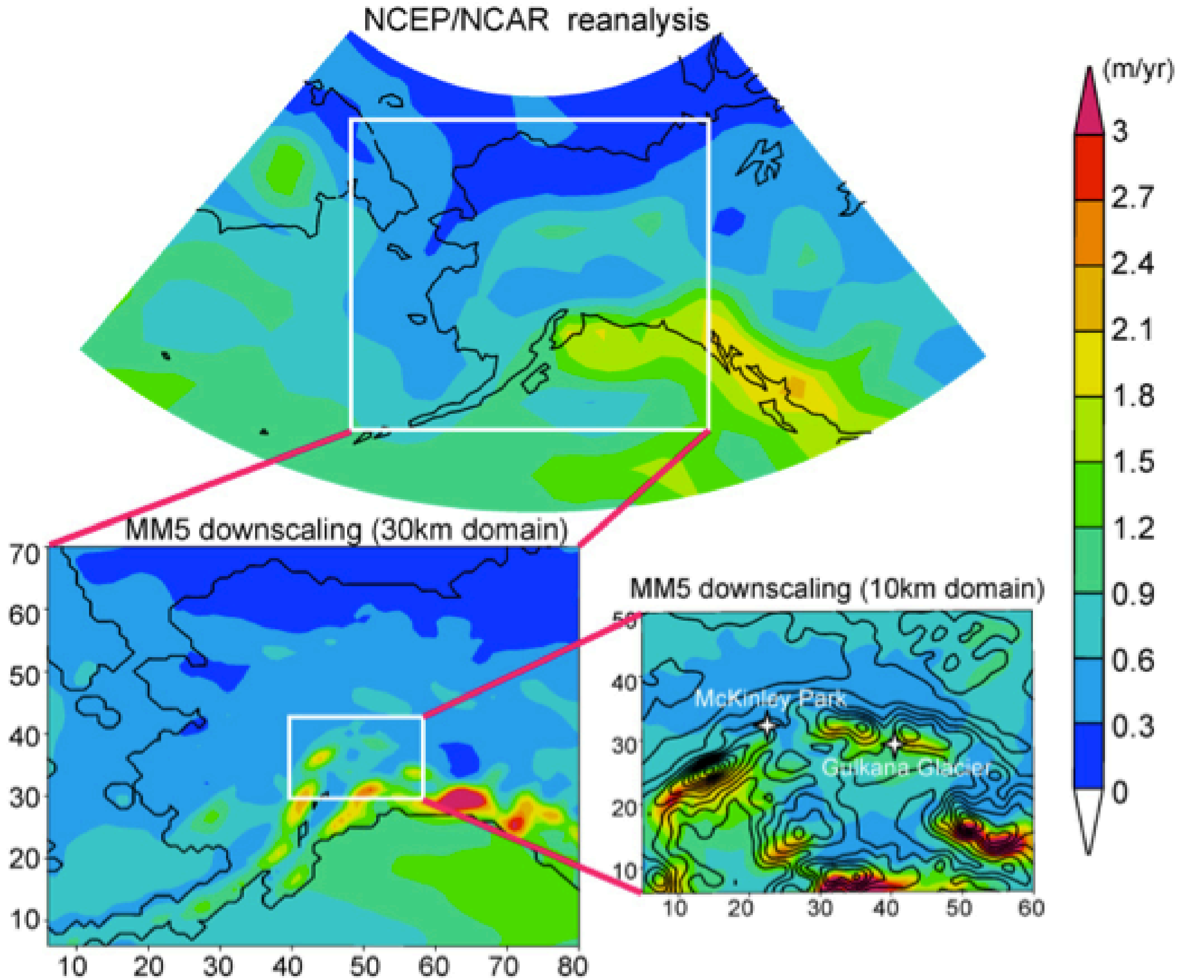

Figure 7.3-1. Comparisons of annual mean precipitation during 1994-2004 from the global reanalysis (2.5^ox2.5^o), 30km and 10km downscaling (topography in black contour and precipitation in color) (Zhang et al. 2007a).