AN ABSTRACT OF THE THESIS OF

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Title: Estimating Freshwater Fluxes into the Gulf of Alaska

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David F. Hill

Freshwater flowing into the Gulf of Alaska is tremendously difficult to quantify, given extreme geologic, topographic, and climatic conditions. Regression equations for mean monthly streamflow in watersheds running into the Gulf of Alaska have been determined in lieu of complete station data availability. The equations were obtained by regressing observed streamflow at 246 United States Geological Survey (USGS) and Environment Canada gaging stations against a number of relevant meteorological and basin physical parameters. Meteorological parameters include mean monthly precipitation, cumulative water year precipitation, and mean monthly temperature. High-resolution grids of these parameters were obtained through statistical downscaling methods. Basin physical parameters include area, mean elevation, and percent forest cover, and were selected from a larger set based upon initial regression efforts. Regionalization was used in order to organize the entire ensemble of gaged watersheds into several hydrologically similar groups, each with a unique set of equations. When

comparing regression-calculated flow to measured flow, the groups showed typical average errors of 40%, a value consistent with previously obtained USGS equations for other runoff quantities such as peak flows. Once the regression equations were finalized, they were applied to a set of ungauged watersheds making up the entire Gulf of Alaska drainage, yielding approximately 792 km^3/yr of freshwater flowing off the coast of Alaska. This prediction of freshwater runoff to the Gulf is comparable to previous studies, with watershed-scale spatial resolution and monthly temporal resolution. Implementation of a distributed hydrological model then evaluated snow water equivalent to begin to describe sources of freshwater runoff.

Estimating Freshwater Fluxes into the Gulf of Alaska

by

Noa Bruhis

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APPROVED:

Major Professor, representing Water Resources Engineering

Director of the Water Resources Graduate Program

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Noa Bruhis, Author

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Chapter 1: Introduction

1.1 Statement of Problem

Alaska is characterized by extremes. Its coastline includes dramatic variety, from the peaks in the Alaska Range to the marshes of Potter Marsh, from permanent ice around Glacier Bay to dense vegetation in Tongass National Forest, and from the Kenai Fjords to the trail of Aleutian Islands. Furthermore, its latitude subjects the region to extremes in weather and daylight hours both spatially, and from season to season. These geographical and climatic extremes have made instrumentation and data acquisition more difficult in Alaska than in the lower 48 states. As of 2013, the United States Geological Survey (USGS) maintains 110 streamflow gauging stations in the state of Alaska for current conditions[1]. With a surface area on the order of 600,000 square miles, there are approximately 0.00018 stations per square mile in Alaska. For comparison, Oregon has 224 gauging stations in an area on the order of 100,000 square miles, or 0.00224 stations per square mile. This means that Alaska has less than 1/10th the stations per square mile that Oregon has.

The Mississippi-Atchafalaya River Basin drains about 41% of the contiguous United States into the Gulf of Mexico at a mean annual flow of approximately 600,000 cubic feet per second (cfs) or 536 cubic kilometers per year (km^3/yr)[2]. Dividing by

[1] http://waterdata.usgs.gov/ak/nwis/sw

[2] http://water.epa.gov/type/watersheds/named/msbasin/marb.cfm

its 3,224,535 km^2 drainage area, this is a runoff depth of 17 centimeters per year (cm/yr). On the Mississippi, the tributaries feed into one major stream, which is easy to gauge as freshwater flows out the mouth and into the gulf. By contrast, the coast of Alaska encompasses such extremes and geologic and topographic diversity that large drainages are prevented from building up, thereby creating complexity in estimating freshwater flow into the Gulf of Alaska (GOA). Specifically, five major rivers (Susitna, Copper, Alsek, Taku, and Stikine) account for approximately 25% of the total freshwater discharge off the coast of Alaska per year [Wang et al., 2004, Neal et al., 2010]. The other 75% of freshwater runs off from countless ungauged regions such as small streams and glaciers trickling into the gulf. This study will demonstrate an average of approximately 792 km^3/yr, or an equivalent runoff depth of 170 cm/yr (as compared with the Mississippi's mere 17 cm/yr) of freshwater draining into the Gulf of Alaska off the coast of Alaska, excluding much of Canada's contribution.

1.2 Motivation

The total quantity of freshwater discharged affects many processes, habitats and dynamics. Accurate highly-resolved spatial and temporal flow data is of use to researchers from a spread of backgrounds and studies. Scientists in fields such as marine biology, chemistry, and oceanography use freshwater input values to further their research. This study fills gaps in streamflow data for all watersheds draining into the GOA from 1961 through 2009, and provides equations for interested parties seeking to estimate the flow for any historical or present time for which basin characteristic parameters, and precipitation and temperature information are available. One component of this study created the meteorological products needed for analysis. For the remainder of the document "GOA drainage" will refer to all watersheds that eventually drain into the Pacific Ocean, as outlined in purple in Figure 1.1. In addition to the drainage basin, Figure 1.1 shows a digital elevation model (DEM) of the region. While in previous studies the GOA drainage has drawn its southern boundary at the border between Alaska's panhandle and Northern British Columbia, including only the parts of Canada that flow through Alaska's coast, this purple boundary extends down to the Fraser River basin in order to include contributions to coastal freshwater discharge that originate in parts of British Columbia.

Ecologists studying periodically disturbed environments note the influence of salinity and temperature on habitats along the coast and in estuaries and bays. For example, studies in wildlife conservation and biology may examine habits of salmon and other fish populations in rivers and streams and demonstrate interest in the seasonal as well as inter-annual timing of freshwater flows. One such study noted freshwater's influence on juvenile Pacific herring habitats in the Prince William Sound [Gay & Vaughan, 2001]. In order to perform these studies, ecologists need to know answers to questions such as: How much freshwater flowed this month, based on the snowpack that has built up since the start of the water year? How will herring habitats be affected by this?

Scientists from a spectrum of backgrounds are interested in saltwater-freshwater mixing patterns, driven by freshwater inputs. For example, physical scientists and chemists can study the transport of nutrients and pollutants, such as an oil spill event,

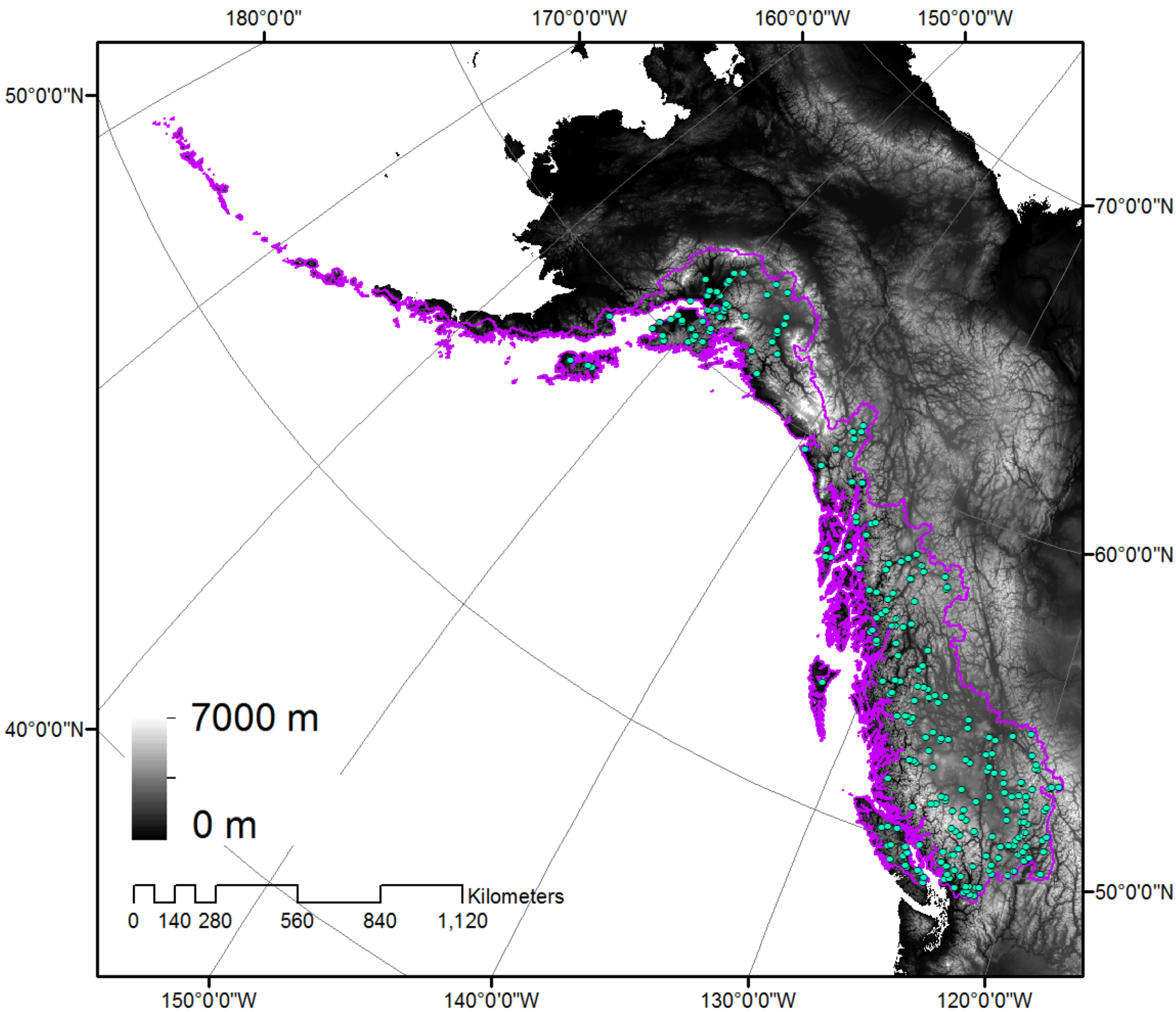

Figure 1.1: GOA drainage outlined in purple, with streamflow gauging stations denoted by teal dots.

given appropriate estimates of freshwater contributions. Information may help predict spill trajectories in such an event and offer an opportunity to efficiently mitigate damage. Similarly, marine biologists studying mixing patterns can follow plankton movement in salt water, and subsequently follow other species up the food chain.

Oceanographers note that freshwater coming off the coast of Alaska is a major driver of the Alaska Coastal Current (ACC), among other things playing a role in biological changes farther North. The ACC may be described as a freshwater river in the gulf, which carries freshwater contributions from as far south as Canada along the northeastern border of the Pacific Ocean, and carrying them to as far north as the Chukchi Sea, north of Alaska, at an annual average rate of 880 km^3/yr [Weingartner et al., 2005]. Separate from the ACC, general coastal circulation patterns in the gulf are driven by freshwater fluxes out off the shores of Alaska and Canada, such as a study evaluating freshwater inputs of glaciers and their effects on fjord estuaries in Glacier Bay [Etherington et al., 2007].

The most direct way to acquire necessary data for these scientific fields is to take in situ measurements. However, streamflow gauging stations are difficult and expensive to install and maintain due to the remote, harsh conditions, and adverse weather typical of much of Alaska. Hence, in order to adequately provide the many interested parties with high-resolution information on the quantity of flow coming from the GOA drainage, the use of modeling is essential.

The primary goal of this study is to provide high-resolution information on freshwater discharge into the Gulf of Alaska. The first phase of this project generates gridded weather datasets based on climatological norms and anomalies. The second phase makes use of these datasets, as well as basin characteristics and observed streamflow station data (teal dots in Figure 1.1) to develop predictive equations. These equations are then applied to all subwatersheds making up the GOA drainage in order to arrive at estimates of freshwater runoff into the GOA. Finally, the third phase of this study uses a distributed meteorological model to evaluate the temporal variation of snow-water equivalent (SWE) in the entire GOA drainage basin. These data are computed on a three-hour time step and will be incorporated into future efforts to model runoff with a physical-process approach.

Chapter 2: Background

2.1 Physical and Oceanographic Characteristics

The GOA study area falls within the bounds: 49ºN to 64ºN and 118ºW to 180ºW, including parts of both Alaska and Canada (Figure 1), and covering 892,206 km^2. This study considers all watersheds that drain into the Gulf of Alaska from the state of Alaska, as well as parts of British Columbia and the Yukon Territory. Many researchers are interested in all or part of the region that drains to the gulf and drives the Alaska Coastal Current, so for the sake of completeness this study includes the entire coastline from just south of the Fraser River in British Columbia to the westernmost Aleutian Islands and all watersheds in between that drain through this coastline.

This coastline includes a multitude of fjords, bays and islands. Its associated relevant interior watersheds include peaks and valleys with varying land cover types. One such land cover type is glacier cover, whose contribution to streamflow is particularly difficult to quantify. Glacier mapping may be done a number of ways, however difficulties consistently arise in distinguishing snow from ice. For this reason it is non-trivial to determine how much of the frozen water may be attributed to permanent ice. A difference between glaciers and snow is the melting patterns. Snow pack may deplete by the end of a melt season, but glaciers remain for far longer, contributing both an annual melt/freeze cycle and a long-term melt.

2.2 Climate characteristics

Due partly to the vast area of the study region and partly to its location and orientation, the GOA drainage experiences a wide range of values for precipitation (Figure 2.1) and temperature (Figure 2.2). Its span of latitudes subjects the region to annual precipitation depth ranges from 0 m to as high as 10.5 m in the Alaska Range, and annual temperature ranges from -31°C to 25°C [Calos et al., 2013].

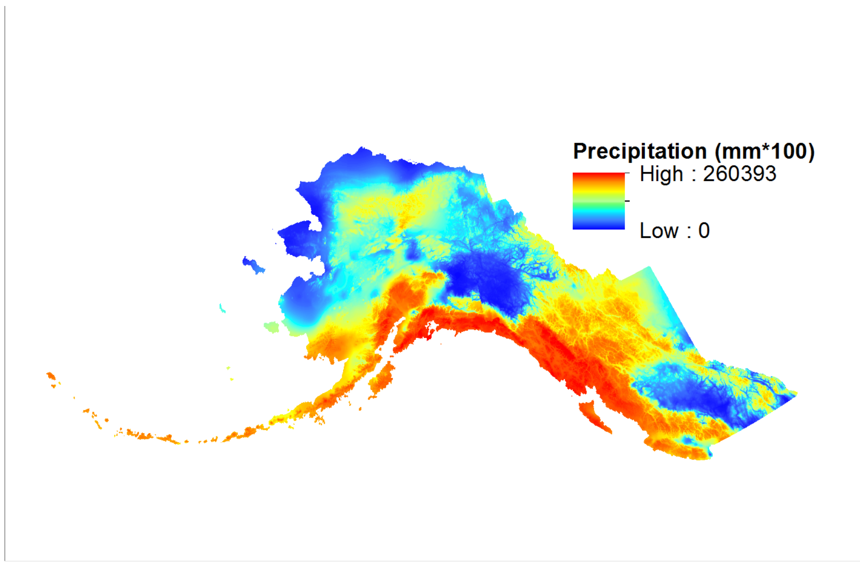

Figure 2.1: Example of monthly precipitation grid, showing spatial distribution of precipitation for October 1986.

Many non-uniformities contribute to complexity in describing streamflow. One such non-uniformity in precipitation is known as orographic lifting. As moist air is blown into a mountain range, it is forced upward where it cools and condenses, eventually forming high-elevation precipitation. In the case of the West Coast, the side of the mountain range closer to the ocean, the windward side, receives more

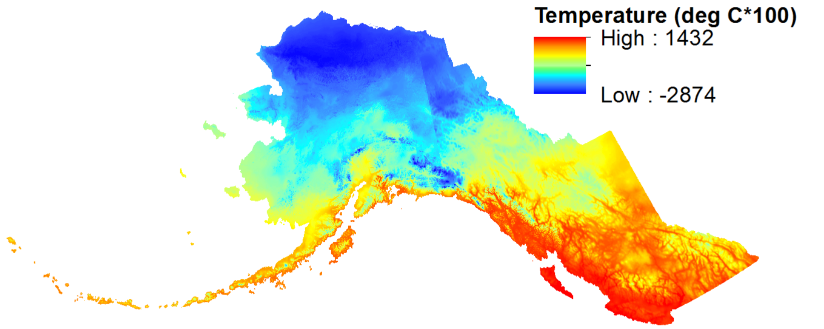

Figure 2.2: Example of monthly temperature grid, showing spatial distribution of temperature for October 1986.

precipitation than the leeward side. Additionally, the higher elevations are exposed to more precipitation than are the lower elevations. The GOA drainage for this study includes elevations ranging from sea level to Mt. McKinley's nearly 6,200 m (see Figure 1.1 in Chapter 1 for digital elevation model). Further, localized coastal effects in fjords and bays play a large role in regional wind and weather patterns, creating more precipitation in watersheds within close proximity to the coast.

2.3 Runoff Characteristics

A majority of freshwater discharge flowing off the coasts of Alaska and Canada into the Gulf of Alaska comes from small, distributed sources, rather than large rivers [Royer, 1982, Wang et al., 2004, Neal et al., 2010]. Over the course of this study, between 1961 and 2009, the area of gauged watersheds represents 557,624 km^2 or approximately 62.5% of the drainage area, leaving the remaining 37.5%, which have never been gauged, to be described by modeling techniques (Figure 2.3).

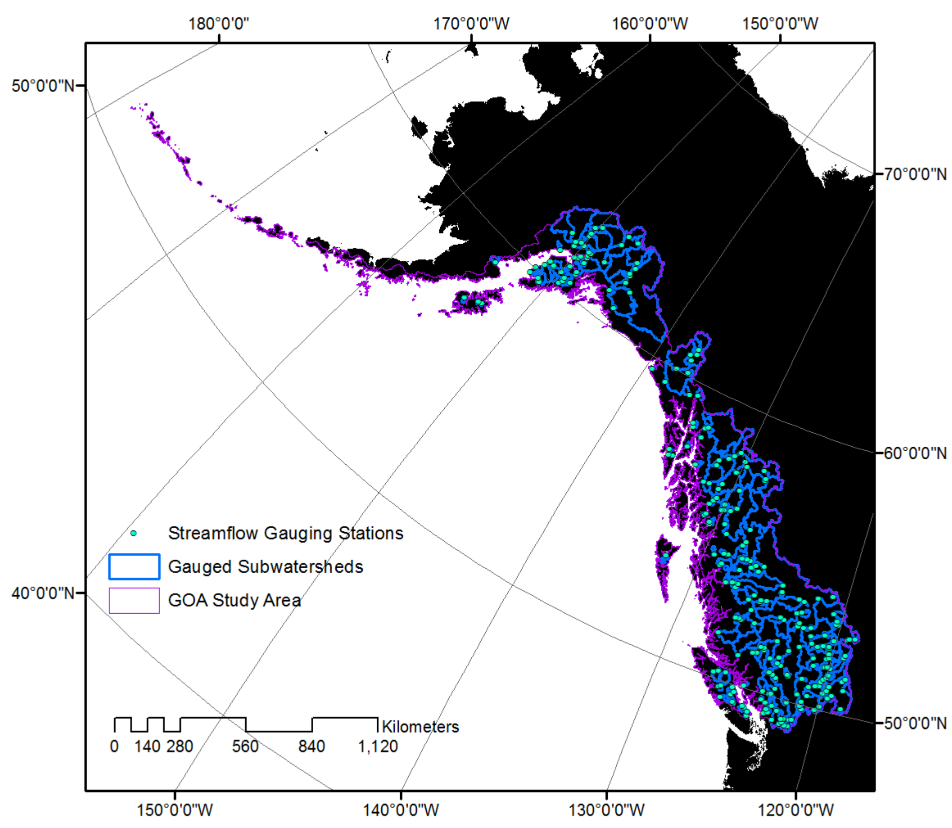

Figure 2.3: Gauged watersheds in GOA study area (blue polygons) and their associated streamflow gauging stations (teal dots).

Three unique types of watersheds exist in the GOA region: rain dominated, snow dominated, and glacier dominated. Rain dominated watersheds show a pulse in streamflow coinciding with the rainy season, generally in late fall and winter. Snow dominated watersheds experience a streamflow pulse that lags the rainy season since snow is stored until it warms enough to melt. Glacier dominated watersheds show a majority of the flow in the summer months when they experience enough heat to melt the ice. Some watersheds share a combination of these watershed types.

2.4 Previous Modeling Work

Given obstacles in obtaining empirical data, modeling efforts have historically been implemented to estimate freshwater flow off the coasts of Alaska and Canada. These models use a combination of available weather and streamflow station data and various derived downscaled datasets including climate information. Previous studies have recognized the inaccuracies of making a single broad estimation for such a large region and have progressively improved in spatial resolution over time. Since these studies began, more data have become available and tools have improved, providing opportunity for higher resolution and more accurate models.

Some major error sources have reduced with the availability of more and higher-resolution information. For example, using low-elevation coastal stations, as early models did, may not accurately account for some of the high elevation precipitation that results from orographic lifting. As models improve, they take into account various natural complexities, such as geologic and topographic diversity and their resulting direct and indirect influences on streamflow.

2.4.1 Alaskan Freshwater Discharge into the Gulf of Alaska

Several sequential efforts were made to describe streamflow into the Gulf of Alaska. The following paragraphs describe these studies and Table 2.1 offers a summary of the efforts in Alaska alone (excluding Canadian contributions to the Gulf of Alaska).

Study	Estimated Flow (km^3/yr)	Temporal Resolution	Spatial Resolution	Spatial Extent	Data Range
Royer (1982)	725	Monthly	2 Divisions	60°N to 50°N; 150W to 140W at 60N and 150W to 130W at 50N	1931-1979
Wang et al. (2004)	728	Daily	5 Major watersheds + line sources	53N to 64N; 159W to 130W	1958-1998
Neal et al. (2010)	870	Single estimate	7 geographic regions	SE border of AK to Kupreanof Point on AK Peninsula	1960-1990

Table 2.1: Weighted mean percent errors for baseline scenario of GOA drainage, including three subdivisions of streamflow stations.

One of the first streamflow models for the region [Royer, 1982] estimated the quantity of freshwater flowing into the Gulf of Alaska via rivers and streams off the coast of Alaska, recognizing its importance to dynamics in the gulf. Discharge was calculated for the coast running from Southeast to Southcentral Alaska, neglecting the Copper River and the entirety of British Columbia, both of which have significant freshwater contributions to the Gulf of Alaska. This was done by dividing the study region into two subregions split by the northernmost part of the Alaskan panhandle, using coastal station data to develop a runoff relation for each region. Evaluation of these equations in coastal Alaska yielded an estimate of 23,000 cubic meters per second (cms), or approximately 725 km^3/yr of flow. Using a salt flux balance for the northeast Pacific Ocean combined with this value of flow, the total influx of freshwater into the Gulf of Alaska, including the previously excluded Copper River and British Columbia region, was estimated at 43,000 cms, or 1,356 km^3/yr. At the time, a transect of the coastal current off the coast of Seward, called the Seward Line, was used to validate estimates of freshwater flow. A bias toward underestimation of streamflow resulted from using low-elevation weather stations, given orographic effects in the coastal mountain range of Alaska.

[Wang et al., 2004] attempted to better represent the spatial distribution of runoff along the coast of Alaska. Their work differed from that of Royer [1982] in that it used a Digital Elevation Model (DEM) to delineate watersheds, as well as gridded weather datasets to increase the spatial resolution of the estimate. The DEM allowed for delineation of watersheds for Alaska's five major rivers (Susitna, Copper, Alsek, Taku, and Stikine Rivers) described as pour points, or point sources, along the coast. Freshwater flows between each pair of adjacent point sources were aggregated into a line source (Figure 2.4). To create the gridded weather datasets, Wang et al. [2004] evaluated National Centers for Environmental Prediction (NCEP) reanalysis data as well as National Climate Data Center (NCDC) station data. Their study considered processes of glaciers, snow storage, and melting by separating flow into components of base flow, glacier flow, and non-glacier flow, and developing appropriate coefficients for each term. Values again likely represented an underestimate since sparse NCEP reanalysis climate data were interpolated to create grids (on the order of 25 stations for the entire study area), and small streams were not calibrated with reported gauge data. The estimate by Wang et al. [2004] for total flow into the gulf off the coast of Alaska came close to that of Royer's [1982], at a mean of 23,100 cms or approximately 728 km^3/yr.

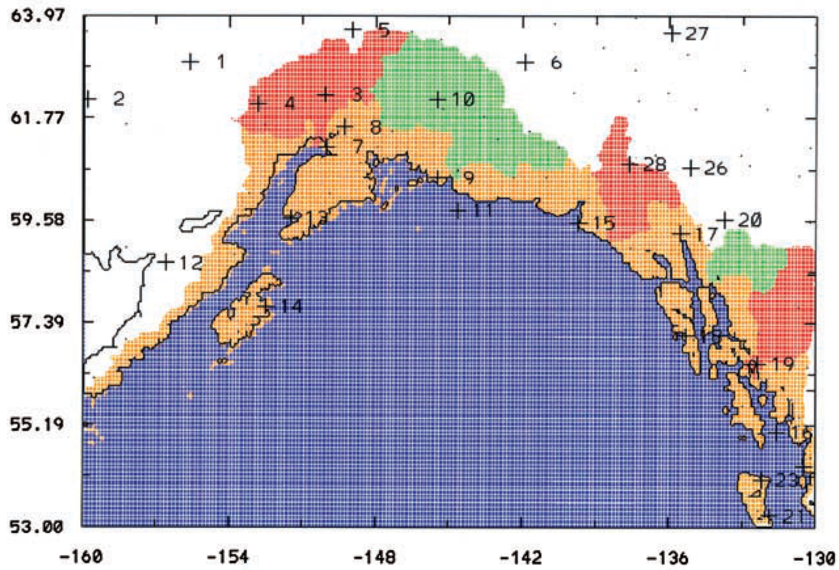

Figure 2.4: Map of Wang et al. study domain, showing line sources in yellow and five major drainages [Wang et al., 2004].

Efforts to improve estimates of freshwater discharge into the gulf continued with Neal et al. [2010]. First, Neal et al. [2010] used available gauged data for the major pour points along the coast, as in Wang et al. [2004]. Second, runoff ratios, describing the ratio of streamflow to precipitation, were developed for gauged watersheds using precipitation models and regional streamflow data for calibration. The goal in this was to parameterize all physical processes not being modeled, such as evaporation and infiltration. To develop runoff ratios, Neal et al. used the Parameter-elevation Regression on Independent Slopes Model (PRISM)[Daly et al., 1994, 2008] along with DEMs for the region, to delineate watersheds. This study evaluated 7 study subregions shows in Figure 2.5. The PRISM climatology grids provided a 30-year average for each month of the year, giving precipitation information for the 30 years between 1960 and 1990 on a 2 km x 2 km scale. Runoff ratios were calculated as the gauged mean annual runoff volume divided by mean annual PRISM precipitation volume, and were then applied to ungauged watersheds to estimate the runoff where station data do not exist. Finally, glacier volume loss (GVL) datasets were created using airborne laser altimetry data collected by Arendt et al. [2002] in order to estimate glacier volume change from the mid-1950's through 2001. Neal et al.'s study [2009] yielded a total estimated flux of 870 km^3/yr of freshwater off the coast of Alaska, 47% of which may be attributed to discharge from glaciers and icefields.

2.4.2 Canadian Freshwater Discharge into the Gulf of Alaska

Similar studies were performed in Canada to estimate monthly discharge into the GOA. Morrison et al. [2011] used runoff ratios in the same way that Neal et al. [2010] did. Morrison et al. sorted watersheds into two categories: those dominated by rainfall and those dominated by snowfall. All watersheds that lie 100 km from the coast and closer with an elevation below 1,000 m were classified as rainfall-dominated, or pluvial. All other watersheds were classified as snowfall-dominated, or nival-glacial. In this way, Morrison et al. were able to factor in the effects that

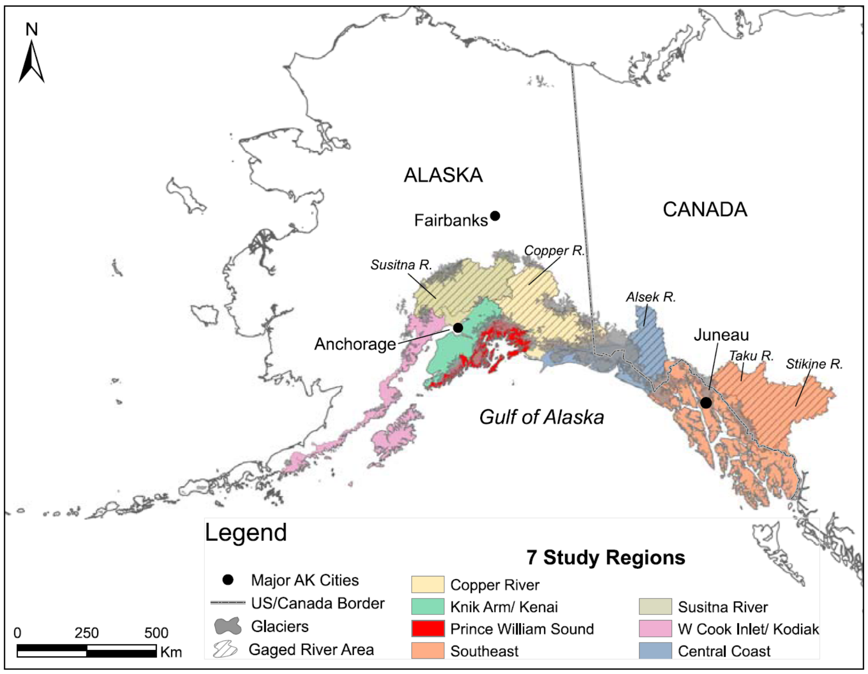

Figure 2.5: Map of Neal et al. [2010] study domain showing 7 study regions, from Neal et al. [2010].

take place in the presence of snowpack, namely a streamflow peak in late May or early June that is out of phase with an autumn rainfall peak. The precipitation input used in Morrison et al.'s study was a gridded dataset provided by the National Oceanic and Atmospheric Administration [NOAA, 2009]. A simple water balance equation was modified to include time-sensitive parameters that account for seasonal variation. Analogous to Wang et al. [2004], flow was divided into a base flow, a direct rainfall runoff term, and a term for flow stored as snow accumulation. Morrison et al. estimated a total average runoff of 998 km^3/yr into the GOA from all watersheds that drain through the coast of British Columbia, including parts of Southeastern Alaska and Northern Washington.

Addressing the issue of glacier representation, Jost et al. [2012] performed a study evaluating effects of glacier cover on streamflow in the Mica Basin in British Columbia. This study used a model called HBV-EC to perform calculations of streamflow that compared simulations with and without glacier cover. The design of this model was based on the concept of grouped response units (GRUs), encompassing areas of similar elevation, aspect, slope, and land cover. Each simulated GRU drains water as either a glacier or non-glacier unit. The idea is that regardless of land cover each GRU will drain a non-glacial contribution. Then GRUs with glaciers have an added glacial component. The simulations that included glacier cover used aerially photographed extents from 1985, and Landsat Thematic Mapper scenes from 2000 and 2005, pausing the simulation to update extents as they became current to the model. Jost et al. found that GRUs with as little as 5% glacier cover showed up to a 25% increase in streamflow in August and up to a 35% increase in September over those with no glacier cover at all.

2.4.3 Regression Analysis

Regression analysis offers a very different tool than the above physical-process-based approaches. With minimal available information, this statistical model may be implemented in place of a deterministic model. In statistics, simple linear regression analysis offers a way to describe an output variable given a known input variable, such as drawing a line of best fit through a scatter plot. Multiple linear regression analysis evaluates several input variables that describe a single output variable. In this case, there are many inputs that describe the magnitude and timing of streamflow. Some inputs are more important than others and will have correspondingly higher coefficients to describe them. For example, the drainage area of the watershed may be far more important to total streamflow than is the percentage of the watershed covered by glaciers.

In an effort to describe Alaska's spatially heterogeneous system, a study performed by the USGS [Curran et al., 2003] developed log-form multiple linear regression equations for daily mean flow-duration statistics and low-flow frequencies of freshwater discharge. These equations were produced using basin characteristics including drainage area, mean channel length, mean channel slope, mean basin elevation, basic land cover information, mean annual precipitation, and mean minimum January temperature as parameter inputs. Equations were developed for the entire state of Alaska, for a range of peak flow statistics, divided into 7 hydrologically similar regions (Figure 2.6). The 7 sets of equations allowed for a more precise approximation of streamflow in each watershed than one set of equations would have provided.

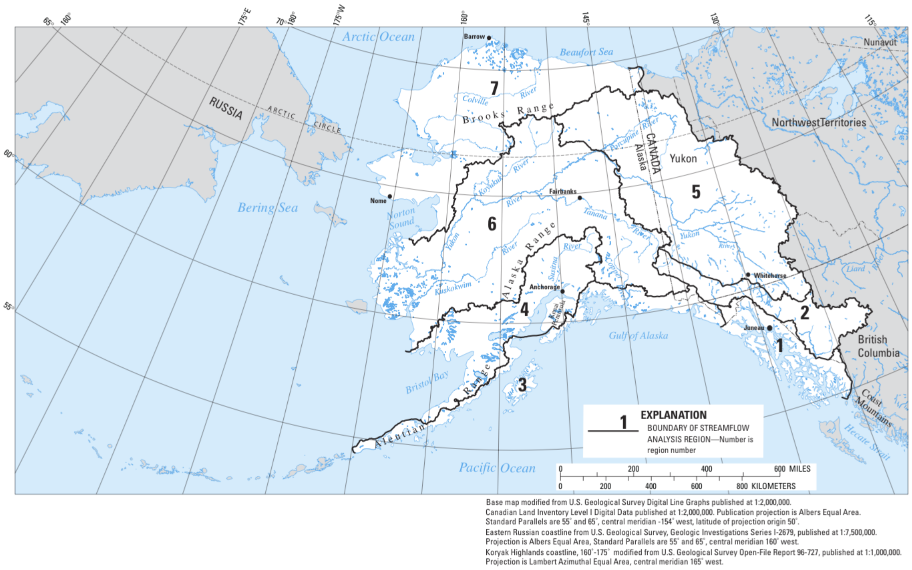

Figure 2.6: USGS subdivisions of hydrologically similar units in Alaska Curran et al. [2003].

Studies have also been performed in subsets of the GOA drainage. For example, in Glacier Bay, located in the panhandle of Alaska, Hill et al. [2009] provided estimates of peak freshwater runoff and flow duration statistics for a far more localized scenario (covering an area 10,250 km^2 in size, as compared to the present study's 892,206 km^2). First the region was divided into subwatersheds flowing into the bay. Existing regression equations [Curran et al., 2003] were then applied to these watersheds and validated using acoustic Doppler current profiler (ACDP) measurements. Fairly good agreement was found between calculated values and measured values. The flow values were then used in a barotropic tidal modeling program, Advanced CIRCulation model (ADCIRC) [?]. This study served to prove the appropriateness of the USGS's methods.

Each of these models showed that there is a significant contribution of ungauged freshwater flow to the Gulf of Alaska. Work in this field will be ongoing and continually updated as technology advances, more models are developed and implemented, and data become available with higher spatial and temporal resolution.

Chapter 3: Methods

3.1 PHASE I: Climate Grids

3.1.1 Data Acquisition

Calos et al. [2013] produced climate grids for the Gulf of Alaska region, including Alaska and the parts of Canada as far south as the Fraser River basin, which flow through the coast into the gulf. These grids have a 2 km x 2 km resolution for monthly mean temperature and monthly cumulative precipitation volume from 1961 through 2009, and were created using station data and Parameter-elevation Regressions on Independent Slopes Model (PRISM) climatological norms, the latter of which exists on a 771-meter resolution grid [Daly et al., 1994, 2008]. These climatological norm grids represent 30-year averages of precipitation and temperature for the region for each calendar month of the year.

For Alaska, National Climatic Data Center mean monthly weather station data from 1961 through 2009 were included as input[1]. For Canada, data for the same time period was obtained from the National Climate Data and Information Archive[2]. For precipitation data, 469 stations were included in analysis for Alaska and 1,315 for Canada. For temperature data, 402 stations were found for Alaska and 1,111 stations

[1] www.ncdc.gov

[2] climate.weatheroffice.gc.ca

were found for Canada. Of these stations, many were temporary installations with insufficient lengths of data record for the purposes of this study. Stations with fewer than 36 (not necessarily consecutive) months of record were eliminated from analysis. This yielded a reduction in the dataset to 322 and 802 precipitation stations for Alaska and Canada, respectively, and 261 and 875 temperature stations for Alaska and Canada, respectively.

In calculating gridded anomalies, strong spatial gradients between adjacent stations would occasionally yield nonphysical oscillations. To resolve this issue, a "minimum distance" filter was applied, removing one station from each pair of adjacent stations [Calos et al., 2013]. The final precipitation dataset included 200 stations in Alaska and 500 in Canada. The final temperature dataset included 150 stations in Alaska and 500 in Canada. Figure 3.1 shows the spatial distribution of the weather stations used in the analysis, overlayed on the topographic relief of the study area.

3.1.2 Grid Generation

To create the grids, the delta method, a statistical downscaling method, was implemented [Jones & Fahl, 1994, New et al., 2000, Fowler et al., 2007]. The goal was to create a product with high spatial resolution and monthly temporal resolution. Available datasets included: (i) the PRISM climatology[3], which had high spatial resolution, but no temporal resolution, and (ii) weather station data, which had very high temporal resolution (sub-daily), but poor spatial resolution in Alaska and were

[3]http://www.prism.oregonstate.edu

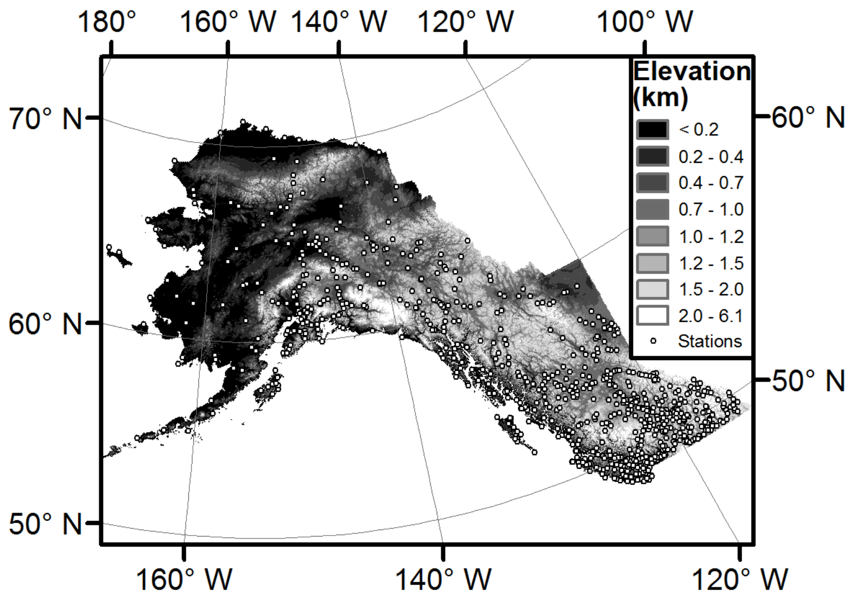

Figure 3.1: Topographic relief of Alaska, British Columbia and the Yukon Territory. Symbols indication the location of weather stations used in the analysis.

biased to low elevations, since most stations were low-lying. As a result of this bias, the available station data did not accurately capture orographic effects. In order to obtain a product with high spatial resolution and sufficient temporal resolution, the two available datasets were used together as follows.

First, station anomalies, describing the departure of station data from the climatological norm, were created for precipitation and temperature each month from 1961 through 2009. The precipitation anomalies were calculated as a ratio of station data to PRISM data so that no negative precipitation anomaly values populated the dataset. A negative precipitation value does not make physical sense, so any negative values on the anomaly grid were set to zero. The temperature station anomalies were calculated as PRISM data subtracted from station data, giving an absolute difference for each station location. These scattered anomalies were then interpolated onto a regular grid having the same resolution as the PRISM grid, using a "splines in tension" approach, with a tension parameter of 0.8. Splines in tension is a method of smoothly interpolating data on an equidistant grid, while controlling unrealistic oscillations between data points [Wessel & Bercovici, 1998]. Figures 2.1 and 2.2 show a sample month of the final product for each grid.

For the case of precipitation, the anomaly grids and PRISM grids were multiplied for each month in each year to yield a final high-resolution grids. For the temperature grids, the anomaly was added to the PRISM grid to yield the final high-resolution grids. This approach muted the effects of incomplete station records, as well as issues of a low-elevation bias because while weather has very high spatial gradients, the anomalies are much more gradually varying yielding a much weaker spatial gradient. This made it such that the density of weather stations that existed in the GOA study area was satisfactory for resolving the anomaly field.

Other parties, such as the Scenarios Network Alaska Planning (SNAP)[4] project produced gridded datasets using coarsely-resolved historical Climate Research Unit (CRU) grids [Mitchell & Jones, 2005]. In contrast to SNAP's datasets, those of Calos et al. [2013] offer the direct use of scattered station data. A comparison of results from Calos et al. with those of SNAP's was achieved via a cell-by-cell-subtraction of each dataset from the PRISM grid for every month, such that the differences may be compared. Tables 3.1 and 3.2 show the results of these comparisons for precipitation and temperature, respectively. The agreement between the two datasets

[4]http://www.snap.uaf.edu/

is generally good, however those of Calos et al. more accurately capture inter-annual variability, particularly in the precipitation grids, and give better agreement to the PRISM climatology, both in terms of mean and standard deviation.

	Present Results		SNAP Dataset	
Month	μ (mm)	σ (mm)	μ (mm)	σ (mm)
1	-2.6	10.6	6.5	41.0
2	-2.4	9.3	-3.1	28.7
3	-3.3	11.0	-5.5	26.7
4	-3.0	9.5	-3.6	24.4
5	-3.1	6.7	-2.4	22.0
6	-1.7	7.2	4.8	21.2
7	-2.3	7.6	1.1	22.0
8	-1.5	9.5	-0.8	33.6
9	-3.3	13.4	-3.9	49.8
10	-5.5	18.9	-3.0	47.2
11	-3.3	12.3	-8.7	35.7
12	-3.4	12.4	-7.3	40.8

Table 3.1: Spatial means (μ) and the standard deviations (σ) of the cell by cell differences between the 30 year average of the computed precipitation results (present method and SNAP) and the PRISM data.

3.2 PHASE II: Regression Analysis

Regression analysis is a common method for fitting data to a curve. A dataset including input variables and their associated output variables is plotted, and an equation is determined to describe the dataset by minimizing the sum of the squares of the residuals of the curve, called least squares fitting. Multiple linear regression analysis considers a scenario where several inputs describe one output with a linear function, such as:

$$y = B + b_1 n_1 + b_2 n_2 + b_3 n_3 + \ldots \tag{3.1}$$

	Present Results		SNAP Dataset	
Month	μ (mm)	σ (mm)	μ (mm)	σ (mm)
1	0.26	0.89	0.19	1.92
2	-0.06	0.80	0.0	2.18
3	0.10	0.76	0.47	1.55
4	0.21	0.76	0.75	1.33
5	0.31	0.74	0.56	1.03
6	0.35	0.74	0.59	1.00
7	0.37	0.64	0.70	1.00
8	0.34	0.63	0.68	0.84
9	0.28	0.60	0.51	0.77
10	0.24	0.59	-0.29	0.96
11	0.12	0.74	-0.78	1.50
12	-0.32	0.89	-0.75	1.83

Table 3.2: Spatial means (μ) and the standard deviations (σ) of the cell by cell differences between the 30 year average of the computed temperature results (present method and SNAP) and the PRISM data.

where y describes the desired output, n_1, n_2, etc. describe input parameters, b_1, b_2, etc. describe derived regression coefficients, and B is a constant coefficient determined by regression analysis. In the case of this study, basin characteristic and climate information are the input parameters that describe streamflow, the output. As noted in Curran et al. [2003], a linear fit is not as representative of streamflow as is a fit of the form:

$$Q = Ax_1^{a_1}x_2^{a_2}x_3^{a_3}\dots \tag{3.2}$$

where Q describes streamflow, x_1, x_2, etc. describe input parameters, a_1, a_2, etc. describe derived regression coefficients, and A describes the constant coefficient. With some logarithmic manipulation, multiple linear regression analysis may still be implemented to determine these coefficients. That is to say that Equation 3.2 may take the form of Equation 3.1 as follows.

First, the log-transform is applied to both sides of Equation 3.2.

$$log(Q) = log(Ax_1^{a_1} x_2^{a_2} x_3^{a_3} \ldots) \tag{3.3}$$

Next, the following log identity (Equation 3.4) is implemented, yielding Equation 3.5:

$$log(yz) = log(y) + log(z) \tag{3.4}$$

$$log(Q) = log(A) + log(x_1^{a_1}) + log(x_2^{a_2}) + log(x_3^{a_3}) + \ldots \tag{3.5}$$

Then the log identity in Equation 3.6 is used to arrive at Equation 3.7.

$$log(y^z) = zlog(y) \tag{3.6}$$

$$log(Q) = log(A) + a_1 log(x_1) + a_2 log(x_2) + a_3 log(x_3) + \ldots \tag{3.7}$$

Now, let log(Q) = y, log(A) = B, and let a_1, a_2, etc. for log transformed x_1, x_2, etc. be b_1, b_2, etc. Finally, let log(x_1), log(x_2), etc. be n_1, n_2, etc. such that Equation 3.7 yields Equation 3.1 again:

$$y = B + b_1 n_1 + b_2 n_2 + b_3 n_3 + \ldots$$

3.2.1 Data Acquisition

Streamflow data were collected between 1961 and 2009 for all gauged undammed watersheds that drain into the Gulf of Alaska. Alaskan station data was acquired from the United States Geological Survey (USGS), and Canadian station data from British Columbia and the Yukon Territory, was acquired from Environment Canada (EC) stations. Stations affected by human intervention, dams or otherwise, were excluded from analysis. Many of these stations were temporary installations with very short data records. In an effort to exclude these temporary installations from analysis, any records with less than 36 months of flow data, though not necessarily 36 consecutive months, were eliminated from analysis.

Basin characteristic data including drainage area, mean elevation, slope and length of stream, and percent forest, glacier and lake covers were obtained for USGS stations from scientists at the Alaska Science Center, who collected the information from several sources [Jones & Fahl, 1994, Curran et al., 2003]. In addition to these characteristic data, the climate grids produced by Calos et al. [2013] were integrated over the watersheds corresponding to the USGS and Environment Canada gauging stations in order to provide information on cumulative monthly precipitation and mean monthly temperature for each basin. A third parameter was derived from climate grids: cumulative precipitation from the start of the water year in October, through the month of analysis.

While climate grids made it easy to acquire information for Canadian and ungauged basins, the remaining basin characteristic information was not as readily available for Canadian stations. The following datasets were acquired in order to obtain these data. For the collection of subwatershed drainage areas and mean elevations of Canadian watersheds as well as all ungauged GOA watersheds, a Global 30 Arc-Second Elevation (GTOPO30) digital elevation model (DEM) for North America was acquired from the USGS Earth Resources Observation and Science Center[5] was acquired. This DEM had an approximately 1 km^2 resolution and was completed in late 1996. For the purposes of this study, it was cropped to include only parts of Alaska and Canada that surrounded an estimate of the watersheds draining into the gulf (Figure 3.2).

Land cover data for Canadian watersheds and all ungauged GOA watersheds were obtained from the Commission for Environmental Cooperation's (CEC) North American Land Change Monitoring System's (NALCMS) Land Cover 2005 map. These data include 19 land cover types and are resolved to grid cells of 250 m (Figure 3.3). For the purposes of this study, all classifications of forest were given a "forest" flag and were lumped into one category.

Initial analysis was done only for Alaska due to availability of information. Data were obtained for Canada for only those parameters deemed necessary following parameter elimination in regression analysis (parameter elimination is described in Appendix A).

[5] https://lta.cr.usgs.gov/GTOPO30

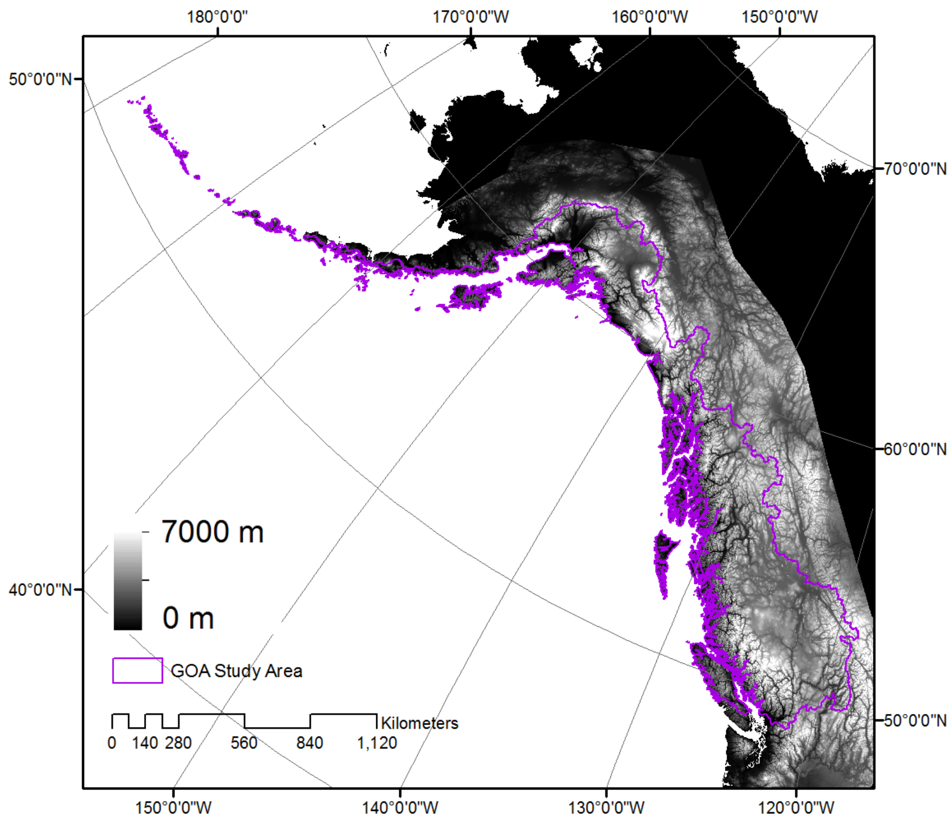

Figure 3.2: Clipped DEM, generally outlining the GOA drainage.

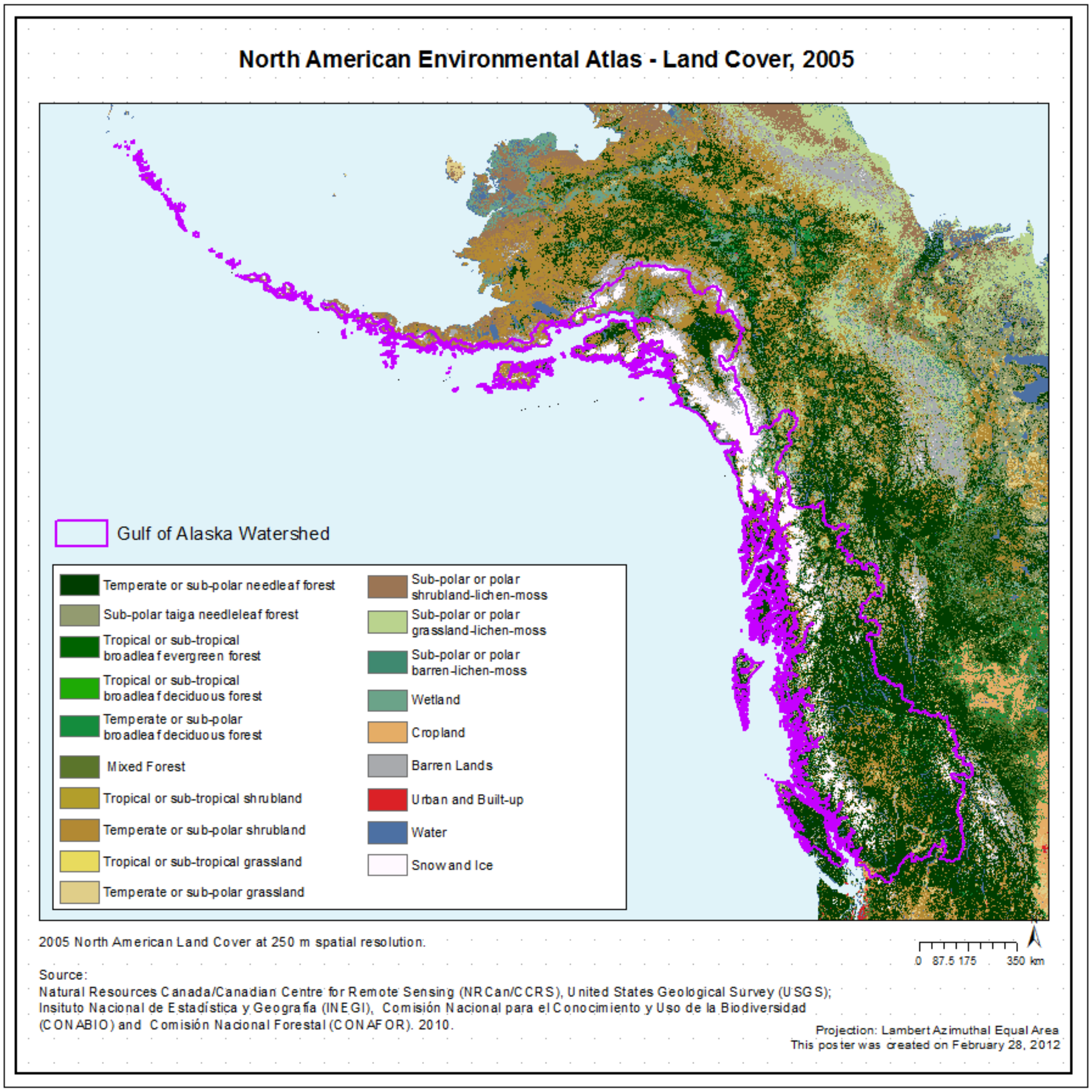

Figure 3.3: CEC 2005 land cover map [NRCan/CCRS, 2005].

3.2.2 Subwatersheds

Gauged watersheds had to be distinguished from ungauged watersheds for the purposes of this study. All gauged watersheds were used in analysis to develop regression equations. Those regression equations were then applied to all ungauged watersheds for an estimate of total flow into the GOA. To delineate a region into subwatersheds, ArcHydro from ESRI's Arc suite[6] takes a DEM as input and delineates subwatersheds to a certain size based upon a user-defined threshold. This study used a stream watershed threshold of 1,000 km^2, meaning the smallest basin area was 1,000 km^2. This 1,000 km^2 size was chosen because it produced a reasonable number of watersheds for the analysis. Smaller thresholds produced too many watersheds, such that the quantity of ungauged watersheds far outnumbered the quantity gauged watersheds. Larger thresholds produced too few watersheds for analysis. The watersheds deemed relevant for the study were those that drained into the gulf from the Aleutian Islands in the West through the Fraser River basin in the East (Figure 3.4). All other watersheds were excluded from analysis.

3.2.3 Regionalization

It is common practice for very large study domains to be subdivided into smaller regions, as it improves the accuracy of regression equations. Regionalization of the GOA drainage was roughly guided by Curran et al.'s [2003] seven subregions (Figure

[6] http://www.esri.com/industries/water_resources

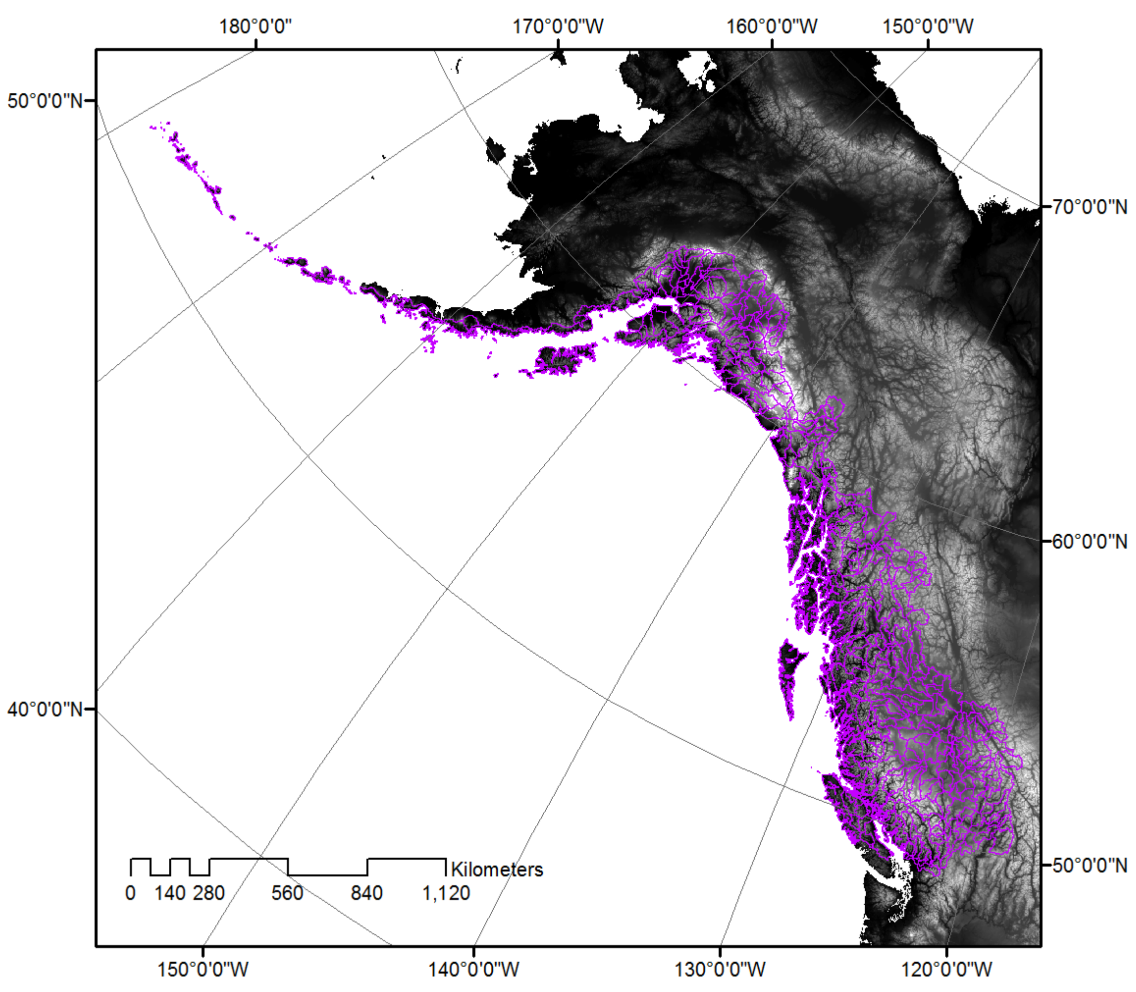

Figure 3.4: GOA region delineated into subwatersheds that drain into the gulf, denoted by purple boundaries.

2.6 in Chapter 2). While logic may lend that continually subdividing into smaller regions would yield improved results, regression analysis requires sufficient station information in order to be performed. The decision in this study to divide Alaska into two subregions struck a balance between maintaining a sufficient number of stations per region, and achieving improvement of errors as compared to treating Alaska as one region. This is discussed in further detail in Chapter 4.

3.2.4 Parameter Elimination

The next step was to eliminate parameters that had little effect on the final coefficients and associated errors. While including all input parameters intuitively gives a more complete picture of the output, the goal of this project phase was to develop a product with the ideal compromise between accuracy and required data layers. The fewer the required parameters, the easier the equation is to acquire information for and implement.

For the sake of eliminating statistically insignificant parameters, a performance metric was evaluated to determine how well the regression equation described the measured streamflow in different scenarios of input parameters. This performance metric is described by the mean percent error:

$$\frac{1}{n}\sum_{i=1}^{n}\left|\frac{c_i - m_i}{m_i}\right| * 100 \tag{3.8}$$

Here, n refers to the number of streamflow gauging stations in a region, m refers to measured data acquired from streamflow gauging stations and c refers to the flow that was calculated by applying the derived regression equations.

The elimination of parameters was performed manually, both for individual parameters and in varying combinations of parameters. Parameters were eliminated if their effect on percent error was not more than approximately 5%. This process was subjective, with the overall goals being consistency and simplicity from equation to equation, and a good overall representation of streamflow. The most important parameters were found to be: drainage area, mean basin elevation, percent glacier cover, total monthly precipitation depth, mean monthly temperature, and cumulative precipitation depth from the start of the water year through the month of interest. Please refer to Appendix A for more information and tables on parameter elimination.

Once regression equations were developed for each region and each month in Alaska, the determined necessary input parameter information was acquired for gauged watersheds in Canada. Repeating the methods used to develop multiple linear regression equations for Alaska, similar equations were then determined for Canada. Watershed drainage areas and elevations were determined from the delineated watersheds in ArcGIS, % glacier cover was determined using the aforementioned CEC 2005 land cover map, and the climate grids by Calos et al. [2013] were used to acquire precipitation and temperature information. The justification for excluding Canadian data from the parameter elimination process lies in the lack of a consolidated list of downloadable basin characteristic information that matched the USGS's. Due to limitations in time and resources, only parameters deemed relevant by Alaska's regression analysis were acquired for Canada, so as to avoid acquiring parameter information that would later be deemed unnecessary.

3.2.5 Implementation

Using logarithm operators causes issues if the input value is equal to or less than zero. Following guidance of Curran et al. [2003], a constant value of 1 was added to both precipitation and percent land cover input values so that there was never a case of taking log(0). Likewise, a constant value of 32 was added to all Celsius temperatures, so that there was never a negative value or zero inside the log operator, since the minimum temperature in the dataset was -31°C. In implementing these equations, these same values must be added to the appropriate input parameters, such that the final equation reads as follows, with terms listed in Table 3.3:

$$Q = AD^{a_1}E^{a_2}P^{a_3}C^{a_4}T^{a_5}G^{a_6}$$

Q	Streamflow (cms)	A	Constant coefficient
D	Drainage area (km^2)	a_1	Area coefficient
E	Elevation (m)	a_2	Elevation coefficient
P	Precipitation (m) + 1	a_3	Precipitation coefficient
C	Cumulative precipitation (m)	a_4	Cumulative precipitation coefficient
T	Drainage area (°C) + 32	a_5	Temperature coefficient
G	Glacier cover (%) + 1	a_6	Glacier cover coefficient

Table 3.3: Regression model terms.

3.3 PHASE III: Distributed Model

The goal in the regression analysis of Phase II was to provide non-specialists with an accessible product. Those researchers seeking information regarding seasonal and annual variation in streamflow can easily implement the derived equations. However, there is another audience that desires higher temporal resolution than monthly or seasonal data. For example, those interested in flooding events may seek daily or sub-daily information. Phase III of this project lays the groundwork for a complete hydrological model of the GOA drainage. The following paragraphs report findings from initial efforts.

Liston & Mernild [2012] developed a distributed hydrological model to route streamflow through a grid, called HydroFlow. Implementation of this model requires three distinct steps. First, a meteorological distribution system called MicroMet [Liston & Elder, 2006a] must be implemented to determine how much precipitation fell into each grid cell over a given time. Second a runoff availability prediction is made via SnowModel [Liston & Elder, 2006b], using meteorological input from MicroMet. Finally HydroFlow [Liston & Mernild, 2012] routes the predicted available runoff from SnowModel. This project executed SnowModel, however HydroFlow would be add interesting insight for future work.

MicroMet requires as input a meteorological station network. In this case a North American Regional Reanalysis (NARR)[7] data block, was acquired for the entire GOA region and was then significantly trimmed to include only a subset of the GOA study

[7] http://www.emc.ncep.noaa.gov/mmb/rreanl/

area from Phases I and II, which excludes much of the Aleutian Islands and Canada (Figure 3.5). NARR was chosen over other reanalysis products for its high spatial resolution of approximately 0.3 degrees. While in principle MicroMet is able to process any dataset, in practice files get too large for the computational resources available to this project. Meteorological variables from the NARR data block included information such as air temperature, wind speed and direction, and other weather information. These variables were then interpolated to fine spatial and temporal scales (in the case of this study: 1 km^2 spatial resolution and 3-hourly temporal resolution) in the MicroMet pre-processing steps using the Barnes objective analysis scheme [Barnes, 1964]. MicroMet then corrected these interpolations using known parameter relationships between temperature and elevation, wind and topography, and solar radiation and topography.

Following implementation of MicroMet, SnowModel [Liston & Elder, 2006b] was run to determine snow water equivalent in the region. Three data sources were required to run SnowModel: a meteorological station dataset, a DEM, and a land cover map. MicroMet served as the meteorological distribution and the DEM and land cover map were re-used from Phases I and II. The land cover map had to be manipulated because it contained 19 land cover types, whereas the predefined SnowModel vegetation types observed 23 different classifications. For this study, a 10-year simulation was run from the start of the water year in October of 2001 through the end of the water year in September of 2011, evaluating only the snow water equivalent output.

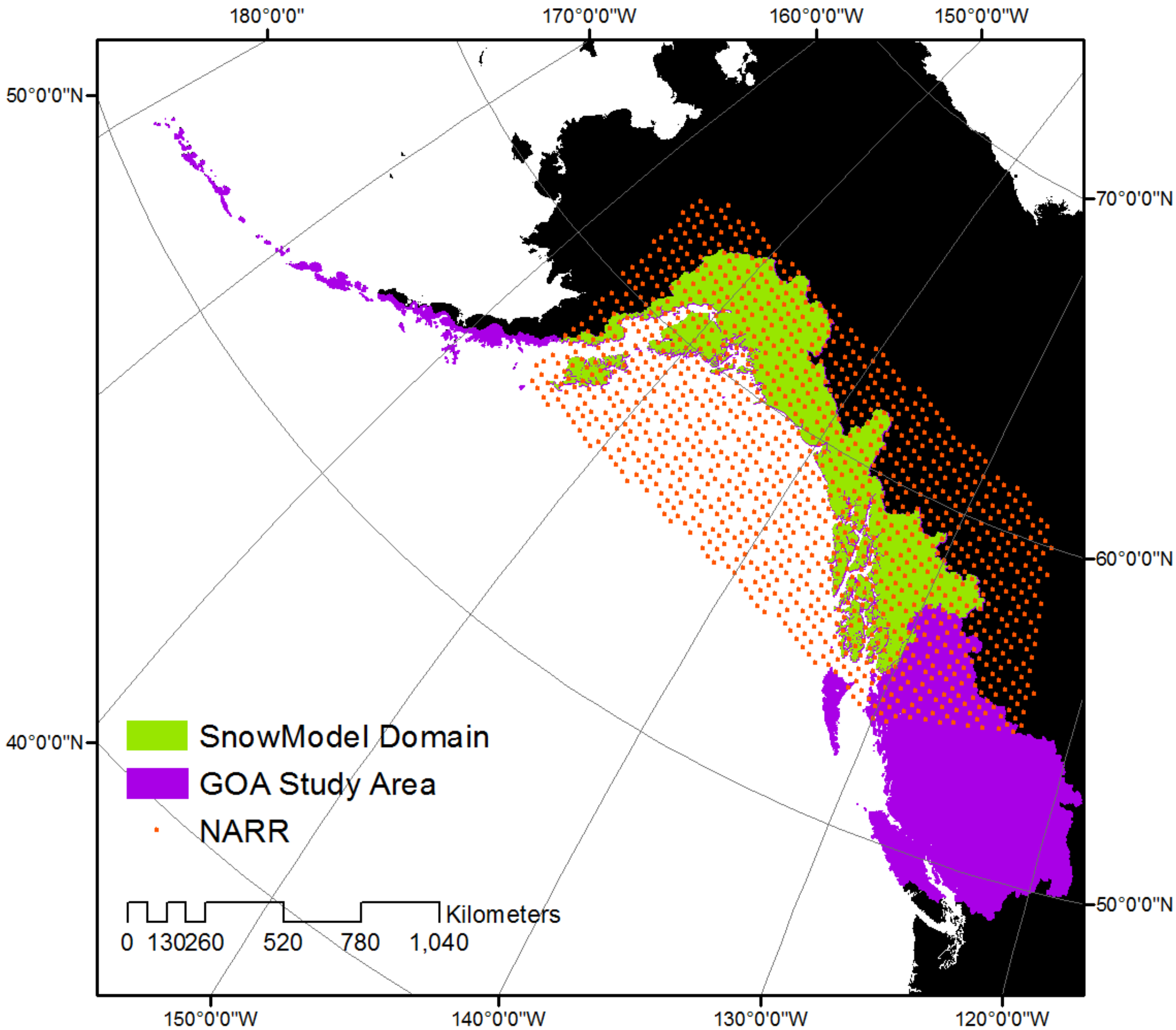

Figure 3.5: SnowModel domain as subset of GOA study area, with cropped NARR data block.

Chapter 4: Results

4.1 Regression analysis

4.1.1 Subdivision of GOA drainage

Previous studies have subdivided Alaska to yield numerous subregions describing hydrologically unique units [Curran et al., 2003, Jones & Fahl, 1994]. The goal in subdividing a large area is to improve the accuracy of descriptive equations within each subregion. In order to effectively describe many subwatersheds in a region with a single governing equation, the subwatersheds must be hydrologically similar. This means that they must behave in similar ways with respect to streamflow.

The goal of hydrologic similarity must be balanced by the need for a sufficient number of stations in order to perform regression analysis. Dividing into too many subregions may leave each subregion with insufficient station information to derive equations, while not dividing enough may mean that each watershed is misrepresented, yielding large errors. Curran et al.'s USGS report [2003] was used as a starting point for dividing into subregions. Regions 1 and 2 from their study were categorized as Region 1 for this study. Regions 3 and the parts of Regions 4 and 6 which flowed to the GOA were categorized as Region 2 for this study. Figure 2.6 in Chapter 2 of this document shows USGS regionalization for Alaska and some of

Canada [Curran et al., 2003], and Figure 4.1 shows regionalization for this study. In Curran et al.'s study, the division of regions was guided by Jones & Fahl [1994] and by hydrologic unit boundaries [USGS, 1987]. They then refined these boundaries using the geographic distribution of available data and comparison of results from regression analysis. While it would be ideal to keep hydrologic unit boundaries in the regionalization process, insufficient stations fell in each of these regions for the purposes of regression analysis in this study and hence needed to be combined.

In this study, the final regionalization for Alaska was determined by a natural geographical subdivision at Alaska's panhandle. The regionalization was mainly guided by the limited station data with records that were long enough for statistical analysis. A similar subdivision was attempted for Canada, however when comparing results via associated errors for several versions of subdivision, there was little benefit gained by splitting Canada into multiple subregions (see Appendix B). Hence, the final regionalization for this study included three subregions: Southeast Alaska (SE AK), Southcentral Alaska (SC AK), and Canada (CA).

The dividing line between Southeast Alaska and Canada was chosen to be at the international border at the coast. Any Canadian watersheds that drained through Southeast Alaska were grouped into the Southeast Alaska subregion (no Canadian watersheds drained through the Southcentral Alaska subregion).

Upon division, Southeast Alaska had 49 streamflow gauging stations and 81 total watersheds (gauged and ungauged) in it, Southcentral Alaska had 55 stations and 112 total watersheds, and Canada had 164 stations and 217 total wateseheds. Some gauged watersheds included more than one station representing the same stream.

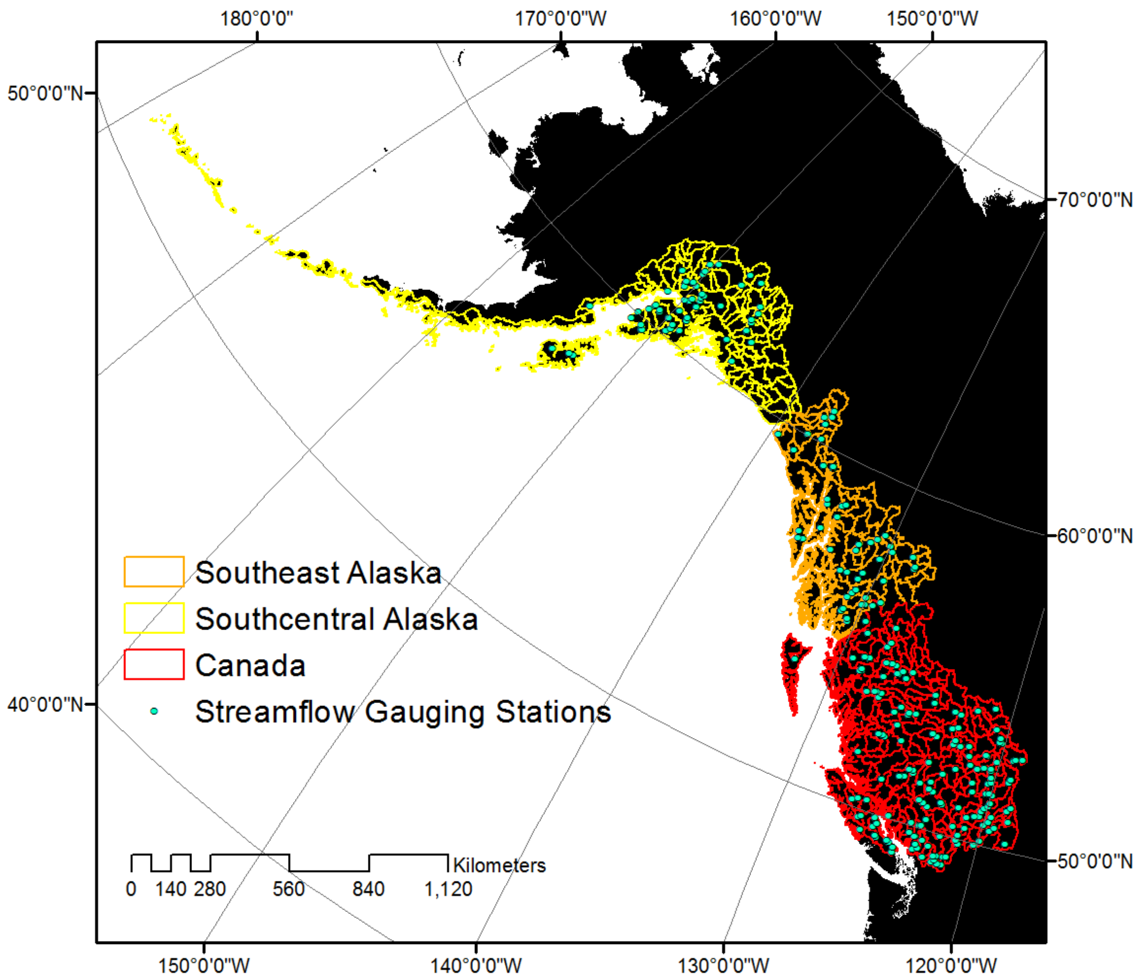

Figure 4.1: Regionalization for this study showing three subdivisions for which unique regression equations were developed. Teal dots represent streamflow gauging stations.

USGS subdivisions ranged from 25 stations per region to 97 stations per region [Curran et al., 2003].

4.1.2 Equations per Month and Region

Six input parameters were deemed necessary to describe flow, as per the process covered in the Chapter 3, as well as Appendix A of this document. These parameters include area, elevation, precipitation, cumulative precipitation, temperature, and percent glacier cover. For all months in each region, seven coefficients are listed, to include a constant coefficient (Tables 4.1-4.3).

The governing equation for all three regions is:

$$Q = AD^{a_1}E^{a_2}P^{a_3}C^{a_4}T^{a_5}G^{a_6}$$

the terms of which are listed in Table 3.3 of Chapter 3. The regression coefficients, a_1, a_2, etc. are listed in Tables 4.1-4.3. As discussed in Chapter 3 of this document, the precipitation and glacier cover parameters had a constant value of 1 added to them to avoid taking the log of zero in analysis. Similarly, the temperature parameter had a constant value of 32 added to it.

4.1.2.1 Area

Values for the area coefficient range between 0.89 in August in Southeast Alaska to 1.24 in August in Canada. The average area coefficient for Southeast Alaska is 0.97, for Southcentral Alaska is 1.02, and for Canada is 1.07. For Southeast Alaska these values are generally lower in the summer and higher in the winter, whereas for Southcentral Alaska the opposite is true, and for Canada the value is almost constant from month to month. In all regions, there is little variation in the area coefficient from month to month.

4.1.2.2 Elevation

In Southeast Alaska for the summer months of June, July and August, the elevation coefficient is positive, indicating that an increase in elevation yields an increase in flow. In Southcentral Alaska, the snow melts from May through October. Finally, in Canada, the snowpack melts from May through September. During non-summer months the coefficient for elevation is negative, indicating that an increase in elevation correlates to lower flow.

4.1.2.3 Precipitation

For Southeast Alaska, the months of June, July, November and December show a negative correlation between precipitation and streamflow. For Southcentral Alaska, February through June and October through December show negative correlation. And for Canada, only October through December have negative coefficients. Precipitation is among the smallest contributors (lowest/weakest coefficients) to streamflow. This seems to be because the contribution from direct precipitation is less important than those from cumulative precipitation and temperature.

4.1.2.4 Cumulative Precipitation

The cumulative precipitation coefficient describes the effect of the quantity of water that fell between October (the start of the water year) and the current month of interest. This input parameter value is identical to “precipitation” for the month of October. For Southeast Alaska, the coefficients for this parameter show a peak in June, and low values at the start of the water year. Southcentral Alaska shows two peaks, one in February and one in June, as well as low values at the start of the water year. Finally, Canada shows a trend similar to that of Southcentral Alaska’s with a peak in winter, a peak in late summer, and low values for the start of the water year.

4.1.2.5 Temperature

Tables 4.1-4.3 show that each region has one or more summer months with negative temperature coefficients. In general, temperature has among the highest coefficients, demonstrating its strong influence on streamflow. For Southeast Alaska, the temperature coefficient peaks in spring and in October, jumping from a low of -0.51 in July to a high of 7.51 in May and a local peak of 5.45 in October. Canada shows a low of -2.88 in August, a high of 5.33 in April, and a local high of 3.72 in November. Finally, Southcentral Alaska shows local peaks in May and October, though these peaks are less exaggerated than in both Southeast Alaska and in Canada.

4.1.2.6 Glacier Cover

The percent glacier coefficients shown in Tables 4.1-4.3 are very low in late winter and spring for all regions, and increase in summer through late fall to early winter. Moving south from Southcentral Alaska to Southeastern Alaska to Canada, the general trend shows the absolute value of the coefficients increasing with proximity to the equator. The magnitudes of these coefficients are among the lowest two for all months in all regions.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Constant Coefficient	1.44	0.75	-1.68	-8.02	-13.8	-7.49	-3.06	-4.55	-4.16	-6.20	0.87	2.46
Area (km2)	1.04	1.04	1.04	0.99	0.98	0.96	0.93	0.89	0.91	0.90	0.96	0.99
Elevation (m)	-1.58	-1.49	-1.29	-0.98	-0.05	0.55	0.65	0.19	-0.18	-1.16	-1.79	-1.94
Precipitation (m)	0.20	0.29	0.50	0.19	0.12	-0.23	-0.01	0.23	0.33	0.01	-0.06	-0.11
Cumulative Precipitation (m)	0.54	0.53	0.35	0.51	0.79	0.87	0.69	0.46	0.63	0.13	0.14	0.17
Temperature (C)	0.41	0.60	1.88	5.57	7.51	2.45	-0.51	1.25	1.57	5.45	1.90	0.88
Glacier (%)	-0.02	-0.01	0.02	0.11	0.04	0.09	0.32	0.47	0.30	0.29	0.18	0.12

Table 4.1: Southeastern Alaska (SE AK) regression coefficients

Month	1	2	3	4	5	6	7	8	9	10	11	12
Constant Coefficient	-2.71	-2.81	-3.41	-4.62	-5.94	-3.87	-4.43	-8.30	-7.48	-8.09	-4.95	-2.90
Area (km2)	1.00	1.02	1.03	1.01	0.97	0.97	1.07	1.10	1.06	1.01	1.00	0.95
Elevation (m)	-0.18	-0.24	-0.29	-0.42	0.18	0.76	0.68	0.53	0.34	0.10	-0.13	-0.26
Precipitation (m)	0.06	-0.16	-0.21	-0.16	-0.07	-0.04	0.01	0.54	0.84	-0.05	-0.10	-0.19
Cumulative Precipitation (m)	0.71	0.85	0.78	0.70	0.50	0.67	0.80	0.73	0.62	0.07	0.06	0.09
Temperature (C)	0.43	0.47	0.93	2.10	2.31	-0.04	0.10	2.55	2.45	4.05	2.36	1.18
Glacier (%)	-0.01	-0.03	0.00	0.00	-0.07	0.01	0.16	0.17	0.05	0.16	0.15	0.16

Table 4.2: Southcentral Alaska (SC AK) regression coefficients

Month	1	2	3	4	5	6	7	8	9	10	11	12
Constant Coefficient	-2.98	-4.81	-8.53	-10.4	-9.29	-7.76	-4.70	-3.42	-2.52	-2.98	-3.23	-1.39
Area (km2)	1.06	1.07	1.06	0.97	0.96	1.07	1.18	1.24	1.19	1.03	0.99	1.00
Elevation (m)	-0.71	-0.63	-0.41	-0.14	0.64	1.26	1.41	1.23	0.71	-1.21	-1.41	-1.61
Precipitation (m)	0.06	0.00	0.44	0.46	0.32	0.22	0.37	0.54	0.64	-0.10	-0.05	0.00
Cumulative Precipitation (m)	1.33	1.31	1.05	0.76	0.80	1.18	1.42	1.48	1.39	0.13	0.10	0.07
Temperature (C)	1.30	2.26	4.29	5.33	3.25	0.64	-2.03	-2.88	-2.48	2.89	3.72	2.87
Glacier (%)	0.01	0.02	0.03	0.04	0.05	0.14	0.29	0.44	0.41	0.76	0.57	0.49

Table 4.3: Canada (CA) regression coefficients

4.1.3 Validation and Verification

Equations were applied to the subwatersheds described in Figure 3.4 of Chapter 3 as per their appropriate regions in order to check that the equations functioned as they were expected to function. Figure 4.2 shows an example of applied equations, where each watershed is shaded based on the sum of its flow and the flow of all contributing watershed. Drawing attention to the dark stripe in the Southeastern Canadian portion of GOA, for example, it is apparent that the Fraser River accumulates water from surrounding watersheds.

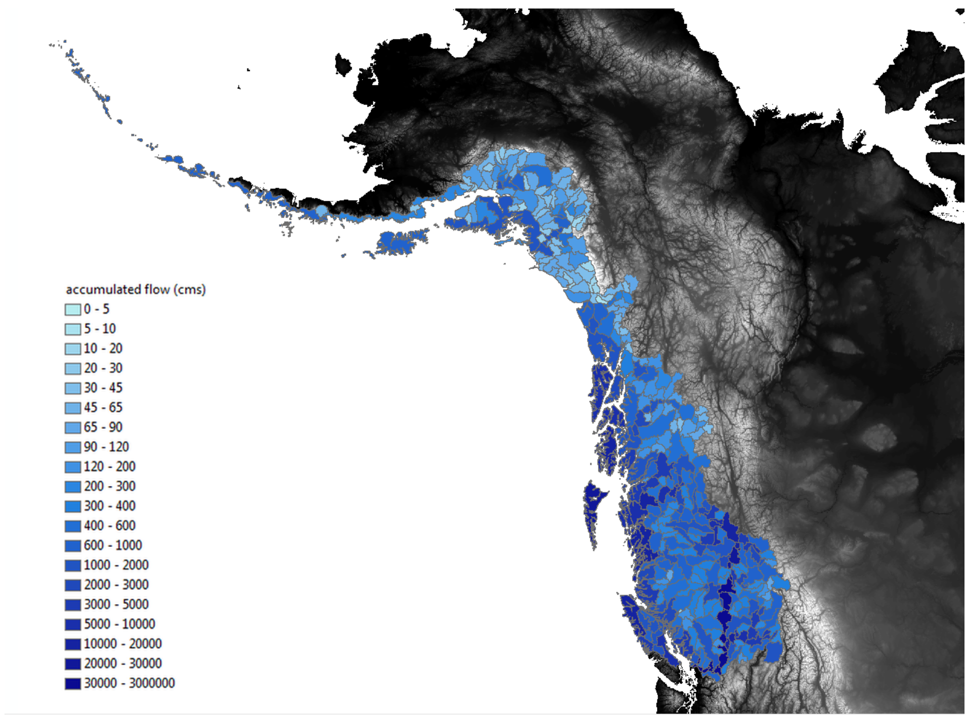

Figure 4.2: Sample month, October 1962. Cumulative flow in each watershed as calculated by applied regression equations.

4.1.3.1 Time Series Hydrograph Examples

To verify results, a time series hydrograph was plotted for several watersheds that coincided with gauging stations such that the two may be compared. In order to perform this comparison, the accumulation of all watersheds upstream of a coastal watershed was computed and plotted alongside a gauge within the most downstream watershed that lies along the coast. One such example for the Copper River (Figure 4.3) shows good agreement between the regression output and the reported flow (Figure 4.4), where the regression output clearly captures the seasonal variability as well as some inter-annual variability in flow.

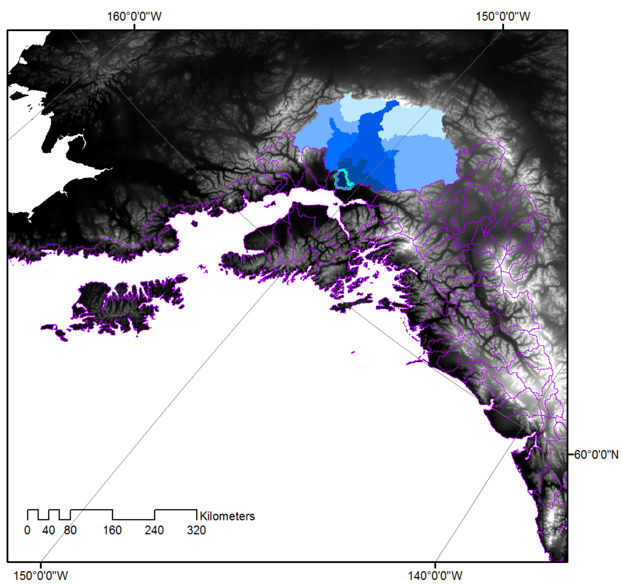

Figure 4.3: Teal-outlined watershed was compared to station data. All other blue watersheds describing the Copper River contribute to the coastal watershed being analyzed.

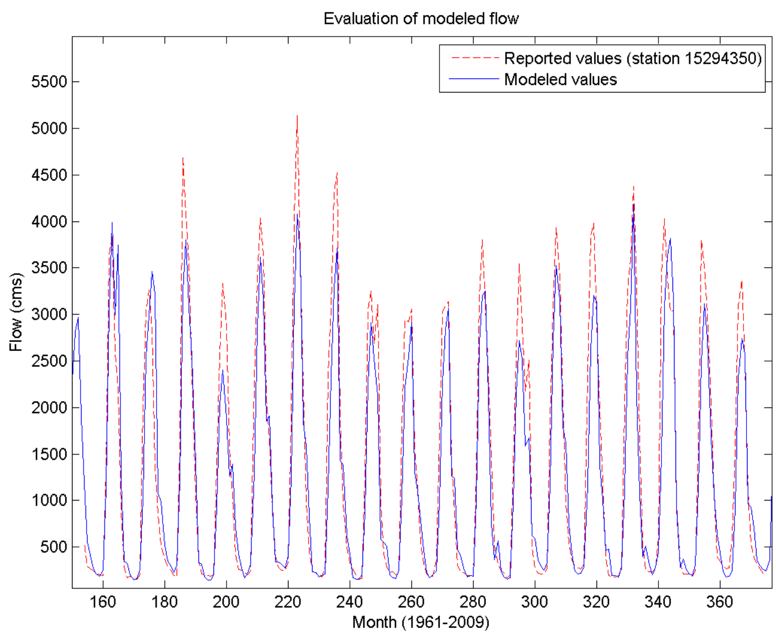

Figure 4.4: Copper River verification. Reported flow is shown in dashed red and modeled regression output is shown in blue.

4.1.3.2 Weighted Mean Percent Error

The accuracy of regression equations can be considered using weighted mean percent errors (WMPE) (Equation 4.1, Figure 4.5). This metric describes how well the equations perform when evaluated against measured station data, using weighting to take into consideration that large errors in low-flow months are less important (and incidentally more common) than large errors in high-flow regions. Due to very low-flow streams skewing the overall percent error, a weighted mean percent error of the following form was calculated to measure performance of the regression model with respect to station data, using the equation:

$$\frac{\sum_{i=1}^{n} m_i * |\frac{c_i - m_i}{m_i}|}{\sum_{j=1}^{n} m_j} * 100 \tag{4.1}$$

If for example, a stream with a measured flow of 10 cms had a calculated value of 20 cms, this 100% error would be muted in a sample including streams of 1,000 cms. With this method, the reduced error is better representative of the performance of regression equations because low-flow streams do not dominate the error.

4.1.3.3 Bootstrapping

As a test of accuracy, bootstrapping analysis was performed. Each station has gauging station flow data for at least 36 months of record. In bootstrapping, or leave-one-out analysis, all months of flow data for one station at a time, say station "X" were left out of the regression analysis. Once a representative equation was developed for the

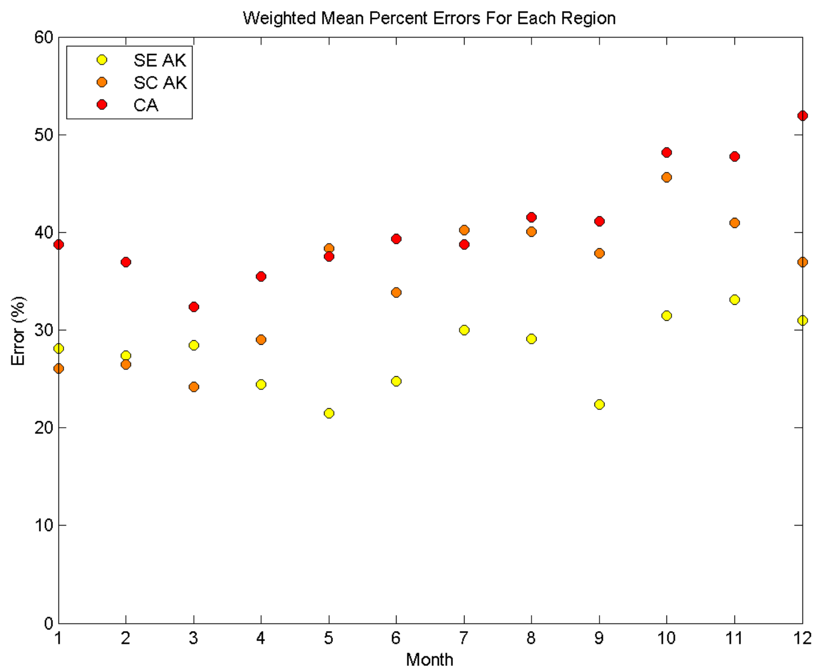

Figure 4.5: Weighted Mean Percent Errors

region in which X resides, this equation was applied to all months of X for which station data exist. The resulting flows from applied equations were then compared to measured station data for X. The weighted mean absolute percent errors were then averaged to give a representative error for the watershed which X represents. These errors were slightly higher than those calculated when X was left in the analysis to derive equations (Figure 4.6), but this was to be expected, given the nature of the two methods.

4.1.3.4 Comparison with Previous Studies

Average annual flows (Figure 4.7) were calculated for the portion of the GOA drainage that drains through the state of Alaska's coastline, namely the Southcentral and Southeast Alaska regions. The average of these mean annual flows between 1961 and 2009 is 792 km^3/yr, ranging from 645 to 960 km^3/yr. The drainage area for this region is 461,699 km^2, demonstrating an effective runoff of 170 cm/yr. This average value falls within previous estimates of 725 km^3/yr [Royer, 1982], 728 km^3/yr [Wang et al., 2004], and 870 km^3/yr [Neal et al., 2010]. The fact that this study's value is slightly higher than that of Royer's and Wang et al.'s may be attributed to this study's inclusion of Canadian watersheds that drain through Alaska's coast. This study's value is less than that of Neal et al.'s because the latter included a major glacier volume loss component, which is responsible for approximately 10% [Neal et al., 2010] of total freshwater to the gulf.

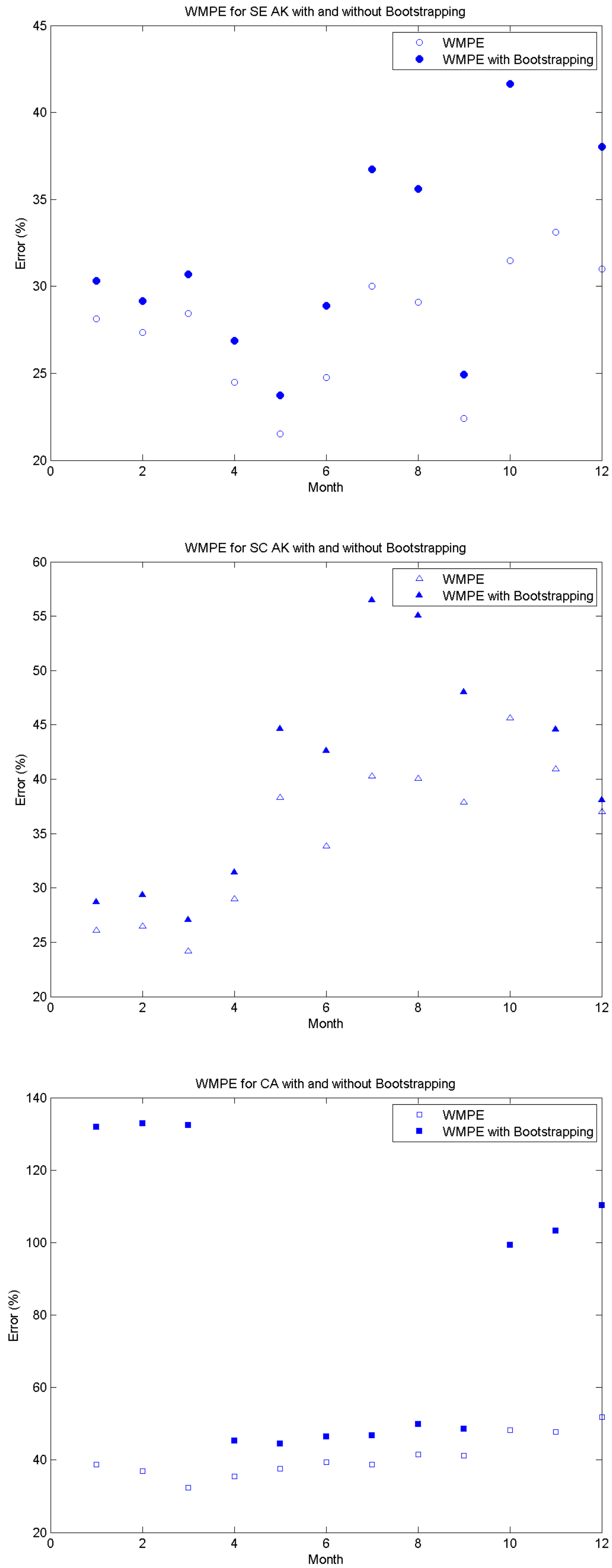

Figure 4.6: Results of Weighted mean percent error with and without bootstrapping for all three regions (top to bottom) Southeastern Alaska, Southcentral Alaska, and Canada.

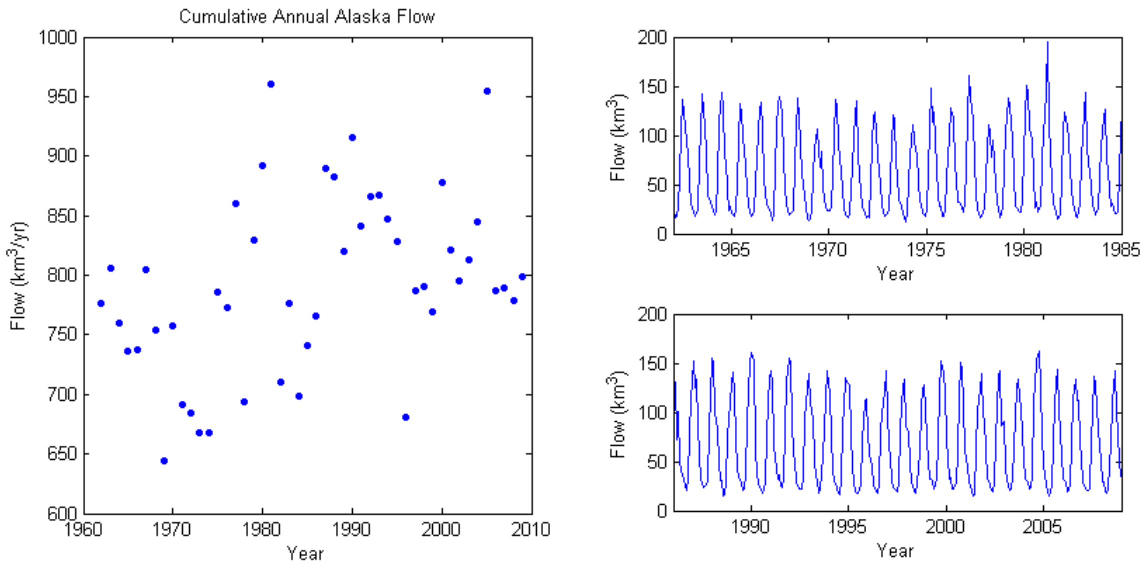

Figure 4.7: Left panel: each blue dot represents cumulative flow for all watersheds draining out of the Alaska portion of the GOA region in one year (Regions 1 and 2). Right panel shows time series for Regions 1 and 2.

4.2 Distributed Model

A 10-year run of SnowModel was executed (Figure 4.8), yielding total snow water equivalent (SWE) for the SnowModel domain depicted in Figure 3.5. The peaks in Figure 4.8 show the maximum snow water equivalent per year and the troughs show the minimums. By evaluating the difference between peak and trough in a given year, the total expelled SWE may be deduced. For the years between 2001 and 2011, an average of approximately 260 km^3 SWE were expelled each year. The area of the domain being modeled by SnowModel is 418,877 km^2, so the effective SWE loss is 62 cm/yr. Likewise, by calculating the amount of snow represented on the rising limbs of these peaks, one may determine how much snow accumulates. For 2001-2011, this number is approximately 300 km^3/yr. This means that each year, about 40 km^3 SWE is stored in the SnowModel domain for this study.

Initially the model starts with no snowpack anywhere in the model domain. Figure 4.9 shows that, barring annual oscillations over the course of the simulation, it may be that the model generally stabilizes toward equilibrium in the later years with a low around 290 km^3 and a high of around 550 km^3. This simulation was too short to draw such conclusions.

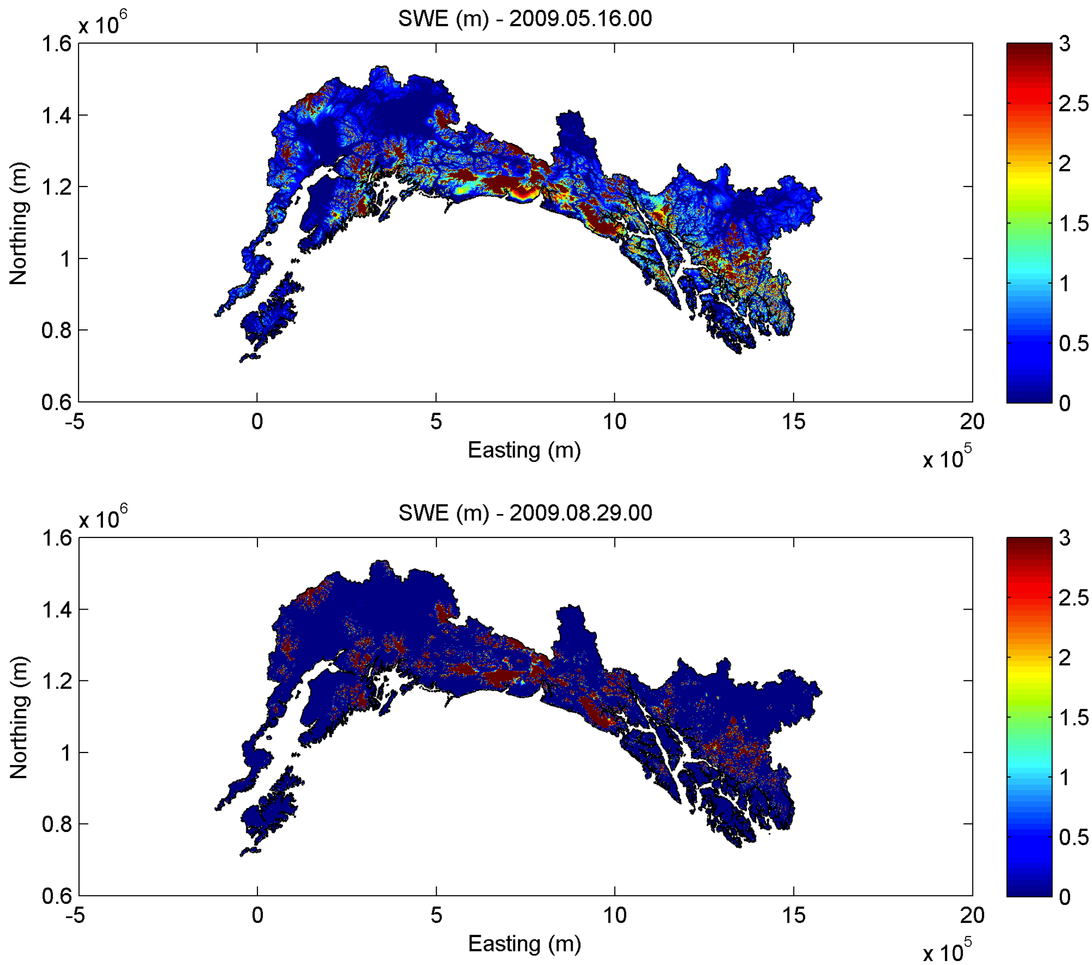

Figure 4.8: SnowModel output showing max snow water equivalent (top) and min snow water equivalent (bottom).

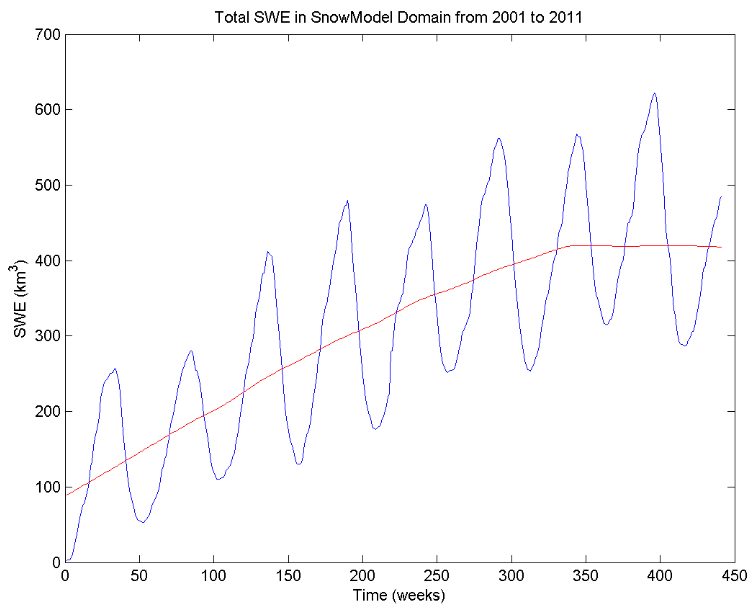

Figure 4.9: SnowModel output showing cumulative snow water equivalent for the entire study domain, each week from 2001 to 2011. Red line shows moving average.

Chapter 5: Discussion

5.1 Regression Equations

5.1.1 Implications of Coefficients

Tables 4.1-4.3 list coefficients for all parameters across all months in each region. As described previously, the governing equation is:

$$Q = AD^{a_1}E^{a_2}P^{a_3}C^{a_4}T^{a_5}G^{a_6} \tag{5.1}$$

Again, Table 3.3 in Chapter 3 describes this equation's terms. When a coefficient is positive, it indicates that a greater input parameter value yields a greater streamflow output. When negative, the opposite correlation is true. The magnitude of each parameter's coefficient indicates its importance to streamflow, where a greater coefficient has a stronger affect on flow than does a lesser coefficient. Below is an assessment of each input parameter's corresponding coefficient.

5.1.1.1 Area

As expected, area was positively correlated to streamflow, indicating that the greater the area the higher the streamflow. This number should be close to 1 since there is a direct correlation between the area and flow. The resulting coefficients are appropriate for area in all regions across all months (Tables 4.1-4.3).

5.1.1.2 Elevation

The coefficient for elevation was expected to change throughout the year, since precipitation will freeze or melt depending on season and the presence of snowpack. All regions show a peak in summer months (June - August), demonstrating the presence of a melting snowpack. Each region has a unique set of months with negative coefficients, indicating high-elevation freezing of precipitation during the cold season. While all three regions show a similar trend (Figure 5.1), Southcentral Alaska has the least variance from month to month, likely attributed to its less variable climate.

5.1.1.3 Precipitation

Precipitation should intuitively have a strong positive correlation to flow. That is to say that the more it rains, the higher the flow out will be. This can be offset in the winter by freezing of precipitation, to be released in later months. Some unexpected results are shown in Tables 4.1-4.3. The occurrence of negative values is not strictly limited to winter months where any precipitation may freeze and be held until the snowpack is warm enough to melt.

Since the precipitation coefficient is consistently smaller than both the cumulative precipitation coefficient and the temperature coefficient, the rain which fell in a given

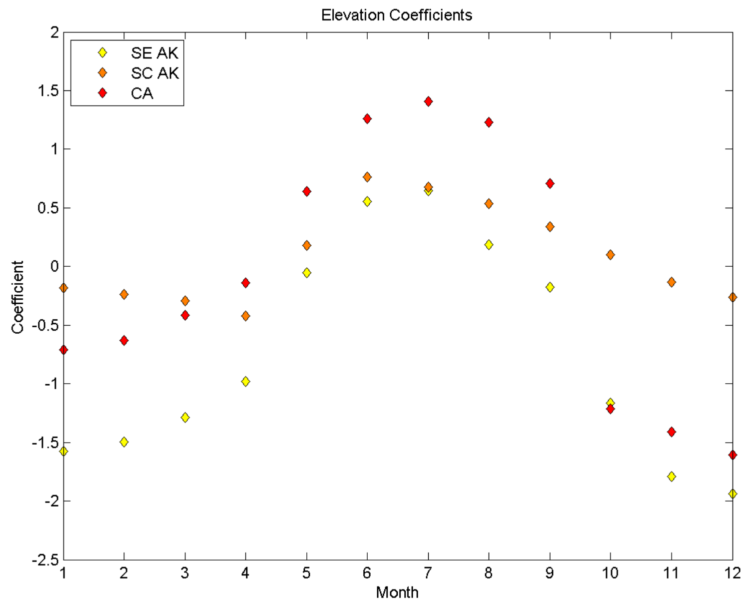

Figure 5.1: Elevation coefficients by month for each region.

month is not as important to flow as is the size of the snowpack that month and how much heat it receives.

5.1.1.4 Cumulative Precipitation

The cumulative precipitation coefficient is expected to be positive for all months since there is no situation where an increase in cumulative precipitation should result in a decrease of streamflow. Indeed, the results for this coefficient are logical in that all are positive and lowest in the fall, near the start of the water year. Additionally of note, this coefficient is consistently among the highest, indicating its strong influence on streamflow.

5.1.1.5 Temperature

Tables 4.1-4.3 show that each region has one or more summer months with negative temperature coefficients (Figure 5.2). In general, temperature has among the highest coefficients, demonstrating its strong influence on streamflow. All regions are subjected to approximately the same range of temperatures: Southeast Alaska experienced temperatures as low as -31°C and as high as 18°C from 1961 to 2009, Southcentral Alaska experienced -30°C to 16°C, and Canada saw -30°C to 20°C. Values are lowest in summer, when snow pack has depleted, minor streams have dried, and warm temperatures no longer yield more flow.

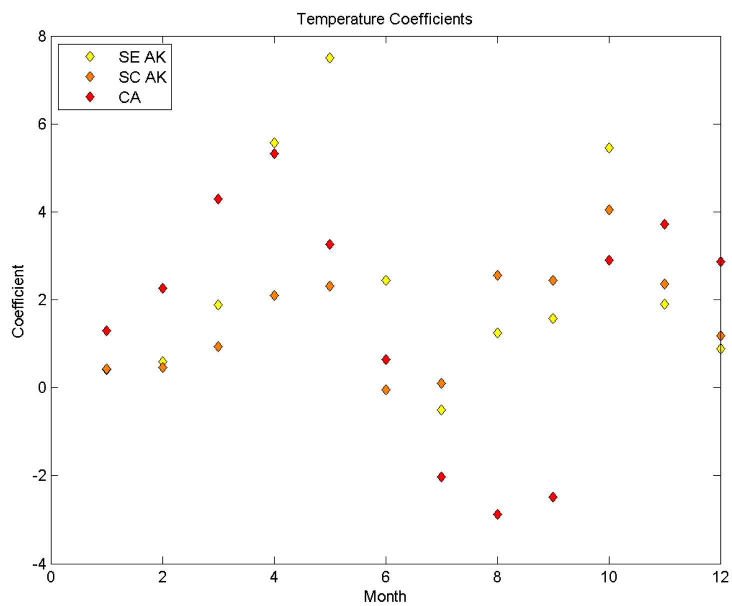

Figure 5.2: Temperature coefficients by month for each region.

5.1.1.6 Glacier Cover

The percent glacier cover coefficient is positive if glaciers are contributing to streamflow in a melting state, and may be negative when they are in a freezing state. The particularly low magnitudes of the coefficients for percent glacier cover indicate a low correlation between percent glacier cover and streamflow as compared to other input parameters. The increase in magnitude with decrease in latitude is indication that lower latitudes and their associated climates increase the glacial pulse.

5.1.2 Implications of Mean Annual Flow

The strong influence of elevation, cumulative precipitation and temperature imply that most of the freshwater draining from the GOA study area rely heavily on snowpack. High elevation allows for precipitation to freeze and build up, and warm temperatures force melting in the spring and summer.

The calculated 792 km^3/yr flowing out of the GOA drainage from the state of Alaska is higher than all prior estimates of this value. This may be explained by a higher-resolution representation of smaller streams and glacial pulses, a quantity which may have been lost in previous studies. The higher value may also be attributed to the fact that earlier studies had a low-elevation bias, where snowpack was misrepresented.

5.1.3 Limitations of Regression Analysis

Geographically subdividing into regions within the GOA drainage was a good step toward tailoring equations to specific watersheds. However, some smoothing will always occur with regression analysis in an effort to describe multiple slightly varying systems with one equation. These derived equations apply only to natural watersheds that lie within each region. The equations do not apply to any urbanized or dammed streams, or any streams otherwise governed by human interference.

Pacific Decadal Oscillation (PDO) describes a long-term climate variability pattern in the Pacific Ocean, whereby a long period of cool sea surface temperatures is followed by a long period of warm sea surface temperatures and vice versa. The record of this study begins in 1961 and ends in 2009, spanning at least two different Pacific Decadal Oscillations (PDO) [Mantua & Hare, 2002], a cool cycle from 1961 through 1976 and a warm cycle from 1977 through at least the mid-1990's. These sea surface temperature cycles impact climate on the coast including temperature and precipitation. If a future inquiry involves the domination of one of these PDO cycles over the other, the regression coefficients determined here may become less descriptive of true streamflow, since this study effectively averages the two cycles.

The percent glacier cover input parameter for every month was taken from the same map, created in 2005, and is unchanging throughout the course of this study. This creates two limitations: only the top view of the glacier is represented, and the glacier size is not allowed to change from month to month or from year to year. The total contribution of glaciers to streamflow in each watershed may be poorly estimated, without information on the volume of the ice and without consideration of glacier variation. Hence, the influence of glaciers on streamflow and their resulting regression coefficients may be also be poorly represented.

5.1.4 Measures of Error

Weighted mean percent errors were calculated in Chapter 4 of this document, shown in Figure 4.5. The errors for Southcentral Alaska are generally slightly higher and more variable than those of Southeast Alaska, likely because Southcentral Alaska has more glacier cover. Another common performance metric used in hydrology is the Nash-Sutcliffe Efficiency (NSE), described by the equation:

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_r - Q_m)^2}{\sum_{t=1}^{T}(Q_r - \bar{Q}_r)^2} \tag{5.2}$$

where Q_r is the reported discharge from the gauging station, Q_m is the discharge calculated by the regression model, and t is time. NSE describes an efficiency, from negative infinity to one, showing how well the model matches the reported flow as compared to the mean of reported flows. A NSE of zero means that the regression model performed as well as the mean of reported flows. A NSE of one means that the regression model exactly equaled the reported flow. Any NSE lower than zero means that the model does a worse job describing flow than does the mean of reported values. In short, the closer the NSE = 1, the better the model is for predicting flow. Figure 5.3 plots Nash-Sutcliffe efficiencies for all regions. Note that Southeastern

Alaska shows highest efficiency of the three regions for the later nine months of the year, while Southcentral Alaska performs well for the first three months of the year.

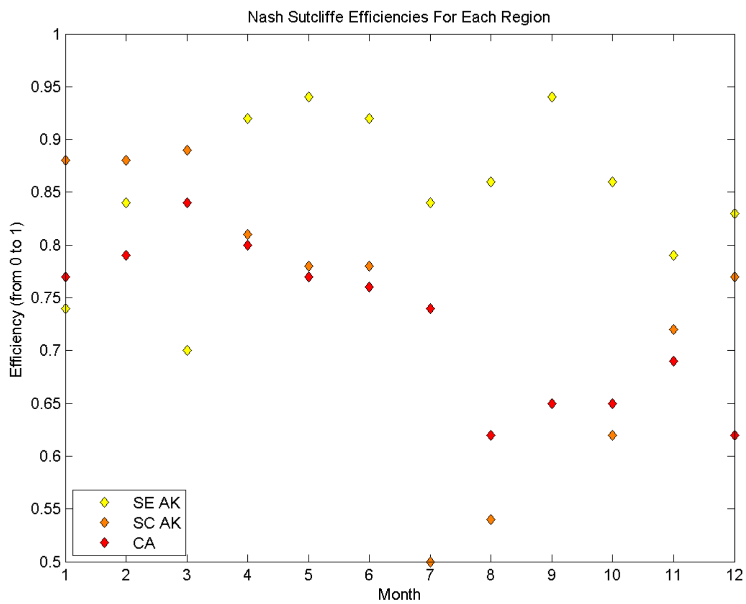

Figure 5.3: Nash Sutcliffe Efficiencies showing all months of all regions, starting in January.

Recalling that the goal of the regression phase of the project was to provide researchers with a very accessible tool, the challenge was to strike a balance between appropriately describing flow, and limiting input requirements from researchers using the model. Appendix A shows the parameter elimination process.

5.2 Distributed Model

5.2.1 Implications of Output

In this method, snowpack is assumed to be at zero depth at the start of the simulation. Snow accumulates and ablates each year, with an overall accumulating oscillating trend, until an equilibrium oscillating trend is reached. It is impossible to be sure from this simulation that the model, in fact, reaches equilibrium, however the moving average suggests that it is possible.

5.2.2 Limitations and Error Sources of Distributed Model

Given that this method requires a multi-year run in order to equilibrate, the years near the start of the simulation may be unreliable since snow water equivalent did not actually start at zero depth. The GOA drainage is sensitive to the effects of climate change on its many glaciers. A much longer run of this model could potentially show equilibrium in SWE prior to the onset of climate change, and an upward trend in more recent years as SWE increases each year. Data for the simulation were available from 1961 through 2009, however time constraints did not allow for a model run of that length.

Several parameters were adjustable in the model's parameter file. Best efforts were made to choose parameters that accurately described the natural system, however the default values were used for the most part, since the study domain had such vast expanse and covered such a range of values that it was not feasible to accurately describe all parts of the system. Specifically, the GOA domain is a very large region for MicroMet and SnowModel to consider, encompassing great elevation differences. As noted in Liston & Elder [2006a], MicroMet simulates air temperature and precipitation distributions based on applied temperature lapse rates and precipitation scaling factors. These parameters are difficult to adjust without sufficient data. No parameter options were available to adjust the initial conditions of snow water equivalent. Having this option would allow for shorter model runs, in eliminating the need for the model to stabilize.

An important limitation of SnowModel is that it considers only snow accumulation and ablation, and does not consider glacier flow. Glaciers and snowpacks behave quite differently with respect to movement and melting. Advancement and retreat, as well as lateral movement of glaciers each year may affect model equilibrium in a way that is not accounted for by simply considering snowpack. Another complication of glaciers that is not true of an accumulated snowpack assumed by SnowModel is that glaciers cleave and break off, losing mass at a very inconsistent rate.

In consideration of land cover, the source obtained for the regression analysis phase of this project did not align with the predefined SnowModel vegetation types and thus had to be adjusted to match the model types. The land cover map obtained for this study had 19 vegetation types, whereas the land cover requirements for SnowModel had 23 vegetation types. Additionally, the land cover map obtained had a finer resolution (250 m) than the digital elevation model (1 km) and thus had to be resampled.

Chapter 6: Conclusion

6.1 Summary

This study explained freshwater flowing to the Gulf of Alaska through Alaska and parts of Canada. Contrary to previous studies for freshwater flow into the gulf, Alaska and Canada were considered in the same domain in order to include all freshwater which may contribute to and help drive the Alaska Coastal Current. Two sets of high-resolution climate grids, one for precipitation and one for temperature, were developed for Alaska and parts of Canada in the Yukon Territory and British Columbia, which flow into the Gulf of Alaska. These grids provided 2 km x 2 km monthly information from 1961 through 2009. Gridded information was accumulated per watershed such that for each watershed, a mean temperature and a precipitation depth were reported.

The second phase of the project performed multiple linear regression analysis. Following Curran et al. [2003], the regression model took the form:

$$Q = Ax_1^{a_1}x_2^{a_2}x_3^{a_3}\dots \tag{6.1}$$

where Q describes streamflow, x_1, x_2, etc. describe input parameters, a_1, a_2, etc. describe derived regression coefficients, and A describes the constant coefficient. The study domain was divided into three subregions, each with a unique set of equations. One equation was derived per month per region, yielding 36 final equations. Equations were then applied to all watersheds to determine the total modeled flow out of the GOA drainage. This mean value, at 792 km^3/yr out of Alaska, was comparable to previous studies for the same area. This study showed a total of 1,331 km^3/yr flowed out of the entire GOA drainage, including Alaska and parts of Canada.

Finally, initial steps toward implementing a distributed hydrological model were completed. In order to determine the freshwater flowing into the gulf on a sub-daily 1 km x 1 km resolution, three models must be executed. First, MicroMet [Liston & Elder, 2006a] provides a meteorological distribution of the domain of interest. Second, SnowModel [Liston & Elder, 2006b] yields the available water per grid cell. Finally, HydroFlow [Liston & Mernild, 2012] routes the available water per grid cell through the domain. This study carried out MicroMet and SnowModel from 2001 through 2011, leaving HydroFlow and a longer model run as tasks for future work. The results showed that approximately 260 km^3/yr of freshwater flowing to the gulf may be attributed to snowmelt.

6.2 Overarching Conclusions

Given a mean outflow of 792 km^3/yr from regression equations and an average snowmelt of 260 km^3/yr from SnowModel, we see that one third (33%) of freshwater flow to the gulf originates in the snowpack. The flow that does not come from snowpack must be explained by factors that the distributed hydrologic model does not take into consideration, such as direct runoff from precipitation, and recharge via saturated soils.

Typical precipitation values from the developed climate grids for the Northern portion of the GOA drainage (excluding watersheds which drains through coastal Canada), showed that approximately 970 km^3/yr fell on the region. For 2001-2011, regression models in this study showed that roughly 825 km^3/yr drained out of the same region. Snowmodel shows a snow accumulation of 40 km^3/yr. This means that 105 km^3/yr of freshwater input is unaccounted for. In the forested areas of the region, the water is likely taken up by plants. In the glacier-dominated areas it likely sublimates.

6.3 Future Work

Continuing the distributed hydrological model phase of this research, a longer run of SnowModel would be paramount in drawing conclusions of any potential system equilibrium. Obtaining a baseline for the region in earlier decades could provide insight to any recent trends occurring due to climate change. Comparing the model output with local SNOTEL sites, which measure snow water equivalent[1], would give insight as to how well the model performs.

Finally, as was mentioned in the introduction to this document, work in this field will be ongoing and will continue to improve as more data become available and new technologies are implemented. For example, remote sensing data are likely to improve estimates of glacial coverage in these watersheds. It will be necessary for models to be updated as the availability of land cover information changes in the

[1] http://www.wcc.nrcs.usda.gov/snow/

coming years and decades.

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APPENDICES

Appendix A: Parameter Elimination

A regression equation must balance an adequate description of flow with a realistic requirement of inputs. This study started with a large number of input parameters and systematically eliminated them until only a handful of the most important remained. Due to availability of data, the process of eliminating parameters was done only for Alaska regions and is described below. Once necessary parameters were determined for Alaska, those same parameters were obtained for Canada (using DEM, land cover map, and climate grids) in order to determine regression coefficients for Canada.

First, the following 10 parameters were included in analysis, and a percent error, describing how well the regression-modeled output compared with measured station data, was calculated in order to establish a baseline performance.

- Area
- Slope
- Mean channel length
- Elevation
- Mean January minimum temperature (from USGS)
- Mean January snowfall (from USGS)

- %Lake cover
- %Forest cover
- %Glacier cover
- Precipitation (from climate grids)
- Temperature (from climate grids)
- Cumulative precipitation (derived from climate grids)

The performance of the model in each scenario of parameter elimination was calculated using a mean percent error:

$$\frac{1}{n}\sum_{i=1}^{n}\left|\frac{c_i - m_i}{m_i}\right| * 100 \tag{A.1}$$

Table A.1 shows the resulting performance for Southeast and Southcentral Alaska each month.

Parameters were sequentially eliminated, and percent error was computed and compared to the baseline to assess the importance of each parameter on the streamflow output. If an input parameter had little effect on the percent error when excluded from analysis, its necessity was deemed suspicious.

Geometry

Area, Slope, Length, Elevation

	Southeast Alaska	Southcentral Alaska
January	42.0	40.2
February	42.3	44.8
March	43.3	49.8
April	42.3	38.3
May	35.2	52.3
June	39.0	33.0
July	41.8	30.0
August	35.9	29.2
September	31.0	32.3
October	42.2	53.7
November	49.3	59.6
December	54.8	55.0

Table A.1: Mean percent errors for baseline scenario of GOA drainage, including all parameters in analysis.

Climate

Mean January minimum temperature, Mean January snowfall, Precipitation, Temperature, Cumulative precipitation

Land Cover

Lake, Forest, Glacier

One by one these groups were excluded from analysis and suspicious parameters were eliminated in groups. Figure A.1 shows a representative plot for August demonstrating the baseline for each region as stripes across the bar graph at 36% and 29% for regions 1 and 2, respectively.

It became clear, for example, that pulling out all land cover changed the performance of the model signiciantly, while taking forests and lakes out of analysis with temperature parameters, geometry parameters, and the snow parameter seemed to

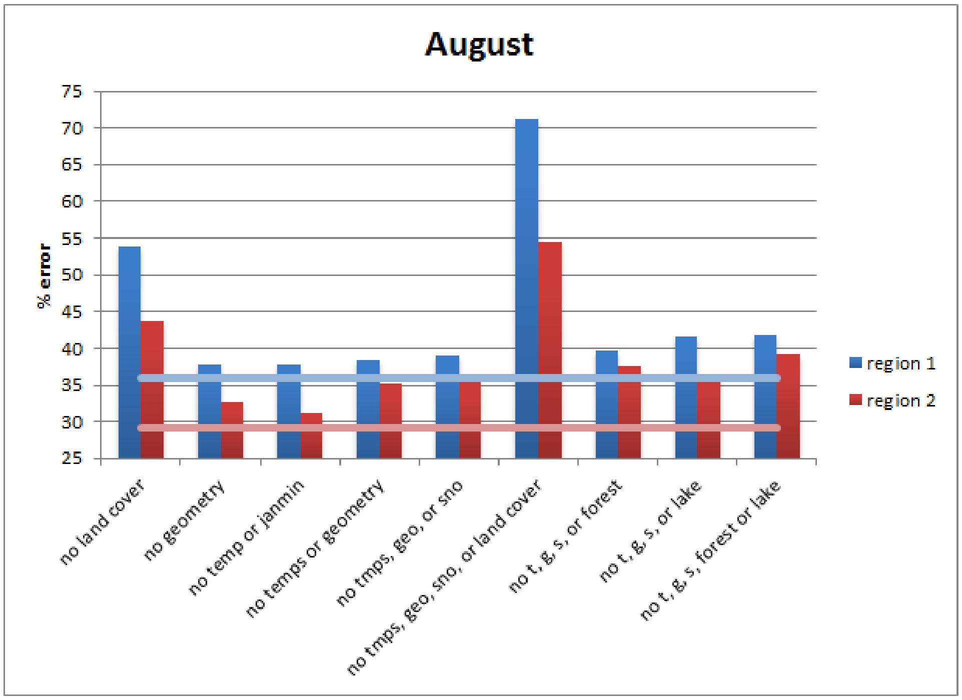

Figure A.1: Example of plotted mean percent errors with different parameter elimination scenarios.

affect the error very little (farther right bar in Figure A.1). These data were collected for each month and the assessment determined that all months in both regions required information on area, mean elevation, monthly precipitation, cumulative water year precipitation, and monthly temperature. Most months (7 months in SE AK and 8 in SC AK) found % glacier cover to greatly affect the performance of the model. For SC AK in May, forest cover was found to be quite important. However, in the interest of simplicity and uniformity from one equation to the next, forest cover was not included for any month.

Appendix B: Regionalization

The following analysis sought to appropriately subdivide Canada into regions described by unique regression equations. As a baseline, Canada was left as one region, except that the Canadian watersheds that flowed through coastal Alaskan watersheds fell into Alaska regions (Figure B.1). Then upon each alternate subdivision of the region, errors were compared to this baseline to determine whether or not the subdivision was appropriate.

Performance for this process was measured using weighted mean absolute errors, described by the equation:

$$\frac{\sum_{i=1}^{n} m_i * |\frac{c_i - m_i}{m_i}|}{\sum_{j=1}^{n} m_j} * 100 \tag{B.1}$$

where, n refers to the number of streamflow gauging stations in a region, m refers to measured data acquired from streamflow gauging stations and c refers to the flow that was calculated by applying the derived regression equations. Weighted mean errors were calculated for each month in each region for each subdivision scenario.

The baseline errors describing the three subdivisions in Figure B.1 are shown in Table B.1. The next scenario treated coastal regions in Canada as an independent subregion, as shown in Figure B.2. The resulting performance is shown in Table B.2. The third scenario included a separate regionalization for glacial/lake-dominated watersheds (Figure B.3, Table B.3). Finally, the Fraser River Basin was treated as its own region, in addition to all other regions from previous scenarios (Figure B.4, Table B.4).

This process was enlightening in that it became clear how poorly the coastal region is described by the regression equations, particularly in late summer to early fall. However, the goal was to determine whether or not the Canadian region was worth subdividing further. For the purpose of this task, "Canada" from Table B.1 was compared with "Interior Canada" from Tables B.2-B.4, since it was the Interior Canada region was the original Canada region minus any stations lumped into new subdivisions.

Figure B.5 shows a plot of all errors for Table B.1's "Canada" and Table B.2-B.4's "Interior Canada". For every month, the more subdivisions there are, the better the model performs (the lower the error). The greatest improvement of errors was shown between 3 regions and 6 regions in June, where the error improved nearly 13% by including more subdivisions. However, in many months the error improved by a very small amount (as little as less than 1%). For the sake of avoiding a situation where different months of the year subdivide the study domain differently, the baseline scenario of three subdivisions (Southeast Alaska, Southcentral Alaska, and Canada) was deemed adequate.

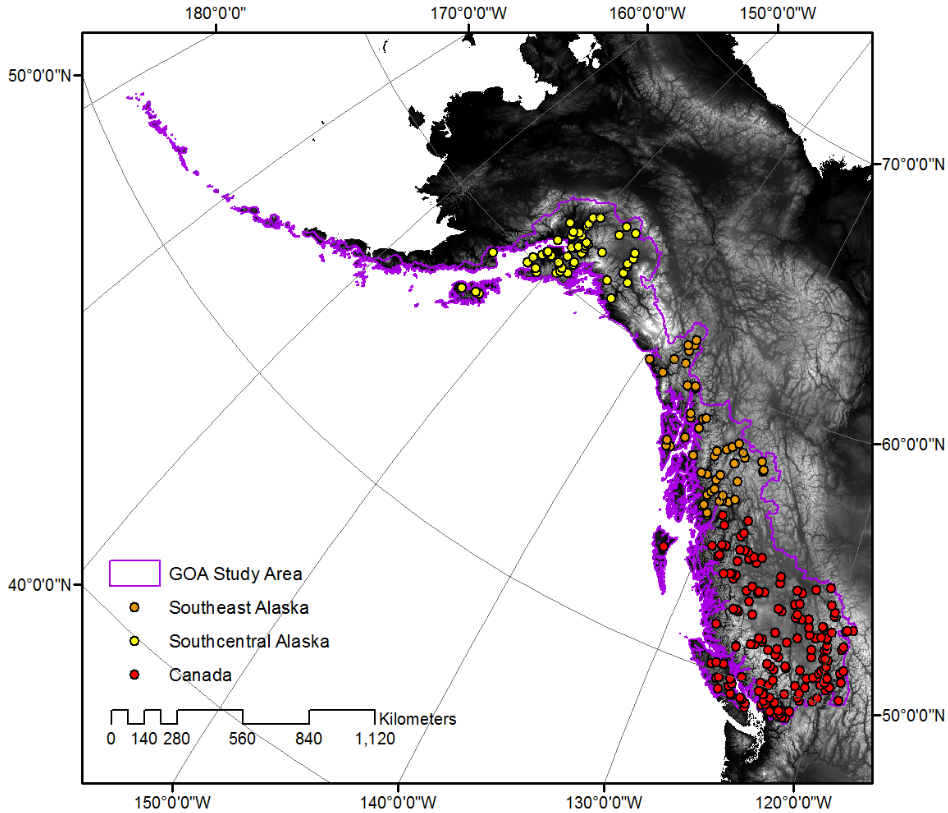

Figure B.1: Baseline scenario of GOA drainage, including three subregions.

	Southeast Alaska	Southcentral Alaska	Canada
January	28.59	26.07	38.76
February	27.68	26.48	36.87
March	28.85	24.15	32.35
April	24.66	29.00	35.52
May	21.91	38.33	37.48
June	24.93	33.83	39.47
July	29.70	40.25	38.80
August	28.74	40.06	41.58
September	22.38	37.86	41.28
October	32.42	45.60	48.04
November	33.83	40.95	47.37
December	31.58	36.98	51.82

Table B.1: Weighted mean percent errors for baseline scenario of GOA drainage, including three subdivisions of streamflow stations.

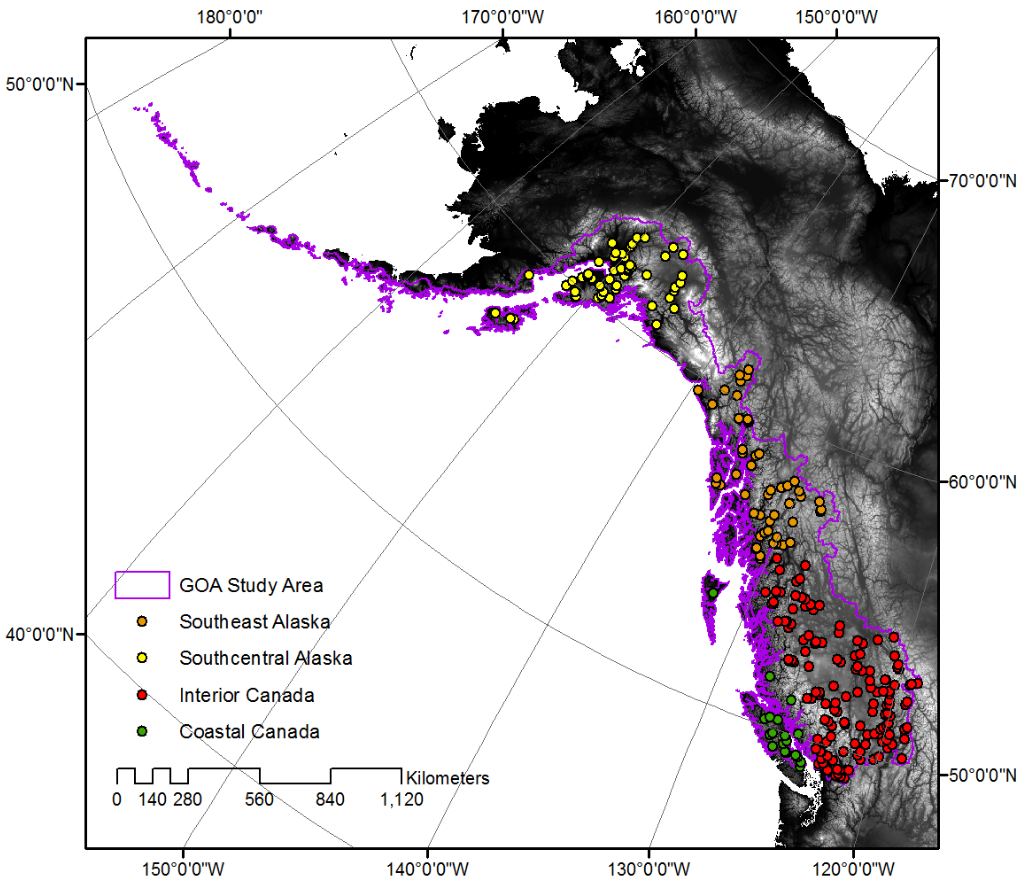

Figure B.2: GOA drainage with four subdivisions of stations.

	Southeast Alaska	Southcentral Alaska	Interior Canada	Coastal Canada
January	28.59	26.07	38.49	39.92
February	27.68	26.48	36.59	39.90
March	28.85	24.15	31.88	37.60
April	24.66	29.00	34.94	49.04
May	21.91	38.33	35.83	53.79
June	24.93	33.83	36.35	56.47
July	29.70	40.25	34.09	63.46
August	28.74	40.06	35.27	96.67
September	22.38	37.86	34.88	85.66
October	32.42	45.60	46.16	42.89
November	33.83	40.95	45.82	38.49
December	31.58	36.98	50.33	40.66

Table B.2: Weighted mean percent errors for GOA drainage with four subdivisions of streamflow stations.

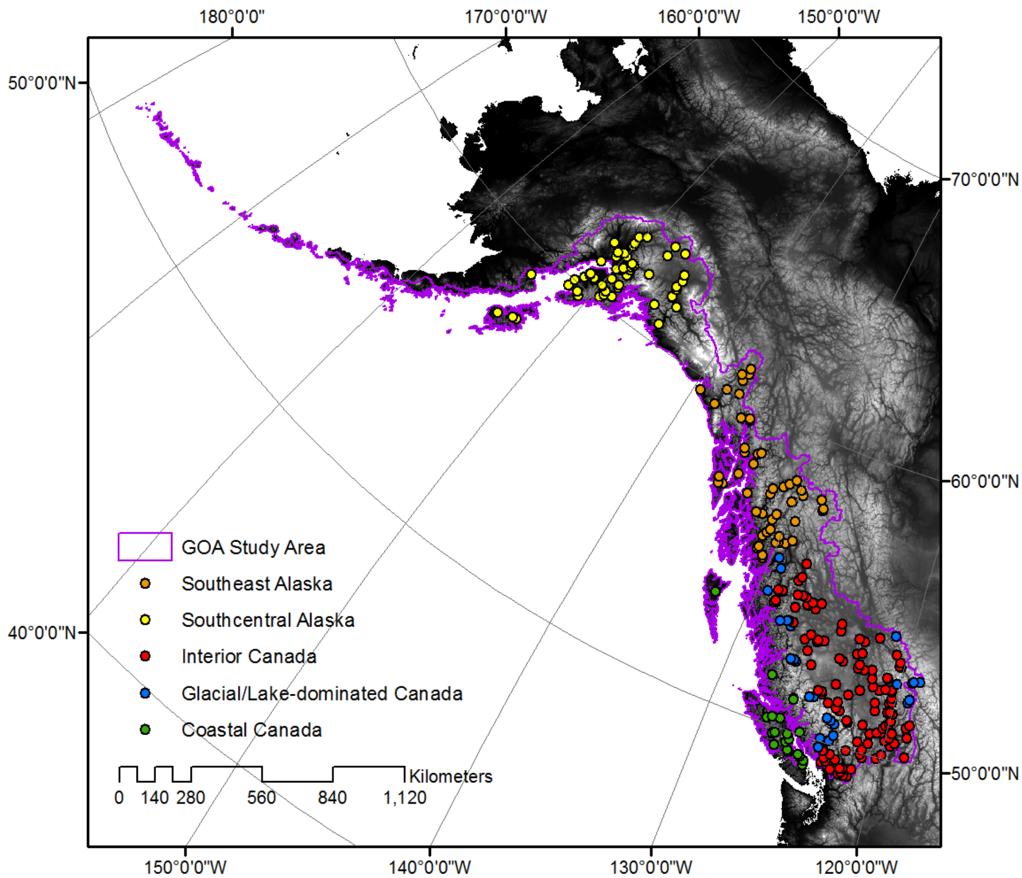

Figure B.3: GOA drainage with five subdivisions of stations.

	Southeast Alaska	Southcentral Alaska	Interior Canada	Coastal Canada	Glacial/Lake Dominated Canada
January	28.59	26.07	37.27	39.92	37.58
February	27.68	26.48	35.22	39.90	36.57
March	28.85	24.15	31.17	37.60	29.38
April	24.66	29.00	34.36	49.04	28.20
May	21.91	38.33	34.92	53.79	27.31
June	24.93	33.83	34.14	56.47	31.06
July	29.70	40.25	32.06	63.46	29.35
August	28.74	40.06	34.49	96.67	22.98
September	22.38	37.86	33.26	85.66	23.88
October	32.42	45.60	47.33	42.89	30.54
November	33.83	40.95	46.70	38.49	32.27
December	31.58	36.98	50.07	40.66	41.99

Table B.3: Weighted mean percent errors for GOA drainage with five subdivisions of streamflow stations.

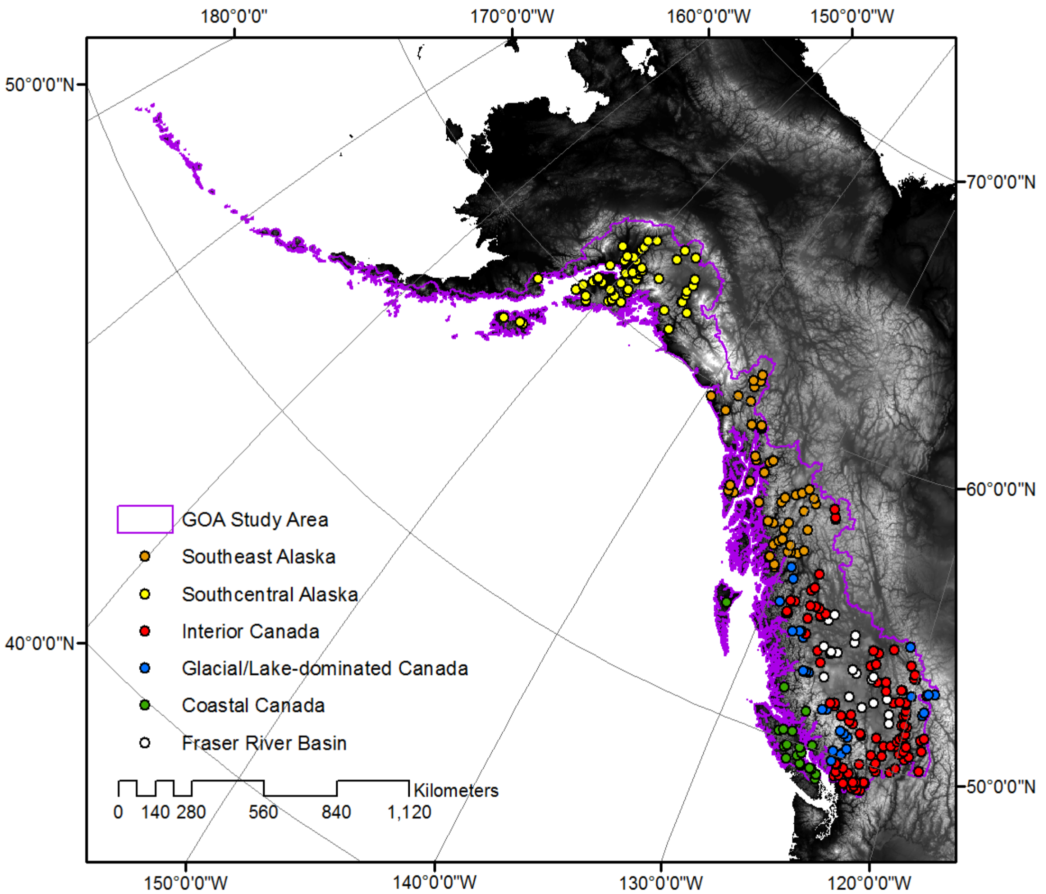

Figure B.4: GOA drainage with six subdivisions of stations.

	Southeast Alaska	Southcentral Alaska	Interior Canada	Coastal Canada	Glacial/Lake Dominated Canada	Fraser River Basin
January	28.59	26.07	36.71	39.92	37.58	31.92
February	27.68	26.48	34.75	39.90	36.57	26.67
March	28.85	24.15	31.35	37.60	29.38	19.83
April	24.66	29.00	34.25	49.04	28.20	33.95
May	21.91	38.33	29.53	53.79	27.31	30.25
June	24.93	33.83	26.68	56.47	31.06	40.42
July	29.70	40.25	28.28	63.46	29.35	41.01
August	28.74	40.06	31.87	96.67	22.98	50.34
September	22.38	37.86	30.60	85.66	23.88	44.88
October	32.42	45.60	41.90	42.89	30.54	51.93
November	33.83	40.95	43.04	38.49	32.27	50.37
December	31.58	36.98	47.36	40.66	41.99	49.22

Table B.4: Weighted mean percent errors for GOA drainage with six subdivisions of streamflow stations.

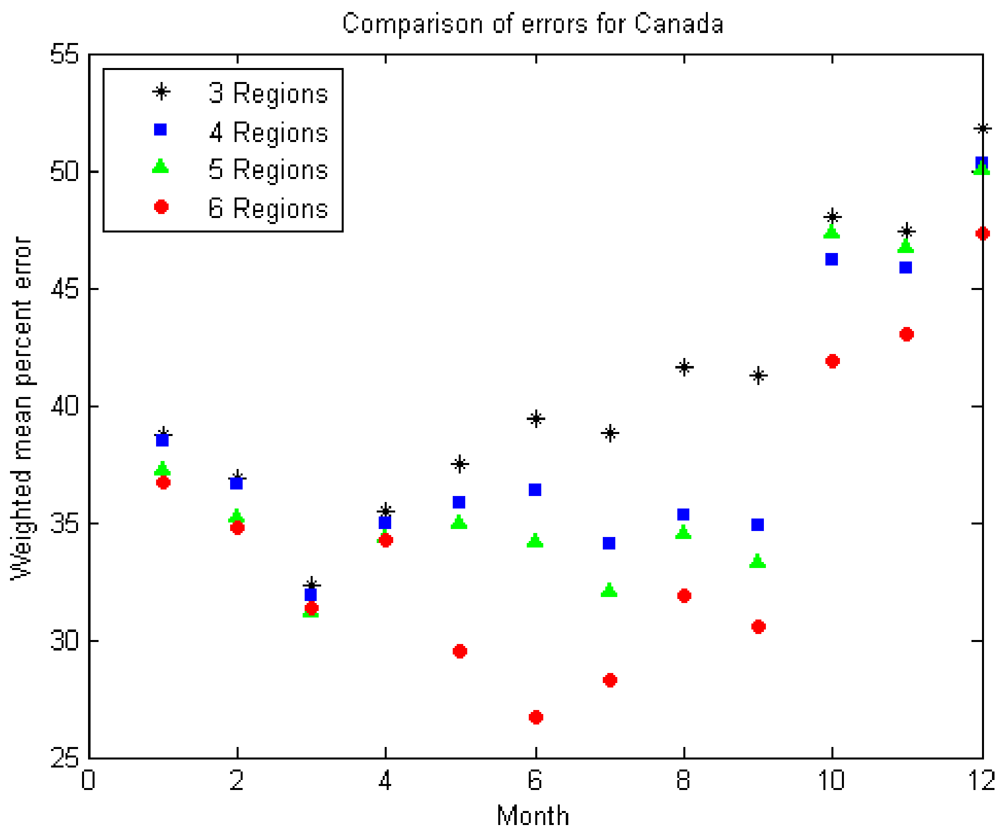

Figure B.5: Errors for Canada region for various subdivision scenarios.