Impacts of Climate Change and Variability on Hydropower in Southeast Alaska:

Planning for a Robust Energy Future

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TABLE OF CONTENTS

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ABSTRACT: The useful lifespan of hydroelectric power infrastructure is 50 years or more; this is long enough that long-term climate change and shorter-term climate variability should be considered when planning new facilities and maintaining existing ones. This study examines observed historical climate variability in Southeast, Alaska, where several new and expanded hydropower facilities are proposed. Analysis suggests that climate trends in this region since the 1920s are modest, while trends since the mid-1940s are somewhat stronger. Sparse data collection increases the uncertainty associated with these trends. Variability in temperature, precipitation, snow, and discharge is largely dominated by random interannual fluctuations, as well as semi-decadal to decadal climate modes such as the El Niño-Southern Oscillation and the Pacific Decadal Oscillation (PDO). The dominance of these modes of variability on the regional climate is useful for risk management because prediction tools exist for season-ahead forecasting. Longer-term climate trends, while smaller in magnitude, will likely lead to warmer and wetter conditions in the coming century. The persistence of a negative PDO may lead to cooler, drier conditions in the short term. Climate variability and change both have implications for shifts in the timing and magnitude of river discharge that could pose challenges to management of capacity-limited reservoir systems. An increasingly interconnected power grid in Southeast Alaska might help mediate these climate impacts, but there are still large data gaps that contribute to management risk. Enhanced monitoring of snow, temperature, runoff, and glacial melt, particularly at elevation and in the watersheds feeding hydropower reservoirs, could help operators reduce risk by eliminating some of the uncertainty about the relationships between climate and water resource availability.

1. INTRODUCTION

This study is motivated by several issues at the forefront of Earth system research and the practical need to plan for the future energy sector. While there is little expansion of hydropower capacity in the contiguous United States anticipated in the near future, Alaska has a number of new facilities and facility expansions proposed over the next two decades. While dams are being decommissioned in the Pacific

Northwest to help revitalize salmon habitat, Alaska has maintained a number of hydropower facilities in areas where topography is extreme enough that there are relatively few impacts on anadromous fish habitat. These geographic features make hydroelectric capacity growth attractive in Southeast Alaska.

Much of the existing hydropower capacity in the United States was built long before engineers and the general public were aware of the impacts of climate change on large infrastructure. With the development of increasingly sophisticated numerical climate models and the science coordination and publication associated with the Intergovernmental Panel on Climate Change (IPCC) assessment reports, there is an increasing awareness of the rapidity of climate change and its impacts, particularly in high latitudes. The scientific consensus is that climate change, particularly warming in winter, is amplified in the high latitudes because of several fundamental physical properties of the climate system. These include feedbacks associated with melting snow and ice, which leads to more absorption of solar radiation and additional warming, feedbacks associated with warming leading to increased formation of clouds and the trapping of additional heat near the surface, and the overall increase in heat transport by the ocean and atmosphere from the lower to the higher latitudes driven by planetary gradients (ACIA, 2005; IPCC, 2007).

Because Alaska is recognized as a 'front line' of climate change (Serreze, 2000; ACIA, 2005; Hinzman et al., 2005), agencies and municipalities are increasingly struggling with how to anticipate and mitigate the impacts. Large infrastructure on the scale of hydropower dams, reservoirs, and transmission systems are typically engineered with a lifespan of 50 years or more, under historical environmental conditions. A number of factors make it difficult to predict the impacts of climate change on large-infrastructure in Alaska: the general harshness and remoteness of the environment; the sparseness of long-term historical or even current records of temperature, precipitation, and snow depth; complex system features such as permafrost, glaciers, and seismic activity; and the high likelihood that the environment is undergoing rapid change. Southeast and South Central Alaska, where most of the existing hydropower facilities are located, have a mild, maritime climate relative to the rest of the state. The regional climate characteristics and facility descriptions will be provided in more detail below.

There are underlying economic conditions in Southeast Alaska that make planning for and responding to climate change impacts on the hydropower resources particularly challenging. The Southeast Alaska panhandle is a mountainous archipelago fused to Canada's British Columbia. Communities are small and isolated--not only from each other but from the rest of Alaska and the United States. Many are accessible only by air or boat. Some communities have relatively healthy tourist and/or fishing sectors, including the state capital of Juneau; others maintain subsistence economies with very few wage-based jobs. While Southeast Alaska represents a 'Saudi Arabia' of hydropower resources, the high cost of building facilities in mountainous terrain and transmitting power (often underwater) for such a small market, makes large-scale development prohibitive. Many of these communities continue to depend on diesel power generation, paying upwards of $1.00 kWh, in contrast to the U.S. average of $0.12 kWh (*EIA, 2010*). Even Juneau, which already has a multiple-reservoir hydropower system, was forced to rely on diesel fuel when avalanches wiped out transmission lines during spring of 2008 and again in January 2009 (*Juneau Empire, April 17 2008 and January 13, 2009*). Electricity prices increased nearly five times overnight; not only were diesel prices at a historical high, but drought had reduced the hydropower supply and the utility was already using diesel to supplement hydropower generation.

Facility operators and agency representatives began asking, "Is drought in Southeast Alaska tied to climate change?' around this time. The spring of 2008 and the preceding winter were influenced by a strong episode of cool conditions in the equatorial Pacific known as 'La-Niña.' In addition to the La Niña episode, the Pacific Decadal Oscillation, another mode of climate variability in this region, was also in a cool phase associated with offshore winds and decreased winter precipitation in Southeast Alaska (*JISAO, 2010*). How much of observed change in Southeast Alaska's hydrologic system is attributable to long-term climate change versus normal climate variability? And how might normal variability change as the global climate enters a new regime? As stakeholders try to plan for a robust future energy sector, they must account for changes in risk associated with climate, and they need guidance from scientists on how best to quantify and attribute climate impacts.

Our work represents a case study in Southeast Alaska for a process that is occurring all over the world; communities are trying to prepare for the impacts of climate change. Sitka is used as an example in the study because the municipality has applied for a license amendment to raise the height of their Blue Lake dam. In many senses, the effort herein is not new; most individuals are accustomed to using weather forecasts produced either through numerical modeling or through local or traditional knowledge to make decisions about their actions for the short term. Some sectors use longer-term forecasts to make decisions for the upcoming season. However, it is only with the advent of global climate models that it is possible to project changes in the climate far out into the future. Regional, downscaled models and numerical techniques are now being used to estimate the likelihood of various future climate outcomes. While many of these questions are pushing the state-of-the-science of present research, stakeholders are asking for this information to support their decisions right now; and attempts must be made to provide them what they need to develop resilient public infrastructure.

To summarize this introduction, this study addresses the following questions:

1. What are the patterns of observed climate change and variability in Southeast Alaska?
2. How are these patterns likely to change in the future?
3. How will existing hydropower and future facilities be impacted?

These questions will be explored below, as well as the potential utility of seasonal and longer-term forecasting for management of water resources in Southeast Alaska.

To some extent the effort here can be generalized to other climate impacts studies. Increasingly, agencies and other stakeholders are being asked to consider downscaled climate projections in their planning process. These include applications such as building design criteria, impacts on wildlife habitat, disturbance frequency by fire, and many other systems subject to climate-related risk. To help others pursue similar analyses, we have provided a guidance document, as an appendix, that outlines the steps taken in this study.

2. A DESCRIPTION OF THE HYDROELECTRIC POWER FACILITIES IN SOUTHEAST ALASKA

The Southeast Alaska Intertie Study Phase 2 final report (D. Hittle & Associates 'DHA', 2003) has a comprehensive description of Southeast's installed hydropower facilities, though several new facilities have been constructed since that time. This report was published about the same time that the Institute of Social and Economic Research at the University of Alaska Anchorage published a report on Alaska Electric Power Statistics 1960-2001 (ISER, 2003). Table 1 shows the facilities described in the DHA report. Electricity is generated at one or more facilities and typically transmitted a short distance to the community served. Service is generally provided by community-based utilities with few transmission links between communities. This intertie study, and those that preceded it, lay out the potential costs and benefits of increased transmission between communities, some of which have now been constructed. Falls Creek is a new 800 kW (2,160 MWh/year) facility near Gustavus; Kasidaya Creek is a new 3-MW (11,900 MWh/year) project near Skagway; and the 14.3-MW Lake Dorothy project is supplying additional electricity to Juneau (Levitt et al., 2010).

One interesting thing to note in Table 1 is that some communities are operating, on average, significantly below their maximum operating capability, but are still burning diesel fuel. Sitka and Petersburg/Wrangell stand out in this regard. This points to limitations in the availability of water, inefficiencies in generation, or other structural problems. Possible solutions depend on the costs and benefits of facility expansion, transmission interties, and future load growth. The Southeast Conference, which is a regional group of governmental and business stakeholders, is advocating for the development of a comprehensive regional energy plan that could explore these options. The present study raises some of the climate-related issues that may impact costs and benefits in this long-term planning.

Several findings in the DHA study point to features of the hydropower sector in Southeast that might make it particularly sensitive to climate variability and change. First, total power supply requirements can be strongly affected by the gain or loss of a single industrial load or water use such as a pulp mill or mine. If the industry depends on a self-contained electrical supply, there is little impact on the community. However, if the supply depends on the municipal power source, or is tied via transmission lines, change in industrial loads may have a big impact on the price paid per kWh. Future commercial uses for water in the region may include bottling of drinking water (rights have been sold in Sitka's Blue Lake for this purpose, Walton, 2010) or generating power for docked cruise ships, which is already occurring in Juneau. Any changes in industrial or commercial uses have a large impact on electrical prices in these small communities.

Second, the predominance of diesel generation has created air quality concerns and the future energy generation costs may be impacted by regulations, including the costs of monitoring and compliance. Sitka, for example, has recently installed an EPA approved air quality monitoring site because of air pollution associated with the diesel-generation they need to make up for shortfalls in hydropower availability. The fluctuation in the cost of diesel fuel itself creates a large uncertainty in regional energy planning.

TABLE 1: 2002 Hydropower Statistics In MWh.

Load Center	Hydro Generated	Average Generation Capability	% of Capability Used	Electricity Load	Hydro Generated Minus Load	Projected Load (2012)	Hydro Generated Minus Projected Load (2012)
Upper Lynn Canal Region							
Skagway + Haines	22,247	23,200	95.9	23,614	-1,367	26,090	-3,843
Chilkat Valley/ Klukwan	1,668	1,800	92.7	1,668	0	2,040	-372
North Region							
Juneau	327,934	353,000	92.9	337,785	-9,851	372,700	-44,766
West Central Region							
Sitka	98,832	115,700	85.4	99,205	-373	109,560	-10,728
Tyee-Swan Region							
Wrangell + Petersburg	66,452	131,000	50.7	67,386	-934	72,300	-5,848
Ketchikan	140,684	139,300	101.0	153,972	-13,288	169,900	-29,216
Metlakatla	14,356	25,045	57.3	14,356	0	15,870	-1,514
Prince of Wales Region							
Craig/ Klawock/ Thorne Bay/ Kasaan	19,992	22,000	90.9	23,279	-3,287	27,020	-7,028
Total	692,165	811,045	83	721,265	-29,100	795,480	-103,315

3. GENERAL TRENDS OF CLIMATE IN SOUTHEAST ALASKA OVER THE 20TH CENTURY

Like many places in Alaska and the far North, long-term records of climate and hydrology in Southeast are sparse. The National Climate Data Center publishes a quality-controlled monthly climatological product that includes nine weather stations in Southeast, which were used for this study: Annette Island, Annex Creek, Gustavus, Haines, Juneau, Ketchikan, Little Port Walter, Sitka-Japonski, and Wrangell. These stations are primarily located at airports. The earliest of these records starts in 1922. There are older stations in the region, including Sitka's Magnetic Observatory, but they are either no longer be in operation (such as in Sitka), were moved, have operated for only a short period, or have some other inconsistency in their record.

Long-term records of river discharge in Southeast are even more sparse. For this reason, all available gage records were analyzed, even where records are short. These include the following stations: Alsek River (near Yakutat), Antler River, Fish Creek (near Ketchikan), Kakuhan Creek (near Haines), Mendenhall River and Montana Creek (both near Juneau's Auke Bay), Situk River (near Yakutat), Staney Creek (near Klawock), Stikine River (near Wrangell), Taiya River (near Skagway), Taku River (near Juneau), and Upper Earl West Creek (near Wrangell). A map of hydrology and climate stations is shown in Figure 1.

Several key parameters are explored in detail, while the summary of variables is shown in Table 2. The annual time series of mean temperatures at the climate stations shows considerable variability between sites and strong interannual variability over time (Figure 2a). If the long-term station mean is subtracted from each station, the results are station anomalies that are more easily compared (Figure 2b). Not only does interannual variability look consistent between stations, but it is easier to see long-term trends over the whole record, as well as distinct decadal-scale swings in temperature. The overall station mean is shown in heavy black. The trend line (using a least-squares method) is also shown in heavy black. The record for the Sitka station and its trend are shown in red. The mean trend from the 1920s to the

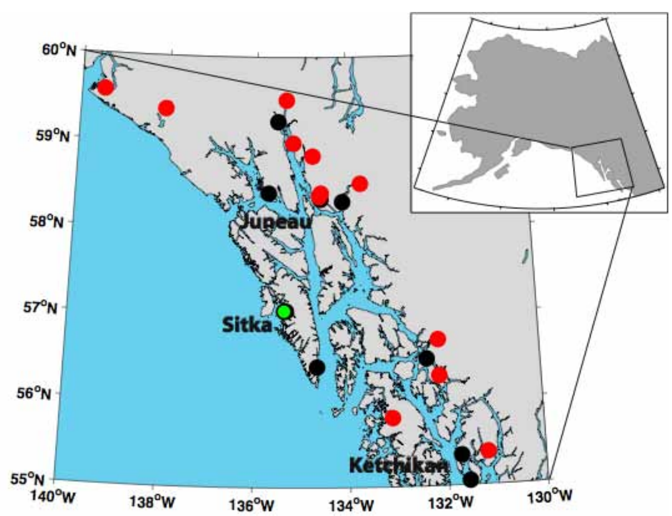

FIGURE 1: locations for climate (black) and hydrologic (red) stations in Southeast Alaska (inset). The Sitka station is shown in green and will be described as a case study.

present is approximately 0.45 ˚C of warming. If the trend analysis is started in the cool part of the 1940s, as it is for Sitka, the trend looks more like 1.7 ˚C. The trend at Sitka since mid-century is representative of other stations since that time.

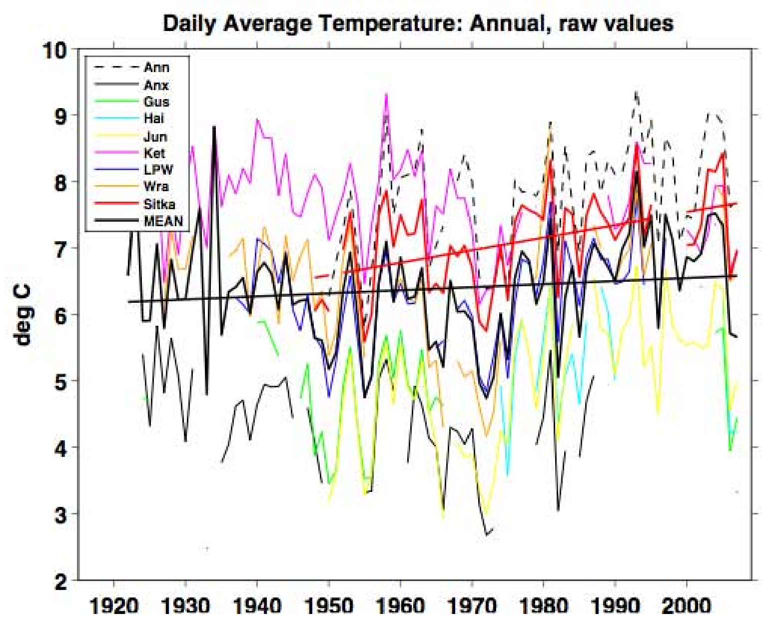

FIGURE 2a

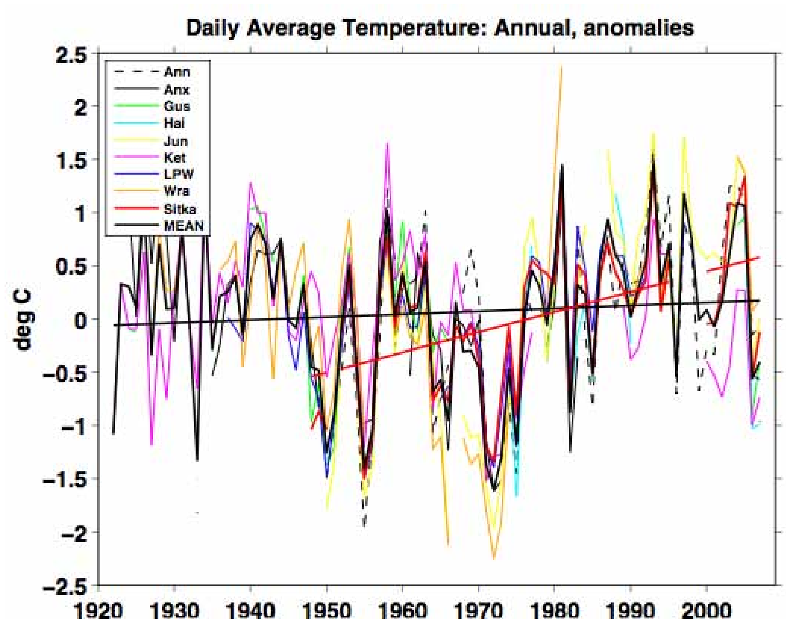

FIGURE 2b

FIGURE 2: (a) shows time series of annual mean temperatures (raw values) and the all station mean (black). Black and red lines show least-squares trend for all stations and Sitka, respectively. (b) Same as for (a) but for the anomalies, i.e. each station's long-term mean has been subtracted from its record.

Analysis similar to that of average daily temperature is performed for all of the station data by season and for the following variables: daily minimum and maximum temperatures, precipitation, maximum snow depth, and discharge. The results are summarized in Table 2. Winter is defined as December-February, spring is March-May, summer is June-August, and autumn is Sept-November. This trend analysis was conducted on both raw data and the anomalies. The raw data trends are shown in the tables below. If the trend in the anomaly differs in sign from that of the raw data, the numbers are shown in italic. This suggests that those trends are sensitive to changes in the number of stations over time and may not be statistically robust. A Student's T-test is performed to determine statistical significance at the 0.05 level.

TABLE 2a,b: trends in °C or mm per decade for all seasons and climate variables. Negative trends are coded in blue to denote decreasing temperatures and positive trends are coded with pink to denote increasing temperatures. For precipitation, snowfall, and maximum snow depth, drying is denoted in brown and wetting is denoted in green. Trends that are significant at the 0.05 level are underlined. Trends that are shown in italic switch signs when the anomalies are considered instead of the raw data shown.

TABLE 2a

OBSERVED HISTORICAL TRENDS (C OR MM/DECADE): ALL STATION MEAN 1920-2009

	Winter	Spring	Summer	Autumn	Annual
Average Temp	0.15	0.04	0.01	-0.01	0.05
Min Temp	0.17	0.09	0.16	0.05	0.12
Max Temp	0.12	-0.01	-0.13	-0.09	0.00
Precipitation	*-9.60*	-11.98	*-9.13*	-30.12	*-69.16*
Snowfall	-4.26	-1.84	--	*-0.12*	-8.82
Max Snow Depth	-12.69	-18.75	--	-0.78	-5.06

TABLE 2b

OBSERVED HISTORICAL TRENDS (C OR MM/DECADE): SITKA 1948-2009

	Winter	Spring	Summer	Autumn	Annual
Average Temp	0.39	0.14	0.08	0.05	0.19
Min Temp	0.36	0.19	0.20	0.08	0.24
Max Temp	0.41	0.07	-0.04	0.01	0.14
Precipitation	7.09	-10.78	-14.28	9.41	-20.54
Snowfall	-7.59	-4.26	--	2.19	-5.84
Max Snow Depth	-20.63	-16.59	--	2.13	-7.81

Several interesting results emerge from the trend analysis. Winter is warming: moderately since the 1920s and strongly since the 1940s. In spring, summer, and autumn, daily minimum temperatures have increased since 1920, while daily maximum temperatures have actually cooled. This asymmetry in temperature changes has been noted globally and is generally attributed to global changes in cloud cover (Karl et al., 1993).

Another key finding from the observations is that annual precipitation, snowfall, and daily maximum snow depth have all declined, but that only some of these trends (precipitation and snowfall since 1920 and maximum snow depth since 1940) are statistically significant. Spring precipitation and snow depth have decreased since both the 1920s and 1940s, while autumn has grown drier since the 1920s but slightly wetter since the 1940s (although this increase in precipitation is not statistically significant). Some of the precipitation trends since the 1920s switch signs if the anomalies are considered instead of the raw data. This suggests that short or discontinuous station records, coupled with high variability in the measurements, affect the statistical robustness of these trends.

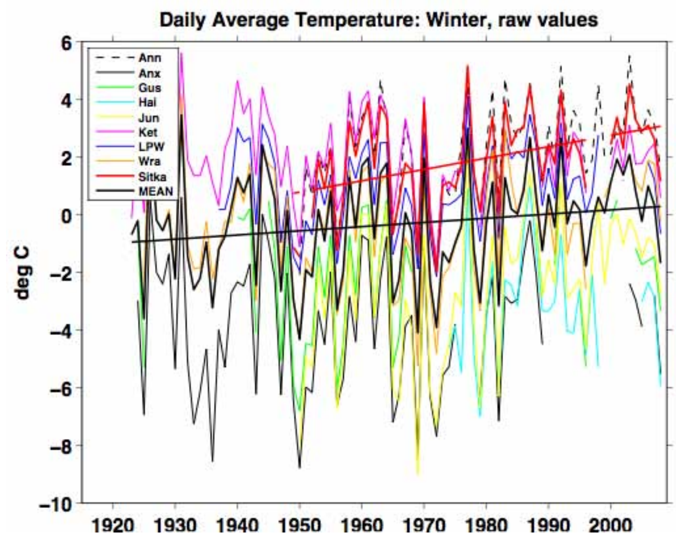

FIGURE 3a

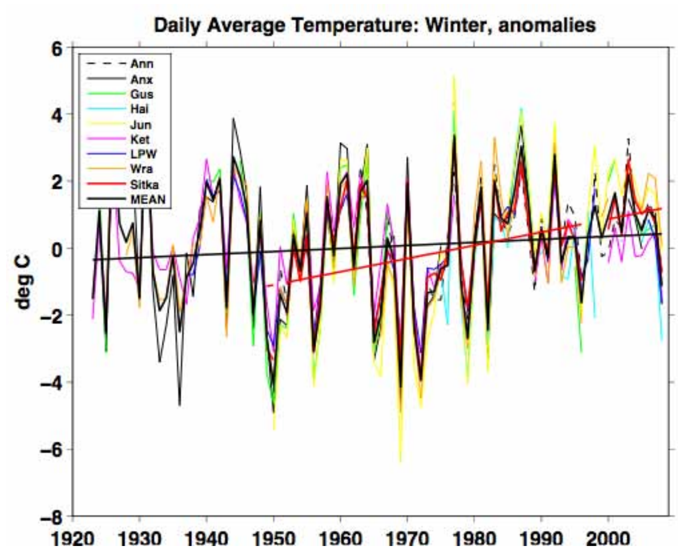

FIGURE 3b

FIGURE 3: (a) shows time series of winter mean daily temperatures (raw values) and the all station mean (black). Black and red lines show least-squares trends for all stations and Sitka, respectively. (b) Same as for (a) but for the anomalies, i.e. each station's long-term mean has been subtracted from its record.

One key temperature change affecting hydroelectric power is the winter daily temperature minimum, as it directly influences the amount of precipitation that falls as rain versus snow, having major implications for storage. Hydropower watersheds in Southeast tend to store snow starting in late autumn through spring, but this is dependent on the temperature at higher elevations. The average daily temperature minimum in winter has increased in Southeast Alaska by approximately 1.5 ˚C since 1920 and closer to 3.2 ˚C since the late 1940s, as seen in the anomalies (Figure 3b). The raw values show that these stations (at sea level, Figure 3a) are very close to the freezing point throughout the winter, such that a warming of 1-2 degrees can often change the phase of precipitation from frozen to liquid. This winter warming is also likely to increase the number of rain on snow events, which can lead to snow melt and an increase in mid-winter reservoir levels.

This sensitivity to changes near the freezing point can be seen in the daily snow maximum data in Figure 4. It is important to remember that while the temperature, precipitation, and snow depth are measured near sea level, where snow rarely falls, the mountain air cools with elevation and the winter snow pack is far deeper in the watersheds feeding the hydropower facilities. Unfortunately, few long-term records of snow pack or temperature at elevation exist in Southeast. The best estimate (used, for example, by the National Weather Service's River Forecast Center) of conditions in the mountains is to assume a standard lapse rate (change in temperature with height) or to use a dynamical weather model to estimate lapse rates that are dictated by synoptic events.

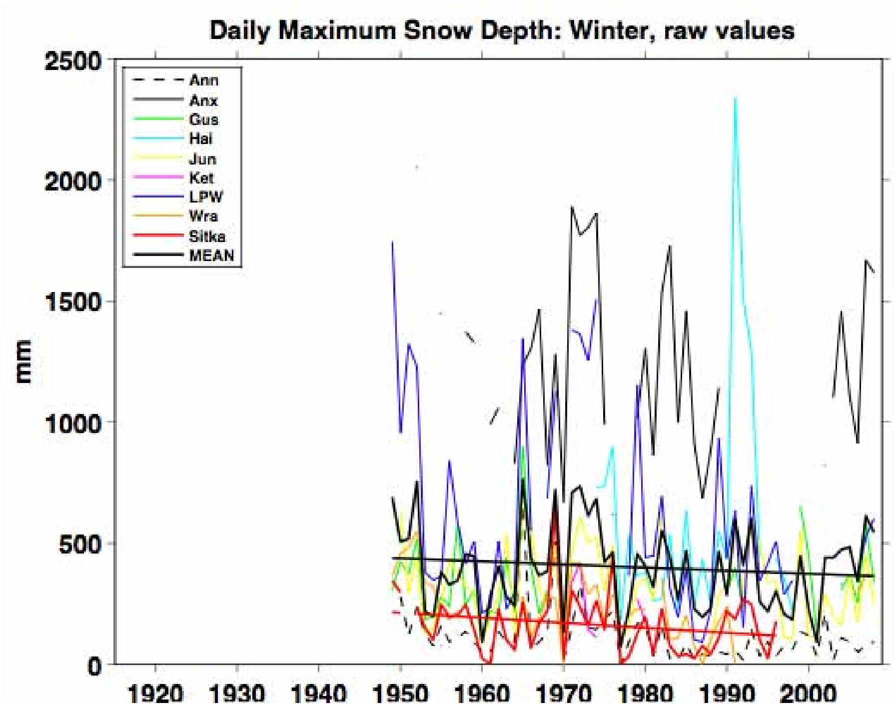

FIGURE 4: raw values for maximum winter snow depth at the stations typically located at sea-level airports. Multi-station means and trends lines are like those in the preceding figures.

Precipitation, of course, is the primary factor determining the supply of hydropower. The sector is sensitive to the total annual precipitation, as well as both the timing and amount in spring, when reservoir levels are low and awaiting recharge from snowmelt. Total precipitation for Southeast stations shows statistically significant decreases over the twentieth century on average (Figure 5), autumn, and for spring (Figure 6). In the Sitka records, slight increases in precipitation are shown during autumn and winter since 1948, and decreases during the other seasons. Because of weak trends and strong interannual variability, none of the Sitka trends are statistically significant. The trend of the anomalies versus the raw data values shows the strong effect of station record inhomogeneity (i.e. inconsistency) here. Compared to temperature changes, precipitation changes are far less robust. The long-term variability appears to be largely dictated by decadal-scale swings in precipitation 'regime', the cause of which will be discussed in more detail below.

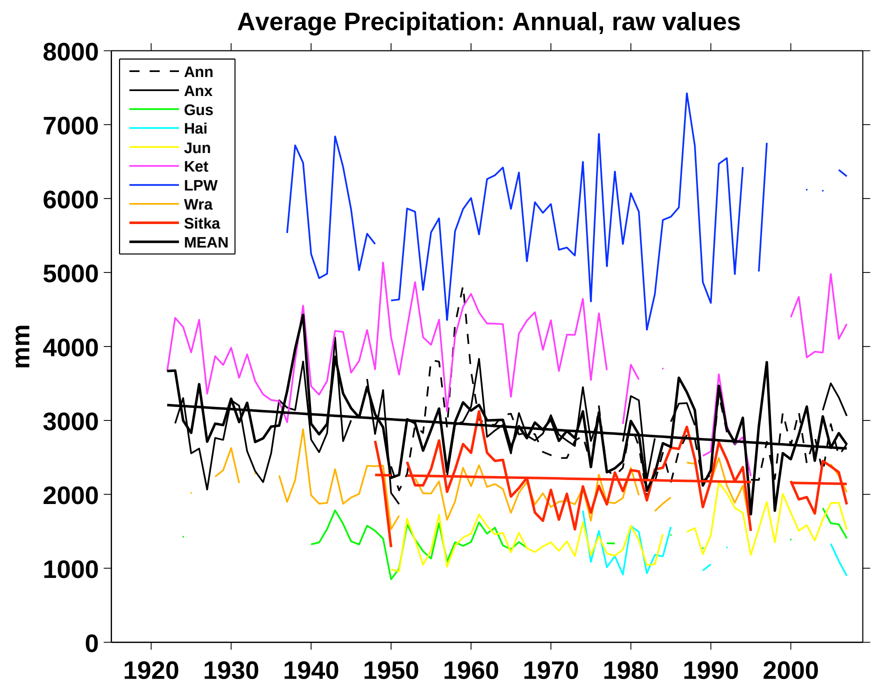

FIGURE 5a

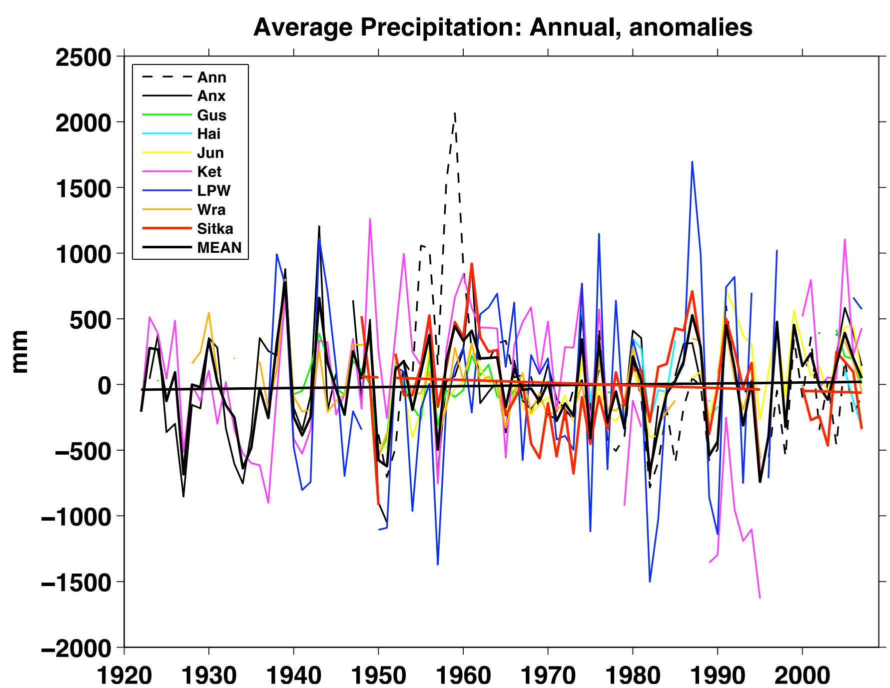

FIGURE 5b

FIGURE 5: (a) raw values for annual means of monthly precipitation totals and (b) the corresponding anomalies. Multi-station means and trends lines are like those in the preceding figures.

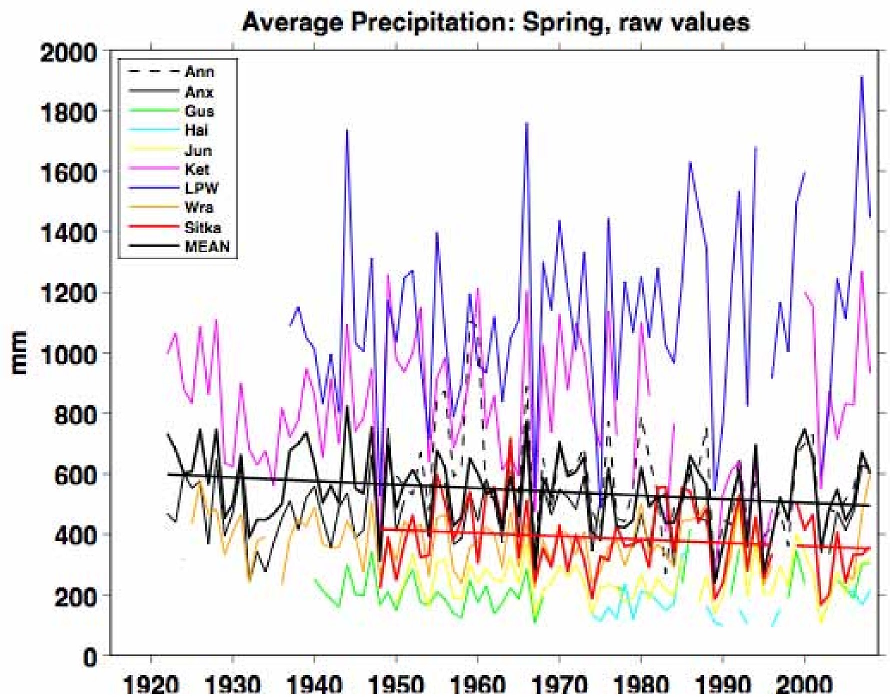

FIGURE 6a

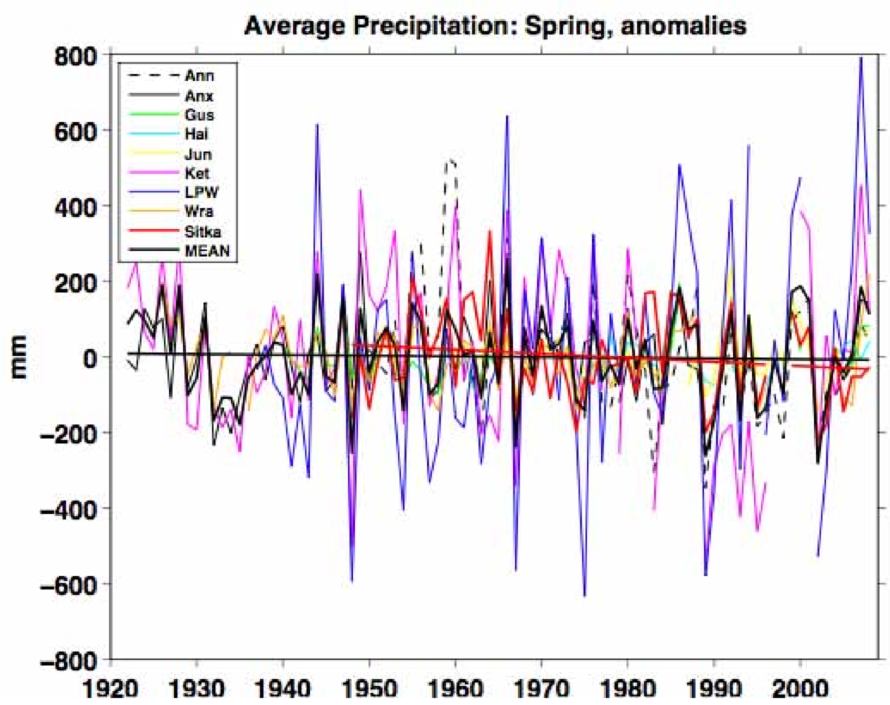

FIGURE 6b

FIGURE 6: (a) raw values for spring means of monthly precipitation totals and (b) the corresponding anomalies. Multi-station means and trends lines are like those in the preceding figures.

Increases in autumn precipitation, since the 1940s, have implications for these changes in storage and spill. Autumn is a time when reservoirs such as the Blue Lake in Sitka are already full to capacity because rainfall is plentiful. Additional precipitation at this time, if it falls as a liquid, cannot necessarily be stored for use in the winter or spring. If the lake levels exceed the reservoir capacity, and there is not enough power demanded or no additional turbines to turn on, the water is simply spilled, without being used to generate power. The typical surplus of water this time of year is one reason Sitka and other utilities are planning to raise the height of their dam and thereby increase storage capacity.

Unfortunately, there are too few accurate measurements of evapotranspiration in Southeast to analyze here. In general, atmospheric warming is associated with increased evaporation. The construction of reservoirs can also lead to increased evaporation, although the evaporative potential is less in an already moist climate such as the one in Southeast. The long-term changes in evapotranspiration associated with vegetation are more complex, as they involve changes in the growing seasons length, vegetation type, fire frequency, and forestry. Kelley et al. (2007) summarize a number of studies of climate-driven changes to vegetation in Southeast Alaska, but do not discuss the impact on evapotranspiration. With few historical measurements, any future projections are highly uncertain.

River discharge data were analyzed like the climate data, but raw discharge and seasonal and annual anomalies were calculated for specific discharge (i.e. divided by the drainage area for the river). This makes it easier to compare trends between watersheds of considerably different sizes. The long-term trends for specific discharge are shown in Table 3, but only for three stations: the Fish Creek (near Ketchikan), because it is the only continuous, long-term record in Southeast Alaska, the Stikine (a large, glacial dominated river gaged near Wrangell), and the Mendenhall River (near Auke Bay in Juneau). Fish Creek is a small (83.1 km^2) drainage with a relatively small glacial melt contribution to discharge. The Mendenhall is also small (220.4 km^2) but has a large glacial contribution to runoff. The Stikine is a large glacial-dominated watershed (51,592.8 km^2) which originates in Canada and

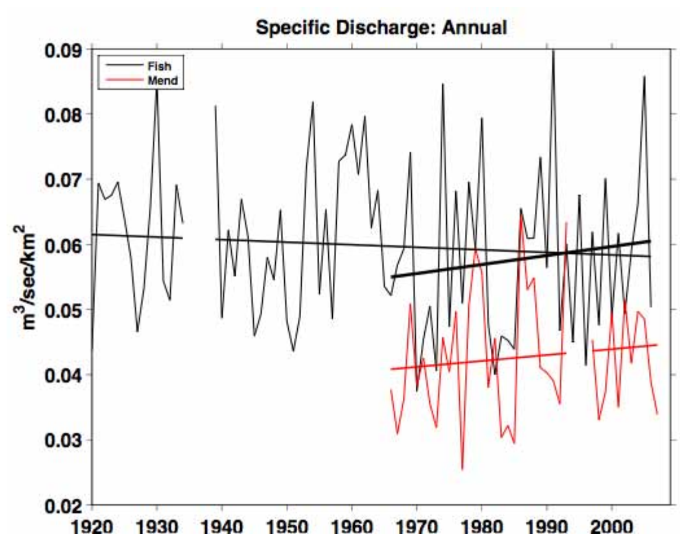

FIGURE 7: Annual specific discharge for two continuous records in Southeast Alaska. Trends are shown for Fish Creek for the whole period, as well as for the period for which that record overlaps with the record at Mendenhall.

where gaging began in 1976. The record at Fish Creek started in 1915 and Mendenhall record started in 1965. Annual discharge for the common period of the Fish Creek and Mendenhall records is similar: discharge has increased, as shown in Figure 7. In contrast, longer-term record at Fish Creek and the shorter-term record at Stikine both show a decrease in annual discharge. Few of the trends in the discharge records are statistically significant, according to the Student's T-test, however. The most robust results for discharge show increases in winter, which suggest impacts of air temperature warming such as precipitation phase change, a decline in snowpack storage in lieu of rainfall runoff, and possibly rain on snow. These observed changes in winter are unlikely to be related to changes in glaciers. Changes in other seasons are not statistically significant due to the large interannual variability. Attribution of observed trends to glacial processes requires a more in depth study than is possible here. *Neal et al.* (2010) suggest that 10% of total freshwater discharge into the Gulf of Alaska is associated with glacier volume loss.

TABLE 3: trends in discharge per decade for all seasons and various rivers. Negative trends are coded in brown to denote decreasing discharge and positive trends are coded with green to denote increasing discharge. Trends underlined are significant at the 0.05 level.

OBSERVED HISTORICAL TRENDS (((M^3/sec)/km^2)/decade): DISCHARGE

	Winter	Spring	Summer	Autumn	Annual
Fish (1915-2007)	1.38E-03	-9.14E-05	-2.03E-04	-2.68E-03	-3.91E-04
Fish (1965-2008)	<u>9.01E-03</u>	-8.05E-05	-1.00E-03	-1.71E-03	1.38E-03
Stikine (1976-2008)	3.98E-05	2.55E-05	-2.28E-04	-1.83E-03	-2.90E-04
Mendenhall (1965-2008)	<u>2.39E-03</u>	9.86E-04	-2.70E-03	4.27E-03	9.09E-04

4. GENERAL PATTERNS OF CLIMATE VARIABILITY IN SOUTHEAST ALASKA

As mentioned above, Southeast Alaska is strongly influenced by large-scale modes of climate variability in the Pacific sector. These 'modes' such as the Pacific Decadal Oscillation (PDO) and the El Nino-Southern Oscillation (ENSO) have distinct patterns in time and space that help drive temperature, precipitation, and wind anomalies. These two modes of variability in the ocean-atmosphere system have similar spatial patterns, but while the PDO varies on a temporal scale of a decade or longer, ENSO tends to vary more on a scale of 2-4 years. Figure 8 shows the typical sea surface temperature anomalies associated with a positive PDO event, as well as the PDO and ENSO indices. The PDO index is determined using a statistical technique known as Principal Component Analysis. The leading principal component of North Pacific monthly sea surface temperature, poleward of 20˚N, is used to define the index (*JISAO, 2010*), and simply represents the leading pattern of variability. The ENSO index shown here is known as the Nino 3.4 index, which is based on the sea surface temperature anomalies in the equatorial Pacific, from 120˚W-170˚W and 5˚N-5˚S. In Alaska, warm events (both PDO and ENSO) tend to be paired with winds blowing from South to North, bringing in warm, moist air from lower latitudes. In Southeast, the PDO tends to have a much stronger effect on temperatures than ENSO. *Papineau* (2001) and *Bond and Harrison* (2006) explore the larger influence of these and other climate modes over the entire state.

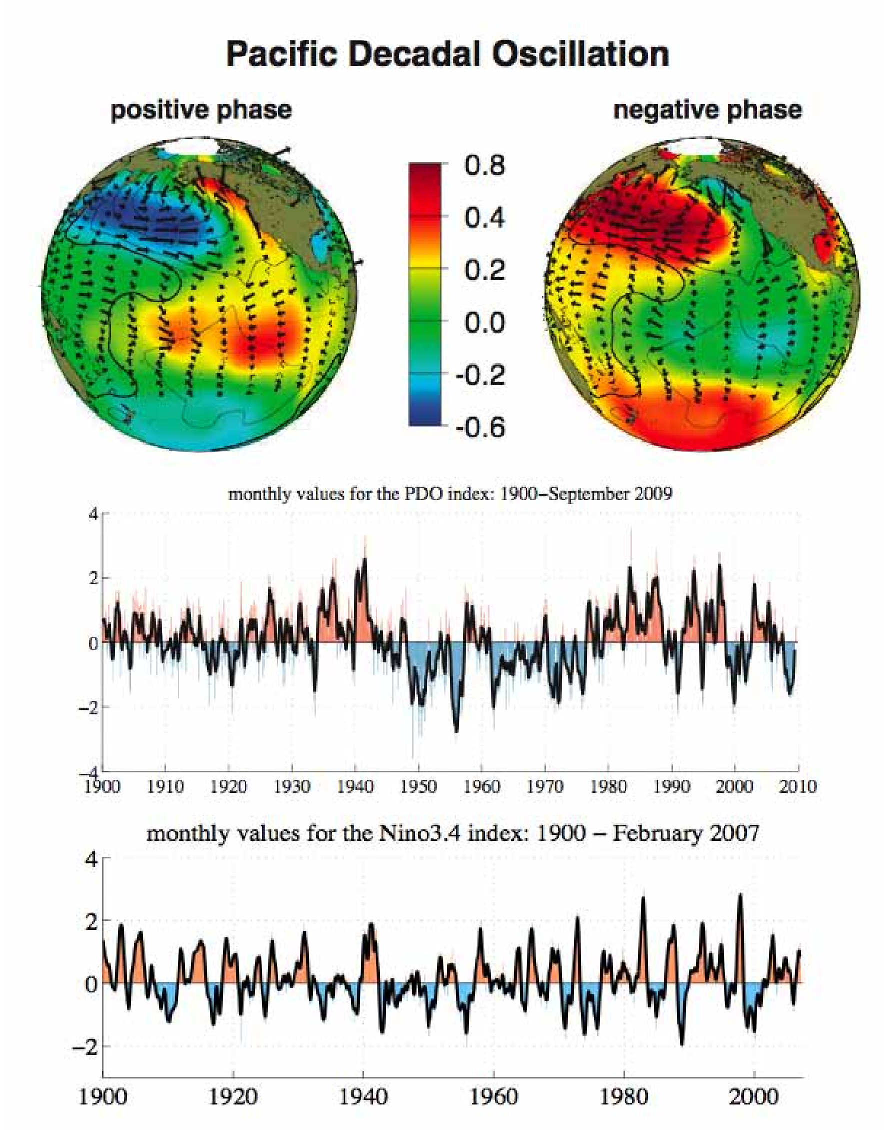

FIGURE 8: the Pacific Decadal Oscillation's pattern in space (a, b) and time (c), as well as the El Niño Southern Oscillation's pattern in time (d). The PDO index is defined using the principal component of North Pacific monthly sea surface temperature variability, as described in the text. The units in the top panel are anomalies in degrees C. Figures are reproduced from JISAO, 2010*.*

Composite analysis was used to examine the influence of the PDO and ENSO modes on climate of Southeast. Climatologies were constructed for stations based on the whole period of record, as well as the average (composite) of the 10 strongest PDO positive years and 10 strongest PDO negative years, defined by the index's average winter values. A composite was also constructed based on the Nino-3.4 index for ENSO. The impacts of the PDO at Juneau, Ketchikan, and Sitka are shown in Figure 9. Changes induced by ENSO are very similar. The biggest temperature impacts in the region occur during winter. Juneau shows an 8 degree C warming during positive PDO in January relative to negative PDO events. Sitka shows a difference of 6 ˚C between positive and negative

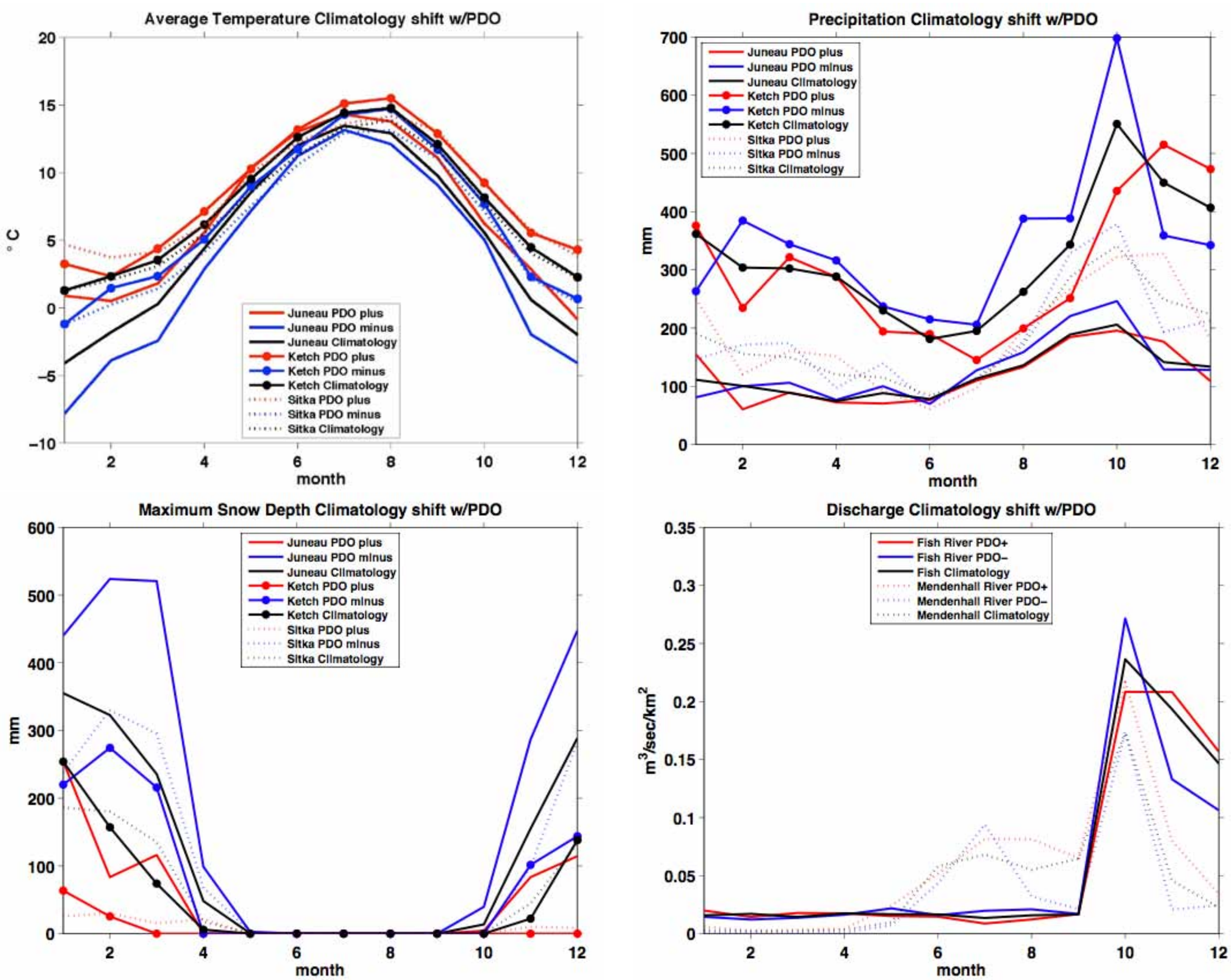

FIGURE 9: shows the PDO-driven climatological shift in various climate parameters (clockwise from upper left: Average Temperature, Precipitation, Maximum Snow Depth and Discharge) at stations in Southeast. Composited climatologies during PDO positive events are show in red, PDO negative events, and the climatologies over all events are shown in black.

PDO events, also in January. The impacts on precipitation are largest in autumn and winter, when a timing shift is obvious. Positive PDO events are associated with a dry anomaly in October, followed by a wet anomaly in November and again in January. The winter temperature anomalies associated with the PDO tend to push the average temperatures either above or below freezing, which impacts the snow climatology. Winter has significantly more snow during negative PDO events, suggesting the temperature effect dominates over the precipitation effect. Positive PDO events are associated with very low snow packs. Finally the result on discharge is somewhat different in glacier-dominated versus non-glacier dominated basins. Examples are shown for the Fish River (non-glacier dominated) versus the Mendenhall (glacier dominated). Both types of rivers have a discharge increase during winter in positive PDO events, but autumn has less discharge during positive events in the non-glacier dominated catchments and more discharge from the glaciated basins. Late summer/autumn melt in glacier-dominated catchments is shifted later in the negative PDO events, driven by increased rain, despite cooler air temperatures. Spring melt happens about a month earlier during positive PDO events, in part, because less of the winter precipitation arrived as snow and more of it as rain. Early onset of snowmelt is also driven by a warmer spring during positive PDO events.

One trend to be noted in Figure 8c is the high likelihood that the PDO is shifting back to a negative phase. While this trend may be countered by longer-term warming, it is still likely to have the sort of impacts shown in Figure 9, for Southeast: cooler winters with more precipitation arriving as snow instead of rain. The result is a delay in the availability of the water resource until the snow melts in the spring. The challenges to management may start even earlier, however. The increase in precipitation during a negative PDO occurs when the reservoir is already full in capacity limited systems such as Sitka's Blue and Green Lakes. The operator is already being forced to spill water without generating power during peak precipitation. By mid-winter, Southeast sees a large deficit of precipitation during a negative PDO, making it difficult to manage the spring dry season. This is a key finding of our study.

Longer-term warming may have an impact that more closely resembles a positive PDO event. Some climatologists have discussed the possibility of a 'permanent El Niño.' In both glaciated and non-glaciated basins positive PDO and warm El Niño events appear to have the impact of smoothing out the discharge over the course of the water year because less water is tied up in the snowpack, even though more precipitation arrives in winter. Southeast's winter climatology is warm enough that liquid water will fall in lower elevations in some of these watersheds through December and beyond. Further implications of these changes on managing these water resources will be discussed after an examination of projected long-term climate changes in Southeast.

5. PROJECTIONS OF FUTURE CLIMATE IN SOUTHEAST ALASKA AND THEIR ROBUSTNESS

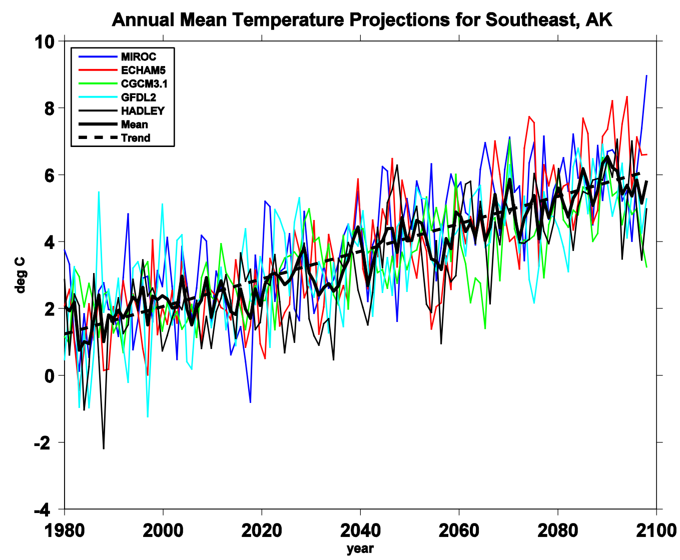

FIGURE 10a

The Scenarios Network for Alaska Planning has provided a suite of climate projections for this analysis. From all fifteen models used in the Coupled Model Intercomparison Project (IPCC, 2007), five different climate models were selected for their fidelity in reproducing historical (1958-2000) surface air temperature, surface air pressure, and precipitation in Alaska. An 'Intermediate' future emissions scenario (A1B) was used to force these climate models, which were then downscaled to 2 km using a biased map statistical technique based on the 1961-1990 PRISM monthly climatologies (Simpson et al., 2005) for Alaska. More details are described at (http://www.snap.uaf.edu/about). Results are shown for the Southeast Alaska region only and slopes were calculated for the multi-model mean.

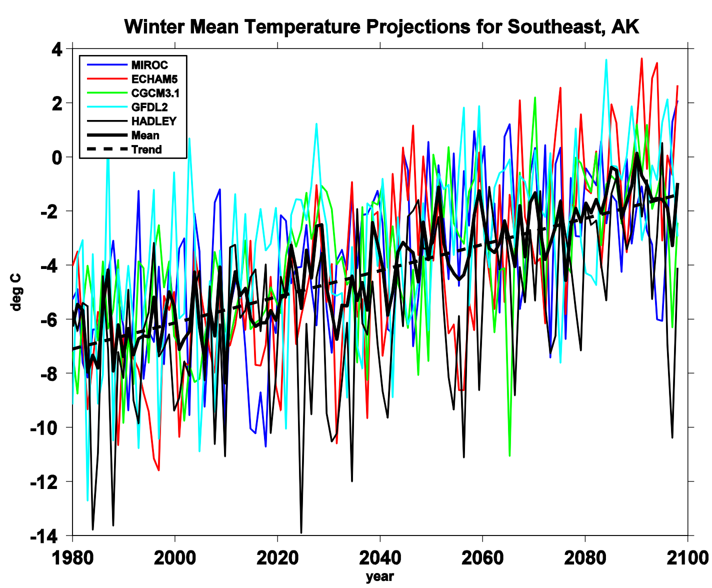

FIGURE 10b

FIGURE 10: projected changes in mean annual (a) and winter (b) temperature from downscaled output of five climate models.

Like much of Alaska and the Far North, Southeast Alaska is projected to warm considerably by the end of the century (3-8 ˚C per model), with much of this warming concentrated in winter (4.6 ˚C multi-model mean), Figure 10. All five models are consistent in this result, with differences only in the rate of warming. Mean annual precipitation is expected to increase 30-50 percent by the end of century (Figure 11). Changes by season for both temperature and precipitation are shown in Table 4. These projections show considerable interannual variability. There are still cool and dry years projected. What is less evident is the strong decadal variability shown in the observed record. This may due to 'missing physics' in the models that underestimate thermal inertia and feedbacks in the climate system.

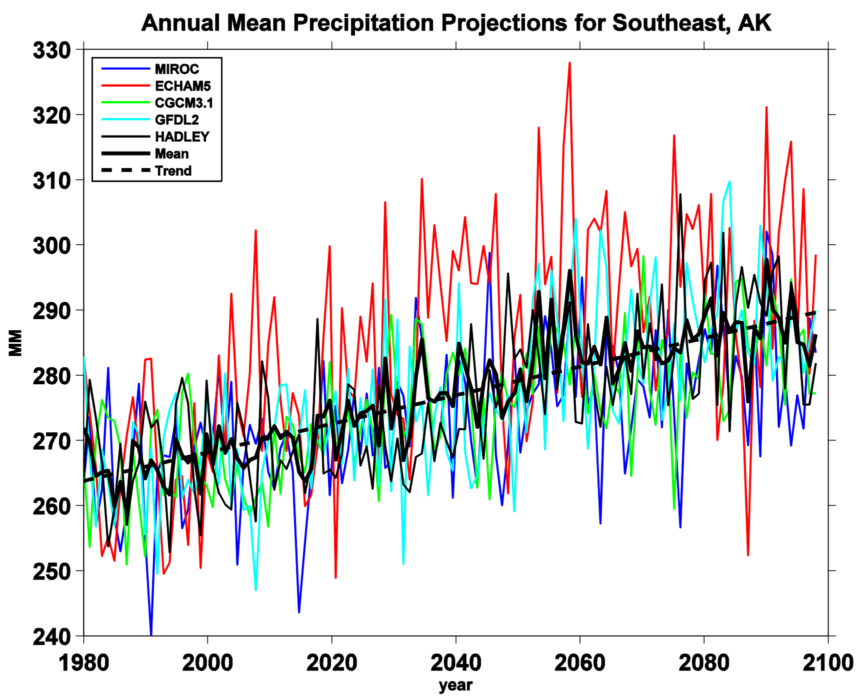

FIGURE 11: projected trends in precipitation from downscaled output of five climate models.

TABLE 4:

MULTI-MODEL MEAN TRENDS IN TEMP, PRECIPITATION FOR 2011-2099

	Winter	Spring	Summer	Autumn	Annual
Degrees C per Decade	0.510	0.382	0.395	0.450	0.434
mm per Decade	2.939	1.214	1.931	2.613	2.174

A few inconsistencies emerge when comparing the historical trends and the projected trends. Historical trends in the climate models are shown in Table 5. Looking at the trends in historical precipitation, for example, long-term change in precipitation is not very robust and generally shows a decreasing trend. The trends in the mean raw station data are largely the statistical effect of new stations being installed, and then later, some stations missing data. The trends in the anomalies show a very slight increase in annual precipitation since 1920 and a slight decrease at Sitka since the 1940s. The spring anomalies show a slight decline in precipitation over both periods, showing a possible increasing vulnerability during the spring season, when reservoir levels are particularly low because the snowpack has just begun to melt. While the historical drying trends in the raw data are partly a statistical illusion, there is certainly no evidence of the large precipitation increases suggested in the climate projections. Similarly, long-term trends in the anomalies in maximum snow depth are also nearly flat. While temperatures have risen significantly, most of that warming is only since the 1940s. Over that same period snow depths have actually increased, while precipitation trends have been dominated by interannual variability.

TABLE 5:

MULTI-MODEL MEAN TRENDS IN TEMP, PRECIPITATION FOR THE HISTORICAL PERIOD 1980-2010

	Winter	Spring	Summer	Autumn	Annual
Degrees C per Decade	0.123	0.440	0.332	0.153	0.262
mm per Decade	3.432	1.303	0.809	-0.742	1.200

Some of these inconsistencies may point to shortcomings in the measurement of precipitation. Standard precipitation gages are subject to a whole host of undercatch biases caused by the shape of the gage itself and mechanical failures, etc. These biases tend to be largest for frozen and mixed precipitation, and mechanical failures are especially common during heavy, wet snowfalls. Snow depth can be a more reliable indicator of frozen precipitation changes. Another source of variability between precipitation stations in Southeast is the extreme topography. While all of the climate stations that were analyzed here are near sea level, their orientation on the windward or leeward side of fjord topography varies. Orographic and microclimate effects on precipitation are very large. Variability between temperature stations is far more consistent. This is another argument for enhanced monitoring in the region, especially of snowpack in the watersheds feeding reservoirs.

Does the downscaling process affect the historical fidelity of the model runs? The statistically based downscaling and bias correction method calibrated the projections to consistent, historical spatial patterns of temperature and precipitation, not long-term trends. These bias corrections are based on the same station data that were analyzed here and suffer the same issues: almost no sampling at higher elevations. The PRISM model attempts to account for this deficiency by taking slope, elevation, and aspect into account via multivariate interpolations, but the results are largely unverifiable.

Another issue is that the climate models currently lack important feedbacks in the Southeast region, particularly the impact of temperature and precipitation changes on glacier mass balance. The majority of glaciers in Southeast Alaska are thought to be retreating (Arendt et al., 2002) suggesting that the temperature changes have lead to a decline in snow deposition on glaciers, despite an increase in precipitation. General circulation models also lack realistic vegetation responses to changes in climate. Measurements of evapotranspiration in Southeast are too sparse to analyze for regional variability over time. However, the feedbacks between climate change and vegetation change may be significant and will also impact the regional freshwater cycle.

6. DISCUSSION: IMPACTS OF CLIMATE VARIABILITY AND CHANGE ON EXISTING AND FUTURE HYDROELECTRIC POWER FACILITIES

Several facts emerge from the above analysis. Natural climate variability has a strong impact on Southeast Alaska on both interannual and decadal time scales. Longer-term climate change is more difficult to detect, when looking at the anomalies of stations and accounting for the effect of inhomogeneous climate records when calculating trends. However, separating the effects of climate change and climate variability, while attributing observed changes to climate mechanisms to one or the other, may be difficult using only the sparse historical record and the current generation of climate models. The authors suggest that adaptation to climate change and variability could include enhanced monitoring of variables such as snow pack depth, snow water equivalent, precipitation, discharge, and temperature. A second useful tool may be use of short-term and seasonal hydrologic forecasting by the facility operators, particularly for delayed spring snowmelt during negative PDO and La Niña events for which models have moderate skill predicting one season in advance.

The Blue Lake and Green Lake facilities at Sitka will be used as an illustration. Figure 12 shows the capacity of the Sitka system, which started with the Blue Lake dam in 1961. The Green Lake dam came on line in 1982 and nearly doubled the system's capacity. However, even at that time, the system remained 'under powered' in low precipitation years. Electricity from hydropower is supplemented with diesel-generated power to meet the local demand. Had climate data been thoroughly analyzed during project planning in the 1950s, it may have proved more cost effective to build the Blue Lake dam higher from the start. Currently, the municipality has begun the licensing process with the Federal Energy Regulatory Commission to raise the dam and add a third turbine, though demand was only slightly higher in the past five years than it was in the early 1980s. As Sitka considers a completely new facility at Takatz Lake, it may be in their best interest to revise the estimates of energy generation in dry years, based on updated climate statistics that include recent warming and drought years. As these figures are based on precipitation near sea level, uncertainty could also be reduced by monitoring the snow pack properties in the elevated watersheds, using manual or automated instrumentation.

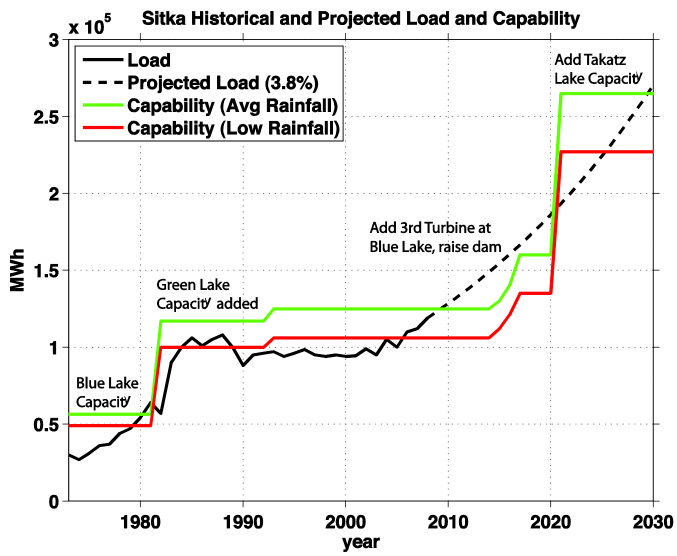

FIGURE 12: Historical and proposed capacity and generation in the Sitka, Alaska hydropower facility. Figure courtesy of Chris Brewton, Utility Director, City of Sitka.

Historically, operators like those in Sitka may not have seen tremendous value in seasonal forecasting. Their system is capacity limited such that 'when it's full, we spill,' and that's that. However, the vision of the regional energy managers and the Alaska Energy Authority is to link the facilities of the region in a grid. As discussed above, several interties have already been built, and more are proposed. A grid system, like that in climatically similar Norway, makes it possible to take advantage of spatial variability in precipitation and runoff. If a community had plenty of supply, but not enough demand, power can still be generated and transmitted, instead of the water being spilled. Sitka is particularly isolated such that they may benefit more from expanding their current facilities and developing the Takatz Lake project. Regardless, use of seasonal forecasting would help alert the operators to oncoming ENSO and PDO events. Use of seasonal forecasts must go hand in hand, however, with enhanced monitoring, so that the detailed impact of these modes of variability throughout the watersheds could be better understood. Figure 13 shows a plot of the discharge into Blue and Green Lakes versus the PDO index. There are so few data, it is difficult to establish a robust relationship between the two.

Figure 14 shows example output from a management software (CHEOPS Hydropower Operations Model, HDR Engineering, Inc.) used by the Sitka facility operators. The bars show the portion of the electrical load being met by hydropower generation at the Blue Lake and Green Lake facilities, and the portion being met by diesel generation. One of the inputs to the model is inflow and other hydrologic variables from a typical year. As seen in Figure 13, measured or estimated inflows have not been observed consistently over the multitude of different climate conditions in Southeast Alaska. The model would be even more accurate if, for example, data from the predicted 'type' of hydrologic year (i.e. La Niña or negative PDO event) were ingested, rather than an arbitrary past hydrologic year.

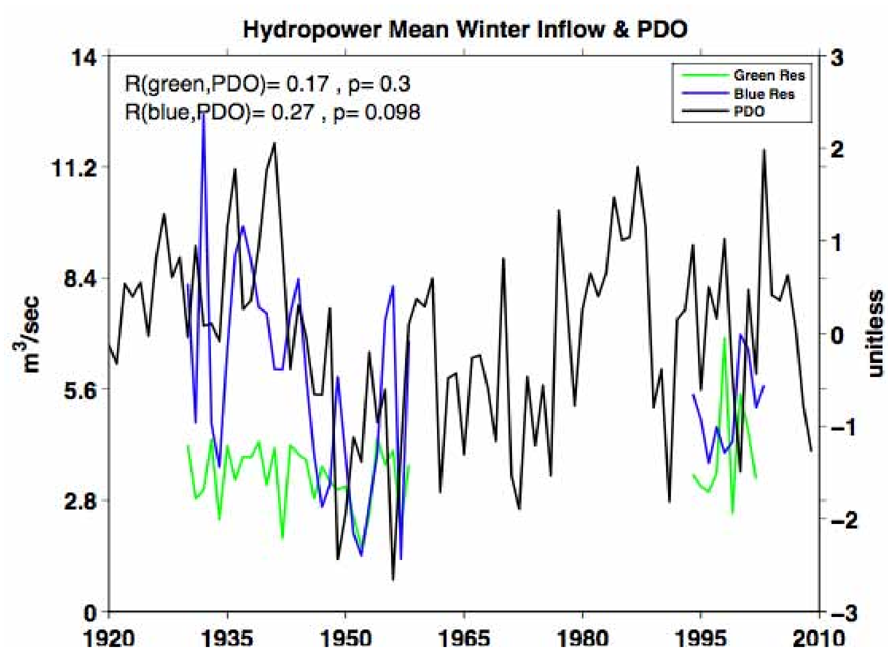

FIGURE 13: inflow into the Blue Lake and Green Lake reservoirs in the Sitka system versus the PDO index.

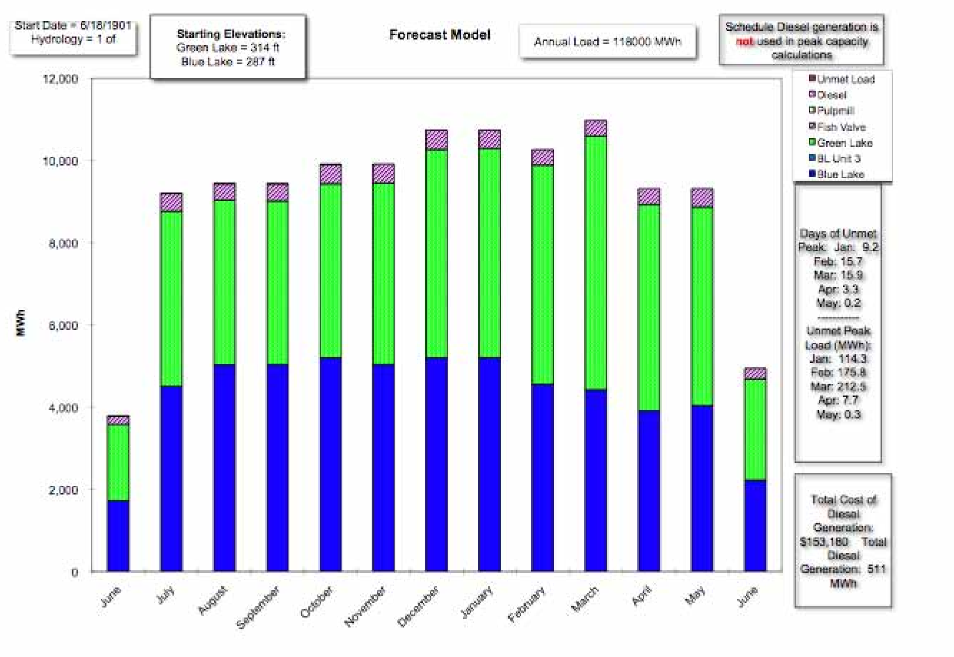

FIGURE 14: Example of a management year at the Sitka facility as modeled by the CHEOPS management software. Diesel generation is shown as a hatched purple bar. Blue and Green bars are MW-hr generated by the Blue and Green reservoirs, respectively.

In summary, as hydroelectric capacity grows in Southeast Alaska and the system grows increasingly interconnected along a physical grid, the region will have more options for managing climate risk. These options will require more extensive monitoring of snow water resources, particularly at elevation in the watersheds feeding the reservoirs. Without knowledge of snow water equivalent, for example, it is impossible to verify a synoptic scale or season-ahead hydrologic model. What operators can use now, however, are the seasonal forecasting products from the National Oceanic and Atmospheric Administration's Climate Prediction Center (http://www.cpc.noaa.gov/) and the International Research Institute for Climate and Society (http://portal.iri.columbia.edu). For the relatively small cost of reservoir inflow measurements, a robust relationship between inflow and the modes of variability such as ENSO and the PDO might be established, which would give operators specific information on what to anticipate when a particular climate event is established. Another value to enhanced long-term climate monitoring would be that the changes of complex features such as glaciers and their impact on local hydrology could be better estimated.

This study is followed by a brief outline, or template, describing the procedure that was used to assess the impacts of climate variability and change on hydroelectric power in Southeast Alaska (Appendix). This template may provide useful guidance to others embarking on similar climate impact studies.

7. APPENDIX: TEMPLATE FOR CLIMATE PROJECTION STUDIES

The following procedure was used to assess the impacts of climate change and variability on hydropower in Southeast Alaska.

a. *We identified the socio-economic system of interest* (Hydro-electric power in Southeast) *and assessed the availability of quantitative measures of impacts* (sparse reservoir inflow data, sparse time series of power generation data).
b. *We identified which underlying components of the climate system were relevant for the study of impacts.* In this case, it was the hydrologic system, the atmosphere-ocean system, glaciers, and changes in evapotranspiration that might relate to climate and anthropogenically-forced changes in the biosphere.
c. *These components were assessed for availability of quantitative data.* Weather station data, gage records, and large-scale climate indices are available. What were not readily available were long-term measurements of stream flow into the reservoirs in Sitka, consistent measurements of evapotranspiration, any time series of the glacial contributions to river discharge, or definitive estimates of how changes in climate, fire, and logging have impacted regional biosphere-hydrology interactions.
d. *We assessed the need for pre-processing station data.* In this case, we decided against creating mean areal temperature, precipitation, and other climate variables from the station data because of the sparseness of observations, the extreme fjord topography, and systematic sampling biases (only observations near sea level). Anomalies were calculated for each variable and each season.
e. *Climate model projections were obtained for the period of interest* (100 years in this example) *and a subset of models were chosen because they represented fidelity to observed climatologies.* One or more emissions scenarios may be chosen to represent one source of uncertainty. In our example the effort to select a subset of models was done in advance by the Scenarios Network for Alaska Planning. We only worked with a single emissions scenario because we ascertained that the uncertainty associated with emissions may be modest relative to other sources of uncertainty.
f. *The model output was downscaled to a grid cell size closer to the area 'sampled' by the weather stations.* In this case the model output was downscaled to 2 km. For looking at regional trends, downscaling may not be necessary. In this study, downscaling made it possible to separate changes over land and the ocean more precisely. Normally, a climate model grid cell in a coastal region might straddle both the land and water, leading to errors in the interpretation of modeled change.
g. *We analyzed whether or not the historical data show statistically significant trends and how those are affected by inhomogeneities in station records.* We used Student's T-tests on the slope of the historical records over two

different time periods (1920s to present and 1940s to present) and compared these to the slopes of the anomalies.

h. *We performed correlation analysis between seasonal hydroclimate variables and climate indices.* We found direct correlations to be weak, but that the number of independent samples of 'Pacific Decadal Oscillation negative events', for example, was very few; the climate system has a strong persistence (i.e. autocorrelation) on very long time scales as well as strong interannual variability.

i. *Composite analysis (averaging over a subset of years during particular climate mode phases) made it possible to attribute month-to-month changes in some fields to natural climate variability.* Our analysis was performed with El Nino-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) indices.

j. *The scales of long-term trends were compared to those driven by natural modes of variability.* In our study, this was the best form of attribution that could be achieved robustly, given the limitation of our datasets.

k. *We analyzed the trends in the historical period in the climate projections and compared those to the station observations.* Few observational data are included in the climate runs, so the magnitudes of fields such as temperature and precipitation are unlikely to match those of the historical observations. The trends, however, should ideally be similar. If they are not, this introduces further uncertainty into the analysis.

l. *We analyzed the trends in the climate models future projections and discussed some of the underlying climate physics that explain these trends.* The climate projections are consistent with historical trends for some variables (temperature) but not others (precipitation). Because hydropower is so strongly tied to precipitation, the impacts of long-term climate change are highly uncertain. The impacts of interannual to decadal climate variability are more clearly understood.

m. *We met with some of the stakeholders and ascertained how the results of our study could be used to inform decision-making.* It was clear that hydropower facility operators could benefit from more extensive use of seasonal forecasting and knowledge of large-scale modes of climate variability.

8. ACKNOWLEDGEMENTS

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