Chapter 4 - Spatial and temporal climate

Changes in glacier volume result from temporal variations in climate. While mass input is largely from snowfall, mass output is controlled by the energy flowing to or from a glacier. Energy is generally gained or lost in the form of short-wave and long-wave radiation, sensible heat, and latent heat transferred by phase changes (Benn and Evans, 1998). Since temperature is an expression of energy exchange; annual and seasonal mass balance can be estimated using both air temperature and precipitation data from low elevation climatestations (Tangborn, 1980a). Snowfall at upper elevations is related to winter and annual temperature and precipitation at these stations, while ablation is related to their summer temperature and temperature range. For instance, while snowfall increases with decreased winter temperature or increased winter precipitation, ablation increases with increased summer temperature and temperature ranges. The significance of temperature range (difference between average maximum and minimum) is that it can be used to estimate cloud cover, which when combined with average temperature produces a measure of incoming short-wave radiation. Based on these concepts, glacier mass loss should take place during periods of increased annual and seasonal temperature, which may or may not be accompanied by decreased precipitation. The goal of the analysis described in this chapter is to test this hypothesis using station based climate data and climate indices to determine regional trends in both temperature and precipitation.

Background

Dyurgerov and Meier (2000) determined that glacier mass loss on a global scale started in the middle of the 19th century at the end of the Little Ice Age and has occurred in several stages. They argue that glacier loss in the Northern Hemisphere has occurred because of a shift toward a warmer and moister climate. In the Pacific Northwest, glacier and climate change during 1957-1997 is described by dividing the period into two intervals. The first interval, 1957-1976, is characterized by glacier advance, stagnation, or modest decrease. The second, 1977-1997, saw major glacier mass losses (McCabe and Fountain, 1995; Meier and Dyurgerov, 2000) and a shift toward warmer, wetter weather (JISAO, 2000).

To explore the relationship between regional climate and glacier change, three types of data were used: data from individual climate stations, division climate data, and climate indices. The principle advantage of the station data is that it contains detailed information on numerous weather variables (e.g. wind, air temperature, precipitation). The principle disadvantage is that station data are point values, and for the North Cascades stations are located at elevations lower than that of the glaciers (Daly et al., 1994).   Divisional climate data are regional statistics produced by averaging the data from all the individual stations in that region. The advantage of divisional data is that it gives a simple, regional climate picture. A major problem is that the spatial representation depends on the distribution of stations. As previously mentioned, all permanent climate stations in the North Cascades are located in lower elevations.   For both division and station data, differences in the data may be produced by changes in the operation of the stations rather than actual climatic events (Taylor, Oregon Climate Service, personal communication, 2000). Most of the National Park complex is located in the Cascade West Climate Division with small sections located in Cascade East and Cascade Foothills divisions (Fig. 4.1). However, none of the eight meteorologic stations in or adjacent to the complex are located in Cascade West, indicating that temperature and precipitation data for this division are based on climate stations in the Southern Washington Cascades and nearby stations in the Cascade Foothills and Cascade East.

A climate index is a single climatic factor that can be used to describe and predict other climatic factors in a region. Because of teleconnections, linkages over great distances of atmospheric and oceanic variables, a climate index from one hemisphere can be linked to climate variations in the other hemisphere.   For instance, Southern Oscillation Index (SOI) is based on the difference in air pressure at Darwin, Australia, and the Tahiti Islands. Fluctuations in SOI correspond to El Niño and La Niña events

(Rasmussen 1985), hence, the name El Niño Southern Oscillation or ENSO. In general, years with negative SOI tend to be El Niño events, while years with positive SOI tend to be La Niña years. In the North Cascades, years of negative SOI tend to be warmer and drier than average, while positive SOI years tend to be cooler and wetter (Redmond and Koch, 1991). Therefore, it seems logical to presume that a period of glacier reduction in the North Cascades would be marked by a higher frequency of negative SOI years.

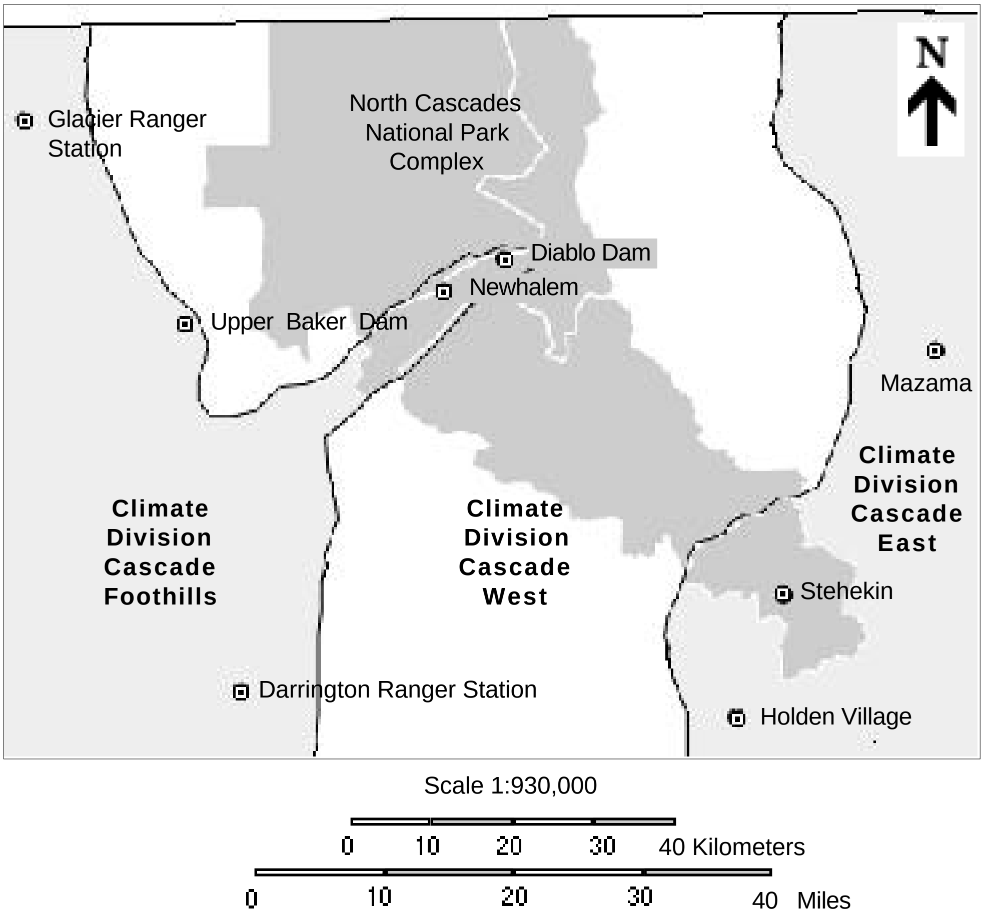

Figure 4.1 - Climate division boundaries and the location of climate stations in and around the national park complex.

Another index, called the Pacific Decadal Oscillation (PDO), is based on differences in sea level air pressure and sea surface temperature over the subtropical north Pacific Ocean and western North America (McCabe and Dettinger, 1998). Like SOI, PDO fluctuations correspond with tendencies in precipitation and temperature in the Pacific Northwest. Periods of positive PDO, referred to as “warm phase”, correspond in the Northwest to above average October through March air temperature, below average precipitation and below average spring time snow pack. “Cool phase” PDO is generally characterized by the opposite. The major difference between PDO and SOI, is that PDO is significantly more persistent. For instance, while El Niño /La Nina events last for a few months or years, PDO cycles last a decade or longer(Mantua, 2000). During the past century cool phase PDO has taken place twice, once from 1890-1928 and again in 1947-1976. Warm PDO phases occurred from 1925-1940 and 1977-1997(Mantua, 2000). Recent changes in Pacific climate suggest that 1998 began a new cool phase (Mantua, 2000).

Climate trends based on station data

Daily average temperature and total precipitation data for eight stations in and around the National Park Complex (Fig. 4.1) were obtained from the Western Regional Climate Center’s web site (http://www.wrcc.dri.edu/summary/climsmwa.html). These data were used to calculate average annual and seasonal temperature and precipitation, as well as average ablation season temperature range for 1957-1997, 1957-1976, and 1977-1997. The two periods, 1957-1976 and 1977-1997, were chosen on the basis of a switch from a largely cool phase PDO to largely warm phase PDO beginning in 1977 (Taylor and Hannan, 1999; JISAO, 2000). The seasons, October-May (winter) and June-September (summer), were selected to account for the accumulation and ablation seasons that control a glacier’s mass balance.

To calculate average annual and seasonal air temperature and total precipitation for each climate station, only years and seasons having complete records for all twelve months of the water year were included. A complete monthly record is one in which average air temperature and total precipitation exists for all days of the month. Of the eight climate stations examined, only three (Darrington Ranger Station, Diablo Dam, and

Stehekin) had records that are more that 96% complete for the entire 1957-1997 period, and are included in this discussion of climate trends. The other five had temperature and precipitation records which are between 44 and 94% complete.

Table 4.1 - Temperature and precipitation summaries for Diablo Dam, and Darrington and Stehekin ranger stations.

	Temperature (°C)				Precipitation (cm)		
Station	Annual	Accum	Ablation	Range'	Annual	Accum	Ablation
1957-1997 Averages							
Darrington	9.4	7.0	16.4	13.5	201.3	166.0	35.3
Diablo Dam	12.4	10.2	16.7	13.1	195.9	164.3	31.6
Stehkin	8.7	4.2	17.9	15.7	88.3	77.3	11.0
1957-1976 Averages							
Darrington	9.1	6.7	15.9	12.8	212.5	178.0	34.5
Diablo Dam	12.2	10.0	16.7	13.3	195.2	163.8	31.4
Stehkin	8.6	4.3	17.2	16.3	85.8	75.0	10.7
Deviation of 1957-1976 averages from 1957-1997 average							
Darrington	-3.2%	-4.3%	-3.0%	-5.2%	5.6%	7.2%	-2.3%
Diablo Dam	-1.6%	-2.0%	0.0%	1.5%	-0.4%	-0.3%	-0.6%
Stehkin	-1.1%	2.4%	-3.9%	3.8%	-2.8%	-3.0%	-2.7%
1977-1997 Averages							
Darrington	9.7	7.3	16.7	14	192.1	156.1	35.9
Diablo Dam	12.5	10.3	16.7	12.9	196.4	164.7	31.7
Stehkin	8.8	4.1	18.5	15.3	90.3	79.1	11.2
Deviation of 1977-1997 averages from 1957-1997 average							
Darrington	3.2%	4.3%	1.8%	3.7%	-4.6%	-6.0%	1.7%
Diablo Dam	0.8%	1.0%	0.0%	-1.5%	0.3%	0.2%	0.3%
Stehkin	1.1%	-2.4%	3.4%	-2.5%	2.3%	2.3%	1.8%

The general climate of the Pacific Northwest during 1977-1997 was warmer and wetter than in 1957-1976 (JISAO, 2000). Climate changes at the three stations were not always consistent with this trend. While changes in annual temperature for all three stations were in sync with regional variation, Darrington was drier during 1977-1997. Since 1977-1997 was a period of increased mass loss, it is likely that ablation season temperature range would be higher during that time period. Only Darrington behaved in this manner. Furthermore, deviations in precipitation for one of the stations, Diablo

Dam, had statistical significance's less than 0.05 for both 1957-1976 and 1977-1997. These results seriously challenge the use of data from the selected stations to explain regional glacier change. Not only is a portion of the data statistically insignificant, but the inconsistency in climate trends is contrary to index glacier mass balance data that points toward consistent climate change throughout the park complex.

Climatic trends based on divisional data

Of the three divisions, Cascade West had the lowest 1890-1997 average annual temperature and the highest total precipitation (Table 4.2). Cascade East had the lowest average annual precipitation, while Cascade Foothills had the highest annual temperature. Between 1890 and 1997 the average annual temperature increased for all three divisions at a rate of 2.1 to 2.3°C per 100 years, while total precipitation increased 0.2 to 0.9 cm per 100 years (Fig. 4.2 and 4.3). For all three divisions, average annual temperature was higher in 1977-1997, than in 1957-1976. Accumulation and ablation season average temperature also increased during this period, though deviations for ablation season temperatures were significantly lower than deviations in accumulation season temperatures. Annual and accumulation season precipitation was lowest in 1977-1997, while ablation season precipitation was highest during this same period, meaning that a higher fraction of this precipitation fell during the ablation season.

In general, divisional climate data shows that glaciers in the North Cascades lost mass despite increasing precipitation. This is possible because higher winter temperatures mean that less of the seasonal precipitation would fall as snow. Likewise, higher summer temperatures would cause increased ablation. Divisional data can also be used to explain accelerated mass loss during 1977-1997. During this period snowfall decreases because of increased winter temperature and decreased precipitation. Likewise, summer ablation increases primarily because of seasonal temperature increase.

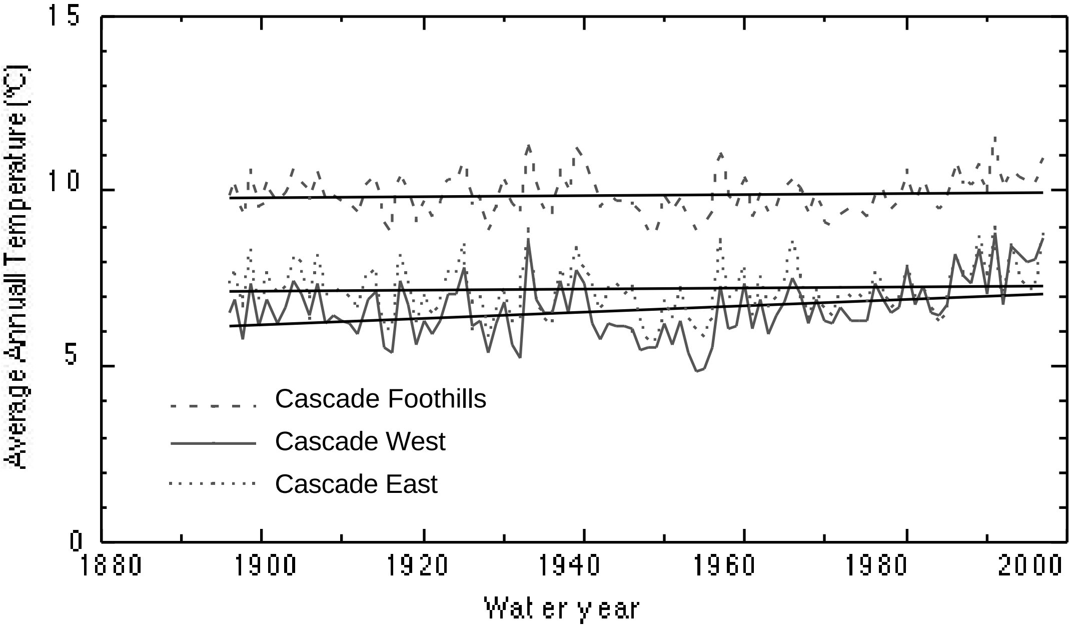

Figure 4.2 - Average annual temperature versus water year for Cascade Foothills, Cascade West, and Cascade East climate divisions. The dotted line shows average temperatures for individual years. The solid black line is a line regression of the data set.

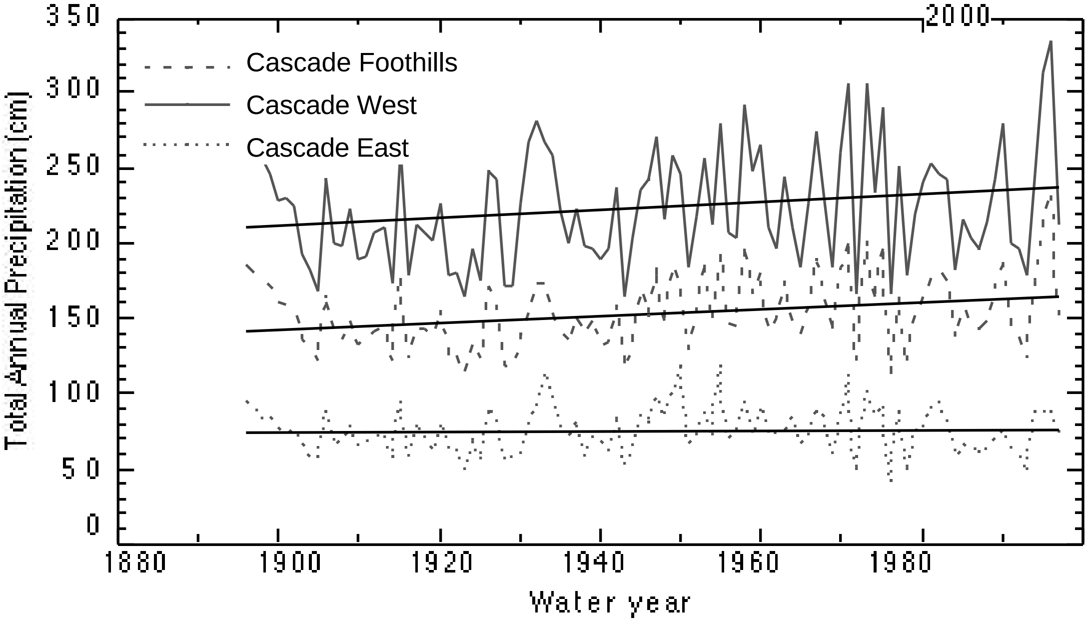

Figure 4.3 - Total annual precipitation versus water year for Cascade Foothills, Cascade West, and Cascade East climate divisions. The dotted line shows total precipitation for individual years. The solid black line is a line regression of the data set.

Table 4.2 - Temperature and Precipitation summary for Cascade Foothills, West, and East Climate Divisions.

	Temperature (°C)			Precipitation (cm)		
Division	Annual	Accum	Ablation	Annual	Accum	Ablation
1890-1997 Averages						
Cascade Foothills	9.8	7.1	15.4	154.3	132.1	22.2
Cascade West	6.6	3.5	12.7	223.9	195.7	28.2
Cascade East	7.2	3.1	15.3	74.8	66.7	8.0
1957-1997 Averages						
Cascade Foothills	9.9	7.2	15.5	163.0	139.6	23.4
Cascade West	7.0	3.9	13.2	233.1	204.8	28.3
Cascade East	7.4	3.3	15.6	74.8	66.7	8.1
1957-1976 Averages						
Cascade Foothills	9.7	6.9	15.2	166.5	143.7	22.8
Cascade West	6.5	3.4	12.8	234.2	212.0	26.7
Cascade East	7.2	3.2	15.3	79.9	72.8	7.2
Deviation of 1957-1976 averages from 1957-1997 average						
Cascade Foothills	-2.7%	-3.7%	-1.7%	2.2%	2.9%	-2.4%
Cascade West	-6.8%	-13.8%	-2.6%	2.4%	3.5%	-5.5%
Cascade East	-2.2%	-2.6%	-2.0%	6.9%	9.1%	-11.2%
1977-1997 Averages						
Cascade Foothills	10.2	7.4	15.7	159.9	136.1	23.9
Cascade West	7.4	4.4	13.5	228.2	198.5	29.6
Cascade East	7.5	3.4	15.8	70.3	61.5	8.8
Deviation of 1977-1997 averages from 1957-1997 average						
Cascade Foothills	2.3%	3.2%	1.5%	-1.9%	-2.5%	2.1%
Cascade West	5.9%	12.0%	2.3%	-2.1%	-3.0%	4.8%
Cascade East	1.9%	2.3%	1.7%	-6.0%	-7.8%	9.7%

Climatic Trends based on SOI and PDO

Average annual SOI and PDO data were obtained from the International Research Institute for Climate Prediction (Columbia University) and the Joint Institute for the Study of the Atmosphere and Ocean (University of Washington) via their web sites at <http://iri.ldeo.columbia.edu/ and http://tao.atmos.washington. edu/main.html>. SOI and PDO were obtained for both water and calendar years.

For the period 1957-1997, average SOI was -0.4 and years of negative SOI were significantly more frequent than positive SOI (Fig. 4.4). The average PDO for the period was 0.1, with positive PDO years occurring more often than negative PDO (Table 4.3). The SOI indicate that El Niño events were more frequent than La Niña events, while PDO trends pointed toward more frequent warm phase years. During 1957-1976, the average SOI was 0.2 and average PDO was -0.6, while during 1977-1997 SOI was -0.7 and PDO 0.6. Both indexes suggest that 1977-1997 was drier and warmer than the earlier period (Table 4.3).

Table 4.3 - Summary of SOI and PDO statistics. Frequency (%) is the percentage of each of the three periods where SOI and PDO was positive or negative.

	SOI			PDO		
		Frequency (%)			Frequency (%)	
Periods	Ave	SOI < 0	SOI > 0	Ave	PDO < 0	PDO > 0
1957-97	-0.4	63.6	36.4	0.1	47.5	52.5
1957-75	0.2	47.6	52.4	-0.6	88.9	11.1
1977-97	-0.7	78.3	21.7	0.6	17.4	82.6

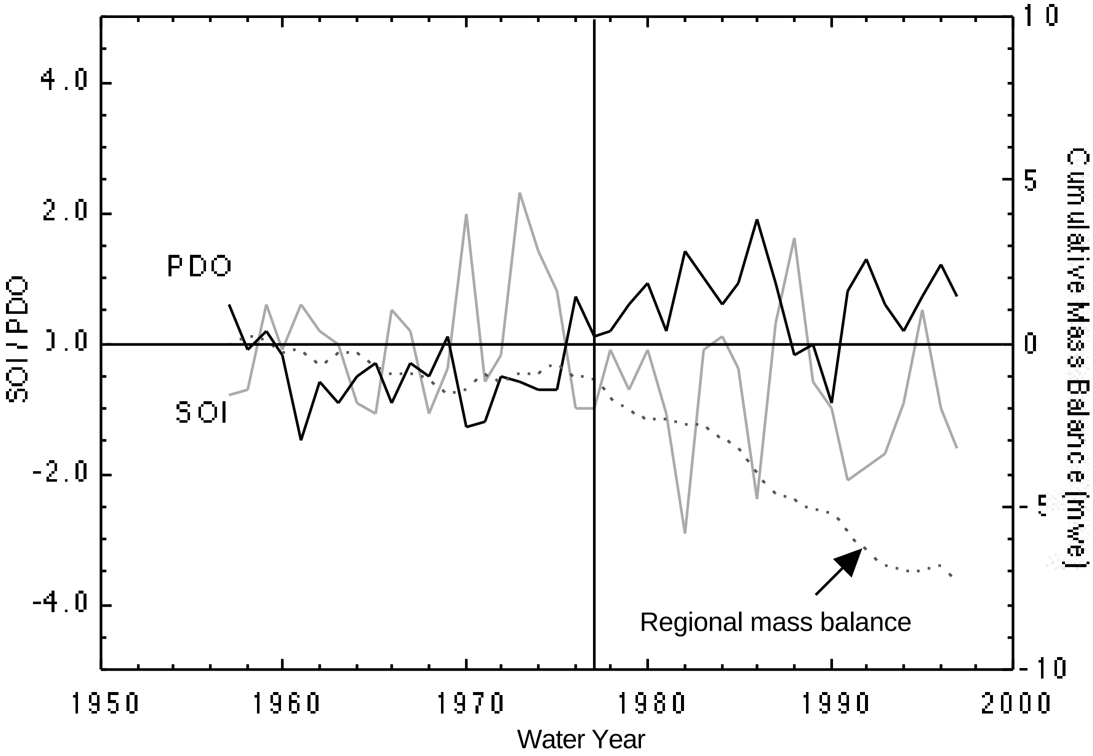

Figure 4.4 - Plot of SOI and PDO versus Water Year. Average SOI and PDO for 1957-1976 and 1977-1997 are shown by the indicated lines. The regional mass balance is estimated by techniques described in chapter 3.

Summary

Regional glacier data show that the water years 1957-1997 were characterized by glacier shrinkage. Changes in regional mass balance indicate that 92% of this loss took place between 1977 and 1997 (Fig. 4.4). Climate division data, PDO, and SOI provide the clearest explanation for this change. Based on SOI and PDO, during 1957-1997 water years that were warmer and drier than average were more frequent than cooler, wetter years. According to divisional climate data (Table 4.2), 1957-1976 was cooler and wetter than the 1957-1997 average, while 1977-1997 was warmer and drier. This trend was consistent for both annual and accumulation season temperature and precipitation. However, the average 1977-1997 ablation season was warmer and wetter than the 1957-1997 average, and the 1957-1976 ablation season was cooler and drier. Consequently, increased mass loss during 1977-1997 resulted not only from changes in temperature and precipitation, but also from changes in the timing of the precipitation.

Abrupt changes in climate during 1977-1997 are consistent with the climatic shifts noted by McCabe and Fountain (1995) and Dyurgerov and Meier (2000). However, the change toward warmer, drier conditions in the North Cascades during 1977-1997 seems to be contrary to Dyurgerov and Meiers's (2000) conclusion that glacier mass loss in the Northern Hemisphere is taking place in a warmer and wetter environment. This is explained by noting that divisional data shows increases in annual temperature and precipitation for 1890-1997 that are consistent with the hemispheric trend. Furthermore, the average precipitation for the entire 1957-1997 period was higher than the 1890-1997 for all three divisions. Consequently, the shift toward warmer, drier conditions is relative to 1957-1976, not to the entire century. What is more problematic is that the change to warmer, drier conditions concluded from divisional data is inconsistent with the shift toward warmer, wetter climate for the entire Pacific Northwest.

The use of data from individual climate stations to explain regional glacier change could not be done because of inconsistencies in climate variations for individual stations and the incompleteness of the records from many of these stations. Of the eight stations located in or around the park complex, only three had records that were more than 95% complete for the water years 1957-1997. Though all three showed annual temperature variations consistent with divisional climate data and climate indices, there was little agreement in terms of variations in seasonal temperature, and annual and seasonal precipitation. Furthermore, a bulk of the variations calculated for one of the stations failed tests of statistical significance.