Relationship of Lemon Creek Glacier, Alaska and North Cascade glacier mass balance to climate indices

Mauri S. Pelto, Dept. of Environmental Science, Nichols College, Dudley, MA 01571
peltoms@nichols.edu

ABSTRACT

The relationship of glacier annual mass balance to climate has been an ongoing endeavor. In this study we relate both the longest record in North America and the most extensive regional record in North America to ten separate climate indices. The glaciers range in latitude from 59° north to 48° north providing an opportunity to better define the limit of significant influence of both Arctic systems, temperate Pacific and tropical Pacific circulation on glaciers in western Washington and southeast Alaska. Anova is used to develop the most accurate model for mass balance estimation for each region.

The Annual balance measurements on the Lemon Creek Glacier, Alaska conducted by the Juneau Icefield Research Program from 1953 to 1998 provide a continuous 46-year record (Miller and Pelto, 1999). This is the longest glacier mass balance record in North America. These data have been verified by repeat geodetic mapping of the glacier in 1957, 1995 and 1998. The mean annual balance of the 46-year record is -0.48 m/a, a loss of at least 24.7 m of ice thickness for the entire period. The mean annual balance decreased from –0.23 m/a from 1953-1975, to –0.65m/a from 1975-1991, and finally –1.12 m/a from 1992-1998.

In the North Cascades of Washington annual mass balance records from ten glaciers over a 19-year period represent the most extensive regional network of glacier mass balance observations in North America. The mean annual balance from 1984-2002 has been –0.28 m/a (Pelto and Riedel, 2001). This is a significant cumulative loss of over 5 m, for glaciers that average only 50 meters in thickness (Figure 1). The pattern reflected less variability and a more negative trend from 1984-1995. Since,1996 their has been increasing annual variability with both alternately extreme positive and negative years in 1998 and 1999 and again in 2001 and 2002 and it would appear 2003.

To determine the relationship between glacier mass balance and larger climate patterns the annual mass balance records are analyzed with 10 key indices. Besides annual mass balance the climate indices are also related to climate data from one location in each study area. The key indices utilized are: Arctic Oscillation (AO), Pacific Decadal Oscillation (PDO), Aleutian Forcing Index (AFI), Aleutian Pressure Index (API), North Atlantic Oscillation (NAO), Southern Oscillation Index (SOI), Pacific Northwest Index (PNI), North Pacific Index (NP), Pacific North American Index (PNA), and West Pacific (WP).

Indices Background

Each indices reflects a teleconnection pattern, which is a recurring and persistent, large-scale pattern of pressure and circulation anomalies that spans vast geographical areas. Teleconnection patterns indicate preferred modes of low-frequency (or long time scale) variability, shaping our climate for the period in which a particular mode endures. In some regions teleconnections have proven useful in predicting glacier mass balance. Both study areas are on the west coast of North America and are mainly influenced by climate systems that develop over the Eastern North Pacific Ocean.

The Pacific Northwest Index (PNI), developed by Ebbesmeyer and Strickland (1995), is a terrestrial climate index useful for studying climate effects on salmon productivity trends. It is a composite index that characterizes the Pacific Northwest climate pattern. As such it should be well correlated with North Cascade Glacier mass balance.

The NAO exhibits little variation in its climatological mean structure from month-to-month, and consists of a north-south pressure anomaly between one center located over Greenland and the other center of opposite sign spanning the central latitudes of the North Atlantic between 35°N and 40°N. The positive phase of the NAO reflects below-normal heights and pressure across the high latitudes of the North Atlantic and above-normal heights and pressure over the central North Atlantic, the eastern United States and western Europe. The negative phase reflects an opposite pattern of height and pressure anomalies over these regions. Both phases of the NAO are associated with basin-wide changes in the intensity and location of the North Atlantic jet stream and storm track (Hurrel, 1995). NAO should not directly be a critical input to the glaciers on the east side of the Pacific.

The Arctic Oscillation (AO) is a major source of intra-seasonal variability over the United States, the North Atlantic and Europe during winter. It modulates the circulation pattern over the middle and high latitudes, thereby regulating the number and intensity of significant weather events affecting the U.S (Thompson and Wallace, 1998). The positive phase features a strong polar vortex, with the mid-latitude jet stream shifted to the north of its normal position. Associated with this phase is an increase in the occurrence of extreme warm days over much of the contiguous United States. The negative phase features high-latitude blocking, frequently in the vicinity of Greenland and/or Alaska. Associated with this phase, there is an increase in the occurrence of extreme cold days, especially from the Great Plains to the Southeast (Figure 4). The AO typically influence is notable over central Alaska, but how far does the influence extend down the coast?

The Southern Oscillation Index (SOI) is calculated from the monthly or seasonal fluctuations in the air pressure difference between Tahiti and Darwin. Sustained negative values of the SOI often indicate El Nino episodes. These negative values are usually accompanied by sustained warming of the central and eastern tropical Pacific Ocean. Positive values of the SOI are associated with stronger Pacific trade winds and warmer sea temperatures to the north of Australia, popularly known as La NIna episodes. This tropical pattern should of course have more influence in the North Cascades and in general El Nino events are associated with warm and drier conditions in the North Cascades (Ebbesmeyer et al, 1991) (Figure 3).

Aleutian Low Pressure Index (ALPI) measures the relative intensity of the Aleutian Low pressure system of the north Pacific (December through March). It is calculated as the mean area (km^2) with sea level pressure <= 100.5 kPa and expressed as an anomaly from the 1950-1997 mean. A positive index value reflects a relatively strong, or intense Aleutian Low (Beamish et al., 1997). This index is similar to the PDO and reflects conditions in the North Pacific that heavily influence both glaciers. A stronger Aleutian Low is associated with warm and dry conditions in the Pacific Northwest.

The Pacific Decadal Oscillation (PDO) Index is the leading principal component of North Pacific monthly sea surface temperature variability (poleward of 20N for the 1900-93 period). It is a long-lived El Niño-like pattern of Pacific climate variability (Zhang et al., 1997). While the two climate oscillations have similar spatial climate fingerprints, they have very different behavior in time, 20th century PDO events persisting for 20-to-30 years, while typical ENSO events persisted for 6 to 18 months (Mantua et al., 1997); second, the climatic fingerprints of the PDO are most visible in the North Pacific/North American sector, while secondary signatures exist in the tropics, the opposite is true for SOI. The spatial patterns are very similar: both favor anomalously warm sea surface temperatures near the equator and along the coast of North America, and anomalously cool sea surface temperatures in the central North Pacific. In the past century: "cool" PDO regimes prevailed from 1890-1924 and again from 1947-1976, while "warm" PDO regimes dominated from 1925-1946 and from 1977 through the mid-1990's (Mantua et al., 1997). The cool PDO regimes are clearly associated with higher glacier annual balances and reduced retreat rates, while the warmer PDO regimes is associated with negative annual balances and increased glacier retreat (Figure 2 and 5).

The North Pacific pattern is prominent from March through July. This pattern consists of a primary anomaly center, spanning the central latitudes of the western and central North Pacific, and weaker anomaly region of opposite sign, which spans eastern Siberia, Alaska and the intermountain region of North America (Trenberth and Hurrell, 1994). Positive phases of the NP pattern are associated with a southward shift and intensification of the Pacific jet stream from eastern Asia to the eastern North Pacific, followed downstream by an enhanced anticyclonic circulation over western North America, and by an enhanced cyclonic circulation over the southeastern United States (Trenberth and Hurrell,1994). Pronounced negative phases of the NP pattern are associated with circulation anomalies of opposite sign in these regions. This phase should reflect greater influence in the North Cascades dampening precipitation.

The Atmospheric Forcing Index utilizes standardized scores of the first component from a principal components analysis on the ALPI, PDO and the northwesterly atmospheric circulation anomalies for the North Pacific (December through March). Positive values represent intense Aleutian lows, above average frequency of westerly and southwesterly winds, cooling of sea surface temperatures in the central North Pacific, and warming within North American coastal waters (McFarlane et al., 2000).

The PNA pattern reflects a quadripole pattern of height anomalies, with anomalies of similar sign located south of the Aleutian Islands and over the southeastern United States. Anomalies with sign opposite to the Aleutian center are located in the vicinity of Hawaii, and over the intermountain region of North America (central Canada) during the Winter and Fall (Spring). As an indicator of more meridonal flow this pattern should have a more pronounced affect on the North Cascades.

The West Pacific Index (WP) pattern is a primary mode of low-frequency variability over the North Pacific in all months(Barnston and Livezey, 1987). During winter and spring, the pattern consists of a north-south dipole of anomalies, with one center located over the Kamchatka Peninsula and another broad center of opposite sign covering portions of southeastern Asia and the low latitudes of the extreme western North Pacific. Therefore, strong positive or negative phases of this pattern reflect pronounced zonal and meridional variations in the location and intensity of the entrance region of the Pacific (or East Asian) jet steam.

Glacier Mass Balance

Glacier mass balance is a measure of the difference between annual accumulation and annual ablation. The key climate variables for glacier mass balance are winter precipitation and summer temperature. The cumulative mass balance records for the North Cascades and Alaska show a broad similarity in trend but striking differences in specific years (Figure 1). Both areas rely on winter precipitation from storms coming off of the Pacific and tracking from the southwest to the northeast. The focused storm track at a given time favors one location over the other, the study areas are separated by 1880 km. Thus, over short time scales the accumulation on glaciers in these two areas is inversely related (Pelto, 1989; Hodge et., 1998) This is only reflected in the different relationship to the PNA. In the North Cascades annual balance correlates well with local weather records 0.65 and –0.64 for total winter precipitation and mean summer temperature respectively. For the Lemon Creek Glacier the relationship with weather records from Juneau just 15 km distant is poor 0.05 and –0.37 for total winter precipitation and mean summer temperature.

The best model fit for Lemon Creek Glacier incorporates PDO, AFI, API, AO and year. That a power coefficient of 0.997, and R-squared of 0.48, and a mean error of $\pm$0.24 m/a can be achieved for Lemon Creek Glacier with this best fit model. PDO, AFI and API all reflect the strength and position of the Aleutian Low with a weaker more easterly positioned low relating to negative values of these indices and positive values of glacier mass balance, thus they are quite similar (Figure 2). It should be possible to develop a model that relies on just one of these three indices. The Arctic Oscillation in its negative phase increases the Lemon Creek Glacier mass balance. The long-term trends in mass balance have been increasingly negative for the Lemon Creek Glacier from 1953-1998 (Figure 6). This fits no climate indices, however, year turns out to be an important predictor. It is of course only an indirect marker of some progressive change with time. The most likely is the global warming that has occurred. Thus, it appears that the mass balance of the Lemon Creek Glacier can be more accurately predicted if a global warming factor is included. The record from the North Cascades is too short and not consistent enough to show such a relationship.

For North Cascade glaciers the shorter record reduces the significance. A combination of utilizing the AO, PNA, PNI and SOI yield the best result. That a power coefficient of 0.95, and R-squared of 0.60, and a mean error of ±0.60 m/a can be achieved for North Cascade glaciers with this best fit model. The PNI is the dominant predictor, with SOI and AO surprisingly being of equal importance. The PDO which in the big picture is correlates well with mass balance and terminus trends, does not perform well on the annual record. This in part reflects the noted variability of the last seven years. It has been postulated that the PDO is changing back to a cold phase which would enhance mass balance at both sites (Hare and Mantua, 2000). However, this trend has been inconsistent and it not clear whether a regime shift is occurring.

Table 1 summarizes the influence of each climate indices on each glacier study area. The relative sign of influence is the same for the study areas for each shared variable of importance. The PDO signal is crucial to water resource forecasting in the Pacific Northwest, and the complications noted here in its correlations on annual time scales, indicate that considerably more effort needs to be focused on the amplifiers and dampeners of the PDO regimes.

Indices	North Cascades	Lemon Creek
AO	negatively	negatively
AFI	insignificant	negatively
API	insignificant	negatively
NOA	insignificant	insignificant
NP	insignificant	insignificant
PDO	insignificant	negatively
PNA	negatively	positively
PNI	negatively	insignificant
SOI	positively	insignificant
WP	insignificant	insignificant

Table 1. The type of relationship between glacier annual mass balance and each of the climate indices.

Conclusions

Key findings are: 1) The Arctic Oscillation Index has a small but significant impact on mass balance of the Lemon Creek Glacier and North Cascade glaciers. 2) That SOI is important only for North Cascade glaciers and has a similar influence as the AO. 3) That both glacier systems benefit from a weaker and more easterly positioned Aleutian Low. 4) That the PDO which is the key parameter in long term mass balance regime, is not the best predictor of annual mass balance. 5) That a power coefficient of 0.997, and R-squared of 0.48, and a mean error of ±0.24 m/a can be achieved for Lemon Creek Glacier with a best model of four coefficients PDO, AFI, AO and year. 6) Year was accidentally included in the initial run, and after removal model performance declined. Year is obviously a proxy, in this case likely the continuing increase in global and particularly Alaskan temperatures. 7) That the best fit model for North Cascade glaciers includes SOI, PDO, and PNI.

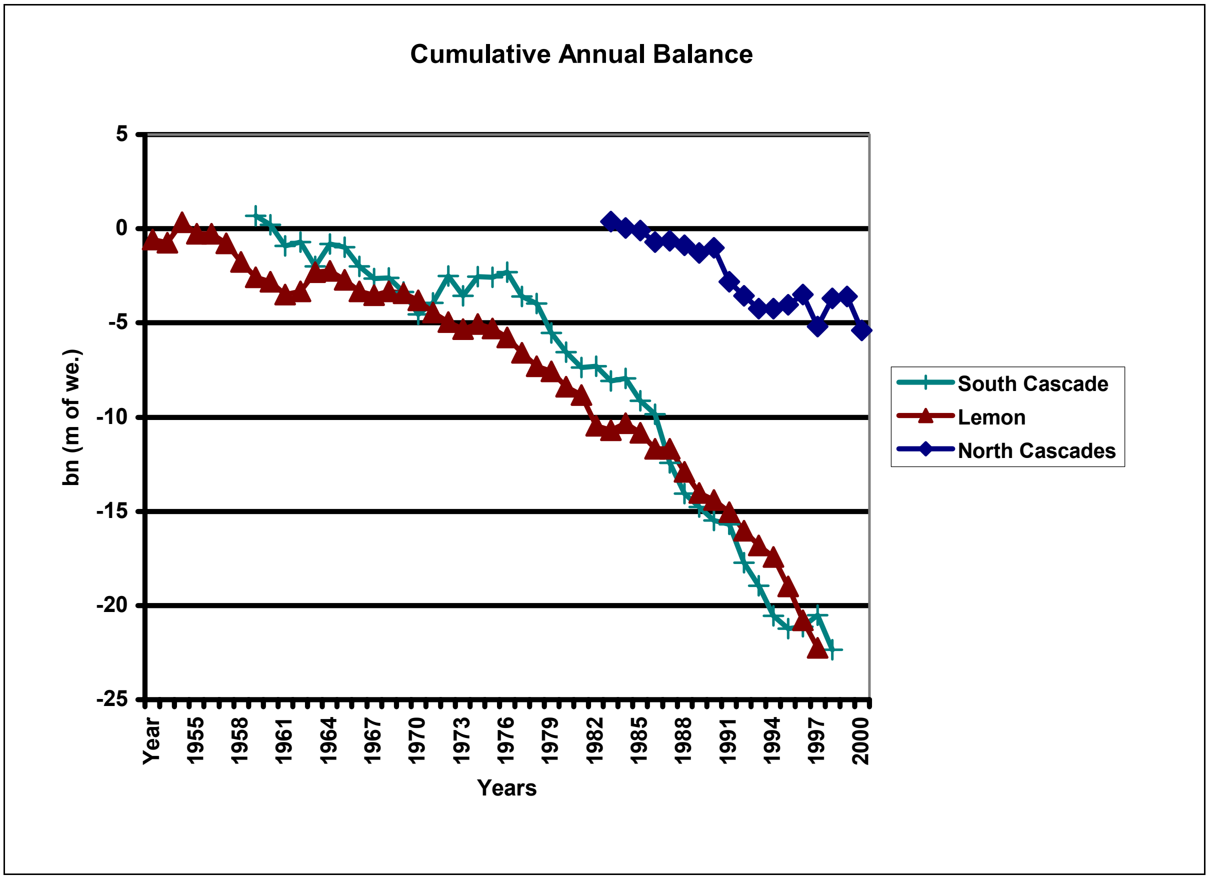

Figure 1. The cumulative annual balance of the Lemon Creek Glacier, AK, South Cascade Glacier, WA and combined balance of nine North Cascades, WA glaciers. The overall trend is remarkably similar though the annual correlation is poor between the North Cascade glaciers and Lemon Creek Glacier. It is clear that all of these glaciers are losing substantial volumes.

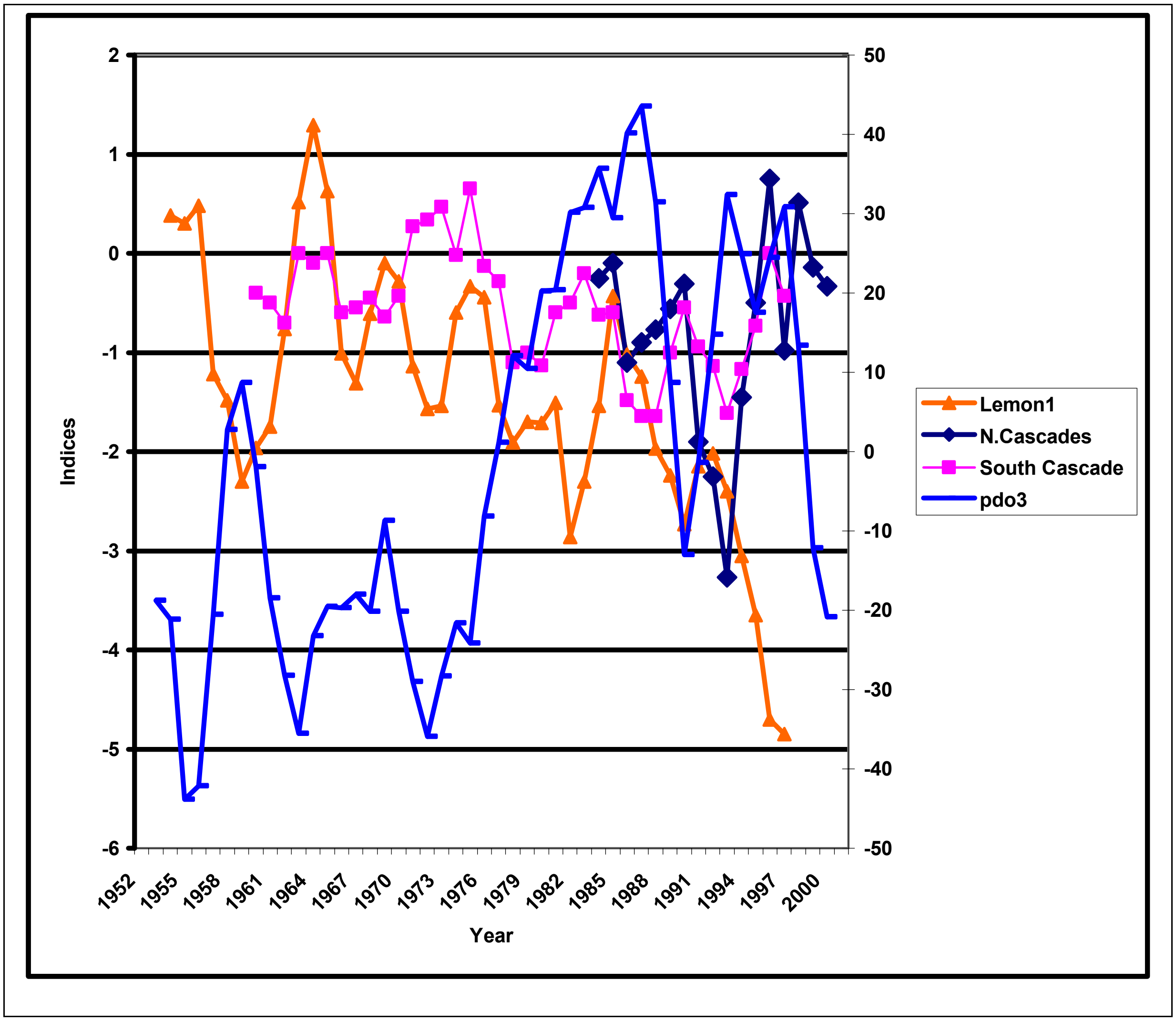

Figure 2. Fluctuations in glacier annual balance and PDO, all shown with a 3-year running mean. When the PDO is low the annual balances are higher, and when the PDO is high balances tend to be more negative> This relationship is evident for long time periods, but not as clear for individual years or in the last five years On an annual basis PDO is not part of the best fit model.

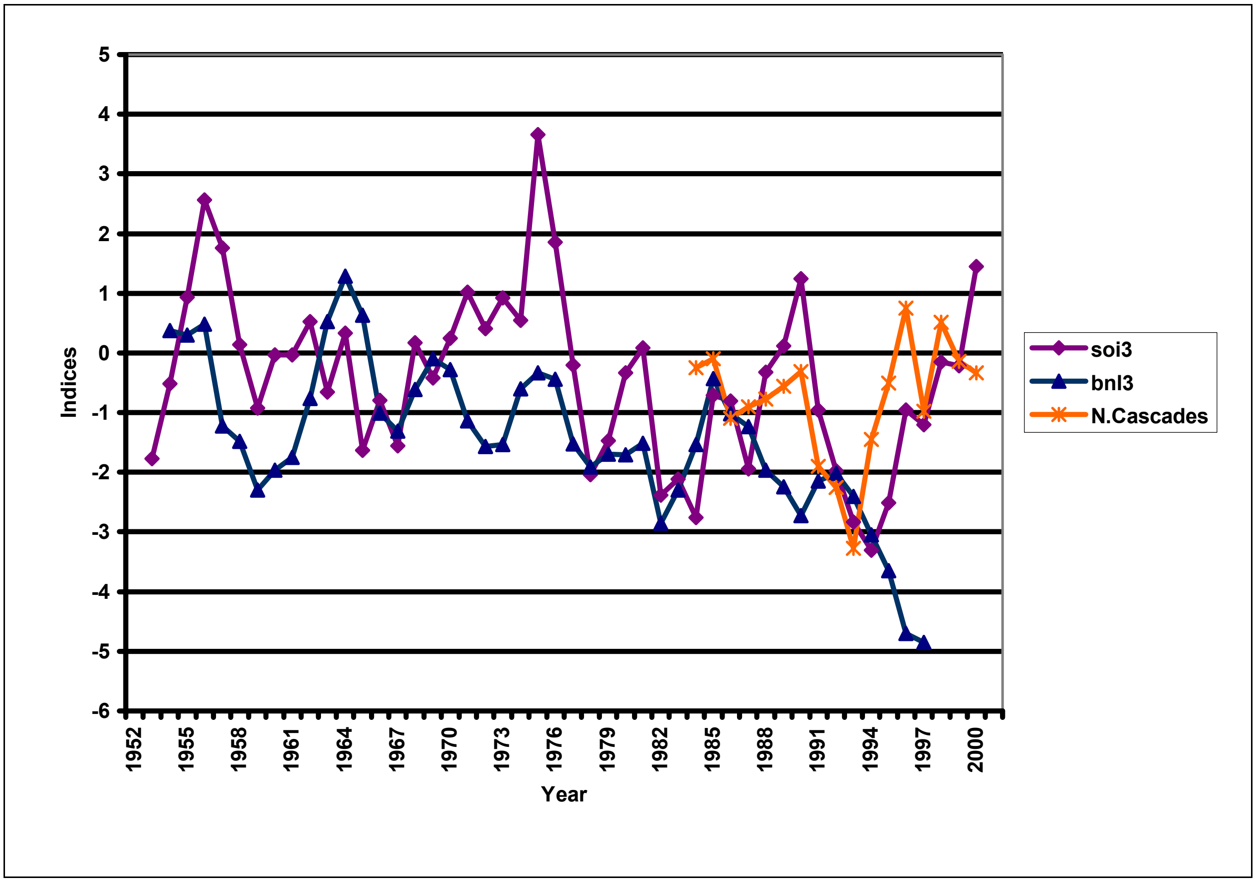

Figure 3. Comparison of variations in the Southern Oscillation Index and glacier mass balance, using three year running means. The lack of correlation with the Lemon Creek (bnl3) record is evident. The North Cascade glacier mass balance has an observable relationship.

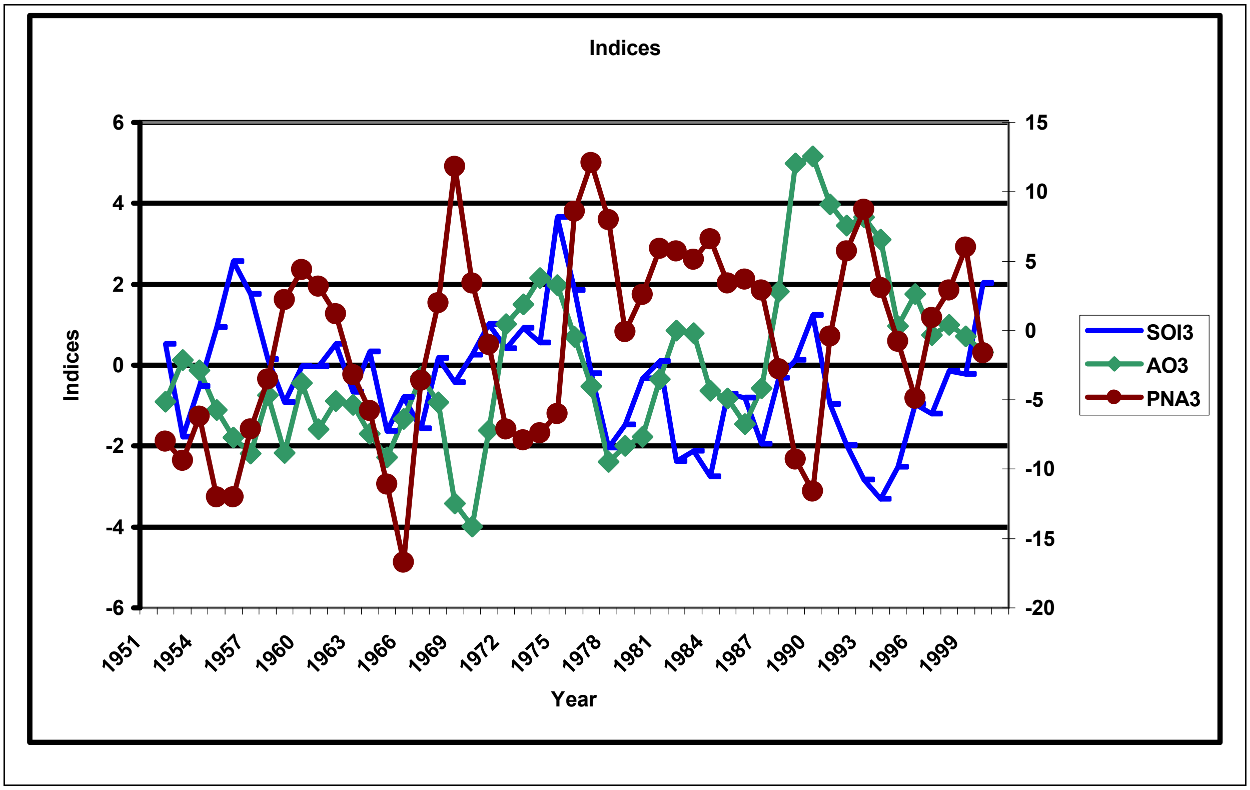

Figure 4. Comparison of the Arctic Oscillation Index with SOI and PNA , using three year running means. The relatively poor relationship is obvious. The PNA and the SOI have a weak inverse correlation.

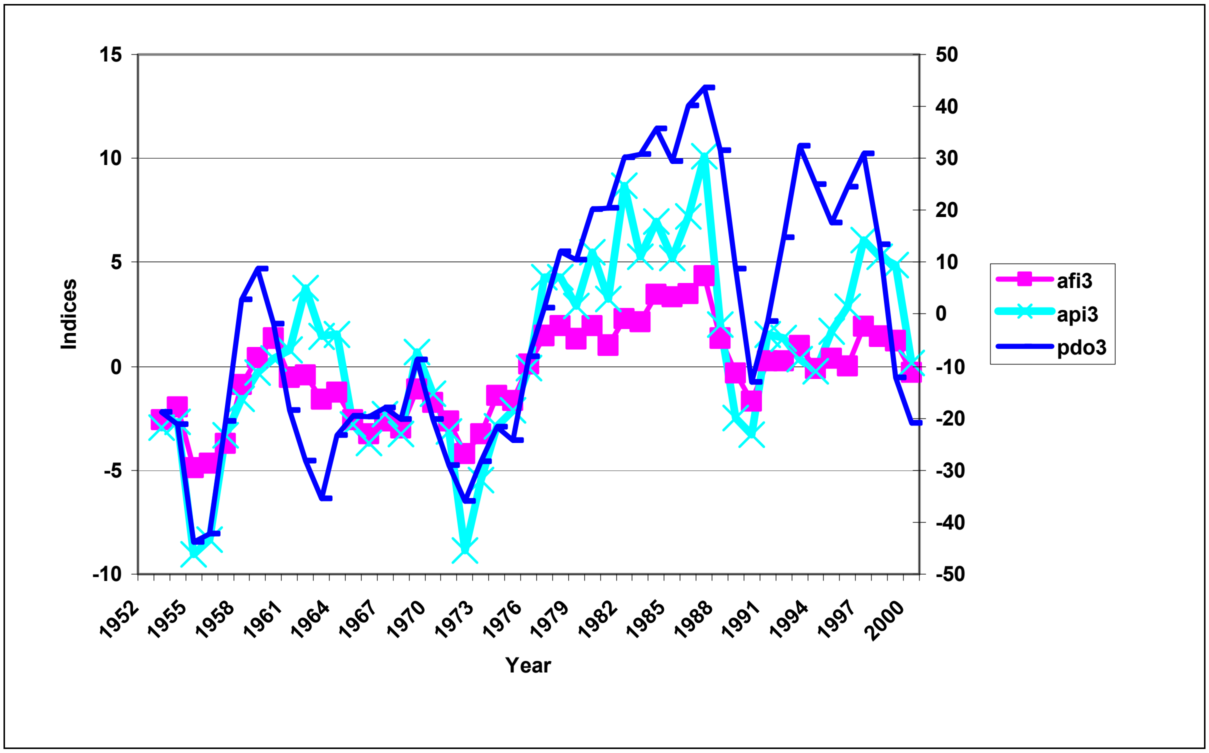

Figure 5. The similarity in nature of the AFI, ALPI and PDO, all as three year running means. The AFI is the best fit index for annual mass balance of the Lemon Creek Glacier.

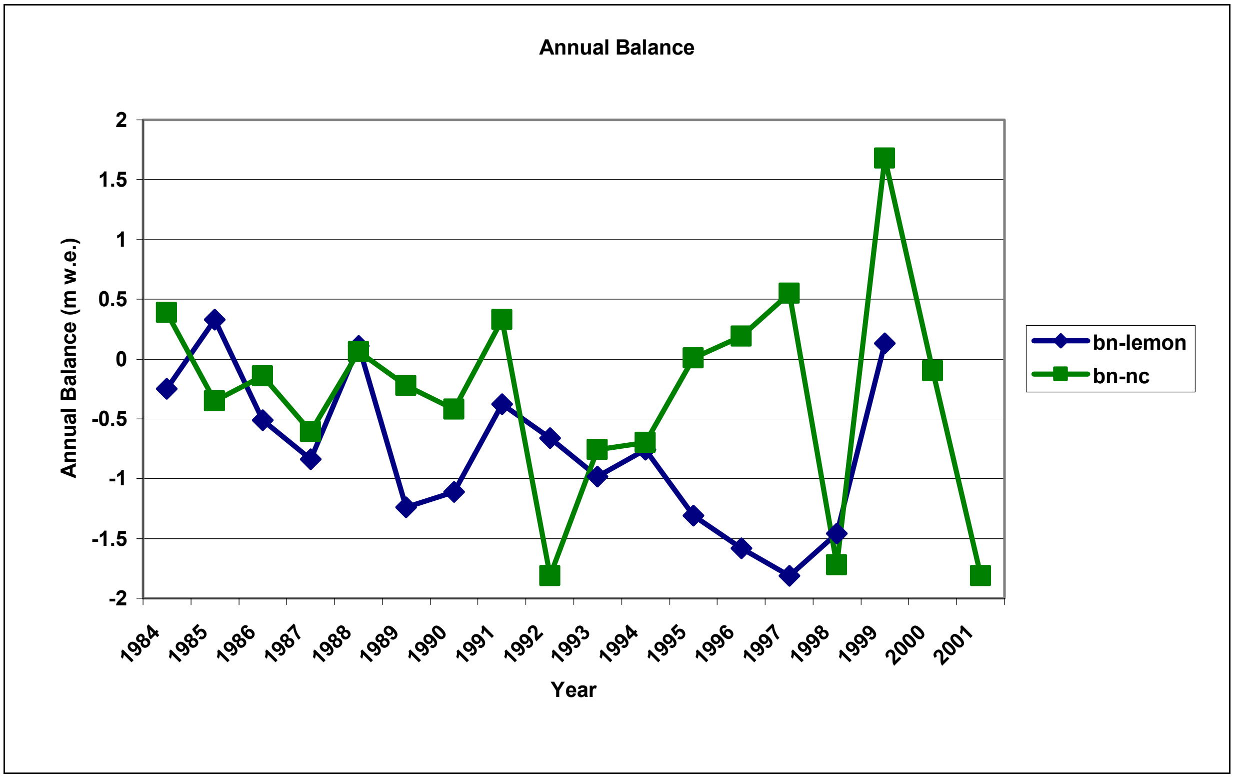

Figure 6. The annual balance of the North Cascades versus Lemon Creek Glacier. There is not a consistent relationship at this time scale.

References:

Barnston, A. G., and R. E. Livezey, 1987: Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. Mon. Wea. Rev., 115, 1083-1126.

Beamish, R.J., C.E. Neville and A.J. Cass. 1997. Production of Fraser River sockeye salmon (Oncorhynchus nerka) in relation to decadal-scale changes in the climate and the ocean. Can. J. Fish. Aquat. Sci. 54: 543-554.

Bitz, C.C. and D.S. Battisti, 1999. Interannual to decadal variability in climate and the glacier Mass balance in Washington, Western Canada and Alaska. Journal of Climate, 12, 3181-3196.

Ebbesmeyer, C.C. and R.M. Strickland. 1995. Oyster Condition and Climate: Evidence from Willapa Bay. Publication WSG-MR 95-02, Washington Sea Grant Program, University of Washington, Seattle, WA. 11p.

Hodge, S.M., D.C. Trabant, R.M. Krimmel, T.A. Heinrichs, R.S. March and E.G. Josberger, 1998. Climate variations and changes in mass of three glaciers in western North America. Journal of Climate, 11, 2161-2179.

Hurrell, J. W., 1995: Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. Science, 269, 676-679.

Krimmel, R.M. 1997. 'Water, ice and meteorological measurements at South Cascade Glacier, Washington, 1996 balance year'. USGS OFR-97-4143.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society, 78, pp. 1069-1079.

McFarlane, G.A., J.R. King and R.J. Beamish. 2000. Have there been recent changes in climate? Ask the fish. Prog. Oceangr. 47 (2000) 147-169.

Pelto, M.S. and Miller, M.M. 1999. Mass Balance of the Lemon Creek Glacier, Alaska 1953-1995. Geografiska Annaler, 81, 671-681.

Pelto, M.S. and Riedel, J. 2002. Spatial and temporal variations in annual balance of North Cascade glaciers, Washington 1984-2000. Hydrologic Processes 15, 3461-3472.

Trenberth, K.E., and J.W. Hurrel, 1994. Decadal atmosphere-ocean variations in the Pacific. Climate Dynamics 9, 30.

Thompson, D. W. J., and J. M. Wallace, 1998:The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. Geophys. Res. Lett., 25, No. 9, 1297-1300.

Zhang y., J.M. Wallace, D.S. Battisti, 1997. ENSO like interdecadal variability: 1900-1993. Journal of Climate, 10, 1004-1020.