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Snowpack and Runoff Responses to Climatic Variability, Southern Coast Mountains, British Columbia

Abstract

Climatic variability and change occur at a range of time scales and can influence environmental processes and human activity. For example, interannual variations in winter snow accumulation can control water availability for human consumption and hydroelectric generation, while tree-limit may respond to decadal or longer-term shifts in climatic regimes. This study examined variations in temperature, precipitation, April 1 snowpack water equivalent, and annual and summer runoff in the southern Coast Mountains of British Columbia, particularly in relation to interannual and decadal variations in atmospheric circulation over the North Pacific. Temperatures averaged over each winter (November to March) are correlated with the strength of the Pacific North America (PNA) atmospheric circulation pattern as a result of the warm, southerly airflow during enhanced-PNA winters. Winter precipitation is not clearly correlated with the strength of the PNA circulation pattern. However, winters with an enhanced PNA pattern tend to experience more rain and less snowfall, resulting in decreased April 1 snowpack water equivalent. Streamflow response to variations in the strength of the PNA pattern depends on elevation and glacier cover. Following 1976, there was a statistically significant decrease in snowfall, April 1 snowpack and summer runoff from an unglacierized, mountainous catchment. These decreases are consistent with the post-1976 shift toward the strong phase of the PNA pattern during winter which has been documented in the literature.

Introduction

Climatic variability and change can influence environmental processes and human activity. For example, interannual variations in winter snow accumulation can control water availability for human consumption and hydro-electric generation, while the altitudinal limit of tree growth may respond to decadal or longer-term shifts in climatic regimes (Kullman, 1986). An understanding of the nature and causes of climatic variability at a range of time scales can therefore aid in interpreting environmental change and planning resource allocation.

In many areas in the U.S. and Canada, local climatic and hydrologic conditions are related to the strength of the Pacific North America (PNA) circulation pattern over the North Pacific Ocean, especially in winter (e.g. Cayan and Peterson, 1989; Leathers et al., 1991). The PNA pattern is a natural, internal mode of variability in which the strong phase is characterised by southerly air flow along the west coast with a ridge of high pressure over the Rocky Mountains; westerly zonal flow dominates the weak phase (Wallace and Gutzler, 1981). The strong phase of the PNA pattern in winter appears to be favoured when sea surface temperatures (SSTs) in the equatorial Pacific are above normal, and it is therefore related to the El Niño-Southern Oscillation (ENSO) phenomenon (Trenberth and Hurrell, 1994). An understanding of the relations between local climate and circulation patterns can provide a basis for interpreting past hydroclimatic variability (Trenberth, 1995), for "down-scaling" output from General Circulation Models (GCMs) to generate predictions of the local consequences of global climatic change (Matyasovszky and Bogardi, 1996), and potentially for forecasting water supply with lead times of one to two seasons ahead (Cayan and Peterson, 1989).

Many previous studies of hydroclimatic variability have examined relatively extensive areas, such as the western U.S. (Redmond and Koch, 1991) and British Columbia, Canada (Moore and McKendry, 1996). The present study documents variations in local climate, snowpack water equivalent and streamflow in a more restricted region, the southern Coast Mountains of British Columbia. This study adds to and builds on previous studies within the Pacific Northwest (e.g. Greenland, 1995), and contributes to a more detailed regional picture of climatic variability and its environmental consequences. This study addresses two questions: (1) are interannual variations in snowpack and streamflow related to the strength of the winter PNA circulation pattern, and (2) is there evidence of the climate-related step change beginning in 1977 which was documented by Trenberth (1990) and Ebbesmeyer et al. (1991). Winter is defined here as comprising the months November to March, inclusive, as opposed to at least one study that defined a winter half-year as October to March (Redmond and Koch, 1991). The November-March period is used here because it better represents the period of major snow accumulation, and it is the period when "winter" circulation patterns are best expressed (Trenberth, 1990).

The Study Area

This study focuses on the southern Coast Mountains and adjacent portions of the Cascades north of the Canada-U.S. border (Figure 1). The Coast Mountains rise to over 3000 m elevation. The glaciation limit varies from about 1900 m in the western, maritime-influenced areas to 2700 m in the eastern portions of the Coast Mountains (Østrem, 1966). Mean annual precipitation varies with elevation, but ranges from over 4000 mm in the west to less than 1000 mm in the east. Over 60% of mean annual precipitation falls between November and March. Treeline occurs between about 1500 and 2000 m.

The study area includes the Greater Vancouver Regional District (GVRD), which has a rapidly growing population and demand for water. The water supply for the GVRD depends on the spring snowpack to provide reservoir inflows through the spring and summer. Water use restrictions have been applied in years in which a dry summer has followed a winter with low snow accumulation

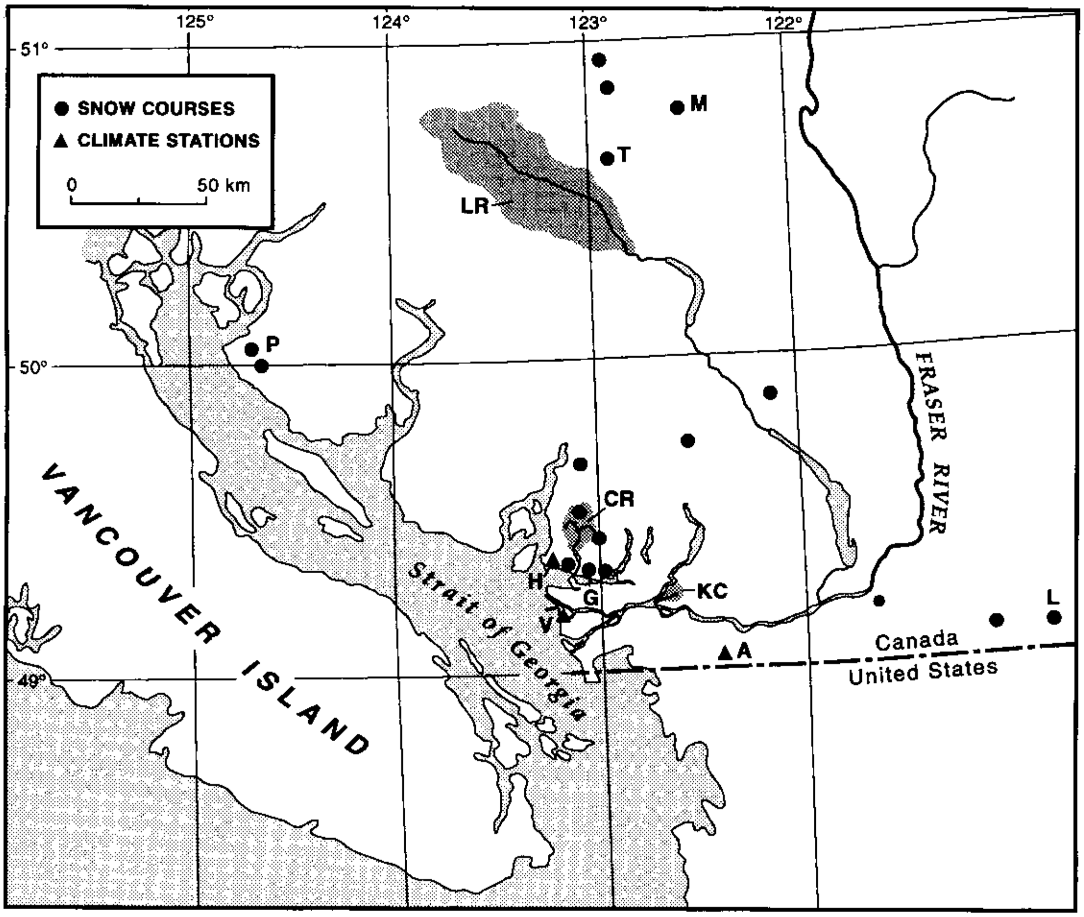

Figure 1. Map of study area, showing station locations. Letter codes identify stations referred to in the text and/or figures: A, Abbotsford Airport; CR, Capilano River; G, Grouse Mountain; H, Hollyburn; KC, Kanaka Creek; L, Lightning Lake; LR, Lillooet River; M, McGillivray Pass; P, Powell River (Upper and Lower); T, Tenquille Lake; V, Vancouver Airport.

(e.g. 1992). The winter snowpack also provides an important resource for both resort-based and back-country recreation.

Methods

Atmospheric Circulation

The values of the NP index described by Trenberth and Hurrell (1994), averaged over each November-March period, were used as an index of the strength of the PNA circulation pattern during winter. The NP index is the area-weighted average sea level pressure over the region from 30 to 65°N and from 160°E to 140°W. The NP index is highly correlated with the PNA index of Wallace and Gutzler (1981) (r = -0.91), and is believed to be a more robust index of atmospheric circulation over the North Pacific (Trenberth and Hurrell, 1994). Figure 2 shows the time series of NP. Low values of NP correspond to winters with an enhanced PNA pattern, high values to winters with dominantly zonal airflow over the North Pacific.

Hydroclimatic Data

Analysis of network hydroclimatic data always involves compromising between spatial coverage and length of record. In this study, stations were chosen that had at least 9 years of record prior to the 1977 step change, to provide some representation of the earlier regime.

Monthly temperature and precipitation data were obtained from the Atmospheric Environment Service. Three stations met the criterion that there had to be no station re-locations or other obvious sources of discontinuity in the record. Station locations are shown on Figure 1. Station elevations are: Vancouver Airport, 3 m; Abbotsford Airport, 58 m; and Hollyburn Ridge, 951 m. Mean temperatures and total snowfall, rainfall and precipitation were calculated for each November-March winter period.

April 1 snow course data were obtained from the B.C. Ministry of Environment. Each value represents the average snowpack water equivalent (SWE) based on 5 to 10 snow cores.

Streamflow data were obtained from Water Survey of Canada. Stations were selected which had natural flow conditions or minimal regulation. Runoff was calculated for each water year (October to September), as well as for each summer half-year (April to September). The three catchments meeting the selection criteria, shown in Figure 1, represent a range of hydrologic regimes found within the region. Kanaka Creek's catchment has a peak elevation of 920 m and is dominated by winter rainfall. Capilano River's basin has a peak elevation of about 1750 m and in many years has a substantial seasonal snowpack which lasts into spring and early summer. The drainage area for Lillooet River has 17% glacier cover and has peak elevations up to 3120 m. Most winter

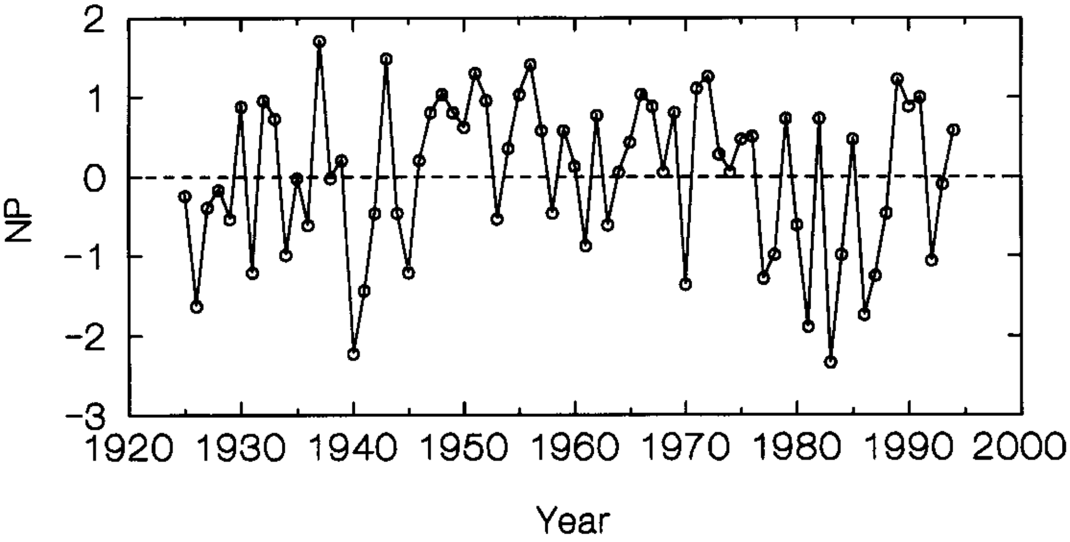

Figure 2. Time series of Trenberth's North Pacific (NP) index.

precipitation in the Lillooet catchment falls as snow which melts in the spring and summer.

The Greater Vancouver Water District regulates Capilano River flows by draining a mountain lake to augment late-summer low flows. However, under normal operations the volume of water released would be at most equivalent to 56 mm of runoff, or about 3.5% of the mean summer runoff of 1575 mm (for the period 1961-1992). The effects of this regulation on interpretation of the analyses will be considered in the discussion.

Data Analysis

The relations between hydroclimatic elements and the NP index were assessed by examination of scatterplots and calculation of Spearman's coefficient of rank correlation. The use of rank correlation helps accommodate possible non-linearity in the relations as well as violation of the assumption of bivariate normality (Steele and Torrie, 1980, p. 550). The existence of a step change beginning in 1977 was tested by splitting the data into two periods, one from 1961 to 1976 and the other from 1977 to 1992 (which is when many of the data series end). Student's t statistic was used to test the null hypothesis that there was no change in the mean value between the earlier and later periods. Only stations having relatively complete records (fewer than 10% missing values) for the period 1961 to 1992 were included in this analysis. This criterion maximizes the sample size and provides approximately equal sample sizes in the two periods, thereby maximizing the power and robustness of the t test in the face of possible non-normality and heteroscedasticity of the parent distributions (Zar, 1984, p. 137).

It should be noted that the significance levels indicated by the value of a test statistic are valid in the case of one comparison. Where multiple tests are conducted, as in this study, the risk of incorrectly rejecting the null hypothesis will exceed the calculated significance level for a single test. Therefore, in interpreting the analyses, emphasis will be placed on consistency of trends amongst the variables as well as on the apparent statistical significance of the trends.

Results

Temperature and Precipitation

Seasonal temperatures and precipitation at Vancouver Airport are generally correlated with those at the other two stations, especially Abbotsford Airport. Time series of Vancouver Airport data are shown in Figure 3. Although there is no obvious trend in winter temperatures, years with low values of NP generally coincided with warm winters (e.g. 1970, 1977, 1981, 1983). This correlation is also apparent in Figure 4 and Table 1. There is no clear association between winter total precipitation and NP (Table 1, Figure 5). Some years of enhanced PNA circulation (low NP) had low precipitation (e.g. 1970, 1977) while others had high precipitation (e.g. 1981, 1983). Unlike total winter precipitation, snowfall is significantly correlated with NP (Table 1, Figure 5, Figure 6).

Student's t tests revealed no significant differences in winter temperatures or total precipitation between the two periods (Table 2). Summers in the 1977-1992 period were significantly warmer by about 0.5°C, at least at the lower elevation stations (Hollyburn Ridge had too many missing values for this analysis). A summer warming trend appears to have started in 1977 (Figure 3). Winter snowfall was substantially lower in the 1977-1992 period at the two lower-elevation stations, but the difference is not quite significant at the 95% confidence level at Abbotsford Airport. This marginal lack of significance may be caused by the fact that winter snowfall in a given year at the low elevation stations can be dominated by one or two events, leading to great interannual variability.

TABLE 1. Spearman's coefficient of rank correlation (r) between climatic data and the NP index (T_w = winter temperature; P_w = winter precipitation; S_w = winter snowfall).

	Hollyburn Ridge			Vancouver Airport			Abbotsford Airport		
	T_w	P_w	S_w	T_w	P_w	S_w	T_w	P_w	S_w
r	-0.66	0.21	0.74	-0.67	0.07	0.71	-0.61	0.24	0.66
n	26	34	34	55	54	50	45	46	46
p-value[1]	<0.01	ns	<0.01	<0.01	ns	<0.01	<0.01	ns	<0.01

[1] ns indicates $p > 0.05$.

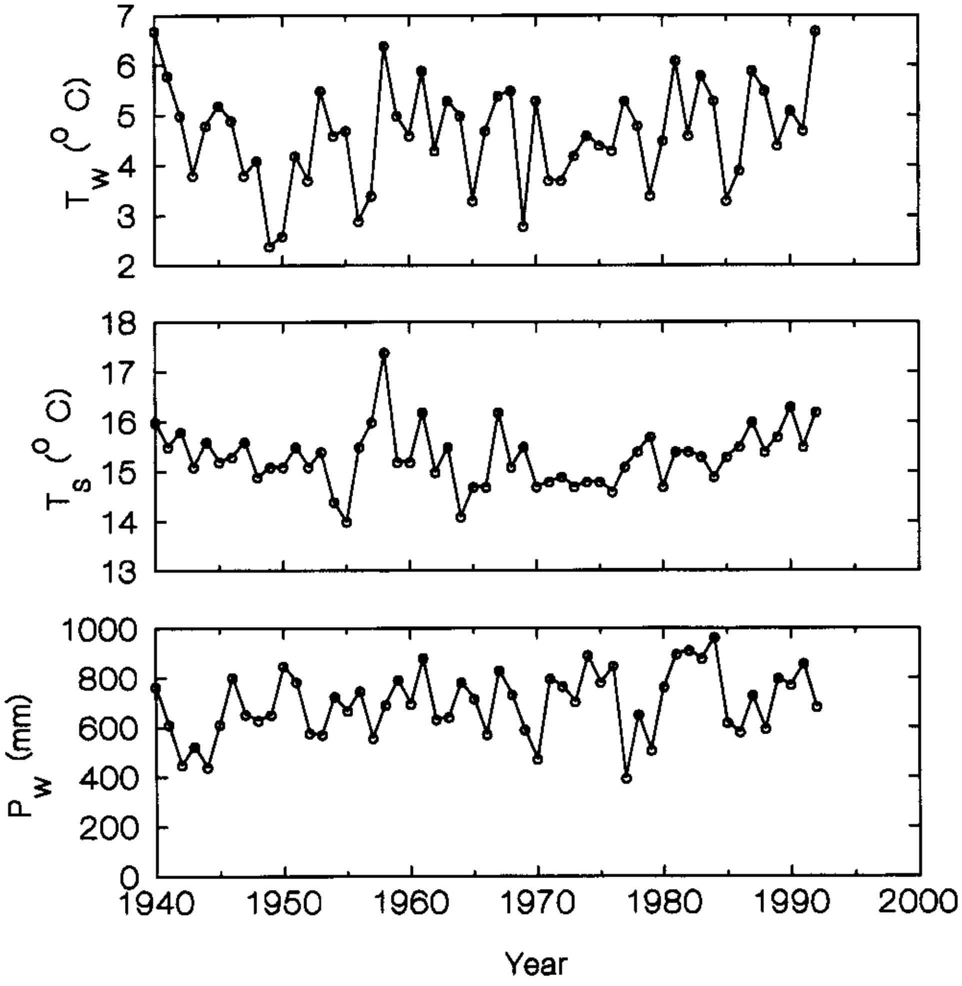

Figure 3. Time series of winter temperature, summer temperature and winter precipitation at Vancouver Airport.

April 1 Snowpack Water Equivalent

All of the stations analysed for a step change experienced lower average SWE following 1976 (Table 3). Decreases relative to the 1961-1976 mean averaged 31%. The smallest decreases (16% to 25%) occurred at stations located between the Lillooet and Fraser Rivers, where the maritime influence is weaker and station elevations are highest. At seven of the stations the decrease had significance levels of about $p = 0.01$ or less, while the shift at the eighth station, McGillivray Pass, was not quite significant with $p = 0.054$. Figure 7 shows time series for selected stations.

Rank correlation coefficients between SWE and NP ranged from 0.30 to 0.73. Correlation coefficients tended to be lower for stations between the Fraser and Lillooet Rivers (0.30 to 0.47). Of the 17 stations included in the analysis, only one, McGillivray Pass, had a correlation which was not quite significant ($r = 0.30$ and $p \approx 0.06$). Figure 8 illustrates the SWE-NP relation for selected stations.

Runoff

Annual runoff decreased for all three rivers by 6% to 11% relative to the 1961-1976 means. However, these decreases are not significant at $\alpha = 0.05$ (Table 4). The only statistically significant change was for summer runoff for Capilano River, which decreased 18% following 1976 (Figure 9).

TABLE 2. Results of Student's t tests for climatic data.

	Vancouver Airport				Abbotsford Airport			
	T_w	T_s	P_w	S_w	T_w	T_s	P_w	S_w
Change[1]	0.43°C	0.47°C	-3 mm	-36 mm	0.35°C	0.49°C	-81 mm	-40 mm
change[2]			-0.4%	-51%			-8%	-43%
t	1.35	2.64	-0.06	-2.25	0.9	2.38	-1.14	-1.95
p-value	0.19	0.01	0.95	0.03	0.36	0.02	0.26	0.06

[1] mean for 1977-1992 - mean for 1961-1976

[2] for precipitation and snowfall, change as a percentage of the 1961-1976 mean

TABLE 3. Results of analyses for snowpack data. Sub-regions are defined as follows: (1) Coast Mountains west of Lillooet River; (2) Coast Mountains east of Lillooet River; (3) Cascade Range.

			Results of t test			Results of correlation analysis		
Station	Elevation (m)	Sub-region	Change (%)	t	p-value	r	n	p-value[1]
Grouse Mountain	1100	1	-42	3.90	<0.001	0.51	57	<0.01
Palisade Lake	880	1	-37	3.38	0.002	0.46	46	<0.01
Dog Mountain	1080	1	-34	2.97	0.006	0.56	48	<0.01
Powell River Lower	910	1				0.73	35	<0.01
Powell River Upper	1040	1				0.67	32	<0.01
Hollyburn	1100	1				0.40	43	<0.01
Loch Lomond	900	1				0.51	37	<0.01
Mount Seymour	1070	1				0.65	30	<0.01
Stave Lake	1210	1				0.56	25	<0.01
Tenquille Lake	1680	2	-20	2.76	0.010	0.32	40	<0.05
McGillivray Pass	1800	2	-16	2.01	0.054	0.30	40	ns
Green Mountain	1630	2	-25	2.80	0.009	0.45	30	<0.05
Bralorne	1450	2				0.47	30	<0.01
Nahatlatch River	1520	2				0.42	25	<0.05
Wahleach Lake	1400	3				0.72	25	<0.01
Lightning Lake	1220	3	-29	3.30	0.003	0.54	45	<0.01
Klesilkwa	1130	3	-43	2.39	0.024	0.71	45	<0.01

[1] ns indicates $p > 0.05$

Table 5 summarizes the correlations between annual and summer runoff and NP. None of the correlations for annual runoff is significant. For summer runoff, only Capilano River has a significant correlation with NP. Figure 10 illustrates runoff-NP relations for Capilano River.

Table 6 shows that, although summer runoff for Lillooet River is more highly correlated with variations in spring snow accumulation, summer temperatures at Vancouver Airport also account for a significant proportion of the variance of summer runoff. The correlation between Lillooet River's summer runoff and air temperature results from contributions of glacier melt, which is positively correlated with summer air temperatures (Collins, 1987).

Discussion

The weak correlations between winter precipitation and NP found in this study are not consistent with those reported for adjacent areas in the U.S. Pacific Northwest by Redmond and Koch (1991), who found highly significant negative correlations between October-March precipitation and

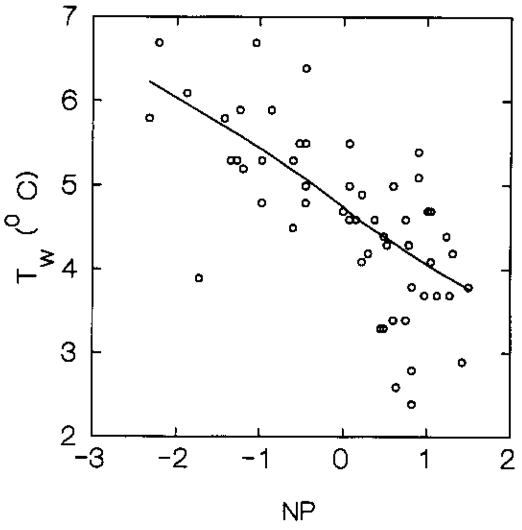

Figure 4. Scatterplot of winter temperature at Vancouver Airport against the NP index. The smoothed fits in this and following figures were calculated using the LOWESS algorithm (Cleveland, 1979).

a PNA index for the period 1947-48 through 1983-84. The difference cannot be explained by the use of November-March as an integrating period in this study: the correlation between October-March total precipitation at Vancouver Airport and October-March average NP is 0.141, which is not statistically significant at the 0.05 significance level. The weak correlation probably reflects the relatively heavy precipitation during some enhanced PNA years, particularly 1981 and 1983. Moore and McKendry (1996) found weak correlations between winter precipitation and NP, and the occurrence of heavy precipitation in 1981 and 1983, for several stations in southern British Columbia. Stations in Washington such as Concrete, on the other hand, received relatively light precipitation in 1981 and 1983 (Harper, 1993), consistent with the results of Redmond and Koch (1991). Further research should investigate the nature and causes of precipitation variability in the Pacific Northwest region.

TABLE 4. Results of Student's t tests for streamflow data

	Kanaka Creek		Capilano River		Lillooet River	
	annual	summer	annual	summer	annual	summer
change[1]	-169 mm	10 mm	-419 mm	-305 mm	-117 mm	-81 mm
change[2]	-9%	2%	-11%	-18%	-6%	-5%
t	-1.08	0.2	-1.75	-2.75	-1.60	-1.47
p-value	0.29	0.84	0.09	0.01	0.12	0.15

[1] mean for 1977-1992 - mean for 1961-1976 (mm)

[2] change as a percentage of the 1961-1976 mean

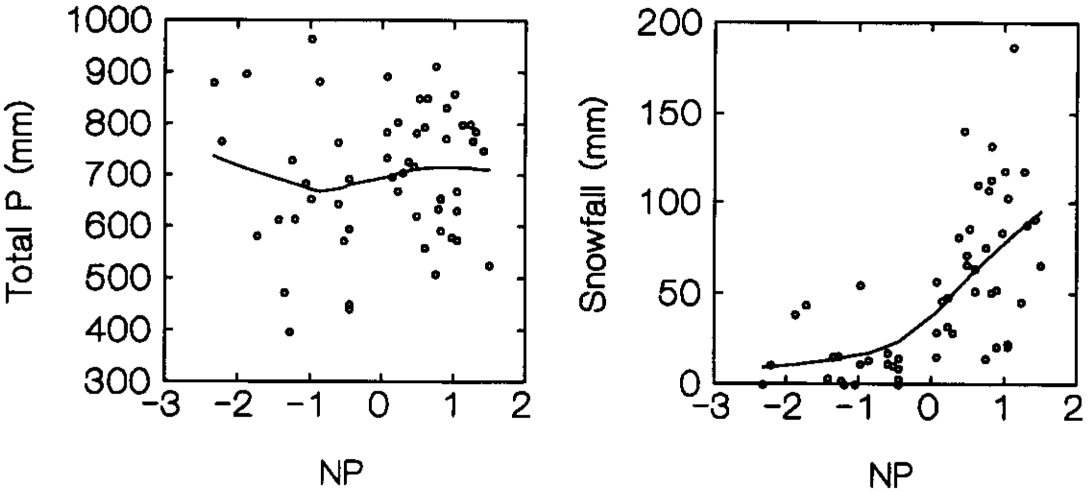

Figure 5. Relations between winter total precipitation and snowfall at Vancouver Airport and the NP index.

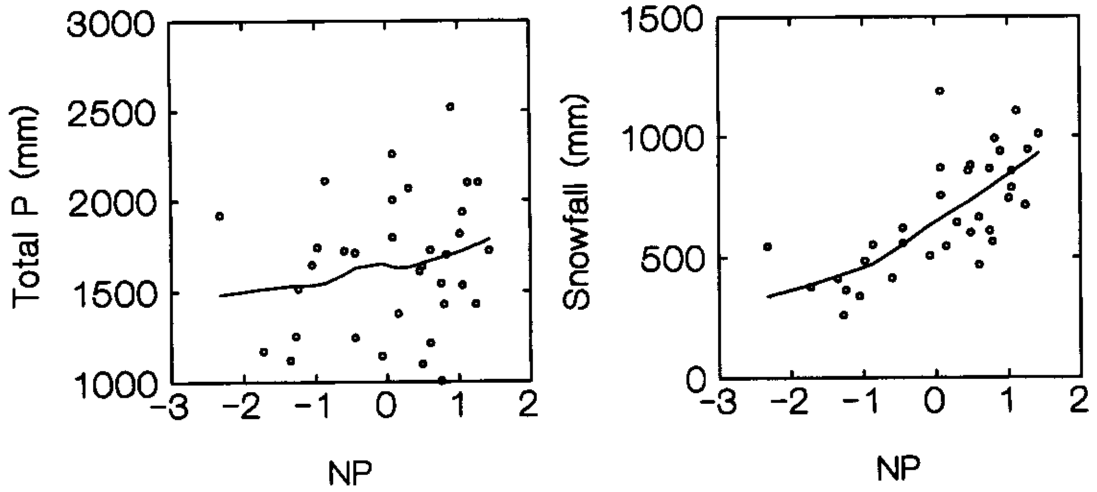

Figure 6. Relations between winter total precipitation and snowfall at Hollyburn Ridge and the NP index.

TABLE 5. Spearman's coefficient of rank correlation between streamflow and the NP index.

	Kanaka Creek		Capilano River		Lillooet River	
	annual	summer	annual	summer	annual	summer
r	0.34	0.08	0.03	0.47	0.07	0.08
n	31	32	64	65	64	67
p-value	ns	ns	ns	<0.01	ns	ns

TABLE 6. Regression analysis of Lillooet River summer runoff as a function of April 1 SWE at Tenquille Lake and Vancouver Airport summer temperature.

Fitted equation	$\tilde{R}^2$	df	s.e.	p
$\hat{Q} = -380 + 119 \cdot T_s$	0.20	38	149	0.002
$\hat{Q} = 1017 + 0.356 \cdot SWE$	0.34	38	135	<0.001
$\hat{Q} = -943 + 0.372 \cdot SWE + 127 \cdot T_S$	0.58	37	108	<0.001

$\hat{Q}$ = predicted summer runoff (mm)

$\tilde{R}^2$= coefficient of determination adjusted for degrees of freedom

df = degrees of freedom

s.e. = standard error of the estimate (mm)

The negative correlation between winter temperatures and NP is consistent with previous studies, and results from the advection of warm, southerly air along the North American west coast during periods of enhanced PNA circulation (Leathers et al., 1991). During storms, the warmer temperatures would produce higher freezing levels and therefore more rain and less snow, even at higher elevations. The generally lower snowpack water equivalent associated with enhanced PNA circulation is caused by this freezing level effect in wet winters such as 1980-81 and 1982-83, rather than by lack of precipitation as was the case in 1969-70 and 1976-77. However, in the lee portion of the Coast Mountains (i.e. between the Lillooet and Fraser Rivers), the weaker maritime influence would have depressed freezing levels relative to areas nearer the coast. These depressed freezing levels, combined with the higher station elevations in the lee side (Table 3), probably account for the weaker SWE-NP correlations observed there.

Streamflow variations are consistent with the temperature, precipitation and snowpack data. At Kanaka Creek and Capilano River, where annual storage changes are minimal, the lack of correlation between annual runoff and NP reflects the

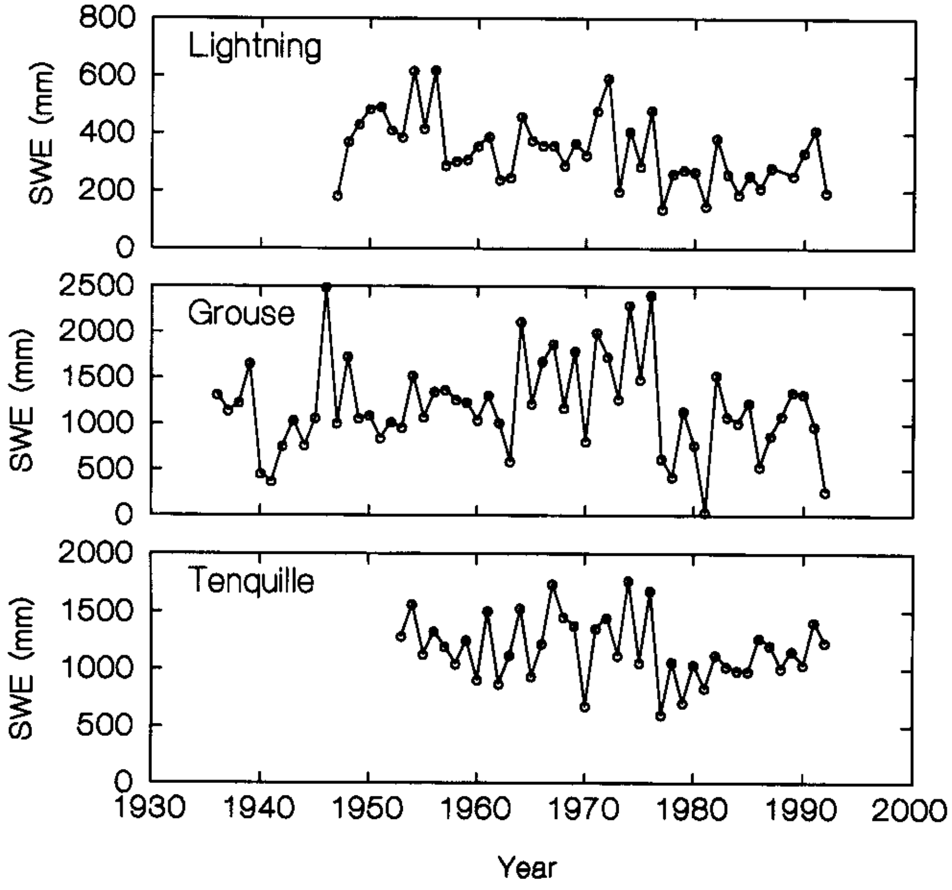

Figure 7. Selected time series of April 1 snowpack water equivalent.

fact that precipitation is not correlated with NP. However, summer runoff at Capilano River is positively correlated with NP, because in years with an enhanced PNA pattern (low NP), there is more rain and less snowfall, and therefore more of the runoff occurs in winter and less during the following spring and summer. The correlation between summer runoff and NP is likely understated by the data, since flow augmentation would tend to be greater following low snowpack (low NP) winters, effectively reducing the contrast in summer runoff following low- and high-NP winters. The lack of correlation between summer runoff and NP at Kanaka Creek reflects the low elevation of its catchment, and the consequent lack of a significant snowpack.

The lack of correlation with NP for both annual and summer runoff for Lillooet River is due to the effects of glacier melt. The increased summer temperatures since 1976 have likely produced more glacier melt, tending to offset the decrease in runoff from seasonal snowmelt. However, many glaciers in the south Coast Mountains and adjacent U.S. Pacific Northwest currently have a negative mass balance (Brugman, 1992; Pelto, 1996). If the current climatic regime continues, the effects of glacier melt will eventually diminish as the glaciers recede.

Generalization of these results within the study region must be tempered by consideration of the limitations of data coverage. The climate stations represent the weakest coverage, and only sample the maritime edge of the region. The snow courses are better distributed across the region, but not necessarily with elevation. The snow courses west of the Lillooet River and in the Cascades sample the zone below about 1200 m elevation, while those east of the Lillooet River sample the zone

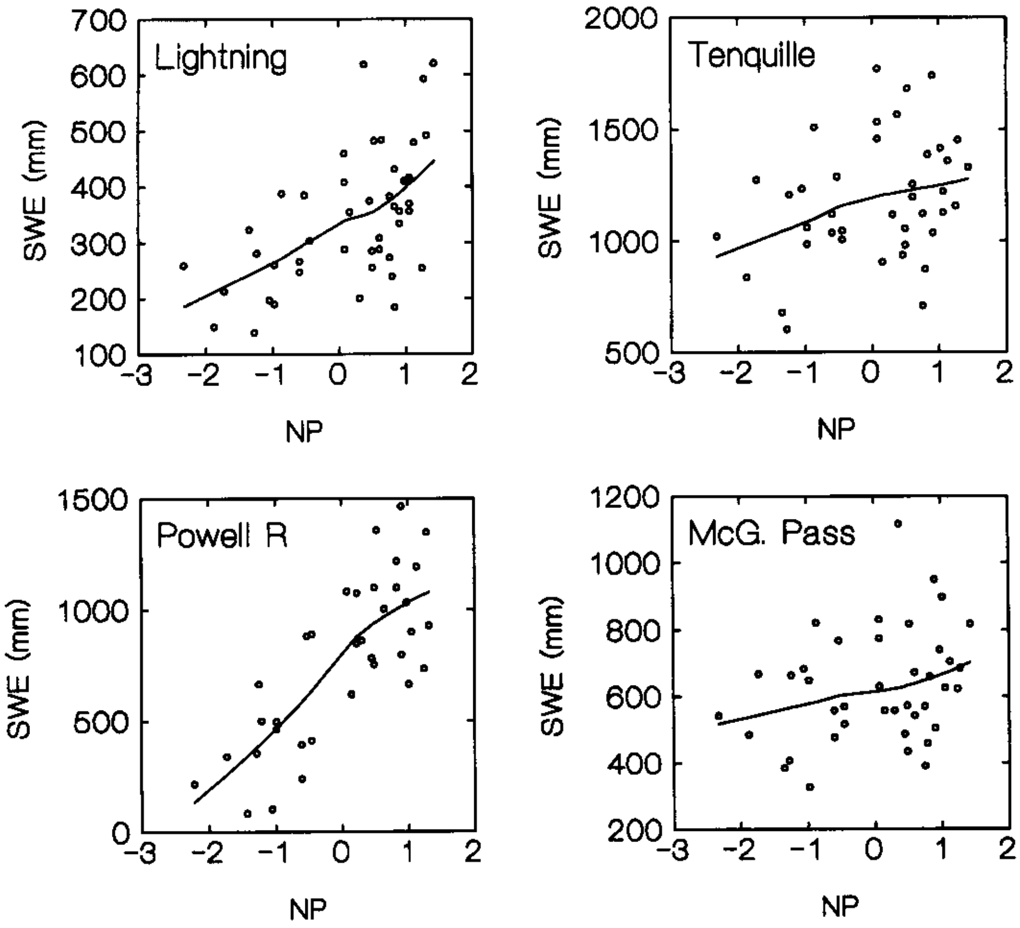

Figure 8. Scatterplots of SWE vs. NP for selected stations.

above 1400 m. In terms of streamflow data, there is only one catchment for each of the flow regimes (i.e. winter rainfall, winter rainfall/spring snowmelt, and spring-summer snow/glacier melt). Despite these considerations, the consistency of trends amongst the variables indicates that the regional-scale relations between surface hydroclimate and atmospheric circulation are probably real.

Trenberth (1990) and Ebbesmeyer et al. (1991) documented a tendency for sea surface temperatures to be warmer than normal in the equatorial Pacific since 1976, and these SST anomalies are believed to be the cause of an increased tendency to the strong phase of the PNA circulation pattern beginning in the winter of 1976-77 (Trenberth, 1995). The statistically significant step changes in snowfall, April 1 snowpack and summer flow in Capilano River are consistent with this shift in circulation patterns. However, the climatic significance of these shifts must be considered within a longer time frame. For example, in Fig. 2, the NP index appears to exhibit a shift in the 1940s from dominantly negative values to dominantly positive values, in addition to the shift following 1976. Karl (1988) demonstrated that similar types of decadal-scale climatic fluctuations may not reflect a climatic "change," but could result from a stationary process with low-order autocorrelation caused by some "physically-based weak year-to-year persistence." On the other hand, Trenberth (1995) hypothesised that the anomalously warm tropical Pacific SSTs beginning in the late 1970s may be one of the first manifestations of global warming due to increased concentrations of greenhouse gases, and that the strong phase of the PNA pattern may occur more

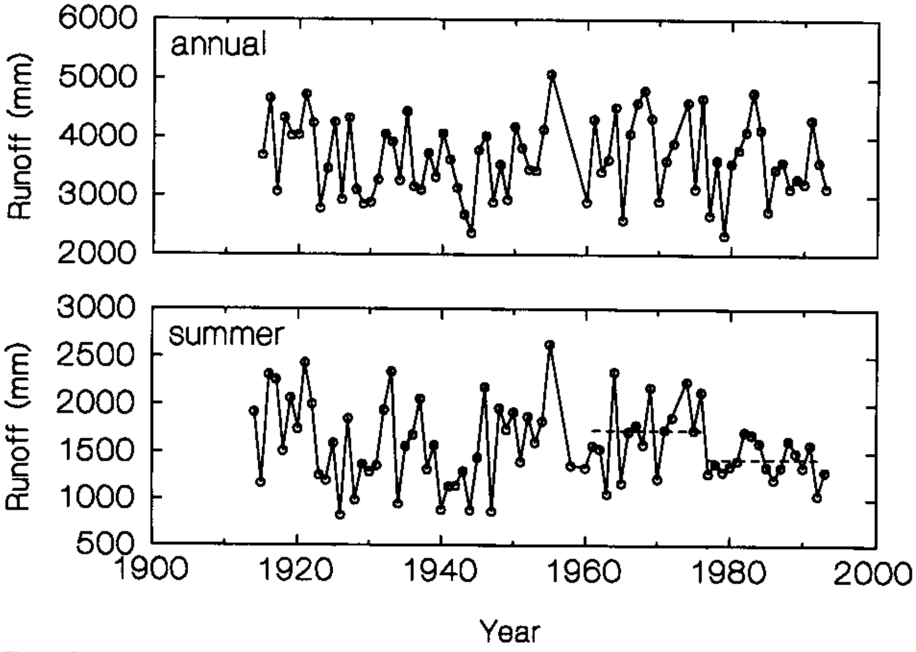

Figure 9. Time series of annual and summer runoff, Capilano River. The horizontal lines in the plot for summer runoff indicate the 1961-76 and 1977-92 means.

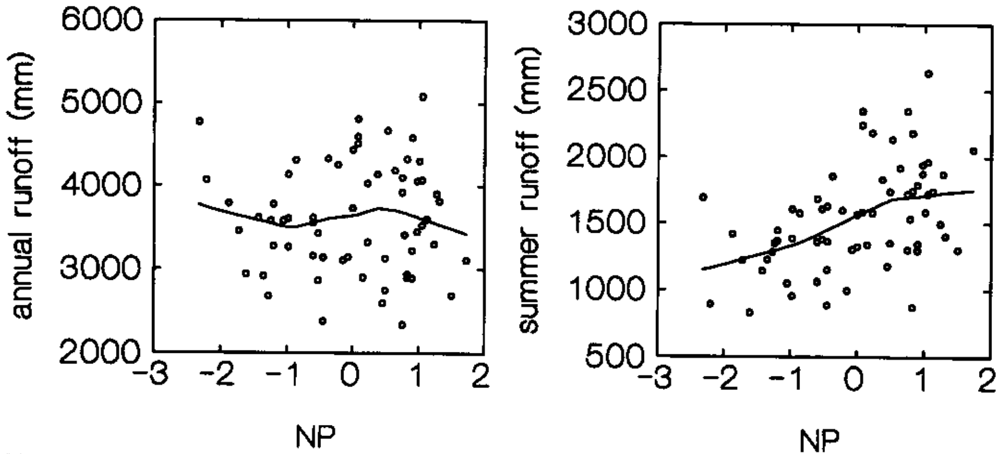

Figure 10. Relations between annual and summer runoff for Capilano River and the NP index.

frequently than in the past. Palmer (1993) similarly hypothesised that climatic responses to global-scale forcing are likely to be manifested in changes in the frequencies of the dominant modes of atmospheric circulation, rather than in the emergence of new modes. If these hypotheses are correct, further examination of past climatic variability and environmental responses in relation to atmospheric circulation may provide insight into the effects of future climatic change.

Conclusions

Winter temperatures in the south Coast Mountain region are correlated with the strength of the PNA circulation pattern as a result of warm, southerly airflow during enhanced-PNA winters. Winter precipitation is not clearly correlated with the strength of the PNA circulation pattern. However, winters with an enhanced PNA pattern tend to experience more rain and less snowfall, resulting in decreased April 1 snowpack water equivalent even in wet years.

Streamflow response depends on elevation and glacier cover. For a low-elevation catchment with minimal seasonal snow storage, there is no relation between the strength of the PNA pattern and either annual or summer runoff. For a mountainous, unglacierized catchment, there is no relation between PNA strength and annual flow, but there tends to be less summer flow following enhanced-PNA winters because of the decreased spring snowpack. In a glacierized catchment, glacier melt confounds relations between runoff and climate.

Following 1976, there was a statistically significant decrease in snowfall, April 1 snowpack and summer runoff from an unglacierized, mountainous catchment. These decreases are consistent with the post-1976 shift toward the strong phase of the PNA pattern during winter that has been documented in the literature.

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