SPATIAL AND TEMPORAL SNOWPACK VARIATION IN THE CROWN OF THE CONTINENT ECOSYSTEM

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ABSTRACT

Snowpack related ecosystem changes such as glacier recession and alpine treeline advance have been documented in the Crown of the Continent Ecosystem (CCE) over the course of the previous 150 years. Using data from the Natural Resource Conservation Service's SNOTEL sites and snow course surveys, we examined the spatial and temporal variation in snowpack in the region. SNOTEL data suggest CCE snowpacks are larger and more persistent than in most regions of the Western U.S., and that water year precipitation, rather than mean temperature, is the primary control on April 1 snow water equivalent (SWE). Snow course data indicate a statistically significant downward trend in mean April 1 SWE for the period 1950-2001 but no statistically significant trend in mean May 1 SWE for the longer period 1922-2001. Further analysis reveals that variations in both April 1 and May 1 mean SWE are closely tied to the Pacific Decadal Oscillation, an ENSO-like interdecadal pattern of Pacific Ocean climate variability. Despite no significant trend in mean May 1 SWE between 1922-2001, glaciers in Glacier National Park receded steadily during this period, implying changing climatic conditions crossed a threshold for glacier mass balance maintenace sometime between the Little Ice Age glacial maxima and 1922.

INTRODUCTION

Long-term climatic variability across the world's mountains is being studied because mountains cover approximately one-fifth of the terrestrial surface of the globe, provide 50% of the freshwater humans consume, are ranked high in biodiversity and, because of their spatial complexity, present a challenge to our understanding of atmosphere-landscape interactions. The Rocky Mountains of northern Montana and southern Alberta and British Columbia comprise the Crown of the Continent Ecosystem (CCE), an area that encompasses more than 10,000 km^2 of designated wilderness and national parks (Figure 1). Within this region, numerous ecosystem changes have been documented since the end of the Little Ice Age (ca 1850) that are likely driven by changes in climate. In Glacier National Park, Montana, USA, fewer than 37 glaciers remain of the 150 estimated to have been present around 1850 (Carrara 1989). Key et al. (in press) document a reduction in glacial ice and perennial snow cover from 99 km^2 to 27 km^2 during the past 150 years and Hall and Fagre (in press) estimate that all glaciers are likely to melt by 2030. Alpine treelines have advanced upward in elevation (Butler and DeChano 2001), have increased in biomass as spaces between patches have filled in (Klasner and Fagre 2002), and many trees have changed from the prostrate, krummholz form to begin growing as upright trees (Klasner and Fagre 2002). Annual mean precipitation for nearby Kalispell has actually increased during the last century (0.09 cm/year, $p=0.03$). Because winter snow accumulation is a major contributor to glacier mass balances, and the timing and magnitude of seasonal snowpacks are the proximate drivers for tree seedling establishment and growth at upper elevation sites (Peterson 1998), we hypothesized that long-term decreases in snowpack size and duration had occurred in the CCE despite increases in annual precipitation. Furthermore, changes in glacier mass balance and alpine tree establishment and growth have occurred in episodic fashion rather than incrementally, suggesting that snowpack variation may have similar periodicity.

Efforts have been made to examine the spatial and temporal characteristics of mountain snowpack in the western United States, trends in snow cover, and potential future responses to simulated climate change scenarios. Dettinger and Cayan (1995) indicated that snowmelt and runoff are beginning earlier in northern and central California, particularly in mid-elevation basins sensitive to changes in mean winter temperatures. Cayan (1996) demonstrated that precipitation anomalies have a greater effect on April 1 snow water equivalent (SWE) than temperature anomalies, excluding low elevation areas in the Pacific Northwest. Using data from SNOTEL stations, Serreze et al. (1999) compared eight regions in the West and found that, while variations in the SWE/precipitation ratio can have a large effect on snowpack variability in the coastal mountain ranges and in the Southwest,

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snowpack variability in the colder interior regions of the West is driven primarily by available precipitation. Based on General Circulation Model simulations of future climate, McCabe and Wolock (1999) predicted that, despite increases in winter precipitation, increases in temperature over the next century will result in large decreases in April 1 SWE throughout the western U.S. McGinnis (1997) estimated that the duration of snow cover on the Colorado Plateau will decrease by an average of 58 days, based on a 2 x CO_2 scenario. Leung and Wigmosta (1999) estimated that, based on a Regional Climate Model, snowpack will decrease by 60% in a representative watershed in the Pacific Northwest but only by 18% in a representative watershed in the CCE. More recently, multi-decadal patterns in western North American snowpack variation have been linked to Pacific Decadal Oscillation (PDO) indices (McCabe and Dettinger 2002).

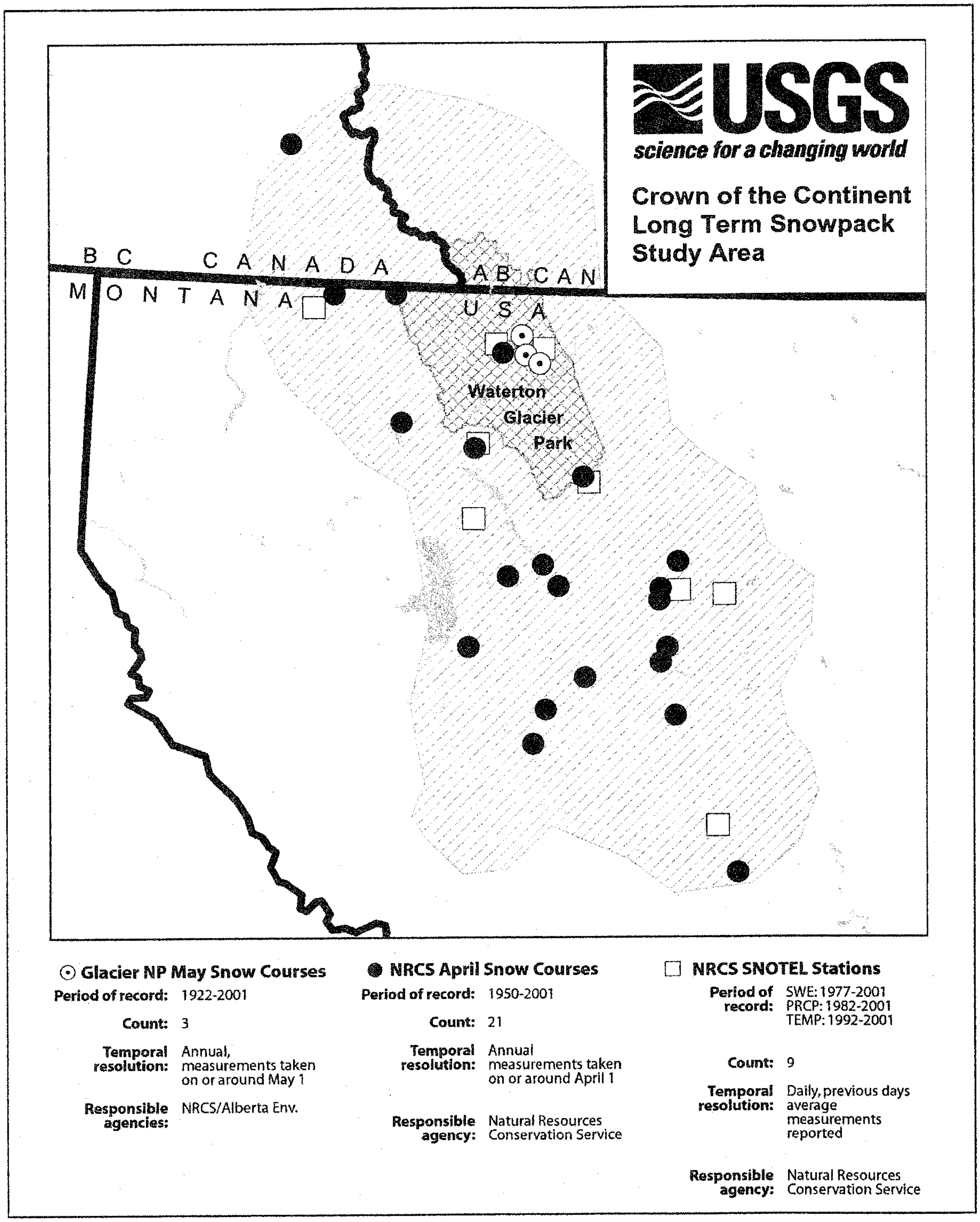


Figure 1: The Crown of the Continent Ecosystem, with snow courses and SNOTEL stations examined in this study.

The CCE is well suited for an examination of long-term trends in snowpack because there are relatively few local influences on climate patterns such as large urban areas, extensive irrigation, or major changes in land cover. This makes it easier to attribute changes in regional snowpack to long-term climatic variability without the confounding influence of landscape change. Moreover, the CCE has some of the earliest systematically collected snow data in the western U.S. (dating back to 1922) with which to examine snowpack trends and relate them to ecosystem responses. As part of a 12-year global change research program, several modeling studies have demonstrated the CCE's potential sensitivity to long-term snowpack changes (White et al. 1998). Under one scenario of reduced snowpack, tree growth rates increased at upper elevations but were reduced at lower elevations, streamflows peaked earlier during spring run-off and many streams became ephemeral, and competitive relationships between grassland and forest communities were altered (White et al. 1998). Thus, cascading ecological effects of reduced snowpack have the potential to significantly alter the CCE.

Our objectives were to examine CCE snowpacks for spatial and temporal patterns that might explain the observed changes in key ecosystem features. Relevant long-term temporal patterns included trends that might reflect climate change (i.e. global warming), changes in interannual variability, or multi-decadal patterns. The PDO has been recently described by Mantua et al. (1997) and Zhang et al. (1997) and shown to have a strong influence on the state of natural resources in the Pacific Northwest regions of the U.S. (e.g. salmon productivity). Peterson et al. (2001) have described synchrony between high elevation tree growth and PDO signals. Because similar natural resources have shown distinct changes in the CCE region, we examined our regional snowpack in relation to the PDO.

STUDY SITE

The "Crown of the Continent" term was first applied to the Rocky Mountains near the United States-Canada border by George Bird Grinnell, an early advocate of establishing national parks in this region. The Crown of the Continent Ecosystem extends from Fernie, British Columbia south to just north of Missoula and Helena in Montana. It encompasses Waterton Lakes National Park (Canada) and Glacier National Park (U.S.), which were designated the Waterton-Glacier International Peace Park in 1932. The Bob Marshall Wilderness Complex, extensive national, state, and provincial forest lands, and the Blackfeet Indian Reservation surround the national parks to form a relatively unaltered landscape when contrasted to other areas of western North America. The CCE is a snow-dominated region with over 70% of the annual precipitation falling as snow at higher elevations, which remain snow-free for as little as six weeks in late summer. The CCE is the headwaters for its region. Elevations range from 800 m in valley bottoms to 3200 m peaks comprised of sedimentary rock up to 1.3 billion years old. The mountain topography was extensively reshaped by glaciation. Expansive conifer forests cover approximately 75% of the area. This region contains relatively intact floral and faunal assemblages. Species distribution and abundance vary along elevational gradients (extending to alpine vegetation) and from west to east (including grassland). Climate is controlled by dominant air masses with areas west of the Continental Divide receiving a stronger maritime influence from the Pacific Ocean and areas east of the Divide having a distinctly more continental climate. Precipitation varies dramatically between high elevation sites located near the Divide and lower elevation sites along the plains near the eastern edges of the region. For example, precipitation varies from 350 cm/yr (west side, high elevation) to 40 cm/year (east side, low elevation). Other factors, including dessicating east side winds, can enhance smaller differences in precipitation regimes between the east and west sides. This contrast in precipitation and other climatic factors over relatively small distances has a profound impact on microclimate, vegetation distribution and disturbance regimes (Peterson et al. 1997).

DATA AND METHODS

The data analyzed in this study were drawn primarily from two distinct but related snow sampling networks, both created and maintained by the Natural Resources Conservation Service (NRCS). Both the snow course survey network and the more recent SNOTEL network were designed to monitor the water equivalence of mountain snowpacks, which typically provide the majority of available water in the western United States. Both networks contain a large number of sampling points located throughout the mountains of the western states and Alaska.

The NRCS snow course network includes some snow courses that date back to the early part of the 20th century. A large number of snow courses in the network have been monitored since the 1940's. Snow courses generally consist of a line of points in an open, sheltered area below treeline. Depth and SWE are measured at each point. The average values for these points are then archived as the representative depth and SWE measurements for the snow course. Surveys are conducted on or about the first of each month between January and May, although generally only a few priority sites are surveyed for all of these months. More data are available from April 1 snow surveys than from any other month.

NRCS maintains 34 snow courses in the CCE. These are supplemented by 12 similar snow courses in the Provinces of British Columbia and Alberta maintained by the provincial governments. Twenty-one of these 46 snow courses were selected based on the availability of a continuous or near-continuous time series of April 1 measurements between 1950 and 2001. Twenty of these snow courses are located in Montana; the remaining snow course is located near Fernie, British Columbia. Measurements from the period 1950-2001 for these 21 snow courses will be referred to as the April 1 snow course dataset. Three additional snow courses, each with 80 years of continuous May 1 measurements, were selected to provide a longer but limited dataset. All three of these snow courses are located in the Many Glacier Drainage of Glacier National Park and are conducted jointly by water supply forecasters in Montana and Alberta. Measurements from the period 1922-2001 for these 3 snow courses will be referred to as the May 1 snow course dataset.

The NRCS SNOTEL network provides daily measurements of SWE, and more recently, other climate parameters including precipitation and temperature. SNOTEL data allow for a detailed examination of the seasonal evolution of the snowpack. Like snow courses, SNOTEL stations are generally located in sheltered, open areas below treeline. SNOTEL stations utilize pillows filled with solution and a transducer that converts pressure from the weight of accumulated snow on the pillow into SWE measurements. In recent years, SNOTEL stations have been equipped to measure precipitation and temperature as well. The majority of SNOTEL stations do not currently measure snow depth.

Nineteen SNOTEL stations are located in the Montana portion of the CCE. Nine stations with SWE records extending back to water year 1977 or before were selected to provide daily SWE measurements to augment the monthly snow course survey measurements. In addition, these stations each contain at least 20 years of precipitation measurements and 10 years of temperature measurements, allowing for a limited analysis of the effects of precipitation and temperature on the evolution of seasonal snowpacks.

A small number of missing SWE values in the April 1 snow survey dataset were estimated to allow for the inclusion of four sites that would have otherwise been excluded from a time series analysis. These values were calculated based on correlations with values at nearby sites for more than 50 years of data. Three sites required the calculation of 1 missing value and 1 site required the calculation of 2 missing values.

All of the selected SNOTEL stations and all of the snow courses in the April 1 dataset were divided into subgroups based on elevation, relationship to the continental divide, and whether north or south of the Marias Pass/Route 2 corridor. These classifications were designed to facilitate analysis regarding the spatial distribution of snowpack and the spatial dimensions of changes in snowpack. The elevation classification criteria (Table 1) were designed to classify an approximately equal amount of sites in each category, and consequently they differ for SNOTEL and snow courses. After SNOTEL data indicated strong similarities between snowpacks in the high elevation and mid elevation categories, the mid elevation category was not included in the classification of snow courses.

Table 1: Elevation classification scheme for SNOTEL and snow course sites.

	SNOTEL	Snow Course
Low Elevation	< 1600 m	< 1650 m
Mid Elevation	1600-1900 m	
High Elevation	> 1900 m	> 1650 m

SNOTEL and snow course data for the period 1922-1999 were obtained from the NRCS anonymous ftp server, ftp.wcc.nrcs.usda.gov. Snow course and SNOTEL data for water years 2000 and 2001 were obtained via a remote connection to the NRCS Western Climate Center Centralized Forecast System Database.

The PDO is a pattern of Pacific Ocean climate variability driven by sea surface temperature anomalies, similar to the El Nino Southern Oscillation but played out over a much longer time period (Zhang et al. 1997). The PDO index is defined as the first principal component of North Pacific (greater than 20°N) monthly sea surface temperature variability (Mantua et al. 1997). Monthly indices for the PDO were obtained from the University of Washington's Joint Institute for the Study of Atmosphere and Ocean at ftp.atmos.washington.edu.

RESULTS

CCE Snow Database

All standard snow course records for the defined CCE were compiled and merged into a single database consisting of 6543 individual SWE measurements from 46 snow courses. April 1 SWE measurements from 21 of these snow courses met the 50 year minimum criterion for inclusion in the analysis dataset. Three additional sites with 80 year records were included as a second analysis dataset. Nine SNOTEL sites with 25 years or more of SWE measurements were identified and included as a third analysis dataset. SWE, temperature, and precipitation data from these nine sites were also merged into a single database.

Spatial Variations in the Seasonal Distribution of Daily SWE

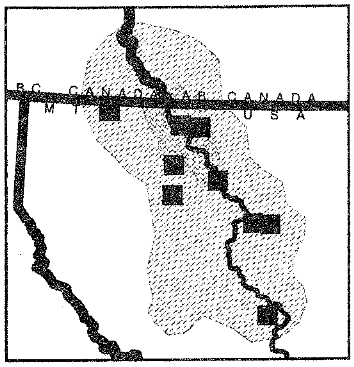
Data from the 9 SNOTEL sites with 25-year SWE records provide an indication of the typical evolution of seasonal snowpacks in the CCE and reveal differences between accumulation-ablation patterns across spatial and elevation gradients (Figure 2). The accumulation-ablation curve incorporating data from all 9 SNOTEL sites indicates a mean annual maximum of 60.6 cm of SWE on April 13. Mid and high elevation snowpacks tended to develop similarly and typically contained more than twice the water equivalent of lower elevation snowpacks. Relationship to the Continental Divide is also indicated as a key factor in snowpack accumulation and ablation, with sites west of the divide exhibiting higher peak SWE and longer persistence. Latitude appears to be a less important factor in determining snow accumulation and ablation in the CCE, with sites in the northern half of the region exhibiting slightly higher peak SWE and slightly longer persistence than sites in the southern half of the region.

Precipitation and Temperature as Drivers of SWE

At wind-sheltered SNOTEL sites and snow courses, precipitation, temperature, and solar radiation are assumed to be the primary drivers of measured snow accumulation and ablation. April 1 water-year-to-date precipitation in the CCE is highly correlated with April 1 SWE, with an overall correlation coefficient of 0.898 and subset values ranging from 0.6 to 0.972 (Table 2). April 1 water-year-to-date precipitation is better correlated with SWE at higher elevation sites and sites to the west of the Continental Divide. October-March temperature averages are not as strongly correlated with April 1 SWE (Table 3). Most temperature data subsets, composed of a limited set of observations, are not significantly correlated with SWE.

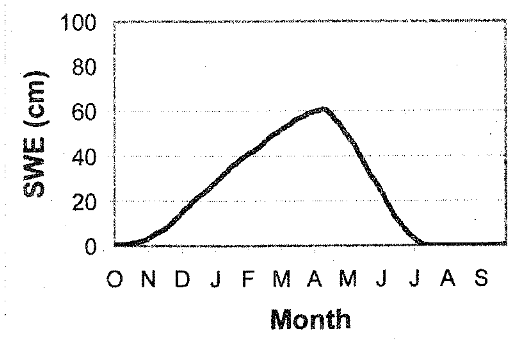
Table 2: Relationship between April 1 water-year-to-date precipitation and April 1 snow water equivalent.

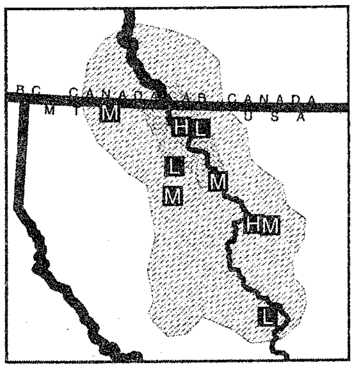
	CORRELATION COEFFICIENT	SIGNIFICANCE
SWE vs PRCP, ALL	0.898	0.000
SWE vs PRCP, LOW	0.600	0.000
SWE vs PRCP, MID	0.972	0.000
SWE vs PRCP, HIGH	0.944	0.000
SWE vs PRCP, EAST	0.669	0.000
SWE vs PRCP, WEST	0.955	0.000



All 9 SNOTEL Sites

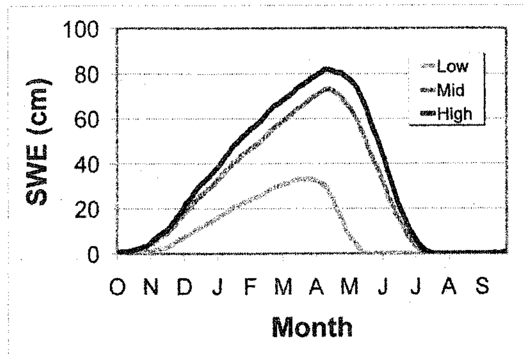
Mean Elevation: 1719 m
Max SWE: 60.6 cm on April 13

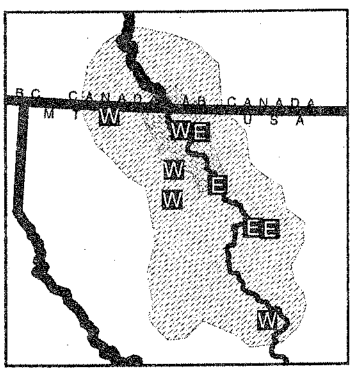




Sites Classed by Elevation

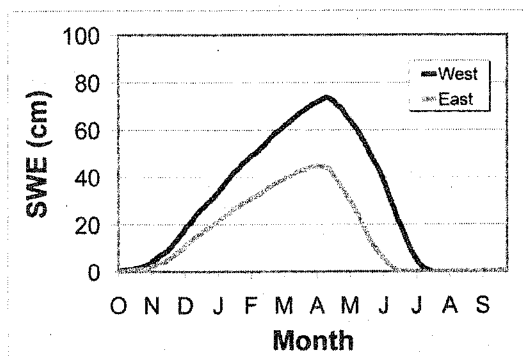
Low Elevation Sites (L)
Mean Elevation: 1468 m
Max SWE: 33.1 cm on March 28
Mid Elevation Sites (M)
Mean Elevation: 1798 m
Max SWE: 73.1 cm on April 16
High Elevation Sites (H)
Mean Elevation: 1935 m
Max SWE: 81.8 cm on April 16

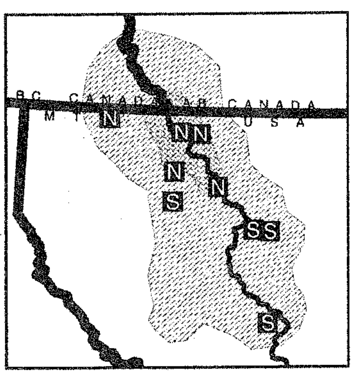




Sites Classed by Relationship to the Contintental Divide

West of Divide Sites (W)
Mean Elevation: 1702 m
Max SWE: 73.6 on April 14
East of Divide Sites (E)
Mean Elevation: 1740
Max SWE: 44.7 on April 3





Sites Classed by Latitude

Northern Sites (N)
Mean Elevation: 1677 m
Max SWE: 66.8 on April 13
Southern Sites (S)
Mean Elevation: 1771
Max SWE: 52.7 on April 12

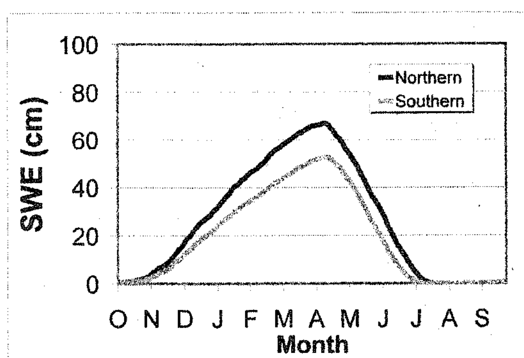


Figure 2: SNOTEL accumulation-ablation curves with site locations.

Table 3: Relationship between October-March temperatures and April 1 snow water equivalent.

	CORRELATION COEFFICIENT	SIGNIFICANCE
SWE vs TAVG, ALL	-0.399	0.000
SWE vs TAVG, LOW	-0.136	0.473
SWE vs TAVG, MID	-0.284	0.076
SWE vs TAVG, HIGH	-0.425	0.061
SWE vs TAVG, EAST	-0.350	0.027
SWE vs TAVG, WEST	-0.368	0.009

SNOTEL vs Snow Course Survey Data

The mean April 1 snow course measurements and mean April 1 SNOTEL measurements are highly correlated ($r = 0.96$). Consequently it is reasonable to assume that CCE seasonal snowpack evolution patterns depicted by SNOTEL data are representative of the seasonal snowpack evolution patterns for snow courses in the region as well.

Temporal Variations in SWE

Interannual variation in April 1 SWE in the CCE averaged 26.8% for all 21 sites and ranged from 24.3% at high elevation sites to 38.1% at low elevation sites (Table 4). Variation was also higher for sites east of the continental divide (36.2%) than for sites west of the continental divide (24.9%). Increased interannual variation generally corresponded with decreased mean April 1 SWE.

Table 4: Means, standard deviations, and coefficients of variation for April 1 snow water equivalent by elevation band and geographic zone.

	Mean	Standard Deviation	Coefficient of Variation
All 21	47.7	12.8	26.8
Low Elevation	30.6	11.7	38.1
High Elevation	58.2	14.2	24.3
East of the Continental Divide	33.2	12.0	36.2
West of the Continental Divide	55.0	13.7	24.9
Northern	53.0	15.0	28.4
Southern	45.6	12.5	27.5

Residuals from the linear regression of the April 1 SWE time series were normally distributed and not significantly autocorrelated, indicating the appropriateness of linear regression for trend analysis. Mean April 1 SWE exhibited a downward trend in the complete 21 site dataset (Figure 3 and Table 5) and all of the data subsets (Table 5).

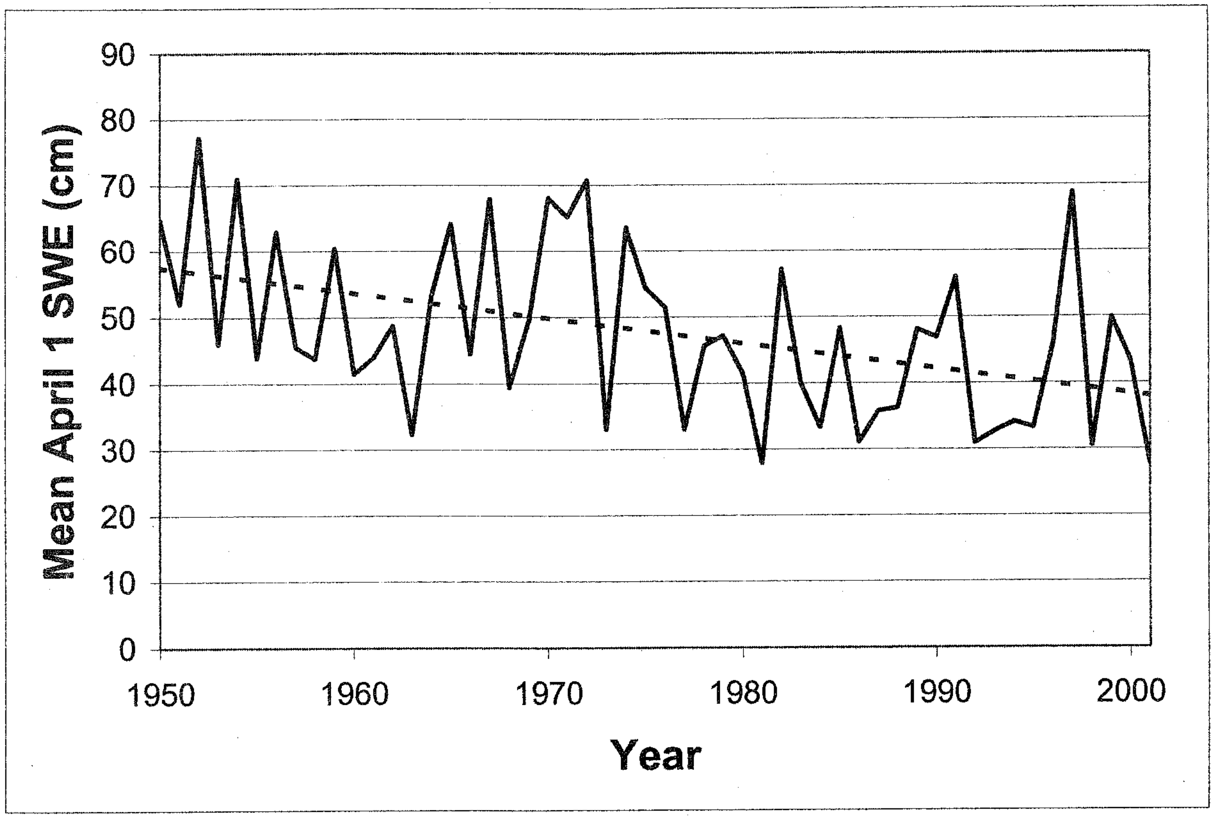


Figure 3: Mean April 1 snow water equivalent at 21 snow courses in the Crown of the Continent region, 1950-2001.

Table 5: Slope, significance, and upper and lower slope confidence intervals for linear trends in April 1 snow water equivalent for different elevation bands and geographic zones.

	Slope	Significance	Lower Confidence Interval	Upper Confidence Interval
All 21 Snow Courses	-0.383	0.001	-0.603	-0.164
Low Elevation	-0.356	0.001	-0.554	-0.157
High Elevation	-0.400	0.002	-0.646	-0.155
East of the Continental Divide	-0.373	0.001	-0.577	-0.168
West of the Continental Divide	-0.389	0.002	-0.626	-0.152
North of Marias Pass	-0.460	0.001	-0.716	-0.205
South of Marias Pass	-0.353	0.002	-0.570	-0.135

Residuals from the regression of mean May 1 SWE values were also normally distributed and not significantly autocorrelated. The linear regression of this 80 year time series had no significant trend in mean May 1 SWE (Figure 4 and Table 6). A linear regression of the May 1 time series excluding the points prior to 1950 did, however, indicate a significant downward trend in mean May 1 SWE (Table 6), similar to trends for the April 1 dataset over the same period.

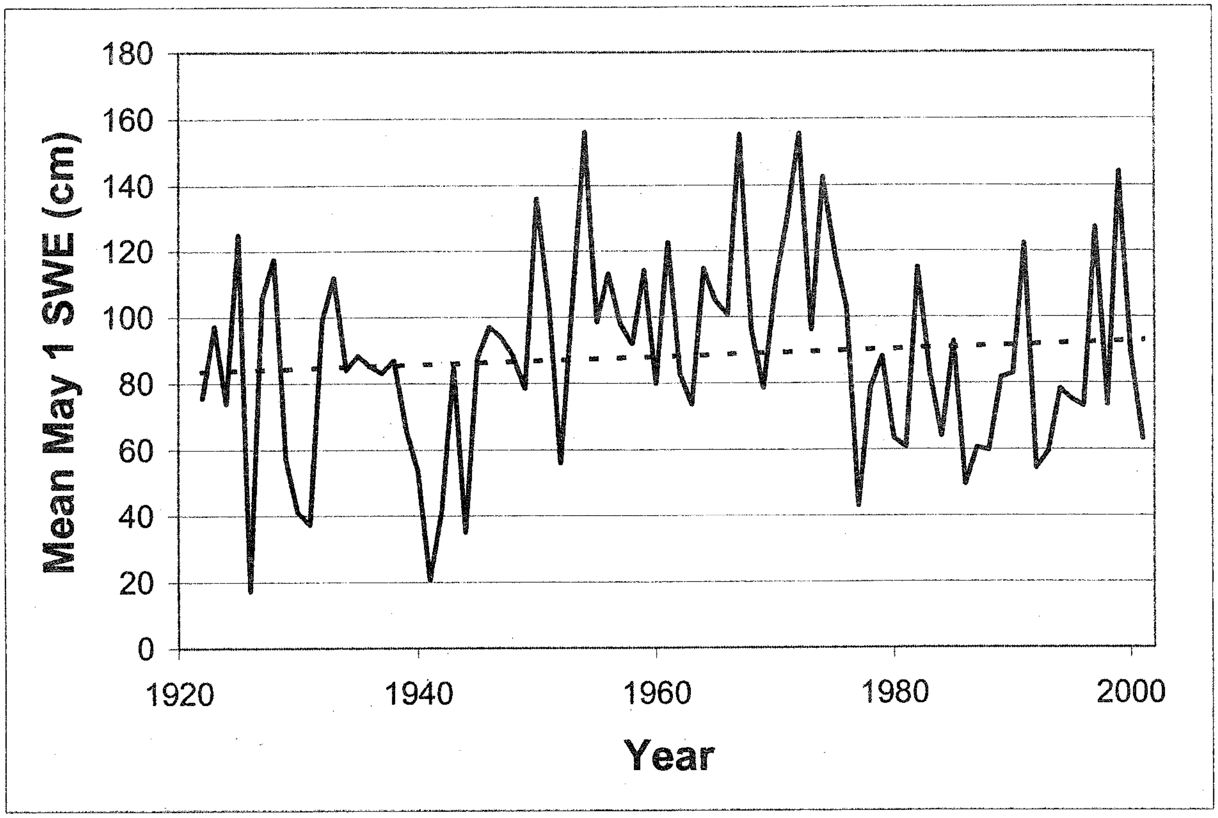


Figure 4: Mean May 1 snow water equivalent at 3 snow courses in the Many Glacier drainage, Glacier National Park, 1922-2001.

Table 6: Slope, significance, and upper and lower slope confidence intervals for linear trends in May 1 snow water equivalent at 3 sites in the Many Glacier Drainage, Glacier National Park.

	Slope	Significance	L. Confidence Interval	U. Confidence Interval
May 1 Data, Many Glacier Drainage, 1922-2001	0.118	0.421	-0.172	0.408
May 1 Data, Many Glacier Drainage, 1950-2001	-.260	.013	-0.462	-0.058

Interannual SWE Variations and the PDO

Standardized indices calculated for April 1 SWE and October-March PDO index values indicate a strong relationship between the PDO and April 1 SWE in the CCE for the period 1950-2001 (Figure 5). Comparing indices for the May 1 SWE time series and October-March PDO indicate that the relationship existed for the period 1922-2001 as well (Figure 5). The average of the October-March PDO index explains 26.7% of the variability in mean May 1 SWE values from 1922-2001. However, the explanatory ability of the October-March PDO index increases to 61.9% when the 5 year moving averages for October-March PDO and May 1 SWE are compared. In a similar fashion, the October-March PDO index can explain 28.4% of the variability in April 1 SWE measurements for the period 1950-2001, while using moving average values increases the explanatory ability to 70.4%.

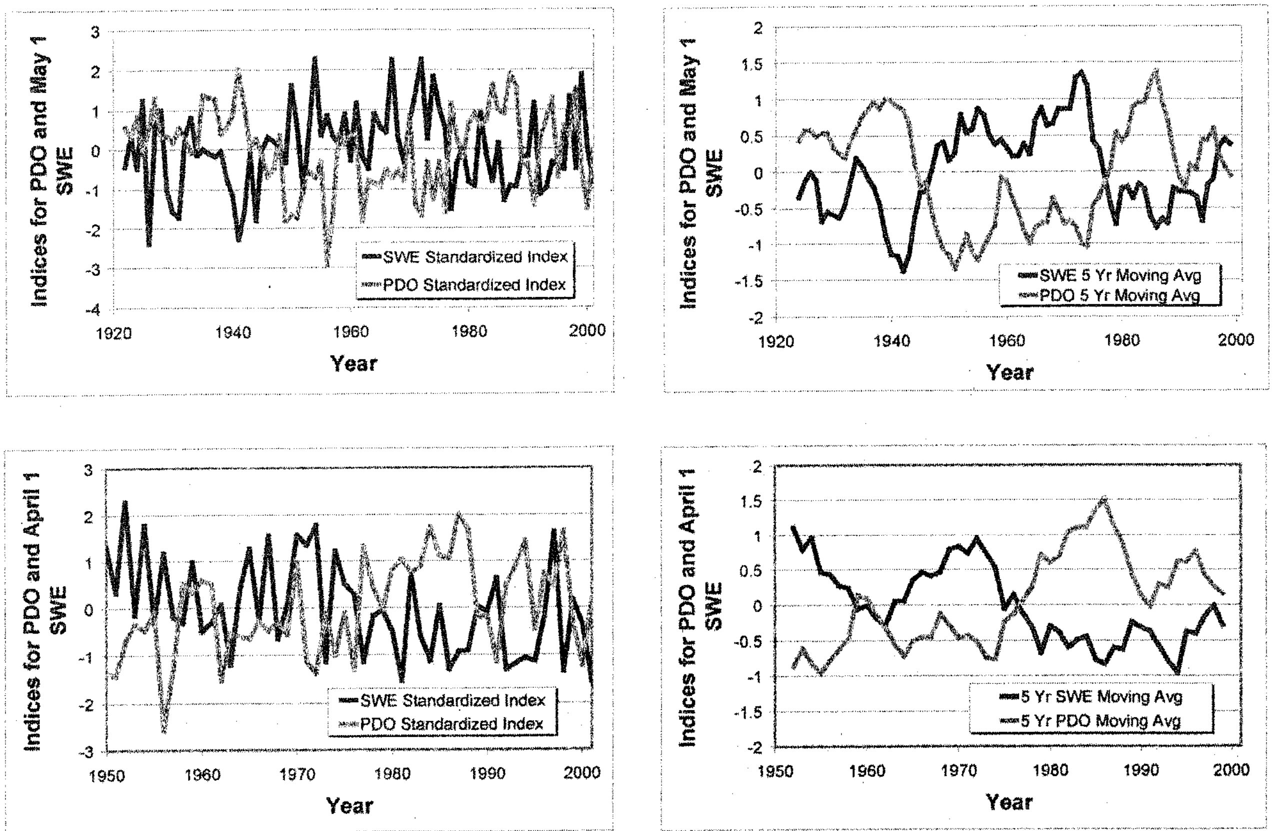


Figure 5: October-March Pacific Decadal Oscillation indices and April 1 and May 1 mean SWE. The strength of the relationship between PDO and SWE is far more apparent when 5 year moving averages for SWE and October-March PDO indices are considered.

DISCUSSION

Prior to discussing spatial patterns of snowpack accumulation and ablation or interannual variations in snowpack in the CCE, it is useful to compare the CCE snowpack with other snowpacks across the western United States. Serreze et al. (1999) summarized the basic patterns of snow accumulation and ablation at SNOTEL sites in 8 regions they define in the western U.S. The accumulation-ablation pattern for the CCE is similar to the pattern they found for the Idaho/Western Montana region, with mean maximum SWE in the CCE slightly higher and occurring one day later than mean maximum SWE in Idaho/Western Montana. Both mean maximum SWE and snowpack persistence are greater in the CCE than in all regions defined by Serreze et al. (1999), with the exception of the Sierra Nevada and Pacific Northwest.

As expected, higher elevation SNOTEL sites have larger, more persistent snowpacks in the CCE. The similarity between the accumulation-ablation patterns for mid and high elevation sites probably reflects the small difference in mean site elevations between the two categories and the small sample size for each category. Consequently, this similarity should not be interpreted as an indication that high elevation snowpacks are very similar to mid elevation snowpacks in the region. It is also worth noting that true high elevation snowpacks are not included in this analysis, as all SNOTEL stations and snow courses in this study are located below treeline.

The indication that snowpacks at sites to the west of the Continental Divide tend to be larger than snowpacks at sites to the east of the Divide is not surprising but does merit some consideration. A precipitation gradient decreasing from west to east could be hypothesized to explain this difference, but Finklin (1986) indicates that, at least for the Waterton-Glacier International Peace Park, precipitation appears to be approximately equal on both sides of the Divide and that major decreases in precipitation only occur along the far eastern edges of the region. Mean April 1 water-year-to-date precipitation values do indicate more precipitation at sites west of the Divide (81.7 cm) than at sites east of the Divide (63.8 cm), but this relatively small difference is insufficient to explain the larger difference in mean maximum SWE between west side sites (73.6 cm) and east side sites (44.7 cm). The unexplained difference is most likely the result of the effects of temperature, wind, and humidity. In particular, periodic warm Chinook winds that race downslope on the east side of the Divide may be responsible for rapid snowmelt at times when snowpacks to the west of the Divide remain stable.

The relationships between April 1 water-year-to-date precipitation and April 1 SWE and October-March mean temperatures and April 1 SWE demonstrate that, as previously indicated for the interior Northwest by Cayan (1995) and Serreze et al. (1999), precipitation is the dominant control of April 1 SWE in the CCE. October-March mean temperatures are much less important and, surprisingly, appear to have a more significant influence on April 1 SWE at higher elevations. The limited datasets for each elevation band (10 years of data for 2-4 sites per band) prohibit the formulation of any strong conclusions based on these results. Further research into the relationship between mean winter temperatures and April 1 SWE in the CCE is necessary.

Based on April 1 data from 21 snow courses, interannual variation in snowpack is high throughout the CCE, averaging 26.8%. It appears to be most variable at low elevation snow courses and snow courses east of the Continental Divide. Snow courses at low elevations and to the east of the Divide also have the lowest mean April 1 SWE values. This has important ecological implications, since vegetation in low elevation areas and areas to the east of the Continental Divide are commonly limited by moisture availability. Higher variability at lower elevation sites also suggests that orographic precipitation in the CCE is a more consistent source of snowfall than frontal precipitation.

The statistically significant negative trend in April 1 SWE between 1950 and 2001 is most likely the result of positioning of PDO phases (negative PDO from 1947 to 1977, positive PDO from 1977 to the present) and does not necessarily stand as evidence of a climate change related decrease in April 1 SWE in the CCE. This is supported by the lack of any statistically significant trend in mean May 1 SWE for the 3 snow courses in the Many Glacier Basin that incorporate more PDO cycles. Nevertheless, this 52 year downward trend in April 1 SWE still has important implications for physical and ecological systems in the region, affecting the timing and magnitude of runoff, thermal variability in streams, and growth patterns of alpine plants. Another climate change hypothesis suggests that negative trends in April 1 SWE may be more significant for lower elevation sites, where snowpacks are more sensitive to slight increases in temperature. The data do not indicate that this is the case either, as both high elevation and low elevation sites exhibit very similar negative trends and significance levels for the period 1950-2001. Finally, ecosystem modeling, under a variety of climate change scenarios, suggests areas to the east of the Continental Divide will begin to dry out while areas to the west of the Divide remain more stable (White et al. 1998). At least in terms of April 1 SWE, however, that at least in terms of April 1 SWE, trends have been similar on both sides of the Divide.

Despite the positive, statistically nonsignificant trend in mean May 1 SWE at the three sites in the Many Glacier drainage (all located near major glaciers), glaciers in and around Glacier National Park have continued to recede steadily (Key et al., in press). Clearly, stability in winter snowpacks over the period 1922-2001 does not counteract overall climatic conditions in the CCE that are no longer conducive to maintenance of positive glacier mass balances. This implies that a reduction in CCE snowpacks could have occurred between ca 1850, when area glaciers were at their Little Ice Age maxima, and 1922, the beginning of the May 1 snow course period of record. Because no snowpack records exist for that period, we cannot determine if such a shift in the snow regime occurred, but this is also the period when tree establishment above Little Ice Age treeline is first recorded (Bekker et al. 2000). Peterson (1998) has shown that high elevation tree establishment patterns are related to variations in snowpack.

The relationship between PDO and snowpack has been suggested previously, most recently by McCabe and Dettinger (2002). They found that April 1 snowpack variation is more strongly linked to the PDO at snow courses in the Northwestern U.S. and Southwestern Canada than anywhere else. The fact that April 1 SWE variation is much more closely related to 5 year averages of October-March PDO indices than to single year PDO indices emphasizes the importance of the PDO phase over the specific strength of the signal for one year. Because PDO is generally slow to evolve (McCabe and Dettinger 2002), and follows a somewhat regular cycle, it can potentially explain past changes in physical and biological systems of the CCE as well as improve models of these same systems in the future.

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