Modeling and Measuring Snow for Assessing Climate Change Impacts in Glacier National Park, Montana

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Abstract: A 12-year program of global change research at Glacier National Park by the U.S. Geological Survey and numerous collaborators has made progress in quantifying the role of snow as a driver of mountain ecosystem processes. Spatially extensive snow surveys during the annual accumulation/ablation cycle covered two mountain watersheds and approximately 1,000 km^2. Over 7,000 snow depth and snow water equivalent (SWE) measurements have been made through spring 2002. These augment two SNOTEL sites, 9 NRCS snow courses, and approximately 150 snow pit analyses. Snow data were used to establish spatially-explicit interannual variability in snowpack SWE. East of the Continental Divide, snowpack SWE was lower but also less variable than west of the Divide. Analysis of snowpacks suggest downward trends in SWE, a reduction in snow cover duration, and earlier melt-out dates during the past 52 years. Concurrently, high elevation forests and treelines have responded with increased growth. However, the 80 year record of snow from 3 NRCS snow courses reflects a strong influence from the Pacific Decadal Oscillation, resulting in 20-30 year phases of greater or lesser mean SWE. Coupled with the fine-resolution spatial snow data from the two watersheds, the ecological consequences of changes in snowpack can be empirically assessed at a habitat patch scale. This will be required because snow distribution models have had varied success in simulating snowpack accumulation/ablation dynamics in these mountain watersheds, ranging from R^2=0.38 for individual south-facing forested snow survey routes to R^2=0.95 when aggregated to the watershed scale. Key ecological responses to snowpack changes occur below the watershed scale, such as snow-mediated expansion of forest into subalpine meadows, making continued spatially-explicit snow surveys a necessity.

Keywords: snow depth, snow water equivalent, variability, Pacific Decadal Oscillation, modeling

1. Introduction

Mountain environments are particularly difficult to understand and model because their strong environmental gradients and complex topography interact with climate variability at multiple scales. Snow is a dominant driver of many mountain ecosystem processes, determining forest growth, basin hydrology and glacier dynamics in many temperate mountain ranges. A 12-year research program in the Northern Rocky Mountains, USA, has focused on how mountain ecosystem processes in Glacier National Park, Montana have responded to changes in climate patterns. Modeling and monitoring spatial and temporal variability in seasonal snowpacks has been critical to our understanding of those responses. We have conducted intensive snow surveys across the Glacier Park landscape since 1993 to augment long-term historical records from a small number of sites.

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Currently, we have 7,224 measurements of snow water equivalence (SWE) and snow depth across 1,000 km^2 within Glacier Park for the past 9 years. Additionally, we have data from more than 150 snowpits, and 4 years of snow chemistry analyses. Because some of the oldest Natural Resource Conservation Service (NRCS) snow courses (dating back to 1922) and SNOTEL sites (dating back to 1969) are located in our study area, our spatially extensive snow datasets complement the single site snow records from SNOTEL installations and NRCS snow courses. Together, these provide a robust spatial and temporal snow database with which to examine trends and variability in snow characteristics. In this paper we summarize snow studies and present new data on spatial variability of snow in mountain watersheds along the Continental Divide.

2. Study Area

Glacier National Park is located in the northwestern part of Montana along the U.S.-Canada border and straddles the Continental Divide (Figure 1). It encompasses 4, 080 km^2 of mountain wilderness in a largely undisturbed state. Along with its sister park, Waterton Lakes National Park (Canada), Glacier National

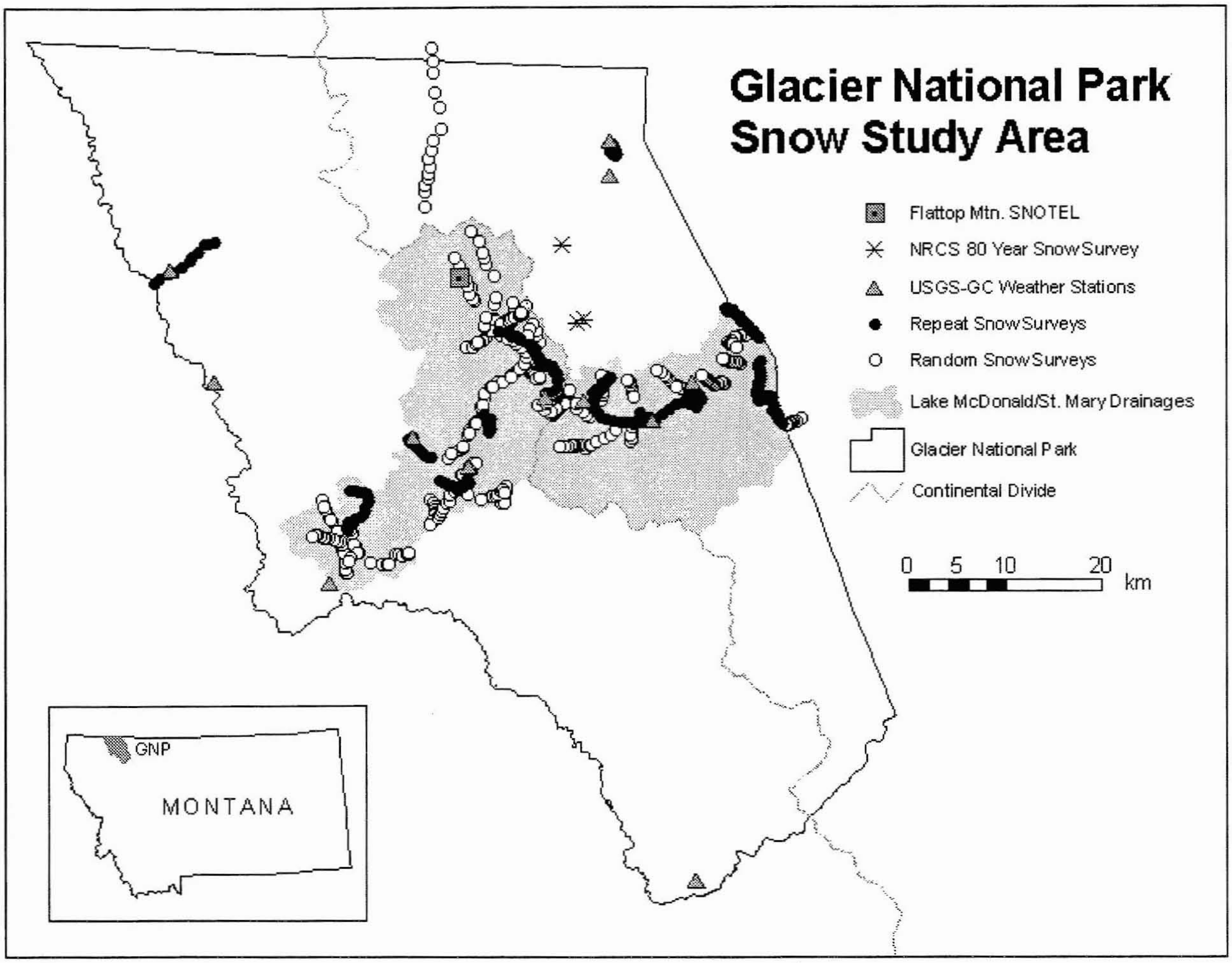

Figure 1: Snow data sources in Glacier National Park, including snow surveys, high elevation weather stations, and SNOTEL sites.

Park was designated part of the Waterton-Glacier International Peace Park in 1932. The U.S. Forest Service Bob Marshall Wilderness Complex, extensive national, state, and provincial forest lands, and the Blackfeet Indian Reservation surround these national parks to form a relatively unaltered landscape when contrasted with other areas of western North America. Glacier Park is a snow-dominated landscape 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. 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. 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. The Lake McDonald and St. Mary watersheds were the focus of more intensive snow surveys and continue to be monitored monthly. Each watershed is approximately 440 km^2 and contains a large lake.

3. Temporal Analyses

Annual SWE measurements from NRCS snow courses on April 1 and May 1 approximate the maximum snowpack accumulation for a mountain watershed for use in water supply forecasting. Selkowitz et al. (in

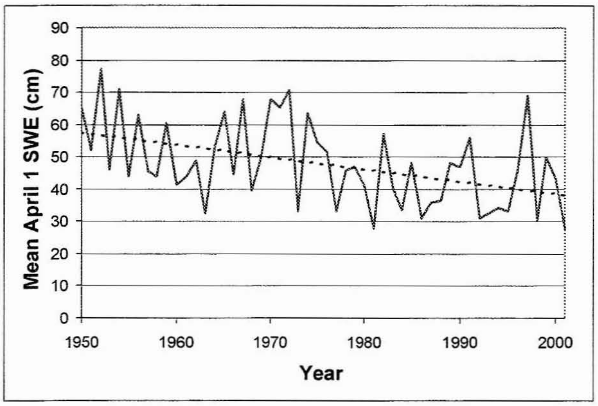

Figure 2: Mean April 1 SWE at 21 snow courses in the Crown of the Continent Ecosystem, 1950-2001.

press) compiled all available records for Glacier Park and the surrounding region, deriving 21 snow course datasets that were complete for 52 years. A statistically significant decline ($p=0.001$) in April 1 mean SWE for snow courses was evident from 1950 – 2001 (Figure 2). The drop in mean annual SWE for all snow courses was from approximately 58 cm in 1950 to 39 cm in 2001, a 33% decrease. During this same period, annual precipitation in the region increased slightly. This indicated a reduction in the snow-to-rain ratio, making Glacier Park and environs less snow-dominated than during the mid 1900s. A reduced snowpack means significant changes for mountain ecosystems and, indeed, several elements of the Glacier Park landscape changed during the same 52-year period of diminishing SWE. Glaciers require enough snow to offset summer ablation. Most glaciers continued to shrink in area and mass throughout the park (Key et al., in press). Grinnell Glacier, for example, lost 0.17 km^2 between 1993 and 2001.

The timing of snowmelt also is important. Along with less SWE accumulation is a shift toward earlier melt out dates for SNOTEL sites in Glacier Park and the surrounding region (Figure 3). This influences rates of invasion of young conifers into subalpine meadows and tree establishment at treeline (Peterson 1998). Alpine and subalpine meadows and alpine tundra in Glacier Park have had noteworthy increases in tree establishment, tree growth, and density (Bekker et al. 2000, Butler and DeChano 2001, Klasner and Fagre 2002) as reduced snowpacks have lengthened the functional growing season for younger trees . Earlier snowmelt also affects herbaceous plants and soil chemistry, facilitating numerous changes in high elevation portions of Glacier Park.

Three of the NRCS snow courses in Glacier Park were established in 1922 and provided a longer-term perspective on trends in SWE, as measured on May 1. In contrast to the 52-year trend, the 80-year record from these three snow courses did not show the same decline but, instead, a slight increase in SWE when viewed as a linear trend. However, the multi-decadal pattern of SWE for these snow courses was closely tied to fluctuations of the Pacific Decadal Oscillation (PDO) (Figure 4), an index of sea surface temperature anomalies with a 20-30 year cycle (Zhang et al. 1997). McCabe and Dettinger (2002) demonstrated that PDO influences other western snowpacks as well. Thus, the snowpacks of Glacier Park have been significantly influenced by the PDO and can be expected to respond similarly in the future. Because the PDO is likely entering a negative phase, average SWE for the Glacier Park area should increase over the next decade or so, assuming that the relationships of the past 80 years continue. This also suggests that some of the ecosystem responses to declining SWE during the past 52 years will be lessened or even reversed. Thus, some of the tree invasions into subalpine meadows may slow or stop if the PDO-influenced increases in SWE are great enough.

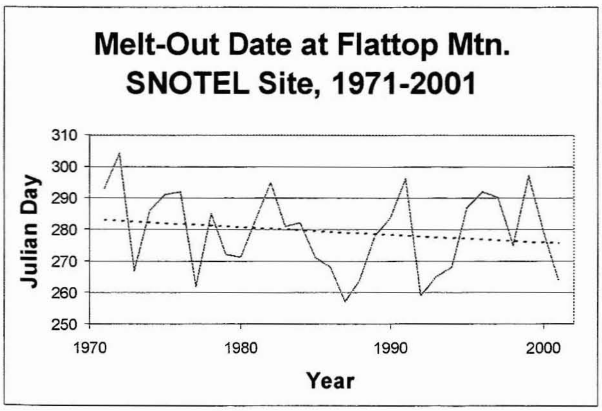

Figure 3: Melt-out date at Flattop Mountain SNOTEL site, 1971- 2001.

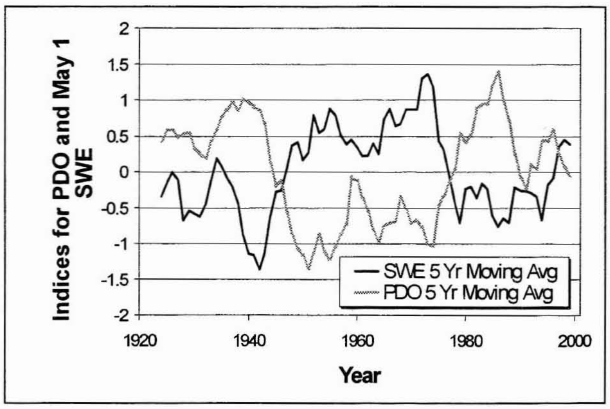

Figure 4: Standardized indices for the Pacific Decadal Oscillation and mean May 1 SWE in the Many Glacier Basin, Glacier National Park.

The interannual variation in Glacier Park SWE determined from snow courses with an annual measurement on April 1 was also examined using SNOTEL data with a shorter record. Daily SNOTEL SWE measurements were plotted to determine the peak annual SWE for each of 30 years and contrasted to April 1 snow course measurements. The peak annual SNOTEL SWE generally occurred later than April 1 and the date varied each year. Nonetheless, a strong correlation was evident between the interannual variation of SNOTEL SWE and snow course SWE on April 1(R = 0.96) (Figure 5). Although the peak annual SWE patterns seem generally well represented by both snow courses and SNOTELs, the intra-annual variation is not. SNOTEL SWE accumulation/ablation curves for each year were examined for the Flattop SNOTEL site (Figure 6). Although most years followed the composite curve there is clearly large variation (65-158%) in SWE between some years during the 31-year record. Large SWE years can act as major disturbance events by generating more frequent and destructive snow avalanches during winter and by suppressing summer alpine plant growth with late season snow cover. Thus, these large SWE years can alter competitive relationships between plants in addition to triggering abiotic disturbances such as debris flows or channel scouring in streams during spring run-off. Of particular note, however, is that the large SWE years have significant late spring snowfall events such as those that occurred during 1972 and 2002. Fagre and Klasner (2000) demonstrated that SWE at Flattop SNOTEL is most variable immediately following the annual average peak accumulation through the end of

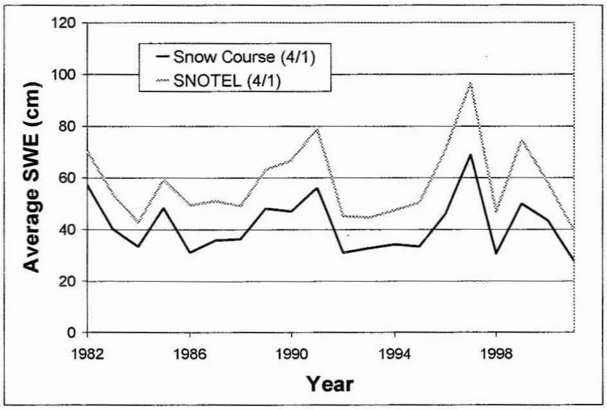

Figure 5: Mean April 1 SWE for 21 snow courses and 9 SNOTEL stations in the Crown of the Continent Ecosystem.

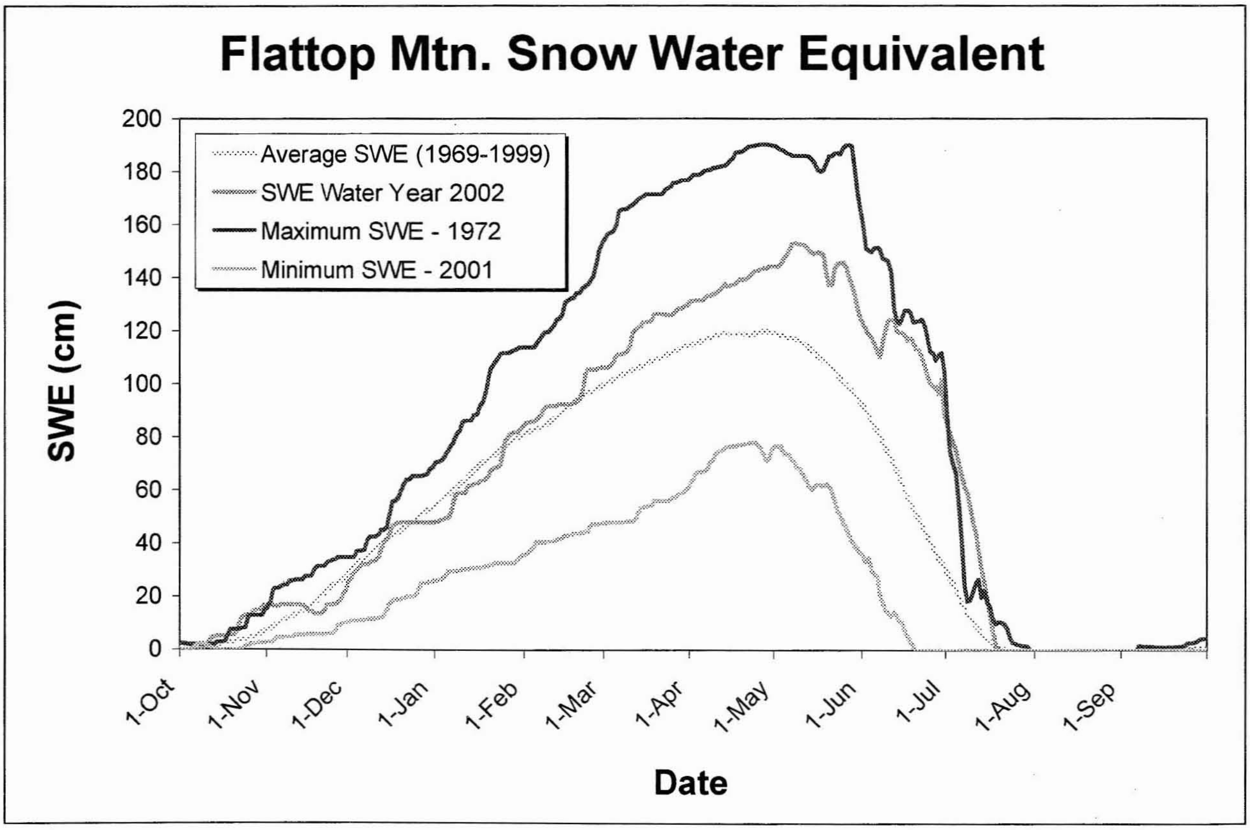

Figure 6: SWE variability in relation to 1969-1999 mean SWE for three water years at Flattop Mountain SNOTEL site.

June. Because seasonal warming has already occurred in Glacier Park, the late spring events significantly impact run-off and have led to flooding and greatly delayed snow removal operations on the Going-to-the-Sun Road (GTSR) that traverses the park over the Continental Divide. In fact, Fagre and Klasner (2000) could account for twice as much variation in GTSR opening dates by including such late spring events in their statistical model. This underscored the dominant role that late spring events play over peak annual snow accumulation in determining snow removal progress from GTSR.

The late spring events of 2002 clearly demonstrate this climatic pattern in Glacier Park and the region. Between April 1 and June 21 snowfall was recorded near the GTSR at Flattop SNOTEL 38 of 81 days (47%), leaving over 270 cm of settled snow on the ground. The two largest storms of the winter occurred on May 22 and beginning on June 8, the latter storm leaving 13.7 cm of SWE. The result is that approximately 32% of the winter snowpack accumulated during the April-June period as opposed to 10% for a typical year. Although the Flattop SNOTEL peak SWE was 127% of the 30-year average (sixth highest since 1970), the significant feature is that it peaked on May 8 and that on June 21 there was still an average peak SWE snowpack in place. Only one year had more snow on June 21 during the past 30 years. Not only did such late snowfall influence park operations such as delaying the GTSR opening, but particularly large magnitude avalanches occurred throughout the park following the June 8 storm.

To place the 2002 snowfall patterns in context, we analyzed the distribution of storms by month for the past 32 years (Figure 7). We defined "storm" as any day with snow accumulation exceeding 5 cm of SWE. For the Flattop SNOTEL area it appears that only December and June tend to have storms more frequently than expected when contrasted to the overall SWE accumulation for the month. As stated earlier, the ecological effects of June storms should be greater as biological activity (e.g. bear emergence) is well underway unlike December when biological activity is at a minimum.

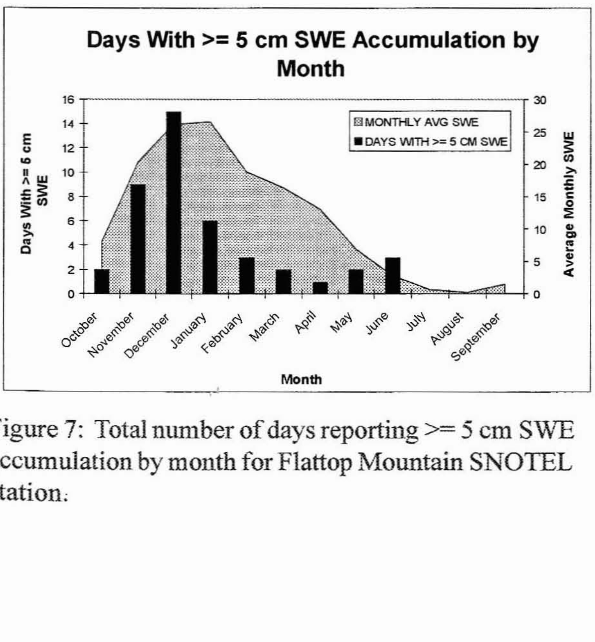

Figure 7: Total number of days reporting >= 5 cm SWE accumulation by month for Flattop Mountain SNOTEL station.

4. Spatial Analyses

To support ecosystem modeling of Glacier Park, snow data were needed for parameterization and validation of simulations. The Regional Hydro-Ecological Simulation System (RHESSys) had estimated the ecological impact of reduced snowpack in northwest Montana (Running and Nemani 1991). This system makes spatially-explicit estimates of snowfall and snowpack accumulation/ablation in mountainous terrain using base station climate data. It provides SWE estimates for the entire basin. It does not characterize wind redistribution of snow within the

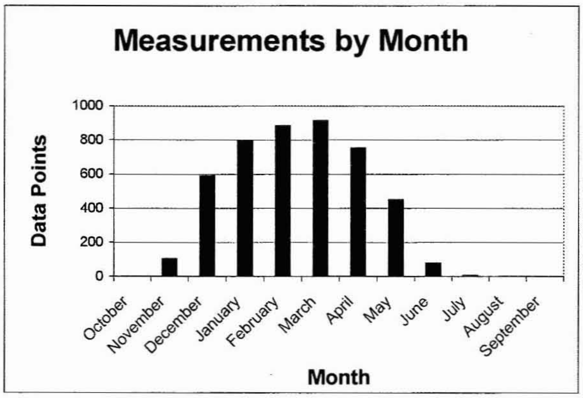

Figure 8: Snow measurements by month for six snow survey routes in the Lake McDonald and St. Mary Drainages, Glacier National Park.

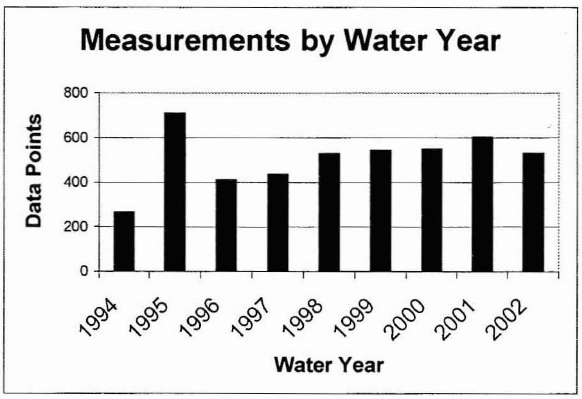

Figure 9: Snow measurements by water year for six snow survey routes in the Lake McDonald and St. Mary Drainages.

basin. Our snow survey routes were established in Lake McDonald watershed and, later, the St. Mary watershed to include all diversity of elevations, slopes and aspects within each basin. Generally, transects started at valley bottom, traversed different forest canopy densities and ended slightly above treeline. Due to avalanche safety concerns and the extensive wind redistribution of snow that occurs above treeline, we did not record snow at ridgetops. The distribution of snow measurements during the winter (Figure 8) is somewhat parallel to the accumulation/ablation curve because the low elevation sites had no snow to measure during the early and late parts of the season. These data provide a spatially-extensive description of seasonal snowpack evolution across the mountain landscape not provided by either the SNOTEL or snow courses. The number of measurements per year (Figure 9) indicates our monthly snow measurements of the 1,000 km^2 study area were fairly consistent during the 9-year period. The 1994 measurements were for the Lake McDonald basin only and the 1995 measurements were at bi-weekly intervals during March-May. Results from the RHESSys simulations using data from 1994-1996 were reported by Fagre et al. (1997) and White et al. (1998). Individual site snow measurements were well-correlated ($R^2 = 0.78$) with model estimates but it was concluded that better estimates of snow sublimation in tree canopies depended upon accurate leaf area index estimates (Fagre et al. 1997). Because LAI was derived from 30 m satellite imagery, further improvements in remote sensing will be necessary to improve snow estimates. However, at the watershed scale, the spatially aggregated SWE were better correlated with observed values ($R^2 = 0.95$)(White et al. 1998) and proved to be accurate enough to predict stream discharge closely (Fagre et al. 1997).

The snow surveys for both Lake McDonald and St. Mary basins were continued through spring of 2002. The SWE measurements for each year in Glacier Park are presented in Figure 10. These annual patterns generally reflect those for Flattop SNOTEL site but demonstrate the degree of variability in SWE across a topographically complex landscape over time. An initial spatial analysis (Figure 11) indicates the degree of variability in SWE for each year between the western and eastern sides of the Continental Divide. The site-to-site variability is greater on the western side that consistently has greater or equal SWE than the eastern side. Even when the western and eastern sides had the same annual average SWE (e.g. 1997 and 2002), the western side was more variable. Climatologically, the eastern side has greater temperature swings and

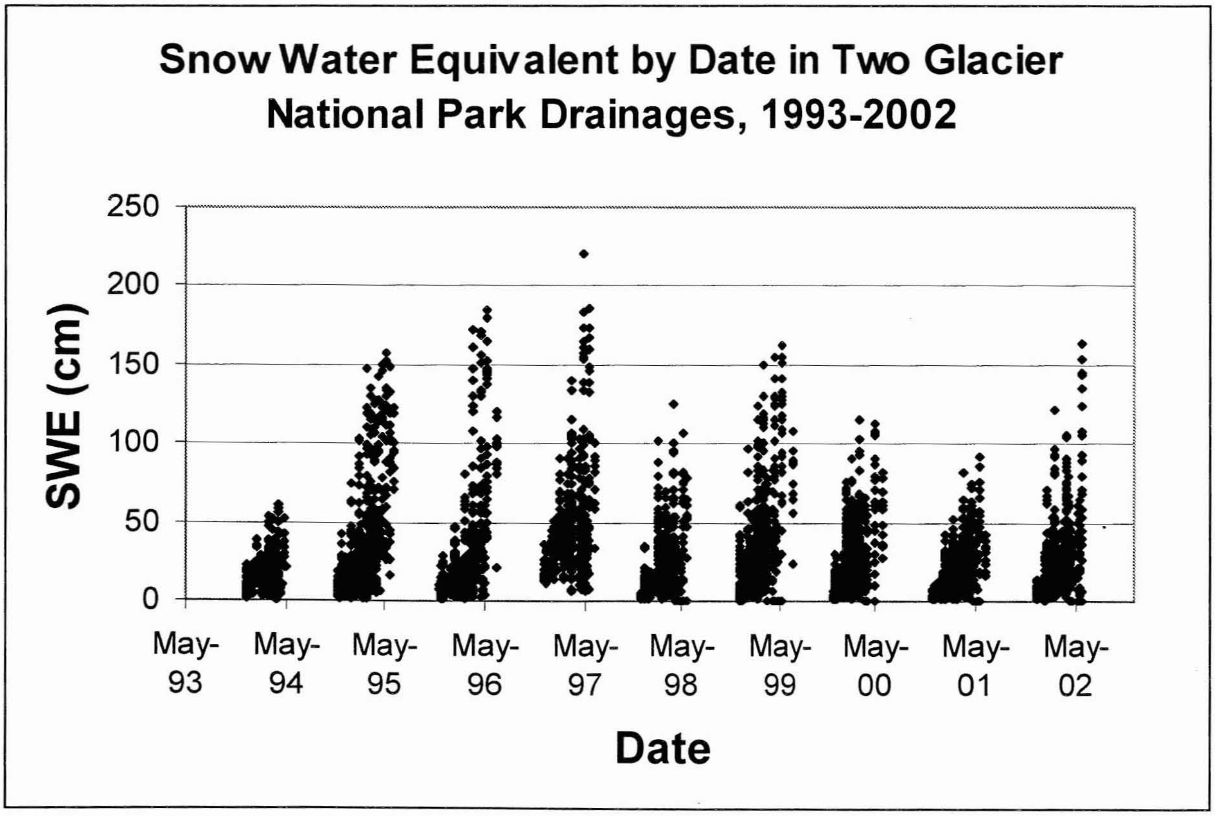

Figure 10: Snow water equivalent by date in the Lake McDonald and St. Mary Drainages, Glacier National Park.

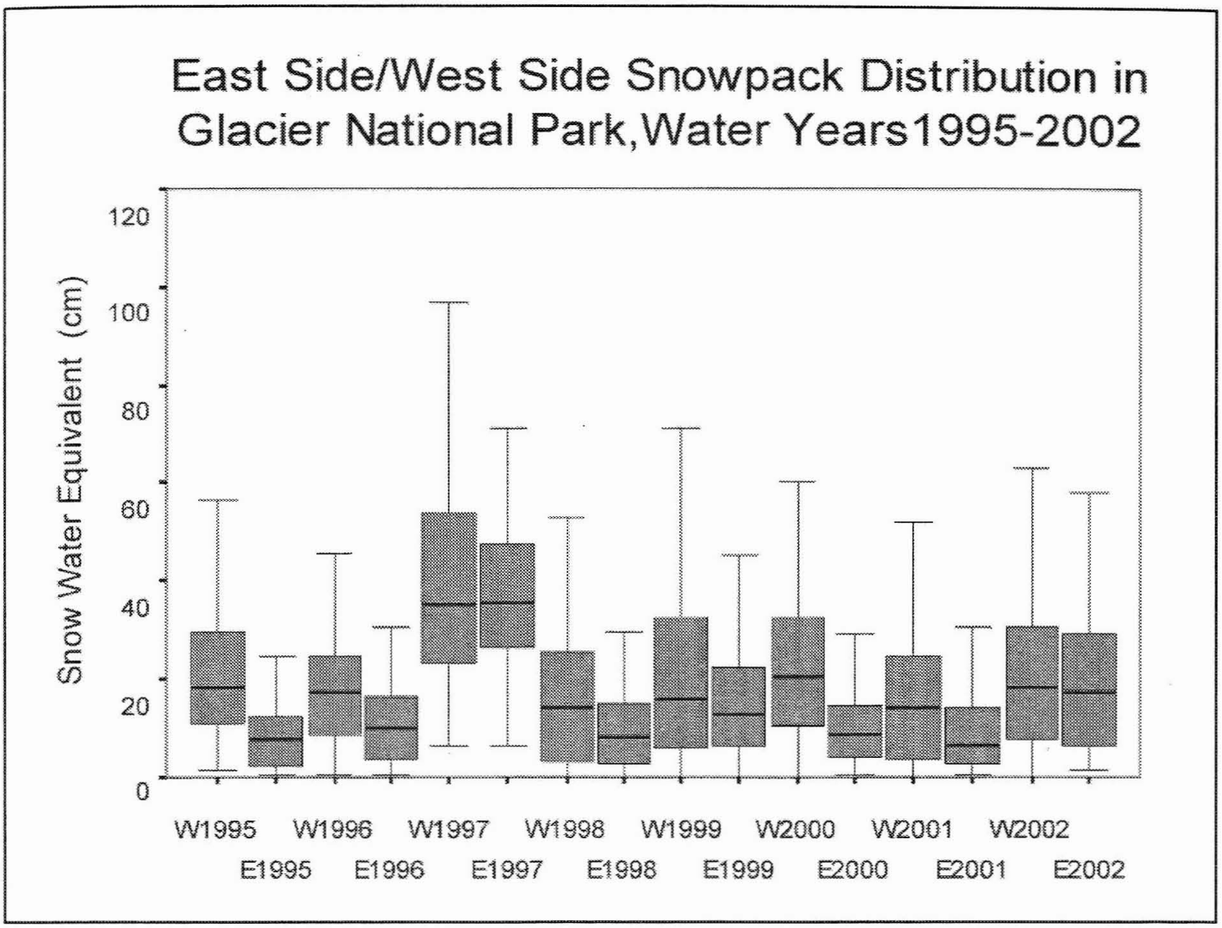

Figure 11: Variability in snow water equivalent for East Side and West Side snow survey measurements, 1993-2002.

generally more wind and would be expected to vary more. Selkowitz et al. (in press) demonstrated that, of 21 snow courses examined, western side snow courses had greater average SWE than eastern side snow courses but that eastern snow courses showed greater variability (36.2% for east; 24.9% for west). Our snow survey sites on the western side, however, may be more variable in canopy density and topographic setting than those on the eastern side. This will be investigated in a future paper.

References

Bekker MF, Alftine KJ, Malanson GP. 2000. Effects of biotic feedback on the rate and pattern of edge migration. *Ecological Society of America, Abstracts* **85:** 247.

Butler DR, DeChano LM. 2001. Environmental change in Glacier National Park, Montana: An assessment through repeat photography from fire lookouts. *Physical Geography* 22:291-304.

Fagre DB, Comanor PL, White JD, Hauer FR, Running SW. 1997. Watershed responses to climate change at Glacier National Park. J American Water Resources Assoc 33:755-765.

Fagre DB, Klasner FL. 2000. Application of snow models to snow removal operations on the Going-to-the-Sun Road, Glacier National Park. Proceedings of the 2000 International Snow Science Workshop, Big Sky, Montana, 266-272.

Finklin AI. 1986. *A climatic handbook for Glacier National Park—with data for Waterton Lakes National Park.* USDA Forest Service, Intermountain Research Station General Technical Report INT-204.

Key CH, Fagre, DB, Menicke RK. In press. Glacier recession in Glacier National Park, Montana. *In*

Satellite Image Atlas of Glaciers of the World, Williams RS, Ferrigno J (eds), U.S. Geological Survey Professional Paper 1386-J, United States Government Printing Office: Washington, D.C.

Klasner FL, Fagre DB. 2002. A half century of change in alpine treeline patterns at Glacier National Park, Montana, U.S.A. *Journal of Arctic, Antarctic and Alpine Research* **34**: 53-61.

McCabe GJ, Dettinger MD. 2002. Primary modes and predictability of year-to-year snowpack variations in the western United States from teleconnections with Pacific Ocean climate. *Journal of Hydrometeorology* **3**: 13-25.

Peterson DL. 1998. Climate, limiting factors, and environmental change in high-altitude forests of western North America. *In The Impacts of Climate Variability on Forests*, Beniston M, Innes JL (eds), Springer, Heidelberg: 191-208.

Running SW, Nemani RR. 1991. Regional hydrologic and carbon balance responses of forests resulting from potential climate change. *Climatic Change* **190**: 214-251.

Selkowitz DJ, Fagre DB, Reardon BA. In press. Interannual variations in snowpack in the Crown of the Continent Ecosystem. Hydrological Processes.

Serreze MC, Clark MP, Armstrong RL, McGinnis DA, Pulwarty RS. 1999. Characteristics of the western United States snowpack from snowpack telemetry (SNOTEL) data. Water Resources Research **35**: 2145-2160.

White JD, Running SW, Thornton PE, Keane RE, Ryan KC, Fagre DB, Key CH. 1998. Assessing simulated ecosystem processes for climate variability research at Glacier National Park, USA. *Ecological Applications* **12**: 805-823

Zhang Y, Wallace JM, Battisti D. 1997. ENSO-like interdecadal variability: 1900-1993. *Journal of Climate* **10**: 1004-1020.