MANAGING WATER RESOURCES FOR CLIMATE VARIABILITY AND CHANGE USING SNOTEL DATA

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ABSTRACT

Seasonal snowpack throughout the West is vulnerable to year-to-year climate variability. SNOTEL observations of daily snow accumulation, snow loss, and air temperature can be exploited to create seasonal forecast products to estimate April 1 SWE and the rate of spring melt. The April 1 SWE forecasts are based on historical observations of late winter snowfall, while the spring melt forecasts are based on anticipated spring temperatures. These forecast products could be useful for managers since they are mathematically simple, provide lead-time for planning purposes, and are delivered in terms of hydrologically-useful variables (such as April 1 SWE) with easy-to-understand estimates of uncertainty. The transparency of the uncertainty information allows users to devise and examine climate-driven "scenarios," which can incorporate their tolerance for risk. These forecast products can also be applied to longer timescales to consider the impact of warming on snow accumulation and melt. (KEYWORDS: SNOTEL, seasonal forecasting, Pacific Northwest, degree-day model, adaptation)

In this paper, forecast products for April 1 SWE and the rate of spring melt are presented for the Skagit watershed in the Washington Cascades. For the seasonal accumulation forecast, a skillful prediction range for April 1 SWE can be generated as early as February 1. Forecasts of spring melt demonstrate that the snowpack of the Skagit is very sensitive to mean temperature, as the melt-out date at SNOTEL stations can advance by approximately a week for a mean springtime temperature 1°C warmer than the long-term mean.

INTRODUCTION

Resource managers across the United States are faced with many challenges as they try to adapt to climate variability and climate change (e.g., National Research Council, 2010; Climate Impacts Group, 2007). These include:

- Determining their resource's sensitivity to climate, which is typically translated into a relationship between resource abundance or quality and temperature or precipitation[1].
- Generating relevant uncertainty information that can be used to assign probabilities to potentially important resource outcomes (e.g., estimating the chance for a best case scenario, worst case scenario, or median scenario).
- Creating tools that can be incorporated into established decision-making calendars (i.e., information must be available with a sufficient lead-time).

This paper focuses on how water managers can use data from local SNOTEL stations to face some of these challenges. Water managers are well-suited to engage in adaptation decision-making since these same types of challenges also underlie routine seasonal planning decisions, which require information about the sensitivity of water supplies to climate and the proper use of uncertainty information.

[1] Other climate-related variables could be also important, such as incoming solar radiation, wind speed, wind direction, relative local sea level, or soil moisture. However, the bulk of currently available information regarding past climate and climate change is in terms of temperature and precipitation. In addition, several of these climate-variables (e.g., soil moisture) can be related to temperature and precipitation.

Paper presented Western Snow Conference 2010
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The analyses presented here focus on the operations of Seattle City Light (SCL) in the Skagit River watershed. Following a brief description of SCL's infrastructure along the Skagit, the methodology for converting SNOTEL records into indices for daily snow accumulation and snow loss is described. These indices are used as the statistical and dynamic bases of seasonal prediction tools for estimating April 1 snow water equivalent (SWE) and the rate of spring melt-out. The paper concludes with a brief discussion of applying the melt tool to longer-term decisions that take into account warming likely to occur in the coming decades.

SEATTLE CITY LIGHT AND THE SKAGIT RIVER WATERSHED

Seattle City Light is a public utility that serves approximately 750,000 customers within the Seattle metropolitan area. Hydroelectricity accounts for over 90% of the electricity that SCL provides to its customers (fuel mix for 2007; Seattle City Light, 2008), with the remainder coming from a mix of nuclear, wind, coal, natural gas, biomass, and petroleum. In a typical year, nearly half of this hydroelectricity is generated from SCL-owned dams, while the other half is purchased from the Bonneville Power Administration, the federal agency that markets the power produced by dams along the Columbia River, and from other entities operating dams in the North American West. Of the electricity generated by SCL-owned hydroelectric projects, almost 60% is generated by the Boundary Dam, located along the Pend Oreille River in northeastern Washington, and nearly 40% by the dams that are located along the Skagit River in northwestern Washington (Figure 1).

Although a large portion of SCL's generating capacity resides at Boundary Dam on the Pend Oreille River, SCL has more management flexibility in operating its Skagit project, making it a better location to study. The Pend Oreille River has four other dams located along it, each operated by different interests. The Pend Oreille flows through Idaho, Washington, and British Columbia, ultimately feeding into the Columbia River in southern British Columbia. Thus, SCL's ability to make decisions regarding the flow of the Pend Oreille is constrained by the operators of upstream dams, as well as by many regulations (local, state, federal, and provincial), water users, and dam operators located downstream along the Columbia River Basin. In contrast, the only other large hydropower project in the Skagit watershed is located on the Baker River (owned by Puget Sound Energy). Since the Baker River is a separate tributary and located downstream of SCL's dams (see Figure 1), the operations of the two hydroelectric projects can be considered nearly independent of each other. Additionally, there are fewer water users and diversions of the Skagit River in comparison the Columbia River. SCL has worked cooperatively with many of these users. Its involvement in the Skagit Climate Consortium also indicates its desire for including stakeholders when making climate and water management decisions.

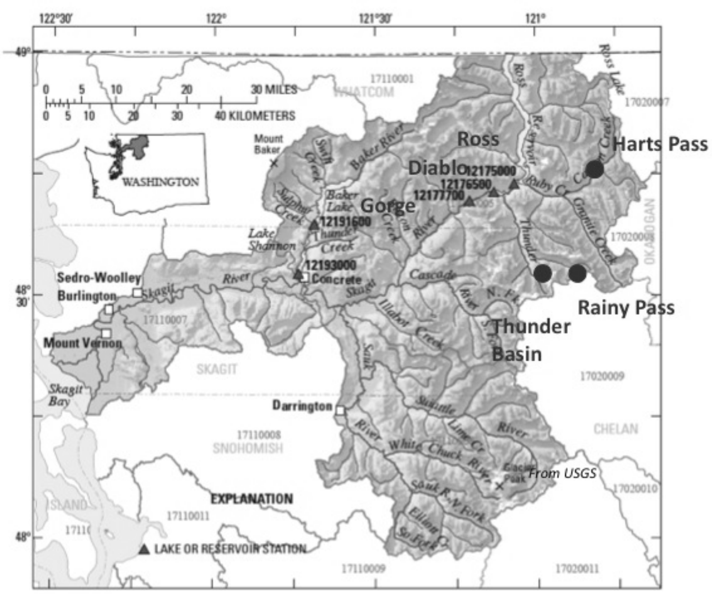

Figure 1. The Skagit River watershed. Filled circles indicate location of three SNOTEL stations (Harts Pass, Rainy Pass, and Thunder Basin) used in this study. Triangles indicate the location of SCL's large dams (Ross, Diablo, and Gorge). Dams along the Baker River are also denoted by unlabeled triangles. From USGS.

DAILY INDICES OF ACCUMULATION AND LOSS

To characterize the timing and magnitude of accumulation and melting throughout the winter and spring, daily indices of SWE accumulation and loss (one index for each process) were calculated from the SNOTEL data. The data are drawn from observations of daily SWE for the water years 1990-2006. The three stations that have records extending back to water year 1990 are listed in Table 1. The 1990 start-year was chosen since it coincides with the beginning of reliable temperature observations at the SNTOEL sites.

Site	NRCS ID	Elevation
Thunder Basin	20A07S	1316 m
Rainy Pass	20A09S	1490 m
Harts Pass	20A05S	1978 m

Table 1. Skagit SNOTEL used to calculate daily indices for SWE accumulation and loss.

For each of the three SNOTEL stations, the time series of the daily derivative of SWE was calculated (e.g., for Day *X*, the daily derivative is equal to the SWE measured on Day *X+1* minus the SWE measured on Day *X;* middle column of panels, Figure 2) for each water year, beginning November 1.[2] The daily derivative is positive for days experiencing accumulation and negative for days experiencing loss

To obtain an *accumulation index* that is representative of the Skagit watershed as a whole, the derivative time series is reset to zero on all days on which it is less than zero. Then, the three time series for the individual stations are averaged to yield a single accumulation index for the Skagit watershed as whole (rightmost panel, Figure 2). A *loss index* is generated in an analogous manner by replacing all positive values in the daily derivative time series by zeros prior to averaging. Calculating the accumulation and loss indices separately prevents losses at one station from offsetting gains at another station.

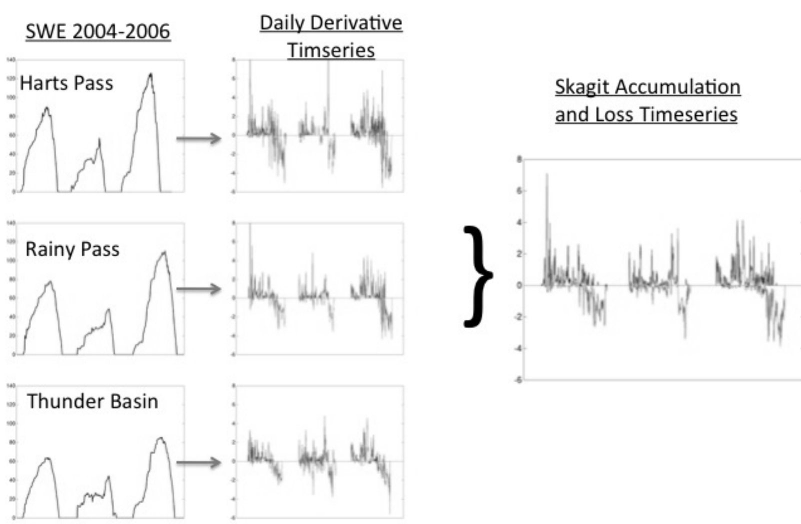

Figure 2. Illustration of the calculation of daily accumulation and melt indices, using water year 2004-2006 data. Left column of panels: accumulated SWE as recorded by the snow pillows at each SNOTEL stations. Middle column of panels: daily derivative time series calculated from accumulated SWE observations. Horizontal line indicates zero values. The curve is above (below) the horizontal line for days experiencing SWE accumulation (loss). Rightmost panel: accumulation and loss index for the Skagit watershed.

[2] October was excluded from the analysis since snowpack rarely accumulates during this month across much of the range of elevations of the Cascades. Even when snow does fall in the Washington Cascades during October, it is often ablated relatively quickly.

Combining the Skagit-wide accumulation and loss indices with the daily mean temperature demonstrates the strong seasonality of accumulation and the controlling role of temperature. Figure 3 shows sums of the accumulation and loss indices, composited by month and binned by the mean of the daily mean temperatures observed at the three SNOTEL stations. Figure 4 shows histograms of the mean of the daily mean temperatures. These figures indicate that:

- Accumulation dominates from November through March;
- Both accumulation and loss occur during April;
- Loss dominates in May and June, leaving only vestiges of the snowpack, if any, in July.
- The seasonal progression appears strongly modulated by daily mean temperature – months with median temperatures below (above) zero are dominated by accumulation (loss).
- No particular winter months appear as preferred times for accumulation. The total monthly accumulations for November, December, January, February, and March are roughly comparable.

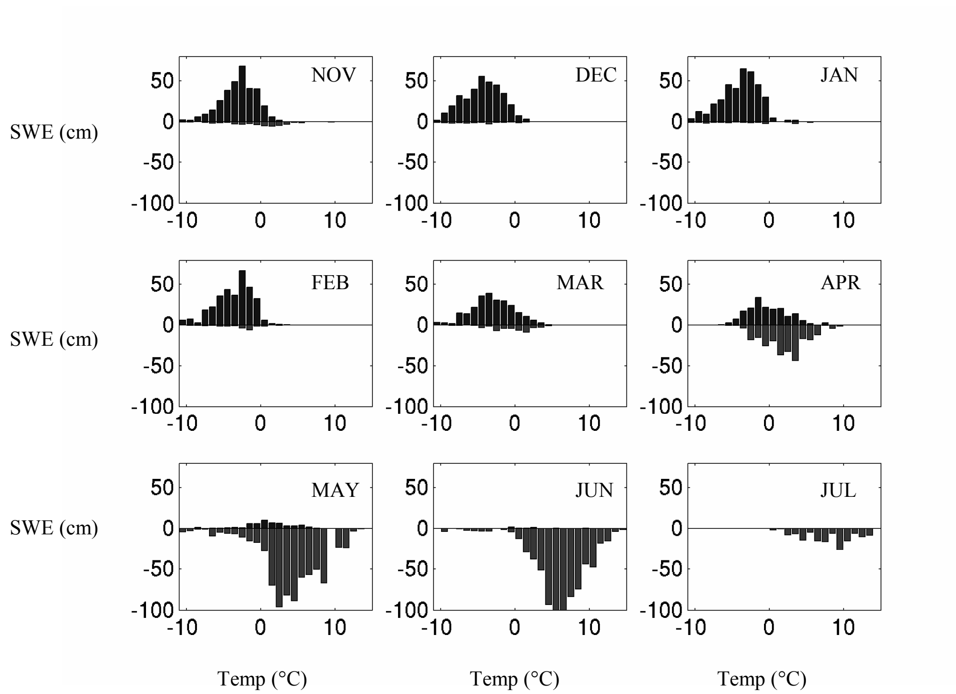

Figure 3. Sums of the Skagit indices representing daily accumulation and loss. Horizontal line represents zero values; accumulation (loss) corresponds to bars extending upward (downward) from the horizontal line. The sums have been binned by daily mean temperature and composited by month. The data include days in the water years 1990-2006.

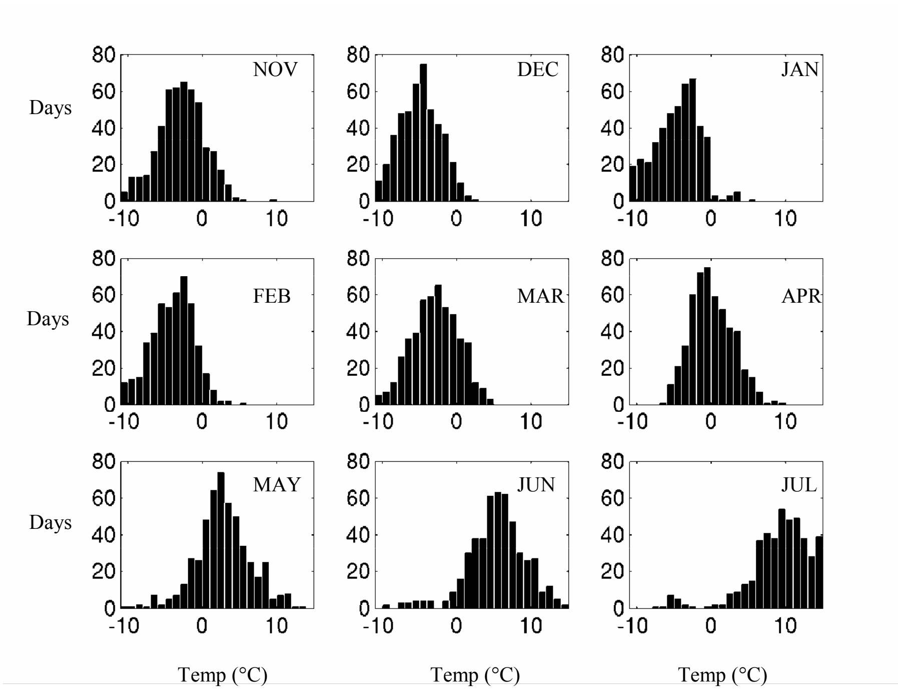

Figure 4. Histograms of daily mean temperature, averaged for the three Skagit SNOTEL.

SEASONAL ACCUMULATION TOOL

Predictions of season-ending SWE can be made during the winter as a consequence of the lack of preferred timing for accumulation of SWE. Table 2 shows that season-ending SWE (taken as April 1 SWE) is well predicted by the SWE observed in mid-winter, especially following February 1. Using February 1 SWE as a predictor for April 1 SWE explains 90% of the variance in April 1 SWE. Using March 1 SWE as a predictor explains 97% of the variance in April 1 SWE. Essentially, the nearer one gets to the end-of-season, fewer chances are available to experience a significant accumulation event.

Probabilistic information can be added to the prediction by drawing on the daily accumulation index for the mid- and late-winter. The accumulation observed during February and March for the 1990-2006 water years can provide a range of possible outcomes for April 1 SWE (Figure 5). A user can then specify the likelihood of a particular outcome. For example in Figure 5, the ranges have been added to represent the 75% and 90% confidence intervals for a winter with February 1 SWE equal to the 17-year average (~60 cm SWE). The regression equation (Table 2 – row labeled "February 1") yields a prediction of approximately 90 cm SWE on April 1; the uncertainty information indicates that there is roughly a 75% chance that April 1 SWE would be between 80 cm and 100 cm, and roughly a 90% chance that the April 1 SWE would fall between 70 cm and 110 cm. The same process can be carried out to create a probabilistic forecast using March 1 SWE, and each of the errors bars narrow by approximately a factor of 2. While the error bars for 75% and 90% confidence are shown here, they are merely illustrative. Users could choose to focus on the types of outcomes that are appropriate for their risk tolerance (i.e., a user could focus on the worst case, the median case, the best case, or some other confidence interval).

It is important to note that the estimates of uncertainty are drawn only from the observations for the last 17 water years. While it could be argued that the distribution of April 1 SWE observed during this short period provides a crude estimate of forecast uncertainty, it is important to point out that the last 17 years includes some of the snowiest (e.g. water years 1998, 2000) and least snowy periods (e.g., water year 2005) observed during the last 50 years in the Cascades. Thus, the *range* of estimates observed over the last 17 years provides a representative estimate of the range of historical variability, even if the distribution of values of April 1 SWE over this period might not represent the distribution observed over a longer period of observations or that derived from a hydrological model.

	Slope (cm SWE/cm SWE)	y-int (cm SWE)	r^2
December 1	2.32	51.63	0.44
January 1	1.51	33.31	0.57
February 1	1.49	1.18	0.90
March 1	1.09	5.19	0.97

Table 2. Regressions results for prediction equations using December 1 SWE, February 1 SWE, and March 1 SWE as predictors for April 1 SWE.

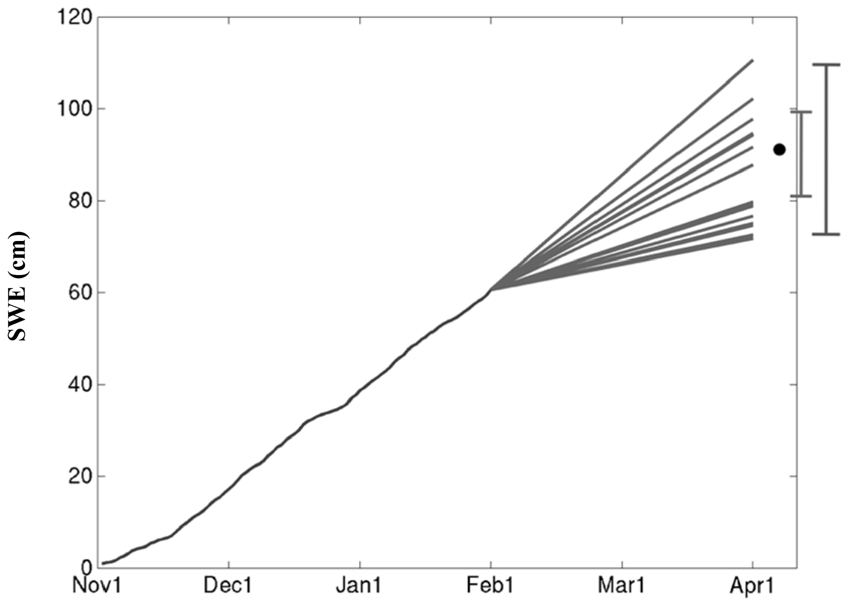

Figure 5. Illustration of the accumulation forecast tool. Average seasonal SWE accumulation is shown for November 1 – February 1. The trajectories between February 1 and April 1 represent the accumulation observed during those months during the 17 water years during the 1990-2006 period. The dot represents the average April 1 SWE for the 1990-2006 period; the narrower (longer) error bar range represents the 75% (90%) confidence interval associated with that average.

SEASONAL MELT TOOL

The indices of spring SWE loss and daily mean temperature can be used to form a degree-day model for daily spring melt. Figure 6 shows the plot of daily SWE loss index values versus daily mean temperature for the Skagit SNOTEL for the months April through June. The regression equation, which explains 60% of the variance in the daily SWE loss, is:

$$M_{DAILY} = -.1408 \text{ cm/°C } (T_{MEAN}) - .4701 \text{ cm};$$

where M_{DAILY} is the daily melt (in cm SWE) for and T_{MEAN} is the daily mean temperature.

This equation can be used to generate melt trajectories for the spring season. Figure 7 shows the progression of the spring melt in the Skagit. From November through March, the line represents the average accumulation of the Skagit snowpack. The lines following April 1 represent a spring that exhibits average temperatures (middle lines), a warmer-than-average spring (leftmost/lower lines), and a colder-than-average spring (rightmost/upper lines). These projections for the Skagit show that the melt-out date would fall in mid-June for a year exhibiting spring temperature near that of the climatological mean; a warm (cold) spring would exhibit an early June (early July) melt-out date. The sensitivity of the melt-out date to the mean temperature is approximately 7-8 days per °C. The melt-out date is also affected by the amount of SWE present on April 1 – a change in April 1 SWE of approximately 10% corresponds to a change in the melt-out date of approximately 5 days.

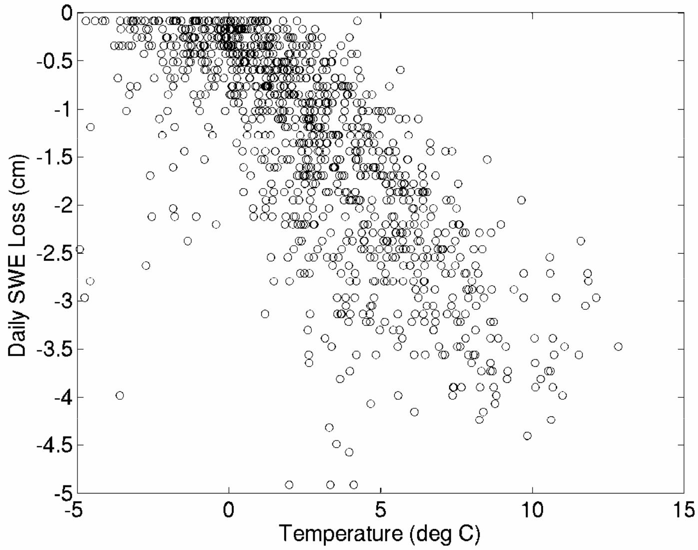

Figure 6. Daily SWE loss index values versus daily mean temperature for the Skagit in April, May, and June in the water years 1990-2006.

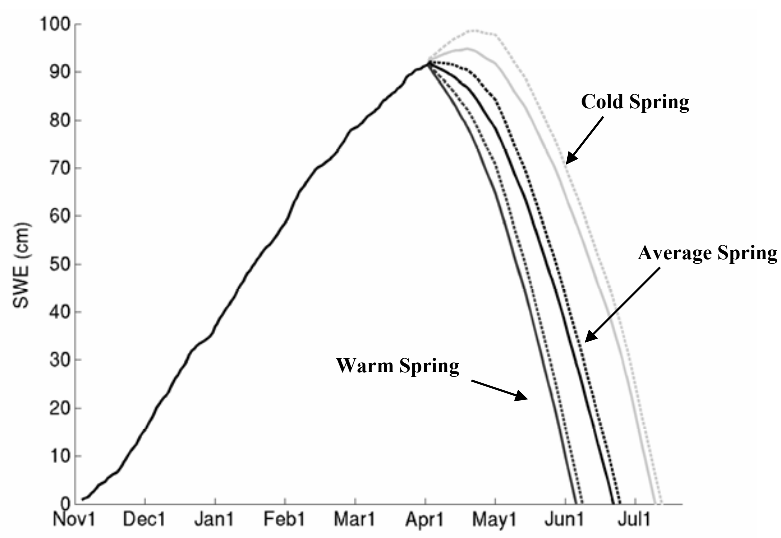

Figure 7. Scenarios of spring melt. The average accumulation is shown for November 1 through April 1. The rightmost/upper curves represent melt for a spring that is 2°C colder than the long term average; the middle curves represent melt for a spring exhibiting average temperatures; and the leftmost/lower curves represent melt for a spring that is 2°C warmer than the long term average. The dotted curves represent further scenarios for a snowier than average April.

SUMMARY OF SEASONAL FORECAST TOOLS

The above tools can aid water managers as they confront the three planning challenges outlined in the Introduction.

- Sensitivity to Climate – The accumulation tool exploits the historical relationship between mid-winter snowpack and April1 SWE, as well as historical observations of late winter snowfall. The melt tool exploits the temperature sensitivity of the spring melt.
- Uncertainty Information – The accumulation tool draws on recent variability of late winter snowfall to generate and estimate of uncertainty. Although the melt tool does not have any explicit uncertainty in the algorithm, a probabilistic forecast of spring temperature, such as that provided by Climate Prediction Center/National Oceanic and Atmospheric Administration (http://www.cpc.noaa.gov/), could be used to easily add an estimate of uncertainty for the melt trajectories.
- Useful Forecast Lead-time – Both forecasts can be made months in advance of key milestones. For example, April 1 SWE can be predicted as early as February 1; the rate of melt-out or the melt-out date could also be estimated as early as late winter.

The presentation here is meant to be illustrative for managers in watersheds in Pacific Northwest and across the West in general. While some of the physical or statistical relationships may be different in other regions (e.g., in the Intermountain West, the split between the timing of accumulation and loss would likely be later than April 1 and terms representing incoming solar radiation may need to be added to the degree-day model), the basic framework for using daily SNOTEL data for estimating the relationships among SWE accumulation, SWE loss, and temperature could provide useful tools for decision making.

APPLICATIONS FOR CLIMATE CHANGE

Information regarding longer-term climate change can be gleaned by combining estimates of the sensitivity of SWE accumulation to temperature (Casola et al., 2009) with the seasonal melt tool. Figure 8 shows an example of how 1°C of warming could affect both the winter accumulation of SWE and the spring melt.

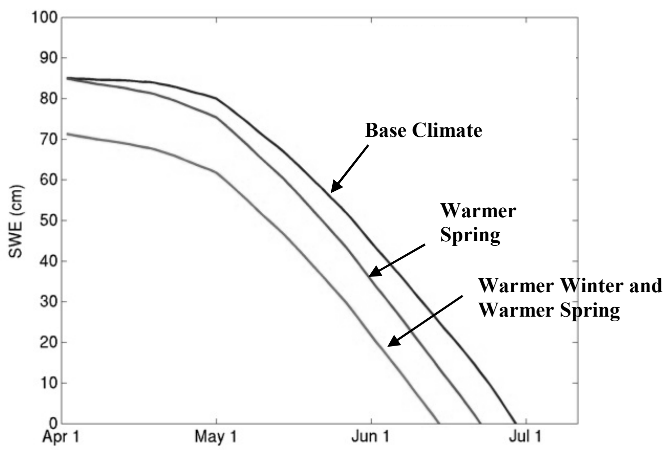

Figure 8. Application of the loss tool to potential future climate that is 1°C warmer than the 1990-2006 average. The loss tool simulation has been combined with a 16% loss in April 1 SWE to generate the "Warmer Winter and Warmer Spring Curve." This curve combines the impacts of warming on winter accumulation and spring melt.

The rate of warming (1°C warming over 30 years) is similar to the amount of regional warming in the Pacific Northwest that has occurred over the last 30 years and is a reasonable estimate of warming for the next 30 years (e.g., Salathé et al., 2007). For the Skagit, 1°C warming reduces the mean April 1 SWE by approximately 16% (see Casola et al., 2009 for details) and accelerates the rate of melting. The combined affect of the reduction in winter accumulation and acceleration of spring melt leads to an advance in the melt out date by nearly 2 weeks (lower curve, Figure 8). This could have significant repercussions for management practices that have been designed with the expectation of historically-observed spring snowpack and historically-observed spring melt trajectories.

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