

# CHARACTERISTICS OF SNOW WATER EQUIVALENT TO PRECIPITATION RATIOS IN UTAH

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## ABSTRACT

Snow water equivalent (SWE) to precipitation (PCP) ratios have recently been used as evidence to support climate change. The assumption is that when a site or region's SWE to PCP ratio declines, temperature is a driving mechanism. In fact, there is a reasonable linear statistical relation between these two variables, but there may be other influencing factors involved in both the site and regional SWE to PCP relations. There are distinctly different physical phenomena occurring at land surface relative to the location of the orifice of a precipitation gage some distance above that surface, such as vegetation and wind direction, run and general velocity. There also is a large 'scale' difference in exposed area of data collection between a 3.05 meter diameter snow pillow and a 30.5 cm diameter precipitation gage. SWE to PCP ratios change throughout the snow accumulation season and SWE, in general, outpaces precipitation accumulation. Individual storm events may have a SWE to PCP ratio in excess of 3 to 4 depending on the storm direction, duration and intensity. Therefore, a SWE to PCP ratio analysis on some arbitrary date such as April 1 may have strong systematic bias due to the total number and magnitude of storm events and may be entirely independent of any temperature trends. The result is that the overall magnitude of SWE in any given year may be a strong indicator of the eventual SWE to PCP ratio. Long-term vegetation change at specific sites has been demonstrated to change snow accumulation characteristics, generally in a strongly negative direction. Declining SWE values resulting from vegetation changes could impact SWE to PCP ratios. Therefore, trend analysis research demonstrating declining SWE to PCP ratios may have some systematic bias in the relations not specifically attributable to temperature changes.

## INTRODUCTION

The concept of SWE to PCP ratios has long been used within the Natural Resources Conservation Service (NRCS), United States Department of Agriculture (USDA) Snow Survey Program as an aid in editing operational SNOTEL snow and precipitation data. In fact, running SWE to PCP ratios are constructed for each site and compared to historical curves for operational data editing purposes. Each site has very unique characteristics that influence the accumulation of snow on the ground as well as precipitation into the 30.5 cm diameter storage precipitation gage. The SWE to PCP ratio at each site may be used to edit missing or erroneous data. Each individual year, month and event may have differences in the SWE to PCP ratio depending on a suite of factors, such as snow event density, wind run, direction and velocity, snowfall intensity and duration, and measurement error. Measurement error can include phenomena such as snow bridging and ice layers in a snowpack that can result in underestimates of density and therefore SWE (there are cases of observed increases in SWE post storm). Likewise, measurement error can exist in the collection of precipitation data. Storage precipitation gages are designed to catch all precipitation and the precipitation subsequently mixes with an antifreeze solution in the gage. However, during high intensity snowfall events, snow physically overwhelms the mixing capability of the gage and depending on a multitude of factors, may freeze to the side of the gage. There typically is a large amount of frozen precipitation inside these storage gages during the winter months that normally is free floating and thus registers as observed precipitation. Again, during high intensity snowfall events as well as very low temperatures, this plug can freeze to the side of the gage.

Variations in instrument types and settings can affect comparisons between sites. Long-term trends also may be biased by comparisons utilizing gages of different orifice size. National Weather Service gages range from the standard 20.3 cm orifice, 1.52 meter height to a 10.2 cm version and, in some cases, smaller. NRCS has used both 20.3 cm and 30.5 cm orifices at heights ranging from 2.4 meters to as much as 7.9 meters. There also is a surface-to-gage height factor that is always changing during the winter months. In Utah, many SNOTEL gages are 2.4 meters to 4.9 meters in height with a few in the 6.1 meter range. During the winter months, snow accumulation constantly changes the height between the snow surface and the height of the gage and, in some cases, the surface to height distance may only be 0.6 to 1.2 meters. In his classic precipitation catch research "How Much Rain Does A Rain Gage Gage" Earl Neff demonstrated that pit or surface gages always have greater precipitation catch than

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any elevated gage tested (Neff, 1977). The height of a gage above land surface has direct bearing on the catch, and therefore a gage with varying surface height due to increasing snow depth may have a more variable catch efficiency throughout the accumulation season than perhaps a gage located at a fixed distance to land surface. In Utah, snow depths at SNOTEL sites typically range from several feet up to more than 3.7 meters. In drought years, these depths may be half of average which may yield systematic bias in the catch not related to other factors. Drought may have a large impact on SWE to PCP ratios due to the initial offset and possibly to the gage orifice being much higher from the snow surface.

Other sources of error may include changes to the physical conditions at a particular site. Over long periods of time, SWE to PCP ratios will be impacted by site vegetation changes. Tree growth can impact both the accumulation of snowpack on the ground as well as precipitation accumulation characteristics at the precipitation gage (Julander and Bricco, 2006). Any factor that will decrease snow accumulation at a site has the potential to systematically bias long-term trends in the SWE to PCP ratios.

There also are the simple mathematic characteristics of the ratio of two related but different variables that can influence certain portions of a seasonal curve. In an idealistic setting without the above mentioned influences, precipitation would begin accumulation on October 1 of the water year and SWE would begin at some later date giving an initial offset of some depth of precipitation. The SWE to PCP ratio for each individual event would be 1, indicating that SWE equals PCP for each event. In this setting, the initial offset and the total magnitude of the seasonal catch determine, to a large extent, the shape and eventual outcome of the curve which will be logarithmic and asymptotically approach a ratio of 1.

### METHODS

A general examination of the mathematical properties of the SWE to PCP ratio was first examined. A set of curves were constructed wherein the event SWE to PCP ratio and time step were set to 1 and the initial offset - that amount of precipitation that occurs prior to the onset of seasonal snowpack - was varied (Figure 1). This simple exercise was done by constructing an array of numbers starting at 1 and incrementing by 1 to an end of 50. The next arrays were given the same SWE to PCP ratio increment (1) and offsets of 1, 2, 3 and 4, which represent inches of precipitation up to the onset of SWE accumulation. This simple exercise demonstrates the critical effect of the initial offset or that precipitation that precedes annual snow accumulation. Curves also were developed to examine the potential impacts of drought on SWE to PCP ratios. These curves simply used an event increase of 0.5 rather than 1.

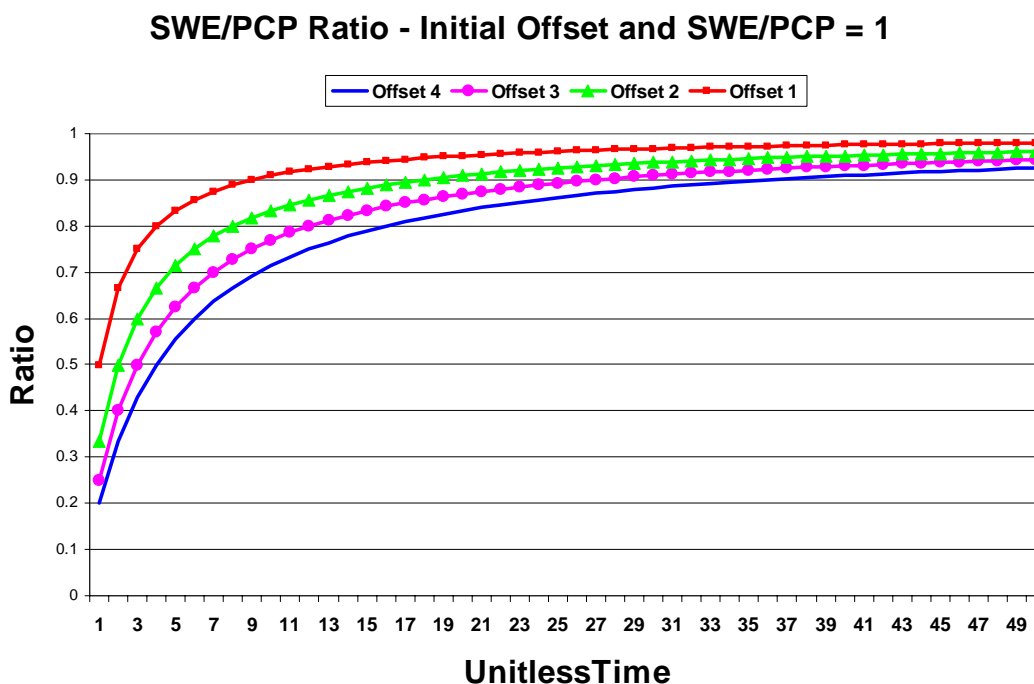


Figure 1. SWE to PCP Ratio of 1 with differing initial offsets

It should be noted that in these synthetic curves that each curve approaches a SWE to PCP ratio of 1 and that all curves are above a ratio of 0.80 within 18 time steps. The small offset of 1 has a SWE to PCP ratio of 0.98 at step 50 and the curve offset of 4 has a ratio of 0.93. The initial offset has a large impact on the eventual ending ratio, in this case about 5%. The next factor in these curves is the total number and magnitude of time steps or, related to the real world, the number and magnitude of storm events. In these curves, each event is arbitrary and equal, set to 1. However, the larger the storm event and particularly early season large events, the closer the running SWE to PCP ratio approaches 1.0 early in the snow accumulation season. The outcome of each SWE to PCP curve is highly dependent on the magnitude and number of events, which concludes that the eventual SWE to PCP ratio at some arbitrary position at the end of the curve such as April 1 is very susceptible to drought. Under ideal conditions illustrated by synthetic curves, there is virtually no impact of above average SWE years on SWE to PCP ratios towards the end of the curve as it marginally proceeds to unity. On the front end of the synthetic curves, above average years would accelerate the slope. Drought, on the other hand, decreases both the slope and the outcome and can have a substantial impact on the SWE to PCP ratio outcome absent of any other climatic influences.

The next step examines the ending portion of the curve for sensitivity. All curves come close to each other toward the end of the sequence with a total separation of 5%. If the snow accumulation season were shortened by some percentage of time, for example due to climate change, would SWE to PCP ratios accurately reflect that in the same proportion as a change to the front part of these curves?

Figure 2 shows that the difference between the family of SWE to PCP curves in a snow accumulation season reduced by 10% is about 0.25% - this would be the equivalent of a snow season decreased by 15 days assuming a snow season from November through March. If the season were shortened by 40% the impact on SWE to PCP ratios ranges from 1.3% with an initial offset of 1 to 4.4% if the initial offset is 4. This demonstrates that with this mathematical construct, there is very little variability in the later stages of the snow season and that, proportionately, the initial offset or that amount of precipitation that falls early in the season as well as the total magnitude of the season may be more important in the eventual SWE to PCP ratio than is the length of the season. This indicates that SWE to PCP ratios may not accurately index snow seasons shortened in the spring and that there is a heavier weight given to precipitation that falls prior to the onset of snow, regardless of cause. Given this apparent latent insensitivity to later portions of the curve and the natural variability of observed SWE to PCP ratios, one could question the validity of such an index to adequately represent specific climatic influences in the later stages of winter or spring.

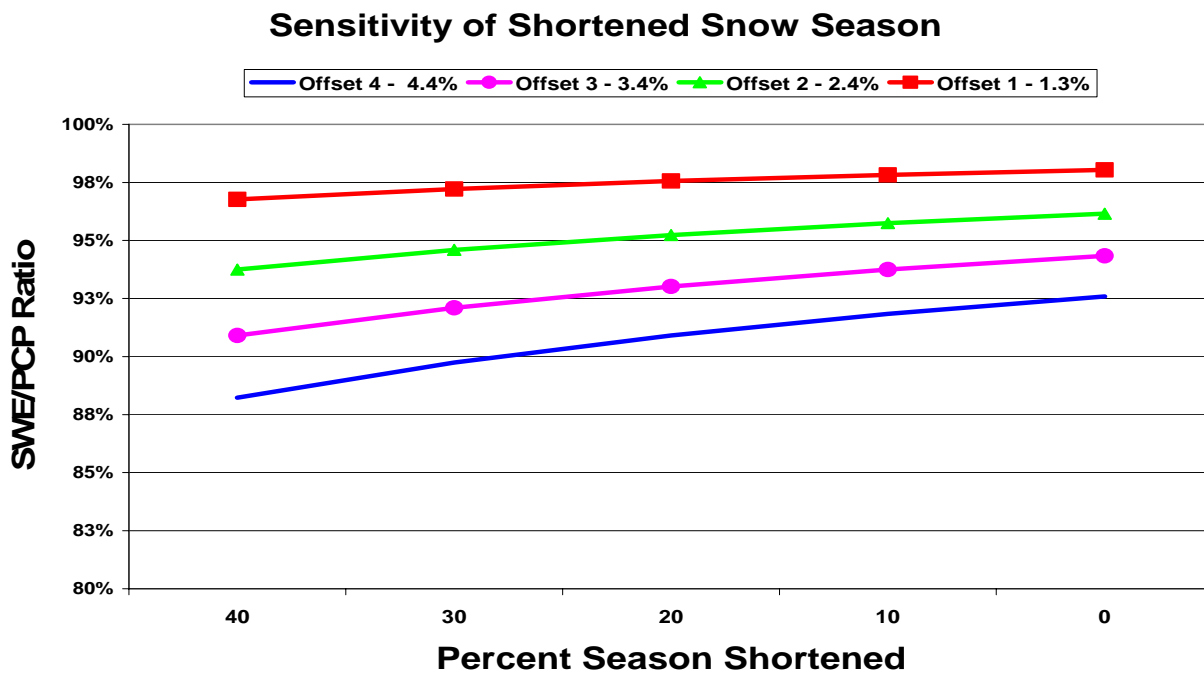


Figure 2. Percent Reduction of Snow Accumulation Season

Figure 3 shows observed daily SWE to PCP ratios for Ben Lomond Peak, Utah for the 1997 and 2007 water years. This observed set of SWE to PCP ratios is similar in form to the synthetic curves of Figure 1. There are exceptions in that the observed data do not reach an asymptotic symmetry as early as the synthetic curves, there is a great deal of variability with increases and decreases in the observed data, and the observed curve exceeds a ratio of 1 to 1 in 1997. This last point indicates that far more SWE was accumulated on the pillow than was caught in the precipitation gage, which is typical for snow accumulation. There is a huge difference (39%) between the high accumulation year and the low accumulation year. Much of this overall difference is maintained throughout the entire season but note specifically that the slope and shape of both curves are very similar starting in December. In the high snowpack year, it is difficult to maintain a SWE to PCP ratio greater than 1.1 and in the low snowpack year the flattening of the curve is due to lack of storm events producing in both cases later season symmetry dependent on early season events. The drought year of 2007 has the potential to increase the SWE to PCP ratio and indeed there is a bump in the curve in February. Coincidentally, February precipitation was 106% of average, the only near average accumulation month in year 2007. Looking at average monthly temperatures at this site for the years 1997 and 2007 reveals that during the critical melt months of April and May, 2007 was actually colder than 1997 with a difference of -4 and -3 degrees C, respectively. Fall temperatures were much warmer with October and November both 7 degrees greater in 2007 compared to 1997.

### Ben Lomond Peak Daily SWE/PCP Ratios Above Average to Below Average Accumulation Years

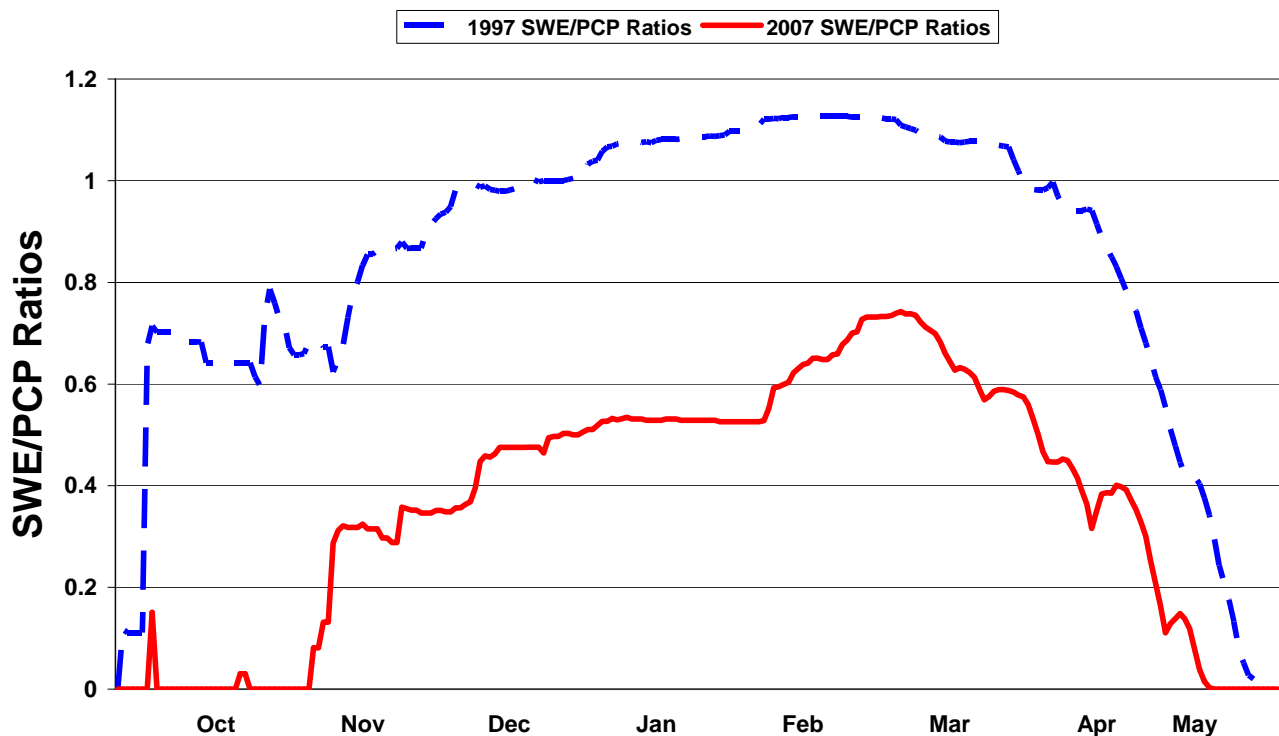


Figure 3. Ben Lomond Peak SWE to PCP Ratios for High SWE Water Year 1997 and Low SWE Water Year 2007

Figure 4 shows 29 years of daily SWE to PCP ratios for the Ben Lomond Peak SNOTEL site. The SWE to PCP ratio often exceeds 1.0 (9 years) and is less than 0.9 for 7 years. It would be erroneous to correlate the April 1 SWE to PCP ratio with the total percent of average April 1 snow accumulation even though the correlation appears to be strong. The technique is biased due to the fact that SWE is a component of the SWE to PCP ratio. Surrogate indices of the total season snow accumulation such as correlations between the number of events during an accumulation season as well as the magnitude of events greater than 0.5 inch accumulation were unsuccessful.

Figure 5 shows individual event SWE to PCP ratios for Ben Lomond Peak, Utah. These events were calculated by dividing the total daily pillow SWE accumulation by the daily precipitation accumulation. Ideally,

### Ben Lomond Peak SWE/PCP Ratio - Observed Daily SWE to Daily Accumulated PCP

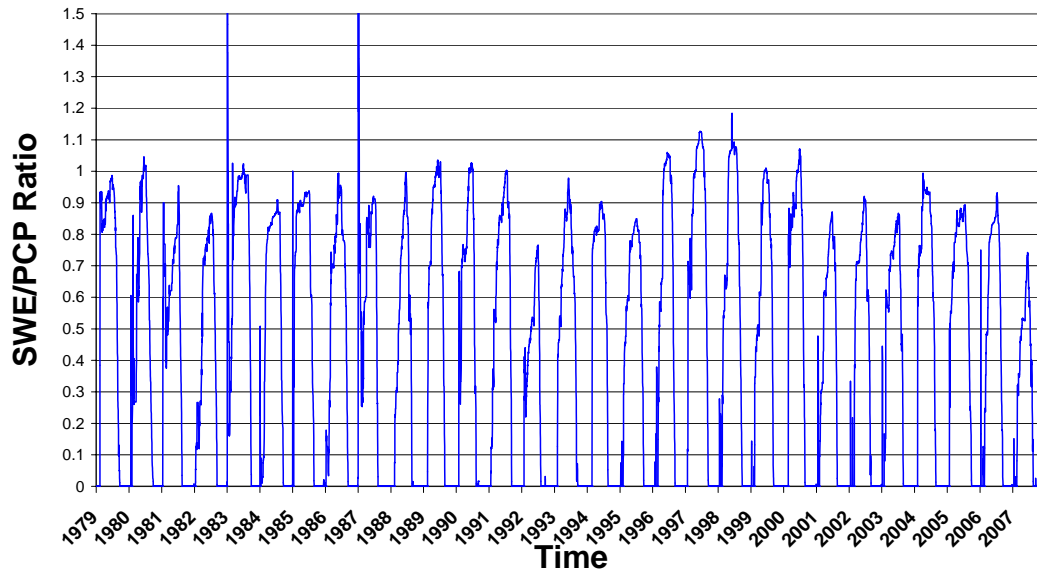


Figure 4. 29 Years of Daily SWE to Accumulated PCP Ratios for Ben Lomond Peak, Utah

without the influence of wind and vegetation and with perfect instrumentation, each of these events would be 1.0, where SWE equals PCP. However, a large number of events are greater than 1.0 and often exceed 2.0. Individual events can exceed a SWE to PCP ratio of 10. All these events become smoothed in the accumulated SWE and PCP time series but it is important to address individual events and the in situ circumstances producing them to understand the eventual outcome. As noted earlier, land surface instrumentation will accumulate greater amounts of snow than elevated instrumentation. Thus, with SNOTEL data, it is common for event SWE data to exceed PCP data at the same site and, as demonstrated in Figure 3, it is not uncommon for annual SWE to PCP ratios to exceed 1.0 due to differing efficiencies of processes working at the surface versus elevated

### Ben Lomond Peak SWE/PCP Ratio - Individual Events

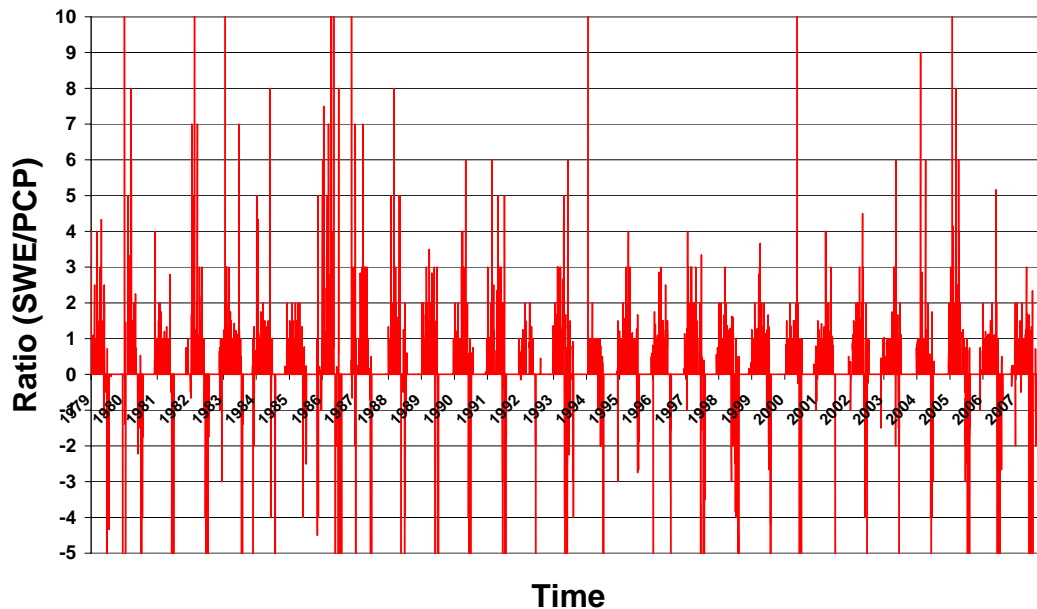


Figure 5. 29 Years of Individual Event SWE to PCP Ratios at Ben Lomond Peak, Utah

instrumentation. Each site has specific conditions that may increase or decrease these efficiencies, most of which are related to wind. Vegetation is a substantial contributor to altering wind and therefore SWE and PCP catch. Changes in vegetation can alter SWE to PCP ratios whether it occurs from slow and steady increases due to growth or instantaneous events such as fire. Storm patterns can impact SWE to PCP ratios; therefore prevailing jet stream directions, if relatively consistent through the accumulation season, may increase or decrease ratios.

Figure 6 shows the Summit Meadows SNOTEL site SWE to PCP ratios and wind data for 2008. For each precipitation event, the SWE to PCP ratio is strongly correlated with the total wind run for that event. The greater the wind, the higher the SWE to PCP ratio with the exception of one event where in early February, wind was low and the SWE to PCP ratio was near 3. In the majority of events at this site, wind direction was from the south to southwest - 180 degrees. This early February storm had prevailing winds from nearly north at 356 degrees. This is strong evidence that wind direction and run can influence event SWE to PCP patterns at individual sites. Thus, if a given year has a preponderance of storm events from a specific direction, SWE to PCP ratios may be significantly different than those of years where the storm track is substantially from a different direction absent any other climatic influences. Utah has situations such as described where in some years, the majority of storms come from the southwest and in others, from a more northerly direction, depending on where the jet stream sets up for the majority of the season. In theory, the general timing or seasonal distribution of storm events may have some bearing on SWE to PCP ratios in that cold, light-density winter storm accumulations may have greater SWE to PCP ratios than warm high-density fall or spring accumulations. Figure 5 shows some tendency towards higher SWE to PCP events mid season with a general ascending peak and descending shape for individual years.

### SWE/PCP Ratio and Wind

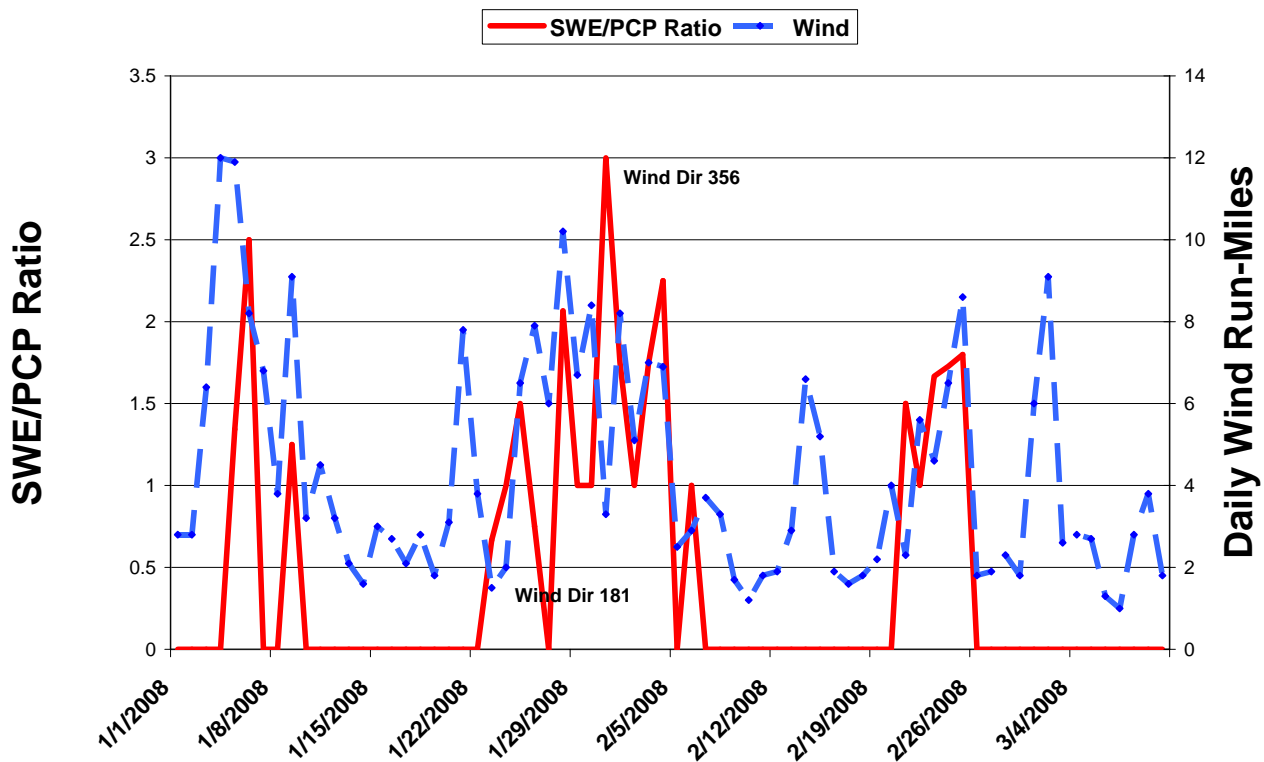
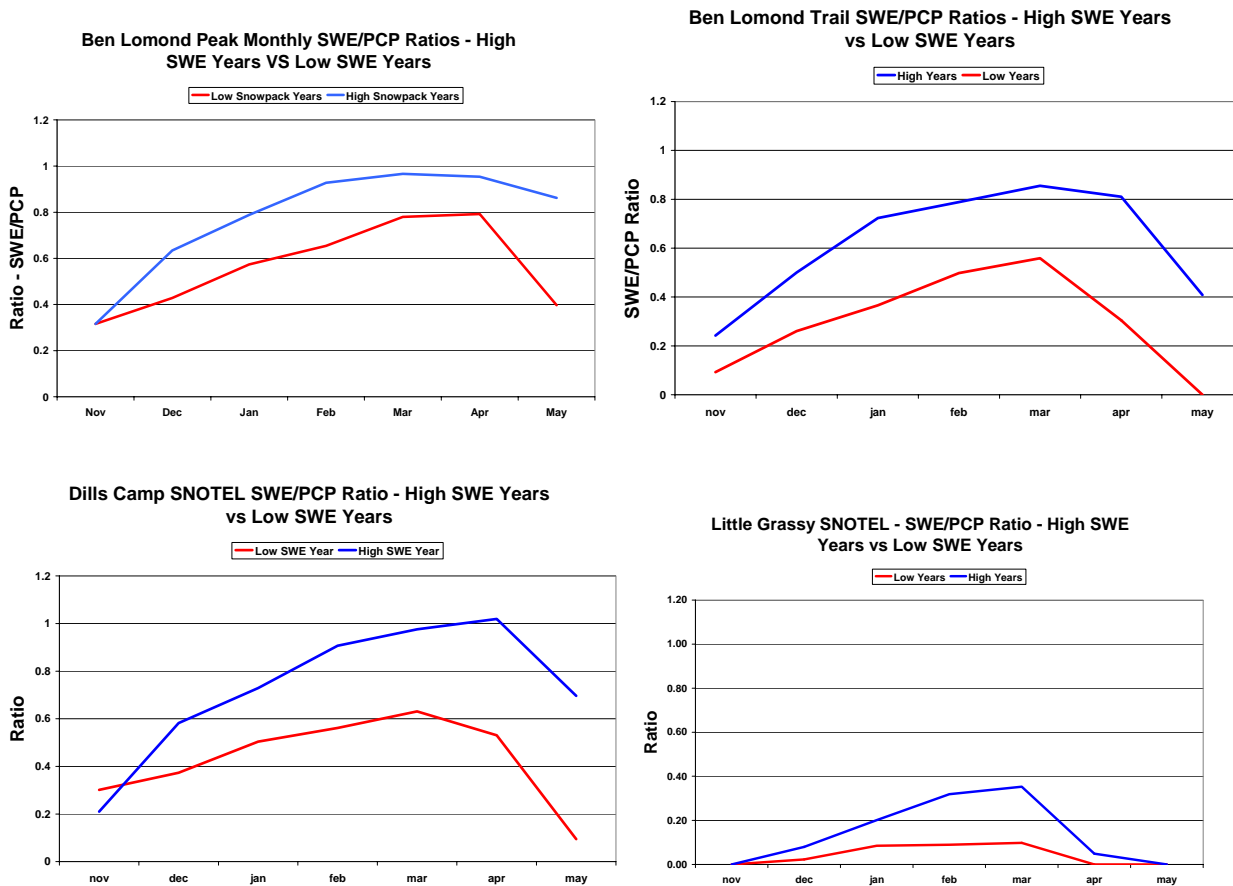


Figure 6. Summit Meadows SWE to PCP Ratios and Wind for 2008

The question whether elevation and latitude play a role in the SWE to PCP ratios was examined. A few sites were analyzed that represent lower elevations and different latitudes. A set of 5 high and 5 low SWE accumulation years for each site were used to determine if the signature of drought is a dominant feature of SWE to PCP ratios (Figures 7-10).





Figures 7, 8, 9, 10 – SWE to PCP Ratios of High and Low Snowpack Years

These 4 sites are: Ben Lomond Peak - elevation 2438meters, latitude - 41° 22'.5" N (figure 7), Ben Lomond Trail - elevation 1777 meters, latitude 41° 22'.5" N (figure 8), Dills Camp - elevation 2799 meters, latitude - 39° 2'.7" N (figure 9) and Little Grassy - elevation 1859 meters, latitude - 37° 29'.2" N (Figure 10). The average high versus low snow accumulation year SWE to PCP ratios all exhibit the same general pattern - that is high accumulation years have higher ratios than drought years regardless of elevation or latitude. When examining the curves for the Ben Lomond sites, essentially the same location but with an elevation difference of 610 meters, the higher elevation site curves max out at nearly 1 and about 0.8 for drought years whereas the lower elevation site has its peaks at 0.85 and 0.55, respectively. The shape of the curves is the same for both sites, but the magnitude of the SWE to PCP ratios increases with elevation. Little Grassy, a low elevation, low latitude site, has peak SWE to PCP ratios for high and drought years of 0.35 and 0.10, respectively, whereas Dills Camp has peak SWE to PCP ratios for high and drought years of 1.0 and 0.60, respectively. SWE to PCP ratios may increase in magnitude with increasing latitude. The difference in the magnitude of these various SWE to PCP ratios for high snowpack and drought years is partially tied to the mathematical construct of the index and specifically to the average April 1 SWE accumulation at each site: Ben Lomond Peak - 105 cm of SWE, Ben Lomond Trail - 49.5 cm of SWE, Dills Camp - 37.8 cm of SWE and Little Grassy - 0.1.8 cm of SWE. Site specific characteristics also play a significant role in the average ratios as demonstrated by the difference between Ben Lomond Trail and Dills Camp, which have similar SWE accumulations but with some difference in the higher snowpack year ratios (0.85 to 1.0). From these observed data, it is clear that drought has a major impact on SWE to PCP ratios throughout the entire snow accumulation season. It is also clear that this could have a substantial impact on long-term trend analyses. If a Utah SWE to PCP trend analysis begins in the early 1950's (extremely high snowpack in 1952) and ends in the 2000 to 2004 period (extreme drought), it will have a dominant declining trend due to drought in addition to any other signature in the data series. One potential impact that drought might have on SWE to PCP ratios involves the total mass of the snowpack. Larger snowpacks require more total energy to melt than do shallow snowpacks. This impact can be seen in Figures 7, 8, 9 and 10 where the high SWE years continue to rise or show a much smaller decline a month past where the low SWE years begin to decline for the same site. Only one of these sites, Little Grassy, has a temperature record that covers all of the years compared in Figure 10. The average November-May temperature of the high snowpack years for the Little Grassy SNOTEL is 3.54 degrees C

whereas the average for the low snowpack years (and also the low SWE to PCP ratio years) was 2.63 degrees C, 0.9 degrees C lower than the higher years. The low SWE to PCP years had both the coldest and the warmest individual years of temperature at -3.43 and 5.86 degrees C, respectively. For Dills camp, for the years temperature data were available, the drought years were 0.42 degrees C cooler than the higher snowpack years. At Ben Lomond Peak, again with some years unavailable, the drought years were 1.57 degrees C warmer than the high years, a reverse in pattern from Little Grassy and Dills Camp and consistent with warmer temperatures and decreased snowpack. At Ben Lomond trail, again with limited data, the drought years were 1.1 degrees C warmer than the high snowpack years, consistent with the upper elevation Ben Lomond Peak site. The summary of the temperature data indicate that drought does not necessarily accompany warmer temperatures nor do higher snowpack years necessarily mean cooler temperatures. Julander and Bricco (2006) showed that many snow sites in Utah have been impacted by vegetation change and that, at snow courses with substantial vegetation change, SWE also has declined. This would cause a decline in SWE to PCP ratios without any change in other climate variables. Garden City Summit is one such example where declines in SWE and SWE to PCP ratios have been specifically attributed to changes in site vegetation. A reverse example of vegetation impacts is occurring at East Fork of Blacks Fork snow course. The snow course is in a large open meadow and the corresponding precipitation gage is in a campground a short distance away. The precipitation gage is being impacted by nearly 50+ Lodgepole Pines that are now 10 to 20 feet high. This has decreased the precipitation catch at this gage while the SWE at the snow course has not been impacted, thus the SWE to PCP ratio is slowly increasing.

### **CONCLUSIONS**

SWE to PCP ratios have both conceptual and operational limitations to accurately index a single climatic variable such as temperature. SWE to PCP ratios may have latent insensitivity to shortened winter seasons. The shape and outcome of the curve can be theoretically determined by climatic characteristics in the fall and early winter. They are shown to be heavily influenced by drought. They are subject to systematic changes and bias from physical impacts and vegetation changes at individual sites. They may also reflect some influence from weather modification in specific areas and specific years. Individual SWE to PCP events and thus the accumulative curve are heavily influenced by specific storm characteristics such as wind direction, run and overall velocity, storm intensity and duration. Individual events also may be negatively influenced by sensor limitations such as the timing of weight distribution over the pillow and within the precipitation gage and other physical limitations. These factors and possibly others must be isolated and quantified in order to identify a properly attributed signature of temperature based on climate change. Some of these factors, such as drought, may be linked to temperature change making the quantification of such variables difficult.

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