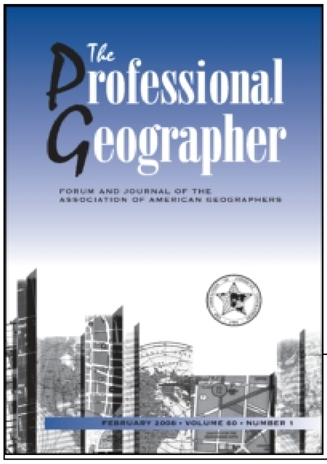

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Changing Properties of Snowpack in the Great Salt Lake Basin, Western United States, from a 26-Year SNOTEL Record

Daniel Bedford [a]; Andrea Douglass [a]
[a] Weber State University,

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Changing Properties of Snowpack in the Great Salt Lake Basin, Western United States, from a 26-Year SNOTEL Record

Daniel Bedford and Andrea Douglass
Weber State University

Daily observations from automated snowpack telemetry (SNOTEL) stations from within the drainage basin of the Great Salt Lake over the period from 1982 to 2007 are analyzed. The major finding is a shift toward an earlier date of peak snow water equivalent (SWE) by around fifteen days. Less robust findings are reductions in the amounts of peak SWE and 1 April SWE. This suggests increased chances of late-summer water shortages, especially when combined with rapid recent population growth. Less freshwater is likely to be available to flow into the Great Salt Lake, increasing its salinity and potentially affecting its ecology. **Key Words: climate change, Great Salt Lake, mountain snowpack.**

我们分析了设置于大盐湖流域内的自动遥测积雪站(SNOTEL)从1982年至2007年期间所收集的每日观测。我们得到的主要结论是达到山顶积雪水当量(SWE)的日期提前了大约15天。较弱的结果显示山顶积雪水当量以及四月一日的积雪水量有所减少。这意味着夏季下旬会更有可能出现缺水的状况，尤其是加上近来人口增长的趋势。流入大盐湖的淡水数量多半会减少，因此会增加该湖的盐度并且可能会影响到它的生态环境。**关键词：气候变化，大盐湖，山区积雪。**

Se analizaron las observaciones diarias de estaciones de telemetría de la cubierta de nieve (“snowpack”), SNOTEL (de SNOwpack TELemetry), desde el interior de la cuenca de drenaje del Gran Lago Salado durante el periodo de 1982 a 2007. El principal hallazgo es un desplazamiento hacia una fecha anterior del valor máximo del equivalente en agua de la nieve (snow water equivalent, SWE) de aproximadamente quince días. Entre los hallazgos menos sólidos se encuentran las reducciones de las cantidades del SWE máximo y del SWE del 1.° de abril. Esto sugiere mayores probabilidades de escasez de agua a finales del verano, especialmente cuando se considera el rápido crecimiento reciente de la población. Es posible que haya menos agua dulce disponible para fluir al Gran Lago Salado, aumentando así su salinidad y posiblemente afectando su ecología. **Palabras claves: cambio de clima, Gran Lago Salado, acumulación de nieve en las montañas.**

Much of the western United States is heavily dependent for its spring and summer water supplies on the melting of mountain snowpack accumulated during winter. Changes in winter snow accumulation, either in the short term or long term, can be of great importance to the region, especially considering recent and projected near-future high rates of population growth. The main agency responsible for monitoring this mountain snowpack is the U.S. Department of Agriculture’s Natural Resources Conservation Service (NRCS), which relies on two main approaches: snow courses, which involve regular field measurement by human experts, and snowpack telemetry (SNOTEL) stations, which utilize automated instruments and radio transmission of field data back to a base station. Data archives (available at http://www.wcc.nrcs.usda.gov/snow) typically provide monthly or twice-monthly measurements for snow courses and daily measurements for SNOTEL stations.

Detailed analysis of western U.S. snowpack from snow course data has shown an overall decline in snow water equivalent (SWE) over the second half of the twentieth century, as measured on 1 April (Mote et al. 2005; Regonda et al. 2005), the standard estimated date

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of peak snowpack across the region. Analysis of precipitation and temperature data has further demonstrated that this reduction in 1 April SWE is most likely attributable to regionwide warming rather than changes in precipitation patterns, and these findings have been used to help make the case that concerns about global warming should be taken seriously (Mote et al. 2005). This trend in 1 April SWE fits well with trends in regional streamflow, in which "pulses" of spring runoff are occurring progressively earlier (Cayan et al. 2001; Stewart, Cayan, and Dettinger 2004, 2005).

To date, however, only a small number of studies have utilized the higher temporal resolution SNOTEL data set (see Serreze et al. 1999). SNOTEL stations provide daily records of SWE (and other variables), and can therefore add considerable detail to the picture of changes in western U.S. snowpack derived thus far from snow course measurements. Specifically, use of the daily SNOTEL data can shed light on the timing of snowpack accumulation and depletion, as well as simply the absolute quantities of snow accumulating in the mountains. In the absence of this information, reliance on 1 April SWE to indicate snowpack changes could potentially give a misleading, or at least oversimplified, picture of snowpack trends, as 1 April SWE changes could be attributable to shifts in the timing of snowpack accumulation and depletion, rather than changes in the magnitude of total snowpack. Conversely, the absence of change in 1 April SWE could potentially conceal changes in the dynamics of snowpack accumulation and depletion, as shown in Figure 1. Here, daily SNOTEL SWE observations for Lily Lake, Utah, for 1993 and 2006 are graphed over time. The 2006 data show a markedly earlier onset of melting and commencement of snowpack depletion compared with 1993 data, and shows a much lower peak SWE value (39.4 cm and 47.2 cm for 2006 and 1993, respectively). The two SWE values for 1 April are quite similar, however, with 2006 being slightly higher (39.4 cm and 36.1 cm for 2006 and 1993, respectively). Thus, a focus entirely on 1 April SWE might suggest a minor increase in snowpack between 1993 and 2006, even though the reality shown in Figure 1 is very different. This is a simple example, but illustrates the value of using higher temporal-resolution data. Although SNOTEL records are short relative to snow course archives, many stations began

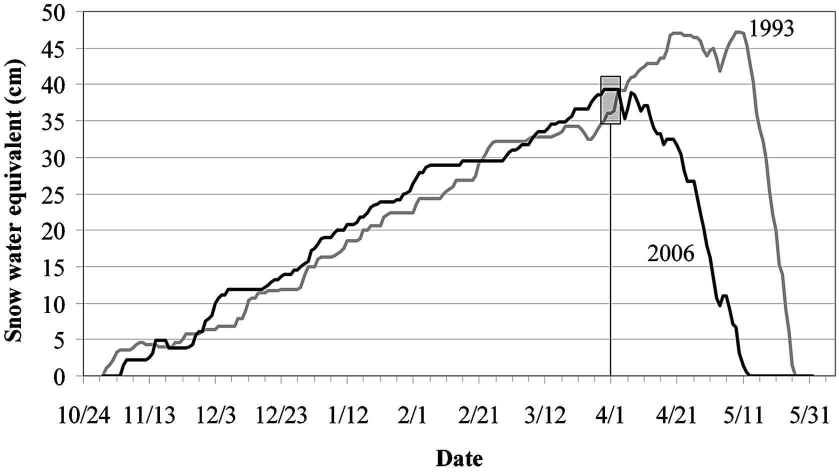

Figure 1 *Snow water equivalent (SWE) records for the SNOTEL site at Lily Lake, Utah, for 1993 (gray line) and 2006 (black line). SWE values for 1 April are highlighted. Note that these values are similar for both years, with a small increase between 1993 and 2006, even though 2006 shows considerably reduced total snowpack. Relying only on 1 April SWE data would therefore produce a misleading picture of how snowpack properties differ between the two years.*

operations in the early 1980s, providing over a quarter-century of measurements, enough to provide some insight into western U.S. snowpack trends.

This article builds on the existing literature identifying changes in western U.S. snowpack (reduced 1 April SWE; earlier onset of spring snowmelt pulse) by adding temporal and spatial detail. First, use of daily SNOTEL records adds temporal detail, as already discussed. Second, changes in mountain snowpack magnitude and dynamics relate strongly to water management, and water management decisions are generally made at a scale below that of the entire western U.S. region. Consequently, this article adds spatial detail by considering snowpack dynamics in one major drainage basin within the region, the basin of the Great Salt Lake.

Study Area: The Great Salt Lake Drainage Basin

The Great Salt Lake (GSL) is located in northeastern Utah. It is a terminal/playa lake with no outlet to the oceans; water inputs are primarily from snow-fed rivers rising in the mountains to the GSL's northeast, east, and southeast, and water outputs are primarily from evaporation. The drainage basin of the GSL encompasses parts of the states of Idaho and Wyoming as well as Utah (see Figure 2).[1] The GSL itself is a highly saline remnant of pluvial lake Bonneville, a freshwater body that covered some 47,800 km^2 at its peak extent around 14,000 to 15,000 years BP (Hostetler et al. 1994); desiccation of the region since the end of the last glacial period has caused the lake to shrink to an average of around 4,400 km^2, concentrating salts to an average of around 14 percent (five times the salinity of the ocean). As a terminal/playa lake, the GSL's water balance is highly sensitive to mountain snow conditions: A series of wet years causes the lake level to rise (and salinity to drop), and a series of dry years has the opposite effect. The GSL is therefore a highly dynamic physical and ecological system.

The GSL drainage basin is a useful unit of analysis for this study for several reasons. First, it is a small enough unit that potential impacts of changes in snowpack accumulation and depletion dynamics can be clearly identified and brought to the attention of policymakers (see Edwards 1996). Second, the GSL itself is very important ecologically, providing food (brine shrimp and brine flies) and a relatively predator-free environment for literally millions of birds migrating between Canada and South America, as well as providing wetland habitat for perennial shorebird populations (e.g., see Williams 1992; Aldrich and Paul 2002). Any changes in winter snowpack dynamics in the GSL drainage basin are therefore ecologically important at the hemispheric scale, because lake ecology (including lake productivity) has been shown to be highly sensitive to lake salinity beyond key thresholds (Wurtsbaugh and Berry 1990). Third, the GSL is a central (although often unrecognized) feature in a complex environmental–societal system, providing employment, waste disposal, recreation, and local weather and climate influences for an urban corridor that is home to nearly two million people, including the major conurbations of Salt Lake City and Ogden (Gwynn 2002; Bedford 2005). Finally, mountain snowpack is an important resource in itself, in a region that is home to several major ski resorts, such as Snowbird, Alta, and Snowbasin; hosted the 2002 Winter Olympic Games; and where Utah vehicle license plates proudly proclaim the state as home to "the greatest snow on Earth." Economically, and as an icon of place, snow is important in this region, and changes in snowpack behavior are therefore also important. Consequently, the GSL basin is an interesting and useful geographical unit of analysis within which to examine the details of any trends in snowpack properties over time.

Data and Methods

Daily SWE records were extracted from the NRCS archive (http://www.wcc.nrcs.usda.gov/snow) for twenty-eight SNOTEL stations throughout the GSL drainage basin (twenty-three in Utah, four in Idaho, and one in Wyoming), as shown in Figure 2. Stations were selected on the basis of length of record, all of which had to date back at least until 1982, thereby providing over a quarter of a century of SWE measurements. Records prior to 1982 were ignored in the few cases where they existed, as were any SNOTEL stations

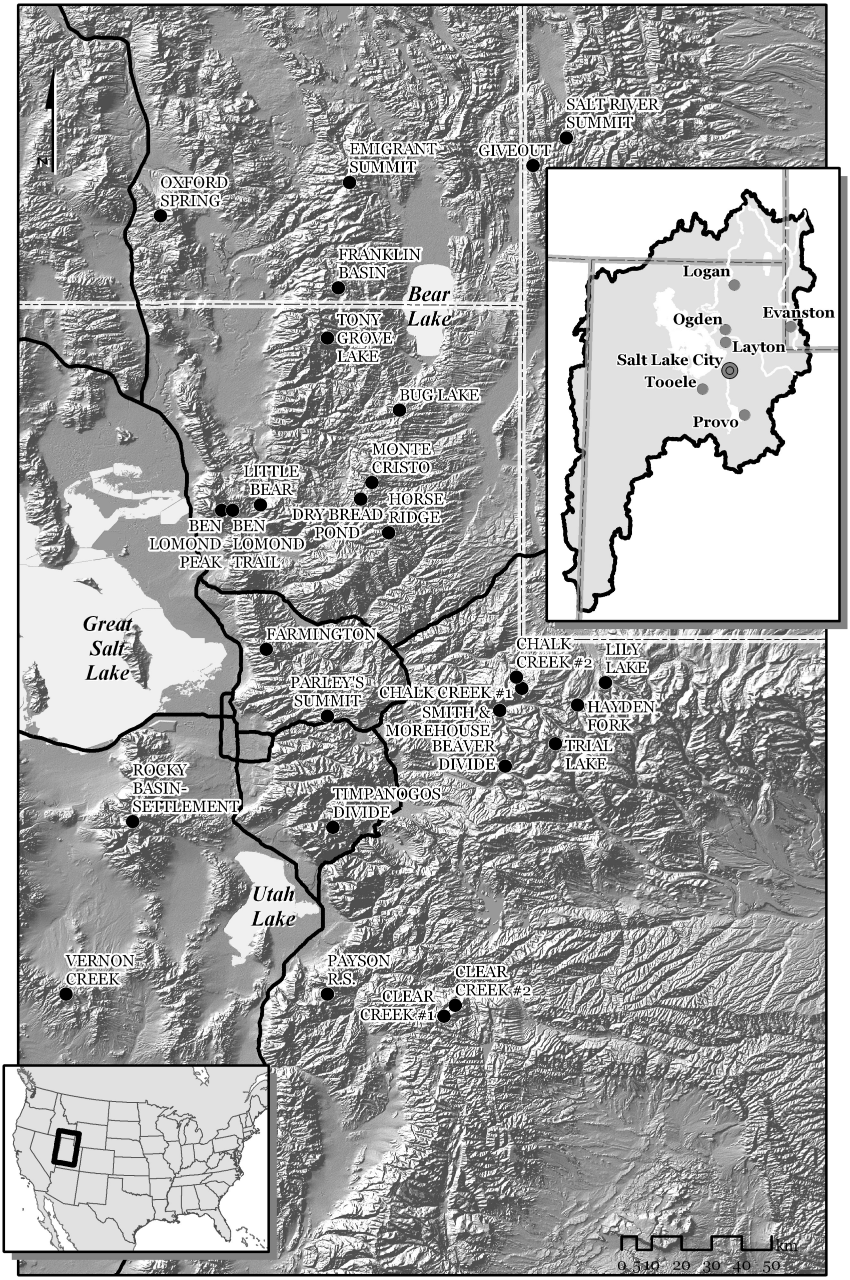

Figure 2 *Map showing location of the twenty-eight SNOTEL stations used in this study. Inset maps show the drainage basin of the Great Salt Lake (top right) and the general location of the region within the continental United States (bottom left). The great majority of the GSL's water is derived from the mountains to the lake's northeast, east, and southeast. (Source: Cartography by Andrea Douglass.)*

becoming operational after 1982. The twenty-eight SNOTEL stations meeting the selection criteria range in altitude from 1,777 m (Ben Lomond Trail, Utah) to 3,046 m (Trial Lake, Utah), with mean and median altitudes of 2,451 m and 2,461 m, respectively. Altitudes for all SNOTEL sites used in this analysis are shown in Table 1.

The SWE records from these stations were analyzed using simple linear regression to identify trends over time in four variables: Julian date and amount of peak SWE, amount of 1 April SWE, and length of melt period (time from the date of peak SWE to the first instance of zero SWE). The basin average (averaged across all twenty-eight stations) was analyzed in addition to the records for individual stations. This suite of properties gives a good indication of any changes in the overall shape of the snowpack accumulation and depletion curve.

Table 1 *Summary of statistics calculated for trends in date and amount of peak snow water equivalent (SWE), and amount of SWE on 1 April, showing correlation coefficient r, slope of the regression line, and the Durbin–Watson statistic (DW)*

		Peak SWE date			Peak SWE amount			1 April SWE		
SNOTEL station name	Height (m)	*r*	Slope	DW	*r*	Slope	DW	*r*	Slope	DW
Trial Lake	3,046	−0.12	−0.28	2.21	−0.35	−0.48	1.90	−0.37	−0.41	1.76
Hayden Fork	2,808	−0.42	−0.91	2.31	−0.34	−0.21	1.24	−0.37	−0.24	1.82
Lily Lake	2,791	−0.39	−0.86	2.28	−0.30	−0.14	1.53	−0.20	−0.08	1.68
Chalk Creek 1	2,741	−0.32	−0.76	2.21	−0.39	−0.39	2.17	−0.39	−0.29	1.90
Monte Cristo	2,731	−0.34	−0.86	2.23	−0.38	−0.46	1.93	−0.33	−0.32	1.68
Clear Creek 1	2,715	−0.17	−0.38	1.43	−0.25	−0.21	1.68	−0.30	−0.23	1.86
Rocky Basin Settlement	2,713	−0.22	−0.52	2.28	−0.35	−0.54	1.30	−0.39	−0.46	1.34
Tony Grove Lake	2,583	−0.27	−0.71	1.76	−0.12	−0.20	1.57	−0.09	−0.14	1.70
Dry Bread Pond	2,545	−0.44	−0.89	2.12	−0.48	−0.51	1.51	−0.45	−0.46	1.52
Beaver Divide	2,524	−0.23	−0.36	2.16	−0.33	−0.16	1.81	−0.39	−0.24	1.83
Horse Ridge	2,487	−0.32	−0.64	1.62	−0.33	−0.32	1.46	−0.30	−0.29	1.61
Chalk Creek 2	2,487	−0.31	−0.45	1.94	−0.31	−0.14	1.98	−0.25	−0.10	2.10
Timpanogos Divide	2,481	−0.22	−0.40	2.03	−0.21	−0.29	1.63	−0.27	−0.35	1.77
Franklin Basin	2,464	−0.21	−0.55	1.92	−0.27	−0.37	1.56	−0.25	−0.27	1.58
Payson RS	2,459	−0.46	−0.92	2.50	−0.66	−0.62	1.49	−0.70	−0.70	1.69
Ben Lomond Peak	2,438	−0.30	−0.72	1.85	−0.27	−0.58	1.57	−0.25	−0.50	1.62
Farmington	2,438	−0.37	−0.87	2.31	0.03	0.04	1.52	0.11	0.16	1.67
Bug Lake	2,423	−0.31	−0.64	1.71	−0.28	−0.24	1.53	−0.26	−0.22	1.69
Salt River Summit	2,365	−0.27	−0.34	1.75	−0.13	−0.07	1.51	−0.10	−0.05	1.45
Clear Creek 2	2,334	−0.19	−0.26	1.78	−0.40	−0.23	1.61	−0.44	−0.23	1.54
Smith and Morehouse	2,316	−0.36	−0.58	2.08	−0.36	−0.18	1.60	−0.36	−0.19	1.87
Parleys Summit	2,286	−0.16	−0.31	1.95	−0.48	−0.36	1.27	−0.48	−0.39	1.47
Vernon Creek	2,256	−0.22	−0.42	1.93	−0.28	−0.20	1.45	−0.35	−0.25	1.48
Emigrant Summit	2,252	−0.51	−1.01	2.75	−0.42	−0.56	1.56	−0.19	−0.24	1.20
Giveout	2,112	−0.20	−0.30	1.51	−0.37	−0.18	2.14	−0.44	−0.24	1.77
Oxford Spring	2,054	−0.36	−0.68	1.89	−0.15	−0.09	1.84	−0.30	−0.22	1.64
Little Bear	1,995	−0.41	−0.81	1.78	−0.36	−0.27	1.32	−0.39	−0.34	1.09
Ben Lomond Trail	1,777	−0.34	−0.47	1.98	−0.20	−0.20	1.63	−0.28	−0.31	1.47
Average	2,451	−0.40	−0.60	1.88	−0.35	−0.29	1.45	−0.35	−0.27	1.46

Note: Shading for r and slope indicates statistical significance (dark for >95 percent, light for >90 percent <95 percent, no shading for <90 percent); shading for DW indicates values in the region of uncertainty for autocorrelation.

For all analyses, precautions were taken against serial autocorrelation, an ever-present risk when using time series data (e.g., see Weatherhead et al. 1998). Mountain snowpack in this region has a very high level of interannual variability (Serreze et al. 1999), thus reducing this risk. Nevertheless, Durbin–Watson (DW) statistics were calculated for each analysis to provide a quantitative determination of the presence or absence of first-order serial autocorrelation. In addition, the autocorrelation function for the basin average was calculated out to five years for each property examined.

Results and Discussion

Tables 1 and 2 summarize the results of the statistical analyses described earlier. For each analysis, the variable listed is regressed against time. The correlation coefficient, r, the trend magnitude (slope of the regression line), and the DW statistic are listed for each analysis and each SNOTEL site (twenty-six observations per site, one for each year 1982–2007), as well as for the basin average. SNOTEL sites are listed in order of altitude, from highest to lowest. Table 1 shows results for date and amount of peak SWE, and amount of 1 April SWE. Table 2 shows results for melt period length.

Statistical significance is indicated in Tables 1 and 2 by gray highlighting. Results that are statistically significant at the 95 percent level are highlighted in dark gray. If the more relaxed 90 percent confidence interval is applied, following aspects of Stewart, Cayan, and Dettinger (2005), many more results become statistically significant. Consequently, results significant at the 90 percent (but not 95 percent)

Table 2 *Summary of statistics calculated for trends in length of melt period, showing correlation coefficient r, slope of the regression line, and the Durbin–Watson statistic (DW).*

		Length of melt period		
SNOTEL station name	Height (m)	*r*	Slope	DW
Trial Lake	3,046	–0.34	–0.52	2.29
Hayden Fork	2,808	0.29	0.36	2.60
Lily Lake	2,791	0.30	0.34	1.50
Chalk Creek 1	2,741	0.10	0.13	2.00
Monte Cristo	2,731	0.34	0.50	2.22
Clear Creek 1	2,715	–0.09	–0.14	2.04
Rocky Basin Settlement	2,713	0.14	0.21	2.54
Tony Grove Lake	2,583	0.23	0.39	2.10
Dry Bread Pond	2,545	0.26	0.40	2.12
Beaver Divide	2,524	–0.25	–0.47	2.97
Chalk Creek 2	2,487	0.16	0.17	2.36
Horse Ridge	2,487	0.06	0.10	2.58
Timpanogos Divide	2,481	0.03	0.05	2.75
Franklin Basin	2,464	0.13	0.22	2.17
Payson RS	2,459	0.06	0.09	2.52
Ben Lomond Peak	2,438	0.24	0.48	2.31
Farmington	2,438	0.51	0.77	1.72
Bug Lake	2,423	0.21	0.30	2.02
Salt River Summit	2,365	0.20	0.30	2.38
Clear Creek 2	2,334	–0.11	–0.14	2.53
Smith and Morehouse	2,316	0.03	0.06	2.34
Parleys Summit	2,286	–0.13	–0.23	2.84
Vernon Creek	2,256	0.00	0.00	2.70
Emigrant Summit	2,252	0.09	0.14	1.61
Giveout	2,112	–0.30	–0.47	1.52
Oxford Spring	2,054	–0.03	–0.05	1.94
Little Bear	1,995	0.09	0.18	1.85
Ben Lomond Trail	1,777	0.11	0.15	2.41
Average	2,451	0.14	0.12	2.47

Note: Shading for r and slope indicates statistical significance (dark for >95 percent, light for >90 percent <95 percent, no shading for <90 percent); shading for DW indicates values in the region of uncertainty for autocorrelation.

level are highlighted in light gray in Tables 1 and 2.

Serial autocorrelation does not seem to be a significant problem, as shown by the DW statistics and autocorrelation functions. Using critical values for DW from Neave (1978), no results showed first-order serial autocorrelation at the 99 percent confidence level, although four fell into the region of uncertainty (two, for melt period length, falling toward negative first-order autocorrelation). These are highlighted in light gray in Tables 1 and 2. Of these, only one result (trend in 1 April SWE for Little Bear SNOTEL station) is statistically significant at the 95 percent confidence level. Thus, although there is uncertainty about a small number of results, for the overwhelming majority the DW statistics do not show first-order serial autocorrelation at the 99 percent confidence level. The autocorrelation functions calculated out to five years for basin averages showed autocorrelation coefficients never exceeding 0.3 (and generally much lower), which further supports this finding.

Regression analysis of trends in the date of peak SWE indicates that, averaged across the drainage basin, a statistically significant (95 percent confidence level) and quite substantial trend exists toward progressively earlier peak snowpack ($r = -0.40$, slope $= -0.60$). This trend is shown in Figure 3, which indicates that, on average, peak SWE now occurs some fifteen days earlier across the GSL basin than it did in 1982. All twenty-eight SNOTEL stations show this trend, although to differing strengths and levels of statistical significance, as summarized in Table 1 and mapped in Figure 4. Individually, six stations show substantial and statistically significant trends, with slopes ranging from −0.81 to −1.01, averaging −0.90. These six stations account for nearly 20 percent of long-term average 1 April SWE for the basin, calculated from 1971 through 2000 snow course data compiled by the NRCS. Figure 4 and Table 1 show that these statistically significant results are widely distributed across the drainage basin from north to south, and over a wide range of altitudes; this is a basinwide trend with little, if any, spatial heterogeneity. This result of earlier peak SWE dates is consistent with Cayan et al.'s (2001) and Stewart, Cayan, and Dettinger's (2004, 2005) findings of earlier pulses of spring runoff in western U.S. rivers.

Trends in the magnitude of peak SWE and 1 April SWE are much less distinct, and generally weaker. The basin average shows a slight downward trend over time ($r = -0.35$, slope $= -0.29$), but this is not significant at the 95

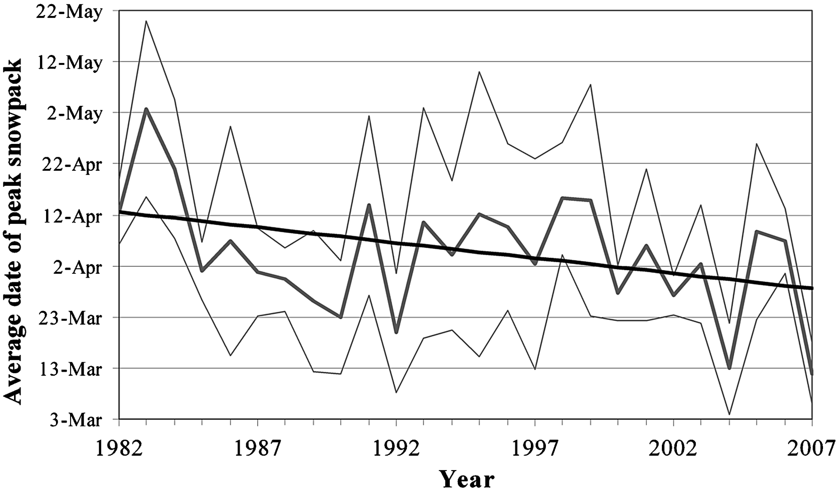

Figure 3 *Date of peak snowpack, averaged for twenty-eight SNOTEL stations across the Great Salt Lake drainage basin, for 1982–2007 (heavy gray line), and calculated trend with time (heavy black line). Light gray lines show ±1 standard deviation from the annual average peak snowpack date.*

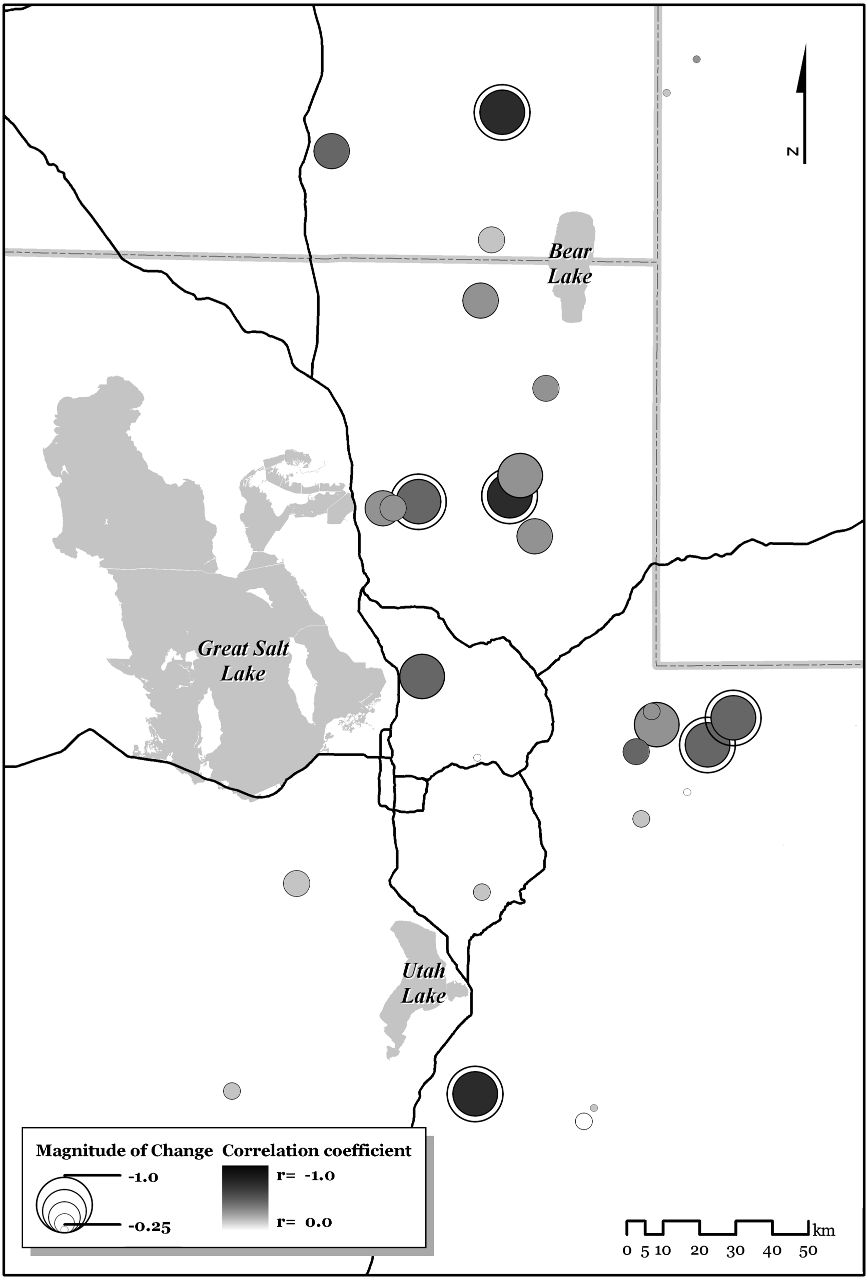

Figure 4 *Map showing spatial pattern of trends in timing of peak snow water equivalent (SWE). Circles show the location of each SNOTEL station. Shading indicates magnitude of correlation coefficient r (darker is closer to −1.0, lighter is closer to 0.0); circle size indicates trend magnitude (slope of regression line); double circles indicate statistical significance >95 percent. (Source: Cartography by Andrea Douglass.)*

percent level. Analyzed individually, however, six stations show moderate downward trends in peak SWE significant at the 95 percent level (slopes ranging from −0.23 to −0.62). Together, these six stations account for nearly 20 percent of long-term average 1 April SWE for the basin. As with the results for date of peak snowpack, little or no spatially coherent pattern is evident: The six stations are widely distributed across the drainage basin from north to south, and across a wide range of altitudes (see Table 1 and Figure 2). Results for 1 April SWE are similar: The basin-average trend ($r = -0.35$, slope $= -0.27$) is not statistically significant at the 95 percent level, but seven stations show statistically significant downward trends in 1 April SWE of moderate magnitude (slopes from −0.23 to −0.70). Again, these stations account for nearly 20 percent of long-term 1 April SWE and are widely distributed across the basin.

Using the 90 percent confidence level, many more stations, as well as the basinwide averages, show statistically significant trends for both amount of peak SWE and amount of 1 April SWE. For peak SWE, an additional nine stations show statistically significant negative trends, bringing the total to fifteen, with slopes averaging −0.36. These fifteen stations together account for nearly 50 percent of basinwide long-term 1 April SWE. For 1 April SWE, an additional seven stations show statistically significant negative trends, bringing the total to fourteen, with slopes averaging −0.34. Together, these stations account for over 40 percent of basinwide long-term 1 April SWE. Thus, the trends in amount of peak SWE and amount of 1 April SWE amount to moderate but significant reductions, if statistical significance is relaxed to the 90 percent confidence level.

Again at the 90 percent confidence level, Table 1 shows that thirteen stations have trends in amounts of both peak and 1 April SWE, and only three stations have trends in one or the other, but not both. This would seem to undermine the earlier point that an exclusive focus on 1 April SWE could provide an incomplete picture of snowpack changes in some cases, as for the most part Table 1 suggests that changes in peak and 1 April SWE occur together. At the more compelling 95 percent confidence level, however, only four stations have trends in both properties, and five stations have trends in one or the other, but not both. These stations account for nearly 17 percent of basinwide long-term 1 April SWE, and an exclusive focus on 1 April SWE in these cases would indeed produce an incomplete or misleading picture of snowpack behavior. Examination of other properties, made possible by the higher temporal resolution of the SNOTEL data, does appear to make a useful contribution to the study of snowpack changes.

Table 2 shows the results of the analysis of melt period length, and indicates a general absence of trends, even at the 90 percent confidence level. Two stations show trends toward longer melt periods, one shows a trend toward shorter melt periods, and the remaining twenty-five stations and the basin average show no statistically significant trend. Thus, the earlier dates of peak SWE suggest earlier onset of melt, but the snowpack seems to be melting at about the same rate—around forty-two days on average from peak to zero, with a standard deviation of around seven days. Figure 5 graphs peak SWE and first zero dates and melt period length. This is at odds with the faster snowmelt expected in a warmer climate (e.g., Lettenmaier and Gan 1990; Rango 1992; Price and Barry 1997; Barry and Seimon 2000) and recently observed across the western United States (Pagano et al. 2004; Dettinger et al. 2007). It is possible that rapid melt early in the period is balanced by slower melt later, masking the faster melt by producing a melt period of unchanged length. There is some evidence for this possibility, as discussed later.

Overall, these results add up to a picture of a mountain snowpack undergoing change. This is summarized in Figure 6, which illustrates snowpack accumulation and depletion averaged across the GSL drainage basin and averaged over time for three ten-year periods: 1982–1991, 1990–1999, and 1998–2007. The difference between 1982–1991 and 1998–2007 is also shown. Figure 6 shows that, in common with the western United States as a whole, 1 April SWE in the GSL drainage basin has declined. In addition, the higher temporal resolution of the SNOTEL data further shows that the date of peak snowpack has shifted to earlier in the year, although use of ten-year averages somewhat underplays this compared with Figure 3. Thus, the shapes of the three snowpack

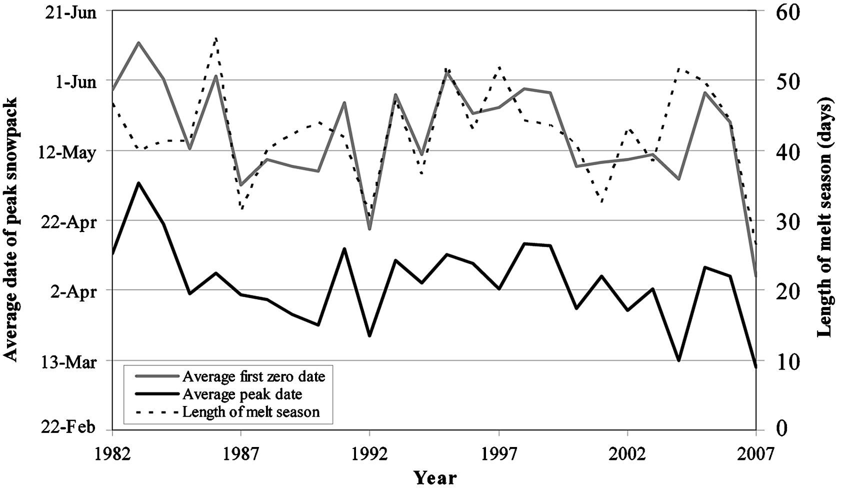

Figure 5 *Basinwide averages for date of peak snow water equivalent (SWE; black line) and first zero SWE (gray line), read from left-hand axis, and length of melt period (dashed line, read from right-hand axis).*

curves in Figure 6 are different along both axes: time and SWE.

The major snowpack changes appear to be related to spring rather than autumn or winter, as shown by the difference curve (1982–1991 minus 1998–2007). Small changes occur in this curve in late autumn and early winter, but the curve is essentially flat from December to mid-March. Differences then increase as 1982–1991 snowpack continues to accumulate but 1998–2007 snowpack levels off and begins to melt. A gradual reduction in differences in early April is replaced with a sharp increase in late April, as 1998–2007 snowpack melts rapidly compared with 1982–1991; differences gradually drop to zero as late-season melting occurs more slowly

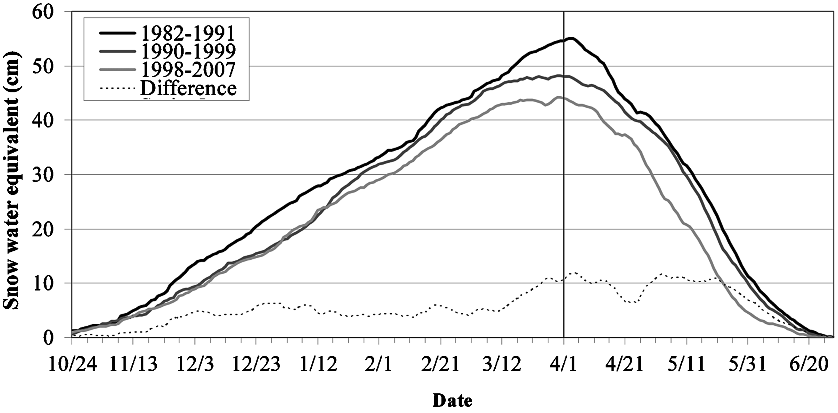

Figure 6 *Changes in snowpack accumulation and depletion from 1982 to 2007, as tracked by three ten-year average curves for the twenty-eight SNOTEL stations in the Great Salt Lake drainage basin. Curves shown are for 1982 to 1991 (black line), 1990 to 1999 (dark gray line) and 1998 to 2007 (light gray line). The difference between 1982–1991 and 1998–2007 is shown by the thin dashed line.*

in 1998–2007 versus 1982–1991. This provides support for the suggestion that faster melt early in the melt period is balanced by slower melt later, as mentioned earlier.

Although it is beyond the scope of this article to ascertain causes of the observed trends, two immediately obvious possibilities exist: regional teleconnection forcing from El Niño events and a recently observed regional warming that may be associated with global warming. Snowpack in the region generally, and the GSL basin specifically, is known to be sensitive to El Niño events (e.g., Alder 2002; Regonda et al. 2005), and wet periods (late peak SWE dates in Figure 3) in the mid-1980s and late 1990s correspond with El Niño years. Alternatively, the observed trends are consistent with regionwide warming observations and with global warming scenarios. Mote et al. (2005) found a warming of 2.0°C to 4.0°C in the GSL basin over the period from 1950 to 1997, and a more or less neutral precipitation trend (some locations increased, some decreased). Dettinger et al. (2007) found that Utah's 2006 April and May temperatures were more than +1°C warmer than normal, in the top 10 percent of the historical record, with a rapid transition from winter to summer conditions (compressed spring) occurring across the western United States. This is consistent with the findings discussed earlier, that changes in spring appear to be driving the overall snowpack changes in the GSL basin.

Limitations and Cautions

Several limitations of this study serve to emphasize that the results are tentative, not definitive. First, the correlation coefficients tend to be relatively low, and even when using the 90 percent confidence interval, only about half the stations in the basin show statistically significant trends. Second, the period of record is relatively short. This is the trade-off for the higher temporal resolution afforded by the SNOTEL data versus the longer but lower resolution snow course data. Third, interannual variability in snowpack is very high in this region—one of the highest of any continental interior region examined by Serreze et al. (1999)—making trend detection and attribution difficult. To exemplify this point, the period of record used here begins with a run of exceptionally wet years, 1982 to 1986, which caused flooding in Salt Lake City and record high levels of the GSL. This is clearly evident in Figure 3. The 1971–2000 average 1 April SWE for the GSL basin as a whole is 52.8 cm; in 1982 to 1986 the GSL basin average was 72.8, 63.6, 74.0, 60.7, and 70.0 cm for each year, respectively. Thus, it is possible that the trends identified here simply mark a return to long-term average conditions after a series of anomalously wet years; indeed, the basinwide average trend toward earlier peak SWE identified for 1982–2007 all but disappears if these wet years are ignored and only 1987 through 2007 data are considered. A second shift toward earlier peak SWE is evident in Figure 3, beginning in the mid- to late 1990s, and if the period 1995 to 2007 is analyzed, a strong trend appears again ($r = -0.58$, slope $= -1.65$, 95 percent confidence level). This illustrates the strong dependence of trend on the length of record, thus warranting caution in interpreting the results discussed earlier. Nevertheless, the results are consistent with regionwide trends toward earlier spring, including river behavior (noted earlier) and timing of blooming flowers (Cayan et al. 2001), suggesting they should be taken cautiously, but seriously.

Conclusions and Implications for the Great Salt Lake Drainage Basin

The high temporal resolution of SNOTEL data relative to other records allows its use to reveal important nuances in western U.S. snowpack trends. In particular, SNOTEL data can resolve the issue of whether changes in 1 April SWE represent changes in total amounts of snow accumulated, or simply shifts in timing of snow accumulation and depletion. In the drainage basin of the GSL, although reduced peak and 1 April SWE are apparent, the stronger trend is toward earlier peak SWE and earlier onset of melt. Possible forcing mechanisms include El Niño events as well as recent regional (and possibly global) warming. Trends in the GSL basin are consistent with observations of river behavior and other indicators of earlier onset of spring across the western United States. If these trends represent the future of the GSL basin's snowpack, water managers will face significant challenges in coming decades, especially in light of anticipated population growth in northern Utah. Long-term averages may no longer serve as an adequate guide to snowpack behavior; earlier melt, and consequent longer snow-free periods, may become the norm.

Given these circumstances, it is reasonable to speculate that the GSL itself may receive progressively less freshwater, as a consequence of snowpack changes and increased demand due to population growth. The GSL could enter a phase of desiccation, shrinking, and increased salinity—indeed, this may already be happening. The ecology of the GSL can sustain such changes up to a point, but beyond a certain threshold, the salinity becomes too great even for the brine shrimp *Artemia franciscana* to survive in large numbers. Exactly where this threshold lies is unclear (Stephens and Birdsey 2002), but the northern part of the GSL, cut off from freshwater inputs by a railroad causeway, has a salinity around 28 percent and is effectively devoid of brine shrimp. If the southern part of the GSL were to become as salty, the brine shrimp population could suffer. In this instance, the migratory bird populations would be affected, as some species (such as the Eared Grebe) are heavily or entirely dependent on brine shrimp for food (Aldrich and Paul 2002). The brine shrimp egg harvesting industry, which provides brine shrimp eggs as food to the global aquaculture industry and generates millions of dollars of revenues each year, would also be affected under these circumstances. It should be noted that during the GSL's historic low level in 1963, salinities for the southern part of the lake were around 26 percent (Stephens 1998), so this scenario is not impossible. Careful monitoring of snowpack and of the GSL is needed in the future.

Note

[1] Although the U.S. Geological Survey classifies the GSL and Bear River drainage basins as separate units (both are subbasins of the Great Basin), both drain water into the GSL. In this article, the term *GSL drainage basin* is used to apply to the area draining into the GSL.

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DANIEL BEDFORD is an Associate Professor in the Department of Geography at Weber State University, Ogden, UT 84408. E-mail: dbedford@weber.edu. His research interests include the environmental–societal system of the Great Salt Lake, and of the Aral Sea in central Asia.

ANDREA DOUGLASS received her Bachelor of Science degree in geography from Weber State University in 2005, and is currently a GIS specialist for Ogden City, UT 84401. E-mail: AndreaDouglass@ci.ogden.ut.us.