

## ASSESSING THE SENSITIVITY OF WASATCH MOUNTAIN SNOWFALL TO TEMPERATURE VARIATIONS

Leigh P. Jones and John D. Horel<sup>1</sup>

### ABSTRACT

Three methods are employed in this study to estimate the sensitivity of snow falling in the Wasatch Mountains of northern Utah to observed and projected changes in atmospheric temperature. Daily precipitation data from 1 October to 30 April 1979-2008 are examined from selected snowpack telemetry (SNOTEL) sites in northern Utah. Profiles of wet bulb temperature from near crest level (700 mb) to elevations along the mountain slopes of selected watersheds are estimated on days with precipitation soundings launched from the nearby Salt Lake City airport. The rain-snow line is assumed to correspond uniformly to the elevation of the wet bulb temperature equal to 1°C. Probability distribution functions of the fraction of precipitation falling as snow as a function of daily wet-bulb temperature are computed. The percentage of precipitation estimated to fall at wet-bulb temperatures in the range 0-1°C is assumed to switch from snow to rain if temperatures increase by 1°C. While the sensitivity to temperature depends strongly on elevation within the watershed, an increase in tropospheric temperatures of 1°C is estimated to lead to an 8-10% decrease in snow when averaged over the selected watersheds. (Keywords: climate change, snow sensitivity)

### INTRODUCTION

The demand for water in northern Utah is high and much of the region's hydrologic needs are met with the annual springtime melt of the montane seasonal snowpack. Additionally, northern Utah's winter tourism depends to a large extent on snow-related recreation. The seasonal snowpack in this region is likely to be affected by projected trends in temperature and precipitation over the next century resulting from anthropogenic climate change. The summary of climate research in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) found that global land masses have warmed, on average, about a quarter of a degree Celsius per decade since the late 1970s (Trenberth et al., 2007). Northern Hemispheric land has warmed at a rate 1.3 times the global average, with continental interiors (such as the Intermountain West) contributing the most to warming (Trenberth et al., 2007). 21<sup>st</sup> century temperature projections from IPCC General Circulation Model (GCM) runs show continued increasing trends in temperature (Meehl et al., 2007). GCM simulations of free atmospheric temperatures in the vicinity and close to the elevation of the Wasatch suggest an increase of 1C during the first half of the 21<sup>st</sup> century and an increase of 2.5 by the second half.

The projected changes in temperature are part of complex nonlinear changes, which include alterations in storm tracks and thus the distribution of moisture and precipitation. Decreases in precipitation in the southwestern United States and increases in the northwestern United States have already been observed (Trenberth et al., 2007). 21<sup>st</sup> century GCM projections suggest that precipitation over the western United States will likely continue to increase to the north and decrease to the south (Meehl et al., 2007). Utah falls within the transition zone between these large-scale northern and southern precipitation trends.

Observational studies suggest that impacts from a changing climate in snow-dominated regions have already begun to be realized (Cayan et al., 2001; Stewart et al., 2005; and Regonda et al., 2005; Hamlet et al., 2005; Mote et al., 2005, 2006; Barnett et al., 2008; Pierce et al., 2008). A number of studies have sought to estimate whether the observed fraction of precipitation falling as rain is increasing during winter storms. These changes have been noted in the mountainous northeastern and western United States (Huntington et al., 2004 and Knowles et al., 2006, respectively). The latter study showed that lower elevation mountain ranges, where average winter temperatures are closer to the melting temperature, such as the northern Sierra Nevada and Washington Cascades, are most sensitive to temperature changes during storms; a clear signal was not evident in the Wasatch Mountains of northern Utah. Casola et al. (2009; hereafter referred to as CAS09) used empirical and hydrologic modeling approaches to estimate the sensitivity of spring snowpack to past and future temperature rises in the Cascades. For

---

Paper presented Western Snow Conference 2009

<sup>1</sup> Department of Atmospheric Sciences, University of Utah, Salt Lake City, UT, [leigh.jones@utah.edu](mailto:leigh.jones@utah.edu)

<sup>1</sup> Department of Atmospheric Sciences, University of Utah, Salt Lake City, UT, [john.horel@utah.edu](mailto:john.horel@utah.edu)

this range, they estimated a 20% decrease in spring snowpack per °C temperature rise.

The hydrologically-significant elevations of the Wasatch Mountains extend from around 1900 m to over 3000 m where the seasonal accumulation of snow occurs. Around 80% of the annual mountain precipitation falls in the autumn, winter and spring, and mostly as snow. Average seasonal SWE varies by location from 40 to over 100 cm and can vary annually from half to two times the average. This large interannual variability, as well as documented non-climatic influences to the observational data (Julander and Bricco, 2006), have made it difficult to identify any long term trends in the Wasatch snowpack.

Since GCMs do not resolve mountain ranges of the size of the Wasatch Mountains, confidence in the precipitation estimates from GCM simulations in this region is low (Randall et al., 2007). Global GCM simulations at higher resolution (~50 km) and regional climate models embedded within GCMs are beginning to become available for this region as part of the North American Regional Climate Change Assessment Program (available: [www.narccap.ucar.edu](http://www.narccap.ucar.edu)). However, such regional simulations remain too coarse to be able to resolve the precipitation processes over the narrow mountain ranges of northern Utah in sufficient detail. Furthermore, given the complex terrain embedded within GCM and regional GCM grid boxes for northern Utah mountain ranges, direct estimates of variability and trends in surface temperature from such model simulations are likely less reliable than the model estimates of variability and trends in free atmospheric temperature above the mountains.

Since direct estimates of surface temperature and precipitation trends in GCMs and regional GCMs for the mountain ranges of northern Utah are subject to large uncertainty, this study focuses on empirically assessing the sensitivity of snow falling in two catchments of northern Utah to observed variability in tropospheric temperature. The approaches used follow prior empirical research, such as that developed by CAS09, which have been applied to other mountain ranges, typically with much lower base elevations than the catchments examined here: Ben Lomond watershed of the Wasatch Mountains and the Oquirrh range immediately to the west of the Salt Lake Valley (Figure 1). These two catchments serve as representative regions for northern Utah watersheds to test the applicability of these empirical methods.

## **PROCEDURE**

### **Data**

This study utilizes precipitation and temperature measurements from NRCS SNOpack TELemetry (SNOTEL) stations. Both catchments in this study contain 2 SNOTEL stations. Ben Lomond contains Ben Lomond Peak (BLPU1, elev. 2389 m) and Ben Lomond Trail (BLTU1, elev. 1777 m); the Oquirrh contains the Rocky Basin Settlement (RBSU1, elev. 2650 m) and Dry Fork (DRFU1, elev. 2162 m). The climatological distribution of precipitation over the terrain was used to establish precipitation-elevation relationships for each area. Climatological precipitation data came from 30-arc-second (~800-m) monthly normal (1971-2000) gridded Parameter-elevation Regression on Independent Slopes Model (PRISM; Daly et al., 1994) datasets (Doggett et al., 2004; available: <http://www.prism.oregonstate.edu/products/matrix.phtml?vartype=ppt&view=maps>). Free atmospheric temperature and moisture were derived from twice-daily soundings from the Salt Lake City airport (KSLC). The time period examined was each accumulation season in the Wasatch (October-April) of the water years 1979-2008.

### **Methods**

Sensitivity is defined as the percent of snowfall that is changed to rain per degree Celsius warming. More specifically, it examines what fraction of the precipitation currently falls just at or above the rain-snow threshold wet-bulb temperature ( $T_{RS}$ ). Here we assume that the wet-bulb temperature at which snow turns to rain is 1°C. Indeed, there are multiple instances in which that threshold may be a couple degrees cooler or warmer than 1°C, but for purposes here, this single value suffices, and has been shown to be accurate for these locales. The threshold was derived locally from observational work done by Randy Graham and others (2008, personal communication) from the Salt Lake City NWS Forecast Office. Their study was conducted at the KSLC airport sounding site (Figure 1), where they documented precipitation type as a function of surface wet-bulb temperature. They found that 0°C roughly marked the transition from all snow to mixed-phase precipitation and 2°C marked the transition from mixed-phase to all rain. Similar results completed by the U.S. Army Corps of Engineers in 1956 and from studies in other mountainous regions in the West (Yuter et al., 2006; Lundquist et al., 2008; D. Kingsmill 2008, personal communication) further confirm the  $T_{RS}$  value used in this study.



Here we make the crude assumption that future precipitation amounts will not change in northern Utah, given GCM simulations that place the region in the transition zone between increasing precipitation to the north and decreasing precipitation to the south. Holding precipitation constant and varying temperature, we can estimate the amount of wintertime precipitation in the Wasatch likely to fall as rain rather than snow as temperatures increase. We create probability distribution functions of daily precipitation that currently falls at a given temperature. To simulate a warming, we simply shift the distribution function to warmer temperatures. The fraction of the distribution that is currently below  $T_{RS}$ , and which would be warmed to greater than threshold, is the fraction of precipitation assumed to change to rain.

Three methods were used to derive estimates of snowfall sensitivity in the Wasatch:

1. SNOTEL precipitation vs. SNOTEL temperature
2. SNOTEL precipitation vs. estimated wet-bulb temperature
3. Estimated area-wide precipitation vs. estimated area-wide wet-bulb temperature

The first two methods use precipitation measured by the SNOTEL station, but method #1 plots it against temperature at the station, and method #2 plots it against wet-bulb temperature ( $T_w$ ) at the station. Since the stations do not have humidity instrumentation, the values were estimated from the KSLC sounding.  $T_w$  was obtained from the 700-mb level, which is close to crest-level for the Wasatch, and, using a saturated adiabatic lapse rate, could be used to estimate the  $T_w$  at the elevation of the SNOTEL. This would essentially be the temperature to which the precipitation would be responding as it falls at the SNOTEL. Method #3 utilizes the spatial climatology provided by PRISM, and, for each storm, estimates the precipitation distribution over the terrain, based on the PRISM distribution. The  $T_w$  distribution can also be estimated by calculating the  $T_w$  at every elevation using the KSLC sounding information and the saturated adiabatic lapse rate.

## **RESULTS**

### **1. SNOTEL Precipitation vs. SNOTEL Temperature**

Figure 2 shows the distribution of precipitation vs. temperature as measured at each SNOTEL. The Ben Lomond stations are on the left, the Oquirrh stations are on the right. If temperatures were uniformly increased 1 C, the distribution function would be shifted one degree to the right, and the bin just below the  $T_{RS}$  (assumed to be snow, highlighted blue), would become rain. Thus, the sensitivity for the SNOTELs on Ben Lomond are 8%  $^{\circ}\text{C}^{-1}$  and 17%  $^{\circ}\text{C}^{-1}$ ; and those in the Oquirrhs are 5%  $^{\circ}\text{C}^{-1}$  and 10%  $^{\circ}\text{C}^{-1}$ .

### **2. SNOTEL Precipitation vs. Estimated $T_w$**

Wet-bulb temperature was estimated at each SNOTEL, and the same distributions were created using SNOTEL precipitation. Figure 3 shows the results. Using this method, the sensitivity for the SNOTELs on Ben Lomond are 9%  $^{\circ}\text{C}^{-1}$  and 20%  $^{\circ}\text{C}^{-1}$ ; and those in the Oquirrhs are 5%  $^{\circ}\text{C}^{-1}$  and 8%  $^{\circ}\text{C}^{-1}$ .

### **3. Estimated Area-wide Precipitation vs. Estimated Area-wide $T_w$**

Wet-bulb temperature and precipitation amount was estimated over the terrain, and the same distributions were created, incorporating the entire area. Figure 4 shows the results. The average area-wide sensitivity over Ben Lomond (the Oquirrhs) is 8%  $^{\circ}\text{C}^{-1}$  (10%  $^{\circ}\text{C}^{-1}$ ). Figure 5 displays this result spatially, and additionally computes the fraction of snow lost under a 2, 3 and 4  $^{\circ}\text{C}$  warming. For a single degree increase, the area-wide snowfall lost over Ben Lomond ranges from ~20% at the base to ~4% at the top. Oquirrhs sensitivities ranged from ~16% to ~2%. The elevational-dependence of the sensitivity can be seen here, as climatologically-warmer elevations have the highest percentage of their snow falling at warmer temperatures and have the highest chances of losing snow to warming.

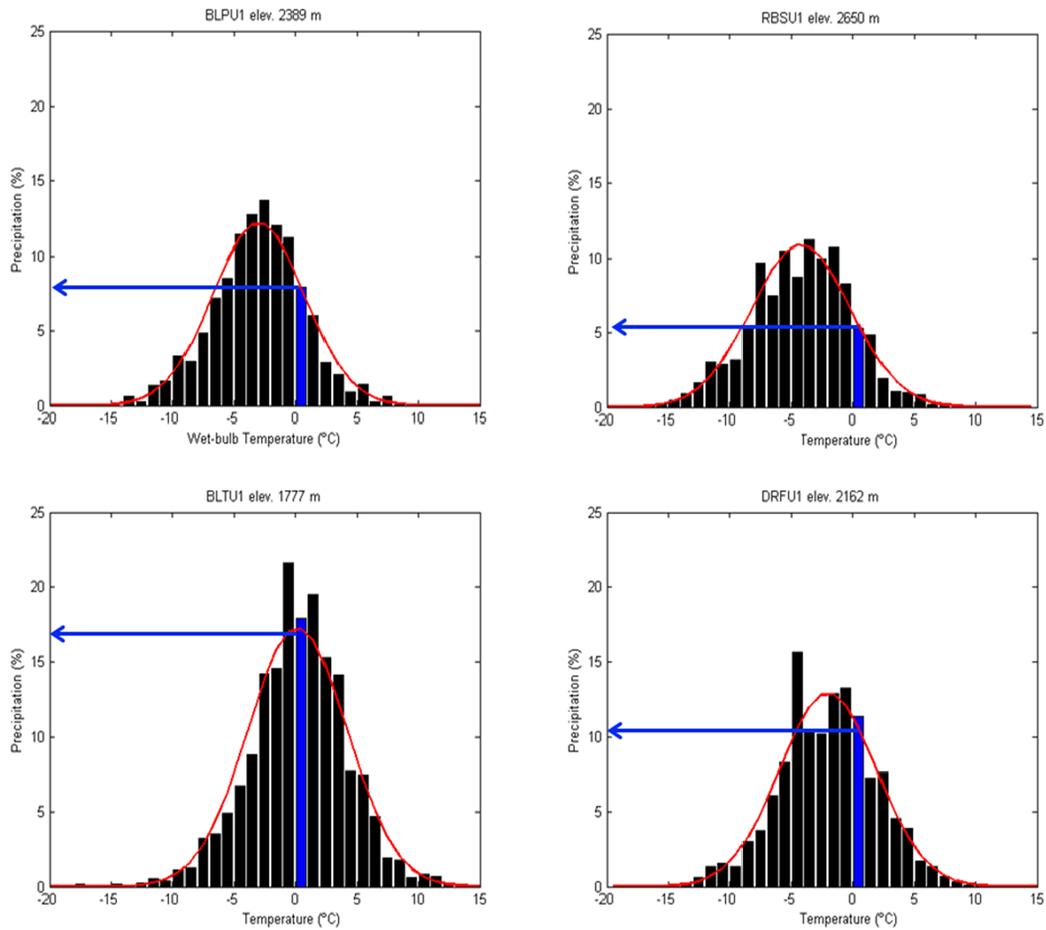


Figure 2. Distribution of October-April water equivalent precipitation as percentages of total snow water precipitation over each station's period of record binned by the observed temperature. The percentage in the 0-to-1°C bin (blue bar) represents the fraction of snow water precipitation that would change to rain if temperatures were to increase 1°C. A Gaussian curve (red line) has been fitted to the data.

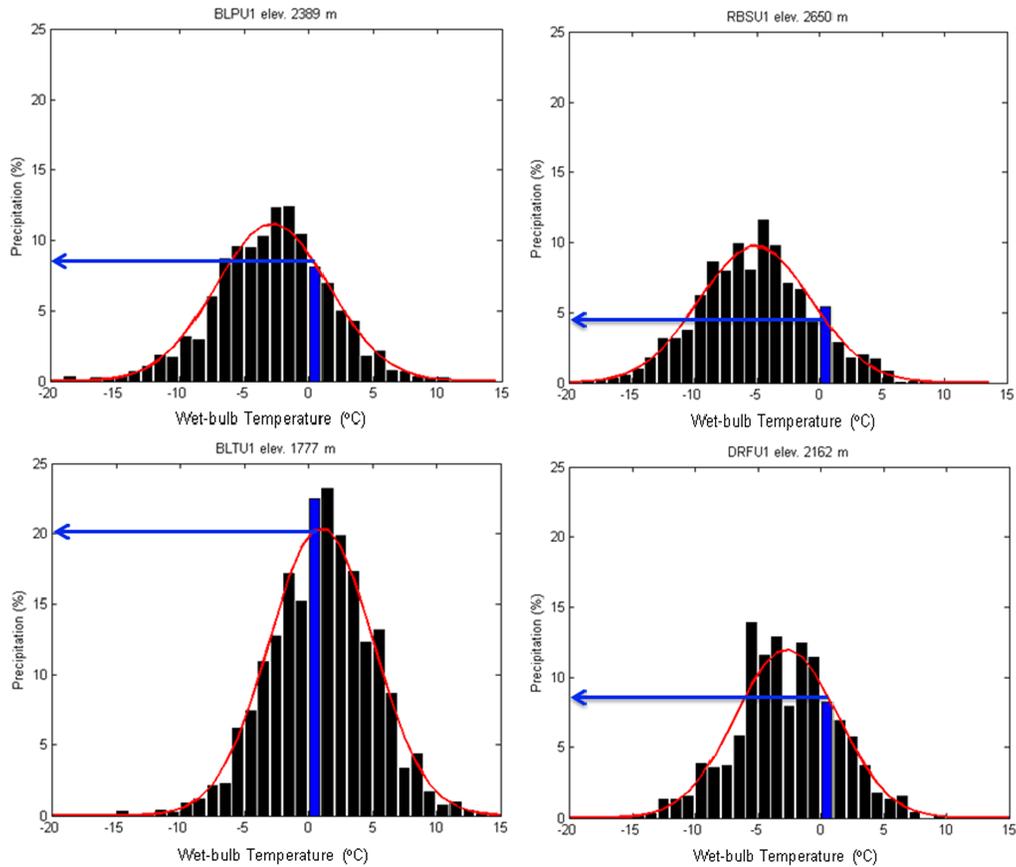


Figure 3. Distributions of October-April water equivalent precipitation as percentages of total snow water precipitation over each station's period of record binned by the estimated station  $T_w$  at which the precipitation fell. Being that the RST is 1°C, the 0-to-1°C interval represents the fraction of snow water precipitation that would change to rain if temperatures were to increase 1°C. A Gaussian curve (red line) has been fitted to the data.

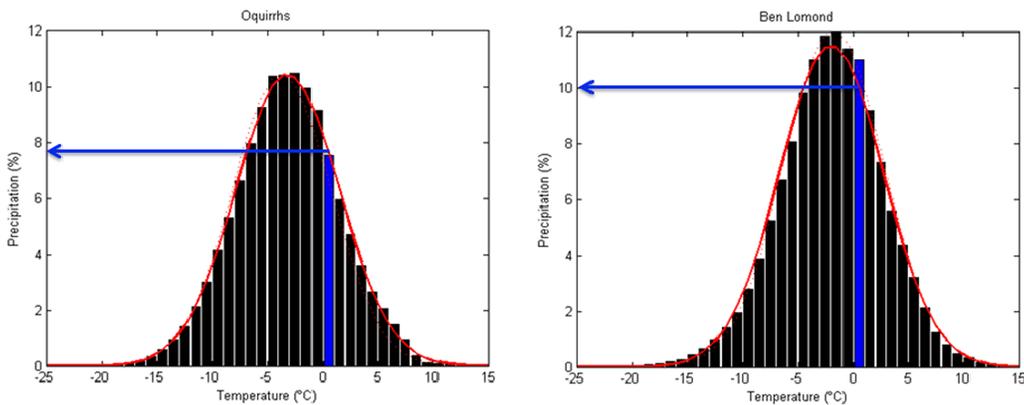


Figure 4. Area-wide October-April water equivalent precipitation as percent-ages of total snow water precipitation binned by the extrapolated  $T_w$  at which it fell for Ben Lomond (top) and the Oquirrh (bottom), using BLPU1 and RBSU1 in each region, respectively. A Gaussian curve (solid red line) has been fitted to the data.

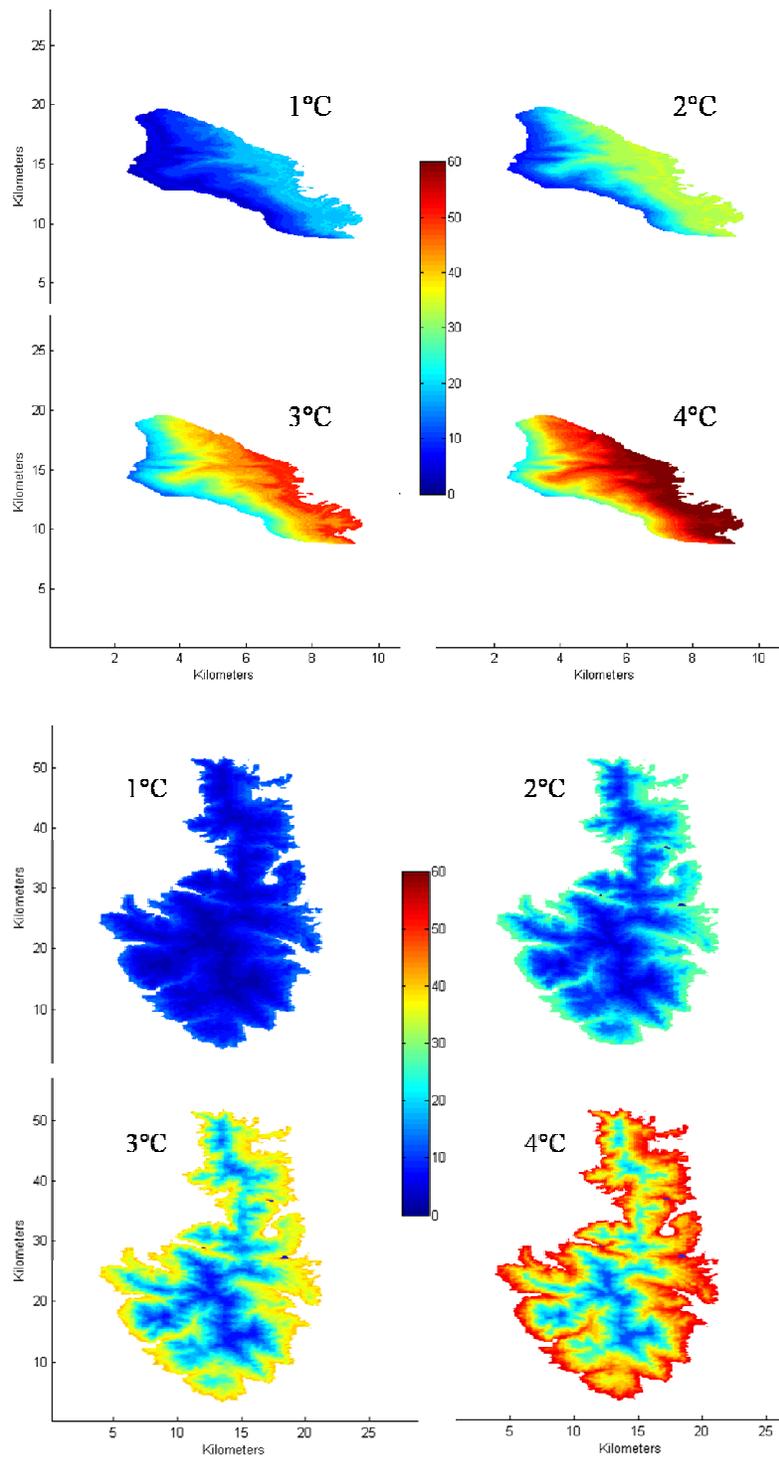


Figure 5. Estimated, area-wide percentage of snow lost as a function of increasing temperature for Ben Lomond (top) and the Oquirrhis (bottom).

## SUMMARY/CONCLUSIONS

The driving factors for this study were the importance of the seasonal mountain snowpack for water supply in northern Utah and the threat posed to it by GCM-projected temperature increases over the next century. Precipitation changes associated with global warming are difficult to assess at this time, but it may be assumed that there will be no change to precipitation amount in northern Utah. This study examined the fraction of precipitation currently falling as snow in the mountains of northern Utah which may fall instead as rain as temperatures warm. Two regions in the Wasatch were chosen for analysis. We found that, averaged over each region, an increase of 1°C would lead to 8-10% decrease in snow. These estimations are largely elevationally-dependent, with sensitivities ranging from near 0% at the colder summits to 20% at warmer, lower elevations. Far greater losses could be seen with increased warming.

## ACKNOWLEDGEMENTS

This research was funded by the Kennecott Land Corporation.

## REFERENCES

- Barnett, T. P., and Coauthors. 2008. Human-Induced Changes in the Hydrology in the Western United States. *Science*, **319**:1080–1083.
- Casola, J. H., L. Cuo, B. Livneh, D. P. Lettenmaier, M. T. Stoelinga, P. W. Mote, and J. M. Wallace. 2009. Assessing the Impacts of Global Warming on Snowpack in the Washington Cascades. *J. Climate*, In Press.
- Cayan, D. R., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio, and D. H. Peterson. 2001. Changes in the Onset of Spring in the Western United States. *Bull. Amer. Meteor. Soc.*, **82**:399–415.
- Daly, C., R. P. Nelson, D. L. Phillips. 1994. A Statistical-Topographic Model for Mapping Climatological Precipitation over Mountainous Terrain. *J. Appl. Meteor.*, **33**:140–158.
- Doggett, M., C. Daly, J. Smith, W. Gibson, G. Taylor, G. Johnson, and P. Pasteris. 2004. High-resolution 1971-2000 mean monthly temperature maps for the western United States. Proc. 14<sup>th</sup> AMS Conf. on Applied Climatology, Seattle, WA, January.
- Hamlet, A. F., P. W. Mote, M. P. Clark, and D. P. Lettenmaier. 2005. Effects of Temperature and Precipitation Variability on Snowpack Trends in the Western United States. *J. Climate*, **18**:4545–4561.
- Huntington, T. G., G. A. Hodgkins, B. D. Keim, and R. W. Dudley. 2004. Changes in the Proportion of Precipitation Occurring as Snow in New England (1949-2000). *J. Climate*, **17**:2626–2636.
- Julander, R. P., and M. Bricco. 2006. An Examination of External Influences Imbedded in the Historical Snow Data of Utah. Proc. 74<sup>th</sup> Western Snow Conference, Las Cruces, NM, 61–72.
- Knowles, N., M. D. Dettinger, and D. R. Cayan. 2006. Trends in Snowfall versus Rainfall in the Western United States. *J. Climate*, **19**:4545–4559.
- Meehl, G. A., and Coauthors. 2007a. Global Climate Projections. *Climate Change 2007: The Physical Science Basis*, S. Solomon et al., Eds., Cambridge University Press, 747–846.
- Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier. 2005. Declining Mountain Snowpack in Western North America. *Bull. Amer. Meteor. Soc.*, **86**:39–49.
- . 2006. Climate-Driven Variability and Trends in Mountain Snowpack in Western North America. *J. Climate*, **19**:6209–6220.

Pierce, D. W., and Coauthors. 2008. Attribution of Declining Western U.S. Snowpack to Human Effects. *J. Climate*, **21**, 6425–6444.

Randall, D. A., and Coauthors. 2007. Climate Models and Their Evaluation. *Climate Change 2007: The Physical Science Basis*, S. Solomon et al., Eds., Cambridge University Press, 589–662.

Regonda, S. K., B. Rajagopalan, M. Clark, and J. Pitlick. 2005. Seasonal Cycle Shifts in Hydroclimatology over the Western United States. *J. Climate*, **18**, 372–384.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger. 2005. Changes toward Earlier Streamflow Timing across Western North America. *J. Climate*, **18**, 1136–1155.

Trenberth, K. A., and Coauthors. 2007. Observations: Surface and Atmospheric Climate Change. *Climate Change 2007: The Physical Science Basis*. S. Solomon et al., Eds., Cambridge University Press, 235–336.

U.S. Army Corps of Engineers. 1956. *Snow Hydrology: Summary Report of the Snow Investigations*. Portland, OR: US Army Corps of Engineers, North Pacific Division.