The Cryosphere Discuss., doi:10.5194/tc-2016-66, 2016
Manuscript under review for journal The Cryosphere
Published: 21 March 2016

The Cryosphere Discussions

Future Snow? A Spatial-Probabilistic Assessment of the Extraordinarily Low Snowpacks of 2014 and 2015 in the Oregon Cascades

Eric A. Sproles[1,2], Travis R. Roth[2], Anne W. Nolin[2]

[1]Centro de Estudios Avanzados en Zonas Áridas, Universidad de La Serena, Raul Bitran 1305, La Serena, Chile
[2]College of College of Earth, Ocean, and Atmospheric Sciences; Oregon State University, 104 CEOAS Admin Bldg, Corvallis, OR, 97331-5503, USA

Correspondence to: Eric A. Sproles (eric.sproles@gmail.com)

Abstract. In the Pacific Northwest, USA, the extraordinarily low snowpacks of winters 2013–2014 and 2014–2015 stressed regional water resources and the social-environmental system. We introduce two new approaches to better understand how seasonal snowpack during these two winters would compare to snowpacks under warmer climate conditions. The first approach calculates a spatial-probabilistic metric representing the likelihood that the snowpacks of 2013–2014 and 2014–2015 would occur under +2ºC perturbed climate conditions. We computed snow water storage (basin-wide and across elevations), and the ratio of snow water equivalent to cumulative precipitation (across elevations). We applied these computations to calculate the occurrence probability for similarly low snowpacks under climate warming. Results suggest that, relative to +2ºC conditions, basin-wide snow water storage during winter 2013–2014 would be above average while that of winter 2014–2015 would be far below average. April 1 snow water storage corresponds to a 40% (2013–2014) and 90% (2014–2015) probability of being met or exceeded in any given year. The second approach introduces the concept of snow analogs to improve the anticipatory capacity of climate change impacts on snow derived water resources. The use of a spatial-probabilistic approach and snow analogs provide new methods of assessing basin-wide snowpack in a non-stationary climate, and are readily applicable in other snow dominated watersheds.

1 Introduction

In the Pacific Northwest (PNW), mountain snowpacks during the winters of 2013–2014 and 2014–2015 were at or near record lows and well below 50% of the historic median value (National Resource Conservation Service, 2014, 2015b). For several decades the Natural Resources Conservation Service (NRCS) Snowpack Telemetry (SNOTEL) network has provided measurements of snow water equivalent (SWE; the amount of water contained within the snowpack) and meteorological data. These station-based measurements have historically served as a proxy for basin-wide snow storage and provide an effective SWE index for estimating streamflow, however under a shifting climate these statistical relationships have also

The Cryosphere Discuss., doi:10.5194/tc-2016-66, 2016
Manuscript under review for journal The Cryosphere
Published: 21 March 2016

changed (Montoya et al., 2014). The extreme low snowpacks of 2013–2014 and 2014–2015 highlight the limitations of location-specific measurements in a shifting climate.

On March 1, 2015, 47% of snow monitoring sites in the Willamette River Basin (29 730 km^2, Fig. 1) registered zero SWE while snow was still present at higher elevations. The absence of snow during the winter of 2014–2015 stands in contrast to cumulative winter precipitation, which was at 83% of normal (688 mm) for November–February (derived from PRISM data (Daly et al., 2008)). While the concurrent drought in California received substantial attention, the economic and environmental impacts in the PNW were also profound. These two extreme low snowpacks in the PNW led to ski area closures, recreation restrictions, municipal water limitations, severe wildfires, low streamflows, nearly dry reservoirs, harmful algal blooms, and high fish mortality. These types of externalities highlight the importance of mountain snowpack and the implications of snow drought.

Mountain snowpack in the western Oregon Cascades and across the western United States serves as vital inter-seasonal storage from cool, wet winters with low water demand to hot, dry summers when demand peaks (Oregon Water Supply and Conservation Initiative, 2008; United States Army Corps of Engineers, 2001). The western Oregon Cascades form the eastern boundary of the Willamette River Basin (Fig.1), and abundant winter precipitation falling in these mountains (up to 3000 mm yr^{-1}) sustains the 13th highest streamflow in the conterminous United States (Hulse et al., 2002). Even in such a wet place, snowmelt is critical. Brooks et al. (2012) estimated that over 60–80% of summer base flow in the Willamette River derives from the snow zone at elevations over 1200 m, though this elevational zone represents only 12% of the land area and 15.6% of the annual precipitation in the basin.

The maritime snowpacks of the western Oregon Cascades and the PNW are deep (>1.5 m), relatively warm (Sturm et al., 1995), and SWE typically reaches its basin-wide maximum on approximately April 1 (Serreze et al., 1999; Stewart et al., 2004). Nolin and Daly (2006) identified snow in the western Oregon Cascades as climatologically "at-risk" since it typically accumulates at close to 0ºC and so can convert to rainfall with just a slight increase in temperature. As a result of changes in circulation patterns and warmer temperatures there have been declines in April 1 SWE in the PNW (Barnett et al., 2005; Kapnick and Hall, 2012; Luce and Holden, 2009; Mote, 2006; Mote et al., 2005; Service, 2004; Stoelinga et al., 2010), and peak streamflow has shifted to earlier in the year (Fritze et al., 2011; Stewart, 2009).

These shifts in streamflow highlight the challenges of using location specific measurements of SWE for prediction in changing climate. SNOTEL sites typically occupy a limited elevation range, which leads to an under-sampling of both the high elevation snow zone and the lower elevation rain-snow transition zone (Molotch and Bales, 2006; Montoya et al., 2014; Nolin, 2012). Elevational shifts in snowpack accumulation due to observed temperature increases make the past less representative of the future (Dozier, 2011; Milly et al., 2008). Additionally, patterns of snow accumulation and melt in the PNW vary as non-linear functions of elevation, slope, aspect, and landcover (Tennant et al., 2015). Augmenting point-based measurements of SWE with metrics that effectively estimate snow water storage in a mountain landscape would include calculations for normal and extreme years across elevations and at the basin scale—especially under current climate trends (Dozier, 2011). Rosenberg et al. (2011) incorporated process-based modeling of SWE as a component of statistical

The Cryosphere Discuss., doi:10.5194/tc-2016-66, 2016
Manuscript under review for journal The Cryosphere
Published: 21 March 2016

regression equations to predict streamflow. The inclusion of SWE did improve the skill of streamflow predictions, however the spatial resolution of the modeled SWE in the study (~5–7 km) would not capture the non-linearity of snow accumulation and melt in the PNW.

The dimensionless ratio of SWE to precipitation (SWE:P) represents the proportion of snow water equivalent relative to cumulative precipitation (snowfall plus rainfall) over a specified time interval (Serreze et al., 1999). This ratio normalizes snow water storage by cumulative precipitation, emphasizing the impacts of temperature on snowpack accumulation and melt. When computed for April 1, the time of year when maximum basin-scale SWE is considered to occur, this ratio can be an effective measure of the stages of accumulation and melt (Clow, 2010).

Understanding how relationships between snowpack, precipitation, and temperature will be expressed at the basin scale is particularly important in the maritime PNW. Physically- based modeling studies of climate impacts in the PNW describe reduced snowpack and earlier streamflow across the region (Elsner et al., 2010; Hamlet, 2011; Sproles et al., 2013). These deterministic approaches provide a range of outputs of future conditions, but are not analogous to current or historic snowpack conditions. Based on the premise that future snowpack conditions will resemble previous winters that were warm, Luce et al. (2014) developed spatial and temporal analogs of snowpack sensitivity to temperature and precipitation across the western United States using point-based SNOTEL data. While informative, the limitations of point-based data may not capture the basin-wide conditions in projected warmer conditions (Dozier, 2011; Milly et al., 2008).

The concept of climate analogs has been used as a tool for examining potential impacts on a range of predictands (e.g. crops, migration, urban areas) and uses previous conditions to represent potential future conditions (Hallegatte et al., 2007; McLeman and Hunter, 2010; Ramírez-Villegas et al., 2011; Webb et al., 2013). For example, Ramírez-Villegas et al. (2011) developed analogs of climate and agricultural practices to identify previous climatic events that may provide insights into the impacts of future climate change in both time and space.

An analog approach allows planners and managers to develop anticipatory capacity, the ability to better anticipate changing scenarios as needs and context change over time (Nelson et al., 2008; Rhodes and Ross, 2009). Using the extreme low snowpacks of 2014-2015 as an example, residents of the Willamette Valley raised concerns regarding the safety and taste of domestic drinking water during the summer months. These changes in water characteristics led public works departments to examine future strategies and equipment to mitigate future water quality concerns. From a hydrological perspective, this same analog approach is also used in describing streamflow, and is most commonly framed using statistical metrics. For example, the spatial extent for a previous 100-year flood event serves as an analog of floodplain dynamics and provides anticipatory capacity for land use planners and water managers.

Developing statistically valid snowpack analogs at the basin scale requires a spatially explicit, probabilistic approach to calculate the statistical likelihood of SWE across a topographically complex mountain basin. The concept of spatial probability is based upon a study of floodplain dynamics by Graf (1984) who used 107 years of channel migration records to calculate the probability of subsequent erosion in a given parcel. Snow hydrology models can readily incorporate climate

The Cryosphere Discuss., doi:10.5194/tc-2016-66, 2016
Manuscript under review for journal The Cryosphere
Published: 21 March 2016

change projections (Adam et al., 2009; Sproles et al., 2013) and model outputs can be assessed using a spatial-probabilistic framework that explicitly accounts for elevation.

This research examines the extraordinarily low snow winters of WY 2014 and WY 2015 (WY=Water Year, defined as 1 October – 30 September in the western United States) in the context of projected future climate. We demonstrate the efficacy of a spatial-probabilistic approach and snowpack metrics that express the temperature sensitivity of snow over an elevation gradient in a maritime snow environment. Our study area is the McKenzie River Basin, a well-studied watershed that is characteristic for maritime snow in the Pacific Northwest.

Specifically, we ask:

- How do snowpacks from WY 2014 and WY 2015 compare to snowpacks under a warmer climate?
- What is the probability that similar snowpacks will occur in the future?
- How do snowpacks of WY 2014 and WY 2015 vary by elevation?

Answering these questions will provide effective snowpack analogs and allow us to consider how can we use these two anomalously low snow years to build anticipatory capacity for climate change impacts in the PNW. Regional sensitivity to climate warming makes PNW snowpack, and those in similar maritime climates, acutely vulnerable to snow drought.

2 Research Methods

Our approach uses a spatially distributed and physically based snow hydrology model to compute spatial probabilities of SWE and SWE:P for historic and +2C winter conditions. We then model WY 2014 and WY 2015 snowpacks and these outputs to provide probabilistic context for the snowpack of those two winters. Below we provide details on the study area and specific methods used in this approach.

This study focuses on the McKenzie River Basin (MRB, 3 041 km^2), a major tributary to the Willamette River (Fig. 1). Located in the main part of the Willamette's "at-risk" snow zone (Nolin and Daly, 2006), snowmelt in MRB is critical to meeting environmental and societal demands of the Willamette River, supplying almost 25% of the river's summer discharge at its confluence with the Columbia River near Portland, Oregon (Hulse et al., 2002). The MRB has four dams for flood control and hydropower, serves as the primary source of domestic water for 200 000 people, and is home to federally protected salmonids, amphibians, and mussels. The MRB is characterized by wet winters and dry summers, with average annual precipitation ranging from 1000 mm to 3000 mm that follows the elevation gradient (114–3147 m). Elevations between 1000 and 2000 m comprise 42% of the MRB's total area (Fig. 1) and 93% of the total snow water storage in the MRB (Sproles et al., 2013). While elevations above 2000 m accumulate the most SWE, that zone comprises only 1% of total area and 6% of the total snow water storage for the MRB. In terms of volume, snow is the primary seasonal water storage mechanism in the MRB with historic mean basin-wide snow water storage (SWE × area; 1989–2009) of 1.26 km^3 on April 1 (Sproles et al., 2013), compared with total reservoir storage of 0.39 km^3. By comparison groundwater storage for the MRB was estimated to be roughly 4 km^3, with a mean transit time of seven years (Jefferson et al., 2006).

The Cryosphere Discuss., doi:10.5194/tc-2016-66, 2016
Manuscript under review for journal The Cryosphere
Published: 21 March 2016

Spatially distributed values of precipitation and SWE were computed using SnowModel (Liston and Elder, 2006a, 2006b; Sproles et al., 2013) for WY 1989–2009. SnowModel is a spatially distributed, process based model that computes temperature, precipitation, and the full winter season evolution of SWE including accumulation, canopy interception, wind redistribution, sublimation, evaporation, and melt. Because the modeling framework is physically based and spatially distributed, perturbations to temperature inputs will propagate throughout the model including absolute humidity and energy balance calculations. WY 2005 was excluded due to prolonged regional temperature inversions that were not resolved in the model (Sproles et al., 2013). Model input data were derived from station data within the study area, nearly spanning the full elevation range of the MRB (Fig. 1). The 20-year set of model forcing data includes winters with above average, normal, and below average snowpack; positive, negative, and neutral ENSO climate patterns; and a warm phase of the Pacific Decadal Oscillation (Brown and Kipfmueller, 2012). The model was run at a daily time step and 100-m grid resolution.

The calibration period for our model was WY2006 through WY2012. Model forcing data include temperature and precipitation from the SNOTEL network and additional meteorological data as described in Sproles et al. (2013). Oyler et al. (2015) identified a step-like function associated with SNOTEL temperature measurements, specifically maximum and minimum temperature due to a network-wide modification of SNOTEL temperature sensor instrumentation, placement, and height. The result was a systematic temperature bias that can provide an amplification of warming trends in long-term climate change studies. By limiting our calibration period to WY2006-2012 our inputs did not include the step-function, and were more representative of on the ground conditions. Additionally we did not perform long-term climate analysis, but rather used measurements to drive a model.

Using the validated model, we perturbed the daily temperature data by +2ºC and re-ran the model over the same timeframe and spatial domain. This temperature increase is considered to be the mean annual average temperature increase in the region by mid-century (Mote and Salathé, 2010), and is also a key climate change threshold set by the Intergovernmental Panel on Climate Change (Pachauri et al., 2014). We extracted SWE and precipitation (P) data and computed 5-day averages for each, centered on the first day of each month for January–June, for every year in the model run, and for each grid cell in the model domain. These 5-day mean values were used to minimize any effects from individual events (melt, snowfall) while still capturing the overall snowpack characteristics.

Exceedance probability (EP) is a widely used hydrologic metric describing the statistical likelihood that a value of a given magnitude or greater will occur in a specified time period (e.g. annually) (Sadovský et al., 2012; Salas and Obeysekera, 2013). Expressed as a percent, it is calculated as:

$$\mathrm{EP} = \left(\frac{m}{n+1}\right) \times 100 \qquad (1)$$

where, m is the rank of the data value (ranked from highest to lowest) and n is the total number of data values (Dingman, 2002). For example, a low annual exceedance probability, 20% EP is the statistical likelihood that a value could be met or exceeded 20% of the time, or a 1 in 5 chance of occurring in any year, and here represents a relatively high SWE value. A high annual exceedance probability, 90% EP describes the statistical likelihood of a measurement that would be met or exceeded in 90% of the time, or a 9 in 10 chance of occurring in any year, and represents a relatively low SWE value.

Using 20 years of model output, we computed exceedance probability for the first of the month (January–June) based upon the 5-day averaged SWE and SWE:P values for each grid cell in the model domain. The dimensions of the model domain has a grid of 759 rows × 1121 columns. Here, each of the 20 two-dimensional data sets (759 rows × 1121 columns) was decomposed into 20 one-dimensional vectors (1 × 850,839), one for each year, then combined to create a 20 × 850,839 matrix. The location information of each grid cell was retained for subsequent mapping and analysis. For each year, the 20 values in each row were sorted from highest to lowest. The 20 × 850,839 data matrix was recomposed into 20 data matrices of dimension 759 × 1121 creating a corresponding spatial exceedance probability matrix. This was completed for each month (January–June).

To respond to the question "How do snowpacks from WY 2014 and WY 2015 compare to snowpacks under a warmer climate?" we modeled SWE and SWE:P using SnowModel with meteorological forcing data from WY 2014 and WY 2015 for the MRB, with the same stations as from our previously validated model runs. These model runs were also validated using the same methods as described in Sproles et al. (2013). We then compared the snowpack metrics from these two winters with model output from the +2°C climate scenario.

Elevation is the most important physiographic variable in determining SWE in this basin (Nolin, 2012) so we aggregated the data into 50-m elevation bands (inset chart in Fig.1). In each of these bands we computed snow water storage (km^3) and SWE:P (km^3/km^3). This allowed us to understand the variation of snowpack properties by elevation, their spatial probability of occurrence, and the statistical context for the extraordinary snowpacks of WY 2014 and WY 2015.

An important point to bear in mind is that the EP values were computed using perturbed meteorological forcing data (+2ºC), while values for WY 2014 and WY 2015 were derived from unperturbed meteorological forcing data.

3 Results

In the MRB, monthly precipitation data from PRISM gridded climate data (Daly et al., 2008) show that historically 62% of precipitation falls in the November–March (N–M) time period. Within that period, December–February (DJF) are historically the coldest and wettest months. For N–M in WY 2014, precipitation was at 112% of the 30-year normal and temperatures at SNOTEL stations in the MRB were 0.9ºC warmer than normal (National Resource Conservation Service, 2015a). For the DJF period, WY 2014 monthly precipitation was 103% of normal and SNOTEL temperatures were 0.7ºC warmer than normal. During WY 2015, N–M precipitation was 79% of the 30-year average but temperatures in the snow zone were 2.9ºC warmer than average. For the DJF period of WY 2015, monthly precipitation was 76% of normal and temperatures in the snow zone were 3.3ºC warmer than normal (National Resource Conservation Service, 2015a). Fig. 2 graphically presents these climate data to provide historical context for comparisons with snowpack simulations.

The Cryosphere Discuss., doi:10.5194/tc-2016-66, 2016
Manuscript under review for journal The Cryosphere
Published: 21 March 2016

3.1 Snow Water Storage

In the context of our exceedance probability framework, we see that the April 1 basin-wide snow water storage for WY 2014 corresponds to 40% EP, meaning that WY 2014 snowpack storage is slightly above average for a +2ºC model perturbation (Figs. 3, 4, and 5a and c). Snowfall occurring after April 1, 2014 improved late season snow water storage corresponding to 29% and 19% EP for May and June, respectively (Figs. 3 and 4). In WY 2015 basin-wide snow water storage was well below average, even when compared with +2ºC conditions. April 1 snow water storage for WY 2015 corresponds to 90% EP (Figs. 3, 4, 5b, and 5d). In that year, there was little late spring snowfall, so unlike WY 2014 basin-wide snow water storage did not increase (Fig. 3). WY 2015 was also notable in that peak snow water storage occurred in January and was only 0.21 km^3, corresponding to 76% EP (Figs. 3 and 4).

Fig. 4 shows the spatial exceedance probabilities for the +2ºC model runs, aggregated into 50-m elevation increments. For most years, the total amount of April 1 snow water storage is greatest within the elevation range of 1300–1800 m. Historically, MRB seasonal snow accumulates above 1200 m, which also represents the elevation threshold for summer baseflow contributions (Brooks et al., 2012). However in both WY 2014 and 2015 this mid-elevation zone, representing 393 km^2 is essentially snow-free (Fig. 4). From a spatial perspective, Fig. 5 presents the distribution of SWE in the MRB in WYs 2014 and 2015 on April 1, as compared to the 40% and 90% EP, respectively. These figures show snow water storage is almost entirely limited to the upper portions of the basin, and that the more spatially extensive mid-elevations where snow accumulates historically are snow free. In other words, in WY 2014 and 2015 the zone where snow water storage has historically contributed most to groundwater recharge (Jefferson et al., 2008; Tague and Grant, 2009) was instead dominated by rainfall and subsequent runoff.

3.2 SWE:P

This elevation dependent shift from rain to snow is evident in Fig. 6, where at an elevation of 1200 m, SWE:P is below 0.06 for the period January–June in both WY 2014 and 2015. This ratio does not exceed 0.20 below until an elevation of 1500 m in WY 2014, which is still markedly lower than the mean SWE:P at the McKenzie SNOTEL site (0.58, 1454 m). In WY 2015 this 0.20 threshold is not reached until an elevation of 1750 m, approximately 300 m above the highest elevation SNOTEL site in the MRB, and thus was not captured in SNOTEL data. From February–May in WY 2014, SWE:P remains at or near 29–38% EP when compared with +2ºC conditions. From February–May in WY 2015, SWE:P remains below 90% EP when compared with +2ºC conditions.

4 Discussion and Conclusion

The winters of 2014 and 2015 had very low snowpacks due to higher than normal winter temperatures but average or near-average precipitation. As such, these two winters stand as analogs for projected future snow conditions in the region, with

The Cryosphere Discuss., doi:10.5194/tc-2016-66, 2016
Manuscript under review for journal The Cryosphere
Published: 21 March 2016

2014 serving as an analog for slightly warmer conditions (+1–2ºC) and 2015 as an analog for winter temperatures increasing beyond 3ºC.

April 1 snow water storage for 2014 was 470% greater than on the same date 2015. The volumetric difference between the two years (0.56 km^2) is 1.4 times more than the reservoir storage capacity of the MRB. Using spatial exceedance probability, we see that WY 2014 maximum snow water storage was substantially below normal compared with historical average conditions but was slightly above average for +2ºC conditions with an EP of about 40%. In comparison, maximum snow water storage for +2ºC conditions during WY 2015 had an EP of about 90% and would be considered extraordinarily low even for a +2ºC future climate scenario.

The SWE:P metric shows that increased temperature rather than reduced precipitation is the primary reason for the diminished snowpacks of WY 2014 and WY 2015, especially at mid elevations. Basin-wide mean precipitation was 1382 mm (WY 2014) and 1098 mm (WY 2015) for November–June. In the snow zone mean temperatures (November-March) in WY 2014 were 0.9ºC above the 30-year normal, while WY 2015 was 2.9ºC above normal. In WY 2014 at an elevation of 1500 m, the SWE:P conditions were slightly below average (60% EP), but increased to more than 40% EP in May and June due to late season storms. In 2015, EP values for SWE:P were at or below 80% throughout the winter, indicating the effect of warm temperatures. During March and April, which are typically the months with highest annual SWE, the EP for SWE:P ratios were 95%.

Instead of using point-based measurements of SWE and P, computing SWE:P for elevation bands across the basin provides a simple yet telling description of precipitation phase (rainfall vs. snowfall) and snowpack evolution (accumulation and ablation). For example there is little difference between SWE:P at 1200 m in April 2014 (0.04) and April 2015 (0.01), as this elevation band is almost entirely snow free. However, at 1500 m the April SWE:P values for the two years are considerably different (Fig. 6; 2014 SWE:P = 0.22; 2015 SWE:P = 0.04). As precipitation shifts from snow to rain, the SWE:P metric can augment individual values of SWE and P to provide key information on shifts in water storage throughout the course of a winter and valuable insights to water resource managers in a non-stationary climate. A low SWE:P ratio in March under normal winter precipitation conditions could indicate peak streamflow has occurred or most likely would occur earlier in the year, which has important implications for water resource management in subsequent months.

Low snowpacks and shifts in streamflow negatively impact water quantity, water quality, hydropower operations, winter snow sports, and summer recreation. In WY 2015, record low snowpacks led to summer drought declarations, extreme fire danger, and modified hydropower operations in the MRB. The typical consistent flow of the groundwater-fed McKenzie River was at 63% of August-September median flow (United States Geological Survey, 2015). Hoodoo Ski Area, located at Santiam Pass, was open for only a few weekends in WY 2014 and in WY 2015 they suspended operations in mid-January, the shortest season in their 77-year history. In the adjacent Santiam River Basin (north of the MRB), diminished snowpacks and less-than-anticipated spring rains in WY 2015 pushed the Detroit Reservoir (storage capacity 0.35 km^3) to historic low levels. In May harmful blue-green algae concentrations were above acceptable amounts by seven-fold, and July reservoir levels were approximately 21-m below capacity. Concerns over the taste and safety of domestic drinking water in the

Willamette Valley prompted municipal water managers to explore options for upgrading water treatment facilities. Water quality, energy production, and recreation externalities are not well represented in deterministic models but are on-the-ground realities that society and the natural environment face with regard to reduced snowpacks.

Our analog approach combines projected climate impacts with the extreme low snow years of 2013-2014 and 2014-2015 to for insights into improved management in shifting conditions. Intervention strategies can fail because they lack adequate information about the impacts of climate change that are not incorporated into deterministic physical models and play out at the human scale (Ramírez-Villegas et al., 2011). Analogs allow planners and managers to develop adaptation and mitigation strategies that use the past to demonstrate what did or did not work under climate stress, and help build a more informed understanding of ways to improve future planning efforts (Ramírez-Villegas et al., 2011).

Climate change impacts are often expressed in probabilistic terms (Randall et al., 2007) and so it is logically consistent to estimate snowpacks in this manner. This research does not assume that the probabilities presented here are based upon a precise representation of future conditions nor that future climates will be +2ºC warmer every winter. We present these results as a way to frame the likelihood of future basin-wide snow water storage in the context of our current understanding of climate change. These probabilistic insights are then used to identify WY 2014 and WY 2015 as analogs years for managers and decision makers. The WY 2014 snowpack would be slightly above average for +2ºC conditions; and the WY 2015 snowpack would be a very low snowpack for +2ºC conditions, but not a record low. These analog years thus provide guidance for adaptation strategies to mitigate potential failures of existing management plans.

Our spatially explicit approach augments snowpack information from the existing SNOTEL network. While SNOTEL data continue to play a key role for seasonal streamflow forecasting under historic climatic conditions, these statistical relationships have been changing (Montoya et al., 2014). In the MRB all SNOTEL sites in the MRB were snow-free for most of February–March 2015 and therefore incapable of providing predictive skill for water resource management. Our basin-scale probabilistic approach provides a more complete picture of water storage and captures the elevation variability absent in point-based measurements.

The winters of WY 2014 and WY 2015 demonstrate a considerable departure from the stationary snowpack conditions on which present-day management plans are based (Milly et al., 2008). With continued current warmer climates, the snowpack conditions represented by these two winters are more likely to occur. In the mean time, the value of spatially explicit probabilistic metrics rests in the ability of such metrics to better define the range of statistical probabilities of subsequent winters that are representative of basin-wide conditions. Framing the low snowpacks of WY 2014 and WY 2015 as analogs of future snow provides insights into potential climate impacts and externalities on social and environmental systems. Together, probabilistic metrics and snowpack analogs can help build capacity to better anticipate hydrologic changes in a shifting climate.

The Cryosphere Discuss., doi:10.5194/tc-2016-66, 2016
Manuscript under review for journal The Cryosphere
Published: 21 March 2016

Acknowledgements

The initial research that supported the development of the snowpack model and spatially-probabilistic approach was provided by National Science Foundation grant #0903118 and further supported by grant #1039192. The data for Figs. 3, 4, and 6 can be downloaded at http://people.oregonstate.edu/~sprolese/snow_frequency/.

The Cryosphere Discuss., doi:10.5194/tc-2016-66, 2016
Manuscript under review for journal The Cryosphere
Published: 21 March 2016

References

Adam, J. C., Hamlet, A. F. and Lettenmaier, D. P.: Implications of global climate change for snowmelt hydrology in the twenty-first century, Hydrol. Process., 23(7), 962–972, doi:10.1002/hyp.7201, 2009.

Barnett, T. P., Adam, J. C. and Lettenmaier, D. P.: Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, 438(7066), 303–309, doi:10.1038/nature04141, 2005.

Brooks, J. R., Wigington, P. J., Phillips, D. L., Comeleo, R. and Coulombe, R.: Willamette River Basin surface water isoscape (δ18O and δ2H): temporal changes of source water within the river, Ecosphere, 3(5), art39, doi:10.1890/ES11-00338.1, 2012.

Brown, D. P. and Kipfmueller, K. F.: Pacific Climate Forcing of Multidecadal Springtime Minimum Temperature Variability in the Western United States, Ann. Assoc. Am. Geogr., 102(3), 521–530, doi:10.1080/00045608.2011.627052, 2012.

Clow, D. W.: Changes in the timing of snowmelt and streamflow in Colorado: a response to recent warming, J. Clim., 23(9), 2293–2306, 2010.

Daly, C., Halbleib, M., Smith, J. I., Gibson, W. P., Doggett, M. K., Taylor, G. H., Curtis, J. and Pasteris, P. P.: Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States, Int. J. Climatol., 28(15), 2031–2064, 2008.

Dingman, S. L.: Physical hydrology, Prentice Hall, Upper Saddle River, N.J., 2002.

Dozier, J.: Mountain hydrology, snow color, and the fourth paradigm, Eos, Trans. Am. Geophys. Union, 92(43), 373, doi:10.1029/2011EO430001, 2011.

Elsner, M. M., Cuo, L., Voisin, N., Deems, J. S., Hamlet, A. F., Vano, J. A., Mickelson, K. E. B., Lee, S.-Y. and Lettenmaier, D. P.: Implications of 21st century climate change for the hydrology of Washington State, Clim. Change, 102(1-2), 225–260, 2010.

Fritze, H., Stewart, I. T. and Pebesma, E.: Shifts in Western North American Snowmelt Runoff Regimes for the Recent Warm Decades, J. Hydrometeorol., 12(5), 989–1006, doi:10.1175/2011jhm1360.1, 2011.

Graf, W. L.: A Probabilistic Approach to the Spatial Assessment of River Channel Instability, Water Resour. Res., 20 [online] Available from: http://dx.doi.org/10.1029/WR020i007p00953, 1984.

Hallegatte, S., Hourcade, J.-C. and Ambrosi, P.: Using climate analogues for assessing climate change economic impacts in urban areas, Clim. Change, 82(1-2), 47–60, 2007.

Hamlet, A. F.: Assessing water resources adaptive capacity to climate change impacts in the Pacific Northwest Region of North America, Hydrol. Earth Syst. Sci., 15(5), 1427–1443, doi:10.5194/hess-15-1427-2011, 2011.

Hulse, D., Gregory, S., Baker, J. P. and Pacific Northwest Ecosystem Research, C.: Willamette River Basin planning atlas : trajectories of environmental and ecological change, Oregon State University Press, Corvallis, OR., 2002.

Jefferson, A., Grant, G. and Rose, T.: Influence of volcanic history on groundwater patterns on the west slope of the Oregon High Cascades, Water Resour. Res., 42(12), 2006.

Jefferson, A., Nolin, A., Lewis, S. and Tague, C.: Hydrogeologic controls on streamflow sensitivity to climate variation, Hydrol. Process., 22(22), 4371–4385, doi:10.1002/hyp.7041, 2008.

Kapnick, S. and Hall, A.: Causes of recent changes in western North American snowpack, Clim. Dyn., 38(9-10), 1885–1899, 2012.

Liston, G. E. and Elder, K.: A Distributed Snow-Evolution Modeling System (SnowModel), J. Hydrometeorol., 7(6), 1259–1276 [online] Available from: http://dx.doi.org/10.1175/JHM548.1, 2006a.

Liston, G. E. and Elder, K.: A Meteorological Distribution System for High-Resolution Terrestrial Modeling (MicroMet), J. Hydrometeorol., 7(2), 217–234 [online] Available from: http://dx.doi.org/10.1175/JHM486.1, 2006b.

Luce, C. H. and Holden, Z. A.: Declining annual streamflow distributions in the Pacific Northwest United States, 1948–2006, Geophys. Res. Lett., 36(16), L16401, doi:10.1029/2009gl039407, 2009.

Luce, C. H., Lopez-Burgos, V. and Holden, Z.: Sensitivity of snowpack storage to precipitation and temperature using spatial and temporal analog models, Water Resour. Res., 50(12), 9447–9462, doi:10.1002/2013WR014844, 2014.

McLeman, R. A. and Hunter, L. M.: Migration in the context of vulnerability and adaptation to climate change: insights from analogues, Wiley Interdiscip. Rev. Clim. Chang., 1(3), 450–461, 2010.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P. and Stouffer, R. J.: Stationarity Is Dead: Whither Water Management?, Science (80-.)., 319(5863), 573–574, doi:10.1126/science.1151915, 2008.

Molotch, N. P. and Bales, R. C.: SNOTEL representativeness in the Rio Grande headwaters on the basis of physiographics and remotely sensed snow cover persistence, Hydrol. Process., 20(4), 723–739, 2006.

Montoya, E. L., Dozier, J. and Meiring, W.: Biases of April 1 snow water equivalent records in the Sierra Nevada and their associations with large-scale climate indices, Geophys. Res. Lett., 41(16), 5912–5918, 2014.

Mote, P. and Salathé, E.: Future climate in the Pacific Northwest, Clim. Change, 102(1), 29–50, doi:10.1007/s10584-010-9848-z, 2010.

Mote, P. W.: Climate-Driven Variability and Trends in Mountain Snowpack in Western North America&#42, J. Clim., 19(23), 6209–6220 [online] Available from: http://dx.doi.org/10.1175/JCLI3971.1, 2006.

Mote, P. W., Hamlet, A. F., Clark, M. P. and Lettenmaier, D. P.: Declining Mountain Snowpack in Weatern North America, Bull. Am. Meteorol. Soc., 86(1), 39–49 [online] Available from: http://dx.doi.org/10.1175/BAMS-86-1-39, 2005.

National Resource Conservation Service: Weekly Snowpack / Drought Monitor Update, Washington, D.C., 2014.

National Resource Conservation Service: NRCS SNOTEL data, edited by United States Department of Agriculture, [online] Available from: http://www.nrcs.usda.gov/wps/portal/nrcs/main/or/snow/ (Accessed 9 September 2015a), 2015.

National Resource Conservation Service: Weekly Water and Climate Update, Washington, D.C. [online] Available from: http://www.wcc.nrcs.usda.gov/ftpref/support/drought/dmrpt-20150326.pdf, 2015b.

Nelson, N., Geltzer, A. and Hilgartner, S.: Introduction: the anticipatory state: making policy-relevant knowledge about the future, Sci. Public Policy , 35 (8), 546–550, doi:10.3152/030234208X370648, 2008.

Nolin, A. W.: Perspectives on Climate Change, Mountain Hydrology, and Water Resources in the Oregon Cascades, USA, Mt. Res. Dev., 32(S1), S35–S46, doi:10.1659/mrd-journal-d-11-00038.s1, 2012.

Nolin, A. W. and Daly, C.: Mapping "At Risk" Snow in the Pacific Northwest, J. Hydrometeorol., 7(5), 1164–1171 [online] Available from: http://proxy.library.oregonstate.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=22988202&site=ehost-live, 2006.

Oregon Water Supply and Conservation Initiative: Southern Willamette valley municipal water providers final report., 2008.

Oyler, J. W., Dobrowski, S. Z., Ballantyne, A. P., Klene, A. E. and Running, S. W.: Artificial amplification of warming trends across the mountains of the western United States, Geophys. Res. Lett., 42(1), 153–161, 2015.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., Church, J. A., Clarke, L., Dahe, Q. and Dasgupta, P.: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2014.

Ramírez-Villegas, J., Lau, C., Kohler, A. K., Jarvis, A., Arnell, N., Osborne, T. and Hooker, J.: Climate analogues: finding tomorrow's agriculture today, CGIAR Research Program on Climate Change, Agriculture and Food Security, Cali, Colombia., 2011.

Randall, D. A., Wood, R. A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Srinivasan, J., Stouffer, R. J., Sumi, A. and Taylor, K. E.: Climate Change 2007 - The Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2007.

Rhodes, D. H. and Ross, A. M.: Anticipatory capacity: Leveraging model-based approaches to design systems for dynamic futures, in Model-Based Systems Engineering, 2009. MBSE'09. International Conference on, pp. 46–51, IEEE., 2009.

Rosenberg, E. A., Wood, A. W. and Steinemann, A. C.: Statistical applications of physically based hydrologic models to seasonal streamflow forecasts, Water Resour. Res., 47(3), W00H14, doi:10.1029/2010WR010101, 2011.

Sadovský, Z., Faško, P., Mikulová, K. and Pecho, J.: Exceptional snowfalls and the assessment of accidental snow loads for structural design, Cold Reg. Sci. Technol., 72, 17–22, doi:10.1016/j.coldregions.2011.12.003, 2012.

Salas, J. and Obeysekera, J.: Revisiting the Concepts of Return Period and Risk for Nonstationary Hydrologic Extreme Events, J. Hydrol. Eng., 19(3), 554–568, doi:10.1061/(ASCE)HE.1943-5584.0000820, 2013.

Serreze, M. C., Clark, M. P., Armstrong, R. L., McGinnis, D. A. and Pulwarty, R. S.: Characteristics of the western United States snowpack from snowpack telemetry (SNOTEL) data, Water Resour. Res., 35(7), 2145–2160, doi:10.1029/1999wr900090, 1999.

Service, R. F.: As the West Goes Dry, Science (80-.)., 303(5661), 1124–1127 [online] Available from: http://www.jstor.org/stable/3836265, 2004.

Sproles, E. A., Nolin, A. W., Rittger, K. and Painter, T. H.: Climate change impacts on maritime mountain snowpack in the Oregon Cascades, Hydrol. Earth Syst. Sci., 17(7), 2581–2597, doi:10.5194/hess-17-2581-2013, 2013.

Stewart, I. T.: Changes in snowpack and snowmelt runoff for key mountain regions, Hydrol. Process., 23(1), 78–94, doi:10.1002/hyp.7128, 2009.

Stewart, I. T., Cayan, D. R. and Dettinger, M. D.: Changes in Snowmelt Runoff Timing in Western North America under a `Business as Usual' Climate Change Scenario, Clim. Change, 62(1), 217–232 [online] Available from: http://dx.doi.org/10.1023/B:CLIM.0000013702.22656.e8, 2004.

Stoelinga, M. T., Albright, M. D. and Mass, C. F.: A New Look at Snowpack Trends in the Cascade Mountains, J. Clim., 23(10), 2473–2491, doi:10.1175/2009JCLI2911.1, 2010.

Sturm, M., Holmgren, J. and Liston, G. E.: A Seasonal Snow Cover Classification-System for Local to Global Applications, J. Clim., 8(5), 1261–1283, doi:10.1175/1520-0442(1995)008<1261:assccs>2.0.co;2, 1995.

Tague, C. and Grant, G. E.: Groundwater dynamics mediate low-flow response to global warming in snow-dominated alpine regions, Water Resour. Res., 45(7), W07421, doi:10.1029/2008wr007179, 2009.

Tennant, C. J., Crosby, B. T., Godsey, S. E., VanKirk, R. W. and Derryberry, D. R.: A simple framework for assessing the sensitivity of mountain watersheds to warming-driven snowpack loss, Geophys. Res. Lett., 42(8), 2814–2822, 2015.

United States Army Corps of Engineers: Comprehensive water supply study - An examination of current water supply issues, edited by T. M. Hillyer., 2001.

United States Geological Survey: USGS Current Conditions for Oregon, [online] Available from: http://waterdata.usgs.gov/or/nwis/uv? (Accessed 18 August 2015), 2015.

Webb, L. B., Watterson, I., Bhend, J., Whetton, P. H. and Barlow, E. W. R.: Global climate analogues for winegrowing regions in future periods: projections of temperature and precipitation, Aust. J. Grape Wine Res., 19(3), 331–341, 2013.

The Cryosphere Discuss., doi:10.5194/tc-2016-66, 2016
Manuscript under review for journal The Cryosphere
Published: 21 March 2016

Figures:

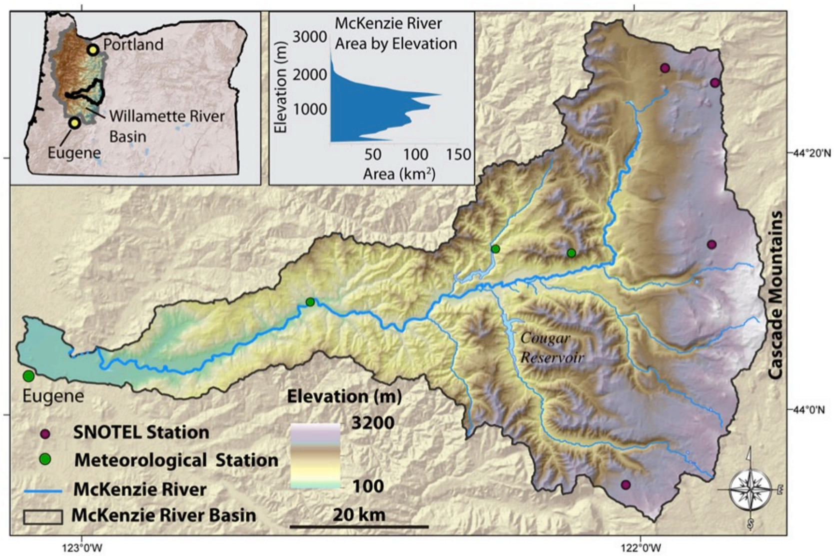

Figure 1: Context map of the McKenzie River basin, and its geographic relationship to the Willamette River basin. The geographic locations of the SNOTEL other meteorological stations used as model forcings show the altitudinal range of inputs. The inset figure of area by elevation refers to the McKenzie River basin separated into 50m bins.

The Cryosphere Discuss., doi:10.5194/tc-2016-66, 2016
Manuscript under review for journal The Cryosphere
Published: 21 March 2016

The Cryosphere
Discussions
Open Access

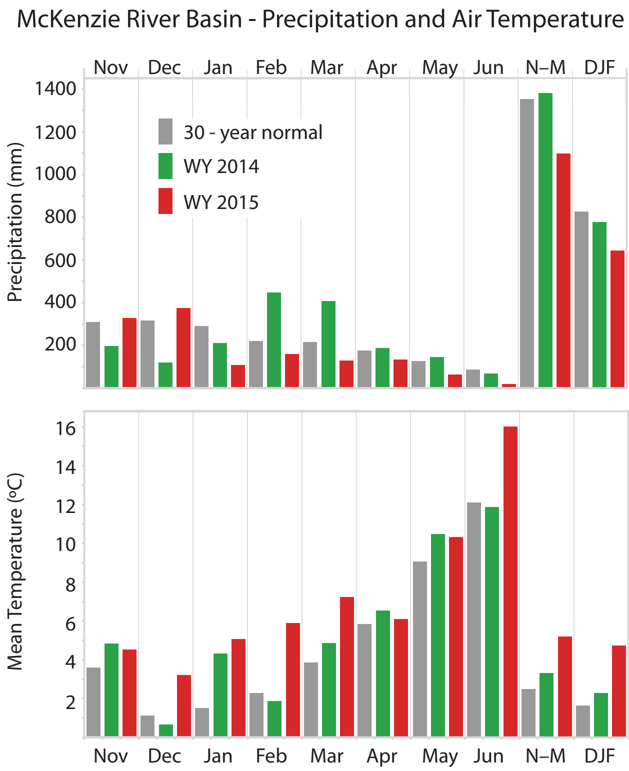

Figure 2: The total precipitation (upper) and mean temperatures (lower) for the McKenzie River basin for water years 2014 and 2015 as compared to the 30-year normal.

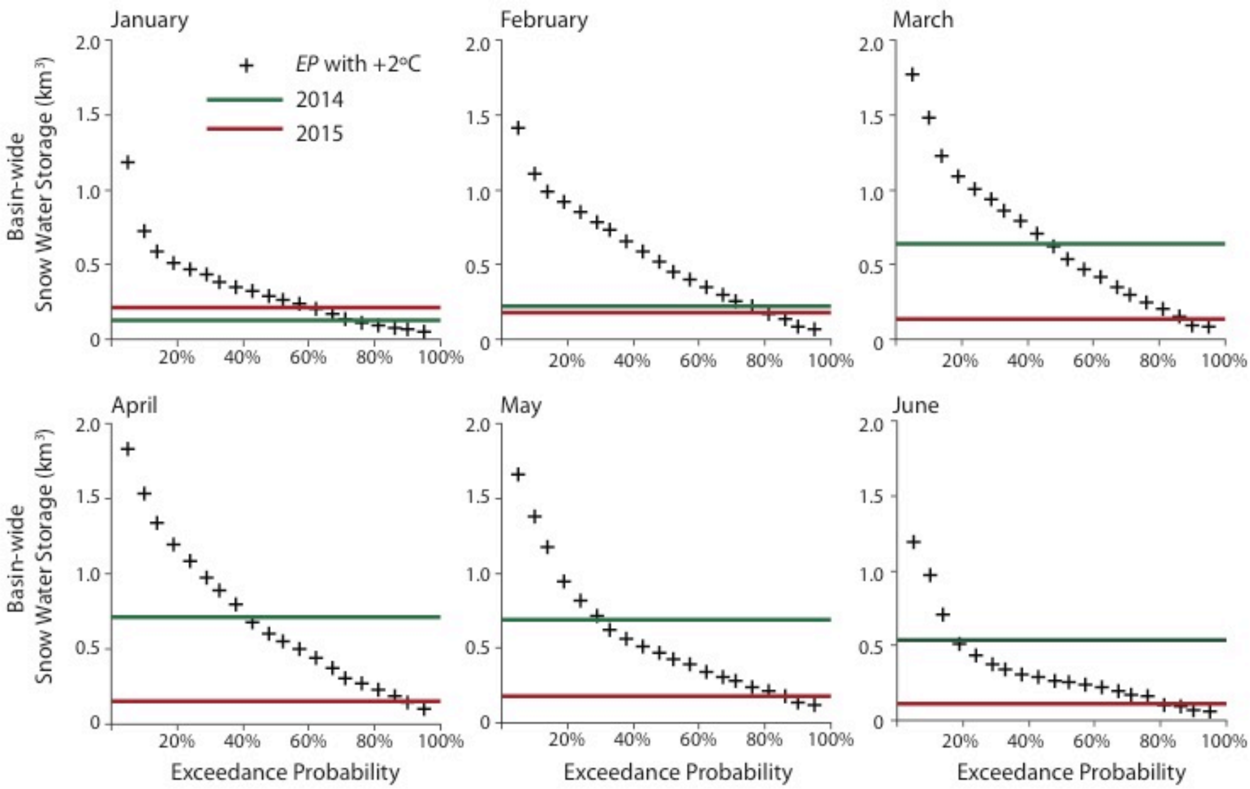

Figure 3: The exceedance probability of basin-wide snow water storage under +2°C conditions. During 2014 snow water storage increased considerably in March to reach above average conditions. The snowpack during the winter of 2015 was extremely low, and never increased beyond 0.21 km^3.

The Cryosphere Discuss., doi:10.5194/tc-2016-66, 2016
Manuscript under review for journal The Cryosphere
Published: 21 March 2016

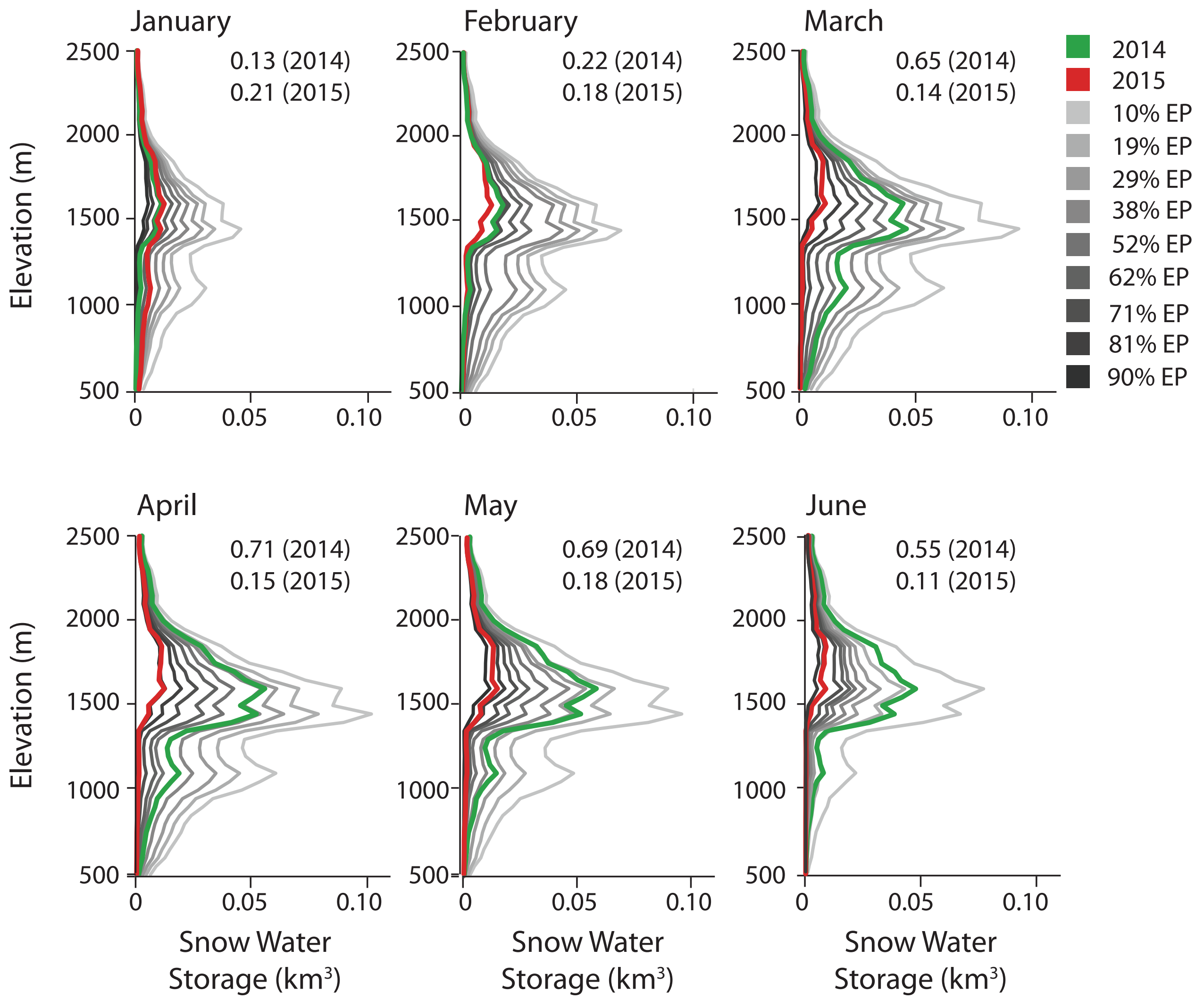

Figure 4: Volumetric snow water storage binned by 50 m elevation bands. The corresponding basin-wide snow water storage (km^3) for 2014 and 2015 is provided for each month. Larger snowpacks (lower exceedance probability) have considerable contributions at between 1000 – 1300 m. During 2014 and 2015, this elevation range had minimal snowpack, despite close to normal precipitation. Note that on the vertical axes, snow water storage below 500 m and above 2500 m are not included for visual clarity. These elevations contribute minimally to basin-wide snow water storage.

The Cryosphere Discuss., doi:10.5194/tc-2016-66, 2016
Manuscript under review for journal The Cryosphere
Published: 21 March 2016

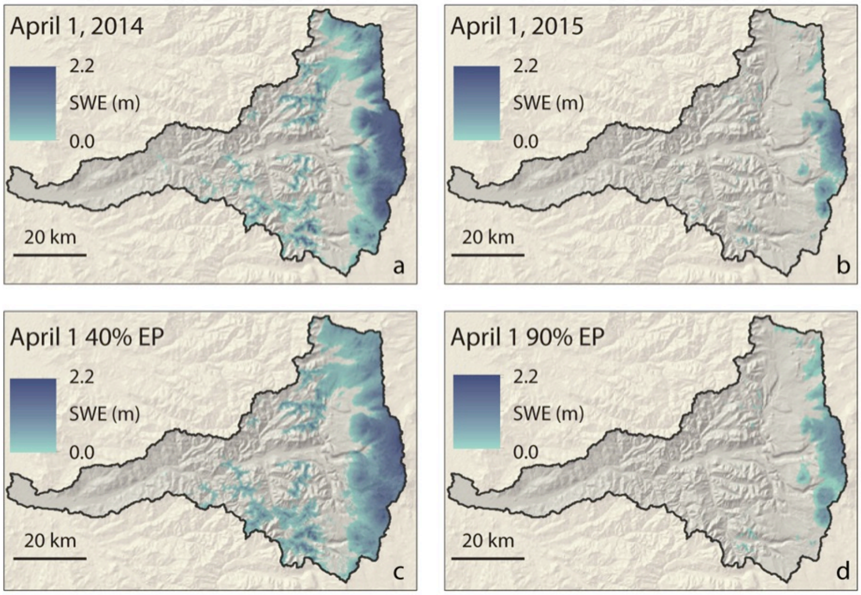

Figure 5: The spatial distribution of SWE on April 1st from water years 2014 and 2015 as compared to the corresponding EP. Both the distribution and magnitude of SWE are strikingly similar.

The Cryosphere Discuss., doi:10.5194/tc-2016-66, 2016
Manuscript under review for journal The Cryosphere
Published: 21 March 2016

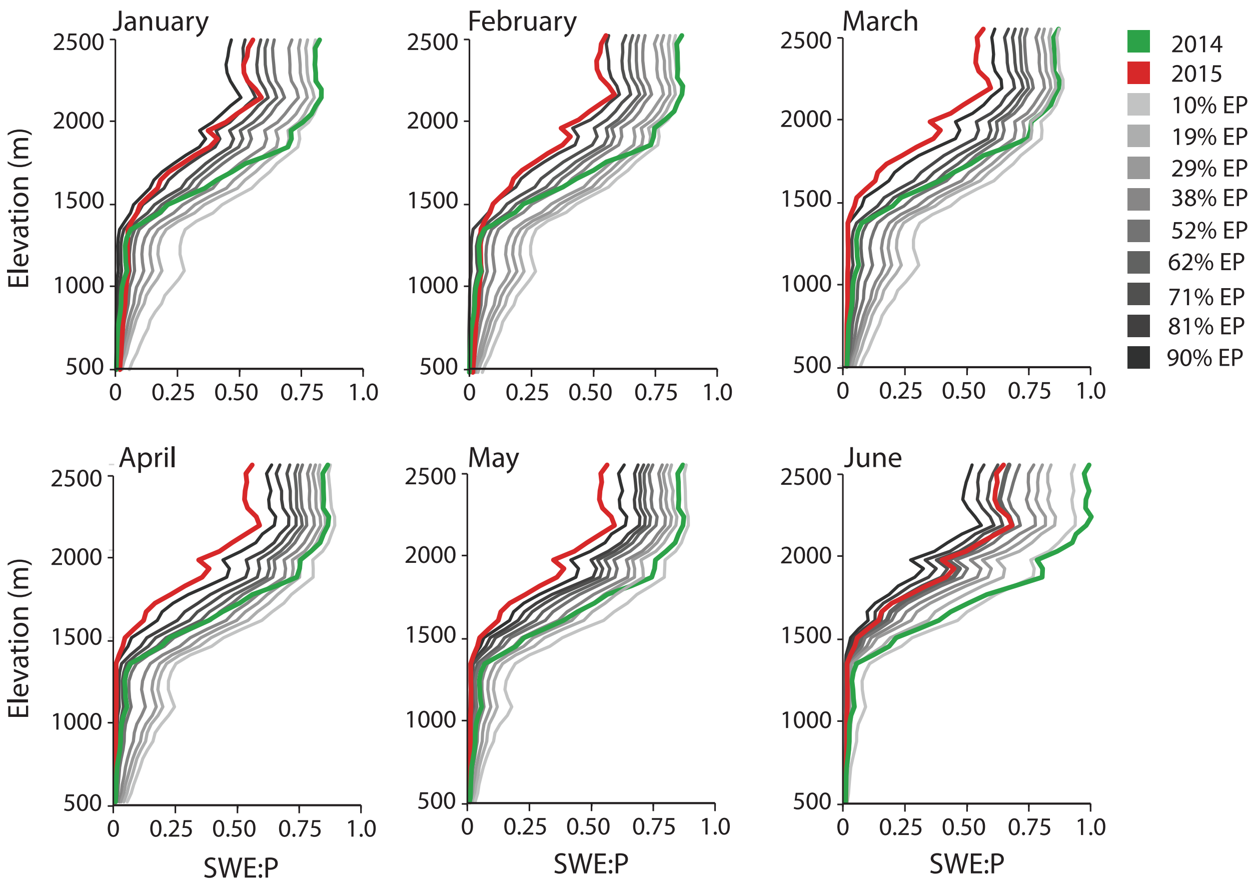

Figure 6: The ratio of SWE:P binned by 50 m elevation bands. The relationship between elevation and SWE:P is evident across all exceedance probabilities. Under +2ºC simulations and in 2014 and 2015, roughly 1500 m is the elevation at which SWE:P begins to increase substantially along the horizontal axis. Note that on the vertical axes, snow water storage below 500 m and above 2500 m are not included for visual clarity. These elevations contribute minimally to basin-wide snow water storage.