Exploring Seasonal Snow in a Changing Climate

with a focus on the Southern Rocky Mountains

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Introduction

The earth's climate is changing, and so is our planet's frozen water. The three most recent decades have been warmer than any others on record since 1850[1]. According to a January 2016 NASA news release, the earth's globally-averaged surface temperatures in 2015 were the warmest on record since modern record-keeping began in 1880. Earth's average surface temperatures are 1.5° F (.85° C) warmer today than they were 136 years ago when Mark Twain was writing his *Adventures of Huckleberry Finn* and Coca-Cola sold its first glass of soda.

This warming has already initiated noticeable changes to the earth's cryosphere, including glacier recession[2], shrinking Arctic sea ice extent[3], thawing permafrost[4] and less seasonal snow[5—8]. Rapid human-caused global warming is essentially reducing the amount and residence time of water in the solid phase on earth[9]. These cold components of the earth system contribute to human well-being, ecosystem health, and economic productivity around the world. An astounding one-sixth of people on earth rely on glaciers and seasonal snow for their water supply[2].

Before I was a mountain dweller, I spent my youth in midwestern Ohio where water towers were a common sight. Great big storage tanks on top of a giraffe-legged tower for each town provided plenty of pressure and back-up water in an otherwise flat and humid place. For the last six years, I've called Fort Collins, Colorado home. Like many other towns in the semi-arid, high plains Southern Rocky Mountain Front Range our summers are hot and dry; we get about half as much rain a month as Ohio does in the summer. Instead of water towers, here we rely on meltwater from

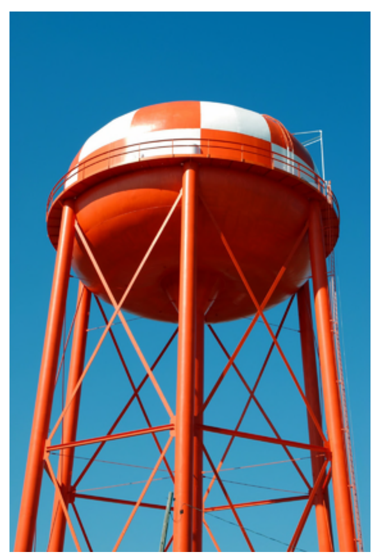

Figure 1 Water tower. Photo credit www.publicdomainpictures.net.

snow that accumulates each winter in the rugged mountain region to our west.

Recent studies suggest that seasonal snow is changing. Over the past few decades, scientists have been studying and publishing with increasing frequency on the changing dynamics of seasonal snowpacks across the western United States (US). Given the importance of water availability to this region, this isn't too surprising. Many studies indicate a shift toward earlier snowmelt initiation in the spring and earlier headwater peak streamflow, both of which could have significant implications for the amount of water stored in snowpacks and the timing of meltwater released from seasonal snow[2,5,8,10—12]. Other studies have shown that as mountain regions continue to experience warmer temperatures, we may also see more winter and springtime precipitation fall as rain instead of snow, particularly at lower elevations and where surface temperatures are already hovering around the freezing point[13—15]. Rain-on-snow events can contribute to melting and the potential for flash floods, and at least one study suggests that such events may be increasing in frequency at higher elevations in the inter-mountain west[16].

Warmer conditions in already arid regions of the southwest dry out soils, and can lead to more airborne dust. Additional climate warming in the future may therefore lead to more dust settling onto the surface of western US snowpacks[17,18]. This matters because dust deposition on snow increases melting rates by lowering surface reflectivity (albedo) and absorbing more solar energy, which adds heat to a snowpack leads to snowpack reductions. Warmer air temperatures and retreating seasonal snow are expected to impact forest fire patterns as well, by lengthening the dry season and increasing evapotranspiration of forest fuels[19]. All of these changes impact ecosystem health and add complexity to the important tasks of interpreting trends and predicting future outcomes for water resources in the western US.

Meanwhile, the early effects of climate change can be seen and felt in our own backyards and snow-capped mountains. As I thought about how climate change might affect the snow I care about, I began to ask questions. What kinds of changes can we expect in these mountains in the coming years, decades, centuries? Will seasonal snow go away completely, or only shrink in some places? And how do we know all this – what are scientists doing to answer these questions?

There are many hydrologic, ecological, and socio-economic implications of snowpack responses to climate change worth significant consideration. For example, water supply for cities, industry, and agriculture will all be affected by changes in the timing and amount of snowmelt runoff, while projected future warming will strain existing water resources by increasing evapotranspiration and lengthening irrigation seasons beyond historical norms. Alpine and sub-alpine environments, riparian and aquatic ecosystems, and downstream water quality are all vulnerable to changes in seasonal snow as well. A comprehensive exploration of these interacting factors is beyond the scope of this article. The Western Water Assessment project is an excellent resource investigating the intersection of water-related societal impacts, ecological systems, and climate change.

My goals for this synthesis are to provide in plain language 1) a review of seasonal snow patterns and trends in the Southern Rocky Mountain region, 2) a consideration of how forest fires reflect snowpack responses to climate change, and 3) an opportunity for action using place-based connections to facilitate engagement with local climate change issues. To accomplish this, I will review natural patterns and evidence for change, consider how seasonal snow is monitored, and consider how computer model simulations help us understand current and future snowpack patterns. Next, I'll consider how forest fire patterns and trends reflect sensitivity to climate change in similar ways to seasonal snow. Finally, I will explore how personal connections with places experiencing environmental change can be leveraged to enhance communication efforts and inspire informed action, and end with a brief summary.

Figure 2 Seasonal snow in the Southern Rocky Mountains as seen from Araphahoe Basin (2014). Photo credit Claire Moore.

Seasonal snow patterns and trends in the Southern Rocky Mountains

Background

Frozen water stored in seasonal snowpacks contributes 50-80% of the runoff that mountain snowmelt-dominated areas in the western United States receive throughout the entire year[11]. Meltwater from seasonal snow soaks into the surrounding soils and provides a key source of moisture to ecosystems across a range of elevations[20,21]. Extra snowmelt runoff flows into rivers, lakes, and man-made reservoirs at relatively predictable annual intervals, and is partitioned and allocated in a multitude of ways.

A remarkable 90% of Colorado's water consumption goes to irrigation alone, according to a 2005 Western Water Usage report[22]. In addition to the role seasonal snow plays in ecosystem health and principal consumptive water uses, snowy mountains of the west and the rivers they supply present endless opportunities for outdoor recreation pursuits such as skiing, snowboarding, and boating. According to the Outdoor Industry Association's 2012 report on *The Outdoor Recreation Economy*, the American public spends about as much on snow sports alone as they do on internet access each year ($53 billion and $54 billion, respectively)[23]. Among others, this industry is an example of one that is highly vulnerable to climate change impacts on seasonal snow[24]. Yet, people engaging in outdoor experiences improve their well being and form meaningful place-based connections with natural locations already undergoing measurable climate change effects[25—27].

About 5.5 million people currently live in the rain shadow of the Southern Rockies, and that number is expected to approach 8 million by 2050[28]. Prevailing winds typically blow from west to east across the Rocky Mountains, carrying moisture from the Pacific Ocean up and over the rugged terrain. As air rises up the western side of the range, it cools and releases moisture as rain and snow. By the time this air makes it over the mountains, little moisture remains to produce precipitation on the eastern side. In this rain shadow is precisely where the highest density of people in the Southern Rocky Mountain region live **(figures 3 and 4)**. We have plenty of reasons to care about changes in our snow-covered mountains and annual water supply.

Figure 3 Google map of Southern Rocky Mountain rain shadow effect. Notice the moist/green western slope and the dry/brown eastern slope. Maps.google.com.

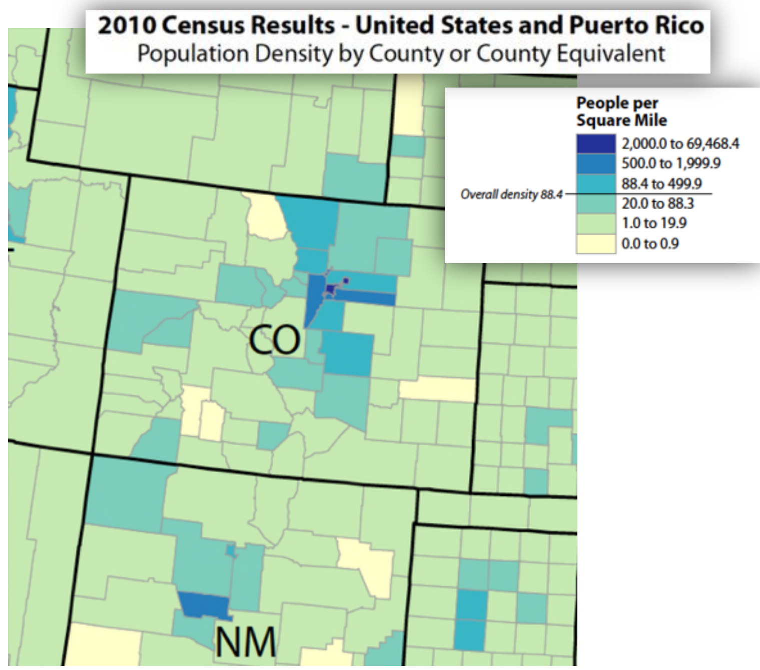

Figure 4 Population density of Southern Rocky Mountain region as of 2010. http://www.census.gov/geo/maps-data/maps/thematic.html

So how do we know things are changing? Studying seasonal snowpacks in the western US has historically required taking measurements in the field. Regular manual collection of snow depth and water content quantities began at fixed elevation snow course sites in the 1930s. By 1980, a network of monitoring stations known as Snow Telemetry (SNOTEL) was established by the Natural Resources Conservation Service (NRCS). Since then, we have been consistently monitoring snow depth and water content (typically reported as Snow Water Equivalent, or

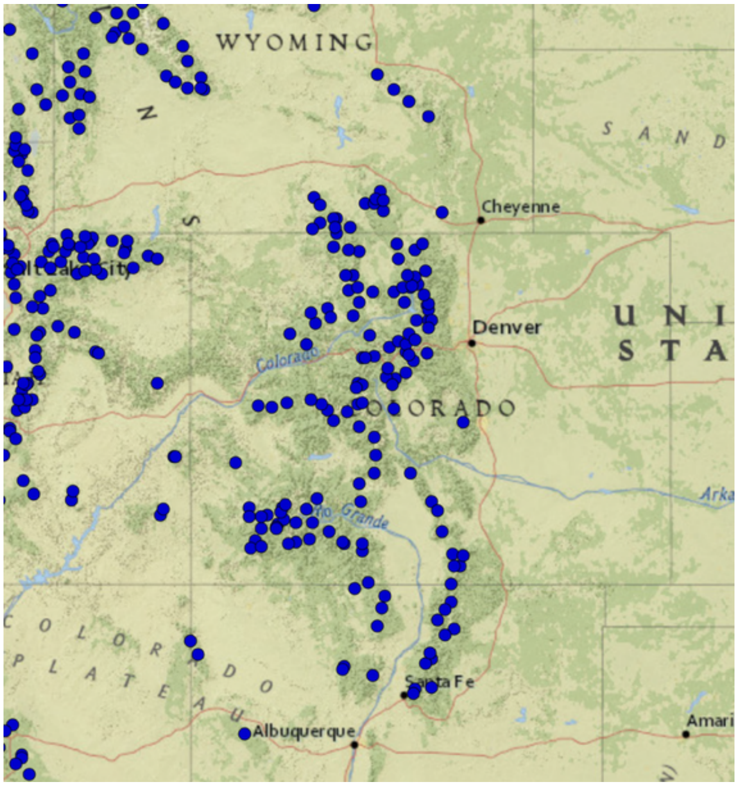

Figure 5 Blue dots indicate automated snow telemetry (SNOTEL) stations operated by the NRCS in the Southern Rockies as of January 2016.

SWE) where snow courses and SNOTEL stations exist **(figure 5)**. With the advancement of earth-orbiting remote sensing technologies over the past few decades, we now also monitor the geographical extent and persistence of snow-covered areas by satellite[29—32]. Cutting-edge campaigns like NASA's SnowEx strive to improve the ability of remote sensing technology to accurately measure SWE and snow depth, two key snowpack quantities that have traditionally proven difficult to estimate remotely. Furthermore, scientists use hydrological models suitable for snow in conjunction with climate model data to explore the boundaries of our understanding about how seasonal snowpacks may respond to additional warming in the future[2,33,34]. This is an area ripe for further investigation, particularly as increasing computational power becomes more affordable.

In order to recognize if something is changing, we have to look at how it has been in the past (the baseline state) to have something to compare new information to. It's also important to remember that the baseline state commonly fluctuates. We know anecdotally that some years are wetter or drier than the year before. Seasonal snow's base state reflects both regional geographic relationships and natural variability over time.

Seasonal snow trends vary with space and time

Seasonal snow is studied at many different scales, from global snow covered area to interactions between the snow surface and overlying air that occur over scales of centimeters. Studies often seek to determine driving factors that influence snow accumulation and persistence and to detect snowpack response patterns at a scale and location of interest. The snow science and hydrology communities monitor seasonal snow in many ways, a few of which include snow covered area, snow cover persistence, snow water equivalent (SWE), maximum SWE on April 1 (conventionally assumed to be the approximate average date of peak SWE), and ratio of precipitation falling as rain versus snow. Scientists also study seasonal snow patterns by looking at streamflow dynamics to measure peaks in the timing and discharge (volume flow rate) of snowmelt-fed headwater tributaries and rivers. With so many ways of describing seasonal snowpack properties, it can be challenging for the non-specialist to grasp how one measurement relates to another. Yet a comprehensive understanding of the factors influencing seasonal snow in a changing climate requires scientists to use multiple approaches. And, different metrics are more or less relevant depending on the end use. For example, total volume of spring runoff is important for water resource managers. But snowmelt timing might be even more important to ecologists seeking to understand the impacts of a longer snow-free season on the moisture levels in forest soils and vegetation, since dry vegetation is potential fire fuel.

Each geographic region across the western US has its own distinct seasonal snowpack trends relating to its latitude, geography, and local climate. For example, lower elevation mountain ranges in the Pacific Northwest (W Washington and W Oregon) are relatively warmer compared to their continental interior counterparts despite being higher in latitude, due in large part to their proximity to the Pacific Ocean (oceans provide a source of moisture and temperature regulation to nearby land masses). Mid-continent, the Southern Rockies (located in SE Wyoming, Colorado, and N New Mexico) have a higher average elevation, steeper topography, and are relatively cooler and drier compared to Pacific Northwest ranges. The Northern Rocky Mountains (Montana, Idaho, and NW Wyoming) sit somewhere geographically and climatically between the lower elevation mountains of the Pacific Northwest and the higher peaks of the Southern Rockies[7]. Seasonal snow regions also have varying degrees of responsiveness to changes in Pacific sea surface temperatures and periodic, multi-year climate patterns like the El Niño Southern Oscillation and Pacific Decadal Oscillation, which predominantly affect precipitation rather than temperature influences on seasonal snowpacks[5,35].

Serreze et al. (1999) defined eight distinct regions in all across the western US to study snowpack characteristics and identify regional relationships between snowpack moisture content, temperature, precipitation, and topography, as shown in **figure 6**[36]. More recently, Trujillo and

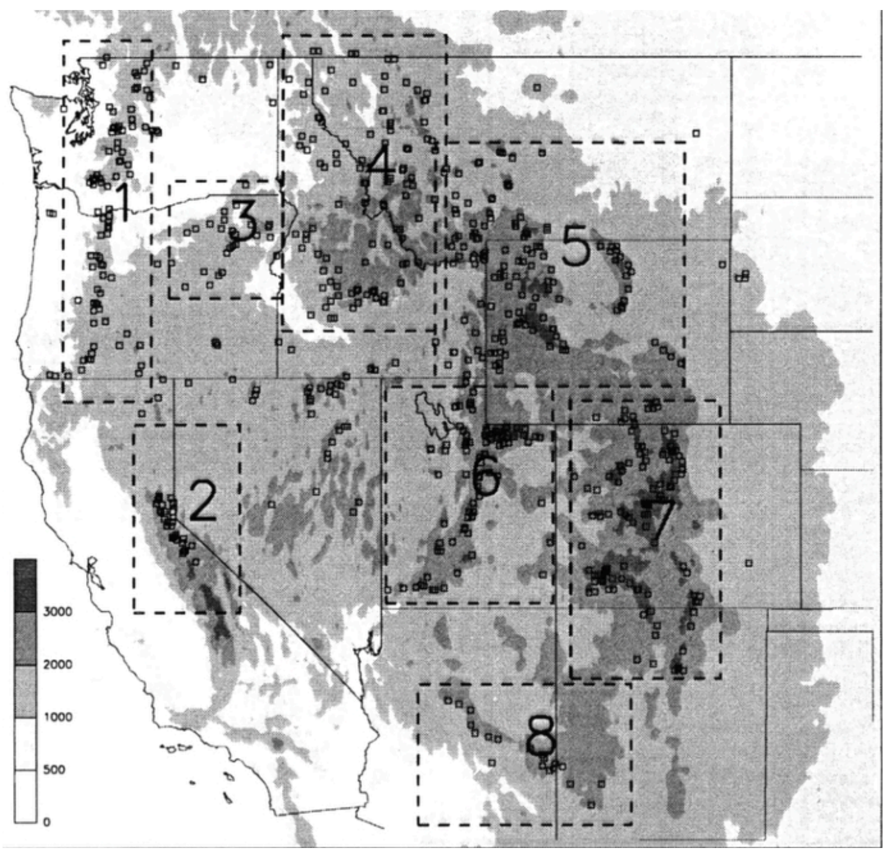

Figure 6 Distribution of SNOTEL stations and topography, showing regions for focused analyses as in Mark Serreze et al. (1999)[36].

Molotch (2014) studied several snowpack metrics across the western US to look for regionally similar relationships[37]. Based on areas with comparable peak SWE values, accumulation season lengths, and snowmelt onset dates, they identified three distinct regional regimes which they named maritime, inter-mountain, and continental. The Middle and Southern Rockies fall within their continental regime, along with Utah's Wasatch and Uinta mountains.

Snowpacks are variable at the scale of individual peaks and mountain ranges as well, because local topography, wind redistribution, and land cover all influence where snow collects. The NRCS's Snow Survey & Water Supply Forecasting Program operates 858 automated SNOTEL stations and 1,185 manually-measured snow courses in 13 western states to address inherent snowpack variability in different places. Even with such a robust observation network, any particular SNOTEL station many not provide a sufficiently representative estimate of basin-scale snowpack properties depending on the station elevation and surrounding environment. An exciting area of ongoing research strives to improve our understanding of snowpack variability in diverse terrain[20,38,39].

Seasonal snowpacks also vary through time independently of rapid human-caused climate change. For example, the Southern Rockies can experience a wet winter with a deep and persistent snowpack one year and a dry winter with a small snowpack the next. **Figure 7** illustrates this variability with annual snowpack water content graphed for four years (2009-2012) against the average shown in bold red. Snowpack variability from year-to-year is influenced by both local weather and large-scale atmospheric circulation patterns. Long-term average prevailing conditions define an area's **climate** whereas **weather** describes the state of the atmosphere at a particular place and time. To account for natural year-to-year variability and recognize long-term trends, scientists typically use datasets spanning 30+ years to define a region's climate.

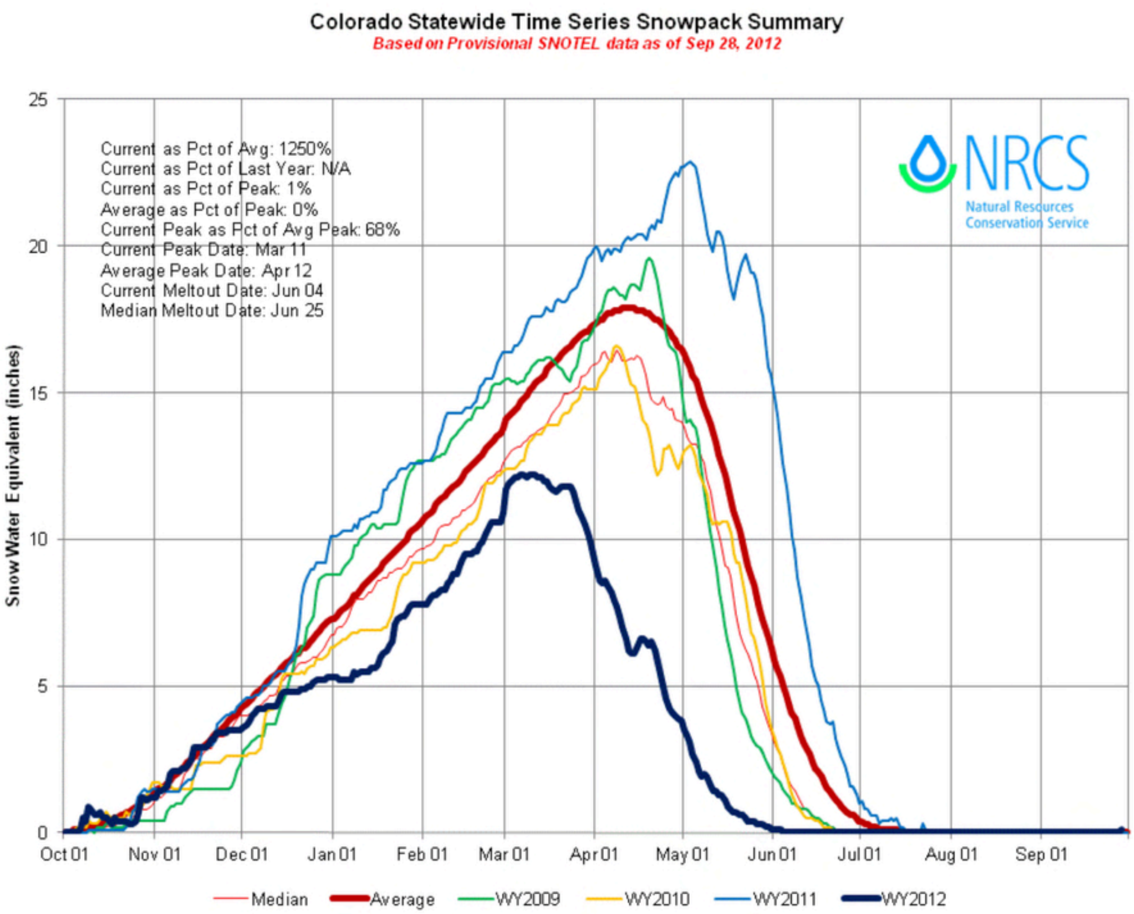

Figure 7 Graph of Colorado statewide snowpack water content for water years (WY) 2009, 2010, 2011, and 2012 with average plotted in bold red. WY2011 was well above average and the very next year WY2012 was below average, peaking in early March instead of early April. (For reference, WY2012 is October 1, 2011 – September 30, 2012.) Graphs and data are available at http://www.nrcs.usda.gov/wps/portal/nrcs/detail/co/snow/?cid=nrcs144p2_063323.

Regional and year-to-year variations add complexity to the unfolding story about the fate of seasonal snow in a changing climate, and make it difficult to broadly apply the results of studies that suggest evidence for change. Still, each study contributes to a larger body of knowledge and presents opportunities for further exploration of patterns and trends in different contexts.

Earlier snowmelt, earlier peak streamflow, lower Snow Water Equivalent

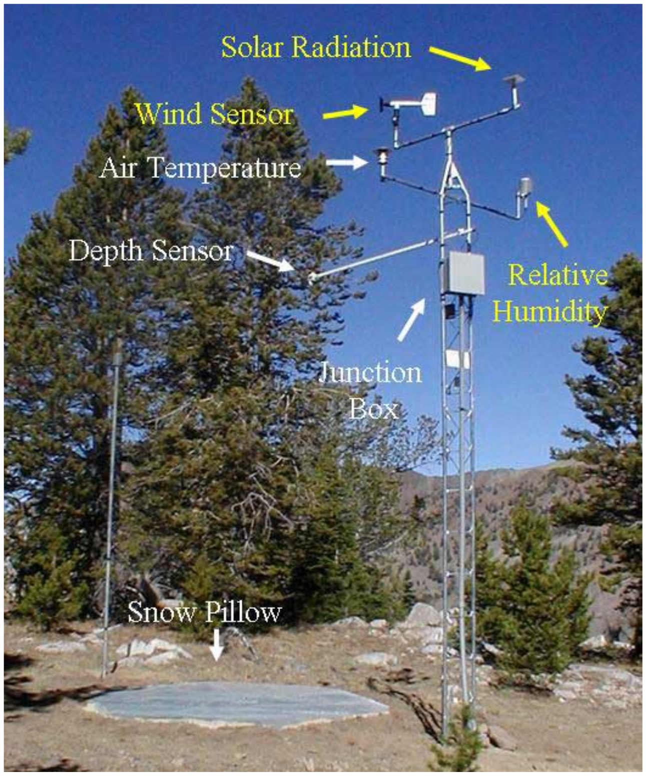

Figure 8 SNOTEL site. Image credit National Resources Conservation Service, US Dept. of Agriculture.

Snow Water Equivalent (SWE) describes the depth of water that would result from melting an entire snowpack instantaneously. One foot of heavy wet snow has a higher SWE than a foot of light fluffy snow. SWE is a helpful measurement for water resource managers, because it describes the amount of moisture held in mountain snowpacks that may eventually become spring and summer runoff available to downstream users. Actual runoff amount depends on other factors like how much moisture is lost to the atmosphere via evaporation and how much soaks into the ground and is taken up by plants. The most accurate SWE measurements currently come from hand-collected snow course measurements and automated SNOTEL sites, such as the one above, shown during the summer season.

Snowpack accumulation seasons vary regionally in average length; the Southern Rockies snow season typically begins in October and ends with the last snow melting sometime in June or July. For example, **figure 9** lists the date of maximum SWE, date of disappearance of seasonal snow, and the duration of the snowmelt season, calculated as

Region	Date of Max SWE	Date of Disappearance of Snow	Days of Snowmelt
1	March 30	July 19	110
2	March 30	July 21	112
3	March 27	June 27	91
4	April 12	July 9	88
5	April 13	July 5	83
6	April 3	June 30	88
7	April 6	July 7	92
8	February 20	May 8	77

Figure 9 Table from Mark Serreze et al. (1999) shows mean dates of maximum SWE, disappearance of the snowpack, and mean length of the snowmelt season according to region (see figure 6)[36].

the difference in days between the first two values, by region[36]. These date averages were calculated with available SNOTEL and snow course data from the mid-1960s through the mid-1990s and offer a background to which we can compare the results of more recent studies.

Once conditions are cold enough for snow to persist, the seasonal snowpack begins to grow. Throughout the winter months, snow accumulates and periodically ablates (melts, evaporates, etc.) according to local weather patterns and storm paths. In general, the total snowpack water content makes a steady upward climb until it reaches a maximum or peak, although sometimes SWE plateaus or has multiple peaks per season. The average peak historically occurs around April 1, so this date has become a standard metric for tracking SWE and reporting an estimated total for the season to help with runoff predictions. The April 1 standard is exactly halfway through a US Geological Survey water year, which begins on October 1 at the beginning of mountain snow season.

For an idea of what a typical SWE plot throughout a single snow season looks like, see **figure 10**[12]. The figure includes symbols marking the approximate point in time when the snowpack began to melt (SM-onset) and the half-way point through the snowmelt period (SM50). In this figure, snowmelt onset occurs just prior to a final accumulation peak, which could be the result of a late-season storm that deposited more snow on top of a snowpack that had reached its ripened, ready to melt state.

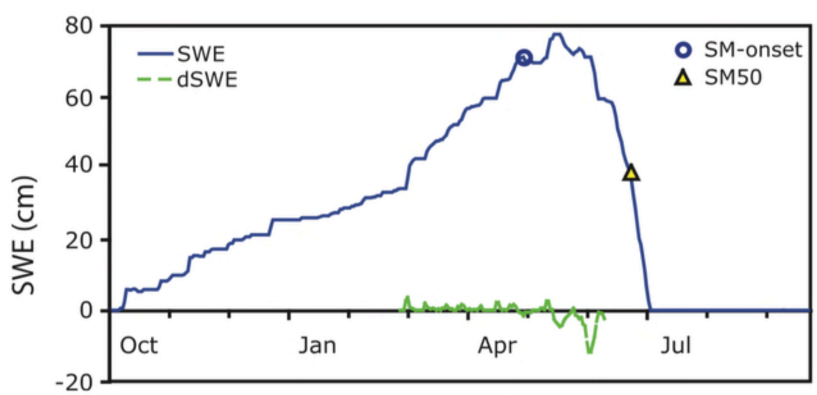

Figure 10 An example plot of seasonal snowpack accumulation and melting[12]. SWE increases and the change in SWE is positive until the snowpack begins to melt. Date of snowmelt onset is SM onset; date when half of snowpack has melted is SM50 (determined by maximum SWE/2).

Since snow acts as an insulator from cold winter air, a snowpack is usually warmer near the ground than it is at the surface. In fact, if you dig down through several feet of seasonal snow above a non-rock ground surface, you may find un-frozen soil even in the middle of winter. As air temperatures warm in the spring and a higher sun angle provides more direct energy input, the seasonal snowpack begins to ripen. A snowpack is considered ripe once it has reached a consistent temperature of 32° F (0° C) throughout, at which point it is warm enough to produce snowmelt. Until then, incoming energy goes towards warming cold parts of the snowpack up to this critical temperature. After this threshold has been crossed, the snowmelt process happens relatively quickly, and the moisture held within the seasonal snowpack is released. The resulting meltwater initiates an increase in streamflow that scientists use as another indication that snowmelt has begun for the season.

Scientists are finding that warmer winter and springtime air temperatures are correlated with earlier snowmelt timing and lower April 1 SWEs[5,12], though determining causality between seasonal snowmelt shifts and climatic variables remains an area of ongoing research interest. Indeed, a recent article explained how sensor equipment changes in the SNOTEL network during the 1990s and 2000s produced an artificial temperature amplification signal in the data the sensors collected – a discovery with significant implications[40]. Using a statistical method to account for the sensor changes the authors suggested that while there was still some warming at even the highest elevations, it was not as much as was originally thought. Because of this, it's important to interpret with caution the results of studies that use un-corrected SNOTEL temperature data.

Computer simulations of future climate warming in the Southern Rockies suggest that temperatures will continue to increase in all seasons under a medium-low greenhouse gas emission scenario[41,42]. To investigate the timing of snowmelt and streamflow in conjunction with maximum seasonal SWE in Colorado, a 2010 study by David Clow used data collected from 70 SNOTEL stations and 58 snow-fed headwater streams around the state for the period of 1978-2007[12]. Results suggested that snowmelt and streamflow timing shifted 2-3 weeks earlier and average maximum seasonal SWE declined by a median of about 1.6 inches (4 cm) per decade over the 29-year study period. In other words, average maximum seasonal SWE declined by a fifth. We don't know if things will keep changing at the same rate moving forward, and like all research endeavors, this study acknowledges its necessary limitations. Certain areas within Colorado showed larger declines in maximum SWE (western and southern mountains) while other areas were less affected (north-central mountains) and therefore seem somewhat sheltered from the early effects of climate change[12]. Once again, we find evidence of regional differences in snow patterns at a variety of scales.

Latitude and elevation affect air temperatures and therefore naturally constrain snowmelt timing in the mountains. The aspect, or direction a hillside is facing, also affects snowmelt timing because some slopes receive much more direct sunlight than others do. Low elevations and latitudes typically melt first because these areas are warmer than high elevations and latitudes.

As air temperatures continue to warm in a changing climate, we can expect this to contribute to earlier snowmelt[12], especially at low to mid-elevations where a small shift in temperature would have a large relative impact. In general, when a snowpack melts earlier, the overall snow accumulation season is shorter. When the accumulation season is shortened, we expect to see a shift toward lower peak SWE. This means smaller snowpacks, and ultimately less meltwater.

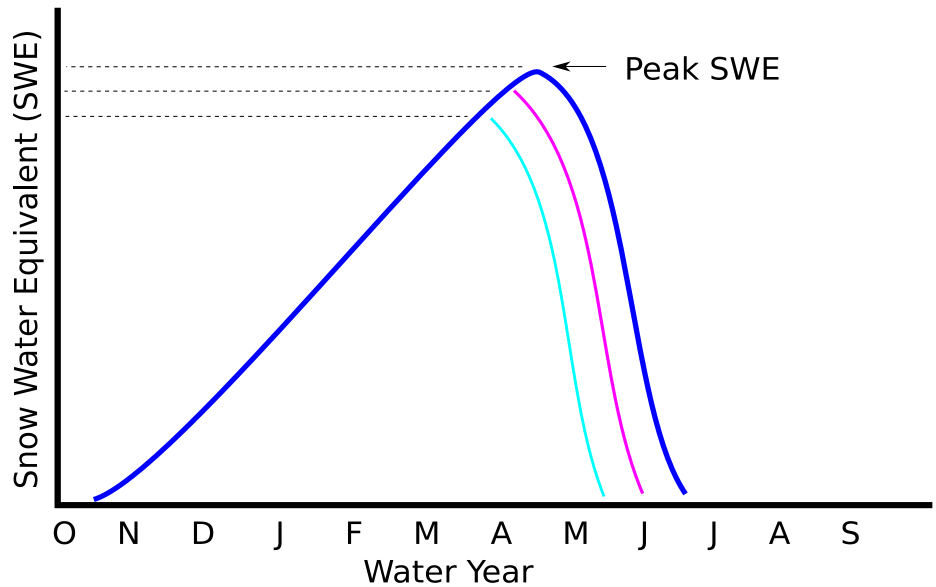

Figure 11 Schematic example showing potential impact of earlier snowmelt on maximum or peak seasonal SWE.

The schematic diagram in **figure 11** helps illustrate this concept with a hypothetical SWE plot affected by consecutively earlier snowmelt shown with the magenta and teal lines marching earlier in the year along the X-axis, and the corresponding lower peak SWE values on the Y-axis.

Studying snow covered area and snow cover persistence via satellite is another way to look for evidence of climate change effects on seasonal snow. In their 2013 study, Richer et al. used remote sensing data from a Colorado Front Range seasonally snow-covered basin topping out at 13,549 feet (4130 meters) to define snow cover patterns in time and space[31]. Their results suggested that intermediate elevations between about 8,300 and 10,000 feet (2550 and 3050 meters), where average annual air temperatures are above freezing and snow cover persistence declines with decreasing elevation, may be particularly vulnerable to loss in a warming climate[31]. This transitional snow zone is where we might expect to see more trends towards earlier snowmelt and lower peak SWEs in the coming decades. Since SNOTEL stations are positioned at permanent locations the information they collect is not necessarily comprehensive enough to track changes in seasonal snow at a variety of elevations within a study area. This limitation of a fixed point observation system means that continued monitoring of seasonally snow covered area via remote sensing will be a valuable way to notice elevation-dependent change.

Earlier snowmelt means earlier spring runoff, which will affect how water is partitioned for downstream uses like farming irrigation and municipal water supply for the millions of people living in the Southern Rockies Front Range. Shortfalls between shrinking supply and increasing water demand from a growing population and warmer summers could eventually lead cities to buy out water rights leaving less for farming, potentially shifting the ways land is used in these areas. Earlier snowmelt will likely also have significant impacts on the snow sports industry. Ski resorts and favorite backcountry spots at low-to-mid elevations where a small shift in temperature could mean big changes, and smaller resorts without the capacity to manufacture snow, are most vulnerable to the effects of earlier snowmelt.

Cold-weather precipitation falling as rain instead of snow

Shorter snow seasons do not necessarily mean less precipitation overall. In some areas, winter and springtime precipitation that historically fell as snow is beginning to fall as rain instead. This trend is currently stronger in Pacific Northwest and Northern Rocky Mountains and weaker in the Southern Rockies, which makes sense given what we know about the diversity of seasonal snow patterns by geographic region[13,43,44]. In their 2006 study, Nolin and Daly identified "at risk" areas in the Pacific Northwest for this snow-to-rain transition as those with wintertime precipitation presently falling within +/- 2° C of 0° C (32° F)[43]. In other words, the closer air temperatures are to the freezing point in an area that typically receives snow, the more vulnerable that snow is to becoming rain in a warmer climate. Other places with similar conditions may be at risk for this transition as temperatures continue to warm, though

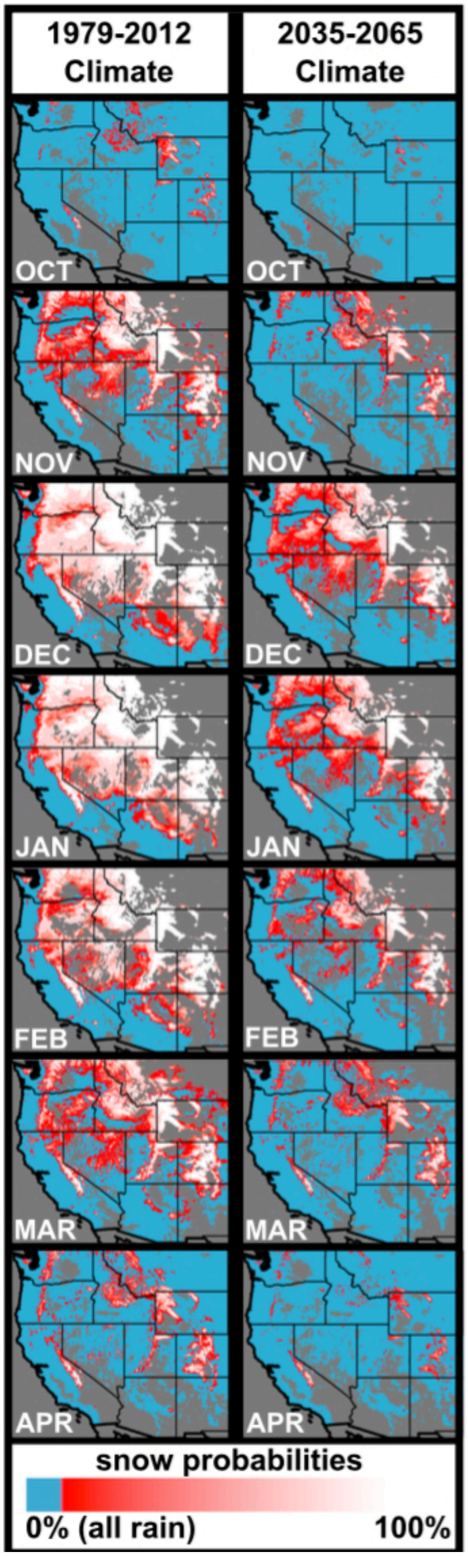

Figure 12 Current and future extent of the strongly rain-dominated (blue), strongly snow-dominated (white), and rain-snow mix (pink to red) areas within the western US based on wet-day mean temperature from Klos et al. (2014)[44]. Future extents are based upon the high-level greenhouse gas emissions scenario RCP8.5 using a 20-model global climate model (GCM) mean.

determining susceptibility to this snow-rain transition requires attention to the geographically-dependent relationships between precipitation and temperature.

More recently, Klos et al. assessed the extent of current and future rain-snow transition zones across complex terrain in the western US and the visual impact of their results is striking **(figure 12)**[44]. The authors looked at average daily temperatures on days with appreciable precipitation (more than 5 mm or about .2 inches) during typical snow accumulation months. They used this relationship to map the probability of rain versus snow where precipitation on a -2° C (28.4° F) day meant 100% snowfall and precipitation on a +4° C (39.2° F) day produced 100% rain. They show side-by-side past and future results using datasets developed from real observations for 1979-2012[45,46] and temperature and precipitation values from the averaged results of 20 global climate models, each initiated with a high greenhouse gas emissions scenario. The results of this study suggest that seasonally snow dominated areas in the western US will have shorter seasons by about two months by midcentury[44]. This is qualitatively evident in **figure 12** by comparing the coverage area patterns of November and March for 1979-

2012 to the coverage patterns in December, January, and February for 2035-2065[44].

The highest and therefore coldest elevations in the Southern Rockies seem to have the potential to defy this snow-to-rain trend, at least in mid-winter for now.

Dust-on-snow albedo effects contribute to melting

Snow is very reflective (it has a high albedo), so almost all of the sun's incoming energy reflects off of a clean snow surface back into the atmosphere. Because of this property, the presence and persistence of snow directly affects how much of this incoming energy is reflected or absorbed by a landscape. As snow melts and exposes the underlying ground, this lowers the surface reflectivity and facilitates additional energy absorption to the system. When dust falls onto the surface of a snowpack, it absorbs energy and affects the snow around and underneath. Imagine a windy day in a dry place like the desert southwest. When the wind blows, it picks up loose dust from the ground and lifts it into the air where it can be carried on strong gusts many hundreds of miles. Sometimes this dusty air makes it far enough north in the wintertime to encounter snowy mountains. There, it settles out onto snowpacks, reduces reflectivity and absorbs more solar energy, and increases surface melting rates.

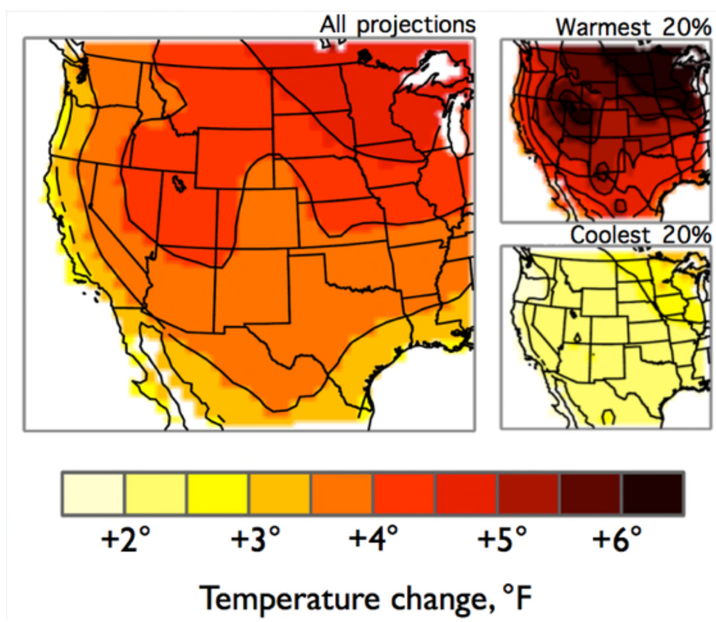

Figure 13 Climate models project several degrees F of warming for the western US by 2015 under mid-level greenhouse gas emissions scenario RCP 4.5. Data source CMIP5 projections re-gridded to 1-degree grid, http://gdo-dcp.ucllnl.org[42], Reclamation 2013 as appeared in J. Lukas et al. 2014[41].2

We have already seen evidence of recurring dust-on-snow episodes that contribute to snowpack melt across the mountain west[17,18,47]. And studies suggest that climate warming will contribute to increasing US southwest aridity by increasing evaporation in already dry areas[41,42,48]. This warming and drying will likely result in changes to vegetation, and a less consistent root system to hold soils in place. Additionally, ongoing land cover disturbance and bare soil exposure from energy exploration and development may also lead to more windblown dust. While dust-on-snow is not necessarily a direct impact of warming temperatures, it is something that contributes to increased melting and is facilitated by the same climate warming that threatens seasonal snow. It's definitely something to consider when looking at the overall picture.

Using computer model simulations to understand current and future conditions

As we have seen, seasonal snow around the western US is already showing signs of climate change impacts. And we know that more warming is on its way. Communities, businesses, and governments throughout the world are engaging in discussions about how best to reduce global greenhouse gas emissions in hopes of curbing the effects of climate change and creating a more sustainable future. In fact, December 2015 in Paris, France marked an historic event at which 196 countries around the world adopted the first universal agreement to combat climate change. Meanwhile, here in the Southern Rockies and other similar mountain areas, land managers, water-use planners, and ski industry partners are looking for real-world, research-based information to plan for a variety of possible future scenarios. What can we expect for our mountains in winters 20, 50, or 100 years from now? If land managers and water-use planners aren't already asking this question, they probably will be soon.

To search for answers, scientists use computer models to simulate a variety of possible future outcomes. Computer models, also known as programs or simulations, use mathematical equations describing physical processes and relationships to reconstruct a virtual version of the real world. Beyond earth system modeling applications, we have computer models today that simulate the economy, track celestial orbit trajectories, mimic the spread of a disease, and reconstruct an athlete's biomechanics. We also use the results of computer models to help us anticipate if we should bring an umbrella to work tomorrow (i.e. Numerical Weather Prediction) and to explore what the earth's climate may be like next century (i.e. General Circulation Model, GCM). Every year seems to yield computational power increases, which means computer models can run faster and more affordably, though complex long-term simulations are admittedly still expensive to run. Our ability to simulate the world around us with computers is remarkable, especially considering only 70 years ago the very first electronic general purpose computer ever made was as big as a room and required operators to manually set wires and switches for each new problem.

We can simulate snow in the present day for a particular area given a set of input criteria using computer programs like SnowModel[49]. SnowModel is intended to help with understanding the processes and mechanisms affecting snow accumulation, distribution, persistence, and melt on timescales of a few minutes to a few years. To look farther ahead, scientists use planet-scale climate models like the GCMs I mentioned earlier to observe potential changes in future earth at different levels of climate warming. GCMs are incredibly complex, and consist of many virtual three-dimensional grid boxes covering the planet's skin like the panels on a soccer ball. Even though it takes tens of thousands of them to cover the earth, each one of those grid boxes is still big (about 100+ kilometers or 62+ miles on each side). Too big, in fact, to zoom in and see how things might be affected in regions that are smaller than the size of an individual grid box. Each one provides a single set of average values to describe everything contained within. This is true for seasonal snow, which is affected by many interacting factors at a variety of scales over complex terrain. So what's a solution to the problem of not enough detail? Downscaling.

There are two common ways to accomplish downscaling for the purposes of modeling future trends in seasonal snow, using either statistical or dynamical methods. Dynamical downscaling involves running a high-resolution climate model (like a GCM with really small grid boxes) in a particular area or region of interest. The downscaled high-resolution model uses output from global GCMs for its input conditions. While the dynamically downscaled model uses physical principles govern what happens within each grid box, it can only provide a more detailed view of what happens in the full-scale GCM. Still, dynamical downscaling is currently the most accurate way to model potential future regional climate change scenarios. It is computationally demanding, but uses much less computational power than running a high-resolution GCM over the whole earth.

Statistical downscaling requires developing statistical relationships between the local variables of interest, like snow covered area or maximum SWE, and large-scale climate predictors, like temperature and precipitation. By applying these relationships to the results of GCM simulations, we can see how current trends might react in the future. Statistical downscaling is less computationally expensive and is relatively easier to perform than dynamical methods. However, it is also potentially less accurate. Rather than using first-order physical principles, it assumes current statistical relationships between large and small scale variables will apply in future climates, which may or may not be the case.

While current downscaling methods are imperfect, they provide a valuable opportunity to explore an assortment of future scenarios and consider the potential effects of climate change on seasonal snow[34,49,50].

Forest fires reflect snowpack responses to climate change

Ecosystem responses to shifting seasonal snow patterns and the climate changes behind them will likely manifest in a variety of ways. From effects on local soil moisture to energy budget modifications to impacts on wildlife and aquatic species that require snow and runoff to meet lifecycle needs, ecologists have much to consider. One place to look for ecosystem signals in conjunction with seasonal snow changes is in the direction of forest fires in the western US. Many seasonally snow covered areas overlap with forested ecosystems that evolved within naturally occurring burn cycles. So, as climate warming impacts seasonal snow it stands to reason that forest fire seasons may also shift over time in response. Causality between shifting seasonal snow patterns and forest fire increases in the western US remains conceptual until additional research is conducted to explore this relationship. In the mean time, evidence suggests that the climatic conditions contributing to seasonal snow losses also enable increased forest fire activity. Let's take a closer look.

Context of forest fires in western US mountain ecosystems

Forest fires are a naturally occurring ecosystem process that directly impacts forest community structure and function, nutrient mobility, and other forest ecosystem processes such as the ability to retain and filter water. Forest fires are not an inherently bad or new thing. They've been around since forests first evolved and exhaled enough oxygen into the atmosphere to facilitate combustion, around 360-400 million years ago[51]. Nature's most common ignition source, lightning, has likely existed throughout earth's history. Indeed, certain species that grow in fire prone forests have evolved competitive advantages that are best served when fires occur with some regularity[52]. So what role does fire serve in a forested ecosystem?

Fire breaks down organic matter, recycling nutrients locked up in above ground plants back into the soil, making these often limiting nutrients accessible to biological life again. Some plants even require fire to initiate new growth by releasing seeds and promoting germination, while other plants make quick use of the extra available sunlight that reaches recently burned areas. Certain organisms are specially adapted to recolonizing a freshly burned area and their existence may facilitate or inhibit the subsequent establishment of other species. Without fire, dead plant material or fuel can accumulate, leading to the possibility of increased fire severity when the fuel does finally burn. An extremely hot forest fire has the potential of damaging seeds in the soil, slowing down or preventing new growth. Forest fires can also alter the flow patterns of water within an ecosystem by increasing surface runoff which can lead to soil and nutrient losses as well as a decrease in water quality downstream.

The management of western US mountain forests includes a long history of activities that supported fire suppression and promoted a lack of tree species and age diversity[52—54]. This eventually lead to an abundance of available fuels which, in conjunction with other environmental factors like bark beetle outbreaks, has impacted current forest fire regimes. Through research and trial and error, fire management practices now include intentional and targeted techniques like prescribed burns and specific removal of trees to avoid fuel build-up. Earlier management techniques did contribute to our forests becoming prone to large, damaging fires. Looking farther ahead, the relative impact of climate warming, including less seasonal snow to provide a slow-release of moisture into mountain forested ecosystems, could outweigh the contribution of past practices. An area of future research could aim to tease apart the relative contributions of each.

The climatic trends that contribute to less seasonal snow facilitate more forest fires

The authors of a 2014 study looking at wildfires across the western US found that over the 28-year period of study (1984-2011), the number of large (1,000+ acre) fires in the west increased by seven per year[55]. The entire western US is a very large area, but that's 196 more fires per year on average in 2011 than in 1984. They also found over the study period that total area burned in wildfires grew by about 90,000 acres per year. This study used satellite technology to measure burn covered area in a similar way as other recent studies[8,31] used satellite data of snow covered area to explore relationships between climate and snow. The wildfires considered for this study did include other ecosystem types besides mountain forests, such as grasslands and sagebrush steppe. Nonetheless, their findings suggested that climate-related variables like temperature and precipitation contributed to drought severity during the same period of time that wildfires increased. And, they pointed out that the Rocky Mountains were among the ecoregions defined within their study that experienced the strongest increase in fire activity[55].

Other evidence from recent studies suggests that in the future, forest fires may continue to become more prevalent in the western US and that fire patterns may change as forested areas continue to experience the effects of a warming climate, including hotter, drier summers and less seasonal snow[19,56]. Indeed, warmer air surface temperatures in all seasons, especially summer and fall, will lead to increases in ecosystem evapotranspiration. If the hottest days get a little bit hotter and the summer season lasts a little bit longer, it makes sense that forest fuels could dry out. Earlier snowmelt will expose land surfaces to the air for longer, and lower peak SWEs over time would mean less stored moisture for prolonged infiltration, further drying forests and fuels[56].

Additionally, forest fire burn scars are dark (low albedo) and absorb a great deal of energy from the sun. This could affect snowmelt rates, especially if snow in a post-burn area were thin or patchy to begin with. An exciting new study funded by the State of Washington Water Research Center called "Climate Change Effects on Water Supply: Linkages Between Wildfire and Accelerated Snowmelt" strives to explore the particular relationship between seasonal snow loss and forest fires, and if successful should provide some new insight into potential connections.

Figure 14 Seasonal snow in a forest near Steamboat Springs, Colorado (2015). Photo credit Claire Moore.

A logical follow up question to all of this is, if forest fires occur naturally and serve an ecologically important role, why should we be concerned? The short answer is because people and ecosystems are potentially affected. In a future warmer climate with less seasonal snow, post-fire community structure and function may not return to the same as pre-fire, particularly if the climatic and ecological conditions in which the original species grew have changed to the point that they no longer meet environmental requirements. For example, sagebrush-steppe or grassland could eventually replace a conifer forest after a fire if the future climate there is warmer and drier than the conifers can tolerate to initiate growth[19,21]. **Figure 15** illustrates this concept[57]. In addition to constituting major ecological community and aesthetic changes, grass

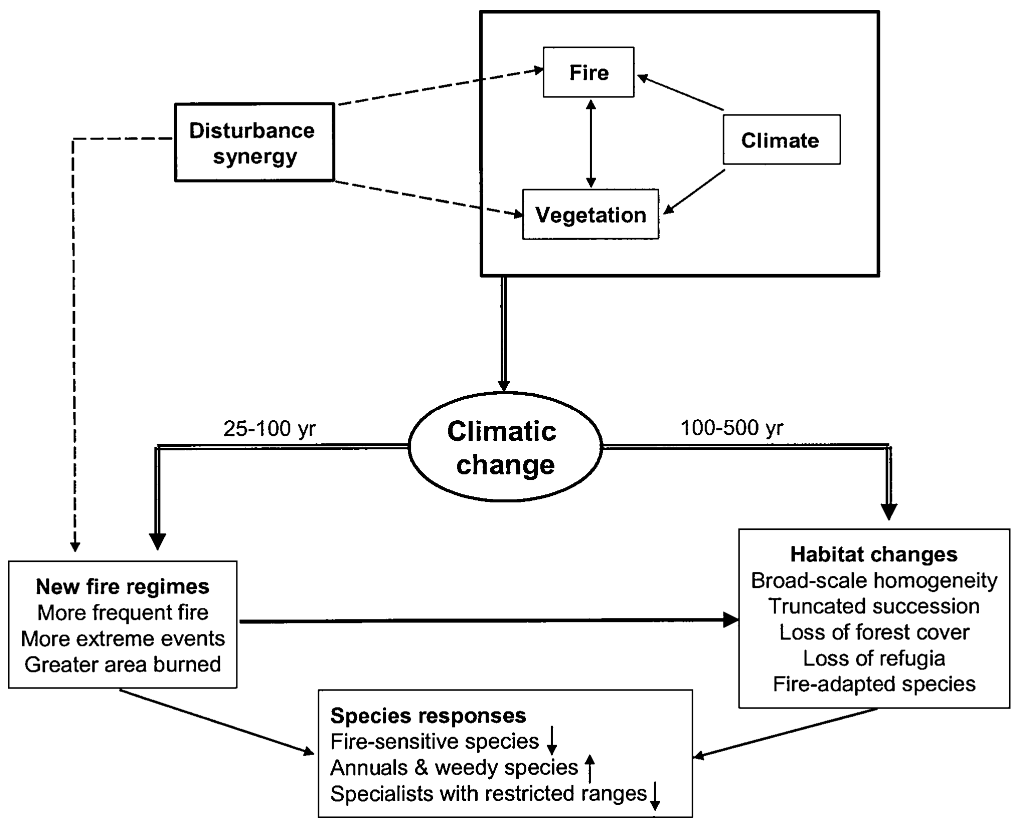

Figure 15 Schematic from McKenzie et al. (2004) demonstrating that interactions among climate, vegetation, and fire will shift with global climatic change. Fire will provide the main constraints on vegetation in the western US because fire regimes will change more rapidly than vegetation can respond to climate alone (numbers are approximate). Species responses will vary, but the synergistic effects of climatic change and fire are expected to encourage invasive species[57].

and shrubs store less carbon in their tissues than trees do, so over time this represents a net source of carbon to the atmosphere if the forests do not grow back. And while they're burning, forest fires are a major source of local air pollution that can negatively affect human respiratory health[58].

Also, people continue expanding into the wildland-urban interface (WUI), which presents a greater risk for loss of life and property as fire activity increases. Earlier snowmelt and lower peak SWE could further challenge our ability to fight forest fires in the WUI as fire seasons progress because earlier snowmelt means earlier streamflow timing and lower peak SWE means less runoff to pull from later on. Water quality is affected at least in the short term downstream of post-burn areas as well. A study from the Colorado Front Range found increased amounts of sediment-associated carbon and nutrients in streams after high-intensity summer storms in the post-burn Four Mile Canyon area. The authors of the study suggest the spikes in nutrients and dissolved carbon could both affect aquatic ecosystems and present significant challenges for drinking-water treatment downstream[59]. Sometimes soils become hydrophobic and repel water after a forest fire, so precipitation that falls on post-fire burn scars contributes to erosion and doesn't benefit from filtering through healthy root systems prior to entering rivers and reservoirs[19].

While forest fires are a naturally occurring and important ecological process, they also present challenges to ecosystem and human health in certain circumstances. And as climate change continues to impact mountain areas with both forest fires and seasonal snow, we could expect more of one and less of the other.

Using place-based connections to enhance the impact of climate change communication

In addition to direct contributions like providing a source of water, snowy mountains of the west also present endless opportunities for outdoor recreation pursuits like skiing and snowboarding. Snow sports and the winter outdoor recreation industry generate billions of dollars of revenue every year in the United States[23,60]. But it's not all about money. People who spend time in natural places experience enhanced recovery from stress and relief from attention fatigue[61—63] and tend to care more about the environment[64]. Participants in outdoor activities often form deep personal connections with the places that facilitate positive experiences and contribute to their self-identity[65]. Tapping into these qualities, along with relating to an individual's values and beliefs, helps with effective communication about local climate change effects and can even potentially spur positive behavior changes[25—27].

It's safe to say I'm one of those people with a personal connection to places with seasonal snow. On a snowy day in the mountains, tiny swirling ice crystals and big clusters of snowflakes whisper weightlessly around and form a peaceful, fluffy blanket below. In moments like this I am filled with the kind of tranquility that's cultivated by adventurous pursuits in natural places. I enjoy skiing at resorts, and even more so in the boundless backcountry. A journey through backcountry snow entails physical endurance and mental acuity. A commitment to preparedness and managing risk. And an appreciation of beauty and understanding of the natural environment. It requires clear communication, informed decision making, efficient teamwork, resolute self reliance, and a genuine acceptance of both the known and unknown. I even broke my ankle backcountry skiing earlier this winter and have no regrets. Through the pursuit of exploring snow, I test my limits and become a better person.

As a skier, I rely on wintertime precipitation that falls as snow in mountainous terrain to create the canvas on which I paint deep, carving turns. I am connected to these places and I care about them. I have a memory bank full of snowy adventures with friends and loved ones playing, learning, and evolving. And, I know that in a warming climate that things are beginning to change. Skiers, boarders, and mountain snow enthusiasts alike represent a valuable audience to connect with about climate change impacts in places we care about.

Figure 16 Author skiing Mt. Sherman in Colorado (2015). Photo credit Doug Stolz.

Place-based climate change communication

Since the 1990s, social science research has been exploring what makes climate change communication effective and what challenges communicators and environmental educators face in achieving this goal[26,66]. One central challenge is general misinformation and lack of environmental and climate literacy to begin with. While 63% of American's believe that global warming is happening, the average citizen would score a failing 52% on an 81-question test about earth systems and climate science, indicating that most do not understand why[67]. Another challenge is focused on the general public's understanding of what climate-related action is needed and what is being done about it. Simply alarming people about rapid human-caused climate change without suggesting concrete actions for individuals, communities, and governments to take can leave people feeling understandably overwhelmed. On the other hand, fostering complacency by demonstrating that governments and international mitigation policies will solve the climate problem for us can also lead to individual and community-level inaction.

In *Changing the Conversation about Climate Change: A Theoretical Framework for Place-Based Climate Change Engagement* the authors offer a potential solution to address these communication challenges[25]. They empirically tested a communication framework grounded in relevant research on place attachment, place-based education, and norm activation theories and developed to inform effective climate change communication on public lands[26,27,68]. In their 2012 article, Schweizer et al. proposed that climate change will resonate with diverse audiences when: (1) it is situated in cultural values and beliefs, (2) it is meaningful to that audience, and (3) it empowers specific action. This makes sense, but often remains an elusive goal for may communicators. The authors' framework emphasizes the importance of understanding your target audience and what its priorities are in order to effectively communicate a message.

To test the viability of their proposed framework, the authors administered surveys (n=4,181) and interviews (n=359) in 16 national parks and wildlife refuges around the US (all beginning to experience the impacts of climate change)[25]. They asked the participants specific questions to help determine the receptivity of diverse audiences to place-based climate change information. These audiences self-selected to visit national parks and wildlife refuges, so they demonstrated an interest in appreciating landscapes and learning about natural places. The results suggested that those surveyed would be open and interested in receiving place-based climate change information as outlined in the authors' framework.

Specifically, the framework advises communicators to "(1) use place as a medium and (2) connect that place to emotional and social meanings through (3) messages about localized impacts of climate change[25]." Tell a story using a local landscape that people care about, the authors argue, and change the conversation about climate change.

> Creating messages with a systems-based explanation will highlight the changes and impacts observed at a specific site and how those impacts are connected to individual decision-making and behavioral choices. This study demonstrates that many people need to see the effects of climate change before they can believe it is real and make sustainable decisions and behavioral changes. In addition, coupling meaningful social interaction with experiential learning opportunities is a way to build community and facilitate deeper understanding of climate change impacts through the lens of place (p. 59)[25].

The preferred learning methods for visitors surveyed included websites, trailside exhibits, interpretive programs, and brochures. Websites and trailside exhibits were the two most popular choices identified by survey and interview participants.

An opportunity exists to connect meaningful place-based information about environmental change with broader audiences like skiers and snowboarders who care about places with seasonal snow. Herein lies a reason to be optimistic about our future, and to do something about the change we see coming. The time has come to look beyond scientists, land managers, and decision makers who are currently served by research articles and summary reports on these issues. Every-day people who self-identify with a place undergoing change or have personal connections with seasonal snow are a prime example audience for place-based climate change engagement.

Figure 17 Author backcountry skiing in Teton Valley, Idaho (2008). Photo credit Jeremy Estroff.

Enhancing communication efforts and inspiring informed action

The *Theoretical Framework for Place-Based Climate Change Engagement*[25] could be applied to develop seasonal snow related climate change communication efforts for Southern Rockies front-country (i.e. ski resorts) or back-country (i.e. public land agencies and outdoor recreation organizations) winter sports communities. If leaders and educators within these communities want to take on a more prominent role in teaching their constituents about climate change, this framework can serve as starting point with tools and the empirical evidence to support it. As we have seen, knowing your audience, including their level of concern and willingness to learn about climate change is key. This could be identified via in-person survey and interview methods[25] or via a digital survey administered to a representative sample population. Many ski resorts and winter sports groups are already growing their sustainability initiatives, as evidenced by their web presence and environmentally-minded campaigns. This is a great first step. And, I argue that more can be done within the winter sports and outdoor recreation communities to acknowledge the vulnerability of these industries and of seasonal snow to climate change. Place-based connections can enhance the impact of climate change communication efforts and inspire informed action at individual and organizational levels.

Public land management agencies like the National Park Service are often viewed as trusted, neutral authorities on landscape-related issues. This positions them well to provide accurate, place-based climate change information specific to the park or place of interest. On the other hand, some for-profit recreation companies may have diverse clients they are wary of upsetting at least in the short-term for logical fear of losing business. This is a candid reality, and I'm not sure what to suggest as the right way to address it. High elevation resorts and backcountry areas in the Southern Rockies come to mind, because they may be relatively protected from the early impacts of climate warming on their seasonal snowpacks due to their altitude and cold temperatures. But this challenge is precisely the one that Schweizer et al. (2012) try to address head on. "Adhering to the framework, communicators or stewards of any place, can (1) illustrate the impacts of climate change by emphasizing impacts in the immediate local context, (2) connect climate impacts to human behavioral choices through systems-based explanations, and (3) provide concrete suggestions for specific actions, thus, overcoming the typical challenges of communicating about climate change."

What might this look like at the intersection of seasonal snow and winter sports? Examples of applications in this context include developing a place-based climate change education campaign for a single ski resort, ski area management company, or outdoor recreation organization[69]. Or creating unique, place-based signage about regional effects of climate change in backcountry ski access areas equipped with website links or Quick-response (QR) codes. The codes should link to relevant, mobile friendly websites with high quality content and provide additional resources and specific action ideas. To facilitate an interactive public dialogue, trail-side signs and mobile friendly platforms could include a citizen-science component. Visitors could provide their own real-life, time-and-date stamped experiences (e.g. photos, snow depth, dust-on-snow, personal accounts) with seasonal snow changes, including year-to-year variability and long-term trends. A collection of empirical knowledge created by a community who cares could eventually serve as yet another dataset for scientists to explore when it comes to documenting and understanding regional effects of climate change.

The right approach will depend on the organization, place, audience, and available resources. Regardless, efforts should strive to connect broader audiences with place-based evidence for change in understandable and relevant ways and empower people with an informed ability to act.

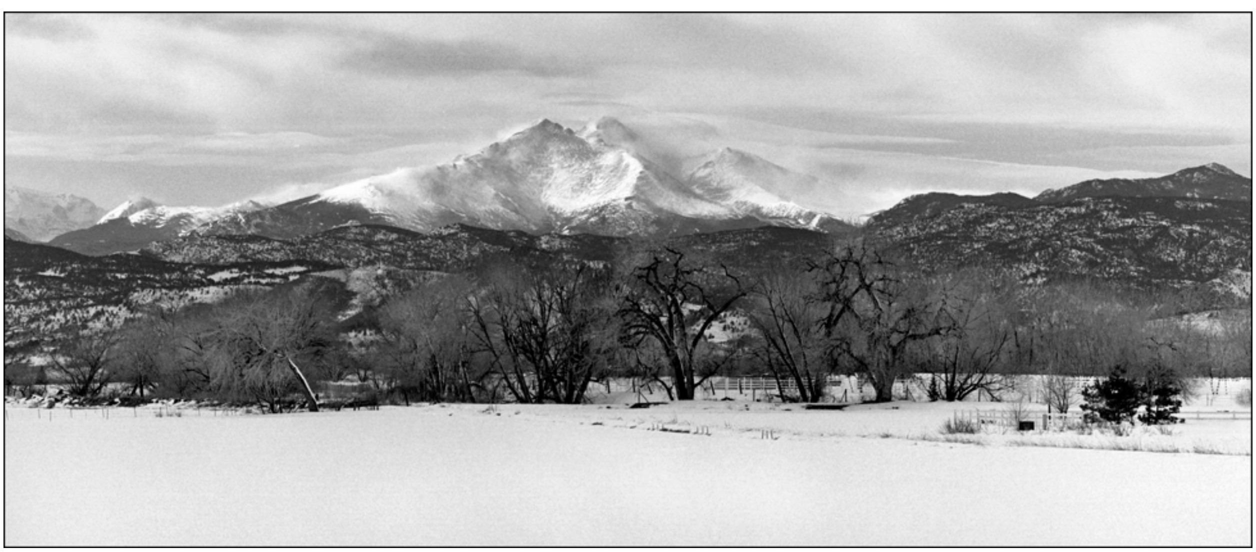

Figure 18 Longs Peak, Colorado. Photo credit David Spohn.

Summary

By now we know that the ongoing use of non-renewable fossil fuels has rapidly changed the composition of our atmosphere to the point that it is trapping and re-radiating more energy back to the earth's surface than it has in recorded history[1]. This in turn is causing global average temperatures to rise, resulting in a suite of changes to our climate system with distinct regional and local effects, including shrinking our valuable cryosphere[9]. Frozen water stored in seasonal snowpacks in the western US contributes 50-80% of the runoff that mountain snowmelt dominated areas receive throughout the entire year[11]. Like many of these western US mountains-meet-plains places, the Southern Rocky Mountain Front Range is vulnerable to changes in its water supply already, and millions more people are expected to move here by mid-century.

In this synthesis we looked at how seasonal snow is monitored and what differences exist in seasonal snow trends over space and time. We reviewed evidence that indicates our mountains are experiencing earlier snowmelt, earlier headwater peak streamflow timing, and less total snowpack water content. We explored the rain-to-snow transition and compounding effects of windblown dust-on-snow. And we considered how computer simulations help scientists understand current snowpack patterns and potential future changes in a warming climate. All of these changes affect diverse ecosystems, people, and industries that rely on seasonal snow. And all of these changes will intensify as our climate continues to warm.

To consider an ecological impact of seasonal snow response to climate change, we reviewed forest fires in the western US and noted the potential for fire regime shifts from historical norms. This may be a result of compounding factors including forest management strategies, increased evaporation and longer fire seasons, and less seasonal snow on the ground. An increase in forest fire frequency and severity has cascading ecological effects and impacts human health, so exploring the relationship between climate change, seasonal snow, and forest fires is an important area for ongoing research.

Lastly, we investigated a potential application for this knowledge by reviewing a theoretical place-based climate change engagement framework[25]. Using a similar framework, winter sports communicators can explore opportunities to connect with their constituencies in meaningful ways about the effects of climate change on seasonal snow, and provide suggestions for actions that interested individuals can take.

I firmly believe it is well within our reach to respond and adapt to a shifting environmental context with imagination and purpose. Globally, we have already begun this process by engaging in meaningful discourse about climate change and mitigation strategies, by expanding renewable energy markets and exploring sustainable technologies, and by studying mechanisms and tracking patterns of environmental change. Communities are becoming passionate about how climate change is affecting the places that matter to them and sharing this knowledge with others. Every journey begins with a single step.

Figure 19 Plenty of sunshine and friends to share it with at Steamboat Mountain Resort (2016). Photo credit Claire Moore.

Further Reading

Snow science and seasonal snow

National Snow & Ice Data Center
https://nsidc.org
Natural Resources Conservation Service SNOTEL network
http://www.wcc.nrcs.usda.gov/snow/
Center for Snow & Avalanche Studies
http://snowstudies.org
Colorado Dust-on-Snow program
http://www.codos.org/#codos

Water in the west

Western Water Assessment
http://wwa.colorado.edu/index.html
Colorado Water Conservation Board
http://cwcb.state.co.us/Pages/CWCBHome.aspx

Science of global climate change

Intergovernmental Panel on Climate Change (IPCC)
http://www.ipcc.ch
NASA – Global Climate Change Facts
http://climate.nasa.gov/scientific-consensus/
NOAA – Global Climate Change Indicators
https://www.ncdc.noaa.gov/indicators/

Forest fires in a changing climate

US Geological Survey Western Ecological Research Center – fire ecology
http://www.fs.usda.gov/ccrc/topics/wildland-fire
US Forest Service Climate Change Resource Center – wildland fire
http://www.fs.usda.gov/ccrc/topics/wildland-fire

Snowsports community climate change initiatives

Protect Our Winters
http://protectourwinters.org
Save Our Snow
http://www.saveoursnow.com
Colorado Ski Industry climate change initiatives
http://www.coloradoski.com/climate-change-industry-initiatives
National Ski Areas Association Climate Challenge program
http://www.nsaa.org/environment/climate-change/

Responding to climate change

Environmental Protection Agency on climate change: What You Can Do
https://www3.epa.gov/climatechange/wycd/
NASA's list of resources for solutions
http://climate.nasa.gov/solutions/resources/
Climate Voices science speakers network
http://climatevoices.org

In-text hyperlinks (order of appearance)

NASA news release http://www.giss.nasa.gov/research/news/20160120/

cryosphere https://nsidc.org/cryosphere

snowmelt runoff http://www.wcc.nrcs.usda.gov/factpub/sect_2.html

Western Water Assessment http://wwa.colorado.edu/index.html

8 million by 2050 http://america2050.org/front_range.html

snow course sites http://www.wcc.nrcs.usda.gov/factpub/sect_4a.html

Snow Telemetry (SNOTEL) http://www.wcc.nrcs.usda.gov/snow/

Snow Water Equivalent http://www.nrcs.usda.gov/wps/portal/nrcs/detail/or/snow/?cid=nrcs142p2_046155

satellite http://modis-snow-ice.gsfc.nasa.gov

SnowEx http://neptune.gsfc.nasa.gov/hsb/index.php?section=322

Seasonal snow http://www.cryosphericsciences.org/snowClassification.html

snow covered area http://modis-snow-ice.gsfc.nasa.gov

streamflow http://water.usgs.gov/edu/measureflow.html

climate vs weather http://www.nasa.gov/mission_pages/noaa-n/climate/climate_weather.html

water year http://water.usgs.gov/nwc/explain_data.html

ripen http://link.springer.com/referenceworkentry/10.1007%2F978-90-481-2642-2_676

artificial temperature amplification signal http://blogs.agu.org/geospace/2015/01/14/mountain-monitoring-system-artificially-inflates-temperature-increases-higher-elevations/

water rights http://water.state.co.us/surfacewater/swrights/Pages/default.aspx

albedo https://nsidc.org/cryosphere/seaice/processes/albedo.html

an historic event http://www.cop21.gouv.fr/en/195-countries-adopt-the-first-universal-climate-agreement/

agreement http://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf

computer models https://student.societyforscience.org/article/explainer-what-computer-model

Numerical Weather Prediction https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/numerical-weather-prediction

General Circulation Model http://www.ipcc-data.org/guidelines/pages/gcm_guide.html

very first electronic general purpose computer http://www.computerhistory.org/revolution/birth-of-the-computer/4/78

Downscaling https://gisclimatechange.ucar.edu/question/63

forest fires https://www.nps.gov/fire/wildland-fire/learning-center/fire-in-depth/ecology.cfm

2014 study looking at wildfires across the western US http://news.agu.org/press-release/more-bigger-wildfires-burning-western-u-s-study-shows/

evapotranspiration http://water.usgs.gov/edu/watercycleevapotranspiration.html

"Climate Change Effects on Water Supply: Linkages Between Wildfire and Accelerated Snowmelt" https://swwrc.wsu.edu/wrra-104b-grant-program/

wildland-urban interface http://www.fs.fed.us/openspace/fote/reports/GTR-299.pdf

an 81-question test http://environment.yale.edu/climate-communication-OFF/article/Americans-knowledge-of-climate-change/

Changing the Conversation about Climate Change: A Theoretical Framework for Place-Based Climate Change Engagement http://www.tandfonline.com/doi/abs/10.1080/17524032.2012.753634?journalCode=renc20#.Vy0L8Md-f0d

place attachment http://web.uvic.ca/~esplab/sites/default/files/2010%20Tripartite%20Scannell.pdf

place-based education http://www.ecoliteracy.org/article/teaching-strategies

norm activation theories http://www.sciencedirect.com/science/article/pii/S0065260108603585

Quick-response (QR) codes https://nrelscience.org/2015/09/29/link-and-learn-how-to-use-qr-codes-to-communicate-science/

snow depth http://www.cascadedesigns.com/msr/blog/backcountry-basics-use-avalanche-probe-shovel-snow-saw/

References

[1] IPCC (2014), 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 [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)], IPCC, Geneva, Switzerland, 151 pp.

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

[3] Serreze, M. C., M. M. Holland, and J. Stroeve (2007), Perspectives on the Arctic's Shrinking Sea-Ice Cover, *Science*, *315*(5818), 1533–1536, doi:10.1126/science.1139426.

[4] Romanovsky, V. E., S. Gruber, A. Instanes, H. Jin, S. S. Marchenko, S. L. Smith, D. Trombotto, and K. M. Walter, (2007), Frozen Ground, Chapter 7, *In: Global Outlook for Ice and Snow*, Earthprint, UNEP/GRID, Arendal, Norway, pp. 181-200.

[5] Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier (2005), Declining mountain snowpack in western North America, *Bulletin of the American Meteorological Society*, doi:10.1175/BAMS-86-1-39.

[6] Brown, R. D., and D. A. Robinson (2011), Northern Hemisphere spring snow cover variability and change over 1922–2010 including an assessment of uncertainty, *The Cryosphere*, doi:10.5194/tc-5-219-2011.

[7] Pederson, G. T., S. T. Gray, T. Ault, W. Marsh, D. B. Fagre, A. G. Bunn, C. A. Woodhouse, and L. J. Graumlich (2011), Climatic controls on the snowmelt hydrology of the northern Rocky Mountains, *J. Climate*, *24*(6), 1666–1687, doi:10.1175/2010JCLI3729.1.

[8] Peng, S., S. Piao, P. Ciais, and P. Friedlingstein (2013), Change in snow phenology and its potential feedback to temperature in the Northern Hemisphere over the last three decades, *Environmental Research Letters,* doi:10.1088/1748-9326/8/1/014008.

[9] Fountain, A. G., J. L. Campbell, and E. Schuur (2012), The disappearing cryosphere: impacts and ecosystem responses to rapid cryosphere loss, *BioScience*, doi:10.1525/bio.2012.62.4.11.

[10] Cayan, D. R., M. D. Dettinger, S. A. Kammerdiener, J. M. Caprio, and D. H. Peterson (2001), Changes in the Onset of Spring in the Western United States, *Bulletin of the American Meteorological Society,* doi: http://dx.doi.org/10.1175/1520-0477(2001)082<0399:CITOOS>2.3.CO;2.

[11] Stewart, I. T., D. R. Cayan, and M. D. Dettinger (2004), Changes in snowmelt runoff timing in western North America under a "business as usual" climate change scenario, *Climatic Change*, doi:10.1023/B:CLIM.0000013702.22656.e8.

[12] Clow, D. W. (2010), Changes in the timing of snowmelt and streamflow in Colorado: a response to recent warming, *J. Climate*, *23*(9), 2293–2306, doi:10.1175/2009JCLI2951.1.

[13] Knowles, N., M. D. Dettinger, and D. R. Cayan (2006), Trends in snowfall versus rainfall in the western United States, *J. Climate*, *19*(18), 4545–4559.

[14] McCabe, G. J., and D. M. Wolock (2010), Long-term variability in Northern Hemisphere snow cover and associations with warmer winters, *Climatic Change*, doi:10.1007/s10584-009-9675-2.

[15] Klos, P. Z., T. E. Link, and J. T. Abatzoglou (2014), Extent of the rain-snow transition zone in the western US under historic and projected climate, *Geophysical Research Letters,* doi:10.1002/(ISSN)1944-8007.

[16] McCabe, G. J., M. P. Clark, and L. E. Hay (2007), Rain-on-snow events in the western United States, *Bulletin of the American Meteorological Society*, doi:10.1175/BAMS-88-3-319.

[17] Neff, J. C., A. P. Ballantyne, G. L. Farmer, N. M. Mahowald, J. L. Conroy, C. C. Landry, J. T. Overpeck, T. H. Painter, C. R. Lawrence, and R. L. Reynolds (2008), Increasing eolian dust deposition in the western United States linked to human activity, *Nature Geoscience*, *1*(3), 189–195, doi:10.1038/ngeo133.

[18] Painter, T. H., J. S. Deems, and J. Belnap (2010), Response of Colorado River runoff to dust radiative forcing in snow, *PNAS,* 107(40)17125-17130, doi:10.1073/pnas.0913139107.

[19] Rocca, M. E., P. M. Brown, and L. H. MacDonald (2014), Climate change impacts on fire regimes and key ecosystem services in Rocky Mountain forests, *Forest Ecology and Management*, doi:10.1016/j.foreco.2014.04.005.

[20] Molotch, N. P., P. D. Brooks, S. P. Burns, M. Litvak, R. K. Monson, J. R. McConnell, and K. Musselman (2009),

Ecohydrological controls on snowmelt partitioning in mixed-conifer sub-alpine forests, *Ecohydrol.*, *2*(2), 129–142, doi:10.1002/eco.48.

[21] Schlaepfer, D. R., Lauenroth, W. K. and Bradford, J. B. (2012), Consequences of declining snow accumulation for water balance of mid-latitude dry regions. *Glob Change Biol*, 18: 1988–1997. doi:10.1111/j.1365-2486.2012.02642.x

[22] Ivahnenko, Tamara, and Flynn, J.L., 2010, Estimated withdrawals and use of water in Colorado, 2005: U.S. Geological Survey Scientific Investigations Report 2010–5002, 61 p. *http://pubs.usgs.gov/sir/2010/5002/.*

[23] Outdoor Industry Association (2012), *The Outdoor Recreation Economy 2012*, Boulder, Colorado, *https://outdoorindustry.org/pdf/OIA_OutdoorRecEconomyReport2012.pdf* .

[24] Burakowski, E., M. Magnusson, and P. O. Winters (2012), Climate impacts on the winter tourism economy in the United States, *https://www.nrdc.org/sites/default/files/climate-impacts-winter-tourism-report.pdf.*

[25] Schweizer, S., S. Davis, and J. L. Thompson (2012), Changing the Conversation about Climate Change: A Theoretical Framework for Place-Based Climate Change Engagement, *Environmental Communication*, *7*(1), 42–62, doi:10.1080/17524032.2012.753634.

[26] Brownlee, M., R. B. Powell, and J. C. Hallo (2013), A review of the foundational processes that influence beliefs in climate change: opportunities for environmental education research, *Environmental Education Research*, doi:10.1080/13504622.2012.683389.

[27] Scannell, L., and R. Gifford (2013), Personally relevant climate change the role of place attachment and local versus global message framing in engagement, *Environment and Behavior*, doi:10.1177/0013916511421196.

[28] America 2050 (2016), *america2050.org/front_range.html.*

[29] Bales, R. C., N. P. Molotch, T. H. Painter, M. D. Dettinger, R. Rice, and J. Dozier (2006), Mountain hydrology of the western United States, *Water Resources Research*, *42*(8), n/a–n/a, doi:10.1029/2005WR004387.

[30] Clow, D. W., L. Nanus, K. L. Verdin, and J. Schmidt (2012), Evaluation of SNODAS snow depth and snow water equivalent estimates for the Colorado Rocky Mountains, USA, *Hydrol. Process.*, *26*(17), 2583–2591, doi:10.1002/hyp.9385.

[31] Richer, E. E., S. K. Kampf, S. R. Fassnacht, and C. C. Moore (2013), Spatiotemporal index for analyzing controls on snow climatology: application in the Colorado Front Range, *Physical Geography*, *34*(2), 85–107, doi:10.1080/02723646.2013.787578.

[32] Moore, C., S. Kampf, B. Stone, and E. Richer (2014), A GIS-based method for defining snow zones: application to the western United States, *Geocarto International*, *30*(1), 62–81, doi:10.1080/10106049.2014.885089.

[33] McCabe, G. J., and D. M. Wolock (1999), General-Circulation-Model Simulations of Future Snowpack in the Western United States, *Journal of the American Water Resources Association*, *35*(6), 1473–1484.

[34] Battaglin, W., L. Hay, and M. Steve (2011), Simulating the Potential Effects of Climate Change in Two Colorado Basins and at Two Colorado Ski Areas, *Earth Interact.*, *15*(22), 1–23, doi:10.1175/2011EI373.1.

[35] 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*(21), 4545–4561.

[36] Serreze, M. C., M. P. Clark, R. L. Armstrong, D. A. McGinnis, and R. S. Pulwarty (1999), Characteristics of the western United States snowpack from snowpack telemetry (SNOTEL) data, *Water Resources Research*, 35(7), 2145–2160, doi:10.1029/1999WR900090.

[37] Trujillo, E., and N. P. Molotch (2014), Snowpack regimes of the Western United States, *Water Resources Research*, *50*(7), 5611–5623, doi:10.1002/2013WR014753.

[38] Fassnacht, S. R., K. A. Dressler, and R. C. Bales (2003), Snow water equivalent interpolation for the Colorado River Basin from snow telemetry (SNOTEL) data, *Water Resources Research*, *39*(8), n/a–n/a, doi:10.1029/2002WR001512.

[39] Meromy, L., N. P. Molotch, T. E. Link, S. R. Fassnacht, and R. Rice (2013), Subgrid variability of snow water equivalent at operational snow stations in the western USA, *Hydrol. Processes*, 27, 2383–2400, doi:10.1002/hyp.9355.

[40] Oyler, J. W., S. Z. Dobrowski, A. P. Ballantyne, A. E. Klene, and S. W. Running (2015), Artificial amplification of warming trends across the mountains of the western United States, *Geophysical Research Letters*, 42,

doi:10.1002/2014GL062803.

[41] Lukas, J., Barsugli, J., Doesken, N., Rangwala, I., and K. Wolter (2014). Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation. A Report for the Colorado Water Conservation Board. Western Water Assessment. *http://wwa.colorado.edu/climate/co2014report/Climate_Change_CO_Report_2014_FINAL.pdf*

[42] Maurer, E. P., L. Brekke, T. Pruitt, and P. B. Duffy (2007), 'Fine-resolution climate projections enhance regional climate change impact studies', *Eos Trans*. AGU, 88(47), 504.

[43] Nolin, A. W., and C. Daly (2006), Mapping "at risk" snow in the Pacific Northwest, *Journal of Hydrometeorology*, *7*(5), 1164–1171, doi:10.1175/JHM543.1.

[44] Klos, P. Z., T. E. Link, and J. T. Abatzoglou (2014), Extent of the rain-snow transition zone in the western US under historic and projected climate, *Geophysical Research Letters*, doi:10.1002/(ISSN)1944-8007.

[45] Abatzoglou, J. T. (2013), Development of gridded surface meteorological data for ecological applications and modelling. *Int. J. Climatol*., 33: 121–131. doi:10.1002/joc.3413

[46] Daly, C., M. Halbleib, J. I. Smith, W. P. Gibson, M. K. Doggett, G. H. Taylor, J. Curtis, and P. P. Pasteris (2008), Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States, *Int. J. Climatol*., 28(15), 2031–2064, doi:10.1002/joc.1688.

[47] Painter, T. H., A. P. Barrett, C. C. Landry, J. C. Neff, M. P. Cassidy, C. R. Lawrence, K. E. McBride, and G. L. Farmer (2007), Impact of disturbed desert soils on duration of mountain snow cover, *Geophysical Research Letters*, *34*(12), doi:10.1029/2007GL030284.

[48] Cook, E. R., Woodhouse, C. A., Eakin, C. M., Meko, D. M. & Stahle, D. W. (2004), Long-term aridity changes in the western United States, *Science,* 306, 1015–1018.

[49] Liston, G. E., and K. Elder (2006), A distributed snow-evolution modeling system (SnowModel), *Journal of Hydrometeorology*, *7*(6), 1259–1276.

[50] Pierce, D. W., T. P. Barnett, H. G. Hidalgo, T. Das, C. Bonfils, B. D. Santer, G. Bala, M. D. Dettinger, D. R. Cayan, and A. Mirin (2008), Attribution of declining western US snowpack to human effects, *J. Climate*, *21*(23), 6425–6444, doi:10.1175/2008JCLI2405.1.

[51] Pausas, J. G., and J. E. Keeley (2009), A burning story: the role of fire in the history of life, *BioScience*, doi:10.1525/bio.2009.59.7.10.

[52] Habeck, J. R., and R. W. Mutch (1973), Fire-dependent forests in the northern Rocky Mountains, *Quaternary Research*, *3*(3), 408–424, doi:10.1016/0033-5894(73)90006-9.

[53] Veblen, T. T., T. Kitzberger, and J. Donnegan (2000), Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range, *Ecological Applications*, doi:10.2307/2641025.

[54] BACKER, D. M., S. E. JENSEN, and G. R. McPHERSON (2004), Impacts of Fire-Suppression Activities on Natural Communities, *Conservation Biology*, *18*(4), 937–946, doi:10.1111/j.1523-1739.2004.494_1.x.

[55] Dennison, P. E., S. C. Brewer, J. D. Arnold, and M. A. Moritz (2014), Large wildfire trends in the western United States, 1984–2011, *Geophysical Research Letters*, 41, 2928–2933, doi:10.1002/2014GL059576.

[56] Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam (2006), Warming and earlier spring increase western US forest wildfire activity, *Science*, *313*(5789), 940–943, doi:10.1126/science.1128834.

[57] McKenzie, D., Z. Gedalof, and D. L. Peterson (2004), Climatic change, wildfire, and conservation, *Conservation Biology*, doi:10.1111/j.1523-1739.2004.00492.x.

[58] Moore D, Copes R, Fist R, Joy R, Chan K, Brauer M. (2006), Population health effects of air quality changes due to forest fires in British Columbia in 2003. *Can J Public Health,* 97(2):105–108.

[59] Writer, J. H., and R. B. McClesky (2012), Effects of wildfire on source-water quality and aquatic ecosystems, Colorado Front Range. *Wildfire and Water Quality: Processes, Impacts and Challenges*, Proceedings of a conference held in Banff, Canada, 11–14 June 2012, IAHS Publ. 354, 2012.

[60] The Outdoor Foundation (2011), 2011 Outdoor Recreation Participation Report, Boulder, Colorado, *http://www.outdoorfoundation.org/pdf/ResearchParticipation2011.pdf.*

[61] Herzog, T. R., and S. J. Strevey (2008), Contact With Nature, Sense of Humor, and Psychological Well-Being, *Environment and Behavior*, 40(6), 747–776, doi:10.1177/0013916507308524.

[62] Ulrich, R. S. (1983), Aesthetic and affective response to natural environment. In I. Altman & J. F. Wohlwill (Eds.), *Behavior and the natural environment*, (6), 85-125.

[63] Kaplan, S. (1995), The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology*, (15) 169-182.

[64] Nisbet, E. K., J. M. Zelenski, and S. A. Murphy (2008), The nature relatedness scale: Linking individuals' connection with nature to environmental concern and behavior, *Environment and Behavior*, doi:10.1177/0013916508318748.

[65] Alagona, P. S., and G. L. Simon (2010), The Role of Field Study in Humanistic and Interdisciplinary Environmental Education, *Journal of Experiential Education*, 32(3), 191–206.

[66] Wolf, J., and S. C. Moser (2011), Individual understandings, perceptions, and engagement with climate change: insights from in-depth studies across the world, *WIREs Clim Change*, *2*(4), 547–569, doi:10.1002/wcc.120.

[67] Leiserowitz, A., Smith, N. & Marlon, J.R. (2010) *Americans' Knowledge of Climate Change.* Yale University. New Haven, CT: Yale Project on Climate Change Communication. *http://environment.yale.edu/climate/files/ClimateChangeKnowledge2010.pdf.*

[68] Corner, A., E. Markowitz, and N. Pidgeon (2014), Public engagement with climate change: the role of human values, *WIREs Clim Change*, 5(3), 411–422, doi:10.1002/wcc.269.

[69] Hoover, J. (2013), Skiing in the Time of Climate Change: How US Ski Areas Can Become Environmental Educators and Climate Activists. Masters Thesis for American University.