ROCKY MOUNTAIN SNOWPACK:

Investigating the patterns of snowpack levels throughout Colorado and the primary mechanisms for trends in snowpack decline

anon

Introduction

Seasonal snowfall in the high mountains of Colorado plays an integral role in the regional hydrologic cycle, as water supplies within the state rely heavily on melted springtime runoff from snowpack accumulations to meet the water needs of that state.

In this essay, I will address how snowpack levels in the interior Rocky Mountains have experienced significant declines over the past century, and investigate how both climatic factors such as temperature and precipitation, as well as nonclimatic factors such as canopy cover, soil quality and moisture, and dust deposition could be responsible for the observed decrease of one of Colorado's most valuable resources.

_____

The Basics of Snowpack

As is the case with the majority of Western states, available water in Colorado is vastly dependent on snowpack stored high in the alpine ecosystems that releases water as snowmelt and runoff as seasonal temperatures increase (Gergel, Nijssen, Abatzoglou, Lettenmaier, & Stumbaugh, 2017). Snowpack serves as a key function of the western hydrological cycle in that it is able to store reserves from the highest precipitation months for water availability during the spring, summer, and fall when economic demands for water are typically at their peak and large scale precipitation events are infrequent (Mote, Hamlet, Clark, & Lettenmaier, 2005). Beyond meeting the needs of human populations within the state, a healthy level of snowpack is also crucial in the reduction of ecological disturbances such as seasonal wildfires, the

promotion of diverse and healthy ecosystems and biotic communities, and the potential for recreation opportunities.

In order for management institutions and agencies to make decisions regarding the usage and allocation of water for the year, a number of density and distribution analysis strategies must be deployed to calculate not only the amount of snow covering a location, but also the subsequent Snow-Water Equivalent (SWE). SWE refers to the amount of water that will be available from a given amount of snow, and since a cubic foot of snow will not necessarily yield a cubic foot of water, additional calculations need to be made to determine exactly how much water will be available once the section of snow in question melts. A variety of factors can influence these calculations, such as the density of the snow and the type of precipitation that occurred. New snow is comparatively far less dense than snow that is aged and compacted under pressure and the elements, and precipitation can have a massive effect on the crystalline structure of the snow layers due to fluctuations in atmospheric moisture and temperature. Less complex snow crystals have the ability to form a far denser layer than more complex snow crystals as they can pack together tighter and thus become more compressed (Seibert, Jenicek, Huss, & Ewen, 2015). Additionally, changes in density can occur within a snowpack as the weight of fresh snow above older layers increases thermal conductivity and causes shifts in spatial distribution and overall reserve density.

The most rudimentary, yet effective way of measuring snowpack and subsequent SWE dates back to 1909, when the western states implemented the usage of Federal Snow Samplers at snow courses throughout the mountains. Over the past century, more than 1100 snow courses have been implemented to provide data regarding snowpack levels and SWE. To

determine SWE at a snow course, up to ten predetermined points are sampled using a snow

sampler, and then averaged together to give an estimate of the conditions at that location. A

snow sampler consists of an aluminum tube with a spring scale that allows the user to take

measurements of both snow depth and density (Chen et al., 2014).

Snowpack Telemetry, or SNOTEL, is a system of hydrology and climate sensors

established by the Natural Resources Conservation Service. Data obtained from SNOTEL sites

provide some of the most valuable information in determining snowpack levels, SWE, and springtime runoff forecasting. At each SNOTEL location, a large bladder equipped with water and antifreeze (also known as a snow pillow) fills with snow, which triggers a sensor within the systems' plumbing to convert the amount of pressure into a measurement of SWE (Chen

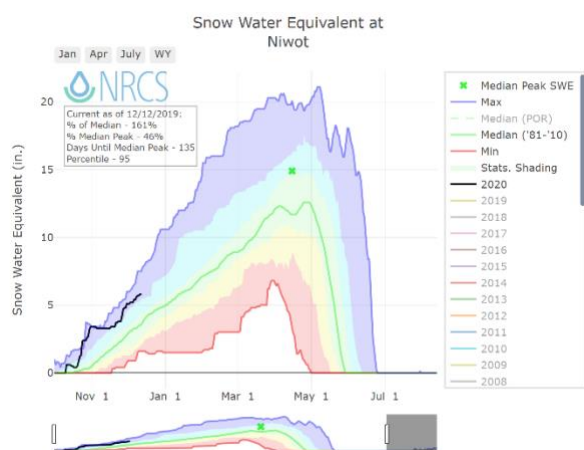*Figure 1: SNOTEL Data from Niwot Ridge. (Natural Resources Conservation Service Colorado, 2019)*

et al., 2014).

With the development of more modern technologies, snowpack mapping is becoming

an increasingly more sophisticated science. Remote sensors controlled by satellite and aircraft

can now permit the collection of data including coverage, melting, wetness, depth and density,

and even snow water equivalent with dependable accuracy using parameters such as

brightness temperature. While there is still much room for error and variability in data collected

via remote sources, these trends in technology offer promising advances in terms of acquiring

large scale information in substantially shorter time than could be accomplished by manual

labor of hydrologists (Kim, Durand, & Liu, 2018; Tsang, Tan, Xiong, & Shi, 2018).

Snowpack Trends

Over the past century, significant declines in snowpack throughout the West have been

observed, especially in regard to April 1 SWE (Clow, 2010; Steven R. Fassnacht, Venable,

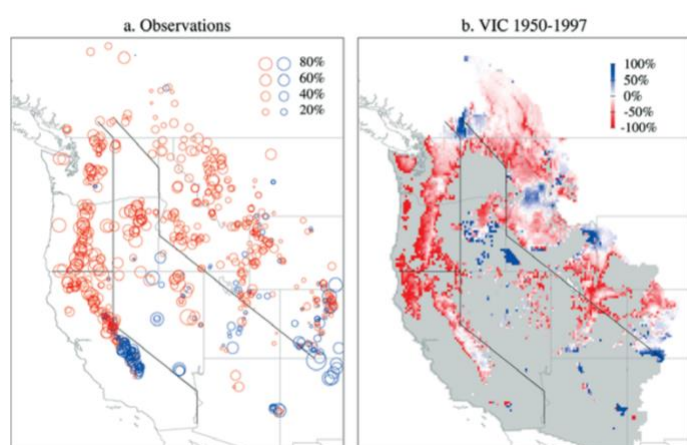McGrath, & Patterson, 2018; Mote et al., 2005). The VIC hydrological model, or Variable

Infiltration Capacity model, provides hydrologists insight into fluxes in both energy and water at a surface level, as well as up to three soil layers and soil moisture of a given area. It offers hydrologists a practical model for predicting streamflow forecasting, as well as producing climate change

Figure 2: VIC models displaying April 1 SWE at 824 snow course locations from 1950-97. (source: Mote et al., 2005)

scenarios where variables can be modified in order to make predictions about changing future

conditions and their implication for snowpack and water basin health. Using data collected

from both snow course sites and the VIC model system, hydrologists conclude that snowpack

decreases in the Rockies over a fifty year period can be estimated to be somewhere in the 15%-

20% range (Mote et al., 2005).

Furthermore, these models also produced interesting results when comparing snowpack

losses over varying elevations. According to the 2005 Mote study, the largest relative losses to

April 1 snowpack occurred in areas of lower elevation, where the midwinter temperature is generally warmer. Thus, areas such as the Colorado Rocky Mountains are less likely to experience significant snowpack losses than areas such as the BC Rockies, due to the fact that general elevation is much higher, and midwinter temperatures are experiencing less variability or increases than other western mountain ranges (Mote et al., 2005).

Additionally, many multidecadal studies of the region have concluded that while some areas are experiencing higher rates of precipitation over the core winter months, this precipitation is not translating into an increase in available SWE for the dry season. First, general trends suggest that continued warming and drying in the early winter season (November) is contributing to a decreased amount of initial winter season snowpack. Second,
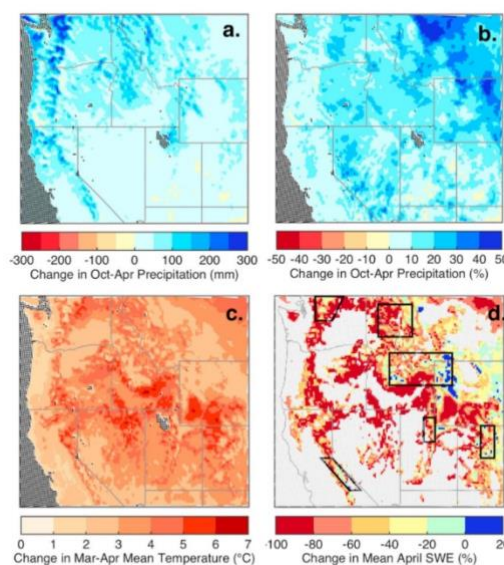

Figure 3: Average changes in precipitation and surface temperatures for simulated study years. (source: Scalzitti et al., 2016)

spring months such as April and May are observed to be becoming wetter, with much of the needed precipitation falling as rain rather than accumulating as snow and adding in additional snow to the end of the snowpack growth season (S. R. Fassnacht & Hultstrand, 2015; McGinnis, 1997).

Lastly, both observed trends and future predictive models show not only a decrease in April 1 SWE, but that the decrease in in part caused by a shift in the timing of spring melt and runoff events. With temperatures generally increasing across regions, snowmelt is beginning to initiate spring runoff at far earlier dates than historically observed, leading to an earlier dry

season and disparities between allocation policy dependent on historic dates and actual runoff occurrence (Gergel et al., 2017). While earlier spring runoff can still be stored in reservoirs for human consumption, it has significantly negative consequences for the health of water systems and soil moisture. The earlier the runoff begins each year, the longer the dry season and subsequently, the higher the risk for extreme wildfire seasons (Clow, 2010).

Causation of Observed Losses

Studies regarding considerable observed declines in Colorado snowpack since the midcentury generally conclude that climatic factors such as increasing temperature and
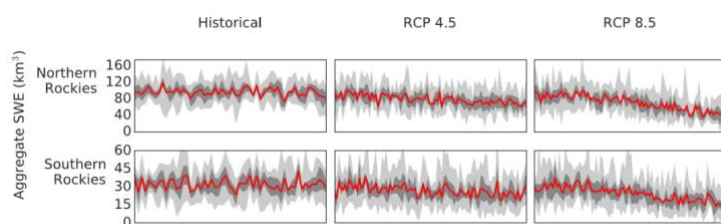

Figure 4: Simulated Apr 1 SWE aggregated by volume for the region. Red indicates the Ensemble Mean, Light Grey shows the full range projected, and Dark Grey depicts the interquartile range. (source: Gergel et al., 2017)

variation in precipitation events are the primary reason for subsequent snow loss. Additionally, it is highly likely that nonclimatic factors, such as changes in landscape use, changes to

canopy cover, soil moisture, and dust deposition could also be influential factors in the decrease from historic snowpack levels.

Climatic Factors:

Average winter temperature increases show warming rates up to 5°C in areas such as the Northern and Southern Rockies (Gergel et al., 2017). Using data from USHCN throughout the November-March snow season, a concerning trend in increasing winter temperatures was identified for 1930 to 1997, with the majority of temperature increases happening at 90% of research stations between 1950-1997 (Mote et al., 2005). These rises in temperature cause a

number of issues for snowpack levels and SWE, first in that melting and warming events are more likely to occur throughout the early winter season leading to reduced initial snowpack. Secondly, warm weather and sunny days can contribute to melting and sublimation effects throughout the winter months that reduce the snowpack level before April 1. Lastly, a warmer climate and an early onset of higher temperatures has led to the runoff season occurring early and earlier each year, which means that snowpack is melting off at an increasingly earlier date and thus posing problems for long term water availability throughout the dry season (Mote et al., 2005).

Predicted precipitation changes are varied across the entire Rocky Mountain region, with increases of up to 30% expected for everywhere besides the Lower Colorado region, where precipitation is expected to be reduced substantially by 2080 (Gergel et al., 2017). Increasing precipitation does not necessarily mean an increase in SWE, as precipitation is far less likely to result in snow accumulations as mid-winter temperatures increase. Therefore, it should be noted that an increase in precipitation is insufficient to cover the declines in SWE caused by regional warming, considering that snow is melting at a faster rate, and precipitation is forming as rain or wet snow that does not contribute to the snowpack.

Canopy Cover:

Forest canopies can have a significant impact on both the amount of snowpack stored in an area, but also the quality and chemical composition of the snow. Canopy interception plays an important role in determining the overall snowpack stored beneath. In a study conducted in Fraser experimental forest, Colorado, hydrologists found that the forest canopy intercepted

approximately 36% of all snowfall in the area, and interception was further correlated with snowpack peak water equivalent on the surface. Removal of the dense canopy resulted in an increase of SWE to >90% cumulative snowfall inputs, and studies concluded a notable increase in snowpack levels in areas that were clear cut to remove the dense canopy when compared to study areas within the canopy cover (Stottlemyer & Troendle, 2001). Interception is significant because not only does it reduce the amount of snow covering the ground, but it increases the amount of snow that is returned to the atmosphere by sublimation (Varhola, Coops, Weiler, & Moore, 2010).

Further, forest canopy cover reduces rates of ablation (the removal or melting of snow) when compared to open areas, due to the fact that shelter and shading can protect snowpack under the canopy from variable elements and solar radiation. This means that snow stored under the shade of forest canopies is less likely to melt off quickly, or simply sublimate back into the atmosphere as vapor. Thus, forest canopies contribute a complex element to snow studies due to the large variability in the nature of their effect, both positive and negative (Sexstone et al., 2018; Varhola et al., 2010).

Dust Deposition:

Deposition of dust can impact the lifespan of snowpack because of its ability to lower snow albedo. Albedo refers to a surfaces ability to absorb or reflect light. Fresh snow is bright and white; therefore, it has a high albedo and is able to reflect a large amount of incoming radiation, subsequently
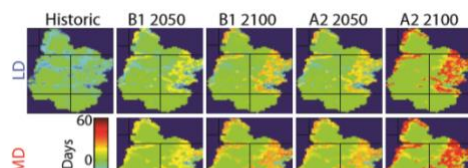

Figure 5: Change in "snow-all-gone" dates compared to historic climate, moderate dust (MD) results by grid cell for various scenarios. (source: Deems et al., 2013)

extending its lifespan. The lower the albedo of a surface, the more light and radiation will be absorbed (Clow, Williams, & Schuster, 2016). In the case of dust loading, particles of dust cover the fresh snow and lower the areas albedo, leading to snow cover duration that can be shortened by several weeks relative to conditions expected of fresh, undisturbed snow (Deems, Painter, Barsugli, Belnap, & Udall, 2013).

Temporal trends indicate that winter and spring aeolian dust deposition increased upwards of 81% in the southern Colorado Rocky Mountains over an observed period from 1993 to 2014. Subsequently, these increases combined with a decrease in precipitation accounted for a significantly accelerated time to melt regional snowpack over an 18-day period. Dust emissions are additionally predicted to have doubled globally over the 20th century, primarily due to increased periods of drought and changes in local land use. These figures are especially concerning in that this process creates a negative cycle – areas that are experiencing greater instances of drought contribute to dust deposition at a higher rate, which in turn melts snowpack faster and results in longer periods of drought (Clow et al., 2016; Deems et al., 2013).

Soil Moisture

While the majority of these studies focus on springtime snow runoff that fills the rivers and surface level water reserves, another crucial aspect to the importance of winter snow is the potential for recharging of groundwater systems. Soil surface temperatures underneath the snow reserve can fall well below 0 °C and water typically freezes within 10cm of soil depth, however deeper soil horizons tend to remain unfrozen and melted water is able to penetrate the lower, partially frozen layers and seep back into the groundwater of an area. The amount of

water that can be absorbed by the soil is largely dependent on how much water was absorbed

prior to the formation of the snowpack as well as characteristics of the soil, the soils' quality,

and any usage by surrounding

vegetation (Sutinen, Hänninen,

& Venäläinen, 2008).

Studies investigating the

relationship between

snowpack, SWE, and soil

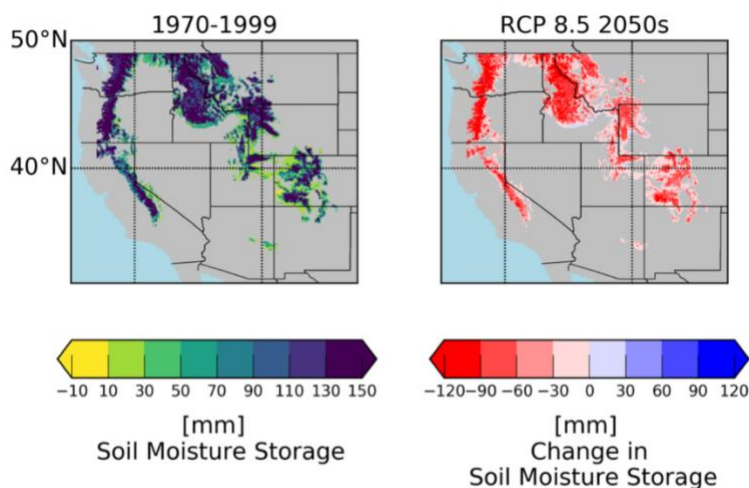suggest that changes in

seasonal snowpack in Colorado

Figure 6: Simulated summer soil moisture in storage and change in storage for Western mountain regions. (source: Gergel et al., 2017)

is likely to be accompanied by changes in the temporal and spatial patterns of soil moisture.

Snowpack both isolates and promotes soil moisture and prevents loss of moisture from

underground environments until after snow ablation begins in the late spring. Delays in the

formation of snowpack, and earlier melting of the snow in the spring would thus result in a

smaller window for soil to become permeated with snowmelt that could end up back in the

groundwater reserve (Maurer & Bowling, 2014). Moreover, a decrease in moisture trapped

within the soil can contribute to an increase in dust deposition as described previously. Soil

lacking healthy levels of water are more likely to experience drought conditions, reducing

vegetation, increasing dust particles, and increasing an areas chance for large scale fire regimes

(Gergel et al., 2017).

Conclusion

In conclusion, while snowpack accounts for a majority of the state of Colorado's freshwater supply, ample evidence suggests that seasonal snowpack is following a pattern of decline when compared relatively to historic levels. Snowpack decline can be attributed to changes in climatic conditions, such as increased temperature and change in precipitation events, as well as nonclimatic conditions such as forest canopy cover and distribution, dust deposition, soil conditions, and other land use changes. With the prediction of increased global warming due to greenhouse gas emissions, it is highly likely that the trends observed in snowpack conditions are likely to continue and even accelerate in the future. Thus, for a region that already deals with an incredibly dry climate and issues accommodating both the needs of the human population and the ecological communities, further decline from healthy snowpack amounts could have profoundly negative consequences in terms of supplying water for municipal and agricultural use, recreation, and maintaining diverse and thriving biotic systems.

References

Chen, F., Barlage, M., Tewari, M., Rasmussen, R., Jin, J., Lettenmaier, D., … Yang, Z.-L. (2014).

Modeling seasonal snowpack evolution in the complex terrain and forested Colorado

Headwaters region: A model intercomparison study. *Journal of Geophysical Research:*

Atmospheres, *119*(24), 13,795-13,819. https://doi.org/10.1002/2014JD022167

Clow, D. W. (2010). Changes in the Timing of Snowmelt and Streamflow in Colorado: A Response to

Recent Warming. *Journal of Climate*, *23*(9), 2293–2306. Retrieved from JSTOR.

Clow, D. W., Williams, M. W., & Schuster, P. F. (2016a). Increasing aeolian dust deposition to

snowpacks in the Rocky Mountains inferred from snowpack, wet deposition, and aerosol

chemistry. *Atmospheric Environment*, *146*, 183–194.

https://doi.org/10.1016/j.atmosenv.2016.06.076

Deems, J. S., Painter, T. H., Barsugli, J. J., Belnap, J., & Udall, B. (2013). Combined impacts of current

and future dust deposition and regional warming on Colorado River Basin snow dynamics and

hydrology. *Hydrology and Earth System Sciences; Katlenburg-Lindau*, *17*(11), 4401.

http://dx.doi.org.colorado.idm.oclc.org/10.5194/hess-17-4401-2013

Fassnacht, S. R., & Hultstrand, M. (2015). Snowpack variability and trends at long-term stations in

northern Colorado, USA. Proceedings of the International Association of Hydrological Sciences;

Gottingen, 371, 131–136. http://dx.doi.org.colorado.idm.oclc.org/10.5194/piahs-371-131-2015

Fassnacht, S. R., Venable, N. B. H., McGrath, D., & Patterson, G. G. (2018). Sub-Seasonal Snowpack

Trends in the Rocky Mountain National Park Area, Colorado, USA. *Water*, *10*(5), 562.

https://doi.org/10.3390/w10050562

Gergel, D. R., Nijssen, B., Abatzoglou, J. T., Lettenmaier, D. P., & Stumbaugh, M. R. (2017). Effects of climate change on snowpack and fire potential in the western USA. *Climatic Change; Dordrecht*, *141*(2), 287–299. http://dx.doi.org.colorado.idm.oclc.org/10.1007/s10584-017-1899-y

Kim, R. S., Durand, M., & Liu, D. (2018). Spectral analysis of airborne passive microwave measurements of alpine snowpack: Colorado, USA. *Remote Sensing of Environment*, *205*, 469–484. https://doi.org/10.1016/j.rse.2017.07.025

Maurer, G. E., & Bowling, D. R. (2014). Seasonal snowpack characteristics influence soil temperature and water content at multiple scales in interior western U.S. mountain ecosystems. *Water Resources Research*, *50*(6), 5216–5234. https://doi.org/10.1002/2013WR014452

McGinnis, D. L. (1997). Estimating Climate-Change Impacts on Colorado Plateau Snowpack Using Downscaling Methods. *The Professional Geographer*, *49*(1), 117–125. https://doi.org/10.1111/0033-0124.00062

Mote, P. W., Hamlet, A. F., Clark, M. P., & Lettenmaier, D. P. (2005). Declining Mountain Snowpack in Western North American. *Bulletin of the American Meteorological Society*, *86*(1), 39–50. https://doi.org/10.1175/BAMS-86-1-39

Scalzitti, J., Strong, C., & Kochanski, A. (2016). Climate change impact on the roles of temperature and precipitation in western U.S. snowpack variability. *Geophysical Research Letters*, *43*(10), 5361–5369. https://doi.org/10.1002/2016GL068798

Seibert, J., Jenicek, M., Huss, M., & Ewen, T. (2015). Chapter 4—Snow and Ice in the Hydrosphere. In J. F. Shroder, W. Haeberli, & C. Whiteman (Eds.), *Snow and Ice-Related Hazards, Risks and Disasters* (pp. 99–137). https://doi.org/10.1016/B978-0-12-394849-6.00004-4

Sexstone, G. A., Clow, D. W., Fassnacht, S. R., Liston, G. E., Hiemstra, C. A., Knowles, J. F., & Penn, C.

A. (2018a). Snow Sublimation in Mountain Environments and Its Sensitivity to Forest

Disturbance and Climate Warming. *Water Resources Research*, *54*(2), 1191–1211.

https://doi.org/10.1002/2017WR021172

Sexstone, G. A., Clow, D. W., Stannard, D. I., & Fassnacht, S. R. (2016). Comparison of methods for

quantifying surface sublimation over seasonally snow-covered terrain. *Hydrological Processes*,

30(19), 3373–3389. https://doi.org/10.1002/hyp.10864

Stottlemyer, R., & Troendle, C. A. (2001). Effect of canopy removal on snowpack quantity and

quality, Fraser experimental forest, Colorado. *Journal of Hydrology*, *245*(1–4), 165–176.

https://doi.org/10.1016/S0022-1694(01)00351-1

Sutinen, R., Hänninen, P., & Venäläinen, A. (2008). Effect of mild winter events on soil water content

beneath snowpack. *Cold Regions Science and Technology*, 51(1), 56–67.

https://doi.org/10.1016/j.coldregions.2007.05.014

Tsang, L., Tan, S., Xiong, C., & Shi, J. (2018). 4.05—Optical and Microwave Modeling of Snow. In S.

Liang (Ed.), *Comprehensive Remote Sensing* (pp. 85–138). https://doi.org/10.1016/B978-0-12-

409548-9.10644-X

Varhola, A., Coops, N. C., Weiler, M., & Moore, R. D. (2010). Forest canopy effects on snow

accumulation and ablation: An integrative review of empirical results. *Journal of Hydrology*,

392(3–4), 219–233. https://doi.org/10.1016/j.jhydrol.2010.08.009