Climatology of the Intermountain West an Assessment of Temperature, Precipitation, and Snowpack in a Changing Climate Regime

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Abstract

The western United States, or Intermountain West, is both a variable and intermittent hydroclimate system. Both the natural and human components of the system are dependent on variable temperature, precipitation, and snowpack patterns at different temporal and spatial scales. These dependencies leave the region more susceptible to climate change and the associated impacts. In order to effectively adapt to the changing climate regime, key environmental variables such as temperature, precipitation, and snowpack must be understood via monitoring and modeling. Additionally, effort needs to be focused on developing a better understanding of the large scale teleconnections of the region that drive the variability within the environmental variables. Being able to predict when these teleconnections will arise and how they shift storm tracks within the region will help to constrain management and policy intervention uncertainties for the region. Historically observed trends for the region indicate that temperatures have increased by one to 2.5 degrees Fahrenheit, precipitation trends have been highly variable with a slightly increased trend of 0.5 to 2.1%, and snowpack has declined by 16-22%, over the past 50 years. Global climate models predict similar trends (in several emission scenarios) where temperature increases by two to 5.5 degrees Fahrenheight, precipitation varies between -20% to +15%, and snowpack declines by 21 to 25% by 2055 relative to a 1950-2000 baseline. Water managers should expect to deal with a multivariate and uncertain future that will break down the long standing management strategy of stationarity.

Goals for this paper

The overall goal of this paper was to understand the unique hydroclimatology of the Intermountain West and how the region will respond to a changing climate regime. The drive for this understanding spurs from the need to better understand and predict the water budget of the region in order to create more informed adaptation and mitigation measures. This was accomplished by looking at the major large scale atmospheric drivers of weather events within the region; by investigating the observed trends in key hydroclimate variables such as temperature, precipitation and snowpack; and lastly, by analyzing the predicted changes within each of the aforementioned variables within several projected emission scenarios.

Introduction

The Intermountain West is geographically situated between the Sierra Nevadas in the west and the Rocky Mountains in the east (Figure 1, Wise, 2012). This area is characterized as a semi-arid climate (500 millimeters/year or less of rain), located on a high plateau (2000 meters higher than the surrounding basins), and influenced by orographic rain shadow effects (Knapp, 1997). The region is dominated by extreme diurnal and seasonal temperature swings, winter month controlled precipitation patterns, and a reliance on snowmelt during the summer months. To get an idea of the magnitude of these temperature swings, the maximum recorded temperature was 45 degrees Celsius in July and the minimum recorded temperature was -40 degrees Celsius in January (Wise, 2012). Additionally, the maximum average precipitation for the region is exceptionally heterogeneous compared to regions neighboring it (e.g. coastline of western US and the Great Basin). Maximum precipitation of the region can fall within the months of August through April and more localized maximum precipitation can vary in monthly timing within a mere 10-100 kilometer distance (Figure 2, Wise, 2012). 75 percent of the freshwater that is supplied within the region comes from seasonal snowpack (Cayan et al., 1996). Also, the region has a long history of recurrent drought patterns which puts added stress on best water management practices. Water managers within the region have a non-trivial task. They must balance high natural variability with one of the nation's fastest growing populations in the USA. For example, Nevada boasts an increase in population of 35.1 percent, Arizona had an increase of 24.5 percent, and Utah had an increase of 23.8 percent, comparatively the national average had a population increase of 9.7 percent (Wise, 2012). Moreover, many of the region's major urban centers (e.g. Las Vegas and Reno, NV and Salt Lake City, UT) have some of the highest per capita water use in the nation (Anderson and Woosley, 2005). All of these key issues become magnified within a climate change context as historically assumed hydroclimate quantities may shift in duration, intensity, and timing. The added uncertainty that climate change brings to the Intermountain West emphasizes the importance of maintaining a robust and densely populated climatological dataset. Moreover, it highlights the need for more accurate and resolved (spatial and temporal) modeling of key hydroclimatic variables such as temperature, precipitation, and snowpack. Models can never be perfect, but they are our only tool to predict the future and constrain the plethora of uncertainties associated with managing a highly variable water basin such as the Intermountain West.

Teleconnections of the Intermountain West

The Intermountain West's variability can be correlated to large scale atmospheric and oceanic feedback mechanisms known as teleconnections. These teleconnections act to inhibit and/or modify the storm track systems that pass through the area. As found by Cayan et al. (1998) decadal atmospheric-oceanic fluctuations vary annual precipitation by 20-45 percent in the western USA. For many years, the ability to monitor these teleconnections has been stymied as the remote sensing tools weren't available and the climate datasets couldn't be generated. With the advancement of satellite remote sensing, the ability to see the bigger climate picture at varying spatial and temporal scales can now be achieved. With the ability to observe these phenomena and an understanding that they are a key driver of the system, several of the teleconnections that govern the Intermountain West have been identified. These teleconnections include: the Aleutian Low, the El-Nino Southern Oscillation (ENSO), the North American Monsoon, the Pacific Subtropical High, and the Pacific North American (PNA) pattern (Wise, 2012).

The first teleconnection of importance is the Aleutian Low. The Aleutian Low is a teleconnection that impacts the intensity and location of Intermountain West storm tracks and is characterized as an area of semi-permanent low pressure in the North Pacific, near the coast of

Alaska, that during the winter months create a westerly cyclonic storm movement that propagates itself into the western USA (Wise, 2012). ENSO is another important modifier of Intermountain West storm tracks. This teleconnection heralds from the equator and impacts interannual to decadal trends in Intermountain West hydroclimate variables such as precipitation, snow accumulation, and streamflow (Dettinger et al., 1998). ENSO has two phases: El Nino and La Nina. During La Nina, the "normal" state of the equatorial Pacific, the most southern portions of the Intermountain West are in a state of dry and warm conditions during December – February. Conversely, during El Nino, the southern portions of the Intermountain West experience wetter conditions in December through February. Therefore, these phase transitions between El Nino and La Nina impact the storm track positions entering the Intermountain West which in turn controls the intensity and duration of storms along the track (Cayan et al., 1999). The North American Monsoon is characterized as a moisture transport teleconnection that spans from Mexico into the southwestern United States and is a direct result of differential planetary heating within seasonal changes. During the North American Monsoon, the maximum summer precipitation can be impacted within the southern portions of the Intermountain West (Wise, 2012). Moving to the Pacific coast of California, the Pacific Subtropical High also plays a role in Intermountain West hydroclimatology. The Pacific Subtropical High is a result of large scale atmospheric subsidence (from the general circulation of the atmosphere) that results in divergent surface flow off the coast of California. The impacts associated with this teleconnection include a change in the strength and position of storm tracks entering the region and, more specifically, can create persistent dry summer conditions that can result in prolonged drought conditions within the Intermountain West (Wise, 2012; Trewartha, 1981). The last of the integral Intermountain West teleconnections, to our current knowledge, is the PNA. Generally, the PNA manifests itself as a deviation in the mean tropospheric flow over North America (Rodionov and Assel, 2001). Interestingly, the PNA interplays with the Aleutian Low where a strong positive phase in the PNA results in a stronger Aleutian Low and a stronger atmospheric ridge over the western USA. This promotes dry anomalies in the Intermountain West (Wise, 2012). As a result, more rain events and less snow events can occur, impacting the water availability within the region for both human and natural systems (Mock, 1996).

As shown, the aforementioned teleconnections and their associated impacts have large implications on when, where, and how strong precipitation events will be in the Intermountain West. The mechanisms on how many of these teleconnections manifest themselves are still being understood and debated, but the ability to recognize and identify their presence within the atmosphere, ocean, or atmosphere-ocean linked system is becoming clearer. These teleconnections have played a clear role in the historical trends in temperature, precipitation, and snowpack.

Historical Observations of the Intermountain West

In order to grasp the magnitude and intensity of climate change it is important to first get an idea of the historical observational period and then assess how conditions are changing from this period. Fortunately, the Intermountain West has a fairly long term and densely populated climatological dataset. Within the context of this paper, the key hydroclimate variables of interest will be: temperature, precipitation, and snowpack. Further, these quantities will be assessed for the winter months, where precipitation events usually occur within the region.

Temperature trends in the Intermountain West have been steadily increasing. As shown in Mote et al. (2005), the November through March observed temperature trends throughout the region have been increasing from one to four degrees Celsius (based on location) from the climatologic mean, with maximum increases seen in Utah. In addition to Mote, the CU-NOAA Western Water Assessment (2008) found that the yearly average temperature for the Intermountain West increased by one to 2.5 degrees Fahrenheit across the basin from 1950-2007. Precipitation trends within the Intermountain West are less certain for the months of November through March. The magnitude of precipitation change is highly variable throughout the region and varies from increases/decreases of 15-60%, a huge disparity (Mote et al., 2005). If one delves into the data, as Mote et al. did, the dataset noise for the region shows a slightly increased precipitation trend of 0.5 to 2.1%. Lastly, snowpack within the region, save for the southern Sierra Nevada, has shown a clearly defined decreasing trend. April 1st snow water equivalent (SWE), used as an indicator of how much water will be available via snowpack for the summer months, has shown an overall decline of 16 to 22% (Figure 3, Mote et al., 2009). Furthermore, Harpold et. al (2012) showed that the snow cover duration and SWE maximum for the Intermountain West is decreasing. Decreasing snow cover duration was linked to later snow cover timing in the fall and shorter and faster melting in the spring (Harpold et al., 2012).

The past 50 years of historical observations within the Intermountain West have shown clear trends of a changing mean climatological state. With the continued release of greenhouse gases, modifications in land cover, and potential shifts in the natural variability within the major teleconnections of the region, the future appears to be in an uncertain realm. In order to get a clearer picture of the future and constrain some of the uncertainties presented by these climate shifts, a need for integrated climate models and their predictive powers clearly presents itself.

Future Predictions for the Intermountain West

Modeling the Earth's climate is no trivial task. The climate is a dynamic system dependent on several components including: the atmosphere, the biosphere, the cryosphere, the hydrosphere, and the lithosphere, and the interactions between each of these components. Embedded within each of these components are innumerable variables with varying spatial and temporal frequencies and resolutions. Further complexity arises when one attempts to predict human behavior and their impacts associated with population dynamics, resource demands, land use changes, and the introduction of external forcings associated with aerosols and greenhouse gases from the burning of biomass and/or fossil fuels. To model this multivariate and interacting system, climate scientists must balance the demands between computational efficiency and power with model complexity and resolution. They must also numerically discretize the fundamental equations of fluid motion, radiation, thermodynamics, cloud processes, and bin major chemical processes to allow computers to solve thousands of mathematical solutions. In summary, climate models are an attempt at putting the best available science, across a multitude of disciplines, into a convenient plug and play computer laboratory. No model is perfect, but they are our best foot forward, given limitations in scientific understanding and computational restraints, at attempting to understand and predict the climate system.

Climate modeling of the Intermountain West has a fairly extensive ensemble of datasets. These climate model datasets vary in the underlying assumptions in CO2 emission scenarios, land surface models, grid cell resolution, and sub-grid cell parameterizations. Given the aforementioned variations in underlying assumptions, a certain amount of bias and uncertainty occurs when comparing these model datasets to observed datasets. The comparison of observed datasets to model outputs is common practice to assess the efficacy of models and identify how much weight to place on the predictive capabilities of these models. For example, it was noted in the North American Regional Climate Change Assessment Program (NARCCAP) that regional climate models are producing too dry, too warm, and too little SWE conditions for the Intermountain West (Salzmann and Mearns, 2012). Additionally, snow cover duration was found to start too late and end too early. These biases were associated with inadequate topography, imperfect observation data, and differing land surface model components (Salzmann and Mearns, 2012). With that being said, a best modeling practice is to take an ensemble (a group of models or one model permutated in several ways) of models and take the average of these models for prediction. This is because the average of an ensemble of models almost always outperforms a single model (even the best) in prediction (Fordham et al., 2011). This modeling practice was shown by the work of Christensen and Lettenmaier (2007) when they assessed an ensemble of 11 global climate model outputs using the Intergovernmental Panel on Climate Change (IPCC) AR4 B1 and A2 emission scenarios. They found that by 2055 (relative to 1950-2000) predicted temperature increases may range from +2.0 F to +5.5 F, predicted precipitation may vary from -20% to +15%, with high uncertainty associated with predicted outcome, and snowpack is expected to decline by 21 to 25% across the Colorado River Basin (Figure 4 & 5, Christensen and Lettenmaier, 2007).

Conclusions

If the aforementioned modeled trends hold under a changing climate, water managers can expect to deal with a multivariate water management issue. Increasing temperature trends will put added stress on agricultural, natural, and urban water demand which will impact the allocation and supply management structures for conjunctive (surface and sub-surface) water supplies. Furthermore, uncertainty within precipitation duration, timing, and type coupled with decreasing snowpack supplies will ensure that a shift from long standing stationarity water assumptions will need to occur. Climate change will pressure and test stationarity assumptions likely leading to a need to assess topics such as: surface reservoir stores, dam water release etiquette, water demand and supply optimization, water market pricings, and subsurface water recharge monitoring and management. Integration between hydroclimate modelers, water managers, policy makers, and stakeholders will need to occur in order to comprehensively address the complex issue of climate change within the Intermountain West.

Figures

Figure 1 – An elevation map of the Intermountain West with the three major hydrologic basins emboldened (Wise, 2012).

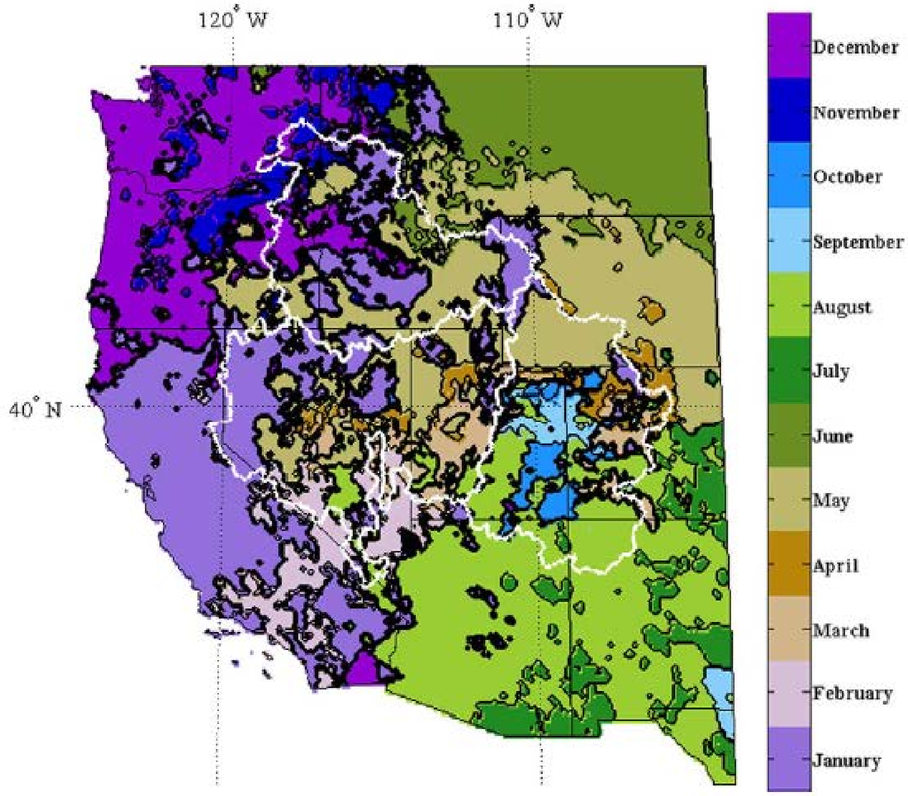

Figure 2 – A map of the month of maximum average precipitation, calculated from the PRISM dataset for 1895-2007. White outlines highlight the three major hydrologic basins of the Intermountain West (Wise, 2012).

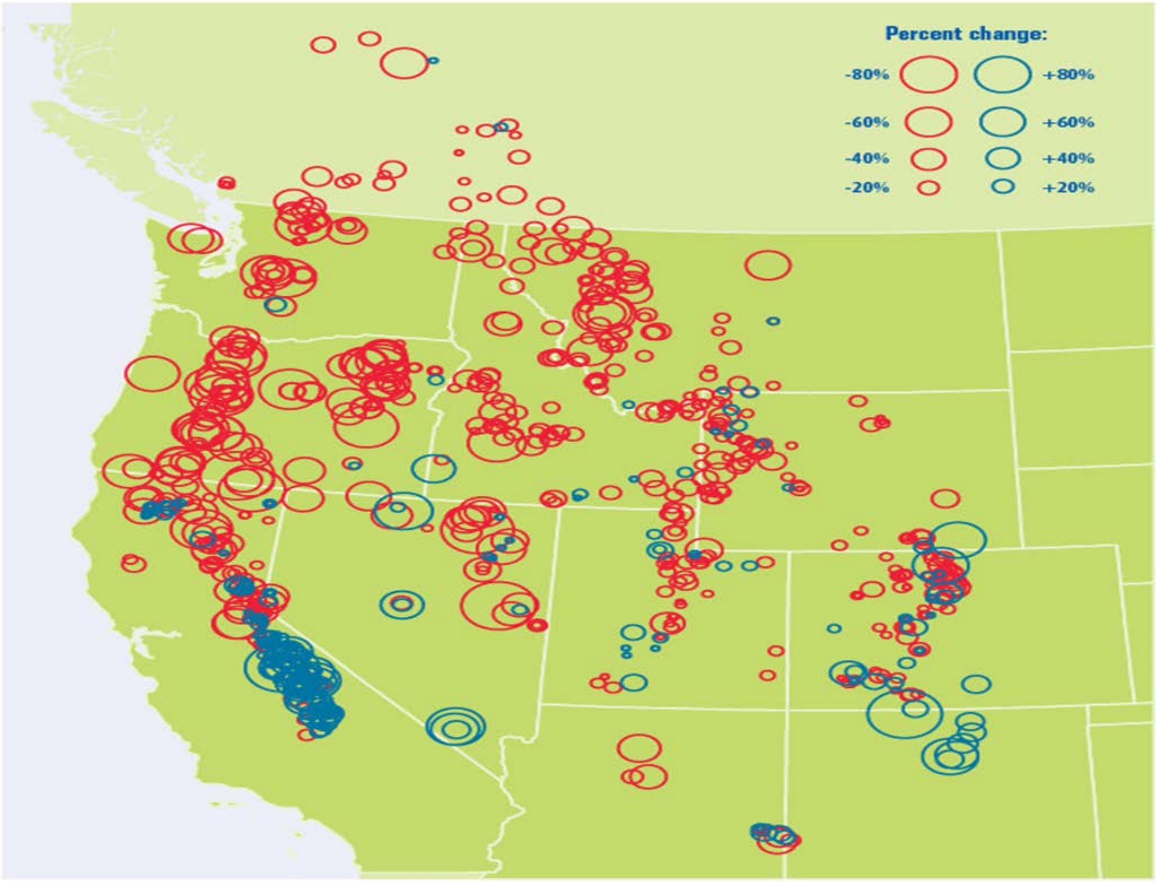

Figure 3 – Trends in observed April snowpack in western North America from 1950-2000 (Mote et al., 2009).

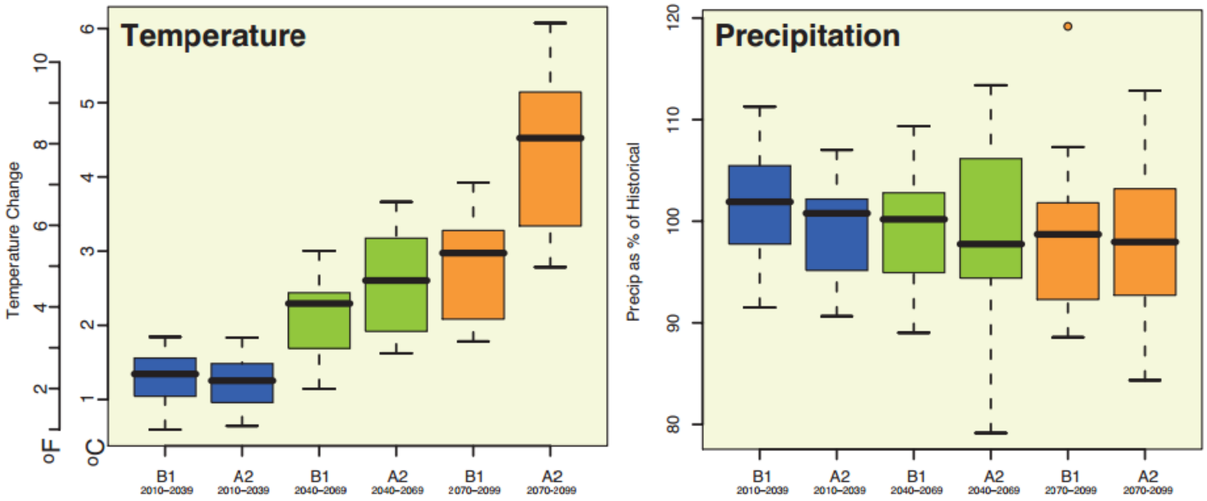

Figure 4 – Temperature and Precipitation projections for the Colorado River Basin based on the IPCC A2 and B1 emission scenarios (Christensen and Lettenmaier, 2007).

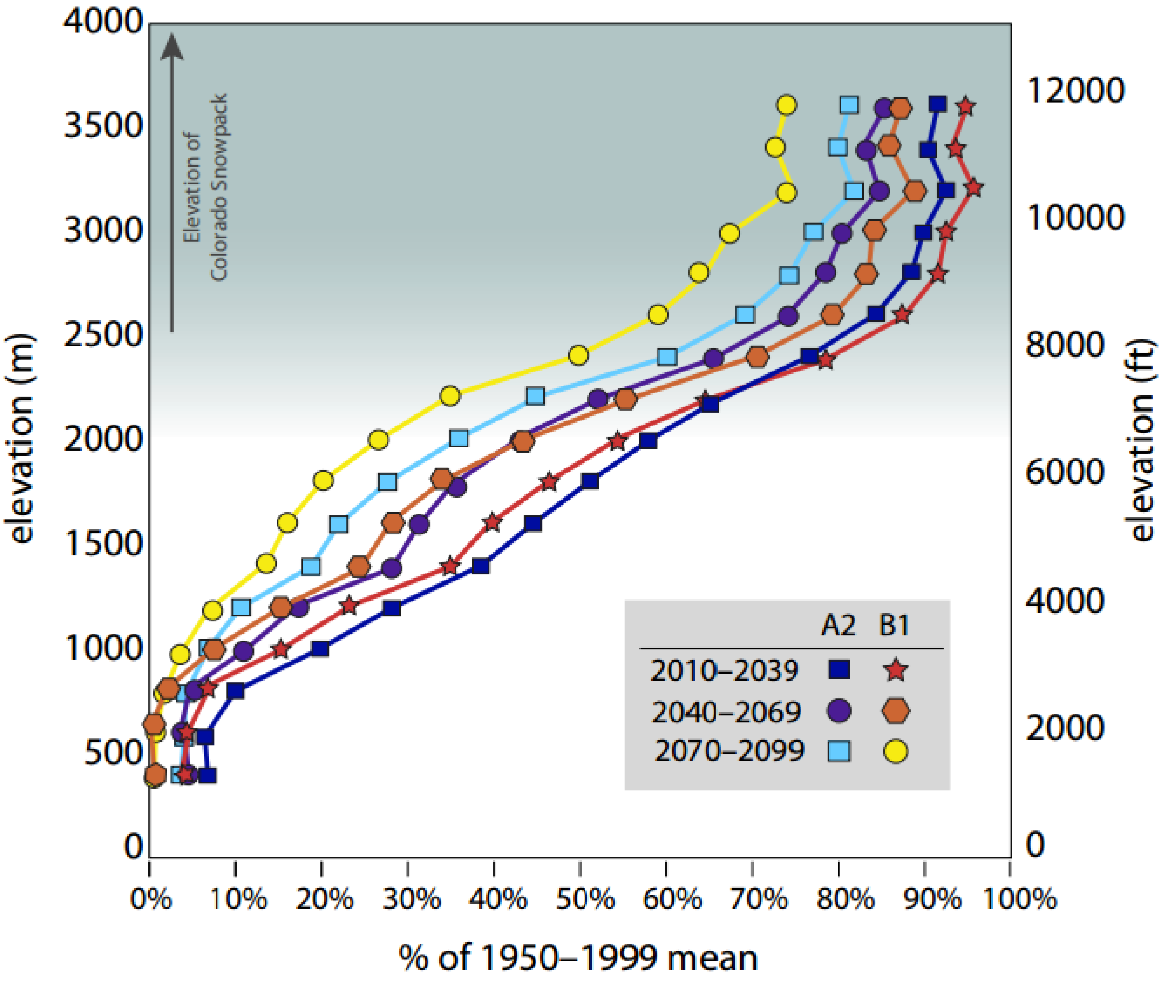

Figure 5 – Predicted changes in Colorado River Basin snowpack (elevation and emission scenario dependency) compared to a 1950-1999 climatological mean (Christensen and Lettenmaier, 2007).

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