Historical Occurrence of and Shift in Snow Drought Drivers in Global Mountain Ranges

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Key Points

- In both the northern and southern hemisphere, there was a historical shift from dry snow droughts to warm snow droughts
- In vulnerable mountain ranges, there was a shift to more mountain ranges with warm snow droughts
- Drivers of snow droughts varied by snow classification type

Abstract

Snow droughts are a new way to understand changes in snowpack and subsequent runoff. Globally, we do not have a good understanding of the drivers of snow droughts or how those drivers have changed historically. Here, we identify what has been the dominant driver of global snow droughts in mountain ranges, how it shifted historically, and what similarities exist in similar snow types. We explore this in all global mountain ranges, ones that are highly dependent on winter precipitation for summer water, and two regional case studies in the Cascade Range and the Himalayan Mountains. We found that in both the northern and southern hemispheres, dry snow droughts (driven by precipitation) are the most common. In both the northern and southern hemisphere, more mountain ranges shifted to having temperature be the main driver of snow droughts in the historical record. In the northern hemisphere, tundra, boreal, prairie, and ice snow type areas had the most area with dry snow droughts. In the southern hemisphere, all snow types except for tundra had the most area with temperature as the main driver of snow droughts. With this global, multivariate methodology, we were able to identify common drivers and patterns of historical snow droughts that exist across similar geographical areas (i.e., northern and southern hemisphere and mountain ranges) and snow type areas. More research is needed to better understand snow droughts, their drivers, and the risk they pose regionally to food and water security.

Plain Language Summary

Climate change is affecting snow accumulation in the mountains because of warming temperatures and changes in precipitation patterns. We do not currently know if temperature or precipitation is the predominant cause of the snow droughts in mountain ranges. We also do not know if the drivers have been historically consistent. We wanted to better understand if there were any common trends or patterns of causes of snow droughts in similar geographic areas or in regions with a similar climate. We found that there were common causes of snow droughts in similar regions and climates and that those drivers shifted over the historical record. However, we found that although we can group them, the mountain ranges have unique patterns in snow drought drivers. We also found that mountain ranges that are highly dependent on winter precipitation for water tend to have snow droughts driven by temperature; there was also a shift toward more mountain ranges having snow droughts driven by temperature. We better understood the drivers of snow droughts because of our method including multiple variables and inclusion of snow classification data. More research needs to be done on impacts from snow droughts.

1. Introduction

Droughts are naturally occurring phenomena yet have historically had a myriad of negative consequences for society. Droughts can cause food and water insecurity (Kang et al., 2021; Sugg et al., 2020), alter the incidence of vector-borne illnesses (Zhou et al., 2004), cause losses in gross domestic product (Naumann et al., 2021), increase wildfire potential (Marlier et al., 2017), and have many other consequences for humans and the environment. Climate change will exacerbate and intensify droughts, making them more of a burden (Wanders et al., 2015). Droughts are generally understood as a lack of water in different components of the hydrologic cycle, including meteorological, agricultural, and hydrological droughts. Other types of droughts have also been suggested, including socioeconomic droughts and more recently, snow droughts (Harpold et al., 2017). While meteorological, hydrologic, and agricultural droughts are very active areas of research, studying snow through the lens of drought research is a recent development (Dierauer et al., 2019; Harpold et al., 2017).

Snow droughts are an emerging area of research that can be used to understand spatio-temporal changes to mountain snowpacks and for early prediction of hydrological drought in snow-dominated watersheds. Mountain snowpack is the accumulation of snow in high elevation or mountain areas, which act as water storage, and is typically measured using snow water equivalent (SWE). Snow droughts refer to the conditions that lead to a smaller than average snowpack. There are currently three proposed snow drought classifications: warm, dry, and combined warm and dry (Dierauer et al., 2019; Harpold et al., 2014). Warm snow droughts describe a lack of snowpack caused by less precipitation falling as snow while dry snow droughts describe a general lack of precipitation (snow and rain) (Harpold et al., 2014). The snowpack for a given year is often described using the April 1st SWE amount, which is then used to determine a basin's water outlook and allocation during the spring and summer months (Bohr & Aguado, 2001). Characterizing a snowpack using the local and regional driving mechanisms can allow for a deeper understanding of the interannual and seasonal variability of SWE and impacts from climate change, such as on food and water resources.

Snow drought intensity and duration have varied regionally. Since the 1980s, the duration and intensity of snow droughts in the western US, Eastern Russia, and Europe have increased but have decreased in the Hindu Kush and Centra Asia, extratropical Andes, and greater Himalayas and Patagonia (Huning & AghaKouchak, 2020). When broken up by ecoregion, the western US has shown different trends in snow drought types and associated risks. For example, warm snow droughts pose the least risk because they have been the least severe and frequent in the Pacific and Nass Ranges and Cascade Ranges, while combined warm and dry snow droughts are the greatest risk because they were the most frequent and severe in most ecoregions in the western US, particularly in the southwest US ecoregions (Dierauer et al., 2019). Changes in the polar vortex and Arctic amplification are hypothesized to have contributed to snow droughts on decadal scales because it affects prevailing precipitation and temperature patterns (Huning & AghaKouchak, 2020). Spatial variation in the occurrence and type of snow droughts is due to elevation, latitude, and coastal proximity (i.e., leeward sides of mountains have a higher risk of experiencing dry snow droughts as opposed to wet snow droughts) (Dierauer et al., 2019). Specifically in the Sierra Nevada Mountains, snow droughts have been hypothesized to have been caused by shifts in the timing of precipitation being more toward earlier in the season, rain-on-snow events driving snowmelt, and a lack of precipitation (Hatchett & McEvoy, 2017).

Snow droughts are projected to increase in frequency and intensity in the future (Cowherd et al., 2023). In the northwestern U.S., the number of days with precipitation falling as snow is projected to decrease by up to 50% by midcentury under a Representative Concentration Pathway (RCP) 8.5 climate (a.k.a. "business-as-usual") (Catalano et al., 2019); the timing of peak SWE is also projected to change (i.e., not consistently April) (Marshall et al., 2019). Temperature is projected to be the major driver of snow droughts in western Canada and Alaska, with snow droughts being the most extreme in southern areas (Shrestha et al., 2021). Years with consecutive snow droughts in the western US, defined as two years that have a maximum SWE amount below the historic 25^{th} percentile, are also projected to increase in frequency 42% by 2050-2079, compared to 1970-1999 (Marshall et al., 2019).

Because the topic of snow droughts is a relatively new concept (Harpold et al., 2017), there are major knowledge gaps in our understanding of snow droughts, their drivers, impacts on regional water resources, and availability of water for agricultural needs. Further, many of the methods are unique and much of the work has been conducted in western North America. The results from these studies show the same general trends: there were snow droughts historically due to climate variability and there will likely be increases in frequency and intensity in the future due to climate change. However, using a univariate analysis with SWE reanalysis data, Huning & AghaKouchak (2020) showed snow droughts were decreasing in intensity and duration in certain regions of the world, demonstrating that there is unexplained variability and that further research is needed. Further research is needed to investigate the driving mechanisms behind snow droughts globally to better understand the regional differences and changes in occurrence.

Herein, we apply a multivariate standardized snow drought index to better understand the short-term, monthly evolution of snow water equivalent (SWE). Our overarching question is:

to what extent are there common global drivers of snow droughts that exist across similar geographic or hydroclimatic regions and how have these drivers shifted over time? We define snow droughts using a multivariate approach to isolate the driving mechanisms for each of the global mountain systems, as well as to observe any shifts that may have occurred in those drivers and assess long-term changes in the historical record. Studies have suggested that changes in precipitation or temperature have caused smaller snowpacks. But herein, we show spatially and regionally where one mechanism is dominating, where there has been a shift in the historical record, and how different types of snow droughts changed over time. Further, using a monthly multivariate approach, including SWE, precipitation, and temperature, will give a better understanding of drought onset and duration compared to a univariate approach (AghaKouchak, 2015). To our knowledge, there is not research identifying drivers in snow droughts in global mountain ranges and how those drivers have shifted historically.

2. Data & Methods

Herin, we combine multiple datasets with different temporal and spatial resolutions to establish a global domain consisting of areas that are snow covered and generate a multivariate snow drought index. We use monthly Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover extent data to find a general snow cover area grid. We use SWE, precipitation, and temperature data from Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) to further refine the monthly snow cover domain as well as generate the multivariate snow drought index. We resample everything to the MERRA-2 grid.

2.1 Data

We conducted a global scale analysis of snow droughts from 1980 to 2021 in snow covered areas and included two case studies to further highlight characteristics of snow drought drivers. We used monthly data from MERRA-2 and MODIS. We used monthly data because we are focused on short term droughts, defined as 1-month droughts, in this analysis (as opposed to 3- and 6-month long droughts).

2.1.1 MERRA-2

We downloaded MERRA-2 data from the Modeling and Assimilation Data and Information Services Center (MDISC). MERRA-2 is a global reanalysis dataset that assimilates a multitude of satellite products into the NASA Goddard Earth Observing System (GEOS) model (Gelaro et al., 2017). From MERRA-2, we used monthly Bias Corrected Total Precipitation, Air Temperature (Global Modeling and Assimilation Office (GMAO), 2015b), and Snow Water Equivalent (SWE) data (Global Modeling and Assimilation Office (GMAO), 2015c). See Table 1 for the data specifications; these data go from 1980-01-01 to current. We also used the constant model parameters describing the fractional landcover and fractional land ice for each grid cell in the global domain (Global Modeling and Assimilation Office (GMAO), 2015c). We used these designations to mask out ocean and land ice pixels from all MERRA-2 maps. This precipitation dataset is considered to be the most effective at capturing land surface fluxes and the effect precipitation has on the surface air temperature dataset we used for this analysis (Reichle et al., 2017).

To capture the dependence of snow accumulation on previous months' conditions, we progressively averaged the precipitation and temperature data. Beginning in October for the northern hemisphere and April in the southern hemisphere, we would average the temperature and precipitation data for each of the progressive months of winter. For example, in the northern hemisphere, January precipitation and temperature data were the averages of October, November, December, and January; February was the average of October, November, December, January and February. We did this for all winter months. Additionally, for the yearly analysis, we averaged the precipitation, temperature, and SWE data for the whole water year, again beginning in October or April for the northern and southern hemispheres, respectively.

Table 1. Datasets we used from MERRA-2.

Variable (name)	Dataset	Shortname	Spatial Resolution	Temporal Resolution
Bias Corrected Total Precipitation (PRECTOTCORR)	tavgM_2d_flx_Nx: 2d,Monthly mean,Time-Averaged,Single-Level,Assimilation,Surface Flux Diagnostics V5.12.4	M2TMNXFLX	0.5° x 0.625°	1 Month
Air Temperature (TLML)	tavgM_2d_flx_Nx: 2d,Monthly mean,Time-Averaged,Single-Level,Assimilation,Surface Flux Diagnostics V5.12.4	M2TMNXFLX	0.5° x 0.625°	1 Month
Snow Water Equivalent (Total_snow_storage_land)	tavgM_2d_lnd_Nx: 2d,Monthly mean,Time-	M2TMNXLND	0.5° x 0.625°	1 Month

	Averaged,Single-Level,Assimilation,Land Surface Diagnostics V5.12.4			
Fractional Land Cover	MERRA-2 const_2d_asm_Nx: 2d, constants V5.12.4	M2C0NXASM	0.5° x 0.625°	Constant

2.1.2 MODIS Snow Cover Extent

We downloaded MODIS data from the National Snow and Ice Data Center (NSIDC). We used the MODIS/Terra Snow Cover Monthly L3 Global 0.05Deg CMG, Version 6 product (Hall & Riggs, 2015). Monthly average snow cover data are derived from the daily snow cover observations. Data are available from 2000-03-01 to present at a 0.05° x 0.05° resolution. We used these data to define the snow-covered area and create a mask to remove areas that would not be relevant for snow drought analysis. Similar to Huning & AghaKouchak (2020), we created average monthly snow cover extent maps by averaging all of the years of data for each of the months; we used only cells that had >5% snow cover. We then used bilinear interpolation to resample the grid to the MERRA-2 spatial resolution (0.5° x 0.625°).

2.2 Methods

Building from the univariate approach by Huning & AghaKouchak (2020), we apply a 1-month multivariate nonparametric snow drought index using temperature, precipitation, and SWE data. We used a nonparametric approach as it allows us to compare different geographic regions and hydroclimate regimes without having to fit a distribution, such as with the commonly used parametric gamma distribution approach. We applied the framework for developing standardized drought indicators presented by Farahmand & AghaKouchak (2015) and used earlier by Hao & AghaKouchak (2014). The framework employs Gringorten's plotting position rule, which gives a marginal probability associated with ranked data:

$$p(x_i) = \frac{i - 0.44}{n + 0.12} \qquad (3)$$

where n is the sample size, *i* is the rank of the variable of interest (i.e., precipitation or soil moisture) starting from the smallest value, and $p(x_i)$ is the corresponding empirical probability. The probability is then standardized to give the univariate standardized drought index with:

$$SI = \Phi^{-1}(p) \qquad (4)$$

where Φ is the standard normal distribution and p is the empirical probability from eq. (3) (Farahmand & AghaKouchak, 2015; Gringorten, 1963). Equation 4 can be standardized using a commonly used approximation (Naresh Kumar et al., 2009):

$$SI = \begin{cases} -\left(t - \dfrac{C_0 + C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) & if\ 0 < p \le 0.5 \\ +\left(t - \dfrac{C_0 + C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) & if\ 0.5 < p \le 1 \end{cases} \qquad (5)$$

where were the coefficients were estimated to be: C_0=2.515517, C_1=0.802583, C_2=0.010328, d_1=1.432788, d_2=0.189269, d_3=0.001308 (Farahmand & AghaKouchak, 2015), and

$$t = \begin{cases} \sqrt{ln\frac{1}{p^2}} & if\ 0 < p \leq 0.5 \\ \sqrt{ln\ \frac{1}{(1-p)^2}} & if\ 0.5 < p \leq 1 \end{cases} \tag{6}$$

Yue et al. (1999) expanded the Gringorten's plotting rule to accommodate a joint probability (p_j) with multiple variables as follows:

$$p_j(x_k, y_k, z_k) = \frac{m_k - 0.44}{n + 0.12} \tag{7}$$

Where again, n is the sample size and m_k is the number of occurrences of the pair (x_i, y_i, z_i) for $x_i \leq x_k$ and $y_i \leq y_k$ *and* $z_i \leq z_k$ *and* $1 \leq i \leq$ n. It can then be standardized as with the univariate approach (equations (4), (5), and (6)) to derive the multivariate standardized drought index (Farahmand & AghaKouchak, 2015; Yue et al., 1999):

$$\text{MSDI} = \Phi^{-1}\ (p_{\text{j}}) \tag{8}$$

This approach can be used to include multiple variables; it has been tested using precipitation and soil moisture data to capture drought conditions (Hao & AghaKouchak, 2014). Further, this method was employed by Huning & AghaKouchak (2020) to establish a univariate snow drought index for a medium length drought (3-month period) using SWE data. This study extends their approach to include multiple variables related to snow droughts and uses a different drought length to capture short term drought characteristics.

Using a nonparametric approach allows us to avoid having to fit a probability distribution function. Therefore, this index is more easily comparable among global mountain ranges (Farahmand & AghaKouchak, 2015). However, given that there is no fitted distribution, nonparametric methods can be prone to overfitting (Tsybakov, 2009). Additionally, it can also be used to monitor the temporal evolution of snow droughts throughout the winter months. We isolated the mechanisms behind the observed snowpack changes by calculating a multiple regression equation between the snow drought index and temperature and precipitation. We calculated the relative importance of temperature or precipitation to the multivariate snow drought index, computed using SWE, temperature, and precipitation.

2.3 Regional Analysis

We aggregated temperature, precipitation, SWE, and snow drought data using the Global Mountain Biodiversity Assessment (GMBA) mountain inventory, which also includes names of the mountain ranges (Körner et al., 2017). We used two of these mountain regions as regional case studies: the Cascade Range and Himalaya Mountains. We select these two mountain ranges because of their similarities in their importance to downstream water users and their differences in climatologies and subsequent potential differences in snow drought drivers. We analyze both findings aggregated by mountain and the unaggregated data to look at the changes in the characteristics of drought as opposed to just differences between mountain systems. We counted mountain ranges in the world that experience snow droughts because of precipitation or temperature, identified and map mountain ranges that switched from one driving mechanism to another from the first half of the study period (1980 to 2000) to the next (2001 to 2021).

We then analyzed the occurrence of snow droughts in vulnerable mountain ranges. Vulnerable mountain ranges in this context are ones that are highly dependent on winter precipitation, having > 40% of their average yearly precipitation coming during December, January, and February and that they are highly dependent on winter precipitation stored in the form of snow. Snow acts as a form of storage that can be released in the summer as it melts when demand is higher. Therefore, without snow, there is a critical temporal mismatch between peak water availability and peak consumptive water use. These mountain ranges are ones where management and adaptation planning need to be targeted.

2.4 Climatological Regime

We use the Global Seasonal Snow Classifications to better understand regional characteristics of snow droughts by snow types and climatologies (Sturm & Liston, 2021). The Global Seasonal Snow Classification dataset provides a global map of 7 snow cover classes at a 300m resolution calculated from meteorological, landcover, and topography data (Sturm & Liston, 2021). The classifications include tundra, montane, ephemeral, boreal forest, maritime, prairie, and ice snow types and are based on thresholds of wind, precipitation, temperature, and snow cover timing and influenced by topography and landcover.

3. Results

3.1 Drivers of Global Snow Drought Trends

In the northern hemisphere, dry snow droughts (driven by precipitation) are the most common and they are prevalent from January to September. During these months, more mountain ranges experienced dry snow droughts driven by precipitation as opposed to warm snow droughts driven by temperature. Figure 1a shows the number of northern hemisphere mountain ranges for each month that had snow droughts driven by temperature or precipitation. The snow droughts were mostly caused by temperature at the start of winter (i.e., October, November, December) and by precipitation at the end of winter (March, April, and May).

In the southern hemisphere, dry snow droughts were again the most common. However, compared to the northern hemisphere, the number of mountain ranges that had precipitation as the main driver of snow droughts was very similar to the number of mountain ranges with temperature as the main driver (see Figure 1b yearly column). Dry snow droughts were the most prevalent in the south from January to March, July to September, and November. Similar to the northern hemisphere, temperature was the main driver at the start of the southern hemisphere winter (i.e., April to June).

Many of the warm snow droughts were in the coastal areas of western North America during May and South America during November (see Figure 2). For example, during May (November), the majority of snow droughts were dry snow droughts (see column 5 in Figure 1a and column 11 in Figure 1b). However, the warm snow droughts appear to be clustered in the Northwest of the United States and Canada and along the Andes range in South America; some were in Central Asia. Other coastal areas, such as the eastern coast of China, do not follow this trend and had precipitation being the main driver of snow droughts. May was selected because it is the end of the winter season and an important time for water management related decision making in the western United States.

Figure 1. Number of mountain ranges by month with the driving mechanism being either precipitation or temperature over the whole record (1980 to 2021) in (a) the northern hemisphere

and (b) the southern hemisphere. The yearly column indicates the number of ranges from the yearly aggregate. Data are separated by mountain ranges in the northern hemisphere and the southern hemisphere.

Figure 2. Global map showing the driving mechanism behind snow droughts over the whole historical record in May (in the northern hemisphere) and November (in the southern hemisphere).

Many mountain ranges in both the northern and southern hemispheres showed a shift in the mechanism driving snow droughts (Figures 3 and 4). In both the northern and southern hemisphere, more mountain ranges shifted to having temperature be the main driver of snow droughts (Figure 3 yearly pie charts). During the core winter months in the northern hemisphere (December, January, February), more mountain ranges shifted from precipitation to temperature driven snow droughts. For example, in December, about ~ 150 mountain ranges shifted from precipitation to temperature, compared to about 100 shifting from temperature to precipitation, and about 100 remained with precipitation being the dominant driver and 130 with temperature. However, more mountain ranges shifted toward snow droughts being driven by precipitation during May.

During the core winter months in the southern hemisphere (June, July, August), more mountain ranges shifted to being driven by temperature, particularly during the earlier winter (April, May) and end of the season (October). However, compared to the mountains in the north, the mountain ranges in the south retained their driving mechanism during the winter months. For example, during July and August, most mountain ranges had no shift and remained with precipitation as the primary driver of snow droughts.

Figure 3. The number of mountain ranges that either showed a shift in the dominant type of snow drought from the first half of the study period (1980-2000) to the second half (2001-2021) or had a stationary driving mechanism. The top row is the northern hemisphere, including the months October to May and the yearly aggregate, and the bottom row is the Southern Hemisphere, including the months April to November and the yearly aggregate. Precipitation indicates mountain ranges that consistently had precipitation as the driving mechanism. Likewise, temperature indicates mountain ranges where temperature was consistently the driving mechanism. Precipitation to temperature indicates mountain ranges that switched from dry to warm snow droughts and temperature to precipitation indicates switches from warm to dry snow droughts. The number of mountain ranges changes every month because of the constraints on snow covered area (i.e., shown by the changing size of empty parts of the pie charts).

In the month of May and November, the mountain ranges in northern and southern hemispheres, respectively, had a stationary snow drought driver (i.e., remained as either precipitation or temperature from the first half to the second half of the record). However, of the ones that shifted, they appear to mainly be in the northwest of North America and Central Asia. Figure 4 shows how snow droughts changed in May from the first half of the study period to the second. In the northwest of North America, more mountain ranges appear to have shifted toward temperature being the main driver of snow droughts, while in Central Asia, it appears to be precipitation. Again, May was selected because it is the end of the winter season and is an important time for water management related decision making in the western United States.

Figure 4. Changes in the key variable driving snow droughts during May (November) from the first half (1980-2000) of the study period to the second half of the study period (2001-2021).

In the northern hemisphere, all months had an increasing trend in snow drought area; however, in the southern hemisphere, this was not always the case. Figure 5 shows the slope of the time series of the percent of the area of the global domain (segmented by hemisphere) that was in drought over the whole historical record for each month. In the southern hemisphere, October and November had a negative slope, indicating that those months had less area over time experiencing drought; April had almost a slope of 0. This pattern of little change or negative slope during the start and end of the cold months is opposite to the northern hemisphere where the tail ends of the cold season are when there is the greatest change in area experiencing drought over time. In the northern hemisphere, March, April, and May, had the greatest changes in the amount of area experiencing snow droughts.

Figure 5. Sen's slope of the trend in % of global area in a snow drought (SI < -0.5). (a) is the northern hemisphere and (b) is the Southern Hemisphere. We calculated a time series of the global domain classified as having a snow drought by month. We then calculated the Sen's slope of that trend line. In the Northern Hemisphere, there was an increasing trend in % of area experiencing snow drought across all months. In the Southern Hemisphere, there was an increasing trend in the % of area experiencing snow droughts across all months; however, in all months except September, it is within the range of variability that there was a decreasing trend.

During the months of September to March and June, snow droughts were mostly driven by temperature (i.e., warm snow droughts) in the vulnerable mountain ranges of the northern hemisphere (Figure 6). Recall that we define vulnerable mountain ranges as ones that are highly dependent on winter precipitation, having > 40% of their average yearly precipitation coming during December, January, and February (Figure 8). The majority of these mountain ranges experienced some shift (mostly toward temperature), showing nonstationary behavior in the characteristics of wintertime conditions (Figure 7).

Figure 6. Number of monthly snow droughts caused by temperature and precipitation in vulnerable mountain ranges (i.e., winter precipitation dependent mountain ranges) in the northern hemisphere over the whole historical record (1980 to 2021). These mountains ranges are areas where snow storage is critical for lowland uses during warmer months. More of these ranges experience warm snow droughts and are more at risk of future snow droughts because of the certainty of future warming.

Figure 7. Changes in snow drought mechanisms for the vulnerable mountain ranges in the northern hemisphere. Vulnerable mountain ranges are the ones that are dependent on winter precipitation. The number of mountain ranges that change the dominant type of snow drought from the first half of the study period (1980-2000) to the second half (2001-2021). Precipitation indicates mountain ranges that consistently had precipitation as the driving mechanism. Likewise, temperature indicates mountain ranges where temperature was consistently the driving mechanism. Precipitation to temperature indicates mountain ranges that switched from dry to warm snow droughts and temperature to precipitation indicates switches from warm to dry snow droughts. The number of mountain ranges changes every month because of the constraints on snow covered area (i.e., shown by the changing size of empty parts of the pie charts).

Figure 8. Percent of yearly precipitation falling during northern hemisphere winter (December, January, February) over the whole study period.

3.2 Regional Trends: Case studies in Cascades and Himalaya Mountain Ranges

Herein, we showcase the Cascade and the Himalaya Mountain Ranges to further understand historical shifts in snow drought occurrence at a more local level. Recall that we used these two mountain ranges because they have different climatologies and the implications of changes in snow drought in these ranges is significant due to their role in water supply and downstream uses, such as agriculture, livelihoods and recreation. Together, they provide examples of what the broader and widespread impacts of snow droughts can be.

In the Cascade Range, there was more area in drought or near normal conditions in the second half of the study period in all months (Figure 9). In October, there is less area in drought in the second part of the study period, compared to the first half of the study period, but a decrease in wet area and a large increase in near normal conditions. For all other months, there is only a slight change from the first half to the second half in the amount of area designated as near normal. November, December, and May had the greatest increase in area in drought, compared to other months. The biggest shifts occurred in November and December in the decrease in wet area from the first half of the second half of the study period.

In the Himalaya mountain range, not all months had more area in drought in the second half of the study and some months had more wet conditions in the second half of the study period than in the first half. For example, January, February, and May had more wet area in the second half of the study period than the first. Further, during those months, there was also less area in drought and more in near normal. Additionally, in the Himalaya Mountain range, the shifts in the amount of area having either wet or drought conditions from the first half to the second half of the study period were much smaller than the Cascade Range. For example, the amount of wet area in October, November, March, and May in both halves of the study period are very similar.

Figure 9. Departure of the percent of the area from the first to the second part of the study period experiencing drought (< -0.5 SI), near normal (>= -0.5 & <= 0.5 SI), or wet (> 0.5) conditions. 'Drought' includes all drought types (i.e., warm and dry snow droughts). The first part of the study period includes the years 1980 to 2000 and the second part includes the years 2001 to 2021. The Cascade Range showed a shift to more dry or near normal area and less wet area in all months; the Himalaya Mountain Range had no consistent shift across all months, with some months having more wet area.

Temperature was the driving mechanism behind snow droughts in the Cascade Range in all months except for February and March while precipitation was the driving mechanism behind snow droughts in the Himalaya mountains for all months (see Figure 10). In the Himalaya Mountain range, precipitation can explain more than 60% of the observed snow drought variability between December and May; in October and November, both temperature and precipitation explain about 50% of the variability. In the Cascade Range, while temperature explains more of the variability in more of the months, it never explains more than 55% of the variability. In the Cascade Range, both temperature and precipitation explain between 45 to 55% of the variability in all months.

Figure 10. Driving mechanism behind snow droughts in the Cascade and Himalaya Mountain Ranges. This was calculated as the percent of the variance in snow droughts explained by either temperature or precipitation.

3.3 Climatological Regime

When looking at the driving mechanism of snow drought by snow classification type at a yearly temporal scale, certain snow types had clear drivers (Figure 11). In the northern hemisphere, tundra, boreal, prairie, and ice snow type areas had the most area with dry snow droughts. Maritime and ephemeral snow had the most area experiencing warm snow droughts; montane snow had about equal amounts of area with temperature or precipitation as the driver. In all snow types except boreal forests, the shift in snow drought driver was more toward the dominant mechanism. For example, the tundra snow type had more area with precipitation as the snow drought driver and in the area where the snow drought driver shifted, it shifted from temperature to precipitation (Figure 11 Northern Tundra column).

In the southern hemisphere, all snow types except for tundra had the most area with temperature as the main driver of snow droughts (Figure 11). However, in the area that had a shift in the main snow drought driver, more area shifted toward being driven by precipitation. For example, the maritime snow type had the most area with temperature as the main driver but the only shift in driver occurred was the temperature to precipitation. In the tundra snow areas, more area had snow droughts being driven by precipitation and had more area shift to being driven by precipitation (compared to shifting to snow droughts being driven by temperature). However, the majority of the southern hemisphere snow type is ephemeral snow and the majority of the area had snow droughts being driven by temperature, although similar to other snow types, more overall area shifted toward snow droughts being driven by precipitation.

Figure 11. Count of driving snow drought mechanism by snow classification type in the (a) northern and (b) southern hemispheres over the whole historical record. Calculated using the yearly snow drought classification showing the dominant snow drought type over the whole record by snow classification type.

4. Discussion

1) Global patterns

Because we calculated the drought index using a 1-month time scale, we were able to see how different months of the winter season were changing. In the northern hemisphere, the tail ends of the season had a much greater rate of increase in drought conditions than the middle of the cold season, whereas in the southern hemisphere, the core of the winter season had a greater rate of increase in drought area. Additionally, we saw that drought conditions were becoming more widespread during certain months over the historical record. Further, we were also able to see that in areas within certain mountain ranges, not all months were becoming drought prone. Much of the broader drought literature has shown that droughts are increasing in frequency due to climate change, severity, and extent, which our results diverge from (Loukas et al., 2008; Naumann et al., 2018; Pokhrel et al., 2021; Vicente-Serrano et al., 2014; Wanders et al., 2015; Wang et al., 2016; Xiao et al., 2016). For example, in the Himalaya mountains, we saw that January and February had a greater amount of area with wet conditions, compared to the first part of the study period. Therefore, by using the temporal drought index calculation and the geographic aggregate, we were able to see these trends at both the yearly and interannual scale.

We focused on short-term snow droughts to better understand trends throughout the winter that could improve water management decision making. While short term droughts are more sensitive to changes in precipitation and temperature (Wilhite & Glantz, 1985), knowing short term drought trends is important because snow anomalies in April and May are more of a control on summer moisture and important for decision making in the western United States (Bohr & Aguado, 2001; Quiring & Kluver, 2009). Additionally, large, late-season snow events can misrepresent conditions and important metrics that water managers look at, such as date of peak SWE, snow disappearance date, and the duration of snow cover (Cooper et al., 2016). With the 1-month approach, we saw that snow droughts were driven by precipitation in more mountain ranges in the northern hemisphere in March, April, and May but by temperature earlier in the season. In some areas, during the start of the season, temperature dominates because it determines the form of precipitation. Once the season is underway, precipitation dominates but diminishes because temperature dictates snowmelt season and so starts to become more important. However, further research can be undertaken to better understand how changes in the later part of the winter connect to changes in storage, such as reservoir, groundwater, and soil moisture storage.

2) Vulnerable ranges

The observed changes in snow droughts drivers in highly vulnerable mountain systems are of particular concern given future projections of temperature and precipitation due to climate change (Calvin et al., 2023; Collins et al., 2012). In highly vulnerable mountain ranges, temperature was the driving mechanism in more of the mountain ranges; the majority of the mountain ranges showed a change in the snow drought driving mechanism from precipitation towards temperature. This set of mountain ranges had a different trend compared to all of the mountain ranges—more of the vulnerable mountain ranges experienced warm snow droughts and when there was a shift, more mountain ranges shifted toward dry snow droughts; in the whole set of northern hemisphere mountain ranges, more ranges had dry snow droughts during the core winter months and when there was a shift, it was not always toward temperature.

The shift toward temperature driving snow droughts is particularly concerning because temperature projections are much more certain than precipitation projections (Calvin et al., 2023). Therefore, areas that continue to have snow droughts driven by temperature will continue to see less of a snowpack, which is consistent with many of the trends in the western US (Dierauer et al., 2019; Li et al., 2017; Marshall et al., 2019; Mote et al., 2005; Shrestha et al., 2021; Siirila-Woodburn et al., 2021). Comparatively, projections about changes in precipitation are much more uncertain, with certain regions having projected increases in precipitation, making the future risk of dry snow droughts more uncertain (Calvin et al., 2023). This is of concern to water managers who allocate water from headwater dependent areas or watersheds where runoff from snowmelt is a major source of water, such as the Cascade Range (Li et al., 2017). Therefore, the shifts in snow drought will have differing regional effects because adaptation capacity of certain regions given current projections as well as the effect on water availability and timing (Harpold et al., 2017). For example, there might only be a mismatch in timing with water supply and demand in a warm snow drought year but there may be a greater water deficit in dry snow drought years. Future work can explore direct regional impacts from dry and warm snow and adaptation potential.

While the highly dependent mountain ranges are more critical areas for preserving water security as it relates to snow, it is still important to know how snow drought types are shifting in mountain regions because mountains systems are critical ecosystems and water towers (Hock et al., 2019; Viviroli et al., 2007). Many mountain ranges showed a shift over the historical record in the key driver of snow droughts (i.e., from warm to dry or dry to warm snow droughts), which would have different implications for downstream managers and users through changes in water availability and timing if they undergo further changes. For example, mountain ranges that were historically experiencing dry snow droughts may have more of a flood concern if warm snow droughts become more frequent (Harpold et al., 2017). In the western US, many of the ecoregions are projected to be much more susceptible to warm snow droughts with future projected warming (Dierauer et al., 2019). However, this may be less of a problem for areas that are adapted to this type of snow drought if there is enough storage capacity (Smith & Edwards, 2021).

3) Regional studies

Snow droughts in Cascade Range were historically driven by temperature (except in February and March) (recall from Figure 10). However, although snow droughts were mainly driven by temperature, it explained no more than 55% of the variability month-to-month, indicating that the Cascade Range may be affected by a combined snow drought type or different local scale variabilities causing temperature and precipitation across the range. When testing the 2014-2015 snow drought (Dye et al., 2023; Mote et al., 2016) as an analog for future warming, it was found that temperature was not the sole factor but rather also the timing and magnitude of precipitation events (Cooper et al., 2016). This may be because the western side of the Cascade Range is mainly classified as maritime snow, which is found in physical environments with wind and high precipitation and has a deep, wet snowpack and the east side of the Cascade Range is mainly classified as montane forest snow, which is found in physical environments that are warm and forested and have a moderate depth, wet, snowpack. These differences in snow types are due to difference in formation processes, such as landcover, wind speed, and precipitation amount, which is evident in the dominant snow drought drivers (Sturm & Liston, 2021). Future research should explore combined dry and warm snow droughts types within mountain ranges to better understand their impacts.

In the Himalayas, snow droughts were historically driven by precipitation (recall from Figure 10). During all months, precipitation explains between 55% to 75% of the variability. The Himalayas have different weather and climate patterns and therefore, different snow types than the western U.S. and Cascade Range. The Himalayas have two periods of increased moisture during the year—one during the northern hemisphere winter months and also during the summer monsoons (Sabin et al., 2020). Additionally, the Himalayas have a combination of tundra, montane forest, prairie, and ephemeral snow types but the majority of the area is tundra or ephemeral snow. Tundra snow is found in areas that are cold and windy, such as high mountain environments, and the snow is usually shallow and hard slabs; tundra snow tends to be colder than other snow types (Sturm & Liston, 2021). Therefore, precipitation has more of a control on the snowpack and snow cover extent, which we saw with the dominant driver of snow droughts being precipitation across all months (Cannon et al., 2017; Clark et al., 1999). These differences between the Himalaya Mountains and Cascade Range highlight the importance of understanding individual mountain systems.

4) Climatological regime

The trends in snow drought drivers by snow type indicate the key snow formation mechanisms that are being most affected by climate change. In both the northern and southern hemispheres, mountain ranges with the types of snow that are characterized by a colder snowpack (i.e., tundra and boreal snow) were dominated by dry snow droughts (i.e., drive by precipitation). Conversely, mountain ranges with snow types that were more characterized by warm snow, such as ephemeral, maritime, and montane forests, had more mountain ranges with warm snow droughts (i.e., driven by temperature). While temperature and precipitation patterns are central to snow accumulation and melt, there are also local scale variations in landcover, elevation, topography, and climate that also contribute to changes in snow patterns (Dadic et al., 2010; Jost et al., 2007). In the northern hemisphere, temperature was becoming more of a driver in all snow type areas (compared to precipitation), except tundra and prairie, which is expected as the climate warms and continues to affect snowpack accumulation and melt (Adam et al., 2008; Barnett et al., 2005; Li et al., 2017). However, there was more area shifting toward dry snow droughts in the tundra snow areas, potentially indicating that temperature was not yet a dominant mechanism in those areas. However, future warming has been projected to impact tundra snow areas, such as the Himalayas (Lutz et al., 2014).

5. Conclusion

We investigated global drivers of snow droughts and identified how those drivers shifted over the historical record. We extended a standardized snow drought index to include precipitation, temperature, and SWE in order to isolate the mechanisms driving snow droughts globally. We were able to identify common drivers of snow droughts that exist across similar geographical areas (i.e., northern and southern hemisphere and mountain ranges) and hydroclimatic regions (snow type areas). Finally, we assess the major drivers of snow droughts in mountain ranges that were highly dependent on winter precipitation. We found that snow droughts were historically driven by precipitation in the majority of mountain ranges. However, many mountain ranges shifted from having snow droughts driven by precipitation to snow droughts driven by temperature. In mountain ranges that were classified as being highly dependent on winter precipitation, the majority of mountain ranges had snow droughts driven by temperature. Regionally, the Cascade Range showed a shift to having more area experiencing drought across all months, while the Himalaya Range had much more inconsistent shifts over the historical record in drought occurrence. Much more research is needed to better understand snow droughts, their drivers, and the risk they pose regionally to food and water security.

Acknowledgements

The authors have no conflicts of interest to disclose. Funding for this work was provided in part by the National Science Foundation grant CBET-2115169 and EAR-1639458. The research described in this paper was partially carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration

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MERRA-2 data are available to download from the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC) (Global Modeling and Assimilation Office (GMAO), 2015a). MODIS Snow Cover Extent data are available to download from the National Snow and Ice Data Center (NSIDC) (Hall & Riggs, 2015). The Snow Classification data are also available to download from NSIDC (Liston & Sturm, 2021)

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