CLIMATE CENTRAL

MELTDOWN

Increasing Rain as a Percentage of Total Winter Precipitation

Jennifer Brady and Todd Sanford, PhD • April 2016

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Increasing Rain as a Percentage of Total Winter Precipitation

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EXECUTIVE SUMMARY

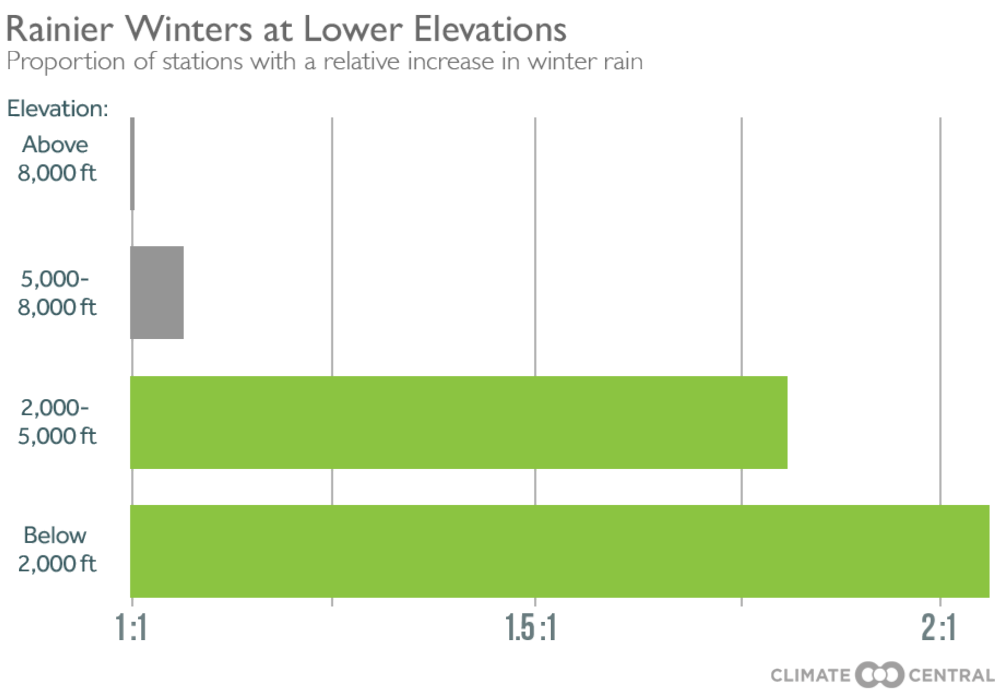
As the world warms, the meaning of winter is changing. In the U.S., a greater percentage of winter precipitation is falling as rain, with potentially severe consequences in western states where industries and cities depend on snowpack for water, and across the country wherever there is a winter sports economy.

A Climate Central analysis of 65 years of winter precipitation data from more than 2,000 weather stations in 42 states, found a decrease in the percent of precipitation falling as snow in winter months for every region of the country. Winter months were defined as the snow season for each station, from the month with the first consistently significant snow, to the last.

In western states where snowpack is critical, we found decreases in the percent of winter precipitation falling as snow at elevations between sea level and 5,000 feet. Above 5,000 feet there is clear regional variation. In California, Colorado, Wyoming, Nevada, Utah, and New Mexico there was either no trend toward rain or a slight trend toward more snow at elevations 5,000 feet and higher. In stark contrast, between 5,000 to 8,000 feet in Montana, Idaho, and Arizona, from 75 to 78 percent of all stations report an increase in rain as a percentage of total winter precipitation. Oregon has only one station above 5,000 feet, but it too reported a strong increase in rain vs snow as winter precipitation. Washington has no stations at this elevation.

These very different results at elevations above 5,000 feet may stem from the different underlying climate and weather patterns in the two regions that has delayed the shift toward more rain above 5,000 feet in Rocky Mountain states, but accelerated it in the Northwest.

In virtually all states with stations below 2,000 feet, the data show a trend toward a higher percentage of rain during the winter precipitation season.



FINDINGS

The Northwest — A Region at Risk

- The Pacific Northwest has been the hardest hit, with low elevation snow on a clear path toward oblivion: 81 and 91 percent of stations under 2,000 feet in Washington and Oregon, respectively, show a trend toward a lower percentage of winter precipitation falling as snow over the 65 years analyzed.

- At 2,000 to 5,000 feet in Washington and Oregon the effect is similar, with 63 and 77 percent of stations recording lower percentage of precipitation falling as snow during the winter snow season, over the period analyzed. In the interior Northwest, Montana and Idaho showed the same basic trend between 2,000 to 5,000 feet, with 64 and 82 percent of stations reporting a shift to more rain as a higher percentage of precipitation than snow.

- At higher elevations in Montana and Idaho, the shift was equally strong, with 75 and 78 percent of stations reporting a decrease in the percentage of precipitation falling as snow at 5,000 to 8,000 feet. Oregon has only one station above 5,000 feet, but it too reported a strong increase.

The Southwest

- In the Southwest, California and Arizona showed the same trend from 2,000 and 5,000 feet, with 68 and 83 percent of stations, respectively, registering a lower percentage of winter precipitation falling as snow. From 5,000 to 8,000 feet 76 percent of stations in Arizona showed a shift to a lower percentage of precipitation falling as snow during the winter precipitation season. In California there was no trend at that elevation. New Mexico showed a slight trend toward more snow.

Great Plains

- The Great Plains states, Nebraska, and Kansas saw particularly dramatic shifts, with between 69 and 81 percent of stations experiencing a lower percentage of winter precipitation falling as snow, from 2,000 to 5,000 feet. South Dakota showed a trend toward a lower percentage of precipitation falling as snow at 2,000 to 5,000 feet, with 67 percent of stations reporting the trend.

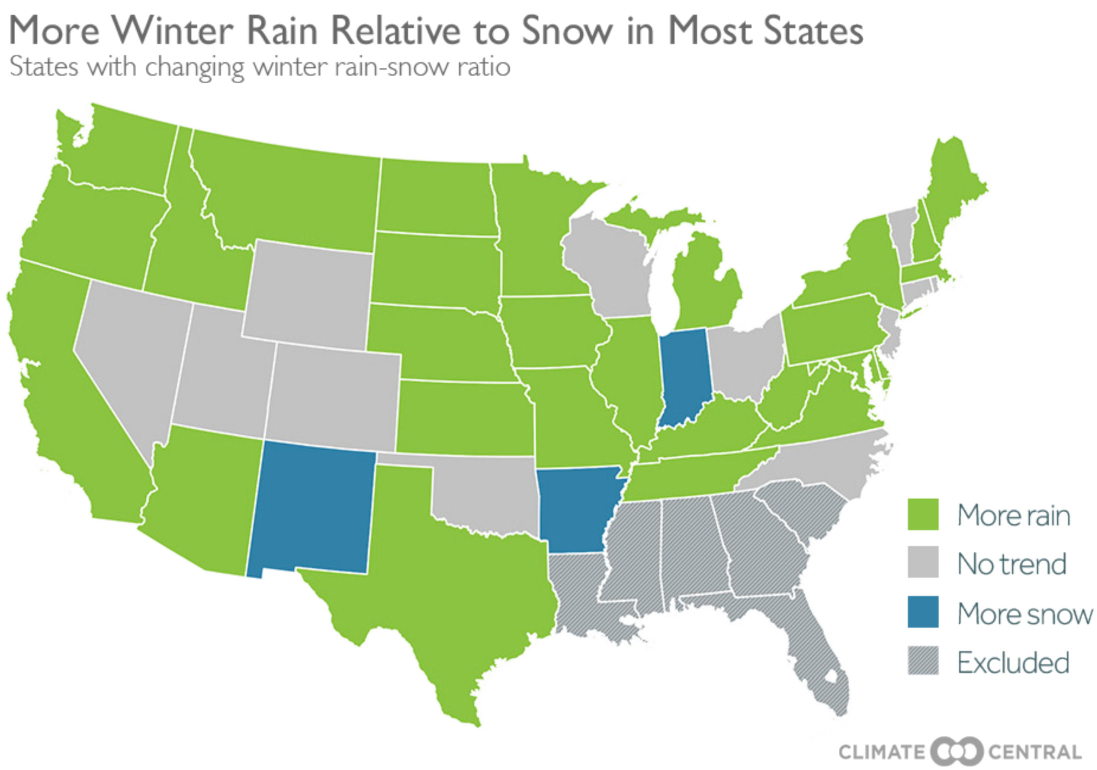
The Rockies

- Notably, in the central Rocky Mountain States, Colorado and Wyoming, where the states are almost entirely above 5,000 feet, as well as Utah, there was no clear trend toward more rain as a percentage of all precipitation during the winter, at any elevation.

The Midwest and the East

- East of the Great Plains the trend toward a lower percentage of winter precipitation falling as snow is equally strong. Between 60 and 82 percent of stations at elevations below 2,000 feet, in 16 states, showed a sizable shift toward a lower percentage of precipitation falling as snow.

- In 6 of these states; Iowa, Michigan, Minnesota, Missouri, Virginia and West Virginia, more than 70 percent of stations showed this trend.



A majority of stations across the entire continental U.S., have an increasing percentage of winter precipitation falling as rain, with the notable exception of regions above 5,000 feet in Central Rocky Mountains and Sierra Nevada in California. These findings suggest that:

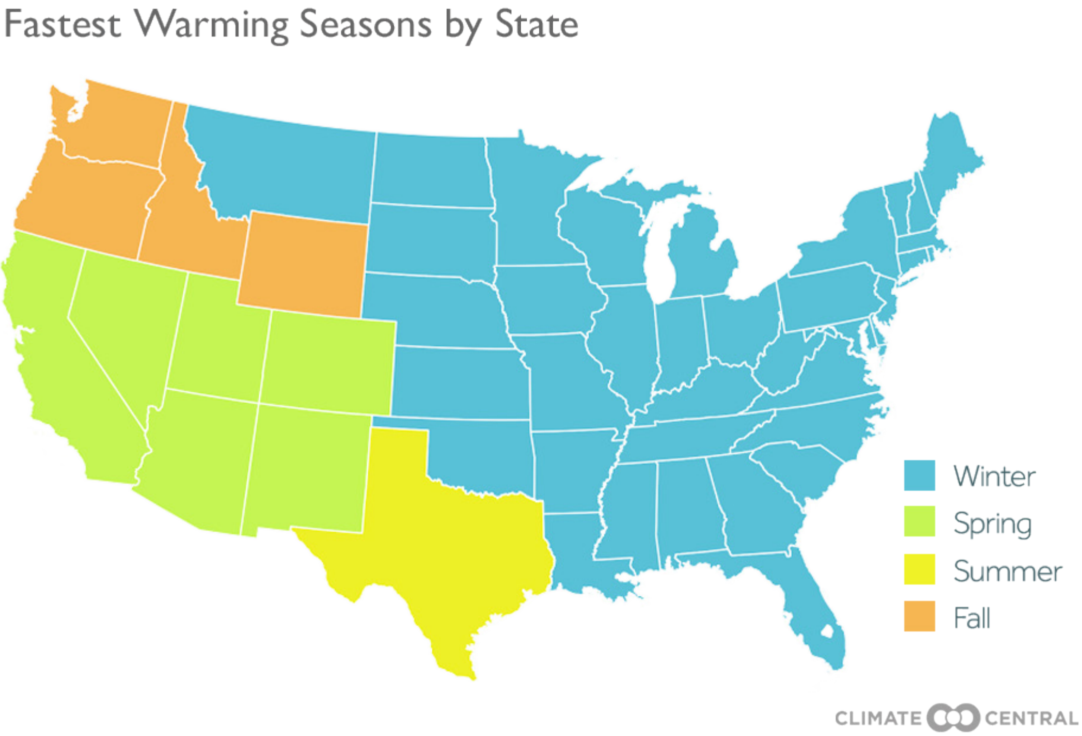
- Serious water reliability issues based on an inconsistent and declining snowpack may be just around the corner in the Pacific Northwest;

- The core Rocky Mountain States of Colorado, Wyoming and Utah, as well as New Mexico, Nevada, and high elevations in California, have yet to experience the shift. It seems unlikely, however, given the strong trend toward rain in other high elevation states, and rising temperatures across the region, that these states will resist forever the trend toward more rain as a percentage of total winter precipitation. When the shift begins, it could have serious consequences for water availability across the West, particularly in Southwestern states and California, and:

- In Midwestern and Northeastern states the strong trend toward a decrease in the percentage of winter precipitation falling as snow in winter months portends dramatic impacts on the winter sports economy across the entire region.

01. INTRODUCTION

Winters have been warming faster than other seasons over the past century in the U.S. Since 1896, winters in the Contiguous U.S. have warmed by 0.21°F per decade, or over 2.5°F during the period. Spring and fall, which snow seasons in many locations, are also experiencing warming (**Map 1**).



Map 1. *Maps shows which season has the steepest linear trend fitted to its average temperature data since1970.*

Warming temperatures can impact how precipitation falls, and whether precipitation falls as rain or snow can impact everything from summer water availability for agriculture and cities, to forest dryness, and susceptibility to wildfires, water reliability for power generation, and the winter sports economy.

The Western U.S. relies on storing water in cold-season snowpack for use in the hotter and drier months of the year. Reduced snowpack, due in part to more rain in the snow-season precipitation mix, can lead to reduced and earlier snowmelt (Georgakakos, 2014). These changes in snowmelt can lower stream flows and leave less water available later in the year. The U.S. Geological Survey estimates that as much as 75 percent of Western water supplies are derived from snowmelt. Reduced water availability can then lead to municipal and agricultural water supply issues, hydroelectric supply reductions, drier soil conditions, and degraded wildlife habitat. When rain falls on snow it can also increase flood risk, though these events are becoming rarer due to reduced Western snowpack (McCabe et al, 2007).

01. INTRODUCTION

Historically, most of the Northwest's watersheds were either mixed rain-snow or snow-dominant, and the region's economy is designed to manage water under this climate regime. If temperatures continue to warm at the current rate, by mid-century there are projected to be very few snow-dominant areas left in the Pacific Northwest. By the 2080s, snow dominant zones are projected to disappear completely, to be replaced with large areas of rain-dominant conditions.

Reduced snowpack from changing winter precipitation can also play a role in increased wildfire risk. Large wildfires have increased across the West since 1970 (Climate Central, 2012). The mid-elevations of the northern Rockies have seen some of the largest increases in wildfires, which are thought to be a result of a combination of factors, including hotter spring and summer temperatures and earlier spring snowmelt (Westerling et al. 2006). Wildfire activity also has been moving up in elevation in the Sierra Nevada and is likely in part related to changing snowpack at higher elevations (Schwartz et al. 2015).

The Northwest region faces two other impacts with important implications for communities in that region. Hydropower provides two-thirds of the region's electricity. Changes in stream-flow timing, particularly late-season flow are projected to reduce hydropower production by 15 percent by 2040 (Dalton et al. 2013). Decreased summer stream flows, increased summer stream temperatures, and higher peak winter flows (all potentially related to more rain than snow during the cold season) can negatively impact the migration and spawning of salmon (Dalton et al 2013).

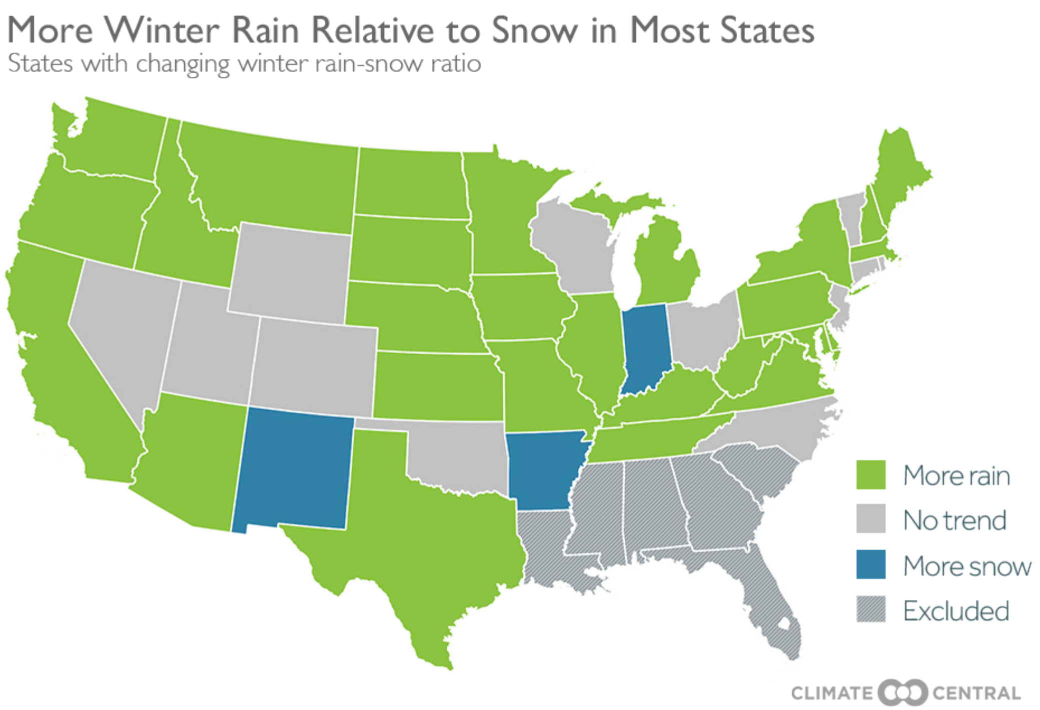
The eastern U.S. is generally not as dependent on building up water supply in snow for later in the year as the West. However, many parts of the East have local economies that thrive on winter recreation. New York has the most ski resorts (51) of any state. A study on Northeastern U.S. ski resorts estimates that only four out of 14 major ski resorts will remain profitable by 2100 under a higher-emissions scenario. An increase in the percent of winter precipitation falling as rain is an issue likely to face many of the 450 ski areas currently in the U.S. (NSAA, 2015). Lower-elevations are particularly at risk.

02. MORE RAIN, LESS SNOW

Average temperatures across the country are rising in seasons that regularily experience snow: fall, spring and winter. As temperatures rise the precipitation that falls during these months will more likely be rain than snow. This "snow drought" already appears to be occurring, as many regions and states in the U.S. have experienced a trend towards a decrease in snow as a percentage of all precipitation during the snow season, on average, since 1949 (**Map 2**).

The results of this analysis are consistent with other peer-reviewed studies, including one that focused on Western states and found declines in the ratio of snow to total winter precipitation from 1949-2004 (Knowles et al 2006), and another that found a decrease in the fraction of total precipitation falling as snow versus rain per degree of warming in the Western U.S. (Dettinger et al 2015, Ecological Applications).

In Climate Central's analysis of more than 2,000 U.S. stations, at least 58 percent of the stations in 30 states reported a trend toward a smaller percentage of all winter precipitation falling as snow since 1949 (**Table 1**). [After testing the statistical significance of the proportions of positive and negative slopes, in almost all cases those with above 58 percent or below 42 percent were significant. See methodology for information on station-level analysis.]



Map 2. *Map shows which type of winter precipitation is increasing as a percentage of overall winter precipitation, at the majority of stations within a state.*

One hypothesis prior to this analysis was that Southern states would show the strongest trends toward a greater percent of winter precipitation falling as rain. That is not the case. Oregon and Iowa lead the way with 86 percent and 82 percent, respectively, followed by northern and western states like Arizona, Washington, Michigan and Idaho. This is important because many of these states are heavily dependent on abundant snowpack for storing water to be used later in the year.

Table 1. *Percentage of stations receiving less snow as a percentage of total precipitation.*

Rank	State	Percentage of Stations Receiving Less Snow
1	Oregon	86%
2	Iowa	82%
3	New Hampshire	80%
4	Arizona	79%
5	Kansas	79%
6	Washington	78%
7	Michigan	78%
8	Idaho	78%
9	Nebraska	74%
10	West Virginia	73%
11	Minnesota	72%
12	Missouri	72%
13	Maryland	69%
14	Tennessee	69%
15	New York	69%
16	Kentucky	69%
17	Virginia	67%
18	Delaware	67%
19	Montana	66%
20	California	62%
21	Texas	62%

Rank	State	Percentage of Stations Receiving Less Snow
22	Pennsylvania	62%
23	South Dakota	61%
24	Massachusetts	59%
25	North Dakota	59%
26	Illinois	58%
27	Maine	58%
28	Wisconsin	58%
29	North Carolina	57%
30	New Jersey	56%
31	Connecticut	56%
32	Oklahoma	56%
33	Nevada	53%
34	Ohio	52%
35	Rhode Island	50%
36	Wyoming	49%
37	Vermont	44%
38	Colorado	43%
39	Utah	42%
40	New Mexico	40%
41	Indiana	40%
42	Arkansas	27%

03. ELEVATION

Snow is vital as a source of water for the Western U.S. and as a key to the economic health of communities throughout the Northern U.S. Climate Central divided the over 2,100 stations in the analysis based on elevation using a hierarchal optimal discriminant analysis. We then evaluated how elevation changed the proportion of precipitation falling as snow.

Our analysis was broken into four elevation zones:

- Less than 2,000 ft
- 2,000 to 5,000 ft
- 5,000 to 8,000 ft
- 8,000 ft and higher

An examination of all stations nationwide found a clear trend toward a great percentage of winter precipitation falling as rain at elevations below 5,000 feet. At these lower and mid elevations, stations trending toward rain outnumbered those trending toward snow, by about 2 to 1.

From 5,000 feet and up, however, there is no nationwide trend at all.

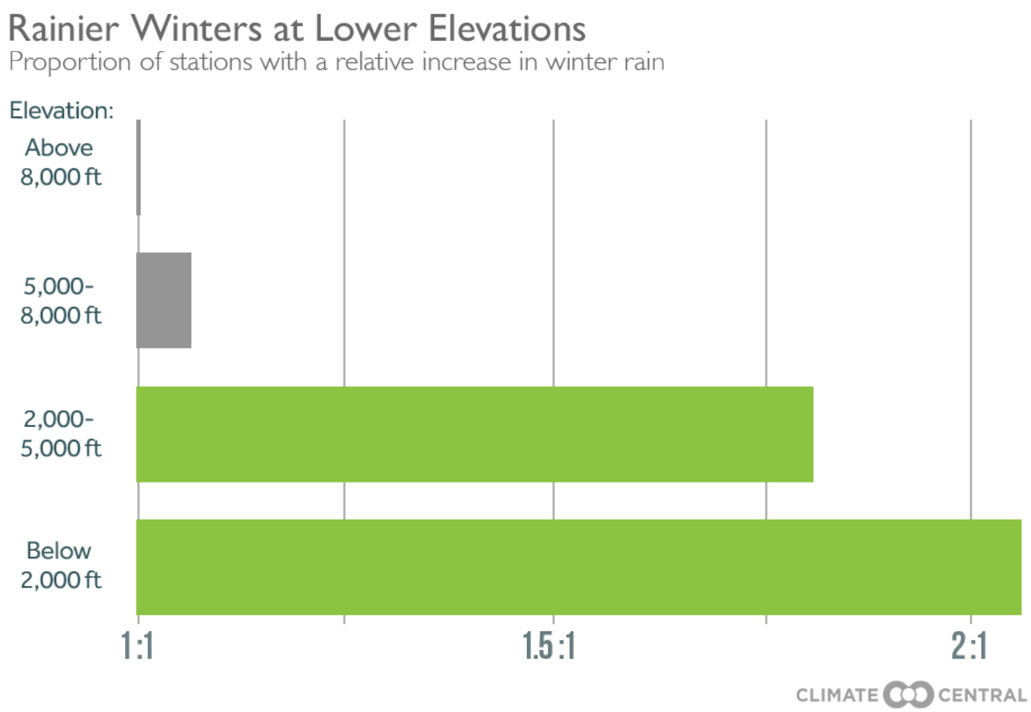


Figure 1. *Figure shows departure from 1:1 ratio at different elevations of stations with a relative increase in rain compared to stations with a relative increase in snow.*

03. ELEVATION

At the same time, within the 5,000 to 8,000 feet zone there are significantly different trends between states, with a pattern emerging that is consistent with the overall trends from all samples, where the core Rocky Mountain states of Colorado, Wyoming, and Utah, along with California, Nevada, and New Mexico show no trend toward rain above 5,000 feet or 8,000 feet, while Montana, Idaho, and Arizona show strong trend toward a greater percentage of winter precipitation falling as rain between 5,000 and 8,000 feet in elevation. Oregon has only one station above 5,000 feet, but it too reported a strong increase in rain vs snow as winter precipitation. Washington has no stations at this elevation.

Above 8,000 feet there are no clear regional difference in the results, although sample sizes are limited.

In virtually all states with stations below 2,000 feet, a majority of stations show a trend toward more rain that snow during the winter precipitation season. At the lowest elevation range (below 2,000 feet) of the 36 states with stations here, 19 of them had 60 percent or more of their stations reporting a transition to more rain days during the snow season. Of these, most of them are in the northern tier regions where the overall changes were most pronounced. Montana, Oregon and Washington all had more than 80 percent of stations below 2,000 showing more rain than snow.

Table 2. *Top ten states with stations receiving less snow as a percentage of total precipitation at <2,000 feet.*

Rank	State	# of Stations	% of Stations Receiving Less Snow
1	Montana	3	100%
2	Oregon	35	91%
3	Iowa	94	82%
4	Washington	57	81%
5	Nebraska	52	79%
6	West Virginia	33	79%
7	Michigan	68	78%
8	Kansas	107	78%
9	New Hampshire	13	77%
10	Virginia	45	73%

The Northwest — A Region at Risk

The Northwest region (Idaho, Washington, Oregon, and Montana), where snowpack is critical for wildlife habitat, energy production, irrigation, and municipal water use, shows the largest regional response with 75 percent of the stations showing a transition to more rain than snow. One measure of snowpack (1 April snow-water equivalent) was found to have been decreasing over most of the region over a 50-year period from both increasing temperature directly, but also more rain than snow at lower elevations (Mote, GRL, 2003). Historically, most of the region's watersheds were either mixed rain-snow or snow-dominant. Under a higher-emissions scenario and larger temperature increases, by mid-century there are very little snow-dominant areas left and by the 2080s they are projected to disappear completely with now large areas of rain-dominant conditions. Likewise, projections for timing and magnitude of stream flow show either a reduction in magnitude or peak stream flow (typically in the summer) or both a reduction in peak flow and a shift in timing, in some cases to the winter months (Dalton et al. 2013). Both affect water supplies for use in the hotter and drier months.

Serious water reliability issues based on an inconsistent and declining snowpack may be just around the corner in the Pacific Northwest. Our analysis found that:

- Low elevation snow is on a clear path toward oblivion: 81 and 91 percent of stations under 2,000 feet in Washington and Oregon, respectively, show a trend toward a lower percentage of precipitation falling as snow over the 65 years analyzed.

- At 2,000 to 5,000 feet in Washington and Oregon the effect is similar, with 63 and 77 percent of stations recording lower percentage of precipitation falling as snow during the winter snow season, over the period analyzed. In the interior Northwest, Montana and Idaho showed the same basic trend between 2,000 to 5,000 feet, with 64 and 82 percent of stations reporting a shift to more rain as a higher percentage of precipitation than snow.

- At higher elevations in Montana and Idaho, the shift was equally strong, with 75 and 78 percent of stations reporting a decrease in the percentage of precipitation falling as snow at 5,000 to 8,000 feet. Oregon has only one station above 5,000 feet, but it too reported a strong increase. Washington has no stations at that elevation.

04. METHODOLOGY

The analysis began with over 3,000 Global Historical Climatology Network (GHCN) stations in the United States with available precipitation data. The stations used in the final analysis were selected based on whether or not they receive snow on a regular basis.

The steps for selecting stations for the analysis are presented in the order in which they were applied:

- Retrieved daily precipitation and snowfall data since July 1949 for each station from the Applied Climate Information System (www.rcc-acis.org).
- Calculated the total amount of snowfall per station per month.
- Counted the number of months that had snowfall of 1 inch or more.
- If there were more than 10 of any month (>10 Januaries, >10 Februaries, etc.) with more than an inch of snow, that month would be included in the analysis for that station.
- If a station did not have more than three months that met the conditions established in the previous step, consecutive or not, they were dropped from the analysis.

After application of these criteria, there were 2,091 stations remaining in the analysis (Figures on next page).

Once we determined the set of stations to include in the analysis, the monthly snow to total precipitation ratio was estimated based on methodologies established in previous research (Huntington, 2004; Knowles, 2006).

- If there was any snowfall on a calendar day (snowfall > 0) then all the precipitation for the day was reclassified as snow water equivalent (SWE) for the day.
- If there was no snowfall on a calendar day (snowfall = 0) than the precipitation was reclassified as rain.
- The monthly snow-total precipitation ratio is the sum of the SWE for the month divided by the total precipitation for the month (SWE+rain).
- Of note is that this binary classification of either a snow day or not may overestimate the actual amount of snow as it would not account for a transition between rain and snow during a day, for instance.

Two representative figures of individual station data are shown below. Both show the percentage of precipitation falling as snow during each snow season beginning in 1949. The first figure shows a negative slope with a decrease in percentage of snow, on average, over the period. For the analysis, this station would then be classified as seeing less snow (or higher percentage of rain). The second figure shows the opposite case, a positive slope, an increasing percentage of snow.

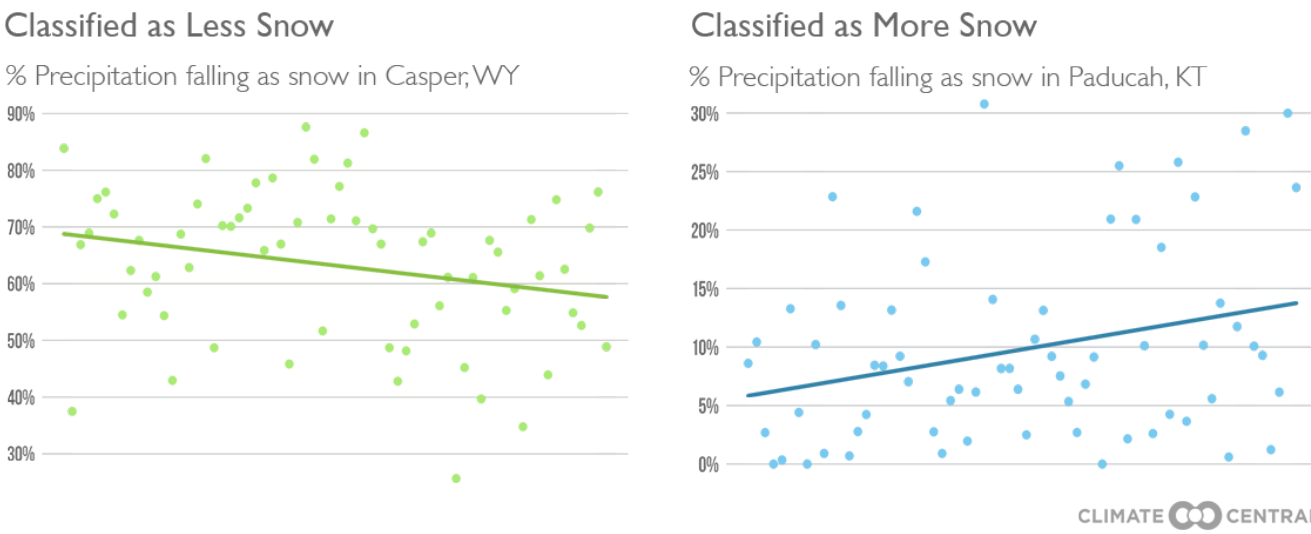
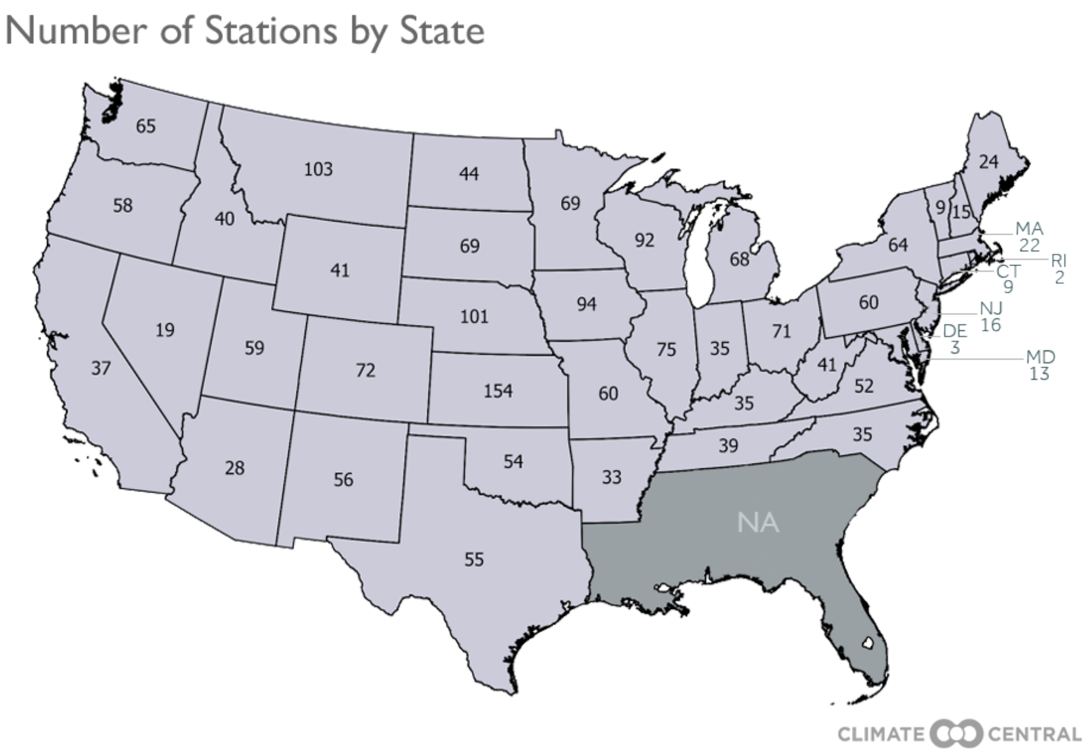


Figure 3. *Data represents yearly ratios of snow as a percentage of total precipitation and the least squares fitted line.*



Map 3. *Map shows total number of stations included in initial analysis.*

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