THE CASE OF THE SHIFTING SNOW

February 5, 2020

Research brief by
Climate Central

CLIMATE CENTRAL

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Whether you live among palm trees or pine trees, snow plays a critical role in our climate. Snow keeps our planet cooler, significantly affects water resources, and is a revealing indicator of climate change.

Forecasting snowfall and determining long-term trends of snow climatology are inherently challenging, but the research team at Climate Central has produced an analysis of snowfall trends across the United States. While no single overall national trend in snowfall can be discerned from the results, clear regional and seasonal patterns do emerge. In almost all areas of the country, snow is decreasing in the "shoulder" seasons—fall and spring. Results from 145 locations show that 116 stations (80%) had decreased snowfall before December, and 96 stations (66%) had decreased snowfall after March 1. Winter showed a mixed record, with more snow in northern climates, and decreasing snow in the southern regions. We also compared total snowfall from the 1970s to the 2010s and ranked the 20 cities with the biggest percentage gains and losses, using endpoint analysis.

The changing patterns of how much, when, and where snow falls have significant impacts on our climate, our economy, and our lives. This report provides a primer on the climatology of snow and includes resources on how to report on snow—or the lack of it—in your area.

GLOBAL WARMING AND ITS IMPACT ON SNOW

Temperature is obviously the major factor in whether precipitation falls to the ground as snow, ice, or rain. As the surface temperature of the earth continues to rise, it's already impacting snowfall patterns and amounts. Common sense tells us that a warmer climate will have less snowfall, as warmer temperatures are likely to make the snow melt to rain before it hits the earth, or melt it quickly when it hits the ground. In the United States, winters are the fastest warming season, the longest cold snaps are becoming shorter, and the number of days with temperatures below 32°F is expected to continue to decline across the country.

Counterintuitively, global warming could actually cause colder regions to experience greater snowfall in the near to medium term. That's because warmer air "holds" more moisture—about four percent more per degree (F)—and that additional moisture can fall as snow when temperatures are below freezing.

According to ongoing academic research, warmer surface temperatures and reduced Arctic sea ice may also be leading to changing atmospheric circulation patterns that bring cold events to the eastern United States.

MEASURING SNOW — IT'S COMPLICATED

Snowfall is hard to measure with consistency and accuracy. Snow blows and drifts, it can become compacted, it can melt on contact. Even during the same snow event, one community may receive a light dusting, while a nearby neighborhood with a slightly higher elevation may get a few inches.

Examining how snowfall measurements are recorded is critical in comparing snow data across time and locations, including such things as observer instructions, time of observation, observer changes, and where the measurements were taken. Different results can occur if observations were taken on a natural surface, pavement, on a picnic table, or on a "snowboard." Besides measuring actual snowfall amounts, there are also other types of snow measurements, including the equivalent water it contains and snowpack, which includes the depth of both old and new snow on the ground.

To study long-term trends and minimize data inconsistencies, Climate Central looked at snowfall trends in two ways. First, we adapted a methodology employed by a number of academics who have been studying snowfall for decades. We collected snowfall data for 244 locations from 1970 to 2019. Weather stations with an average annual snowfall of less than five inches were excluded, as were stations that were missing 20% or more of their data. This allowed us to look at 145 stations in total for seasonal trends over 50 years (Table 1). In addition, we compared average annual snowfall totals in the first and last decades of the study period, a method known as endpoint analysis. A number of stations have large gaps in snowfall data related to the installation of Automated Surface Observing Systems (ASOS), which replaced human observations at a number of locations. By comparing data at the endpoints of the study period, we were able to include 142 stations in our rankings of stations that have experienced the greatest losses or gains in snowfall (Tables 2 and 3). Data near the endpoints of a time series have been shown to have a large influence on the overall trend.

REGIONAL RESULTS: LESS SNOW IN SHOULDER SEASONS, A MIXED RECORD IN ACCUMULATION

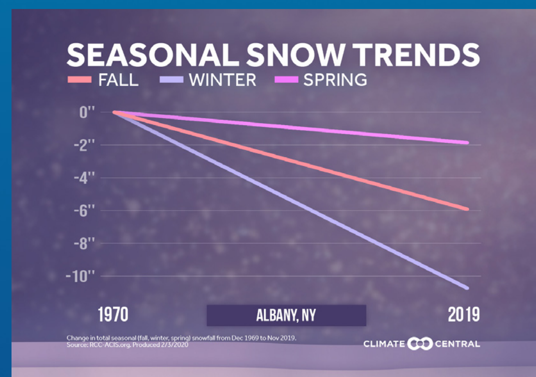
Results of Climate Central's analysis do not show a single overall national trend in snowfall, but by looking at snow station records by region, a number of clear patterns emerged. One of the clearest trends to emerge in almost all areas is that snow is decreasing in the "shoulder" seasons—fall and spring. Over the last 50 years, snowfall before December 1 decreased in every region of the country for which results could be assessed. After March 1, snowfall decreased in all regions except for the Northeast and the East North Central regions. Winter showed a mixed record, with more snow in northern climates, and decreasing snow in the southern regions.

Percentage of stations with decreasing snow by region, 1970-2019.
States are grouped according to NOAA's U.S. climate regions.

Region (# of stations)	Fall	Winter	Spring
Central (43)	74%	58%	77%
East North Central (14)	93%	7%	50%
Northeast (31)	71%	32%	45%
Northwest (11)	91%	36%	64%
South (14)	93%	79%	71%
Southeast (11)	82%	91%	82%
Southwest (5)	100%	80%	100%
West (1)	Too few stations to measure regional trends		
West North Central (15)	73%	13%	67%
National total (145)	**80%**	**46%**	**66%**

Central (Illinois, Indiana, Kentucky, Missouri, Ohio, Tennessee, West Virginia)
These states saw decreasing snowfall totals in all three seasons, with the fall season showing the greatest decrease—32 out of 43 stations recorded lower snow totals. Nashville (-60%) and Knoxville (-52%) ranked at the top of the list for declining snowfall for the endpoint periods, namely 1970-79 and 2010-19. Nashville experienced annual average snowfall of nearly a foot of snow in the 1970s, but less than 5 inches annually on average during the last decade.

Check out our local graphics of seasonal snow trends for 145 locations online, which show how snow has been increasing or decreasing over the last 50 years.



East North Central (Iowa, Michigan, Minnesota, Wisconsin)
Nearly all stations in these Midwestern states saw a long-term snowfall increase during winter. Lake-effect snowfall has been increasing around Lakes Superior and Michigan, although the changes are not uniform. Ice cover impacts lake-effect snowfall, as frozen lakes cut off the moisture supply for snow to form. Overall, lake ice cover has decreased in recent years due to warmer temperatures and as lakes remain ice-free for longer stretches, they support more snow. Marquette, Mich. had some of the biggest gains, with a 45% increase, meaning the average year in the 2010s had 56 more inches of snow than in the 1970s. In the fall, 13 out of 14 stations saw a decline in snow, and half showed snowfall decreasing during the spring season.

Northeast (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont)
The Northeast is the only region with two seasons showing increasing amounts of snowfall. During the winter season, more than two-thirds of stations recorded an increase in snow, and the spring shows 17 out of 31 stations recording a long-term increase from 1970 to the 2019. However, in the fall, there was a decrease in snowfall levels at 22 stations. A number of Northeastern cities experienced significant gains in average annual snow totals since the 1970s, including Atlantic City, N.J. (71%), New York City (66%), and Philadelphia (37%). Separately, warming ocean waters off the coast are also making for favorable conditions for larger and more extreme winter storms, particularly along the East Coast. The National Oceanic and Atmospheric Administration (NOAA) notes that the eastern two-thirds of the United States experienced about twice as many extreme snowstorms in the second half of the 20th century versus the first half.

Northwest (Idaho, Oregon, Washington)
Analyzing 50 years of data shows snow amounts declining at 91% of stations in the Northwest during the fall. Snowfall increased at 7 out of 11 stations during the winter months, but decreased again during the spring season. This is a region where accumulated winter snowpack in the mountainous areas is essential to the annual water cycle, as snowmelt supplies freshwater that sustains local watersheds through the drier summer months. A growing share of the West has endured worsening droughts since the beginning of the 20th century, straining water supplies and increasing the risk for wildfires. A 2019 study by researchers at Portland State University found that snowfall frequency in the mountainous Northwest declined the most at low- and mid-elevation sites. The study also projected that by the end of the 21st century, many of the sites in the SNOTEL observation network will experience more precipitation falling as rain than snow.

South (Arkansas, Kansas, Louisiana, Mississippi, Oklahoma, Texas)
Southeast (Alabama, Florida, Georgia, North Carolina, South Carolina, Virginia)
Across most of the southern states, the analysis showed declining trends in snow for a region of the country that had fairly low amounts of snow to begin with. In the South region, 11 out of 14 stations recorded lower snowfall totals during the winter, and 13 saw declines in the fall. More than two-thirds of stations in the South saw losses in the spring. In the Southeast region, 10 out of 11 stations recorded less snow in the winter, and 9 stations registered lower snowfall during the fall and spring seasons. Snowfall in El Paso, Texas, shrank from 5.73 inches in the 1970s to just 2.76 inches annually in the 2010s. Charlotte, N.C., saw a 39% decrease, from 7.25 inches to just 4.42 inches.

Southwest (Arizona, Colorado, New Mexico, Utah)
Our analysis showed snow levels decreasing across the Southwest, with all five stations recording declines in the fall and spring, and four stations declining in the winter. Both a lack of precipitation and temperatures that are increasingly too warm are leading to snow droughts, which have contributed to recent severe water shortages in the Colorado River Basin and the Rio Grande. The Albuquerque/Santa Fe station showed a 50% drop in snowfall, a loss of nearly 7 inches on average annually over the last decade. Salt Lake City, the host of the 2002 Winter Olympics, had a 42% decline, going from an annual average of 72 inches per year to 42 inches.

Top 20 cities with snow losses, ranked by percentage decrease

City	% Change	Annual Avg. 1970-79 (inches)	Annual Avg. 2010-19 (inches)	Difference (inches)
Nashville, Tenn.	-59.79%	11.59	4.66	-6.93
Knoxville, Tenn.	-52.07%	13.02	6.24	-6.78
El Paso, Texas	-51.83%	5.73	2.76	-2.97
Albuquerque/Santa Fe, N.M.	-50.29%	13.78	6.85	-6.93
Springfield, Mo.	-46.15%	22.19	11.95	-10.24
Evansville, Ind.	-41.99%	19.36	11.23	-8.13
Salt Lake City	-41.99%	72.12	41.84	-30.28
Lubbock, Texas	-41.57%	11.45	6.69	-4.76
Grand Junction Area, Colo.	-41.35%	28.66	16.81	-11.85
Jackson, Tenn.	-39.54%	7.36	4.45	-2.91
Ottumwa, Iowa	-39.42%	30.54	18.5	-12.04
Charlotte, N.C.	-38.53%	7.19	4.42	-2.77
Juneau, Alaska	-38.14%	114.7	70.95	-43.75
State College, Pa.	-36.93%	58.54	36.92	-21.62
Elmira, N.Y.	-35.45%	48.94	31.59	-17.35
Columbia, Mo.	-35.07%	29.51	19.16	-10.35
Abilene/Sweetwa-ter, Tex.	-34.13%	5.83	3.84	-1.99
Wichita Falls, Kan.	-33.07%	6.23	4.17	-2.06
Fayetteville, Ky.	-32.78%	11.99	8.06	-3.93
St. Louis	-31.56%	26.27	17.98	-8.29

142 stations out of 244 met the criteria for ranking snow gains and losses from 1970-79 compared to 2010-19

West (California, Nevada)

Only 1 station in California and Nevada met the criteria for snowfall measurements in this analysis, a sample size too small to draw conclusions about trends. Other research that included more western states found that snowpack at higher elevations in the western U.S. has decreased by 41%, or an area the size of South Carolina, from 1982 to 2016. Another study of Pacific states found declining snowpack trends across all months, states, and climates, but largest in spring. And, another study found that as temperatures warm, the amount of precipitation that falls as snow rather than rain is expected to decrease, accelerating snowmelt. Snowfall is essential for water resources in this region, as one-third of the water used by California's cities and farmland comes from melted snowpack.

West North Central (Montana, Nebraska, North Dakota, South Dakota, Wyoming)
In the Northern Rockies and Plains, winter snowfall increased, with only 2 out of 15 stations showing declining amounts of snow. But snowfall decreased in both the fall and spring seasons—with 11 stations registering lower amounts in the fall, and 10 in the spring. Over the last decade, Mitchell, S.D., experienced a 77% increase in snowfall compared to the 1970s, with 43 inches average annually.

Top 20 cities with snow gains, ranked by percentage increase

City	% Change	Annual Avg. 1970-79 (inches)	Annual Avg. 2010-19 (inches)	Difference (inches)
Mitchell, S.D.	76.80%	24.35	43.05	18.7
Atlantic City, N.J.	71.08%	14.97	25.61	10.64
New York City	66.22%	22.2	36.9	14.7
Newark, N.J.	51.04%	24.96	37.7	12.74
Marquette, Mich.	45.25%	124.54	180.89	56.35
Odessa, Texas	42.58%	4.11	5.86	1.75
Allentown, Pa.	38.45%	27.7	38.35	10.65
Philadelphia	36.89%	21.58	29.54	7.96
Youngstown, Ohio	36.05%	54.78	74.53	19.75
Wilmington, Del.	34.84%	18.77	25.31	6.54
Bluefield, W. Va.	33.66%	31.43	42.01	10.58
Norfolk, Va.	33.38%	7.25	9.67	2.42
Sioux Falls, S.D.	31.34%	34.78	45.68	10.9
Baltimore, Md.	30.48%	16.93	22.09	5.16
Sioux City, Iowa	29.68%	26.65	34.56	7.91
Mason City, Iowa	28.99%	37.46	48.32	10.86
Cheyenne, Wyo.	25.16%	56.76	71.04	14.28
Waterloo, Iowa	22.59%	34.92	42.81	7.89
Wausau, Wis.	22.48%	54.41	66.64	12.23
Little Rock, Ark.	21.65%	5.59	6.8	1.21

142 stations out of 244 met the criteria for ranking snow gains and losses from 1970-79 compared to 2010-19

DECLINING SNOW HAS CONSEQUENCES

Winter storms can be costly and even deadly, particularly when heavy snow and extreme wind events occur in highly populated areas. Since 2000, six winter storms have caused at least $1 billion in damage, according to NOAA's tracking of billion dollar disasters. Four of those storm events occurred just within the last six years, all of them in January or later. But decreasing snow can have negative consequences for our climate, our agricultural output, and our economy.

The reflectivity of fresh snow, known as its albedo, is very high, reflecting more than 80% of incoming sunlight back into the atmosphere (by contrast, darker surfaces such as open oceans reflect only about 6% and trees, plants, and soil reflect 10 to 30%). This high reflectivity is most important during the springtime, when longer days in the Northern Hemisphere lead to more sunshine and snow-covered areas reflect solar energy back, keeping the planet cooler. Snow also has insulation qualities, acting like a blanket for the soil and its organisms, and protecting them from variability in the air temperature above the snow's surface. When soil freezes, it cannot easily absorb new liquid water, leading to more runoff and potential flooding. Research has also shown that flood sizes increase exponentially as a higher fraction of precipitation falls as rain rather than as snow, suggesting that flood risk during the winter and spring could increase as our climate warms. The severe flooding that impacted thousands of homes, as well as agriculture and infrastructure across the Southern Plains in 2019 is estimated to have caused $6.2 billion in damages.

Snow is an important economic resource for many communities around the country. According to a 2018 report by Protect Our Winters, consumer spending by snowboarders, skiers and snowmobilers added an estimated $20.3 billion to the U.S. economy in the 2015-16 winter season. Compared to an average season, high snow years generate an extra $692.9 million and 11,800 extra jobs; low snow years see over $1 billion in economic value lost and cost 17,400 jobs.

Changes in snow also affect the farming industry, especially in western states that depend on snowpack as a water source. As a greater percentage of winter precipitation has begun to fall as rain, this has potentially severe consequences. In most parts of the West, the annual water cycle begins as deep mountain snowpack in the winter and melts slowly during spring. Without snow, there is less water supply for the area's reservoirs. The Sierra Nevada snowpack alone is estimated to sustain $47 billion in agribusiness annually in California.

So whether or not the first sign of a snowflake has you waxing up your snowboard and skis, or has you diving back under the covers, the changing snowfall patterns are a sign of our changing climate. Future winters are likely to be warmer and wetter for many of us.

METHODOLOGY. *Total annual and seasonal (fall, winter, and spring) snowfall data from 1970–2019 were obtained from the Applied Climate Information System. For the seasonal analysis that spanned the full fifty-year period, stations missing more than 20% of daily data (10 years) for any season over the study period were excluded. Fifty-year seasonal snowfall trends were analyzed using linear regression analysis. For endpoint analysis, average annual snowfall in the first (1970–1979) and last (2010–2019) decades of the study period was compared at each location that receives an average annual snowfall of at least five inches. Stations with more than 20% missing daily data (2 years) in either the first or last decade were excluded from the analysis.*

ACKNOWLEDGMENTS. *Research efforts were supported by Dr. David Robinson, Distinguished Professor & New Jersey State Climatologist, Department of Geography & NJ Agricultural Experiment Station, Rutgers University.*

GLOSSARY OF SNOW TERMS:

Albedo is how much sunlight the Earth's surface reflects back into the atmosphere. Fresh snow reflects 80 to 90 percent of incoming sunlight (high albedo). By contrast, trees, plants, and soil reflect only 10 to 30 percent of sunlight (low albedo).

Blizzards are severe winter storms with snow and wind. The National Weather Service defines a storm as a blizzard when falling or blowing snow with winds in excess of 35 miles (56 kilometers) per hour and visibilities of less than 0.25 miles (0.40 kilometers) persist for more than 3 consecutive hours.

Freezing rain is liquid precipitation that freezes on contact with surfaces, such as vegetation, power lines, buildings, etc.

Snow cover is the area of land or ice covered by accumulated snow at any given time. Snow cover helps regulate Earth's surface temperature when it is present, and it helps fill rivers and reservoirs once it melts. National and regional snow cover maps can be found at the National Operational Hydrologic Remote Sensing Center, which provides information on snow depth, snow water equivalent, and other data.

Snow water equivalent (SWE) is the amount of water contained within the snowpack, or theoretically, the amount of water that would be released if the entire snowpack melted. Information about snow water equivalent is used in flood forecasting, controlling the water level of power plant reservoirs, planning for agricultural irrigation, and other water uses. In the western U.S., the majority of the water supply comes from snowpack melt.

Snowmelt is the melting of the snow cover, and also the period during which melting of the snow cover occurs at the end of the winter.

Snowpack, or **snow depth**, is the total snow and ice on the ground, including both new snow and the previous snow and ice that have not melted. In mountainous areas with persistently below-freezing temperatures, snowpack can last for many months, until warmer weather arrives. Measuring and modeling snowpack is important for water resource management, especially in the western U.S.

SNOTEL (or snow telemetry) is an automated measurement system operated by the Natural Resources Conservation Service (NRCS) in 11 Western states, including Alaska. SNOTEL sensors measure for snow water content, accumulated precipitation, and air temperature. Sensors may take other readings, including snow depth, soil moisture and temperature, wind speed, solar radiation, humidity, and atmospheric pressure. These data are used to forecast yearly water supplies, predict floods, and for general climate research. The 730+ SNOTEL sites are generally located in remote high-mountain watersheds where access is often difficult or restricted, and accessible only by hiking, skiing, or helicopters.