Snowpack

Identification

1. Indicator Description

This indicator describes changes in springtime mountain snowpack in the western United States between 1955 and 2023. Mountain snowpack is a key component of the water cycle in the western United States, storing water in the winter when the snow falls and releasing it in spring and early summer when the snow melts. Changes in snowpack over time reflect a changing climate, as temperature and precipitation are key factors that influence the extent, duration, and volume of snowpack. In a warming climate, more precipitation will be expected to fall as rain rather than snow in most areas—reducing the extent and depth of snowpack (Payton et al., 2023). Higher temperatures in the spring can cause snowpack to stop accumulating and begin melting earlier (Elsner et al., 2010; Payton et al., 2023). The seasonal characteristics of snowpack and its spatial distribution are important to understand as they are coupled to hydrologic, atmospheric, and biogeochemical systems through runoff, heat and energy fluxes, soil moisture distributions, and growing season.

Components of this indicator include:

- Changes in the amount of snowpack on or around April 1—a date commonly used for forecasting spring and summer water supply (Figure 1).
- Changes in the annual date of peak snowpack (i.e., the day on which the most snowpack is present) (Figures 2 and 3).
- Changes in snowpack season length (i.e., the number of days that seasonal snow is present) (Figure 4).

2. Revision History

April 2010:	Original indicator published (Figure 1).
May 2014:	Updated indicator with data through 2013.
June 2015:	Updated indicator with data through 2015.
August 2016:	Updated indicator with data through 2016.
April 2021:	Updated indicator with data through 2020; added peak snowpack analysis (Figures 2 and 3).
July 2022:	Updated Figure 1 with data through 2022 and Figures 2 and 3 with data through 2021. Added season length analysis (Figure 4) with data through 2021.
June 2024:	Updated indicator with data through 2023.

Data Sources

3. Data Sources

This indicator (all figures) is based on data compiled by the U.S. Department of Agriculture's (USDA's) Natural Resources Conservation Service (NRCS). NRCS compiles snowpack measurements collected by USDA staff as well as other agencies and organizations (for example, many measurements in California come from the California Department of Water Resources).

Dr. Philip Mote at Oregon State University had published an earlier version of the analysis shown in Figure 1 (Mote et al., 2005) with data from about 1930 to 2000 and a map of trends from 1950 through 1997. Mote et al. (2018) provide an updated version of the analysis. Figure 1 of this indicator applies Mote et al.'s methodology to the most recent available data set.

4. Data Availability

EPA obtained the data for this indicator directly from NRCS's database of snowpack measurements, available at: www.wcc.nrcs.usda.gov/snow/index.html. This database includes measurements collected throughout the western United States, Alaska, and western Canada, all available to the public with no confidentiality or accessibility restrictions. The website provides descriptions of the data.

For selected sites, Figure 1 of this indicator also incorporates historical data points provided by the authors of Mote et al. (2018) as a product of their published analysis. Specifically, it uses a set of adjusted snowpack measurements that were derived through calibration of co-located automated and manual data collection stations. Section 6 provides more detail about this supplementary data set and how it was used.

Methodology

5. Data Collection

This indicator uses snow water equivalent (SWE) measurements to assess trends in snowpack. SWE is the amount of water contained within the snowpack at a particular location. It can be thought of as the depth of water that would result if the entire snowpack were to melt. Because snow can vary in density (depending on the degree of compaction, for example), converting to the equivalent amount of liquid water provides a more consistent metric than snow depth. When this indicator refers to "depth" or "amount" of snowpack, it is simply a convenient shorthand for SWE.

Snowpack measurements have been extensively documented and have been used for many years to help forecast spring and summer water supplies, particularly in the western United States. This indicator focuses on the western United States (excluding Alaska) because this broad region has the greatest density of stations with long-term records.

Snowpack data have been collected over the years using a combination of manual and automated techniques. All of these long-term measurement techniques are ground-based observations, as SWE is difficult to measure from aircraft or satellites—although development and validation of remote sensing for snowpack is a subject of ongoing research (for example, LIDAR laser-based measurement has shown promise for covering large areas). Consistent manual measurements from “snow courses” or observation sites are available beginning in the 1930s, although a few sites started earlier. These measurements, typically taken near the first of each month between January and May or June, require an observer to travel to remote locations, on skis or snowshoes or by snowmobile or helicopter, to measure SWE. At a handful of sites, an aircraft-based observer photographs snow depth against a permanent marker.

In 1979, NRCS and its partners began installing automated snowpack telemetry (SNOTEL) stations. Instruments at these stations automatically measure snowpack and related climatic data. The NRCS SNOTEL network now operates more than 900 remote sites in the western United States, including Alaska. In contrast to monthly manual snow course measurements, SNOTEL sensor data are recorded every 15 minutes and reported daily to two master stations. In most cases, a SNOTEL site was located near a snow course, and after a period of overlap to establish statistical relationships, the co-located manual snow course measurements were discontinued. Hundreds of other manual snow course sites are still in use, however, and data from these sites are used to augment data from the SNOTEL network and provide more complete coverage of conditions throughout the western United States.

NRCS describes both manual and telemetric snowpack measurement techniques in more detail through publications at: www.nrcs.usda.gov/wps/portal/wcc/home/aboutUs/publications. A training and reference guide for snow surveyors who use sampling equipment to measure snow accumulation is also available on the NRCS website at: www.nrcs.usda.gov/programs-initiatives/sswsf-snow-survey-and-water-supply-forecasting-program/national-water-and.

Figure 1. Trends in April Snowpack in the Western United States, 1955–2023

Figure 1 examines trends at the same date each year, for consistency. This indicator uses April 1 as the annual date for analysis because it is the most frequent observation date and it is extensively used for spring streamflow forecasting, representing an estimate of the total water available for runoff (Mote et al., 2005). Data are nominally attributed to April 1; in reality, for some manually operated sites, the closest measurement in a given year might have been collected slightly before or after April 1. The collection date is noted in the data set. For evaluating long-term trends, there is little difference between the data measured on the date given and the estimates adjusted to April 1.

More than 1,000 locations have recorded SWE measurements within the area of interest. Figure 1 is based on 652 stations with sufficient April 1 records spanning the period from 1955 through 2023, per the filtering criteria described in Section 6. The year 1955 was selected as a starting point because it is early enough to provide long records but late enough to include many sites in the Southwest where measurement began during the early 1950s.

Figures 2 and 3. Peak Snowpack Timing in the Western United States, 1982–2023

Figures 2 and 3 examine trends in peak SWE by year, based on a subset of sites with daily records from 1982 through 2023. Because daily data are needed to determine the precise date of peak snowpack in each year, this part of the indicator is necessarily limited to SNOTEL sites. EPA selected 1982 as a starting point because it represents a point at which a “critical mass” of SNOTEL sites had been installed and become operational. Evan (2019) published a related analysis of snowpack season characteristics and shows that there was a large increase in the number of SNOTELs between 1978 and 1982—hence 1982 was selected for Evan’s analysis as well as EPA’s.

Altogether, more than 400 SNOTELs were in operation by 1982 (Evan, 2019) The latest dataset shows 422 with data for 1982. EPA applied data quality criteria consistent with Evan (2019) to narrow the list to a set of 325 stations within the contiguous 48 states with sufficiently complete data over the full period of analysis. Data quality criteria are described in Section 6.

Figure 4. Change in Snowpack Season Length in the Western United States, 1982–2023

Figure 4 examines the duration in days of the snowpack season based on SNOTELs that were operational by 1982. EPA applied data quality criteria outlined by Petersky and Harpold (2018) to arrive at 340 stations with sufficient data over the period of analysis. Data quality criteria are described in Section 6.

6. Indicator Derivation

EPA used the following steps to prepare the data for this indicator.

All Components

EPA harvested all available data from the NRCS database. EPA removed stations that were outside the geographic area of interest. This means the indicator excludes Alaskan and Canadian stations that are part of the NRCS database.

EPA inspected the data to identify any possible duplicate stations, which could have resulted from multiple organizations reporting data that ended up being captured by the NRCS database. In practice, there are several locations where multiple discrete sites exist in close proximity: sometimes a SNOTEL and manual snow course that both continue to collect data and both meet the filtering criteria, sometimes a set of stations placed at different altitudes in mountainous terrain. In the most recent data set, all potential duplicates turned out to be discrete stations, so no duplicates were removed.

Figure 1. Trends in April Snowpack in the Western United States, 1955–2023

For many SNOTEL sites, EPA was able to extend the record back to years that preceded SNOTEL installation by using historical data points developed as part of the earlier Mote et al. analysis. These historical data points came from manual snow courses that were in place for many years before being replaced by automated SNOTELs at the same locations. As noted above, these snow courses continued to be measured for a few years after the SNOTELs were installed, for calibration purposes. For this analysis, each pre-SNOTEL snow course data set was adjusted to align with the corresponding SNOTEL record, then appended to the beginning of the SNOTEL record to create a unified long-term record (snow course + SNOTEL) capable of meeting the data availability criteria described below.

EPA filtered sites based on the availability of nominal “April 1” data points, according to the following criteria for including stations in this analysis:

- The station must have data back to at least 1955.
- The station cannot be lagging by more than five years—i.e., the most recent year of data must be 2018 or later.
- For 1955–2023, the station must have data for 80 percent of the years.

- For 1955–2023, the station must have non-zero April 1 SWE values in at least 50 percent of the years. This ensures that trends are only calculated for stations that actually had snowpack on the ground in at least half of the years of interest.

Once the data set was narrowed to stations with sufficient data, EPA calculated linear trends in April 1 SWE measurements from 1955 through 2023. Trends were calculated for 1955 through 2023 at each snow course or SNOTEL location, and then these trends were converted to percent change since 1955, using the 1955 regression estimate as the baseline. Note that this method can lead to an apparent loss exceeding 100 percent at a few sites (i.e., more than a 100 percent decrease in snowpack) in cases where the line of best fit passes through zero sometime before 2023, indicating that it is now most likely for that location to have no snowpack on the ground at all on April 1. It can also lead to large percentage increases for sites with a small initial value for the linear fit. For more details about the analytical procedures used to calculate trends and percent change for each location, see Mote et al. (2005).

EPA plotted the results on a map using ArcGIS software. Figure 1 shows trends at individual sites with measured data, with no attempt to generalize data over space.

Figures 2 and 3. Peak Snowpack Timing in the Western United States, 1982–2023

This part of the indicator uses water years, which run from October 1 to September 30. Water year 2021 started on October 1, 2020, for example. Using water years ensures that each snowpack season (nominally each winter, plus the months on either side of the winter) is evaluated as a contiguous whole even though it happens to straddle two calendar years. That said, the unweighted all-station average peak date shown in Figure 3 happens to have occurred after January 1 in every water year covered by this analysis. Figures 2 and 3 expand the evaluation of trends in snowpack beyond the single-day (April 1) approach reported in Figure 1.

EPA selected all stations with daily SNOTEL records for the period of interest, then filtered the list based on the same data completeness criteria used by Evan (2019):

- First date of measurement must be no later than October 1, 1981 (start of water year 1982).
- There must not be any water years where the count of missing data (N/A) for the winter of that water year is greater than or equal to 30 days.
- There must not be any January, February, or March where the SWE for the entire month is measured to be 0.

Before applying these criteria, the filtering script identified any cases where one daily snowpack depth (in SWE) was more than 20 centimeters higher or lower than the previous day's measurement. A change in SWE of more than 20 centimeters in a single day is highly unlikely and suggests a possible error, so—following Evan (2019)—such instances were replaced by "N/A."

Applying this approach led to a subset of 325 stations for analysis. For each station, EPA identified the date of maximum SWE in each water year and recorded the day of year for further analysis (for example, October 1 is considered "day 1"). If the same maximum depth occurred on multiple dates during one water year, this analysis used the latest measurement (i.e., the last day on which that depth occurred).

Trends in day of the year were calculated for each station for 1982–2023 using least-squares linear regression. EPA multiplied each annual rate of change by the length of the period (41 years) to derive an estimate of total change, then plotted the results on a map (Figure 2) using ArcGIS software. The map shows trends at individual sites with measured data, with no attempt to generalize data over space.

The graph in Figure 3 shows the results of an unweighted average of all sites in each year. That is, all sites are weighted equally in this simple average, regardless of variations in regional station density and the heterogeneous nature of the various sites, their terrain, and statistics regarding the extent and volume of snowpack they receive.

Figure 4. Change in Snowpack Season Length in the Western United States, 1982–2023

EPA selected SNOTEL stations that had a first date of measurement no later than October 1, 1981 (start of water year 1982) and had data through the 2023 water year. EPA then removed stations that had more than seven days of continuous missing data, following the criteria used by Petersky and Harpold (2018). Applying this approach led to 340 stations used for analysis.

EPA found the duration of seasonal snow (as defined by Petersky and Harpold, 2018) by identifying periods of at least 60 consecutive days with snow on the ground, then calculating the full duration of these periods. Thus, snowpack season length reflects the number of days in each water year that were snow-covered and were part of a series of at least 60 consecutive snow-covered days. Many researchers have used the 60-day threshold to distinguish between seasonal snowpack and more ephemeral snow cover. A day was considered snow-covered if the SWE at a SNOTEL site was greater than 0.1 centimeter.

EPA calculated trends in snowpack season length for each station for the 1982–2023 water years using least-squares linear regression. EPA multiplied each rate of change (regression slope) by the length of the period (41 years) to derive an estimate of total change, then plotted the results on a map (Figure 4) using ArcGIS software. The map shows trends at individual sites with measured data, with no attempt to generalize data over space.

7. Quality Assurance and Quality Control

Automated SNOTEL data are screened by computer to ensure that they meet minimum requirements before being added to the database. In addition, each automated data collection site receives maintenance and sensor adjustment annually. Data reliability is verified by ground-truth measurements taken during regularly scheduled manual surveys, in which manual readings are compared with automated data to check that values are consistent. Based on these quality assurance and quality control (QA/QC) procedures, maintenance visits are conducted to correct deficiencies. Additional description of QA/QC procedures for the SNOTEL network can be found at: www.nrcs.usda.gov/sites/default/files/2023-02/J%20American%20Water%20Resour%20Assoc%20-%202023%20-%20Fleming%20-%20SNOTEL%20%20the%20Soil%20Climate%20Analysis%20Network%20%20and%20water%20supply%20forecasting%20at_1.pdf

QA/QC procedures for manual measurements by NRCS and by other agencies are largely unavailable online.

When this analysis was originally developed, additional QA/QC activities were conducted on the data obtained from NRCS. For Figure 1, station data were checked for physically unrealistic values such as SWE larger than snow depth, or SWE or snow depth values far beyond the upper bounds of what would even be considered exceptional (i.e., 300 inches of snow depth or 150 inches of SWE). In these cases, after manual verification, suspect data were replaced with a “no data” value. In addition, the April-to-March ratio of SWE was evaluated, and any station that had a ratio greater than 100 was evaluated manually for data accuracy. These supplemental checks were used to establish the set of stations eligible for inclusion in this analysis. Figures 2 and 3 also included steps to eliminate data points that were suspect due to unrealistically large day-to-day changes (see Section 6).

Analysis

8. Comparability Over Time and Space

In general, while trend analysis methods have been applied consistently across all sites, the metrics in this indicator are not standardized in the way that, for example, a drought index is standardized. Thus, the observations from different locations or different periods of time could have different statistical properties or probability of occurrence. For example, a 10 percent change in different locations could correspond to different occurrence probabilities.

Figure 1. Trends in April Snowpack in the Western United States, 1955–2023

For consistency, Figure 1 examines trends at the same point in time each year. This indicator uses April 1 as the annual date for analysis because it is the most frequent observation date and it is extensively used for spring streamflow forecasting (Mote et al., 2005). Data are nominally attributed to April 1; in reality, for some manually operated sites, the closest measurement in a given year might have been collected as much as two weeks before or after April 1. In the vast majority of cases, however, the April 1 measurement was made within a few days of April 1.

Data collection methods have changed over time in some locations, particularly as automated devices have replaced manual measurements. Agencies such as NRCS, however, have taken careful steps to calibrate the automated devices and ensure consistency between manual and automatic measurements (see Section 7). They also follow standard protocols to ensure that methods are applied consistently over time and space.

Figures 2, 3, and 4. Peak Snowpack Timing and Changes in Snowpack Season Length in the Western United States, 1982–2023

These three figures apply consistent analytical methods to all stations and all years of data. These figures are limited to data from SNOTEL devices, which are routinely calibrated, as described above.

9. Data Limitations

Factors that may impact the confidence, application, or conclusions drawn from this indicator are as follows:

1. EPA selected 1955 as a starting point for Figure 1 because many snow courses in the Southwest were established in the early 1950s, thus providing more complete spatial coverage. Some researchers have examined snowpack data within smaller regions over longer or shorter time frames and found that the choice of start date can make a difference in the magnitude of the resulting trends. For example, Mote et al. (2008) pointed out that lower-elevation snow courses in the Washington Cascades were mostly established after 1945, so limiting the analysis to sites established by 1945 results in a sampling bias toward higher, colder sites. They also found that starting the linear fit between 1945 and 1955—an unusually snowy period in the Northwest—led to somewhat larger average declines. Across the entire western United States, though, the median percentage change and the percentage of sites with declines are fairly consistent, regardless of the start date.

2. Figures 2, 3, and 4 are limited to a shorter period of record and a smaller set of stations than Figure 1, due to the reliance on automated SNOTEL stations that measure snowpack daily. All the same mountainous regions covered in Figure 1 are also represented in Figures 2 and 4, but some—like the Sierra Nevada—have a noticeably lower station density.

3. Although the trends shown in this indicator are based on a linear regression of all years within the period of analysis, overall trends could be disproportionally influenced by the anomalies at the beginning and end of the record as well as large year-to-year natural variability in how much seasonal precipitation is received (e.g., high snowpack years in 1982–1984, low in 2015–2017). The earliest years of SNOTEL data availability for the peak snowpack metrics (Figures 2 and 3) happen to coincide with higher-than-average snowpack years, whereas 2015–2017 were particularly dry. This could influence the magnitude of some of the trends shown. However, it does not negate the overall strong evidence from multiple metrics that shows long-term declines in snowpack across much of the West.

4. Although most parts of the West have seen reductions in snowpack, consistent with overall warming trends, observed snowfall trends could be partially influenced by non-climatic factors such as observation methods, land-use changes, and forest canopy changes. A few snow course sites have been moved over time—for example, because of the growth of recreational uses such as snowmobiling or skiing. Mote et al. (2005) also report that the mean date of "April 1" observations has grown slightly later over time.

5. Snowpack measurements are available from more than 1,000 sites across the western United States; however, this represents a relatively small sample area in terms of the overall snow production area in the mountainous West. Point measurements do not necessarily represent the snowpack distribution, especially in areas with spatially heterogeneous terrain.

10. Sources of Uncertainty

Uncertainty estimates are not readily available for this indicator, although NRCS has published some accuracy and precision estimates for the underlying snowpack measurements in past handbooks. The regionally consistent and in many cases sizable changes shown in Figure 1, along with independent hydrologic modeling studies (Ashfaq et al., 2013; Mote et al., 2005, 2018), strongly suggest that this indicator shows real secular trends, not simply the artifacts of some type of measurement error. Zeng et al. (2018) provide corroborating evidence of widespread snowpack decline across the western United States using a gridded approach that incorporates additional data sources. Luce et al. (2014) examine the sensitivity of snowpack storage to temperature and precipitation using snowpack data as measured from SNOTEL sites. These findings provide further insight into temporal and spatial trends in snowpack.

11. Sources of Variability

Snowpack trends are influenced by large, natural year-to-year variations in precipitation, temperature, and other climate variables. To reduce the influence of year-to-year variability, Figure 1 of this indicator looks at longer-term trends over the full 69-year time series. Over a longer timeframe, snowpack variability can result from variations in the Earth's climate or from non-climatic factors such as changes in observation methods, land use, and forest canopy.

12. Statistical/Trend Analysis

Figure 1. Trends in April Snowpack in the Western United States, 1955–2023

Figure 1 shows the results of a least-squares linear regression of annual observations at each individual site from 1955 through 2023. The statistical significance of each of these trends was examined using the Mann-Kendall test for significance and the Durbin-Watson test for serial correlation (autocorrelation) of the regression residuals. Of the 652 stations in this analysis, 175 had trends that were significant to a 95 percent level ($p < 0.05$) according to the Mann-Kendall test, with 10 of those sites showing autocorrelation (p-value of the Durbin-Watson test < 0.1, indicating that the test resulted in an extreme value [indicating autocorrelation] and there is a low probability that such an extreme value could have been observed in a non-autocorrelated data set [the null hypothesis]). A block bootstrap (using both three- and five-year blocks) was applied to those 10 sites that had both significant autocorrelation and significant trends. In all but two cases, the Mann-Kendall test indicated a significant trend ($p < 0.05$) even after applying the block bootstrap. Of the 175 sites with a significant trend, in all but three cases the trend was decreasing.

Figures 2 and 3. Peak Snowpack Timing in the Western United States, 1982–2023

Figure 2 shows the results of a least-squares linear regression of annual observations at each individual site from 1982 through 2023 (water years). Standard p-values were used to assess statistical significance to a 95 percent level ($p < 0.05$). Of the 325 stations in the analysis, 61 (19 percent) had a significant change in peak snowpack timing, and 57 of these significant trends were negative (shifting to earlier over time).

Figure 3 shows an aggregate time series. It is not significant to a 95 percent level. The aggregate trend is -1.66 days per decade ($p = 0.138$).

Figure 4. Change in Snowpack Season Length in the Western United States, 1982–2023

Figure 4 shows the results of a least-squares linear regression of annual observations at each SNOTEL site from 1982 through 2023 (water years). Standard p-values were used to assess statistical significance to a 95 percent level ($p < 0.05$). Of the 340 stations analyzed, 79 (23 percent) had a significant change in snowpack season length, and all these significant trends were negative (i.e., snow season becoming shorter over time).

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