Snowfall

Identification

1. Indicator Description

Warmer temperatures associated with climate change can influence snowfall by altering weather patterns, causing more precipitation overall, and causing more precipitation to fall in the form of rain instead of snow. Thus, tracking metrics of snowfall over time can provide a useful perspective on how the climate may be changing aspects of precipitation. This indicator examines how snowfall has changed across the contiguous 48 states over time.

Components of this indicator include:

- Trends in total winter snowfall accumulation in the contiguous 48 states since 1930 (Figure 1).
- Changes in the ratio of snowfall to total winter precipitation since 1949 (Figure 2).

2. Revision History

December 2012:	Indicator published.
May 2014:	Updated Figure 2 with data through 2014.
June 2015:	Updated Figure 2 with data through 2015.
August 2016:	Updated Figure 2 with data through 2016.
April 2021:	Updated Figure 2 with data through 2020.

Data Sources

3. Data Sources

The data used for this indicator are based on two studies published in the peer-reviewed literature: Kunkel et al. (2009) (Figure 1) and an update to Feng and Hu (2007) (Figure 2). Both studies are based on long-term weather station records compiled by the National Oceanic and Atmospheric Administration's (NOAA's) National Centers for Environmental Information (NCEI).

4. Data Availability

Figure 1. Change in Total Snowfall in the Contiguous 48 States, 1930–2007

EPA acquired the data for Figure 1 directly from Dr. Kenneth Kunkel of NOAA's Cooperative Institute for Climate and Satellites (CICS). Dr. Kunkel's analysis is based on data from weather stations that are part of NOAA's Cooperative Observer Program (COOP). Complete data, embedded definitions, and data descriptions for these stations can be found online at: www.weather.gov/coop. State-specific data can be found at:
www.ncdc.noaa.gov/IPS/coop/coop.html;jsessionid=312EC0892FFC2FBB78F63D0E3ACF6CBC. There are

no confidentiality issues that may limit accessibility. Additional metadata can be found at: www.weather.gov/coop.

Figure 2. Change in Snow-to-Precipitation Ratio in the Contiguous 48 States, 1949–2020

EPA maintains this portion of the indicator using an algorithm developed through a formal agreement with Dr. Song Feng at the University of Nebraska–Lincoln. To run this algorithm, EPA acquired data from the Global Historical Climatology Network, Daily version (GHCN-Daily), a compilation of weather station data maintained by NOAA. The GHCN-Daily allows users to download daily data at: ftp://ftp.ncdc.noaa.gov/pub/data/ghcn/daily. This FTP site also provides data descriptions and other metadata. The data were taken from GHCN-Daily Version 3.28. In 2014, NOAA stopped updating the U.S. Historical Climatology Network (USHCN) dataset that was previously used for Figure 2. Now, data for Figure 2 come from GHCN-Daily, as NOAA has improved the GHCN dataset and generally adopted USHCN's methods such that GHCN-Daily is comparable to USHCN in quality.

Methodology

5. Data Collection

Systematic collection of weather data in the United States began in the 1800s. Since then, observations have been recorded at 23,000 different stations. At any given time, observations are recorded at approximately 8,000 stations.

NOAA's National Weather Service (NWS) operates some stations (called first-order stations), but the vast majority of U.S. weather stations are part of the COOP network, which represents the core climate network of the United States (Kunkel et al., 2005). Cooperative observers include state universities, state and federal agencies, and private individuals. Observers are trained to collect data following NWS protocols, and equipment to gather these data is provided and maintained by the NWS.

Data collected by COOP are referred to as U.S. Daily Surface Data or Summary of the Day data. General information about the NWS COOP data set is available at: www.weather.gov/coop. This site also provides links to full metadata for the COOP data set, sampling procedures, and training that includes information about specific instruments and how they work.

NCEI also maintains the GHCN-Daily, which contains data from more than 100,000 stations in 180 countries and territories that meet certain selection criteria and undergo additional levels of quality control. GHCN-Daily contains precipitation data from thousands of stations within the contiguous 48 states. The period of record varies for each station. To be included in the GHCN-Daily, a station has to meet certain criteria for consistency of location (identifiable name, latitude, and longitude), data availability (at least 100 values for at least one of the GHCN-Daily elements), and uniqueness of data (i.e., more than 50% of the station's data are unique). Included with the data set are metadata files and journal articles that contain information about station moves, instrumentation, observing times, and elevation. NOAA's website (www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-daily) provides more information about GHCN-Daily data collection.

Figure 1. Change in Total Snowfall in the Contiguous 48 States, 1930–2007

The analysis in Figure 1 is based on snowfall (in inches), which weather stations measure daily through manual observation using a snow measuring rod. The measuring rod is a stick that observers use to measure the depth of snow.

The study on which this indicator is based includes data from 419 COOP stations in the contiguous United States for the months of October to May. These stations were selected using screening criteria that were designed to identify stations with the most consistent methods and most reliable data over time. Screening criteria are described in greater detail in Section 7.

Figure 2. Change in Snow-to-Precipitation Ratio in the Contiguous 48 States, 1949–2020

The analysis in Figure 2 is based on snowfall and precipitation measurements collected with standard gauges that "catch" precipitation, thus allowing weather stations to report daily precipitation totals. These gauges catch both solid (snow) and liquid (rain) precipitation. At each station, total daily precipitation is reported as a liquid equivalent depth based on one of two types of calculations: 1) precipitation is melted and the liquid depth measured, or 2) the precipitation is weighed. These methods are described by Huntington et al. (2004) and Knowles et al. (2006). Some stations occasionally use snow depth to calculate liquid equivalent by assuming a 10:1 density ratio between snow and rain. However, stations using this method extensively were excluded from the analysis because the assumed ratio does not always hold true and because such an assumption could introduce a bias if snow density were also changing over time. Indeed, other analyses have cited changes in the density of snow over time, as warmer conditions lead to denser snow, particularly in late winter and early spring (Huntington et al., 2004).

This study uses data from 177 GHCN-Daily stations in the contiguous United States. Stations south of 37°N latitude were not included because most of them receive minimal amounts of snow each year. Additional site selection criteria are described in Section 7. This analysis covers the months from November through March, and each winter has been labeled based on the year in which it ends. For example, the data for "2015" represent the season that extended from November 2014 through March 2015.

6. Indicator Derivation

Figure 1. Change in Total Snowfall in the Contiguous 48 States, 1930–2007

At each station, daily snowfall totals have been summed to get the total snowfall for each winter. Thus, this figure technically reports trends from the winter of 1930–1931 to the winter of 2006–2007. Long-term trends in snowfall accumulation for each station are derived using an ordinary least-squares linear regression of the annual totals. Kunkel et al. (2009) describe analytical procedures in more detail. The lead author of Kunkel et al. (2009) conducted the most recent version of this analysis for EPA.

Figure 2. Change in Snow-to-Precipitation Ratio in the Contiguous 48 States, 1949–2020

EPA developed Figure 2 by following an approach published by Feng and Hu (2007). Using precipitation records from GHCN-Daily Version 3.28, EPA calculated a snow-to-precipitation (S:P) ratio for each year by comparing the total snowfall during the months of interest (in terms of liquid-water equivalent) with total precipitation (snow plus rain). Long-term rates of change at each station were determined using a Kendall's tau slope estimator. This method of statistical analysis is described in Sen (1968) and Gilbert (1987). For a more detailed description of analytical methods, see Feng and Hu (2007).

7. Quality Assurance and Quality Control

The NWS has documented COOP methods, including training manuals and maintenance of equipment, in resources posted at: www.weather.gov/coop. These training materials also discuss quality control of the underlying data set. Additionally, pre-1948 data in the COOP data set have been digitized from hard copy. Quality control procedures associated with digitization and other potential sources of error are discussed in Kunkel et al. (2005).

Quality control procedures for GHCN-Daily are summarized at: www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-daily.

Figure 1. Change in Total Snowfall in the Contiguous 48 States, 1930–2007

Kunkel et al. (2009) filtered stations for data quality by selecting stations with records that were at least 90-percent complete over the study period. In addition, each station must possess at least five years of records during the decade at either end of the trend analysis (i.e., 1930s and 2000s) because data near the endpoints exert a relatively heavy influence on the overall trend. Year-to-year statistical outliers were also extensively cross-checked against nearby stations or *Climatological Data* publications when available. Any discrepancies with apparent regional trends were reviewed and evaluated by a panel of seven climate experts for data quality assurance. A more extensive description of this process, along with other screening criteria, can be found in Kunkel et al. (2009).

Figure 2. Change in Snow-to-Precipitation Ratio in the Contiguous 48 States, 1949–2020

Following the methods outlined by Feng and Hu (2007), EPA applied a similar filtering process to ensure data quality and consistency over time. Stations missing certain amounts of snow or precipitation data per month or per season were excluded from the study. Additional details about quality assurance are described in Feng and Hu (2007).

With assistance from the authors of Feng and Hu (2007), EPA added another screening criterion in 2012 that excluded sites that frequently used a particular estimation method to calculate snow water equivalent. Applying this criterion to the most recent data, along with the other filters described above, resulted in 177 stations, or 197 fewer stations compared with the dataset used in Feng and Hu (2007). Specifically, instructions given to observers in the early to mid-twentieth century provided an option to convert the measured snowfall to precipitation using a 10:1 ratio if it was impractical to melt the snow. Many observers have used this option in their reports of daily precipitation, although the number of observers using this option has declined through the years. The actual snowfall-to-liquid precipitation density ratio is related to factors such as air temperature during the snow event; the ratio varies spatially and it may be changing over time (e.g., Huntington et al., 2004). The median ratio in recent decades has been approximately 13:1 in the contiguous United States (Baxter et al., 2005; Kunkel et al., 2007), which suggests that using a 10:1 ratio could generally overestimate daily precipitation. Total winter precipitation in a snowy climate would thus be problematic if a large portion of the daily precipitation was estimated using this ratio, and apparent changes in S:P ratio over time could be biased if the average density of snow were also changing over time. To reduce the impact of this practice on the results, this analysis excluded records where winter (November to March) had more than 10 days with snowfall depth larger than 3.0 cm and where more than 50 percent of those snowy days reported total precipitation using the 10:1 ratio.

EPA also reviewed other analyses of snow-to-precipitation ratios. Knowles et al. (2006) used substantially different site selection criteria from those used for EPA's indicator. The study underlying EPA's indicator, Feng and Hu (2007), uses stricter criteria that exclude several stations in the Southern Rockies and other higher elevation sites. Further, Knowles et al. (2006) relied on an older version of the methods than what was used for EPA's indicator.

Analysis

8. Comparability Over Time and Space

Techniques for measuring snow accumulation and precipitation are comparable over space and time, as are the analytical methods that were used to develop Figures 1 and 2. Steps have been taken to remove stations where trends could be biased by changes in methods, location, or surrounding land cover.

9. Data Limitations

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

1. While steps have been taken to limit this indicator to weather stations with the most consistent methods and the highest-quality data, several factors make it difficult to measure snowfall precisely. The snow accumulations shown in Figure 1 are based on the use of measuring rods. This measurement method is subject to human error, as well as the effects of wind (drifting snow) and the surrounding environment (such as tall trees). Similarly, precipitation gauges for Figure 2 may catch less snow than rain because of the effects of wind. This indicator has not been corrected for gauge catch efficiency; however, a sensitivity analysis described by Knowles at el. (2006) found that undercatch should have relatively little effect on overall trends in S:P ratios over time. It is not possible to account for gauge catch efficiency precisely because station-specific gauge efficiency assessments are generally unavailable (Knowles et al., 2006).

2. Both figures are limited to the winter season. Figure 1 comes from an analysis of October-to-May snowfall, while Figure 2 covers November through March. Although these months account for the vast majority of snowfall in most locations, this indicator might not represent the entire snow season in some areas.

3. Taken by itself, a decrease in S:P ratio does not necessarily mean that a location is receiving less snow than it used to or that snow has changed to rain. For example, a station with increased rainfall in November might show a decline in S:P ratio even with no change in snowfall during the rest of the winter season. This example illustrates the value of examining snowfall trends from multiple perspectives, as this indicator seeks to do.

4. Selecting only those stations with high-quality long-term data leads to an uneven density of stations for this indicator. Low station density limits the conclusions that can be drawn about certain regions such as the Northeast and the Intermountain West.

5. Most of the data shown for mountainous regions come from lower elevations (towns in valleys) because that is where permanent COOP weather stations tend to be located. Thus, the results are not necessarily representative of higher elevations, which might not have the same sensitivity to temperature change as lower elevations. Another monitoring network, called SNOTEL, measures snow depth at higher-elevation sites. SNOTEL data are an important part of EPA's Snowpack indicator. SNOTEL sites are limited to mountainous areas of the West, however—none in the East—and they do not measure daily rainfall, which is necessary for the analysis in Figure 2. Thus, EPA has not included SNOTEL data in this indicator.

10. Sources of Uncertainty

Quantitative estimates of uncertainty are not available for Figure 1, Figure 2, or most of the underlying measurements.

Figure 1. Change in Total Snowfall in the Contiguous 48 States, 1930–2007

Snow accumulation measurements are subject to human error. Despite the vetting of observation stations, some error could also result from the effects of wind and surrounding cover, such as tall trees. Some records have evidence of reporting errors related to missing data (i.e., days with no snow being reported as missing data instead of "0 inches"), but Kunkel et al. (2009) took steps to correct this error in cases where other evidence (such as daily temperatures) made it clear that an error was present.

Figure 2. Change in Snow-to-Precipitation Ratio in the Contiguous 48 States, 1949–2020

The source study classifies all precipitation as "snow" for any day that received some amount of snow. This approach has the effect of overestimating the amount of snow during mixed snow-sleet-rain conditions. Conversely, wind effects that might prevent snow from settling in gauges will tend to bias the S:P ratio toward rainier conditions. Section 9, however, explains that gauge catch efficiency should not substantially affect the conclusions that can be drawn from this indicator.

11. Sources of Variability

Snowfall naturally varies from year to year as a result of typical variation in weather patterns, multi-year climate cycles such as the El Niño–Southern Oscillation and Pacific Decadal Oscillation (PDO), and other factors. The PDO switches between "warm" and "cool" phases approximately every 20 to 30 years (see: http://research.jisao.washington.edu/pdo and publications cited therein), so the 70+-year record shown in this indicator may be affected by a few PDO phase transitions. Overall, though, the length of data available for this indicator should support a reliable analysis of long-term trends.

Snowfall is influenced by temperature and a host of other factors such as regional weather patterns, local elevation and topography, and proximity to large water bodies. These differences can lead to great variability in trends among stations—even stations that may be geographically close to one another.

12. Statistical/Trend Analysis

Figure 1. Change in Total Snowfall in the Contiguous 48 States, 1930–2007

This indicator reports a trend for each station based on ordinary least-squares linear regression. The significance of each station's trend was not reported in Kunkel et al. (2009).

Figure 2. Change in Snow-to-Precipitation Ratio in the Contiguous 48 States, 1949–2020

Feng and Hu (2007) calculated a long-term trend in S:P ratio at each station using the Kendall's tau method. EPA used the same method for the most recent data update. EPA also determined a z-score for every station. Based on these z-scores, Figure 2 identifies which station trends are statistically significant based on a 95-percent confidence threshold (i.e., a z-score with an absolute value greater than 1.645). A total of 67 sites (37.9 percent) had statistically significant changes in S:P ratio according to this measure.

References

Baxter, M. A., Graves, C. E., & Moore, J. T. (2005). A climatology of snow-to-liquid ratio for the contiguous United States. *Weather Forecast*, *20*, 729–744. https://doi.org/10.1175/WAF856.1

Feng, S., & Hu, Q. (2007). Changes in winter snowfall/precipitation ratio in the contiguous United States. *Journal of Geophysical Research: Atmospheres*, *112*(D15), D15109. https://doi.org/10.1029/2007JD008397

Gilbert, R. O. (1987). *Statistical methods for environmental pollution monitoring*. Van Nostrand Reinhold. www.osti.gov/servlets/purl/7037501

Huntington, T. G., Hodgkins, G. A., Keim, B. D., & Dudley, R. W. (2004). Changes in the proportion of precipitation occurring as snow in New England (1949–2000). *Journal of Climate*, *17*(13), 2626–2636. https://doi.org/10.1175/1520-0442(2004)017<2626:CITPOP>2.0.CO;2

Knowles, N., Dettinger, M. D., & Cayan, D. R. (2006). Trends in snowfall versus rainfall in the western United States. *Journal of Climate*, *19*(18), 4545–4559. https://doi.org/10.1175/JCLI3850.1

Kunkel, K. E., Easterling, D. R., Hubbard, K., Redmond, K., Andsager, K., Kruk, M. C., & Spinar, M. L. (2005). Quality control of pre-1948 Cooperative Observer Network data. *Journal of Atmospheric and Oceanic Technology*, *22*(11), 1691–1705. https://doi.org/10.1175/JTECH1816.1

Kunkel, K. E., Palecki, M. A., Hubbard, K. G., Robinson, D. A., Redmond, K. T., & Easterling, D. R. (2007). Trend identification in twentieth-century U.S. snowfall: The challenges. *Journal of Atmospheric and Oceanic Technology*, *24*(1), 64–73. https://doi.org/10.1175/JTECH2017.1

Kunkel, K. E., Palecki, M., Ensor, L., Hubbard, K. G., Robinson, D., Redmond, K., & Easterling, D. (2009). Trends in twentieth-century U.S. snowfall using a quality-controlled dataset. *Journal of Atmospheric and Oceanic Technology*, *26*(1), 33–44. https://doi.org/10.1175/2008JTECHA1138.1

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, *63*(324), 1379–1389. https://doi.org/10.2307/2285891