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. 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 2011: Indicator developed
May 2012: Updated Figure 2 with data through 2011

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 a 2012 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 Climatic Data Center (NCDC).

4. Data Availability

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

EPA acquired Figure 1 data directly from Dr. Kenneth Kunkel of NOAA's Cooperative Institute for Climate and Satellites (CICS). 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.ncdc.noaa.gov/doclib/. State-specific data can be found at: www7.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.nws.noaa.gov/om/coop/.

Figure 2. Change in Snow-to-Precipitation Ratio in the Contiguous 48 States, 1949–2005

EPA acquired data for this indicator from Dr. Song Feng of the University of Nebraska, Lincoln, based on results published in Feng and Hu (2007) and updated in 2012. Underlying data come from the U.S. Historical Climatology Network (USHCN), a compilation of weather station data maintained by NOAA. The USHCN allows users to download daily or monthly data at: www.ncdc.noaa.gov/oa/climate/research/ushcn/. This website also provides data descriptions and other metadata. The data were taken from USHCN Version 2.

Methodology

5. Data Collection

Systematic collection of weather data in the United States began in the 1800s. Since then, observations have been recorded from 23,000 different stations. At any given time, observations are recorded from 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.nws.noaa.gov/os/coop/what-is-coop.html. Sampling procedures are described in the full metadata for the COOP data set available at: www.nws.noaa.gov/om/coop/.

NCDC also maintains the USHCN, which contains data from a subset of COOP and first-order weather stations that meet certain selection criteria and undergo additional levels of quality control. USHCN contains precipitation data from approximately 1,200 stations within the contiguous 48 states. The period of record varies for each station but generally includes most of the 20th century. One of the objectives in establishing the USHCN was to detect secular changes of regional rather than local climate. Therefore, stations included in this network are only those believed to not be influenced to any substantial degree by artificial changes of local environments. To be included in the USHCN, a station had to meet certain criteria for record longevity, data availability (percentage of available values), spatial coverage, and consistency of location (i.e., experiencing few station changes). An additional criterion, which sometimes compromised the preceding criteria, was the desire to have a uniform distribution of stations across the United States. Included with the data set are metadata files that contain information about station moves, instrumentation, observing times, and elevation. NOAA's website (www.ncdc.noaa.gov/oa/climate/research/ushcn) provides more information about USHCN 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 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, 1949–2011

The analysis in Figure 2 is based primarily on snowfall and precipitation measurements collected with standard gauges that "catch" precipitation, thus allowing weather stations to report daily precipitation totals. This study uses data from 289 USHCN 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 "1949" represent the season that extended from November 1948 through March 1949.

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.

Figure 2. Change in Snow-to-Precipitation Ratio in the Contiguous 48 States, 1949–2011

Using precipitation records from the USHCN Version 2, the liquid-water equivalent of daily snowfall was calculated according to methods described by Huntington et al. (2004) and Knowles et al. (2006). For each station, a snow-to-precipitation (S:P) ratio was calculated 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, at: www.nws.noaa.gov/os/coop/training.htm. These training materials also discuss quality control of the underlying data set. Additionally, pre-1948 data in the COOP data set have recently 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 USHCN Version 1 are summarized at: www.ncdc.noaa.gov/oa/climate/research/ushcn/ushcn.html#QUAL. Homogeneity testing and data correction methods are described in numerous peer-reviewed scientific papers by NCDC. Quality control procedures for USHCN Version 2 are summarized at: www.ncdc.noaa.gov/oa/climate/research/ushcn/#processing.

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, 1949–2011

Feng and Hu (2007) 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).

The 2012 update to Feng and Hu (2007) added another screening criterion that excluded sites that frequently used a particular estimation method to calculate snow water equivalent. This resulted in 85 fewer stations in the 2012 data set. 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 ratio is related to the air temperature during the snow event, and it also varies spatially. 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. To reduce the impact of this practice on cold season precipitation, the 2012 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.

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. 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 error 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, 1949–2011

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.

10. 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, and other factors. However, both components of this indicator cover more than 50 years of data, thus allowing for 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.

11. 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 has not been reported.

Figure 2. Change in Snow-to-Precipitation Ratio in the Contiguous 48 States, 1949–2011

Feng and Hu (2007) calculated a long-term trend in S:P ratio at each station using the Kendall’s tau method. The same method was used for the 2012 update. The authors 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).

12. Data Limitations

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

1. 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, snow gauges for Figure 2 may catch slightly less snow than rain because of

the effects of wind. However, steps have been taken to limit this indicator to weather stations with the most consistent methods and the highest-quality data.

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.

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