Snowpack

Identification

1. Indicator Description

This indicator describes changes in springtime mountain snowpack in the western United States between 1955 and 2015. 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 can reflect a changing climate, as temperature and precipitation are key factors that influence the extent and depth 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. Higher temperatures in the spring can cause snow to melt earlier.

2. Revision History

April 2010:	Indicator posted.
April 2014:	Updated indicator with data through 2013.
June 2015:	Updated indicator on EPA's website with data through 2015.

Data Sources

3. Data Sources

This indicator is based largely on data collected by the U.S. Department of Agriculture's (USDA's) Natural Resources Conservation Service (NRCS). Additional snowpack data come from observations made by the California Department of Water Resources.

4. Data Availability

EPA obtained the data for this indicator from Dr. Philip Mote at Oregon State University. Dr. Mote had published an earlier version of this analysis (Mote et al., 2005) with data from about 1930 to 2000 and a map of trends from 1950 through 1997, and he and colleague Darrin Sharp were able to provide EPA with an updated analysis of trends from 1955 through 2015.

This analysis is based on snowpack measurements from NRCS and the California Department of Water Resources. Both sets of data are available to the public with no confidentiality or accessibility restrictions. NRCS data are available at: www.wcc.nrcs.usda.gov/snow/index.html. California data are available at: http://cdec.water.ca.gov/snow/current/snow/index.html. These websites also provide descriptions of the data.

Methodology

5. Data Collection

This indicator uses snow water equivalent (SWE) measurements to assess trends in snowpack from 1955 through 2015. 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. 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.

Snowpack data have been collected over the years using a combination of manual and automated techniques. All of these 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. 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, snowshoes, snowmobile, or by 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 650 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. However, hundreds of other manual snow course sites are still in use, 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.

Additional snowpack data come from observations made by the California Department of Water Resources.

For information about each of the data sources and its corresponding sample design, visit the following websites:

- NRCS: www.wcc.nrcs.usda.gov/snow/index.html.
- California Department of Water Resources: http://cdec.water.ca.gov/snow/info/DataCollecting.html.

The NRCS website describes both manual and telemetric snowpack measurement techniques in more detail at: www.wcc.nrcs.usda.gov/factpub/sect_4b.html. 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.wcc.nrcs.usda.gov/factpub/ah169/ah169.htm.

For consistency, this indicator examines trends at the same date 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, but 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, and the California Department of Water Resources also estimates the additional SWE that would have accumulated between the collection date and April 1. For evaluating long-term trends, there is little difference between the data measured on the date given and the estimates adjusted to April 1.

This indicator focuses on the western United States (excluding Alaska) because this broad region has the greatest density of stations with long-term records. A total of 1,769 locations have recorded SWE measurements within the area of interest. This indicator is based on 712 stations with sufficient April 1 records spanning the period from 1955 through 2015.

The selection criteria for station inclusion in this analysis were as follows:

- The station must have data back to at least 1955.
- For the 10 years 2006–2015, the station must have at least five data points.
- Over the period 1955–2015, the station must have more April 1 SWE values greater than 0 than equal to 0.
- For the 61 years 1955–2015, the station must have data for 80% of the years (i.e., 49 data points).

6. Indicator Derivation

Linear trends in April 1 SWE measurements were calculated from 1955 through 2015. For this indicator, 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. Trends were calculated for 1955 through 2015 at each snow course or SNOTEL location, and then these trends were converted to percent change since 1995. 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 2015, 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 obtained a data file with coordinates and percent change for each station, and 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.

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 on the NRCS website at: www.wcc.nrcs.usda.gov/factpub/sect_4b.html.

QA/QC procedures for manual measurements by NRCS and by the California Department of Water Resources are largely unavailable online.

Additional QA/QC activities were conducted on the data obtained from NRCS and the California Department of Water Resources. 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.

Analysis

8. Comparability Over Time and Space

For consistency, this indicator 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, but, 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. However, in the vast majority of cases, 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. However, agencies such as NRCS 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.

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 this analysis 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. 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.

10. Sources of Uncertainty

Uncertainty estimates are not readily available for this indicator or for the underlying snowpack measurements. However, the regionally consistent and in many cases sizable changes shown in Figure 1, along with independent hydrologic modeling studies (Mote et al., 2005; Ashfaq et al., 2013), strongly suggest that this indicator shows real secular trends, not simply the artifacts of some type of measurement error.

11. Sources of Variability

Snowpack trends may be influenced by natural year-to-year variations in snowfall, temperature, and other climate variables. To reduce the influence of year-to-year variability, this indicator looks at longer-term trends over the full 61-year time series.

Over a longer time frame, 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 shows the results of a least-squares linear regression of annual observations at each individual site from 1955 through 2015. 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 712 stations in this analysis, 237 had trends that were significant to a 95 percent level ($p < 0.05$) according to the Mann-Kendall test, with 20 of those sites showing autocorrelation (Durbin-Watson < 0.1). A block bootstrap (using both three- and five-year blocks) was applied to those 20 sites that had both significant autocorrelation and significant trends. In all but one case, the Mann-Kendall test indicated a significant trend ($p < 0.05$) even after applying the block bootstrap. Of the 236 sites that were still determined to have a significant trend, in all cases the trend was decreasing.

References

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