Snow Cover

Identification

1. Indicator Description

This indicator measures changes in the amount of land in North America covered by snow. The amount of land covered by snow at any given time is influenced by climate factors such as the amount of snowfall an area receives, the timing of that snowfall, and the rate of melting on the ground. Thus, tracking snow cover over time can provide a useful perspective on how the climate may be changing. Snow cover is also climatically meaningful because it exerts an influence on climate through the albedo effect (i.e., the color and reflectivity of the Earth's surface).

Components of this indicator include:

- Average annual snow cover since 1972 (Figure 1).
- Average snow cover by season since 1972 (Figure 2).
- Average length of the U.S. snow cover season since 1972 (Figure 3).

2. Revision History

April 2010:	Indicator published.
January 2012:	Updated indicator with data through 2011. Added Figure 2 to show snow cover by season.
August 2013:	Updated indicator on EPA's website with data through 2012.
May 2014:	Updated indicator with data through 2013.
June 2015:	Updated indicator on EPA's website with data through 2014.
August 2016:	Updated indicator with data through 2015. Added Figure 3 to show U.S. snow cover season length.

Data Sources

3. Data Sources

Figures 1 and 2 are based on a Rutgers University Global Snow Lab (GSL) reanalysis of digitized maps produced by the National Oceanic and Atmospheric Administration (NOAA) using their Interactive Multisensor Snow and Ice Mapping System (IMS). Data in Figure 3 come from an analysis of the underlying NOAA maps.

4. Data Availability

Complete weekly and monthly snow cover extent data for North America (excluding Greenland) are publicly available for users to download from the GSL website at: http://climate.rutgers.edu/snowcover/table_area.php?ui_set=2. A complete description of these data can be found on the GSL website at: http://climate.rutgers.edu/snowcover. The underlying NOAA gridded maps are also publicly available. To obtain these maps, visit the NOAA IMS website at: www.natice.noaa.gov/ims.

The analysis in Figure 3 is based on a specific set of NetCDF-format maps that are hosted by NOAA and linked from the GSL website. The link goes to: ftp://eclipse.ncdc.noaa.gov/pub/cdr/snowcover, which contains files that are updated regularly.

Methodology

5. Data Collection

This indicator is based on data from instruments on polar-orbiting satellites, which orbit the Earth continuously and are able to map the entire surface of the Earth. These instruments collect images that can be used to generate weekly maps of snow cover. Data are collected for the entire Northern Hemisphere. Figures 1 and 2 of this indicator includes data for all of North America, excluding Greenland. Figure 3 covers the contiguous 48 states plus Alaska.

Data were compiled as part of NOAA's IMS, which incorporates imagery from a variety of satellite instruments (e.g., Advanced Very High Resolution Radiometer [AVHRR], Geostationary Satellite Server [GOES], Special Sensor Microwave Imager [SSMI]) as well as derived mapped products and surface observations. Characteristic textured surface features and brightness allow for snow to be identified and data to be collected on the percentage of snow cover and surface albedo (reflectivity) (Robinson et al., 1993).

NOAA's IMS website (www.natice.noaa.gov/ims) lists peer-reviewed studies and websites that discuss the data collection methods, including the specific satellites that have provided data at various times. For example, NOAA sampling procedures are described in Ramsay (1998). For more information about NOAA's satellites, visit: www.nesdis.noaa.gov/about_satellites.html.

6. Indicator Derivation

NOAA digitizes satellite maps weekly using the National Meteorological Center Limited-Area Fine Mesh grid. In the digitization process, an 89-by-89-cell grid is placed over the Northern Hemisphere and each cell has a resolution range of 16,000 to 42,000 square kilometers. NOAA then analyzes snow cover within each of these grid cells.

Rutgers University's GSL reanalyzes the digitized maps produced by NOAA to correct for biases in the data set caused by locations of land masses and bodies of water that NOAA's land mask does not completely resolve. Initial reanalysis produces a new set of gridded data points based on the original NOAA data points. Both original NOAA data and reanalyzed data are filtered using a more detailed land mask produced by GSL. These filtered data are then used to make weekly estimates of snow cover. GSL determines the weekly extent of snow cover by placing an 89-by-89-cell grid over the Northern Hemisphere snow cover map and calculating the total area of all grid cells that are at least 50 percent snow-covered. GSL generates monthly areal averages based on an arithmetic mean of all weeks within a given month. Weeks that straddle the end of one month and the start of another are weighted proportionally.

Figures 1 and 2. Snow-Covered Area in North America, 1972–2015

EPA obtained weekly estimates of snow-covered area and averaged them temporally to determine the annual average extent of snow cover in square kilometers. EPA obtained monthly estimates of snow-covered area to determine the seasonal extent of snow cover in square kilometers. For each year, a season's extent was determined by temporally averaging total snow-covered area for the following months:

- Winter: December (of the prior calendar year), January, and February.
- Spring: March, April, and May.
- Summer: June, July, and August.
- Fall: September, October, and November.

EPA converted all of these values to square miles to make the results accessible to a wider audience.

NOAA's IMS website describes the initial creation and digitization of gridded maps; see: www.natice.noaa.gov/ims. The GSL website provides a complete description of how GSL reanalyzed NOAA's gridded maps to determine weekly and monthly snow cover extent. See: http://climate.rutgers.edu/snowcover/docs.php?target=vis and http://climate.rutgers.edu/snowcover/docs.php?target=cdr. Robinson et al. (1993) describe GSL's methods, while Helfrich et al. (2007) document how GSL has accounted for methodological improvements over time. All maps were recently reanalyzed using the most precise methods available, making this the best available data set for assessing snow cover on a continental scale.

Figure 3. Snow Cover Season in the United States, 1972–2013

Figure 3 is based on an analysis of gridded daily map data, with key variables (first date of snow cover, last date of snow cover, and duration) calculated for each individual pixel and then spatially averaged across all pixels for each year. The date of first snow cover for each pixel was determined as the first date after August 1 in which snow was present. The date of last snow cover was determined as the last date before July 31 of the following calendar year in which snow was present. The first and last dates for the entire United States presented in Figure 3 were calculated as an average of all first and last dates for all included pixels within one year. Only pixels with at least one day of snow cover in every year from 1972 to 2013 were included in the analysis. This spatial averaging weighted each pixel equally, regardless of the actual land area represented. The analysis included pixels whose centroid was within the boundaries of the United States. Thus, a pixel centered in Canada but containing a small portion of U.S. land would not be included.

The analysis identified first and last snow cover dates in terms of Julian days (i.e., the number of days since January 1). Figure 3 is based on Julian days, but the corresponding non-leap year calendar dates have been added to the y-axis to provide a more familiar frame of reference. This means that a last snow cover date of March 31 in a leap year will actually be plotted at the same level as April 1 from a non-leap year, for example, and it will appear to be plotted at April 1 with respect to the y-axis. Plotting the data this way facilitates consistent year-to-year comparison.

The snow cover season typically runs from fall of one calendar year to spring of the following calendar year. Figure 3 plots the data on the starting year. For example, the 2010–2011 snow season is plotted at 2010.

7. Quality Assurance and Quality Control

Quality assurance and quality control (QA/QC) measures occur throughout the analytical process, most notably in the reanalysis of NOAA data by GSL. GSL's filtering and correction steps are described online (http://climate.rutgers.edu/snowcover/docs.php?target=vis) and in Robinson et al. (1993). Ramsey (1998) describes the validation plan for NOAA digitized maps and explains how GSL helps to provide objective third-party verification of NOAA data.

Analysis

8. Comparability Over Time and Space

Steps have been taken to exclude less reliable early data from this indicator. Although NOAA satellites began collecting snow cover imagery in 1966, early maps had a lower resolution than later maps (4 kilometers versus 1 kilometer in later maps) and the early years also had many weeks with missing data. Data collection became more consistent with better resolution in 1972, when a new instrument called the Very High Resolution Radiometer (VHRR) came online. Thus, this indicator presents only data from 1972 and later.

Mapping methods have continued to evolve since 1972. Accordingly, GSL has taken steps to reanalyze older maps to ensure consistency with the latest approach. GSL provides more information about these correction steps at: http://climate.rutgers.edu/snowcover/docs.php?target=cdr.

Data have been collected and analyzed using consistent methods over space. The satellites that collect the data cover all of North America in their orbital paths.

9. Data Limitations

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

1. Satellite data collection is limited by anything that obscures the ground, such as low light conditions at night, dense cloud cover, or thick forest canopy. Satellite data are also limited by difficulties discerning snow cover from other similar-looking features such as cloud cover.

2. Although satellite-based snow cover totals are available starting in 1966, some of the early years are missing data from several weeks (mainly during the summer), which would lead to an inaccurate annual or seasonal average. Thus, the indicator is restricted to 1972 and later, with all years having a full set of data.

3. Discontinuous (patchy) snow cover poses a challenge for measurement throughout the year, particularly with spectrally and spatially coarse instruments such as AVHRR (Molotch and Margulis, 2008).

4. Summer snow mapping is particularly complicated because many of the patches of snow that remain (e.g., high in a mountain range) are smaller than the pixel size for the analysis. This leads

to reduced confidence in summer estimates. When summer values are incorporated into an annual average, however, variation in summer values has relatively minimal influence on the overall results.

5. The U.S. snow season in Figure 3 is based on spatial averaging of the first and last dates of snow cover for the set of pixels that had at least one non-zero snowfall measurement in every year during the period of study. Any pixel that did not receive snow during any one year was excluded from the dataset, even if it received snow in every other year. This constraint was needed because a reliable average of dates requires a non-zero date for every year. It does limit the geographic scope of the analysis, though.

10. Sources of Uncertainty

Uncertainty measurements are not readily available for this indicator or for the underlying data. Although exact uncertainty estimates are not available, extensive QA/QC and third-party verification measures show that steps have been taken to minimize uncertainty and ensure that users are able to draw accurate conclusions from the data. Documentation available from GSL (http://climate.rutgers.edu/snowcover/docs.php?target=vis) explains that since 1972, satellite mapping technology has had sufficient accuracy to support continental-scale climate studies. Although satellite data have some limitations (see Section 9), maps based on satellite imagery are often still superior to maps based on ground observations, which can be biased due to sparse station coverage—both geographically and in terms of elevation (e.g., a station in a valley will not necessarily have snow cover when nearby mountains do)—and by the effects of urban heat islands in locations such as airports. Hence, satellite-based maps are generally more representative of regional snow extent, particularly for mountainous or sparsely populated regions.

11. Sources of Variability

Figures 1, 2, and 3 show substantial year-to-year variability in snow cover. This variability naturally results from variation in weather patterns, multi-year climate cycles such as the El Niño–Southern Oscillation and Pacific Decadal Oscillation, and other factors. Underlying weekly measurements have even more variability. This indicator accounts for these factors by presenting a long-term record (several decades) and calculating annual and seasonal averages.

Generally, decreases in snow cover duration have been most pronounced along mid-latitude continental margins where seasonal mean air temperatures range from -5 to +5°C (Brown and Mote, 2009).

12. Statistical/Trend Analysis

EPA performed an initial assessment of trends in square miles (mi^2) per year using ordinary least-squares linear regression, which led to the following results:

- Annual average, 1972–2015: -3,327 mi^2/year ($p = 0.035$)
- Winter, 1972–2015: +3,756 mi^2/year ($p = 0.18$)
- Spring, 1972–2015: -6,698 mi^2/year ($p = 0.022$)
- Summer, 1972–2015: -14,579 mi^2/year ($p < 0.001$)
- Fall, 1972–2015: +4,228 mi^2/year ($p = 0.088$)

Thus, long-term linear trends in spring, summer, and annual average snow cover are significant to a 95-percent level ($p < 0.05$), while winter and fall trends are not. To conduct a more complete analysis would potentially require consideration of serial correlation and other more complex statistical factors.

EPA performed an initial assessment of trends of snow cover season for Figure 3 and the "Key Points" section of the indicator. This analysis used ordinary least-squares linear regression slopes for the full period of record (1972–2013). Trends in last snow cover date and season length are significant to a 95-percent level ($p < 0.05$), while the trend in first snow cover date is not. Specific trends are as follows:

- First snow cover: - 0.115 days/year (earlier) ($p = 0.24$)
- Last snow cover: - 0.452 days/year (earlier) ($p < 0.001$)
- Length of snow cover season: -0.336 days/year (shorter) ($p = 0.023$)

References

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