Arctic Sea Ice

Identification

1. Indicator Description

This indicator tracks the extent and age of sea ice in the Arctic Ocean. The extent of area covered by Arctic sea ice is considered a particularly sensitive indicator of global climate because a warmer climate will reduce the amount of sea ice present. The proportion of sea ice in each age category can indicate the relative stability of Arctic conditions as well as susceptibility to melting events.
Components of this indicator include:

- Changes in the March and September average extent of sea ice in the Arctic Ocean since 1979 (Figure 1).
- Changes in the proportion of Arctic sea ice in various age categories at the September weekly minimum since 1983 (Figure 2).

2. Revision History

April 2010:	Indicator of Arctic sea ice extent posted.
December 2011:	Updated with data through 2011; age of ice added.
October 2012:	Updated with data through 2012.
December 2013:	Updated with data through 2013.
June 2015:	Updated indicator on EPA's website with data through 2014; added annual March sea ice extent to Figure 1 with data through 2015.
December 2015:	Updated with data through September 2015.
April 2016:	Updated with data through March 2016.

Data Sources

3. Data Sources

Figure 1 (extent of sea ice) is based on monthly average sea ice extent data provided by the National Snow and Ice Data Center (NSIDC). NSIDC's data are derived from satellite imagery collected and processed by the National Aeronautics and Space Administration (NASA). NSIDC also provided Figure 2 data (age distribution of sea ice), which are derived from weekly NASA satellite imagery and processed by the team of Maslanik and Tschudi at the University of Colorado, Boulder.

4. Data Availability

Figure 1. March and September Monthly Average Arctic Sea Ice Extent, 1979–2016

Users can access monthly map images, geographic information system (GIS)-compatible map files, and gridded daily and monthly satellite data, along with corresponding metadata, at: http://nsidc.org/data/seaice_index/archives.html. From this page, users can also download monthly extent and area data. From this page, select "FTP Directory" under the "Monthly Extent and Concentration Images" heading, which will lead to a public FTP site (ftp://sidads.colorado.edu/DATASETS/NOAA/G02135). To obtain the March or September monthly data that were used in this indicator, select the "Mar" or "Sep" directory, then choose the "…area.txt" file with the data. To see a different version of the graph in Figure 1 (plotting percent anomalies rather than square miles), return to the parent directory and open the "…plot.png" image.

NSIDC's Sea Ice Index documentation page (http://nsidc.org/data/docs/noaa/g02135_seaice_index) describes how to download, read, and interpret the data. It also defines database fields and key terminology. Gridded source data can be found at: http://nsidc.org/data/nsidc-0051.html and: http://nsidc.org/data/nsidc-0081.html.

Figure 2. Age of Arctic Sea Ice at Minimum September Week, 1983–2015

NSIDC published a map version of Figure 2 at: http://nsidc.org/arcticseaicenews/2015/10/2015-melt-season-in-review. EPA obtained the data shown in the figure by contacting NSIDC User Services. The data are processed by Dr. James Maslanik and Dr. Mark Tschudi at the University of Colorado, Boulder, and provided to NSIDC. Earlier versions of this analysis appeared in Maslanik et al. (2011) and Maslanik et al. (2007).

Satellite data used in historical and ongoing monitoring of sea ice age can be found at the following websites:

- Defense Meteorological Satellite Program (DMSP) Scanning Multi Channel Microwave Radiometer (SMMR): http://nsidc.org/data/nsidc-0071.html.
- DMSP Special Sensor Microwave/Imager (SSM/I): http://nsidc.org/data/nsidc-0001.html.
- DMSP Special Sensor Microwave Imager and Sounder (SSMIS): http://nsidc.org/data/nsidc-0001.html.
- NASA Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E): http://nsidc.org/data/amsre.
- Advanced Very High Resolution Radiometer (AVHRR): http://nsidc.org/data/avhrr/data_summaries.html.

Age calculations also depend on wind measurements and on buoy-based measurements and motion vectors. Wind measurements (as surface flux data) are available at: www.esrl.noaa.gov/psd/data/reanalysis/reanalysis.shtml. Data and metadata are available online at: http://iabp.apl.washington.edu/data.html and: http://nsidc.org/data/nsidc-0116.html.

Methodology

5. Data Collection

This indicator is based on maps of sea ice extent in the Arctic Ocean and surrounding waters, which were developed using brightness temperature imagery collected by satellites. Data from October 1978 through June 1987 were collected using the Nimbus-7 SMMR instrument, and data since July 1987 have been collected using a series of successor SSM/I instruments. In 2008, the SSMIS replaced the SSM/I as the source for sea ice products. These instruments can identify the presence of sea ice because sea ice and open water have different passive microwave signatures. The record has been supplemented with data from AMSR-E, which operated from 2003 to 2011.

The satellites that supply data for this indicator orbit the Earth continuously, collecting images that can be used to generate daily maps of sea ice extent. They are able to map the Earth's surface with a resolution of 25 kilometers. The resultant maps have a nominal pixel area of 625 square kilometers. Because of the curved map projection, however, actual pixel sizes range from 382 to 664 square kilometers.

The satellites that collect the data cover most of the Arctic region in their orbital paths. However, the sensors cannot collect data from a circular area immediately surrounding the North Pole due to orbit inclination. From 1978 through June 1987, this "pole hole" measured 1.19 million square kilometers. From July 1987 through December 2007 it measured 0.31 million square kilometers. Since January 2008 it has measured 0.029 million square kilometers. For more information about this spatial gap and how it is corrected in the final data, see Section 6.

To calculate the age of ice (Figure 2), the SSM/I, SMMR, and AMSR-E imagery have been supplemented with three additional data sets:

- AVHRR satellite data, which come from an optical sensing instrument that can measure sea ice temperature and heat flux, which in turn can be used to estimate thickness. AVHRR also covers the "pole hole."

- Maps of wind speed and direction at 10 meters above the Earth's surface, which were compiled by the National Oceanic and Atmospheric Administration's (NOAA's) National Centers for Environmental Prediction (NCEP).

- Motion vectors that trace how parcels of sea ice move, based on data collected by the International Arctic Buoy Programme (IABP). Since 1955, the IABP has deployed a network of 14 to 30 *in situ* buoys in the Arctic Ocean that provide information about movement rates at six-hour intervals.

For documentation of passive microwave satellite data collection methods, see the summary and citations at: http://nsidc.org/data/docs/noaa/g02135_seaice_index. For further information on AVHRR imagery, see: http://noaasis.noaa.gov/NOAASIS/ml/avhrr.html. For motion tracking methods, see Maslanik et al. (2011), Fowler et al. (2004), and: http://nsidc.org/data/nsidc-0116.html.

6. Indicator Derivation

Figure 1. March and September Monthly Average Arctic Sea Ice Extent, 1979–2016

Satellite data are used to develop daily ice extent and concentration maps using an algorithm developed by NASA. Data are evaluated within grid cells on the map. Image processing includes quality control features such as two weather filters based on brightness temperature ratios to screen out false positives over open water, an ocean mask to eliminate any remaining sea ice in regions where sea ice is not expected, and a coastal filter to eliminate most false positives associated with mixed land/ocean grid cells.

From each daily map, analysts calculate the total "extent" and "area" covered by ice. These terms are defined differently as a result of how they address those portions of the ocean that are partially but not completely frozen:

- **Extent** is the total area covered by all pixels on the map that have at least 15 percent ice concentration, which means at least 15 percent of the ocean surface within that pixel is frozen over. The 15 percent concentration cutoff for extent is based on validation studies that showed that a 15 percent threshold provided the best approximation of the "true" ice edge and the lowest bias. In practice, most of the area covered by sea ice in the Arctic far exceeds the 15 percent threshold, so using a higher cutoff (e.g., 20 or 30 percent) would yield different totals but similar overall trends (for example, see Parkinson et al., 1999).

- **Area** represents the actual surface area covered by ice. If a pixel's area were 600 square kilometers and its ice concentration were 75 percent, then the ice area for that pixel would be 450 square kilometers. At any point in time, total ice area will always be less than total ice extent.

EPA's indicator addresses extent rather than area. Both of these measurements are valid ways to look at trends in sea ice, but in this case, EPA chose to look at the time series for extent because it is more complete than the time series for area. In addition, the available area data set does not include the "pole hole" (the area directly above the North Pole that the satellites cannot cover), and the size of this unmapped region changed as a result of the instrumentation changes in 1987 and 2008, creating a discontinuity in the area data. In contrast, the extent time series assumes that the entire "pole hole" area is covered with at least 15 percent ice, which is a reasonable assumption based on other observations of this area. See https://nsidc.org/data/docs/noaa/g02135_seaice_index/#pole_hole for more information about the "pole hole" and how NASA's data address it.

NASA's processing algorithm includes steps to deal with occasional days with data gaps due to satellite or sensor outages. These days were removed from the time series and replaced with interpolated values based on the total extent of ice on the surrounding days.

From daily maps and extent totals, NSIDC calculated monthly average extent in square kilometers. EPA converted these values to square miles to make the results accessible to a wider audience. By relying on monthly averages, this indicator smoothes out some of the variability inherent in daily measurements.

Figure 1 shows trends in March and September average sea ice extent. September is when Arctic sea ice typically reaches its annual minimum, after melting during the summer months. By looking at the month with the smallest extent of sea ice, this indicator focuses attention on the time of year when limiting conditions would most affect wildlife and human societies in the Arctic region. Six months later, March is when Arctic sea ice typically reaches its annual maximum, after cold winter months freeze new ice. Presenting the month with the greatest extent of sea ice highlights the extent to which the Arctic region recovers melted sea ice.

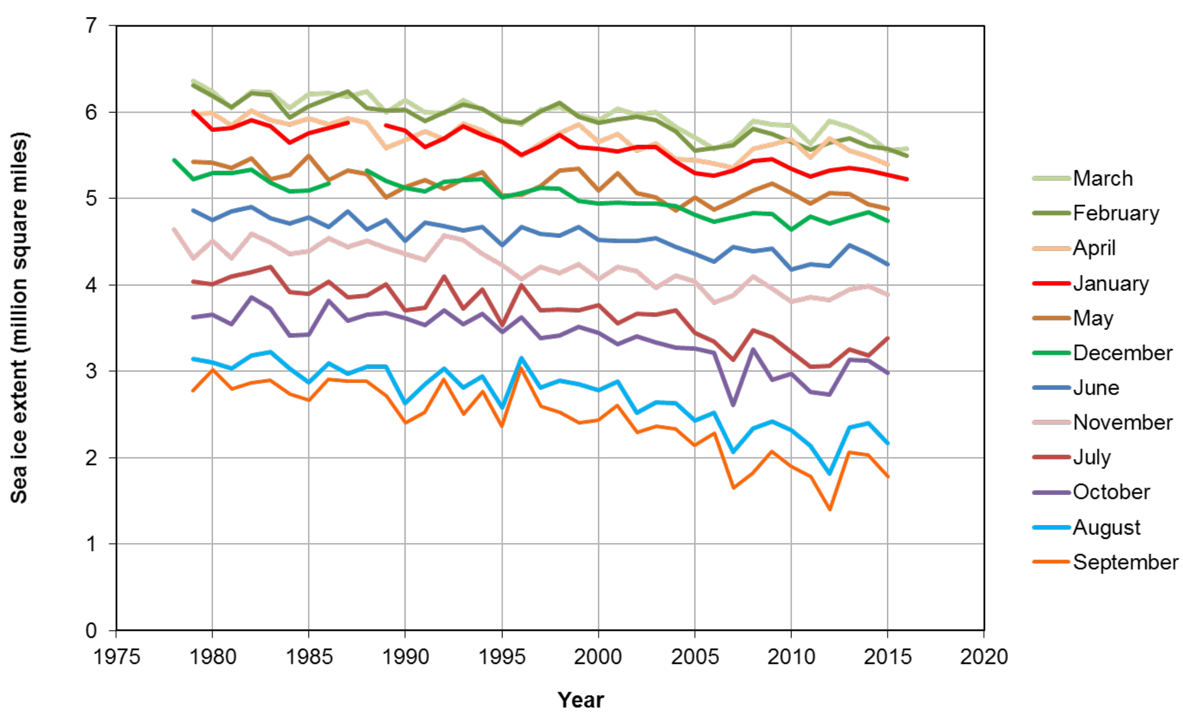
This indicator does not attempt to estimate values from before the onset of regular satellite mapping in October 1978 (which makes 1979 the first year with March and September data for this indicator). It also does not attempt to project data into the future.

For documentation of the NASA Team algorithm used to process the data, see Cavalieri et al. (1984) and: http://nsidc.org/data/nsidc-0051.html. For more details about NSIDC methods, see the Sea Ice Index documentation and related citations at: http://nsidc.org/data/docs/noaa/g02135_seaice_index.

Other months of the year were considered for this indicator, but EPA chose to focus on March and September, which represent the annual maximum and minimum extent of sea ice. September extent is often used as an indicator. One reason is because as temperatures start to get colder, there may be less meltwater on the surface than during the previous summer months, thus leading to more reliable remote sensing of ice extent. Increased melting during summer months leads to changes in the overall character of the ice (i.e., age and thickness) and these changes have implications throughout the year. Thus, September conditions are particularly important for the overall health of Arctic sea ice. Conversely, March is the month when sea ice experiences its peak extent for the year.

Evidence shows that the extent of Arctic sea ice has declined in all months of the year. Comiso (2012) examined the seasonal pattern in Arctic sea ice extent for three decadal periods plus the years 2007, 2009, and 2010 and found declines throughout the year. Figure TD-1 shows monthly means based on an analysis from NSIDC—the source of data for this indicator. It reveals that Arctic sea ice extent has generally declined over time in all months, with the most pronounced decline in the summer and fall.

Figure TD-1. Arctic Sea Ice Extent for each Month, 1978/1979–2015/2016



Data source: NSIDC: http://nsidc.org/data/seaice_index/archives.html. Accessed April 2016.

Figure 2. Age of Arctic Sea Ice at Minimum September Week, 1983–2015

A research team at the University of Colorado at Boulder processes daily sequential SSM/I, SMMR, AMSR-E, and AVHRR satellite data from NASA, then produces maps using a grid with 12 km-by-12 km cells. The AVHRR data help to fill the "pole hole" and provide information about the temperature and thickness of the ice. Like Figure 1, this method classifies a pixel as "ice" if at least 15 percent of the ocean surface within the area is frozen over. Using buoy data from the IABP, motion vectors for the entire region are blended via optimal interpolation and mapped on the gridded field. NCEP wind data are also incorporated at this stage, with lower weighting during winter and higher weighting during summer, when surface melt limits the performance of the passive microwave data. Daily ice extent and motion vectors are averaged on a weekly basis. Once sea ice reaches its annual minimum extent (typically in early September), the ice is documented as having aged by one year. For further information on data processing methods, see Maslanik et al. (2011), Maslanik et al. (2007), and Fowler et al. (2004). Although the most recently published representative study does not utilize AMSR-E brightness data or NCEP wind data for the calculation of ice motion, the results presented in Figure 2 and the NSIDC website incorporate these additional sources.

Figure 2 shows the extent of ice that falls into several age categories. Whereas Figure 1 extends back to 1979, Figure 2 can show trends only back to 1983 because it is not possible to know how much ice is five or more years old (the oldest age class shown) until parcels of ice have been tracked for at least five years. Regular satellite data collection did not begin until October 1978, which makes 1983 the first year in which September minimum ice can be assigned to the full set of age classes shown in Figure 2.

Like Figure 1, Figure 2 is based on the most recent data available. The December 2015 data update involved a slight adjustment that NSIDC applied to previous data points to better account for the "pole hole."

7. Quality Assurance and Quality Control

Image processing includes a variety of quality assurance and quality control (QA/QC) procedures, including steps to screen out false positives. These procedures are described in NSIDC's online documentation at: http://nsidc.org/data/docs/noaa/g02135_seaice_index as well as in some of the references cited therein.

NSIDC Arctic sea ice data have three levels of processing for quality control. NSIDC's most recent data come from the Near Real-Time SSM/I Polar Gridded Sea Ice Concentrations (NRTSI) data set. NRTSI data go through a first level of calibration and quality control to produce a preliminary data product. The final data are processed by NASA's Goddard Space Flight Center (GSFC), which uses a similar process but applies a higher level of QC. Switching from NRTSI to GSFC data can result in slight changes in the total extent values—on the order of 50,000 square kilometers or less for total sea ice extent.

GSFC processing requires several months' lag time. At the time EPA published this report, the GSFC data for 2015 had not yet been finalized.

Analysis

8. Comparability Over Time and Space

Both figures for this indicator are based on data collection methods and processing algorithms that have been applied consistently over time and space. NASA's satellites cover the entire area of interest with the exception of a "hole" at the North Pole for Figure 1. Even though the size of this hole has changed over time, EPA's indicator uses a data set that corrects for this discontinuity.

The total extent shown in Figure 2 (the sum of all the stacked areas) differs from the total extent shown for September in Figure 1 because Figure 2 shows conditions during the specific week in September when minimum extent is reached, while the series in Figure 1 shows average conditions over the entire month of September. It would not make sense to convert Figure 2 to a monthly average for September because all ice is "aged" one year as soon as the minimum has been achieved, which creates a discontinuity after the minimum week.

9. Data Limitations

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

1. Variations in sea ice are not entirely due to changes in temperature. Other conditions, such as fluctuations in oceanic and atmospheric circulation and typical annual and decadal variability, can also affect the extent of sea ice, and by extension the sea ice age indicator.

2. Changes in the age and thickness of sea ice—for example, a trend toward younger or thinner ice—might increase the rate at which ice melts in the summer, making year-to-year comparisons more complex.

3. Many factors can diminish the accuracy of satellite mapping of sea ice. Although satellite instruments and processing algorithms have improved somewhat over time, applying these new methods to established data sets can lead to trade-offs in terms of reprocessing needs and compatibility of older data. Hence, this indicator does not use the highest-resolution imagery or the newest algorithms. Trends are still accurate, but should be taken as a general representation of trends in sea ice extent, not an exact accounting.

4. As described in Section 6, the threshold used to determine extent—15 percent ice cover within a given pixel—represents an arbitrary cutoff without a particular scientific significance. Nonetheless, studies have found that choosing a different threshold would result in a similar overall trend. Thus, the most important part of Figure 1 is not the absolute extent reported for any given year, but the size and shape of the trend over time.

5. Using ice surface data and motion vectors allows only the determination of a maximum sea ice age. Thus, as presented, the Figure 2 indicator indicates the age distribution of sea ice only on the surface, and is not necessarily representative of the age distribution of the total sea ice volume.

10. Sources of Uncertainty

NSIDC has calculated standard deviations along with each monthly ice concentration average. NSIDC's Sea Ice Index documentation (http://nsidc.org/data/docs/noaa/g02135_seaice_index) describes several analyses that have examined the accuracy and uncertainty of passive microwave imagery and the NASA Team algorithm used to create this indicator. For example, a 1991 analysis estimated that ice concentrations measured by passive microwave imagery are accurate to within 5 to 9 percent, depending on the ice being imaged. Another study suggested that the NASA Team algorithm underestimates ice extent by 4 percent in the winter and more in summer months. A third study that compared the NASA Team algorithm with new higher-resolution data found that the NASA Team algorithm underestimates ice extent by an average of 10 percent. For more details and study citations, see: http://nsidc.org/data/docs/noaa/g02135_seaice_index. Certain types of ice conditions can lead to larger errors, particularly thin or melting ice. For example, a melt pond on an ice floe might be mapped as open water. The instruments also can have difficulty distinguishing the interface between ice and snow or a diffuse boundary between ice and open water. Using the September minimum minimizes many of these effects because melt ponds and the ice surface become largely frozen by then. These errors do not affect trends and relative changes from year to year.

NSIDC has considered using a newer algorithm that would process the data with greater certainty, but doing so would require extensive research and reprocessing, and data from the original instrument (pre-1987) might not be compatible with some of the newer algorithms that have been proposed. Thus, for the time being, this indicator uses the best available science to provide a multi-decadal representation of trends in Arctic sea ice extent. The overall trends shown in this indicator have been corroborated by numerous other sources, and readers should feel confident that the indicator provides an accurate overall depiction of trends in Arctic sea ice over time.

Accuracy of ice motion vectors depends on the error in buoy measurements, wind fields, and satellite images. Given that buoy locational readings are taken every six hours, satellite images are 24-hour averages, and a "centimeters per second" value is interpolated based on these readings, accuracy depends on the error of the initial position and subsequent readings. NSIDC proposes that "the error would be less than 1 cm/sec for the average velocity over 24 hours" (http://nsidc.org/data/docs/daac/nsidc0116_icemotion/buoy.html).

11. Sources of Variability

Many factors contribute to variability in this indicator. In constructing the indicator, several choices have been made to minimize the extent to which this variability affects the results. The apparent extent of sea ice can vary widely from day to day, both due to real variability in ice extent (growth, melting, and movement of ice at the edge of the ice pack) and due to ephemeral effects such as weather, clouds and water vapor, melt on the ice surface, and changes in the character of the snow and ice surface. The intensity of Northern Annular Mode (NAM) conditions and changes to the Arctic Oscillation also have a strong year-to-year impact on ice movement. Under certain conditions, older ice might move to warmer areas and be subject to increased melting. Weather patterns can also affect the sweeping of icebergs out of the Arctic entirely. For a more complete description of major thermodynamic processes that impact ice longevity, see Maslanik et al. (2007) and Rigor and Wallace (2004).

According to NSIDC's documentation at: http://nsidc.org/data/docs/noaa/g02135_seaice_index, extent is a more reliable variable than ice concentration or area. The weather and surface effects described above can substantially impact estimates of ice concentration, particularly near the edge of the ice pack. Extent is a more stable variable because it simply registers the presence of at least a certain percentage of sea ice in a grid cell (15 percent). For example, if a particular pixel has an ice concentration of 50 percent, outside factors could cause the satellite to measure the concentration very differently, but as long as the result is still greater than the percent threshold, this pixel will be correctly accounted for in the total "extent." Monthly averages also help to reduce some of the day-to-day "noise" inherent in sea ice measurements.

12. Statistical/Trend Analysis

This indicator does not report on the slope of the apparent trends in sea ice extent and age distribution, nor does it calculate the statistical significance of these trends.

References

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