Arctic Sea Ice

1 Describe the physical, chemical, or biological measurements upon which this indicator is based. Are these measurements widely accepted as scientifically and technically valid? Explain.

This indicator is based on maps of sea ice extent in the Arctic Ocean and surrounding waters. These maps have been developed from daily satellite brightness temperature imagery. Satellites can identify the presence of sea ice because sea ice and water have different passive microwave signatures.

Daily data from October 1978 through June 1987 were collected using the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) instrument. Data since July 1987 have been collected using a successor instrument, the DMSP Special Sensor Microwave/Imager (SSM/I).

2 Describe the sampling design and/or monitoring plan used to collect the data over time and space. Is it based on sound scientific principles? Explain.

This indicator is based on data from satellite instruments. These satellites orbit the Earth continuously, collecting images that can be used to generate daily maps of sea ice extent. This indicator relies on monthly averages, which smooth out some of the variability inherent in daily measurements.

The satellites that supply data for this indicator are able to map the Earth's surface with a resolution of 25 kilometers. The resultant maps have a nominal pixel size of 625 square kilometers. Because of the curved map projection, however, actual pixel sizes range from 382 to 664 square kilometers. The satellites are able to cover the entire Arctic region except for a small area directly around the North Pole. For more information about this spatial gap and how it is corrected in the final data, see the response to Question 8.

3 Describe the conceptual model used to transform these measurements into an indicator. Is this model widely accepted as a scientifically sound representation of the phenomenon it indicates? Explain.

Satellite data are used to develop daily ice extent and concentration maps using an algorithm developed by the National Aeronautics and Space Administration (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 somewhat arbitrary, and using a 20 percent or 30 percent cutoff gives different numbers 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 was 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.

This 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. The available area data set does not include a region directly around the North Pole that the satellites do not cover, and the size of this unmapped region changed as a result of the instrumentation change in 1987, creating a discontinuity in the area data. The extent time series assumes that the entire unmapped region is covered by ice, and hence does not have a discontinuity. For more information about this data gap and the appropriateness of the correction steps, see the response to Question 8.

From daily maps and extent totals, the National Snow and Ice Data Center (NSIDC) calculated monthly average extent in square kilometers. EPA converted these values to square miles to make the results accessible to a wider audience.

Figure 1 shows trends in 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.

4 What documentation clearly and completely describes the underlying sampling and analytical procedures used?

NSIDC provides extensive online documentation of sampling and analytical methods, including citations for a variety of reports and peer-reviewed articles that describe methods in greater detail. See NSIDC's Sea Ice Index documentation at: www.nsidc.org/data/docs/noaa/g02135_seaice_index. For documentation of the NASA Team algorithm used to process the data, see Cavalieri et al. (1984).

5 To what extent is the complete data set accessible, including metadata, data-dictionaries, and embedded definitions? Are there confidentiality issues that may limit accessibility to the complete data set?

Users can download monthly extent and area data from: www.nsidc.org/data/seaice_index/archives/index.html. From this page, select "Get Extent and Concentration Data," which will lead to a public FTP site (ftp://sidads.colorado.edu/DATASETS/NOAA/G02135). To obtain the September monthly data that were used in this indicator, select the "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 "Sep" directory and open the "…plot.png" image.

NSIDC's Sea Ice Index documentation page (www.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.

From www.nsidc.org/data/seaice_index/archives/index.html, users can also access monthly map images, GIS-compatible map files, and gridded daily and monthly satellite data, along with corresponding metadata.

6 Are the descriptions of the study or survey design clear, complete, and sufficient to enable the study or survey to be reproduced? Explain.

NSIDC's Sea Ice Index documentation page (www.nsidc.org/data/docs/noaa/g02135_seaice_index) provides a clear explanation of how daily satellite maps have been used to calculate monthly sea ice extent totals. NSIDC's documentation also explains how users can download and interpret the data. The response to Question 3 above explains the additional steps that EPA followed to create Figure 1.

7 To what extent are the procedures for quality assurance and quality control of the data documented and accessible?

As described in the response to Question 3, 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: www.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 "PRELIM" preliminary data product. The final data are processed by NASA's Goddard Space Flight Center (GSFC), which uses a higher level of QC. Because PRELIM and

GSFC processing requires several months' lag time, the data set available for this indicator at the time of publishing included data at all three levels of quality control.

The NRTSI and PRELIM fields are processed in a similar manner to the GSFC product, but the input brightness temperature data have a lower level of quality control. NRTSI data will later be replaced with PRELIM values and finally replaced with values from GSFC. 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.

This indicator reports GSFC data for the years 1979 to 2007, a PRELIM data point for the year 2008, and a NRTSI data point for 2009. At the time EPA published this report, the final GSFC data for 2008 and 2009 had not yet been finalized.

8 What statistical methods, if any, have been used to generalize or portray data beyond the time or spatial locations where measurements were made (e.g., statistical survey inference, no generalization is possible)? Are these methods scientifically appropriate?

This indicator does not attempt to estimate values prior to the onset of regular satellite mapping in October 1978 (which makes 1979 the first year with September data for this indicator). It also does not attempt to project data into the future. Within the period of record (1979 to 2009), there were occasionally days with data gaps due to satellite or sensor outages. As part of NASA's processing algorithm, these days were removed from the time series and replaced with interpolated values based on the total extent of ice on the surrounding days.

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. Since July 1987 it has measured 0.31 million square kilometers. In calculating extent for this indicator, NASA and NSIDC assumed 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.

9 What uncertainty measurements or estimates are available for the indicator and/or the underlying data set?

NSIDC's Sea Ice Index documentation (www.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: www.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.

NSIDC has calculated standard deviations along with each monthly ice concentration average.

10 To what extent do uncertainty and variability impact the conclusions that can be inferred from the data and the utility of the indicator?

Many factors contribute to uncertainty and variability in this indicator. In constructing the indicator, several choices have been made to minimize the extent to which uncertainty and variability affect the results.

On a daily scale, the apparent extent of sea ice can vary widely, 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. Monthly averages reduce some of this daily "noise" and thereby reduce uncertainty.

According to NSIDC's online documentation at: www.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 15 percent sea ice in a grid cell. 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 15 percent, this pixel will be correctly accounted for in the total "extent."

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.

11 Describe any limitations or gaps in the data that may mislead a user about fundamental trends in the indicator over space or over the time period for which data are available.

Limitations to this indicator include the following:

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.
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 the response to Question 3, 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.

12 References

Cavalieri, D.J., P. Gloersen, and W.J. Campbell. 1984. Determination of sea ice parameters with the NIMBUS-7 SMMR. J. Geophys. Res. 89(D4):5355–5369.

Parkinson, C.L., D.J. Cavalieri, P. Gloersen, H.J. Zwally, and J.C. Comiso. 1999. Arctic sea ice extents, areas, and trends, 1978–1996. J. Geophys. Res. 104(C9):20,837–20,856.