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A long-term Northern Hemisphere snow cover extent data record for climate studies and monitoring

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Abstract

This paper describes the long-term, satellite-based visible snow cover extent NOAA climate data record (CDR) currently available for climate studies, monitoring, and model validation. This environmental data product is developed from weekly Northern Hemisphere snow cover extent data that have been digitized from snow cover maps onto a Cartesian grid draped over a polar stereographic projection. The data has a spatial resolution of 190.5 km at 60° latitude, are updated monthly, and span from 4 October 1966 to present. The data comprise the longest satellite-based CDR of any environmental variable. Access to the data are provided in netCDF format and are archived by the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA) under the satellite climate data record program (doi:10.7289/V5N014G9). The basic characteristics, history, and evolution of the dataset are presented herein. In general, the CDR provides similar spatial and temporal variability as its widely used predecessor product. Key refinements to the new CDR improve the product's grid accuracy and documentation, and bring metadata into compliance with current standards for climate data records.

1 Introduction

The annual and interannual variability of the cryosphere are characterized by changes in hemispheric sea ice (e.g., Cavalieri et al., 1997) and snow cover extent (e.g., Robinson et al., 1993). They are important factors in detecting climate change, validating climate simulations from general circulation models, and improving the understanding of climate–cryosphere interactions. According to IPCC Assessment Report 4 (Anisimov et al., 2007; McBean et al., 2005), the Arctic warms more than subpolar regions when subject to increasing levels of atmospheric greenhouse gases (GHG). This response in the Northern Hemisphere (NH) has become widely known as the polar amplification of climate change (e.g., Manabe and Stouffer, 1980) and affects other aspects of the

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earth–climate system. These effects include threatening ecosystem structure and stability, changes in surface air temperature, declining sea ice and its feedback effects, and negative anomalies in snow cover extent.

To capture changes within the global environment, NOAA's Climate Data Record (CDR) Program was tasked with generating, archiving, and stewarding easily accessible, robust, sustainable, consistent, and scientifically defensible climate data records derived from global satellite monitoring (Robinson et al., 2004). To increase its holdings of cryospheric CDR products, which includes the passive microwave sea ice concentration CDR (Meier et al., 2014; Peng et al., 2013), the NH Snow Cover Extent (SCE) CDR has recently been added to the NOAA CDR suite of products. Per the guidelines of the CDR Program (CDR, 2011a, b), this new CDR product has met all software, product validation, documentation, data archive, and access requirements with a score of three or higher according to NCDC's CDR Maturity Matrix described by Bates and Privette (2012). This paper highlights various aspects of the NH SCE CDR especially as it relates to its historical beginnings, comparison with its predecessor product, dataset description, access, and its seasonal and spatial characteristics.

2 Historical description of data product

The high albedo of surface snow extent in visible-band satellite imagery makes delineation between snow covered and snow-free land relatively simple over many land surfaces (Frei et al., 2011). Trained meteorological analysts incorporate multiple satellite observations (Table 1) and other derived products to create the NH SCE product in a near-consistent manner without a formal algorithm. The earliest part of the NH SCE CDR time series begins in 1966 and is comprised of hand drawn weekly SCE maps based on visual interpretation of photographic copies of shortwave imagery from meteorological satellites with a subpoint resolution of ~ 4 km. These maps were operationally digitized onto an 89 × 89 Cartesian grid laid over a NH polar stereographic

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projection and used as a NOAA environmental data product in National Weather Service numerical models.

After October 1972, SCE data production increasingly relied on satellite imagery from the Very High Resolution Radiometer (VHRR), which had a spatial resolution of 1.0 km. Incorporating this higher resolution data considerably improved snow charting (Kukla and Robinson, 1981). Over time, additional products incorporated into the mapping of SCE included earth observing satellite imagery such as the Advanced Very High Resolution Radiometer (AVHRR) and Visible Infrared Spin-Scan Radiometer (VISSR).

In 1997, the National Ice Center (NIC) introduced the Interactive Multisensor Snow and Ice Mapping System (IMS). Inputs for IMS evolved to a more diverse set of products that included satellite imagery, snow/ice analysis maps, National Centers for Environmental Prediction (NCEP) model data, and surface observations. Among these inputs, time sequenced satellite imagery is of considerable benefit in discriminating snow from clouds. Since its inception, the IMS has served as a more effective and modernized approach to snow mapping compared to the historical approach. Using the IMS tool, snow extent output has been produced at spatial and temporal resolutions corresponding to a 24 km daily product (Ramsey, 1998; Helfrich et al., 2007). Both the historical weekly and higher resolution IMS SCE products were independently produced from June 1997 to May 1999. Comparison between the two datasets was completed by Rutgers University and showed that under conditions when 42 % or more of the IMS land cells falling within the larger weekly historical grid cell indicate snow, the historical product indicates snow. Since June 1999, the NH SCE data record has been completely derived using IMS by reducing its spatial resolution via an automated process to produce weekly granules conforming to the historical weekly NH SCE product.

The combination of both the historical and IMS data records form a continuous record of NH SCE that extends from October 1966 to present. Although the original Northern Hemisphere Snow Cover Extent (NH SCE) data product has been widely used by the cryospheric community to study long-term climate changes, initialize weather

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prediction models, estimate snow melt runoff, and analyze surface albedo, the climate data record (CDR) product is an improved version of the data series. Updates incorporated to improve the CDR product are described in the following sections.

3 Data set description

The NOAA visible satellite NH SCE CDR consists of weekly snow cover boundaries over Northern Hemisphere land surfaces. Knowledge of surface elevation, vegetation and other factors are combined to best estimate the spatial characteristics of SCE during a given week. Map quality relies on the expertise of the trained analyst and the availability of cloud-free visible satellite imagery (Ramsay, 1998). Human analysts have produced the NH SCE CDR from visible satellite imagery for almost five decades and some changes in mapping methodologies have occurred over time. The transition from weekly to daily maps has not resulted in a major artificial step change in SCE (Robinson et al., 1999). While there are differences in the production of the historical data compared with IMS, the conversion of IMS snow output to weekly SCE maps is reproducible.

Starting from the beginning of the record on Tuesday, 4 October 1966 each weekly NH SCE granule represents SCE for seven days spanning from Tuesday–Monday. Each weekly map shows snow boundaries on the last day the land surface was observed in a given region. Using this approach, pre-IMS weekly maps are heavily weighted towards the end of the mapping week. Weekly SCE granules derived from the IMS are generated using Monday IMS output. Although IMS SCE output is dated Monday, satellite imagery from the 36 h leading up to the analysis time can be used to more accurately delineate SCE boundaries (Robinson et al., 1999).

A land mask was developed to resolve inconsistencies found in the coastal land/sea mapping in digitized SCE maps produced by NOAA analysts (Robinson et al., 1993). This correction has been applied to the time series and results in a consistent coastline for the entire period of record. The CDR data file includes pixel areas in km^2, pixel

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center point latitude and longitude coordinates, and a binary land mask (land/water) as ancillary netCDF data variables.

3.1 File format and metadata standards applied

The weekly data are available in netCDF (Network Common Data Form) format, which is self-describing and machine-independent. The file metadata conform to the guidelines recommended by the NCDC CDRP (CDRP, 2011b). All weekly CDR granules are included in one netCDF-4 file.

To generate the NH SCE CDR, values from an 88 × 88 subset of the weekly 89 × 89 SCE matrices are used to populate the SCE variable in the netCDF-4 binary file. This allows the CDR product to provide data only for grid cells that lie entirely north of the equator. Metadata elements comply with Climate and Forecast (CF-1.6) conventions and collection-level metadata adheres to ISO 19115-2 standards for geographic information, to facilitate dataset discovery.

3.2 Primary CDR variable

The primary CDR variable is SCE, which is provided as a binary value (snow/no snow) in each grid pixel. Historical weekly charts were hand-drawn (Fig. 1) and subsequently digitized onto an 89 × 89 polar stereographic grid. Grid cells were historically determined to be snow covered based on a ≥ 50 % snow cover threshold within each cell. From June 1999 forward the IMS snow output is reduced in resolution using a ≥ 42 % snow cover threshold in an automated process to produce weekly granules. Each week in the CDR delineates the boundary of snow extent (Fig. 2). The NH SCE CDR is a complete record with the exception of nine months falling within the summer and fall seasons that are missing satellite imagery. These months include July 1968, June–October 1969, and July–September 1971 and are absent from the data record. From the weekly data, monthly maps can be produced. Monthly maps show intra-annual variability, with maximum mean SCE occurring in January (Fig. 3).

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3.3 Definition of the CDR grid

The CDR product includes refinements to the NH SCE CDR grid. The corner points of the CDR grid outer boundary fall near the equator at 125° W, 145° E, 55° E, and 35° W. Previous versions of the NH weekly SCE product utilize an 89 × 89 half mesh grid, while only an 88 × 88 subset of this grid falls entirely within the Northern Hemisphere (Fig. 4). For this reason, the CDR provides an 88×88 (7744-point) half mesh-Cartesian grid with a spatial resolution of 190.5 km at 60 ° latitude. The grid has been draped over a NH polar stereographic projection oriented along the 80° W–100° E parallel. Cell areas range from ∼ 10 700 km^2 near the equator to ∼ 41 800 km^2 near the pole.

It is also important to note that when the CDR grid is extended to cover the entire NH, this results in a 128 × 128 square with outer boundaries tangent to the equator (Fig. 5). The 24 km NIC IMS snow maps use this same polar stereographic grid base on a 1/16 mesh grid that corresponds to a 1024 × 1024 matrix. Only a subset of this region measuring 704 × 704 cells is utilized during CDR processing. In this approach, each CDR grid cell consists of 64 smaller IMS grid cells (8 × 8). Both the IMS subset of 704×704 grid cells and the corresponding weekly 88×88 half mesh grid appear square with outer boundary corners nearly touching the equator when the NH is mapped using a polar stereographic projection.

Another improvement to the CDR product was the evaluation of cell center geographic coordinates and cell areas provided in v01r00 of the NH SCE CDR product (Fig. 6). These data were evaluated against a regular grid in Polar Stereographic Coordinates (PSC) with a cell size of 190.5 km × 190.5 km. The total calculated area of the two grids agreed within −0.74 % and indicated that the half mesh grid provided by NOAA (B. H. Ramsay, personal communication, 1998) and released in v01r00 of the NH SCE CDR slightly underestimates total area. With three exceptions, the longitude and latitude coordinates were found to be accurate to within ±26 km and the areas were accurate to within ±459 km^2. The three grid cell exceptions have been corrected to correspond to the regular grid in PSC in v01r01 of the CDR product. These

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refinements in the geographic coordinates and cell areas provided in the latest version of the NH SCE CDR product do not impact the presence or absence of snow in these grid locations since the determination of snow is made in row and column space rather than by latitude and longitude coordinates.

4 Basic characterization of the CDR

SCE area values have been calculated in a consistent manner for over two decades using the Rutgers routine (Robinson et al., 1993). The area summation of all grid pixels that indicate snow in a given week generates the weekly snow cover extent for the entire Northern Hemisphere.

4.1 Annual SCE variability

Mean NH snow cover extent reaches its maximum in January and minimum in August, ramping up quickly in the fall and melting at a slower pace in the spring (Fig. 7). The mean annual CDR SCE is 25.1 million km^2, with a SD of 0.9 million km^2. Mean annual maximum SCE totals 47.4 million km^2 (SD = 1.5), which is 44.4 million km^2 more extensive than the mean annual minimum of 3.0 million km^2 (SD = 0.7). The highest annual maximum SCE occurred in February 1978, totaling 51.3 million km^2. At the opposite end of the rankings, the lowest annual minimum SCE of 2.21 million km^2 was observed in August 1968 (Table 2).

The CDR shows 1978 as the snowiest year, with an annual mean SCE of 27.2 million km^2. In contrast, annual mean SCE in 1989 was the lowest, totaling 23.5 million km^2. During the most recent 26 years of the CDR, mean annual SCE has continued to exhibit lower snow extents relative to the data period ending in mid-1987 (Fig. 8). This step change in NH SCE was first identified in the early 1990s (Robinson and Dewey, 1990; Robinson et al., 1993; Robinson, 1997).

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4.2 Long-term trends apparent in CDR snow extent

Seasonal trends observed in the CDR include a pronounced decline in SCE during the spring melt season (Fig. 9). Fall and winter show an opposite trend towards increased extent, with winter SCE growing 0.19 million km^2 $decade^{-1}$. Fall seasonal SCE means have increased by 0.26 km^2 $decade^{-1}$. Over the same data period, spring SCE has decreased by −0.58 million km^2 $decade^{-1}$, declining at three times the pace of the winter trend. This has also left the summer season with less snow on the ground, with summer SCE decreasing by −0.81 million km^2 $decade^{-1}$.

Brown and Derksen (2013) suggest that the fall SCE trend is internal to the CDR and is likely a result of improved mapping. SCE observations from other sources do not exhibit this trend. Brown et al. (2010) suggest that the spring Arctic SCE trend shown by the CDR is similar to observations from other sources and that the June decline in SCE in the Arctic coincides with reductions in sea ice.

5 Conclusions

A long-term, satellite-based visible SCE CDR is available for climate studies, monitoring, and model validation. The CDR is provided in netCDF format with CF-1.6 compliant metadata, and is forward processed operationally every month. Trends and spatial variability are consistent with the predecessor NOAA weekly SCE product. Version 1 revision 1 provides improved grid accuracy and an 88 × 88 subset of pixels falling entirely within the NH. CDR documentation and product traceability meet current guidelines for climate data records. Generation of the weekly CDR from June 1999 forward using the NIC IMS snow output is reproducible.

The CDR is a foundational product, used in other data products such as the Northern Hemisphere EASE-Grid 2.0 Weekly Snow Cover and Sea Ice Extent, Version 4 available at the National Snow and Ice Data Center (NSIDC). Two data products from the NASA Making Earth System Data Records for Use in Research Environments

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(MEaSUREs) program also incorporate the CDR: MEaSUREs Northern Hemisphere Terrestrial Snow Cover Extent Weekly 100 km EASE-Grid 2.0, and MEaSUREs Northern Hemisphere State of Cryosphere Weekly 100 km EASE-Grid 2.0, both published at NSIDC.

IMS version 3 will incorporate additional improvements to analyst workstations and snow output (S. R. Helfrich, personal communication, 2014). Consistency is important to the forward processing of the CDR. As SCE inputs continue to evolve, the need to be vigilant and ensure ongoing consistency of these data records is critical to the identification and tracking of changes in the cryosphere.

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Table 1. Satellites and date of incorporation into weekly snow mapping analysis for the NH SCE CDR.

Platform	First used for CDR	
ESSA	Oct 1966	
NOAA POES	Oct 1972	
NOAA GOES	May 1975	
DMSP	Jun 1977	
METEOSAT	Feb 1988	
GMS	Jan 1989	
AQUA/TERRA	Feb 2004	(IMS)
MTSAT	Nov 2005	(IMS)

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Table 2. NH SCE CDR monthly statistics (and year of max/min) in million km^2. Calculated using a data period spanning November 1966 to June 2014. Missing months (July 1968, June–October 1969, July–September 1971) are not included.

Month	Mean	Max (Year)	Min (Year)	SD
Jan	47.09	50.28 (2008)	41.89 (1981)	1.57
Feb	46.07	51.32 (1978)	42.67 (1995)	1.84
Mar	40.62	44.28 (1985)	37.12 (1990)	1.82
Apr	30.57	34.61 (1979)	28.00 (1968)	1.69
May	19.34	23.09 (1974)	15.38 (2010)	1.93
Jun	9.80	14.97 (1978)	4.92 (2012)	2.34
Jul	4.06	8.21 (1967)	2.33 (2012)	1.24
Aug	3.03	5.31 (1967)	2.09 (1968)	0.74
Sep	5.32	7.76 (1972)	3.84 (1990)	0.93
Oct	18.08	25.72 (1976)	12.78 (1988)	2.54
Nov	33.91	38.60 (1993)	28.28 (1979)	2.04
Dec	43.68	46.85 (2012)	37.44 (1980)	1.93

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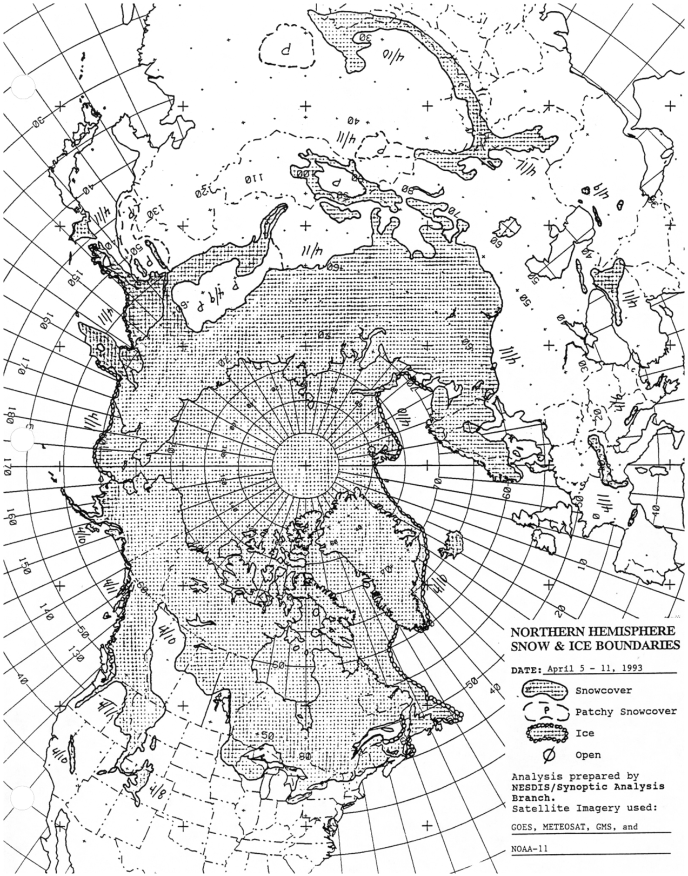

Figure 1. NOAA hand–drawn SCE corresponding to week 15 of 1993.

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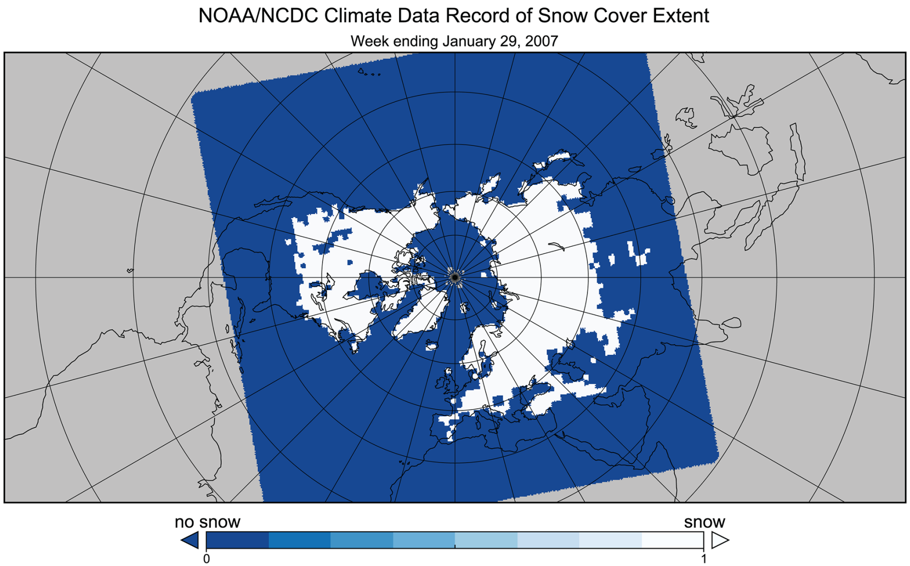

Figure 2. NH CDR SCE plot corresponding to week 4 of 2007.

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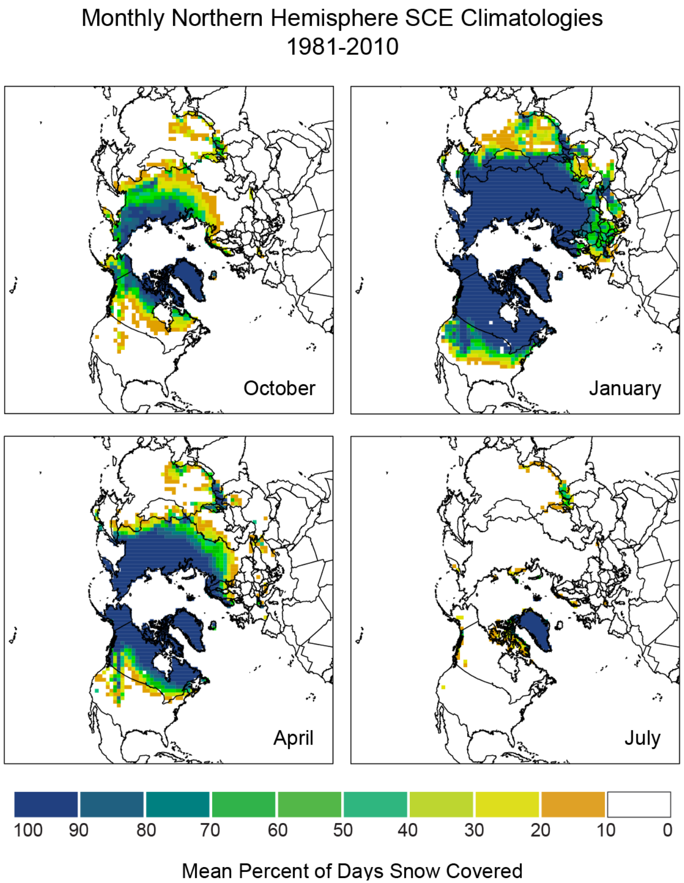

Figure 3. Mean monthly spatial distribution of SCE over Northern Hemisphere lands for October, January, April, and July. These monthly maps show intra–annual variability each quarter, with maximum mean SCE occurring in January. Data period used to calculate mean spans from 1981–2010.

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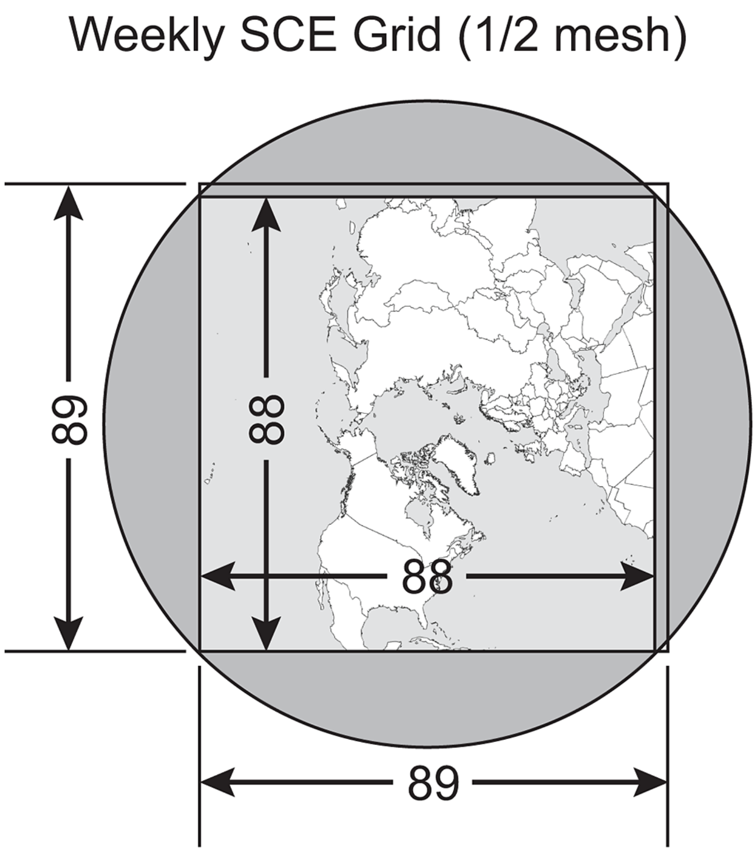

Figure 4. Historical 89 × 89 weekly SCE matrix compared to the 88 × 88 subset used for netCDF output. The row and column falling partially outside the Northern Hemisphere are not included in the CDR.

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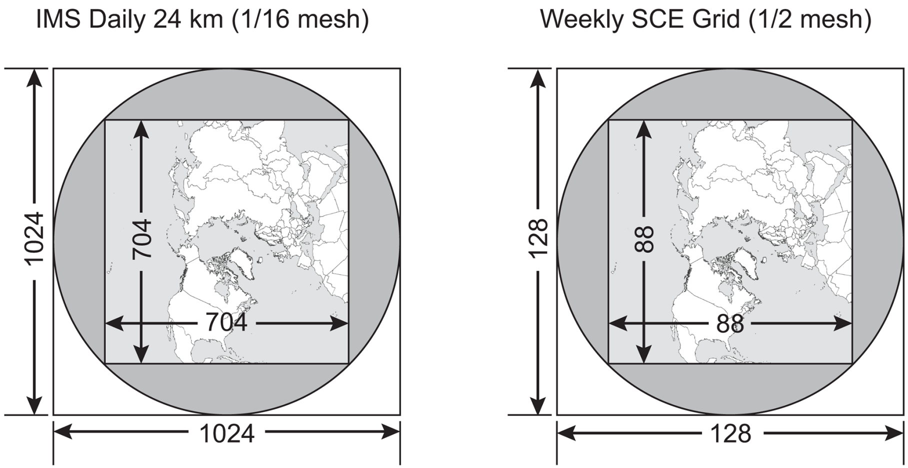

Figure 5. IMS daily 24 km grid and corresponding weekly SCE grid cells. The gray circle represents the Northern Hemisphere.

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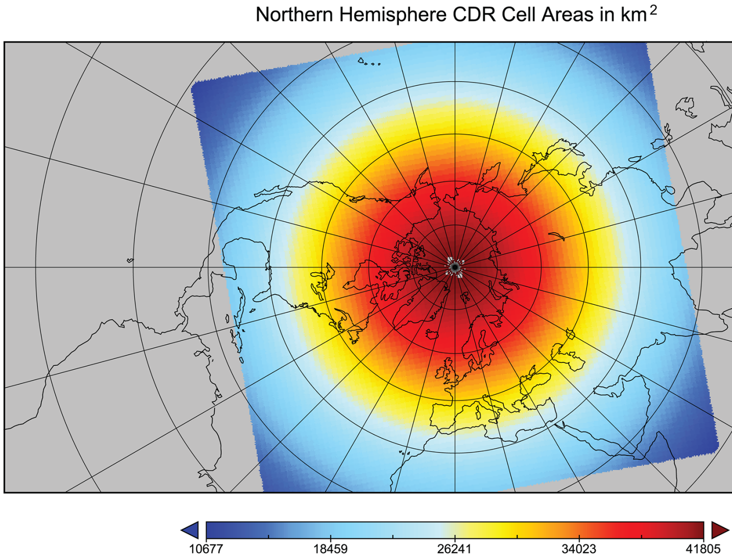

Figure 6. Distribution of cell areas (km^2) in the 88 × 88 CDR grid, here displayed on a polar stereographic projection.

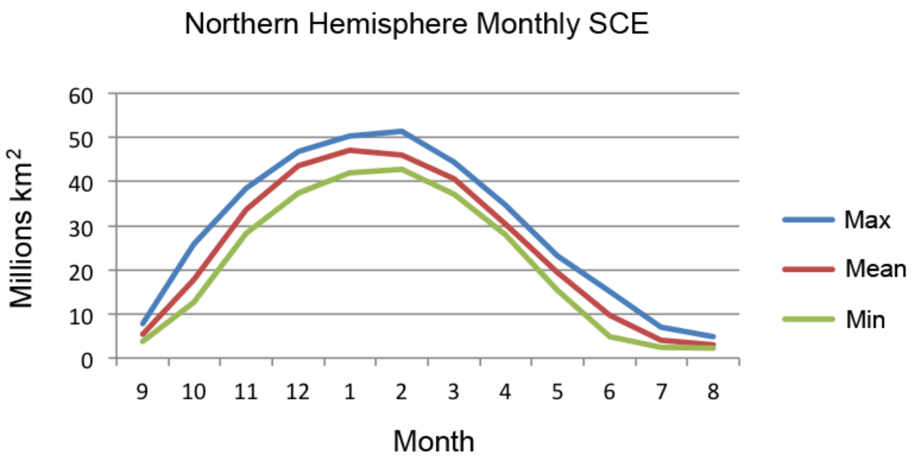

Figure 7. Mean monthly CDR SCE (red line) for Northern Hemisphere. Mean maximum and mean minimum extents are indicated in blue and green respectively. Means in millions km^2 calculated using a data period spanning January 1972 to December 2013 (42 years).

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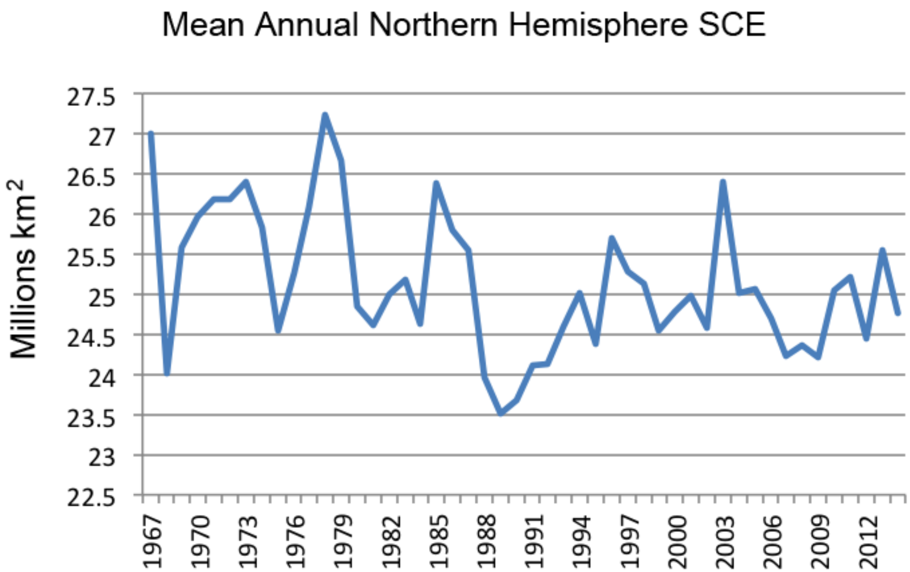

Figure 8. Mean annual (September to August) CDR SCE for Northern Hemisphere (1967–2014) in millions km^2. Missing months (August–September 1966, July 1968, June–October 1969, July–September 1971) replaced with period of record means.

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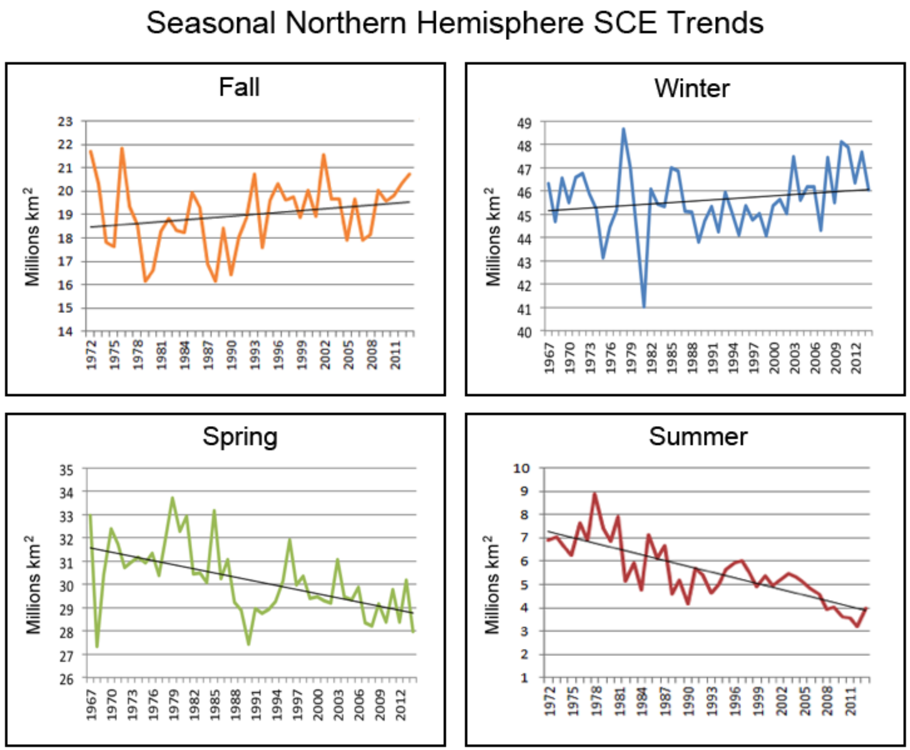

Figure 9. Seasonal SCE trends for Northern Hemisphere in millions km^2. Each season calculated using 3–month mean starting with DJF in Winter (December 1966). Summer and Fall calculated from June 1972 forward, due to missing months in years 1968–69 and 1971. No winter or spring months missing.