

Abstract

A long-term, consistent, and reproducible satellite-based passive microwave sea ice concentration climate data record (CDR) is available for climate studies, monitoring, and model validation with an initial operation capability (IOC). The daily and monthly sea ice concentration data are on the National Snow and Ice Data Center (NSIDC) polar stereographic grid with nominal 25 × 25 km grid cells in both the Southern and Northern Hemisphere Polar Regions from 9 July 1987 to 31 December 2007 with an update through 2011 underway. The data files are available in the NetCDF data format at <http://nsidc.org/data/g02202.html> and archived by the National Oceanic and Atmospheric Administration (NOAA)'s National Climatic Data Center (NCDC) under the satellite climate data record program (<http://www.ncdc.noaa.gov/cdr/operationalcdrs.html>).

The description and basic characteristics of the NOAA/NSIDC passive microwave sea ice concentration CDR are presented here. The CDR provides similar spatial and temporal variability as the heritage products to the user communities with the additional documentation, traceability, and reproducibility that meet current standards and guidelines for climate data records. The dataset along with detailed data processing steps and error source information can be found at: [doi:10.7265/N5B56GN3](https://doi.org/10.7265/N5B56GN3).

1 Introduction

The depletion of the Arctic sea ice coverage is occurring faster than most of the climate model predictions (Stroeve et al., 2007, 2012). In September 2012, a record low Arctic sea ice extent minimum was reached, well below the previous Arctic sea ice extent minimum record set in September 2007 (<http://nsidc.org/arcticseaicenews/>). While numerous sea ice products are available, with the substantial changes in the Arctic sea ice and the associated impacts of the change in weather and climate system, ecosystems, and coastal communities, it is valuable to have a climate data record (CDR) quality sea ice concentration product.

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readiness is examining the maturity of the algorithms and application of the product in peer-reviewed publications.

In this paper, we present a description of the NOAA/NSIDC sea ice concentration CDR dataset and basic characteristics of the CDR such as long-term mean and trend to provide a baseline for users.

2 Dataset description

The NOAA/NSIDC CDR sea ice concentrations are daily and monthly estimates of the fraction of ocean area covered by sea ice. They are derived from the brightness temperature from the Defense Meteorological Satellite Program (DMSP) series of Special Sensor Microwave Imager (SSM/I) passive microwave radiometers: F-8, F-11, and F-13 (Meier et al., 2011; see also Table 1 for an outline of passive microwave sensor sources for the sea ice concentration CDR). The CDR leverages two well-established and well-validated passive microwave sea ice concentration algorithms developed at the NASA Goddard Space Flight Center (GSFC): the NASA Team (NT) algorithm (Cavaliere et al., 1984, 1996, 1999) and the Bootstrap (BT) algorithm (Comiso, 1986, 2000; Comiso and Nishio, 2008). The algorithms use adjusted coefficients, based on overlap of sensor operations, to assure consistency through the series of sensors. The input DMSP SSM/I brightness temperatures are daily gridded fields archived at NSIDC (Maslanik and Stroeve, 2004) derived from swath fields generated by Remote Sensing Systems, Inc. (RSS) (Wentz et al., 2007).

Variables in both daily and monthly data files are gridded on the same NSIDC polar stereographic grid with nominal 25×25 km grid size, covering the ocean surface area from 31.1 to 89.84° N in the Northern Hemisphere and 39.36 to 89.84° S in the Southern Hemisphere. The NSIDC's polar stereographic projection sets the projection plane tangent to the Earth's surface at 70 degrees northern and southern latitude to minimize the distortion of the cell area in the marginal ice zones. With the normal polar projection which usually sets the plane tangent to the Earth's surface at the poles, the distortion

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2.1 Primary CDR variables

- *CDR sea ice concentration* – this field provides sea ice concentration (fraction ice cover) for each grid cell. The processing includes several automated quality control steps. Two weather filters, based on ratios of passive microwave frequencies, are used to eliminate false ice due to atmospheric moisture and wind roughening over the open ocean. A land-spillover correction is used to filter false ice near the coast that results from mixed land-ocean grid cells. Finally, monthly ocean masks are applied to remove sea ice in regions where it is never likely to occur; in the Arctic, the masks are based on maximum extent through the time series with an added buffer, while the Antarctic uses sea surface temperature (SST) climatologies. There are masks for each month in each hemisphere. The Antarctic masks are much more conservative (i.e., larger region of potential sea ice).
- *Concentration standard deviation* – the standard deviation field is derived at each valid grid cell from the NT and BT concentration values at that cell and the surrounding eight cells. It thereby accounts for two sources of variability: (1) the difference between NT and BT estimates, and (2) the spatial variation within the neighborhood of each grid cell. Thus the standard deviation is calculated from up to 18 values (9 grid cells each of NT and BT sea ice concentrations, Fig. 3). The rationale for this approach is that grid cells where NT and BT differ significantly have higher uncertainty than cells where the two agree. Also, regions where there is high spatial variability tend to have higher uncertainty. Such high variability regions include near the ice edge (where the low spatial resolution of the sensors results in limited precision of the ice edge location) and isolated ice-covered grid cells near the coast (which indicates possible land-spillover error). Thus while the values are quantitatively largely measuring spatial variability, the field provides a quantitative relative estimate of uncertainty because regions of high errors tend to be well-correlated with regions of high spatial variability. Standard deviations associated with spatial variability are typically a few percent (Cavaliere et al., 1984)

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and can potentially serve as a quantitative upper limit of the concentration error (Gloersen et al., 1993). Melt also tends to result in higher variability in the concentrations, particularly in terms of differences between NT and BT.

- *Data quality field* – in addition to the quantitative local standard deviation field, a data quality field is included to provide further information about the nature of the concentration values. Flag values are assigned to denote several conditions at each grid cell: (1) algorithm value selected (NT or BT), (2) masked by ocean climatology, (3) low concentration (< 50 %), (4) adjacent to coast, and (5) melt occurred during summer (Arctic only). Multiple flag values can be assigned to each grid cell.

2.2 Additional variables included

- *Merged Goddard concentration* – combined NT and BT sea ice concentration estimates, assembled in the same manner as the concentration CDR variable, but using the Goddard produced fields as a source.
- *Goddard NASA Team* – NT concentrations produced by Goddard. Concentrations are re-scaled to 0–100 percent for consistency with other variables.
- *Goddard Bootstrap* – BT concentrations produced by Goddard. Concentrations are re-scaled to 0–100 percent for consistency with other variables.
- *Latitude/longitude* – included as a part of NetCDF CF-compliant file-level metadata requirements
- *Other metadata* – variables and attributes to satisfy NetCDF4 CF-compliant file-level metadata requirements, including projection information and grid size and resolution.

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2.3 Input data sets to the CDR

- DMSP SSM/I daily polar gridded brightness temperatures (<http://nsidc.org/data/nsidc-0001.html>)
- NASA Team sea ice concentrations from DMSP SSM/I, processed at NSIDC
- Bootstrap sea ice concentrations from DMSP SSM/I, processed at NSIDC
- NASA Team sea ice concentrations from Nimbus-7 SMMR and DMSP SSM/I Passive Microwave Data, Version 1, created by NASA GSFC (<http://nsidc.org/data/nsidc-0051.html>)
- Bootstrap sea ice concentrations from Nimbus-7 SMMR and DMSP SSM/I, Version 2, created by NASA GSFC (<http://nsidc.org/data/nsidc-0079.htm>)
- Snow melt onset estimate for the Northern Hemisphere (Drobot and Anderson, 2001)
- Climatological minimum sea ice mask (CMIN) (based on 1992)
- Ocean masks (http://nsidc.org/data/smmr_ssmi_ancillary/ocean_masks.html)
- Land masks (http://nsidc.org/data/polar_stereo/tools_masks.html#land_masks)

An archived source code package that includes source code for processing NSIDC NT and BT sea ice concentrations from DMSP SSM/I brightness temperatures and producing the NOAA/NSIDC passive microwave sea ice concentration CDR along with a README file can be downloaded from <http://www.ncdc.noaa.gov/cdr/operationalcdrs.html>. In this source code package, one can also find the input data sets that are not archived elsewhere such as climatological minimum sea ice mask (CMIN).

A detailed description of the climate algorithm for the CDR and algorithm validation and error assessment can be found in Meier et al. (2011). The CDR has been shown

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to capture well the seasonal and inter-annual variability when compared with other satellite-based sea ice products with no significant systematic bias (Meier et al., 2013; Peng and Meier, 2013).

Twenty years of monthly CDR data from January 1988 to December 2007 are used next to show the basic characteristics of the CDR. From hereafter, we will refer NOAA/NSIDC CDR sea ice concentrations as CDR and merged Goddard sea ice concentrations as GSFC. As stated previously, CDR and GSFC are produced using the same methodology and based on the same algorithms – the main differences are additional manual quality control of input brightness temperature and output sea ice concentration fields, gap-filling in both time and space and correction/replacement of obviously erroneous data for GSFC (e.g., remaining weather effects). Because of the interpolation and manual corrections, GSFC represents a higher quality research product that can be used as a benchmark for evaluating and characterizing model or other satellite-based sea ice products such as we have done in Meier et al. (2013) for CDR; however, the higher quality comes at the expense of traceability and reproducibility and longer data latency (about 12 months or longer). CDR, on the other hand, aims to ensure the consistency and sustainability of the sea ice time series with planned updates on a quarterly basis (monthly in the future and effort is also underway to extend the time series through year 2011) of the primary CDR fields and offers transparency, traceability, and reproducibility with the NetCDF-4 data format and CF-1.5 compliant file-level metadata elements along with collection-level metadata that follows the ISO 19115-2 standards.

3 Basic characterization of the CDR

The basic characterization of the CDR is provided here using monthly sea ice extent from monthly sea ice concentration data files for a period of 20 yr (January 1988–December 2007) in terms of mean and long-term trend to provide a baseline for users. The sea ice extent is computed by summing the grid cell area of all cells that have

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15 percent or greater sea ice concentrations, assuming the area not measured by the sensor at the North Pole is entirely covered by at least 15 % ice.

The CDR sea ice extent values are in good agreement with estimates from GSFC (Fig. 4, see Meier et al., 2013 for detailed comparison and analysis). As expected, the sea ice extent undergoes distinct seasonal cycles in both Polar Regions. It peaks in March and reaches the minimum in September in the Northern Hemisphere but peaks in September and reaches the minimum in February in the Southern Hemisphere (Fig. 5). The mean annual CDR sea ice extent is about 12 million km² for both hemispheres with mean biases relative to GSFC of 0.1 and -0.05 million km² for the Northern and Southern Hemispheres, respectively (Table 2). The standard deviation (SD), which is mainly associated with seasonal variability, is nearly twice as large in the Southern Hemisphere (compared 5.64 to 2.92 million km²). However, the inter-annual variability, represented by the range of the shaded area for each month in Fig. 4, tends to be smaller in the Southern Hemisphere than that in the Northern Hemisphere.

With the predominant seasonal cycle, the cross-correlation coefficients between the CDR and GSFC sea ice extents are very close to one for both hemispheres with very small bias and root-mean-square (RMS) error (Table 2), largely reflecting the spatial homogeneity of the concentrations over much of the field. A lot of variability does occur near the ice edge, but that is a small portion of the total grid cells. It has been shown that regional variability can be large (e.g., Cavalieri and Parkinson, 2008). More in-depth examination of the regional variability will be carried out but is beyond the scope of this paper.

Least-square linear regression of this twenty-year annual mean CDR sea ice extent time series indicates a sea ice coverage decrease of 0.597 million km² per decade in the Northern Hemisphere, which is significant at the 95 % confidence level. This decadal trend is about 4.94 % per decade of the annual mean sea ice extent of 12.076 million km². The margin of error is about 0.18 million km² per decade (Fig. 6). On the other hand, an almost zero but slightly positive trend (0.04 ± 0.21 million km² per decade) is found in the Southern Hemisphere (Fig. 6). This trend represents an

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increase rate of less than 0.3% per decade relative to the 20 yr average of annual mean sea ice extent of 12.179 million km² and is not significant at the 95% confidence level. For the Northern Hemisphere, while the annual maximum sea ice extent decreases at a rate that is similar to the annual mean sea ice extent rate, i.e., 0.556 ± 0.23 million km² per decade, the annual minimum sea ice extent decreases at a faster rate, 0.99 ± 0.48 million km² per decade (Fig. 7), indicative of the effect of enhanced summer melt (Markus et al., 2009), thinning of the ice cover and loss of older ice types (e.g., Maslanik et al., 2011). Both annual maximum and minimum sea ice extent decadal trends are significant at the 95% confidence level.

On the other hand, both annual maximum and minimum sea ice extents at the Southern Hemisphere experience increase, with a rate of more than double for the annual maximum sea ice extent (0.35 million km² per decade, which is significant at the 95% confidence level) than that of the annual minimum sea ice extent (0.138 million km² per decade, which is not significant at the 95% confidence level). This difference in magnitudes is in part due to the large difference in absolute mean extent at the minimum and maximum, as well as climate factors such as atmospheric and oceanic circulation. Therefore, while the Arctic region experienced diminishing sea ice coverage for the two decades, with a faster reduction rate for the annual minimum sea ice coverage, the Antarctic Region, as a whole, has experienced a small increase in its sea ice coverage with a noticeable increase in its annual maximum sea ice coverage, significant at the 95% confidence level. These trends and variability are consistent with trends and variability observed in other passive microwave sea ice products and in particular, they are in close agreement with the Goddard estimates.

4 Conclusions

A long-term satellite-based sea ice concentration climate data record derived from passive microwave brightness temperatures is available for climate studies and monitoring as well as climate model validation. The CDR sea ice extent compares well with that

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computed from GSFC with distinct seasonal cycles in both Polar Regions. The mean CDR sea ice extent is about 12 million km² for both hemispheres with mean biases of 0.1 and −0.05 million km² relative to the GSFC fields for the Northern and Southern Hemisphere Polar Regions, respectively.

In comparisons between the CDR and GSFC variables, no significant systematic bias was found. Trends and variability are also consistent. Thus the sea ice concentration CDR provides similar spatial and temporal variability as the GSFC fields to the user communities with the additional documentation, traceability, and reproducibility that meet current standards and guidelines for climate data records.

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Table 1. Sources and attributes of passive microwave sensors for NOAA/NSIDC sea ice concentration CDR.

Satellite	Sensor	Data Period*	Swath Width (km)
DMSP F-8	SSM/I	7/9/87–12/30/91	1400
DMSP F-11	SSM/I	12/3/91–9/30/95	1400
DMSP F-13	SSM/I	5/3/95–12/31/07	1400

* Data periods in this table are for sensor data used in generating CDR, which may not coincide with and tend to be within sensor data available periods.

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Table 2. The basic statistics of CDR and GSFC sea ice extents (million square kilometers).

	Northern Hemisphere		Southern Hemisphere	
	CDR	GSFC	CDR	GSFC
Mean	12.076	11.975	12.179	12.225
SD	2.92	2.96	5.64	5.64
Bias	0.100		−0.0458	
RMS	0.085		0.050	
Correlation	0.9997		1.000	

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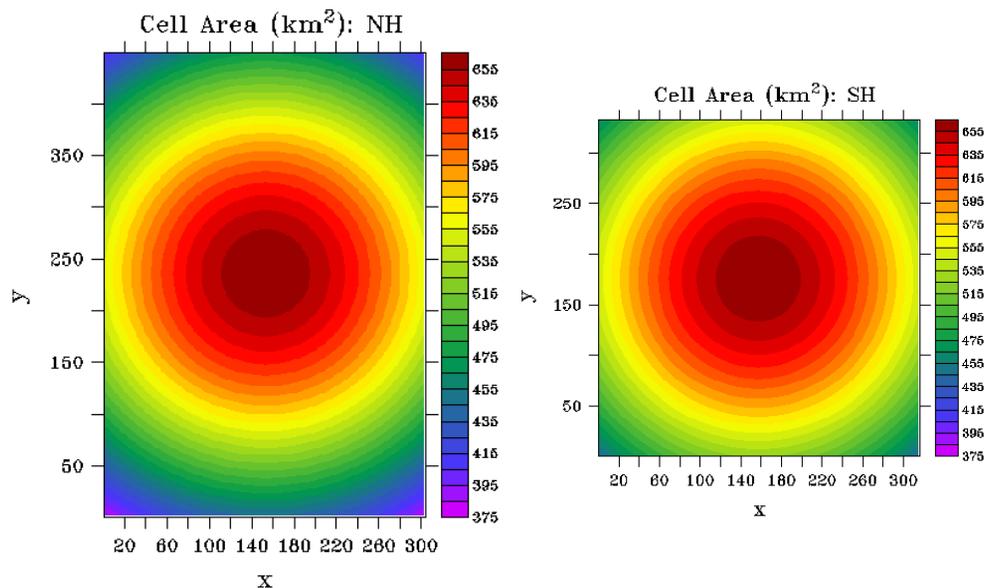


Fig. 1. Distribution of cell areas (km²) of the NSIDC polar stereographic grid for the Northern (left) and Southern Hemisphere grid (right).

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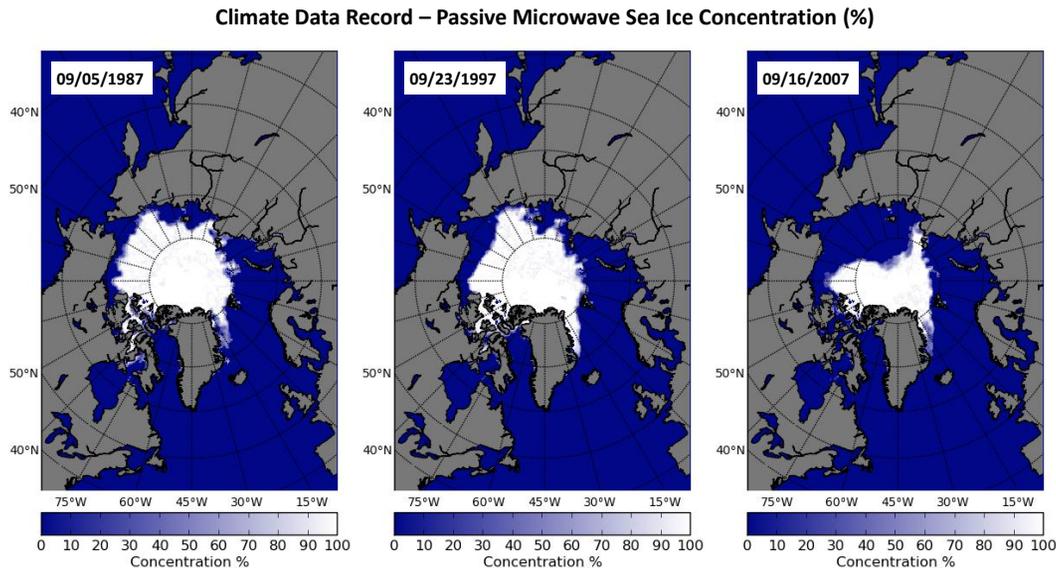


Fig. 2. Spatial distribution of sea ice concentration from daily CDR data on the minimum sea ice extent day (based on a 5-day average) in year 1987, 1997, and 2007 to show decadal variability (i.e., shrinking) of Arctic sea ice coverage. The area not measured by the satellite sensor over the North Pole is assumed to be entirely covered by ice.

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1	2	3	10	11	12
4	NT (I,J)	6	13	BT (I,J)	15
7	8	9	16	17	18

$$StDev = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (C_i - \bar{C})^2} \quad 6 \leq N \leq 18$$

	CDR (I,J)	

Fig. 3. Schematic of grid cell values used in calculation of the CDR standard deviation field. All non-missing ocean/sea ice concentration values (C), from both the NASA Team and Bootstrap algorithm, of the 3×3 box surrounding each (I, J) grid cell (up to 18 total values) are used to calculate the standard deviation. A minimum of six grid cells with valid values is used as a threshold for a valid standard deviation.

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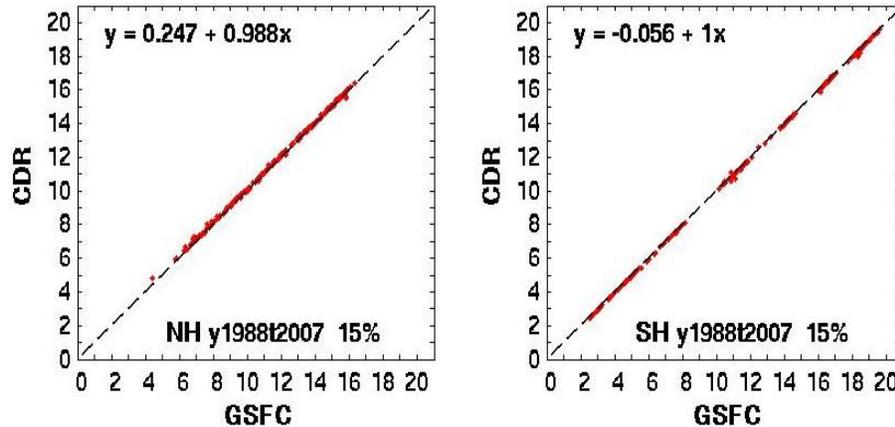


Fig. 4. The scatter-diagram of sea ice extents (million square kilometers) based on monthly CDR and GSFC (20 yr from January 1988 to December 2007). Left panel is for the Northern and the right is for Southern Hemisphere.

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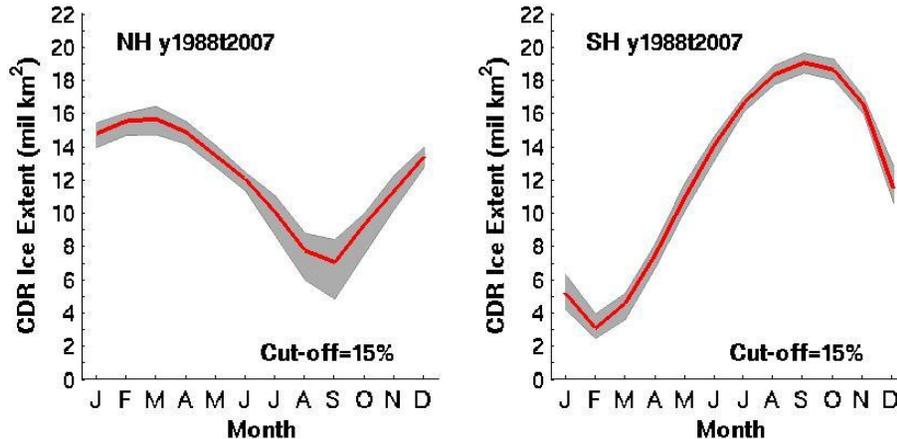


Fig. 5. 20 yr mean monthly CDR sea ice extent (solid line) for the Northern (left) and Southern (right) Hemispheres. The shaded areas are bounded by the minimum and maximum extent values for each month. The period of the record is from January 1988 to December 2007.

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Interactive Discussion

A long-term and reproducible passive microwave sea ice concentration CDR

G. Peng et al.

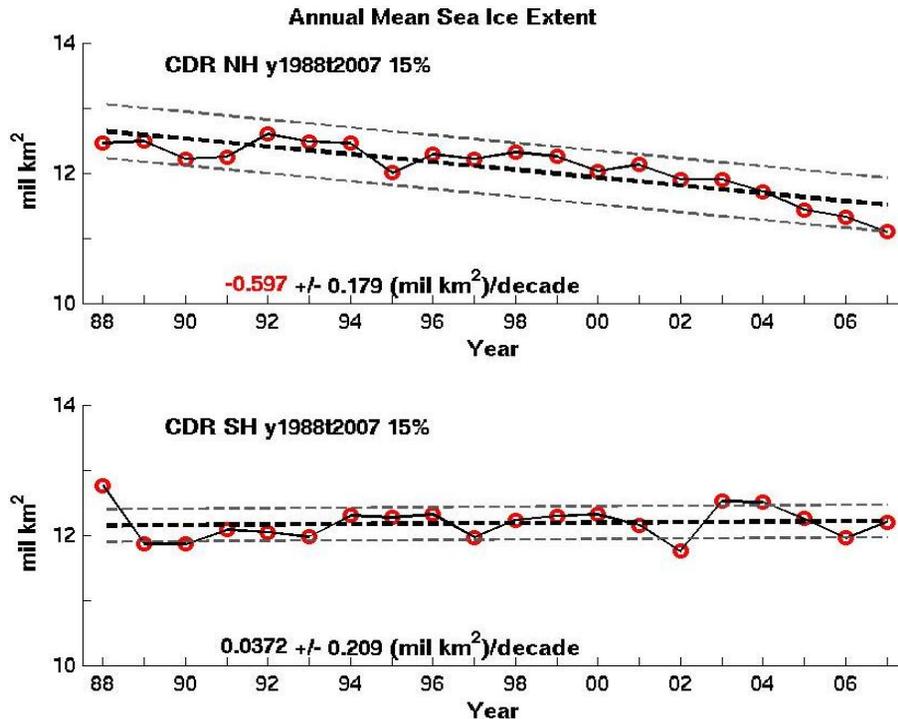


Fig. 6. Annual mean CDR sea ice extent from 1988 to 2007 (red circles), with the linear regression ± 1 standard deviation of the annual mean sea ice extent (black and grey dashed lines, respectively) for the Northern (top) and Southern Hemisphere (bottom) with the decadal trend and its margin of error – trend in red is significant at the 95 % confidence level.

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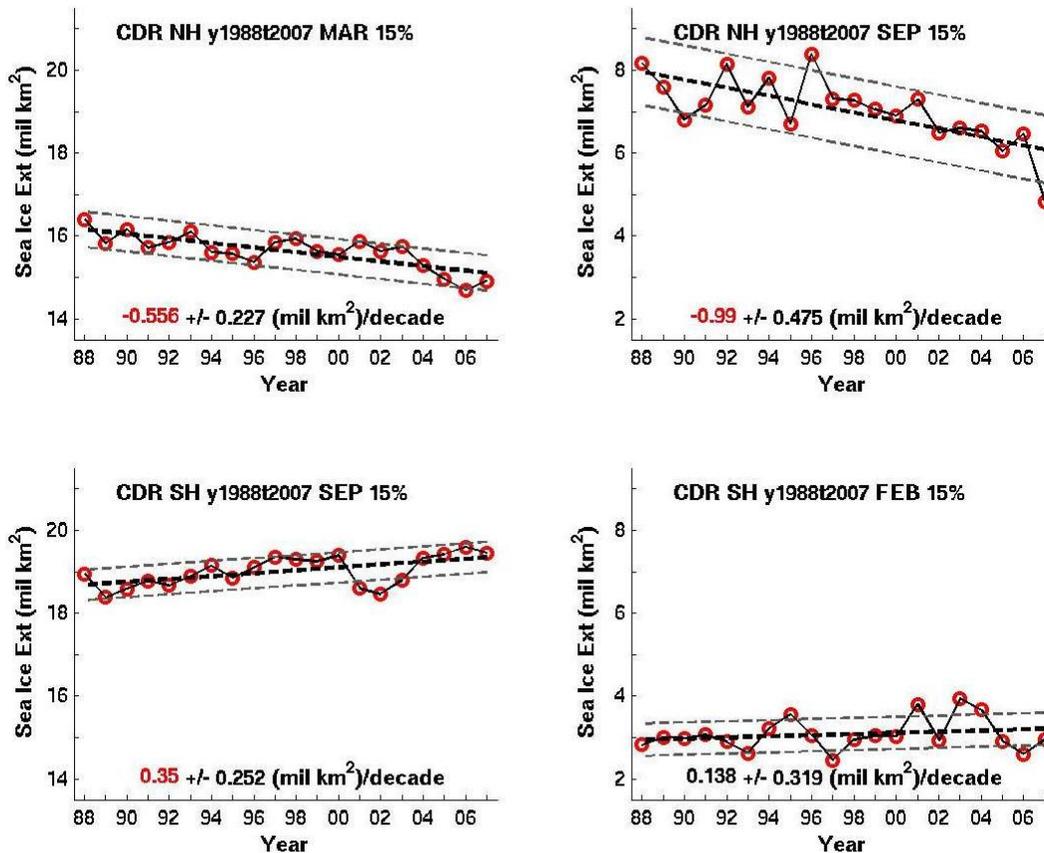


Fig. 7. Same as Fig. 6 but for the annual maximum sea ice extent (left panels) and minimum (right panel) for both Northern (top panels) and Southern (bottom panels) Hemispheres. The decadal trend in red is significant at the 95 % confidence level.