Sea ice extent annual extreme in the Arctic regions

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Introduction

This work investigates the Arctic Sea Ice Extent (SIE) variability through its annual minima and maxima time series, estimated over the entire region and some sub-regions. The SIE was computed from the daily sea ice concentration data provided by the National Snow and Ice Data Center. The analysis, which covers the 1979-2017 period, aims to suggest answers to the following questions: 1) Do annual SIE maxima and minima trends of the various Arctic sub-regions show "substantial" differences among them? 2) Is the time span between annual SIE maximum and minimum changing over the analysed period? 3) Which information do the SIE minima and maxima time series contain for providing extreme value time series? 4) Can the cross-correlations between the annual SIE maxima and minima and monthly climatic oscillation indices be useful for understanding the regional SIE variability?

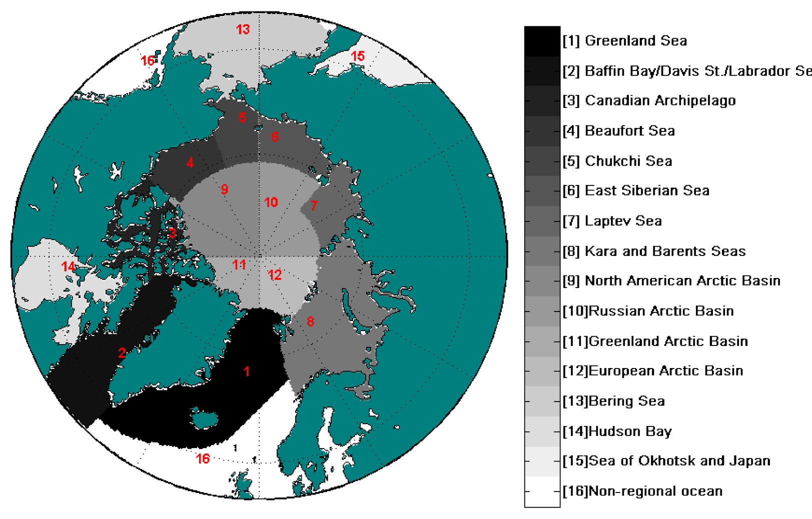
Data

The Sea Ice Concentration (SIC) dataset over the Arctic, for the period 1979-2017, as distributed by the National Snow and Ice Data Center (NSIDC) and computed with the Nasa Team (NT) algorithm [1], is the basis of this study.

The SIC daily dataset was used to compute daily Sea Ice Extent (SIE), both for the overall NSIDC Arctic area and for some of its regions, the largest of them being the so-called "Arctic Ocean".

As the Arctic Ocean is much larger, in terms of SIE, than the other sub-regions, we decided to further divide it into sub-regions, whose borders are based on the work of Welsh et al. [2].

A total of 18 sub-regions were hence defined.



Dissimilarities of annual SIE maxima and minima trends in the Arctic sub-regions

Both maxima and minima SIE trends show substantial qualitative and quantitative differences among all sub-regions.

For example, about SIE minima, the shrinkage of the summer SIE on the whole Arctic had a significant onset at the end of the 90s, with the major contribution to this decrease coming from the Asian Arctic sector. However, after 2012, the summer SIE remained fairly stable.

About SIE maxima, the Arctic winter sea ice decreasing seems to be dominated by the European sector (Greenland Sea, Kara and Barents Sea).

SIE maxima and minima time series are usually very irregular; however we evaluated their annual linear trends using the SEN's slopes together with the Mann-Kendall test for trend (Tab. 1).

All regions, except those having a null SIE minimum and maximum, have a negative statistically significant trend (at $\alpha = 0.05$).

Table 1. SIE minima and SIE maxima annual linear trends (LT) in the 1979-2017 period. Statistically significant at $\alpha = 0.05$ trends are shown in boldface.

Region	SIEMN LT (km^2/yr)	SIEMX LT (km^2/yr)
Whole NSIDC Arctic region	**-78016**	**-49271**
Greenland Sea	**-3646**	**-10875**
Baffin Bay/Davis St./Labrador Sea	**-1172**	**-8207**
Canadian Archipelago	**-3628**	0
Beaufort Sea	**-11903**	0
Chukchi Sea	**-7500**	0
East Siberian Sea	**-12150**	0
Laptev Sea	**-7768**	0
Kara and Barents Seas	**-7115**	**-12917**
North American Arctic Basin	**-2983**	0
Russian Arctic Basin	**-9236**	0
Greenland Arctic Basin	**+89**	0
European Arctic Basin	**-4042**	0
Bering Sea	0	+1298
Hudson Bay	**-625**	0
Sea of Okhotsk and Japan	0	**-10286**
Gulf of St. Lawrence	0	**-1970**
Non-regional ocean	0	**-3828**
Lakes, extended coast	+375	-1750

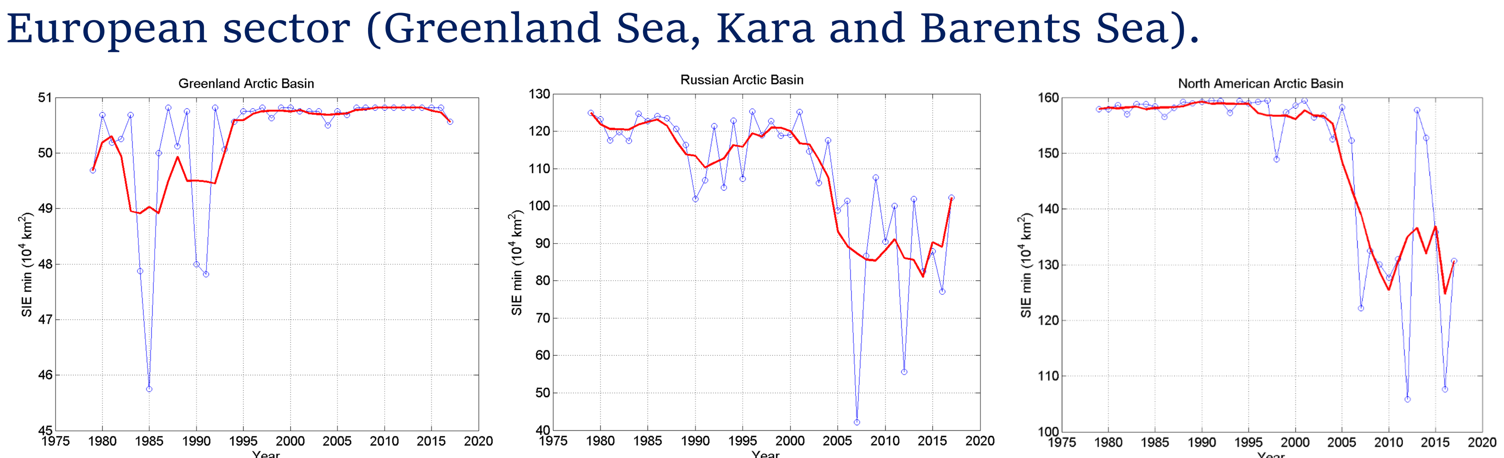


Fig. 1 – (Examples) SIE minima for the Greenland, the Russian and the North American Arctic basins. In red colour the smoothing curve (5 days moving average).

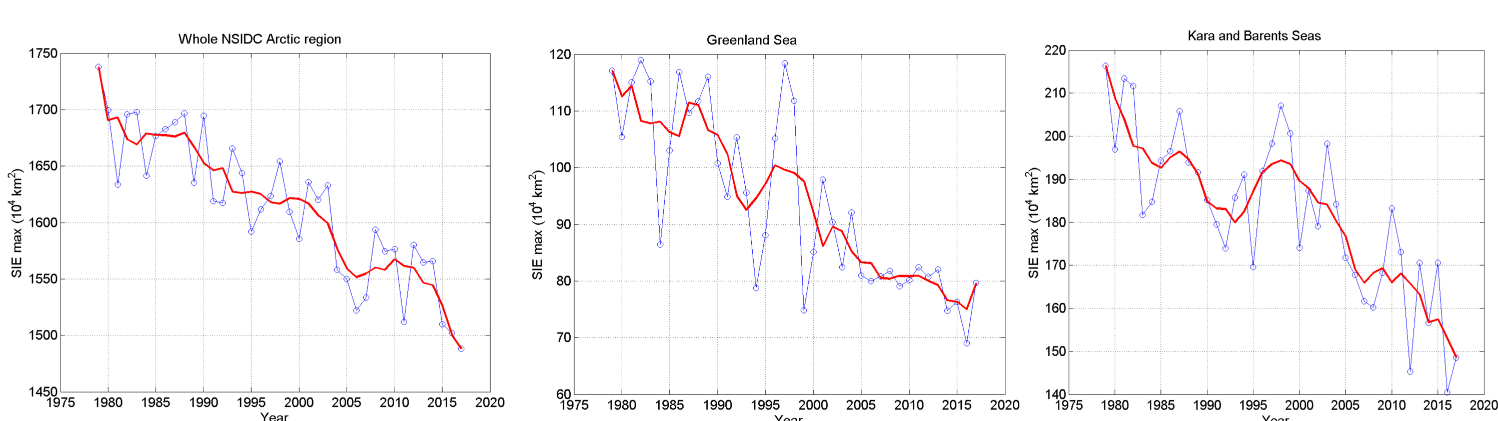


Fig. 2 – (Examples) SIE maxima for the whole NSIDC Arctic region, for the Greenland Sea and for the Kara and Barents Seas. In red colour a smoothing curve (5 days moving average).

SIE maxima and minima as extreme values

Events corresponding to large SIE anomalies have been described in several papers appeared in the literature.

In this work, rather than detecting all large anomalies, we analysed annual SIE maxima and minima from the viewpoint of the theory of extreme events. Indeed, Anderson-Darling, Kolmogorov-Smirnov and chi-square tests, confirmed that all SIE maxima and minima samples (for each sub-region) are very well represented as Generalized Extreme Value (GEV) random variables.

SIE minima and maxima for all sub-regions were hence fitted with a GEV distribution. Expansion and contraction of SIE minima and maxima were both considered. It was also considered that, in some sub-regions, during the summer season, sea ice completely disappears, while in other ones, during the winter season, sea ice occupies the entire available surface. In both cases, it is clearly impossible to talk about extreme values. Moreover, as the extreme value theory implies that the statistical properties of the extremes are stationary while our time series are not, we had to use a software suited for fitting non-stationary series.
The **Non-stationary Extreme Value Analysis** (NEVA) software, which implements a framework for estimating stationary and non-stationary return levels, return periods, and risks of climatic extremes using Bayesian inference [3], was employed.
In Table 2, the years in which data passed the return level, corresponding to some return periods, are shown. They should be carefully investigated in order to understand the physical processes involved.

Table 2. Years in which the data have passed the return level corresponding to the return period of 25 years. In red and green, when they passed the return period of 50 and 100 years, respectively.

Region	SIE minima		SIE maxima	
	MIN EXT CONTRACTION	MAX EXT EXPANSION	MIN EXT CONTRACTION	MAX EXT EXPANSION
Whole NSIDC Arctic region	2012	1996 2001	1981	
Greenland Sea	1985 2001	1992 1995		1997
Baffin Bay/Davis St./Labrador Sea		1983 1996	2010	1993
Canadian Archipelago	1981 1998	2004		
Beaufort Sea		1991 1996		
East Siberian Sea	1990			
Laptev Sea	1995	1996 2001 2004		
Kara and Barents Seas		2003		1998 2003
European Arctic Basin	2012 2013	2003		
Bering Sea			2015	
Sea of Okhotsk and Japan			1984 2015	2001
Gulf of St. Lawrence				1990 2003
Non-regional ocean			1992	1985 1987
Lakes, extended coast	1997-1999 2004			2014 2015

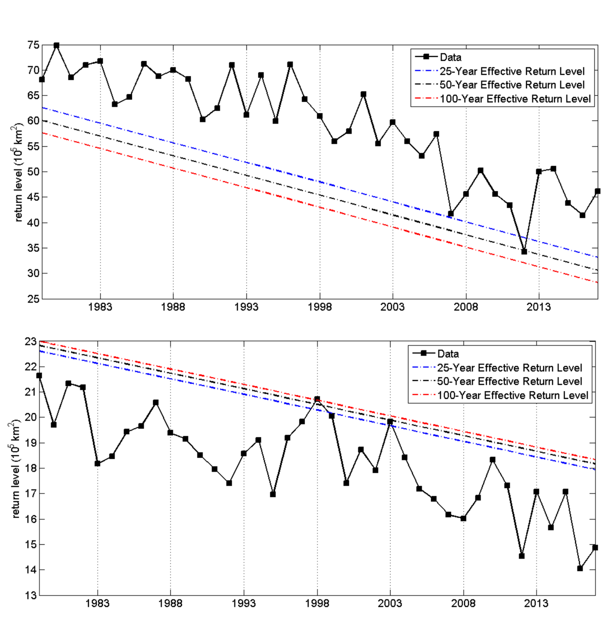


Fig. 3. [EXAMPLES] SIE minima as "block minimum" values of the whole NSIDC Arctic region (upper), and SIE maxima as "block maximum values of Kara and Barents Seas (lower), with the medians of return levels corresponding to some return periods (25, 50 and 100 yrs).

Cross-correlations between annual SIE maxima and minima and some relevant climate oscillations

Relevant modes of variability in the Arctic region are the Arctic Oscillation (AO), the Pacific North America pattern (PNA), the Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation (NAO) [4].
It was reasonable to look for significant correlations between SIE minima and maxima time series and the monthly indices of these climatic oscillations (AO, PDO and PNA). Besides, we also evaluated the cross-correlations with the Southern Oscillation (SO) given its importance in global climate variability; however, SO is indirectly linked to the PDO.

Tab. 3 shows the statistical significant (at α = 0.01) cross-correlations between annual SIE minima and maxima, and monthly AO, SO, PDO and PNA indices. The month of the index to which the correlation refers is placed in brackets. In Fig 4, the sub-regions having high cross-correlations ($\alpha = 0.01$) independently by the month, are shown.

Table 3. Cross-correlations (at $\alpha = 0.01$) between annual SIE maxima minima and AO, SO, PDO and PNA indices. In brackets the month of the corresponding oscillation.

Region	SIEMAX				SIEMIN			
	AOI	SOI	PDOI	PNAI	AOI	SOI	PDOI	PNAI
Baffin Bay/ Davis St./ Labrador Sea	0.48(Jan) 0.42(Mar)	−0.40(Oct)					0.43(Jul)	
Canadian Archipelago						−0.46(Nov) −0.45(Dec)	0.40(Aug) 0.45(Sep) 0.41(Oct)	
Chukchi Sea					0.50(Aug)			−0.40(Aug) −0.46 (Sep)
Beaufort Sea			−0.42(Jul) −0.41(Aug) −0.42(Sep) −0.46(Oct)					
Laptev Sea				0.43(Aug)				
East Siberian Sea					−0.53(Jan)			
North American Arctic Basin		0.40(Nov)	−0.49(Jul) −0.39(Aug)					
Russian Arctic Basin			−0.40(Jul)					
Greenland Arctic Basin								0.41(Oct) 0.40(Nov)
European Arctic Basin				0.41(Aug)				0.39(Dec)
Bering Sea			−0.49(Jan) −0.40(Feb) −0.46(Mar) −0.46(Apr) −0.48(May) −0.42(Jun) −0.41(Jul) −0.44(Aug) −0.44(Sep)					
Hudson Bay		0.39(Nov)	−0.40(Mar) −0.43(Jul) −0.40(Aug)			−0.40(Feb)		
Gulf of St. Lawrence	0.42(Mar)	−0.42(Aug) −0.55(Sep) −0.39(Oct) −0.41(Nov) −0.42(Dec)		−0.49(Mar)				
Non-regional ocean	−0.67(Jan) −0.40(Feb)		0.39(Jan)					

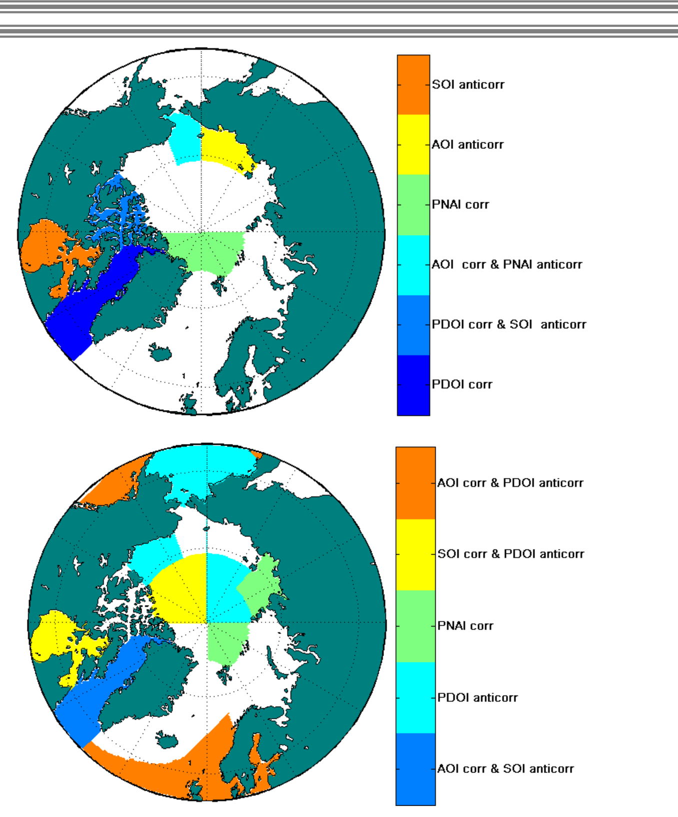


Fig 4. Maps of sub-regions having SIE maxima (lower) and SIE minima (upper) cross-correlations (at $\alpha = 0.01$) with at least one oscillation index, independently by the month.

Time span between SIE maxima and SIE minima for each sub-region

For each sub-region, the number of days from the SIE maximum (the most recent, if it is repeated) to the SIE minimum (the first one that appears, if it is repeated) was counted. More precisely, the counting was made on the smoothed daily SIE time series. Moreover, we fixed that the maximum had to be, at most, at the end of June, while the minimum only after the end of May; finally, if the time span resulted less than 40 days, it was set to zero. Again, linear trends were computed using Mann-Kendall test for trend and Sen's slope.

Table 4 gives the median, the IQR and the linear trend of the number of days (time span) for each sub-region.

Tab 4. Median, IQR and linear trends (LT) of time span (Δt) between SIE maxima and minima. In bold, the linear trend is statistically significant at $\alpha = 0.05$.

Region	Δt median (days)	Δt IQR (days)	Δt LT (days/yr)
Whole NSIDC Arctic region	192	14	-0.05
Greenland Sea	170	43	**-1.10**
Baffin Bay/Davis St./Labrador Sea	181	29	**-0.83**
Canadian Archipelago	117	15	0.33
Beaufort Sea	109	31	0.46
Chukchi Sea	127	31	0.47
East Siberian Sea	90	28	-0.13
Laptev Sea	107	22	0.17
Kara and Barents Seas	175	34	-0.25
North American Arctic Basin	69	77	**1.97**
Russian Arctic Basin	108	41	0.67
Greenland Arctic Basin	27	53	**-0.45**
European Arctic Basin	88	28	**0.83**
Bering Sea	143	30	-0.31
Hudson Bay	145	17	0.06
Sea of Okhotsk and Japan	121	18	0.10
Gulf of St. Lawrence	122	19	-0.22
Non-regional ocean	132	28	0.20
Lakes, extended coast	164	110	**-2.44**

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