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Sea Ice as an Essential Climate Variable from Remote Sensing and Modelling

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Sea ice covers the polar oceans on both hemispheres and it has a large seasonal variability. Sea ice is an important component of the climate system because it has a high surface albedo compared to open water, together with the polar surface water it insulates the relatively warm ocean from the cold atmosphere, and it forms a barrier to the exchange of momentum and gases such as water vapor and CO_2 between the ocean and atmosphere. Regional climate changes affect the sea ice characteristics and those changes can feed back on the climate system, both regionally and globally.

Systematic and long-term observations of the major sea ice variables is only possible using past and present satellite Earth Observation (EO) data. Sea ice data from satellites has been collected for more than four decades and sea ice mapping is one of the most successful applications of EO data in climate change studies. Several sensors and retrieval methods have been developed and successfully utilized to measure sea ice area, concentration and drift. There are also other sea ice parameters of importance for climate research such as thickness, albedo, snow cover, temperature, duration of the melting season, the density of leads/polynyas and the volume of ridges. [e.g. GCOS, 2010; IGOS, 2007]. Satellite remote sensing can contribute to retrieving quantitative measurements of most of these variables, even though GCOS defines sea ice in general as one **essential climate variable** (ECV). In order to provide quantitative data on sea ice it is necessary to define the variables that can be measured. For climate change studies it is generally accepted that the most important and mature variables, where quantitative data have been obtained over several decades, are ice extent (area), thickness, and drift.

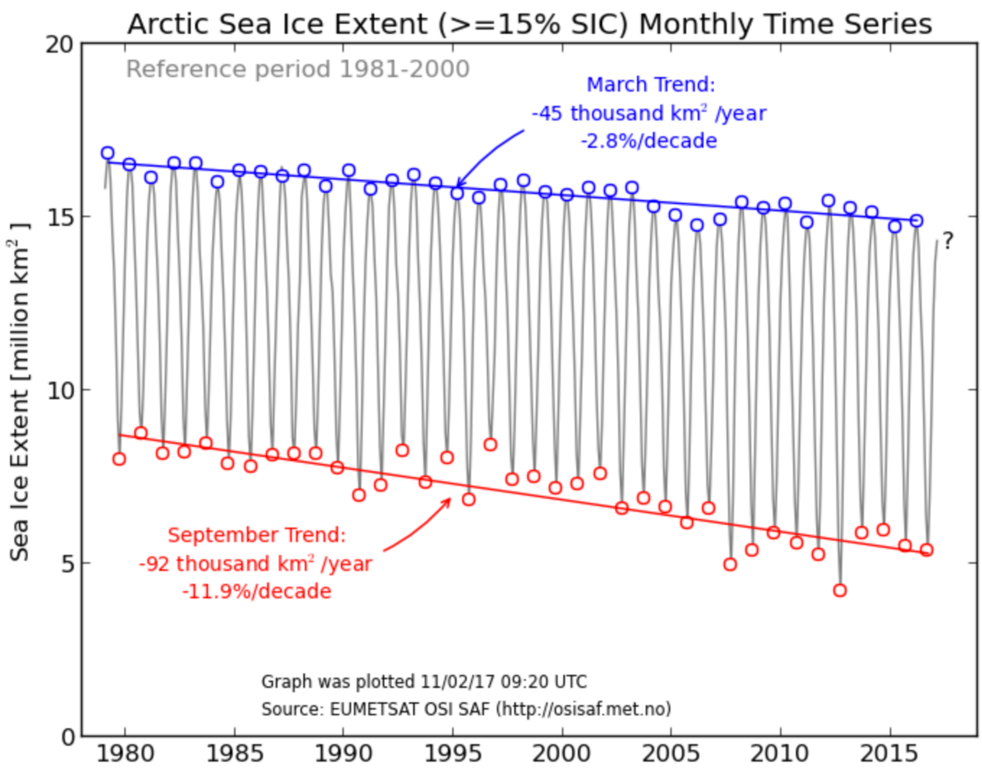
There is evidence that the polar amplification of global climate change affects the sea ice covers of the Arctic and the Antarctic in different ways – in line with contrasting observations of climate relevant parameters during the last decades. The most pronounced change in the Arctic sea ice over the last three decades is the reduction of the sea ice extent observed from time series of passive microwave data in particular the reduction of the summer ice (Fig. 1). This change is also observed in reduction of multiyear ice fraction (Fig. 2), the increase of the length of melt season and as well as in reduction of the ice thickness [e.g. Vaughan et al. 2013, Lindsay and Schweiger, 2015]. The reduction in Arctic ice thickness has been documented by combined observations from submarine sonar data, airborne surveys, in situ measurements and recently by satellite altimeter data from ICESat-1 and CryoSat-2 [e.g. Fig. 3, Kwok and Cunningham, 2015].

The integrated estimate of ice thickness reduction reported by IPCC is 0.62 m per decade, corresponding to about -19.4 % per decade (Table 1). An important aspect for the Arctic is that the thickness reduction is closely linked to the decline of the multiyear ice cover [Vaughan et al. 2013]. While ice extent has decreased at a rate of -3.8 % per decade, the multiyear ice cover has decreased by -13.5 % per decade (Table 1).

Table 1. Trends in Arctic sea ice.

Parameter	Change per decade	Parameter	Change per decade
Ice extent: annual mean	-3.8±0.3 %	Ice thickness (1980-2000, submarine)	-16.5 %
Ice extent: winter	-2.3±0.5 %	Ice thickness (2004-2008, IceSat)	-22.7 % per 5 years
Ice extent: spring	-1.8±0.5 %	Ice thickness (Integrated)	-19.4 %
Ice extent: summer	-6.1±0.8 %	Ice drift (winter average)	+ 10.6 ± 0.9 %
Ice extent: autumn	-7.0±1.5 %	Length of melt season (total)	+ 5.7 days/decade
Ice extent: MY fraction	13.5±2.5 %	Length of melt season (margins)	+10 days/decade

(ref. IPCC, Vaughan et al., 2013)



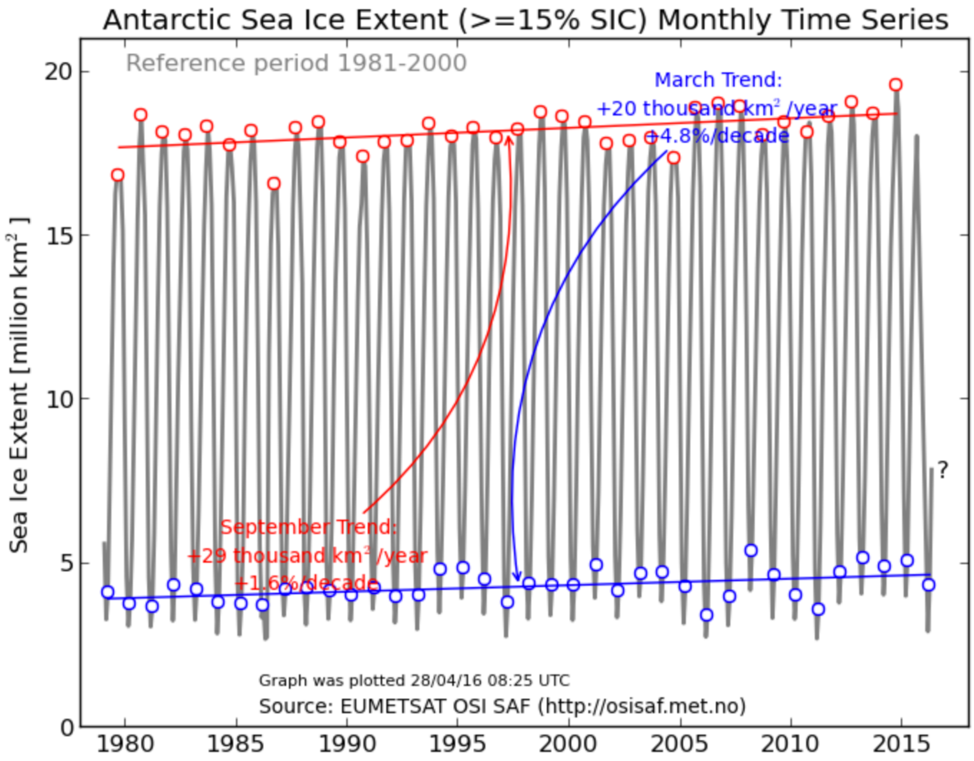


Figure 1. The trend and seasonal cycle of sea ice extent in the Arctic (upper graph) and Antarctic (lower graph) based on passive microwave satellite data from 1978 to present. The data are provided by the Eumetsat Ocean and Sea Ice Application Facility (http://osisaf.met.no).

The multiyear ice extent is a very sensitive climate variable that is not yet established as an ECV. The amount of multiyear ice is important to quantify because multiyear ice is thicker, it has thicker layer of snow and has different physical properties compared to first-year ice. Methods to derive multiyear ice fraction exist but a thorough investigation and quantification of the uncertainties involved has not been undertaken yet. Algorithms combining radiometer and scatterometer data have the potential to improve current time series of the multiyear ice extent. A longer high-quality time series of the multiyear ice extent is also required for improved sea ice thickness retrieval because it permits an improved choice of sea ice densities [Kern et al., 2015].

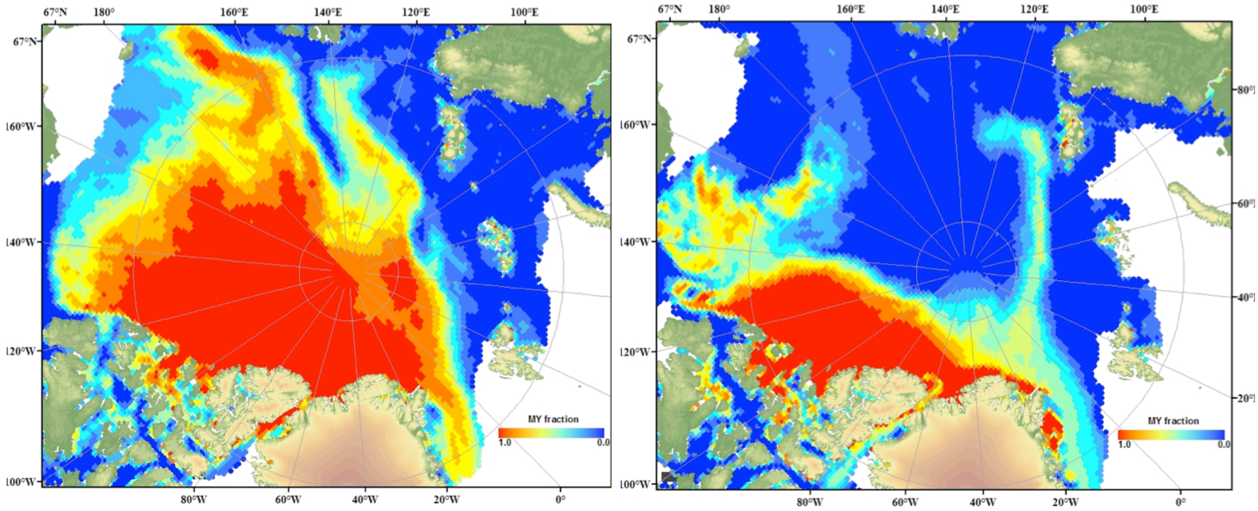


Figure 2. Multiyear fraction of sea ice concentration in the Arctic for March 2002 (left graph) and March 2008 (right graph). Red and yellow areas indicate where multiyear ice is dominating , while ble areas indicate firstyear ice. The maps are produced from scatterometer data from Quikscat available at http://nsidc.org.

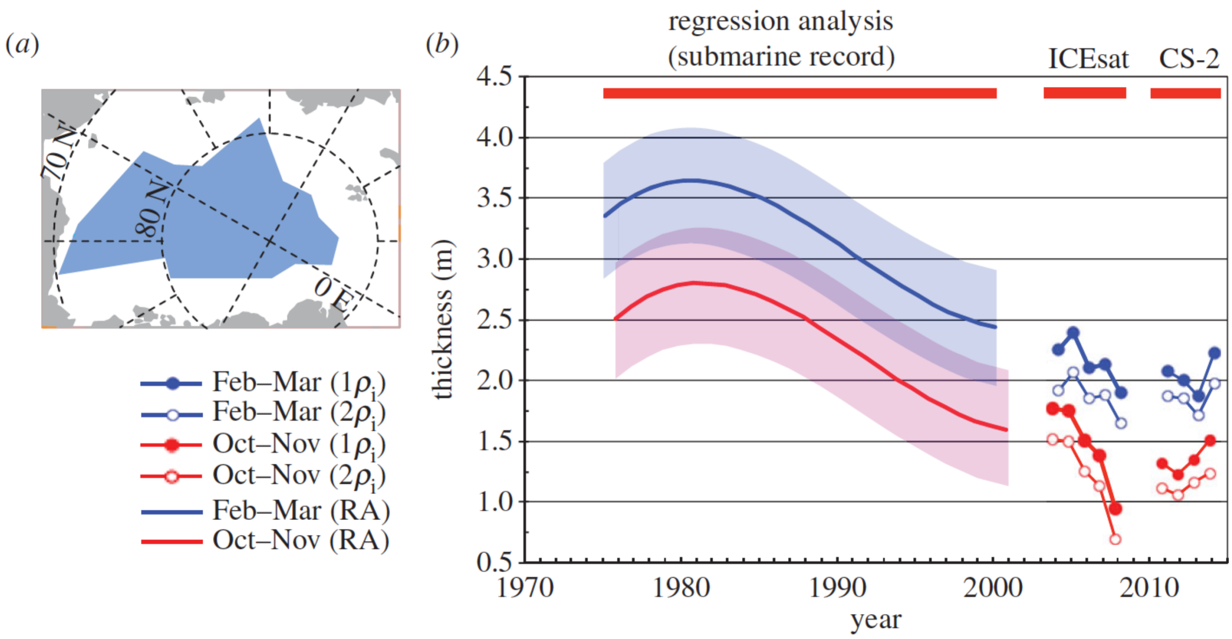


Figure 3. Average winter and autumn ice thickness from regression of submarine data, ICESat, and CryoSat-2 data. (a) data coverage area, (b) ice thickness decline between 1980 and 2014 (Kwok and Cunningham, 2014).

In the Antarctic, there is an increase in sea ice extent (Fig. 1), however, regional trends are diverse [Parkinson and Cavalieri, 2012]. Long, consistent, and error-characterized time series for the other parameters like thickness and drift as well as onset and length of melt season are not available. These are often less thoroughly analyzed and far less mature than their Arctic counterparts. The Antarctic sea ice is, on average, younger and hence thinner than Arctic sea ice while its snow load is, on average, thicker than on Arctic sea ice. As a consequence the large areas of the seasonal Antarctic sea ice have a sea ice freeboard, i.e. the part of the sea ice above the water line, which is close to zero if not even negative. Only the old, thick Antarctic sea ice or deformed seasonal sea ice can exhibit substantially larger sea ice freeboards.

Today operational sea ice monitoring and analysis is fully dependent on use of satellite data. However, new and improved satellite systems, such as multi-polarisation SAR, radar and laser altimeters, require further studies to develop more advanced sea ice remote sensing methods. In climate change studies based on satellite data, it is a major challenge to construct homogeneous time series from a series of consecutive satellite sensors needed for detection of changes over several decades [e.g. Meier et al. 2013]. At the same time there is progress in sensors and observation technology, which makes it possible to observe new parameters in the future.

It is important that the observational community works closely with the modeling community in order to communicate caveats and usefulness of satellite data products from the observational side and requirements to data and their importance from the modeling side. Available sea ice drift data are not necessarily free of inconsistencies due to changes in sensor technology used. Available sea ice thickness data may be based on sub-optimal assumptions.

The ESA CCI Sea Ice project, running from 2012-2018, represents an extensive effort to combine and extend ongoing research to develop improved and validated timeseries of ice concentration and ice thickness for use in climate research (http:// http://esa-cci.nersc.no/). Since sea ice is a sensitive climate indicator with large seasonal and regional variability, the climate research community requires long-term and regular observations of the key ice parameters in both Arctic and Antarctic. The project provides global data sets on ice concentration for Arctic and Antarctic, and ice thickness data sets for the Arctic, to support climate research and monitoring according to the GCOS requirements for generation of satellite-based data sets and products. This implies provision of data sets with associated metadata, software systems, technical documentation and scientific reports/publications.

A prototype ECV production system for ice concentration has been developed, which has been integrated in to the Eumetsat OSI SAF system by Met.no (http://osisaf.met.no). For ice thickness from radar altimetry, an operational processing system has been developed by AWI for ENVISAT and CryoSat data, as well as for Sentinel-3 data. The processing system is described in detail by Hendricks et al., 2016.

Improved satellite observations of the global sea-ice cover are required by the GCM mainly for two applications: First, the improved observations allow researchers to more accurately monitor and quantify past and ongoing changes in the ice cover. Second, these observations are needed to improve the quality of numerical models that aim both at understanding the drivers for past sea-ice changes and at estimating the future evolution of the sea-ice pack (Fig. 4). The main objective of involving the global climate modeling community deals with this second application: we will answer the question to what extent the improved satellite observations allow us to also improve the representation of sea-ice in coupled Earth-System Models (ESMs) and in turn to what extent modern Earth-System Models allow us to improve the quality of the observational record

In addition to the climate modelling community, there are other climate research groups who need sea ice ECV data. These include scientists working with sea ice data assimilation in regional models, scientists working with creation of longer time series of sea ice data, by combining historical records with modern satellite data, and scientists developing new observing systems using aircraft, in situ and under-ice platform to collect various sea ice data that are complementary to EO data and can be used for validation of the EO-retrievals. The polar regions are severely undersampled regarding observational data for climate research. It is therefore of high priority to improve the collection and retrieval of climate parameters from both EO and non-EO observations. With access to regular sea ice data in the polar regions, it will be possible to use data assimilation for reanalysis and improvement of the climate models in the polar regions. Data assimilation has been proven to be a useful tool in atmospheric and ocean modeling for many years, but assimilation of sea ice data has only started recently.

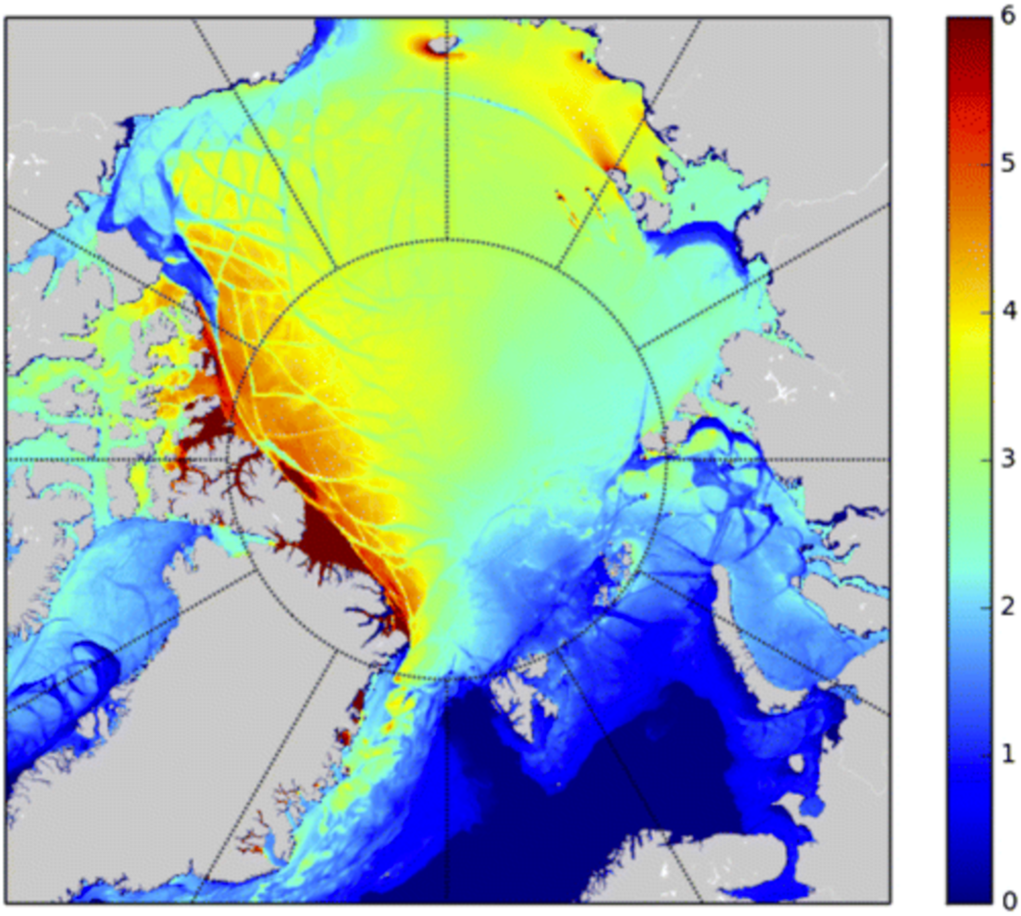


Figure 4. Sea ice thickness (m) on 30 Mar 2001 as simulated by the MITgcm (sea ice–ocean model forced with reanalysis data) at a horizontal resolution of about 4 km (Jung et al., 2016). The simulation is very similar to the one described in Nguyen et al. (2012).

In recent years, Arctic sea ice has been retreating at a rate much faster than that projected by the Earth-System Models (ESMs) used for the last IPCC report. Overcoming this discrepancy is crucial for an improved modelling of the future evolution of the sea-ice cover and will therefore be the ultimate aim for involvement of the GMC.

It will be particularly important to be in dialogue with the group of scientists working in the Climate Model Intercomparison Project. This group plays a key role to analyze climate model results for the Arctic and Antarctic and provide input to the IPCC reports. The ESA CCI Sea Ice project will be completed in early 2018.

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