Satellite thermal microwave sea ice concentration algorithm comparison

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ABSTRACT:
Seven of the most common radiometer algorithms, used to compute the sea ice concentration, are compared to ScanSAR data estimates of ice concentration. Our focus is on the near 100% ice cover in winter. The sensitivity of the algorithms to the variable sea ice surface emissivity and temperature is the most significant hindrance for correct estimates of ice concentration in this ice regime. The skill of the best radiometer algorithms is significantly better than the worst set, but all correlate poorly to and display higher variability than the SAR data at high ice concentrations. On a climatological time scale the differences between algorithms amounts to 14% and 22% of the down-going trend in winter Arctic sea ice extent and area, respectively. The climatological changes in atmospheric and water surface emissivity primarily affects the extent trend while the changes in sea ice surface emissivity affects the sea ice area trend.

1 INTRODUCTION

The use of thermal microwave data for mapping the sea ice extent and area is perhaps the most successful application of satellite remote sensing for sea ice monitoring. Today time-series, covering the arctic regions daily from the early 1970s, are most significant for estimating inter-annual and decadal trends in this important climate parameter. Applications also include climate oriented coupled general circulation and numerical weather prediction models. These data are important input to numerical sea ice models where the ice thickness is estimated. Ice concentration is not directly linked with ice thickness, but the minimum ice extent in summer is a measure of the amount of thick multiyear ice. The reduction over the past decades in the multiyear ice extent is an indication of an ongoing climate change process that affects the ice thickness as well.

"…a thick slab of arctic pack ice reduces the wintertime sensible heat loss from ocean to atmosphere by a factor of 100 to 1000, compared to fluxes from open water." (Moritz, 1988, p. 1). Even small changes in the sea ice concentration thus have a significant impact on energy fluxes between the ocean and the atmosphere, i.e. a change from 100% to 99% may double the fluxes. Once sea ice cover the ocean surface, the impact of ice thickness on heat flux is relatively small. From a climate change perspective, the key question is how fast the

total volume of sea ice is changing. This requires reliable estimates of ice concentration for the derivation of the sea ice area. Therefore, ice concentration is an important ice cover parameter and must be estimated accurately (Steffen & Schweiger, 1991). The Mean accuracy of some of the more common algorithms, used to compute ice concentration from SSM/I data, such as NASA Team (Cavalieri et al., 1984) and Bootstrap (Comiso, 1986) are reported to be 1-6 % in winter (Steffen & Schweiger, 1991; Emery et al., 1994; Belchansky & Douglas, 2002). These uncertainties are in general caused by atmospheric opacity, wind roughening of open water areas, sensor noise and anomalous ice surface emissivity.

Acronym	Algorithms	Channels used	Tie-points ref.	Reference
BRI	Bristol	19V, 19H, 37V, 37H	Comiso et al. (1997)	Smith (1996)
CF	Bootstrap frequency mode	19V, 37V	Comiso et al. (1997)	Comiso (1986)
CP	Bootstrap polarisation mode	37V, 37H	Comiso et al. (1997)	Comiso (1986)
N90	Near 90 GHz algorithm	85V, 85H	Kaleschke et al (2001)	Svendsen et al. (1987)
NT	NASA TEAM	19V, 19H, 37V	Comiso et al. (1997)	Cavalieri et al. (1984)
NT2	NASA TEAM2	19V, 19H, 37V, 37H, 85V ,85H	Markus and Cavalieri (2000)	Markus and Cavalieri (2000)
TUD	Technical University of Denmark hybrid	19V, 37V, 85V, 85H	Pedersen (1998)	Pedersen (1998)

Table1
Radiometer ice concentration algorithm overview and their acronyms used in the text.

Each of the algorithms may perform better under certain conditions (Emery et al., 1994). Their sensitivity to emissivity and thermometric temperature of the target depends on the selection of brightness temperatures at different polarisations and frequencies (Comiso et al., 1997). The computed ice concentration accuracy is further degraded by particular atmospheric constituents like cloud liquid water, where NASA Team ice concentration can increase by erroneously by 10 % (Oelke, 1997), and changes in the ice emissivity, where the computed concentration can be depressed by about 20 % (Tonboe et al., 2003). The sensitivity of the different ice concentration algorithms to the two main error sources in the ice covered ocean, i.e. atmospheric- and ice brightness temperature variability, is not the same. Here a set of seven different sea ice concentration algorithms are compared with wide swath SAR. The analysis draws largely on the results presented in Andersen et al. (2006) and focuses on the near 100% ice cover, typical for the Arctic Ocean in winter. The ice concentration algorithms considered, their acronyms and channel combinations are summarised in table 1. Note that the NT2 algorithm is also run in a modified version, NT2u, that allows solutions to be found in an extended concentration interval [0%,120%]. This is to capture the full variability of the retrievals at the 100% limit.

2 OBSERVING SEA ICE CONCENTRATION WITH SPACE-BORNE RADIOMETERS

Microwave radiometers have continuously monitored arctic regions daily since the 1970s. The spectral and polarisation information makes it possible to derive the ice concentration for every pixel independently. Other data can be used to monitor ice concentration, e.g. visual or infrared scanner (VIS/IR) and SAR data. The use of VIS/IR is limited by cloud cover and the visual data further by darkness (during winter). The coverage is therefore not continuous and in some regions it is only sporadic. The coverage with SAR in the Arctic Ocean is not continuous and the classification of the data still requires manual guidance. SAR data are very useful in case specific comparisons, such as this study.

Reliable estimates of atmospheric cloud liquid water and the ice brightness temperature variability are not readily available and it is therefore important to find ice concentration algorithms that are least sensitive to these atmospheric and surface properties. Other parameters, such as atmospheric water vapour and open ocean surface wind, are quantified rather well by numerical weather prediction models. It is therefore feasible to correct brightness temperatures for the influence of these effects using radiative transfer models before computing the ice concentration (Breivik et al. 2001). This is not done here since we would like to evaluate the true natural variability of different ice concentration algorithms.

3 COMPARISON OF RADIOMETER ICE CONCENTRATION WITH SAR DATA

During winter, the variability of the SSM/I concentration estimates in the perennial ice is larger than the true variability of the ice concentration (Kwok, 2002). This is confirmed by extensive SAR comparisons in Andersen et al. (2006). The ice concentration estimates from the seven algorithms within the near 100% ice cover have large regional differences. Figure 1 shows these differences. The N90, NT2U, NT and CP have a negative bias stretching from the Fram Strait across the North Pole. The CF has a negative bias near land, e.g. north of Greenland and Canada. These depressions are consistent while other patterns change from year to year.

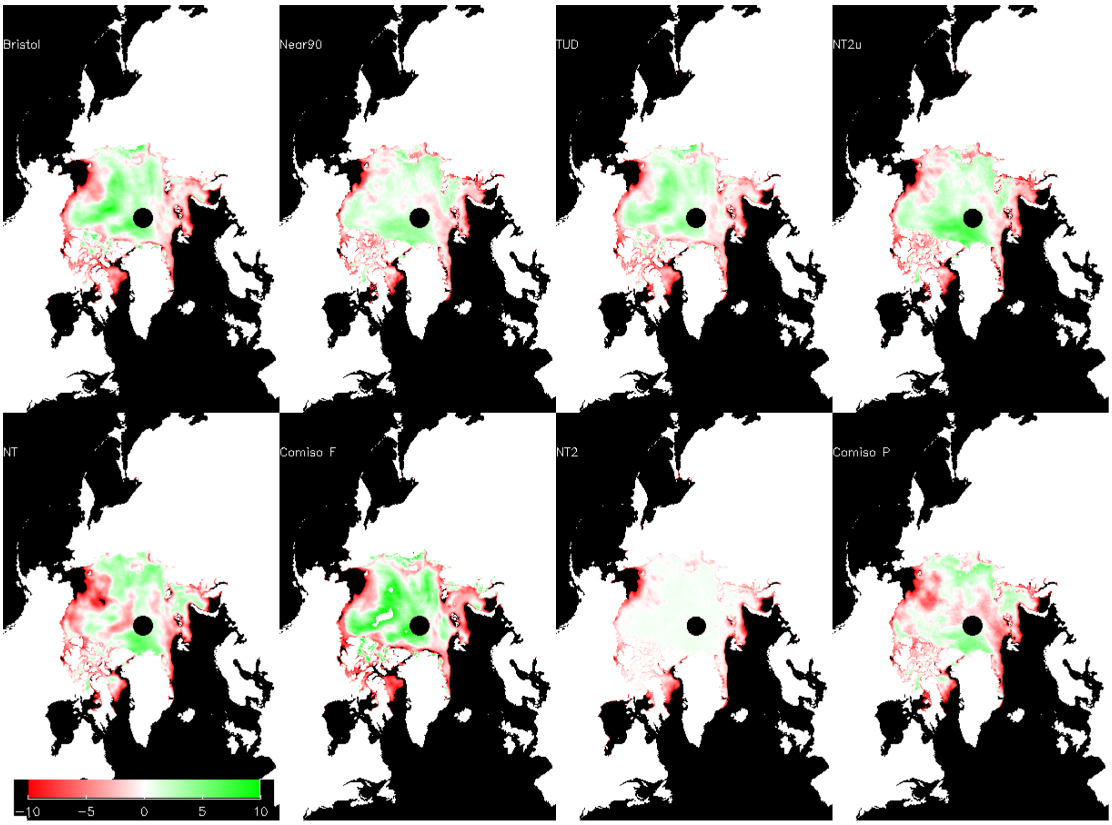

Figure 1
Radiometer ice concentration anomalies Σ(daily field - seasonal average) winter 2003-2004 for the 7 different algorithms and the 2 versions of the NT2 algorithm.

The ice concentration estimates from the seven different algorithms are compared to SAR data classified into areas of ice and open water. The RADARSAT-1 and ENVISAT SAR wide swath scenes from 2003 and 2004 in locations with near 100% ice cover are distributed geographically across the Arctic. 68 scenes were analysed and 59 scenes were found to be useful after classification and masking. Trained ice analysts from the operational Greenland ice service did the selection of useful scenes and the classification procedure. Andersen et al. (2006) describes the details. Figure 2 shows the correlation between the SAR and radiometer derived ice concentrations. The correlation coefficient between the datasets is about 0.9 at lower concentrations giving justification to both methods in this ice regime. However, at higher concentrations this high correlation is reduced. In the near 100% ice regime, assuming a constant ice concentration actually matches SAR ice concentrations better than radiometer ice concentrations. The color code in Figure 2 shows that the small correlation coefficient at high concentration is not only dependent on the smaller variability of the SAR concentrations.

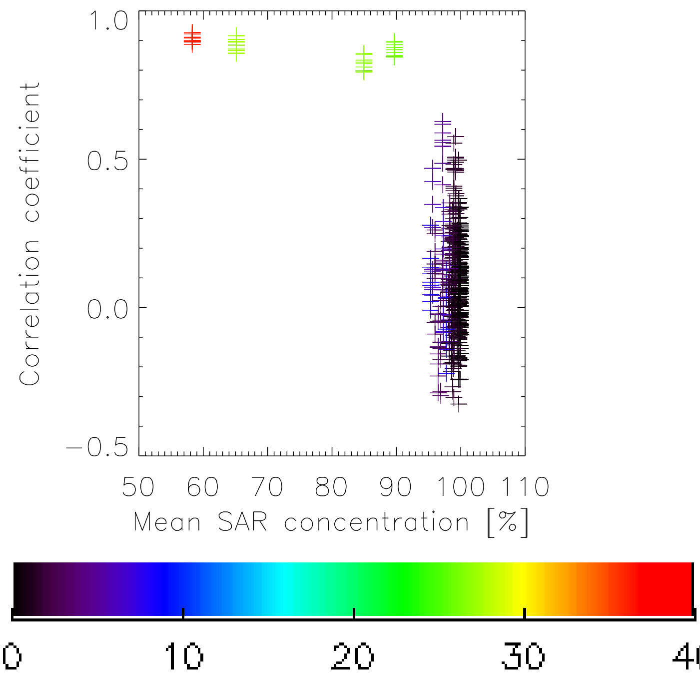

Figure 2
Scene correlations between SAR and SSM/I derived ice concentrations as function of average SAR scene ice concentration. Colour is assigned according to the standard deviation of the concentrations within the SAR scene.

Table 2 shows the results of the comparison in the winter Arctic Ocean where ice concentrations are near 100%. The SAR ice concentration estimate is 99.7% for this dataset with a STDEV of only 0.7 for coincident pixels. Error standard deviations (STDEV) from the seven algorithms range from 2.5-4.9%. The correlation coefficient is not a meaningful measure with the near constant SAR concentration. The primary error source in these comparisons are the thin ice types whose radiative properties mimic a mixture of sea ice and water in most radiometer ice concentration algorithms and is ambiguous in the SAR data. The SAR concentrations are biased towards high variability by the misclassification of thin ice as open water. Even then, the variability of the SAR ice concentrations is significantly lower than the radiometer ice concentrations STDEV. Therefore, the high STDEV of the radiometer ice concentration cannot be explained only by sea ice concentration variability. The fact that the 85GHz algorithms, i.e. N90 and TUD, have lower STDEV than algorithms using 19 and 37GHz channels indicates that atmospheric variability is not significant. It suggests that it is the ice emissivity variation that leads to the high radiometer ice concentration STDEV. The skill of the best radiometer algorithms including TUD, N90 and Bristol are significantly better than the worst set including the CP, CF and NT, but none of them seems adequate at high concentration.

	Average	**Stdev**	**No. obs.**	
SAR (lores):	99.7	0.7	3669	
	Bias	**Error stdev**	**Correlation**	**Sensor noise**
BRI	2.1	3.0	-0.02	1.4
CF	3.5	4.6	-0.10	1.7
CP	-0.3	4.9	0.11	1.8
N90	-2.1	3.9	0.10	2.6
NT	-1.5	4.5	0.21	1.7
NT2	-0.4	1.4	0.03	1.7
NT2u	6.9	4.7	0.07	1.7
TUD	4.4	2.7	0.05	2.5

Table 2
Comparison between coincident SAR and SSM/I radiometer ice concentrations. The SAR scenes are all located inside the Arctic Ocean from November 2003 to April 2004.

4 SEA ICE EXTENT AND AREA TRENDS

Trends in sea ice extent and area use the radiometer ice concentration data from the 1970s to the present day. Parkinson et al. (1999), using the NT, show that the Arctic sea ice extent and area are shrinking by -34000 km^2/yr and -29300 km^2/yr respectively. The ice area is the sum of all ice concentration pixels multiplied by the area of these pixels while the extent is the extent of ice pixels. At the same time the arctic atmosphere and sea ice surface properties are changing. Different satellite microwave radiometer ice concentration algorithms used to map sea ice extent and area have different sensitivities to the atmosphere and the ice surface properties. The sea ice trend mapped with different algorithms is therefore different. The ice surface emissivity variability is in fact the primary error source for the microwave radiometer ice concentration estimate over the near 100% ice cover in the Arctic Ocean. Figures 3 show the sea ice area and extent trends using SSM/I time series and the 7 different algorithms. The independent variations between the algorithms are larger for ice area than extent consistent with the more complicated sensitivities to trends in ice surface parameters, that influence the ice area estimates. In constrast it is mainly atmospheric humidity and water surface roughness that affects the extent. The long time series trend including all SSM/I data (1987-2004) shown with grey bars in figures 3 a) have a smaller annual ice area reduction than the shorter time series trend with functional 85GHz channels on SSM/I (1991-2004) shown with black bars indicating that the reduction has accelerated. For example the Bristol extent trend is -32700km2/yr and -46900km2/yr for the long and short period respectively. Similarly the area trend is -27400k2/yr and -41100km2/yr, respectively.

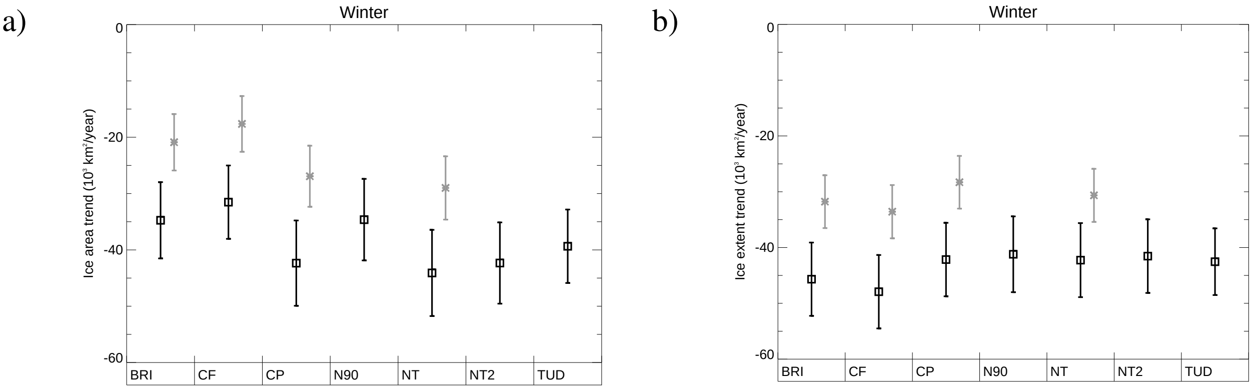

Figure 3
Observed trends in a) ice area and b) ice extent during winter (Oct. – Apr.) for the SSM/I dataset excluding the F8 satellite (1991-2004, black) and the entire dataset (1987-2004, grey). The 85GHz channels were not reliable on F8. Bars show ±1 STDEV.

To study the accelerated retreat, 35 years of average monthly sea ice extent is constructed from two datasets: 1) the 30 year record of Cavalieri et al (2003), and 2) the continuously updated sea ice index at the NSIDC (Fetterer and Knowles, 2002 updated 2006). The first record includes the ice extent derived from the Nimbus 5 Electrically Scanning Microwave Radiometer (ESMR) and the National Ice Center (NIC) digital sea ice data set as well as SMMR and SSM/I data. The second record is based on SMMR and SSM/I data only. The overlap of both records was used to merge both datasets by fitting mean and standard deviations. This new merged record goes from January 1972 to July 2006. The sea ice eextent increase slightly during the 1970's, reaching its maximum in 1978, the same year when the first space borne multi-channel microwave instrument, SMMR, was launched. The trends are highly dependent on the selected period. Changing the starting point of the linear trend calculations from 1972 to 1987 results in an accelerated rate of retreat of approximately 8000 km^2/y, whereas the change in period from 1991-2004 to 1996-2006 results in a change in rate of 39000 km^2/y. This change is large in comparison to the differences between algorithms recorded above and is mainly the result of the large near present accelerated reduction.

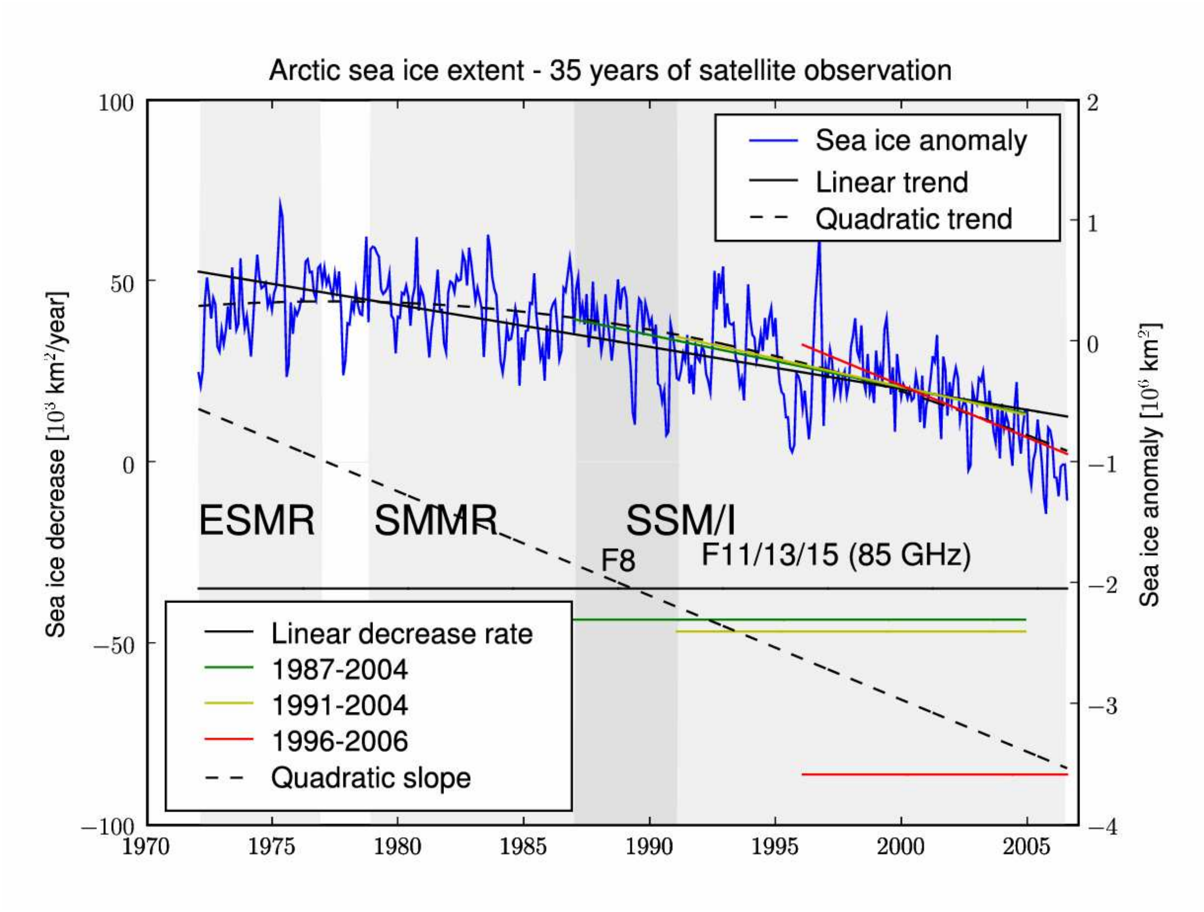

Figure 4
Observed sea ice extent anomaly over the combined ESMR, SMMR and SSM/I time series. Linear trends with different start and end points as well as a quadratic fit to the extent anomalies are shown along with their associated rate of decrease.

5 CONCLUSIONS

For all algorithms during winter, the STDEV exceed the STDEV of the coincident SAR ice concentrations and there is no correlation between the datasets at high concentration. In the perennial winter sea ice, the prevailing ice concentrations are very high (>99%) and the variability in radiometer ice concentration is mainly due to variations in ice brightness temperature. In this ice regime, a constant ice concentration actually matches SAR ice concentrations better than radiometer ice concentrations. However, at intermediate concentrations, the correlation between SAR and radiometer is between 0.8 and 0.9.

Analysis of the entire SSM/I time series (1987-2004) shows that there are significant differences between trends in both area and extent using the 7 different radiometer ice concentration algorithms. All algorithms compute a significant ice retreat consistent with earlier studies. For the ice extent trend the algorithm sensitivity to atmosphere seems crucial for the differences. The differences between the CF and N90 extent trend amounts to 14% of the total down-going trend in winter. The differences between the N90 and NT area trend are 22% of the total trend in winter. The differences are similar for extent if summer data are included but the differences in area trend (NT and N90) are smaller 16%. This indicates that all algorithms have comparable (poor) skills during summer melt.

Applications using ice concentrations within the perennial ice during winter, e.g. for estimation of ice volume and in numerical weather prediction modelling, should not rely exclusively on radiometer ice concentrations. Since the high ice concentration variability is primarily due to ice brightness temperature variations, high-resolution observations such as SAR and VIS/IR observations should be important supplements. Particular care should be exercised when temporal trends are analysed, since the trends in radiometer ice concentrations are significantly different depending on the algorithm. However, it is beyond discussion that the Arctic ice extent and area is retreating and is doing so with an increased pace in later years. In the past, much effort has been invested in the development of radiometer sea ice concentration algorithms with low sensitivity to atmospheric opacity and open water roughness. In the near future, it is necessary to minimize sensitivity to ice surface brightness temperatures at high ice concentrations. In the longer term it should be investigated if the wide spectral range on AMSR and the fully polarimetric WindSat may be useful in distinguishing surface emissivity effects from true ice concentration variations.

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