Popular Summary: Much of what we currently know about the large scale variability of and trends in the global sea ice cover has been based on data provided by satellite passive microwave sensors. While large changes in the sea ice cover have been observed during the satellite era, uncertainties in the trends have been difficult to assess because of the lack of adequate validation data. With the launched of the Advanced Microwave Scanning Radiometer in May 2002 on board the EOS-Aqua satellite (referred to as "AMSR-E"), however, ability to assess the accuracy of historical data has improved considerably because of much better resolution and hence accuracy in the former. This study shows that during the overlap period from June 2002 to 2006, highly consistent ice concentration maps can be derived from both AMSR-E and SSM/I data if the two data sets are inter-calibrated and the same algorithm is used to derive geophysical parameters. The ice extent estimates from SSM/I data, however, are consistently higher than those from AMSR-E while the ice area estimates are almost identical. This is shown to be caused by more precise definition of the ice edge provided by AMSR-E compared to that of SSM/I due to better resolution. Since the data record of AMSR-E is too short at less then 5 years, change studies using AMSR-E data can only be done if the latter are combined with historical satellite data. We show that this can be done successfully for ice area without any normalization of the data. It can also be done with ice extent through proper normalization of SSM/I and SMMR data. The estimates for trends in ice extent and ice area from the resulting data sets are shown to be consistent with those derived from historical data. The higher accuracy of the AMSR-E data, however, provides improved reliability in the data set and greater confidence in the trend values.

Significant Findings: With higher resolution and improved accuracy, AMSR-E data provide a good baseline for sea ice cover studies and can be used to validate geophysical parameters derived from historical data. Comparative studies of AMSR-E and SSM/I data during the 5 year period of overlap shows basically good consistency in the derived geophysical products. The most serious source of discrepancy is in the characterization of the ice edge and marginal ice zone in which AMSR-E clearly show improvements because of higher resolution. Thus SSM/I shows an ice edge location that is on the average about 6 to 12 km further away from the ice pack than AMSR-E data. Biases if uncorrected contribute to errors in the estimates of trends in extents by as much as 0.62%/decade in the Arctic and 0.26%/decade in the Antarctic. The biases in the trends of ice area are less with the error in the trend being at 0.30%/decade in the Arctic and 0.05%/decade in the Antarctic. Using time series data from SMMR, SSM/I and AMSR-E (starting June 2002) and after correcting for the aforementioned bias, the results of our regression analysis for period from November 1978 to December 2006 yielded trends in extent and area of sea ice in the Arctic region are -3.4 ± 0.2 and -4.0 ± 0.2 % per decade, respectively. The corresponding values for the Antarctic region are 0.9 ± 0.2 and 1.7 ± 0.3 % per decade. These trends are basically the same as those derived using SMMR and SSM/I data only, but with AMSR-E providing more accurate values for the last few years of the data set, the degree of confidence in the trend is higher with the latter included. With time, the data from AMSR-E and similar instruments will increase the reliability of the trend values.

Title: Trends in the Sea Ice Cover using Enhanced and Compatible AMSR-E, SSM/I and SMMR Data

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Abstract

Arguably, the most remarkable manifestation of change in the polar regions is the rapid decline (of about -10 %/decade) in the Arctic perennial ice cover. Changes in the global sea ice cover, however, are more modest, being slightly positive in the Southern Hemisphere and slightly negative in the Northern Hemisphere, the significance of which has not been adequately assessed because of unknown errors in the satellite historical data. We take advantage of the recent and more accurate AMSR-E data to evaluate the true seasonal and interannual variability of the sea ice cover, assess the accuracy of historical data, and determine the real trend. Consistently derived ice concentrations from AMSR-E, SSM/I, and SMMR data were analyzed and a slight bias is observed between AMSR-E and SSM/I data mainly because of differences in resolution. Analysis of the combine SMMR, SSM/I and AMSR-E data set, with the bias corrected, shows that the trends in extent and area of sea ice in the Arctic region is -3.4 ± 0.2 and -4.0 ± 0.2 % per decade, respectively, while the corresponding values for the Antarctic region is 0.9 ± 0.2 and 1.7 ± 0.3 % per decade. The higher resolution of the AMSR-E provides an improved determination of the location of the ice edge while the SSM/I data show an ice edge about 6 to 12 km further away from the ice pack. Although the current record of AMSR-E is less than 5 years, the data can be utilized in combination with historical data for more accurate determination of the variability and trends in the ice cover.

1. Introduction

Much of what we currently know about the large scale variability of the global sea ice cover has been based on data provided by satellite passive microwave sensors (Parkinson et al., 1999; Bjorgo et al., 1999; Zwally, 2002). This capability for studying the sea ice cover has recently been improved considerably with the launched of the Advanced Microwave Scanning Radiometer in May 2002 on board the EOS-Aqua satellite (referred to as "AMSR-E") and in December 2002 on board Midori-2 (called "AMSR"). In this paper, we will use results primarily from AMSR-E which is the only sensor of the two that is currently providing data because of the unexpected power failure in the Midori-2 satellite after 9 months of operation. The improvements of AMSR-E over the Special Scanning Microwave Imager (SSM/I), which has been the primary source of data since July 1987, include higher resolution at all frequencies, wider spectral range, and less radiometer noise. In particular, AMSR-E has integrated field-of-views of 26.2 by 16.5 km and 13.7 by 10.3 km with its 18.7 and 36.5 GHz channels for mean resolutions of 21 and 12 km, respectively. On the other hand, SSM/I has integrated field-of-views of 70 by 45 km and 38 by 30 km with its 19.35 and 37.0 GHz channels for mean resolutions of 56 and 33.8 km, respectively. AMSR-E scans conically with a swath width of 1450 km at an incidence angle of 55° while SSM/I scans with a swath width of 1390 km at an incidence angle of 53.1°. The wider swath for AMSR has enabled almost complete coverage near the poles where data are usually missing due to satellite inclination. Also, AMSR-E has twelve channels from 6 GHz to 89 GHz, while SSM/I has only 7 channels from 19 GHz to 85 GHz. The lower frequency channels (6.9 and 10.65 GHz) of AMSR-E provide the ability to retrieve Sea Surface Temperature (SST) and Surface Ice Temperature (SIT) that are useful not only as climate data sets but also in removing ambiguities in the retrievals due to atmospheric and surface temperature effects. Furthermore, the higher resolution minimizes the uncertainties associated with the use of mixing algorithms to retrieve geophysical sea ice parameters.

The polar regions are expected to provide early signals of a climate change primarily because of the so called "ice-albedo feedback" which is associated with the high reflectivity of ice and snow covered areas compared to ice free areas. Recent reports have indeed shown that the perennial ice cover in the Arctic has been declining at a rapid rate of about 10 % per decade (Comiso, 2002; Stroeve et al., 2004, Comiso, 2006). While this has led to speculations of an ice free Arctic in summer within this century, hemispherical changes including those from seasons other than summer have been more modest at about 2 to 3% per decade (Bjorgo et al., 1997; Parkinson et al., 1999; Serreze, 2000). Moreover, in the Antarctic, the trend is also modest but in the opposite direction (Cavalieri et al., 1997; Zwally et al., 2002). The significance of estimates in the trends, have not been fully evaluated because of unknown uncertainties in the parameters derived form historical satellite data. A key problem is that data from a number of different sensors have to be assembled together to make up the historical time series of satellite data we currently have. There are also mismatches in calibration and resolution and there are no measurements that can be used to assess the true large scale characteristics of the sea ice cover and evaluate the accuracy of existing ice data.

The launch of AMSR-E is thus timely in this regard in that the data provide the much needed baseline for evaluating the historical record of satellite ice data including the validity of aforementioned trends. Although the time series of AMSR-E data is still short it can also be used in conjunction with historical data to obtain even more accurate trend values. Analysis of

AMSR-E data benefits from the availability of the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Aqua satellite which provides concurrent observations of the same surface as AMSR-E at a much higher resolution (250 m) during clear skies conditions. Preliminary studies have shown that ice characterization from AMSR-E agrees favorably with those MODIS data in the visible channels obtained during clear sky conditions (e.g., Comiso, 2004).

2. Consistent Retrieval of Sea Ice Concentrations

The spatial distributions of sea ice in the two hemispheres are quite different in that sea ice is surrounded by continental land masses in the Northern Hemisphere while in the Southern Hemisphere, it is sea ice that surrounds a land mass, which in this case is continental Antarctica (Figure 1). In the winter, the Arctic basin is basically covered by consolidated ice that is more confined, thicker and colder than those in the Antarctic. In the Arctic, a large fraction of the ice floes survives the summer melt and can be as old as 7 years (Colony and Thorndike, 1985), while in the Antarctic, it is rarely the case that an ice floe is older than 2 years, the reason being that the ice that survives the summer melt in the region usually gets flushed out of the original location and to the warmer waters by strong ocean currents (e.g., Weddell gyre) during autumn and winter. Also, the impact of divergence on Antarctic sea ice is stronger than in the Arctic because of the lack of an outer boundary in the former, causing more and larger leads and basically more new ice than in the former.

Sea ice is an inhomogeneous material consisting of ice, brine, air pockets, and other impurities, the relative percentages of which are different depending on formation conditions and history of the ice (Weeks and Ackley, 1986; Tucker et al., 1992; Eicken, 1991). We now know that these inhomogenieties affect the dielectric properties of sea ice in the two regions and hence the emissivity or radiative characteristics (Vant et al., 1974; Grenfell, 1992). Hemispherical differences in environmental conditions thus make the radiative signatures of sea ice in the Arctic generally different from those in the Antarctic. This leads to differences in the brightness temperatures as measured by passive microwave sensors, especially for consolidated ice, making it necessary to use different input data for the sea ice algorithms used to retrieve sea ice parameters in the two hemispheres (Comiso et al., 2003a; Comiso, 2004).

Among the most basic geophysical cryospheric parameters that are derived from passive microwave data is sea ice concentration. Sea ice concentration, C_I, has been defined as the percentage fraction of sea ice within the field of view of the sensor. Such percentage has been calculated using a linear mixing equation (Zwally et al., 1983) given by

$$T_B = T_I C_I + T_O(1-C_I) \qquad (1)$$

where T_B is the observed brightness temperature while T_I and T_O are the brightness temperature of sea ice and open water, respectively, in the region of observation. The sea ice algorithms are formulated with a goal of estimating T_I and T_O within the satellite footprint as accurately as possible. In the Rayleigh-Jeans' approximation, the brightness temperature of a surface is equal to its effective emissivity multiplied by the physical temperature of the emitting surface. The equation (1) suggests that data from only one channel is required but ability to obtain the appropriate T_I and T_O values would be limited because of known spatial and temporal variability of emissivity and temperature within the ice pack (Comiso, 1983; Parkinson et al., 1987; Comiso, 1995). The advent of multichannel systems, such as SMMR, allowed the development of algorithms that circumvents this problem (Cavalieri et al., 1984; Svensen et al., 1984; Swift et al., 1986; Comiso, 1986). Such algorithms have been further refined to take advantage of the added capabilities of the AMSR-E sensor (Markus and Cavalieri, 2000; Comiso et al., 2003). This study makes use of the Bootstrap algorithm, that utilizes the 19 and 37 GHz channels at vertical polarization and the 37 GHz channels at horizontal polarization for both hemispheres, as described in Comiso(2004).

Change studies, especially in relation to climate, require as long historical record as possible. Unfortunately, current record on global sea ice cover data has not been that long since such data did not exist until the advent of the satellite era. The era started with the Nimbus-5/Electrically Scanning Microwave Radiometer (ESMR) which was launched in December 1972 and was the first microwave imaging (or scanning) system. The sensor is a one-channel system with a peak frequency of about 19 GHz and acquires data at variable incidence angles (since scanning is done cross-track). The more current sensors like SMMR, SSM/I and AMSR-E are conically scanning sensors that acquire data at fixed angles thereby making the latter easier to interpret and to be used in the retrieval of geophysical parameters. The ice concentrations derived from the ESMR sensor are thus not as accurate as those from the other sensors mainly because single channel data do not provide the means to resolve ambiguities associated with the presence of many ice types that have different emissivities. Furthermore, the ESMR data set has lots of gaps (sometimes several months for each year) because of hardware related problems. While ESMR provided some useful sea ice data during the 1973 to 1976 period, trend studies of the sea ice cover usually starts with the SMMR data and covering the period from November 1978 to the present for optimum accuracy. But even with this restriction, putting together a data set using SMMR, SSM/I and AMSR-E is not trivial because of different attributes and characteristics of the different sensors. As will be discussed, mismatches in the locations of the ice edges can occur because of different resolutions and other factors. There can also be mismatches in ice concentration from different sensors on account of slightly different peak frequencies, different incident angles and different calibration for the different sensors.

The initial step for this study is to create a time series of sea ice data from the different sensors that are as consistent as possible. In particular, we made the brightness temperatures (TBs) for the different sets of channels used to generate the ice concentration maps to match to each other as closely as possible. This in part minimizes effects of inconsistent calibration, incident angle, and peak frequency. This was done by first making SSM/I TBs to be consistent with those of AMSR-E TBs for each set of channels by normalizing the values of the former using parameters derived from linear regression of data from the two sensors during overlap periods. This was followed by making data from the different SSM/I sensors consistent and after that by getting the SMMR TBs consistent with SSM/I TBs. The next step is to use same sea ice concentration algorithm (i.e., the Bootstrap Algorithm as indicate above) for data from all sensors. Although it is the same formulation, the Bootstrap Algorithm will be called ABA when applied to AMSR-E data and SBA when applied to SSM/I data. Finally, the same techniques are used for the land mask, ocean mask, and land/ocean boundary masks as described in Comiso (2004) when generating the ice concentration maps.

To illustrate how well we succeeded with the aforementioned strategy, ice concentration maps from AMSR-E and SSM/I on 15 February 2003 in the Northern Hemisphere and on 15 September 2003 in the Southern Hemisphere are shown in Figure 2. In general, the technique appeared to have worked very well with the resulting daily ice concentration maps from different sensors showing very good agreement during overlapping periods. There are subtle differences especially near the ice margins associated with differences in resolution and antenna patterns of the different sensors but ice concentration values in practically all regions are virtually identical.

The good agreement in ice concentration is encouraging since it means that the same features of the ice cover are reproduced by the different sensors. The minor differences, which are mainly confined near the marginal ice zones, are inevitable because of innate differences in resolution, the peak frequencies for the radiometer channels used in the algorithm, the incident angle and the antenna side lobes. To gain insight into these differences, we first examine the procedure for masking open ocean areas which is basically done by setting a threshold below which the data is considered as open ocean. The large contrast of the passive microwave signature of sea ice and open water at some of the channels has enabled estimates of the ice concentration at almost all values except at some low ice concentration values where the signature of open water and ice covered surfaces are virtually identical. Moreover, areas in the open ocean that are under the influence of abnormal weather conditions can have signatures similar to those of ice covered ocean. The use of a combination of 19, 22, and 37 GHz channels for the sensors, however, allows for effective discrimination of open ocean data under unusual conditions as illustrated in the scatter plots in Figure 3. In figures 3a and 3b, we show scatter plot of TB(19,V) versus the difference TB(22,V) – TB(19,V) using SSM/I and AMSR data , respectively, while in figures 3c and 3d, we show the corresponding plots but of TB(19,V) versus TB(37,V). The blue data points in the scatter plot along OW actually represent data from the open ocean at all weather conditions while the black data points are those from ice covered ocean. Open water within the pack is usually relatively calm and provides the lowest emissivity of data points along OW and is therefore represented in the algorithm as a data point close to the label O. In the open ocean the surface gets disrupted occasionally by strong winds and bad weather causing big waves and foam, causing the signature to move to higher values and towards W in the scatter plot, depending on the strength of the disruption. In the algorithm, data points along OW are masked to represent open water only with the red line, representing approximately 10% ice concentration used as the threshold as described in Comiso et al. (2003). To obtain consistent ice extent and ice area from SSM/I and AMSR-E data, it is thus important to have the same threshold for both sensors. The set of data points between O and W which are considered as open water areas and should be separated from the ice covered surfaces with 10% ice concentration and above in the same way.

The higher resolution of AMSR provides a better definition of the marginal ice zone and a more precise location of the ice edge as previously indicated by Worby and Comiso (2000). This is clearly illustrated in the plots of brightness temperatures at different frequencies across the marginal ice zone (i.e., 35° W longitude) in the Antarctic for both AMSR and SSM/I (Figure 4).

The plots show that the brightness temperatures are relatively low and uniform in the open water (left side) and gradually increase over the marginal ice zone and reached their highest values over the consolidated ice region. Over the marginal ice zone that includes the ice edge, the changes in TBs are coherent and consistent at all AMSR-E frequencies. The TBs are not so consistent for the different SSM/I channels (not shown). The corresponding plots for ice concentration, as shown in Figure 4c, indicate that AMSR-E provides a more defined ice edge than SSM/I with the latter further away from the pack by about 12 km. Such discrepancy makes it almost impossible to get a perfect match in the estimates of ice extent using data from the two sensors as will be discussed later. Similar plots for ice concentration in the Barents Seas in the Northern Hemisphere along the 35 ^{o}E and 45 ^{o}E longitudes (Figures 5a and 5b) show basically the same effect but sometimes, the difference can be more modest. It is apparent that a bias exists, with the SSM/I data showing a location of the ice edge that is further away from the pack than the AMSR-E data. This phenomenon is associated with differences in resolution and side lobes of the antenna. The coarser the resolution is, the more the ice covered areas overlap with the open ocean. The effect of the antenna sidelobe is to cause a smearing at the ice edge since higher brightness temperature is observed as the satellite crosses the ice edge from the pack to the open ocean than vice versa. Such smearing is more pronounced with the SSM/I than the AMSR-E data which has a narrower field-of-view (and higher resolution) than the former.

3. Comparison of Sea Ice Extents, Area and Ice Concentration during Overlap Period

The ice parameters derived from satellite ice concentration data that are most relevant to climate change studies are sea ice extent and ice area. Ice extent is defined here as the integrated sum of the areas of data elements (pixels) with at least 15% ice concentration while ice area is the integrated sum of the products of the area of each pixel and the corresponding ice concentration. Ice extent provides information about how far north the ice goes in winter and how far south it retreats towards the continent in the summer while the ice area provides the means to assess the total area actually covered by sea ice, and also the total volume and therefore mass of the ice cover, given the average thickness. In the previous section we discussed the technique we used for obtaining consistent ice concentrations from the various sensors. We now show how consistently we can get the ice extent and ice area from these sensors as well as average ice concentrations during periods of overlap. Figures 7a-7f show distributions of daily average ice extent, ice area and ice concentration over an entire annual cycle using AMSR-E and SSM/I data in 2005 for both Northern and Southern Hemispheres. The plots in Figures 7a and 7b show that the extents derived from SSM/I data (in blue) are consistently higher than those from AMSR-E data (in red) with the difference in winter relatively smaller than those in the summer period. The plots in Figures 7c and 7d show that the ice areas derived from SSM/I are still higher but much more consistent with those derived from AMSR-E data. These results sugest that the mismatch in resolution affects estimates of the extent more than the ice area with the coarser resolution system (i.e., SSM/I) providing the higher extent because of smearing effect as described earlier. The average ice concentrations from AMSR-E (Figures 7e and 7f) are also shown to be consistently higher by about 1 to 2% than that of SSM/I. This in part made the ice area from the two sensors more compatible. The main reason for the difference in extents from the two sensors is that there are more data elements with ice for SSM/I than AMSR-E, mainly because the ice edges in the former extends further beyond the MIZ than the latter, as discussed earlier. These additional data elements have low concentration values the inclusion of which causes the average ice concentration to be lower. The additional low ice concentration data also makes the average ice concentration lower for SSM/I than AMSR. The discrepancy is not so apparent with the ice area because the ice concentrations maps (see Figure 2, for example) basically match each other and the contribution of low concentration pixels at the ice edge is not as significant for ice area as with the ice extent estimates.

Similar comparative analysis of ice extents, ice area and ice concentration using data from two SSM/I sensors (i.e., F11 and F13) during the period of overlap from May to September 1995 is presented in Figure 8. The plots show very good agreement of data from the two sensors. This is not a surprise since the two sensors have virtually the same attributes. Slight differences in ice concentration estimates occur (e.g., 20 July 1995) but this may be associated with radiometer noise. It should be noted, that the good agreement was obtained after the two sensors were intercalibrated and the TBs were made consistent. Although the resolutions of F11 and F13 are expected to be the same, consistency in the derived ICs is needed to get consistency in the extent and area.

During the overlap of SSM/I and SMMR data in mid July to mid-August in 1987 the extents and areas are also in relatively good agreement (Figure 9) during this summer period in the Arctic and the winter period in the Antarctic. It is interesting to note that the agreement was better during August than in July in the Northern Hemisphere but the opposite is true in the Southern Hemisphere. Also, the SSM/I values tend to be higher than those of SMMR in the

Northern Hemisphere in July while the reverse is true in the Southern Hemisphere in August. Furthermore, the differences in the average ice concentrations are larger in the Northern Hemisphere than in the Southern Hemisphere and in July, SSM/I values are higher than those of SMMR while the opposite is true in July of the Southern Hemisphere. Because of these inconsistencies, it is not easy to establish whether there is a bias or not, especially since the overlap period is quite short.

Degradation in the quality of the SMMR data was occurring during this period and it is likely that the SMMR observations were not as accurate as those of SSM/I. An overlap of at least one annual cycle would have been desirable if only to establish that the seasonal differences are similar to those shown in Figure 8. In the time series that requires monthly averages, SMMR data were used to generate monthly data for July 1987 while SSM/I data were used for the August monthly. This procedure appears good for the Antarctic data since there is good consistency of the two sensors in this region in July but such advantage is not apparent the Northern Hemisphere.

It is encouraging that the agreement between AMSR-E and SSM/I ice extents and area data is as good as indicated in the plots despite the vast differences in resolution. The use of ice concentration is expected to take care of the resolution problem but not completely especially in the estimates of ice extent. As indicated earlier, the data with lower resolution will find the ice edge further away from the pack than the one with higher resolution. Although the same algorithm is applied on the two data sets, the fields of view and side lobes of the two sensors are different and hence the observed radiances from the two sensors cannot be identical even if the calibration of each is perfect. Also, the location of the ice margins as observed by the two sensors are not expected to be same. One key reason for this is the differences in revisit time of the two sensors: one (SSM/I) crossing the equatorial line at about 10 am while the other (AMSR-E) at about 1 pm. Since the ice cover is dynamic and the ice edge can easily be altered by winds, the ice edge location can be significantly changed within the three hour difference.

It is apparent that errors (or biases) in ice extent has to be considered when combining data from different sensors with different resolutions. This already assumes that the ice concentrations are derived in a similar fashion and the masking for open water, land and ice/ocean boundaries are similar if not identical. There are also mismatches in the estimates for ice area but they are basically small and negligible.

4.0 Monthly Changes and Interannual Trends in the Sea Ice Extents and Areas

4.1 The Northern Hemisphere

The time series of monthly sea ice extents and areas in the Northern Hemisphere from 1978 to the present, as presented in Figure 10, provides the means to evaluate how the ice cover in the entire Northern Hemisphere has been changing during the satellite era. The variabilities in both extent and area are similar and are dominated by a very large seasonality of the ice cover in the region as has been cited previously (e.g., Parkinson et al., 1987). The ice minimum usually occurs in September while the ice maximum occurs either in February or March. The time series shows data from the different sensors in different colors and show basically a smooth transition from one sensor to the other. Although there is overlap of SMMR and SSM/I data for about a month from mid-July to mid-August 1987, the plot shows averages from SMMR for July 1987 and that for SSM/I for August 1987. The only overlap presented is that of SSM/I and AMSR-E which started in June 2002 and continued through 2006. During overlap period, SSM/I extent and area are slightly higher than those of AMSR-E as expected from previous discussions.

The monthly data show large interannual variability in the peak values, the amplitude and also the minimum values for both extent and area. The patterns are also not so predictable with high values in winter not necessarily leading to high values in the summer (e.g., 1974 and 1990). To assess how the length of the growth period has changed over time, the dates of ice minimum and maximum were identified for each year. The length of growth in our case is defined as the time period between the date of ice minimum in one year to the date of ice maximum the following year and for the period 1979 to 2005 and the results gave an average length of 179 days and a declining trend of about -2.5 days per decade. The minimum and maximum dates changes with time but it appears that the difference changes only by a few days and the length of growth had so far been basically stable. It is also apparent that the peak values have been going down since 2002 while the minimum values have been abnormally low during the same years.

To assess interannual trends in the ice cover, we use monthly anomalies as has been done previously (Parkinson et al., 1999; Zwally et al., 2002) in order to minimize the effect of the large seasonal variations. These anomalies were obtained by subtracting the monthly climatological averages from each monthly average. The climatology for each month is the average of all data for this month from November 1978 to December 2006. The monthly anomalies for the ice extents in the Northern Hemisphere are presented as three different combinations of combining the data in Figure 11, namely: (a) SMMR and SSM/I extents only, (b) SMMR, SSM/I and AMSR-E extents with SSM/I data ending where AMSR-E data starts, and (c) normalized SMMR and SSM/I and original AMSR-E extents. Normalization parameters for the last case are derived from data during SSM/I and AMSR-E overlap and are meant to get the two data sets consistent during the period. The first case provides the data that is currently being utilized for trend studies while the second case make use of AMSR-E data instead of SSM/I when appropriate. The trend values for SMMR and SSM/I data only is -3.39 ± 0.18 % per decade while that for SMMR, SSM/I and AMSR-E data is -3.99 ± 0.20 % per decade. There is a difference of -0.60 % per decade in the trends but this is likely associated with the bias as described earlier, due in part to the difference in resolution between AMSR-E and SSM/I. When the bias is removed through aforementioned renormalization, the trend for a combined SMMR, SSM/I and AMSR-E data is -3.37 which is consistent with that for SSM/I and SMMR data only. Taking advantage of the overlap thus enables the AMSR-E data to be utilized in trend analysis. Since the latter is more accurate, the net error in the trend analysis is going to be less and the importance of AMSR-E data in trend studies will increase with time.

The range of variability in the anomalies is about 1×10^6 km^2 while that for seasonal ice, as revealed by the monthly averages, is about to 8×10^6 km^2. It is also apparent that the variability is significantly less for the period 1996 to 2006. This is intriguing since the slope of the data during the latter period appears different from those of the earlier period. Linear regression using only data from 1996 to 2006 yields a trend of more than -8% per decade, which is more than twice the trend from 1978 to 2006. During the last ten years, many unusual events happened in the Arctic. First, there was a record high ice free region in the Beaufort Sea in 1998 (Comiso et al., 2003) which was then the warmest year on record globally over a century (or since temperature sensors started to be used). There was also a record low perennial ice cover in 2002 which at the same time became the warmest year on record. The perennial ice cover was a record low again in 2005 which also became the warmest year on record. The intervening periods were low ice years as well including that of 2006. It is possible that the values before 1996 are representative of the natural variability of sea ice cover in the Arctic but the changes after that may not be part of the natural variability as previously suggested (Overland, 2005). The Arctic ocean surface is expected to warm up as the perennial ice continues to retreat on account of the so called "ice-albedo feedback," and a warmer ocean would delay the onset of ice growth in the autumn and cause an earlier melt onset, thereby causing a shorter ice season and hence thinner and less extensive ice cover. With additional warming expected from increasing greenhouse gases in the atmosphere the trend is expected to continue in the near future.

Similar plots but for the ice area are presented in Figure 12, and it is apparent that the variabilities are similar but the trends are more negative with the corresponding trends for the three cases being -4.01 ± 0.18, -4.38 ± 0.19 and -4.00 ± 0.18 %/decade. The more negative trend for ice area compared to those for ice extent is in part associated with a negative trend in the sea ice concentration during the period. Changes in ice concentration may be caused by changes in wind strength and wind patterns that in turn cause changes in the area affected by divergence. In the summer, it can also be caused by changes in the areal extent of meltponding which causes large errors in the estimate of ice concentration (Comiso and Kwok, 1995).

For completeness, regional trends in the ice extent are presented in Figure 13. While overall, the trend for the entire hemisphere is moderate at about -3.4 ± 0.2 %/decade there are regions where significantly higher negative trends are apparent. Among these regions are the Greenland Sea, the Kara/Barents Seas, the Okhotsk Sea, Baffin Bay/Labrador Sea, and the Gulf of St. Lawrence where the trends are -8.0, -7.2, -8.7, -8.6, and -10.7, respectively. In these regions, some cyclical patterns are also evident especially in the first 15 years of data. The only region that show positive trend is the Bering Sea which appears to be growing but at a negligible rate of 1.7 ± 2.0 %/decade. This region is one of the few sea ice covered areas in the Arctic that has exhibited some cooling in the last few decades (Comiso, 2003).

4.2 The Southern Hemisphere

Monthly extents and ice areas in the Southern Hemisphere, as derived from SMMR, SSM/I and AMSR data (Figure 14) show an even more seasonal ice cover than that of the Northern Hemisphere. Minimum ice extents and ice areas usually occurs in February while maximum ice extents and ice areas occurs in September. This means that the growth period takes a longer time than the melt period in the Southern Hemisphere (see also, Figure 6). The maximum and minimum extents and areas go though interannual fluctuations but they look relatively stable. However, it appears that since the winter of 2002, the maximum values have been increasing but at the same time, the minimum values have been decreasing. It would be interesting if the subsequent years would follow the same pattern and show some modulation in the ice cover.

The monthly ice extent anomalies are again presented for the three cases in the Southern Hemisphere (Figure 14) as in the Northern Hemisphere. It is apparent that there is large fluctuation in the monthly anomalies (of about 2 x 10^6 km^2) from 1978 through 1987 and then a much more moderate variation (of about 1 x 10^6 km^2) from 1987 to 1994 that is followed by a larger fluctuation from 1994 through 2006. The monthly extents (Figure 13) do not show large interannual changes during the 1987 to 1994 period and it is not known why the sea ice cover anomalies would go into such transition from high to low variability and then higher variability in the Southern Ocean. Using SMMR and SSM/I data only, the trend in the hemispheric ice extent is 0.945 ± 0.230 %/decade while with SMMR, SSM/I, and AMSR-E data, the trend is slightly lower at 0.684 ± 0.230 %/decade. The difference is again likely associated with differences in resolution as discussed earlier and if SMMR and SSM/I data are normalized to make them consistent with AMSR-E data, the trend is similar to the first, being 0.94 %/decade. Again, in this way, AMSR-E data can be used in trend analysis in conjunction with historical data.

The corresponding monthly anomalies for ice area as presented in Figure 15 show the same variability as the ice extent. However, the trends are much more similar in all three cases the values being 1.72 ± 0.25, 1.77 ± 0.26 and 1.72± 0.25 %/decade. Again, the difference of the first two are minor because the contribution of additional pixels along the ice edge caused by differences in resolution does not affect the estimate of area as much as that of the ice extent. After the application of the normalization factors on the SMMR and SSM/I data, the trend in as indicated in Figure 15c of 1.72%/decade is virtually identical to that of Figure 15a.

Except for the summer, the sea ice cover around the Antarctic continent is contiguous and therefore, there is no natural boundary as in the Arctic region. For regional studies, we adapt the same sectors used in Zwally et al. (1983). The monthly anomalies for the entire hemisphere and for the different regions, as presented in Figure 16, have very similar variabilities with the possible exception of those in the Ross Sea Sector. The trends in ice extent for the various regions are all positive except that of the Belingshausen-Amundsen Seas Sector, which has been previously identified by Jacobs and Comiso (1997) as a climatologically anomalous region. The trend in this region is currently -5.7 %/decade but this is compensated by a positive trend of 4.2 %/decade in the Ross Sea. Some declines in the Ross Sea ice cover is apparent in recent years but they are more than compensated by increases at the Indian Ocean and the West Pacific Ocean.

5. Sensitivity and Error Analysis

To evaluate quantitatively how errors in the determination of the ice edge affects the estimates for the trends in ice extent and ice area we use the original values of SMMR and SSM/I and added a data element at the ice edge in the AMSR-E data. Since each data element has a grid size of about 25 by 25 km this means having an ice edge about 25 km further away. We also did the same for half a pixel and a quarter of a pixel to assess the effect of an ice edge being 12.5 and 6.25 km further away as well. The results are presented in Figures 17 and 18, respectively, for the Northern Hemisphere and the Southern Hemisphere. In the Northern Hemisphere, the trend in extent ranges in value from -3.03%/decade for a bias of a full pixel to -3.99 % per decade for no bias. Comparing with our previous results, the bias at the ice edge is likely about 14 km. In the Southern Hemisphere, the trend in extent ranges from 2.16% per decade for a one pixel bias to 0.68% per decade for no bias. Comparing with our previous results, this translates a bias at the ice edge of about 6 km. The changes in trend for the areas are much smaller.

6. Discussion and Conclusions

The AMSR-E data provide opportunities to study the sea ice cover at higher accuracy and in greater spatial detail than ever before. The greater spectral range and higher resolution data set will enable more in depth studies of many mesoscale processes that occurs in polynyas, divergence areas and marginal ice zones. Comparative studies shows a good match of high resolution AMSR-E data with those of high resolution satellite data providing confidence that the interpretation of large scale as well as mesoscale features identified in the former are indeed accurate. With only about 5 years of good data available, however, the record length is too short for change studies. Change studies using AMSR-E data can thus be made effectively when it is combined with historical satellite data.

This study shows that during the overlap period from June 2002 to 2006 that the ice concentration maps derived from AMSR-E and SSM/I are virtually identical. The ice extents and ice areas estimated from the two sensors are also in very good agreement and both basically provide the same information about seasonal and interannual variability. The historical data therefore provide a reasonably accurate estimate of the trends in the ice cover. However, there are subtle differences, especially in the characterization of the Marginal Ice Zone and the ice edge. Because of higher resolution, AMSR-E is able to provide more precise locations and more accurate gradients in these regions that that provided by SSM/I. This difference is reflected in the estimates of ice extents with the latter providing slightly higher values on account of coarser resolution. With proper normalization, however, the AMSR-E data can still be combined with the historical satellite data for more accurate determination of trends in ice extent. In the estimates of ice area, AMSR-E and SSM/I data provides almost identical values basically since the ice concentrations generally agree and the effect of additional low concentration ice at the ice edges detected by one but not the other is negligible in this estimate.

With the higher resolution and improved accuracy, AMSR-E data provide a good baseline for ice cover studies and to test the estimates in extent and area from other sensors. We show that because of coarser resolution, SSM/I data provides a location of the ice edge that is on the average about 6 to 12 km further away from the ice pack than AMSR-E data. Biases if uncorrected could also contribute to errors in the estimates of trends in extents of as much as 0.62%/decade in the Arctic and 0.26%/decade in the Antarctic. The biases in ice area are less with the error in the trend of areas being at 0.30%/decade in the Arctic and 0.05%/decade in the Antarctic.

Using data from SMMR, SSM/I and AMSR-E and after correcting for the aforementioned bias, the results of our regression analysis for period from November 1978 to December 2006 yielded trends in extent and area of sea ice in the Arctic region are -3.4 ± 0.2 and -4.0 ± 0.2 % per decade, respectively. The corresponding values for the Antarctic region are 0.9 ± 0.2 and 1.7 ± 0.3 % per decade. These trends are basically the same as those derived using SMMR and SSM/I data only, but with better accuracy since AMSR-E provides more accurate data. With time, the data from AMSR-E and similar instruments will increase the reliability of the trend values.

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Figure Captions:

Figure 1. Location map for (a) the Northern Hemisphere; and (b) the Southern Hemisphere. The two shades of gray correspond to the climatological average of the location of the ice cover during minimum and maximum extent.

Figure 2. Daily ice concentration maps during winter in the (a) Northern Hemisphere using AMSR-E data; (b) Northern Hemisphere using SSM/I data; (c) Southern Hemisphere using AMSR-E data; and (d) Southern Hemisphere using SSM/I data.

Figure 3. Scatter plots of TB(V19, V) versus TB(22, V) - TB(19, V) for (a) SSM/I and (b) AMSR-E data. Also, scatter plots of TB(19,V) versus TB(37,V) for (c) SSM/I and (d) AMSR-E data.

Figure 4. Transects along the ice edges of brightness temperatures using AMSR-E (a) vertically polarized and (b) horizontally polarized data and (c) comparison of ice edges as inferred from ice concentration values of AMSR-E and SSM/I.

Figure 5. Ice concentrations along the ice edge in the Barents Sea at (a) 35 ^{o}E and (b) 45 ^{o}E.

Figure 6. Daily ice extents (a &b), ice area (c & d), and ice concentration (e & f) during a period of SSM/I and AMSR-E overlap (2005) in the Northern and Southern Hemispheres

Figure 7. Daily ice extent (a &b), ice area (c & d), and ice concentration (e & f) during a period of SSM/I (F11) and SSM1(F13) overlap (May to September 1995) in the Northern and Southern Hemispheres.

Figure 8. Daily extent (a &b), ice area (c & d), and ice concentration (e & f) during a period of SMMR and SSM/I operlap in the Northern and Southern Hemispheres (July to August 1987).

Figure 9. Monthly extent and area from 1978 to 2006 in the Northern Hemisphere using SMMR, SSM/I and AMSR-E data time series data.

Figure 10. Monthly anomaly and trend in extents from 1978 to the present in the Northern Hemisphere using (a) original SMMR and SSM/I data; (b) original SMMR, SSM/I (up to May 2002) and AMSR-E data (June 2002 to 2006); and (c) normalized SMMR and SSM/I data and original AMSR-E data.

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Figure 12. Monthly anomalies of ice extent in the (a) Northern Hemisphere and in the following regional sectors: (b) Arctic Ocean; (c) Greenland Sea; (d) Kara/Barents Sea, (e) Bering Sea; (f) Okhotsk/Japan Seas; (g) Canadian Archipelago; (h) Baffin Bay/Labrador Sea; (i) Hudson Bay; and (j) Gulf of St. Lawrence.

Figure 13. Monthly extent and area from 1978 to the present in the Southern Hemisphere using SMMR SSM/I and AMSR-E data

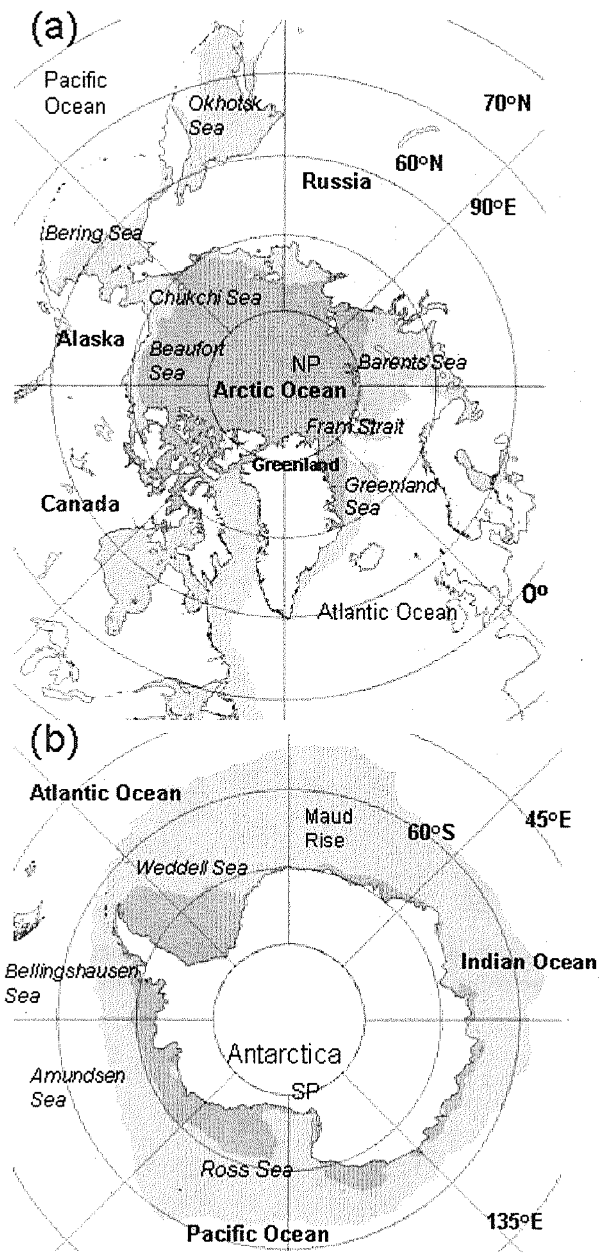
Figure 14. Monthly anomaly and trend in extents from 1978 to the present in the Southern Hemisphere using (a) original SMMR and SSM/I data; (b) original SMMR, SSM/I (up to May 2002) and AMSR-E (from June 2002 to 2006) data; and (c) normalized SMMR and SSM/I data and original AMSR-E data.

Figure 15. Monthly anomaly and trend in ice area from 1978 to the present in the Southern Hemisphere using (a) original SMMR and SSM/I data; (b) original SMMR, SSM/I and AMSR-E data; and (c) normalized SMMR and SSM/I data and original AMSR-E data.

Figure 16. Monthly anomalies of ice extent in the (a) Southern Hemisphere and in the following regional sectors: (b)Weddell Sea; (c) Indian Ocean; (d) West Pacific Ocean; (e) Ross Sea; (f) Bellingshausen/Amundsen Seas.

Figure 17. Sensitivity of trends to (a) ice extent and (b) ice area with adjustments of AMSR-E data by making the ice edge 6.25, 12.5, and 25 km further away from the ice pack in the Northern Hemisphere during an entire ice season.

Figure 18. Sensitivity of trends to (a) ice extent and (b) ice area with adjustments of AMSR-E data by making the ice edge 6.25, 12.5, and 25 km further away from the ice pack in the Southern Hemisphere during an entire ice season.



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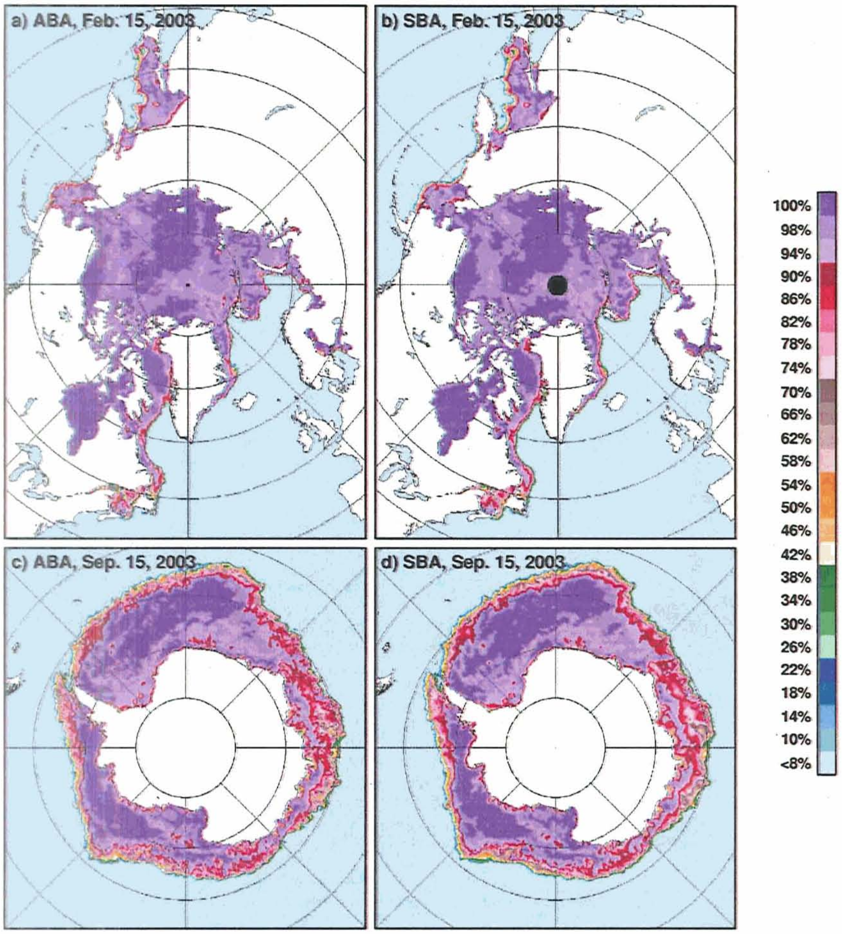

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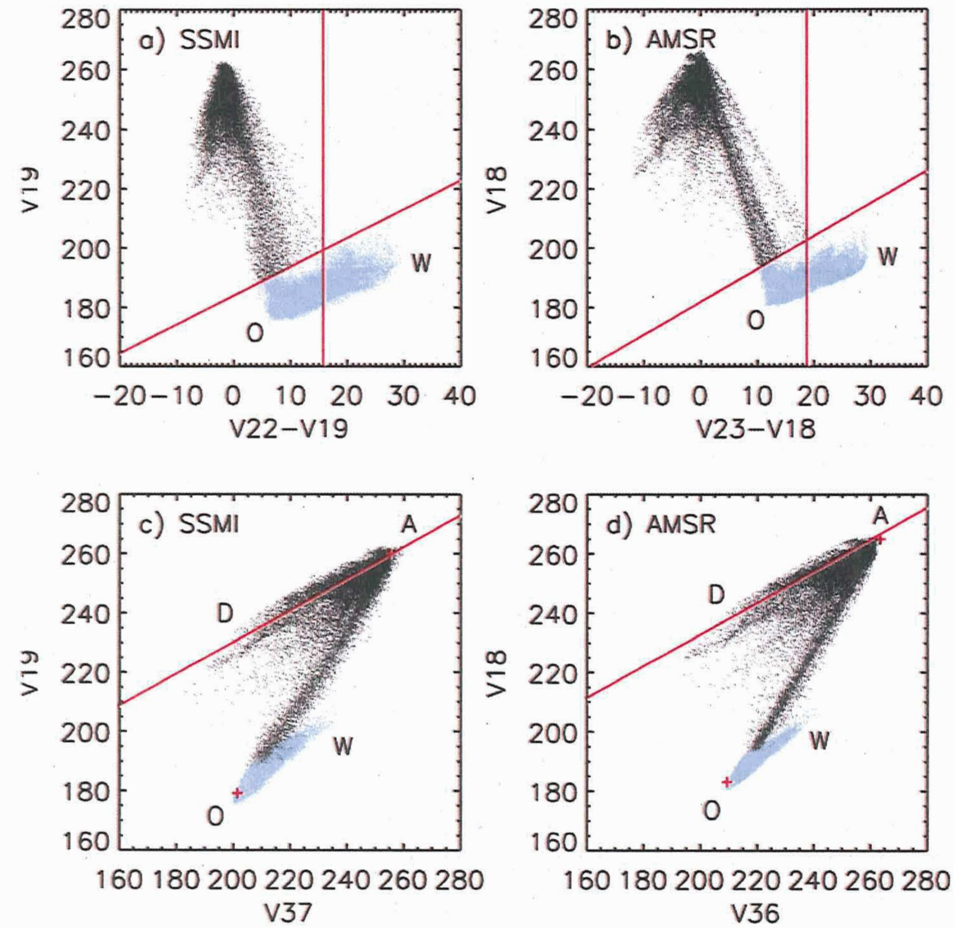

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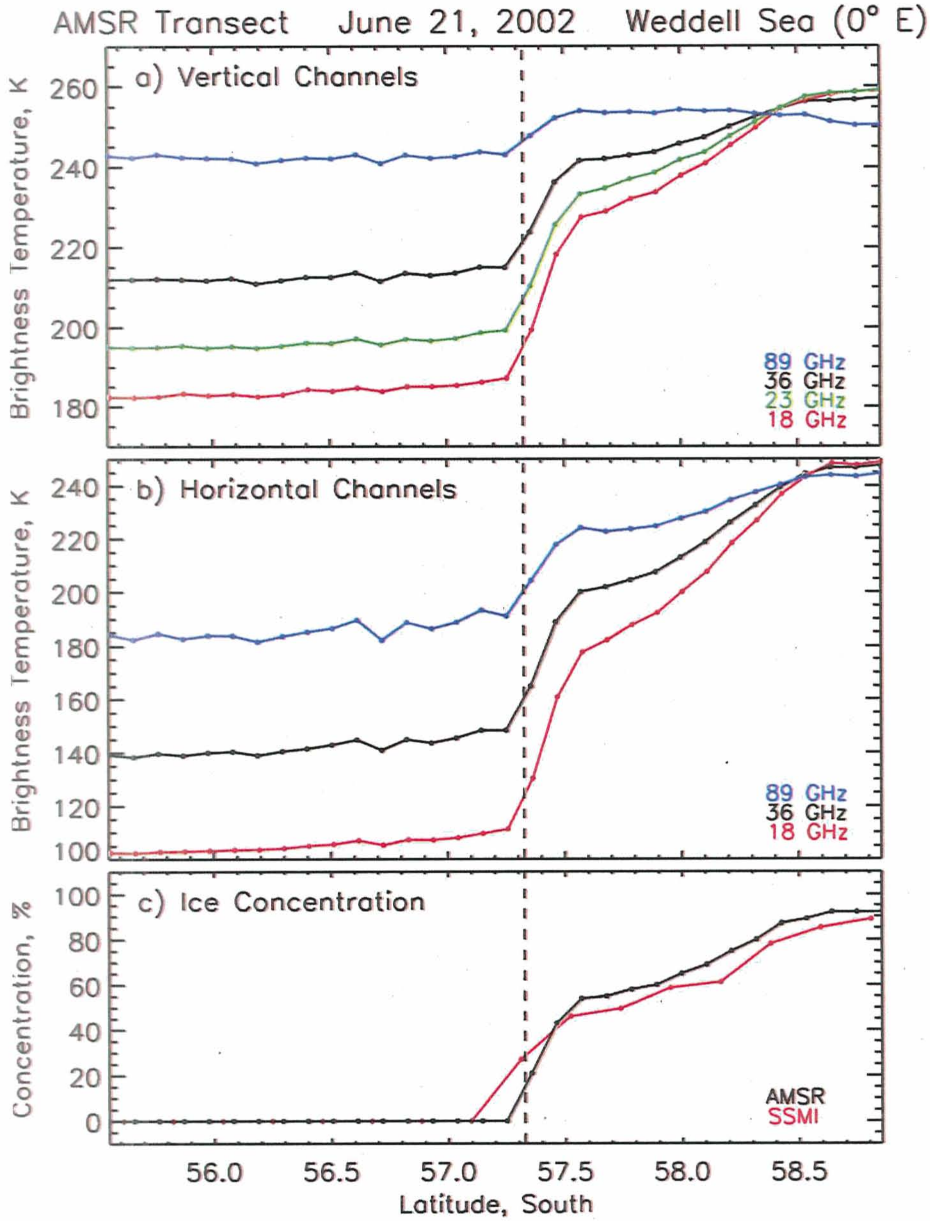

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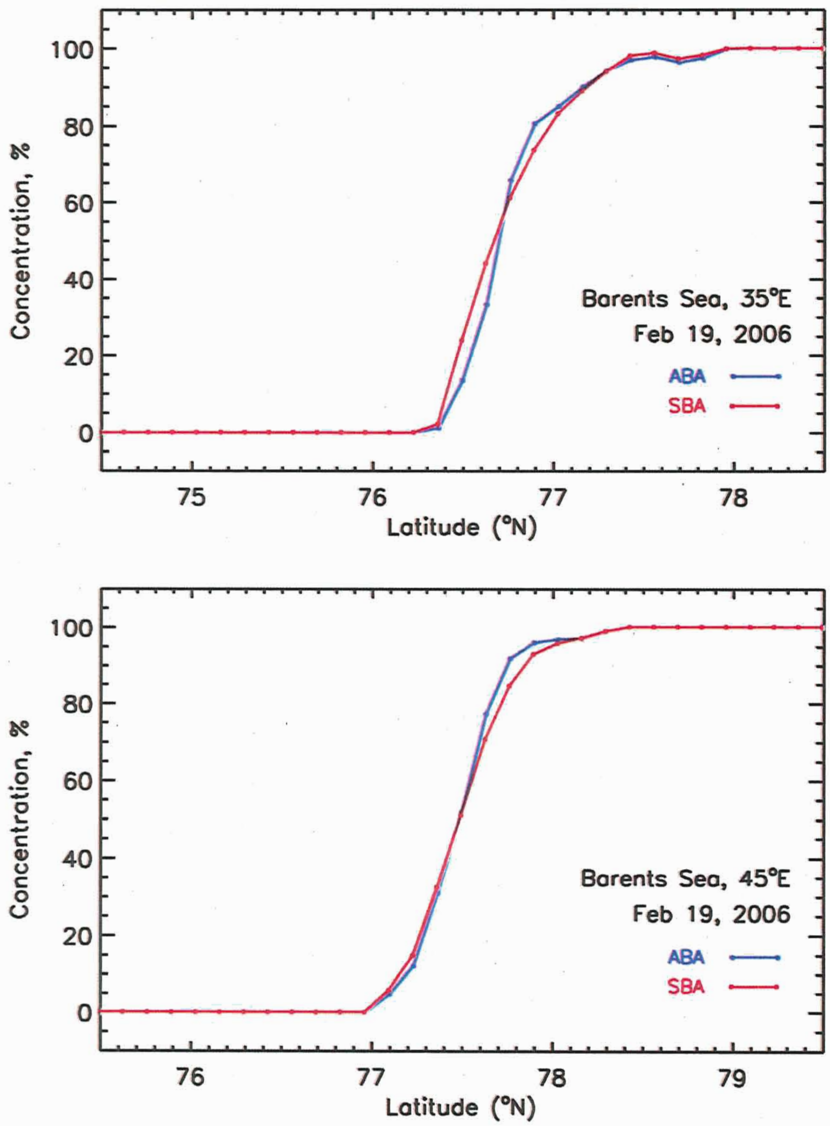

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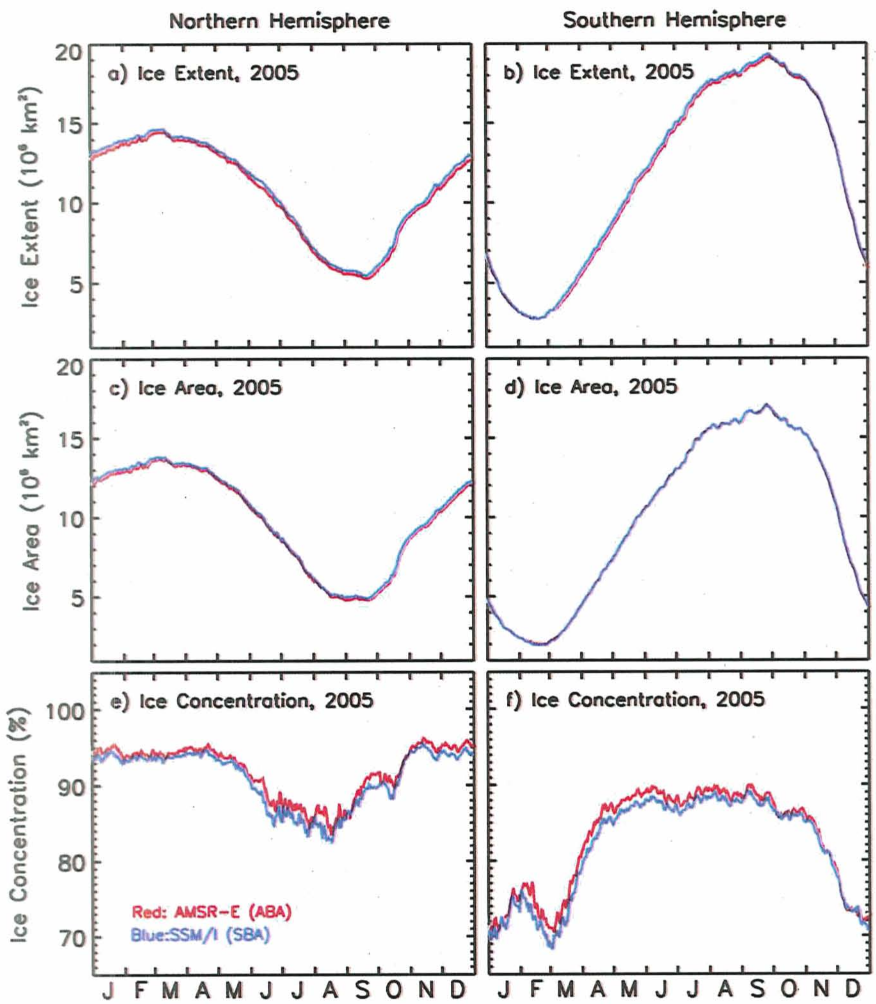

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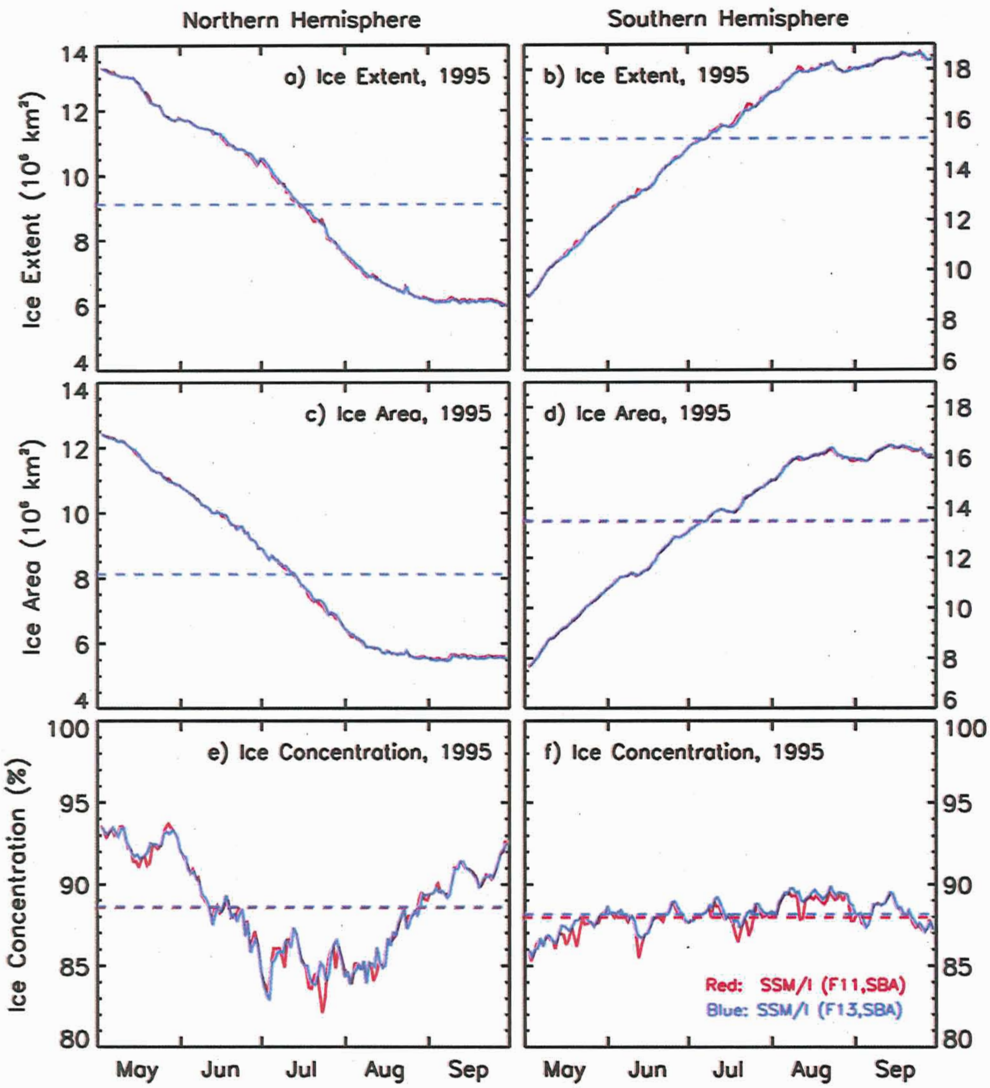


Figure 7. Daily ice extent (a &b), ice area (c & d), and ice concentration (e & f) during a period of SSM/I (F11) and SSM1(F13) overlap (May to September 1995) in the Northern and Southern Hemispheres.

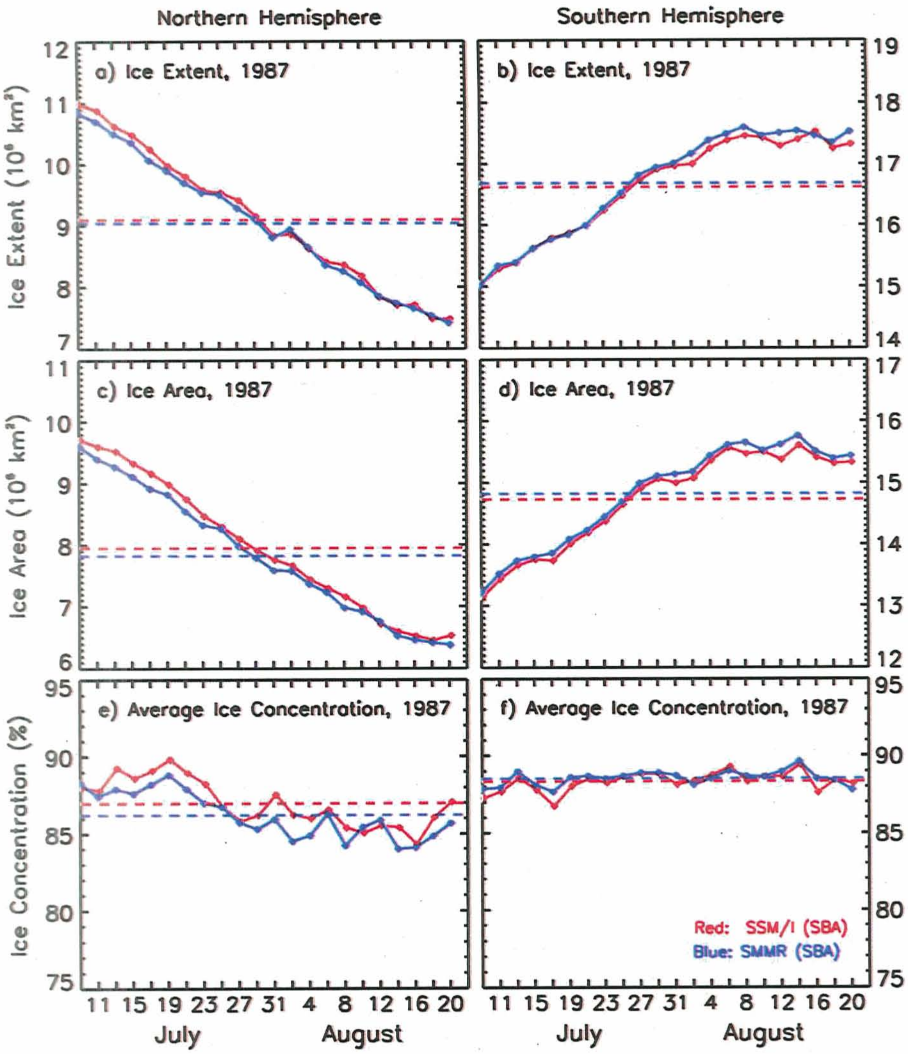
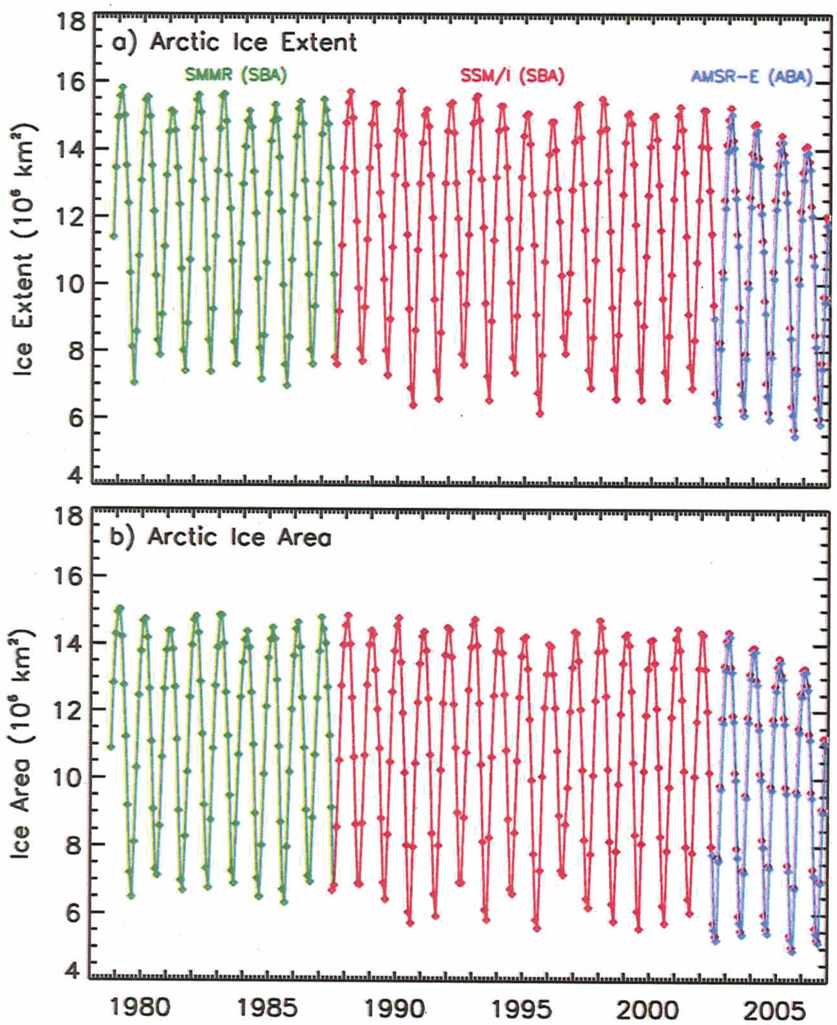


Figure 8. Daily extent (a &b), ice area (c & d), and ice concentration (e & f) during a period of SMMR and SSM/I operlap in the Northern and Southern Hemispheres (July to August 1987).



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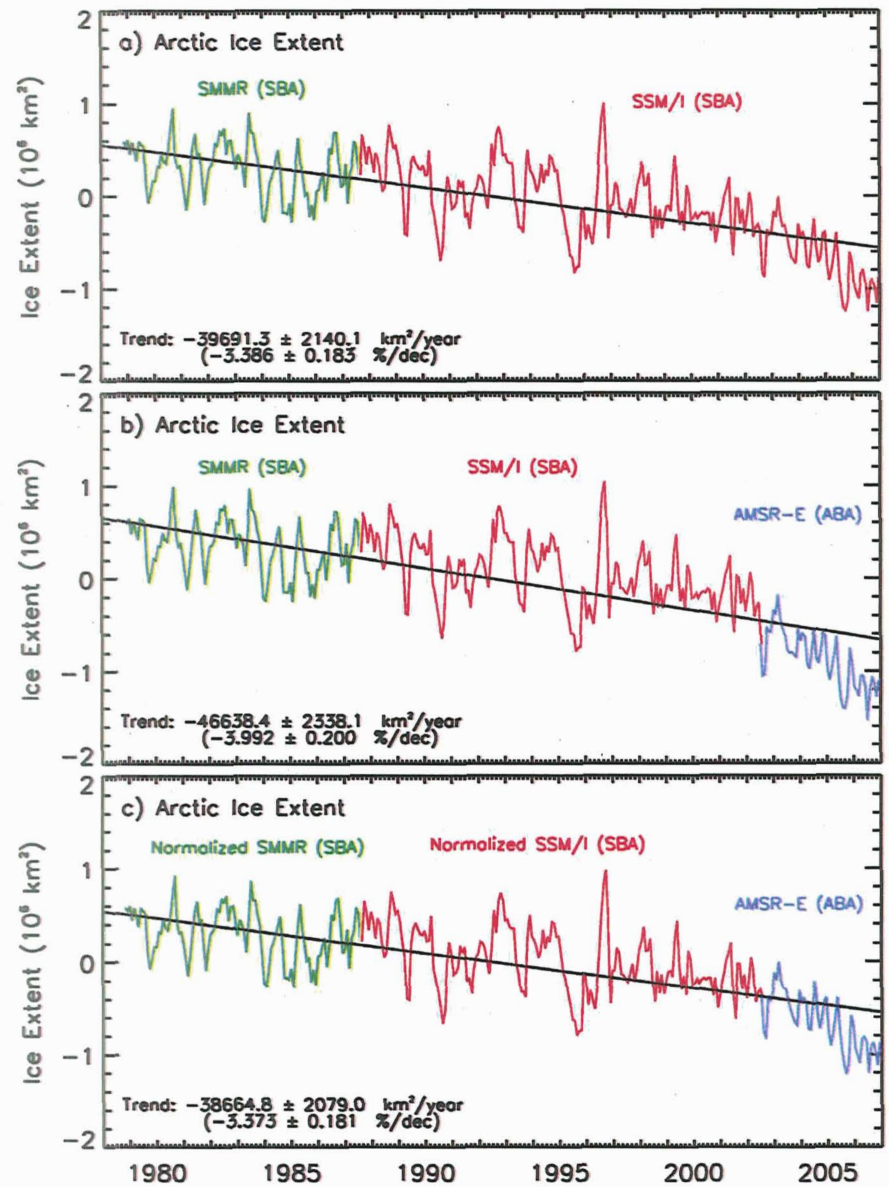

Figure 10. Monthly anomaly and trend in extents from 1978 to the present in the Northern Hemisphere using (a) original SMMR and SSM/I data; (b) original SMMR, SSM/I (up to May 2002) and AMSR-E data (June 2002 to 2006); and (c) normalized SMMR and SSM/I data and original AMSR-E data.

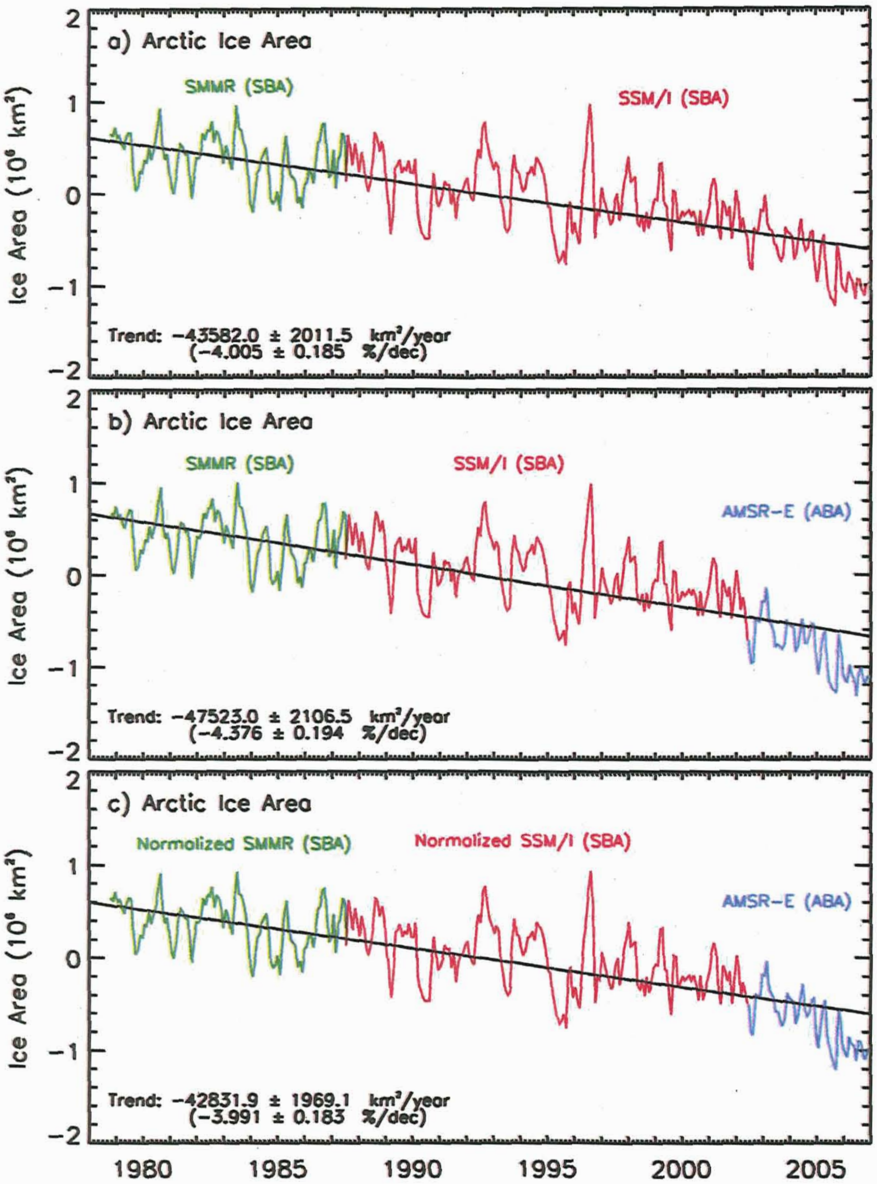

Figure 11. Monthly anomaly and trend in ice area from 1978 to the present in the Northern Hemisphere using (a) original SMMR and SSM/I data; (b) original SMMR, SSM/I (up to May 2002) and AMSR-E (June 2002 to 2006) data; and (c) normalized SMMR and SSM/I data and original AMSR-E data.

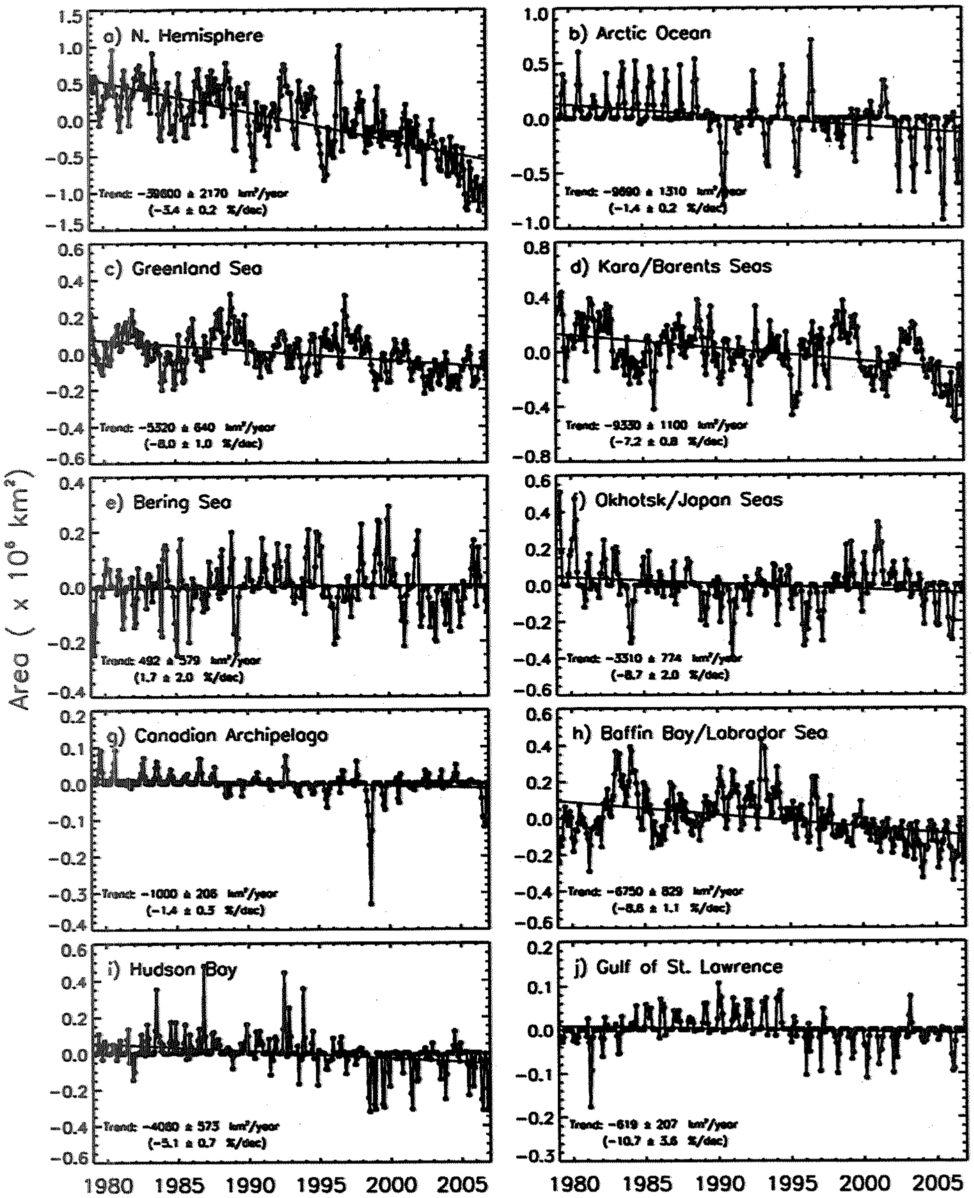

Figure 12. Monthly anomalies of ice extent in the (a) Northern Hemisphere and in the following regional sectors: (b) Arctic Ocean; (c) Greenland Sea; (d) Kara/Barents Sea, (e) Bering Sea; (f) Okhotsk/Japan Seas; (g) Canadian Archipelago; (h) Baffin Bay/Labrador Sea; (i) Hudson Bay; and (j) Gulf of St. Lawrence.

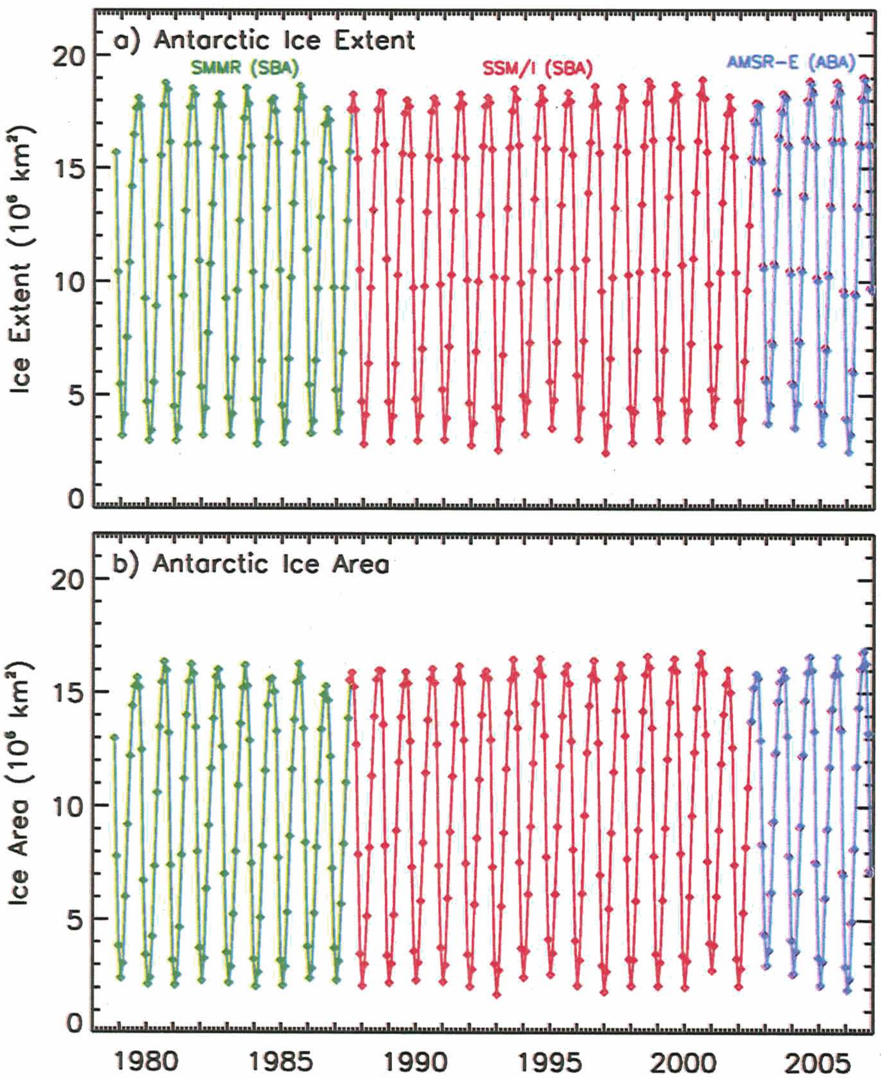

Figure 13. Monthly extent and area from 1978 to the present in the Southern Hemisphere using SMMR SSM/I and AMSR-E data

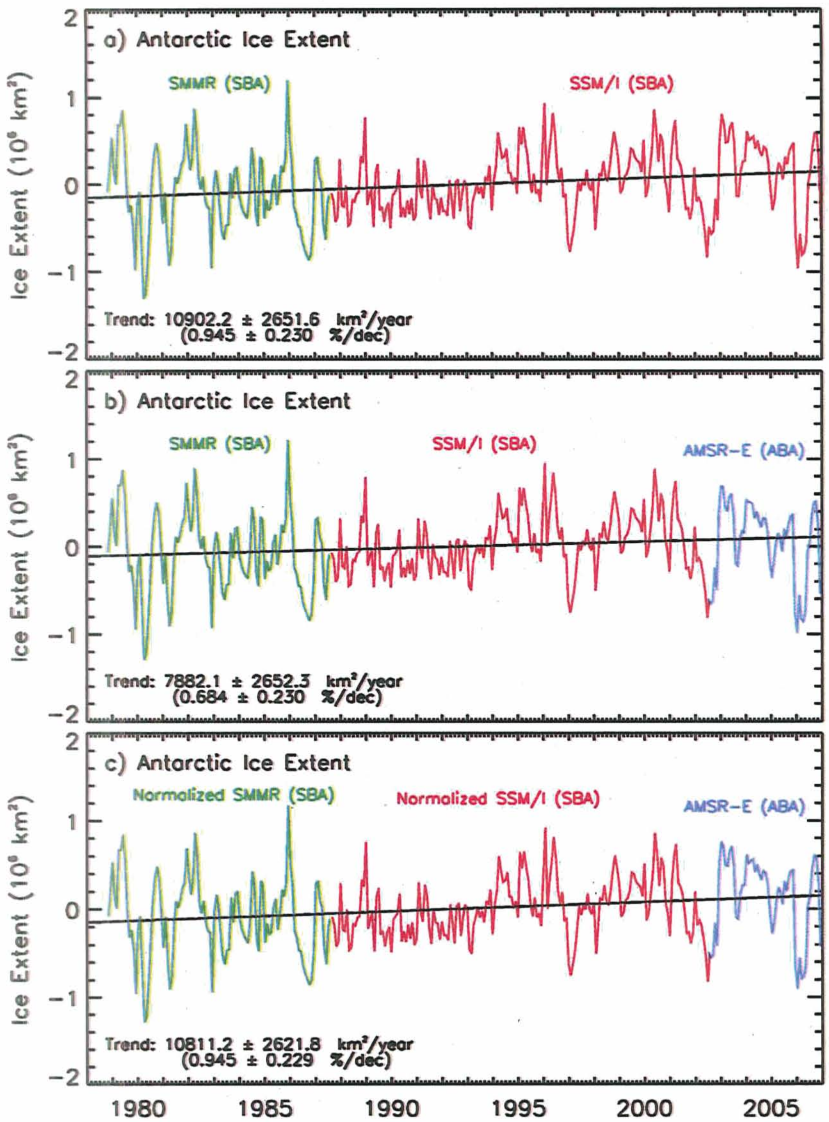

Figure 14. Monthly anomaly and trend in extents from 1978 to the present in the Southern Hemisphere using (a) original SMMR and SSM/I data; (b) original SMMR, SSM/I (up to May 2002) and AMSR-E (from June 2002 to 2006) data; and (c) normalized SMMR and SSM/I data and original AMSR-E data.

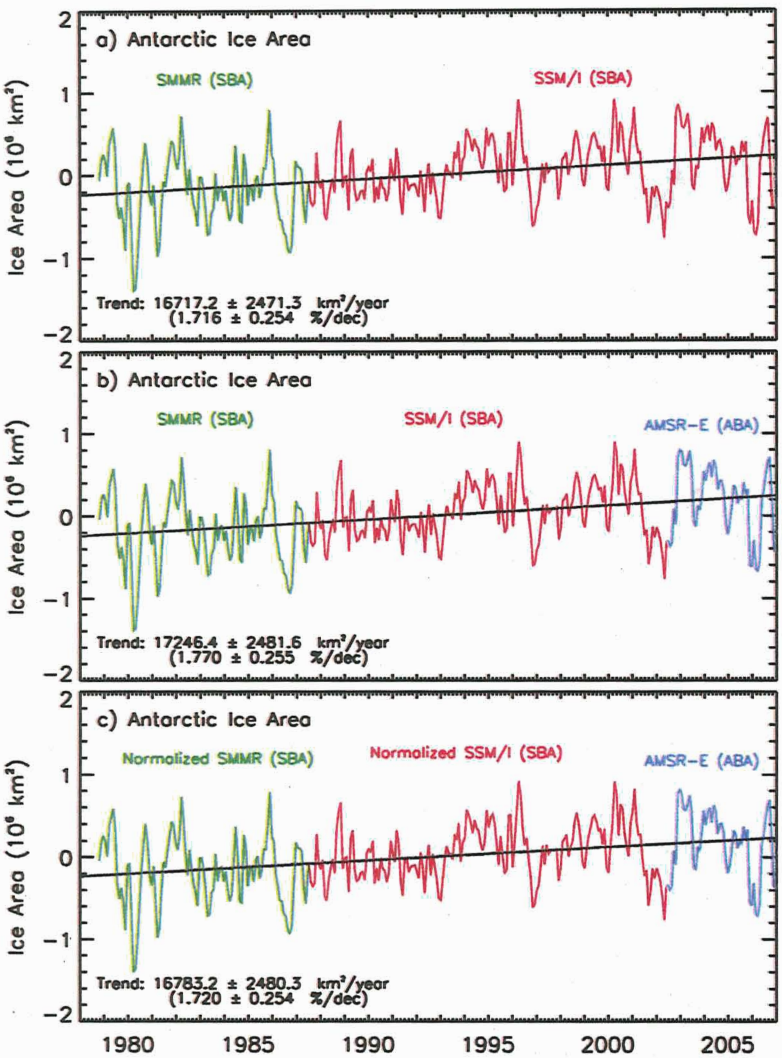

Figure 15. Monthly anomaly and trend in ice area from 1978 to the present in the Southern Hemisphere using (a) original SMMR and SSM/I data; (b) original SMMR, SSM/I and AMSR-E data; and (c) normalized SMMR and SSM/I data and original AMSR-E data.

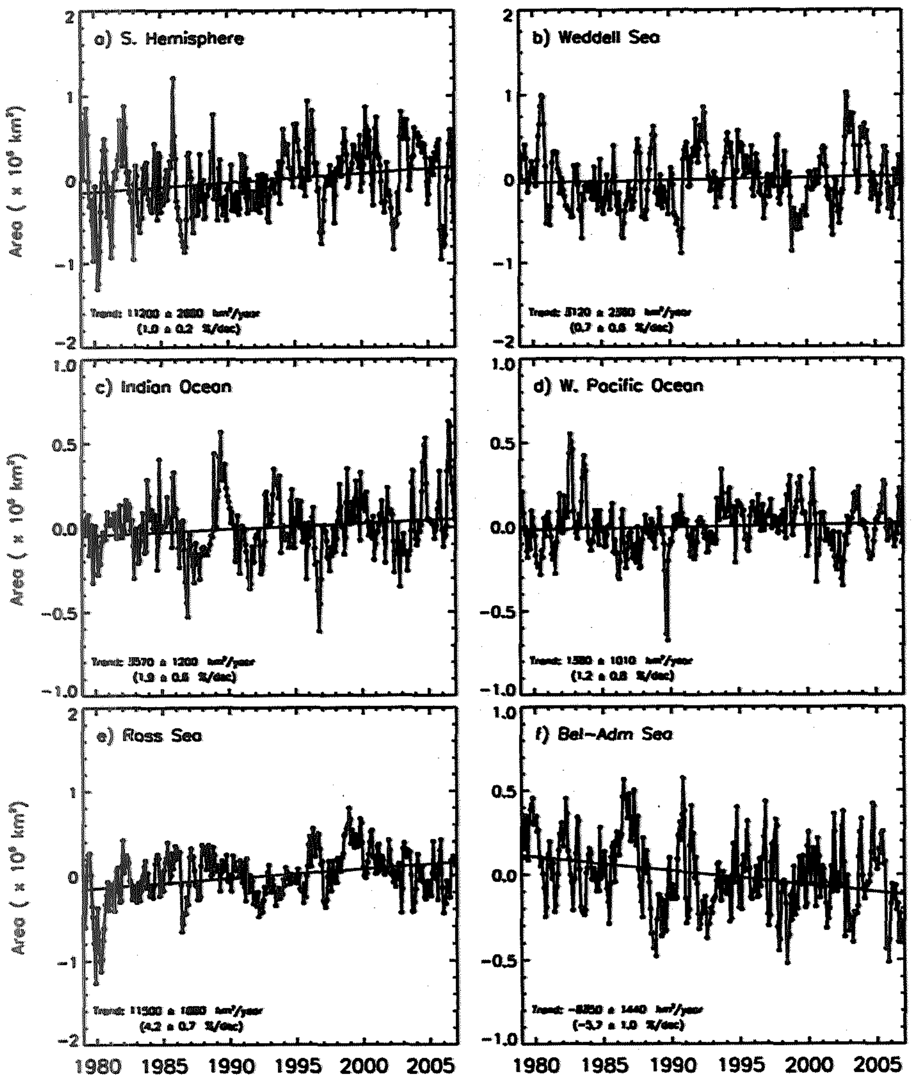

Figure 16. Monthly anomalies of ice extent in the (a) Southern Hemisphere and in the following regional sectors: (b)Weddell Sea; (c) Indian Ocean; (d) West Pacific Ocean; (e) Ross Sea; (f) Bellingshausen/Amundsen Seas.

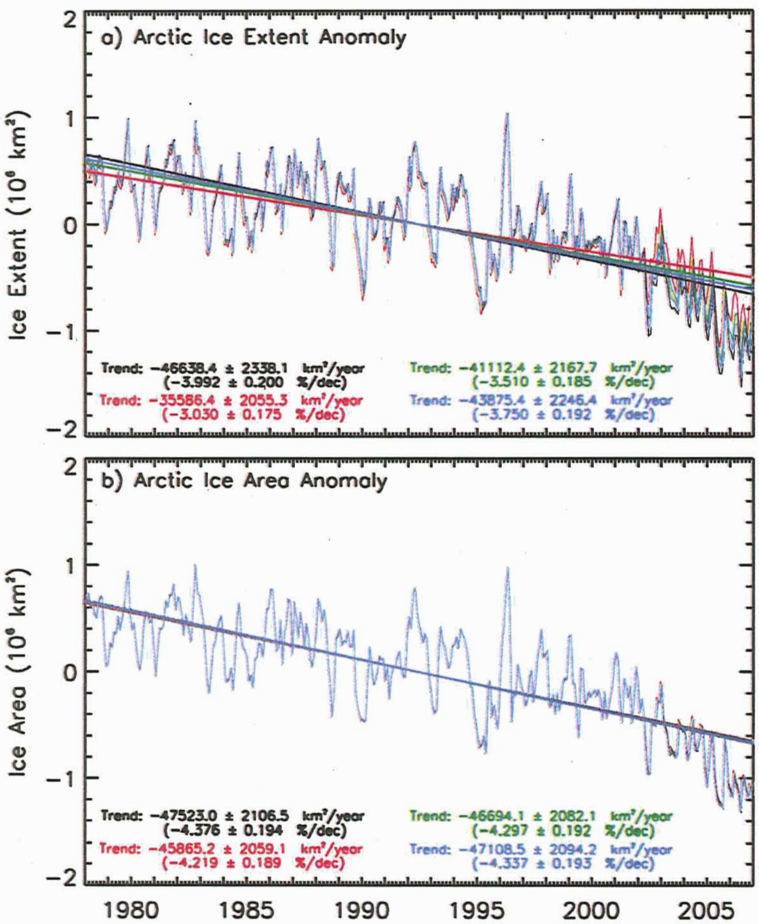

Figure 17. Sensitivity of trends to (a) ice extent and (b) ice area with adjustments of AMSR-E data by making the ice edge 6.25, 12.5, and 25 km further away from the ice pack in the Northern Hemisphere during an entire ice season.

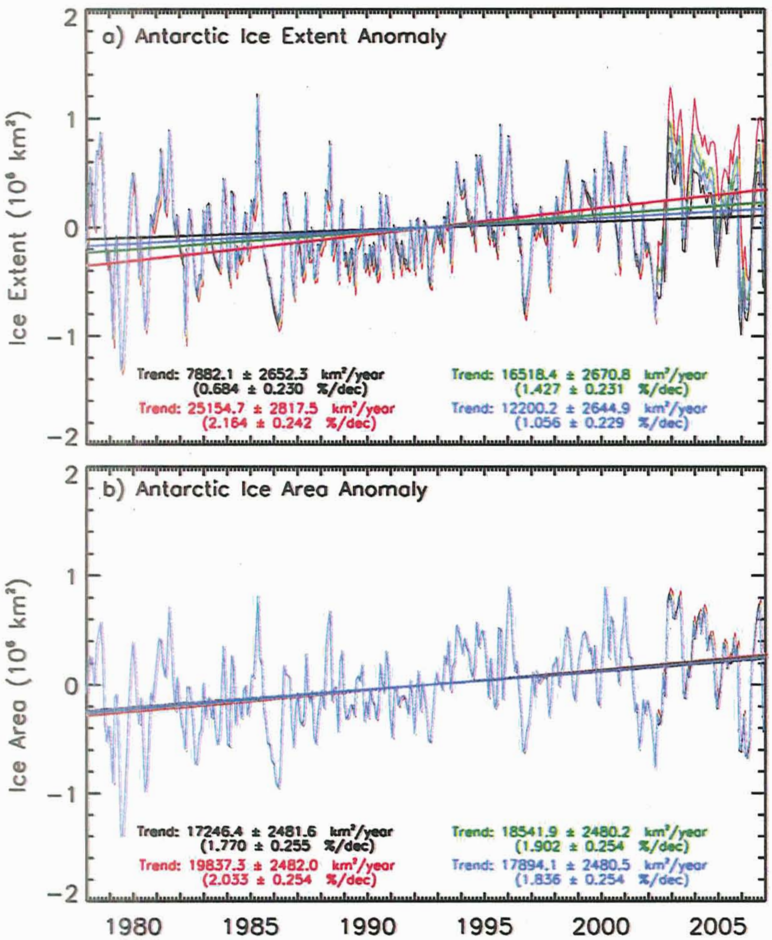

Figure 18. Sensitivity of trends to (a) ice extent and (b) ice area with adjustments of AMSR-E data by making the ice edge 6.25, 12.5, and 25 km further away from the ice pack in the Southern Hemisphere during an entire ice season.