Sudden increase in Antarctic sea ice: Fact or artifact?

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[1] Three sea ice data sets commonly used for climate research display a large and abrupt increase in Antarctic sea ice area (SIA) in recent years. This unprecedented change of SIA is diagnosed to be primarily caused by an apparent sudden increase in sea ice concentrations within the ice pack, especially in the area of the most-concentrated ice (greater than 95% concentration). A series of alternative satellite-derived records do not display any abnormal sudden SIA changes, but do reveal substantial discrepancies between different satellite sensors and sea ice algorithms. Sea ice concentrations in the central ice pack and SIA values derived from the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSRE) are consistently greater than those derived from the Special Sensor Microwave Imager (SSMI). A switch in source data from the SSMI to AMSRE in mid-2009 explains most of the SIA increase in all three affected data sets. If uncorrected for, the discontinuity artificially exaggerates the winter Antarctic SIA increase (1979–2010) by more than a factor of 2 and the spring trend by almost a factor of 4. The discontinuity has a weaker influence on the summer and autumn SIA trends, on calculations of Antarctic sea ice extent, and in the Arctic. **Citation:** Screen, J. A. (2011), Sudden increase in Antarctic sea ice: Fact or artifact?, *Geophys. Res. Lett.*, *38*, L13702, doi:10.1029/2011GL047553.

1. Introduction

[2] The Earth's sea ice cover is highly sensitive to climate variability and is a key indicator of climate change. Over recent decades, the northern and southern hemispheres have exhibited strikingly different sea ice trends. Arctic sea ice has decreased dramatically [*Stroeve et al.*, 2007; *Parkinson and Cavalieri*, 2008], initiating strong climate feedbacks that have enhanced the warming in the region [*Screen and Simmonds*, 2010]. In stark contrast, the Antarctic sea ice has been increasing over recent decades [*Comiso and Nishio*, 2008; *Cavalieri and Parkinson*, 2008], albeit at a much slower rate than the loss of Arctic ice.

[3] Our knowledge of recent sea ice change is largely based upon satellite passive microwave retrievals, available since late 1978. Prior to this, sea ice observations were sparse in space and time, particularly in the Southern Ocean. Even over the modern era, no single satellite has been in operation continuously. Therefore, to construct multi-decadal time series of sea ice cover it is necessary to combine information from multiple satellites and sensors [see, e.g., *Cavalieri et al.*, 1999]. Several synthesized data sets exist and have been invaluable for the observation and understanding of polar climate change. They have been used, for example, to examine sea ice variability and trends, to validate model sea ice output, and as boundary conditions for atmospheric reanalyses and models.

[4] Developing homogeneous records suitable for long-term trend analyses is not a simple task. Difficulties arise because different data sources provide varying estimates of the sea ice cover [e.g., *Cavalieri et al.*, 1999; *Rayner et al.*, 2003; *Comiso and Nishio*, 2008], which can result in discontinuities and induce artificial trends. Despite substantial efforts to prevent discontinuities entering data sets, it is almost inevitable that they arise occasionally in response to changes in the observational network. It is vital that these are documented, so that data-users are aware of them and can act accordingly; and understood so that they can be eliminated or avoided in the future. This study reports a discontinuity in three sea ice data sets commonly used for climate research, which causes an artificial sudden increase in Antarctic sea ice.

2. Sea Ice Data and Diagnostics

[5] We analyze Antarctic sea ice concentrations from a range of sources. These data sets can be divided into three broad categories: products that combine data from multiple instruments and satellites; products derived from a single type of instrument on-board multiple satellites; and products derived from a sole instrument on a single satellite.

[6] The multi-instrument, multi-satellite data sets are the Hadley Centre Ice and Sea Surface Temperature analyses (HadISST; http://hadobs.metoffice.com) [*Rayner et al.*, 2003], National Oceanic and Atmospheric Administration Optimum Interpolation (NOAA-OI; http://www.esrl.noaa.gov/) [*Reynolds et al.*, 2002] and the National Centers for Environmental Prediction Ice analyses (NCEP; http://polar.ncep.noaa.gov/) [*Grumbine*, 1996]. These data sets utilize measurements from the Scanning Multichannel Microwave Radiometer (SMMR) sensor on the Nimbus-7 satellite prior to 1987; then values from the Special Sensor Microwave Imager (SSMI) instruments on the series of Defense Meteorological Satellite Program (DMSP) satellites; and since May 2009, data from the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSRE) on the satellite Aqua. Here, HadISST data are used from 1979–2010, and NOAA-OI and NCEP from 1982–2010.

[7] The single-instrument, multi-satellite data sets are derived from the SSMI on the various DMSP satellites. Here we use three SSMI products, for the period 2003–2010, derived using three different sea ice algorithms: data determined using the ARTIST Sea Ice (ASI) algorithm [*Spreen et al.*, 2008], distributed by the Center for Satellite Exploitation and Research (CERSAT; http://cersat.ifremer.fr/); data processed using the NASA Team (NT) algorithm [*Cavalieri et al.*, 1996], distributed by the National Snow

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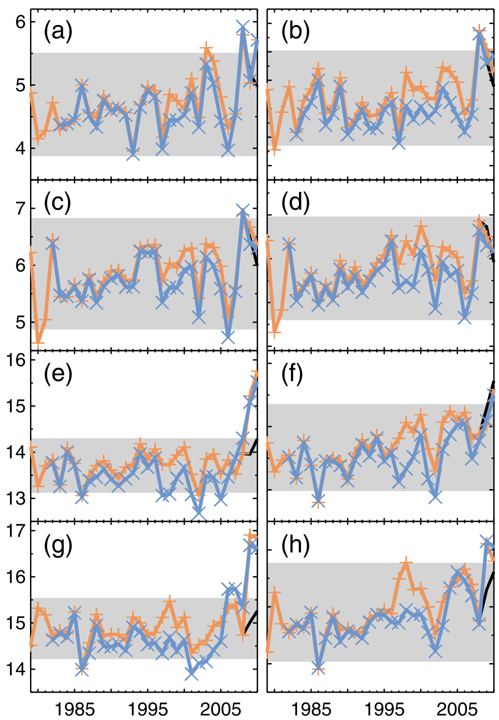

Figure 1. (a) Summer [December-February (DJF)] Antarctic SIA (million km^2). The orange line is for HadISST data and the blue line for NCEP data, and the gray band denotes two standard deviations from the long-term mean (1979–2008) in HadISST. The black line is for the corrected HadISST data [see text]. (b) As Figure 1a but for SIE. (c-h) As Figures 1a and 1b but for autumn [March-May (MAM)], winter [June-August (JJA)] and spring [September-November (SON)].

and Ice Data Center (NSIDC; http://nsidc.org); and data derived from the enhanced NT algorithm (NT2) [*Markus and Cavalieri*, 2000; *Comiso et al.*, 2003], distributed by the NASA Goddard Space Flight Center (GSFC; http://neptune.gsfc.nasa.gov/csb/).

[8] The single-instrument, single-satellite products are data from the AMSRE, for the period 2003–2010, calculated using the ASI algorithm and distributed by the University of Bremen (http://www.iup.uni-bremen.de); AMSRE data processed using the NT2 algorithm courtesy of the NSIDC; and for the period 2008–2010, data from the SSMI-Sounder (SSMIS) [*Maslanik and Stroeve*, 1999], processed using the NT algorithm and also available from the NSIDC.

[9] Sea ice concentration data downloaded as daily-means were converted to monthly-means. All data were analyzed on their native grids. The primary sea ice diagnostics calculated are the Antarctic sea ice area (SIA)

$$SIA = \sum_{i=1}^{i=n} A_i \times c \tag{1}$$

and the sea ice extent (SIE)

$$SIE = \sum_{i=1}^{i=n} A_i \tag{2}$$

where A is the area of the grid-box i, n is the number of grid-boxes with a sea ice concentration of 15% or greater (in the southern polar region) and c is the ice cover fraction (or percentage sea ice concentration divided by 100).

3. Sudden Increase in Antarctic Sea Ice

[10] Figure 1 shows the seasonal-mean Antarctic SIA and SIE from HadISST and NCEP. The data from NOAA-OI and NCEP plotted on top of each other and were almost indistinguishable. This is because the sea ice fields in NOAA-OI are calculated directly from the 7-day median of the NCEP daily sea ice concentration analyses. Therefore here and in what follows, NOAA-OI and NCEP are treated as identical data sets and are referred to collectively as NCEP. HadISST differs slightly from NCEP, particularly in the period 1997–2006, with a overall tendency for higher SIA and SIE in HadISST. However, the data sets are largely within 5% of each other and are highly correlated. Both data sets show gradual increases of Antarctic SIA and SIE in all seasons, consistent with those reported by other authors [*Cavalieri and Parkinson*, 2008; *Comiso and Nishio*, 2008]. The HadISST SIA trends (1979–2010) are 0.24, 0.25, 0.23 and 0.27 million km^2 per decade for summer, autumn, winter and spring, all statistically significant at the 95% level based on a two-sided Student's t-test. The corresponding SIE trends are 0.47, 0.32, 0.28 and 0.36 million km^2, all significant at the 99% level.

[11] Of particular interest to this study is the sudden increase in austral winter (JJA) and spring (SON) SIA over the last two years of the records (Figures 1e and 1g). The winter SIA for 2010 is 15.8 million km^2 and for 2009 is 15.2 million km^2 in HadISST. The long-term mean (1979–2008) for winter SIA is 13.7 million km^2. The spring SIA for 2010 is 16.8 million km^2 and for 2009 is 16.9 million km^2, compared to a long-term mean of 14.9 million km^2. In short, during winter and spring 2010, sea ice apparently covered roughly 2 million km^2 more than normal: this is an area approximately the size of the Greenland or West Antarctic ice sheets. Similar conclusions can be drawn from the NCEP data. There is weaker evidence for a corresponding sudden SIA increase in summer or autumn in either data set (Figures 1a and 1c). Comparable plots were also computed for the Arctic but no step-changes were immediately apparent in recent years (not shown). However, *Meier et al.* [2007] noted an inconsistency in Arctic SIE from HadISST between 1996 and 1997 due to a change in source data.

[12] Figure 2 contrasts the long-term mean (1979–2008) austral winter sea ice concentrations with those depicted in HadISST during the last two winters. The most prominent difference between the two periods are the higher sea ice concentrations within the ice pack during the latter period. In particular, there is a much greater area of the most highly-concentrated ice. In other words, there are fewer leads (areas of open water) within the ice pack. In what follows, sea ice of greater than 95% concentration is called "lead-free" ice (LFI). The area of LFI (shown by the solid black contour in Figure 2) is significantly greater than average in the last two years. In the long-term winter-mean, LFI is predominantly confined to the embayments of the Ross and Weddell Seas and off the coast of Dronning Maud Land (30°E-30°W). In contrast, during winters 2009 and 2010, LFI encircles the entire continent and extends much farther from the coastline.

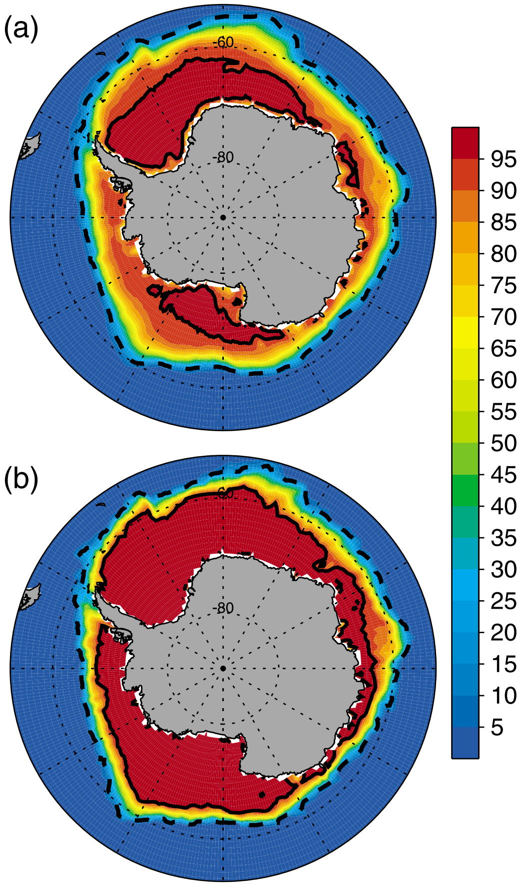

Figure 2. (a) Long-term mean (1979–2008) JJA sea ice concentrations (%) from HadISST. The dotted line denotes the 15% concentration contour and the solid line denotes the 95% concentration contour. (b) As Figure 2a but for the period 2009–2010.

[13] Interestingly, the SIE (defined by the 15% concentration contour, as is standard practice; dashed lines in Figure 2) shows only minor differences between the two periods. This can also be seen in the SIE time series in Figure 1, which in comparison to the SIA series do not show such a marked increase in recent years. Thus, it is the apparent decrease in leads, and not an equator-ward expansion of the sea ice edge, that is primarily responsible for the sudden increase in Antarctic SIA depicted in HadISST. Similar conclusions can be drawn from the spring sea ice concentrations in HadISST, and both the winter and spring patterns in NCEP (not shown).

[14] Figure 3 shows the temporal evolution of sea ice in five different concentration classes: 15–35, 35–55, 55–75, 75–95 and >95%. Within each season, the different concentration classes generally show similar inter-annual variability, and the gradual long-term increase in SIA is also seen in each concentration class individually. However, there is a clear and abrupt increase in LFI (>95%) between 2008 and 2009 in winter and spring. LFI tends to cover around 4–5 million km^2 in winter in HadISST (approximately one third of the winter SIA). In stark contrast, during winter 2009 and 2010, LFI appeared to cover more than 11 million km^2 (around three quarters of the winter SIA). This area of LFI is unprecedented in the previous 30 years. Similar conclusions arise from the spring data.

[15] The HadISST and NCEP data suggest a consolidation (fewer leads) of the winter and spring ice packs in the most recent two years. The unprecedented and abrupt nature of this change raises the question: is it a real climate signal or could it be an artifact in the data?

4. Fact or Artifact?

[16] To shed some light on the realism of the sudden increase in SIA we turn to a series of alternative data sets. Figure 4a shows the SIA, split into the five different concentration classes, derived from the AMSRE using the ASI algorithm. Unlike HadISST and NCEP, the AMSRE record comes from a single instrument and satellite, and provides a more homogeneous record since 2003. The large annual cycle of SIA is clearly evident, both in terms of the SIA and area of ice in each concentration class. Focusing on the LFI, an annual minimum occurs in February-March and an annual maximum in July-August, slightly earlier than the SIA annual maximum in September. The area of LFI is relatively constant from year-to-year, with a winter-mean of around 10 million km^2. Importantly, there is no sharp increase in LFI or SIA between 2008 and 2009 in the AMSRE data (cf. HadISST in Figure 4e and NCEP in Figure 4g).

[17] Figure 4b shows the corresponding evolution of SIA from the AMSRE using the NT2 algorithm. It has often been noted that different sea ice algorithms give varying estimates of the Antarctic SIA [e.g., *Parkinson and Comiso*, 2008; *Spreen et al.*, 2008]. Comparing Figures 4a and 4b gives an indication of the sensitivity of the SIA and LFI to the choice of sea ice algorithm. The NT2 algorithm gives higher SIA

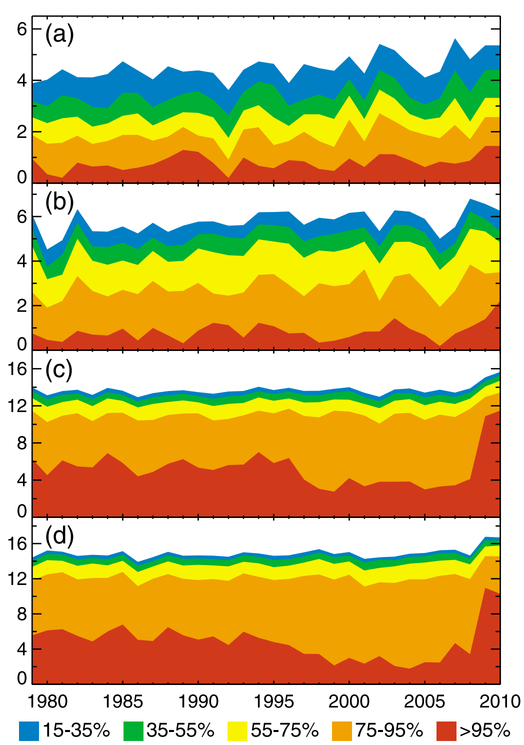

Figure 3. (a) DJF Antarctic SIA (million km^2) from HadISST. The colors show the area covered by sea ice in five concentration ranges. (b-d) As Figure 3a but for MAM, JJA and SON.

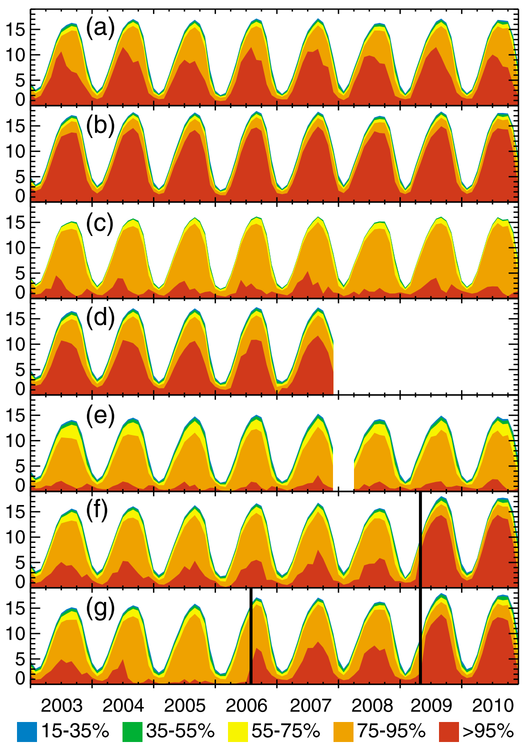

Figure 4. (a) Monthly-mean SIA (million km^2) derived from the AMSRE using the ASI algorithm. The colors show the area covered by sea ice in five concentration ranges. (b) As Figure 4a but derived using the NT2 algorithm. (c-e) As Figure 4a but derived from the SSMI using the ASI, NT2 and NT algorithms, respectively. Note that in Figure 4e the last 3 years of data are from the SSMIS. (f, g) As Figure 4a but for HadISST and NCEP, respectively. The solid vertical lines denote changes in source data or processing methods [see text].

and more LFI than the ASI algorithm. However, neither record displays a sudden increase in SIA or LFI.

[18] In addition to differences between sea ice algorithms, different satellite sensors may give varying estimates of the Antarctic SIA. Figures 4c and 4d show the SIA from the SSMI derived using the ASI and NT2 algorithms, respectively. The differences between Figures 4a and 4c, and between Figures 4b and 4d, relate to the different satellite sensors and not to the data processing. Three salient features arise from these comparisons. Firstly, the SIA estimates from the SSMI are less than those from the AMSRE. This applies to both the ASI- and NT2-derived data, although the differences are less pronounced in the latter. This may in part reflect deliberate efforts to reduce such differences during the development of the NT2 algorithm [*Markus and Cavalieri*, 2000; *Comiso et al.*, 2003]. Secondly, the area of LFI is consistently and significantly lower in the SSMI data than the AMSRE data. The winter-mean area of LFI is around 7 million km^2 greater when derived from the AMSRE than the SSMI using ASI, and around 4 million km^2 greater from the AMSRE than the SSMI using NT2. Thirdly, neither SSMI record shows a shift in SIA or LFI in the most recent years, in agreement with the AMSRE data but in conflict with HadISST and NCEP.

[19] Figure 4e shows the SIA from the SSMI (or SSMIS post-2007) derived using the original NT algorithm, which can be compared to the NT2 results in Figure 4d. The NT2 algorithm gives much higher SIA, in agreement with previous comparisons [e.g., *Markus and Cavalieri*, 2000] and more LFI than the older NT algorithm. This probably reflects the underestimation of ice concentrations by the NT algorithm [*Markus and Cavalieri*, 2000; *Rayner et al.*, 2003]. The SSMIS record from 2008–2010 displays no sudden increase in SIA or LFI. It is also worth noting that the change from SSMI to SSMIS in early 2008 results in no systematic change in SIA or the proportion of SIA in each individual concentration class, which is unsurprising given that the two sensors have been intercalibrated by the NSIDC [*Meier et al.*, 2011].

[20] In summary, none of the alternate records considered depict an abrupt change in SIA or LFI. Therefore, it is very unlikely that the apparent sudden increase in SIA and LFI depicted by HadISST (Figure 4f) and NCEP (Figure 4g) is a real climate signal.

[21] So, what caused the discontinuity? In early 2009, the SSMI instrument used in NCEP (f-13) suffered a severe degradation in performance. As a result, from the middle of May 2009, NCEP stopped using the SSMI and instead started using AMSRE data (R. Grumbine, personal communication, 2011). The AMSRE consistently depicts greater SIA and LFI than the SSMI (Figure 4). Thus, the switch in source data has caused a discontinuity in the NCEP data set, which propagates into HadISST and NOAA-OI as the NCEP fields are used in their construction.

[22] In HadISST, the switch from SSMI to AMSRE was accompanied by a simultaneous change in the method used to derive the sea ice concentrations, from the NT to NT2 algorithm (N. Rayner, personal communication, 2011). This data processing change may also contribute to the increase of HadISST SIA and LFI occurring in May 2009, as the NT2 algorithm consistently depicts higher SIA and more LFI than the NT algorithm (Figure 4). In NCEP, the switch from NT to NT2 occurred in August 2006 and caused an increase in amount of LFI (Figure 4g). Note, a parallel version of NCEP using the original NT algorithm continued to be produced for inclusion in HadISST from August 2006 to May 2009.

[23] To estimate what proportion of the apparent sudden increase in SIA occurring in May 2009 is due to the discontinuity, and how much is a real climate signal, the author has applied a simple correction factor to the HadISST data, using the homogeneous AMSRE record as a reference. SIA anomalies were calculated from the AMSRE data for each season in 2009 and 2010, relative to and as a percentage of the 2003–2008 AMSRE seasonal means. These seasonal anomalies were then used to scale the HadISST 2003–2008 seasonal means and generate corrected values for HadISST during 2009 and 2010 (black lines in Figure 1). It should be noted that the uncorrected values for 2009 and 2010 may be more realistic than the earlier record because they are based on higher-resolution satellite data (AMSRE) and an improved sea ice algorithm (NT2). Thus, the corrections applied here may actually worsen the values for 2009 and 2010. However, they adjust the most recent data to make them consistent with the earlier record, resulting in more realistic trends, and it is these trends that are of primary concern to this study.

[24] The corrections reduce the winter SIA by 1.2–1.3 million km^2 and the spring SIA by 1.7–1.8 million km^2. It is noteworthy that even after the corrections have been applied, winter 2010 has the highest SIA and SIE in the satellite record. Although the discontinuity is less pronounced in summer and autumn, the corrections still reduce the SIA by 0.8 million km^2 in summer 2010 and 0.4 million km^2 in autumn 2010 (note, the "corrected" values for summer and autumn 2009 are very close to the "uncorrected" values because the switch from SSMI to AMSRE occurred at the end of autumn 2009). The corrections have only minor influences on the SIE values, again indicating that the discontinuity primarily effects concentrations within the central ice pack and not the sea ice edge.

[25] The corrections have an strong impact on SIA trends calculated over the period 1979–2010. They reduce the winter SIA trend from 0.23 to 0.09 million km^2 per decade and the spring SIA trend from 0.27 to 0.07 million km^2 per decade. Thus, the discontinuity artificially exaggerates the winter SIA increase by a factor of 2.5 and the spring trend by a factor of 3.9. The corrected winter and spring trends are no longer statistically significant (at the 90% level). The summer and autumn SIA trends are reduced by about 0.03, giving corrected increases of 0.21 and 0.22 million km^2 per decade, both remaining significant at the 95% level. The autumn and winter SIE trends are almost unchanged, whilst the spring and summer SIE trends are slightly reduced.

[26] Of course, previously published values based on unaffected data remain valid.

5. Conclusions and Closing Remarks

[27] The sudden increases in Antarctic SIA depicted by three "climate-suitable" data sets are primarily caused by higher sea ice concentrations within the central ice pack in the two most recent years. However, this apparent consolidation of the ice pack is not a real climate signal, but instead the result of a switch in source satellite data and processing methods. Failure to correct for this discontinuity will lead to significantly exaggerated Antarctic SIA increases.

[28] Arguably, the AMSRE offers a more realistic depiction of the sea ice cover than previous sensors due to its increased horizontal resolution and wider spectral range [*Comiso and Nishio*, 2008; *Comiso and Parkinson*, 2008; *Spreen et al.*, 2008] and therefore, inclusion of AMSRE measurements into sea ice data sets is desirable. However, from a climate research perspective, data continuity is essential for accurately monitoring sea ice changes and may be jeopardized by the inclusion of new sources of data. As this paper demonstrates, it is imperative that climate data set developers test for and then correct for any discontinuities that enter the data record due to changing satellite sensors or sea ice concentration algorithms. Work is ongoing towards a compromise solution that can harness the increased precision of the AMSRE without degrading the homogeneity of valuable long-term sea ice records (R. Grumbine, personal communication, 2011). For example, *Comiso and Nishio* [2008] recently demonstrated a method of normalizing brightness temperatures from the SSMI to be consistent with those from the AMSRE, prior to the calculation of sea ice concentrations. Other authors have suggested it is more appropriate to calibrate at the geophysical product level (i.e., sea ice concentrations) rather than at the level of measured radiances [*Zabel and Jezek*, 1994]. This is in fact the approach the sea ice community has generally adopted [see, e.g., *Cavalieri et al.*, 1999; *Meier et al.*, 2011].

[29] When improved data sets become available they will be announced and made readily available at the online data depositories (see the URLs given in Section 2). In the meantime, the most recent years of HadISST and NCEP data cannot be considered compatible with earlier data. Furthermore, data users should be aware that atmospheric models or reanalyses that use these sea ice fields for their surface boundary conditions, may also contain discontinuities in variables that are strongly dependent on the prescribed ice cover, such as the air-sea fluxes.

[30] Finally, is it noted that no obvious discontinuities were found for the Arctic SIA, although small discrepancies between the SSMI- and AMSRE-derived data have been noted by others [*Comiso and Nishio*, 2008; *Comiso and Parkinson*, 2008]. In part, the reason why the discontinuity in SIA is observed mostly in the Antarctic, and to a much lesser degree in the Arctic, is that the algorithm change (from NT to NT2) primarily effects Antarctic sea ice concentrations [*Markus and Cavalieri*, 2000].

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