



A spurious jump in the satellite record: has Antarctic sea ice expansion been overestimated?

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Abstract. Recent estimates indicate that the Antarctic sea ice cover is expanding at a statistically significant rate with a magnitude one-third as large as the rapid rate of sea ice retreat in the Arctic. However, during the mid-2000s, with several fewer years in the observational record, the trend in Antarctic sea ice extent was reported to be considerably smaller and statistically indistinguishable from zero. Here, we show that much of the increase in the reported trend occurred due to the previously undocumented effect of a change in the way the satellite sea ice observations are processed for the widely used Bootstrap algorithm data set, rather than a physical increase in the rate of ice advance. Specifically, we find that a change in the intercalibration across a 1991 sensor transition when the data set was reprocessed in 2007 caused a substantial change in the long-term trend. Although our analysis does not definitively identify whether this change introduced an error or removed one, the resulting difference in the trends suggests that a substantial error exists in either the current data set or the version that was used prior to the mid-2000s, and numerous studies that have relied on these observations should be reexamined to determine the sensitivity of their results to this change in the data set. Furthermore, a number of recent studies have investigated physical mechanisms for the observed expansion of the Antarctic sea ice cover. The results of this analysis raise the possibility that much of this expansion may be a spurious artifact of an error in the processing of the satellite observations.

1 Introduction

Observational estimates of the sea ice cover in both hemispheres are available at approximately daily resolution from satellite passive microwave measurements from the late 1970s onwards. The microwave emissivity of sea ice is typically higher than that of the ocean, causing ice-covered regions to emit with greater intensity (i.e., have a higher brightness temperature) than regions with an ice-free ocean surface of the same temperature. Because warmer surfaces also emit with higher intensity, however, it is difficult to distinguish between cold sea ice and a warm ice-free ocean surface using brightness temperature measurements at a single frequency and polarization. Hence simultaneous measurements at multiple frequencies and polarizations are normally used to estimate the sea ice concentration (i.e., the fraction of each ocean pixel that is covered with ice), because the difference in emissivity between sea ice and open ocean varies as a function of frequency and polarization. A suite of other issues further complicate estimates of sea ice concentration from passive microwave data, including interference from weather effects; the similarity in microwave emissivity between sea ice and regions within a sensor footprint containing both land and ice-free ocean; and the similarity in microwave emissivity between ice-free ocean, melt ponds on thick ice floes, and thin ice (e.g., Maslanik, 1992; Cavalieri et al., 1995).

Two separate algorithms for estimating sea ice concentrations from passive microwave satellite measurements of brightness temperatures at multiple frequencies and polarizations were developed concurrently in the 1980s at the NASA Goddard Space Flight Center. Both algorithms are physically motivated but highly empirical in their implementation. The

first, called the “Bootstrap” algorithm, is based on interpolation between clusters of points in scatter plots of brightness temperatures (Comiso, 1986) (note that it does not involve the statistical bootstrapping technique). The second, called the “NASA Team” algorithm, is based on difference ratios between brightness temperatures (Cavalieri et al., 1984). Here we focus on the Bootstrap algorithm, which is one of the most widely used ice concentration products and forms the basis of the discussion of observed sea ice changes in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) (IPCC, 2007) and Fifth Assessment Report (IPCC AR5) (IPCC, 2013).

In recent years, there has been substantial interest in the trend in Antarctic sea ice extent (i.e., the sum of the surface areas of all grid cells that have an ice concentration above 15 %) primarily due to the observed asymmetry between increasing ice extent in the Antarctic and rapidly diminishing ice extent in the Arctic (e.g., Cavalieri et al., 1997) and the inability of current climate models to capture this (e.g., Eisenman et al., 2011).

The IPCC AR5 reported the observed Antarctic sea ice extent to be expanding at a highly statistically significant rate (monthly anomalies from the mean seasonal cycle increasing at $16.5 \pm 3.5 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$), with a magnitude one-third as large as the sea ice retreat in the Arctic ($-48.0 \pm 3.0 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$). This is in substantial contrast with the IPCC AR4, which reported the trend in Antarctic sea ice extent to be small and statistically indistinguishable from zero ($5.6 \pm 9.2 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$; see Appendix A). The Antarctic sea ice extent trend was highlighted as a bullet point in the *Summary for Policymakers* of both the IPCC AR4 and IPCC AR5, and the substantial increase in this trend is one of the notable differences between the two reports.

The contrast in trend is also apparent in the literature preceding each IPCC report, with a modest Antarctic sea ice extent trend reported in the early 2000s (Comiso and Steffen, 2001; Comiso, 2003), and reported trends that were considerably larger in later papers that used ostensibly nearly the same data set with several additional years of observations (Comiso and Nishio, 2008; Comiso, 2010) (see details in Appendix A).

This change in the trend has generally been attributed within the community to the lengthening time span and associated addition of new data. However, the results presented below demonstrate that much of the change in the trend actually occurred due to the previously undocumented effect of a change in the Bootstrap sea ice data set in the late 2000s.

2 Data

The data and methods are summarized here and described in detail in Sect. S1 in the Supplement. We analyze daily Bootstrap sea ice concentration fields for the time period November 1978 through December 2012, which are available for

public download from the National Snow and Ice Data Center (NSIDC) (Comiso, 2000). In September 2007, NSIDC documented an update to the Bootstrap algorithm for consistency with other satellite measurements (see Sect. S1.3 in the Supplement), and the entire data set was reprocessed. NSIDC refers to the current data set as “Version 2”, a convention we follow here. This update to the data set was generally viewed within the community as having a negligible impact on the trend (Comiso and Nishio, 2008).

We also analyze the version of the data set that was posted on the NSIDC website prior to the September 2007 version update, which we acquired from NSIDC User Services, and we refer to this earlier data set as “Version 1”. This data set covers the time period November 1978 through December 2004. We calculate a monthly ice extent time series from each of the two ice concentration data sets.

For comparison with studies published previously, we truncate each data set at a range of endpoints and calculate the trend. We follow the standard practice for estimating trends in the ice cover by using ordinary least squares linear regression of monthly anomalies from the mean seasonal cycle, with the regression confidence interval being treated as an error bar that accounts for uncertainty associated with natural variability about the linear trend (e.g., Parkinson et al., 1999). We note that this method assumes that the trend is linear in time and that natural variability can be treated as white noise drawn from a zero-mean normal distribution. It should be emphasized that the error bar constructed in this way does not include any uncertainty associated with the satellite retrieval, which the results of this study suggest may expand the error bar considerably. Although superior measures of error could be identified, here we follow this standard convention. Hence for each endpoint (computed for every month), anomalies are computed with respect to the mean seasonal cycle averaged over all months in the truncated record, and then the trend estimate and confidence interval for the anomaly time series are calculated.

3 Results and discussion

The time series of annual-mean ice extent anomalies for both versions of the Bootstrap data set are plotted in Fig. 1a. There is a readily discernible bias between the two versions of the Bootstrap data set. Although both versions have similar values for each year, Version 2 has slightly lower values before 1991 and slightly higher values afterward. This is associated with a substantial difference in the 1979–2004 trend (dashed lines in Fig. 1a), implying that studies using Version 2 of the Bootstrap data set will estimate larger rates of expansion of the Antarctic sea ice cover.

In order to assess how this issue influences how the published trend has evolved during the past decade, we vary the endpoint in each version of the Bootstrap record and then compute the trend (Fig. 1b). For all plotted endpoints,

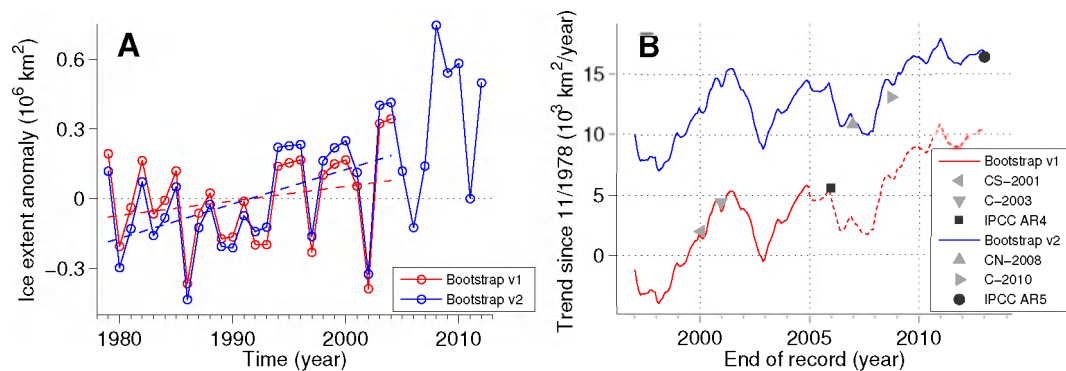


Figure 1. Antarctic sea ice extent calculated with the current Bootstrap data set (Version 2, blue), as well as an ostensibly nearly equivalent version of the data set that was distributed previously (Version 1, red). **(A)** Annual-mean ice extent anomalies from the 1979–2004 mean. Trends for the two annual time series, calculated for the period 1979–2004, are indicated by dashed lines. **(B)** Trends in the monthly-mean ice extent records truncated at a range of endpoints (curves) and compared with values published previously (symbols). Trends reported in the literature, which are plotted above the end date of the data set considered in each study, are from four studies (Comiso and Steffen, 2001; Comiso, 2003; Comiso and Nishio, 2008; Comiso, 2010), the IPCC AR4 (IPCC, 2007), and the IPCC AR5 (IPCC, 2013) (see Appendix A). The red dashed line is an approximate continuation of the Version 1 data set using Version 1B (see Sect. 3). Values published in the early to mid-2000s align with the Bootstrap Version 1 curve, and values published more recently align with the Bootstrap Version 2 curve.

Version 2 (blue curve) has a substantially larger positive trend than Version 1 (red curve).

Previously published values for the trend in Antarctic sea ice extent are plotted in Fig. 1b (symbols) above the end date of the record that was analyzed in each study. The trends reported in the IPCC AR4 and papers published before it match the values computed here using Version 1, whereas the trends reported in later papers and the IPCC AR5 match the substantially higher values computed here using Version 2. Similarly, an earlier study that analyzed data through 1998 reported that the Bootstrap algorithm produced “a small negative trend for ice extent” in the Antarctic (Zwally et al., 2002), which is consistent with Version 1 in Fig. 1b.

Although there is some variability in the red and blue curves in Fig. 1b, it is clear that much of the change in the reported trend between the IPCC AR4 (black square) and IPCC AR5 (black circle) is due to the transition from Version 1 to Version 2. Specifically, if the Version 2 data set had been used in the IPCC AR4 analysis of ice extent during 1979–2005, the trend would have been $14.1 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$, a value fairly similar to the trend of $16.5 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$ reported in the IPCC AR5 analysis of 1979–2012 and in marked contrast with the trend of $5.6 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$ that was reported in the IPCC AR4 based on Version 1 data. Overall, we find that most of the increase in trend between the IPCC AR4 and AR5 is associated with the update from Version 1 to Version 2, with the remainder being due to the additional years in the record (see Table S1 in the Supplement).

The two data sets can be compared to determine the temporal structure of the difference between them. The difference in ice extent between Version 2 and Version 1 is plotted in Fig. 2. There is a clear transition in December 1991, which coincides with a satellite sensor change (vertical dashed

line; see Sect. S1.1 in the Supplement): on 3 December 1991, there was a transition from the Special Sensor Microwave/Imager (SSM/I) flown on the Defense Meteorological Satellite Program (DMSP) F8 satellite to the SSM/I flown on the DMSP F11 satellite. Version 2 has a smaller value in nearly all months prior to the sensor change and a larger value in nearly all months after it.

This implies that the 2007 update of the entire data set from Version 1 to Version 2 included a substantial change in the intercalibration across the December 1991 sensor transition. Hence the difference in trend between the two curves in Fig. 1b appears to be associated with an erroneous sensor change intercalibration in one of the two Bootstrap versions.

Although an update to the Bootstrap algorithm was documented on the NSDIC website (see Sect. S1.3 of Supplement) and we compare the data set before (Version 1) and after (Version 2) this update occurred, we cannot be certain that the two data sets we analyze contain only the differences discussed in the documented update for several reasons. First, there is some ambiguity in the Bootstrap data set version control. For example, we find that the “original” data set discussed in Comiso and Nishio (2008) coincides with our Version 2 data set, implying that the salient change in the data set preceded the analysis in Comiso and Nishio (2008), which is the paper typically cited for the version update. Further ambiguities in the documentation of the Bootstrap version update are discussed in Sect. S1.3 of the Supplement. Second, the Bootstrap algorithm uses brightness temperature measurements which are processed by Remote Sensing Systems, and the version has changed over time due to new temperature calibrations and corrections of small errors. However, this is unlikely to be the source of the jump in December 1991, because intercalibration across sensor changes

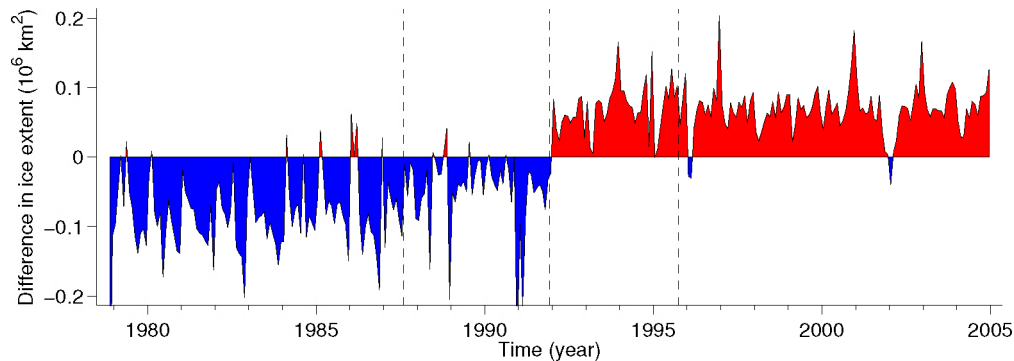


Figure 2. Difference between sea ice extents in the two Bootstrap data sets, plotted as Version 2 – Version 1. Both records are monthly-mean anomalies from the 1979–2004 mean seasonal cycle. Transitions between satellite sensors are indicated by vertical dashed lines (see Sect. S1.1 in the Supplement). The difference in ice extent appears to be dominated by a spurious jump in one of the data sets coinciding with the December 1991 sensor transition.

occurs at the algorithm level through the adjustment of algorithm coefficients (tie points), and this should account for any basic inconsistency in brightness temperatures across a sensor change.

To the extent that Fig. 2 resembles a step function, we can generate an approximate extension of Version 1 by subtracting a constant offset from Version 2 after the sensor change. We refer to this time series as “Version 1B”, which we generate by subtracting $0.16 \times 10^6 \text{ km}^2$ from Version 2 in all months after December 1991. Whereas the Version 1 data set ends in December 2004, Version 1B spans the longer time period from November 1978 through December 2012 (the same time period as Version 2). Version 1B has a trend that is nearly equivalent to Version 1 for the range of endpoints plotted in Fig. 1b (see Fig. S5c in the Supplement), and it is used to approximately extend Version 1 for comparison with Version 2 (red dashed line in Fig. 1b; see also Table S1 in the Supplement).

In the Supplement (Sect. S2), several methods are investigated to identify whether the change from Version 1 to Version 2 introduced an error or removed one. None of these methods unequivocally resolves the issue. Specifically, we compare the two Bootstrap versions with ice extents computed using the NASA Team algorithm, examine the temporal and spatial features of the differences between data sets, and also consider the Arctic sea ice cover in the three data sets. The main findings discussed in Sect. S2 include (1) that the difference between the NASA Team data set and each Bootstrap version is too noisy to definitively identify which Bootstrap version has an error (Fig. S2); (2) that there also appear to be differences in the Arctic between the two Bootstrap versions as well as the NASA Team data set across some sensor changes (Fig. S4); (3) that the differences in trend between the two Bootstrap data sets and the NASA Team data set in both the Antarctic and the Arctic are considerably larger than the error bar that typically accompanies reported trend estimates (Figs. S5–S8), implying that the re-

gression confidence interval substantially underestimates the uncertainty in the sea ice trends by failing to account for errors associated with the ice concentration retrieval; (4) that there was also a change in the Arctic sea ice extent trend associated with the Bootstrap data set update, but it was relatively small compared with the real change in trend associated with adding several more years to the record between the IPCC AR4 and IPCC AR5 (Fig. S7); (5) that there is little overall seasonal structure in the Antarctic sea ice trend in any of the records (Fig. S9); and (6) that the spatial structure of the difference in Antarctic sea ice concentration between the two Bootstrap versions appears to be relatively spatially uniform, consistent with an error in the intercalibration across a sensor change (Fig. S11).

4 Conclusions

In summary, we find that much of the large increase in the reported rate of Antarctic sea ice expansion since the IPCC AR4 occurred due to the previously undocumented effect of a change in the way the observations are processed, rather than being simply due to the addition of several years of data. Specifically, we find that the current Bootstrap Antarctic sea ice extent data set (Version 2) produces substantially larger trends for a given time period than the ostensibly nearly identical data set used prior to 2007 (Version 1). We are able to reproduce the results of pre-2007 studies and the IPCC AR4 using the Version 1 data set and to reproduce the results of more recent studies and the IPCC AR5 using the Version 2 data set, and we demonstrate the difference in the trend by comparing the two data sets. We find that the cause of the difference in the trend is a previously undocumented change in the intercalibration across a 1991 sensor transition when the data set was reprocessed in 2007.

With the lack of a more precise version control for the Bootstrap sea ice concentration data set (see Sect. S1.3 in the Supplement), it is difficult to determine exactly what caused this change in the trend. Importantly, there was no documentation of any change in the Bootstrap data set directly influencing the intercalibration across the sensor transition in December 1991. Hence we cannot be certain whether the change that caused the increase in the trend corrected a problem or introduced one, and we lay out two possibilities that are consistent with the results of this analysis. The first possibility is that Version 1 is approximately correct, and a spurious jump in 1991 from a sensor transition intercalibration error was inadvertently introduced into the Bootstrap data set in the 2007 update from Version 1 to Version 2. In this case, the rate of Antarctic sea ice expansion has been overestimated in recent years, and recent literature including the IPCC AR5 *Summary for Policymakers* contains an error that needs to be corrected. The second possibility is that Version 2 is approximately correct, and a spurious jump in 1991 from a sensor transition intercalibration error that existed in Version 1 was corrected in the 2007 update to Version 2, although this correction was never explicitly documented. In this case, earlier literature including the IPCC AR4 *Summary for Policymakers* contains a previously undocumented error, and the substantial body of science generated prior to 2007 that relied on Bootstrap Antarctic sea ice concentration to reach its conclusions needs to be reexamined to assess how this correction to the data set influences the results of the studies.

We note that while we focus here on the Bootstrap data set, which was the source for the conclusions in the IPCC AR4 and IPCC AR5, such issues can arise in other satellite sea ice data sets (or any climate data record) due to factors including inconsistencies in source data, changes in processing method, and the addition of new data sources (e.g., Screen, 2011).

A number of studies have proposed physical mechanisms for the reported expansion of the Antarctic sea ice cover during recent decades. The ozone hole was suggested as a possible cause (Thompson and Solomon, 2002; Turner et al., 2009), but recent modeling studies have found that Antarctic ozone depletion causes sea ice retreat rather than advance (Sigmond and Fyfe, 2010; Bitz and Polvani, 2012). Other studies have proposed more ice growth associated with a stronger halocline due to increased freshwater flux from ice sheet discharge (Bintanja et al., 2013) or precipitation (Liu and Curry, 2010), less ice melt from a weakened ocean heat flux associated with stronger ocean stratification (Zhang, 2007), or suppressed warming due to ocean heat uptake (Kirkman and Bitz, 2011), although an observational analysis suggests that the ice cover changes have been driven primarily by winds (Holland and Kwok, 2012). Natural variability has also been suggested as the cause (Zunz et al., 2013; Polvani and Smith, 2013), although this requires a relatively low probability event to be occurring. The results of this analysis raise an alternative and potentially complementary possibility. If Version 1 is approximately correct and Version 2 contains an error, then much of the apparent sea ice growth in the Southern Hemisphere is a spurious artifact in the satellite record.

These results illustrate the need for thorough documentation and version control in observational data sets. Ideally all observational data sets, especially those used widely and included in IPCC assessment reports, would have sufficient documentation of algorithms and algorithm changes for previous and current versions of the data to be independently replicated from the raw sensor data. Such transparency is particularly essential for highly visible and at times controversial climate change parameters such as the sea ice cover.

Appendix A: Previously published trends

Here we summarize the Bootstrap Antarctic sea ice extent trends reported in previous publications that are included as symbols in Fig. 1b.

A series of papers have reported trends computed using monthly-mean Bootstrap ice extent anomalies from the mean seasonal cycle including error bars that represent the 68 % linear regression confidence interval. All used records that begin in either November 1978 or January 1979 but end at different times. With data until January 2000, the trend was reported to be $2.0 \pm 3.9 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$ (Comiso and Steffen, 2001); with data until December 2000, the trend was reported to be $4.4 \pm 3.7 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$ (Comiso, 2003); with data until December 2006, the trend was reported to be $10.9 \pm 2.7 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$ (Comiso and Nishio, 2008); and with data until September 2008, the trend was reported to be $13.2 \pm 2.5 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$ (Comiso, 2010).

The IPCC AR4, which used annual-mean Bootstrap data during 1979–2005 and an error bar representing the 90 % linear regression confidence interval, reported the trend in Antarctic sea ice extent to be $5.6 \pm 9.2 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$. This point is included in Fig. 1b above December 2005 (see also Table S1 in the Supplement). The IPCC AR4 *Summary for Policymakers* reported that Antarctic sea ice showed “no statistically significant average trends”.

The IPCC AR5, which used monthly-mean Bootstrap data during November 1978 through December 2012 and an error bar representing the 90 % linear regression confidence interval, reported the trend in Antarctic sea ice extent to be $16.5 \pm 3.5 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$ (see also Table S1 in the Supplement), with the uncertainty range being included in the IPCC AR5 *Summary for Policymakers*.

The slight differences in Fig. 1b between previously reported trends (symbols) and those computed here (curves) are expected to arise due to issues including rounding errors associated with the number of significant figures used to report trends, slight differences in the data sets, and slight differences in the methodology such as how missing data are treated and how ice extent is calculated from the gridded ice concentration fields.

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