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A spurious jump in the satellite record: is Antarctic sea ice really expanding?

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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 the increase in the reported trend occurred primarily due to the effect of a previously undocumented change in the way the satellite sea ice observations are processed for the widely-used Bootstrap algorithm dataset, rather than a physical increase in the rate of ice advance. Although our analysis does not definitively identify whether this undocumented change introduced an error or removed one, the resulting difference in the trends suggests that a substantial error exists in either the current dataset 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 dataset. 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 this expansion may be a spurious artifact of an error in the satellite observations, and that the actual Antarctic sea ice cover may not be expanding at all.

1 Introduction

Observational estimates of the sea ice cover in both hemispheres are available at approximately daily resolution from satellite passive microwave measurements since the late 1970s. 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, brightness temperature measurements at a single frequency and polarization have difficulty accurately distinguishing between cold sea ice and a warm ice-free ocean surface. 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 total area of pixels with 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 ($16.5 \pm 3.5 \times 10^3\ \mathrm{km^2\,yr^{-1}}$), with a magnitude 1/3 as large as the sea ice retreat in the Arctic ($-48.0 \pm 3.0 \times 10^3\ \mathrm{km^2\,yr^{-1}}$). Although it has not been widely noted, this is a substantial contrast with the IPCC AR4, which reported the trend in Antarctic sea ice extent to be small and statistically indistinguishable from zero ($5.6 \pm 9.2 \times 10^3\ \mathrm{km^2\,yr^{-1}}$; 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 as much as 7× larger in later papers that used ostensibly the same dataset with several additional years of observations (Comiso and Nishio, 2008; Comiso, 2010) (see details in Appendix A).

These changes in trends have generally been attributed within the community to the lengthening timespan and associated addition of new data. However, the analysis presented here demonstrates that this large change in trend with only a small change in timespan occurred primarily due to an undocumented change in the Bootstrap sea ice dataset that occurred shortly after the IPCC AR4 (IPCC, 2007).

2 Data

The data and methods are summarized here and described in detail in Sect. S1 of 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, the entire dataset was reprocessed with the updated Bootstrap algorithm from Comiso and Nishio (2008) (see Sect. S1 of the Supplement), and NSIDC refers to the current dataset as "Version 2", a convention we follow here. We also analyze the version of

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the dataset that was posted on the NSIDC website prior to September 2007, which we acquired from NSIDC User Services, and we refer to this earlier dataset as “Version 1”. This dataset covers the time period November 1978 through December 2004. We calculate a monthly ice extent time series from each of the two ice concentration datasets. In order to compare with the IPCC AR4, which analyzed a dataset that continued a year longer than the Version 1 dataset that we acquired from NSIDC, we also consider a continuation of the Bootstrap Version 1 dataset for 2004–2005 based on the ice extent data presented in the IPCC AR4 (see Sect. S1.2 of the Supplement). This continuation is treated separately and clearly identified, rather than being spliced onto the Version 1 dataset.

For comparison with studies published previously, we truncate each dataset 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). It should be noted 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. Although superior measures 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 of the anomaly time series is calculated.

3 Results

The time series of annual-mean ice extent anomalies for both versions of the Bootstrap dataset are plotted in Fig. 1a. There is a readily discernible bias between the two versions of the Bootstrap dataset. Although both versions have similar values for each year, Version 1 has slightly lower values after 1991 and slightly higher values before-

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hand. 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 dataset will estimate larger rates of expansion of the Antarctic sea ice cover.

In order to assess how these two issues influence how the published trend has evolved during the past decade, we vary the end point in each version of the Bootstrap record and then compute the trend (Fig. 1b). For all plotted endpoints, Version 2 (blue curve) has a substantially larger positive trend than Version 1 (red curve), with the magnitude of the trend in Version 2 often being more than 10× larger than in Version 1.

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 we compute 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 the change in the reported trend between the IPCC AR4 (black square) and IPCC AR5 (black circle) is dominated by the spurious effect of the jump between Version 1 and Version 2. Specifically, if the Version 2 dataset had been used in the IPCC AR4 analysis of ice extent during 1979–2005, they would have found the trend to be $14 \times 10^3\,\mathrm{km}^2\,\mathrm{yr}^{-1}$, a value fairly similar to the trend of $16.5 \times 10^3\,\mathrm{km}^2\,\mathrm{yr}^{-1}$ reported in the IPCC AR5 analysis of 1979–2012 and in stark contrast with the trend of $5.6 \times 10^3\,\mathrm{km}^2\,\mathrm{yr}^{-1}$ that was actually reported in the IPCC AR4 based on Version 1 data.

A change in the Bootstrap algorithm was documented in Comiso and Nishio (2008), who made an adjustment for consistency between instruments on different satellites and reported the change to have a negligible effect on the Antarctic ice extent trend (see Sect. S1.3 of the Supplement). The trend reported in Comiso and Nishio (2008) for the "original" dataset is indicated by the the gray upward-pointing triangle in Fig. 1b.

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This matches what we compute using the Version 2 dataset (blue curve). Hence the change that caused the jump from the red curve to the blue curve in Fig. 1b has already occurred in the "original" dataset considered in Comiso and Nishio (2008). The results in Fig. 1b indicate that the undocumented change in the Bootstrap sea ice dataset occurred after the IPCC AR4 (IPCC, 2007) and before the results of Comiso and Nishio (2008).

The two datasets 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 of the Supplement), with Version 2 having a smaller value in nearly all months prior to the sensor change and a larger value at nearly all months after it. Indeed, subtracting 0.15×10^6 km^2 from Version 2 in all months after December 1991 causes the trend to be nearly equivalent to Version 1 for the range of endpoints plotted in Fig. 1b (not shown). Hence the issue appears to be associated with erroneous calibration across the December 1991 sensor change in one of the two Bootstrap versions.

In the Supplement (Sect. S2), several methods are investigated to identify whether the undocumented change from Version 1 to Version 2 introduced an error or removed one, although none of the methods unequivocally resolves the issue. 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 datasets, and consider the Arctic sea ice cover in the three datasets. The main findings discussed in Sect. S2 include (1) that the difference between NASA Team data and each Bootstrap version is too noisy to identify which Bootstrap version has an error (Fig. S2), (2) that there also appear to be differences between the two Bootstrap versions in the Arctic in some calibrations across sensor changes (Fig. S4), (3) that the difference in trend between the two Bootstrap datasets and the NASA Team dataset in both the Antarctic and the Arctic are considerably larger than the error bar that typically accompanies reported trend estimates (Figs. S5, S6), (4) that there was also a spurious jump in the

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Arctic sea ice extent trend between the IPCC AR4 and IPCC AR5 but it was relatively small compared with the real change in trend associated with adding several more years to the record (Fig. S6), (5) that there is little overall seasonal structure in the Antarctic sea ice trend in any of the records (Fig. S7), and (6) that the spatial structure of the difference in Antarctic sea ice cover between the two Bootstrap versions appears to be consistent with an error in the calibration across a sensor change (Fig. S9).

4 Conclusions

In summary, we find that the large increase in the reported rate of Antarctic sea ice expansion since the IPCC AR4 occurred primarily due to a previously undocumented 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 dataset (Version 2) produces substantially larger trends for a given time period than the ostensibly nearly identical dataset 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 dataset and to reproduce the results of more recent studies and the IPCC AR5 using the Version 2 dataset, and we demonstrate the spurious jump in the trend by comparing the two datasets.

Since there is no documentation that such a change was intensionally made, and our analysis does not categorically determine whether Version 1 or Version 2 is more accurate, we can not be certain whether the apparently inadvertent change leading to the increased trend introduced a problem or corrected one. Hence we lay out two possibilities that are consistent with the results of this analysis. The first possibility is that Version 1 is approximately correct, the Antarctic sea ice extent has remained nearly constant, and an error was inadvertently introduced into the Bootstrap dataset sometime around 2007 before the algorithm was adjusted by Comiso and Nishio (2008). In this case, 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, Antarctic sea ice is expanding at a statistically significant rate with a magnitude 1/3 as large as Arctic sea ice retreat, and an error was corrected in the Bootstrap dataset around 2007, but the change was never documented. In this case, earlier literature including the IPCC AR4 *Summary for Policymakers* contains an error, and the substantial body of science generated prior to 2007 that relied on Bootstrap Antarctic sea ice concentration to reach their conclusions needs to be reexamined to assess how this previously undocumented correction to the dataset influences the results of the studies.

We can speculate between the two possibilities on physical grounds. With a warming globe and retreating Arctic sea ice, a smaller rate of expansion of the Antarctic sea ice presents less of a physical enigma, and it also shows less disagreement with current climate models. This suggests the first possibility, i.e., that Version 2 contains the error. In addition to this physical argument, it seems likely that an error that was intentionally corrected in a dataset would be documented, whereas an undocumented change would imply the inadvertent introduction of an error into the dataset. Hence the results of this analysis invite the speculation that the Antarctic sea ice cover is not expanding, in contrast with recent observational studies that have relied on Version 2 of the Bootstrap dataset and found a significant rate of expansion.

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 acceptance that a relatively low probability event is occurring. The results of this analysis raise the alternative possibility that the apparent sea ice growth in the Southern Hemisphere is a spurious artifact in the satellite record, with the actual sea ice extent remaining approximately constant.

These results illustrate the need for thorough documentation and version control in observational datasets. Ideally all observational datasets, especially those used widely and included in IPCC assessment reports, would have sufficient documentation of algorithms and algorithm changes that previous and current versions of the data can 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 and 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 use 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 $2.0 \pm 3.9 \times 10^3\,\mathrm{km^2\,yr^{-1}}$ (Comiso and Steffen, 2001); with data until December 2000, the trend was reported to be $4.4 \pm 3.7 \times 10^3\,\mathrm{km^2\,yr^{-1}}$ (Comiso, 2003); with data until December 2006, the trend was reported to be $10.9 \pm 2.7 \times 10^3\,\mathrm{km^2\,yr^{-1}}$ (Comiso and Nishio, 2008); and with data until September 2008, the trend was reported to be $13.2 \pm 2.5 \times 10^3\,\mathrm{km^2\,yr^{-1}}$ (Comiso, 2010).

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

The IPCC AR5 used monthly-mean Bootstrap data during November 1978 through December 2012 and an error bar representing the 90 % linear regression confidence interval, and they reported the trend in Antarctic sea ice extent to be $16.5 \pm 3.5 \times 10^3\,\mathrm{km^2\,yr^{-1}}$, with the uncertainty range also 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 and slight differences in the methodology such as how missing data is treated and how ice extent is calculated from the gridded ice concentration fields.

Supplementary material related to this article is available online at http://www.the-cryosphere-discuss.net/8/273/2014/tcd-8-273-2014-supplement.pdf.

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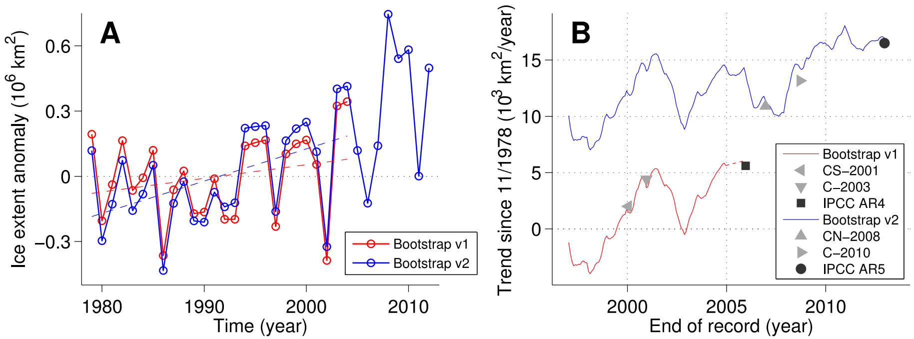

Fig. 1. Antarctic sea ice extent calculated with the current Bootstrap dataset (Version 2, blue), as well as an ostensibly nearly equivalent version of the dataset that was distributed previously (Version 1, red). **(A)** Annual-mean ice extent anomalies from the 1979–2004 mean. Trends for the two annual 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 dataset 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 a continuation of the Version 1 dataset using ice extent data from the IPCC AR4 (see Sect. S1.2 of the Supplement). 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.

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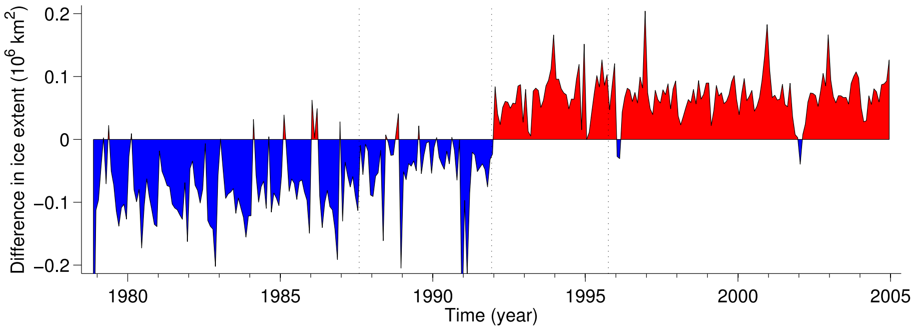

Fig. 2. Difference between sea ice extents in the two Bootstrap datasets, plotted as Version 2 – Version 1. Both records are monthly-mean anomalies from the 1979–2004 mean seasonal cycle. Transitions between satellite sensors are indicated by vertical dotted lines (see Sect. S1.1 of the Supplement). The difference in ice extent is dominated by a step function coinciding with the December 1991 sensor transition.