CrossMark

# Detecting the statistical significance of the trends in the Antarctic sea ice extent: an indication for a turning point

Josef Ludescher[1,2] · Naiming Yuan[3] · Armin Bunde[1]

## Abstract

In the past decades, the Antarctic sea ice extent (SIE) has been steadily increasing, but recently showed a sharp decline. Here we address the questions whether (1) the observed changes in the Antarctic SIE can be fully explained by natural variability and (2) whether the recent unprecedented decline in the SIE can serve as an indication that the long-term positive trend has reached a turning point entailing further decline. To study these questions, we extended the analysis period of previous studies (until 2013) by considering data until May 2018 and applied a statistical model which accurately reflects the natural variability of the SIE. Contrary to earlier detection studies we find that none of the annual trends of the SIE in whole Antarctica and its five sectors are statistically significant. When studying the seasonal changes, we find that the only trends in the Antarctic SIE that cannot be explained by natural variability and are probably tied to the warming of the Antarctic Peninsula, are the negative trends of the SIE in austral autumn ($p = 0.043$) and February ($p = 0.012$) in the Bellinghausen and Amundsen Seas (BellAm). In contrast, when the recent decline is omitted from the analysis and only data until 2015 are included, the (annual and seasonal) increases of the SIE in whole Antarctica and the Ross Sea become significant, while the significance of the decreasing trends in BellAm is slightly decreased. We consider this as a first indication that the Antarctic SIE may have reached a turning point towards a further decrease.

**Keywords** Antarctica · Sea ice extent · Natural variability

## 1 Introduction

Polar sea ice is an important component of the climate system [for review see e.g., (Vaughan et al. 2013)]. It spreads over millions of square kilometers of the earth's surface and has considerable impacts on both the climate system and the marine ecosystem. Polar sea ice also alters the heat and gas exchanges between atmosphere and ocean, regulates the radiation budget, and influences the formation of clouds and precipitation patterns, which in turn affect the mass of the ice sheet and its contribution to sea level rise (Parkinson 2004; DeConto and Pollard 2016). During the past decades, while the Arctic sea ice extent (SIE) has rapidly decreased, the Antarctic SIE estimated from satellites displays a positive trend. This positive trend [which actually has weakened due to the sharp decrease of the Antarctic SIE in the past 2 years (Turner and Comiso 2017)] confounds the most trusted climate models in the world, including the Coupled Model Intercomparison Project Phase 5 (CMIP5) models (Turner et al. 2013; Purich et al. 2016), and is contrary to intuition.

The intriguing question is, whether the trend is of anthropogenic origin (Sigmond and Fyfe 2010, 2014; Thompson et al. 2011; Previdi and Polvani 2014) or if natural forcings are responsible for it (Rind et al. 2001; Stammerjohn et al. 2008; Holland and Kwok 2012; Turner et al. 2009, 2015, 2016; Polvani and Smith 2013). While studies based on different statistical models (and data up to 2013) concluded that the increase of the Antarctic SIE was well outside its natural variability (Turner et al. 2016; Yuan et al. 2017), there are indications from climate model simulations that the

✉ Naiming Yuan
  yuannm@tea.ac.cn

  Armin Bunde
  arminbunde00@googlemail.com

1 Institute for Theoretical Physics, Justus Liebig University Giessen, Heinrich-Buff-Ring 16, 35392 Giessen, Germany

2 Present Address: Potsdam Institute for Climate Impact Research, 14473 Potsdam, Germany

3 CAS Key Laboratory of Regional Climate Environment for Temperate East Asia, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

observed SIE increase may be within the bounds of natural variability (Turner et al. 2016; Polvani and Smith 2013). But since the climate models generally yield a decrease of the Antarctic SIE their ability to represent faithfully the complex Antarctic climate system is in doubt (Turner et al. 2013; Turner and Comiso 2017).

The second challenge concerns the sharp decrease of the Antarctic SIE in the past 2 years. The question is, if this unprecedented decline of the SIE is only a brief anomaly or may be the start of a longer-term decline (Turner and Comiso 2017).

Here we aim to contribute to both puzzles. In our study, we use the advanced statistical model from (Yuan et al. 2017), where the natural persistence of the Antarctic SIE is described by a combination of short- and long-term persistences. We use this model to detect whether the SIE changes in the past 39 years (until May 2018) are statistically significant, in whole Antarctica and its five sectors (Fig. 1). Employing Monte Carlo simulations, we find that as a result of the recent decline of the Antarctic SIE in 2016–2018, the annual increase of the Antarctic SIE is no longer statistically significant. The trends in whole Antarctica and its five sectors (see Fig. 1) have $p$ values above 0.1, considerably above the significance threshold $p = 0.05$, and thus are well inside the bounds of natural variability.

When extending our analysis to the strongest seasonal SIE changes in each region, we find that the positive trends in whole Antarctica and in the Ross Sea during austral



**Fig. 1** The five Antarctic sectors with sketches of the observed sea ice extent (SIE), from June 1979 to May 2018. The five Antarctic sectors are (I) Weddell Sea (60W–20E), (II) Indian Ocean (20–90E), (III) Pacific Ocean (90–160E), (IV) Ross Sea (160E–130W), (V) Bellingshausen and Amundsen Seas (130–60W)

winter (JJA) as well as in the Pacific Ocean, Indian Ocean, and the Weddell Sea during austral autumn (MAM) are all within the bounds of natural variability. The only changes in the Antarctic SIE that cannot be explained by natural variability alone are the *decreases* of the SIE in the Bellingshausen and Amundsen Seas (BellAm) during austral autumn (MAM) and during February, with $p = 0.043$ and $p = 0.012$, respectively. We consider this as a first indication that we may have reached a turning point towards a decrease of the Antarctic SIE, with a similar response to climate change as in the Arctic. Accordingly, the recent decline of the Antarctic SIE may not be a brief anomaly but the start of a longer-term trend.

The rest of this paper is organized as follows. A description of the data and the statistical model used in this work is provided in Sect. 2. In Sects. 3 and 4, we show explicitly how to obtain by Monte Carlo simulations reliable $p$ values for both the annual SIE trends and the strongest seasonal SIE climate trends, in whole Antarctica and its five sectors. In Sect. 5 we conclude the paper.

## 2 Data and model

### 2.1 Data

In this study, the monthly sea ice extent (SIE) data over Antarctica in the past 39 years, between June 1979 and May 2018, 468 months, are calculated from the daily sea ice concentration datasets from the US National Snow and Ice Data Center (NSIDC) (http://nsidc.org/data/NSIDC-0051 and https://nsidc.org/data/nsidc-0081). The daily SIE is first derived by summing the number of pixels with at least 15% ice concentration multiplied by the area per pixel. The monthly SIE data is then calculated by averaging the daily SIE within each month. Besides the SIE of the entire Antarctic, the SIE over the sectors of the Bellingshausen and Amundsen Sea, Pacific Ocean, Indian Ocean, Weddell Sea and the Ross Sea are also calculated, with the same protocol as in (Zwally et al. 2002). It is worth to note that there is a major gap in the passive microwave satellite data record during December 1987. For the SIE data in this month, we used the data from December 1986 and December 1988 to interpolate the missing point. To investigate the SIE trend, annual data as well as seasonal data [September, October, November (SON), austral spring; December, January, February (DJF), austral summer; March, April, May (MAM), austral autumn; June, July, August (JJA), austral winter] are calculated from the monthly SIE data by averaging over the respective 3 months. The five Antarctic sectors, as well as their annual SIE records and the seasonal SIE records with the strongest trend, are shown in Figs. 1 and 2.
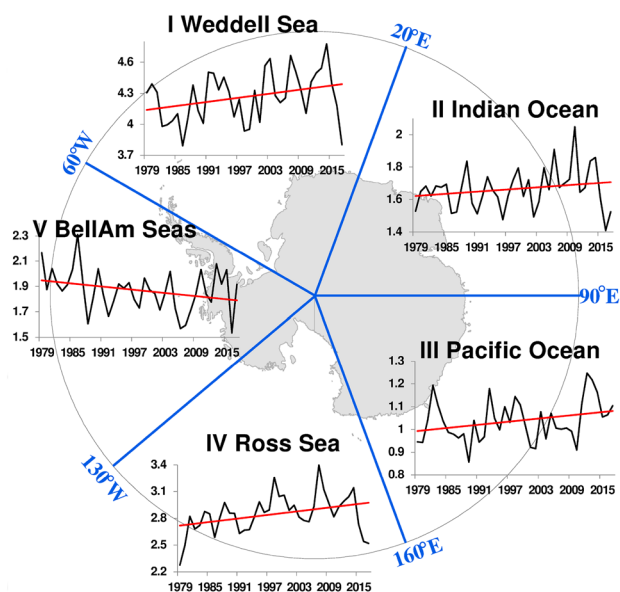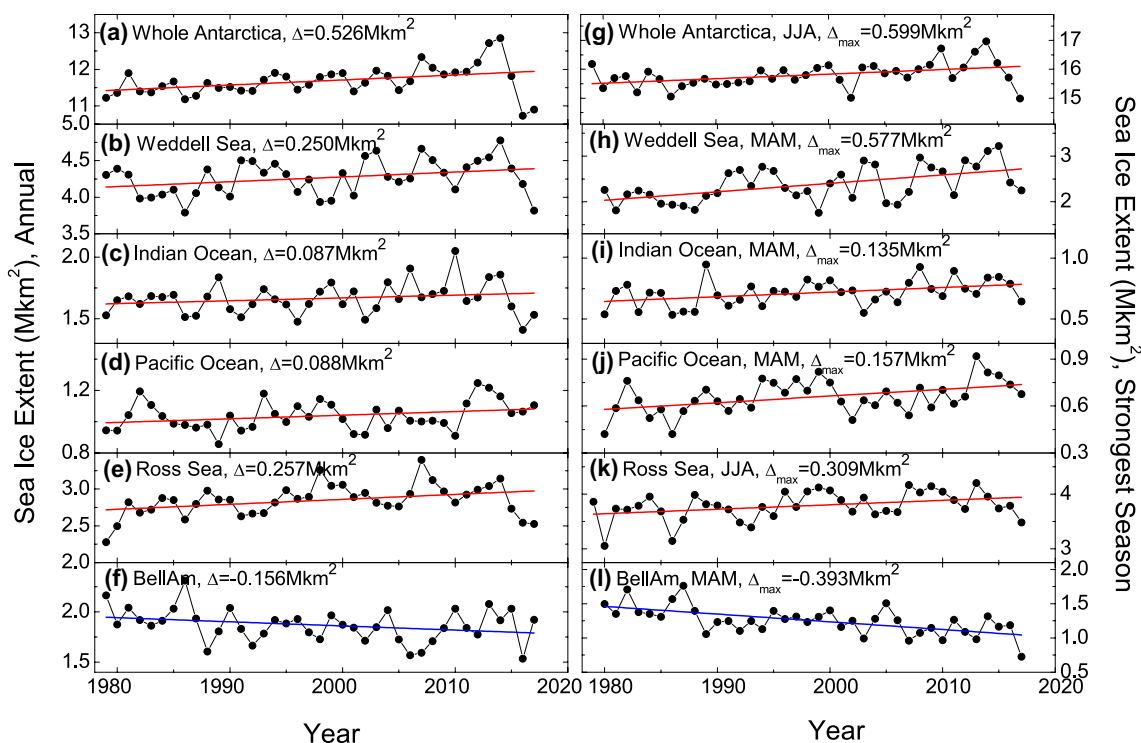
**Fig. 2** Sea ice extent (SIE) in whole Antarctica and its five sectors. **a–f** The annual SIE in each sector, while **g–l** depict the seasonal SIE records with the strongest relative climate trends (compared to the other three seasons). The linear regression lines are shown in red (increase) or blue (decrease), and the magnitudes $\Delta$ (annual) and $\Delta_{max}$ (strongest season) of the respective trends are presented in each sub-figure

## 2.2 Statistical model

For the statistical significance analysis of the trends, we employ the statistical model presented in Yuan et al. (2017). It has been shown in Yuan et al. (2017) that the natural persistence of the monthly SIE anomalies in whole Antarctica and its 5 sectors can be modeled by a combination of short- and long-term processes, according to

$$y(i) = ay(i - 1) + \eta_h(i), \tag{1}$$

where $i$ runs over all $N$ months in the record, here $N = 468$. $a$ is the parameter in an auto-regressive process of first order (AR(1)), and $\eta_h(i)$ represents a long-term correlated Gaussian noise with Hurst exponent $h$. To determine $a$ and $h$, we used the detrended fluctuation analysis DFA2 (Kantelhardt et al. 2001). We calculated the DFA2 fluctuation function $F(s)$ of the model data from (1) for a broad range of $a$ and $h$ values and compared the results with the fluctuation functions of the SIE anomalies in the different regions. Best fits yielded the following values of $a$ and $h$ [for more details see (Yuan et al. 2017)]: 0.5 and 0.7 (whole Antarctica), 0.5 and 0.75 (Bellingshausen and Amundsen Seas), 0.55 and 0.6 (Pacific Ocean), 0.5 and 0.8 (Indian Ocean), 0.5 and 0.75 (Weddell Sea), and 0.55 and 0.6 (Ross Sea).

Basically, Eq. (1) is a generalization of the standard AR(1) process. By setting $\eta_h(i)$ to white noise, Eq. (1) reduces to an AR(1) process, which is useful for the modeling of short-term persistent records. In this case, the autocorrelation function $C(s)$ decays exponentially as $C(s) \cong exp(-s/s_x)$, with the mean correlation time $s_x = 1/|\ln a|$. When setting $a = 0$ and $h > 0.5$, Eq. (1) models purely long-term persistent data, and the autocorrelation function $C(s)$ decays by a power law, $C(s) \cong (1 - \gamma)s^{-\gamma}$, $s > 0$ $(0 < \gamma < 1)$. As a consequence, the mean correlation time $s_x = \int_0^\infty C(s)ds$ is infinite. The exponent $\gamma$ is related to the Hurst exponent by $h = 1 - \gamma/2$ [see, e.g., (Turcotte 1997)].

Note that in a long-term correlated data set with Hurst exponent $h$, its power spectral density $P(f)$, which is the Fourier transform of $C(s)$, also decays by a power law

$$P(f) \sim f^{-\beta} \tag{2}$$

with increasing frequency $f$, $f = 1/N, 2/N, \ldots, 1/2 - 1/N$, $1/2$. The exponent $\beta = 1 - \gamma$ is related to $h$ by $\beta = 2h - 1$ (Peng et al. 1993; Turcotte 1997). For uncorrelated data $\gamma = 1$, $h = 1/2$ and $\beta = 0$. Accordingly, to numerically generate $\eta_h(i)$, one may use Eq. (2) as suggested by (Turcotte 1997; Lennartz and Bunde 2009, 2011).

We like to stress that long-term correlations (sometimes also called long-range correlations) are ubiqitous in nature,

characterizing systems as diverse as river flows (Hurst 1950; Koscielny-Bunde et al. 2006; Mudelsee 2007), DNA sequences (Buldyrev et al. 1995), wind speeds (Govindan and Kantz 2004), volatilities in financial markets (Ding et al. 1993) and temperature anomalies (see, e.g., (Koscielny-Bunde et al. 1998; Kiraly and Janosi 2005; Mudelsee 2010; Lovejoy and Schertzer 2013). Also the Antarctic temperature data are characterized by long-term persistence, with $h$ values in the same range as for the Antarctic SIE (Bunde et al. 2014; Yuan et al. 2015; Ludescher et al. 2016).

## 3 Statistical significance of trends in annual records

From an analysis of the statistical significance of a trend, we can learn if the trend is likely to be of natural origin or not. From the analysis we can also identify that part of the trend which might be explained by natural fluctuations alone and that part of the trend which exceeds the bounds of natural variability and thus constitutes the minimum external trend (usually believed to be of anthropogenic origin).

First we focus on the annual trends. For determining the statistical significance of the annual trends in the 6 annual Antarctic SIE records (Fig. 2a–f), we follow closely the prescription detailed in Yuan et al. (2017). For each SIE record, we first use the statistical model Eq. (1) to generate 200,000 surrogate data of length 468, with the proper values for $h$ and $a$. In each surrogate data set for the monthly data, we determine the corresponding annual data set of length $L = 39$, and use the conventional linear regression to estimate the trend properties: From the regression line $r(j) = bj + c$, we obtain the magnitude of the trend $\Delta = b(L - 1)$ and the fluctuations around the trend, characterized by the standard deviation $\sigma = [(1/L) \sum_{j=1}^{L} (y(j) - r(j))^2]^{1/2}$. The relevant quantity in the significance analysis is the *relative trend*

$$x = \Delta / \sigma. \tag{3}$$

From the 200,000 $x$ values for each region we obtain the histogram $H(x)$ and, by normalization, the probability density function (PDF) $P(x)$ of the relative trend $x$. Since positive and negative values of the anomalies $y(i)$ in (1) occur with the same probability, also natural fluctuations with relative trends $x$ and $-x$ are equally likely, and thus $P(x) = P(-x)$.

The statistical significance $S$ of a relative trend $x$ is defined by $S(x) = \int_{-x}^{+x} P(\tilde{x}) d\tilde{x}$, and its $p$ value is $p(x) = 1 - S(x)$. By definition, $p(x)$ is the probability to find any trend outside the interval $-x$ and $+x$. By definition, $p(x)$ is symmetric in $x$ and decreases monotonically with increasing $|x|$. It is clear that very small trends with large $p$ values are likely to be natural and large trends with low $p$ values probably have a non-natural origin. To quantify this, one assumes that trends $x$ with $p$ values above a certain level $\alpha$ (usually $\alpha = 0.05$)

can be regarded as natural, and trends with $p$ values below $\alpha$ as non-natural. Accordingly, the relation $p(x_\alpha) = \alpha$ (see Fig. 3) defines the upper and lower limits $\pm x_\alpha$ of the considered confidence interval, in which relative trends $x$ can be regarded as natural. If $x$ is above $x_\alpha$ (or below $-x_\alpha$) the part $x - x_\alpha$ (or $x - (-x_\alpha)$) cannot be explained by the natural variability of the record and thus can be regarded as minimum external relative trend.

The $p(x)$-curves obtained by our Monte Carlo simulations for the 6 annual trends are shown in Fig. 4a–f. Since $p(x)$ is symmetric in $x$, we show $p$ as function of the absolute value of $x$. First, we consider the SIE increase in whole Antarctica ($\Delta = 0.526$ Mkm$^2$), Figs. 2a and 4a. Since the standard deviation around the trend is $\sigma = 0.386$ Mkm$^2$, the relative trend is $x = 1.363$. Figure 4a shows that for this $x$ value the $p$ value is $p = 0.17$, well above the significance threshold $p = 0.05$. Since the upper bound of the confidence interval $x_\alpha \equiv x_{0.05} = 2.072$ is well above the observed relative trend $x = 1.363$ of the SIE, the annual increase of the SIE in whole Antarctica is well within the bounds of natural variability.

The results for the 5 sectors are shown in Fig. 4b–f. The positive trends in Weddell Sea ($x = 1.098$), Indian Ocean ($x = 0.694$)), Pacific Ocean ($x = 1.015$)) and Ross Sea ($x = 1.282$)) have $p$ values (0.312, 0.561, 0.194, and 0.110) well above the significance threshold. The upper bounds of the confidence intervals $x_{0.05}$ (2.312, 2.607, 1.602 and 1.626) are well above the observed relative trends $x$. Accordingly, the annual increases of the SIE in these sectors are all within the bounds of natural variability. Also the decrease of the SIE in the Bellingshausen and Amundsen Seas ($x = -0.994$), Figs. 2f and 4f, is well within the bounds of natural variability, with $p = 0.358$ and $-x_{0.05} = -2.312$.
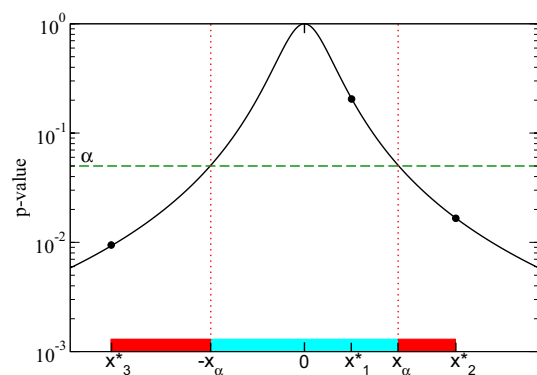


**Fig. 3** Sketch of the $p$ value as a function of the relative trend $x$. The horizontal dashed line is the confidence level $\alpha$ (here $\alpha = 0.05$). The blue range between $-x_\alpha$ and $+x_\alpha$ marks the confidence interval which represents the bounds of natural variability. $x_1^*$, $x_2^*$ and $x_3^*$ represent observational relative trends. $x_1^*$ is within the bounds of natural variability and thus is consistent with natural fluctuations. $x_2^*$ and $x_3^*$ are outside of the bounds of natural variability. The red ranges characterize the minimum external trends $x_2^* - x_\alpha$ and $x_3^* - (-x_\alpha)$
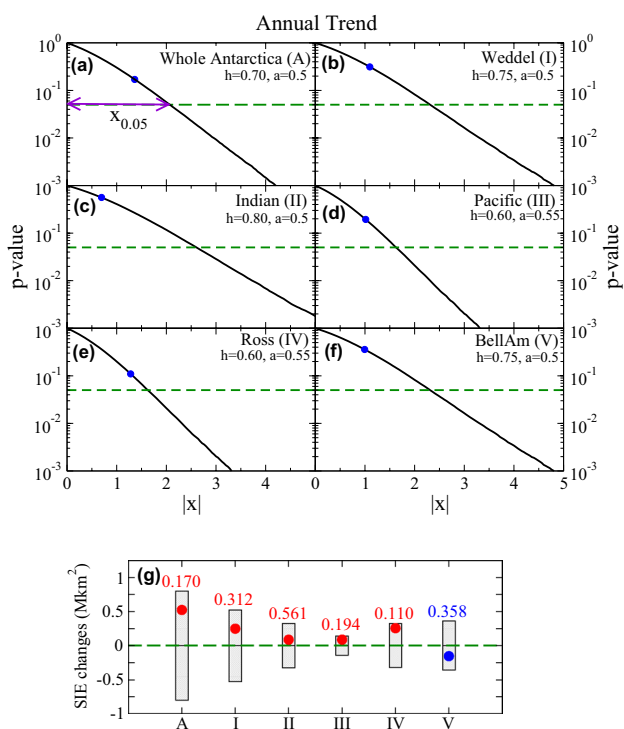
**Fig. 4 a–f** The p values of the annual trends as a function of the absolute value of the relative trends |x| for whole Antarctica and its five sectors, as obtained from the Monte Carlo simulations. For each region, the respective Hurst exponents $h$ and parameters $a$ are shown in the figures. The dashed green lines indicate $p = 0.05$ and the blue points correspond to the observed relative trends. In **a** the violet arrow shows the bounds of the confidence interval $x_{0.05}$ corresponding to a significance level 0.05. **g** Summarizes for the annual data the total change of the SIE $\Delta = x\sigma$ (red and blue points), the corresponding bounds of the confidence interval $\pm\Delta_{0.05} = \pm x_{0.05}\sigma$ (gray boxes), and the $p$ values, for whole Antarctica (A) and its five sectors (I–V, see **b**–**f**)

Figure 4g summarizes our results for the annual SIE records in whole Antarctica (A) and the five sectors Weddell Sea (I), Indian Ocean (II), Pacific Ocean (III), Ross Sea (IV), and the Bellingshausen and Amundsen Seas (V). The figure shows, for each region, the trend $\Delta = x\sigma$ (see Eq. 3) and the corresponding bounds of the confidence intervals, $\pm\Delta_{0.05} = \pm x_{0.05}\sigma$. The standard deviations $\sigma$ around the trendlines, the relative trends $x$, the bounds of natural variability $x_{0.05}$ and the corresponding $p$ values are summarized in Table 1.

## 4 Significance of trends in seasonal records

Next we consider the seasonal changes in the Antarctic SIE. The question is, if also all seasonal SIE changes are within the bounds of natural variability or if some of them show non-natural ("anthropogenic") signals. First we consider, in each region, the 4 records for the meteorological

seasons and focus on the season with the strongest relative trend. If the strongest trend is within the bounds of natural variability, the remaining 3 trends will be also within the bounds of natural variability. The seasonal records with the strongest relative trends are shown in Fig. 2g–l.

To determine the statistical significance of these trends we follow closely the prescription detailed in Ludescher et al. (2017). In each of the 200,000 surrogate data sets (see above) we determine the 4 seasonal sub-records and the corresponding 4 relative trends. The maximum relative trend $x_{max}$ is the relative trend with the largest absolute value. From the 200,000 $x_{max}$ values we obtain, as described in the previous section, the probability density function $P(x_{max})$, the related significance $S(x_{max})$, and the $p$ value $p(x_{max}) = 1 - S(x_{max})$. As above, we obtain the bounds of the confidence interval $\pm x_{max,\alpha}$ of the maximum trend by $p(x_{max,\alpha}) = \alpha$.

Figure 5a–f show the resulting $p(x_{max})$ curves for whole Antarctica and the five sectors. Since $p(x_{max})$ is symmetric in $x_{max}$, we show $p$ as function of the absolute value of $x_{max}$. In whole Antarctica, austral winter (JJA) is the season with the strongest trend ($\Delta_{max} = 0.599$ Mkm$^2$). Since the standard deviation around this trend is $\sigma = 0.388$ Mkm$^2$, the corresponding relative trend is $x_{max} = 1.543$. Figure 5a shows that for this $x_{max}$ value the $p$ value is $p = 0.16$, well above the significance threshold $p = 0.05$. The upper bound of the confidence interval is $x_{max,\alpha} \equiv x_{max,0.05} = 2.080$, which is well above the observed relative trend of the SIE in austral winter. As a consequence, the increase of the SIE in whole Antarctica in austral winter and in the remaining 3 seasons is well within the bounds of natural variability.

Austral autumn (MAM) is the season with the strongest relative trend in Weddell Sea ($x_{max} = 1.634$), Indian Ocean ($x_{max} = 1.397$), and Pacific Ocean ($x_{max} = 1.662$); in Ross Sea ($x_{max} = 1.288$) it is austral winter (JJA). According to Fig. 5b–e, the resulting $p$ values (0.174, 0.314, 0.063, and 0.180) are well above the significance threshold 0.05 and the $x_{max,0.05}$ values (2.305, 2.567, 1.742, and 1.742) are well above the observed relative trends $x_{max}$. This suggests that the seasonal increases of the SIE in these 4 sectors are all within the bounds of natural variability.

In contrast, as shown in Fig. 5f, the decrease of the SIE in the Bellingshausen and Amundsen Seas during austral autumn ($x_{max} = -2.388$) cannot be explained by natural variability alone, since $p = 0.043$ is below the significance level 0.05 and the value of $x_{max}$ is *not* within the bounds of natural variability that range from $-2.305$ to $+2.305$.

Figure 5g summarizes our results. The figure is similar to Fig. 4g and shows, for each region, $\Delta_{max}$ and the corresponding bounds of natural variability $\pm\Delta_{max,0.05} = \pm x_{max,0.05}\sigma$, as well as the $p$ values. All relevant quantities are also summarized in Table 1.

**Table 1** The Antarctic sea ice extent trends $\Delta$ (Mkm$^2$), standard deviation $\sigma$ around the trend line, relative trend $x$, error bar $x_{0.05}$ and the corresponding $p$ values, for the annual trends and the strongest seasonal trends (meteorological seasons and months) for whole Antarctica and the five Antarctic sectors (see Fig. 1)

| Region | Season | $\Delta$ | $\sigma$ | $x$ | $x_{0.05}$ | $p$ |
|---|---|---|---|---|---|---|
| Whole Antarctica | Annual | 0.526 | 0.386 | 1.363 | 2.072 | 0.170 |
| Whole Antarctica | JJA | 0.599 | 0.388 | 1.543 | 2.080 | 0.160 |
| Whole Antarctica | July | 0.590 | 0.397 | 1.487 | 2.211 | 0.260 |
| Weddell Sea | Annual | 0.250 | 0.228 | 1.098 | 2.312 | 0.312 |
| Weddell Sea | MAM | 0.577 | 0.353 | 1.634 | 2.305 | 0.174 |
| Weddell Sea | March | 0.644 | 0.309 | 2.087 | 2.420 | 0.098 |
| Indian Ocean | Annual | 0.087 | 0.125 | 0.694 | 2.607 | 0.561 |
| Indian Ocean | MAM | 0.135 | 0.097 | 1.397 | 2.567 | 0.314 |
| Indian Ocean | April | 0.186 | 0.106 | 1.751 | 2.674 | 0.233 |
| Pacific Ocean | Annual | 0.088 | 0.087 | 1.015 | 1.626 | 0.194 |
| Pacific Ocean | MAM | 0.157 | 0.094 | 1.662 | 1.742 | 0.063 |
| Pacific Ocean | March | 0.175 | 0.094 | 1.861 | 1.921 | 0.061 |
| Ross Sea | Annual | 0.257 | 0.200 | 1.282 | 1.626 | 0.110 |
| Ross Sea | JJA | 0.309 | 0.240 | 1.288 | 1.742 | 0.180 |
| Ross Sea | Dec. | 0.508 | 0.311 | 1.634 | 1.921 | 0.121 |
| BellAm Seas | Annual | − 0.156 | 0.157 | − 0.994 | 2.312 | 0.358 |
| BellAm Seas | MAM | − 0.393 | 0.164 | − 2.388 | 2.305 | **0.043** |
| BellAm Seas | Feb. | − 0.447 | 0.142 | − 3.142 | 2.420 | **0.012** |

$p$ values smaller than 0.05 are marked in boldface

For convenience, the subscript "max" has been dropped in $\Delta$, $x$, and $x_{0.05}$, when referring to the seasonal data
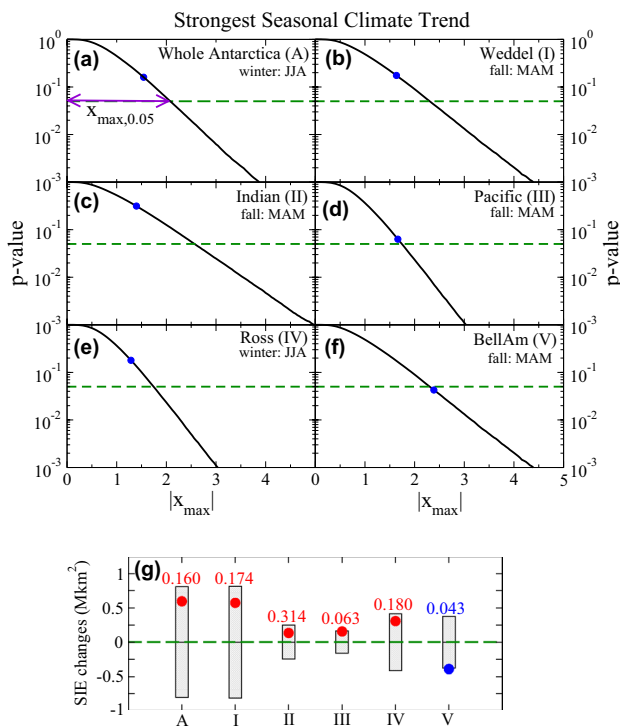


**Fig. 5** Same as Fig. 4 but for the strongest (compared to the other 3 seasons) relative trend $|x_{max}|$. For each region, the season with the strongest relative trend is denoted in the figure. Only the trend in the Bellingshausen and Amundsen Seas (V) is significant. The negative trend − 0.393 Mkm$^2$ exceeds the lower bound of the confidence interval by − 0.014 Mkm$^2$, which thus constitutes the minimum external trend

To complement our analysis, we have also considered each individual month as season and analyzed the resulting 12 sub-records, one for each month. Again, we focus on the maximum relative trend. The results are shown in Table 1. In whole Antarctica, the July record shows the strongest relative trend, with $x_{max} = 1.487$, $x_{max,0.05} = 2.211$, and $p = 0.260$. Accordingly, the increase of the SIE in July (and all in other months) is well within the bounds of natural variability. This also holds for the months with the strongest relative trends in Weddell Sea (March, $p = 0.098$), Indian Ocean (April, $p = 0.233$), Pacific Ocean (March, $p = 0.061$) and Ross Sea (December, $p = 0.121$).

In marked contrast, in the Bellingshausen and Amundsen Seas, the strongest relative trend (a decrease) of the SIE occurs in the February record, with $x_{max} = − 3.142$, $x_{max,0.05} = − 2.42$ and $p = 0.012$. Accordingly, the decrease of the SIE in February is clearly outside the bounds of natural variability.

To obtain a better insight into the amount of the possible anthropogenic trends in the Bellingshausen and Amundsen Seas during austral autumn and February, we next discuss the minimum external trends $x_{ext}^{min}$, i.e., that part of the trends that cannot be explained by natural variability. For MAM we find $x_{ext}^{min} = − (2.388 − 2.305) = − 0.083$. Since $\sigma = 0.164$ Mkm$^2$, this corresponds to a change in the SIE area of $−0.014$ Mkm$^2$. For February we find $x_{ext}^{min} = − (3.142 − 2.420) = − 0.722$. Since $\sigma = 0.142$ Mkm$^2$, this corresponds to a change in the SIE area of $− 0.103$ Mkm$^2$. While the non-explained decrease

in MAM represents only a very small part of the total SIE change in MAM (3.6%), the decrease in February constitutes 23% of the total SIE change in February.

Finally, to see the effect of the rapid decay of the SIE between 2016 and 2018 on the significance of the SIE trends, we have repeated our analysis for the 36 years until 2015. We found that in marked contrast to the results presented above, in whole Antarctica, the annual increase of the SIE ($p = 0.006$) as well as the increase in austral winter (JJA, $p = 0.019$) and July ($p = 0.022$) were statistically significant. Also the increase of the SIE in the Ross Sea was statistically significant, with $p = 0.010$ for the annual trend, $p = 0.028$ for the trend in austral spring, and $p = 0.027$ for the trend in October. In contrast, the $p$ values for the decreasing trends in Bellingshausen and Amundsen Seas during austral autumn ($p = 0.051$) and February ($p = 0.014$) were only slightly changed. Accordingly, while the statistical significance of the increase of the SIE in whole Antarctica and the Ross Sea changed strongly when data up to May 2018 were included, the significance of the decrease of the SIE in BellAm remained nearly unchanged.

# 5 Conclusion

In this study, we addressed the question of whether the Antarctic SIE changes over the past 39 years (until May 2018) can be fully explained by natural variability or not. By employing an advanced statistical model that reflects the natural variability of the Antarctic SIE and employing Monte Carlo simulations, we found that the $p$ values of the annual SIE changes of whole Antarctica and its five sectors are all above 0.1, indicating that the increase of the Antarctic SIE is not statistically significant. This suggests that the increase of the observed annual SIE of Antarctica can be explained by natural variability. In other words, by simply relying on natural variability, one can explain the observed changes in the annual Antarctic SIE. To examine if non-natural trends appear in the seasonal records, we next considered, in each region, the seasonal records with the strongest trends. Using Monte Carlo simulations, we found that the SIE increases in whole Antarctica and the Ross Sea during austral winter (JJA) as well as in the Pacific Ocean, Indian Ocean, and the Weddell Sea during austral autumn (MAM) are all within the bounds of natural variability. The only change in the Antarctic SIE that cannot be explained by natural variability alone is the *decrease* of the SIE in the Bellingshausen and Amundsen Seas (BellAm) during austral autumn (MAM) and during February, with $p = 0.043$ and $p = 0.012$, respectively. For BellAm in MAM, the SIE decrease that cannot be explained by natural variability accounts for 3.6% of the total SIE decrease, while in February, the non-explained SIE

decrease constitutes 23% of the total decrease. By definition, these values represent lower bounds for the influence of external trends. Larger external trends masked by contrariwise natural fluctuations cannot be excluded.

The picture changed, when we limited our analysis to the end of 2015, omitting the rapid decay of the SIE in the past 2 years. In this case, in whole Antarctica as well as in the Ross Sea the annual increases of the SIE were significant. Additionally, in this areas also the seasonal increases of the SIE (austral winter and July in whole Antarctica, austral spring and October in the Ross Sea) were significant. In contrast, the $p$ values of the decrease of the SIE in the Bellingshausen and Amundsen Seas in austral autumn and February were only slightly higher. We consider this twofold development, (1) that the positive trends of the SIE in whole Antarctica and its 5 sectors are no longer statistically significant, while (2) the seasonal decrease of the SIE in the Bellingshausen and Amundsen Seas shows an increased significance, as an indication that we may have reached a turning point towards a decrease of the Antarctic SIE. This would entail that the SIE in Antarctica will show a similar response to climate change as in the Arctic and a continuing decrease of the SIE may be expected in the near future.

We like to stress that for detecting the non-natural contributions to the changes of the Antarctic SIE in the Bellingshausen and Amundsen Seas we used a statistical model for the natural fluctuations of the Antarctic SIE. We did not study what causes these changes of the Antarctic SIE (attribution problem). For an extensive discussion of how changes in the Antarctic SIE may be caused by changes in the atmospheric and oceanic conditions, like the deepening of the Amundsen Sea Low and the positive trend of the Southern Annular Mode, we refer to Turner et al. (2015).

Finally, we like to emphasize that our analysis is more conservative and provides more reliable estimations of the SIE trend significances than previous detection studies [reviewed, e.g., in Turner et al. (2015))], for the following two reasons. First, we used an advanced statistical model to simulate the natural persistence of the Antarctic SIE. In contrast to conventional statistical studies where the persistence of a climate record is modeled by a simple autoregressive model of first order (AR(1)), we fully considered both the short- and long-term persistences in the Antarctic SIE. Omitting the long-term persistence component may lead to a strong overestimation of trend significances. Second, when analyzing the seasonal records, we focused on the season with the strongest trend and evaluated its correct natural distribution using Monte Carlo simulations [following (Ludescher et al. 2017)]. In contrast, the conventional studies incorrectly assume that the trends in all 4 resp. 12 seasons can be regarded separately, neglecting the fact that the strongest of the 4 resp. 12 trends follow a different statistical distribution than the weaker ones. This procedure

leads to a considerable overestimation of the significance of the strongest trend.

# References

Buldyrev SV, Goldberger AL, Havlin S, Mantegna RN, Matsa ME, Peng CK, Simons M, Stanley HE (1995) Long-range correlation properties of coding and noncoding DNA sequences: GenBank analysis. Phys Rev E 51(5):5084

Bunde A, Ludescher J, Franzke CLE, Büntgen U (2014) How significant is West Antarctic warming? Nat Geosci 7:246–247

DeConto RM, Pollard D (2016) Contribution of Antarctica to past and future sea-level rise. Nature 531:591C597

Ding Z, Granger CWJ, Engle RF (1993) A long memory property of stock market returns and a new model. J Empir Financ 1:83

Govindan RB, Kantz H (2004) Long-term correlations and multifractality in surface wind speed. EPL 68:184

Holland PR, Kwok R (2012) Wind-driven trends in Antarctic sea-ice drift. Nat Geosci 5:872–875

Hurst HE (1950) The long-term storage capacity of reservoir. Trans Am Soc Civ Eng 116:2447

Kantelhardt JW, Koscielny-Bunde E, Rego HHA, Havlin S, Bunde A (2001) Detecting long-range correlations with detrended fluctuation analysis. Phys A 295(3–4):441

Kiraly A, Janosi IM (2005) Detrended fluctuation analysis of daily temperature records: geographic dependence over Australia. Meteorol Atmos Phys 88(3–4):119–128

Koscielny-Bunde E, Bunde A, Havlin S, Roman HE, Goldreich Y, Schellnhuber HJ (1998) Indication of a universal persistence law governing atmospheric variability. Phys Rev Lett 81:729

Koscielny-Bunde E, Kantelhardt JW, Braun P, Bunde A, Havlin S (2006) Long-term persistence and multifractality of river runoff records: detrended fluctuation studies. J Hydrol 322:120

Lennartz S, Bunde A (2009) Trend evaluation in records with long-term memory: application to global warming. Geophys Res Lett 36:L16706

Lennartz S, Bunde A (2011) Distribution of natural trends in long-term correlated records: a scaling approach. Phys Rev E 84:021129

Lovejoy S, Schertzer D (2013) The weather and climate: emergent laws and multifractal cascades. Cambridge University Press, Cambridge

Ludescher J, Bunde A, Franzke CLE, Schellnhuber HJ (2016) Long-term persistence enhances uncertainty about anthropogenic warming of Antarctica. Clim Dyn 46:263–271

Ludescher J, Bunde A, Schellnhuber HJ (2017) Statistical significance of seasonal warming/cooling trends. PNAS 114:E2998–E3003

Mudelsee M (2007) Long memory of rivers from spatial aggregation. Water Resour Res 43:W01202

Mudelsee M (2010) Climate time series analysis: classical statistical and bootstrap methods. Springer, Heidelberg

Parkinson CL (2004) Southern ocean sea ice and its wider linkages: insights revealed from models and observations. Antarct Sci 16:387C400

Peng C-K, Buldyrev SV, Goldberger AL, Havlin S, Simons M, Stanley HE (1993) Finite-size effects on long-range correlations:

implications for analyzing DNA sequences. Phys Rev E 47:3730–3733

Polvani LM, Smith KL (2013) Can natural variability explain observed Antarctic sea ice trends? New modeling evidence from CMIP5. Geophys Res Lett 40:3195–3199

Previdi M, Polvani LM (2014) Climate system response to stratospheric ozone depletion and recovery. Q J R Meteorol Soc 140:2401–2419

Purich A, Cai W, England MH, Cowan T (2016) Evidence for link between modelled trends in Antarctic sea ice and underestimated westerly wind changes. Nat Commun 7:10409

Rind D, Chandler M, Lerner J, Martinson DG, Yuan X (2001) Climate response to basin-specific changes in latitudinal temperature gradients and implications for sea ice variability. J Geophys Res 106:20161–20173

Sigmond M, Fyfe JC (2010) Has the ozone hole contributed to increased Antarctic sea ice extent? Geophys Res Lett 37:L18502

Sigmond M, Fyfe JC (2014) The Antarctic sea ice response to the ozone hole in climate models. J Clim 27:1336–1342

Stammerjohn SE, Martinson DG, Smith RC, Yuan X, Rind D (2008) Trends in Antarctic annual sea ice retreat and advance and their relation to El Niño–Southern Oscillation and Southern Annular Mode variability. J Geophys Res 113:C03S90

Thompson DWJ, Solomon S, Kushner PJ, England MH, Grise KM, Karoly DJ (2011) Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. Nat Geosci 4:741–749

Turcotte D (1997) Fractals and chaos in geology and geophysics, 2nd edn. Cambridge University Press, Cambridge

Turner J, Comiso JC (2017) Solve Antarcticas sea-ice puzzle. Nature 547:275

Turner J, Comiso JC, Marshall GJ, Lachlan-Cope TA, Bracegirdle TJ, Maksym T, Meredith MP, Wang Z, Orr A (2009) Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. Geophys Res Lett 36:L08502

Turner J, Bracegirdle TJ, Phillips T, Marshall GJ, Hosking JS (2013) An initial assessment of Antarctic sea ice extent in the CMIP5 models. J Clim 26:1473–1484

Turner J, Hosking JS, Bracegirdle TJ, Marshall GJ, Phillips T (2015) Recent changes in Antarctic Sea Ice. Philos Trans R Soc A 373:20140163

Turner J, Hosking JS, Marshall GJ, Phillips T, Bracegirdle TJ (2016) Antarctic sea ice increase consistent with intrinsic variability of the Amundsen Sea Low. Clim Dyn 46:2391–2402

Vaughan DG et al (2013) Observations: cryosphere. In: Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Yuan N, Ding M, Huang Y, Fu Z, Xoplaki E, Luterbacher J (2015) On the long-term climate memory in the surface air temperature records over Antarctica: a nonnegligible factor for trend evaluation. J Clim 28:5922–5934

Yuan N, Ding M, Ludescher J, Bunde A (2017) Increase of the Antarctic sea ice extent is highly significant only in the Ross Sea. Sci Rep 7:41096

Zwally HJ, Comiso JC, Parkinson CL, Cavalieri DJ (2002) Variability of Antarctic sea ice 1979–1998. J Geophys Res 107:3041