SENSITIVITY ANALYSIS OF THE LONG-TERM TREND IN ANTARCTIC SEA ICE EXTENT

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1. Introduction

There is a rapid diminishing ice extent in the Arctic but an opposite trend in Antarctic. The observed Antarctic sea ice extent to be expanding at a statistically significant rate $16.5 \pm 3.5 \times 10^3 km^2 yr^{-1}$ (IPCC 2013), reported by the IPCC AR5, whereas the trend is statistically insignificant at a rate of $5.6 \pm 9.2 \times 10^3 km^2 yr^{-1}$ in IPCC AR4 (IPCC 2007). The trends are derived from a long time series of passive microwave data, covering both the South Pole and the North Pole regions almost daily since 1970s. The sea ice concentration (proportion of ice area in a pixel) has been retrieved from the brightness temperature of passive microwave data, and the sea ice extent is defined as the area of ice that has an ice concentration no less than 15% (to avoid weather filtering issues near the ice edge). In an conventional way, the daily extents are averaged to monthly mean values, on the basis of those, monthly deviations are derived and linear regression model is applied to determine the rate (Parkinson and Cavalieri 2012). During this process, uncertainties from sensor transitions, processing method update, the addition of new data sources and the choice for a statistical method can all influence the final result (Cavalieri *et al.* 2012; Eisenman *et al.* 2014).

Concerning the averaging method that used to aggregate daily ice extents to monthly extents, there are some alternatives. Arithmetic mean and median can be the first choices. The place of using 15% cutoff, whether before taking the pixel-by-pixel average or after can also influence the outputs. The aim of this study was to test the impact of three commonly used averaging ways and quantify their influence to the long-term trends of sea ice extent in Antarctica.

2. Methods and Data

The sea ice concentration data sets considered in this study are derived by passive microwave measurements from the Scanning Multichannel Microwave Radiometer (SMMR) on the Nimbus-7 satellite, from the Special Sensor Microwave/Imager (SSM/I) sensors on the Defense Meteorological Satellite Program's (DMSP) -F8, -F11, and -F13 satellites and from the Special Sensor Microwave Imager/Sounder (SSMIS) aboard DMSP-F17. The data set has been processed using the Bootstrap Algorithm (version 2) at NASA Goddard Space Flight Center and distributed by the National Snow and Ice Data Center (Comiso 2000, updated 2015). Daily (every other day prior to July 1987) data gridded on the SSM/I polar stereographic grid (25× 25 km) were selected for the south polar regions from 1 November 1978 to 31 December 2014.

We first computed the monthly averaged ice concentration fields from the daily ice concentration data and then identified the monthly ice extent (denoted as M_A) by including grid cells with ice concentrations above 15%. In another way, the 15% threshold was firstly used to determine the spatial extents of daily sea ice in a month, and then we grouped daily extent as a set of objects with randomly varying shapes in a month. In consequence, the monthly average extents were derived as the expectations of random sets. There is no universal definition of the expectation for random sets, while particular definitions highlight certain features in particular contexts (Molchanov 1998). Two commonly used expectations of random sets have been used to derive the monthly average extent, including Vorob'ev expectation (denoted as M_V) and median (denoted as M_M).

A random set for month t, denoted as Γ^t, represents the stochastic shape of the ice extent in that month. The covering function $\mathrm{Pr}_\Gamma(x)$ at pixel x is defined as $P(\Gamma \cap \{x\} \neq \emptyset) = P(x \in \Gamma)$, serves to characterize the distribution of the random set (Stoyan and Stoyan 1994; Zhao *et al.* 2011). It is estimated as:

$$\widehat{\mathrm{Pr}}_\Gamma(x) = \frac{1}{n}\sum_{i=1}^{n} I_{O_i}(x)$$

where O_i is the realization of Γ, e.g., the daily ice extent, and $I_{O_i}(x)$ is the indicator function of $O_i(x)$. Pixels with $\mathrm{Pr}_\Gamma(x) \geq p$ constitute a p-level set of Γ. The median set of Γ^t is the 0.5-level set (denoted as M_M), that delineates the regions that sea ice is covering for half of the time period.

The Vorob'ev mean of random set (M_V) is estimated by first determining the expectation of the covering function $EA(\Gamma) = \int_{R^2} \mathrm{Pr}_\Gamma(x)dx$ and then identifying a p-level set that has an area equal to $EA(\Gamma)$:

$$M_V = \{x \in R^2, 0 \leq p_m \leq 1 : \mathrm{Pr}_\Gamma(x) \geq p_m\}$$

where p_m is determined for the set M_V that has the area $EA(\Gamma)$. If p_m is not unique, then the infimum of all such p_ms can be used. If $p_m = 0.5$, then M_V and M_M are identical. In the sea ice case, if the probability distribution of daily extents within a month is approximately symmetrical, M_V and M_M are likely to be equal.

3. Results

The sea ice extent in Antarctica has typical seasonal pattern. On average over the 36-yr period, the ice extent ranged from a minimum of 3.1×10^6 km^2 in February to a maximum of 19.5×10^6 km^2 in September, e.g. more than six times on the minimum Fig.1(a). This large seasonal difference mainly due to the geographical features of the south pole region. Most of the seasonal sea ice are shifting away from the continent in the melting season without any constraints from surrounding oceans, leading to small area of multi-year ice that surviving at least one summer.

After the seasonal cycle is removed, the existence of an upward trend becomes clear for each month. From Fig.1(b) we can see the difference between the three time series of monthly deviations are quite small. M_V gives the largest positive rate of $24.51\pm2.04\times10^3$km^{2}yr^{-1}, with the biggest standard error 2.04×10^3km^{2}yr^{-1}. M_A and M_M show relatively small but also statistically significant trends, with positive slopes around $23\pm1.9\times10^3$km^{2}yr^{-1}. The slopes for all three different methods are positive and statistically significant at the 99.9% confidence level.

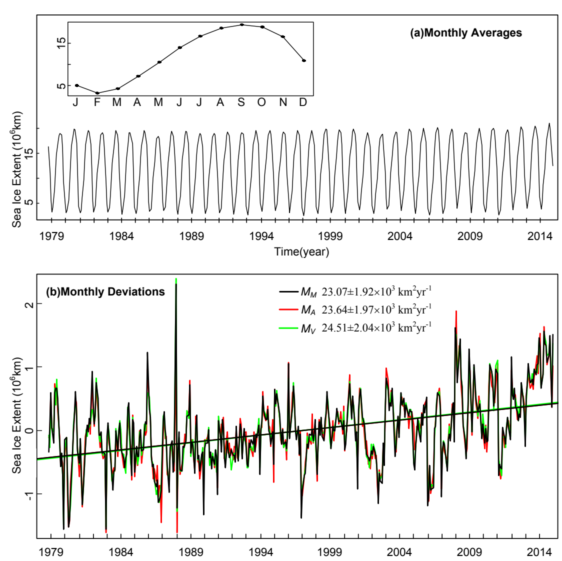

Fig.1. Monthly average and deviations of Antarctic sea ice

extents for November 1978 through December 2014.

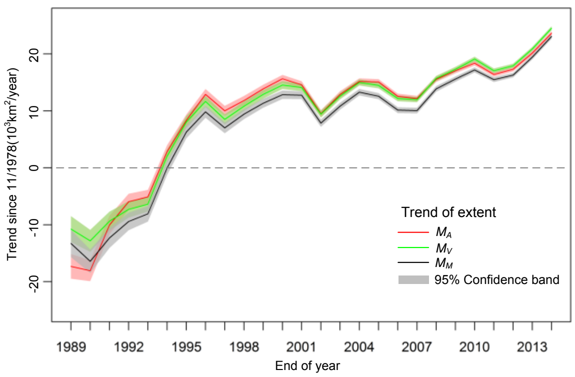

Fig.2. Trends in the monthly mean ice extent records at a range of endpoints.

Fig.1 only shows the time series of monthly deviation until 2014 and the regression lines are derived for the period ending up at 2014. To assess how the rates will be influenced by the observation years, we vary the endpoints of the calculation period (Fig. 2). The year 1989, ten years after the first passive microwave data obtained, was selected as the start point of x-axis of the Fig.2. That is, the first rate is for a decade from 1978 to 1989, and the last rate is for the entire 36-year period from 1978 to 2014. All the curves in Fig.2 show an increasing trend, and the trend rates achieve the maximum at 2014. The year 1994 is a turning point, after which the rates turn positive. The 95% confidence bands presented in transparent colors show substantial overlaps before 2001. But the three methods give significantly different change rates after 2001, even the three curves are fairly close when looking from Fig.2.

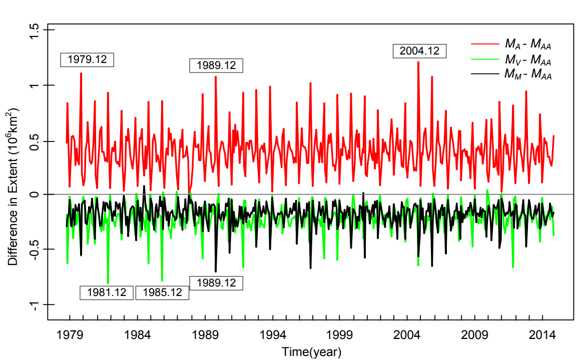

Fig.3. Difference between monthly mean Antarctic sea ice extents computed using five average methods.

The three data sets of monthly averages were compared to their arithmetic mean (the mean of the five monthly average extents, denoted as M_{AA}) to determine the temporal structure of the difference. Generally, M_A shows higher estimations than the other two methods for all months. M_M and M_V show relatively small differences in M_{AA}, among which M_V agrees more closely with M_{AA}. The top three highest difference values were recorded by M_A in Dec-2004, Dec-1979 and Dec-1989. The top three largest negative differences were recorded by M_V in Dec-1991 and Dec-1995, followed by M_M in Dec-1989. Therefore, we found that December is a special month in which use of the three methods results in substantially different monthly extent estimations.

From the maximum extent in September to the minimum extent in February, sea ice experiences a melting process. All the first-year ice that cannot survive a summer are gradually melting out. December is in the middle of this period, and has a relatively fast melting speed. To further explore the daily extent variation in different months, we grouped the daily sea ice extent for each calendar month and checked their statistical distributions. We found that the boxplots have similar size except for December with a wider daily variation. We therefore inferred that when the daily sea ice change dramatically in one calendar month, then it is easier to obtain different mean extents for that month.

Gaps among monthly average boundaries often appear in the area where the covering function changes dramatically. For the five-part Antarctic regional sectoring, the Weddell Sea and Indian Ocean have very different boundaries of the sea ice, followed by Bellingshausen/Amundsen Seas. Average ice extents in Western Pacific Ocean and Ross Sea were relatively more consistent. In the Weddell Sea and Indian Ocean, temporally open water usually appears for a short period in December, causing gradual changes in the covering function and most of the gaps occur there.

4. Conclusions and Discussions

This paper shows a pilot sensitivity analysis of the ice change rates derived from three commonly used averaging methods. Generally, our results confirmed the statistically significant upward trend of Antarctic sea ice extent for the period November 1978-December 2014. Large gaps among monthly sea ice boundaries may occur in the regions where sea ice retreats or expands in a single month like December. Results indicate that M_M is in close agreement with the mean of the three averaging methods. Since there is no benchmark data for monthly extents, the mean of the three methods can be the natural choice for the reference. Moreover, M_M is a robust statistic that extreme observations, e.g., daily ice extent outliers, have little effect on the monthly average result. Since it also has a physical meaning that the region is covered by sea ice for 50% of the time period, some data distributors e.g. NSDI adopt the median contours for the average presentation. As has been noted in (Eisenman *et al.* 2014), M_A is likely to merge unexpected pixels into the ice edge, and thus overrates the ice extent. This study also gets consistent results. M_V gives out similar monthly extents with that calculated by arithmetically averaging daily ice extent in a conventional way. This makes the trend of M_V comparable with the rates of ice extent reported in previous publications. The advantage of M_V, however, is that its output is a geometric object instead of a single average value. We could know where the mean extent is located in space rather than its magnitude only. The calculation of M_V is based on random set theory. There is no unique definition of the expectation concepts of random sets. So we will apply other averaging methods for more intensive comparisons in the future work.

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