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The impact of averaging methods on the trend analysis of the Antarctic sea ice extent and perimeter

Xi Zhao [a], Lei Xu [b], Alfred Stein [c], Xiaoping Pang [a,*]

[a] Chinese Antarctic Center of Surveying and Mapping, Wuhan University, Wuhan 430079, China

[b] School of Resource and Environmental Science, Wuhan University, Wuhan 430079, China

[c] Faculty of Geo-Information Science and Earth Observation, Twente University, The Netherlands

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ABSTRACT

To estimate the long-term trends in changes for the Antarctic sea ice, daily extents of sea ice were integrated to monthly averages. Different integration methods, however, result in monthly ice extents with inconsistent boundaries that may have further impact on the estimated trend rates. We used random sets to model the sea ice extent and we compared five averaging methods to derive the monthly expectation from a set of daily ice extents and examined their differences in the trend analysis. The Antarctic sea ice extent exhibited consistent statistically significant upward trends for the period November 1978–December 2014 at a rate of approximately $24 \pm 2.3 \times 10^3$ km^{2}yr^{-1}. The trends in the sea ice perimeter, however, do not agree and its estimation is more sensitive to the averaging methods. Large gaps among monthly sea ice boundaries occurred in the regions where sea ice retreated or expanded dramatically in a single month, especially in the Weddell Sea and the Indian Ocean during the month of December. The study showed that more attention should be given to these regions during periods that the daily sea ice experiences more notable dynamics. We finally commented that the median set can serve as a widely applicable method for both ice extent and perimeter and that the Vorob'ev expectation is appropriate only for the extent estimation.

* Corresponding author.
E-mail address: pxp@whu.edu.cn (X. Pang).

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1. Introduction

Sea ice is an integral component of the climate system that both affects and also reflects changes in other climate components (Massom and Stammerjohn, 2010). Because sea ice in the polar region is sensitive to climate change on a global scale, trends in its current dynamics and changes are of particular interest to scientific committees and governments (Simmonds, 2015). Satellite passive-microwave images have been used to produce sea ice concentration data, i.e., the percentage of areal ice coverage, since 1978. These have been used to measure the boundaries and areas of sea ice regions, thus providing a daily monitoring of Arctic and Antarctic sea ice for almost four decades. The Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) and Fifth Assessment Report (IPCC AR5) show a rapidly diminishing ice extent in the Arctic but an opposite trend in Antarctic. Interestingly, the IPCC AR5 reported that the observed Antarctic sea ice extent expands at a statistically significant rate of $16.5 \pm 3.5 \times 10^3$ km^2 yr^{-1} (IPCC, 2013). This is in substantial contrast with the small and statistically insignificant rate of $5.6 \pm 9.2 \times 10^3$ km^2 yr^{-1} reported in IPCC AR4 (IPCC, 2007).

To calculate the change rate of sea ice, we used satellite passive-microwave images. First, the ice concentration data (proportion of ice area in a pixel) was derived from passive microwave measurements. The sea ice extent is defined as the area of ice that has an ice concentration of no less than 15%. Next, the daily ice extents are averaged to determine monthly mean values. On the basis of those values, monthly deviations are derived and a linear regression model is applied to determine the rate (Parkinson and Cavalieri, 2012). This is currently a standard practice that started in Parkinson et al. (1999) and has been followed by subsequent works (Parkinson and Cavalieri, 2012; Cavalieri and Parkinson, 2008, 2012). During this process, uncertainties from sensor transitions, processing method updates and the addition of new data sources can all influence the final result (Eisenman et al., 2014; Cavalieri et al., 2012). For example, in using passive microwave measurements to determine ice concentrations, there are more than thirty different algorithms that can be selected, with a portion even having different versions (Ivanova et al., 2015). Eisenman et al. (2014) found that a substantial change in the long-term trend was caused by a change in the intercalibration across a 1991 sensor transition when the Bootstrap data set was updated to Version 2 in 2007. Ivanova et al. (2015) subsequently presented the results of an extensive inter-comparison algorithm to find the optimal SIC algorithm in which a climate time series has a low sensitivity to error sources. Unfortunately, their conclusions showed that no one single algorithm is superior as concerns all criteria. Additionally, for the uncertainties associated with image processing, the choice of a statistical method utilized as the final step can also introduce a large variation in trend analyses. By treating the daily ice extent as a random variable, calculation of an arithmetic monthly mean value based upon the daily extent data is a basic way to determine the monthly extent. In this common practice, however, the spatial information on the distribution of the sea ice is missing and we do not even know where the boundary of the monthly sea ice is located. Moreover, the arithmetic mean is not the only way to summarize the daily data and we may ask how other averaging methods will impact the trend estimation.

Averaging is a basic statistical concept, but it becomes fairly complicated for random sets and for random shapes in a non-linear space. A random set is a generalization of a random variable, whose values are sets (Molchanov, 2005). Because they provide a foundation for set-theoretic statistical approaches, random sets have been successfully employed for developing image averaging methods as well as for the study of randomly varying geometrical shapes (Friel and Molchanov, 1999; Stoyan and Stoyan, 1994). In this study, we first treat the spatial extents of daily sea ice in a single month as a set of objects with randomly varying shapes and then derive the monthly average extent as the expectation of the random set. There is no universal definition of the expectation for random sets; however, some definitions highlight certain features in particular contexts (Molchanov, 1998). The Vorob'ev expectation has been used to extract natural objects with vague boundaries in wetland areas (Zhao et al., 2010) and also to simulate the fire spread with irregular boundaries in a forest (Vorob'ov, 1996). Expectations based on various distance functions were applied to determine an average shape of characters from the collection of scanned newspaper images (Baddeley and Molchanov, 1998; Jankowski and Stanberry, 2010). A Fréchet expectation based on the Hausdorff distance was successfully utilized to identify the mean of geometrically constrained traffic island polygons (Zhou, 2014).