The effect of climate factors on Antarctic Ice Sheet Changes from Radar Altimetry

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Abstract: The Antarctic ice sheet change is one of the key factors affecting global climate change. The influence of climate factors obscures the understanding to elevation change of the ice sheet. Due to the lack of understanding of the quantitative relationship between climate events and elevation change of Antarctic ice sheet, we here combined climate factor data to quantify the impact of climate events on the elevation change of Antarctic ice sheet. A strong correlation between climate factors and elevation change of ice sheet was found. And the influence between them exists time delay in some extent. Meanwhile, the influence of climate factors in the Antarctic ice sheet change was separated from the ice sheet change based on the Independent Component Analysis (ICA) and multivariate linear regression model. The study also indicates that the influence of climate factors may be an important contribution for the accelerated decline of ice sheet elevation in the Amundsen Sea.

1. Introduction
The Antarctic ice sheet is great significance to the survival and development of all mankind. The understanding of relationship between the Antarctic ice sheet change and global climate change is critical to predict the trend of global climate change [23]. And Climate factor is one of the important indicator to investigate the climate change.

A lot of work is conducted on the analysis of the relationship between climate factors and Antarctic sea ice, ice shelf. Researchers show that a strong correlation exists between Atlantic Multidecadal Oscillation (AMO) and changes of Antarctic sea ice[17,20,22,32]. And the strong correlation between El Niño-Southern Oscillation (ENSO) and Antarctic sea ice is also found[5,16,18,32]. Meanwhile, related research also shows that the ice shelf near the Amundsen Sea responds obviously to global and regional climate factors [19]. Such a large number of studies have shown that a strong correlation between climate factors and change in sea ice, ice shelves, and sea level is found. This also indicates that climate factors have a effect on the estimation of sea ice, ice shelves, and sea level changes[13,25,27,28,29]. However, it is not clear for the estimation between Antarctic ice sheet and climate factors. Here, quantitative analysis between climate factors and Antarctic ice sheet elevation change is conducted in this study, which is extremely helpful to understand the influence from climate factors to elevation change of ice sheet.
In summary, two challenges will be discussed and resolved in this study. First, the correlation between climate factors and the Antarctic ice sheet is investigated and the lag time of this effect is clarified. Second, this study will separate the influence of climate factors from the estimated elevation change of Antarctic ice sheet.

2. Data

2.1 Radar data
In this study, Envisat and CryoSat-2 radar altimetry missions are combined to construct a long-term time series of Antarctic ice sheet elevation. Envisat is a satellite launched by ESA to observe changes in the environment of earth [9,12]. The main objective of Envisat is to monitor the atmosphere and topographic features of earth. CryoSat-2 is a satellite launched by ESA specifically for polar region change research. CryoSat-2 has a high dense orbit and the largest area could cover 88oS of latitude[30].

2.2 Climate data
Climate factor is used to describe the corresponding climate change process. The climate factors used in this study are as follows: El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Interdecadal Pacific oscillation (IPO), Southern Annular Mode (SAM).

ENSO is the result of the interaction between the atmosphere and the ocean in the Pacific. Irregular changes of ocean surface temperature and wind could occur in the tropical eastern Pacific. El Niño occurs when the ocean temperature rises and the opposite cooling phase is called as La Niña [28]. The interaction phenomenon between the atmosphere and the ocean in the Indian Ocean is described by IOD [2]. The fluctuation of the interdecadal variation of the Pacific Ocean surface temperature can be interpreted by IPO. The duration of a cycle is generally about 10 years when IPO occurs. SAM is the north-south movement in the strong westerlies of southern hemisphere. SAM describes how the westerlies moves north to the equator and how the westerlies moves south to Antarctica.

3. Method

3.1 ICA and Correlation Analysis
ICA (Independent Component Analysis) can extract the required source signals from multiple mixed signals from different source signals [6]. Then, the independent components will be extracted by the ICA method [7,8]. Compared with traditional filtering algorithms, ICA is an analysis method based on high-order statistical characteristics. So the details of the signal could be better preserved. Different climate factors are not completely independent. We refers to the ICA method of Forootan et al. and Anyah et al. to achieve the extraction of independent components of these climate factors [1,7]. The correlation coefficients between climate factors and independent components based on the ICA method are as follows in Table1.

|          | IC1 | IC2 | IC3 | IC4 | SAM | ENSO | IPO | IOD |
|----------|-----|-----|-----|-----|-----|------|-----|-----|
| IC1      | 1.00|     |     |     |     |      |     |     |
| IC2      | 0.00| 1.00|     |     |     |      |     |     |
| IC3      | 0.00| 0.00| 1.00|     |     |      |     |     |
| IC4      | 0.00| 0.00| 0.00| 1.00|     |      |     |     |
| SAM      | 0.85| -0.50| -0.18| 0.03| 1.00|      |     |     |
| ENSO     | 0.21| -0.03| 0.97| 0.13| 0.03| 1.00 |     |     |
| IPO      | -0.13| -0.06| -0.97| 0.20| 0.10| -0.94| 1.00|     |
| IOD      | -0.20| -0.95| 0.02| 0.25| 0.31| 0.03| 0.11| 1.00|

The bold font part means the the result passes the 95% significance test. A strong positive correlation between IC1 and SAM is shown in Table 1, with the correlation coefficient of 0.85. And the strong negative correlation between IC2 and IOD is found in Table1, with the correlation
coefficient of -0.95. In addition, IC3 also shows strong correlation with ENSO and IPO. In this study, the effect of climate factors on ice sheet change is estimated by these extracted independent components (IC1, IC2, IC3).

3.2 Multivariable least square linear fitting
In this study, we refer to the method of Eicker et al. to separate the influence of climatic factors from groundwater reserves [6]. Then, the extracted three independent components of the climate factors by the ICA method are introduced into the multivariate linear fitting equation. Finally, the effect of climate factors on the Antarctic ice sheet change could be separated. The multivariate linear fitting equation is as follows:

\[ \eta_i = a_0 + a_1(t_i - t_0) + a_2 \cos(t_i - t_0) + a_3 \sin(t_i - t_0) + a_4 IC1 + a_5 IC2 + a_6 IC3 \]  
\[ \eta_{ncf} = \eta_i - (a_1 IC1 + a_2 IC2 + a_3 IC3) \]

In the equation of (1) and (2), \( \eta_i \) is the value at each moment of the elevation time series. IC1, IC2, and IC3 are the three independent main components of the normalized climate factor respectively. \( \eta_{ncf} \) is the elevation change time series of ice sheet without the influence of climate factors.

4. Result and Discussion

4.1 The correlation between independent components and ice sheet elevation
The correlation coefficients, lag time, and significance level between independent components and ice sheet elevation change are shown in Figure 1. After taking into account the effect of lag time, The correlation coefficients between elevation change and independent components of climate factors passed the significance test of the 95% confidence in the almost entire Antarctica.
Figure 1. The correlation coefficients, lag time and level of significance between elevation change and independent components (IC1, IC2, IC3) are shown in Figure 1, respectively.

a) IC1  b) IC2  c) IC3

Figure 1 a) shows that IC1 and ice sheet elevation changes show a strong negative correlation in Queen Maud Land. And a strong positive correlation in the eastern coastal area of East Antarctica and in the Totten Glacier of the East Antarctic ice sheet, with the lag time about 24 months [1,3]. The absolute value of the correlation coefficient between IC2 and ice sheet elevation change is smaller than the value of the correlation coefficient between IC1 and the change in ice sheet elevation (Figure 1. b)). Figure 1 c) shows a strong correlation between IC3 and ice sheet elevation change. And the lag time of this effect of climate factors is less than half a year in most Antarctic regions.

4.2 The Effect of Climate Factors
Figure 2. Antarctic ice sheet elevation change and change rate of each month are estimated. The Red line contains the influence of climatic factors and the blue shows the result without the effect of climate factors. a) Entire Antarctica; b) Queen Maud Land; c) Enderby Land; d) Totten Glacier; e) Near the Amundsen Sea coast

The left side of Figure 2 a) shows the time series results of the entire Antarctic ice sheet elevation change whether the effect of climate factors is considered. The yellow fitted solid line and the blue solid fitted line represent the non-linear trend of the ice sheet elevation change in the whole Antarctic whether the influence of climate factors is taken off, respectively. The right side of Figure 2 a) is the derivative of the nonlinear trend of ice sheet elevation change, which represents the monthly elevation change rate of the ice sheet with the effect of climate factors or not. Compared with the results including the influence of climate factors, the monthly change rate of the entire Antarctic ice sheet elevation after removing the influence of climate factors is more gradual. This indicates that the effect of climate factors may accelerate the monthly elevation change rate of the Antarctica. This result may be that the snowfall caused by climate factors further aggravated the changes in the elevation of the Antarctic ice sheet [4,15].

Figure 2 b) - e) present the results of the time series of ice sheet elevation with the consideration of effect of climate factor or not in several great concern areas. The right side of Figure 2 b) - e) are the monthly elevation change rate of the ice sheet in the selected areas. Figure 2 b) shows that the monthly elevation change rate of ice sheet including the effect of climate factors is increasing all the time in Queen Maud Land. The accumulation of snowfall caused by climate factor may be an important reason for this phenomenon[15]. But after considering the effect of climate factors, the monthly change rate of the ice sheet elevation shows a process of increasing and then decreasing. This indicates that climate factors played a high role in elevation change of Queen Maud Land. The monthly elevation change rate of the ice sheet including the effect of climate factors is similar to the result of monthly rate removing the effect of climate factors, which suggests that the climate factors have little effect on the monthly change rate of ice sheet in the Enderby Land (Figure 2 c)) [10]. Figure 2 d) and e) are the monthly elevation change rate of the ice sheet in the Totten Glacier and near the Amundsen Sea coast, respectively. The monthly rate of change in these two regions is more gradual after removing the influence of climate factors [11,16,21]. Especially in the area near the Amundsen Sea coast, it can be found that climate factors have a greater effect on the accelerated decline of the ice sheet elevation. This process may be the supporting force change of the glacier due to the effect of climate factors, which accelerate the glacier overflow [11,21].

5. Conclusion
In this study, we first explored the correlation between climate factors and Antarctic ice sheet changes.
A strong correlation between them was found by correlation analysis. And different climate factors are not completely independent of each other. Therefore, we performed ICA on ENSO, IPO, SAM, and IOD to extract independent components of each climate factor. Finally, the effect of climate factors on Antarctic ice sheet change is estimated for the first time based on the multivariate linear fitting method.

Further analysis shows that climate factors have different responses to the effect of ice sheet changes in different regions (Queen Maud Land, Enderby Land, Totten Glacier, near the Amundsen Sea coast). Here, we use the monthly rate of change to measure the effect of climate factors on the elevation change rate of ice sheet. The study suggests that the monthly rate of change in the Enderby Land is relatively small after removing the effect of climate factors, which indicates that climate factors have little effect on the ice sheet elevation changes in the Enderby Land. However, the monthly change rate of the ice sheet with the effect of climate factors decreased rapidly near the Amundsen Sea coast. And after removing the effect of climate factors, the monthly change rate of the ice sheet tends to be constant in this region. This results suggests that climate factors may be the main reason for the accelerated rate of ice sheet elevation loss near the Amundsen Sea coast.

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