Elevation change around Dome A region of Antarctica from EnviSat satellite radar altimetry during 2002–2012

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The expected responses of ice sheets to climate warming are growth in the thickness of the inland ice areas and thinning near the margins. In recent decades, researchers have identified glacier acceleration along Antarctic ice sheet coastal margins. However, the study of ice sheet interiors where seasonal accumulation eventually balances ice wastage at the lower elevation is poorly understood. In this paper, the ice sheet elevation change around Dome A region is analyzed from 2002 to 2012 using two million elevation change measurements from EnviSat satellite radar altimeter data covering an area of about 7000 km\textsuperscript{2}. A declining trend of $0.572 \pm 1.31$ mm/year which means that the Dome A region was in balance during the last decade can be captured. In addition, two obvious changes in accumulation which divide elevation change time series into three independent equilibration stages are also extracted. In order to explain this phenomenon, two speculations related to snowfall and firm compaction are proposed in this paper.

**Keywords:** elevation change; satellite radar altimetry; Dome A; Antarctica

1. Introduction

The mass balance of Antarctic ice sheet is of interest because of its complex linkage to climate variability and direct effect on sea-level change \cite{1, 2}. In recent decades, increasing air temperature leads to longer melt seasons and an increase in melt extent on the ice shelves \cite{3}. The expected responses of ice sheets to climate warming are both growing in thickness of the inland ice areas, due to the increasing precipitation, and thinning near the margins, due to the increasing surface melting \cite{2}.

In recent decades, the spatial distribution of mass input and output data has greatly improved as field observations have been complemented by advances in remote sensing. Satellite altimetry over the continental ice sheets is proven to be a valuable tool in studying decadal ice sheet mass balance changes by yielding measurements of elevation changes over the past decades. Using satellite altimeter data from ERS-1/2 missions, Zwally et al. \cite{2} obtained the mass changes of the Greenland and Antarctic ice sheets and shelves and its contributions to sea-level rise from 1992 to 2002. Davis and Ferguson \cite{4} analyzed the Antarctic ice sheet elevation change from 1995 to 2000 using 123 million elevation change measurements covering an area of about $7.2 \times 10^6$ km\textsuperscript{2} and Wingham et al. \cite{5} estimated the ice sheet elevation change over Antarctica. Pritchard et al. \cite{6} also detected the mass balance of the Antarctic ice sheet with ICESat data. Although these efforts were made to identify the underlying causes of glacier acceleration and the link to climate change during the past decade, the above researches mainly focus on the mass balance of the whole basin and the coastal margins of Antarctica.

In this paper, we pay more attention to the magnitude of the inland ice sheet elevation change. The method of crossover analysis is introduced to establish the elevation change time series from 2002 to 2012 around the Dome A region with EnviSat altimetry data. The result of time series is then analyzed and two speculations are proposed to explain the result.

2. Study area and data sets

2.1. Test sites

Dome Argus (Dome A), the highest ice feature in Antarctica, is just over 4000 m a.s.l., located near the center of East Antarctica and approximately midway between the head of Lambert Glacier and the South Pole \cite{7, 8}. It is an international interest point because of its potential for providing a very long and undisturbed ice core paleoclimate record \cite{9}. The determination of the snow accumulation in this region will be useful not only for planning any future ice coring, but also for understanding the meteorological and glaciological characteristics of this data-sparse area of the Antarctic ice sheet. Moreover, the lowest accumulation rate at Dome A is an indicator of responses of the inland ice sheet to climate warming due to having the highest elevation and its distance from the coast.

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To further study the Dome A region, the Kunlun Station and Auto Weather Station (AWS) were built at Dome A during the 25th Chinese National Antarctic Research Expedition. The low snow accumulation, wind speed, and temperature were extracted, respectively, by analysis of ice cores record and AWS data. Regrettably, the ice cores record cannot be used to achieve the mass balance of a large area due to its limited distribution. In this paper, the experimental area centering at Dome A region (Figure 1) is chosen. The mass balance is then estimated on the basis of crossover analysis method with EnviSat data.

2.2. Research data
ESA’s (the European Space Agency) EnviSat, whose maximum latitudinal coverage is ±81.5°, was launched in 2002. It was equipped with a satellite radar altimeter (RA-2) that inherited the preponderance of RA instrument and improved precision over ice compared with its predecessor (10–12).

For the numerical assessment and case study in the experimental region, the ice surface height measurements from the geophysical data record (GDR) of EnviSat over the period from May 2002 to Apr. 2012 are analyzed in this paper. The measurements in GDR are derived from the EnviSat range measurements, which are corrected by the waveform parameters using the ICE-2 algorithm for waveform retracking (13). In addition, a consistent set of corrections, including the atmospheric range corrections, instrument corrections, slope corrections, and the solid earth tides, are applied to the data.

3. Data processing
3.1. Crossover analysis
Elevation differences are determined at the precise locations where satellite ground tracks intersect by interpolating the elevation measurements on either side of the crossover (14). For intra-mission analyses, elevation differences (ΔH) are computed from the surface heights (H) at the intersection or crossover between an ascending satellite track (HA) and a descending satellite track (HD) using

\[ \Delta H_{AD} = H_A(t_2) - H_D(t_1) + E_{inv,A} - E_{inv,D} + E_{msb,A} \]

(1a)

\[ \Delta H_{DA} = H_D(t_2) - H_A(t_1) + E_{inv,D} - E_{inv,A} + E_{msb,D} \]

(1b)

where the subscript A and D denote the ascending/descending orbital directions, respectively; ΔH_{AD} is the elevation differences between ascending track in t_2 and descending track in t_1; ΔH_{DA} is the elevation differences between descending track in t_2 and ascending track in t_1; Δt, defined as t_2 − t_1, is always positive; E_{inv,A} and E_{inv,D} represent possible time-invariant biases in the altimeter measurement (15). For intra-mission analyses, the measurement system bias E_{inv,A} and E_{inv,D} is equal and can be eliminated.

In order to obtain a representative estimate and eliminate the influence brought by E_{inv,A} and E_{inv,D}, spatial

![Figure 1. The Dome A region and PANDA transection of Antarctica. The blue box (79.5°–81.5°S, 76.0°–78.0°E) shows the experimental region. The superimposed figure shows the EnviSat tracks and crossover points over the Dome A region.](image-url)
average is always needed. Then, the elevation differences are determined by

$$\Delta H = \left\{ \sum [H_A(t_2) - H_D(t_1)]/N_{AD} \right\}$$

+ \left\{ \sum [H_D(t_2) - H_A(t_1)]/N_{DA} \right\} / 2 \tag{2}

where $N_{AD}$ is the number of crossovers between ascending track in $t_2$ and descending track in $t_1$, and $N_{DA}$ is the number of crossovers between descending track in $t_2$ and ascending track in $t_1$. Fortunately, over the smooth ice sheet interiors such as Dome A, the number of crossovers is approximately equal ($N_{AD} \approx N_{DA}$). Then, the Equation (2) can be simplified as

$$\Delta H = \sum [H(t_2) - H(t_1)]/(N_{AD} + N_{DA}) \tag{3}

3.2. Elevation change time series

Through Equation (3), individual elevation changes can be obtained. Then satellite altimeter data are typically divided into monthly intervals. Each month is compared with all other months to derive a complete crossover data-set from which a time series can be constructed. For $N$ months of satellite data, the complete crossover data-set can be represented using a one-sided $N \times N$ matrix where each row represents the crossover data computed with respect to a different initial reference month ($13–17$)

$$\Delta H_{ij} = \left[ \begin{array}{cccc} \Delta H_{11} & \Delta H_{12} & \Delta H_{13} & \cdots & \Delta H_{1N} \\
- \Delta H_{21} & \Delta H_{22} & \Delta H_{23} & \cdots & \Delta H_{2N} \\
- & - \Delta H_{33} & \cdots & \cdots & \cdots \\
- & - & - & \cdots & \cdots \\
- & - & - & \cdots & \Delta H_{NN} \end{array} \right] \tag{4}

where matrix elements $\Delta H_{ij}$ represent the average elevation change between months $i$ and $j$. The corresponding standard error (SE) for each matrix element is given by

$$SE_{ij} = \sqrt{N_{AD} \cdot SD_{AD}^2 + N_{DA} \cdot SD_{DA}^2 / (N_{AD} + N_{DA})} \tag{5}

where $SD_{AD}$ and $SD_{DA}$ are the sample standard deviations for the elevation differences. However, due to the different reference, Equation (4) cannot be directly used. Rather, it should be converted into the same reference time. Unlike the method used by Ferguson et al. (15), we define

$$\Delta H'_{ij} = \Delta H'_{ij} + \Delta H_j \quad \text{for } i > 1, j = i + 1 \text{ to } N \tag{6}

where $\Delta H'_{ij} = (\Delta H_{ij} + \sum_{j=2}^{N} \Delta H_{j}^t)/(N - j)$. This is done to ensure that all matrix elements in Equation (4) are referenced to the same initial time period (e.g. month 1). The resulting SE for each element is then

$$SE'_{ij} = \sqrt{SE_{ij}^2 + SE_j^2} \quad \text{for } i > 1, j = i + 1 \text{ to } N \tag{7}

Following above processing, a new one-sided $N \times N$ matrix with the first month as reference can be obtained,

$$\Delta H''_{ij} = \left[ \begin{array}{cccc} \Delta H'_{11} & \Delta H'_{12} & \Delta H'_{13} & \cdots & \Delta H'_{1N} \\
- \Delta H'_{21} & \Delta H'_{22} & \Delta H'_{23} & \cdots & \Delta H'_{2N} \\
- & - \Delta H'_{33} & \cdots & \cdots & \cdots \\
- & - & - & \cdots & \cdots \\
- & - & - & \cdots & \Delta H'_{NN} \end{array} \right] \tag{8}

Then, a weighted average is computed for each column in the matrix above.

$$\Delta \bar{H} = \sum_{i=1}^{j} (w_{ij} \cdot \Delta H''_{ij}) \quad \text{for } i > 1, j = i + 1 \text{ to } N \tag{9}

where the weight for each matrix element is given by $W_{ij} = n_j/n_i$; $n_j$ is the number of elevation change points between months $i$ and $j$; $n_i$ is the number of elevation change points between months $j$ and other months.

The corresponding SE for each column average is then

$$SE_j = \sqrt{\sum_{i=1}^{j} (w_{ij} \cdot SE''_{ij}^2)} \quad \text{for } i > 1, j = i + 1 \text{ to } N \tag{10}

According to the method above, the time series of elevation change where the data are referenced to the first month of the time series (May 2002) in experimental region is established. The result (Figure 2) shows a negative trend from 2002 to 2012 with a rate of 2.57 ± 0.57 cm/year. However, this elevation change time series is strongly correlated with the change in backscattered power. In addition, the seasonal signal variations of 0.3 m peak-to-peak are completely unrealistic for this part of East Antarctica where annual snow accumulation is no more than 3 cm/year water equivalent.

3.3. Backscattered correction on elevation change series

An important issue for correct measurement of seasonal, inter-annual, and longer term elevation change in Antarctica is the correlation between the observed elevation change signal ($\Delta H$) and changes in backscattered power ($\Delta \delta_o$). As reported in Ref. (18), a high degree of correlation between $\Delta \delta_o$ and $\Delta H$ in Envisat altimeter data is found at many regions in Antarctica. To verify the spurious elevation change brought by changes in backscattered power in the experimental region, statistical analysis is carried out between $\Delta H$ and $\Delta \delta_o$ data. The linear regression analysis is then used to estimate the relationship between the height and backscatter changes. Moreover, a correlation gradient of 0.445 m/DB with a high correlation (more than 0.9) is extracted and shown in Figure 3.
This undesired correlation may introduce spurious signals in the $\Delta H$ time series that are a function of the surface and/or subsurface scattering characteristics of the ice sheet. Following the method in Ref. (18), we adjust the time series by subtracting the product of the correlation gradient with the $\Delta \delta_0$ value,

$$\Delta H_{cor} = \Delta H - \Delta \delta_0 \cdot CG$$

(11)

where $\Delta H_{cor}$ is the elevation change after correction, and $CG$ is the average correlation gradient between $\Delta H$ and $\Delta \delta_0$. By modifying the $\Delta H$ time series, the adjusted $\Delta H$ time series can be obtained. Figure 4 shows a negative trend with a rate of $0.572 \pm 1.31$ mm/year from 2002 to 2012 in the experimental region. Compared with Figure 2, the adjusted time series is much more reasonable, with a typical seasonal peak-to-peak variation of 10 cm.

4. Elevation change results and discussion

According to the result of the elevation change time series, a declining trend of $0.572 \pm 1.31$ mm/year from September 2002 to April 2012.
2002 to 2012 around the Dome A region can be captured. Compared with Figure 2, the effect brought by changes in backscattered power ($\Delta \delta_0$) can be easily observed. The corrected change rate is not significantly different from zero and reveals that the Dome A region was in balance during the last decade. However, two noticeable fluctuations in elevation are found. The first change that began in July 2005 shows a negative trend, while the second change that occurred in April 2011 shows a positive one.

In the dry snow region, which is characterized by the absence of seasonal melt, elevation changes are related to change in snow accumulation and variations in firm density ($\delta$) (19). In order to explain this phenomenon, we compare two different hypotheses: (1) the snowfall creates a variation of the elevation, and (2) the snowpack compacts due to the temperature cycle and the heat–vapor transfer. Compared with the temperature of the previous two years, the winter (April–October in Antarctica) of 2011 is warmer (Figure 5). The moisture caused by higher temperature in winter may provide more snowfall. However, a remarkable characteristic of the precipitation regime near the ice sheet crest is the scarcity of regular snowfall from clouds. Ice crystal precipitation which occurs in 2/3 of the days of a year at plateau is the principal origin of precipitation (20). Despite a warmer winter in 2011, the temperature gradient which is closely related to reverse subliming is not so different from the gradient of previous two years. Therefore, the snowfall is not the main factor of this phenomenon.

Variations in firm density is another important factor causing elevation changes. It not only cause the elevation change directly but also change the scattering coefficient of snowpack. For radar altimetry, the strongest backscatter from snowpack is mainly from an ice layer buried beneath the ice surface (Figure 6) (21). Moreover, the altitude detected by waveform depends on several external factors, such as temperature and surface density.

Lacroix et al. (23) shows that a temperature increase causes the values of the waveform parameters to fall, including the backscatter coefficient while the values of altitude increase. This can be explained by the increase of the snow extinction as the temperature increases. In addition, a density increase also has a positive impact on the backscatter coefficient and altitude. As shown in Figure 7, the elevation change time series is divided into three equilibration stages by two noticeable change points. Stage I and II illuminate an inverse correlation

![Figure 5. Time series of temperature change in the experimental region from January 2009 to 2012. The green line indicates the temperature range in the summer of 2011.](image)

![Figure 6. The sketch diagram of scattering from a snow-covered ice layer (22).](image)

![Figure 7. Monthly corrected elevation changes (open triangle) and backscattered power changes (solid point). Dashed boxes show the three equilibration stages (I, II, and III). Solid line shows the increasing trend of ice layer.](image)
between elevation and backscatter coefficient, while stage II reveals a more complicated mechanism. Based on Lacroix’s result (23), stage I and III show that the temperature plays an important role at this stage. Stage II tends to the positive correlation between elevation and backscatter coefficient. It can be inferred that the density is the main factor at this stage. The snowpack compaction mechanism is thus in good agreement with the observations.

In addition, a speculation that a new ice layer is forming by ice densification during stage II is proposed in this paper. If the average lowest point in each stages is regarded as the ice layer mentioned in Figure 6, the increase in the ice layer can be clearly found (solid line in Figure 7). This speculation shows that the accumulation may be quite variable at decadal scales in the experimental region and is agreed with the time scales in Ref. (9).

5. Conclusions
In this paper, we analyze satellite radar altimetry data from EnviSat acquired from 2002 to 2012 to provide an unprecedented view of temporal variability of surface elevation in the experimental region. Over two million individual elevation change measurements are obtained to construct elevation change time series. From analysis of elevation change time series, a declining trend of 0.572 ± 1.31 mm/year which is not significantly different from zero is captured. The conclusion that the experimental region is in balance during the last decade can be drawn.

In addition, two noticeable changes in elevation are also found in the elevation change time series. The change that began in July 2005 shows a negative trend, while the other that began in April 2011 shows a positive one. Moreover, the elevation change time series is divided into three equilibration stages. To explain this phenomenon, two speculations are proposed in this paper. The variation of snowfall is analyzed due to its close linkage to elevation change. However, the fact that the scarcity of regular snowfall from cloudsat plateau rejects this speculation. Compared with the snowfall, the density plays a more important role in the fluctuation of elevation change series. The process of the snowpack compacts can be observed based on the comparison between elevation and backscatter change series. However, the time series ended at the beginning of 2012 due to the termination of EnviSat. A further study with longer time series established with the data of ERS, EnviSat, and CryoSat-2 will be conducted.

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