Ice-sheet surface elevation change from crossover of ENVISAT data

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Understanding the current state of the polar ice sheets is critical for determining their contribution to sea-level rise and predicting their response to climate change. Surface elevation time series especially can be used to study ice-sheet dynamics and the mass or volume balance of the ice sheets, which are relevant to global climate change and sea-level rise. During the last two decades, satellite radar altimetry or airborne laser altimetry could obtain accuracy by an order of magnitude greater than the traditional airborne barometric altimetry, which has a precision of typically several tens of meters at best and only a limited coverage. The widest coverage comes from satellites, especially from the ERS1/2 and ENVISAT, which extends to 81.5° of latitude, covering almost all of Greenland and most of Antarctica. In this paper, an algorithm for time series analysis based on crossover was used to obtain 4-year (September 2002–March 2007) ice-sheet elevation changes from ENVISAT data. The height of the whole Antarctic ice sheet has a decline of about 0.4 ± 0.43 cm from September 2002 to March 2007. The time series data present clearly a seasonal and annual signal feature; that the ice sheet thickens in March. From the time series data, the seasonal and annual signal can be observed clearly.

Keywords: satellite altimetry; ice sheet; time series

1. Introduction

Over the last 100 years, the global sea level has risen by about 10–25 cm. The rate of mean global sea-level rise was 1.8 mm/yr (1). It is likely that much of the rise in sea level is related to the concurrent rise in global temperature over the last 100 years. On this time scale, warming and the consequent thermal expansion of the oceans may account for about 2–7 cm of the observed sea-level rise, while the observed retreat of glaciers and ice caps may account for about 2–5 cm. The rate of observed sea-level rise suggests that there has been a net positive contribution from the huge ice sheets of Greenland and Antarctica. The polar ice sheets in Greenland and Antarctica have sufficient volume such that very small changes can significantly alter global sea level. For example, a 30 cm change in sea level, corresponding to only a 0.4% change in total ice-sheet volume (2), would have substantial and serious social and economic impact on coastal areas. For example, a recent study (3) from aircraft and satellite laser altimeter surveys of the Amundsen Sea sector of west Antarctica shows that local glaciers are discharging about 250 km\textsuperscript{3}/yr of ice to the ocean, almost 60% more than is accumulated within their catchment basins. This discharge is sufficient to raise sea level by more than 0.2 mm/yr.

Now, satellite altimetry (microwave radar or Lidar) allows measurement of the ice-sheet height more accurately, thus obtaining meaningful quantitative estimates. Satellite radar altimeter measurements show that the average elevation of the Antarctic ice-sheet interior fell by 0.9 ± 0.5 cm/yr from 1992 to 1996 (4). Davis et al. (2) analyzed Antarctic ice-sheet elevation change (dH/dt) from 1995 to 2000 using 123 million elevation change measurements from ERS ice-mode satellite radar altimeter data. They found the average values in east Antarctica to be within 3.0 cm/yr, whereas drainage basins in west Antarctica had substantial spatial variability with average values ranging between −11 and +12 cm/yr. The east Antarctic ice sheet had a five-year trend of 0.6 ± 0.7 cm/yr. The west Antarctic ice sheet had a five-year trend of −3.6 ± 1.0 cm/yr due largely to strong negative trends of around 10 cm/yr for basins in Marie Byrd Land along the Pacific sector of the Antarctic coast. The continent as a whole had a five-year trend of 0.4 ± 0.4 cm/yr. In addition, ice-sheet heights also are used for studying the mass balance of the Antarctic ice sheet using ERS1/2 altimeter data from 1992 to 2003 (1).

Time series of ice-sheet surface elevation changes will enable determination of the present-day mass balance of the ice sheets, study of associations between observed ice changes and polar climate, and estimation of the present and future contributions of the ice sheets to global sea-level rise. Short-term changes in surface

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elevation occur both seasonally and interannually, while longer term elevation changes are linked to climate change and global sea level. The most common technique used in analyzing satellite altimetry data to study height changes in ice sheet is the time series (dH/dt) based on the crossover geometry. Davis et al. (8) presented a new method to derive the seasonal elevation signal from a continuous time series of altimeter crossover data. The method uses the complete set of intrasatellite crossover data to provide fine temporal resolution and significantly reduces random measurement errors. Nguyen et al. analyzed the ERS crossover data and ICE-Sat crossover data using a Kalman filter and block Kriging to study height changes in east Antarctica. By combining a Kalman filter with block Kriging, this method also enables modeling surface heights as random fields (5, 6).

2. Data and processing

The ENVISAT, launched in March 2002 by the European Space Agency (ESA), has a repeat period of 35 days and coverage of ±81.5°. It is an advanced polar-orbiting Earth observation satellite that provides a global-scale collection of radar echoes over ocean, land, and ice to measure ocean topography, water-level variation over the large river basins, lakes, land surface elevation, and monitoring of sea ice and the polar ice sheet. The RA-2, loaded by ENVISAT, is a nadir-looking pulse-limited radar functioning at the main nominal frequency of 13.575 GHz (Ku band). The secondary channel at nominal frequency of 3.2 GHz (S band) is also operated to compute corrections for the measured range compensating for the ionosphere delay. The RA-2 telemetry provides 18 range measurements per second corresponding to an along-track sampling interval of about 400 m. Over the ocean, it is common to average 20 of these measurements to yield a sampling interval of 1.1 s or about 8 km. The data set used in this paper is the ENVISAT SGDR from September 2002 to March 2007, from cycles 9 to 56 (excluding cycles 16, 17, 30, 50, and 55).

Radar altimetry has been used to measure sea-level and ice-sheet changes since 1978. However, the large footprint size of 3–8 km in radar creates great uncertainty in height measurements in the range of several tens of centimeters due to slope-induced errors over the ice sheet. Generally, the altimeter antenna boresight is pointed to the nadir. The antenna has a field of view of about 1.3° (half-power). The first part of the reflected echo will come from that part of the surface within the field of view closest to the satellite. Over flat surfaces, the closest point on the surface is at the nadir impact; however, over sloping terrain, this will not be the case. When the echo waveform is retracked, the resulting range measurement is a slant range to a point offset from the nadir. To use this measurement, it must be corrected for the slant and relocated to the point of first return offset from nadir. Over topographic surfaces, an onboard radar altimeter tracking system is unable to maintain the echo waveform at the nominal tracking position in the filter bank due to rapid range variation. This results in an error in the telemetered range known as tracker offset. Retracking is a term used to describe a group of nonlinear ground processing estimation techniques, which attempt to determine the tracker offset from the telemetered echoes and thereby estimate the range to the point of closest approach on the surface.

To calculate precise ice surface elevations and changes in elevation, the altimeter range measurements need to be referenced to a common datum and corrected for tracker misalignment of the waveform due to interpulse variations, atmospheric delays, solid Earth and ocean tides, and slope-induced errors. The corrected altimeter range measurement is then subtracted from a precise orbit to calculate a corrected surface height. The following table shows the corrections in order of their magnitude.

Furthermore, for an unknown reason, a change of behavior of the Ultra Stable Oscillator (USO) clock frequency occurred on February 2006 and impacted the quality of the RA-2 range parameter. Part of cycles 44 and 45 and most of cycle 46 are impacted by this anomaly. Since that time, except for the RA-2 B-side data, all ENVISAT altimetry data are impacted by the USO anomaly. When the anomaly occurs, the USO period increases rapidly during several hours to reach about 12500.090 picoseconds and from then starts to oscillate with a 0.005 ps amplitude. This change of frequency has a direct impact on the altimetric range measurement in both Ku and S bands. The increase of the period implies a range value shorter by about 5.6 m than the nominal value. Thus, the sea-level anomalies are higher than the nominal value by 5.6 m (7).

The data preprocessing in this paper include the terms mentioned previously. They are transmission medium (tropospheric refraction, ionospheric refraction, and tides), slope correction, retracking correction, and USO clock correction. The latter is used for the cycles 46–56.

3. Davis’ algorithm for time series

Davis’ algorithm for time series (8) is based on crossover point height. Generally, the tracks of altimetry satellites have one ascending pass and one descending pass. Thus, the ice-sheet surface elevation differences (dH) are computed from surface heights (H) at the intersection or “crossover” between an ascending satellite track (HA) and a descending satellite track (HD) using the following equations:

$$dH_{AD} = H_A(t_a) - H_D(t_d) + B_A - B_D + \Delta H_6(t)$$  \hspace{1cm} (1)

$$dH_{DA} = H_D(t_a) - H_A(t_d) + B_D - B_A + \Delta H_6(t)$$  \hspace{1cm} (2)

where subscripts A and D represent the ascending and descending tracks, respectively.
The $B_A$ and $B_D$ terms represent possible time-invariant biases in the altimeter measurement that result from directional dependencies in the orbit error and/or the scattering characteristics of the ice sheet. The $\Delta H_S(t)$ term represents spurious change in surface elevation caused by a temporal variation in backscattered power from the ice sheet. If $t_A \lor t_D$, Equation (1) is used to compute the elevation differences $\Delta H_i trailers the mean elevation change between a fixed reference cycle $i$ (row) and a given cycle $j$ (column) including the ascending track in cycle $i$ crossovers with the descending track in cycle $j$ crossovers with the ascending track in cycle $j$. The average elevation change is computed by combining the mean $dH_{AD}$ and $dH_{DA}$ values in the following manner:

$$
\overline{\Delta H}_{ij} = \frac{1}{n_f} [n_{AD} \cdot \overline{\Delta H}_{AD} + n_{DA} \cdot \overline{\Delta H}_{DA}]
$$

where $i$ represents the crossover data computed from cycle $j(i \land j \land N)$ with respect to cycle $i$. Each matrix element represents the mean elevation change between a fixed reference cycle $i$ (row) and a given cycle $j$ (column) including the ascending track in cycle $i$ crossovers with the descending track in cycle $j$ crossovers with the ascending track in cycle $i$. The average elevation change is computed by combining the mean $dH_{AD}$ and $dH_{DA}$ values in the following manner:

$$
\overline{\Delta H}_{AD} = \frac{1}{n_{AD}} \cdot \sum_{k=1}^{n_{AD}} (dH_{AD})_k
$$

$$
\overline{\Delta H}_{DA} = \frac{1}{n_{DA}} \cdot \sum_{m=1}^{n_{DA}} (dH_{DA})_m
$$

The corresponding standard error of the mean value is

$$
SE_{\overline{\Delta H}_{ij}} = \frac{1}{n_f} \sqrt{n_{AD} \cdot SD^2_{AD} + n_{DA} \cdot SD^2_{AD}}
$$

However, using Equations (1)–(6), we can compute many time series. For example, from row 1, we can obtain a time series whose fixed reference cycle is cycle 1. Subsequently, from row 2, the time series whose fixed reference cycle is cycle 2 is obtained. In order to use the complete crossover point in matrix $\overline{\Delta H}$ (Equation (3)), we need to make the time series in the same fixed reference cycle by making the $\overline{\Delta H}_{1 \times j}$ values in row 1 for $j = 2$ to $N$ of the $\overline{\Delta H}$ matrix be added to all elements of the corresponding matrix elements in row $i = j$ for all $j \lor i$, i.e.

$$
\overline{\Delta H}_{1 \times j} = \overline{\Delta H}_{1 \times j} + \overline{\Delta H}_{i \times j}
$$

The total number of crossovers in the $i \times j$ becomes

$$
n'_{ij} = n_{1 \times j} + n_{1 \times i}; \quad i \lor 1, \quad j = i + 1 + \cdots + N
$$

The total number of crossovers in each column of the $\overline{\Delta H}$ matrix will then be

$$
n_j = \sum_{j=1}^{n_j} n'_{ij}, \quad j = 1 + \cdots + N
$$

We let the weight for each matrix element be $w_{ij} = n'_{ij}/n_j$ so that the final weighted column average for the $j$ cycle is

$$
\overline{\Delta H}_j = \frac{1}{n_j} \sum_{i=1}^{n_j} W_{ij} \cdot \overline{\Delta H}_{1 \times j}, \quad j = 1 + \cdots + N
$$

The final SE is

$$
SE_j = \frac{1}{n_j} \sqrt{\sum_{i=1}^{n_j} (W_{ij} \cdot SE_{\overline{\Delta H}_{ij}})^2},
$$

j = 1 + \cdots + N

4. Results and analysis

Davis’ algorithm (8) for time series utilizes the complete set of crossover data to provide the height change over studied area and give the errors of the height change. Figure 1 shows the height change and their errors bar of ENVISAT data where the data are referenced to the first month (September 2002) from row 1 of Equation (3). The heights over Antarctic present a decline from September 2002 to March 2007 but have a seasonal
feature that the ice sheet is thickening from February to April. The mean error is about 1.45 cm and the maximal error is about 4.03 cm occurs in June 2006. Actually, there are $N$ series from the $dH$ matrix in Equation (3) and their referenced cycle is not the same cycle. For example, using the first third row in $dH$, three time series could be obtained (Figure 1(b)). When the fixed cycle is unified and referenced to the first cycle (September 2002) based on Equations (7)–(11), the final weighted column average height change will be obtained. Figure 2 gives the final height change over Antarctic ice sheet from the crossover of ENVISAT data-set. From this plot, there is a bigger error bar about 1.5 cm ahead of the series and a small error bar of about 0.25 cm at the back of the series because more data were used in the latter cycle. The mean error is about 0.43 cm. The height of the whole Antarctic ice sheet has a decline about 0.4 cm from September 2002 to March 2007. The time series presents a clearly seasonal and annual signal feature that shows the ice sheet is thickening in March. Figure 2 also plots the height change of east Antarctic (Figure 2(b)) and west Antarctic (Figure 2(c)), respectively. Generally speaking, the seasonal height change cycle can be affected by snow precipitation/accumulation, melting snow, snow densification (compaction), ice flow, and possibly temporal variations in the backscattered power from the ice sheet (8). In our processing, we ignore the $\Delta H_s(t)$ in Equations (1) and (2), which is a spurious change in surface elevation caused by the radar signal (backscattered power) penetration beneath the ice-sheet surface.

5. Conclusion

Sea levels are expected to rise and are one of the results of melting ice sheets (global warming) with adverse effects on many people living in coastal areas. Ice-sheet height change time series are therefore important for studying global climate. Analysis of the crossover data using Davis’ method (8) to yield an ice height change time series based on the ENVISAT altimetry data-set from September 2002 to March 2007 with a temporal resolution of 1 month (35 days), and the result shows that the Antarctic ice sheet has a decline of 0.40 ± 0.43 cm from September 2002 to March 2007.

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