Remote Sensing of Environment 177 (2016) 192–205

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Constructing improved decadal records of Antarctic ice shelf height change from multiple satellite radar altimeters

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ARTICLE INFO

Article history:
Received 1 July 2015
Received in revised form 10 January 2016
Accepted 30 January 2016
Available online 1 March 2016

Keywords:
satellite radar altimetry
ice shelves
change detection
time series
trend analysis
uncertainty analysis

ABSTRACT

Antarctica's ice shelves, the floating extensions of the ice sheet, exert an important dynamic constraint on the flow of ice from the grounded ice sheet to the ocean and, therefore, on changes in global sea level. Thinning of an ice shelf reduces its ability to restrain the ice discharge from the grounded ice sheet. However, our understanding of how ice shelf processes couple ice-sheet changes to climate variability is still rudimentary. In part, this is due to the brevity and low temporal resolution of surveys of ice shelf thickness relative to the broad range of time scales on which ice-sheet mass fluctuates. Here, we present improved procedures to construct 18-year (1994–2012) time series of Antarctic ice shelf surface height at high spatial resolution (~30 km) by merging data from three overlapping satellite radar altimeter missions (ERS-1, ERS-2, and Envisat). We apply an averaging scheme to enhance the signal-to-noise ratio of height changes over the floating ice shelves, and extract low-order polynomial trends using a robust approach (regularized regression with cross-validation) that accounts for both bias and variance in the fit. We construct formal confidence intervals by bootstrap resampling of the residuals of the fit. The largest source of height error arises from the interaction of the radar signal with the snow and firn surface; on annual time scales, changes in surface and sub-surface scattering and radar penetration lead to apparent height changes that are larger than the true surface-height change arising from densification. Our 18-year time series of surface height provide an insight into how ice shelves respond to the changing atmospheric and oceanic conditions. Our methods could also be applied to grounded portions of the ice sheets, both in Antarctica and Greenland.

1. Introduction

The Antarctic Ice Sheet contains ice above floatation equivalent to ~58 m of global sea-level rise (Fretwell et al., 2013) and plays an important role in pacing sea-level changes on centennial-to-millennial time scales (Alley et al., 2005). Over the past two decades, satellite measurements have revealed mass loss from the grounded ice sheet (Harig & Simons, 2015; Shepherd et al., 2012) including accelerated loss in the Amundsen Sea Embayment (Sutterley et al., 2014), a region with ~1.2 m of potential sea-level rise contribution (Rignot et al., 2014; Joughin et al., 2014). As a step towards predicting Antarctica's contribution to global sea-level change over the next century, there is an urgent need to understand the mechanisms behind the current changes.

Most ice mass loss from Antarctica takes place through iceberg calving and basal melting from the ice shelves, the floating extensions of the ice sheet (Depoorter et al., 2013; Joughin et al., 2012; Rignot et al., 2013). Ice shelves restrain the discharge of grounded ice into the ocean through a buttressing effect (Joughin & Alley, 2011; Schoof, 2007). Small perturbations in regional oceanic and atmospheric conditions can have a large impact on the extent and thickness of ice shelves (Dutrieux et al., 2014; Rignot et al., 2004; Scambos et al., 2004), which reduces their buttressing capability. The response of ice shelves to climate changes is, therefore, a key component in assessing future loss of grounded ice (e.g., Pollard et al. 2015). Our understanding of the many processes that affect ice shelf mass balance is, however, too rudimentary to trust predictions of ice-sheet change under projected future climate states.

There are two complementary paths towards improving our understanding of ice mass loss processes: to develop our theoretical framework of the actual mass loss processes so that they can be better represented in models; and to empirically relate observed ice sheet changes to ocean and atmospheric variability. Following the second approach, in our recent study (Paolo et al., 2015) we reported changes in Antarctic ice shelf height and inferred thickness during the 18-year period 1994–2012. The temporal and spatial resolutions of that thickness record were ~3 months and ~30 km, respectively. This continuous, highly-resolved record overcomes many limitations of previous studies of ice shelf thickness, which analyzed much shorter records and/or predominantly reported simple linear trends for large areas (Pritchard et al., 2012; Shepherd et al., 2010; Zwally et al., 2005). We are using this record to improve knowledge of ice shelf response to climate by

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http://dx.doi.org/10.1016/j.rse.2016.01.026
0034-4257/

comparing observed variability of ice thickness with observed and modeled changes in the ocean and atmosphere.

In this paper, we document our methods for constructing continuous records from multiple satellite radar altimeter missions, providing a detailed justification for the approach used by Paolo et al. (2015). We developed improved procedures for merging data from overlapping satellite missions, enhancing the signal-to-noise ratio of changes in ice shelf height, and extracting 18-year mean trends and acceleration. We introduce an alternative approach to the standard error propagation for the uncertainty analysis; bootstrapping applied to time-dependent data. Our method yields reliable time series of ice shelf height change and their uncertainties over the longest possible time period. The results reveal complex patterns of ice shelf height variability in both time and space.

2. Satellite radar altimeter missions

We used data from three European Space Agency (ESA) satellite radar altimeter (RA) missions, the European Remote Sensing Satellite-1 and Satellite-2 (ERS-1, 1991–1996; and ERS-2, 1995–2011) and the Environmental Satellite (Envisat, 2002–2012). The on-board tape recorder used for the RA data on ERS-2 failed in June 2003, limiting ERS-2 RA measurements to 1995–2003. Each satellite carried a standard pulse-limited radar altimeter, which had a footprint size of ~3–5 km over the predominant flatter portions of the ice sheets. For reasons explained in Section 3.5, below, we do not use the first two years of ERS-1 data; therefore our data span the 18-year period 1994–2012.

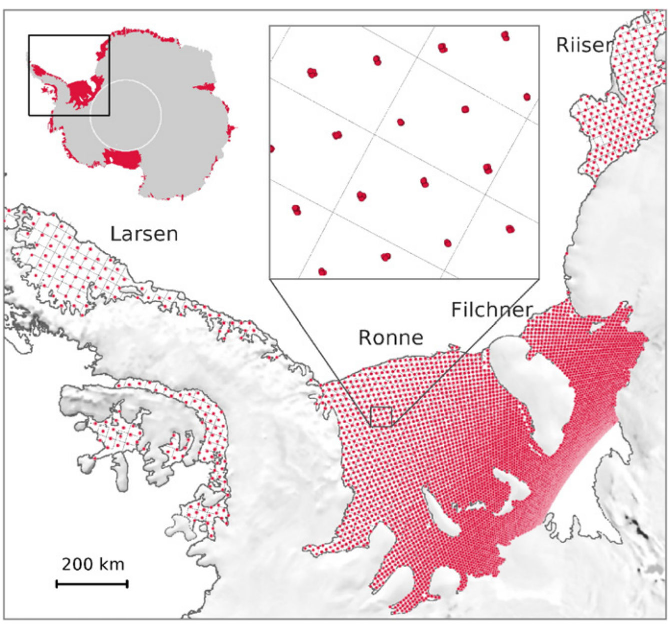

Fig. 1. ERS-1 radar altimeter data coverage over the Weddell Sea region of Antarctica for a typical 3-month period with the 35-day repeat orbit. Dots are crossover locations on the ice shelves. The ~30 km grid that we used to average the crossovers is overlaid.

ERS-1 was launched on July 1991 and operated between December 1991 and June 1996. It operated at an altitude of ~785 km with an inclination of 98.5° (latitude limit of 81.5°), with three different orbital repeat periods: 3-day (Ice Phase, December 1991 to March 1992 and December 1993 to April 1993); 35-day (Multidisciplinary Phase, April 1992 to December 1993 and March 1995 to June 1996); and 168-day (Geodetic Phase, April 1994 to March 1995). ERS-2 was launched on April 1995 and followed the ERS-1 35-day orbit. The RA system on these two satellites used a linearly polarized antenna at 13.8 GHz (Ku-band), yielding along-track measurements that were ~340 m apart (sampling rate of 20 Hz, where each sample was the average of 50 radar echoes).

The ERS-1/ERS-2 orbit covered about 85% of the Antarctic ice shelf area, missing only the southern portions of the large Filchner-Ronne (Fig. 1) and Ross ice shelves. To improve performance over the ice sheets, ERS-1 and ERS-2 operated in both a standard 'ocean mode' and a specialized 'ice mode', with mode switching based on an ocean-ice mask. For ice mode, the 64-bin range window (the segment of return echo that is recorded) was four times wider than for ocean mode (116.48 m vs 29.12 m), increasing the chances of capturing return signals over rough topographic surfaces. However the broader range window resulted in four times coarser sampling of the returned waveform, leading to a less precise estimation of arrival time and, therefore, of the surface height; over land ice, Scott et al. (1994) estimated the height-retrieval precision to be 0.49 m in ice mode and 0.28 m in ocean mode. The ERS RAs alternated between ocean and ice mode every repeat cycle and using an on-board ice sheet mask.

Envisat was launched in March 2002 into the same 35-day orbit as the ERS satellites, and provided averaged data at the same 20 Hz sampling rate. The altimeter on this satellite (RA-2) (Roca et al., 2009) was a linearly-polarized radar that operated via a single antenna dish in the Ku-band (13.6 GHz) and S-band (3.2 GHz). This dual frequency enabled the correction of height-measurement errors introduced by the ionosphere. RA-2 had an improved precision over ice surfaces compared with the ERS altimeters, and operated with three sampling modes, 'fine', 'medium' and 'coarse', which differed in their sampling of the waveform of the return echo. The range window was 128 bins wide, resulting in range-window widths for the three modes of 61 m, 243 m and 960 m, respectively, with corresponding resolutions of 0.47 m, 1.9 m and 7.5 m. The majority of the ice shelf measurements were acquired in fine-mode. Envisat stopped operating in April 2012.

We obtained Level-2 RA data for each mission as Version 5 Ice Data Records (IDRs) from the NASA/GSFC Ice Altimetry group (http://icesat4.gsfc.nasa.gov/). At GSFC, the RA waveforms were retracked using a range-retracking algorithm (the β-retracker; see Section 3.4) (Zwally & Brenner, 2001). The following corrections were applied by GSFC: atmospheric range; instrument; surface slope; ocean and solid earth tides (Brenner et al., 1983; Zwally & Brenner, 2001; Zwally et al., 2005); removal of a 0.41 m bias from ERS-1 heights to account for a change in instrument parameter used for ERS-2 (Femenias, 1996); corrections for drifts in the ultra-stable oscillator and bias changes in the scanning point target response that were obtained from ESA (for ERS); and upgraded orbits (DGM-E04 orbits for ERS) which had a radial orbit precision of 0.05–0.06 m (Scharroo & Visser, 1998).

3. Processing satellite radar altimeter data

Our determination of height changes over the ice shelves from multi-mission satellite RA data is based on 'crossover analysis' (e.g., Davis & Ferguson, 2004; Wingham et al., 2009; Zwally et al., 1989; Zwally et al., 2005), which estimates change in surface height at intersections between time-separated ascending and descending satellite tracks. Along-track analysis methods that provide higher point density have recently been introduced (Flament & Rémy, 2012; Moholdt et al., 2010; Pritchard et al., 2012); however, crossover analysis remains the most precise technique since differences are derived from precisely co-located height estimates on the ascending and descending tracks. For our study, we obtained height estimates at crossovers that were found through interpolation between along-track measurements that were ~340 m apart. These are overlapping pulse-limited footprints along a well-defined surface profile (each orbit). In contrast, for repeat-track analysis each measurement is projected onto a reference ground track with the actual orbits varying up to ~2 km from each other