ANTARCTIC ICE SHEET SURFACE MASS BALANCE ESTIMATES FROM 2003 TO 2015 USING ICESAT AND CRYOSAT-2 DATA

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ABSTRACT:

An assessment of Antarctic ice sheet surface mass balance from 2003 to 2015 has been carried out using a combination of ICESat data from 2003 to 2009 and CryoSat-2 data from 2010 to 2015. Both data sets are of L2 and are currently processed separately using different models. First, a repeat-track processing method that includes terms accounting for the trend and the first order fit of topography is applied to repeat-track measurements of all ICESat Campaigns. It uses the Least Squares fitting of the model to all observations in a box of 500 m x 500 m. The estimated trends in these boxes are then averaged inside a 30 km x 30 km cell. Similarly, the cells are used to estimate basin and ice sheet level surface elevation change trends. Mass balance calculating is performed at the cell level by multiplying the ice density by the volume change and then extended to the basin and the ice sheet level. Second, in CryoSat-2 data processing we applied a model within a cell of 5 km x 5 km considering that CryoSat-2 does not maintain repeated tracks. In this model the elevation trend, and a higher order topography are solved in an iterative way using the least squares technique. The mass change is computed at the cell level in the same way as the ICESat data. GIA correction is applied for both ICESat and CryoSat-2 estimates. Detailed information about the data processing, elevation and mass balance changes, and comparison with other studies will be introduced.

1. INTRODUCTION

Assessing of mass balance in Antarctica has become an important scientific research theme because melting of the Antarctic Ice Sheet and the resulting discharge contribute significantly to changes in sea level (Bamber et al., 2009; Cazenave et al., 2010; Shepherd et al., 2012; Vaugham et al., 2013). The contribution of polar ice sheet changes to sea level rising reveals an accelerating rate compared with changes in the other two major contributors: continental glaciers and expansion of seawater caused by higher temperatures (Domingues et al., 2008; Chen et al., 2009; Cazenave et al., 2010; Rignot et al., 2011; Zwally et al., 2011). Both its vast ice mass and its increasing rate of change make observations of the AIS a high priority. Furthermore, the potential instability of the ice sheet due to effects related to accelerated ice flow, subsurface lakes, and basal ice-shelf melting may significantly affect the overall rate of change, and the ice sheet needs to be closely monitored and modeled using regional and local observations (Ivins, 2009; Flament et al., 2013; Moholdt et al., 2014; Paolo et al., 2015; Liu et al., 2015).

Analysis of mass balance in the Antarctic Ice Sheet can be performed using satellite technologies, including (1) elevation and volume change from radar altimetry (RA) and laser altimetry (LA) (2) mass change from satellite gravimetry (GR), and (3) the input-output method (IOM) using ice-velocity sensing for mass output estimates. In contrast to GR and IOM, satellite altimeters directly measure ice-sheet surface elevations.

Radar altimetry technology was realized in ERS (European Remote Sensing) missions ERS-1 and ERS-2, which completed operations in 2000 and 2011, respectively (Davis, 1992). Another radar altimeter aboard the Envisat (Environmental Satellite) mission operated from 2002 to 2010 (Rémy et al., 2009; Memin et al., 2014). The ICESat (The Ice, Cloud and Land Elevation Satellite) and CryoSat-2 (Earth Explorer Opportunity Mission-2) missions have been supplying laser and radar altimetric data on the vertical changes in the surface of Antarctica from 2003 to the present (Drinkwater et al., 2004; Schutz et al., 2005; Wingham et al., 2006; McMillan et al., 2014), with a short gap from 2009 to 2010 that can be partially filled with data from NASA's Operation IceBridge (Koenig et al., 2010). The ICESat mission acquired valuable data on elevation changes in the Greenland and Antarctic ice sheets between 2003 and 2009 using its geoscience laser altimeter system (GLAS) (Zwally et al., 2002). The GLAS included a 1064-nm laser channel for surface altimetry and achieved an overall accuracy of 14 cm (5 cm in flat areas) in its surface elevation measurements (Schutz et al., 2005; Shuman et al., 2006; Moholdt et al., 2010).

The ICESat and CryoSat-2 missions were expected to provide advanced time series data on changes in the Antarctic Ice Sheet. A comparison of the long-term mass changes in the Antarctica Ice Sheet derived from the two independent ICESat and CryoSat-2 data sets over a 6-year period from 2003 to 2009 indicated a strong correlation between the two (Gunter et al., 2009). A similar study on the estimation of Antarctic elevation

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and mass change rates was introduced by Memin et al. (2014) using Envisat radar altimetry data for 2003 to 2010. A reconciled estimate of the ice-sheet mass balance using a variety of remote sensing and in situ observations, including GRACE and ICESat data, was reported by Shepherd et al (2012). The first comprehensive assessment of Antarctic ice sheet elevation change using 3 years of CryoSat-2 radar altimeter data was developed by McMillan et al (2014). Zwally et al. (2015) presented that mass gains of the Antarctic ice sheet exceed losses.

This study focuses on the Antarctic ice sheet mass balance derived from ICESat data between 2003 and 2009. Ice sheet elevation and mass change in the Lambert Glacier-Amery Ice Shelf System (LAS), East Antarctica, is calculated using CryoSat-2 data from 2010 to 2015. As illustrated in Figure. 1, the LAS study area is located in the region of 66.5-81°S and 40-95°E, covering an area of 2,427,820 km2, including 69,000 km2 of the Amery ice shelf (Fricker et al., 2000). The LAS is the largest glacier-ice shelf system in East Antarctica.
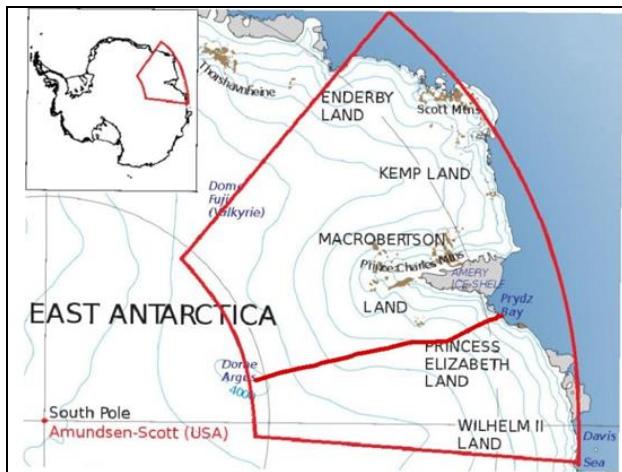

Figure 1. Study area (red boundary) of LAS.

2. DATA AND METHODS

2.1 ICESat Data and Processing

We used the newly released ICESat GLA12 dataset (R634) - Antarctic and Greenland ice sheet altimetry data (ftp://n5eil01u.ecs.nsidc.org/SAN/GLAS/GLA12.034/). This dataset had been recently updated due to the error (called the Gaussian-centroid or "G-C" offset) in the range determination from the transmit-pulse reference-point selection. These inter-campaign biases between the different campaigns have been reported to have a maximum impact on the elevation change of ±10 cm per year (Borsa et al., 2014).

The ICESat data cover the entire mission period from January of 2003 to October of 2009 with a compromised campaign strategy (Table 1) because of the failure of a part of sensor system (Shutz et al., 2005). The first campaign (Campaign 1) works in a different mode whose ground tracks are not repeated as the other campaigns so that we can't apply repeat track analysis to these tracks. Data in campaign 1 is excluded. The last campaign (Campaign 18) was not completed in accordance with its data acquisition plan. Furthermore, Campaign 17 yielded a significant number of empty data areas, based on our data quality examination. Thus, the data from these three campaigns were excluded from this study.

After ICESat data pre-processing above, repeat-track analysis is implemented. First, repeated tracks are separated by track index within GLA12 dataset. Then we fit the repeat track points to a second order polynomial for the tracks. Second, within each 500×500m box, we fit four parameters including elevation change rate, mean elevation in the box and slope in x and y directions.

Third, we calculate the trend at each cell of a 30km×30km grid by aggregating estimates of all boxes within the cell and ensure at least five boxes are inside each cell (Ewert et al., 2011).

Similarly, the cells are used to estimate basin and ice sheet level surface elevation change trends. Mass balance calculating is performed at the cell level by multiplying the ice density by the volume change and then extended to the basin and the ice sheet level. GIA correction is applied for ICESat estimates.

$$h_i = \alpha_x(x_i - \bar{x}) + \alpha_y(y_i - \bar{y}) + \frac{dh}{dt}(t_i - \bar{t}) + \bar{h} \qquad (1)$$

Where

h_i = elevation measurement
$\bar{h}$ = mean elevation measurement
x_i, y_i = projection coordinates
$\bar{x}$, $\bar{y}$ = mean projection coordinates in a box
t_i = time in year
$\bar{t}$ = mean time in year
α_x, α_y = surface terrain term
$\frac{dh}{dt}$ = elevation change rate

Campaign No.	Date	Laser ID	Cycle
1	2003-02-20 ~ 2003-03-21	1A	8-day
	2003-03-21 ~ 2003-03-29	1B	8-day
2	2003-09-25 ~ 2003-10-04	2A	8-day
	2003-10-04 ~ 2003-11-19	2A	91-day
3	2004-02-17 ~ 2004-03-21	2B	91-day
4	2004-05-18 ~ 2004-06-21	2C	91-day
5	2004-10-03 ~ 2004-11-08	3A	91-day
6	2005-02-17 ~ 2005-03-24	3B	91-day
7	2005-05-20 ~ 2005-06-23	3C	91-day
8	2005-10-21 ~ 2005-11-24	3D	91-day
9	2006-02-22 ~ 2006-03-28	3E	91-day
10	2006-05-24 ~ 2006-06-26	3F	91-day
11	2006-10-25 ~ 2006-11-27	3G	91-day
12	2007-03-12 ~ 2007-04-14	3H	91-day
13	2007-10-02 ~ 2007-11-05	3I	91-day
14	2008-02-17 ~ 2008-03-21	3J	91-day
15	2008-10-04 ~ 2008-10-19	3K	91-day
16	2008-11-25 ~ 2008-12-17	2D	91-day
17	2009-03-09 ~ 2009-04-11	2E	91-day
18	2009-09-30 ~ 2009-10-11	2F	91-day

Table 1. ICESat campaigns and data used in this study

2.2 CryoSat-2 Data and Processing

For CryoSat-2, level 2 data for both LRM (Low Resolution Mode) and SIN (Synthetic Interferometric Mode) in baseline B is used. LRM is a conventional pulse-limited radar altimeter that integrates the backscattered energy over the full beam width resulting in a footprint diameter of roughly 15 km considering an average altitude of 730 km. In the SIN mode, SIRAL samples the surface with a higher pulse repetition frequency (18 181 Hz) than in LRM (1970 Hz) (Helm and others, 2014). Though up to now CryoSat-2 newly baseline C data is newly released with announced improvement, especially for SIN data, we do not have enough time to make full downloading and validation based processing.

Altogether from July of 2010 to February of 2015, Cryosat-2 has acquired 3.6 million range measurements across Antarctic LAS, East Antarctica, in pulse-limited and synthetic aperture radar interferometry modes, and we process measurements from each mode in an identical manner. Ice sheet elevation is calculated as the difference between satellite locations and range measurements corrected for the lag of the leading edge tracker (Wingham et al., 2006), fluctuations in dry and wet atmospheric mass, the effects of the ionosphere, isostatic rebound (Ivins et al., 2013; Whitehouse et al., 2012), and for solid Earth and ocean tides.

For quality control, Data quality flags are used according to ESA CryoSat-2 user handbook and (Wang et al., 2015). And data of LRM and SARIn are merged together. After CryoSat-2 data pre-processing, followed the grid segment analysis. First, we mesh the study area into 97497 regularly spaced 5 by 5 km grid. An average of 341 points falls into the 5 by 5km box. The average of time range in each box is 4.28 year. Second, within each 5 by 5 km box, we fit a model with linear elevation change rate, quadratic function of surface terrain and time-invariant function of satellite heading (McMillan et al, 2014). Outliers are removed by iterative three standard deviation filter calculation.

$$h_i = \alpha_x(x_i - \overline{x}) + \alpha_y(y_i - \overline{y}) + \alpha_{xx}(x_i - \overline{x})^2$$
$$+ \alpha_{xy}(x_i - \overline{x})(y_i - \overline{y}) + \alpha_{yy}(y_i - \overline{y})^2 \qquad (2)$$
$$+ \frac{dh}{dt}(t_i - \overline{t}) + \beta_g AD_i + \overline{h}$$

Where

h_i = elevation measurement
$\overline{h}$ = mean elevation measurement
x_i, y_i = projection coordinates
$\overline{x}, \overline{y}$ = mean projection coordinates in a box
t_i = time in year
$\overline{t}$ = mean time in year
AD_i = ascending or descending orbit
$\alpha_x, \alpha_y, \alpha_{xx}, \alpha_{yy}, \alpha_{xy}$ = surface terrain term
$\dfrac{dh}{dt}$ = elevation change rate
β_g = offset between ascending and descending

Third, we calculate the trend at each cell of a 30km×30km grid by aggregating estimates of all boxes within the cell and ensure at least five boxes are inside each cell.
The mass change is computed at the cell level in the same way as the ICESat data. Similarly, GIA correction is implemented for CryoSat-2 estimates.

3. RESULTS AND DISCUSSION

3.1 Calculation Results

Elevation change rates are resampled to a 30 by 30 km grid by calculating mean elevation change rate and median absolute deviation (MAD) of errors. Then we calculate mean elevation changes of each basin with errors by error propagation (Ewert et al., 2011). Maps for the elevation change rate of Antarctic ice sheet derived from ICESat data for the period of 2003-2009 is presented in Figure 2. The final surface elevation change rate and the resulting mass change estimation for the whole Antarctica is 0.39 ± 0.09 cm yr^{-1} and 41.03 ± 9.43 Gt yr^{-1}. Maps for the elevation change rate of LAS, East Antarctica computed from CryoSat-2 data between 2010 and 2015 is displayed in Figure 3.
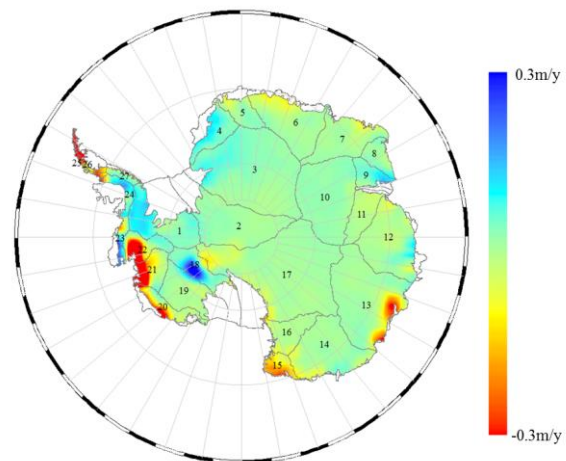

Figure 2. Spatial distribution of elevation change rate of Antarctic ice sheet derived from ICESat data.

3.2 Further Discussion

The final result derived from ICESat data reveals that mass gains of the Antarctic ice sheet exceed losses and the detailed mechanism remains to be interpreted.
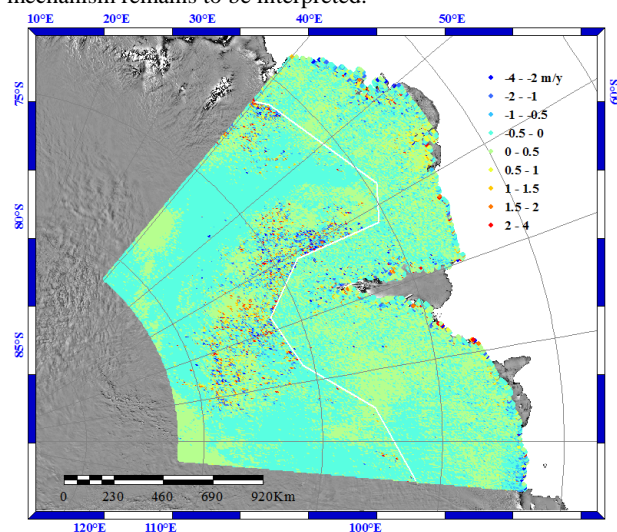

Figure 3. Spatial distribution of elevation change rate of 5×5 km boxes in LAS derived from CryoSat-2 data.

The CryoSat-2 data result map (Figure 3) shows a good spatial and temporal quality in the estimation boxes. There is a zone of

low quality estimates distributed at the margin of LRM mode near upper stream of Amery ice shelf. Further analysis is needed to see if some improvement may be necessary in Level 1 data reprocessing or in our model. We are calculating the mass balance of the whole study area, and a further investigation of the trend from 2010 to 2015 needs to be carried out in terms of detailed data quality, estimation model, snow accumulation data, and others.

4. CONCLUSION

A comprehensive assessment of Antarctic ice sheet surface mass balance is implemented here using ICESat data from 2003-2009 and detailed elevation change estimation and mass balance of LAS, East Antarctica is also presented using CryoSat-2 data from 2010-2015. The Antarctic ice sheet mass gains go beyond losses supported by calculated result from ICESat data. And a zone of low quality estimates in LAS needs more investigation.

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