

ELEVATION AND FREEBOARD CHANGES OF ROSS SEA ICE AND ICE SHELF USING ICESAT

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Abstract—In this paper, ICESat (Ice, Cloud, and land Elevation Satellite)-based estimates of sea ice and ice shelf elevation change and the sea ice freeboard changes in the Ross Sea Region of west Antarctic were studied. To process the data, a 3-step procedure was developed. ICESat datasets of three releases were used for the study: laser 1 and laser 2A (2003) and laser 3D (2005). It was found that all of them have suspect elevation data and extensive quality control was needed to remove the suspect points before a bias-free surface could be generated. Also obtained sea-ice freeboard from ICESat elevation data showed unusual negative results. Simple, universe, and ordinary kriging interpolations as well as inverse distance weights interpolation were tested and evaluated. It is found that the ordinary kriging method based on an unknown mean performed the best and achieved the smallest RMS prediction error (< 1 m) based on cross-validation technique. Seasonal elevation changes of the two complete datasets (laser 1 and laser 2A) have been analyzed and results indicate that (1) the mean elevation of sea ice increased about 0.89 m, with a mean increase of 0.55 m for the sea ice/ice shelf transition zone; (2) the mean elevation of the ice sheet decreased about 0.17 m; (3) maximum elevation of sea ice increased 1.13 m; (4) maximum elevation of ice shelf increased 5.36 m; (5) the transitional region has the largest elevation change: ~60 % of the region shown 48 to 20 m decreases, only small portions shown 20-40 m increases. Inter-annual elevation changes obtained from laser 2A and laser 3D for sea ice indicate that (1) minimum surface elevation has decreased as 5.27 m with increase of mean surface about 0.12 m; (2) maximum surface elevation from Austral spring 2003 to spring 2005 has decreased as 12.69 m. It is suggested that the freeboard directly resulted from ICESat data has large negative values and needs better geoid or mean sea surface.

Keywords- ROSS Ice Shelf, Sea Ice, ICESat, Elevation Change

I. INTRODUCTION

Most of the fresh water on Earth is stored in Greenland and Antarctic ice sheets and sea ice. The ice sheets and ice shelves are critical concern due to their potential for raising the global sea level. Ice shelves are permanent floating ice sheets that are attached to land and are constantly fed by glaciers. It is extremely important to quantify the spatiotemporal changes of ice sheet, ice shelf and sea ice, which will provide critical information to analyze how global or regional climate changes have been impacted and will continue to impact their changes, or vice versa. It has been projected that the Greenland Ice Sheet

may melt entirely from future global warming, whereas the East Antarctic Ice Sheet is likely to grow through increased accumulation for warming not exceeding ~ 5 °C. However, the future of the West Antarctic Ice Sheet remains uncertainty [1].

Scientists confirmed that there is an accelerated movement of glaciers on the West Antarctic ice sheet and the Antarctic Peninsula following the breakup of the floating ice shelf onto which the glaciers flowed. The sea ice cover in both hemispheres is also expected to sensitively respond to the climate change [2]. Many USA, ESA, and Canadian satellites, such as SMMR/SSM/I, Landsat series, AVHRR, EOS Terra/Aqua, ERS-1 and 2, RADARSAT, and EnviSat have provided significant information to quantify following variables: ice sheet elevation or mass balance, sea ice extent and thickness, and precipitation or snowfall. ICESat is the NASA's benchmark EOS mission for measuring ice sheet mass balance using laser altimeter at 1064 nm, with unprecedented vertical accuracy of 10 cm per pulse on slope $< 3^\circ$ and 70 meter footprint [3], [4]. While the primary purpose of ICESat is to determine inter-annual and long-term changes in polar ice-sheet mass balance, it is postulated the freeboard and therefore sea ice thickness can be derived through buoyancy theory [4], [5]. The cryospheric goal of ICESat is to support measurements that will determine elevation change with an accuracy of 1.5 cm yr^{-1} over a 10^4 km^2 region where the surface slope is less than 0.6° [6].

In this paper, ICESat data were used to study the elevation and freeboard of the Ross sea region and their seasonal and annual changes.

II. DATA AND METHODOLOGY

A. Data Description

The ICESat is an Earth Science Enterprise mission using the lidar technique. ICESat mission is to provide multi-year elevation data needed to determine ice sheet mass balance. The ICESat samples the Earth's surface from an orbit with inclination of 94° , with footprints of ~ 70 m in diameter spaced at 170 m intervals, with a pulse rate of 40 per second [3]. ICESat carries the Geoscience Laser Altimeter system (GLAS) measuring its height above the Earth surface, from which the sea surface height and the sea ice freeboard height can be inferred [5]. In this study, GLAS12 ice sheet data and GLAS13 sea ice data were used. Ross region surface elevation

change detection and freeboard estimation based on Laser 1 (Austral late summer and early fall: 2/20/03 to 3/20/03), Laser 2A (Austral spring: 9/27/03 to 11/17/03), and Laser 3D (10/21/05 to 11/23/05) mission phases have been carried out. Essentially it allowed looking at the short-term semi-annual elevation changes between spring and fall of 2003 as well as inter-annual change between spring 2003 and spring 2005. “Fig. 1” shows the study areas of Ross Ice Shelf sub-region (black polygon) and Ross Sea ice sub-region (red polygon).

B. Methodology

A 3-step method was developed to process the ICESat data ordered via NSIDC (“Fig. 2” is the workflow chart for the process). The first step was to convert binary ICESat data to a text file. The second step was to subset the region of interest using a program developed in LabVIEW. The third step, based on ArcGIS, was to first produce shape files of GLA13 and GLA12 for each laser product. The projection was then defined and reprojected as WGS 1984 Stereographic South Pole. Laser altimeter measurements are effected by atmospheric conditions such as pressure and relative humidity, surface characteristics such as slope angle and roughness, and variations in the gravity field that effect satellite orbit heights [7]. So before using the interpolation method, unreliable elevation points caused by such effects were deleted manually from each individual data set. Interpolation method was used to create surface and to see the differences between the surfaces. Ordinary Kriging, Simple Kriging interpolation methods were used and compared. Ordinary kriging was selected because of the root-mean-square (rms) values of all data measurements were less than 1 m. Created surfaces exported to raster to be able to achieve elevation difference. Finally, seasonal surface elevation difference were obtained by basically subtracting fall 2003 data from spring 2003 data for the two sub areas. Inter-annual surface elevation change was obtained by subtracting spring 2003 data from spring 2005 data. Sea ice freeboard was also calculated by subtracting geoid from elevation and then similar steps were used to produce freeboard difference maps. Statistical results were then obtained from those maps.

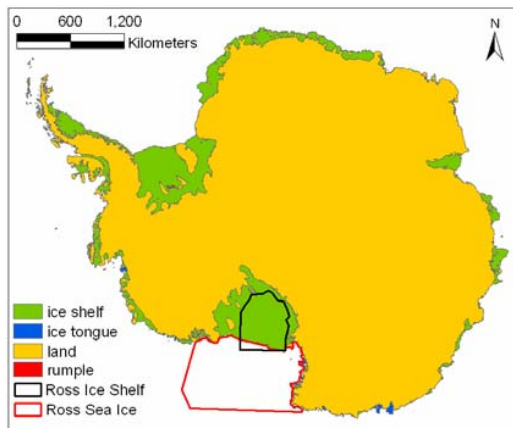


Figure 1. Study area of the west Antarctic region: black polygon area is the Ross Ice Shelf and red polygon area is the Ross Sea Ice.

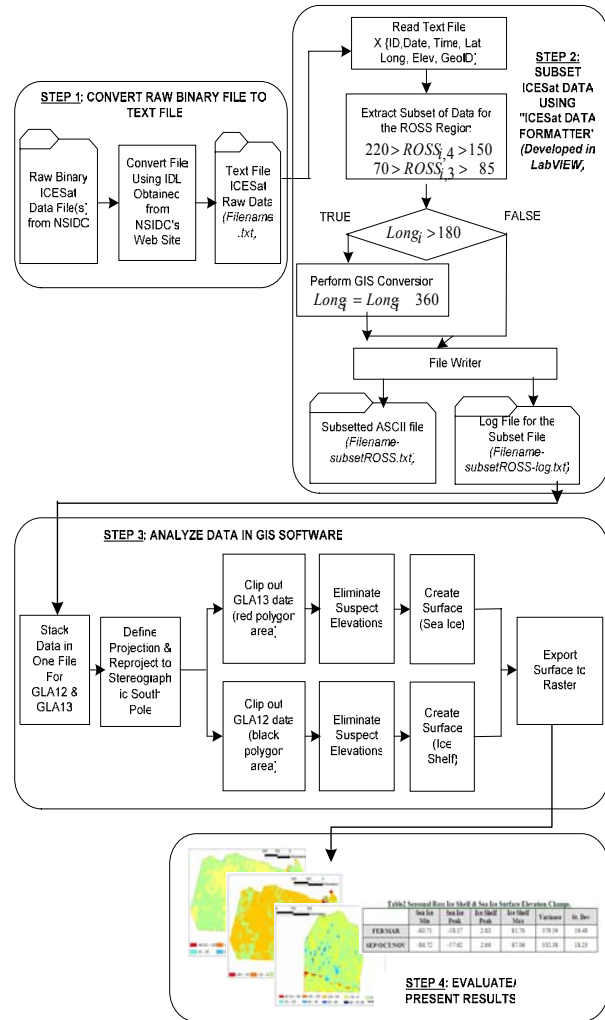


Figure 2. Flowchart for ICESat Data File Processing and Analysis Methodology.

Surface elevation change can be also derived from the crossover residual as the difference in elevation between two altimetry profiles that intersect [8]. Elevations at the crossover can be calculated by linearly interpolating from the two observed elevation side of the intersection point for each pass [9]. To obtain the elevation change by crossover calculation is currently under development.

III. RESULTS

A. Elevation change

Table 1 and Table 2 indicate the seasonal surface elevation change for sea ice and ice shelf from Laser 1 (fall 2003) to Laser 2A (spring 2003). “Fig. 3” shows the elevation difference between the seasons for both parts. Seasonal elevation changes of the two complete datasets indicate that (1) the mean elevation of sea ice increased about 0.89 m, with a mean increase of 0.55 m for the sea ice/ice shelf transition zone; (2) the mean elevation of the ice sheet decreased about 0.17 m; (3) maximum elevation of sea ice increased 1.13 m; (4) maximum elevation of ice shelf increased 5.36 m; (5) the transitional region has the largest elevation change: ~60 % of the region shown 48 to 20 m decreases, only small portions shown 20-40 m increases.

Statistics have also been done for spring 2003 to spring 2005 (not shown). Results indicate that minimum surface elevation for sea ice has decreased 5.27 m, while mean surface elevation for sea ice has increased about 0.12 m. Maximum surface elevation for sea ice from spring 2003 to spring 2005 has decreased as 12.69 m. Sea ice surface elevation difference between the specified years are obtained as -57.26, 39.37, 0.14, 3.37 for min, max, mean, and std. dev, respectively. “Fig. 4” is the image of difference between the years.

TABLE I. SEASONAL ROSS SEA ICE SURFACE ELEVATION STATISTICS

2003	Min	Peak	Mean	Max	Var.	St. Dev
FEB/MAR	-100.58	-58.89	-60.67	-5.34	43.75	6.61
SEP/OCT/NOV	-91.38	-59.24	-59.78	-4.21	38.68	6.22

TABLE II. SEASONAL ROSS ICE SHELF & SEA ICE SURFACE ELEVATION STATISTICS

2003	Sea Ice Min	Sea Ice Peak	Ice Shelf Peak	Ice Shelf Max	Var.	St. Dev
FEB/MAR	-80.71	-58.17	2.83	81.70	379.59	19.48
SEP/OCT/NOV	-86.72	-57.62	2.66	87.06	332.38	18.23

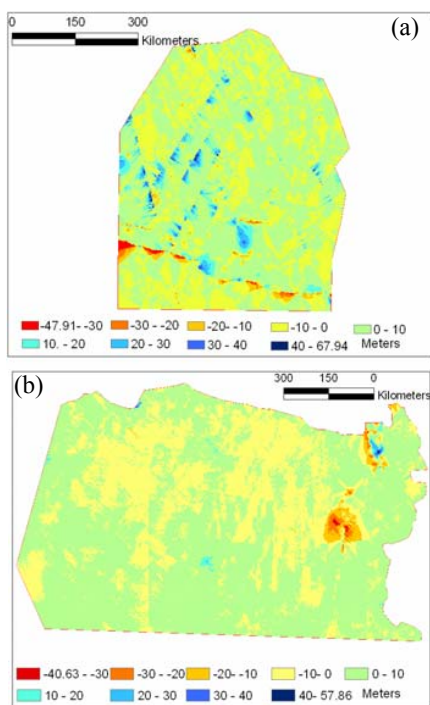


Figure 3. Seasonal Elevation change comparison for (a) Ice Shelf part and (b) Sea Ice part of Ross Region.

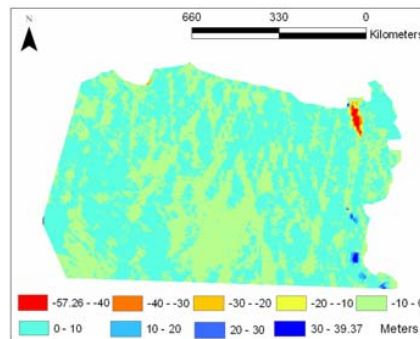


Figure 4. Sea ice surface elevation difference between spring 2003 – 2005.

B. Freeboard estimation

“Fig. 5” and “Fig. 6” are the freeboard differences of fall to spring 2003 to spring 2005, respectively. According to the results minimum freeboard and maximum freeboard of sea ice have increased about 20.18 m and 6.58m, respectively, while the mean freeboard of sea ice has decreased 0.65 m from fall 2003 to spring 2003. Ross Sea Ice freeboard difference from spring 2003 to spring 2005 varies from -48.82 m to 38 m, minimum freeboard of sea ice has increased as 0.38 m, maximum freeboard of sea ice decreased as 5.03m, and mean freeboard of sea ice increased about 0.14m. Negative freeboard heights were found in all freeboard images derived for the area (not shown). Table 3 is statistics for fall and spring 2003. Similar to all altimeter studies, an accurate geoid is a necessary prerequisite to estimate accurate sea ice freeboard [5]. The main cause for the unrealistic large and negative sea ice freeboard variations could be the geoid provided by ICESat data or the other reasons for negative freeboard could be unknown surface roughness, sea surface height anomalies. Therefore other methods are necessary to get a proper geoid and valid sea surface height to be subtracted from the ICESat elevation data to obtain realistic sea ice freeboard [10]. Also large uncertainties in the sea surface topography effects accurate determination of freeboard. Unknown snow depth is also the largest source of uncertainty in the conversion from freeboard to sea ice thickness. Depending on snow depth and freeboard, this uncertainty could be more than a meter [3].

TABLE III. SEASONAL ROSS SEA ICE FREEBOARD STATISTICS

2003	Min	Max	Mean	St. Dev
FEB/MAR	-20.27	41.39	0.16	4.26
SEP/OCT/NOV	-0.09	47.97	-0.49	3.10

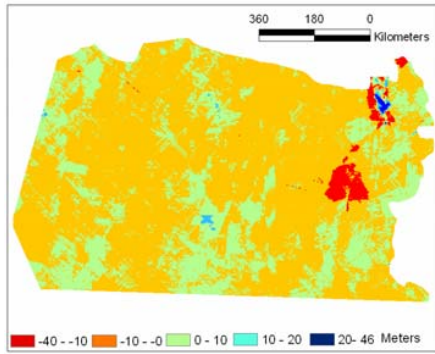


Figure 5. Ross Sea Ice freeboard difference from fall to spring 2003.

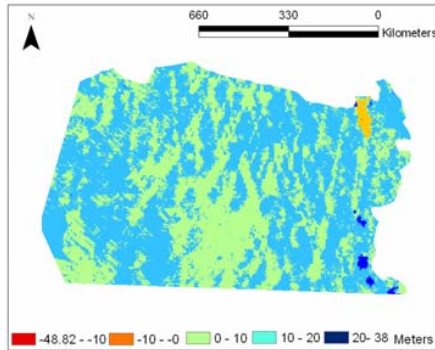


Figure 6 Ross Sea Ice freeboard difference from spring 2003 to spring 2005.

IV. DISCUSSION AND CONCLUSION

We developed a 3-step procedure to process and prepare the ICESat data for GIS-based analysis. Three datasets (Lasers 1, 2A, and 3D) for the Ross Sea region have been used and preliminary results have been presented. Detail data analysis and interpretation are still underway.

Analysis of surface elevation change from ICESat altimetry is complicated because there are missing points or gaps in the provided data. Consequently, analysis of ICESat laser altimeter time series for estimation of longer term trends will be more complicated and involve greater uncertainty.

While the primary purpose of ICESat is to determine inter-annual and long-term changes in polar ice-sheet mass balance, it is postulated the freeboard and therefore sea ice thickness can be derived through buoyancy theory [4]. Our results indicate that there are large uncertainties in the freeboard estimates mainly due to the geoid provided from the ICESat and other causes. In order to verify the accuracy of the freeboard estimates as well as the ice thickness, intensive ground-based ship observations are needed. Unknown snow depth also

introduces the largest uncertainty in the conversion of freeboard to ice thickness. So the three variables of freeboard, snow density, and surface roughness could bring significant error to estimate of sea ice thickness. Therefore, future work will consist of 1) development of empirical relationship between mean surface elevation and mean sea ice thickness using ground measurements and/or ship observations; these empirical relations may directly used to derive sea ice thickness based on ICESat measurements; these thickness can then be compared with thickness derived from buoyancy equation, 2) obtainment of accurate geoid, 3) measurement of snow depth using other satellite data, 4) produce regional error maps on mean elevation by examining the spectra of surface roughness and mean slope based on ICESat return signal.

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