Arctic Sea Ice Freeboard and Thickness, Version 1

USER GUIDE

How to Cite These Data

As a condition of using these data, you must include a citation:

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FOR CURRENT INFORMATION, VISIT https://nsidc.org/data/NSIDC-0393

National Snow and Ice Data Center

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1 DETAILED DATA DESCRIPTION

1.1 Format

1.1.1 ASCII

Each space delimited ASCII vector data file contains file headers followed by columns for latitude, longitude, freeboard, and thickness.

Longitude in WGS 84 degrees in the approximate range of 0 to 360.
Freeboard in meters above local sea level at the time of the measurement.
Thickness in meters.

Freeboard = 0 means the sea ice surface is at sea level. The average of the lowest 1percent reference elevation is used as reference sea level, so about 0.5 percent of the data are below sea level, that is, negative freeboard. Freeboard values less than zero are set to zero.

Note: Thickness values of -999 indicate that a thickness value could not be calculated and should be treated as missing data.

1.1.2 Binary

The freeboard and thickness binary gridded files are 304 columns x 448 rows containing little-endian floating-point values in meters. The grid is the 25 km polar stereographic grid used for SSM/I processing.

1.2 File and Directory Structure

Data are available on the HTTPS site in the following directory:

https://daacdata.apps.nsidc.org/pub/DATASETS/NSIDC0393_GLAS_SI_Freeboard_v01

1.3 File Naming Convention

1.3.1 ASCII File Names

ASCII files are named according to the following convention and as described in Table 1:

Example file name:

`laser3i1343001.txt`

`laserLPTTTTCCC.txt`

Table 1. Valid Values for the ASCII File Name Variables

Variable	Description
laserLP	GLAS Laser Period used to collect data. LP = 3d, 3e, 3f, 3g, 3h, or 3i
TTTT	Laser track number: 0001 through 0432, or 1282 through 1354
CCC	Cycle of Reference Orbit: 001, 002, or 003
.txt	Identifies the file as ASCII data

1.3.2 Binary File Names

Binary gridded files are named according to the following convention and as described in Table 2:

Example file name: `laser3d_freeboard_mskd.img`

Example file name:

`laser3d_freeboard_mskd.img.hdr`

`laserLP_nnnnnnnnn.mskd.zzz`

Table 2. Valid Values for the Binary Grid File Name Variables

Variable	Description
laserLP	GLAS Laser Period used to collect data. LP = 3d, 3e, 3f, 3g, 3h, or 3i
_nnnnnnnnn	Indicating 'freeboard' or 'thickness'
_mskd	Indicating masked image
.zzz	Identifies file type: .img (image), .img.hdr (header), or .png (Portable Network Graphics)

1.3.3 Grid Cell Center Latitude and Longitude Files

The grid cell center files provide the latitude and longitude for the center of each grid cell as a little-endian floating-point number. The files are named according to the following convention, and as described in Table 3.

Example file name:

`PS25km_north_lon.img`

`PS25km_north_mmm.zzz`

Table 3. Valid Values for the Grid Cell Center File Name Variables

Variable	Description
PS	Polar Stereographic

Variable	Description
`25km`	25 kilometer grid
`_north`	northern hemisphere
`mmm`	latitude (lat) or longitude (lon)
`.zzz`	Identifies file type: .img (image), img.hdr (header)

1.3.4 Mask File

The mask file consists of values 0 = water, 1 = land. The file is named `gsfc_25n.msk`. The corresponding header file is `gsfc_25n.msk.hdr`.

1.4 File Size

1.4.1 ASCII File Size

ASCII file sizes range from 2 K to 1 MB

1.4.2 Binary File Size

The `.hdr` files are each 749 bytes.

The `.img` files are each 532 KB.

The `.png` files range from 31 KB to 44 KB.

1.5 Volume

1.5.1 ASCII

The total volume for the ASCII track data files is approximately 932 megabytes.

1.5.2 Binary

The total volume for the binary gridded image, header and masked image files is approximately eight megabytes.

1.6 Spatial Coverage

Arctic region

Southernmost Latitude: 65° N
Northernmost Latitude: 86° N
Westernmost Longitude: 180° W
Easternmost Longitude: 180° E

Note: The ASCII data are reported with longitude of 0 degrees to 360 degrees.

1.6.1 Spatial Resolution

The resolution of the gridded data is 25 km. Vectors have a resolution of about 170 meters in the along-track direction, or the distance between the centers of adjacent GLAS footprints. Several kilometers typically separate the ICESat GLAS data tracks.

1.6.2 Projection and Grid Description

Two geoid models are used in this study. North of 64° N, the Arctic Gravity Project (ArcGP) latitude limit, the ArcGP geoid is used. The Earth Gravitational Model 1996 (EGM96) geoid is used below 64° N. The difference, D, between ICESat measured sea level and the geoid was used to create a 5 km D-grid for each period. The mean of the 5 km D-grids was used as an improved geoid.

1.7 Temporal Coverage

Release 28 Laser Identifier 1AB: 2003-02-20 to 2003-03-29
Release 28 Laser Identifier 2A: 2003-09-25 to 2003-11-19
Release 28 Laser Identifier 2B: 2004-02-17 to 2004-03-21
Release 28 Laser Identifier 2C: 2004-05-18 to 2004-06-21
Release 28 Laser Identifier 3A: 2004-10-03 to 2004-11-08
Release 28 Laser Identifier 3B: 2005-02-17 to 2005-03-24
Release 28 Laser Identifier 3C: 2005-05-20 to 2005-06-23
Release 28 Laser Identifier 3D: 2005-10-21 to 2005-11-24
Release 28 Laser Identifier 3E: 2006-02-22 to 2006-03-27
Release 28 Laser Identifier 3F: 2006-05-24 to 2006-06-26
Release 28 Laser Identifier 3G: 2006-10-25 to 2006-11-27
Release 28 Laser Identifier 3H: 2007-03-12 to 2007-04-14
Release 28 Laser Identifier 3I: 2007-10-02 to 2007-11-05
Release 28 Laser Identifier 3J: 2008-02-17 to 2008-03-21
Release 28 Laser Identifier 3K: 2008-10-04 to 2008-10-19

1.7.1 Temporal Resolution

Each ICESat campaign period represents one Arctic-wide ice thickness assessment. Thus the temporal resolution for this data set is approximately two to three times per year.

1.8 Parameter or Variable

The parameters of this data set are sea ice freeboard, and sea ice thickness.

1.8.1 Parameter Description

Sea ice freeboard is the height in meters of the sea ice above the water level. Thickness is the thickness in meters of the sea ice.

In the ASCII files, the thickness value -999 indicates missing values, possibly due to failure of the thickness algorithm for certain corresponding freeboard measurements.

The binary gridded *.img and *.png files have been masked. Table 4 shows the mask color value assignments to surface features.

Table 4. Binary Image File and PNG File Values

`.img` File Value	**`.png` File Value**	**Surface Feature**
-4	gray = 128	land south of 65° N
-3	gray = 164	land at or north of 65° N
-2	gray = 64	water south of 65° N
-1	gray = 96	water at or north of 65° N
greater than or equal to 0	full color (rainbow) applied across parameter value range	sea ice freeboard or thickness measurements in meters

1.8.2 Sample Data Record

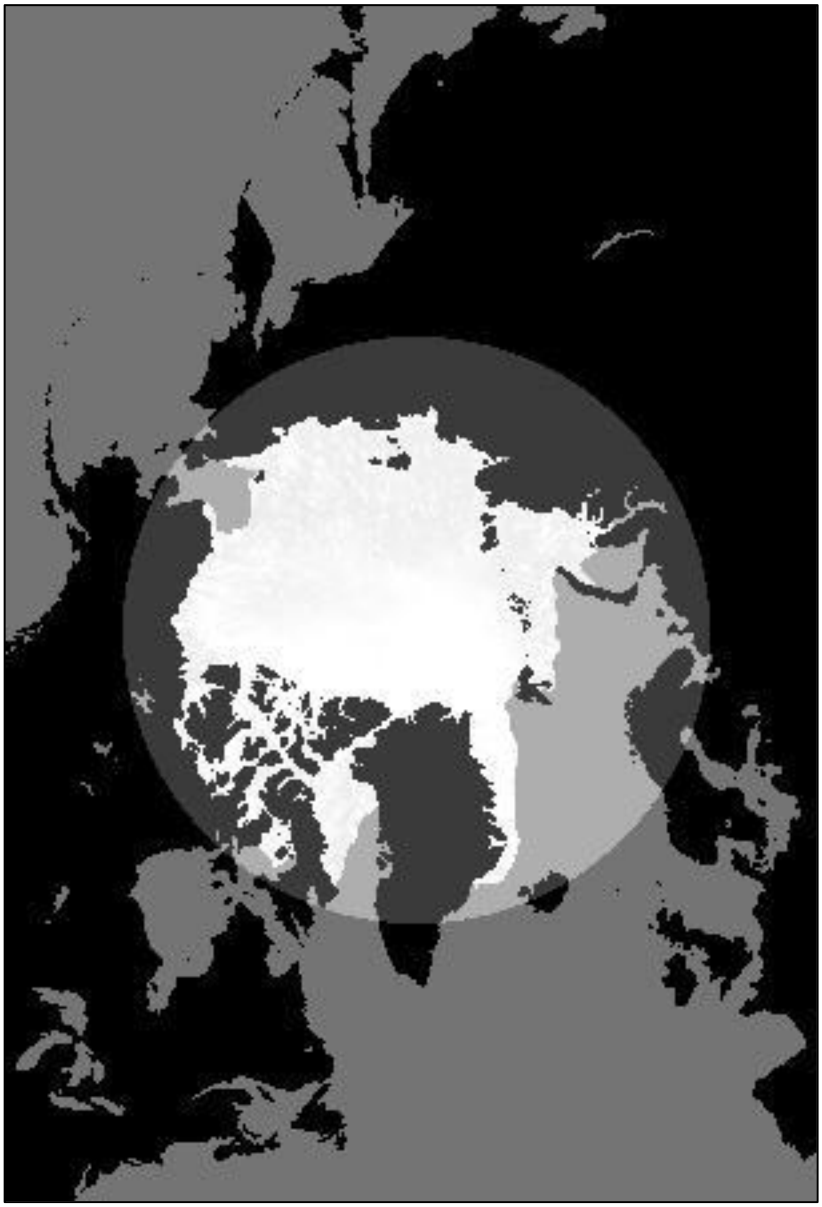
1.8.2.1 ASCII

The following sample of the `laser3d0001002.txt` ASCII file shows header information, and the first four records of Latitude, Longitude, Freeboard and Thickness values.

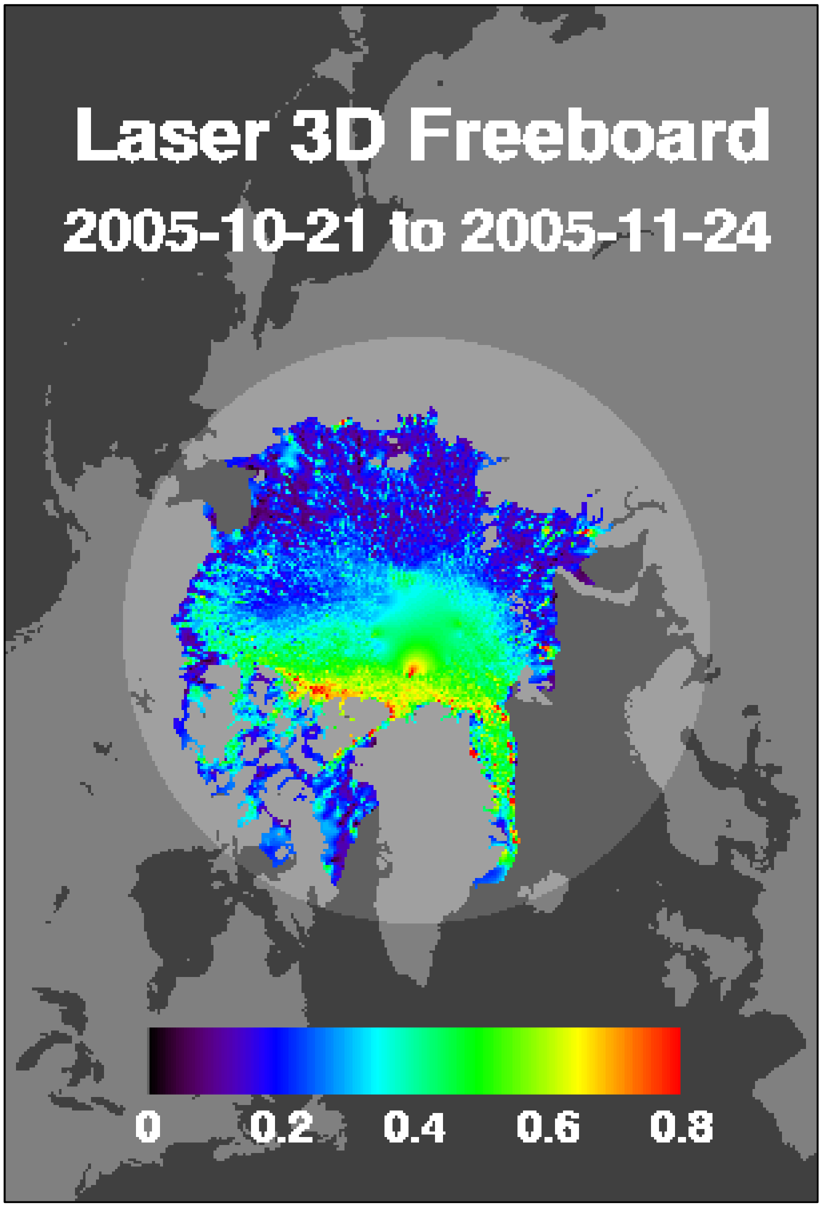
```
Converting ICESat/GLAS binary freeboard vector data to ASCII
Tue Aug 24 17:19:10 2010

write_fb:
  file_in:      laser3d0001002.dat
  laser_period: 3d
  track:        0001
  cycle:        002
  file_out:     laser3d0001002.txt
  non_zero_only:            0
  nan_replace:           -999

read_fb:
  Year:                  2005
  Month:                   10
  Day:                     26
  Hour:                    20
  Minute:                  23
  Doy:                    299
  record_count:          3668
  non_zero_count:        3651
  nan_count:                0

   Latitude      Longitude         Freeboard         Thickness
   72.791718     342.049681        0.373489          0.833361
   72.793225     342.048339        0.301693          0.673164
   72.794733     342.046998        0.356756          0.796025
   72.796242     342.045660        0.319992          0.713994
```

1.8.2.2 Binary

The following sample shows the `laser3d_freeboard_mskd.img` masked binary gridded image.



The following sample shows the `laser3d_freeboard_mskd.png` masked binary gridded image.



2 SOFTWARE AND TOOLS

2.1 Software and Tools

2.1.1 ASCII

The ASCII track data may be displayed with any Web browser or plain text display software.

2.1.2 Binary

The binary gridded data may be displayed using ENVI, ArcGIS, or other similar software packages.

2.2 Quality Assessment

For further discussion on quality assessment of GLAS products, refer to the Quality Assessment section of the NSIDC GLAS/ICESat L1 and L2 Global Altimetry documentation.

3 DATA ACQUISITION AND PROCESSING

3.1 Theory of Measurements

Two geoid models are used in this study. The ArcGP geoid is used north of 64° N since that is the ArcGP latitude limit. The EGM96 geoid is used below 64° N.

Elevations varying more than plus-or-minus 4 meters are not used. This condition filters out some land, island, and iceberg data. These conditions are the same as in Zwally et al. 2008.

ICESat measures a surface elevation profile referenced to an ellipsoid. Due to the limited accuracy of the geoids and ocean tide models, and poor knowledge of the dynamic topography, sea-ice surface elevation referenced to a geoid cannot be regarded as sea-ice freeboard. The information needed to calculate sea-ice freeboard is the elevation difference between the top of the snow surface, local sea levels, and snow height and density above the snow/ice interface. If the elevation difference is known, even if the absolute elevations are biased, the sea-ice freeboard can be determined. Thus, the knowledge of relative elevation is crucial while absolute elevation is less important. This is the underlying concept in the derivation of freeboard.

In this study, constant densities of ρW = 1023.9 kg m-3 and ρI = 915.1 kg m-3 are used to calculate sea ice thickness from the freeboard. There is no spatial variation of now density ρS. Snow density, including the time variation, is based on Kwok 2008. The range of the snow density is 0.16 to 0.40.

Refer to the Processing Steps section below for details on the application of theory of measurements.

3.2 Data Acquisition Methods

Freeboard is measured from ICESat elevation profiles (Zwally et al. 2008). Snow depth is interpolated, both spatially and temporally, from climatology snow depth in situ measurements (Warren et al. 1999). Thickness is estimated from ICESat freeboard and climatology snow depth. SSM/I daily ice concentration data (Gloersen et al. 1992) from January 2003 to October 2008 are used to determine sea ice boundaries.

3.3 Derivation Techniques and Algorithms

The grids of sea ice freeboard and thickness were derived from the corresponding ICESat point measurements of freeboard and thickness using the following steps.

1. Freeboard/thickness values are estimated for each valid ICESat sea ice observation during the laser period.
2. The latitude/longitude of each freeboard/thickness observation is mapped into a column/row for a particular cell of the 25 km resolution 304 by 448 Polar Stereographic grid.
3. All the freeboard/thickness observations that fall into the same Polar Stereographic grid cell are averaged together resulting in a single freeboard/thickness value pair for each cell. This resampling algorithm is commonly referred to as "drop in the bucket" resampling. The cell will be empty if there is no data in that cell.
4. The daily SSM/I Goddard Space Flight Center (GSFC) sea ice concentration values for each cell in the Polar Stereographic grid for the laser periods are averaged together for each ICESat campaign. Those cells that do not have a sea ice concentration value, which are cells that fall within the pole hole poleward of 84.5° N, are assigned values. Values from cells across eight equiangular sectors, nearest to the estimation point, are formed into a weighted average. The weight, w, is based on distance, d, from the estimation point to the nearest cell value in a particular sector, via the following relation in Equation 1 which is described in Table 5:

$$w = \left[1 + \left(\frac{3d}{r}\right)^2\right]^{-1}$$

(Equation 1)

Where:

Table 5. Cell Value Weighted Average Equation Description

Variable	Description
w	Weight
d	Distance
r	Maximum radius from which to draw samples. To interpolate values across the polar region, r was set to 420 km.

5. Assign 0 to freeboard/thickness grid cells where mean ice concentration is less than 20 percent. For freeboard/thickness grid cells having no value and ice concentration greater than or equal to 20 percent, interpolate values.

3.3.1 Processing Steps

Sea ice freeboard and thickness are calculated from ICESat GLAS ground tracks using the following steps.

1. **Elevation data filtering**. Before calculating the sea-ice freeboard and thickness, the following conditions were applied to filter out data contaminated by clouds, saturation, and land or islands.
   a. **Gain limit**. An upper limit of detector gain is applied to filter out stronger atmospheric attenuated waveforms. The upper limit for the laser periods are: 50 counts for L1, L2, L2A, L2B,L3A, and L3B; 80 counts for L3C,L3D,L3E,L3F,L3G,L3H, and L3I; 120 counts for L2C,L3J, and L3K (Yi et al. 2011).
   b. **Pulse broadening limit**. Define a pulse-broadening parameter, S. See Equation 2 which is described in Table 6.

$$S = \frac{c}{2}\sqrt{\sigma_R^2 - \sigma_T^2}$$ **(Equation 2)**

Where:

Table 6. Pulse-Broadening Parameter Equation Description

Variable	Description
S	Measure of the broadening of the transmitted pulse associated with surface topography and the undesirable effects of saturation and atmospheric forward scattering
c	Speed of light
σ_R	Echo waveform 1-sigma pulse width
σ_T	Transmitted waveform 1-sigma pulse width

Heavily saturated waveforms and forward scattering waveforms have broadened pulse widths, so data with S larger than 0.8 m are discarded.

   c. **Reflectivity limit**. Heavily saturated waveforms also tend to have very high apparent reflectivity, and forward scattering waveforms tend to have low reflectivity. Therefore, data with reflectivity smaller than 0.05 or larger than 0.9 are discarded.
   d. **Elevation limit**. Elevation varying more than plus or minus four meters are not used. This condition filters out some land, island, and iceberg data. These conditions are the same as in Zwally et al. 2008.
2. **Geoid**. Two geoid models are used in this study. The ArcGP geoid is used north of 64° N since that is the ArcGP latitude limit. The EGM96 is used below 64° N.

The difference, D, between ICESat measured sea level and the geoid was used to create a 5 km D-grid for each period. The mean of the 5 km D-grids was used as an improved geoid.

3. **Saturation correction and Inverse Barometer correction** are applied as shown in Equation 3 and explained in Table 7. Both corrections are the same as in Zwally et al. 2008. Sea surface response to atmospheric pressure loading, the inverse barometer effect, is computed using the method described in the Aviso and Physical Oceanography Distributed Active Archive Center (PODAAC) User Handbook (Picot et al. 2003).

$$\Delta H_{ib} = 9.948 \times (P_{atm} - P) \quad \textbf{(Equation 3)}$$

Where:

Table 7. Inverse Barometer Effect Equation Description

Variable	Description
ΔH_{ib}	Inverse barometer correction
P_{atm}	Surface atmospheric pressure
P	Time varying mean of the global surface atmospheric pressure over the oceans

ΔHib is applied to the ICESat elevation at the same time as the saturation correction. The surface atmospheric pressures used here are from the National Center for Environmental Protection (NCEP) (Stackpole 1994). The mean global surface atmospheric pressures over the ocean are from Collecte Localisation Satellites (Dorandeu and Le Traon 1999).

4. **SSMI daily ice con**. To avoid open ocean in low ice concentration areas, freeboard = 0 is assigned to areas where ice concentration less than 20 percent. This is an empirical limit to balance the sea ice filtered out and the freeboard contamination introduced by open ocean water waves.
5. **Elevation**. The ICESat measured surface elevation, H_{ie}, the i_elev in product GLA06, is referenced to the TOPEX/POSEIDON ellipsoid. ICESat surface elevations have instrument corrections, dry and wet troposphere corrections, and tidal corrections applied. Elevation, h, is defined in Equation 4 and described in Table 8.

$$h = H_{ie} + \Delta H_{ib} + \Delta H_{sat} - h_g \quad \textbf{(Equation 4)}$$

Where:

Table 8. Elevation Equation Description

Variable	Description
h	Elevation above the geoid
H_{ie}	ICESat measured surface elevation

Variable	Description
ΔH_{ib}	Inverse barometer correction
ΔH_{sat}	Saturation correction
h_g	Geoid height

6. **Calculate 50 km running mean (h_m) of elevation h.** ICESat measures a surface elevation profile referenced to an ellipsoid. Due to the limited accuracy of the geoids and ocean tide models, and poor knowledge of the dynamic topography, sea-ice surface elevation referenced to a geoid cannot be regarded as sea-ice freeboard. The information needed to calculate sea-ice freeboard is the elevation difference between the top of the snow surface on the sea ice and local sea levels. If the elevation difference is known, even if the absolute elevations are biased, the sea-ice freeboard can be determined. Thus, the knowledge of relative elevation is crucial while absolute elevation is less important. Here we describe an algorithm to determine relative elevation and use this relative elevation to estimate sea-ice freeboard. By determining local ocean level and using only the relative elevation, the influences of the longer wavelength (greater than 50 km) factors such as geoid error, long wavelength laser pointing error and tidal error, which affect the absolute elevation, are removed from the freeboard calculation.
7. **Calculate relative elevation**: The relative elevation is calculated using Equation 5 and as described in Table 9.

$$h_r = h - h_m \quad \textbf{(Equation 5)}$$

Where:

Table 9. Relative Elevation Equation Description

Variable	Description
h_r	Relative elevation
h	Elevation above geoid
h_m	50 km running mean of elevation h

8. **Sea level**, h_s, at any given point is determined by averaging the lowest one percent of the h_r values within 50 km of that point. The one percent value was selected empirically. It provides enough points in calculating mean sea level to reduce measurement noise, and also minimizes the influence of thinner ice on the calculation. This value may be optimized further as we learn more about the distribution of leads in the Arctic. In extreme cases when there is no open water within the 100-km range, h_s will measure the height of thin ice, thus underestimating freeboard.
9. **h_d(D)**. The difference between ICESat measured sea level and the geoid used is shown in Equation 6 as described in Table 10.

$$h_d = h_m - h_s \quad \textbf{(Equation 6)}$$

Where:

Table 10. Difference Between ICESat Measured Sea Level and the Geoid Used Equation Description

Variable	Description
h_d	Difference between the ICESat measured sea level and the geoid used
h_m	50 km running mean of elevation h
h_s	Sea level

10. **Freeboard height**, F, at a given point is calculated as shown in Equation 7 and described in Table 11.

$$F = h_r - h_s \quad \textbf{(Equation 7)}$$

Where:

Table 11. Freeboard Height Equation Description

Variable	Description
F	Freeboard height
h_r	Relative elevation
h_s	Sea level

To have a valid F at a point, there must be enough valid elevation measurements available within 50 km of that point. In this study, a point is discarded if less than 50 percent (300 points) of the total 600 points are available.

11. **Sea-ice thickness**, according to Archimedes buoyancy principle, is shown in Equation 8 and described in Table 12.

$$T = (\rho_w/(\rho_w - \rho_I))F - ((\rho_w - \rho_s)/(\rho_w - \rho_I))T_s \quad \textbf{(Equation 8)}$$

Where:

Table 12. Sea-ice Thickness Equation Description

Variable	Description
T	Sea ice thickness
F	Freeboard height
T_S	Snow depth
ρ_W	Water density
ρ_S	Snow density
ρ_I	Sea ice density

In this study, constant densities of ρW = 1023.9 kg m-3 and ρI = 915.1 kg m-3 are used to calculate sea ice thickness from the freeboard. There is no spatial variation of ρS. Snow density, including time variation, is based on Kwok 2008.

Since snow depths and densities available for converting freeboard to thickness are at 25 by 25 km grid scale, these gridded values reflect grid scale mean snow depth and density over the arctic but do not have the small scale variation that can be directly used to do the ICESat shot to shot freeboard/thickness conversion. Snow depth and density must be modeled to apply them to the individual measurements. The following method is used to do the freeboard/thickness conversion at a point.

Due to the dynamic nature of arctic sea ice, snow falls are not always accumulated on the top of sea ice. They may fall on leads or open water. So the snow depth varies from one footprint to another. Here a snow accumulation factor was defined as Fx (= 0.4, 0.4, 0.6, 0.1 for FM, MA, MJ, and ON), shown below with dates and lasers:

Fx = 0.4 February to March (FM) Laser 3E
Fx = 0.4 March to April (MA) Laser 3H
Fx = 0.6 May to June (MJ) Laser 3F
Fx = 0.1 October to November (ON) Laser 3D, 3G, 3I

It was assumed when freeboard is larger than Fx, snow is fully accumulated on sea ice; when freeboard is less than Fx, snow accumulation on sea ice is proportional to the ratio δ=Fi/Fx. The following five conditions are applied when converting Fi to Ti:

< >If Fi < 0, set Fi = 0if Fi < Fx, set δ=Fi/Fx and if Fi ³ Fx, set δ=1Ts=δ Ts', Ts' is snow depth of 25×25 km grids, Ts is snow depth used in the conversionif Ts > Fi, set Ts=Fiif Ci < 20%, set Fi=0, Ci is bilaterally interpolated ice concentration at a point from SSM/I ice concentration Table 13. Snow Accumulation Factor DescriptionVariableDescriptionFifreeboardFxsnow accumulation factordratio Fi/FxTssnow depthCibilaterally interpolated ice concentration at a point from SSMI ice concentrationTisea ice thickness.

3.3.2 Error Sources

Table 13 summarizes the GLAS single-shot error budget for elevation measurements (Zwally et al. 2002).

Table 13. GLAS Single-Shot Error Budget for ICESat Elevation Measurements

Error Source	Error Limit
Precision orbit determination (POD)	5 cm
Precision attitude determination (PAD)	7.5 cm

Error Source	Error Limit
Atmospheric delay	2 cm
Atmospheric forward scattering	2 cm
Other (tides, etc.)	1 cm
RSS	13.8 cm

For further discussion on error sources, see Zwally et al. 2002, and also refer to the Error Sources section of the NSIDC GLAS/ICESat L1 and L2 Global Altimetry documentation.

3.4 Sensor or Instrument Description

The data for this data set were acquired with the GLAS instrument onboard the Ice, Cloud, and land Elevation satellite (ICESat), from the SSM/I instrument on board the Defense Meteorological Satellite Program (DMSP), and from weather stations on the sea ice.

4 REFERENCES AND RELATED PUBLICATIONS

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Zwally, H. J., B. Schutz, W. Abdalati, et al. 2002. ICESat's Laser Measurements of Polar Ice, Atmosphere, Ocean, and Land. Journal of Geodynamics 34(3-4): 405-445.

4.1 Related Data Collections

AMSRIce03 Sea Ice Thickness Data

GLAS/ICESat L1 and L2 Global Altimetry Data (GLAH01, GLAH05, GLAH06, GLAH12-15)

National Ice Center Arctic Sea Ice Charts and Climatologies in Gridded Format

5 CONTACTS AND ACKNOWLEDGMENTS

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6 DOCUMENT INFORMATION

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