Arctic Sea Ice Freeboard and Thickness

Summary

This data set provides measurements of sea ice freeboard and sea ice thickness for the Arctic region. The data were acquired from the Ice, Cloud, and land Elevation Satellite (ICESat) Geoscience Laser Altimeter System (GLAS) instrument, the Special Sensor Microwave/Imager (SSM/I), and climatologies of snow and drift of ice. The data span six GLAS campaigns, laser 3D through 3I, from 21 October 2005 to 05 November 2007. Data parameters include sea ice freeboard and thickness measured in meters derived from GLAS Release 28 data. The data are provided in three formats: ASCII track data derived from binary track data, binary gridded polar stereographic data derived from ASCII gridded polar stereographic files, and Portable Network Graphic (PNG) image files. Also included are mask files used in preparation of the image files, a Mapx grid definition file, and grid cell center latitude and longitude files. The ASCII track data vectors of position and ice thickness have a resolution of about 170 meters in the along-track direction. The binary gridded polar stereographic data have a resolution of 25 km. The data set is approximately 940 megabytes. The data are available via FTP.

Citing These Data

To broaden awareness of our services, NSIDC requests that you acknowledge the use of data sets distributed by NSIDC. Please refer to the citation below for the suggested form, or contact NSIDC User Services for further information. We also request that you send us one reprint of any publication that cites the use of data received from our Center. This helps us to determine the level of use of the data we distribute. Thank you.

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Yi, Donghui and Jay Zwally. 2010. *Arctic Sea Ice Freeboard and Thickness*. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

Overview Table

Category	Description
Data format	Space delimited ASCII text Binary gridded 32-byte little-endian
Spatial coverage and resolution	Spatial Coverage: Arctic Region Southernmost Latitude: 65° N Northernmost Latitude: 86° N Westernmost Longitude: 180° W Easternmost Longitude: 180° E Spatial resolution: The centers of 70 m spots illuminated by the laser on the earth's surface are separated in the along-track direction by 170 m.
Temporal coverage and resolution	Laser 3D 2005-10-21 to 2005-11-24 Laser 3E 2006-02-22 to 2006-03-27 Laser 3F 2006-05-24 to 2006-06-26 Laser 3G 2006-10-25 to 2006-11-27 Laser 3H 2007-03-12 to 2007-04-14 Laser 3I 2007-10-02 to 2007-11-05

	A Release Schedule lists the temporal coverage of each ICESat/GLAS product. Data are sampled 40 times per second, captured during 14.8 orbits per day.
Tools for accessing data	ASCII data: any Web browser, plain text display or spreadsheet software. Binary gridded data: ENVI, ArcGIS, other similar software packages.
Grid/projection description	Binary gridded data are in polar stereographic projection. ASCII track data are provided with latitude and longitude for each data point and are not projected. Geoid models: EGM96 global gravity field model is used below 64° N. ArcGP is used north of 64° N.
File naming convention	ASCII files: laser3h1341001.txt Binary gridded data: laser3d_freeboard_mskd.img laser3d_freeboard_mskd.img.hdr laser3d_freeboard_mskd.png laser3d_thickness_mskd.img laser3d_thickness_mskd.img.hdr laser3d_thickness_mskd.png Mask: gsfc_25n.msk gsfc_25n.msk.hdr Mapx grid definition file: PS25km_north.gpd Grid cell center lat / long files: PS25km_north_lon.img PS25km_north_lon.img.hdr PS25km_north_lat.img PS25km_north_lat.img.hdr
File size	ASCII files range from approximately 2 KB to 1 MB. Binary gridded files: ENVI header files (.hdr) are 749 bytes each. Image files (.img) are 532 KB each. Portable Network Graphics files (.png) range from approximately 31 KB to 42 KB. Mapx grid definition file: 1 KB. Grid cell center lat / long image files are 532 KB each. Grid cell center lat / long files ENVI header files are 1 KB each. Mask file is 133 KB. Mask file ENVI header is 1KB.

Parameter(s)	Sea ice freeboard in meters Sea ice thickness in meters
Procedures for obtaining data	Available via FTP.

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2. Detailed Data Description

Format

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.

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.

File and Directory Structure

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

ftp://sidads.colorado.edu/pub/DATASETS/NSIDC0393_GLAS_SI_Freeboard_v01

File Naming Convention

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

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)

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

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`.

File Size

ASCII File Size

ASCII file sizes range from 2 K to 1 MB

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.

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.

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.

Projection

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.

Temporal Coverage

Release 28 Laser Identifier 3D: 21 Oct 2005 to 24 Nov 2005
Release 28 Laser Identifier 3E: 22 Feb 2006 to 27 Mar 2006
Release 28 Laser Identifier 3F: 24 May 2006 to 26 Jun 2006
Release 28 Laser Identifier 3G: 25 Oct 2006 to 27 Nov 2006
Release 28 Laser Identifier 3H: 12 Mar 2007 to 14 Apr 2007
Release 28 Laser Identifier 3I: 02 Oct 2007 to 05 Nov 2007

A Release Schedule lists the temporal coverage of each ICESat/GLAS product.

Temporal Resolution

Each ICESat campaign period, 3D through 3I, represents one Arctic-wide ice thickness assessment. Thus the temporal resolution for this data set is approximately two to three times per year.

Parameter or Variable

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

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

Sample Data Record

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.

Binary

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

laser3d_freeboard.img binary gridded image

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

laser3d_freeboard_masked.jpg masked binary gridded image

Error Sources

Table 5 summarizes the GLAS single-shot error budget for elevation measurements (Zwally et al. 2002).

Table 5. 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
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 Data Web page.

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 Data Web page.

3. Data Access and Tools

Data Access

Data are available via FTP.

Volume

ASCII

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

Binary

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

Software and Tools

ASCII

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

Binary

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

Related Data Collections

- AMSRIce03 Sea Ice Thickness Data
- GLAS/ICESat L1 and L2 Global Altimetry Data
- National Ice Center Arctic Sea Ice Charts and Climatologies in Gridded Format

4. Data Acquisition and Processing

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 ρ_W = 1023.9 kg m^{-3} and ρ_I = 915.1 kg m^{-3} are used to calculate sea ice thickness from the freeboard. There is no spatial variation of now density ρ_S. 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.

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.

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.

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 6:

   Pulse Broadening Parameter **(Equation 1)**

   Where:

   Table 6. 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.

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 all laser periods, L3C through L3I, is 80 counts.

b. **Pulse broadening limit.** Define a pulse-broadening parameter, S. See Equation 2 which is described in Table 7.

Pulse Broadening Parameter **(Equation 2)**

Where:

Table 7. 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 8. 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 8. 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

ΔH_{ib} 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 9.

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

Where:

Table 9. Elevation Equation Description

Variable	Description
h	Elevation above the geoid
H_{ie}	ICESat measured surface elevation
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 10.

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

Where:

Table 10. 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 11.

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

Where:

Table 11. 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 12.

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

Where:

Table 12. 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 13.

$$T = \frac{\rho_W}{\rho_W - \rho_I} F - \frac{\rho_W - \rho_S}{\rho_W - \rho_I} T_S \qquad \textbf{(Equation 8)}$$

Where:

Table 13. 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 $\rho_W = 1023.9$ kg m^{-3} and $\rho_I = 915.1$ kg m^{-3} are used to calculate sea ice thickness from the freeboard. There is no spatial variation of ρ_S. 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:

1. If Fi < 0, set Fi = 0
2. if Fi < Fx, set δ=Fi/Fx and if Fi ³ Fx, set δ=1

3. Ts=δ Ts', Ts' is snow depth of 25×25 km grids, Ts is snow depth used in the conversion
4. if Ts > Fi, set Ts=Fi
5. if Ci < 20%, set Fi=0, Ci is bilaterally interpolated ice concentration at a point from SSM/I ice concentration

Where:

Table 14. Snow Accumulation Factor Description

Variable	Description
`Fi`	freeboard
`Fx`	snow accumulation factor
`d`	ratio Fi/Fx
`Ts`	snow depth
`Ci`	bilaterally interpolated ice concentration at a point from SSMI ice concentration
`Ti`	sea ice thickness

5. References and Related Publications

Dorandeu, J. and P. Y. Le Traon. 1999. Effects of Global Mean Atmospheric Pressure Variations on Mean Sea Level Changes from TOPEX/POSEIDON. *Journal of Atmospheric and Oceanic Technology*, 16(9): 1279-1283.

Gloersen, P., W. J. Campbell, D. J. Cavalieri, J. C. Comiso, C. L. Parkinson, and H. J. Zwally. 1992. Arctic and Antarctic Sea Ice, 1978-1987: Satellite Passive-Microwave Observations and Analysis. NASA SP-511, 290 pp.

Kwok, R., and G. F. Cunningham. 2008. ICESat Over Arctic Sea Ice: Estimation of Snow Depth and Ice Thickness. *Journal of Geophysical Research* 113(C08010), doi: 10.1029/2008JC004753.

Picot, N., K. Case, S. Desai, and P. Vincent. 2003. AVISO and PODAAC User Handbook, IGDR and GDR Jason Products. SMM-MU-M5-OP-13184-CN (AVISO), JPL D-21352 (PO.DAAC).

Stackpole, J. D. 1994. The WTO Format for the Storage of Weather Product Information and the Exchange of Weather Product Message in Gridded Binary Form. *NOAA Office Note 388*.

Warren, S. G., I. G. Rigor, N. Untersteiner, V. F. Radionov, N. N. Bryazgin, Y. I. Aleksandrov, and R. Colony. 1999. Snow Depth on Arctic Sea Ice. *Journal of Climate* 12: 1814 - 1829.

Zwally, H. J., D. Yi, R. Kwok, and Y. Zhao. 2008. ICESat Measurements of Sea Ice Freeboard and Estimates of Sea Ice Thickness in the Weddell Sea. *Journal of Geophysical Research* 113(C02S15), doi: 10.1029/2007JC004284.

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.

6. Document Information

Acronyms

The acronyms used in this document are listed in Table 13.

Table 13. Acronyms and Abbreviations

Acronym	Description
ArcGP	Arctic Gravity Project
ASCII	American Standard Code for Information Interchange

CIRES	Cooperative Institute for Research in Environmental Science
DMSP	Defense Meteorological Satellite Program
EGM96	Earth Gravitational Model 1996
ENVI	Environment for Visualizing Images
FTP	File Transfer Protocol
GLAS	Geoscience Laser Altimeter System
GSFC	Goddard Space Flight Center
ICESat	Ice, Cloud, and land Elevation Satellite
NCEP	National Center for Environmental Protection
NSIDC	National Snow and Ice Data Center
PNG	Portable Network Graphics
PAD	Precision Attitude Determination
POD	Precision Orbit Determination
PODAAC	Physical Oceanography Distributed Active Archive Center
SSM/I	Special Sensor Microwave/Imager
URL	Uniform Resource Locator
WGS 84	World Geodetic System 1984

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`http://nsidc.org/data/docs/daac/nsidc0393_arctic_seaice_freeboard/index.html`