Greenland 5 km DEM, Ice Thickness, and Bedrock Elevation Grids, Version 1

USER GUIDE

How to Cite These Data

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

Bamber, J. 2001. Greenland 5 km DEM, Ice Thickness, and Bedrock Elevation Grids, Version 1. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/01A10Z9BM7KP. [Date Accessed].

Literature Citation

As a condition of using these data, we request that you acknowledge the author(s) of this data set by referencing the following peer-reviewed publication.

Bamber, J., R. L. Layberry, and S. P. Gogenini. 2001. A new ice thickness and bed data set for the Greenland ice sheet 1: Measurement, data reduction, and errors., Journal of Geophysical Research. 106. 33,773-33,780. https://doi.org/10.1029/2001JD900054

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National Snow and Ice Data Center

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1 DATA DESCRIPTION

A Digital Elevation Model (DEM), ice thickness grid, and bedrock elevation grid of Greenland, acquired as part of the PARCA program, are available in ASCII text format at a 5 km grid spacing in a polar stereographic projection. DEM data are a combination of ERS-1 and Geosat satellite radar altimetry data, Airborne Topographic Mapper (ATM) data, and photogrammetric digital height data. Ice thickness data are based on approximately 700,000 data points collected in the 1990s from a University of Kansas airborne Ice Penetrating Radar (IPR). Nearly 30,000 data points were collected in the 1970s from a Technical University of Denmark (TUD) airborne echo sounder.The ice thickness grid was subtracted from the DEM to produce a grid of bedrock elevation values. Data set applications include studies of gravitational driving stress and ice volume (mass balance) of the Greenland Ice Sheet.

1.1 Parameters

This data set consists of a Digital Elevation Model (DEM), an ice thickness grid, and a bedrock elevation grid, the latter computed as the difference between the first two. DEM data are based on a combination of ERS-1 satellite altimetry data, Airborne Topographic Mapper (ATM) data, and digital height data from Kort & Matrikelstyrelsen (KMS) and Geologiske Undersogelser (GEUS). Ice thickness data were collected with airborne ice penetrating radar (IPR) in the 1990s by the Remote Sensing Laboratory at the University of Kansas and with an airborne radar echo sounder in the 1970s by the Technical University of Denmark.

1.1.1 Usage

Ice thickness data were subtracted from a Digital Elevation Model (DEM) of Greenland to produce a bedrock elevation data set. Both data sets are useful in studying a variety of ice sheet characteristics. Bedrock elevation data contribute to a more detailed analysis of topographic patterns such as channels and basins that affect ice velocity rates. Ice thickness profile data, when combined with sea water density and ice column density data, are used to compute flotation thickness for an ice column. Ice thickness data are also used in estimating gravitational driving stress. In addition, recent elevation and ice thickness data provide scientists with an updated estimate of Greenland ice sheet volume to compare with previous studies.

1.1.2 Parameters

Figure 1 is a visual representation of all the parameters. Bedrock elevation is computed as the difference of DEM surface elevation and ice thickness values. For example, if the surface elevation

(a) is 400 m above sea level, and ice thickness (b) is 100 m, the bedrock elevation (c) is 300 m above sea level (c = a - b).

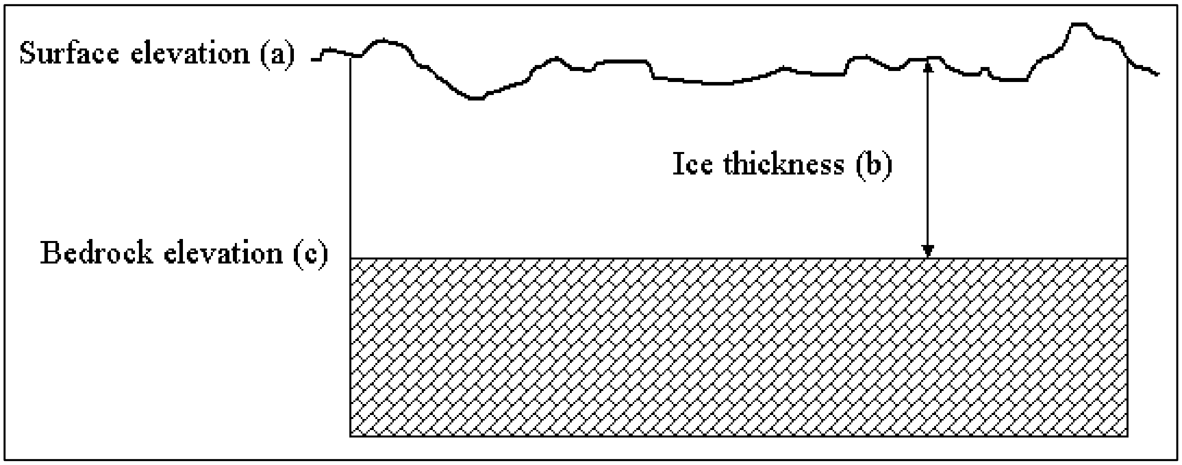

Figure 1. Diagram of surface elevation, ice thickness, and bed elevation.

Unit of Measurement: meters [m]

1.1.3 Parameter Source

- DEM data are based on a combination of the following data sources:
- ERS-1 (geodetic phase) satellite radar altimetry data
- Geosat satellite radar altimetry data
- Airborne Topographic Mapper (ATM) data
- Digital height data from photogrammetric analysis of aerial photos
- Recently unclassified DEMs provided by U.S. National Imaging and Mapping Agency (NIMA)

The primary data set used to compute ice thickness for Greenland was a collection of ice penetrating radar (IPR) data from the University of Kansas, Remote Sensing Laboratory. Beginning in 1993, a 150 MHz IPR was used for yearly airborne surveys across Greenland, which yielded nearly 700,000 ice thickness data points. A secondary source of ice thickness data came from the Technical University of Denmark (TUD) in the late 1970s. The TUD airborne radar collected nearly 30,000 data points throughout Greenland.

1.1.4 Parameter Range

- DEM: -0.1 m to 3278.300 m
- Ice thickness: 0 m to 3366.500 m
- Bedrock elevation: -963.100 m to 3239.000 m

DEM values of -0.1 m represent ocean, so the true minimum elevation value is 0 m. Bedrock elevation values are listed with respect to the WGS84 ellipsoid.

1.2 File Information

1.2.1 Format

The DEM, ice thickness grid, and bedrock grid are each provided as fixed-width, tab-delimited ASCII text grids (301 columns x 561 rows) of floating-point data.

surface_5km_corrected: DEM
thick_5km_corrected: ice thickness grid
bed_5km_corrected: bedrock elevation grid

Grid dimensions for the DEM, ice thickness grid, and bedrock elevation grid are 301 columns by 561 rows in fixed-width, tab-delimited ASCII text format. However, the format of the data file is actually 10 columns by 17391 rows. In other words, one row of 301 data values is represented by 31 lines in the ASCII data file (with a single value in the 31st line).

1.3 Spatial Information

1.3.1 Coverage

Figure 2 shows the extent of flight line coverage for the 1970s and 1990s airborne radar surveys of the Greenland Ice Sheet, which define the spatial coverage of this data set. The 1990's data are plotted in black, and the 1970's data are plotted in grey. (Bamber 2000a).

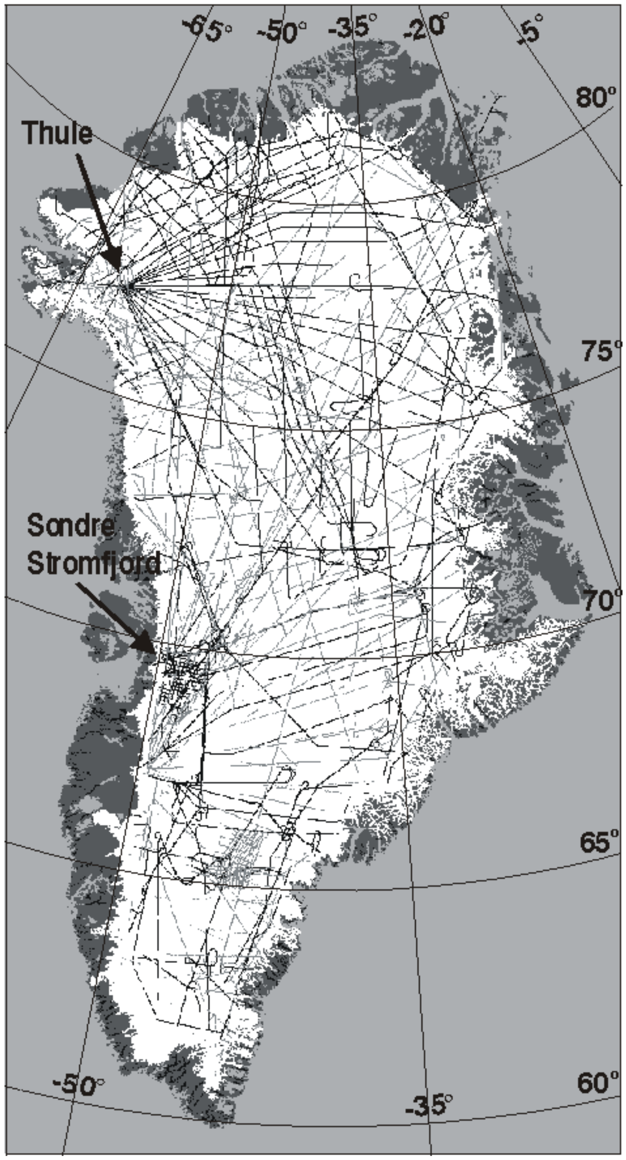

Figure 2. Airborne Radar Flight Lines Showing the Coverage Over the Greenland Ice Sheet

1.3.2 Resolution

The DEM, ice thickness grid, and bedrock elevation grid are interpolated to a 5 km grid resolution. However, the true horizontal resolution varies according to slope and surface characteristics. The DEM originally had a horizontal spatial resolution of 1 km, with accuracy ranging from 20 m to 200 m over bare rock areas, depending on the source data. Horizontal resolution of the ice thickness grid is between 5 km and 50 km, depending on flight line coverage.

1.3.3 Geolocation

All grids are in a polar stereographic projection with reference to the WGS84 ellipsoid. The standard parallel is 71°N, and the projection parallel (latitude of the center of the projection) is 90°N. The North Pole is the origin of the projection. The central meridian is 39°W.

Each grid consists of 301 columns and 561 rows, with data points gridded every 5 km and the origin at the North Pole. Corner points are as follows:

Table 1. Center Point of the Corner Cell

	Longitude	**Latitude**	**x (km)**	**y (km)**
Upper Left	92.1301024° W	80.8152653° N	-800	-600
Lower Left	52.2405199° W	58.6292691° N	-800	-3400
Upper Right	10.3987054° E	81.5294837° N	700	-600
Lower Right	27.3663660° W	58.8136131° N	700	-3400

Table 2. Corner Point of the Corner Cell

	Longitude	**Latitude**	**x (km)**	**y (km)**
Upper Left	92.3305365° W	80.8106358° N	-802.5	-597.5
Lower Left	52.2710201° W	58.6035491° N	-802.5	-3402.5
Upper Right	10.6177120° E	81.5269394° N	702.5	-597.5
Lower Right	27.3342981°W	58.7883271° N	702.5	-3402.5

1.4 Temporal Information

1.4.1 Coverage

Data used to produce the DEM were collected at different times, beginning in March 1985 through September 1986 with the Geosat geodetic phase, and ending in April 1994 through April 1995 with the ERS-1 336-day repeat cycle. Ice thickness data from the University of Kansas IPR were collected from 1993 to 1999. Echo sounding data from the Technical University of Denmark were collected in the late 1970s.

2 DATA ACQUISITION AND PROCESSING

2.1 Background

2.1.1 Radar Altimetry

Satellite radar altimeters measure the time it takes an electromagnetic signal to travel from the altimeter antenna to the ice sheet surface and back to the altimeter's receiver. This "range measurement" allows investigators to determine the satellite's height above the ice sheet. NSIDC's Radar Altimeter document describes the instrument and how it works.

Corrections are applied to the range measurements to account for the fact that returns are different over ice than over the ocean. The correction for interpreting the data over ice is called "retracking," and is described in papers by Davis and Zwally (1993), and Zwally, et al. (1983).

Over sloping terrain, the radar altimeter measurement needs to be corrected because the return comes from a point not directly below the satellite, but to the uphill side. The elevation indicated by the return time in this case is higher than that directly below the satellite. The data are slope-corrected to reduce the errors, using the slope correction algorithm from Brenner et al. (1983).

2.1.2 Echo Sounding

Radar echo sounding is a method of active remote sensing that measures ice thickness. An antenna mounted on a platform moving over the ice surface emits a short electromagnetic pulse which penetrates the surface and is reflected by inhomogeneities in the ice and underlying bedrock, sending an echo back to the antenna. The pulse duration depends on the system resolution requirements and the distance between the measured layers. Ice thickness is determined by analysis of the pulse delay time in the ice. The electromagnetic pulse loses energy as it travels through the ice, causing the returning echo to be smaller than the original pulse. The change in signal strength during the pulse's travel to the bedrock and back to the receiver is described by the following equation (Bogorodskiy 1985):

$N_{sum} = N_G + N_B + N_F + N_D + N_A + N_P$

Where:

N_{sum} = change in signal strength
N_G = geometrical spreading losses
N_B = losses due to reflections from interfaces
N_F = focusing factor, i.e., changes in signal strength due to focusing effects (also called refraction gain)
N_D = losses due to scattering
N_A = losses due to signal absorption in the ice

N_P = apparent losses due to rotation in the polarization of the received signal relative to the orientation of the receiving antenna

Characteristics of the electromagnetic signal are dependent on the physical properties of the ice. Glacial ice has an inhomogeneous structure caused by variations in the ice, air bubbles, and the presence of water. The variation of electrical parameters between different layers and the boundary conditions of those layers are important factors in effective radar sounding (Bogorodskiy 1985).

2.1.3 Source or Platform Collection Environment

Collection platforms were primarily satellite and aircraft. The ERS-1 and Geosat satellite radar altimeters measure surface elevation. Airborne radar echo sounders measure ice thickness. See the Data Collection System section in this document for details about the University of Kansas IPR and TUD radar echo sounder.

2.1.4 Source or Platform Mission Objectives

The primary objective of the missions that collected surface elevation and ice thickness data was to use airborne or satellite-based altimetry in support of scientific research of the mass balance on the Greenland ice sheet.

2.1.5 Source or Platform Program Management

The following sources and programs were used to obtain DEM data:

- The European Space Agency (ESA) manages the European Remote Sensing Satellite (ERS-1) (PDF file).
- The U.S. Navy launched and managed the Geosat satellite.
- Kort & Matrikelstyrelsen (KMS) and Geologiske Undersogelser (GEUS) provided digital height data from photogrammetric analysis of aerial photos.
- The U.S. National Imaging and Mapping Agency (NIMA) provided additional DEM data of Greenland.

Ice thickness data were obtained from two different sources:

- The University of Kansas, Remote Sensing Laboratory managed the 1990s IPR system.
- The Technical University of Denmark managed the 1970s airborne echo sounding data.

2.1.6 Coverage Information

Following the ERS-1 altimetry mission, DEM data were available for nearly 80% of Greenland. Ice thickness data coverage varied according to aircraft flight lines. The 1970s and 1990s flight lines are shown in Figure 4. The along-track sampling from the 1970s was much coarser (1 km) than the 1990s data (150 m average sampling). The across-track spacing is highly variable but averages 20 km. Tracks were dense near the airfields used for field surveys (especially Thule and Søndre Strømfjord), while areas near the southern tip of the ice sheet have gaps up to 120 km between tracks. Ice thickness measurements could not be obtained over the deep, narrow channel beneath the Jakobshavn glacier and near the margins of the ice sheet. Researchers collected much of the radar data over the Jakobshavn area during 1997, where post-processing could not be performed to improve the signal-to-noise ratio (Gogineni 2000).

2.1.7 Data Collection System

See ERS-1 (PDF file) and Geosat platform documents for characteristics of the two satellite radar altimeters, which collected surface elevation data.

The University of Kansas IPR system for collecting ice thickness data transmitted a 150 MHz chirped, 1.6 µs pulse with a peak power of 200 W. The radars used Surface Acoustic Wave (SAW) dispersive delay lines to generate the chirp signal and to compress the received signal. Antennae consisted of two four-element dipole arrays mounted under each wing of the aircraft - one for transmission and the other for reception. The radar transmitter and receiver were mounted in a rack inside the aircraft and connected to their respective antennae with cables and a feed network. The effective transmit power at the antennae was about 100 W. A low noise receiver amplified and detected the received signal, at a compressed pulse width of about 60 ns. The digital signal processor digitized the in-phase and quadrature output signals from the detector and integrated them.

Researchers collected ice thickness data from 1998 and 1999 with an improved radar system which consisted of a Digital Signal Processor (DSP), 12-bit analog/digital (A/D) converters, and high-speed Field-Programmable Gate Arrays (FPGAs). One of the data acquisition cards digitized the data and integrated the data signal, while another card generated the Pulse Repetition Frequency (PRF), the clock signal for the A/D converters, and the delayed PRF signal to start digitization. This system could operate with a maximum PRF of 18.4 kHz, in which case the number of range bins had to be decreased to 800. This corresponded to a maximum ice thickness of 3 km for radar operating at an altitude of 500 m over the ice surface. The normal operating mode was a PRF of 9.2 kHz with the integrator set to sum 256 values coherently. With the aircraft flying at an altitude of about 450 m and the airspeed at 130 m/s, the distance traveled was 3.6 m per 256 samples. The radar also employed a kinematic Global Positioning System (GPS) (Gogineni 2000).

2.2 Acquisition

Satellites transmitted radar signals to the ground in the form of radar echograms. Ice thickness was estimated by tracking the peaks of surface and ice-bedrock signals and computing the number of range cells between the peaks. The result was then multiplied by 4.494, which was obtained by dividing free-space range-cell dimension by the refractive index of ice, to estimate ice thickness. Data were further processed by coherently integrating two to four samples and incoherently integrating 10 to 20 samples to reduce fading. Because of increased absorption loss for warm ice over areas in the south and central parts of the ice sheet, additional processing using the f-k migration algorithm was conducted to extract ice thickness. This algorithm was essentially a correlation processor that reversely migrated the received signals back to their sources within the ice. Processing consisted of a variable that described the migration of the received signal back to the air-ice interface, and a second variable that described the propagation through the ice layer (Gogineni 2000).

2.3 Processing

2.3.1 Surface Elevation (DEM)

The steps described below were followed to improve the accuracy of surface elevation estimates of variable topographic surfaces with minimal biases (Bamber 1994b):

1. Implementation of a range-estimate refinement (waveform tracking) using the offset center of gravity method for calculating the waveform amplitude, with a power threshold of 25 percent.
2. Application of a slope correction using a variation of the relocation method (Bamber 1994b).
3. Implementation of various data filtering techniques, including tests applied to the return-echo waveform shape, backscatter coefficient, and retracking correction value for each altimeter height estimate. Approximately 27% of the data were removed during this procedure.
4. Removal of anomalous orbits by comparing one track with another where they cross (cross-over analysis).
5. Calculation of standard deviations for each filtered group. A significant bias exists in sampling of the surface, from clustering of satellite radar altimetry data points on topographic peaks after using a relocation method for slope correction. To determine the relationship between the local surface slop and the bias, Airborne Topographic Mapper (ATM) along-track profiles were filtered with a high-pass filter with a 30 km threshold. Bias and standard deviation between the satellite radar altimetry data and ATM heights decreased from 3.10 m to -0.68 m, and from 7.15 to 6.68 m, respectively (Bamber, Ekholm, and Krabill 2000).
6. Application of a least squares collocation technique combined with a second order Markov model (that defines the covariances between observed and modeled elevation) to generate

the DEM from the various data sources. Data used to estimate each modeled height were selected by defining a north-south and east-west axis through each model point; the three closest data points from each quadrant were used. The model was interpolated to a Cartesian coordinate grid with a spacing of 0.01° latitude and 0.025° longitude, which corresponds to approximately 1 km (Bamber, Ekholm, and Krabill 2000). The DEM was subsequently regridded to a 5 km resolution to obtain bedrock elevation data with the 5 km ice thickness grid.

2.3.2 Ice Thickness and Bedrock Elevation

Ice thickness data from the University of Kanas and TUD radar sounders was averaged in a polar stereographic projection using a linear distance weighting method to produce a 301 x 561 grid of georeferenced thickness values with 5 km spacing between data points. The thickness at each grid point was calculated as the weighted average of the data within the search radius of the cell center and the mean latitude and longitude values. Data from the 1990s were given a weighting factor value of ten higher relative to the 1970s data based on cross-over analysis. This initial averaging of the data reduced the number of points used in the final interpolation, reduced the disparity between along- and across-track spacing, and allowed filtering on the basis of the standard deviations of the mean ice thicknesses. Initial filtering involved the removal of gridded data points with only one contributing depth estimate. Quality control procedures were implemented by using a histogram to filter anomalous data values (see Quality Assessment section). The coordinates of non-glacier points near the edge of the ice sheet were appended to the mean data values. These were derived from a high resolution (2 km) land ice mask (Weng 1995) to provide a boundary condition at the ice margins with zero ice thickness.

The resulting grid of mean ice thickness was interpolated onto a 301 x 561 grid using a kriging procedure which was suitable for the high range of spatial density of data points. The kriging generates an estimate of the variance of fit of the data to the model it generates. Minimum values of uncertainty lie along the 1990s tracks and have an error of about 10 m. Maximum values lie in areas furthest from a track that have high thickness variability, and have an error of about 100 m. The ice thickness grid was subtracted from the DEM to produce a grid of bedrock elevation values.

2.4 Quality, Errors, and Limitations

Errors in satellite radar altimetry data come from several sources including geographically correlated orbit errors, errors in slope correction procedures, and non-uniform spatial sampling (Bamber, Ekholm, and Krabill 2000). Uncertainties in airborne radar sounding relate to the magnitude of the refractive indices of solid ice, uncertainty in the profile of refractive index in the firn, signal contamination by thermal noise in the equipment, insufficient clarity of the oscilloscope signal, and imperfect signal definition on the recording medium. Large errors in ice thickness measurements can result if pulses reflected from ice inhomogeneities are mistaken for bottom echoes (Bogorodskiy 1985).

2.4.1 Validation by Source

For DEM validation, reference points derived from aerial photogrammetry along the rock outcrops serve as a measure of comparison for surface elevation values. They have a root-mean-square (rms) accuracy of about 10 m. Elevation values computed from aerial photogrammetry have an rms of 25-30 m. For coastal areas where elevation points were digitized from maps, the error is much larger (200 m to 300 m rms). The most accurate and extensive validation data are the ATM measurements. Satellite radar altimetry data was compared to ATM data by estimating the DEM elevation at each ATM point using bilinear interpolation. Areas around the Thule and Petermann glaciers showed a significant mismatch between the aerial photogrammetry and satellite radar altimetry data. Although these two areas encompass ten percent of the high slope ATM data coverage, they are poorly mapped compared to the rest of the DEM. Consequently, the ATM data for these specific areas were excluded from the comparison. Results indicate that the overall bias between the DEM and ATM data is small, but the standard deviation for all points is only 6.96 m. This is a significant improvement on a previous high-resolution Greenland DEM where the standard deviation was 10 to 11 m. The random error in the DEM is a factor of two less. This is attributed primarily to the slope correction scheme used in this data set, which uses a relocation method rather than the simpler, but less accurate, direct approach (Bamber, Ekholm, and Krabill 2000, Bamber 1994a).

Cross-over analysis was used as the primary method for assessing the accuracy of the ice thickness measurements collected by airborne radar echo-sounders. The average cross-over difference is 130 m for the 1970s data, which is primarily due to navigation data errors. The average cross-over difference is 15 m for the 1990s data. Some 1990s tracks were removed due to problems with matching radar data to navigation data. Standard deviations in the data are a combination of the random error in the ice thickness measurements and local variability in bed topography. Rougher areas have a higher standard deviation even though the accuracy of each data point is the same. The average standard deviation of ice thickness is 50 m, with the highest values concentrated around the eastern ice sheet margin where the topography is highly variable. Along-track standard deviations for unaveraged ice thickness data shows a strong correlation with actual ice thickness, with thin ice showing a much greater standard deviation.

A histogram of the standard deviations was constructed for different thickness ranges. Data points with anomalously high standard deviations were removed from the data set using a thickness-dependent threshold where the distribution was one percent of its maximum value. 2% of the gridded data were removed through this method (Bamber, Layberry, and Gogenini 2000).

2.4.2 Confidence Level or Accuracy Judgment

Horizontal resolution varies according to slope and surface characteristics. The DEM originally had a horizontal spatial resolution of 1 km, with accuracy ranging from 20 m to 200 m over bare rock areas, depending on the source data. DEM accuracy varies from -1.04 m (± 1.98 m) to -0.06 m (± 14.33 m) for slopes of 0-1°. Mean accuracy over the whole ice sheet was -0.33 m (± 6.97 m) (Bamber, Ekholm, and Krabill 2000). Horizontal resolution of the ice thickness grid is between 5 km and 50 km, and vertical accuracy is between 10 m and 100 m, depending on flight line coverage. Bogorodskiy reports that a typical radar-sounding survey has an inherent uncertainty of about 15 m for ice depth measurements (1985).

2.4.3 Measurement Error for Parameters

Errors in the estimate of derived ice thickness measurements were calculated by comparing the radar-based measurements with those from the Greenland Ice Sheet Project (GISP) and Greenland Ice Core Project (GRIP) ice cores. Results showed that radar-based measurements were within ± 10 m of ice core measurements. No corrections were done for firn effect.

Since elevation and ice thickness data from the 1970s were much less accurate than the 1990s data, errors in the merged grid were most significant where 1970s and 1990s tracks were in close proximity. Since errors in the 1970s data did not cause anomalously high ice thickness gradients at a distance of three grid points (15 km) away from the 1990s data, gridded data points closer than three gridded cells to the 1990s data were removed (Bamber, Layberry, and Gogenini 2000).

2.4.4 Limitations of the Data

Accuracy of surface elevation and ice thickness data is questionable in the ice sheet margin and coastal areas, due to the highly variable topography. Also, the improved resolution of the DEM does not significantly affect ablation estimates (Bamber, Ekholm, and Krabill 2000).

2.4.5 Known Problems with the Data

In June 2001, NSIDC discovered errors in the data values for 'surface_5km' (DEM). Because the ice thickness grid is subtracted from the DEM to produce the bedrock elevation grid, the incorrect DEM data resulted in inconsistent values for 'thick_5km' (ice thickness grid) and 'bed_5km' (bedrock elevation grid). NSIDC obtained corrected copies of all three grid files to ensure consistency and accuracy among all grids.

2.5 Instrumentation

2.5.1 Description

- ERS-1 and Geosat radar altimeters
- University of Kansas 150 MHz ice penetrating radar (IPR)
- Technical University of Denmark (TUD) 60 MHz radar echo soundergoes here

3 REFERENCES

Bamber, J.L., S. Ekholm, W.B. Krabill. 2001. A New, high-resolution digital elevation model of Greenland fully validated with airborne laser altimeter data. *Journal of Geophysical Research* 106(B4) (April): 6733-6745.

Bamber, J.L., R.L. Layberry, S.P. Gogenini. 2001. A new ice thickness and bedrock data set for the Greenland ice sheet 1: measurement, data reduction, and errors. *Journal of Geophysical Research* 106(D24):33,773-33,780, doi:10.1029/2001JD900054.

Bamber, J.L., Ekholm, S., and Krabill, W. B. 1998. The accuracy of satellite radar altimeter data over the Greenland ice sheet determined from airborne laser data, *Geophysical Research Letters*. 25(16): 3177-3180.

Bamber, J.L. and R.A. Bindschadler. 1997. An improved elevation data set for climate and ice-sheet modeling: validation with satellite imagery. *Annals of Glaciology* 25:438-444.

Bamber, J.L. and P. Huybrechts. 1996. Geometric boundary conditions for modeling the velocity field of the Antarctic ice sheet. *Annals of Glaciology* 23:364-373.

Bamber, J. and C. Bentley. 1994. A comparison of satellite-altimetry and ice-thickness measurements of the Ross Ice Shelf, Antarctica. *Annals of Glaciology* 20:357-364.

Bamber, J. 1994a. A digital elevation model of the Antarctic ice sheet derived from ERS-1 altimeter data and comparison with terrestrial measurements. *Annals of Glaciology* 20:48-54.

Bamber, J. 1994b. Ice sheet altimeter processing scheme. *International Journal of Remote Sensing* 15:925-938.

Bogorodskiy, V.V., C.R. Bentley, P.E. Gudmandsen. 1985. *Radioglaciology*. Dordrecht: D. Reidel Publishing Company.

Brenner, A.C., R.A. Bindschadler, R.H. Thomas, H.J. Zwally. 1983. Slope-induced errors in radar altimetry over continental ice sheets. *Journal of Geophysical Research* 88:1617-1623.

Davis C.H., H.J. Zwally. 1993. Geographic and seasonal variations in the surface properties of the ice sheets by satellite radar altimetry. *Journal of Glaciology* 39:687-697.

Gogineni, S., D. Tammana, D. Braaten, C. Leuschen, T. Atkins, J. Legarsky, P. Kanagaratnam, J. Stiles, C. Allen, and K. Jezek. 2001. Coherent radar ice thickness measurements over the Greenland Ice Sheet. *Journal of Geophysical Research-Atmospheres* 106(D24) (December): 33761-33772.

Hodge, S.M., D.L. Wright, J.A. Bradley, R. W. Jacobel, N. Skou, and B. Vaughn. 1990. Determination of the surface and bed topography in central Greenland. *Journal of Glaciology* 36(122):17-30.

Layberry, R. L., and J. L. Bamber. 2001. A New Ice Thickness and Bed Data Set for the Greenland Ice Sheet: 2. Relationship between Dynamics and Basal Topography, *Journal of Geophysical Research*, 106(D24), 33,781 - 33,788, doi:10.1029/2001JD900053.

Weng, W.L. 1995. Untitled. Arctic 48(2):206.

Zwally, H.J., R.A. Bindschadler, A.C. Brenner, T.V. Martin, R.H. Thomas. 1983. Surface elevation contours of Greenland and Antarctic ice sheets. *Journal of Geophysical Research* 88(C3):1589-1596.

4 DOCUMENT INFORMATION

4.1 Publication Date

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4.2 Date Last Updated

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