Digital elevation models of the Hans Tausen ice cap

By Wolfgang Starzer and Niels Reeh

Abstract

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In the field seasons from 1993 to 1995 several data set describing glacier surface and thickness have been collected at the Hans Tausen Ice Cap in Peary Land, North Greenland. This is the description of how this geophysical data have been used in order to produce digital elevation models for both the surface and the bedrock topography of the area. The two models are consequently used to construct a digital ice thickness model of the Hans Tausen Ice Cap. Based on this model, calculated estimates for both the surface area and the total glacier volume are computed.

Keywords: Digital elevation model; bedrock topography; ice thickness; ice-dynamic modelling and interpolation.

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Introduction

This paper describes the construction of digital elevation models, DEMs, of the Hans Tausen ice cap and surrounding areas. Three DEMs are built for (1) surface elevation, (2) subglacial/bedrock topography and (3) ice thickness. These DEMs will be used as input for ice-dynamic modelling. In the following sections the different data sources used for the compilation of the DEMs are described, geographical and technical decisions are explained and the compilation of each of the three maps is discussed in detail (the words DEM, map and grid refer to the same concept).

Data sources

The different data sources used in the compilation of the maps of surface and subglacial topography include:

1. Surface topography data from photogrammetric mapping based on aerial photographs from 1978. These data are produced at the photogrammetric laboratory of the Geological Survey of Denmark and Greenland, and represent the largest and most important single data source (Fig. 1).
2. Surface elevation and ice-thickness data obtained by airborne radar survey in 1993 over the central higher part of the ice cap (Hammer, 1995).

3. Surface elevation and ice-thickness data obtained by two ground radar surveys, one on the central dome around the drill site (Jonsson, 1994) and one covering a glacier basin in the north-eastern part of the ice cap (Jonsson, 1995).
4. Finally, where no other information was available, surface elevation data from a digital elevation model covering entire Greenland were used. This elevation model was produced by the National Survey and Cadastre of Denmark (Ekholm, 1996).

Method

The DEM for the ice thickness is constructed by subtracting the grid for the subglacial topography from the grid for surface elevation. The DEMs for subglacial topography and surface elevation were constructed from the four original data sets above by using a gridding method. Gridding is the process of using original data points/observations in an XYZ data file to generate interpolated data points on a regularly spaced grid. If extra observation points exist, then their number is reduced to create a firm input file for the interpolation. This file has an even distribution of data points over the total area, and an observation density that is roughly similar to the point density of the resulting grid. The resulting grid was used to generate a contour map.

Different interpolation routines have been tested and Kriging has proven to be the most useful geostatical gridding method for the construction of the DEMs. Kriging produces visually appealing contour and surface plots from irregularly spaced data. The method is developed to express trends that are suggested in the source data. For example, high points might be connected along a ridge, rather than in isolated bulls-eye type contours. Nevertheless, in locations where the interpolation result were not satisfactory, the data source had to be improved by additional data points. It is explained later how these extra points, for both the surface and the subglacial maps, are found.

The three maps of the Hans Tausen ice cap are based on a grid of UTM coordinates. The area is located in UTM zone 23 and stretches from the coordinates 535000 to 640000 from west to east and the coordinates 9120000 to 9230000 from south to north. Thus, the total size of the grid is 105 by 110 kilometres. An optimal grid resolution of 500*500 metres was found, taking into account the distribution of the original data and the characteristics of the interpolation method. Accordingly, the DEMs are defined by a grid of 46,631 data points, laid out by 211 columns by 221 rows.

Surface elevation map

The main data source for the compilation of the surface elevation map is data from photogrammetric mapping. These data are divided into five groups: two specify elevation contours in 100 meter steps on glacier and land, and three specify glacier, river and coastline delineations. Within the frame of the DEM, the photogrammetric data set contains 191,524 points, that are laid out tightly along lines. To break up this line structure and to achieve a more equal data distribution over the total area, the point data, that are used from each of the five groups, was reduced. A most effective factor for this reduction was determined by experimental testing. This testing shows that a useful intersection of elevation points for the interpolation can be constructed by reducing river and coastline data by the factor 1 to 30, contour lines on land by 1 to 24, contour lines on ice by 1 to 6 and the delineation by 1 to 5. Thus the total data set was reduced to 22,389 data points. These selected data points, together with the original photogrammetric delineation lines, are shown in Fig. 1.

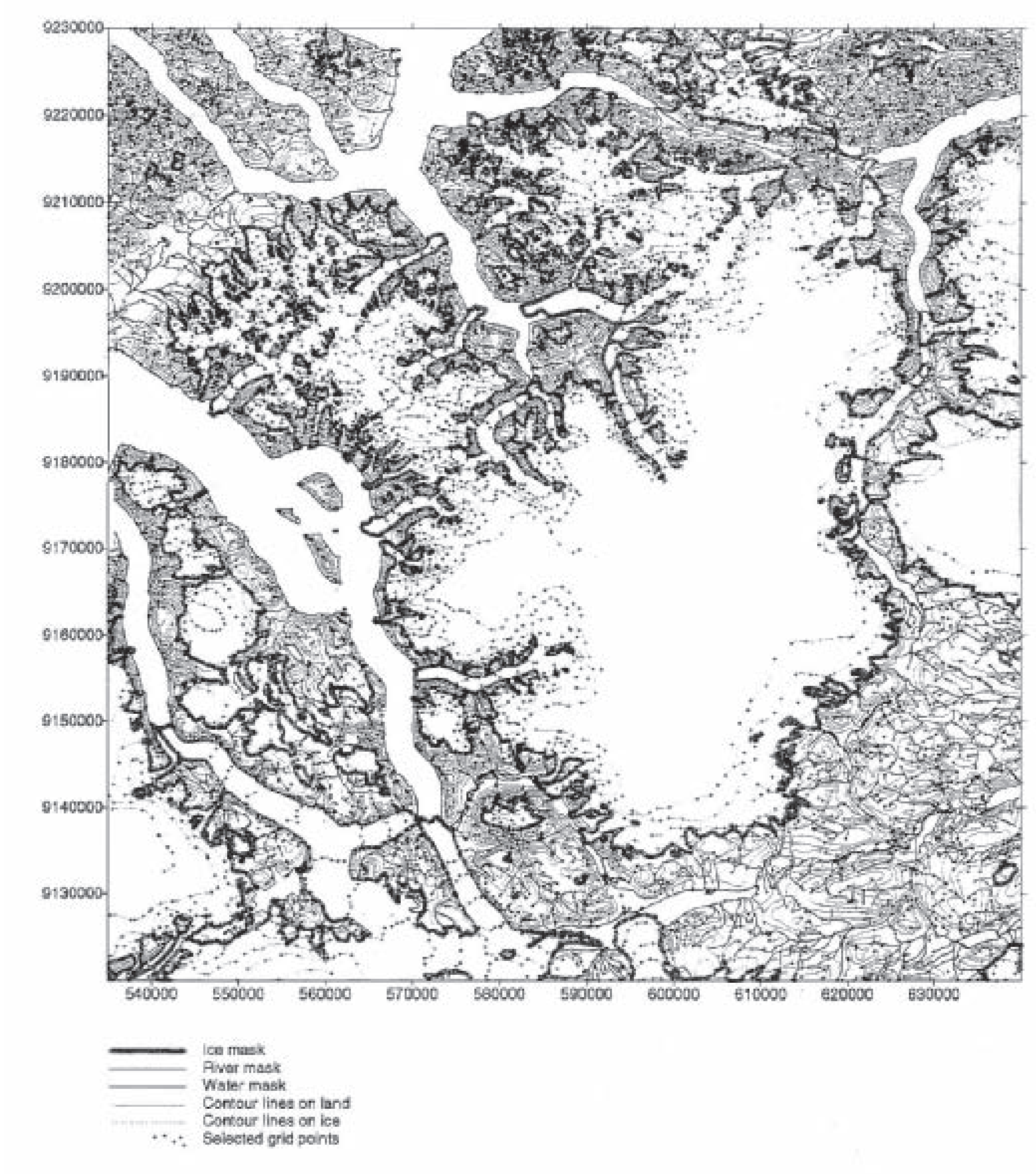

Fig. 1. Topographic data from photogrammetric mapping.

Surface data for the central higher part of the ice cap were measured by airborne radar-echo sounding in 1993. This data set contains a total of 5631 measurements along two separate flying routes, of which every one in five has been selected as input for the interpolation. The chosen set of points is called s2 and is shown in Fig. 2.

Around the central dome ground data describing surface and bedrock elevation were collected in 1994, using a geographical positioning system (GPS) and radar surveys. These data have a better accuracy and a higher density than the flight measurement data from the previous year. Therefore, 538 surface elevation points (1 out of 15) from this data set have been selected as input for the interpolation. Fig. 2 displays the points by the name s3. Simultaneously, 42 data points of the airborne radar measurements of the previous year in the same area have been removed. Thus, a total of 1622 surface points defining the central higher part of the ice sheet were selected as input for the DEM.

The north-eastern part of the Hans Tausen ice sheet was explored by field work in 1994. GPS and radar-echo

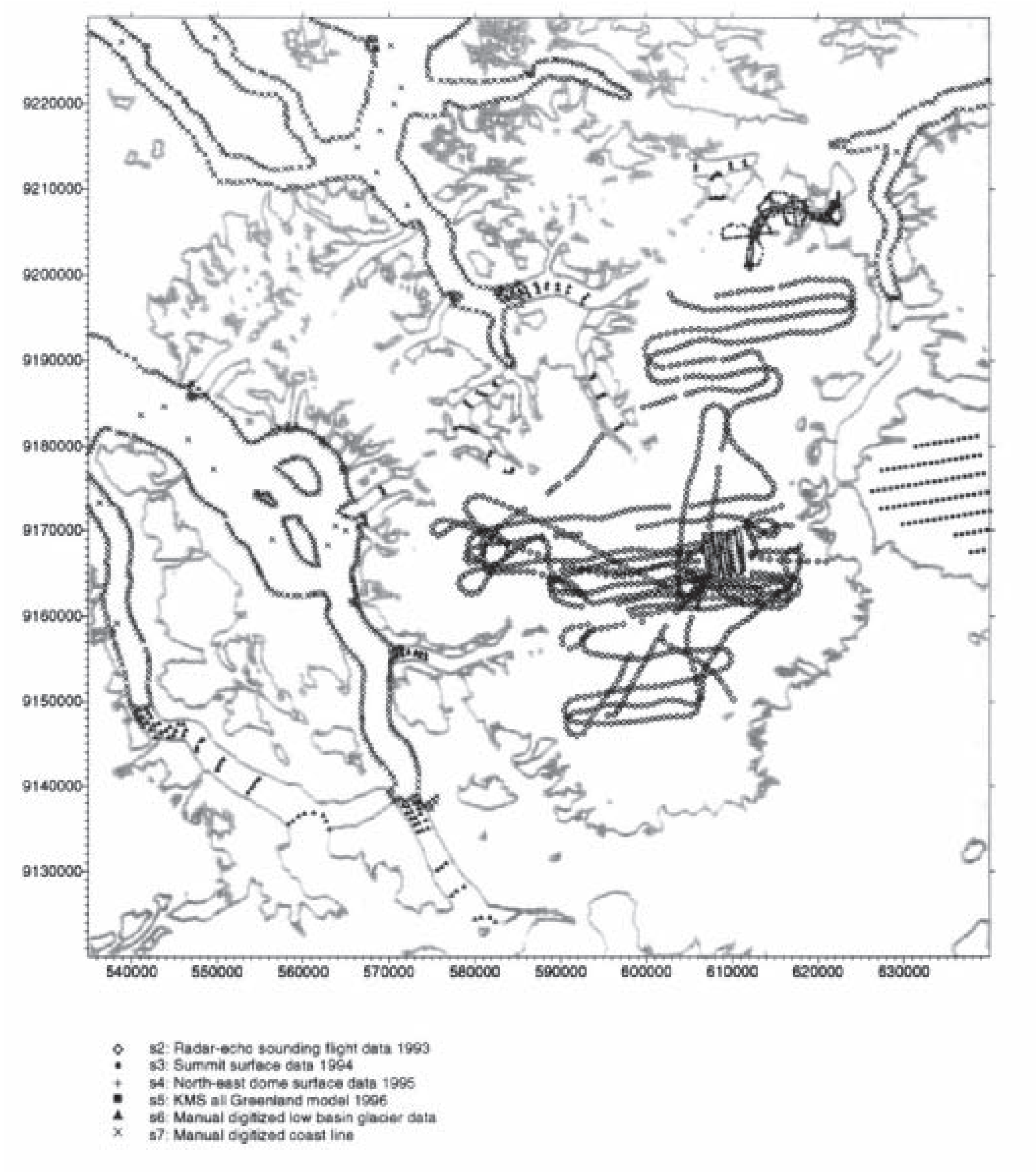

Fig. 2. All data sets used for the compilation of the surface map except photogrammetric data.

sounding measurements were performed in an outlet glacier basin stretching from a local dome at 1300 meter elevation to the glacier terminus near Harebugt at about 300 meter elevation. Along 4 snowscooter trolls a total of 11310 data points were measured with kinematic GPS and every tenth of these was selected as input for the model. The points are called data set s4 and are shown in Fig. 2.

The above data sets define most locations on the surface map, except for the fjords and the Bure ice cap to the east of the Hans Tausen glacier. Surface data for the Bure ice cap were extracted from the topographic Greenland model developed at the Danish National Survey and Cadastre (Ekholm, 1996). This model contains elevation estimations for entire Greenland, in a grid of geographical coordinates with a spacing of 0.02 degree latitude and 0.05 degree longitude. In the Hans Tausen region this results in a grid of about 0.6 by 2 km, and 89 of these points were assigned for input to the DEM. These topographic data are shown in Fig. 2 as dataset s5.

Fjord data defining the water depth have not been measured yet and the first interpolation of the intersection of all selected points so far shows very poor results for the bottom topography of the fjords. For several locations in the fjords the interpolated elevations were hundred m a.s.l. and more. To improve this result, a coastline at elevation zero along selected river and water delineation lines was constructed manually from the photogrammetric data set. Existing photogrammetric coastline data could not be used directly, due to the errors and inconsistency of labelling and the extensive coverage of rivers and lakes, features that are not relate to the coastline. For the coastline, one point in every 200 metre was digitised. This sums up to a total of more than 2000 data points. These points were added to the above intersection of selected source data. The high density of these points assures that any data point situated on land only indirectly influences the interpolation of a grid point in the fjord, as the intersection with the coastline points with value zero m a.s.l. directly corrects the fjord elevation values to below zero m a.s.l..

Interpolating this extended intersection of data now largely improves the surface grid and the values for the depth of the fjords become more realistic. Only in a few locations, namely in areas between flat or smoothly rolling coastal landscapes, the values for the fjord bottom topography are still calculated as above sea level. To improve these interpolation results, additional negative elevation points with an estimated value of minus 50 m b.s.l. are assigned to certain locations in the fjords. Fig. 2 shows these negative elevation points together with the manually digitised coastline as data set s7.

The last problem that had to be solved for the interpolation of the surface DEM is the grid points on narrow glacier tongues. Grid points located on relatively narrow glacier tongues, confined by steep valley walls, acquire negative or otherwise subtracted elevation values due to lack of elevation information on their surface. This problem is solved by locally drawing estimated 10 metre contour lines for every interval, particularly on low lying and/or floating glacier tongues. This manually digitised data set describing additional ice elevation contours was added to the data source as well (Fig. 2).

Now all the source data for the interpolation of the surface grid are defined. The input dataset contains 27,520 data points and the resulting grid exists of 46,631 points. The data are distributed evenly except for the lesser density of elevation data on the top of some glaciers and the missing data for fjord depth. A graphical representation of the result of this interpolation is shown in Fig. 3.

Subglacial Map

The subglacial topography is constructed in a similar way as the surface elevation topography and more than fifty percent of the points were reused. New input data were only needed for ice covered areas and along the boundary line between floating glacier tongues and coastal waters. However, both river, water and glacier delineation lines, and contour lines on land contribute to the main set of data point use for the interpolation and each group was reduced by the same factor as before.

The manually digitised fjord coastline was used once more for the interpolation of grid points in the fjords. The data points at the boundary line between calving glacier tongues and coastal waters, the zero m.a.s.l contour, were removed from the input data as well as photogrammetric glacier front data of floating glaciers. This guarantees the unrestrained interpolation of the subglacial grid, also underneath floating glacier tongues. Removing the described

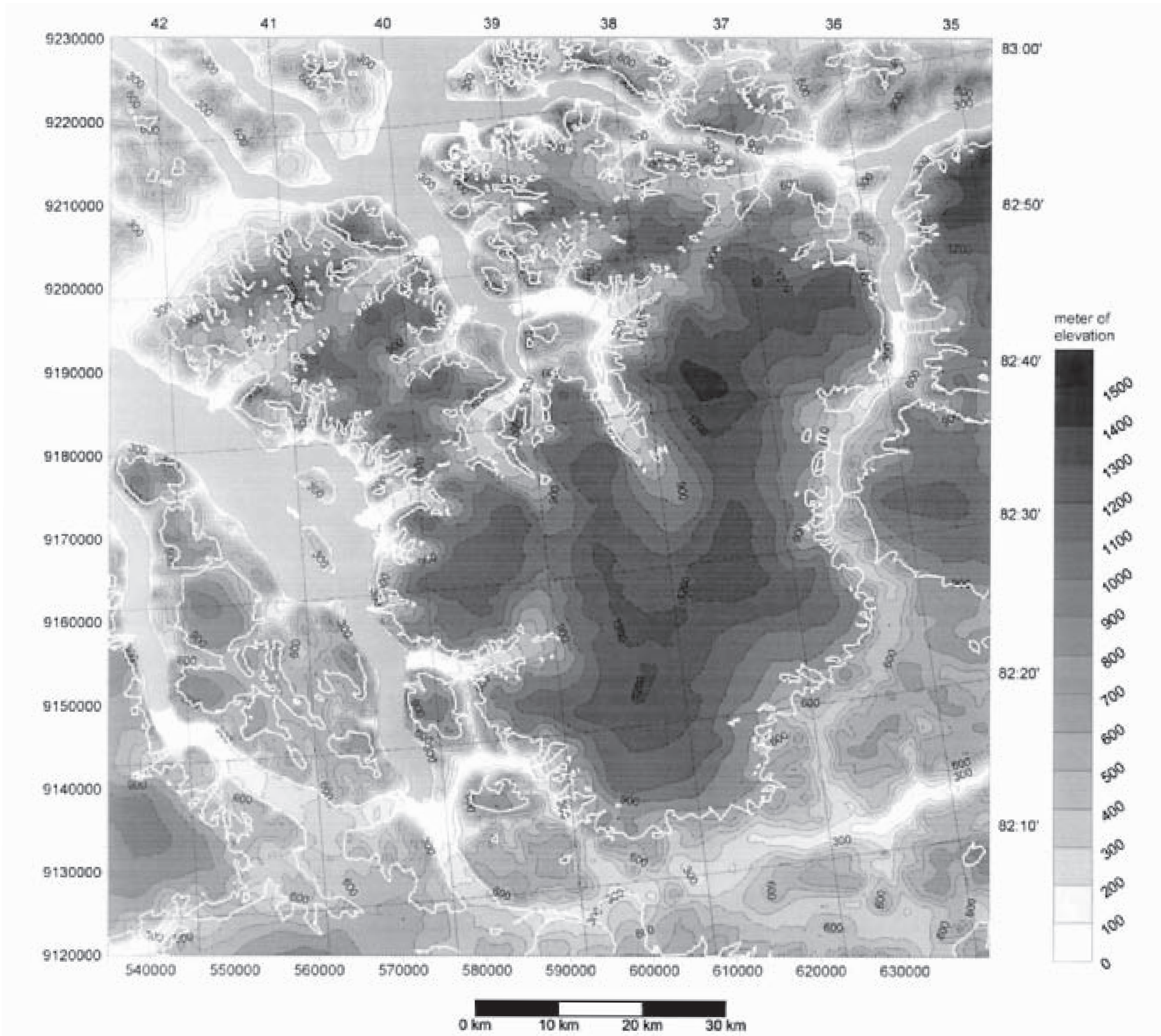

Fig. 3. Contour map of surface elevation.

information from the two data sets leaves respectively 15,354 and 1,920 data points as source for the interpolation of the subglacial DEM. In Fig. 4 both the selected photogrammetric datapoints and the reduced digitised coastline, are shown respectively as data set b1 and b5.

Three data sets containing ground and airborne radar-echo sounding data describe the ice thickness. Each point in this data set was assigned two elevation values: one for surface elevation and one for the underlying bedrock elevation. Since the selected surface points already were used for the construction of the surface map, the same points were used again for the construction of the subglacial DEM. Thus, the points in the data sets b2 (airborne radar echo sounding), b3 (summit data) and b4 (north-east dome data) refer to the same points on the glacier as the points in the sets s2, s3 and s4 as described earlier. The data sets b2, b3 and b4 are shown in Fig. 4.

The five data sets above do only include bedrock information for glaciers that are part of the main Hans Tausen ice

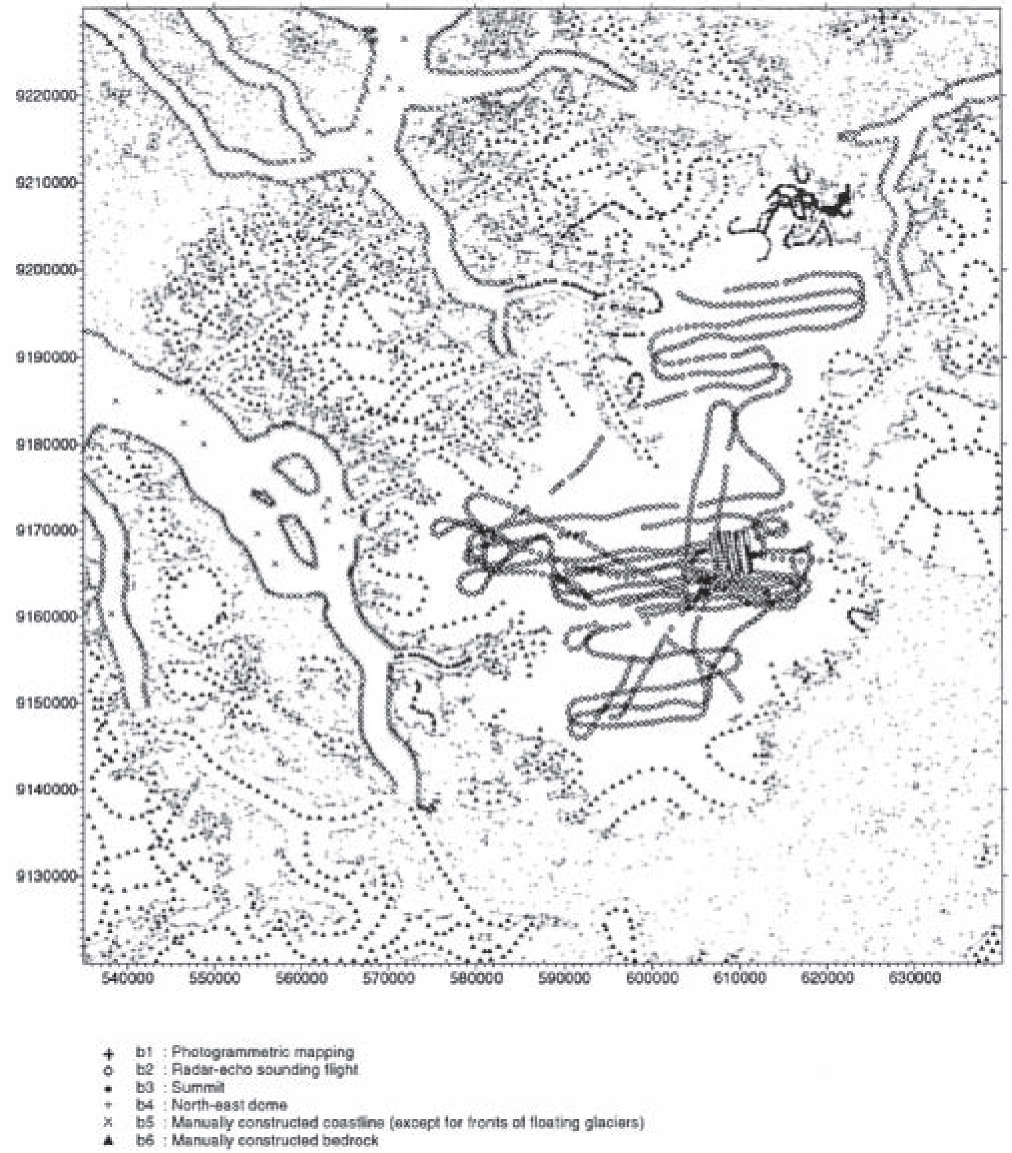

Fig. 4. Data sets used for the compilation of the DEM for bedrock/subglacial topography.

sheet. More than 200 local valley or mountain glaciers, minor ice caps and ice fields in the area need to be specified as well. There is no measured data available for these glaciers and therefore a simple model was constructed to describe the ice thickness. This model is based on the assumption that a relation between ice thickness and surface elevation can be deduced from the radar-echo sounding data of the glacier basin in the north-east, assuming that this glacier basin is typical for all glaciers in the area. In other words: the north-east glacier basin was used to identify the general mid glacier profile for all local glaciers. Accordingly, the quality of this model depended on two data sets: (1) a profile of the 1995 ice thickness data from the outlet glacier basin in the northeast, and (2) photogrammetric data, describing the surface elevation of local glaciers.

The geographical location of this profile and its characteristics are shown in Fig. 5 and Fig. 6. The ice thickness decreases from 300 m a.s.l. at the top to about 150 m a.s.l. at the glacier snout.

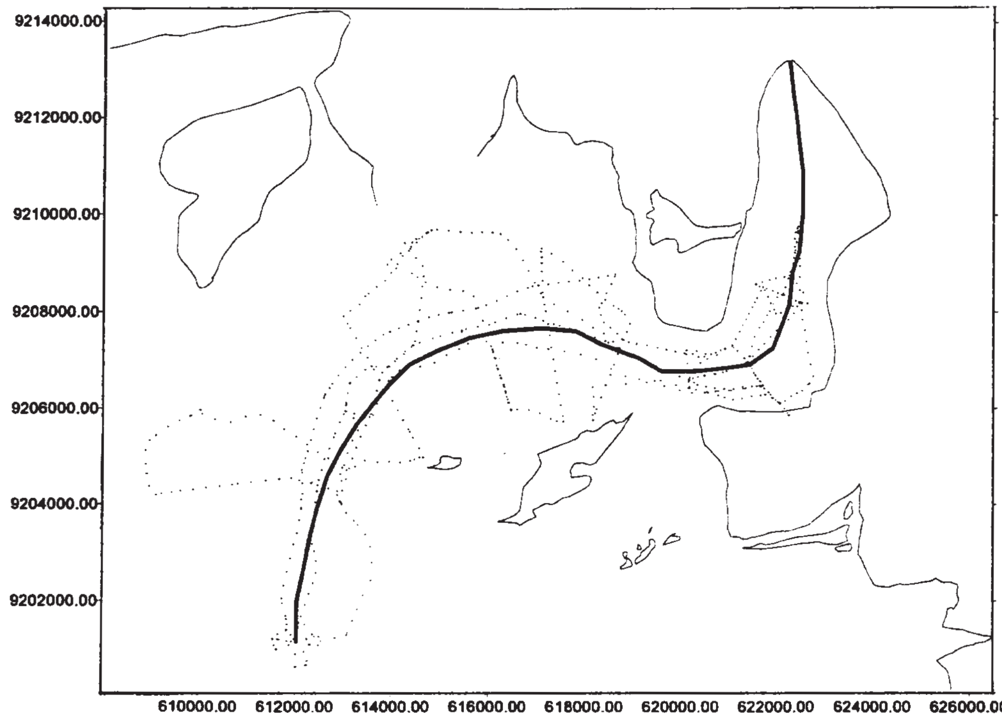

Fig. 5. Central flow-line from the local dome to the glacier terminus of the outlet glacier basin in the north-eastern corner of the Hans Tausen ice cap. The dots represent the measurement points that are used to define surface and subglacial profiles along the flow-line.

The relation between ice thickness and surface elevation can be generalised as:

$$I = 3/20 * E + 105 \qquad (1)$$

where I stands for ice thickness and E for surface elevation in metres. This equation defines the midprofile elevation of an outlet glacier down to about two kilometres upglacier from terminus. It will be used to identify the subglacial topography along flowing lines of similar valley and mountain glaciers in the area and as an estimate for the ice thickness of neighbouring ice fields and local ice caps.

Having specified the relation between ice thickness and surface elevation, the next step was to find the mid glacier

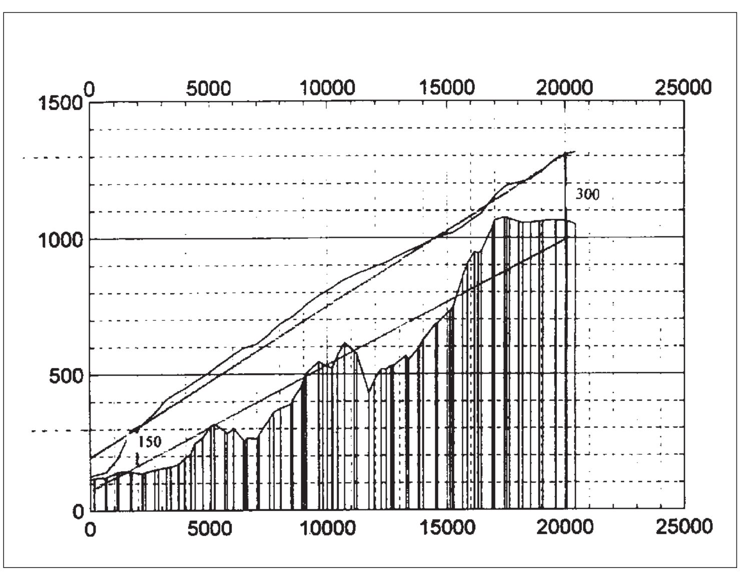

Fig.6. Surface and bottom elevation profiles along the central flow-line from the local dome to the glacier terminus. The two straight lines illustrate an approximate relation between bottom topography and surface elevation. This approximate will be used in the model to determine the ice thickness of neighboring glaciers.

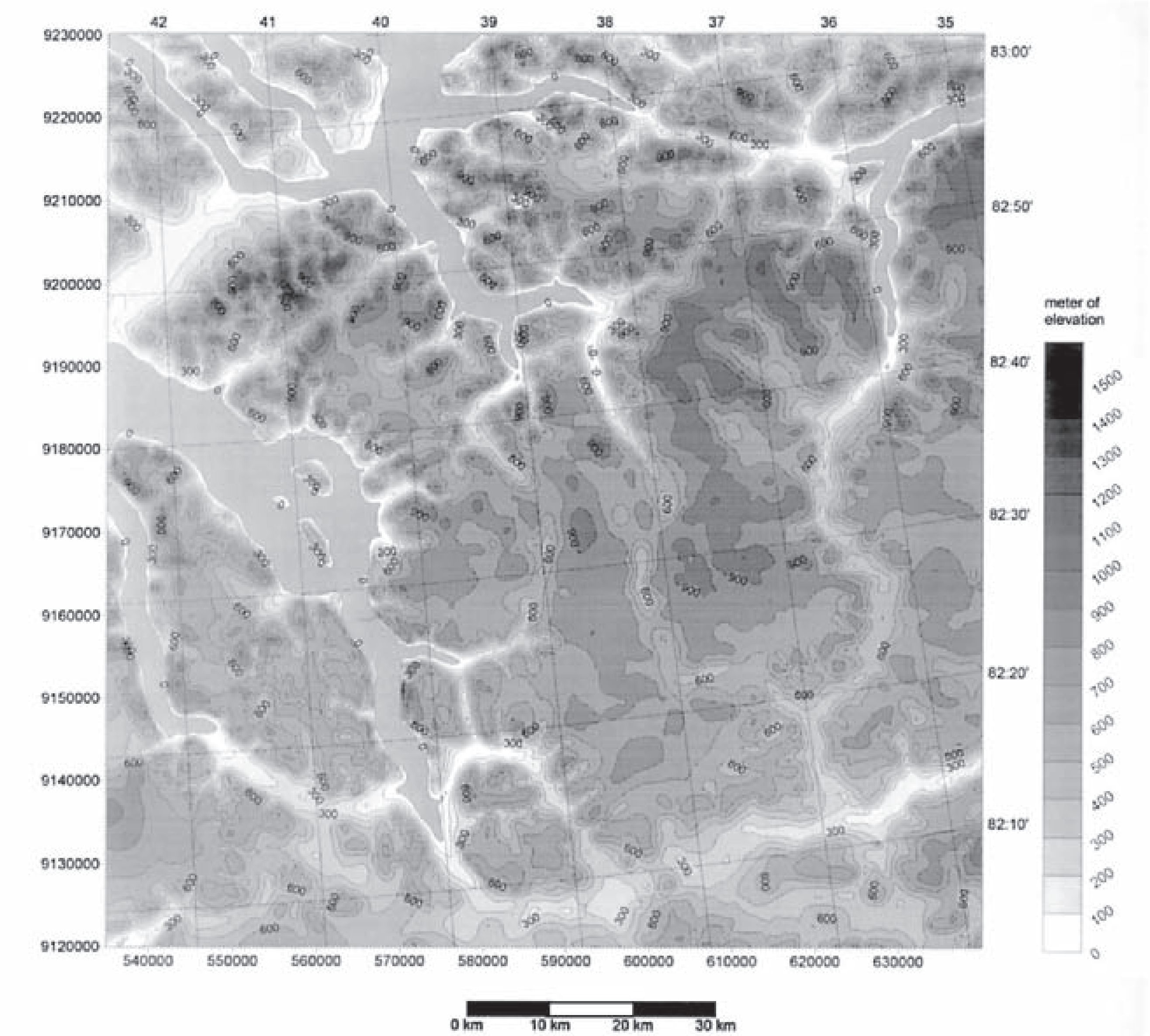

Fig.7. Contour map of subglacial topography.

surface elevation along the flow-line or similar terrain characteristics of neighbouring glaciers. For this purpose, numerous points along 143 profile lines were digitised manually. Then the surface elevations was calculated along these profile lines for every 300 to 500 meter. This was done by cutting slices into the previously constructed DEM for surface elevation and interpolating for each point the elevation values for the selected points. Finally, the subglacial elevation was found applying equation (1) to calculate the ice thickness and then subtracting the ice thickness from the elevation. The result is a data file containing 3,646 bedrock points along 143 profile lines. These points make the data source b6 and are shown in Fig. 4.

By merging of the 6 data sets, the subglacial topography map can be inferred. The intersection of source data for the interpolation now contains 23,723 points. The resulting grid is of the same size as before and exists of 46,631 points. The result of this interpolation is represented as a contour map in Fig. 7.

Glacier Model

The last step in the compilation was the construction of a DEM for ice thickness. This was done by subtracting the subglacial elevation data from the surface elevation data for every grid point in the DEMs. For areas representing floating glaciers is assumed that the whole section between surface and bedrock is glacier ice. This is obviously a generalisation. However, as these areas are relative insignificant in size around the Hans Tausen ice cap, the effects on the model are insignificant. In the resulting grid for ice thickness, all grid values greater than or equal to five metres were accepted for the DEM. Values less that five metres were not used because they are beyond the accuracy of the interpolation routine, and also because these small ice thicknesses are not significant for glaciological modelling. In the grid of the glacier DEM all points with values of less than five metres were assigned a dummy value for ice thickness of -1.

The result of the subtraction procedure showed a final problem, once more con-

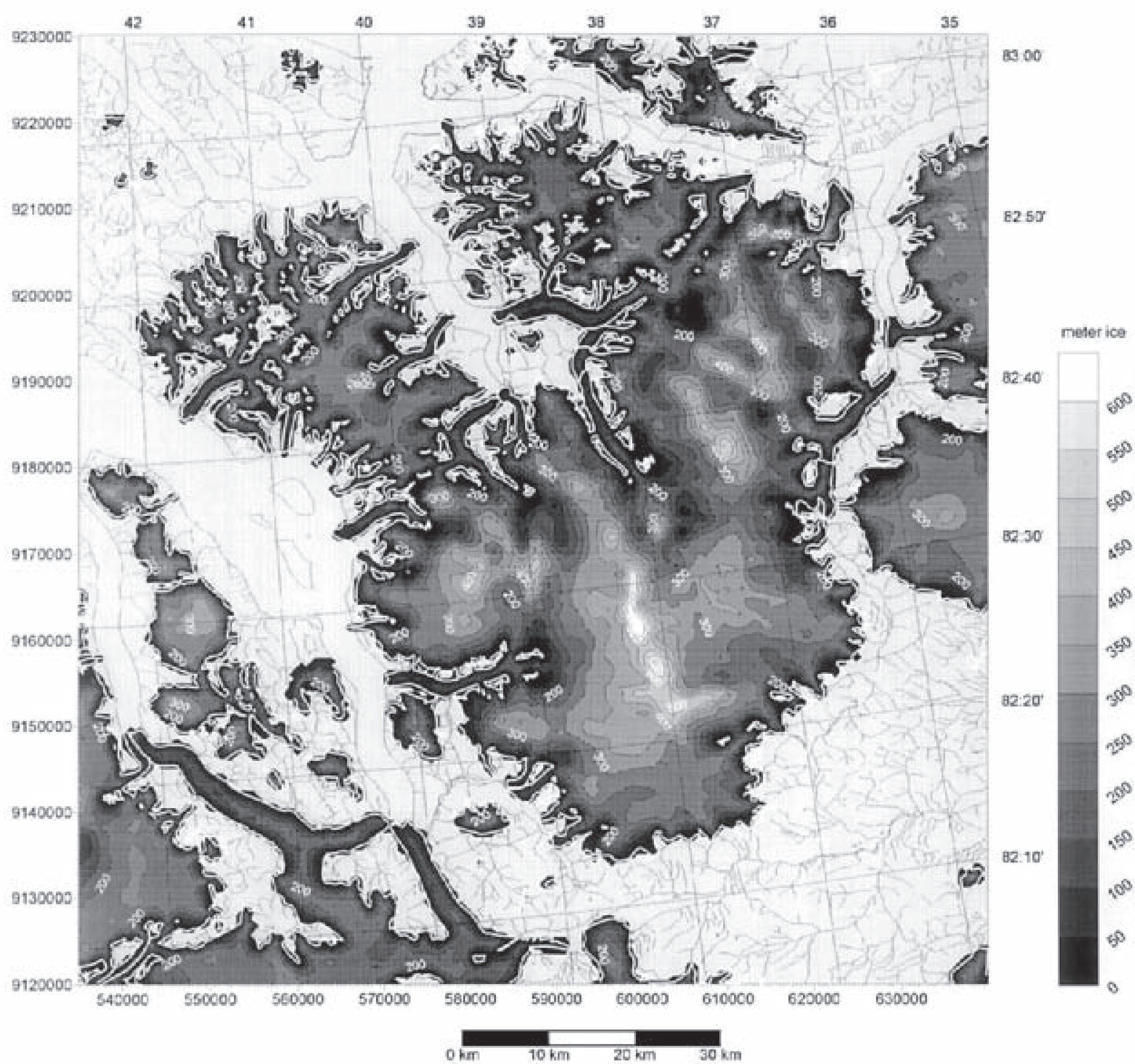

Fig. 8. Ice thickness map.

cerning the calving fronts of floating glaciers. Subtracting the two interpolated maps resulted in an unrealistic situation, because of the elevation step between the surface of the glacier fronts, at zero m a.s.l., and the fjord depth, at up to a hundred m b.s.l.. This elevation step misplaced the calving front of many of these glaciers by several kilometres out into the fjords. The problem was solved by comparing the two DEMs for glacier thickness and surface elevation and removing any glacier ice from open fjords. Technically, every ice thickness grid point that had corresponding surface points at elevations below zero, was set zero.

Finally the grid was edited and checked for its accuracy. The gridding boundaries were compared to the ice delineation lines from the photogrammetric mapping and irregularities along the calving fronts were corrected manually. Fig. 8 shows the result of the construction of the DEM for ice thickness as a contour map.

Volume calculation

The DEM of ice thickness of the HT ice cap can be used to compute the total volume of the ice cap. The volume of ice is calculated using three different methods. The difference in the results of the three methods gives a qualitative measure of the accuracy of the volume calculations and thus an indication of the quality of the selected grid size. The methods used are the Trapezoidal Rule, Simpson's Rule and Simpson's 3/8 Rule. The results of applying the three rules to the ice thickness DEM yields total volume estimates for the HT ice cap of 763.699, 763.358 and 763.465 cubic kilometres respectively. The relative error of the results can be expressed as a percentage of the average volume and can be computed as:

$$RE = 100 * (LR - SR) / AVER \qquad (2)$$

where RE is the relative error, LR is the largest result from the three methods, SR is the smallest result and AVER is the average of the three methods. Applying this formula the relative error is computed to be 0.045 percent. This rather small number shows that the selected grid size of 500 by 500 meters, related to the topographical changes, was reasonable and emphasises the reliability of the volume calculations. Thus, the average volume of the Hans Tausen ice cap is estimated to be 763,507 km3. Given a planar area of the ice cap of 3975 km2, the average ice thickness of the glacier is estimated to be 192 metres.

Conclusion

A DEM of ice thickness of the HT ice cap was constructed by subtracting the bedrock elevation from the ice surface elevation grid. This model was used to compute the total volume of the ice cap. In the future the model can be used as source for all types of glacier modeling in the area.

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