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Unlocking archival maps of the Hornsund fjord area for monitoring glaciers of the Sørkapp Land peninsula, Svalbard

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Abstract. Archival maps are an invaluable source of information on the state of glaciers in polar zones and are very often basic research material for analysing changes in their geometry. However, basing a reliable comparative analysis on them requires they be standardised and precisely matched against modern-day cartographic materials. This can be achieved effectively using techniques and tools from the field of Geographic Information Systems (GIS). The research objective was to accurately register archival topographic maps of the area surrounding the Hornsund fjord (southern Spitsbergen) published by the Polish Academy of Sciences, and to evaluate their potential for use in studying changes in the geometry of glaciers in the western part of the Sørkapp Land peninsula in 1961–90. Comparing the 1961 and 1990 data, glacier surfaces lowered by about 80–85 m for the largest land-terminating glaciers of the peninsula, and by up to more than 90 m for tidewater glaciers (above the line marking their 1984 extents). The dataset is now available from the Zenodo web portal:https://doi.org/10.5281/zenodo.4573130 (Dudek and Pętlicki, 2021)

1 Introduction

Climate warming and the accompanying progressive disappearance of ice is now more dynamic in Svalbard than at any time in history anywhere in the European Arctic – and changes are occurring more dynamically in the European Arctic than anywhere else in the world. Changes in the geometry of glaciers constitute a visible and easily measured parameter that, apart from being a reliable indicator of their condition, is a proxy for changes in the natural environment (Knight, 2006).

The glaciers of Svalbard have received less attention in past research than have those in continental Europe (WGMS, 2020). This is because of their inaccessibility, the harsh climatic conditions and the long polar night, which limit the possibilities for direct measurement. Logistic and economic aspects play a huge role in the selection of research areas, so data collection for documenting glacier changes (including field measurements) focuses mainly on the more accessible western coasts of the Spitsbergen island (Hagen and Liestøl, 1990). The use of traditional research methods is costly and time-consuming, even if

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the research programme is reduced to a minimum, so changes in the geometry of Svalbard glaciers are often inferred from satellite data and aerial photographs (Martín-Moreno et al., 2017).

The use of remote-sensing imaging data has a number of advantages in glacier research, the most important of which are that the data do not require a large team in the field and can be used to quickly generate precise results. These facts have certainly contributed to remote-sensing methods having been used in glaciology since almost the very inception of this scientific field (Finsterwalder, 1954; Stocker-Waldhuber et al., 2019).

In the initial period of polar research based on remote-sensing methods, ground-based photogrammetry techniques were mainly used. In Svalbard, terrestrial photogrammetric methods were first used in 1898 as part of topographic work carried out by a Swedish expedition led by A.G. Nathorst (Nathorst, 1909). Later, these techniques were successfully used on several research expeditions organised, among others, by the prince of Monaco in 1906 and 1907 (Isachsen et al., 1912-14), and on numerous Norwegian expeditions in 1909–26 (Hoel, 1929).

The aim and scientific fruit of the first photogrammetric works on Svalbard were, above all, topographic maps of poorly known areas, which were also valuable material for the study of glacier extents. Polish achievements in this field include a series of photogrammetric images and triangulation measurements made in 1934 as part of the first Polish research expedition to the as-yet-unexplored Torell Land (southern Spitsbergen), which yielded the first accurate map of this area at a scale of 1:50,000 (Zagrajski and Zawadzki, 1936).

The construction of the Polish Polar Station on Isbjørnhamna Bay in 1957 allowed scientific teams to operate in southern Spitsbergen. In the station's first years, a Polish research team led by C. Lipert conducted terrestrial photogrammetric measurements, resulting in the production of detailed maps of glaciers in the vicinity of the Hornsund fjord (Kosiba, 1960; Lipert, 1962). Additionally, topographic sketches of the Antoniabreen and Penckbreen glaciers were made during an expedition to the vicinity of the Van Keulen fjord (Marcinkiewicz, 1961) in the same period.

Changes in the extents of glaciers around the station were also documented in the early 1970s, when summer expeditions of the University of Wrocław (Żyszkowski, 1982) were held there, and, after activity resumed in 1978, on numerous expeditions made mainly by the University of Silesia and the Institute of Geophysics of the Polish Academy of Sciences (*Instytut Geofizyki, Polska Akademia Nauk*, hereinafter referred to as IGF PAN) (Kolondra, 2000). Terrestrial photogrammetric methods are still used today in glaciological studies of this area, and the longest series of measurements has covered the Werenskioldbreen, Torellbreen and Hansbreen glaciers (Kolondra, 2002).

Compared to other areas of Svalbard, the photogrammetric research on the Sørkapp Land peninsula and the number of related cartographic works published are very modest. The area most often chosen for cartographic studies has been the north of the peninsula (which is relatively accessible from the Hornsund fjord), including primarily the vicinity of the Gåsbreen glacier (De Geer, 1923; Pillewizer, 1939; Jania, 1979, 1982; Kolondra, 1979, 1980; Schöner and Schöner, 1996, 1997; Ziaja et al., 2016) and glaciers flowing into the fjord (Heintz, 1953; Błaszczyk et al., 2013).

Terrestrial photogrammetric methods provide reliable and precise results, but for spatially extensive studies, data obtained from the aerial ceiling are much more competitive. Therefore, aerial photogrammetry progressed alongside ground measurement techniques on Svalbard.

Table 1. Photogrammetric overflights of the Sørkapp Land.

Year	Area of Sørkapp Land covered
1936	Entire Peninsula
1948	Western and southern coasts
1960	Western part of the peninsula
1961	Almost entire peninsula except its non-glaciated western part
1970	Isthmus and eastern coast
1971	Eastern coast
1990	Almost entire peninsula except one strip in the north-east
2010	Entire peninsula

Professional photogrammetric overflights by the Norwegian Polar Institute covered all or almost all of the Sørkapp Land peninsula (Table 1). The first, in 1936, resulted in a series of oblique photos that were used to create a 1:100,000 topographic map covering the entire Svalbard archipelago (Luncke, 1936). Another map by the Norwegian Polar Institute was published only in the first decade of the 21st century, and was based on 1:50,000 vertical photos from 1990, this time as colour prints (NPI, 1996).

For the study of glacier evolution and glacial landforms on the Sørkapp Land peninsula, the series of photos taken in 1961 is of great importance because, for the first time in the history of this area, it uniformly covered all its glaciers along with their marginal zones. No other set of data of the same spatial extent was created until 49 years later.

Norwegian photos from two photogrammetric campaigns in 1960 and 1961 have served as the source material for many cartographic and glaciological works (e.g. Klysz and Lindner, 1982; Ostaficzuk et al., 1982; Jania, 1987, 1988; Schöner and Schöner, 1996; James et al., 2012; Błaszczyk et al., 2013; Małecki, 2013). Of the available cartographic studies valid for 1960/61, the 1:25,000 topographic map of the Hornsund fjord area has the greatest spatial coverage. The series of sheets published in 1987 was in part the result of the Institute of Geophysics of the Polish Academy of Sciences (IGF PAN) programme of expeditions to Spitsbergen in the years 1979–84 with the support of officers of Poland's military cartographic institute (*Wojskowe Zakłady Kartograficzne*) in conducting desk research and field work. Field survey reference photogrammetric measurements were made during the 6th expedition of the Polish Academy of Sciences in 1984. The present study attempts to assess its accuracy and its potential for use in research on changes in the geometry of glaciers in the west of the Sørkapp Land peninsula.

2 Study Area

Sørkapp Land is the southern peninsula of Spitsbergen, the largest island of the Svalbard archipelago (Fig. 1a and b).It is separated from the rest of the island by a narrow glaciated isthmus.

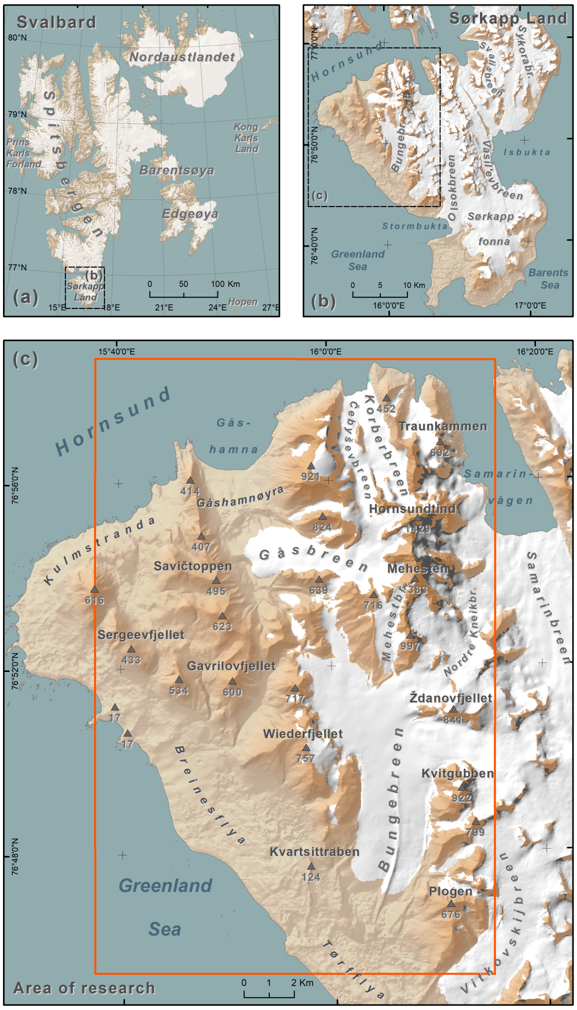

Figure 1. Study area location on the background of: (a) the Svalbard archipelago, (b) the Sørkapp Land peninsula, and (c) its western part.

The western Sørkapp Land region extends between the open Greenland Sea and Hornsund Fjord (Fig. 1c). It contains as many as 14 land-terminating glaciers, as well as several rock glaciers and numerous glacierets and perennial snow patches crowded between the Körberbreen and Petersbreen tidewater glaciers to the north and Bungebreen to the south. The largest land-based glaciers in the analysed area are: Gåsbreen, which is surrounded by the highest mountain massifs of southern Spitsbergen and fed by the Bastionbreen and Garwoodbren tributary glaciers, both of which rest on the slopes of the Hornsundtind massif; and Bungebreen, which extends meridionally between the high Hestskøfflya massif to the north and the Tørfflya coastal lowland to the south. The two largest glacial systems in western Sørkapp Land are surrounded by smaller valley and cirque glaciers.

Of the 16 glaciers flowing into the Hornsund Fjord, four are located in the study area. These include the Körberbreen glaciers with the Čebyševbreen tributary, as well as the Petersbreen, Kvasseggbreen and Eggbreen glaciers, which are to the west of the Samarinbreen Glacier, where they fill deep valleys. These glaciers have a northern exposure and their snouts move northwards.

They are distinguished from other outflow glaciers by their significant vertical range and associated steeper surface, which is due to the fact that their basin boundaries run along the highest mountain ranges of southern Spitsbergen: Čebyševfjellet (914 m a.s.l.), Wesletinden (928 m a.s.l.), Hornsundtind (1,429 m a.s.l.) and Kvasegga (1,004 m a.s.l.) (Jania, 1987). Körberbreen and Petersbreen lie in separate longitudinal mountain valleys whose depth and direction are determined by the geological structure of the substrate, which relates to the course of faults. The two small glaciers Kvasseggbreen and Eggbreen, which run adjacent to them to the east, run latitudinally and flow into Samarinvågen Bay. They formerly served as the tributary glaciers to Samarinbreen, but as its snout has receded they have split from it and today constitute separate calving glaciers.

3 Source Material

3.1 1961 Data

The topographic map, made in a Universal Transverse Mercator (UTM) projection (northern hemisphere, zone 33) based on a European Datum 1950 (ED50) ellipsoid, consisted of ten sheets. This study assessed three of those sheets that represented glaciers with adjacent marginal zones in the territory of western Sørkapp Land. These were the following sheets: No. 5 – Hornsund, No. 8 – Gåsbreen, and No. 10 – Bungbreen (Fig. 2).

The topographic map sheets used presented the general image of the area's surface: relief; permanent and periodic watercourses; water bodies; wetlands; glaciers; triangulation and topographic points; vegetation types (tundra); marine coasts (skerries); and names of geographical features. The relief is presented using contour lines with contour intervals of 5 m for the relatively flat coastal plains and 10 m for steeper areas. Areas too steep to be mapped using contour lines in the assumed scale were presented as rock cliff symbols. The extents of land-terminating glaciers are marked as a change in contour line colour from orange to blue, but lines were not drawn to mark the maximum extent of glacial snouts. Two extents are marked for the Petersbreen, Kvasseggbreen and Eggbreen tidewater glaciers. The first – a dotted line on the surface of the Hornsund Fjord – showed the position of their termini in 1961. The second extent, represented as ice cliffs, was the 1984 update of their boundaries (Fig. 3).

When converting individual sheets to digital form to elaborate results (especially on changes in glacier thickness) it was important to take into account the maps' specificity that resulted from the somewhat non-standard means by which they were created. Initial photogrammetric sketches of individual sheets were made in desk research using the 1961 Norwegian aerial photos from before the expeditions to Spitsbergen of the early 1980s (including the expedition to Sørkapp Land in the summer of 1984 – verbal communication: W. Ziaja). The cartographic material thus prepared constituted a base that, according to the information provided in the map description, was "partially checked and supplemented in the field".

Information on the extent to which the documentation of the extent and elevation of western Sørkapp Land glaciers was "completed in the field" was key in assessing this series' potential for use in analysing the changes in glacier thicknesses in

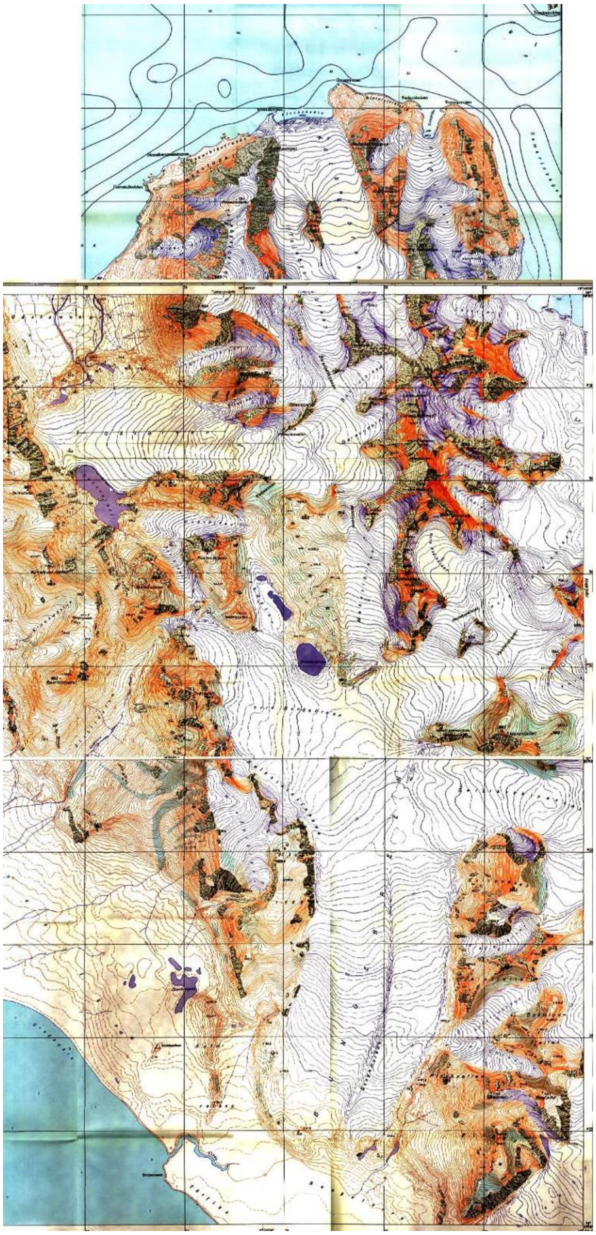

Figure 2. Three sheets of the IGF PAN topographic map published in 1987, showing the glaciers of western Sørkapp Land (Barna and Warchoł, 1987).

the period 1961–90. In the context of this analysis, the most important question was whether the contour lines marking the elevation of the glaciers represent the year 1961 (which would result from the use of aerial photographs from that period) or 1984 (which would result from the contour lines having been updated using field measurements made more than two decades

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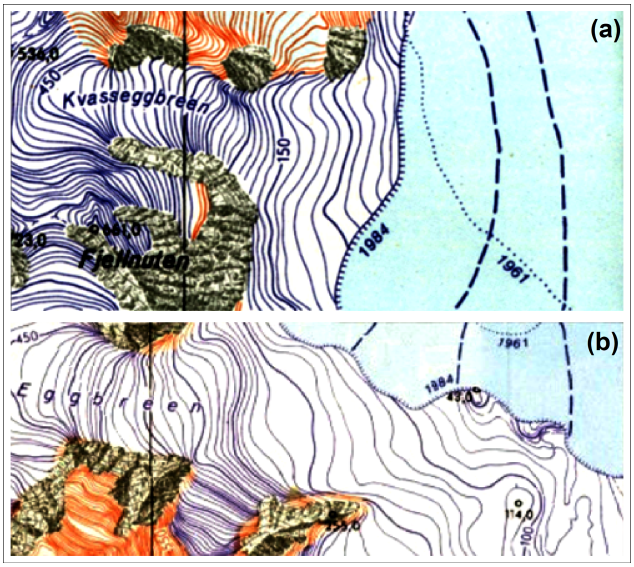

Figure 3. Example visualisations of the extents of tidewater glaciers on IGF PAN maps published in 1987: (a) Kvasseggbreen (Sheet 5 – Hornsund); (b) Eggbreen (Sheet 8 – Gåsbreen).

after the photogrammetric overflight). The question was answered by comparative analyses of the series of IGF PAN maps and other cartographic studies of the area presenting the state of glaciers in the early 1960s.

One such study was a report from an expedition by Austrian scientists Monika and Wolfgang Schöner, who in 1991 made accurate ground-based photogrammetric measurements on the forefield of the Gåsbreen glacier. These studies resulted in a publication that included a map showing the hypsometric variation of the Gåsbreen and hillshade view that was valid for 1960 (based on photos from the Norwegian Polar Institute's photogrammetric overflight over the west of Sørkapp Land in the summer of 1960 – Table 1) (Schöner and Schöner, 1996). Another helpful publication for comparisons of the elevations of Körberbreen and Petersbreen was an article by Jania (1987) that included hypsometric profiles of both these glaciers valid for 1960. Another important cartographic study was a 1:10,000 map of the forefield and lower part of the Bungebreen glacier snout by Warsaw geologists based on aerial photographs from 1961 (Ostaficzuk et al., 1982; Dzierżek et al., 1991).

The comparison of the 1987 series of maps against all the aforementioned studies led to the unequivocal conclusion that the contours contained therein represent the year 1961 (and thus were not corrected based on field research), while their updating (by "in-field supplementation") to reflect the 1984 state of affairs related only to glacier extents, as reflected in the change in contour colours.

Therefore, the changes in the extent of the glaciers in the years 1961–90 presented in this article were analysed using the original aerial photos from the Norwegian Polar Institute, which were subjected to photointerpretation. They comprised five scans of vertical aerial photos from the historical photogrammetric overflight over the Sørkapp Land area on August 24 and

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25, 1961. Black-and-white pictures at a scale of 1:50,000 were made from a ceiling of about 8,000 m using a Wild RC camera with a focal length of 153.45 mm (Jania, 1987).

3.2 1990 Data

The reference dataset for the analysis of map accuracy and changes in glacier extents and thicknesses was 1990 data from the Norwegian Polar Institute. This study used a vector layer with glacier outlines (*S100_Isbree_f.shp*) and a 20-m-resolution Digital Elevation Model (DEM) based on infrared aerial images. The elevation accuracy of the model is 2–5 m in non-glaciated areas and slightly less for glacier surfaces (NPI, 2014).

4 Methods of source-data processing and evaluation of output data accuracy

The maps on which the glacier elevation analysis was based in 1961 in the west of Sørkapp Land were processed in several stages. The analogue maps were first scanned and converted to *TIFF* format. In this form, they were used to generate contour lines and vector layers showing the hydrographic network (rivers and lakes) as well as peaks and other elevation points. For this purpose, R2V software (Raster to Vector) was used, using the semi-automatic vectorisation function (Teng et al., 2008). This tool proved very useful for converting a raster map to vector format, as it allowed for significantly quicker digitisation of contour lines (for western Sørkapp Land, with its very diversified relief, they were very densely packed – every 5 or 10 m – in the altitude range from 0 up to 1,430 m a.s.l.), while maintaining control over the quality of the final result.

The older version of R2V used for this study did not allow data to be saved in *shapefile* format, nor georeferencing, so vector layers were first saved in *dxf* format and then converted to *shapefile* in ESRI ArcGIS 10.0. The resultant GIS layers needed to be assigned a coordinate system. Because it had not been possible to do this earlier on the base raster map (and thus for vector layers based on it), the cartographic grid lines were additionally digitised in places where meridians and parallels intersected (nodes) while the contour lines were being vectorised in R2V. This meant that, after conversion to *shapefile* format, the intersections of the digitised lines could be used as the reference points needed in the georeferencing process. Thematic layers were first defined in the UTM projection (northern hemisphere, zone 33), based on a European Datum 1950 (ED50) ellipsoid, in which the background maps had been developed. Then, the coordinate system was converted and the UTM projection (northern hemisphere, zone 33) was adopted into the WGS 84 reference system. This allowed for cartographic compilation and integration with other data used for the spatial analyses later in this work.

Georeferenced GIS layers – contours, peaks and topographic points – were supplemented with information about the elevation in the attribute table, and then, together with river and lake layers, were used to generate a relief model that was saved as a Triangulated Irregular Network (TIN). In the next step, this model was transformed into a regular GRID (using the TIN-to-raster tool) at a spatial resolution of 20 m.

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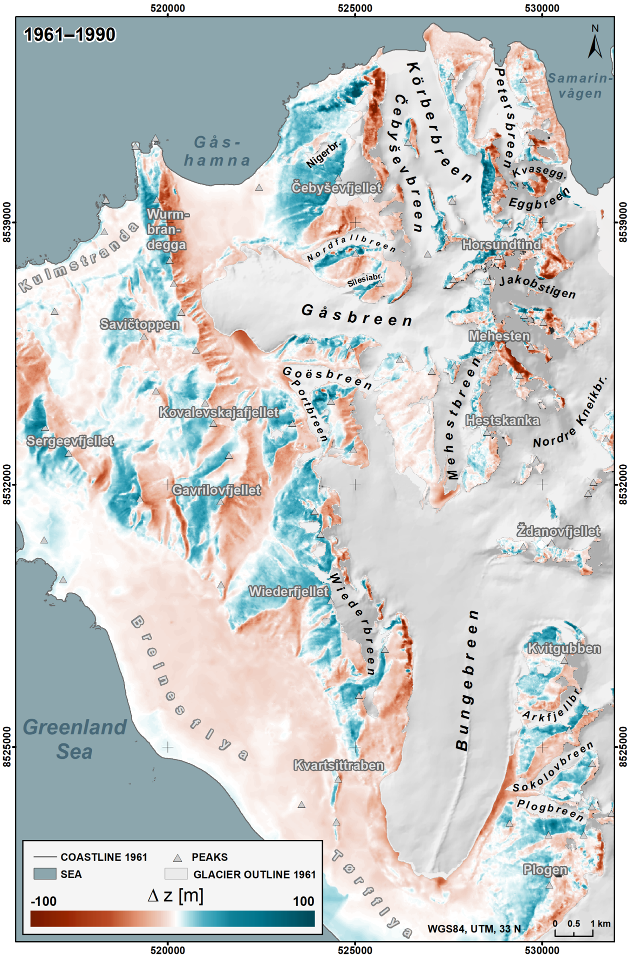

Figure 4. Elevation differences between the 1961 DEM generated from IGF PAN maps issued in 1987 (map rectification based on the nodes of the cartographic grid) and the 1990 DEM generated by NPI (2014).

4.1 Verification of source data accuracy

The final step was to verify the relative accuracy of the obtained model with the working name *DEM IGF 1961*. This was done by checking the extent to which it fitted existing reliable altitude data for areas not subject to large natural changes over time (in practice, this was the majority of non-glaciated areas). The most reliable source of data for comparisons was the 1990 DEM generated by NPI using photogrammetric methods based on aerial photos and field-measured control points. The easiest way to verify the differences between the two models was to subtract one from the other (using the *Spatial Analyst tools/Math/Minus module*). The obtained DEM of Difference (DoD) is shown in Fig. 4.

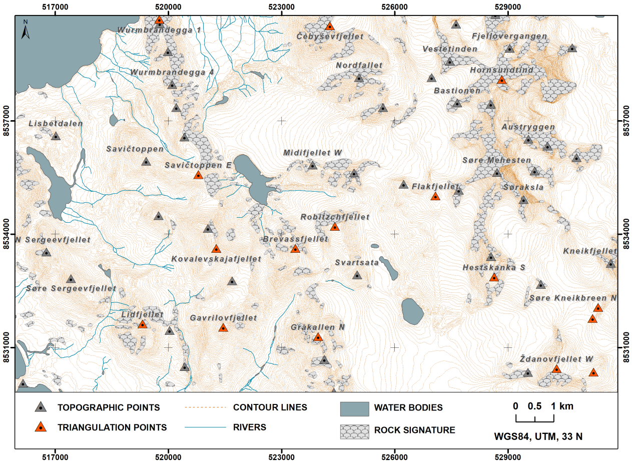

Figure 5. Triangulation and topographic points on sheet 8 – Gåsbreen.

The result of the comparison was not satisfactory. There were large negative values on slopes with an eastern exposure, alongside large positive values on western slopes, indicating that the two models were offset horizontally in relation to each other (Nuth and Kääb, 2011) .

In view of this result, it was attempted to estimate the position errors of the IGF PAN vector layers and then to correct them. The analysis was performed for each of the three sheets separately. Work began with the correction of sheet 8 – Gåsbreen, which covers the largest area of the peninsula (Fig. 5).

In the first stage, the location of the elevation points was assessed. The Gåsbreen map sheet contained as many as 195, while the map of the same area released by NPI in 2007 showed about 50 elevation points. The two maps shared 50 points representing the same places, of which 16 were triangulation points (Fig. 5). The remaining elevation points were mostly peaks, but a few indicated geographical features in the field. For the purposes of this study, both types of points were assigned to a common category of objects called "topographic points". In addition 7 topographic points (including one point showing the position of building Camp Erna) were added in order to match both datasets. The differences in their position in relation to each other are presented in Tables 2 and 3.

Comparing the location of individual points, it can be concluded that the 1961 Gåsbreen map sheet was shifted south-eastwards relative to the 1990 NPI map. The peaks of the mountain massifs around Hornsundtind were reproduced the most accurately. Moving westwards from Hornsundtind, the distance between the topographic points on both maps increased, which led to the assumption that this was not a simple shift between maps, but rather that the problem is a distortion resulting from, among other things, coordinates on the mapping grid being marked incorrectly. The possibility of this problem was already indicated in the description of the IGF PAN map sheets, which explained that the UTM geographic coordinates obtained from NPI that it used differ from the geographic coordinates obtained from astronomical measurements Barna and Warchoł (1987).

The second corrected sheet of the 1961 map – Bungebreen – showed much less land, and hence fewer elevation points, because much of it was covered by the Greenland Sea (Fig. 6). A preliminary assessment of map quality determined a shift

Table 2. Coordinates of triangulation points used to register sheet 8 – Gåsbreen.

Name	Type	08 Gåsbreen. IGF PAN (m)			013 Sørkapp. NPI (m)			Difference (m)		
		x	y	z	x	y	z	Δx	Δy	Δz
Søre Kneikbreen N	triangulation	531398.1	8532055.9	654.4	531373.2	8532064.3	654.0	-24.9	8.5	-0.4
Søre Kneikbreen S	triangulation	531254.1	8531766.0	631.0	531227.9	8531773.9	629.0	-26.1	7.9	-2.0
Ždanovfjellet W	triangulation	530296.6	8530442.0	839.7	530253.2	8530447.4	840.0	-43.4	5.4	-0.3
Ždanovfjellet E	triangulation	531276.9	8530342.5	764.0	531243.2	8530364.0	764.0	-33.7	-21.6	0.0
Hornsundtind	triangulation	528847.1	8538095.6	1431.0	528824.5	8538106.1	1431	-22.7	10.5	0.0
Hestskanka S	triangulation	528643.8	8532864.8	860.0	528613.8	8532859.5	860	-30.0	-5.4	0.0
Flakfjellet E	triangulation	527083.7	8535012.2	712.6	527056.9	8535036.2	713	-26.8	24.0	0.4
Čebyševfjellet	triangulation	524286.1	8539523.6	907.4	524218.6	8539559.9	907.0	-67.6	36.3	-0.4
Robitzchfjellet	triangulation	524416.4	8534203.5	630.6	524358.6	8534230.5	633.0	-57.8	27.0	2.4
Gråkallen N	triangulation	523973.6	8531281.6	716.3	523919.1	8531286.8	716.0	-54.5	5.1	-0.3
Brevassfjellet	triangulation	523371.8	8533622.1	585.0	523324.3	8533646.8	585.0	-47.5	24.7	0.0
Gavrilovfjellet	triangulation	521461.3	8531534.1	598.2	521400.3	8531553.1	598.0	-61.0	19.0	-0.2
Kovalevskajafjellet S	triangulation	521274.3	8533620.7	640.0	521218.5	8533645.4	640	-55.8	24.7	0.0
Savičtoppen E	triangulation	520798.4	8535577.5	493.7	520750.8	8535599.9	494.0	-47.5	22.3	0.3
Wurmbrandegga 1	triangulation	519763.8	8539690.1	391.8	519704.0	8539683.0	392.0	-59.9	7.1	0.2
Lidfjellet	triangulation	519317.0	8531618.0	531.0	519254.9	8531628.5	531.0	-62.1	10.5	0.0

in the topographic points layer relative to the contour lines, which most likely occurred while the map was being prepared for printing. In order to solve this problem, before registering the sheet under development, the two digitised layers were matched against each other such that the elevation points fell within contours delineating summits (Fig. 7).

In addition to the small number of elevation points and their shifting relative to contour lines, the planned map registration was further hampered by the uneven distribution of elevation points within the sheet. Most of the points were located at the peaks of mountain massifs in northern and eastern parts of the map, while points in the coastal zone in the west were missing. The corresponding fragment of the map issued by the NPI for 1990 contained one topographic point at the base of Cape Rafenodden at an altitude of 17 m a.s.l. To match the 1961 and 1990 data, one point was added to the Bungebreen sheet, within a small elevation delimited by a contour at 17.5 m a.s.l (Fig. 6). In the next step, the vector layer of topographic points for 1961 was made more dense by adding a few at the peaks of four massifs. These were points within contours delineating summits of Arkfjellet, Plogen, Wiederfjellet, and Stupprygen. Table 4 shows the coordinates of all points on which the registration of sheet 10 – Bungebreen was based.

For the next IGF PAN map sheet (No. 5 – Hornsund), only the southern part representing the north-western part of the Sørkapp Land peninsula was used (Fig. 8). Table 5 lists the points on which the sheet registration was based.

Table 3. Coordinates of topographic points used to register sheet 8 – Gåsbreen.

Name	Type	08 Gåsbreen. IGF PAN (m)			013 Sørkapp. NPI (m)			Difference (m)		
		x	y	z	x	y	z	Δx	Δy	Δz
vestre Ždanovfjellet	topographic	529536.2	8530335.8	559	529502.6	8530351.0	561	-33.6	15.2	2.0
Hestskanka N	topographic	528559.2	8533404.8	993.0	528531.3	8533405.8	997.0	-27.9	1.0	4.0
Flakfjellet W	topographic	526238.7	8535325.9	613.0	526196.9	8535344.5	613.0	-41.8	18.6	0.0
Gråkallen S	topographic	524136.1	8530680.5	650.0	524081.5	8530681.6	650.0	-54.7	1.1	0.0
Kovalevskajafjellet N	topographic	521051.0	8534156.0	624.5	520995.0	8534182.0	623.0	-56.0	25.9	1.5
Savičtoppen	topographic	519411.7	8535934.0	468.0	519359.9	8535955.4	464.0	-51.8	21.5	-4.0
Wurmbrandegga 2	topographic	519776.1	8539580.8	415.0	519704.8	8539612.5	414.0	-71.3	31.8	-1.0
Wurmbrandegga 3	topographic	519991.1	8538834.2	378.0	519926.4	8538885.8	378.0	-64.7	51.6	0.0
Wurmbrandegga 4	topographic	520107.6	8537967.5	364.0	520046.5	8537994.3	361.0	-61.2	26.8	-3.0
Wurmbrandegga 5	topographic	520212.6	8537356.7	410.5	520158.7	8537372.1	407.0	-54.0	15.3	-3.5
Wurmbrandegga 6	topographic	520428.9	8536571.1	417.0	520364.1	8536607.9	421.0	-64.8	36.8	4.0
Liddalen N	topographic	520034.4	8531447.3	247.0	519968.6	8531468.1	247.0	-65.8	20.8	0.0
Liddalen S	topographic	520435.1	8530489.9	162.0	520368.8	8530518.6	162.0	-66.3	28.7	0.0
Kneikfjellet	topographic	531735.2	8533224.8	708.0	531714.2	8533227.2	708.0	21.0	-2.4	0.0
Austryggen W	topographic	529549.3	8536519.7	1028.0	529514.3	8536529.2	1021.0	-35.0	9.5	-7.0
Austryggen E	topographic	530060.6	8536331.3	955.0	530031.2	8536345.9	957.0	-29.4	14.6	2.0
Søraksla	topographic	529422.0	8534916.9	1025.0	529400.6	8534926.4	1028.0	-21.4	9.5	3.0
Camp Erna	topographic	516150.2	8530052.9	10.0	516062.4	8530068.8	10.0	-87.8	15.9	0.0
Lisbetdalen	topographic	517023.1	8536608.8	129.5	516977.0	8536631.1	131.0	-46.1	22.3	0.0
Sergeevfjellet N	topographic	516786.3	8533514.9	405.5	516719.8	8533533.7	412.0	-66.6	18.8	-6.5
Søre Sergeevfjellet	topographic	517421.7	8532819.1	437.0	517346.6	8532845.8	433.0	-75.1	26.8	4.0
Skiferpasset N	topographic	519741.9	8534487.9	440.5	519688.1	8534510.8	438.0	-53.7	22.9	2.5
Skiferpasset S	topographic	521691.5	8532763.6	499.0	521630.8	8532787.7	501.0	-60.7	24.2	-2.0
Wiederbreen	topographic	524390.1	8529810.5	715.5	524337.8	8529830.9	715.5	-52.3	20.4	0.0
Midifjellet W	topographic	523829.9	8535829.4	406.5	523790.6	8535852.7	407.0	-39.2	23.3	0.5
Midifjellet E	topographic	524927.1	8535621.6	633.0	524872.4	8535636.4	639.0	-54.8	14.8	6.0
Svartsata	topographic	525008.7	8532920.0	522.0	524954.8	8532939.1	525.0	-53.9	19.0	3.0
Nordfallet	topographic	525062.9	8538147.8	823.0	525012.9	8538171.2	824.0	50.0	-23.4	-1.0
Silesiafjellet	topographic	525693.5	8537356.0	668.0	525656.1	8537379.7	669.7	37.5	-23.6	-1.7
Hoven	topographic	527701.5	8535162.3	858.0	527654.1	8535172.5	869.0	-47.4	10.2	11.0
Baranowskipasset	topographic	526981.0	8538147.5	603.0	526939.9	8538164.8	600.0	-41.1	17.4	-3.0
Körberbreen	topographic	527629.4	8539562.5	458.5	527606.5	8539582.4	459.0	-23.0	19.9	0.5
Vestetinden	topographic	527469.1	8538583.7	920.5	527431.8	8538595.1	928.0	-37.3	11.3	7.5
Bastionen	topographic	527662.3	8537477.6	800.5	527626.5	8537487.9	799.0	-35.9	10.4	-1.5
Fjellovergangen	topographic	529052.7	8538921.5	911.0	529030.3	8538944.0	910.0	-22.4	22.5	-1.0
Conwaykammen	topographic	528552.9	8537446.0	1185.0	528537.8	8537442.0	1185.0	-15.1	-4.0	0.0
Søre Mehesten	topographic	528715.5	8535637.0	1378.0	528697.7	8535668.0	1383.0	-17.8	31.0	5.0
Tindegga	topographic	530710.9	8538934.6	255.0	530685.9	8538940.4	255.0	-25.0	5.8	0.0
Austryggnuten	topographic	530828.7	8536027.9	582.0	530804.5	8536030.1	570.0	-24.2	2.3	-12.0
Mehestnuten	topographic	529714.2	8535673.6	813.0	529694.8	8535682.6	816.0	-19.4	8.9	3.0
Kvitknotten	topographic	529877.2	8532666.4	681.0	529849.8	8532672.1	691.0	-27.3	5.7	10.0
Kneikfjellet	topographic	531735.2	8533224.8	708.0	531714.2	8533227.2	708.0	-21.0	2.4	0.0

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Table 4. Coordinates of all points used to register sheet 10 – Bungebreen.

Name	Type	10 Bungebreen, IGF PAN (m)			013 Sørkapp. NPI (m)			Difference (m)		
		x	y	z	x	y	z	Δx	Δy	Δz
Rafenodden	topographic	517252.2	8529448.2	17.5	517252.2	8529448.2	17.5	-50.1	22.1	-0.5
Slaklidalen	topographic	521470.8	8529281.6	110.0	521470.8	8529281.6	110.0	-53.2	50.9	0.0
Vokterpiken	topographic	523387.3	8523632.1	34.0	523387.3	8523632.1	34.0	-27.3	23.7	-2.3
Wiederfjellet 1	triangulation	524388.1	8529220.8	740.0	524388.1	8529220.8	740.0	-54.5	51.5	0.0
Wiederfjellet 2	triangulation	524417.5	8528859.6	754.0	524417.5	8528859.6	754.0	-63.2	40.0	0.0
Wiederfjellet 3	topographic	524673.8	8527848.7	655.0	524673.8	8527848.7	655.0	-53.2	50.8	0.0
Kvartsittrabben N	topographic	524603.8	8524133.5	124.0	524603.8	8524133.5	124.0	-46.2	5.7	-0.2
Kvartsittrabben S	topographic	524563.0	8522934.4	63.0	524563.0	8522934.4	63.0	-55.9	65.7	-0.3
Stupprygen 1	topographic	525838.3	8527582.1	636.0	525838.3	8527582.1	636.0	-40.3	18.2	-1.0
Stupprygen 2	topographic	525960.1	8527151.5	597.0	525960.1	8527151.5	597.0	-36.6	42.5	0.0
Stupprygen 3	topographic	525144.6	8526341.8	475.0	525144.6	8526341.8	475.0	-36.2	34.7	-0.5
Stupprygen 4	topographic	525240.8	8525479.6	333.0	525240.8	8525479.6	333.0	-41.8	39.2	0.0
Kvitgubben 1	topographic	531025.3	8527768.3	724.0	531025.3	8527768.3	724.0	-30.2	31.3	6.7
Kvitgubben 2	triangulation	530518.6	8527020.5	865.8	530518.6	8527020.5	865.8	-33.0	32.1	0.2
Kvitgubben 3	topographic	530075.6	8526247.2	628.0	530075.6	8526247.2	628.0	-24.2	24.0	0.0
Arkfjellet 1	topographic	531178.1	8525895.1	794.0	531178.1	8525895.1	794.0	-29.4	41.0	5.0
Arkfjellet 2	topographic	530756.9	8525435.9	737.0	530756.9	8525435.9	737.0	-32.7	20.3	0.0
Arkfjellet 3	topographic	530350.8	8525316.4	653.0	530350.8	8525316.4	653.0	-28.0	25.7	0.0
Sokolovfjellet N	topographic	531369.6	8524531.5	645.0	531369.6	8524531.5	645.0	-30.7	26.2	6.7
Sokolovfjellet S	topographic	531361.1	8523377.6	724.0	531361.1	8523377.6	724.0	-29.8	22.9	2.0
Plognatten	topographic	529159.0	8522935.6	388.0	529159.0	8522935.6	388.0	-30.6	28.1	4.6
Plogjernet	topographic	530198.6	8522623.7	674.0	530198.6	8522623.7	674.0	-32.4	22.7	1.9
Plogfjellet	topographic	531141.8	8522614.1	705.0	531141.8	8522614.1	705.0	-33.3	33.1	5.7
Plogen	topographic	530229.9	8521300.3	696.0	530229.9	8521300.3	696.0	-33.6	8.3	0.4

4.2 Fitting data from 1961 and 1990

In order to align the 1961 vector layers with the 1990 data, they were merged and registered (*Spatial Adjustment* function/*Rubbersheet* conversion), this time based on triangulation and topographic points (Tables 2-5). The vector data thus processed was then used to generate a DEM with a resolution of 20 m, which was compared against the 1990 NPI model.

A preliminary visual analysis of the obtained DoD (Fig 9) led us to conclude that a significant improvement had been achieved in terms of the models' spatial fit. This was also indicated by a visual assessment of the comparative courses and positions of the 1961 and 1990 contours (Fig. 10-12). Considering the limited possibility of accurately determining the elevation

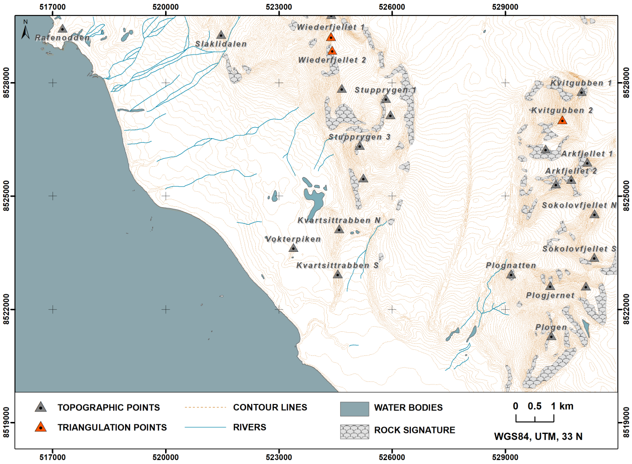

Figure 6. Triangulation and topographic points on sheet 10 – Bungebreen.

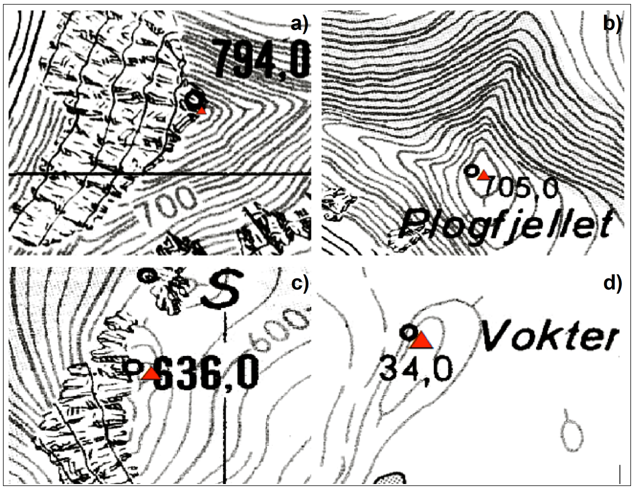

Figure 7. Examples of shifts in elevation points used to register the Bungebreen sheet: (a) Arkfjellet N, (b) Plogfjellet, (c) Stupprygen N, (d) Vokterpiken. Red triangles show new point locations.

points on which the data registration for 1961 was based, the result of comparing both vector layers and both elevation models was considered satisfactory.

4.3 Final elevation model for 1961

220 After correcting all vector data that were based on the IGF PAN map sheets and the digital elevation model processed from them, the end product and its adjustment to the remaining reference elevation data were then assessed for accuracy. To this end,

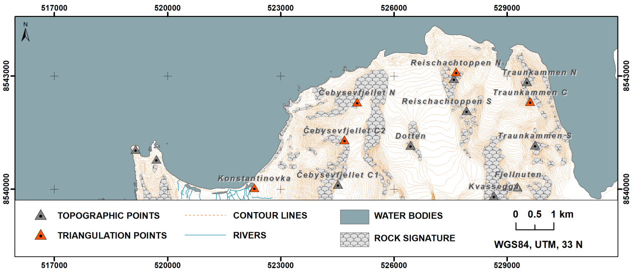

Figure 8. Triangulation and topographic points on sheet 5 – Hornsund.

Table 5. Coordinates of points used to register sheet 5 - Hornsund.

Name	Type	05 Hornsund. IGF PAN (m)			013 Sørkapp. NPI (m)			Difference (m)		
		x	y	z	x	y	z	Δx	Δy	Δz
Hoferpynten	topographic	519164.7	8541050.8	15.2	519135.7	8541046.0	15.2	-29.1	-4.8	0.0
Hansenodden	topographic	519711.0	8540790.9	37.6	519672.8	8540800.3	37.5	-38.2	9.4	-0.1
Konstantinovka	triangulation	522284.6	8540065.2	3.8	522244.1	8540084.2	14.0	-40.5	19.0	10.2
Čebysevfjellet C1	topographic	524520.2	8540115.0	919.9	524476.8	8540131.6	920.0	-43.4	16.5	0.1
Čebysevfjellet C2	triangulation	524669.7	8541313.7	755.7	524680.1	8541290.6	756.0	10.5	-23.1	0.3
Čebysevfjellet N	triangulation	525043.5	8542311.0	677.5	525007.0	8542312.3	678.0	-36.6	1.3	0.5
Dotten	topographic	526460.6	8541162.3	398.0	526421.4	8541149.9	395.4	-39.2	-12.4	-2.6
Reischachtoppen C	topographic	527596.0	8542933.4	450.0	527575.2	8542913.0	452.2	-20.8	-20.4	2.2
Reischachtoppen N	triangulation	527662.3	8543109.1	439.1	527637.1	8543091.1	439.0	-25.2	-18.1	-0.1
Reischachtoppen S	topographic	527920.5	8542097.3	524.0	527897.2	8542066.9	524.9	-23.3	-30.4	0.9
Kvassegga	topographic	528670.8	8539817.7	998.0	528632.3	8539807.8	1003.5	-38.5	-9.9	5.5
Fjellnuten W	topographic	529289.9	8540059.3	723.0	529246.4	8540039.6	729.0	-43.5	-19.7	6.0
Traunkammen N	topographic	529527.8	8542867.9	441.0	529512.3	8542822.4	443.6	-15.5	-45.5	2.6
Traunkammen C	triangulation	529610.0	8542325.8	462.0	529589.5	8542290.0	464.4	-20.5	-35.8	2.4
Traunkammen S	topographic	529745.5	8541198.4	684.0	529719.9	8541160.2	691.7	-25.6	-38.2	7.7
Fjellnuten E	topographic	529681.2	8540024.3	661.0	529629.8	8540008.6	668.1	-51.4	-15.8	7.1

the final 1961 IGF PAN elevation model was subtracted from the 1990 NPI model, and elevation differences between them in non-glaciated areas were analysed in individual slope classes.

In order to assess the usefulness of the DEM in studying changes in glacier thickness, it can be assumed that its vertical accuracy for non-glacial areas with a slope of less than 20° will also apply to the surface of most glaciers, because their slope usually falls into this class. The analysis below will therefore focus on such areas. Apart from the surface of steep slopes, the evaluation also excludes non-glaciated areas that cannot be considered stable because the differences in elevation between the

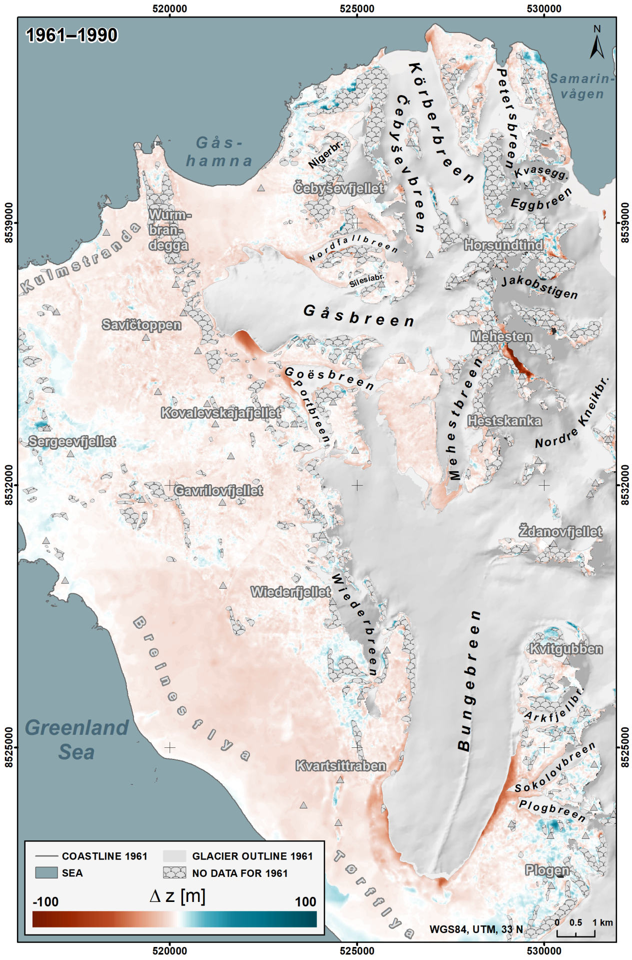

Figure 9. Differences in altitude in non-glaciated areas between the 1961 DEM (data rectification based on elevation points), and the 1990 DEM generated by NPI (2014).

two models may result from natural processes going on in the natural environment, e.g. melting of dead ice in marginal zones of glaciers, or the accumulation or erosion activity of proglacial streams in their forefields. Areas of steep or very steep slopes presented on the IGF PAN maps as a rock signature could also not be verified, for obvious reasons.

After taking into account the aforementioned criteria, the fragment of the IGF PAN model selected for vertical error analysis covered 76.9 km^2, which constituted 42% of non-glaciated areas (183.2 km^2) and 26% of the entire land area (299.6 km^2) analysed within this model. For comparison, the area covered by glaciers was 116.4 km^2 (38.8% of the analysed land area), and the area of steep and very steep slopes was 69.4 km^2 (23.2%).

The verification of the vertical error of the 1961 model began with classifying slopes by gradient. To this end, a slope map was first made (*Spatial Analyst Tool / Surface / Slope* module) and then reclassified (*3D Analyst Tool / Raster reclass / Reclassify* module) to distinguish two slope classes for the area: 0–20° and >20°. Next, the reclassified raster was transformed

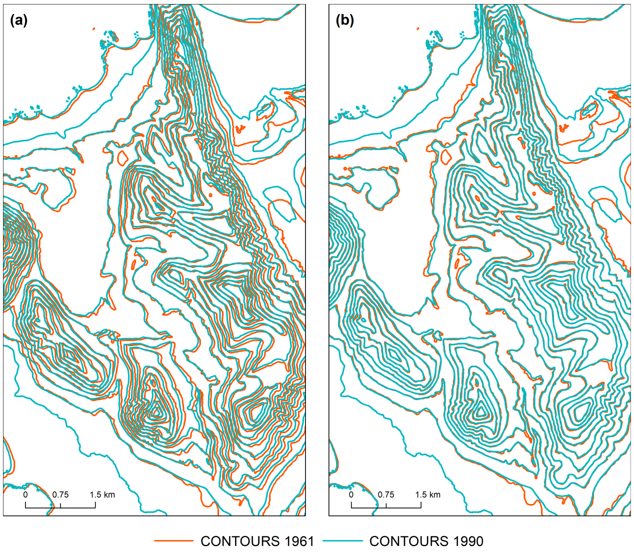

Figure 10. Course of contour lines in the western part of sheet 8 – Gåsbreen: georeference based on: (a) grid nodes; and (b) elevation points.

to a vector layer (*Conversion Tools / From Raster / Raster to Polygon* module), from which polygons of the second slope class (steep and very steep slopes) were removed, as were glacier surfaces (extent from 1961), marginal zones, extra-marginal sandurs, glacial river beds, lakes and seas. The resulting mask was used to select areas of elevation differences between the years 1961 and 1990 from the raster, and these areas were those to be assessed in terms of vertical accuracy (*Data Management Tools / Raster / Raster Processing / Clip* module). The mean elevation difference between the compared models was 3.55 m, with a standard deviation of 2.96 m, indicating that the 1961 model is higher (Fig. 13).

In the last step, this model was corrected by subtracting the obtained mean difference from it. The results of comparisons of the final 1961 model against the 1990 reference model are presented in Figure 14.

4.4 1961–90 changes in glacier geometries

The measure for examining the size and pattern of glacier recession in the years 1961–90 was changes in their surface area, the rate of frontal recession and – where data allowed (i.e. for land-based glaciers) – changes in thickness. The research covered 18 glaciers that lay entirely within the analysed sheets of the 1961 map. After initial classification into two glacier types (land-terminating and tidewater), the changes in their geometry were calculated.

In the study period, most of the glaciers on the mainland of western Sørkapp Land were in recession, as reflected in a decrease in total area of nearly 7.2% – from 74.8 km^2 in 1961 to about 69.4 km^2 in 1990. The average rate of change in surface area of the region's land-based glaciers was 0.19 km^2, i.e. about 0.2% of glaciated area per year (Table 6).

The pace of surface recession on western Sørkapp Land in the period 1961–90 varied between individual land-based glaciers. In terms of surface area and ice mass loss, recession was most intense for the largest glaciers in the region: Gåsbreen and Bungebreen. In these glaciers, the changes are most pronounced in the lower parts of their snouts (Table 5, Fig. 15 and 16 a-b).

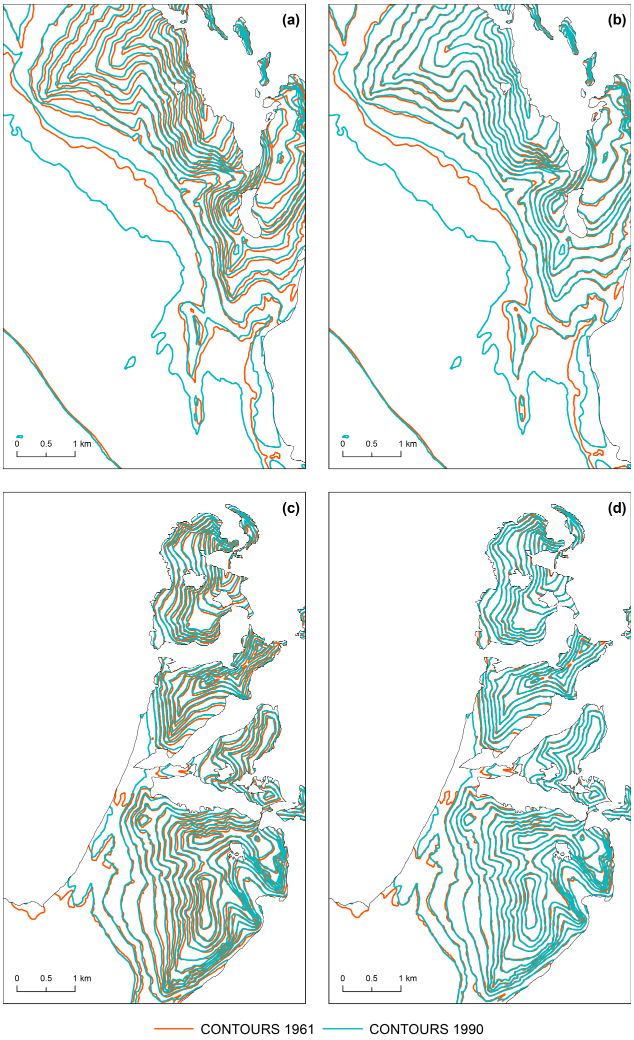

Figure 11. Course of contour lines in non-glaciated areas in the western part of sheet 10 – Bungebreen: georeference based on: (a, c) nodes of the cartographic grid and (b, d) elevation points.

Of the largest glaciers in the region, though in retreat, the snout of the westernmost glacier (Gåsbreen) was in 1961 still piled up on the eastern slopes of the Wurmbrandegga–Savičtoppen ridge to an elevation of 150 m a.s.l. This significant mountain barrier had conditioned glacier transgression in the Little Ice Age (LIA), resulting mainly in the lowest part of the glacier thickening and expanding (Ziaja et al., 2016). Therefore, both just after the end of the LIA and in 1961–90, the Gåsbreen's recession manifested primarily as a narrowing and thinning of the lowest parts of the glacier. In the years 1961–90, the glacier's area decreased by 1.65 km^2, mainly due to the narrowing of the lower parts of the glacier, while the frontal retreat was relatively small, amounting to about 320 m (11 m/year). Meanwhile, its frontal part was significantly lowered, by up to 83 m at the line of

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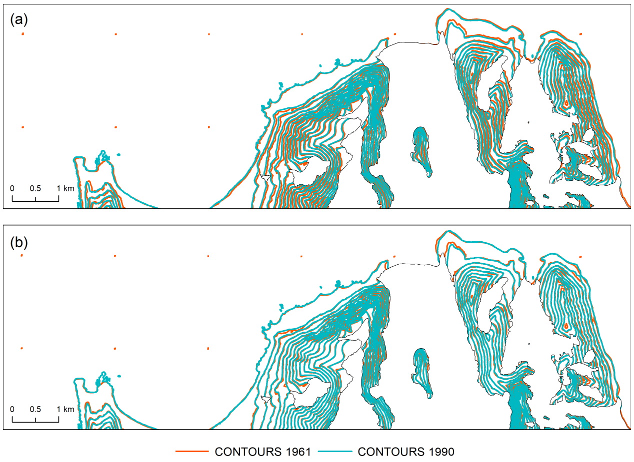

Figure 12. Course of contour lines in non-glaciated areas in the southern part of sheet 5 – Hornsund: georeference based on: (a) nodes of the cartographic grid; and (b) elevation points.

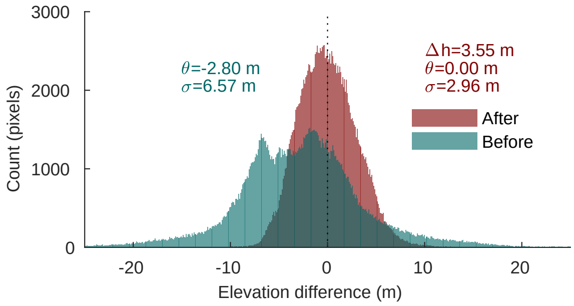

Figure 13. Histograms of elevation differences for stable non-glaciated areas with slopes of less than 20° between the 1961 and 1990 digital elevation models before and after corrections.

its 1990 extent. Outside the frontal and lateral parts, the lowering of the glacier surface became gradually less intense upwards, while thickening was observed in the accumulation zone.

Similar patterns of change in geometry (expressed as thickness increasing in the accumulation zone and decreasing in the ablation zone, combined with a clear retreat of the terminus) were observed for the Bungebreen glacier. In the period 1961–90, the glacier area shrank by 2.9 km^2, and the frontal retreat amounted to over 1,300 m (46 m/year). The changes in the extent of the glacier were accompanied by a severe lowering of the surface of lower parts of the snout, of up to 85 m at the line of its 1990 extent. Against this background, however, the area of medial moraine stood out, as it played a protective role and attenuated the surface lowering. Here and there, upper parts of the glacier were built up in this period. Because Bungebreen is a compound valley glacier, supplied by several firn fields, this building-up was not uniform throughout the accumulation zone. An increase in glacier thickness of up to 20 m was recorded primarily in parts with a favourable topographic situation,

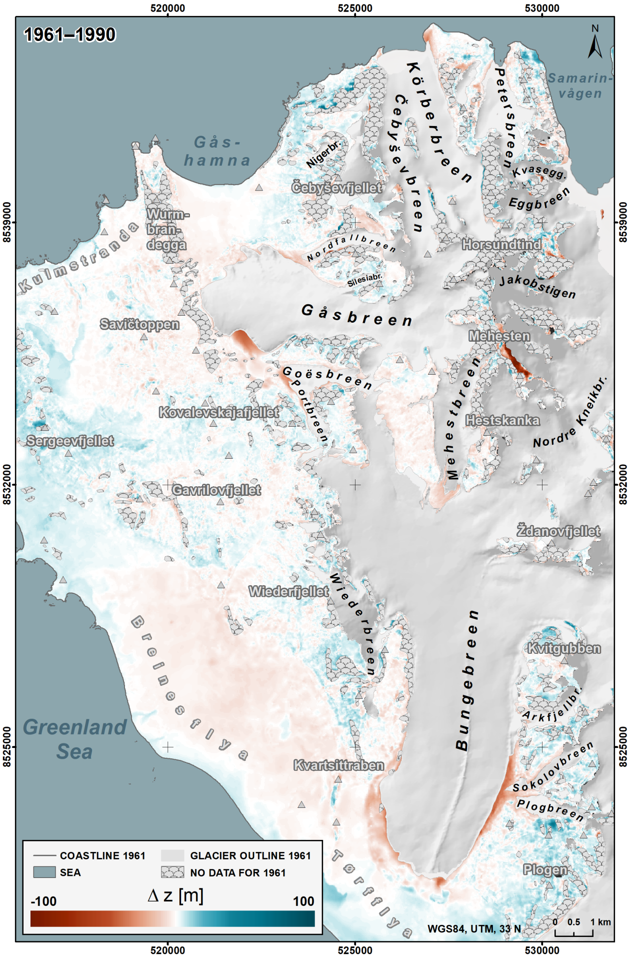

Figure 14. Differences in elevation in non-glaciated areas between the final 1961 DEM generated based on IGF PAN maps published in 1987 (rectification of maps based on elevation points) and the 1990 DEM generated by NPI (2014)

i.e. where ablation is limited by a northern exposure or by being shaded by the steep slopes of the Gråkallen, Kalksteinstupa and Stupryggen massifs. There was also an approximately 10 m increase in thickness in the ice flowing northwards from the Kvitgubben and Lysentoppen massifs. By contrast, zero or slightly negative values were recorded on the upper southerly-exposed parts of ice-filled passes on Hestskankfallet and Vasil'evskaret, although there was also a small area of increased thickness here (Fig. 16 b).

In the years 1961–90, a very large percentage of area loss, too, was observed in the western and low-lying small-valley Gråkallbreen, Goësbreen and Portbreen glaciers. This process was accompanied by significant thinning, often along the longitudinal profile, and totalling from 20 m in the upper parts to 35–40 m in their termini. The decrease in thickness was very clearly marked in these glaciers, especially in the central and lower parts, which in the case of the Portbreen glacier, for ex-

Table 6. Differences in area of land-terminating glaciers in western Sørkapp Land, 1961–90.

Glacier	Area (km^2)		Area change		Area change rate		Length (m)		Change in length (m)	Length change rate (m/yr)
			(km^2)	(%)	(km^2/yr)	(%)				
	1961	1990	1961–90		1961–90		1961	1990	1961–90	1961–90
Arkfjellbreen	0.78	0.73	-0.05	-6.4	-0.002	-0.2	2035	1890	-145	-5.0
Bungebreen	49.61	46.71	-2.90	-5.9	-0.100	-0.2	12385	11040	-1345	-46.4
Gåsbreen	13.99	12.34	-1.65	-11.8	-0.057	-0.4	7620	7302	-318	-11.0
Goësbreen	1.19	0.94	-0.25	-21.0	-0.009	-0.7	2990	2740	-250	-8.6
Gråkallbreen	0.16	0.14	-0.02	-12.5	-0.001	-0.4	930	930	0	0.0
Mehestbreen	3.09	3.04	-0.05	-1.6	-0.002	-0.1	4590	4470	-120	-4.1
Nigerbreen	0.29	0.26	-0.03	-10.3	-0.001	-0.4	1080	1060	-20	-0.7
Nordfallbreen	0.83	0.80	-0.03	-3.6	-0.001	-0.1	2640	2640	0	0.0
Plogbreen	0.76	0.64	-0.12	-15.8	-0.004	-0.5	2045	1730	-315	-10.9
Portbreen	0.56	0.51	-0.05	-8.9	-0.002	-0.3	1870	1800	-70	-2.4
Reischachbreen	0.35	0.31	-0.04	-11.4	-0.001	-0.4	1390	1295	-95	-3.3
Silesiabreen	0.24	0.22	-0.02	-8.3	-0.001	-0.3	1160	1160	0	0.0
Sokolovbreen	0.96	0.92	-0.04	-4.2	-0.001	-0.1	2860	2745	-115	-4.0
Wiederbreen	2.03	1.87	-0.16	-7.9	-0.006	-0.3	3270	3125	-145	-5.0
Total	74.8	69.4	-5.41	-7.2	-0.187	-0.2				

ample, led to the ice cover partially disappearing and fragmenting into smaller ice lobes separated by a rock step (Fig. 15 and 16c-d).

Against the backdrop of the glaciers that have undergone significant changes over the analysed decades (seen mainly in a significant loss of ice mass), two glaciers stand out for having undergone relatively little change in geometry. These are the Nordfallbreen and Mehestbreen glaciers. Between 1961 and 1990, the area of Nordfallbreen decreased by only 0.03 km^2, i.e. 3.6% – among the lowest values in the entire region (Table 6). The extent of the glacier went practically unchanged in 1961–90. However, the slight changes in surface area and extent were accompanied by a thinning. However, this was less than in other glaciers in the region, and ranged from 20–30 m in the ablation zone to 8–13 m in the accumulation zone(Fig. 15 and 16 e). Even smaller changes in geometry were recorded for the Mehestbreen. Over the entire study period, its area decreased by only 0.05 km^2 (i.e. 1.6%) and the glacier terminus receded by only 120 m in 1961–90 (Table 6). Analysis of the elevation differences in the glacier's longitudinal profile reveal that the thinning in the years 1961–90 was greatest in the lower parts of the ablation zone, at 10–20 m, while the accumulation zone actually increased in thickness by about 10–15 m (Fig. 15 and 16 f).

In the north of the area, which is dominated by glaciers flowing into the Hornsund Fjord, the disappearance of the ice cover was mainly the result of icebergs calving off. The surface area of the four analysed calving glaciers fell from 16.3 km^2 in 1961 to 15.5 km^2 in 1990, constituting a 4.7% shrinkage (Table 7). The average rate of recession of the calving glaciers in

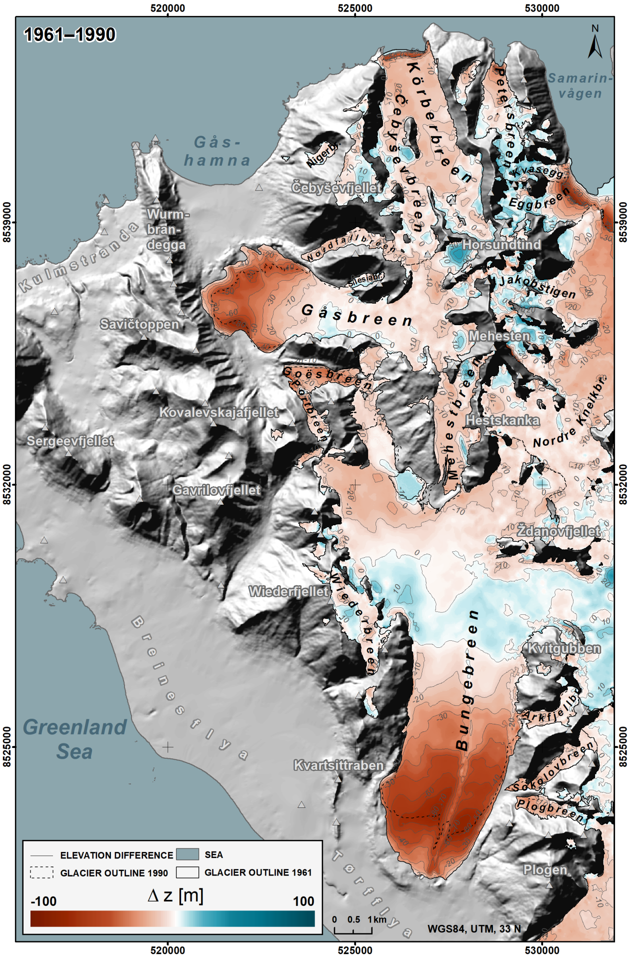

Figure 15. Glacier elevation change in western Sørkapp Land, 1961–90.

1961–90 was 0.2% per year, though this did vary between glaciers. In the region's largest glaciers, which flow directly into the Hornsund fjord (i.e. Körberbreen and Petersbreen), the shrinkage was 0.1% per year, while for the smaller glaciers leading into Samarinvågen Bay it was faster, ranging from 0.3% per year in Kvasseggbreen to 0.5% in Eggbreen (Table 7).

The changes in surface area were accompanied by changes in ice thickness. In their ablation zones, which are subject to greater insolation, thickness decreased and a general frontal retreat was noted. This differed in size and pace for individual glaciers (Fig. 15, Table 7). In the case of the Körberbreen and Petersbreen glaciers, the maximum lowering of the frontal parts (between the 1984 and 1990 extents) did not exceed 65 m. Further eastwards, however, in the former tributaries of the Samarinbreen, this lowering was much greater, reaching 70 m for the Kvasseggbreen snout, and up to as much as 100 m in parts of the Eggbreen. In the higher parts of the studied glaciers, there was a clear building up of firn fields in this period (Fig. 15).

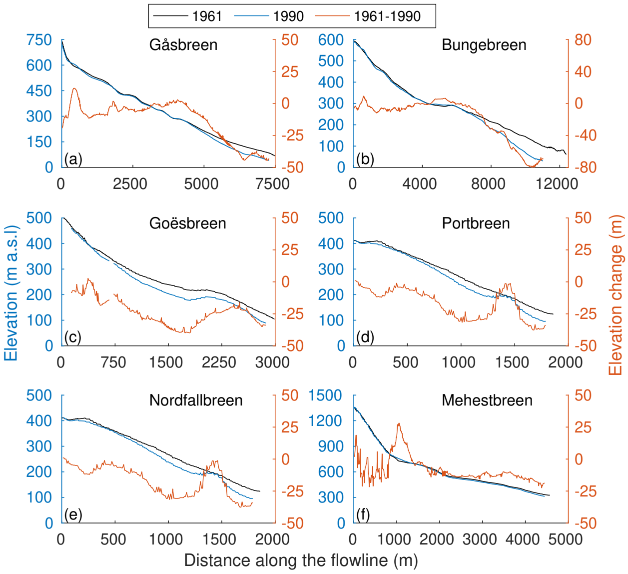

Figure 16. Changes in elevation (along the centre line) of selected glaciers in western Sørkapp Land based on 1961 and 1990 DEMs: (a) Gåsbreen, (b) Bungebreen, (c) Goësbreen, (d) Portbreen, (e) Nordfallbreen, (f) Mehestbreen.

Table 7. Differences in area of land-terminating glaciers in western Sørkapp Land, 1961–90.

Glacier	Area (km^2)		Area change (km^2)	Area change (%)	Area change rate (km^2/yr)	Area change rate (%)	Length (m)		Change in length (m)	Length change rate (m/yr)
	1961	1990	1961–90		1961–90		1961	1990	1961–90	1961–90
Eggbreen	2.29	1.94	-0.35	-15.2	-0.012	-0.5	2670	2230	-440	-15.2
Körberbreen	10.79	10.54	-0.25	-2.3	-0.009	-0.1	5870	5710	-160	-5.5
Kvasseggbreen	0.89	0.80	-0.09	-10.1	-0.003	-0.3	2105	1945	-160	-5.5
Petersbreen	2.31	2.24	-0.07	-2.9	-0.002	-0.1	3075	2930	-145	-5.0
Total	16.28	15.52	-0.76	-4.67	-0.026	-0.2				

5 Discussion

The use of archival cartographic data is one of the key ways to quantify mainly climate-change-related changes in the cryosphere (Surazakov et al., 2006; Weber et al., 2020). On a global scale, such data on the topography of glaciers from the 1960s are relatively scarce – they are mainly based on a few photogrammetric overflights and resultant topographic maps (Tielidze, 2016; Andreassen et al., 2020) and reanalysis of declassified spy satellite images (Bhambri et al., 2011). In the Spitsbergen region, 1930s overflights are a key reference point for the observed changes in area and volume (Nuth et al., 2007).

Modern methods now allow for better and more precise use of these photos and the creation of more accurate elevation models (Mertes et al., 2017; Midgley and Tonkin, 2017).

The accuracy of simulations prognosing changes in glacier volumes based on dynamics models depends largely on the those models having been initialised correctly (Oerlemans, 1997; Collao-Barrios et al., 2018). Glaciers differ in response time to changes in mass balance, and this requires that data on the geometry of glaciers should go back as far as possible – preferably to a state of equilibrium with climatic conditions (Zekollari and Huybrechts, 2015). If this is not possible, these models can properly be calibrated and verified using later data; nevertheless, the further back the data goes the better, and the more accurately future changes can be predicted. Thus, any glacier topography data from the 1960s is extremely valuable (Andreassen et al., 2020). There is little data available for the Svalbard region in this period, highlighting the importance of the results presented here.

The disappearance of ice in western Sørkapp Land in 1961–90 was the result of various processes. It was caused by both surface melting of ice and the breaking-off of icebergs during calving. Both processes had a significant impact on the overall mass loss from the glaciers of Sørkapp Land. It is estimated that they are responsible for 79% and 21%, respectively, of overall mass loss from glaciers across Svalbard (Błaszczyk et al., 2009).

Important factors influencing ablation of glaciers flowing into Hornsund Fjord in the western part of the Sørkapp Land peninsula are the northern and eastern exposures of their accumulation zones and the significant shading of their surfaces by high mountain ranges. For this reason, the winter snow cover here lasts longer and is thicker, and the ablation is weaker relative to neighbouring glaciers with western exposures (Jania, 1987). The greater accumulation and some reduction in glacier ablation also result from their accumulation zones extending upwards to over 700 m a.s.l. and being surrounded by the steep slopes of massifs that supply them with additional snow (Jania, 1987).

The interplay of all these factors can be seen to have clearly increased the thickness of firn and ice in the highest and middle parts of the glaciers flowing into the Hornsund fjord over the years 1961–90 (Fig. 15). At the same time, the changes in position of the thickened parts of the Körberbreen and Petersbreen glaciers are noteworthy, as shown by studies of changes in the range and speed of Körberbreen in shorter time intervals (Pillewizer, 1939; Jania, 1987; Ziaja and Dudek, 2011; Błaszczyk et al., 2013). This suggests, in line with the supposition of Jania (1987), regular short-term displacement of the kinematic waves of ice that are characteristic of surging (especially in relation to the Körberbreen glacier). The research period adopted here (on the order of several decades) is too long to properly detect and illustrate this phenomenon, but other studies for this area provide evidence supporting the thesis.

On land, glacial systems evolved at very variable paces, which can be associated with variable topoclimatic and local conditions in western Sørkapp Land. Recession was fastest in the region's western- and southernmost glaciers, where air masses from the Greenland Sea and the warm West Spitsbergen current are in effect (Ziaja et al., 2016). Aside from clear frontal retreat, there was also a significant decrease in thickness in their longitudinal profiles (Fig. 16). In the small, westward, low-lying valley glaciers this was especially pronounced, especially in the middle and lower parts of the snouts, where smaller patches of dead ice emerged in places.

Although glacial recession was the predominant phenomenon in the land-based glaciers of western Sørkapp Land, the warming effect was in some places mitigated by the terrain and the significant elevation of the mountain massifs from which some of the glaciers originate. Being favourably located either at a significant elevation or in the shadow of high mountains stabilised the situation somewhat for some glaciers here, because their maintenance or local increase of mass was favoured by both an orographic increase in snowfall and additional supply from avalanches. This applies, for example, to Nordfallbreen, which is shaded from the south, and small glaciers originating on the slopes of the Hornsundtind and Kvassegga groups of mountains.

Nordafllbreen is adjacent to the high hill Nordfallet (824 m a.s.l.) to the south, which on the one hand shades it against the sun while also providing it additional supply by avalanche. Mehestbreen is similarly fed, being bordered to the east by the Mehesten (1,383 m a.s.l.) and Hestskanka (997 m a.s.l.) massifs, and by Hoven hill (869 m a.s.l.) to the north. Their influence is seen in the spatial distribution of positive values on the maps of glacier altitude changes, more of which lie closer to the glacier's eastern edge. An additional factor limiting ablation on the Mehestbreen is its significant elevation, which puts a large part of the glacier's surface above the mass balance equilibrium line.

There are few studies that the results of this study of the peninsula's surface glaciation recession can be compared against. In the older literature, such analyses were carried out for individual glaciers (Jania, 1987; Schöner and Schöner, 1997) or at the regional scale at best (Jania, 1988). However, the observed trends in changes in Sørkapp Land glacier elevations in 1961–90 are comparable to other areas of Spitsbergen, although the number of studies of similar temporal coverage is limited (Nuth et al., 2010; Małecki, 2013; Błaszczyk et al., 2013).

6 Conclusions

Correctly assessing the utility of the series of maps issued by the Institute of Geophysics of the Polish Academy of Sciences is very important in order to precisely determine changes in glacier geometries in western Sørkapp Land. Ignorance of the principles on which they were compiled may lead to conclusions drawn as to the glacier recession rate being erroneous and, consequently, recession being overestimated for the years 1984–90, as the apparent status in 1984 would be contrary to reality. Specifically, the misapprehension lies in the fact that, although the IGF PAN field campaign was conducted in the early 1980s, the maps published after the expedition were based on elevation data taken from aerial photos from 1961, upon which only glacier extents were updated (with a change in colour of contours). Crucially, contour lines were not updated in this 1984 edition, and continued to represent the greater elevations of 1961.

In response to this, the map coordinates on the 1961 map have now been corrected, so that it can be used for comparative analyses of changes in glacier surface elevations over the years 1961–90. This is especially true of the glaciers that are entirely land-based, for which data relating to their entire surface area is now corrected and complete.

However, the value of data on tidewater glaciers for various types of comparisons is limited to their upper parts (above the line of their 1984 extents). This is because updating their extents in 1984 required that contour lines between the extents designated for 1961 and 1984 be deleted and that the elevation of this surface be zeroed on the map, i.e. brought to sea level. Therefore, when analysing the IGF PAN sheets, it is impossible to determine the exact height of the ice cliffs of the Körberbreen, Petersbreen, Kvaseggbreen and Eggbreen tidewater glaciers in 1961.

Accordingly, this study finds that, in the years 1961–90, the maximum lowering of surface was about 80–85 m in the largest land-terminating glaciers of the peninsula, and over 90 m in tidewater glaciers (above the line marking their 1984 extents).

Glaciated areas aside, the surface-corrected IGF PAN maps can also be used to analyse landscape dynamics, including changes going on in marginal zones. The only exception is the areas of very steep slopes that are marked with the rock signature on the source maps.

7 Data availability

All data is available at Zenodo service (https://doi.org/10.5281/zenodo.4573130) (Dudek and Pętlicki, 2021). Data format: ESRI shapefile and GeoTIFF. The datasets contain vector layers (topographic and glacier outlines) and Digital Elevation Model (DEM) covering western part of Sørkapp Land peninsula, Svalbard, for the year 1961. The first shape file *glacier_1961_western _Sorkappland.shp* contains the glacier areas manually delineated from vertical aerial photos captured during the historical photogrammetric overflight commissioned by the Norwegian Polar Institute on August 24 and 25, 1961. The shape file *contour_1961_10m_western_Sorkappland.shp* contains contour lines with intervals of 10 m based on digitized historical maps edited in 1987 by Institute of Geophysics of Polish Academy of Sciences and registered using cartographic grid and elevation points. Shape file *peak_1961_western_Sorkappland.shp* contains elevation points – topographic and triangulation – used in the process of vector data registration. Shape file *rock_1961_western_Sorkappland.shp* delineates areas very steep presented on the source maps as a rock cliff symbols. This file also indicates areas where highest elevation errors in the generated Digital Elevation Model are plausible. All shape files were produced in the UTM projection system (northern hemisphere, zone 33) based on WGS84 ellipsoid (datum D_WGS_1984). The raster file *dem_1961_20m_western_Sorkappland.tif* contains Digital Elevation Model (DEM) with 20 m resolution generated from corrected contour lines.

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