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A COMPARATIVE STUDY ON ICE THICKNESS DETERMINATION IN VALLEY GLACIERS OF THE SØR RONDANE, ANTARCTICA: RADIO ECHO SOUNDING AND GRAVIMETRIC METHOD

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Abstract: In the austral summer of 1986–1987 (JARE-27 and -28), both radio echo sounding and gravity surveys were carried out for measuring ice thickness in the Sør Rondane Mountains, Antarctica. Comparative measurements were carried out along test lines across two outlet glaciers, Gjelbreen and Gunnestadbreen. Taking the radar thicknesses as standard, it appears that the reliability of the gravity method depends highly on the number of gravity stations, especially near the side, and on the modeling procedure employed. However, our measurements indicate that the gravity method can give comparable results of ice thickness to those obtained by the radio echo sounding technique when sufficient care is taken. An underestimate of 10% in ice thickness and ice discharge is inferred regarding the previous gravity results in their study to evaluate the total ice flux through the Sor Rondane Mountains.

1. Introduction

Over the vast ice covered areas of the continental ice sheets—remote from steep mountain ranges and nunataks—the infinite slab method to calculate ice thickness from gravity measurements has been widely used in the past. The method was particularly useful for rapid ice thickness determinations between seismic reflection stations of oversnow traverses for more than ten years during and following the IGY.

The method became largely obsolete when airborne radio echo sounding was introduced in the late sixties. The latter method allowed, for the first time, rapid and accurate measurements over terrain which is characterized by difficult and dangerous access. Large scale mapping of the subglacial relief became possible and was carried out both over Eastern and Western Antarctica (DREWRY, 1983).

However, within mountain ranges, over narrow outlet glaciers, cirque glaciers etc., both methods suffer from the disturbing effects of the valley sides. For the gravity method this implies the application of difficult topographic corrections and the choice of an adequate modeling procedure to calculate the subglacial profile. Moraine cover near the valley walls might prove a serious obstacle for radio echo sounding while the non vertical reflections also hinder the straightforward interpretation of the records.

Here we report on a comparison of the gravity method versus the radio echo sounding technique. The test has been carried out along two lines across oultet glaciers of the Sør Rondane in Queen Maud Land. The results allow us to evaluate the global ice flux through the Sør Rondane as previously reported by VAN AUTENBOER and DECLEIR (1974, 1978) based on gravity data only.

2. Ice Thickness Measurement in the Sør Rondane, Antarctica

VAN AUTENBOER and BLAIKLOCK (1966) and VAN AUTENBOER and DECLEIR (1974, 1978) applied the gravimetric method systemactically in an approach to estimate the total glacier discharge through the 220 km long Sør Rondane Mountain Range (Queen Maud Land, Antarctica). In this respect, cross sections of the most important outlet glaciers were constructed using Talwani's method (TELFORD *et al.*, 1976) for modeling 2-D gravity anomalies. With the closing of Base Roi Baudouin in February 1967 the first era of pioneering field investigations in this part of Queen Maud Land came to a standstill. In 1985 a new station, Asuka, 50 km to the north of the Sør Rondane Mountains, was established by the Japanese Antarctic Reseach Expedition (JARE-26) serving both as an observatory and as principal support station for extensive field work in this mountain range close to the polar plateau. Both airborne and oversnow radio echo sounding surveys were carried out for the first time during the austral summer 1986–1987. Use was made of a pulsed radar system operating at a center frequency of 179 MHz, designed by the National Institute of Polar Research (NIPR) and built by Meisei Denki Co., Tokyo. The technical specifications of the different components of this equipment are described by WADA and MAE (1981), and NISHIO *et al.* (in preparation).

That same season, a Belgian team participated in JARE-28 to investigated the subglacial morphology in the central part of the Sør Rondane both by ice radar and gravity measurements (DE VOS and DECLEIR, 1988). For this purpose a newly developed "backpack" radio echo sounder (Scott Polar Research Institute) was used. It was anticipated that, especially near the valley walls and over the moraine covered ice surface, such a portable instrument would be advantageous. However, due to instability and power problems with the radar equipment in the field, the ice thickness determinations were mainly restricted to gravimeter measurements. The gravity was measured with a standard Worden gravimeter. Profiles across valley glaciers were chosen between well identifiable points on the rock at both sides of the glacier so that location and distance between the gravimeter stations could be easily determined from the mileage reader of the snow scooter. In the middle of the glacier, distances between the gravity stations were generally 0.5 or 1 km. Altitudes were determined at every station by aneroid altimetry. However, near the valley-sides, position and altitude of the gravimeter stations, both on the glacier and on the adjacent rock, were determined by theodolite tacheometry. Here the distance varied between 100 and 500 m. As most of the profiles were run back and forth, altitudes and gravimeter mesaurements were taken as means of two values. This procedure eliminated instrument drift.

3. Interpretation of Gravimeter Ice Thickness Measurements

Unlike radio echo sounding, the gravimetric method for ice thickness determination requires difficult modeling and is not always unambiguous. The ice thickness in a valley glacier cross-section is calculated by an iterative procedure in which the computed gravity effect of a model cross-section is compared with gravity values measured on the glacier surface (DE VOS and DECLEIR, 1988). Generally the areal integral representing the gravity effect of the two-dimensional ice mass is replaced by a line integral which is then numerically solved by a polygonal approximation of the periphery of the ice body (Talwani's method, see *e.g.*, TELFORD *et al.*, 1976). In our case the upper vertices of the polygon—which correspond with the gravimeter observation stations— are known, while the lower vertices—vertically beneath the same observation points—relate to the unknown subglacial bedrock (Fig. 1a).

It is also possible to compose the unknown ice mass of a set of rectangular vertical ice prisms extending from the bedrock to the ice surface. Each prism then has a gravimeter station as boundary in the horizontal x-direction (Fig. 1b).

It is clear that the results of both methods, which will henceforth be referred to as the polygonal and the prism method respectively, converge if the number of measuring stations becomes large.

4. The Ice Thickness Profile over Gjelbreen

In 1986–87, a 12 km long oversnow traverse was carried out independently by a Japanese party (F. NISHIO and H. OHMAE, radar sounding) and a Belgian team (H. DECLEIR and L. DE VOS, gravity) over Gjelbreen, one of the central outlet glaciers in the Sør Rondane. Profile 1, which crosses the glacier flow lines more or less orthogonally, is situated between Brattnipane and Austkampane (Fig. 2). The same route was previously covered by VAN AUTENBOER (VAN AUTENBOER and DECLEIR, 1974). While the radar echo was nearly continuously recorded in a moving snow vehicle, the gravity values were obtained at 20 observation stations: 2 stations on rock at each side of the glacier and 16 stations on ice. The radio echo sounding results (Fig. 3) indicate the existence of a typical glacial trough filled with 1400 m thick ice. The lowest part of the valley floor lies some 120 m below sea level. The form of the valley is asymmetric with a steep eastern valley side where—close to the Austkampane Nunatak—no bedrock radar echo could be observed. Figure 3 also shows the gravimeter in-

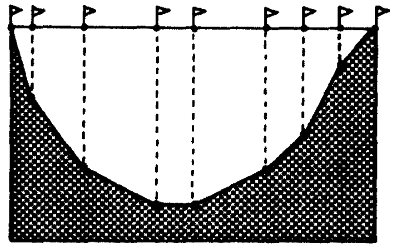

Fig. 1a. Polygonal approximation of glacier cross section.

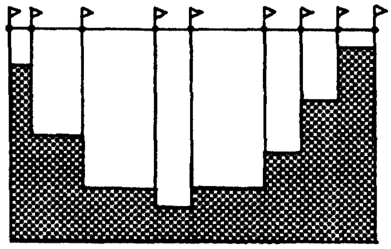

Fig. 1b. Prism approximation of glacier cross section.

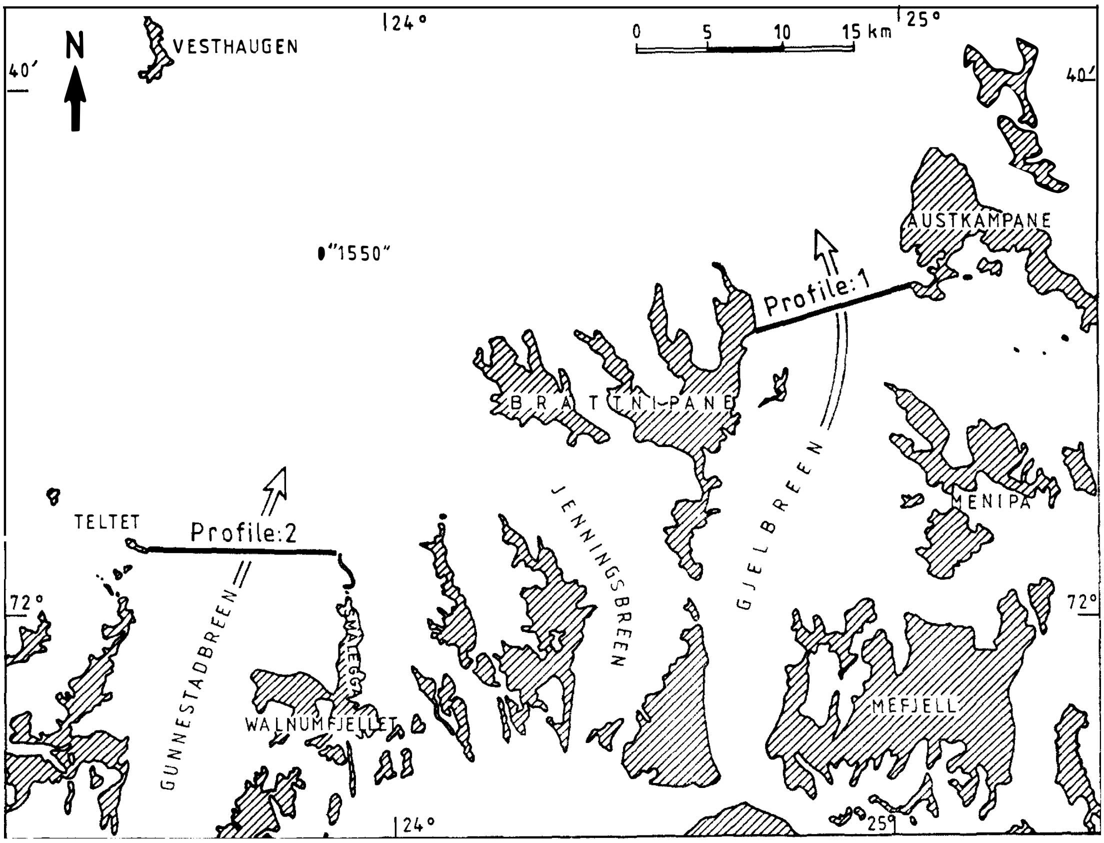

Fig. 2. Situation of test profiles in the Central Part of the Sør Rondane.

Table 1. Modeling results (polygonal method) for Gjelbreen after different iteration steps. Root mean square (rms) of (i) the difference between observed and calculated gravity in mgal. (ii) the difference between radar and gravity ice thickness in meter.

Iteration number	rms (observed-calculated) gravity	rms (radar-gravity) ice thickness
1	8.05 mgal	143 m
5	0.90	103
10	0.53	132
35	0.31	247

terpretation of the profile based on the polygonal method.

As explained above, such a gravimeter profile is obtained by an iteration process, where after each iteration the computed and the observed gravity anomalies are compared for all stations and the rms (root mean square) of the difference is calculated. This difference diminishes rapidly (Table 1), from 8 mgal to 1 mgal during the first 5 iterations. Once it falls below 1 mgal, the difference decreases rather slowly. Table 1 makes clear that, although the difference between observed and computed gravity diminishes with each iteration step, this is not the case for the rms value of the difference between ice radar and gravimeter ice thicknesses. The latter difference also diminishes

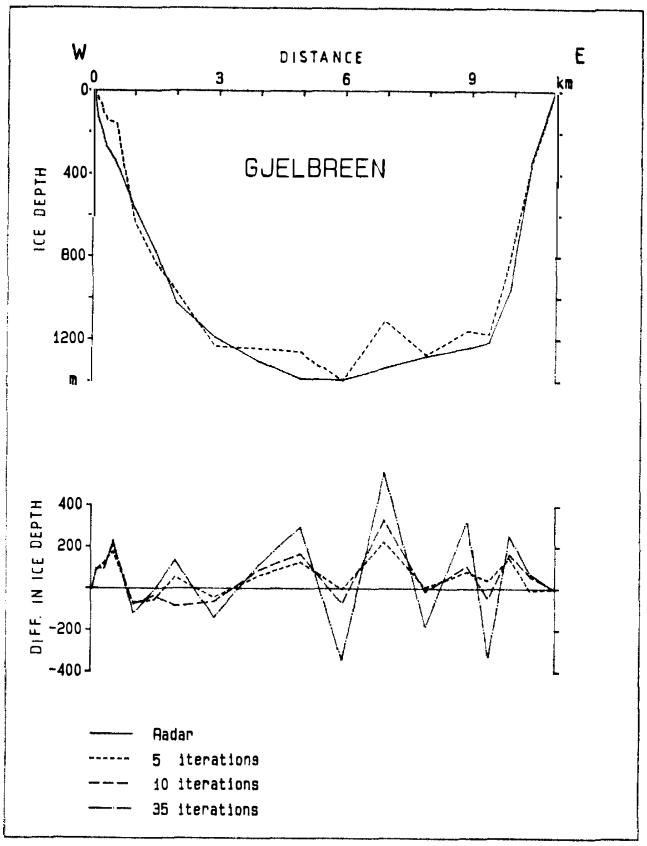

Fig. 3. Top: comparison of radar and gravity (polygonal method) ice thickness for Gjelbreen.
Bottom: difference between radar and modeled gravity ice thickness after different iteration steps.

very rapidly during the first steps but attains a minimum at about 5 iterations (103 m) and then starts to increase again. Figure 3 (bottom figure) and Table 1 show how the increasing fit between observed and computed gravity—once it is below 1 mgal—appears as enhanced zigzag ice thickness profile as the number of iterations increases especially in the lower part of the valley floor. This instability is caused by the extreme low sensitivities of the gravity values which characterize the low density of stations situated over the deepest part of the valley. Here a small change in gravity corresponds to a very large increment in ice thickness. Moreover, because each new profile is adapted from the previous one by changing the vertices—which are precisely located underneath the observation points—a possible measuring error has maximal effect in shifting the subglacial bedrock up and down under the measuring station.

Figure 4 and Table 2 present the results of the gravimeter interpretation obtained by the prism method. While the approximation of the ice mass by rectangular prisms fails to accomplish a better fit between observed and computed gravity (1.17 mgal versus 0.9 mgal after 10 iterations) it produces significantly better ice thickness results. With this method the measuring errors are no longer concentrated in the vertices, but are spread over the entire block. The relatively good agreement between radar and gravity ice thicknesses obtained with the prism method is depicted in Fig. 4. Both the asymmetry of the glacial valley and the maximum ice depth are well represented as compared to the radar results. The discrepancy close to the valley walls might be due to the relative scarcity of radar measurements near the side. Clearly a better designed and coordinated experiment is needed to study the relative merits of both

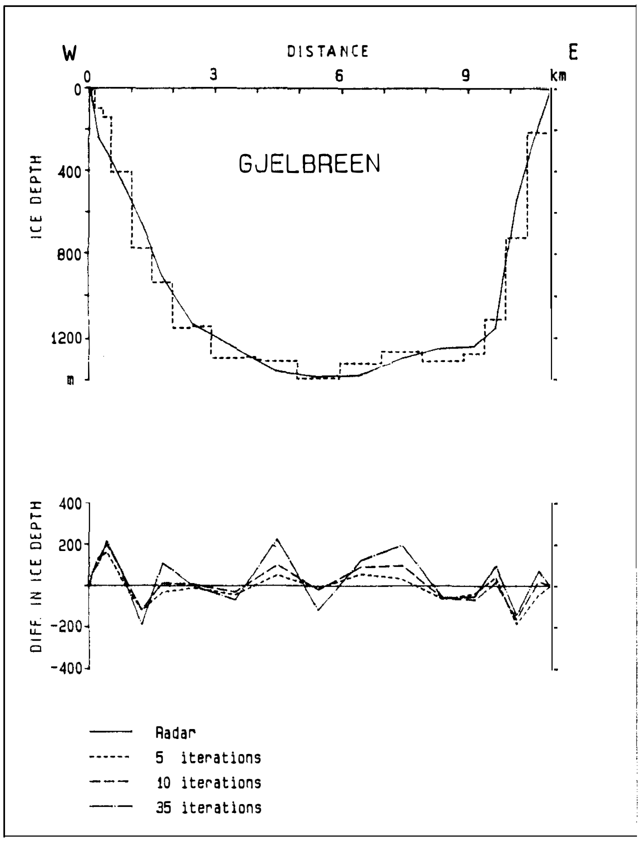

Fig. 4. Top: comparison of radar and gravity (prism method) ice thickness for Gjelbreen.
Bottom: difference between radar and modeled gravity ice thickness after different iteration steps.

Table 2. Modeling results (prism method) for Gjelbreen after different iteration steps. Root mean square (rms) of (i) the difference between observed and calculated gravity in mgal. (ii) the difference between radar and gravity ice thickness in meter.

Iteration number	rms (observed-calculated) gravity	rms (radar-gravity) ice thickness
1	9.85 mgal	124 m
5	1.17	84
10	0.90	93
35	0.77	129

methods at the margin of the glacier.

It is interesting to compare the present gravity results with those obtained during previous Belgian expeditions. The purpose of the ice thickness measurements was then to estimate the total ice discharge through the Sør Rondane so that only six gravity stations were occupied over Gjelbreen. From the data report published by VAN AUTENBOER and DECLEIR (1974) the ice thicknesses were recalculated using the present computing algorithm (DE VOS and DECLEIR, 1988). The polygonal method (Fig. 5, right hand side) gives a significant underestimation of the ice thickness, not withstanding the excellent fit between observed and modeled gravity anomaly (0.64 mgal after 5 iterations). With the prism method, on the other hand (Fig. 5, left hand side),

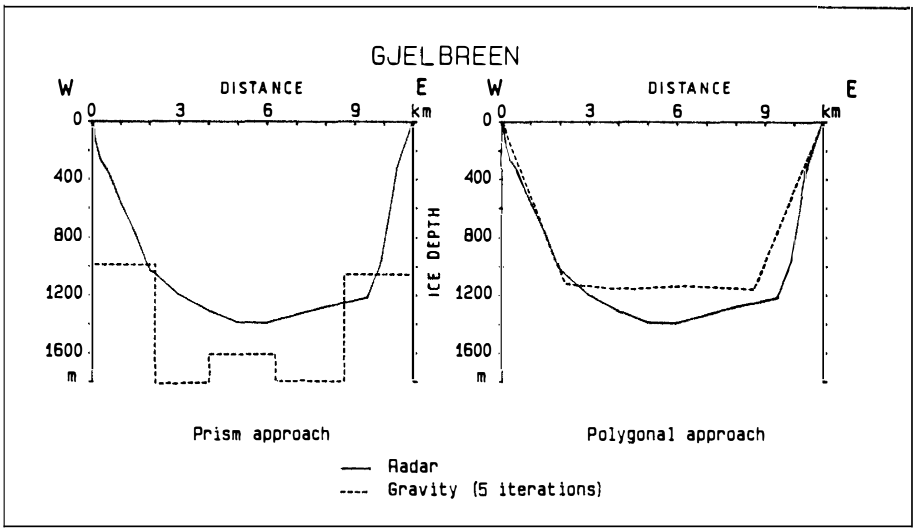

Fig. 5. Comparison of radar and gravity ice thickness (gravity data taken from VAN AUTENBOER *and* DECLEIR *(1974)) for Gjelbreen. Left: prism approach, Right: polygonal approach.*

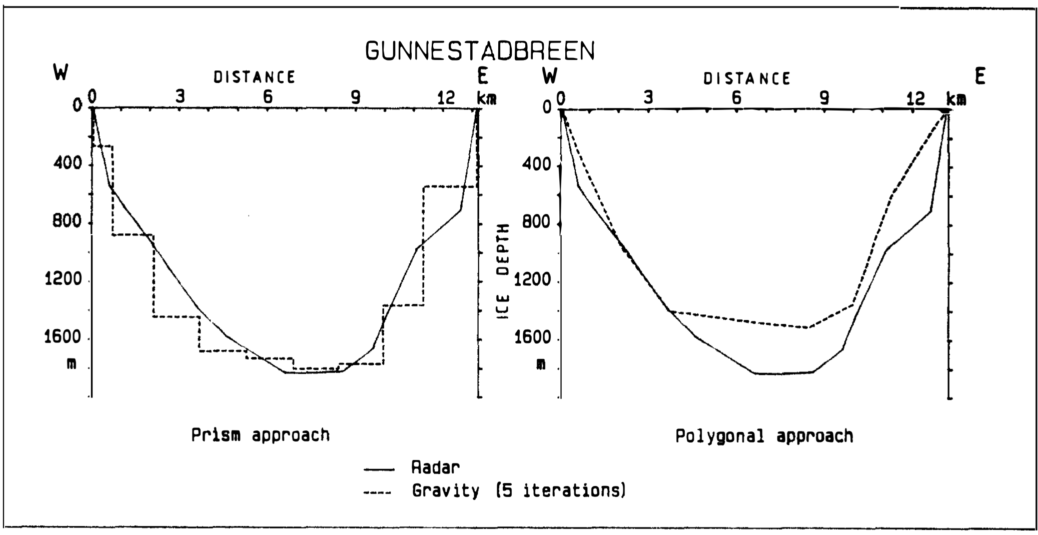

Fig. 6. Comparison of radar and gravity ice thickness (gravity data taken from VAN AUTENBOER *and* DECLEIR *(1974)) for Gunnestadbreen. Left: prism approach, Right: polygonal approach.*

the ice thicknesses are much in excess of what is being observed by radar. This difference in modeling results is clearly due to the fact that the first stations on ice were situated more than 2.5 km from the reference stations on rock. This leads, in the prism method, to the introduction of an exaggerated precipice as valley wall while the opposite is true—*i.e.* a comparatively gentle slope on the eastern side—in the polygonal model. Since similar conclusions can be inferred from the modeling of Gunnestadbreen (Fig. 6), it can be stated more generally that, with a relatively thin density of stations, the polygonal method will result in underestimation and the prism method in gross overestimation of the actual ice thickness.

5. The Ice Thickness Profile over Gunnestadbreen

Another interesting ice thickness cross profile which is suitable for a comparison of the radio echo sounding and gravimeter methods is a 14 km long traverse over Gunnestadbreen (Profile 2, see Fig. 2). Since this line was not included in the 1986–1987 gravimeter survey, one has to use old gravimeter data published by VAN AUTENBOER and DECLEIR (1974) for comparison with the Japanese radio echo sounding measurements. The gravimeter line crosses Gunnestadbreen from Teltet Nunatak to the "Smallega" Ridge, while the 1986–87 radar sounding line runs just north of the nunataks. Practically continuous recording exists for the radio echo sounding profile while data on 10 gravimeter stations were available for the gravity method. Figure 6 shows the results for the polygonal method and the prism method, each of them compared with the radio echo sounding data for ice thickness. The radio echo sounding indicates a very deep glacial valley with the central part more than 500 m below sea level. Once more the prism method gives better results than the polygonal method with a maximum ice depth of 1803 m; this is within 30 m of the radio echo sounding results. The maximum ice depth from the polygonal method reaches only 1517 m. Again this might be explained by the scarcity of gravity stations near the valley side (the first gravity station on the eastern side of the glacier was taken at 2 km where the bedrock is steepest). This leads to an underestimation of the valley side steepness and produces smaller negative gravity anomalies on the reference stations on the rock and hence lower overall ice thickness.

6. Conclusion

One should realize that a strict comparison of gravity and radar ice thickness is only possible when both methods have been carried out simultaneously. This was certainly not the case in the present experiment. Nevertheless the results along two test lines are mutually consistent and the following conclusions can be drawn:

(i) The iterative procedure in gravity modeling leads to an unavoidable instability, especially when using the polygonal method. The increase in number of iterations is certainly no guarantee of better ice depth measurements.

(ii) The best results were obtained after 5 iterations when generally the rms difference between observed and computed gravity anomaly was below 1 mgal.

(iii) In the case of a sufficienty high density of gravity stations the prism method is to be preferred because it is less liable to instability. However, when only very few gravity stations are available, the prism method overestimates the ice thickness because it produces an exaggerated vertical wall effect near the side of the glacier.

(iv) In view of the present results, and since in the previous work of VAN AUTENBOER and DECLEIR (1974, 1978) the gravity modeling was carried out with the polygonal method, an underestimate of 10% both in ice thickness and in ice discharge of these authors' results can be inferred.

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