4. Int. Symposium Glacier Caves and Cryokarst Rudolfshütte/Salzburg

Salzburger Geographische Materialien
Vol. 28, Salzburg, 1998, pp. 73 - 80

4th Int. Symposium on Glacier Caves and Cryokarst in Polar and High Mountain Regions
Sept. 1-7, 1996, Rudolfshütte, Salzburg/Austria

Structure and regime of the King George Island ice sheet, South Shetland Islands, Antarctica, as a typical glacier in the south subpolar region

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Abstract

Results of ground-based radio echo-sounding collected along the main ice divide of the King George Island ice cap in December 1995 using a 40 MHz monopulse radar are presented and discussed. Ice thickness up to 327 m were measured near the top of the larger ice domes B and C. Three internal reflecting horizons were revealed between ice domes A and B, in the area where there are two outlet glaciers flowing in opposite directions. Because the ice temperatures are close to melting point, these reflecting horizons can be caused by englacial water inclusions. Analysis of data available on radar-measured maximum and average ice thickness and areas of island ice caps in the Eurasian Arctic and the South Shetland Islands show the close, but variable relationships for ice caps with and without well-expressed net of outlet glaciers. The King George ice cap belongs to the second group and its maximum and average ice thickness are approximately 55-70 m less than these values for the first group of island ice caps. Therefore further studies of outlet glaciers are important for the understanding of the general response of the King George Island ice cap to climatic changes and their influence should be taken into account in numerical modelling of the dynamics and evolution of the ice caps as a whole.

Introduction

Radio echo-sounding investigations were performed in November-December 1995 by a seasonal detachment of the 41 Russian Antarctic Expedition on Bellinshausen Station and by the International Glaciological Expedition organised by the Federal University of Rio-Grande do Soul, Brazil, as a part of SCAR supported International Program "Glaciology of South Shetlands (GLASS)" aimed at the investigation of contemporary state and evolution of subpolar ice masses of the Antarctic region and at estimation of their response to short-term environmental changes.

King-George Island - the largest (1313 km^2) of the South Shetland Islands (Fig. 1) is suitable for these investigations considering its location on the way of the main moisture-laden cyclones feeding the glaciers in the western section of the Antarctica. This ice cap consists of a few ice domes up to 700 m in elevation that are drained by a series of relatively fast-moved tide-water outlet glaciers (Fig. 2). These glaciers are the main source of ice discharge due to summer melting and ice calving which is filling up by intensive winter and summer solid and liquid precipitation. Therefore a more detailed

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study of these dynamically active parts of the ice cap can be considered as a key for understanding its present state, regime and dynamics in general and its response to short-term climate variations.

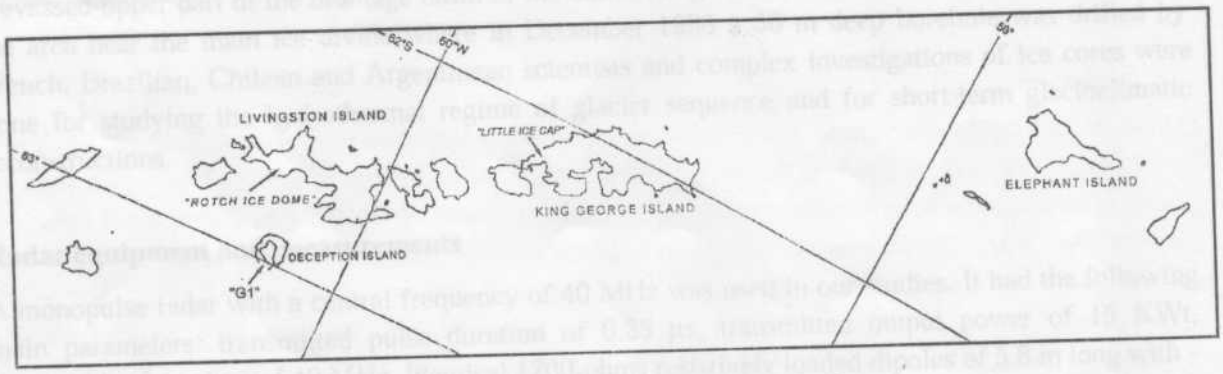

Fig. 1. Index map of South Shetland Islands.

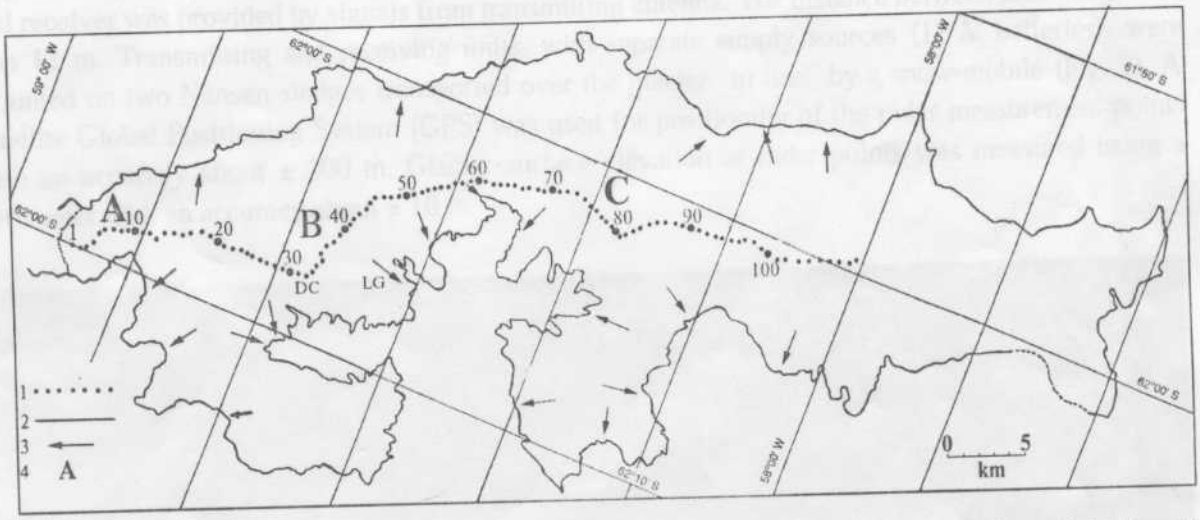

Fig. 2. Ground-based radio echo-sounding measurements on King George ice cap in December 1995. 1 is radar points; 2 are the margins of King George Island; 3 are outlet glaciers; 4 are main ice domes.

To solve this problem it is very important to know such characteristics of glaciers as their structure and hydrothermal regime including ice thickness, subglacial relief and internal structure. These data also are needed for numerical modelling of the response of glaciers on climate change and predict their long-term variations in dynamics and regime.

Previous data on these characteristics were collected in Nelson and King George Islands in 1970-1995 from ice core studies to the depths of 10-70 m [Ren and others, 1995; Estudio, 1993] as well as from ground-based and airborne radio-echo sounding measurements in VHF and UHF ranges [Ren and others, 1995; GOVORUKHA and others, 1974; SIMOES and BREMER, 1995; GLAZOVSKY and MOSKALEVSKY, unpublished]. They have shown that the ice temperatures in accumulation areas of these islands are close to melting point and maximal ice thickness on smaller Nelson ice cap (area 156,6 km^2, maximal elevation 324, 6 m) and larger King George ice sheet are 169 m and 357 m, respectively. However, bedrock reflections were recorded only on some short sections of King George Island ice cap because of strong scattering of radio waves on englacial inhomogenities such as water inclusions, ice layers and lenses of various density and structure.

Taking into account the previous data obtained, one of the basic aims of the field work was to obtain data on ice thickness and subglacial relief along the main ice divide of King George Island ice cap in

order to choose a suitable site for deep ice core drilling and for studying the glacier structure and obtaining information about past glacioclimatic conditions and to measure the ice thickness in non-crevassed upper part of the drainage basin of the outlet Lange Glacier (total area 27,6 km^2) including the area near the main ice divide where in December 1996 a 50 m deep borehole was drilled by French, Brazilian, Chilean and Argentinean scientists and complex investigations of ice cores were done for studying the hydrothermal regime of glacier sequence and for short-term glacioclimatic reconstructions.

Radar equipment and measurements

A monopulse radar with a central frequency of 40 MHz was used in our studies. It had the following main parameters: transmitted pulse duration of 0,25 μs, transmitted output power of 15 KWt, bandwidth of receiver of 40 MHz. Identical 1700-ohms resistively loaded dipoles of 5,8 m long with -10 dB gain were used as transmitting and receiving antennas. A portable oscilloscope and a portable magnetic tape-recorder for registration of received signals were used. Synchronising of transmitter and receiver was provided by signals from transmitting antenna. The distance between antenna centres was 12 m. Transmitting and receiving units, with separate supply sources (12 V batteries), were mounted on two Nansen sledges transported over the glacier "in line" by a snow-mobile (Fig. 3). A satellite Global Positioning System (GPS) was used for positioning of the radar measurement points with an accuracy about ± 200 m. Glacier surface elevation at radar points was measured using a barometer with an accuracy about ± 10 m.

Fig. 3. Radio echo-sounding measurements on King George Island ice sheet with a monopulse radar in December 1995.

Measurements on the glacier were conducted from 8 to 20 December 1995. During 6 days with relatively good weather the radar measurements were carried out at 109 points situated at the distance

of about 0,5 km over a 55 km long profile along the main ice divide on King George Island and crossing some outlet glaciers in their upper parts (Fig. 2).

Results of radar measurements

An example of an oscillogram collected in the western part of King George Island ice cap, at point 6, is shown in Fig. 4. Three groups of signals were distinguished on records: transmitted pulses (T) of constant form as two half-period (as result of double differentiation of transmitted signal by receiving and transmitting antennas); bedrock reflections (B) and internal reflections (R). As a rule, bedrock reflections had a form close to transmitted signals or differed from them by a number of half-periods and the ratio of their amplitudes due to spatial variations in total electromagnetic energy losses and in the character of bedrock, mainly its macroroughness. This criterion, together with small changes in delay time while replacing along the radar profile from point to point, served as the main one for distinguishing the bedrock reflections on oscillograms and magnetic records.

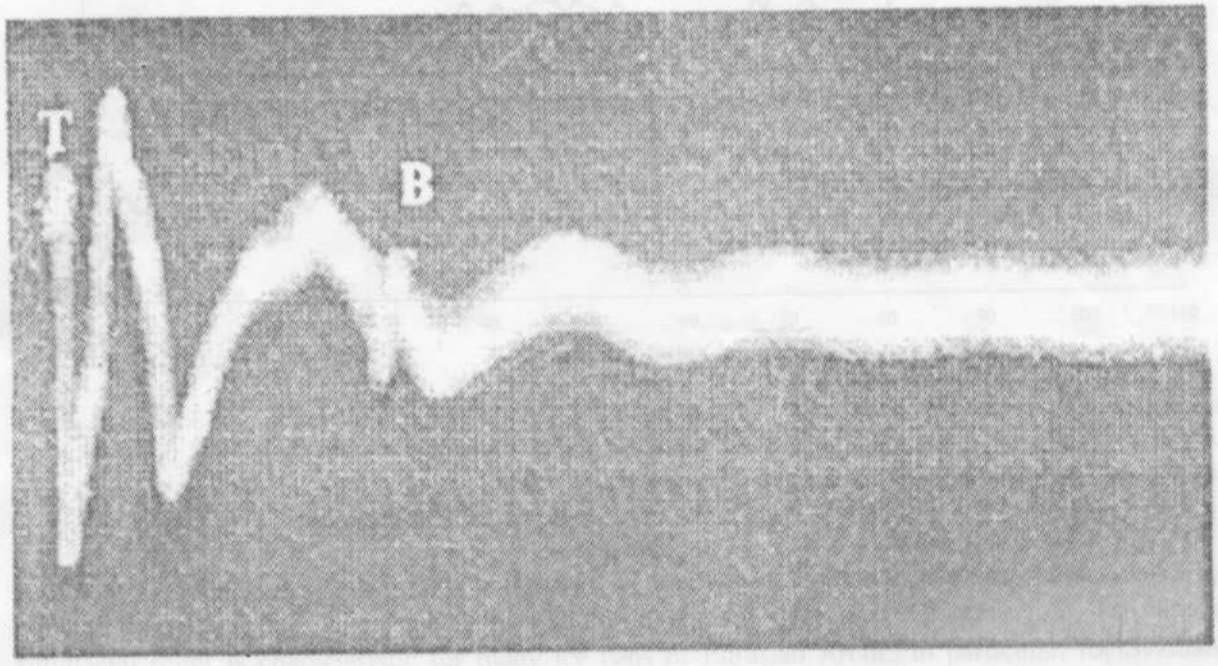

Fig. 4. Examples of radar record with bedrock reflection (B) collected with a monopulse radar in December 1995 at site 6. T is transmitted pulse.

At 78 measurement points (72 % of the total) bedrock reflections from the depths to 250-300 m exceed noise and interference level are distinguished on enlarged oscillograms and look like as in Fig. 4; at nine points (eastward of Collins ice dome) internal reflections were also recorded. In the rest of the points the amplitude of bedrock reflections have confused with the noise of receiver and could be distinguished only on the initial enhanced records.

Taking into account the small distance between antennas, the ice thickness was calculated as $h = V\tau/2$ where V is an average radio wave velocity in glacier ice; τ is delay time of reflected signals from the bedrock measured by oscillograms. According to the data of radio waves velocity measurements in temperate glaciers [MACHERET and others, 1993], value of V is taken equal to 161 m/μs.

The results of radar measurements along the main ice divide of the King George Island ice cap are given in Fig. 5. Along this profile, the largest ice thickness were measured near the top of ice domes B and C (points 34 and 78); they reach 317 m and 327 m being much larger than at points 5 and 6 (99 m and 82 m) at the top of Collins ice dome. In the upper parts of outlet glaciers, between ice domes A

and B (points 7-11), the ice thickness is 82-150 m and bedrock lowering is distinctly noticeable. In this area, between points 8 and 20, three internal reflectional horizons at depths intervals of 50-100, 95-265 and 130-135 m were found which could be connected with englacial water inclusions. In the upper part of the outlet Lange Glacier, at the drill camp (point 32) near the top of ice dome B, the ice thickness is equal to 267-317 m. Between ice domes B and C (points 55-75) ice thickness varies from 140 to 300 m.

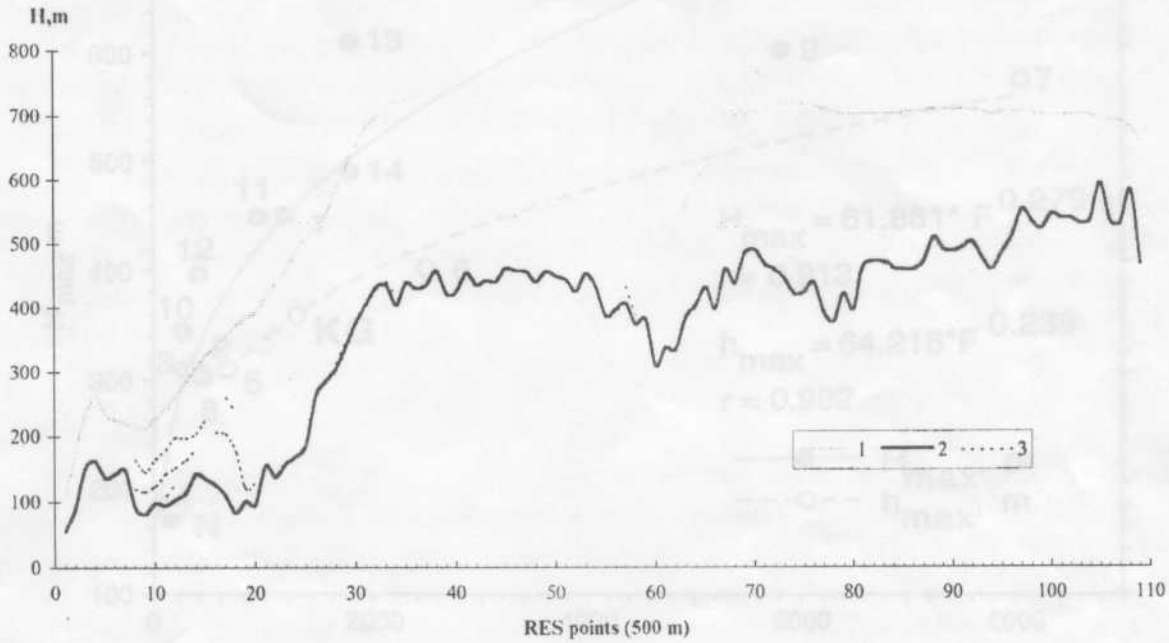

Fig. 5. Results of ground-based radio echo-sounding on King George Island ice cap collected with a monopulse radar in December 1995. 1 is glacier surface; 2 is glacier bottom; 3 are internal reflection horizons. Glacier surface elevation have measured by a barometer at points from 1 to 32 and taken from British map in scale 1:200.000 at points from 33 to 109.

In general, subglacial relief repeats the glacier surface topography and is characterised by comparatively large bedrock irregularities with elevation changes up to 50-100 m (Fig. 5). The similar subglacial relief is characteristic for many ice caps of Eurasian Arctic, in particular, for Svalbard [MACHERET and ZHURAVLEV, 1985; MACHERET and others, 1992] and Franz Josef Land [DOWDESWELL and others, 1996]. Comparison of data obtained (Fig. 5) and radar data by GOVORUKHA and others (1974), taking into account possible differences in positioning of both radar profiles, shows satisfactory coincidence for Collins ice dome (between points 1 and 8) and on the western slope of ice dome B (between points 25 and 31), and large (more than 1,5-2 times larger) differences in all the other parts, especially between points 32 and 36. It can supposed that these differences between points 8 and 15 result from either incoincidence of both radar profiles in position or from misinterpretation of internal reflections by GOVORUKHA and others (1974): internal reflections recorded by us were taken for bedrock reflections. For two other areas on the western slope and near the top of ice dome B, the large differences can be related to incoincidence of radar profiles.

Discussion and conclusions

The main results of ground-based radio echo-sounding survey carried out in December 1995 are a successful application of a portable monopulse radar with a central frequency of 40 MHz for sounding

the temperate ice cap in King George Island and obtaining new data on its ice thickness and internal structure along the main ice divide which change the previous ideas on its subglacial relief. These data show ice thickness (up to 327 m) near the top of the largest ice domes B and C (Figs. 2 and 5) and the absence of abrupt bedrock rises in their top part as it followed from measurements of GOVORUKHA and others (1974) and the important influence of outlet glaciers on subglacial bedrock topography.

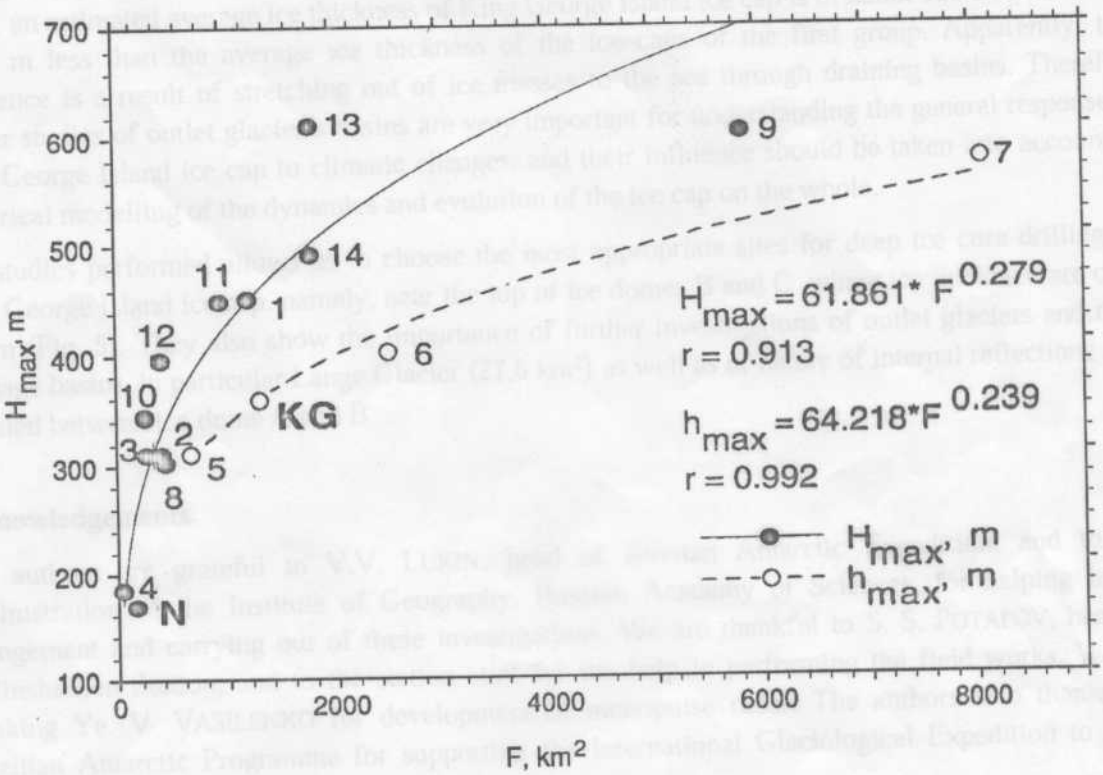

Fig. 6. Relationships between glacier area (F) and maximal ice thickness (h_{max}) on island ice caps in Eurasian Arctic and South Shetland Islands. Svalbard, Nordaustlandet: 1 - Vestfonna, 2 - Austfonna-Sorfonna [Macheret, Zhuravlev, 1995; Macheret and others, 1992]; Franz Josef Land: 3 - Loonney (Alexandra Land) [Macheret and others, 1993], 4 - Graham Bell (Graham Bell Island), 5 - La-Roncier (La-Roncier Island), 6 - Eva-Liv (Eva-Liv Island), Freden (Freden Island) [Dowdeswell and others, 1996]; Severnaya Zemlya: 8 - Shmidta (Shmidta Island), 9 - Academii Nauk (Komsomoletz Island), 10 - Pioneer (Pioneer Island), 11 - Rusanova, 12 - Albanova, 13 - Vavilova, 14 - Universitetsky (Oktyabr'skoy Revolutzii Island) [Bogorodsky and others, 1970; Boyarsky and others, 1981; Semyenov, 1981]; South Shetland Islands: KG - King George (King George Island) (present data), N - Nelson (Nelson Island) [Ren and others, 1995].

Fig. 6 illustrates the contribution of outlet glaciers in the distribution of ice thickness on island ice caps in Eurasian Arctic and South Shetland Islands. It indicates a close link between the area (F) and radar-measured maximum ice thickness (h_{max}) in Nordaustlandet, Franz Josef Land, Severnaya Zemlya and South Shetland Islands which belong to two basic groups - without well-expressed net of outlet glaciers (the first group) and with wide-spread net of them (the second group). For these two groups correlation coefficients of approximating functions in form $F = a\, h_{max}^{\,b}$ are different:

$$H_{max} = 61,861\ F^{0,279} \text{ (correlation coefficient } r = 0,913), \quad (1)$$

$$h_{max} = 64,218\ F^{0,239} \ (r = 0,992). \quad (2)$$

According to data available (MACHERET and ZHURAVLEV, 1985) the relationships between average (h_{av}) and maximum (h_{max}) ice thickness of Svalbard glaciers with negative (group I) and positive (group II) subglacial relief are following:

$$H_{av}/H_{max} = 0.50 \pm 0.11 \text{ (group I)} \quad (3)$$

$$h_{av}/h_{max} = 0.64 \pm 0{,}13 \text{ (group II)} \quad (4)$$

variation between equations (1) and (2) as well as (3) and (4) defines the differences in maximum and average ice thickness of such ice caps.

Taking into account the relationships between area and maximum ice thickness of ice caps given in Fig. 6, an estimated average ice thickness of King George Island ice cap is of about 180-230 m, that is 55-70 m less than the average ice thickness of the ice caps of the first group. Apparently, this difference is a result of stretching out of ice masses to the sea through draining basins. Therefore further studies of outlet glacier's basins are very important for understanding the general response of King George Island ice cap to climatic changes, and their influence should be taken into account in numerical modelling of the dynamics and evolution of the ice cap on the whole.

The studies performed allows us to choose the most appropriate sites for deep ice core drilling on King George Island ice cap, namely, near the top of ice domes B and C where ice thickness are over 300 m (Fig. 5). They also show the importance of further investigations of outlet glaciers and their drainage basins, in particular Lange Glacier (27,6 km^2) as well as of nature of internal reflections lake revealed between ice dome A and B.

Acknowledgements

The authors are grateful to V.V. LUKIN, head of Russian Antarctic Expedition, and to the administration of the Institute of Geography, Russian Academy of Sciences, for helping in the arrangement and carrying out of these investigations. We are thankful to S. S. POTAPOV, head of Bellinshausen Station, and to the station staff for the help in performing the field works. We are thanking Ye. V. VASILENKO for development of monopulse radar. The authors also thanks the Brazilian Antarctic Programme for supporting the International Glaciological Expedition to King George Island in the austral summer of 1995/1996.

References

BOGORODSKY, V.V., L. S. GOVORUKHA & B.A. FEDOROV, 1970, Nekotorye resultaty radiolokatsionnoro zondirovaniya arkticheskikh lednikov [Some results of radio echo-sounding of Arctic glaciers]. Trudy Arkticheskogo i Antarkticheskogo naucho-issledovatel'skogo instituta [Proceedings of Arctic and Antarctic Research Institute], vol. 294, pp. 87-93.

BOYARSKY, V.I., L.S. GOVORUKHA & B.A. FEDOROV,1981, Nekotorye resultaty radioglyatsiologicheskikh issledovaniy na Severnoy Semle [Some results of radioglaciological investigations on Severnaya Zemlya]. - Trudy Arkticheskogo i Antarkticheskogo naucho-issledovatel'skogo istituta [Proceedings of Arctic and Antarctic Research Institute], vol 367, pp. 58-63.

DOWDESWELL, J.A., M.R. GORMAN, A.F. GLAZOVSKY & YU. YA. MACHERET,1996, Airborne radio-echo sounding of the ice caps on Franz Josef Land in 1994. - Materialy Glyatsiologicheskikh Isslidovaniy, no. 81, pp. 218-223.

GLAZOVSKY, A. F. AND M. YU. MOSKALEVSKY (unpublished). Glyatsiologicheskiye issledovaniya na ostrove King-Dzhordzh v yanvare 1995 g. [Glaciological investigations on King-George Island in January 1995]. - Institute of Geography, Russian Academy of Sciences. Moscow, 1995.

GOVORUKHA, L. S., V. I. CHUDAKOV & A. M. SHALYGIN,1974, Radiolokatsionnoe zondirovaniye lednikovogo pokrova o. King-Dzhordzh (Waterloo) [Radio echo-sounding of the ice sheet on King-George (Waterloo) Island]. Informatsionnnyy byulleten Sovetskoy Antarkticheskoy Ekspeditsii [Information Bulleten of Soviet Antarctic Expedition], N89, pp.15-18.

INSTITUTO ANTARCTICO URUGUAYO, Ed., 1993, Estudio de la evolution ambiental y climatica y de glaciologia en general en el casquete Collins, Isla Rey Jorge, -. Actividad Cientifica, vol. 4, pp.55-63.

MACHERET, YU.YA., A. F. GLAZOVSKY, M. YU. MOSKALEVSKY & 5 others,1992, Stroyenie, gidrotermicheskoye sostoyanie i rezhim subpolyarnykh lednikov [Structure, hydrothermal state and regime of subpolar glaciers]. In: V. M. Kotlyakov, ed. Rezhim i evolyutsya polyarnykh lednikovykh pokrovov [Regime and evolution of polar ice sheets]. St-Petersburg, Gidrometeoizdat, pp. 48-115.

MACHERET, YU. YA., M.YU. MOSKALEVSKY & YE.V. VASILENKO,1993, Velocity of radio waves in glaciers as an indicator of their hydrothermal state, structure, and regime. - Journal of Glaciology, vol. 39,no. 132, pp. 373-384.

MACHERET, YU. YA, S. A. SIN'KEVICH, L. I. BOBROVA & L. V. SANKINA,1993, Tolstchina i gidrotermicheskoye sostoyanie lednikovogo kupola Lunnyy na Zemle Frantsa Iosifa po dannym radiozondirovaniya [Ice thickness and hydrothermal state of Loonney ice cap on Franz Josef Land from radio echo-sounding data]. - Materialy Glyatsiologicheskikh Issledovaniy, N77, pp.97-104.

MACHERET, YU.YA. & A.B. ZHURAVLEV,1985, Tolstchina, ob"yem i srtoyenie lednikov [Ice thickness, volume and structure of glaciers]. - In: V.M. Kotlyakov, ed. Glyatsiologiya Shpitsbergena [Glaciology of Spitsbergen], Moscow, Nauka, p. 7-35.

REN JIAWEN, QIN DAHE, PETIT J.R., JOUZEL J., WANG WENTI, LIU CHEN, WANG XIAOJUN, QIAN SONGLIN & WANG XIAOXIANG,1995, Glaciological studies in Nelson Island, South Shetland Islands, Antarctica. - Journal of Glaciology, vol. 41, no. 138, pp. 408-412.

SEMENOV, I.V., 1981, Morfologiya lednikov Severnoy Zemli [Morphology of glaciers on Severnaya Zemlya]. - Trudy Arkticheskogo i Antarcticheskogo nauchno-issledovatel'skogo instituta [Proceedings of Arctic and Antarctic Research Institute], vol. 367, pp.9-20.

SIMOES, J.C. & U.F. BREMER, 1995, Investigation of King George Island ice cover using ERS-1 SAR and SPOT imagery. - SELPER, Special publication - Symposium " La Antarctica: un continento revelado, Ushuaia, 1995. Revista SELPER, vol. 11, No 1-2, pp. 56-60.