ISSN 1068-3739, Russian Meteorology and Hydrology, 2020, Vol. 45, No. 2, pp. 118–123. Allerton Press, Inc., 2020.
Russian Text The Author(s), 2020, published in Meteorologiya i Gidrologiya, 2020, No. 2, pp. 94–102.

Hydrological Studies of Lake Outbursts in the Antarctic Oases

G. V. Pryakhina[a]*, A. S. Boronina[a], S. V. Popov[b, a], and A. A. Chetverova[a, c]

[a]*St. Petersburg University, Universitetskaya nab. 7–9, St. Petersburg, 199034 Russia*
[b]*Polar Marine Geosurvey Expedition, ul. Pobedy 24, Lomonosov, St. Petersburg, 198412 Russia*
[c]*Arctic and Antarctic Research Institute, ul. Beringa 38, St. Petersburg, 199397 Russia*
**e-mail: g65@mail.ru*

Received October 7, 2019
Revised October 30, 2019
Accepted October 31, 2019

Abstract—The results of a detailed hydrological study of the Larsemann Hills Oases (East Antarctica) during field seasons of 2017 to 2019 are presented. The study investigates a variety of lakes' hydrological regime and the characteristics of outburst floods resulting from the lakes' water flowing through tunnels in the snow-ice dams. The hydrographs calculated by the mathematical modeling do not generally contradict the physical essence of the process of outburst flood formation.

DOI: 10.3103/S1068373920020077

Keywords: East Antarctica, hydrology, lake outbursts, mathematical modeling

INTRODUCTION

An integral part of the landscapes of Antarctic oases is water bodies whose hydrological regime is defined by their genesis, morphometric parameters, and climatic conditions. Despite the fact that oases occupy not more than 0.3% of the area of Antarctica, they are characterized by the presence of lakes with different hydrological characteristics: the lakes with the breakup during summer, the lakes with the year-round ice cover, and the lakes of the coastal zone hydrologically connected to the sea, etc. There are englacial water bodies located in the glacier margin the presence and position of which is determined either as a result of the geophysical survey or based on outburst flood traces by the glacier roof collapse. Some lakes are adjacent directly to glaciers or multiyear snowfields and impounded by them. In these cases, the feature of their hydrological regime is a dramatic water level drop resulting from the lake water discharge through subglacial tunnel or supraglacial routeway. Both a single lakes and lake systems can be drained in such a way. For the lake systems, the outburst of one of the lakes is a trigger for the outburst of the entire system. Such events are often catastrophic and lead to the malfunction of transport and logistics systems of polar stations. Subglacial lake outburst located close to Russian Antarctic Progress station (Princess Elizabeth Land, East Antarctica) occurred in January 2017 is a good example of such impact. The resulting flood destructed the road connecting the Russian and Chinese stations with the aerodrome [15]. In late January 2018, the similar outburst of the system of Lake Razlivnoe and Lake Glubokoe occurred in another part of the continent. These lakes are situated close to Molodezhnaya Russian field base (Enderby Land, East Antarctica). Despite the fact that the flood had a smaller scale, the flow demolished several metal trestles supports [3]. Besides, we should mention the outbursts of the lakes located on the territory of the Schirmacher Oasis (Dronning Maud Land, East Antarctica) which the researchers dealt with during the construction of Novolazarevskaya station in the middle of the 20th century [1].

The consequences of climate change, including increasing the hydrological hazards in particular increase of lake outbursts in Antarctica can force significant damage to infrastructure of polar stations and field bases that make the need for the detailed study of lake outbursts processes.

The main results of two-year studies of lake outbursts on the Broknes Peninsula (the area close to Progress station, Princess Elizabeth Land, East Antarctica) are presented in this paper. Their characteristics like hydrological regime and the parameters of outburst flood hydrographs obtained by the mathematic modeling are considered.

MODERN CONCEPT OF ANTARCTIC OUTBURST FLOODS

Till recently, the hydrological studies of the drainage system of Antarctic oases dealt with the determination of their morphometric and hydrochemical characteristics reported in the archival data of the Soviet Antarctic Expedition (SAE) and Russian Antarctic Expedition (RAE) which have not been published till now as well as by the scientific papers of the Russian and foreign researchers. The observations of water level, ice cover, and thermal regime of the lakes were also carried out [6, 8–10, 13, 14]. The water discharge of temporary watercourses and streams was measured under the framework of the balance studies of glaciers. Such works were performed on the lakes of the Schirmacher Oasis (Dronning Maud Land), the Bunger Hills (Wilkes Land), and the Thala Oasis (Enderby Land). The references to the episodes of lake outbursts are available in the archives of the Arctic and Antarctic Research Institute (AARI), in the research reports and information bulletins of SAE and RAE, but they are more like informational messages. As far as the authors know, still there are many investigations missing, such as the descriptions of the outburst process, the estimates of its impact on the changes in surrounding landscape and on the degree of infrastructural damage, the studies dealing with the development of the system of estimates of the outburst danger, the systematization of active lakes of East Antarctica oases based on the outburst mechanisms, the clarification of the main reasons for the cyclicity of lake outbursts, and the identification of trends in their pattern. The monitoring of active lakes is not carried out either. An exception is the hydrological studies organized a year after the catastrophic outburst of Lake Glubokoe close to Novolazarevskaya Antarctic station in January 1969 [7]. Nevertheless, the detailed studies aimed at the clarification of reasons and mechanisms of formation of outburst floods as well as at the estimation of their characteristics, started in the water bodies of the Broknes Peninsula during field season of 2017/2018 (the 63rd RAE) [2]. The glacier roof collapse on the route connecting Progress station and the aerodrome because of the glacial lake outburst forced the investigations. The phenomenological model of this event was hypothesized previously, before the field season [11]. To verify this model, both field measurements and mathematical model describing the outburst flood hydrograph formation were required.

STUDIES IN THE AREA OF THE LARSEMANN HILLS

The Larsemann Hills is an area mostly free of ice that consists of many (about 130) small and two large peninsulas (Stornes and Broknes). The total area is about 50 km^2, the territory borders with the slope of the East Antarctic Ice Sheet in the south and by Dalk Glacier in the southwest.

A typical feature of the Larsemann Hills is the developed drainage system includes more than 150 freshwater lakes. In particular, there is a vast system of water bodies in the negative landforms on the Broknes Peninsula [14]. Lakes Progress, Sibthorpe, Discussion, LH73, LH59, Reid, Scandrett, Boulder, Ledyanoe, and Stepped located close to Progress station were chosen as study objects. They have different morphometric parameters, types of hydrological and ice-cover regimes, and water sources (Fig. 1).

The field works included the installation of gaging stations at eight lakes of the oasis, the water level observation, the water discharge measurement, the bathymetric survey, and the geophysical survey of subglacial or englacial tunnels through which lakes were drained. The methodology of hydrological field studies was presented in detail in [2, 5]. The drilling and GPR study were used to determine depths in the lakes fully or partly covered with ice [5].

Despite the numerous evidence of lake outbursts, for various reasons it is rarely possible to record the course of the process from its origin to the final stage instrumentally. Therefore, when studying the outburst flood formation, the mathematical modeling is often the only method which allows estimating the hydrological characteristics of the outburst flood (flood runoff volume, flood time, and peak discharge). There are many mathematical models describing the formation and development of outburst floods. Among them, the model proposed by Yu.B. Vinogradov can be noted. It is intended for the outbursts of supraglacial lakes impounded by the snow-ice dams [4]. The model is based on the numerical solution to the system consisting of the continuity equation and energy conservation law. In addition, it describes the gradual melting of the tunnel in ice while water is flowing through it. Its advantage over the other models is that input data and model parameters can be obtained during field studies without using calculations based

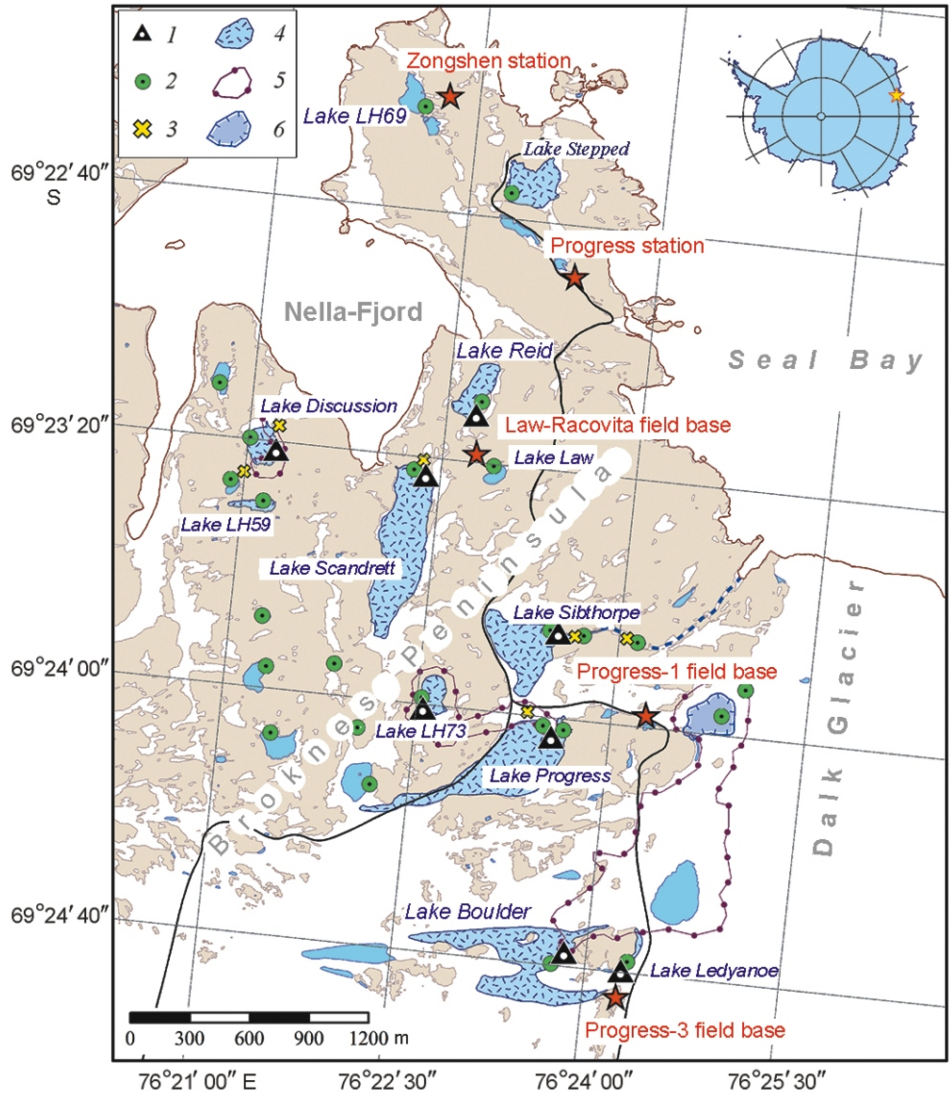

Fig. 1. The scheme of the area of hydrological studies (the Broknes Peninsula, East Antarctica). (*1*) Gaging stations; (*2*) sampling stations; (*3*) flow velocity measurement stations; (*4*) the areas of bathymetric surveys; (*5*) the areas of tachometric surveys; (*6*) the englacial lake in Dalk Glacier.

on empirical relationships. The bathymetric scheme of the lake, water temperature before the outburst, the tunnel length, and the height difference between its beginning and the end are input data for modeling. Thus, it is difficult to use the model without field data; therefore, field works on the lakes had been especially focused on the data which were subsequently used as input information for the modeling. For Antarctica, the authors considered the possible presence of ice cover on the water surface by adapting this model to studying the processes in case of hypothetic outbursts of subglacial water bodies and englacial reservoirs. Besides, the dependence of the water mass volume on depth expressed through the power-function approximation used in the model is replaced by real values from the digital terrain model [12].

The analysis of water level observations during the field seasons of 2017 to 2019 (the 63rd and 64th RAEs) revealed the main regularities of the lake regime formation on the Broknes Peninsula. It was found that most water bodies during the spring-summer period are characterized by the water level rise due to the inflow of meltwater from seasonal snow, snowfields, and glaciers. Lake water outbursts through the tunnels in the snow-ice dams or outflows to a stream leading the dramatic water level drop. However, the time periods of the onset, duration (several hours to several days), and cyclicity (annual to nonperiodic) of the outburst flood for each reservoir are determined by its morphometric and morphologic parameters as well as by meteorological conditions in the specific year. During the period of two-year seasonal works (from late December

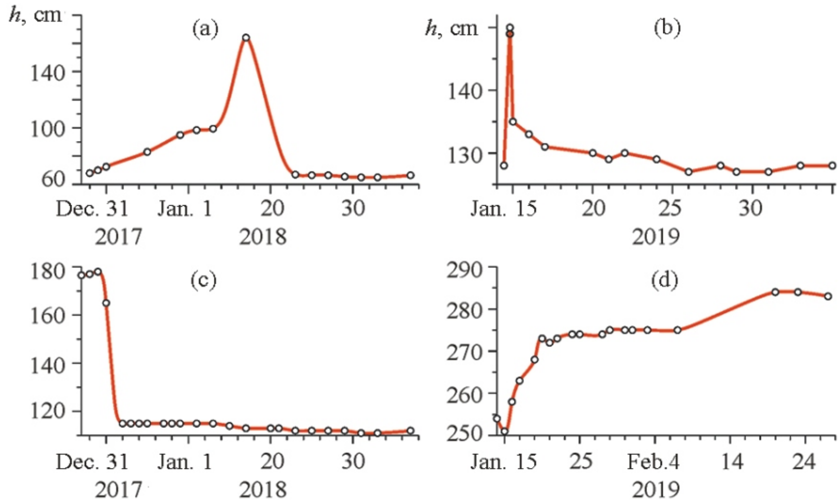

Fig. 2. The diurnal variations in water level above the reference surface for the following lakes: (a) Discussion (63rd RAE); (b) Progress (64th RAE); (c) Scandrett (63rd RAE); (d) Boulder (64th RAE).

to late February), not all lakes completed a full cycle of the lake basin filling to the critical level and its subsequent discharge by the outburst. In particular, the full cycle of the filling and discharge of Lake Discussion (Fig. 2a) and Lake Progress (Fig. 2b) was monitored during the 63rd (2017–2018) and 64th (2018–2019) RAEs, respectively. In the same timeframes, the other lakes were at different stages of the cycle. In particular, the dramatic water level drop was registered on Lake Scandrett on December 31, 2017 (Fig. 2c) that was caused by the snowfield destruction in the northeastern part of the lake; on Lake Discussion, this event occurred only in the middle of January of 2018. The outburst of Lake Progress was recorded in the middle of January 2019. The filling of the lake basin to the critical level took place till January 14; after that its outburst through the snowfield occurred. At the same time, Lake Boulder situated close to Dalk Glacier, was at the stage of water level rise from the middle of January to the end of February in 2019 (Fig. 2d).

According to the pattern of lake water level variations, the reconnaissance survey of outburst conduits and private messages from the station staff revealed that most lakes on the Broknes Peninsula in some years are hydraulically connected with each other. As a result, such systems of water bodies are formed that the outburst of one is a trigger for the others. Lake systems of LH73–Progress–Sibthorpe as well as LH59–Discussion and Boulder–Ledyanoe–unnamed englacial reservoir in the area of Dalk Glacier interact in this way. The authors suppose that it is not the full list of objects, especially if englacial water bodies whose visual detection is impossible and requires special studies, take part in the formation of such systems.

Based on the results of measurements on the lakes, the bathymetric schemes were constructed [2] and the morphometric parameters of some lakes in the oasis at the moment of the survey were determined (see the table). The next step was the preparation of geomorphological schemes which indicate the intensity and direction of exogenous processes whose key factor is water erosion. For example, let us present the results of the modeling for two lakes with different morphometric characteristics and outburst cyclicity: Lake Progress and Lake Discussion. The latter is located in the central part of the Broknes Peninsula, close to the western coast of Nella-Fjord. The interest to this lake is caused by annual outbursts resulting from the quick overfilling of the basin with meltwater from snowfields situated in the catchment area. Additionally, the inflow to the lake is carried out through the stream starting from Lake LH59. The outburst of Lake Discussion on January 22, 2018 occurred through the tunnel formed in the snow-ice dike damming the reservoir. The maximum height of the tunnel was 3 m, the width was more than 8 m, and the length was 128 m. As the water body surface was almost free of ice by the middle of Antarctic summer, the ice cover was not considered during the modeling. The height difference between the entrance to the tunnel and its exit was 2.17 m. Water temperature was assumed equal to 5°C proceeding from in-situ measurements on the surface water layer at the gaging station. The simulation results (Fig. 3) demonstrated that the peak discharge was 1.8 m^3/s and was reached 7 hours 37 minutes after the beginning of the outburst. The flood volume was 26750 m^3, the total duration of the outburst flood to Nella-Fjord was 9 hours 40 minutes.

The morphometric characteristics of the lakes in the area of Progress station (Larsemann Hills, East Antarctica)

Lake	Area, m^2	Volume, m^3	Length	Width	Depth	h_{abs}
			m			
Stepped	44440	51030	290	240	2.2/5.3	18.86
Reid	35530	40450	330	145	1.1/3.5	44.82
Scandrett	157920	1490700	890	240	9.4/17.6	31.15
Discussion	24270	60140	220	140	2.5/4.8	17.64
Sibthorpe	56720	37825	430	250	0.7/8.3	72.30
LH73	23820	39400	230	140	1.7/3.2	99.65
Progress	125730	1526750	665	330	12.1/42.5	72.60

Note: The maximum value of the lake width is given; the mean (numerator) and maximum (denominator) values are presented for depth; h_{abs} is the absolute water level at the survey moment.

A specific feature of Lake Progress, one of the largest and deepest lakes on the Broknes Peninsula, is that its water surface does not always become completely free of ice during the Austral summer. Besides, the lake is a part of the hydrological system a possible result of whose outburst is the destruction of the transport communication between the polar stations and the aerodrome. Due to this fact, it is hard to overestimate a need in the monitoring of characteristics of outburst floods formed in this system. It the model, the length of the tunnel formed in the snowfield as a result of the outburst was assumed equal to 150 m, with the height difference of about 1 m. Water temperature was assumed equal to 8°C proceeding from in situ measurements at the gaging station before the outburst. The simulation results (Fig. 3) showed that the hydrograph is characterized by the smooth but asymmetric shape, without dramatic changes in the water flow. The peak discharge was equal to 3.6 m^3/s and was reached 9 hours after the discharge beginning. The total duration of the outburst flood was about 13 hours. The flood volume was estimated as 76320 m^3.

In general, the presented model hydrographs are characterized by the gradual increase in the values of water flow during the period of destruction of the snow-ice dam and the formation of the runoff tunnel and by the rapid decline after reaching the maximum. This does not contradict the physical essence of the process. In both cases, the modeling was performed in the framework of the model described in [12].

CONCLUSIONS

The study considered the lakes of the Larsemann Hills, which have different morphometric characteristics and outburst formation conditions. The analysis of field data revealed the important feature of their hydrological regime, namely, the discharge of lake water through the tunnels in the snow-ice dams during the spring-summer period. Depending on morphologic and morphometric parameters of lake basins and on the ice and thermal regimes of the concrete year, the outbursts are characterized by different time intervals and cyclicity.

The results of mathematic modeling demonstrated that the calculated hydrographs do not generally contradict the physical essence of the process of outburst flood formation. The model can be used for the estimation of peak discharge, peak time, volume of runoff, outburst flood hydrograph shape and flood time in the absence of direct observations. Under conditions of climate change, the monitoring of active water bodies becomes extremely urgent for providing the safety of the station infrastructure. The monitoring should include not only the complex field studies but also model simulations under different scenarios of the outburst development. The authors suppose that the outburst flood formation process on the Larsemann Hills is similar to the formation of this phenomenon in the other oases of East Antarctica. This fact makes the region a reference object for studying lake outbursts and for improving the methods of physical and mathematical modeling for the estimation of the event parameters.

ACKNOWLEDGMENTS

The authors would like to thank V.I. Kashkevich, N.E. Romanova, and A.L. Borisik from Geofizpoisk; M.P. Kashkevich, S.V. Tyurin, A.M. Belov, and K.V. Titov from St. Petersburg University (SPbU) for the equipment provision and assistance in the preparation for field studies as well as S.D. Grigor’eva and

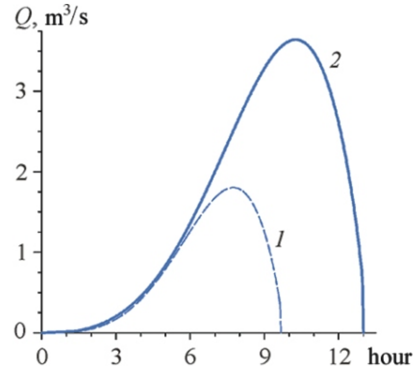

Fig. 3. The calculated hydrographs for the outburst flood on (*1*) Lake Discussion and (*2*) Lake Progress.

A.A. Sukhanova for assistance in the studies; A.V. Mirakin and G.A. Deshevykh from Arctic and Antarctic Research Institute (AARI) and other involved people who supported our fieldwork.

FUNDING

The research was supported by the Russian Foundation for Basic Research (No. 18-05-00421).

REFERENCES

1. V. Aver'yanov, "Flood at Novolazarevskaya Station," Inform. Byulleten' Sovetskoi Antarkticheskoi Ekspeditsii, No. 52 (1965) [in Russian].
2. A. S. Boronina, S. V. Popov, and G. V. Pryakhina, "Hydrological Characteristics of Lakes in the Eastern Part of the Broknes Peninsula, Larsemann Hills, East Antarctica," Led i Sneg, No. 1, **59** (2019) [in Russian].
3. A. S. Boronina, A. A. Chetverova, S. V. Popov, and G. V. Pryakhina, "Review of Potentially Outburst-dangerous Lakes and Consequences of Outburst Floods in the Areas of Thala Hills and Larsemann Hills," in *Proceedings of the 2nd All-Russian Scientific and Practical Conference "Modern Trends and Prospects of Development of Hydrometeorology in Russia," June 5–7, 2019, Irkutsk* [in Russian].
4. Yu. B. Vinogradov, "A Method for Flood Hydrograph Calculation in Case of the Outburst of the Glacier-dammed Lake," Selevye Potoki, No. 1 (1976) [in Russian].
5. S. D. Grigor'eva, E. V. Ryzhova, S. V. Popov, M. P. Kashkevich, and V. I. Kashkevich, "Structure of the Near-surface Part of the Glacier in the Thala Bay Area (East Antarctica) Based on 2018/2019 Ground-penetrating Radar Survey," Problemy Arktiki i Antarktiki, No. 2, **65** (2019) [in Russian].
6. E. B. Kaup, "Water Bodies of the Schirmacher Oasis: General Description, Temperature and Radar Regime," Inform. Bulleten' SAE, No. 102 (1981) [in Russian].
7. V. D. Klokov, "The 15th Soviet Antarctic Expedition. Report on Glaciological and Hydrological Studies in the Area of Molodezhnaya Station during the Season of 1969–1970," Fondy AANII, No. 0-1790 (1970) [in Russian].
8. V. D. Klokov, "Water Outburst from Lake Glubokoe at Molodezhnaya Station," Inform. Bulleten' SAE, No. 72 (1969) [in Russian].
9. Yu. A. Kruchinin and I. M. Simonov, "New Type of Lakes in Antarctica," Inform. Bulleten' SAE, No. 66 (1967) [in Russian].
10. A. A. Loopman, "New Data on the Regime of Lakes in the Schirmacher Oasis," in *The 29th Soviet Antarctic Expedition: Wintering Studies in 1983–1985: General Description and Research Results (Trans. SAE, Vol. 87*), Ed. by L. V. Bulatov (Gidrometeoizdat, Leningrad, 1990) [in Russian].
11. S. V. Popov, A. S. Boronina, G. V. Pryakhina, S. D. Grigor'eva, A. A. Sukhanova, and S. V. Tyurin, "Outbursts of Glacial and Subglacial Lakes in the Area of the Larsemann Hills (East Antarctica) in 2017–2018," Georisk, No. 3, **12** (2018) [in Russian].
12. S. V. Popov, G. V. Pryakhina, and A. S. Boronina, "Estimation of Water Discharge during the Development of Glacial and Subglacial Outburst Floods," Kriosfera Zemli, No. 3, **23** (2019).
13. R. E. Byrd, "Our Navy Explores Antarctica," Nat. Geogr. Mag., No. 4, **92** (1947).
14. D. S. Gillieson, "An Environmental History of Two Freshwater Lakes in the Larsemann Hills, Antarctica," Hydrobiologia, No. 1, **214** (1991).
15. S. V. Popov, S. S. Pryakhin, D. P. Bliakharskii, G. V. Pryakhina, and S. V. Tyurin, "Vast Ice Depression in Delk Glacier, East Antarctica," Ice and Snow, No. 3, **57** (2017).