RESEARCH PAPER

COMMUNITY ICE CELLARS IN EASTERN CHUKOTKA: CLIMATIC AND ANTHROPOGENIC INFLUENCES ON STRUCTURAL STABILITY

Alexey A. Maslakov[1*], Kelsey E. Nyland[2], Nina N. Komova[1], Fedor D. Yurov[1], Kenji Yoshikawa[3], Gleb N. Kraev [4,5]

[1]Lomonosov Moscow State University, Faculty of Geography, Leninskie Gory 1, 119991 Moscow, Russia.
[2]The George Washington University, Department of Geography, 2036 H St. NW, 20052 Washington, DC, USA
[3]International Arctic Research Center, University of Alaska Fairbanks, 2160 Koyukuk Dr. 99775 Fairbanks, Alaska, USA
[4]Vrije Universiteit Amsterdam, Amsterdam 1081, The Netherlands
[5]Institute of Physicochemical and Biological Problems in Soil Science of the Russian Academy
***Corresponding author:** alexey.maslakov@geogr.msu.ru

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ABSTRACT. The large community ice cellar designs in eastern Chukotka are unique within the Arctic due to the mixed influences from the indigenous Chukchi people and western industry. Community ice cellars here were designed and constructed in the 1950s-60s to accommodate both food stores for local indigenous residents and feed stores for Arctic fox fur farms. Like much of the Arctic, this region is undergoing unprecedented climate change. Air temperatures within the study area have been increasing at an average rate of 0.7°C per decade since the 1950s. Exacerbating the adverse effects of the warming climate is the lack of ice cellar maintenance in communities where the fur industry did not survive the transition to a market economy. Today, all but two community ice cellars in eastern Chukotka have flooded or collapsed. Presented in this work are thermal records from two cellars in the region that allow for both climatic and anthropogenic influences on the cellars' structural integrity to be evaluated. Particularly effective ice cellar maintenance practices utilized in the community of Lorino were 1) wintertime ventilation, and 2) placing large blocks of river ice in the cellar in spring to mitigate spring and summer warming.

KEY WORDS: ice cellars, permafrost, indigenous communities, climate change, food security, Chukotka, Russia

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INTRODUCTION

Ice cellars (Russian «lédnik», Chukchi «K'aetyran») are a form of Arctic indigenous technology in which tunnels and/or chambers are excavated into permafrost and used as passive cold food storage. Ice cellars are widespread and can be found in many Eurasian and North American high-latitude settlements (e.g., Yoshikawa et al. 2016; Nyland et al. 2017). Ice cellars as an indigenous technology date back at least one millennium in the Bering Sea region. Whale meat from an abandoned cellar in Gambell, Alaska, roughly 120 km due south of our study area, was radiocarbon dated and likely killed and buried approximately 1000 years ago (George et al. 2008). Traditional cellars, like the ancient one discovered in Gambell, range in size from small field cashes (approximately 1 m^3) to personal or family cellars (approximately 10 m^3), and are still common in Yakutia (Yoshikawa et al. 2016) and northern Alaska (Nyland et al. 2017). Less common are community ice cellars with multiple chambers. For example, the community ice cellar, or ice house, in Tuktoyaktuk, Canada built in the late-1960s with government funding, features three corridors with

19 side rooms (approx. 9 m³ each) (Canadian Museum of Nature 2020; Genest 2017). Ice cellars in eastern Chukotka, constructed in the 1950s-60s, are especially large to accommodate both local subsistence hunting and feed stores for the Soviet fox fur industry (Michael Zelensky, former government official of the Chukotsky Administrative District, personal communication, 2019).

Contemporary climate change (Pachauri et al. 2014) and socioeconomic stressors now threaten the structural stability and continued use of ice cellars in eastern Chukotka. Several examples of ice cellars flooding and collapsing have been documented on the North Slope of Alaska associated with widespread permafrost warming and thaw (Kintisch 2015; Biskaborn et al. 2019). The adverse effects of warming on ice cellars are compounded by local geology, economic development, and other social stressors (Nyland et al. 2017). Eastern Chukotka is also undergoing permafrost degradation (Biskaborn et al. 2019). The dissolution of the Soviet Union and the inability of local fox fur farms to transition to a market economy reduced cellar spendings efforts. Issues impacting the sustainability of these ice cellars are central to larger discussions on food security in indigenous Arctic communities since subsistence-hunted marine mammals continue to make up a significant portion of northern indigenous people's diets (Kozlov et al. 2008; Kenny et al. 2018; Melnikov, Fedorov 2018).

The aim of this paper is to describe the unusual ice cellar designs found in eastern Chukotka and to summarize observations from several communities that include climatic trends and internal ice cellar thermal monitoring from 2014 to 2019. Lastly, we discuss preservation strategies for the sustainable maintenance and use of ice cellars amid warming climate conditions.

STUDY AREA

The Chukchi Peninsula is the easternmost tip of Russia and Eurasia (Fig. 1). This area is occupied by the highly eroded, low-lying, eastern portion of the Chukotka Mountains, surrounded by a narrow coastal plain. The plain is composed of glacifluvial and moraine deposits (Parmuzin 1968) terminating in gravelly to pebbly beaches and bedrock cliffs. The coastal plain valleys and lowlands are overlain by tundra vegetation while the uplands and mountains are largely lichen covered or barren. The study area has a typical polar tundra (ET) climate type according to the Köppen-Geiger updated classification system (Kottek et al. 2006). Mean annual air temperatures within the study area vary from -8.8°C at the Vankarem weather station to -3.0°C in Provideniya (averaged for 1989–2019; data source: Bulygina et al. 2020). Total annual precipitation from 1989–2019 ranged from 350 to 690 mm, but the majority fell as rain during warm periods.

The entire peninsula is underlain continuously by permafrost from 100 to 200 m thick (Gasanov 1969) with mean annual ground temperatures (MAGT) from -1 to -4°C (Obu et al. 2019). Cryogenic relief is abundant along the Bering Sea coast, including ice complexes on the plains, thermokarst, and thermal erosion forms (Maslakov et al. 2018). Slopes and uplands also feature periglacial forms including solifluction lobes and rock stripes.

METHODS

Regional climate analysis was performed with data obtained from weather stations in Uelen, Provideniya, Vankarem, and Egvekinot (Bulygina et al. 2020) and NCEP/NCAR (joint product from the National Centers for

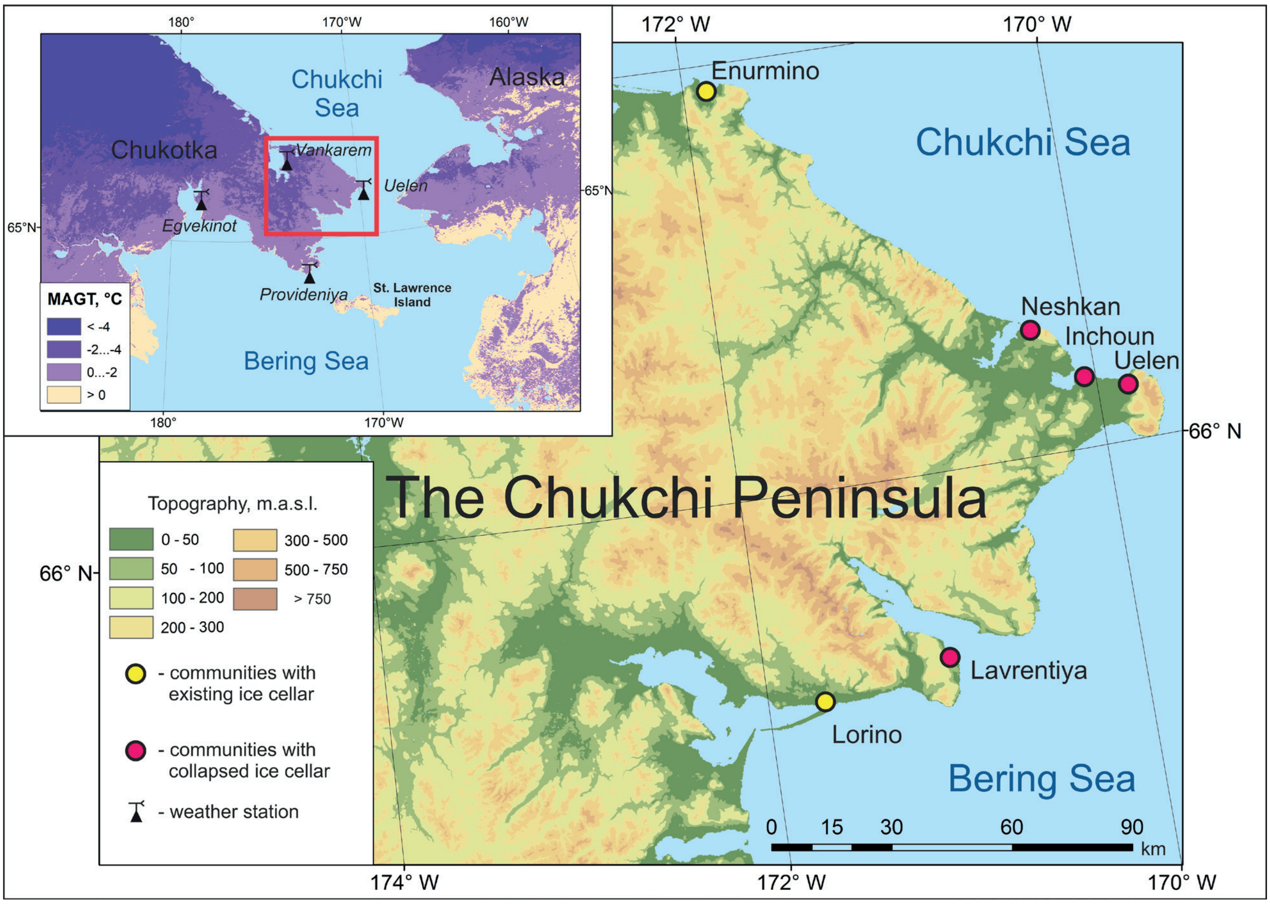

Fig. 1. Study area map highlighting communities with ice cellars currently existing and those that have experienced ice cellar failures. Mean Annual Ground Temperature (MAGT) from Obu et al. (2019) and elevation data are from ArcticDEM v.7 (Porter et al. 2018). Map was compiled in ArcGIS 10.5 software

Environmental Prediction and the National Center for Atmospheric Research) reanalysis data (Kalnay et al. 1996). The comparison of climate model and reanalysis data showed better reliability of the weather characteristics on regional scale rather than in grid cell, therefore we used reanalysis data averaged for whole Chukchi peninsula (63-70°N and 168°-179°W). Details about reanalysis data retrieval are described in Maslakov et al. (2019). Mean daily air temperature data from several weather stations distributed throughout the study area were analysed. Air temperature data are presented here as Degree-Days of Thaw (DDT) and Degree-Days of Freezing (DDF), which are the sums of average daily temperatures for the periods with above-zero and below-zero temperatures over a year, respectively. These values allow for the estimation of climatic forcing (both heating and cooling) on the ground and therefore the permafrost system. We also use degree-days concept to estimate cold capacity in the ice cellars. Repeated field surveys were conducted to collect data on the depth, geometry, and temperature regimes of ice cellars in the communities of Lorino and Inchoun (see Fig. 1). Similar data from other communities in the study area were gathered by locals through a participatory program. Locals were provided thermal data logging equipment to install and maintain in ice cellars in other remote communities. These participants also provided commentary on the use and condition of the cellars they monitor. Several interviews with a former government official, Michael Zelensky, also allowed us a basic understanding of ice-cellar history and function and the ability to reconstruct the ice cellars' construction and appearance in Chukotka in the 20th century.

Onset HOBO Pendant® Temperature/Light 64K data loggers were used to monitor hourly internal ice cellar temperatures. The loggers were installed to be out of the way of those using the cellars for food storage and so they would not be covered by food stuffs. Precise data logger installation locations were dependent on a particular cellar configuration although most were installed on joists supporting the earthen cellar ceilings. Due to difficulties related to the remoteness of these communities, unreliable transportation infrastructure, technical failure, ice cellar collapse, etc., the longest records available are from 2014 to 2019 in the Lorino community ice cellar and from 2014 to 2016 in the Inchoun community cellar.

RESULTS

Cellar Characteristics

Lorino Community Ice Cellar

The community ice cellar in Lorino (pop. 983 in 2019; www.gks.ru) is the largest permafrost food storage facility on the Chukchi Peninsula. The cellar capacity can accommodate an average of 60 gray whales and hundreds of walruses harvested by the community each year (https://prochukotku.ru/20191208/9837.html). The facility was designed and built by Construction Department «Mosmetrostroy» (est. 1931, now the Mosmetrostroy Construction Company), which built the Moscow Metro and many buildings, including The House of the Government of the Russian Federation, the largest European «Rossiya» Hotel, etc. (https://www.metrostroy.com/). The Lorino ice cellar consists of a horizontal tunnel with lateral side gallery and separate chambers (Fig. 2). The cellar is located in a Middle Pleistocene-age marine terrace just 200 m from the coast. At 114 m in length, the Lorino ice cellar is a full 10 m longer than the «old» US Army Corps of Engineers Cold Regions Research and Engineering Laboratory Tunnel in Fairbanks, Alaska (Shur et al. 2004; Darling 2018).

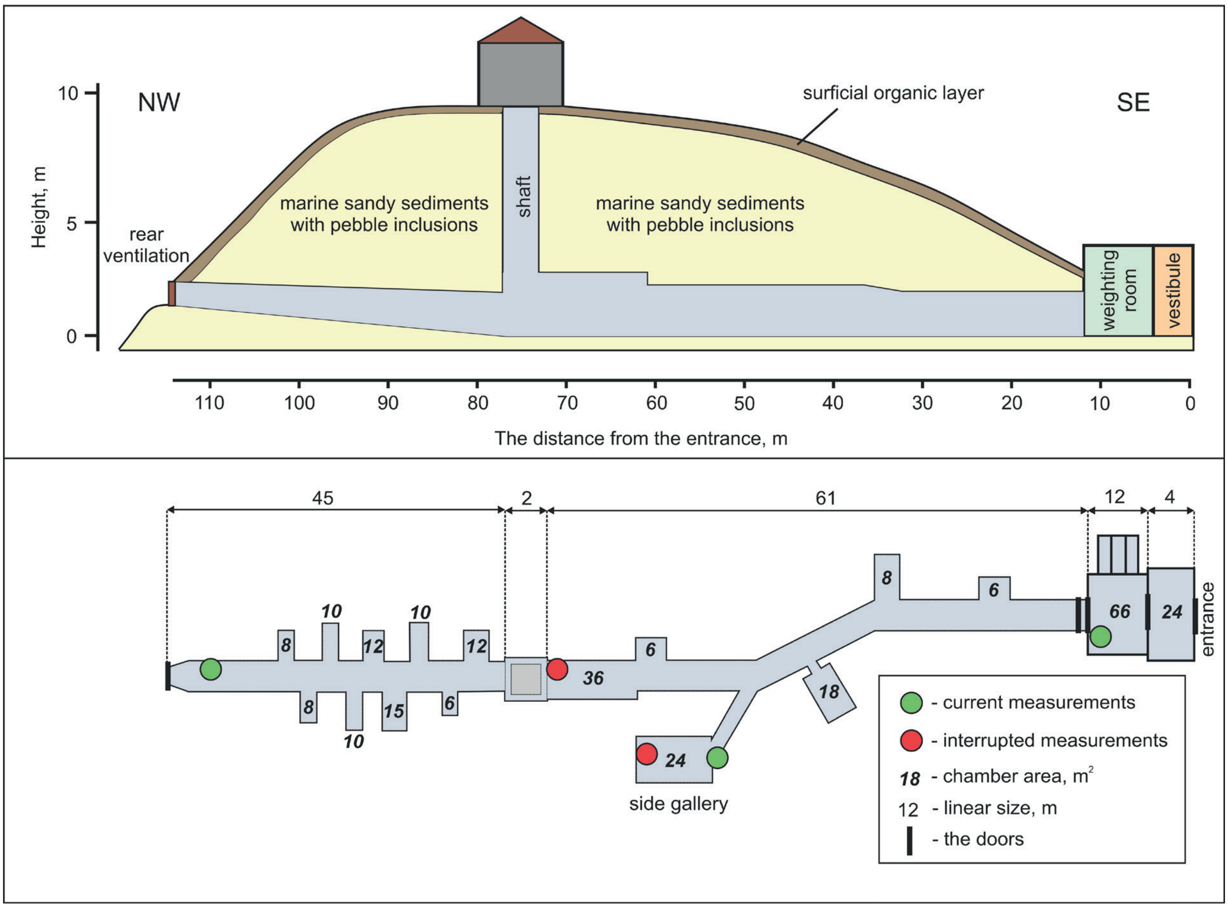

Fig. 2. Schematic of the Lorino community ice cellar (top) in cross section along the main gallery and (bottom) in plan view (source: field measurements in 2019)

Temperature data loggers were installed in different areas of this massive cellar. Thermal monitoring within the vestibule and weighing room showed that summer air temperatures remain consistently between +5 and +7° C. These relatively «warm» rooms occupy 90 m^2 of the cellar. These warm rooms allow meats to develop a particular taste valued in this indigenous culture through fermentation during summer and autumn. These fermented meats are used in traditional recipes including Igunaq, or Kopalhen (Krupnik 1989).

The remaining 330 m^2 of the cellar are considered «cold» rooms, including tunnels and side chambers, separated from the weighing room by three insulated doors. Internal air temperatures in the cold rooms are remain consistently below freezing (0° C). The average winter internal air temperatures in the cellar vary from -4.8° to -6.2° C. Colder temperatures occur closer to the central vertical shaft in the cellar where temperatures can drop to -20°C when open for ventilation. The average summer temperatures inside the cold rooms range generally from -3.5° to -4.0° C, and occasionally reach -1.0° to -2.0° C. One anomaly in the temperature record from the cold rooms were two days in late August 2019 when the temperature near the rear ventilation in the cellar reached +0.4° C. This thermal anomaly was likely due to ventilation repair conducted, requiring this vent to be open for an extended period.

More detailed analysis of the thermal monitoring record from the Lorino cellar was conducted by calculating the integral of daily averaged temperatures in the cellar for warm and cold periods and comparing it with weather station DDT and DDF (Table 1). Accumulated degree-days at the Uelen weather station for the monitoring period show progressively faster warming trends in both summer (45° C *x* days per year) and winter (229° C *x* days per year) compared to the average trend for the last 60 years (Fig. 2). However, ventilation can significantly cool the cellar in winter, aiding stabilization of the surrounding permafrost, although ventilation is highly dependent on variable winter weather conditions. Ventilation contributions to cooling (DDF) during winter and summer seasons vary from 8 to 45% depending on the year.

Inchoun Ice Cellar

The community ice cellar in Inchoun (pop. 365 in 2018; www.gks.ru) resembles a significantly larger version of common personal use cellars with a vertical access shafts down to the main cellar chamber (Nyland et al., 2017) or the community cellar in Tuktoyaktuk, Canada (Canadian Museum of Nature 2020; Genest 2017). The cellar is located on the depth of 4-5 m below surface and consists of a vertical shaft with a ladder that leads down to a chamber roughly 2.5 m wide, 6.0 m long, and 2.0 m in height. This cellar was excavated in ice complex deposits (depressions from melted ice wedges are visible in Fig. 3). Due to contemporary degradation of the regional permafrost table (Maslakov et al. 2019) this cellar collapsed in August 2019. Nevertheless, there is a temperature record from March 2014 to July 2016 for the Inchoun cellar.

Average winter temperatures in the chamber during the observed time period ranges from -6.1 to -7.2° C, and during brief periods of winter ventilation, internal air temperature dropped as low as -18° C. By the end of winter, the internal cellar temperature was typically around -10° C and would then slightly increase during summer from -1.4° to -1.8° C (in 2014–2015). In July of 2016 the data logger installed in the Inchoun cellar registered several anomalously high readings around +1.5° C. The record ends in July 2016 after the data logger was last serviced. The instrumentation went missing sometime during the summer of 2017, but locals reported that the walrus and seal meat stored in the cellar that summer was covered by mold – a sign of consistently positive temperatures. Locals also reported that they heard the sounds of soil falling when going into the ice cellar. It is noteworthy, that the community chose not to invest the time or manpower required to reinforce the ice cellar through additional maintenance, but instead refrained from any future use (personal communications with local entrepreneur Igor Khuramshin and former community head Evgenii Sivsiv, 2017). The community's decisions surrounding the cellar's discontinuation may indicate that, besides natural processes, maintenance plays a significant role in the preservation of ice cellars.

Contemporary Climate Change in Chukotka

Like much of the Arctic, eastern Chukotka is undergoing significant climate warming. The average annual air temperature for the region has increased from 3.8 to 4.4° C (0.67-0.77° C per decade). Fig. 4 shows degree days of thaw (DDT) records from several communities within the study area, since the construction of community ice cellars here between 1955 and 1965. These communities have weather stations with long-term characteristics records. Over the period of ice cellar use total annual DDT has increased from 679 to 831° C *x* days (+22%) and DDF have decreased from 3238 to 2576° C *x* days (-20%). Average annual degree days

Table 1. Degree days of freezing (DDF) and thawing (DDT) variations in atmosphere (Uelen weather station) and cold capacity (°C·day) inside the Lorino ice cellar from March 23rd, 2014 to September 6th, 2019

Year	DDT weather station	DDF weather station	Winter cold capacity in the cellar	Summer cold capacity in the cellar	Accumulated winter DDF from ventilation (per cent from summarized winter and summer cold capacity)
2014	720	2882	-	613	-
2015	793	2432	879	639	134 (8%)
2016	951	2565	1030	745	539 (30%)
2017	823	2122	1062	550	718 (45%)
2018	993	1534	963	432	225 (16%)
2019	947	1905	910	268*	465 (39%)

**Sum of average daily temperatures in the ice cellar were calculated before September 6th, 2019.*

Fig. 3. Photo of the community ice cellar entrance covered by a shed in Inchoun and depressions from the thawing ice complex in the foreground. Photo by A. Maslakov in July 2017.

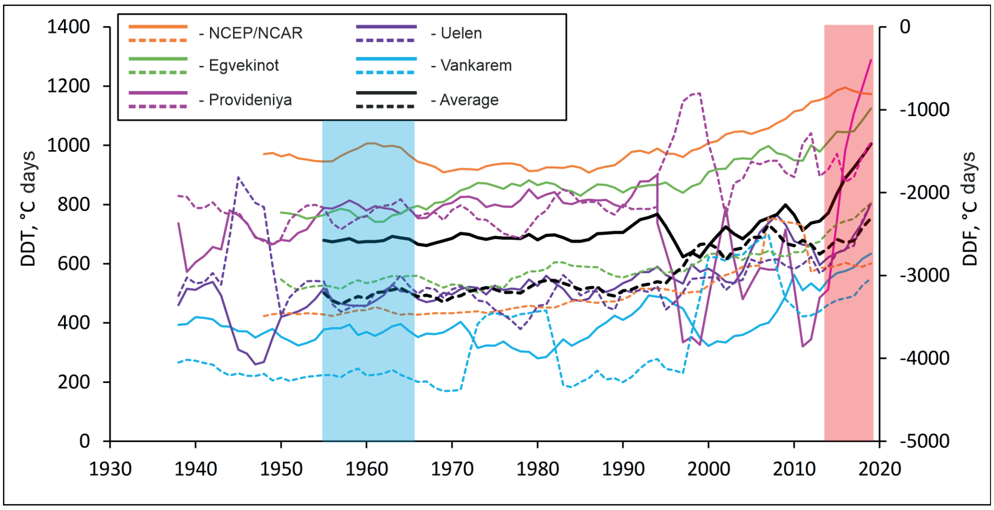

Fig. 4. Five-year sliding averages of degree-days of thaw and freeze derived from weather stations in eastern Chukotka and from NCEP/NCAR reanalysis. Black curve is averaged values for weather stations. The blue bar is the period that the observed ice cellars were constructed and the red bar is monitoring period for this study. Solid lines represent DDT and dashed lines are DDF

have warmed by 16.2° C *x* days per year. These trends indicate both warmer summers and winters within the study area that allows for significant heat propagation into the ground and therefore the permafrost system.

Ice Cellar Designs and Maintenance Practices in eastern Chukotka

Small ice cellars for personal use were common in Chukotkan coastal communities before the Soviet era, but because of population re-location and development of settlements, none of these have been preserved (Krupnik 1989). Most indigenous community ice cellars in eastern Chukotka were constructed during the late 1950s as an efficient solution for storing large amounts of meat from harvested marine mammals, primarily for feed on arctic fox fur farms. These cellars were designed either as large chambers below a vertical access shaft, or as horizontal tunnels with side chambers. One ice cellar was constructed in every coastal settlement of eastern Chukotka, a volume large enough not only for the fur industry needs, but also to store food for general consumption. Ownership is communal and each community appointed one or more persons to be responsible for general admission to and maintenance of the ice cellar.

All ice cellars require specific care to maintain the structure and its cold-storage functionality. All cellar chambers and corridors are cleaned each spring, when old meats are disposed of and excess ice and hoar frost are removed from the walls, floors, and ceilings. If partial collapse or crumbling walls develop, renovations coincide with the annual spring cleaning. Standard maintenance in eastern Chukotka also includes hunters and other cellar users bringing blocks of river ice into the ice cellar in early spring before the hunting season begins, in order to maintain cool temperatures throughout the summer. Lastly, passive ventilation is utilized for several hours a day during cold periods of the year by leaving doors and vents open, which drastically decreases interior cellar air temperatures. For example (Fig. 5), passive ventilation has decreased the internal air temperature in the Lorino ice cellar from -4 to -8°C over the course of 4 months, providing sufficient cold capacity to effectively preserve meats through the next summer.

DISCUSSION

Most of the ice cellars in eastern Chukotka are now in a state of collapse or have flooded. At the time of our last

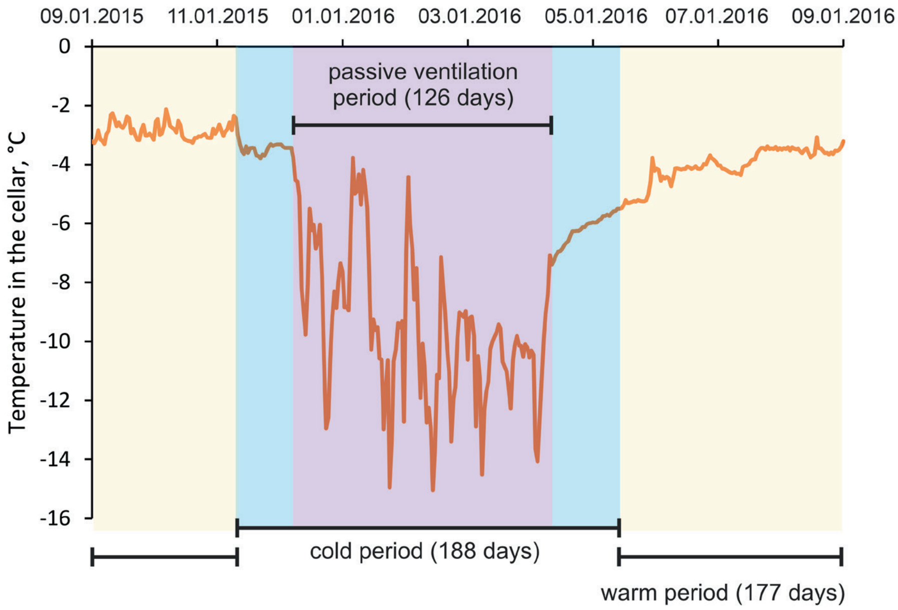

Fig. 5. Daily temperatures in the Lorino community ice cellar from September 1st, 2015 to September 1st, 2016. Note the effectiveness of passive ventilation at lowering the internal ice cellar temperature through the summer of 2016, although summer average temperatures for 2015 and 2016 are -3.3° C and -3.1°C respectively

field survey in September 2019 we know of only two ice cellars, in Lorino and Enurmino, that remain functioning and in use (see. Fig. 1). Unfortunately, we couldn't get to the latter community, so we have only indirect information on its state. The factors that led to the widespread failure of community ice cellars in eastern Chukotka appear to be climate warming, inadequate maintenance, and unfavourable initial locations of ice cellars.

Factors Affecting the Structural Integrity of Ice Cellars in Eastern Chukotka

Ice cellars in eastern Chukotka are currently either in a state of destruction, or imminently threatened by thawing permafrost, flooding, and degradation of the walls and ceiling (Fig. 6). Many of these adverse changes can be attributed to climate warming, but anthropogenic influences are also play an important role in local effects. Informal interviews with locals revealed that each community within the study area managed the threats to their community cellars in a different way, including passive ventilation, use of river ice blocks, and discontinuation of cellar use.

After the collapse of the Soviet Union each of the villages within the study area became significantly more economically independent. For instance, in villages where fur farming in an open market economy became unviable, the large community ice cellars used previously to store feed ceased to be maintained, contributing to their derelict state and eventual flooding or collapse (e.g., the cellar in Uelen community). Active hunting communities and communities with operational fur farms (e.g. Lorino) have continued maintaining their cellars.

Simple trend analysis of mean monthly internal air temperatures in both the Lorino and Inchoun cellars, and for the weather station in Uelen, demonstrate persistent increasing temperature trends (Fig. 7). While ambient air temperatures from the Uelen weather station have increased at a rate of 0.3° C per decade, internal cellar air temperatures have also increased, but at rates 6-10 times less. This indicates that maintenance measures, including ventilation and use of river ice collection, can assist in retarding the warming of the surrounding permafrost. However, annual temperature amplitudes differ between

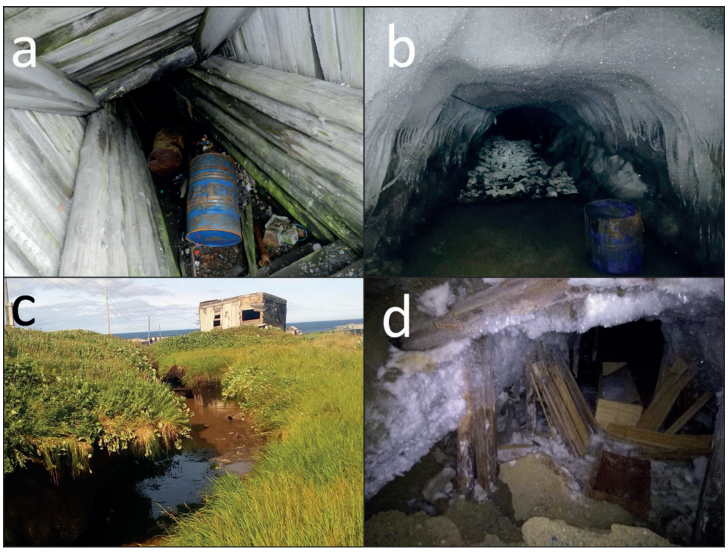

Fig. 6. Primary issues with ice cellars in Chukotka: a) flooded cellar in Uelen (August 2014); b) molds on meat in the Inchoun cellar (August 2017); c) ice wedge thaw near the cellar in Inchoun (September 2019); d) sloughing walls and rock fall in the Lorino cellar (September 2018). Photos by A. Maslakov.

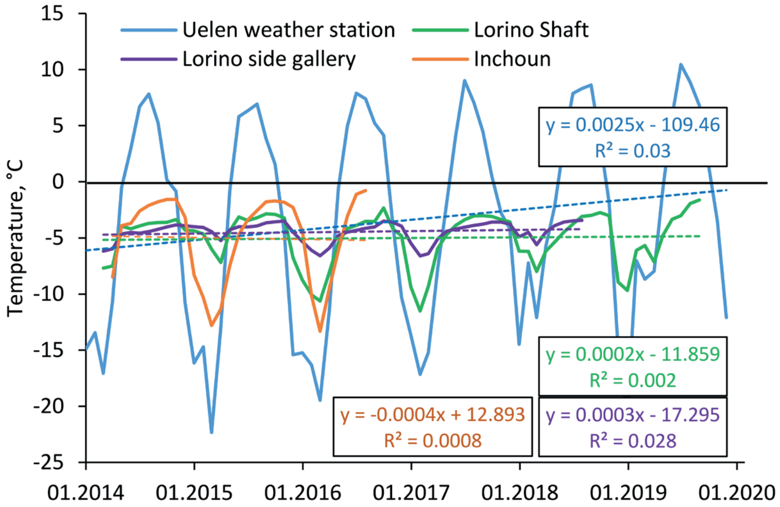

Fig. 7. Monthly dynamics of internal air temperatures in the Lorino and Inchoun ice cellars and at the Uelen weather station from 2014 to 2019.

these two ice cellars. While the community cellar in Lorino exhibits an amplitude of 3° to 8° C, the Inchoun community cellar amplitude is from 11° to 13° C annually. In other words, the Inchoun ice cellar warms and cools faster annually than the Lorino cellar. These differences in annual amplitude can be explained by shallower Inchoun cellar laying, which is more susceptible to seasonal temperature variations in permafrost.

Adaptation Strategies for Community Ice Cellars in eastern Chukotka

Appetites for traditional Chukchi food are increasing, evident from interviews conducted by Kozlov (2004), and the increased marine mammal quotas for subsistence hunting. A total of 135 whales and more than 1,000 walruses were allotted to traditional hunters of Chukotka for 2020 (Krainii Sever 2019). Winter food storage in the community ice cellars poses no problems, but summertime storage presents new challenges to the Chukchi.

In Lavrentiya, the logistical center of the study area with a port that receives ships from the «big land» with commercial goods, is now using 40 ft. industrial refrigerators in place of their ice cellar. Even the giant ice cellar of Lorino with volume of 283 m^3 (approximate volume of all chambers without corridors) is just 4 industrial refrigerators by volume. Given the energy consumption of 2.5-5.0 kW per industrial refrigeration container for three working months (during winter the refrigerator is turned off, and during summer it is turned on for only half of the day) would result in a total electrical consumption of 5.4-10.8 10^3 kW h per year. This total equates to just 5% of the average price of the container and its delivery. These new refrigeration costs are manageable for many of these remote communities given that energy prices were significantly reduced for consumers in Chukotka after 2017 (Weingartner et al., in press). The electric refrigeration contingency used in Lavrentiya however, increases their dependence on fossil fuels and long-distance delivery of spare parts and technicians, and could mean the loss of a traditional technology and practice.

Permafrost provides both cultural and regulatory ecosystem services through ice cellar technology. Storage of food there provides better taste qualities (Kintisch 2015). Thus, the cellars have added value for locals and represents the indigenous cultural heritage, although that is shared with Soviet influence. According to the IPCC (Pachauri et al. 2014), air temperature will continue to increase, exacerbating permafrost warming and degradation (Guo & Wang 2016). Although the majority of community ice cellars in eastern Chukotka have been abandoned or have failed, those remaining will need restoration and protection. In this case refrigerators could be used to initially cool meat before storage in an ice cellar during cold months to preserve the culturally preferred tastes from fermentation (Kintisch 2015). Another solution is to improve and increase the frequency of ice cellar maintenance, including increasing the duration of winter ventilation periods, bringing larger volumes of river ice into the cellars in spring, or adding layers of insulation over the current soil surface above cellar chambers.

CONCLUSIONS

Based on the description of community ice cellars in eastern Chukotka provided above along with regional climate analysis and thermal monitoring from two ice cellars, our preliminary conclusions include:

- The community ice cellars of eastern Chukotka are highly unusual permafrost structures that share indigenous, industrial and Soviet design and construction during the 1950s and 1960s.
- Temperature monitoring within ice cellars facilitates quantitative assessment of the efficiency of maintenance measures.
- The passive winter ventilation of the Lonino ice cellar contributes 8 to 44% of annual wintertime cooling, while bringing river ice into the cellar also moderates spring and summer warming. Both maintenance practices are effective at preventing permafrost thaw processes within cellars.
- Both contemporary climate change and struggling local economies have negatively affected ice cellars, but the loss of the remaining cellars could also seriously threaten Chukchi traditional practices, lifestyles, and food security.
- Proposed adaptation strategies for continued ice cellar use in eastern Chukotka focus on 1) increasing maintenance practices and the frequency which they are performed; and 2) refrigerating meats in industrial freezers before winter ice cellar use.

We recommend that a detailed assessment of whether introducing the refrigerators or improved ice cellar maintenance could be the most effective for Lorino be performed in the near future.

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