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Food Storage in Permafrost and Seasonally Frozen Ground in Chukotka and Alaska Communities

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ABSTRACT. Food cellars, otherwise referred to as ice or meat cellars, (*lednik* in Russian, *k'aetyran* in Chukchi, *siġļuaq* in Iñupiaq, and *siqlugaq* in Yupik) are a natural form of refrigeration in permafrost or seasonally frozen ground used to preserve, age, and ferment foods harvested for subsistence, including marine mammals, birds, fish, and plants. Indigenous peoples throughout the Arctic have constructed cellars in frozen ground for millennia. This paper focuses on cellars in Russian and American coastal and island communities of the Bering Strait, the region otherwise known as Beringia. This area has a unique, culturally rich, and politically dynamic history. Many traditions associated with cellars are threatened in Chukchi communities in Russia because of the impacts of climate change, relocation, dietary changes, and industrial development. However, even with warmer temperatures, cellars still provide a means to age and ferment food stuffs following traditional methods. In cooperation with local stakeholders, we measured internal temperatures of 18 cellars in 13 communities throughout the Bering Strait region and northern Alaska. Though cellars are widely used in permafrost regions, their structure, usage, and maintenance methods differ and exhibit influences of local climates, traditions, and economic activities. Monitoring internal temperatures and recording structural descriptions of cellars is important in the face of climate change to better understand the variety and resilience of living adaptations in different cold regions.

Key words: food cellars; *k'aetyran* (Chukchi); *siqlugaq* (Yupik); *siġļuaq* (Iñupiaq); permafrost; food security; aging; fermentation

RÉSUMÉ. Les caves à denrées, aussi connues sous le nom de caves à glace ou de caves à viande (*lednik* en russe, *k'aetyran* en tchouktche, *siġļuaq* en iñupiaq, et *siqlugaq* en yupik) constituent une forme de réfrigération naturelle dans le pergélisol ou dans le gélisol saisonnier permettant de conserver, de maturer et de fermenter les denrées récoltées à des fins de subsistance, dont les mammifères marins, les oiseaux, les poissons et les plantes. Cela fait des millénaires que les peuples autochtones de l'Arctique construisent des caves dans le gélisol. Cet article porte sur les caves se trouvant dans les localités côtières et insulaires russes et américaines du détroit de Béring, région qui porte également le nom de Béringie. L'histoire de cette région est unique, culturellement riche et politiquement dynamique. De nombreuses traditions liées aux caves des localités tchouktches de la Russie sont menacées en raison des incidences du changement climatique, de la délocalisation, du changement des régimes alimentaires et de l'expansion industrielle. Cependant, malgré les températures plus élevées, les caves constituent toujours un moyen de maturer et de fermenter les denrées alimentaires selon les méthodes traditionnelles. En collaboration avec les parties prenantes de la région, nous avons mesuré les températures internes de 18 caves situées dans 13 localités de la région du détroit de Béring et du nord de l'Alaska. Bien que les caves soient courantes dans les régions de pergélisol, leur structure, leur usage et les méthodes d'entretien diffèrent, et elles sont à l'image des influences des traditions, des activités économiques et des climats locaux. La surveillance des températures internes et l'enregistrement des descriptions structurales des caves revêtent de l'importance à la lumière du changement climatique, car elles permettent de mieux comprendre la variété et la résilience des adaptations de vie dans différentes régions froides.

Mots clés : caves à denrées alimentaires; *k'aetyran* (tchouktche); *siqlugaq* (yupik); *siġļuaq* (iñupiaq); pergélisol; sécurité alimentaire; maturation; fermentation

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Продуктовые хранилища. называемые иногда мясными ямами (лéдник по-русски, к’этыран по-чукотски, Siġḷuaq или Siqlugaq по-эскимосски), обустроены как в вечномёрзлых породах, так и в сезонноталом слое и являются естественной формой заморозки для сохранения, выдержки и ферментации пищевых продуктов, добытых для пропитания: мясо морских млекопитающих, дичь, рыба, растения и др. Коренные жители Арктики обустраивали хранилища в мерзлоте на протяжении тысячелетий. Данная статья посвящена подземным хранилищам в российских и американских поселениях на берегах Берингова пролива – региона, также называемого Берингией. Эта территория имеет уникальную, богатую культурой и политически динамичную историю. Многие традиции, связанные с хранилищами в поселениях Чукотки, находятся под угрозой исчезновения из-за климатических изменений, миграции жителей, изменений в рационе и промышленного освоения территории. Однако даже при повышении температуры воздуха в хранилищах по-прежнему можно выдерживать и ферментировать пищу традиционными способами. При сотрудничестве с местным населением мы измерили температуры внутреннего воздуха в 18 лéдниках в 13 поселениях в регионе Берингова пролива и на севере Аляски. Несмотря на широкое использование таких хранилищ в криолитозоне, их структура, использование и методы обслуживания различаются под влиянием климатических условий, традиций и особенностей промысла. Мониторинг внутренней температуры воздуха в лéдниках и описание их конструкций важны в контексте изменения климата для лучшего понимания разнообразия и эффективности различных способов адаптации к жизни в холодных регионах.

Ключевые слова: Погреб, хранилища пищевых продуктов, вечная мерзлота, сохранность продуктов питания, Вызревание, ферментация

INTRODUCTION

Permafrost (perennially frozen ground) underlies more than one-quarter of Earth’s land surface. Over 90% of Beringia, the region surrounding the Bering and Chukchi Seas, is underlain by permafrost, and the remainder of this area is subject to deep seasonal ground freezing. While not all coastal communities in Beringia have subterranean cellars, most do, including all the whaling communities (Fig. 1). While evidence exists here of human occupation from the time of the Bering Land Bridge during the last ice age (Guthrie, 2006), villages have been located along the modern coastline for at least 2000 years (Ipiutak and Old Bering Sea cultures; Friesen and Mason, 2016). An ancient cellar discovered in 2005 in the Yupik community, Sivuqaq, or Gambell, on St. Lawrence Island, contained whale blubber dated to 1030 – 1070 ± 70 yr BP (George et al., 2008) using ^{14}C dating methods. This ancient cellar is about 3.5 m below ground with whalebone supports (Fig. 2) in a style essentially the same as those used in the region today. The dated material proves that people in Beringia have been hunting whales and storing foods in subterranean cellars for centuries. Before the era of electric refrigeration, such earthen cellars were the only means of thermally controlled food storage during summer months besides food preservation methods such as drying, curing, or smoking (Fig. 3).

Chukchi and Bering Sea coastal communities have a unique history with complex interactions between Indigenous peoples and European and American immigrants to the region associated with trade, mining, and other industries. Chukchi, Inupiaq, and Yupik peoples have been the primary, long-term residents along these coastlines as their subsistence livelihoods focus on catching marine mammals, birds, and fishes (Fig. 3). Food storage in this remote region has always been a challenge for these Indigenous groups and has ranged from temporary shallow holes, sometimes covered with *Sphagnum* moss (or other lower thermal conductive materials such as peat), to more complex cellars designed with reinforced supports. Cellars are an efficient solution for storing large volumes of foods harvested for subsistence, but they are also labor intensive from initial construction to seasonal maintenance. Cellars require intense maintenance including clearing old snow and ice or debris, removing unused goods, and annual cleaning, usually performed just before new harvests are stored (e.g., in spring). The focus of this paper is to document the many ways that local environments, community, hunting season, social structure, ownership, economics, and politics influence construction, maintenance, and use of cellars excavated in permafrost and seasonally frozen ground. We also report on the results of an ongoing education and outreach project to understand the thermal state of 18 cellars in 13 Beringian coastal, island communities and northern Alaska (Utqiaġvik, formerly known as Barrow).

Other publications often refer to these cellars as “ice cellars” (e.g., Nyland et al., 2017; Maslakov et al., 2020) though they are also often called “meat cellars,” much like other cultures have “wine” and “root cellars” where the name indicates what objects are stored. While the phrase “ice cellar” is commonly used in Yakutia, few other cultures use these structures specifically for ice storage (Yoshikawa et al., 2016). We therefore use the generic term “cellars” or local Indigenous language names. In addition to colloquial naming conventions, the design and structure of cellars have both cultural and practical significance related to past and present permafrost conditions. Cellars in the Bering Strait communities are located in more marginal permafrost conditions than those in northeast Siberia or the North Slope of Alaska (Fig. 1; Yoshikawa, 2013) and are designed differently to compensate for these conditions. Concern has been expressed recently over the impact of climate change on cellars throughout the Arctic and the

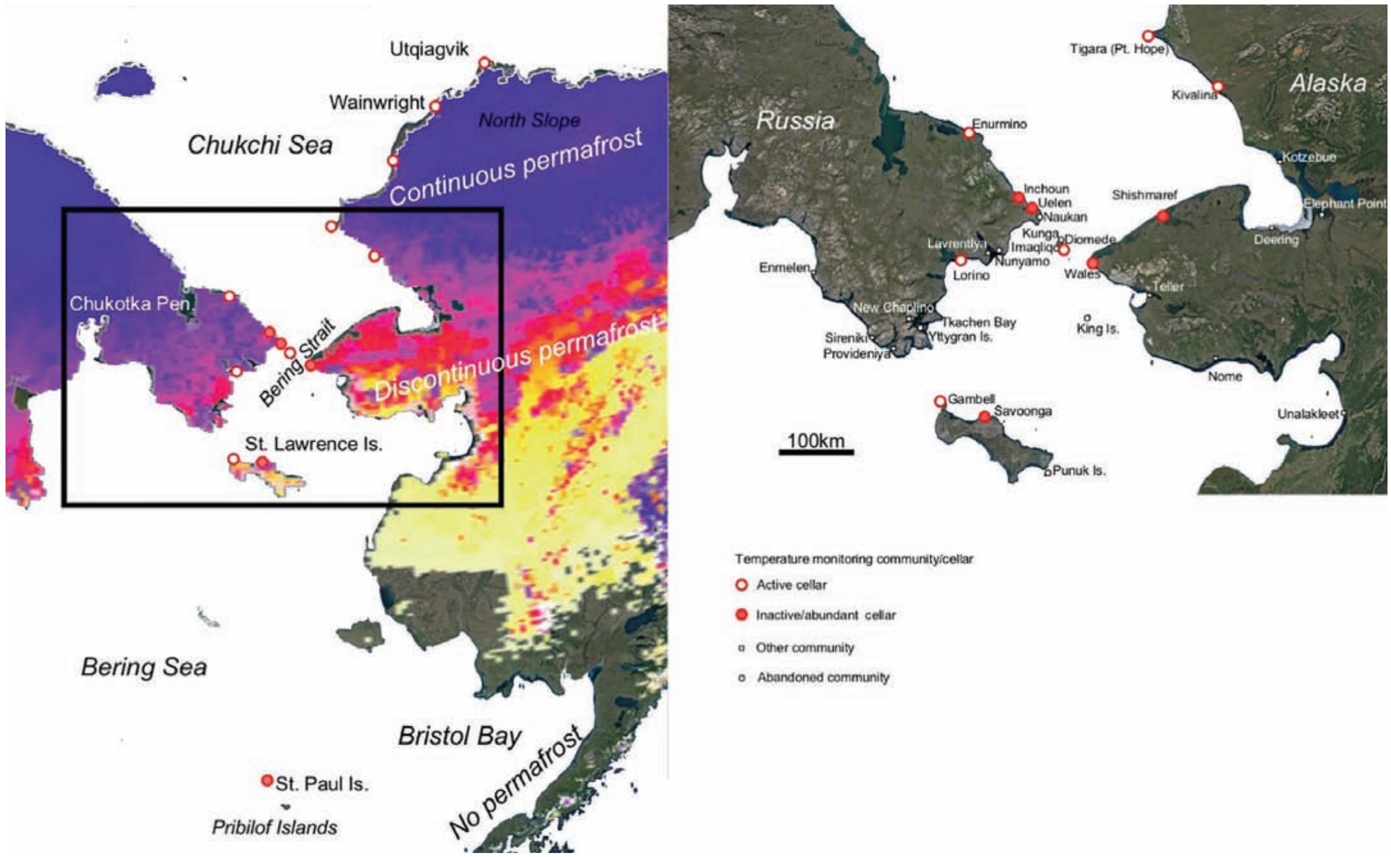

FIG. 1. Chukchi and Alaska community and cellar locations overlaid on permafrost conditions (Gruber, 2012). White-filled red circles indicate active cellars, and red circles are abundant inactive cellars, white squares are communities that were not part of this study, and white circles are abandoned villages.

future sustainability of this resource (Kintisch, 2015). We argue that particular attention is warranted for those cellars located along the southern permafrost boundary, like some of those documented in this survey, as they are particularly vulnerable to warming.

INDIGENOUS CELLAR DESIGNS, PRACTICES, AND HISTORIES IN BERING STRAIT COMMUNITIES

Chukchi Peninsula, Russia

Indigenous peoples on the Chukchi Peninsula were first contacted by Europeans sometime in the 17th century only along the coastal area (Fisher, 1981). As early as the 19th century in Siberia, cellars constructed in permafrost were discussed amongst the scientific community (e.g., von Baer, 1838; Middendorf, 1871), and cellar designs were documented and shared in engineering texts (Zalesskii, 1881; Fig. 4a). Documented Indigenous designs were later influenced by icehouse designs. Many such cellars in contemporary Russia incorporated design concepts including ventilation shafts, though Alaskan Iñupiat and Yupik cellars do not exhibit such features. However, these (St. Lawrence Island) icehouse-like features and general style remained only on the Chukchi Peninsula and did not spread eastward to Alaska, with one exception on the Pribilof Islands (Fig. 5a, b).

The 1867 treaty, in which the U.S. purchased the Alaskan territory from Russia, placed the border between these two nations between the Russian Big Diomede Island and the American Little Diomede Island, where it remains today and serves as the International Date Line. Continued Russian dominion over Indigenous communities on the Chukchi Peninsula, including relocations and required Russian-language boarding schools, rendered these Yupik communities very different culturally from Alaskan Yupik communities. For example, in 1895, there were 90 Iñupiat residents living in two villages, Imaqliq and Kunga, (St. Lawrence Island) on Big Diomede Island. By the 1920s, most residents were moved to Little Diomede for school, and just one family (12 people) remained on the island. In the 1930s, the Soviet government ordered the Yupik living in Naukan on the Chukchi Peninsula mainland to relocate to Big Diomede Island (Krupnik and Chlenov, 2013). Then in 1948, all of the Big Diomede Island residents (25 – 30 people) were relocated back to Naukan. In the 1950s, Naukan was closed and the majority of the residents were moved to other communities and settlements on the Chukchi Peninsula, including Nunyamo village, and later to Lavrentiya, Lorino, or Uelen. Frequent relocation required continual change and lifestyle adaptation by these Chukchi, Iñupiat, and Yupik peoples. Another example is the village of New Chaplino, founded in 1960 when all surrounding Yupik people were relocated there. This site

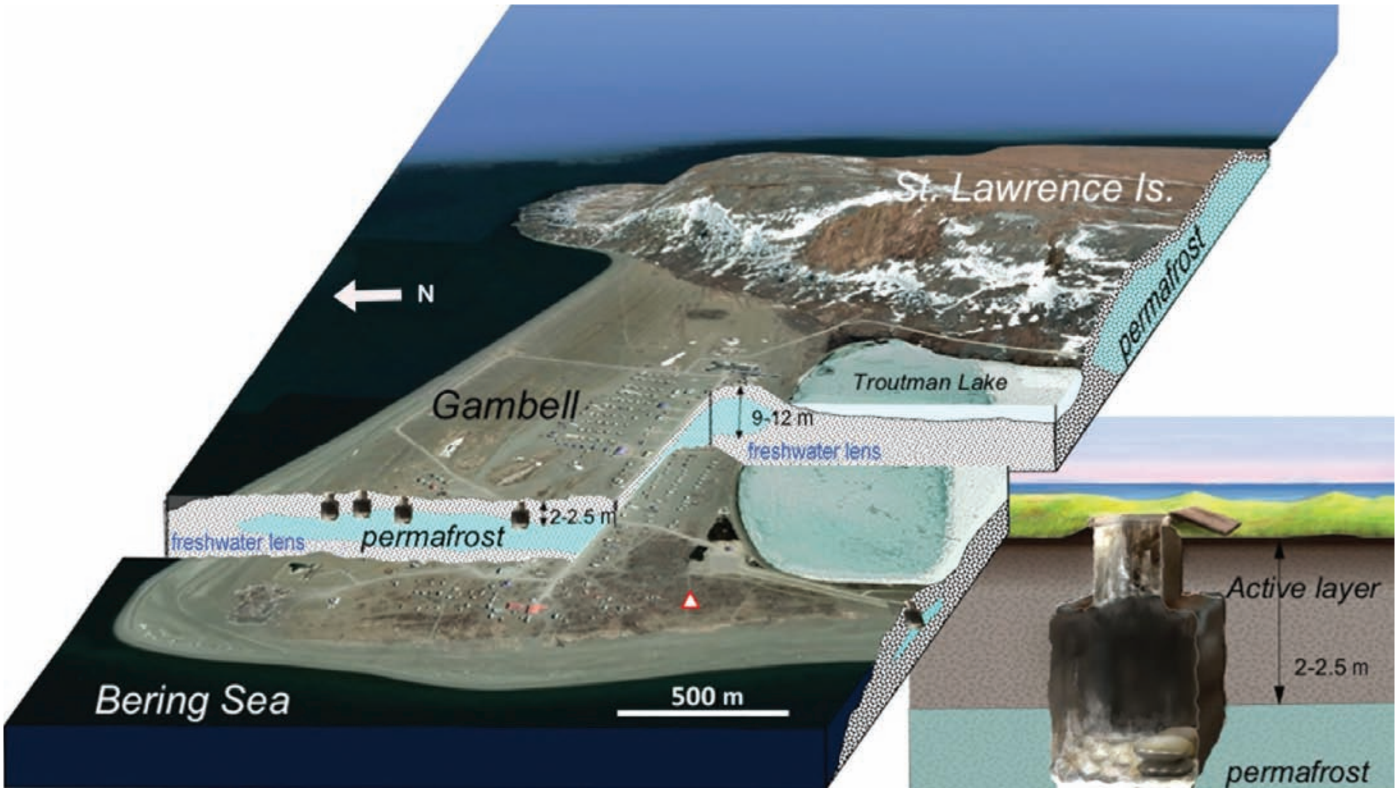

FIG. 2. Thermal and hydrological ground conditions in Gambell, St. Lawrence Island, are based on a drilling operation done as part of an education and outreach program (Yoshikawa, 2013). Permafrost thickness is 9–12 m (active layer is 1.8–2.5 m) in highly permeable beach materials with freshwater lenses. Shore environments have high salinity lenses (5–6 permil) effectively depressing the freezing point to −0.3°C. Cellars with vertical shafts are located near the beach just within the upper permafrost (lower right figure). The ancient cellar location is shown as a white triangle outlined in red.

FIG. 3. Typical foods stored in cellars: a) walrus in Lorino, mainly back up foods for Arctic fox farming, b) aged Arctic char in Kivalina, c) kopalhen (копалгын) in Chukchi, d) leftover meats and skins stitched up to ferment in a "meat ball" (iiqwaq) by St. Lawrence Island Yupik, e) whale blubber from an ancient cellar in Gambell, St. Lawrence Island, and f) meat wrapped in plastic bags inside a cellar.

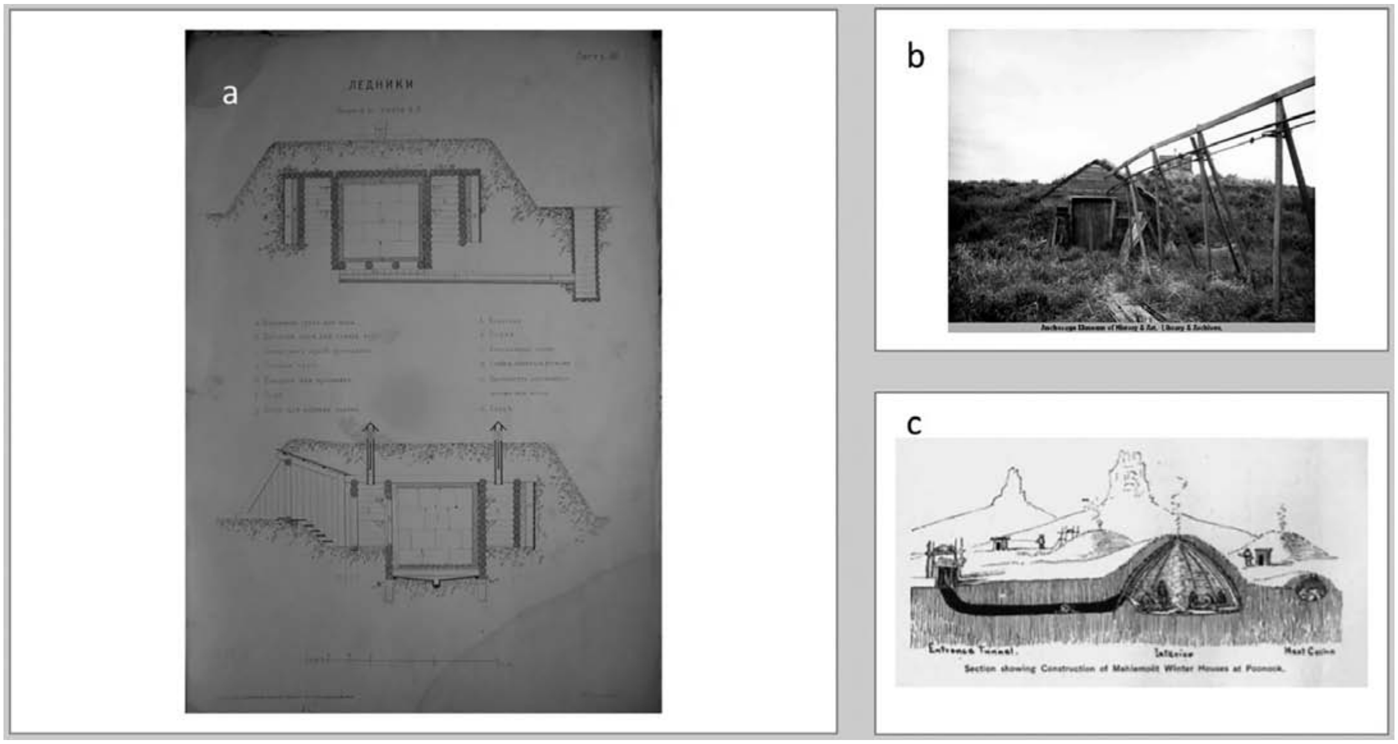

FIG. 4. Historic cellars: a) illustrations including ventilation and wood frame for a Russian *lednik* (Ледники) design by Zalesskii (1881), b) entrance to natural cold storage plant and pipes from an artificial ice machine at Lomen Elephant Point reindeer processing plant (July 1938. AMRC Ickes Collection: AMRC-b75-175-17, Photographer: Ray B. Dame. Original photograph size: 21.6 cm × 25.4 cm), and c) drawing of a St. Lawrence Island Yupik winter house and cellar (meat cache) in 1874 on Punuk Island by Henry W. Elliott (1886).

FIG. 5. Cellars on Alaskan islands: a) entrance of icehouse on St. Paul Island, Pribilof Islands, b) inside of icehouse, c) entrance of Gambell beach shaft-type cellar (without shed), d) inside of Gambell cellar, e) entrance of Little Diomede whaling crew cellar, and f) inside of cellar on Little Diomede Island showing rock fissures and cracks with a stacked rock wall.

on Tkachen Bay was not good for hunting, but chosen by the government. The relocation led to a decline in the local Yupik clan system and hunting culture as well as the number of cellars. Based on communications with locals, the authors believe that there may be one remaining pre-Russian style Yupik cellar in the village of Sireniki and another in Enmelen (Yamin-Pasternak et al., 2014).

Especially during the Soviet era (1917 – 89), the USSR supported the development of community-based or industrial cellars. During that time, cellars were government designed and constructed in each community (*kolkhoz* (колхоз) or *sovkhoz* (совхоз): local or state-owned collective farms) based on perceived community needs and local industry (Maslakov et al., 2020). In Chukotka, contemporary, Soviet-sponsored cellars typically consist of a vertical shaft under the access shed that leads to a small chamber and horizontal tunnel with ventilation excavated into permafrost (Fig. 6a, c, e). These cellars vary in specific dimensions. The vertical shafts range from 2 to 6 m deep, or to a depth such that the ceiling of the chamber is below the permafrost table, which is usually less than 1 m below the ground surface. Older cellars such as the one in Uelen were built with a thick wooden frame with two ventilation shafts and typically consist of a descending tunnel entrance (15˚ to 20˚ slope) that leads to a small chamber excavated into permafrost (Fig. 6c, d). This type of cellar is similar in design to European wine and food cellars and provides easy access and maneuvering of stored goods. In addition to commercial or industrial cellars in most Siberian regions, there are deeper, longer, and larger-capacity cellars, most of which were built during the Soviet era for communal use. Many of these cellars were dug horizontally for hundreds of meters with tracks and cars for moving frozen items within the structure. Though abandoned, these large-capacity cellars today receive limited use, and others have been repurposed. For instance, the community cellar in the village of Tomtor, Yakutia, is now a museum.

Widely used in bigger cellars throughout Siberia, natural ventilation systems were noted as early as 1881 in engineering texts (Zalesskii, 1881). Ventilation is also necessary to allow cold winter air to sink into cellars to maintain low internal temperatures. Many Indigenous Evenk cellars have two ventilation pipes: one near the ceiling and another close to the floor as observed in the Uelen cellar examined by the authors. Different ventilation opening locations and heights allow for easier air convection within a cellar. The addition of a chimney to a ventilation shaft offers still higher ventilation efficiency (Fig. 7). During summer months, cold, heavy air sinks and remains in the cellar, but these ventilation pipes can also be closed to stop air circulation.

Siberian cellars without ventilation structures are often converted root cellars. Potatoes and other tubers are stored in crawl spaces and basements (подвал) beneath houses over winter. These crawl spaces and basements were later excavated to deeper depths for cool to frozen storage through summer months. Entrances to these converted root cellars are typically inside houses above or very close to the cellar.

Russian and Alaskan Bering Strait Islands

Prehistoric houses in central Beringia were often partially excavated into the ground with sod walls and roofs. Cellars constructed this way were often connected to sod houses by passageways (Elliott, 1886; Fig. 4c). Sometimes sod cellars or caches had half walls of stacked stones as noted on Punuk Island in 1886, in modern cellars on St. Lawrence and Little Diomede Islands, Alaska, and on the Russian Yttygran Island, also known by the Yupik name, Sikluk (cellar) Island (Krupnik and Chlenov, 2013).

After the Alaska Purchase, Bering Strait Island communities became more isolated depending on which side of the national border they occupied, although there was some limited interaction through the 1920s. During the 1910s, many of the cellars on Big Diomede were abandoned when the residents immigrated to the US side of the Strait. After this, there was much less interaction between the US and Russian communities in the region. On 13 August 1914, the *Nome Daily Nugget* newspaper reported:

> Little Diomede Island is the only place that can boast of a native teacher in control of a native school in Alaska. The school is said to be in excellent and flourishing condition. The natives of Big Diomede, which is under the Russian government, have no school and move over to the Little Diomede during the winter to get the school advantages.

On Little Diomede Island, steep and rocky terrain limits excavation for cellars, but with seasonal population increases, cellar capacity was needed. In one well-documented use of a cave for food storage on King Island, Alaska, walrus and seal meat were kept in a snowbank at the back of the cave (Ferguson, 2012). On Little Diomede Island, multiple families would store goods together in the whaling captain's bigger and deeper cellar for about three months of the summer season (Fig. 5e, f). After the first snowfall, stored foods were moved to smaller family cellars or even shallower caches (Norbert, 2016).

The Yupik communities of Gambell and Savoonga on St. Lawrence Island both have cellars today, however, the Savoonga cellar, originally intended to support a reindeer farming camp in 1916 was never used consistently and not within the last 20 years (George Noongwook, pers. comm. August 2020). Gambell has a longer history as a whaling community with more consistent cellar use (Fig. 5c, d). Deeper (> 150 cm) vertical shaft style cellars with a space only slightly wider than the shaft at the bottom (Fig. 2) can be found on or near beaches in coastal Alaskan villages such as in Gambell and on the Punuk Islands. Gambell cellar designs align with either clans or families, where the size of the cellar typically correlates with family size. Following the clan-based system and traditions in Gambell,

FIG. 6. Siberian cellars: a) ventilation shafts in Lorino, Chukotka, b) Lorino horizontal cellar with rail, c) wooden old Russian style cellar with double ventilation, d) inside a cellar at Uelen abandoned due to flooding, e) entrance shed of Inchoun cellar on polygonal ground, and f) inside of Inchoun cellar before flooding in 2016.

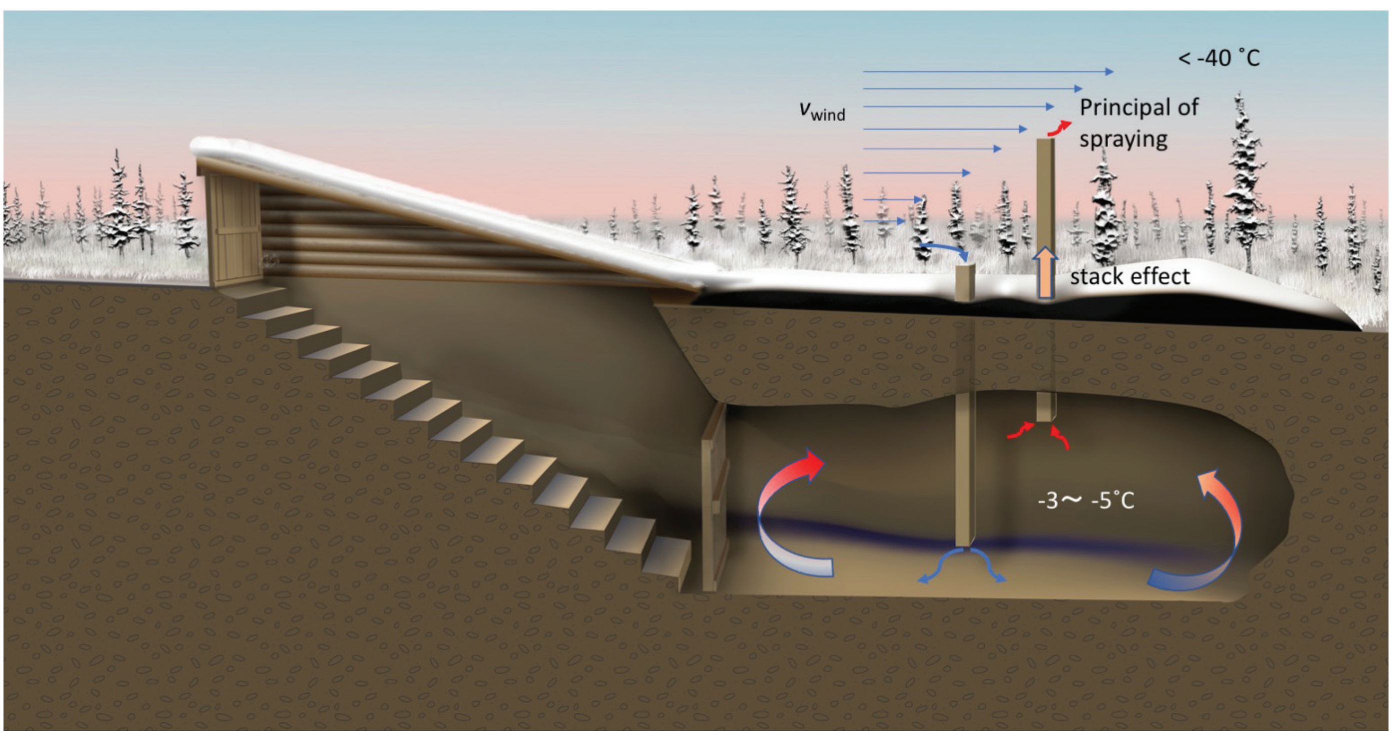

FIG. 7. Natural air circulation within a double ventilation system in Siberian cellars that effectively cools during winter months.

snow and sea ice is laid on cellar floors in spring and harvested foods are placed on top. In the fall, just before the freezing season, water from the melted snow and sea ice on the floor is removed.

Mainland Alaska

In contrast to cellars on the Chukotka Peninsula outfitted with ventilation systems, Alaskan cellars have no such structures. Reasons for not using ventilation in Alaska are the vertical access shaft design and past difficulties acquiring sufficient building materials such as wood planking to reinforce additional shafts for ventilation.

Temporary, shallow holes, or caches, are still widely used in summer in permafrost and non-permafrost affected soils. For instance, in Alaskan Yup'ik communities of Bristol Bay, temporary caches are used for fermenting salmon heads (also called stink heads) during the summer months. In Shishmaref, Alaska, and Igloolik, eastern Canada, ~0.5 – 1.5 m deep holes are dug near beaches to store and ferment walrus and beluga meat and skins (*iiqwaq*/*ignak*/*ooshuck*, Ken Stenek, pers. comm. September 2019). The Indigenous people typically hunt walrus from sea ice flows in spring, bury the harvest in late May to early June, and harvest the fermented meats in late fall (Ken Stenek, pers. comm. September 2019). Similar caches were also used in Teller and Unalakleet, Alaska, during years with unexpectedly rich herring harvests (Norbert, 2016). Elizabeth Pinson (2004:96) commented on a particularly rich herring harvest and a cache in permafrost in her memoir, *Alaska's Daughter* (2004:96):

> It was then pulled onto the beach. Sometimes 300 or 400 pounds of herring would be caught in a single haul. Beluga whales would be right behind the school of herring—many times we could see the mother whale surface with a baby whale lying on her back. The herring were a delicacy. Papa salted them in barrels, smoked them, or pickled them with vinegar and spices. Sometimes he preserved them Eskimo style by putting them into a pit dug six feet or so into the permafrost where they were preserved in nature's cold storage to be eaten later. Smoked, baked, fried, or boiled, they were real good eating.

Sod house-type (or mound-type) cellars are considered one of the oldest storage structures in Tigara (name of the former Point Hope village location near the tip of the cape) and on Little Diomede Island today. These generally provide more consistently cool conditions than a temporary cache, but they are not as cold as deeper cellars in permafrost since they are still prone to ambient air temperature fluctuations. A consistent cool or cold cellar temperature is key for prolonged food storage, but also for the stability and safety of the cellar structure. The historic village site was subject to frequent flooding from fall storm surges. The village was relocated to its more protected location on the Point Hope peninsula in 1975, but some historic cellars at the old site continue to be used rather than excavating new ones. Most cellars are reminiscent of prehistoric sod cellars and houses described from Bering Sea island communities. At the Tigara site in Tikiġaq (area of current and former Point Hope villages and including the runway), sod mounds cover cellars, raising the elevation of the entrance shaft above the surrounding ground (Fig. 8c and 8d) and protecting the cellars from storm surges.

South of Point Hope, Kivalina and Wales are also traditional whaling communities. Older simple vertical-shaft cellars remain in Wales, but are not in use today. These shafts are shallow (50 – 150 cm) and primarily built in the only seasonally frozen surficial soil above permafrost, called the "active layer." Deeper shafts that place the main cellar space well within the permafrost require significantly more labor to construct and maintain, but deeper cellars offer more stable multiyear storage, like those on the North Slope of Alaska or in northern Siberia. Deep shafts or cellars are not common in Bering Strait communities. In Kivalina, the community constructed a much deeper (5 m) cellar at the proposed relocation site, "Kiniktuuraq," in 2000 (Fig. 8a and 8b). The new Kivalina cellar center has a deep vertical access shaft to a horizontal tunnel or room within permafrost that is capable for year-round frozen storage. Kivalina is considering relocation due to rapid coastal erosion. The community relocated previously from a location north of Kivalina Lagoon (now referred to as "old Kivalina") in 1905 following the construction of a school to the south. Other Iñupiat communities in Alaska, such as Wainwright and Utqiaġvik, have more cellar usage because of more active whaling.

Perhaps the most traditional cellar design found on mainland Alaska is a deep vertical shaft with an exposed entrance (only a simple hatch or other closure over the access shaft) and neither a shed or house over top nor ventilation (Fig. 8a). Placing a shed over a cellar access shaft has become commonplace as it makes accessing cellars in winter easier. The protection offered by a shed from falling and drifting snow can also make it easier to leave a cellar open in winter to ventilate and drastically cool the interior as commonly done in Siberia, but without a shed, snow cover offers better protection from polar bears and other scavenging animals accessing or damaging cellars. In the latter half of the 20th century, it became easier to dig into the permafrost with wider access to dynamite and heavy excavation equipment. With the heightened excavation capabilities, permafrost cellars became significantly deeper, wider, and sometimes equipped with sheds. Larger and deeper cellars offer greater storage spaces and more stable interior temperatures throughout the year. Cellar interior temperature depends on surrounding permafrost temperature and ventilation. The depth at which permafrost temperature does not fluctuate in response to seasonality is referred to as the depth of zero annual amplitude (Biskaborn et al., 2019). Zero annual amplitude depth depends on the soil conditions and moisture content, but in

FIG. 8. Cellars on Alaskan mainland: a) entrance of new Kivalina cellar (without shed), b) inside of Kivalina cellar (new and deep vertical shaft design), c) entrance of sod house-type Tikiġaq (Point Hope) cellar, and d) typical structure of a shallow, sod house-type cellar.

permafrost regions of Beringia typically occurs between 3 and 10 m depth. If a cellar is deeper than the depth of zero annual amplitude, the interior storage temperature will be stable throughout the year remaining close to that of the surrounding permafrost.

Deep vertical-shaft designed cellars are common in Iñupiat whaling communities such as Utqiaġvik, Wainwright, and Point Hope. Whaling crews from mainland Alaska will typically store harvested meats in a single cellar maintained by the crew captain. These cellars require maintenance similar to those described previously on St. Lawrence Island, where they are cleaned and fresh snow or ice are laid down within the cellar before a new harvest. The younger members of a whaling crew typically perform these physically demanding tasks. Annual cellar usage and maintenance (cleaning) patterns vary. The bigger permanent cellars in these communities are cleaned in March–April preceding the spring whaling season (Nyland et al., 2017).

NON-INDIGENOUS AND INDUSTRIAL CELLAR DESIGNS

After the turn of the 20th century, industrial construction equipment was used to build large cellars to support industries including commercial whaling, reindeer and Arctic fox husbandry and processing, and military activities on both the Soviet and American sides of the Bering Strait. A big industrial cellar was built by the Lomen Company's Elephant Point facility on the Seward Peninsula of mainland Alaska in the early 1920s, designed to hold 10,000 reindeer carcasses (Postell, 1990; Fig. 4b). Outside of the Bering Strait regions, non-Indigenous whalers constructed cellars similar to the Siberian log stacked storage on Herschel Island, Canada, in the early 1900s (Burn, 2012). Still larger permafrost structures in Alaska and Canada were built with ventilation shafts by the U.S. Army Corps of Engineers, such as the permafrost research tunnel in Fox, Alaska, constructed in 1963, the bunkers constructed in Dutch Harbor in 1942, and those constructed in 1948 in Mould Bay (High Arctic Weather Station) on Prince Patrick Island, Canada.

An impressive example of a Soviet industrial cellar was constructed in 1957–59 by the Moscow Metro Company in Lorino, Chukotka (Maslakov et al., 2020; Fig. 6b). This massive, industrial cellar was 114 m long, complete with rails for small cars to move materials the length of the tunnel with numerous side chambers intended to support both the local population and the Arctic fox farm industry. Smaller cellars in the villages neighboring Lorino also supported Soviet fox farming. Arctic fox farms require several tons of feed per month and the *kolkhoz* (collective farm) would also hunt walrus and gray whale during the open-water periods. Post-Soviet Union and after the dissolution of the collective farms, industrial whaling ceased, and Yupik and Chukchi residents reverted partially to more traditional diets centered on smaller marine mammals, such as seals (Krupnik and Chlenov, 2013).

CELLAR TEMPERATURE MONITORING METHODOLOGY

Between 2008 and 2016, 18 cellars in 13 communities on the Russian mainland, islands, and Alaskan mainland of the Bering Strait and northern Alaska were provided internal air and food temperature monitoring devices, or data loggers. Of the monitored cellars, 16 yielded one to five years of continuous temperature records. While some cellars had unsuccessful temperature monitoring, all 18 cellar structures were examined, descriptions recorded, and local cellar users and community elders interviewed. Each of these cellars is listed and classified by construction type and materials used in Table 1. This regional cellar monitoring network was born of a much larger community-based permafrost monitoring program established in 2005. The larger network consists of 250 Alaskan rural communities and over 300 primarily Indigenous communities in Russia, Mongolia, Canada, and Greenland visited by K. Yoshikawa who drilled and instrumented boreholes in each to enable local stakeholders (e.g., community leaders, educators, and students) to monitor local permafrost temperatures with depth (Yoshikawa, 2013, 2017).

The 13 Bering Strait and northern Alaska communities of interest to this study were each outfitted with a borehole from 1 to 3 m depth and loggers for continuous temperature in the borehole and near stored foods in nearby cellar(s). Onset Computer Corporation's Hobo U12-006 model data loggers recorded measurements at hourly intervals with thermistors accurate to around ± 0.1˚C. Data were downloaded, instrument maintenance was performed on an annual basis, and mean, maximum, and minimum annual temperatures were computed.

The freezing points of various traditional foods such as bowhead whale blubber, Arctic char, and salmon roe were also determined by measuring their internal temperature with a data logger recording at 1-minute intervals from room temperature to -20˚C and back to room temperature using an electric freezer. The freezing point was interpreted here as the consistent temperature during phase change due to the release of latent heat.

Using reconstructed permafrost temperatures back to 1923 in Utqiaġvik (Romanovsky et al., 2007), temperatures for an abandoned cellar on the Utqiaġvik beach were estimated. A lower boundary of 125 m with constant geothermal heat flux at this depth was set for this modeled cellar record. Romanovsky et al. (1997) provided descriptions of the numerical models used for this reconstruction. Site-specific calibrations of these models used annual active layer measurements and permafrost temperature profiles from the "Barrow 2" permafrost observatory (https://permafrost.gi.alaska.edu/site/br2). Daily air temperatures and snow depth measured at the Barrow meteorological station were also used in model calibration and record reconstruction. Drilling records provided lithological and thermal soil properties for frozen and thawed states. The thermal properties (e.g., unfrozen

TABLE 1. List of monitored cellars, temperatures, usage, and dimensions. AE indicates an Arctic Entry or shed on top of the cellar.

Country	Community	Latitude (°)	Longitude (°)	Entrance	Depth (m)	Floor area (m²)	Ventilation	Wall/ceiling materials	MAGT (°C)[1]	MACT (°C)[1]	Max CT (°C)[1]	Min CT (°C)[1]	Annual amplitude (°C)	Thawing days
Russia	Inchuon	66.3	−170.3	AE + double lid	3	15	yes (single)	silt	−2.4	−5.3	1.1	−18.3	17.2	0
Russia	Uelen	66.2	−169.8	AE	3	25	yes (double)	sand/gravel	−1.9	–	–	–	–	–
Russia	Lorino	65.5	−171.2	AE	10	456	yes (shaft)	sand/pebble	−1.9	−4.4	-3.1	−7.3	4.2	0
Russia	Enurmino	66.9	−171.8	AE + double lid	3	> 20	yes	sand	−2.6	–	–	–	–	0
USA	Utqiaġvik	71.3	−156.7	AE + double lid	6.6	6	no	gravel	−7.0	−7.5	−4.3	−11.2	7.0	0
USA	Utqiaġvik	71.3	−156.7	AE + single lid	5.6	9	no	gravel/brine	−7.5	−7.8	−5.7	−12.0	6.4	0
USA	Utqiaġvik	71.3	−156.7	AE + double lid	4.9	9	no	gravel	−8.0	−7.3	−3.6	−11.7	8.1	0
USA	Utqiaġvik	71.3	−156.7	single lid	2.7	6	no	sand/brine	−5.0	−6.4	−3.3	−11.5	8.2	0
USA	Utqiaġvik	71.3	−156.7	AE + double lid	5.3	15	no	gravel	−8.0	−6.3	−4.1	−9.3	5.2	0
USA	Tikiġaq	68.3	−166.8	single lid	2	4	no	woods/whale	−2.8	−1.4	3.4	-9.3	12.6	175
USA	Kivalina	67.7	−164.5	single lid	1.2	1	no	woods	−1.5	−4.3	13.1	−25.8	38.8	120
USA	Kivalina	67.7	−164.5	double lid	4	24	no	silt	−1.5	−2.1	−0.9	−3.9	3.0	0
USA	Little Diomede	65.7	−168.9	single lid	1.5	4	no	stone/woods	−2.3	−2.3	8.0	−14.5	22.5	140
USA	Wales	65.6	−168.1	single lid	1	0.25	no	woods	−2.6	−2.4	27.2	−15.9	43.1	175
USA	Savoonga	63.7	−170.5	single lid	2	5	no	woods	−1.6	−1.7	9.9	−19.8	29.6	170
USA	Gambell	63.7	−171.7	single lid	2	2.25	no	woods/whale	−1.6	−1.2	6.1	−11.2	17.3	185
USA	St. Paul	57.1	−170.3	single door	2.5	9	no	cement	2.9	1.5	6.6	−3.6	10.1	330
USA	Shishemaref	66.3	−166.1	buried	1	0.5	no	sand	−2.1	−1.9	1.7	−8	9.7	–

[1] MAGT = mean annual ground temperature, MACT = mean annual cellar temperature, Max/Min CT = maximum/minimum cellar temperature.

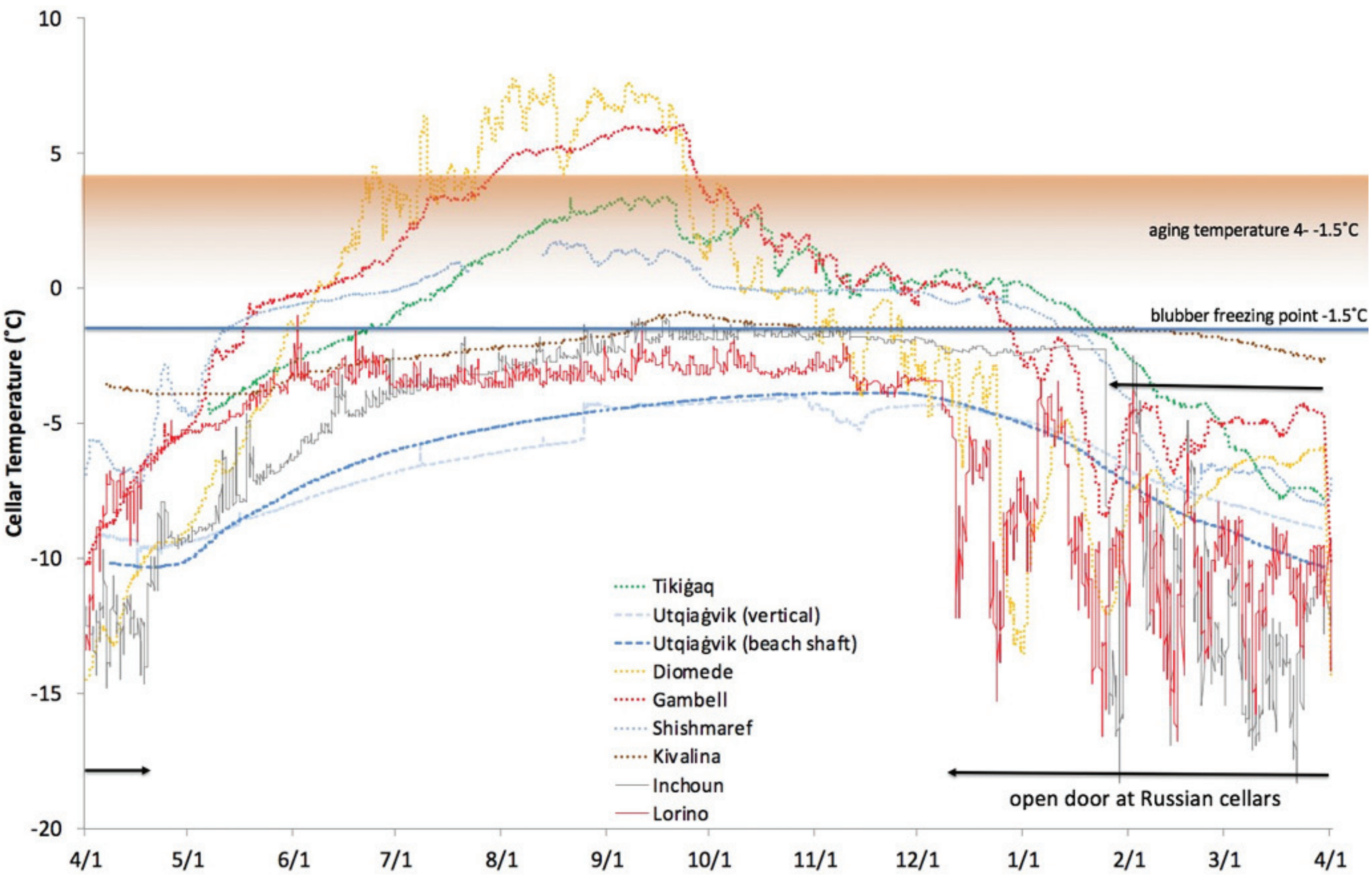

FIG. 9. Annual cellar temperatures as measured in Bering Strait and North Slope communities. Cellar locations indicated in Figure 1.

water content curves) were refined using a trial-and-error method (Osterkamp and Romanovsky, 1997; Romanovsky and Osterkamp, 2000).

RESULTS OF TEMPERATURE MONITORING

Most annual temperature cycles from cellars monitored on the Russian mainland indicate significant cooling during winter months due to open cellar entrances and ventilation shafts as well as bringing in fresh ice and snow during spring cleaning. Alaskan cellars are not traditionally left open for ventilation in winter, so their annual temperature amplitudes are closer to that of the surrounding ground or permafrost (Fig. 9). In deeper cellars (deeper than 5 m) such as those in Lorino and Utqiaġvik, the warmest cellar temperatures were usually observed in the late fall to early winter (September to December; Table 1). This delay in thermal conduction makes for good (cooler) conditions within the cellars for summer storage. Shallow or sod-type cellars, such as those monitored in Shishemaref and on Little Diomede Island, do not have as much thermal conduction delay and warm sooner in response to summer. Snow and sea ice brought inside these shallow or sod-type cellars in spring and even stone or driftwood roofs help to insulate these structures from solar radiation.

Temperatures in some cellars, such as Gambell, Savoonga, Wales, and Tikiġaq, rise above 0˚C in summer (Table 1 and Fig. 9). Some of the cellars (Savoonga and Wales) had been abandoned by the time K. Yoshikawa visited to install monitoring equipment. Cellar temperatures on the North Slope have mostly remained well below 0˚C. Aging food in cellars is a chemical reaction that occurs faster when food is not frozen, but warmer conditions also make botulism a greater concern. The freezing point of whale blubber was determined to be around −1.5˚C, thus, the ideal summer temperature for aging within cellars would be between −1.5 and +2˚C. Most of the cellars in the observed Bering Strait communities (Gambell, Savoonga, Little Diomede, Wales, Tikiġaq) exhibit these ideal thermal conditions for aging, which also control the fermentation process.

The reconstructed temperature record for the abandoned cellar in Utqiaġvik was ideal for modeling because (1) more than a century of consistent meteorological data is available for this locale and (2) the entrance to this cellar has remained closed, maintaining cellar temperatures reflective of the surrounding permafrost. There was a close correspondence between temperatures observed in this cellar at 2.5 m depth from 2009 to 2012 (abandoned soon thereafter) and permafrost temperature at 2.5 m depth where the correlation exhibited a 0.96 coefficient of determination (R^2). The difference between maximum and minimum permafrost and cellar temperatures are related to convection and the heat capacity of the cavity (air in the cellar; Fig. 10). Under this model, the last 88 years of temperatures inside the Utqiaġvik cellar are similar to annual fluctuations today, without any substantial indications of warming. These internal cellar temperatures are still conducive, therefore, to frozen food storage. However, for over 10 months of the year, the ground temperature is above the melting point of brine (−9.5˚C), which allows pooling on the floor of the cellar and weakens its structural stability. Decreased structural stability can lead to collapse, as observed by locals with cellars nearby. Permafrost in coastal regions frequently contain brine, significantly depressing the freezing point of these soils.

DISCUSSION

Based on public media reports (e.g., Kintisch, 2015; D'Oro, 2019; Welch, 2019) and our own field observations, evidence indicates several major problems facing the continued maintenance and use of cellars in Alaska (Klene et al., 2012; Nyland et al., 2017) and Chukotka (Maslakov et al., 2020). Factors other than climate warming negatively impact the structure and operation of cellars include ice-rich and high salinity soils, proximity to flooding from storm surges, and infrastructure development proximity and how this changes local hydrology (Nyland et al., 2017). Potential problems specific to cellars in these Bering Strait communities include increased potential for conditions conducive to botulism, the northward retreat of permafrost due to climate warming, and additional costs associated with the construction of deeper cellars or replacement with electric freezers.

Flooding and Structural Issues

Flooding is a persistent issue in cellars surrounding the Bering Strait, as was repeatedly mentioned in the communities involved in this collaborative monitoring effort. Flooded cellars have been reported, and some subsequently abandoned in Uelen, Tikiġaq, Gambell, and Utqiaġvik. Fall storm surge and sea level rise are the main reasons for flooding. Spring floods can be mitigated by pumping out water that infiltrates a cellar, but flooding in fall is far more complicated despite maintenance efforts. There may not be enough time following a fall storm to pump water out from a flooded cellar before it freezes, rendering a cellar of limited use, if it is usable at all through the winter. Recent fall flooding in Uelen and many other Siberian villages completely filled and froze within the cellars, forcing them to be abandoned (Fig. 6f). During the Soviet era, *kolkhoz* maintained cellars with dedicated full-time workers to avoid issues of this magnitude in their industrial cellars. This kind of intense and immediate maintenance can prevent cellar failures, but is often impractical in terms of available time and labor for communities today.

Brine was noted in several coastal cellars observed in this work. Briny, or highly saline, moisture in cellars make a good environment for fermentation and protects meat from "freezer burn" caused by sublimation. However, cellars are also structurally weakened if the surrounding soil warms in briny conditions. Decreased structural stability is more likely in this situation because of the depressed freezing point of briny soils. In Utqiaġvik for instance, the brine has about 4.2 times higher salt content than the ocean water (Yoshikawa et al., 2004) and therefore a freezing point of −9.5˚C. Over 10 months of the year (from May to March of the subsequent year), the interior cellar temperature is above the briny soil's freezing point in Utqiaġvik, thus, the cellar's structural stability is weakened.

Many villages along the Chukchi Sea are on beaches and in polygonal tundra. Ice wedge polygons are very common here, produced by recurring cycles of frost contraction cracks filling with snowmelt water in the spring and refreezing. The junctions of ice wedges are relatively easy to excavate and were sometimes historically targeted by Indigenous peoples for cellar construction sites. Polygon intersections were excavated, and soil and vegetation mats piled around the entrance shaft. Counteracting the advantages of easier and faster excavation at ice wedge intersections, when a strong temperature gradient (cooling event) occurs in early winter and ice wedges crack open, water seeps in and can be channeled through these networks into cellars. Several instances of water seeping into cellars through contraction cracks in this manner were reported in Utqiaġvik and Wainwright, Alaska.

Whale bone was used for cellar structures historically and was later replaced by wood when it became more readily available through regular shipping and improved trade. Wood has long been used in cellar designs in Russia, where a wooden roof covers an open pit, likened at times to an underground "log house." The lifetime of timber is only 30–50 years or, if chemically treated, up to 100 years. For many of the western whaling cellars (e.g., Uelen), collapse is imminent, and there are no plans within the community to replace rotten wood or construct new cellars in these locations.

Sublimation is common in cellars and is dependent upon the ice content of earthen walls. When sublimation occurs, it can cause serious hazards including sloughing walls and ceiling collapse. In many of the northern Siberian cellars, water was sprayed every three to four years on the interior cellar walls to stabilize them and prevent sublimation. However, we did not see or hear of such techniques being widely used in Alaska.

Botulism, Aging, and Fermentation

Botulism can be a common problem with traditional Indigenous foods (Shaffer et al., 1990). The variable conditions of cellars throughout the year could contribute to this health risk, including temperature, oxygen level, or mold growth in the high relative humidity inside cellars.

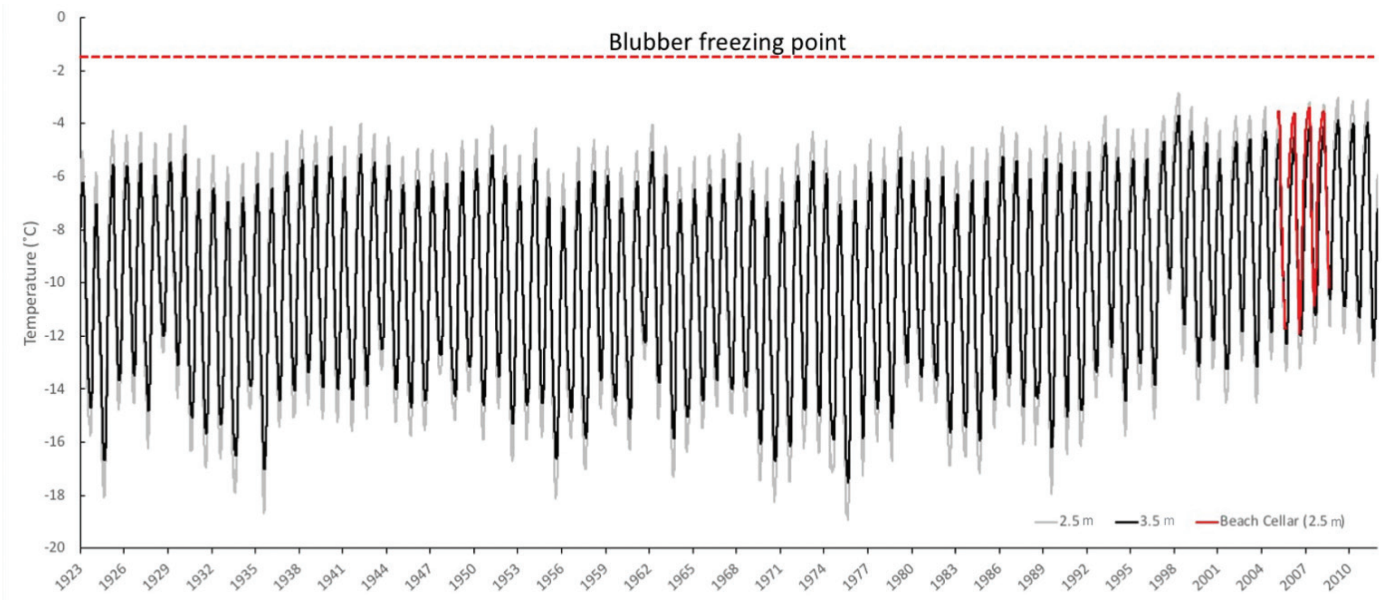

FIG. 10. Reconstructed 88 years of cellar temperatures since 1924 in Utqiaġvik (formerly Barrow). Cellar was warming after 1999 event. Red line shows measured cellar temperatures. The dashed red line indicates the freezing point for whale blubber.

However, botulism cases are most closely related to foods in anaerobic environments within plastic bags which could be used to wrap meats kept in cellars (Fig. 3f). If the temperature in a cellar warms to above 0˚C, meats will continue to undergo the aging and fermentation processes, but should not spoil if there is enough oxygen. This issue underscores the importance of traditional storage without plastic wrappings and for ensuring circulation of air in cellars. For example, the previously mentioned fermented walrus (*iiqwaq*) is an important food in Bering Strait communities where walrus meat is boiled, called "coke," then leftover meats and skins are stitched into a "meat ball" to ferment (*iiqwaq* in St. Lawrence Island Yupik, *kopalhen* (копалгын) in Chukchi, and *igunaq* in Inuit). On St. Lawrence Island, in Gambell and Savoonga, the meat ball is left in the cellar or kept in the cellar entry; in Chukotka, it is kept on a snow patch either on or near a cellar entrance through the summer. The temperatures of these warm storage locations range from 0 to +5ºC, which are good for effective fermentation while maintaining good circulation (Fig. 3a–d).

Climate Change and Warming Cellar Temperatures

Leaving a cellar door open in winter is common practice in Siberian communities and in some contemporary cellars in northern Alaskan communities. The origin of this ventilation practice is unknown, but the technique helps to cool and stabilize cellars through warmer seasons (Fig. 11). Leaving doors open to cool cellars is particularly common in central Yakutia where a strong winter inversion can reach −60˚C. Figure 12 shows the temperature differences between cellars where the door is left open versus closed during winter. Summer internal temperatures after the door is left open over winter are cooler and have improved circulation.

In cases where cellar temperatures are warming beyond the ability of being managed through traditional maintenance methods, engineering options are available to preserve the function of cellars. For example, thermosiphons can be installed to artificially freeze or refreeze ground to stabilize a cellar (Wendler, 2011). Thermosiphons, while costly for initial purchase and installation, already have a long history of use in Siberia and Alaska for other infrastructure (e.g., stabilizing roads, pipelines, buildings), but they have yet to be used to maintain cellars in Bering Strait communities.

CONCLUSIONS

Cellars constructed in permafrost, the active layer, and seasonally frozen ground throughout Beringia constitute an important cultural and economic resource used by both Indigenous and other residents of Arctic communities. This paper has summarized the variability in cellar designs throughout this region, from temporary caches in seasonally frozen ground, to sod structures, to deep vertical shafts in permafrost. Cellar design, maintenance, and community choices to abandon some cellars have been influenced by both climate as well as political and economic forces. It is also evident from temperature records and in-depth examination and description of the 18 cellars in the community-monitoring network (spearheaded by first author K. Yoshikawa) that complicating external influences are local ground thermal regimes, soils, flooding, modern development, and other endemic influences. Interactions among these many variables and their impacts on cellars

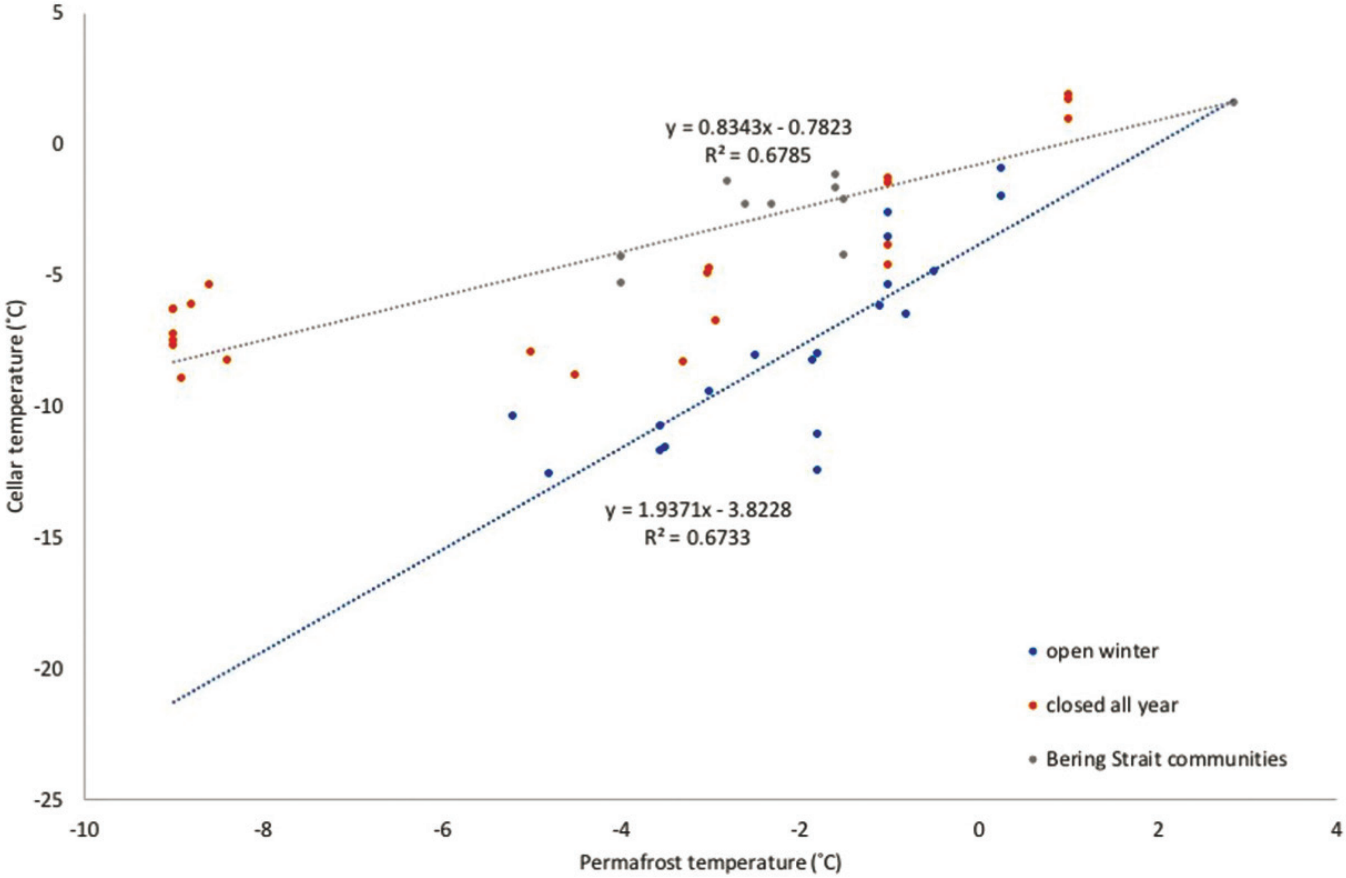

FIG. 11. Mean annual cellar temperature vs. permafrost temperature. Cellars on which the door is left open during the winter are colder than cellars on which doors are kept closed.

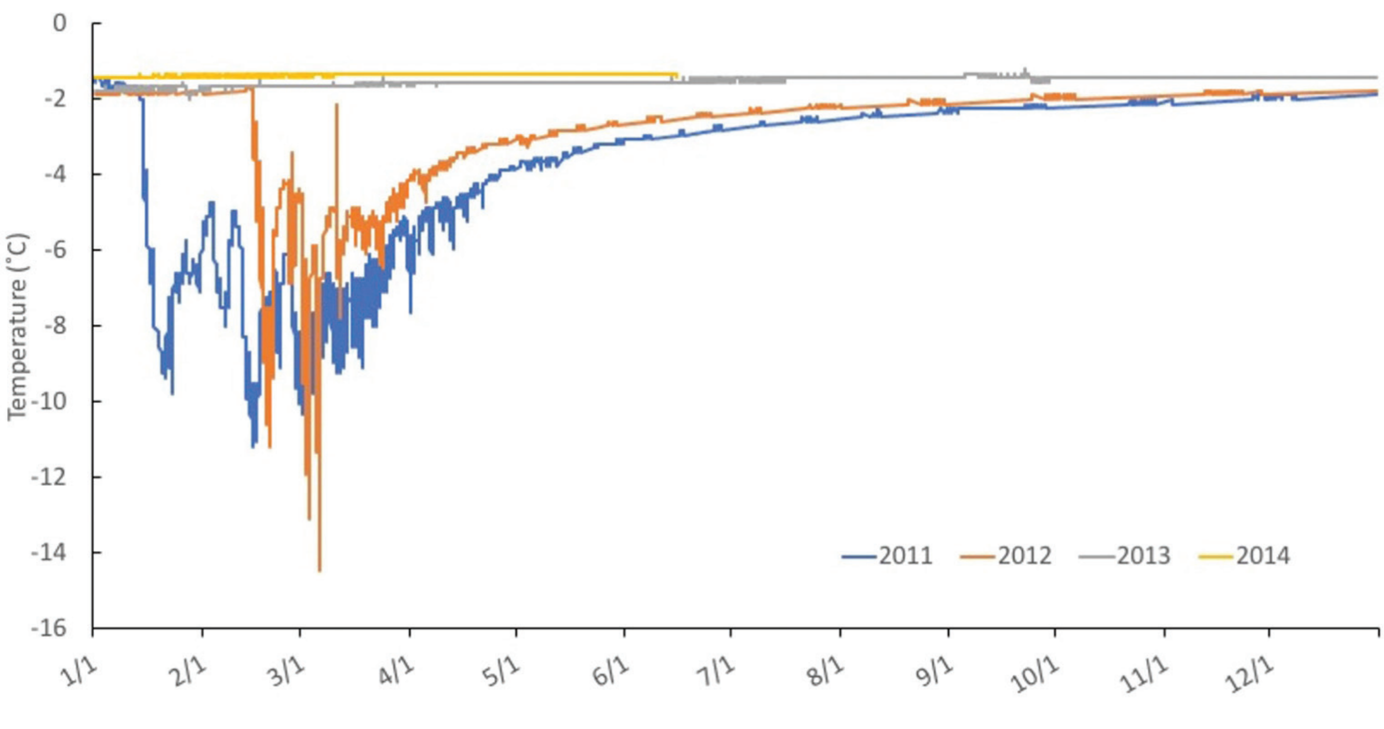

FIG. 12. A four-years door control experiment in an interior Alaska mining tunnel. The tunnel was colder than normal until the end of August when the door was open during winter months of 2011 and 2012 compared to when the door was closed in 2013 and 2014.

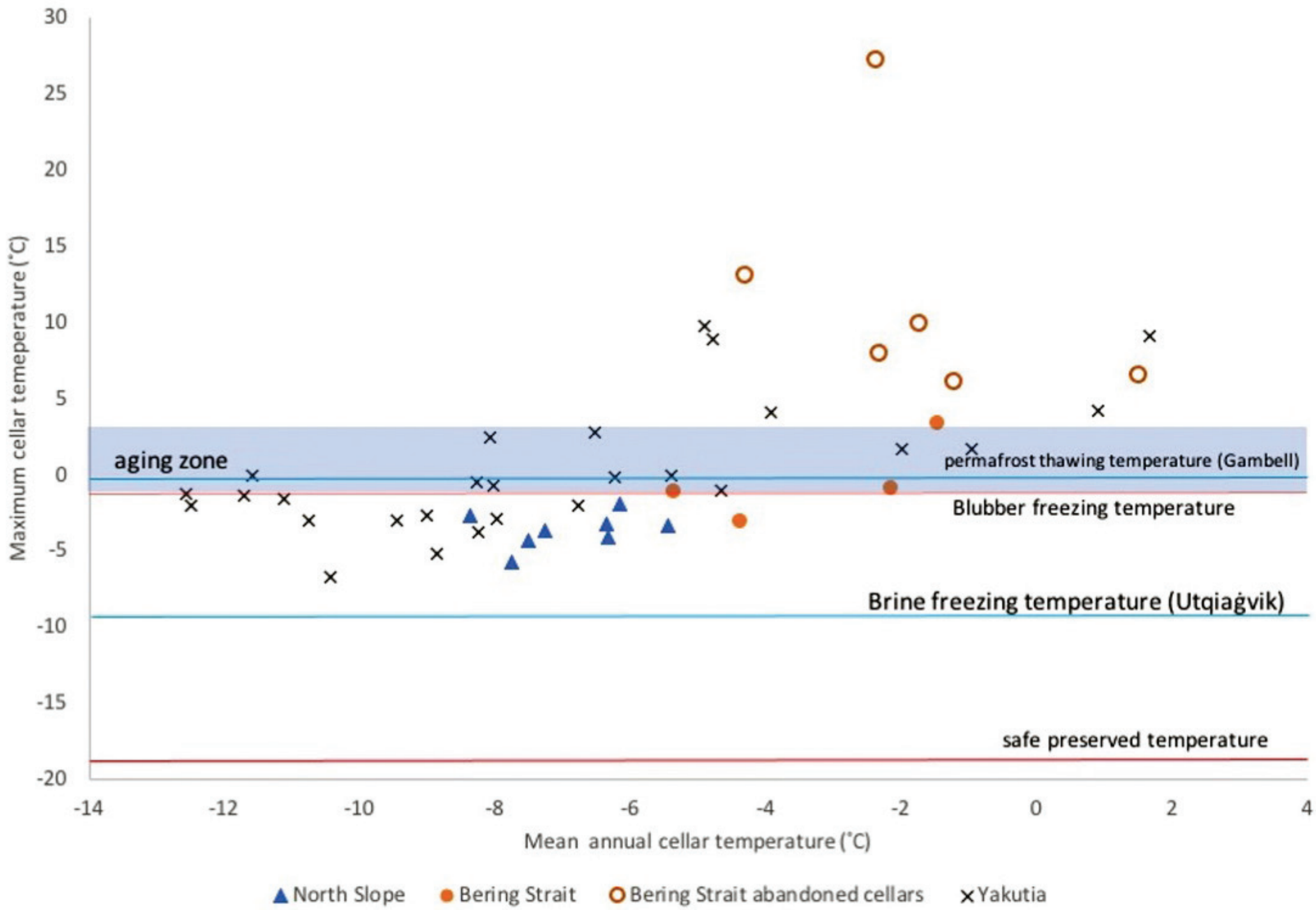

FIG. 13. Maximum vs. mean annual cellar temperature in Bering Strait communities and other areas. Most of the cellars in Bering Strait communities are warmer than the freezing point of whale blubber, however, actively managed cellars may be able to maintain aging temperatures (−1.5 to +4˚ C) during the summer months.

require still further investigation. Each community has a unique suite of local factors to consider in the use and preservation of their cellars, which in turn influences food processing (aging and fermenting) and diets, a primary means of expression and communication of culture.

Most of the 18 cellars examined in this survey of Bering Strait communities including northern Alaska do not provide the consistent frozen storage necessary for traditional subsistence foods (e.g., freezing whale blubber requires temperatures below −1.5˚C). However, cellars still provide a means to age and ferment foods even at temperatures above freezing (Fig. 13). Many traditions associated with cellars in Russian and Chukchi communities are endangered, for example, by multiple forced relocations, political and industrial influences, and changes in diet. Unlike these communities in Chukotka, many Alaskan communities utilize cellars and electric freezers in tandem.

Thoughtful consideration and appreciation of cellar design and maintenance practices are key to understanding the effective storage conditions they offer and reasonable options to ensure sustained safe use that will preserve important cultural traditions. Permafrost conditions and cellar temperatures in the communities studied here have not significantly changed over the last 100 years, and the communities in areas with only seasonally frozen ground have never stored frozen foods during summer months. Historically, food storage was acceptable under +3˚C during summer months in these communities for aging or fermentation. In the future, discussions of risks to “cellar culture” due to climate change should not be centered on storage temperatures, but include the risks posed by natural hazards such as storms, flooding frequency, and changes to structural stability, as well as management of the surrounding built environment.

From the collected descriptions, measured and reconstructed temperature records, and other observations summarized for Beringian communities here, it is clear that cellars provide naturally regulated temperatures, moisture, and oxygen conditions not easily reproduced artificially. The need to preserve cellars and adapt to changing conditions is apparent to these communities already as they explain experimentation with bringing more ice blocks and snow to cover cellar floors, deeper excavation depths, use of multiple insulated hatches or doors to cellar entrances, and more. It will become increasingly challenging to maintain cellars in the future, which makes it all the more important to document cellars and the variety of designs and practices surrounding them to archive and share this Indigenous knowledge.

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