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Nunaaqqit Savaqatigivlugich—working with communities: evolving collaborations around an Alaska Arctic observatory and knowledge hub

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Abstract

Indigenous Peoples across the Arctic have adapted to environmental change since time immemorial, yet recent climate change has imposed unprecedented and abrupt changes that affect the land and sea upon which communities rely. Co-created community-based observing programs offer an opportunity to harness the holistic breadth of knowledge in communities with the goal of tracking Arctic change while simultaneously supporting community priorities and local-scale needs. The Alaska Arctic Observatory and Knowledge Hub (AAOKH) is a network of Iñupiaq observers from northern Alaska coastal communities working in partnership with academic researchers. Here, we describe five core functions that have emerged through AAOKH, which include tracking long-term environmental changes; communicating Indigenous-led observations of the environment and their meaning; place-based and culturally relevant education; enabling scientific and Indigenous Knowledge exchange; and supporting community-led responses to environmental change. We outline and discuss specific actions and opportunities that have been used to increase knowledge exchange of AAOKH observations, make space for the next generation of Indigenous scholars, and create locally relevant data products and syntheses that can inform resource management and community planning. We also discuss our ongoing efforts to increasingly shift toward a knowledge coproduction framework as we plan to sustain AAOKH into the future.

Key words: Indigenous Knowledge, community-based observing, Arctic change, Chukchi Sea, Beaufort Sea, sea ice

Plain language summary (Iñupiaq)

Aippaañin taimaŋŋa qaŋa Iñupiat iñuuŋaruat irituruami nunami. Iñupiat ilitqusiat ikayuutaullaruq sivunmuktaagutauluni. AAOKH-kuayaat kaŋiqsimavlugu taamna tuŋulliḷiqsugait. AAOKH allaŋuaqsiruq. Tuŋulliḷivsaaqtugut qiñiqtiruallumun, suli nunaaqqimiuguruallu. Nunaaqqiruallu, naipiqtuqtillu iḷisaqtuallu taputaurut tavruuna qimilġuurit ilaumiut uvuuna maqpiġaakun. Atauchikunlu sivunniugutaulutiglu. Tikisaksraŋit uvva:

- Tuŋulliḷiqsuglugit naipiqtuqtuat aglaaŋisigunlu.
- Savalgusiglugich ikayuġniagivut iñuuniaġviŋisat irrusiat.
- Aulaqisaagmilugich iḷisaasraŋich nunaaqich iḷisaqtiŋitsalu aulariŋisalu.

Qaunakkutich atuġai sivunniŋat. Atautchikun kaŋiqsillasisugługu.

Introduction

Indigenous Peoples across the circumpolar Arctic have been monitoring, interpreting, and adapting to environmental change since time immemorial because Indigenous Knowledge (IK) integrates observations of the environment, animals, and human health that have been shared and evaluated over generations of continual human habitation in focused spatial regions (Berkes and Jolly 2001; Krupnik and Jolly 2002; Berkes 2007). In recent decades, however, global climate change has imposed unprecedented and abrupt shifts

in temperature, sea ice cover, and associated ecosystem transformations (Post et al. 2013; Huntington et al. 2020). Arctic regions such as the Pacific Arctic are warming at nearly four times the global rate (Stroeve et al. 2014; Stroeve and Notz 2018; Rantanen et al. 2022), and several predominantly Indigenous communities across the Alaska Arctic now find themselves among the "first responders" to experience and describe the dramatic new fluctuations that affect the land and sea upon which they rely (Brinkman et al. 2016; Huntington et al. 2016, 2022). The Iñupiat across northern Alaska have cultivated deep connections to place and an integral reliance on traditional marine and land resources through reciprocal relationships, kinship, and cultural values (ICC-Alaska 2016). Changing environmental conditions are thus inextricably linked to various aspects affecting access and availability of resources, travel safety, nutritional quality and health of wildlife, and harvest effort (Druckenmiller et al. 2013; Huntington et al. 2017; Ford et al. 2019; Hauser et al. 2021; Brinkman et al. 2022). These fluctuating social-ecological relationships affect not only natural resource management but also Indigenous food security, community health and wellness, and opportunities for adaptation planning (Pearce et al. 2015; Heeringa et al. 2019; ICC-Alaska 2020; Proverbs et al. 2020).

Local-scale observations are particularly relevant when considering communities' needs to adapt to and be resilient in the face of a changing Arctic. Past Arctic research has often failed to acknowledge the colonizing history that has discredited Indigenous voices and exploited their knowledge, yet bridging IK systems and science can lead to more inclusive and equitable outcomes to help solve the "wicked" problems associated with climate change (Inuit Circumpolar Council 2022; Yua et al. 2022). Arctic community members have expressed concerns and frustrations about past research experiences that range from extractive and consumptive to insensitive or unresponsive to local needs and interests (Pfeifer 2018; Watt-Cloutier 2018; Latulippe and Klenk 2020). Research results have not always been shared back to communities in formats that are easily understandable, accessible, or timely (David-Chavez and Gavin 2018). Iterative and continuous communication strategies are increasingly seen as opportunities for improvement (e.g., Hovel et al. 2020; Pedersen et al. 2020). Community engagement in research processes has often been limited, which functionally disconnects research from local priorities and often creates information that is impractical for use in decision-making (Ban et al. 2018; Wheeler et al. 2020), much less in efforts to assert Indigenous sovereignty over natural resource management and food security (Raymond-Yakoubian and Daniel 2018; ICC-Alaska 2020; Reid et al. 2021). Creating equitable and engaged community research partnerships within entrenched academic models and western science is slow, deliberate work.

Opportunities to meaningfully relate Indigenous and western science in ways that acknowledge both as complementary ways of knowing and not be used to validate the other are increasingly common but still lacking. Community-based monitoring (CBM) has been acknowledged as a mechanism for IK systems and western science to cooperate in informing sustainable management decisions by bringing together deep knowledge of place, with the nimbleness for inquiry that is offered through classical scientific research (Johnson et al. 2015, 2018; Danielsen et al. 2020). Co-created community-based observing programs provide an opportunity to harness the holistic breadth of knowledge in communities with the goal of tracking Arctic change while simultaneously retaining community priorities and local-scale needs (Moore and Hauser 2019; Fox et al. 2020; Eicken et al. 2021). Furthermore, environmental monitoring that is conducted by and anchored in communities can effectively inform management in rapidly changing regions where more conventional scientific efforts are relatively sparse or expensive for sustained observations (Laidler et al. 2011; Dawson et al. 2020; Simonee et al. 2021), such as in many Arctic coastal and marine areas. CBM also offers opportunities to integrate Indigenous-led observations as surveillance systems for climate change and related impacts on human health, food security, and community wellness (Ostertag et al. 2018; Peacock et al. 2020). There can be applications to planning, comanagement, or short-term decision-making when communities are involved in the definition of meaningful questions, data collection responsive to those questions, and interpretation of results (van Bavel et al. 2020; Breton-Honeyman et al. 2021; Hauser et al. 2021).

The Alaska Arctic Observatory and Knowledge Hub (AAOKH) is a network of Iñupiaq observers from northern Alaska coastal communities working in partnership with academic researchers at the University of Alaska Fairbanks, which has evolved from a CBM program established during the International Polar Year (IPY), called the Seasonal Ice Zone Observing Network (SIZONet). Here, we describe our ongoing efforts to transition a legacy CBM program (Eicken et al. 2014) from a science-centric to a community-centric approach for long-term and local-scale environmental observing. In our evolution from SIZONet, which focused on monitoring sea ice services and hazards, to more holistic monitoring of the coastal realm in AAOKH, we focus on our increasing emphasis on local relevance, education, and establishing platforms for communication and knowledge exchange. We describe AAOKH as an integrated observatory and knowledge hub that provides several core functions, including sustained monitoring of environmental change, communicating Indigenous-led observations of the environment and their meaning, elevating Indigenous scholarship as well as place-based and culturally relevant education, creating space for scientific and IK exchange, and supporting community-led responses to environmental change. Our objective is to illustrate the development of AAOKH and our core functions by discussing specific actions that have been taken to increase local-scale visibility and accessibility of AAOKH observations and syntheses, specifically 1) implementing new methodologies to flexibly respond to local monitoring needs; 2) introducing public-facing, appealing, and accessible communication strategies to summarize recent observing themes and science products; and 3) creating unique opportunities for university students from rural Alaska to develop research skills in support of their development as the next generation of Indigenous scholars. Throughout, we reflect on how our work is guided by our network of Indigenous observers, students,

Steering Group members, and communities. We also discuss ways AAOKH has maintained the foothold in pan-Arctic scientific observing systems that was initiated during SIZONet. We recognize the need to continually tend to and build relationships to support this work, and so we provide additional discussion to put the recent changes undertaken by AAOKH in a broader context of developing conversations about the use and usability of AAOKH observations within local and Indigenous-led decision-making frameworks in the future.

Methods

Author roles and perspectives framing this work

We are sharing research and activities from a diverse group of multidisciplinary academic researchers, Iñupiaq Knowledge holders in rural Alaska coastal communities, and Alaska Native graduate students in scientific disciplines. We each bring individual and sometimes intersectional racial, ethnic, and cultural identities, experiences, and perspectives to this work. We acknowledge the colonial history of academic research across many regions of the Arctic, and that AAOKH communities in particular are part of the homelands of Alaska's Iñupiat. This paper is a scholarly work led by a non-Indigenous author (DH) to specifically respond to calls to action from Indigenous communities within Alaska and the Arctic more broadly for research that supports self-determination and local-scale research priorities, goals for which AAOKH continues to strive. This work to share our process is further influenced by our team of researchers from the ongoing and legacy CBM projects (KH, JJ, ES, AR, OL, and HE) and current and recent university students (RG, EL, and KP). In addition to a diverse Steering Group, AAOKH Iñupiaq observers have continuously guided our efforts and shared their observations as well as frequently provided feedback on our approach in various forms (e.g., formal and informal gatherings, virtual communications, and research surveys), including in their choice to contribute here as co-authors (BA, JL, GO, RS, and CS). Additional individuals who contributed past observations to AAOKH are included in the acknowledgements. We directly quote and attribute comments to specific individuals, with their permission and using their language and terminology, in the following sections. Iñupiaq[1] terminology is also purposely incorporated throughout (led by RG, KP, and JL).

History of SIZONet as a foundation for AAOKH

Our northern Alaska coastal observation network dates to 2006 through the initiation of SIZONet, which established a collaboration between sea ice geophysicists and Iñupiaq and St. Lawrence Island Yupik sea ice experts based in Sivuqaq (Gambell), Kiŋigin (Wales), and Utqiaġvik (formerly Barrow). SIZONet originated in the IPY 2007/08, the first IPY to consider the Indigenous Peoples of the Arctic as key partners in research and science (Krupnik et al. 2011). SIZONet combined Indigenous experts' observations of coastal sea ice environments (Krupnik et al. 2011; Weyapuk and Krupnik 2012; Apangalook et al. 2013; Eicken et al. 2014), autonomous observations of sea ice growth, dynamics, and decay (e.g., Jones et al. 2016), and field campaigns (e.g., Haas et al. 2010), with the aim of meeting sea ice user information needs, centering on access, use of ice as a platform, and ice as a coastal hazard. The community-based observations component of SIZONet sought to document the range of ice uses and ice hazards tracked by Indigenous experts, which could help improve sea ice observations and information products. SIZONet observations also supported the development of the concept of sea ice system services as a means to address the priorities of Indigenous and other ice users in coastal communities. Ultimately, SIZONet fostered the development of partnerships and communities of practice to help track and predict Arctic environmental change and meet long-term information needs (Eicken et al. 2009).

An international team conducted the research and developed common observing protocols and coordinated observation strategies, in collaboration with the World Climate Research Program's Climate and the Cryosphere Sea Ice Working Group. Observations collected by SIZONet included shore-based and drift-ice measurements of ice motion, key mass balance variables, and snow and ice properties such as albedo, as well as airborne ice thickness and property surveys. Measurements in coastal ice, of greatest interest to key stakeholders, included hydrographic moorings, survey measurements, and the integration of satellite imagery (Jones et al. 2016; Ito et al. 2019). Local ice observations by community-based Indigenous observers and joint ice-trail mapping activities provided a link between sea ice geophysics and Indigenous sea ice expertise (Druckenmiller et al. 2013). Community-based observations included narrative and photo descriptions of conditions. Observations, photos, and Iñupiaq and Yupik terminology and names for different conditions were preserved and shared in an online data repository with the Exchange of Local Observations and Knowledge of the Arctic (ELOKA). Over 5000 local observations were collected as part of the SIZONet program during 2006–2016 from communities across the coasts of western and northern Alaska (Eicken et al. 2014).

Transitioning to an Alaska Arctic Observatory and Knowledge Hub: goals, audience, and leadership

Starting in 2016, efforts transitioned to AAOKH. Funding support arose serendipitously through an opportunity to specifically benefit coastal communities along Alaska's North Slope, as a result of community service payments made to the State of Alaska by a corporate defendant found guilty of maritime crimes in the region. Unlike more typical federal or other research grants in the United States, funding provided to AAOKH did not require specific research goals to be predefined and allowed for the flexible community-driven approach that has emerged. Although AAOKH and SIZONet

[1] Iñupiaq is an Inuit language of the Iñupiat in northern and northwestern Alaska and is considered an official language in the State of Alaska. We rely on the North Slope Iñupiaq dialect (MacLean 2014), although we use the terminology and dialects provided when citing contributors.

share similar research foci (e.g., emphasizing changes in sea ice and associated local impacts) and the combined ELOKA data repository, there has been a shift in overarching research goals, data streams, and regional emphasis with AAOKH. Currently, AAOKH is focused on northern Alaska coastal regions (i.e., not currently including western Alaska), includes a diverse suite of standardized and holistic descriptive observations by Iñupiaq observers, expands engagement efforts for knowledge exchange, and involves new training opportunities to support Alaska Native students at collegiate levels. AAOKH activities are guided by a Steering Group consisting of four Indigenous leaders from coastal Alaska communities (Sitŋasuaq (Nome), Qikiqtaġruk (Kotzebue), Utqiaġvik, and Qaaktuġvik (Kaktovik)) and five academic researchers with expertise in community-engaged research, sea ice geophysics, Arctic ecology, or Alaska Native studies. AAOKH was initiated with a goal to provide northern Alaska coastal communities with the tools, resources, and scientific support to share their expertise through community-based observations on changing coastal conditions and associated impacts on their access to traditional marine resources (Anonymous 2015). Since 2016, these goals have been iteratively reviewed through facilitated discussion at the annual meetings of the AAOKH Steering Group, science team, and observing team. Current goals center on 1) providing sustained support to local Indigenous observers as they share their knowledge and document environmental changes; 2) providing services to monitor environmental change to meet community needs; and 3) creating educational opportunities for the next generation of Indigenous leaders and scholars. Following on efforts initiated with SIZONet, AAOKH efforts are also intended to provide sustained and long-term environmental observations of the Arctic that can be used and are useful to coordinated pan-Arctic observing (e.g., Starkweather et al. 2022), academic researchers, students, and scientists, and especially the communities from which observations are collected.

AAOKH observing efforts

AAOKH observers lead traditional Iñupiaq ways of life reliant on the land and sea for cultural, nutritional, and spiritual wellbeing. Each individual self-identified or was nominated by their tribal government to share their local expertise and IK with AAOKH (as well as the previous SIZONet effort for JL and BA). We consider their local and IK as holistic information, integrating environmental and wildlife observations with community activities, that has been shared, refined, and continues to evolve over generations (Huntington et al. 2005; Berkes and Berkes 2009; ICC-Alaska 2016). Although observations often provide somewhat standardized documentation of the local environment, IK and the cultural context of their communities are foundational to the overall perspectives that are shared by observers.

Current AAOKH observations are collected from five communities: Qikiqtaġruk (Kotzebue), Tikiġaq (Point Hope), Ulġuniq (Wainwright), Utqiaġvik (formerly Barrow), and Qaaktuġvik (Kaktovik) (Table 1). Observers collect year-round descriptive observations specifically relevant to each community's local environment and concerns, including sea ice (siku), ocean (taġiuq), land (nuna), weather (siḷa), and wind (anuġi) conditions, as well as fish (iqaluich) and wildlife (niġrun) observations (Fig. 1). Observers also often describe community harvesting activities (aŋuniaġniq) and related events, as well as notable changes in phenology or conditions like coastal erosion (uaq), flooding (ulitit), or the presence of rare or unusual species. Observations are compiled regularly (e.g., daily or weekly, depending on the observer) and contain a combination of quantitative and descriptive information, photographs, and geographic location. The descriptive and narrative observations reflect local conditions that the observer deems relevant and important to note, but some aspects are always recorded: temperature, wind speed and direction, location, and ice or ocean conditions (depending on season). Some communities have also identified particular data interests for which observers have contributed standardized scientific measurements, such as coastal oceanography (conductivity, temperature, and fluorescence measurements at depth via hand-held RBR Concerto CTD instruments) or sea ice thickness and snow cover to understand seasonal melt processes that affect sea ice services such as safety of travel on the ice (Druckenmiller et al. 2013; Mahoney et al. 2021). For example, mapping and measuring ice thickness along snowmobile trails during the spring whaling season (umiaqqa) was initiated during SIZONet and has been carried on during AAOKH at the request of hunters and local partners in Utqiaġvik.

Observers are compensated with a monthly stipend, and equipment is provided to support their observing activities, such as a camera with geo-tagging capabilities, mobile phone or tablet, paper notebooks, and scientific equipment for any community-specific measurements. Several different formats for observations are accepted by AAOKH to accommodate each observer's capabilities with technology, internet connectivity, and preferences. Sometimes observations are handwritten into a notebook and then regularly mailed to scientists, whereas other observers email a descriptive observation with location(s) and photo(s). Several observers also record observations using a customized mobile app (developed in 2018 via FulcrumApp; Spatial Networks, St. Petersburg, Florida) that provides spaces for narrative observations, photos, and some required fields for the observer to note specific temperature and wind conditions, the presence and condition of sea ice, and wildlife observations, as well as whether observations were considered unusual for the time of year and why in those cases.

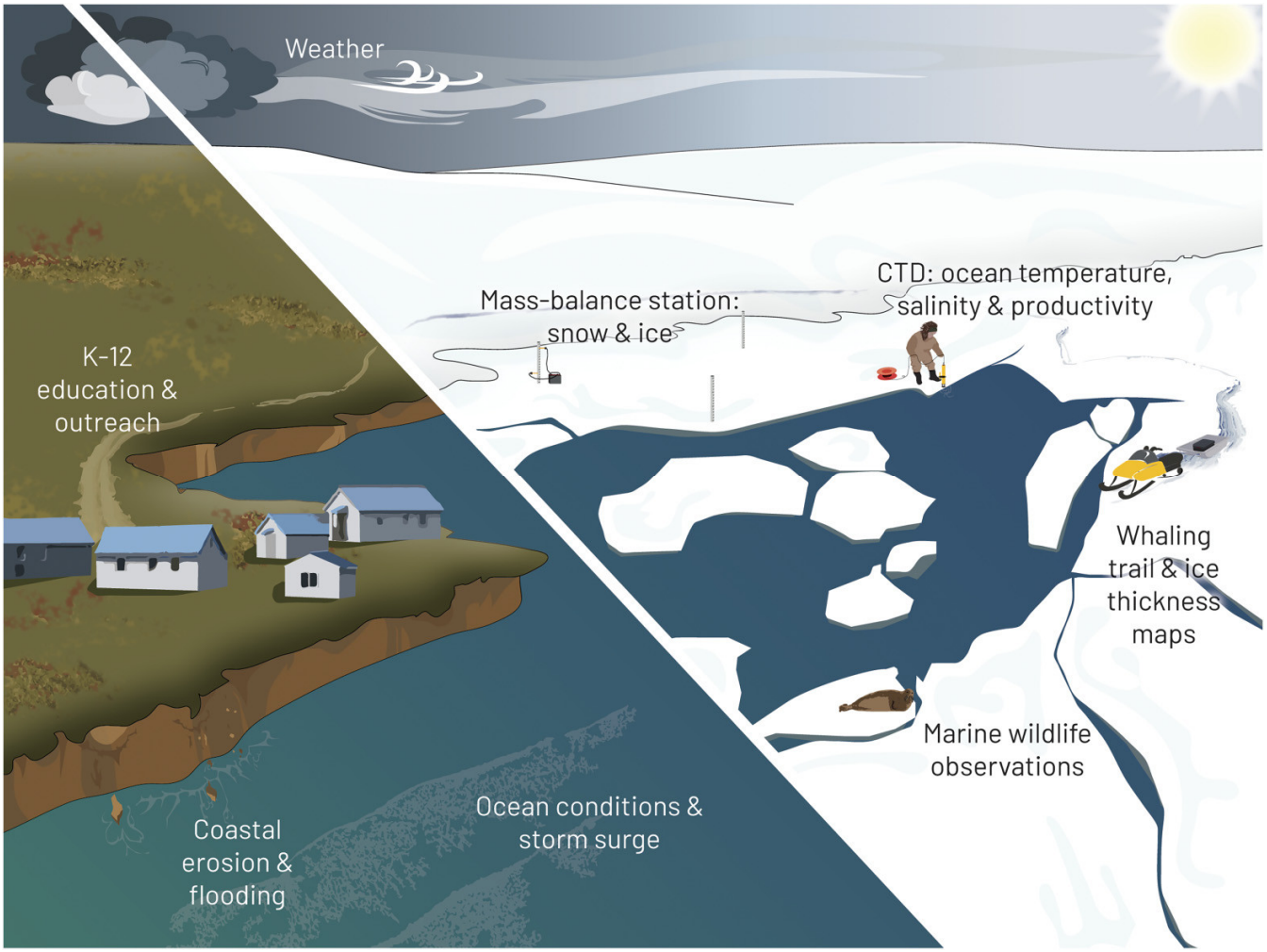
Observers retain ownership of their data, yet provide prior consent for their observations to be archived and broadly shared through AAOKH outreach and knowledge exchange outlets. Data are archived in the existing ELOKA database, which has constraints on user access (Observers of Coastal Arctic Alaska 2022). Observations are searchable online, providing users accept the terms of the use agreement, which include agreeing to give credit to the observers when using the information and preserving the context in which the observations were made (Eicken et al. 2014). Observers also contribute to decision-making in AAOKH activities during an an-

Table 1. Communities with an Alaska Arctic Observatory and Knowledge Hub (AAOKH) observer contributing observations as early as 2016.

Community	Observer(s) and observing period	Approx. frequency of observations	No. of AAOKH observations per community	No. oceanographic measurements*	Snow and ice monitoring activities	K-12 educational activities (estimated number of students included)
Qikiqtaġruk (Kotzebue)	Robert ("Bobby") Schaeffer (2019–ongoing)	Weekly	171	58	Community-monitored sea ice mass balance station to measure sea ice thickness and snow depth in travel corridors, initiated in 2020 (Mahoney et al. 2021)	Highschool classroom visits (55)
	Vincent Schaeffer (2019–2020)					
Tikiġaq (Point Hope)	Jack Lane (2017–2018)	Weekly—monthly	214			
	Guy Omnik (2019–ongoing)					
Ulġuniq (Wainwright)	Steven Patkotak (2018–2022)	Daily	1445	49		
Utqiaġvik (formerly Barrow)	Joseph Leavitt (2006–ongoing)	Daily—weekly	1815	9	Annual trail mapping and measurements of spring whaling trails on the sea ice, initiated during SIZONet in 2007 (Druckenmiller et al. 2013)	8th grade sea ice field trip (75); 8th grade classroom visits (60); community science fair activities (100)
	Billy Adams (2014–ongoing)					
Qaaktuġvik (Kaktovik)	Carla SimsKayotuk (2019–ongoing)	Daily	643			K-4th hands-on field activities (27); middle school hands-on field activities (14); high school student field activities (11); community science outreach activity for youth-Elders (50)

Note: Observations are ongoing in each community, so the number of descriptive observations for each community is inclusive of the period 1 January 2016 to 31 December 2021. Utqiaġvik observers initiated their effort during the predecessor program, the Seasonal Ice Zone Observing Network (SIZONet). Observations contributed by past SIZONet observers and communities no longer active in AAOKH are not considered here. The number of oceanographic measurements (using handheld conductivity–temperature–depth (CTD) instruments) and descriptions of snow and ice monitoring activities and K-12 educational activities are also included.
*In collaborative efforts, AAOKH has also provided CTD instruments and support to research efforts initiated by the Native Village of Diomede and Hilcorp Corporation in Prudhoe Bay. A long-term (~4.5 month) ice-tethered mooring was used to deploy a CTD near Kotzebue during the winter of 2021–2022.

Fig. 1. Conceptual diagram of the suite of observing activities currently supported by the Alaska Arctic Observatory and Knowledge Hub (AAOKH). Each observer provides regular narrative observations (and photos) of sea ice or ocean conditions (depending on season), weather, wildlife, travel (on ice or ocean) conditions, flooding, or erosion, building on the regular narrative observations of the seasonal ice zone established by the Seasonal Ice Zone Observing Network (SIZONet) (Eicken et al. 2014). Some communities also have special K-12 education and outreach events and specialized observing protocols for ocean measurements (temperature, salinity, productivity), sea ice thickness and snow depth to assess travel hazards and break-up processes (e.g., Mahoney et al. 2021), and mapping/measuring ice thickness on snowmachine trails used by whaling crews on the landfast ice (Druckenmiller et al. 2013).



nual gathering of the Steering Group, observers, and science team.

AAOKH knowledge hub development

Changing environmental conditions in northern Alaska are inextricably linked to hunting, gathering, sharing, and preservation of traditional foods in the Arctic marine ecosystem (ICC-Alaska 2016). Correspondingly, AAOKH has increasingly shifted to supporting observing activities and new data collection methodologies that can support efforts to strengthen food security and accessibility. In light of the broader priorities clearly articulated by ICC-Alaska (2016) as part of the food security framework, some monitoring efforts that started with SIZONet continue to be supported by AAOKH as they align with these priorities and local needs, such as mapping the ice thickness of trails across the landfast ice used by whalers during spring in Utqiaġvik (Druckenmiller et al. 2013). However, we also implemented new research objectives based on locally identified research interests and collaborations, such as the use of CTD instruments to monitor ocean conditions (described as an example below). Further, we have the ability to flexibly respond as new monitoring needs are identified.

The shift from SIZONet to AAOKH also required that we increase the visibility and accessibility of information within communities and across scientific forums. We introduced several approaches to sharing and exchanging information, both within AAOKH communities and to the wider public, with an emphasis on multiple modes of communication that aim to be iterative, interactive, frequent, timely, and accessi-

ble in remote regions with connectivity barriers. We describe the development of our information exchange strategies below.

Starting in 2019, AAOKH shifted resources so we could provide direct support to graduate and undergraduate students at the University of Alaska Fairbanks. This shift was prompted by observers and Steering Group members who identified the importance of engaging younger generations in observing environmental change, making linkages back to communities and growing scientific skills that can be applied locally in future careers. With at least partial funding and support from AAOKH, each current and recent student (RG, EL, and KP) developed independent research goals associated with their disciplinary focus, as described below, which also aligned with AAOKH priorities and relied (at least in part) on AAOKH observations. These graduate student projects additionally serve as examples of new communication strategies and information exchange supported by AAOKH while simultaneously advancing early career development and student-led scientific research products.

Results

> *"[That AAOKH has] fostered a level of trust among our community members and the scientific community is important. I think we have a history [in our regions] of people collaborating or doing research that sometimes didn't help [the community], they [scientists] use the information they got from them and then use that to help their efforts which would then sometimes not line up with the efforts with our rural communities. The strongest strength I see of this group is that we've been able to foster that trust…There is also so much knowledge [to be shared]"*—Noah Naylor (March[2] 2021), AAOKH Steering Group member from Qikiqtaġruk.

Overall, since 2006, the combined efforts of AAOKH and SIZONet resulted in the engagement of several observers and communities who have contributed multiple types of coastal observations at various periods over time. A total of 4288 observations were collected by eight AAOKH observers during 2016–2021 (Table 1), building on the 5264 observations contributed to SIZONet and archived in the ELOKA database during 2006–2016. A primary goal of SIZONet was the development of an observational framework and associated data management system. AAOKH then focused on increasing the accessibility and visibility of observations within northern Alaska coastal communities with the goal of expanding their relevance to community priorities, including how research activities are conducted. During the past six years, we developed an observing network that was more holistic of the coastal Arctic environment (e.g., Fig. 2), beyond the seasonal ice zone that was featured in SIZONet, as well as introduced new monitoring techniques. Our approach allowed AAOKH to deepen the work of SIZONet while also pivoting to create new mechanisms for knowledge exchange and communication as well as support structures for the training and education of young Indigenous scholars.

Responsive to and representative of community priorities: new monitoring techniques

> *"Monitoring and collecting data today may allow us the opportunity to derive a plan to replace the subsistence resources we may lose to climate change"*—Bobby Schaeffer (March[2] 2021), AAOKH Observer from Qikiqtaġruk.

Direct feedback and direction from observers and Steering Group members identified new monitoring approaches that could pair AAOKH observing efforts with western scientific methods. For example, observers regularly noted indications of increasing water temperatures in concert with reduced sea ice cover in recent years, which has also been linked to broad-scale ecosystem effects (Thoman et al. 2019; Huntington et al. 2020; Danielson et al. 2020, 2022). To learn more, several observers regularly measured coastal ocean temperature, salinity, and productivity (specifically chlorophyll *a*, as a measure of phytoplankton biomass) using CTD oceanographic instruments and training provided by AAOKH (Table 1). CTD measurements taken near Qikiqtaġruk during April[3]–August[4] 2019 illustrated the timing of sea ice break-up, phytoplankton blooms, and unusually warm water during the summer months (Fig. 3). Taken in concert with observations, a more complete picture of the implications and effects of these physical conditions emerged. For example, the ice covering a channel in front of Qikiqtaġruk broke up uncharacteristically early in 2019 (Hauser et al. 2021), allowing for the earliest ugruk (bearded seal, *Erignathus barbatus*) hunt in the recent memory of Elders. Prior to break-up, incursions of sea water were detected, followed by a dominance of fresh riverine water after break-up, illustrating the influence of ocean and riverine heat sources affecting break-up (Witte et al. 2021). The ocean was also particularly warm in July[5] in Kotzebue Sound, as well as throughout the broader Chukchi Sea (Danielson et al. 2020), which affected the availability of traditional harvests of species like puyyugiaq (king crab, *Paralithodes* spp.). CTD measurements also appeared to capture a potential secondary phytoplankton bloom in August[4]. Warm waters persisted in the fall and apparently contributed to a

[2] March—Paniqsiqsiivik (Coastal dialect), Amiqtuġvik (Point Hope dialect), Paniqhiqhiivik (Anaktuvuk Pass dialect). Month of drying skin boats, month of sewing skins for boats, hunting tools repaired, trail breaking, female polar bears bring cubs out of den (North Slope Borough 2019).

[3] April—Umiaqqavik (Coastal dialect), Nutaqsivik (Point Hope dialect), Qargiḷiġvik (Anaktuvuk Pass dialect). Month when ptarmigan (Aqargiq, *Lagopus* spp.) come, month of Whaling (Whaling Begins), month of renewing whaling equipment, birth of young natchiq (ringed seals, *Pusa hispida*) (North Slope Borough 2019).

[4] August—Tiŋŋivik (Coastal dialect), Amiġaiqsivik (Point Hope dialect), Amiġikhivik (Anaktuvuk Pass dialect). Month with prime tuttu (caribou, *Rangifer tarandus*) skins, tuttu hunting, month when waterfowl migrate south, duck hunting, month when tuttu lose their antler velvet, berry picking, fishing with nets in rivers and lagoons (North Slope Borough 2019).

[5] July- Iñukkuksaivik (Coastal dialect), Iñukkuksaivik (Point Hope dialect), Iñukkukhaivik (Anaktuvuk Pass dialect). Month of animals raising their young, caribou hunting, drying meat and making seal oil, bearded seal and walrus (aiviq, *Odobenus rosmarus*) hunting (North Slope Borough 2019).

Fig. 2. Current Alaska Arctic Observatory and Knowledge Hub (AAOKH) observations are shared across five coastal communities in Arctic Alaska, as shown in the example observation text and photos summarizing key themes from spring–fall 2020 and featured in a two-page spread in Issue 4 of *AAOKH News*. Modified from McFarland et al. (2020), with permission.

late fall freeze-up compared with past years. Qikiqtaġruk observer RS's observation on 7 September[6] 2019 noted, "My sister's birthday. We all remember that we would go skating back in the day. She mentioned it and we got a kick out of it as the temperature was 61 degrees [Fahrenheit]".

Sea ice cover in the Chukchi Sea was unusually low during the winters of 2018 and 2019, and Qikiqtaġruk observer RS further noted that landfast sea ice in Kotzebue Sound was historically 1.2–1.5 m (4–5 ft) thick by spring. To monitor ice thickness near an area that is extensively traveled by the community, two mass balance sea ice and snow monitoring stations were established near Qikiqtaġruk in 2018 and 2019 through a partner program (Ikaaġvik Sikukun; Mahoney et al. 2021), which were subsequently supported by AAOKH during the winters of 2020 and 2022. Regular measurements of ice and snow thickness are considered useful indicators for travel safety in Qikiqtaġruk, which AAOKH intends to continue supporting into the future as well as sharing through frequent communications (as described below).

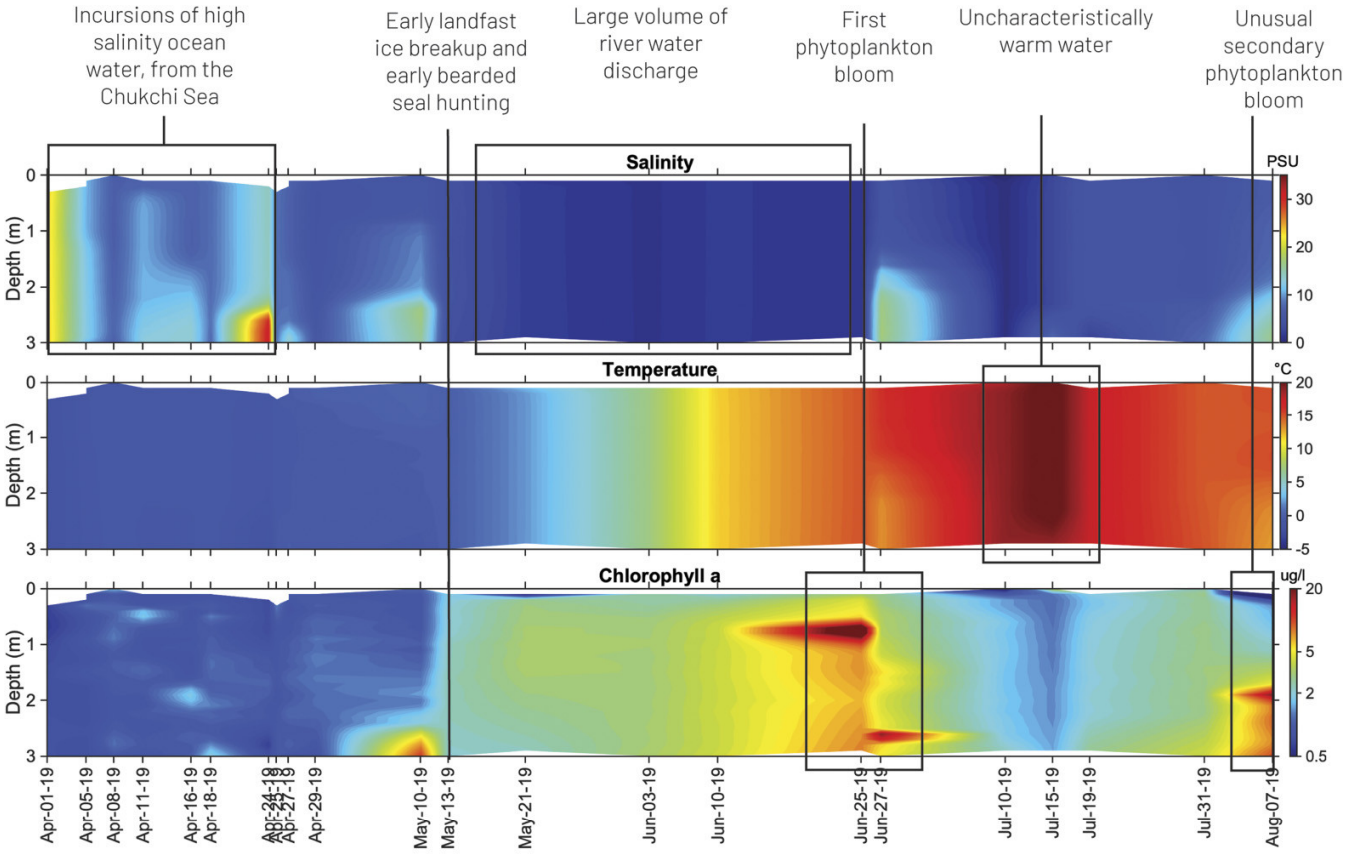
Enabling information exchange: localized, iterative, interactive, and rapid communications

> *"One of the things I wanted to say was the importance of dissemination of information, and getting people to understand the importance of it because we're talking about future generations that are gonna live in a time when it's a challenge to wake up and wonder what's going to happen with the weather today"*—Bobby Schaeffer (March[2] 2021), AAOKH observer from Qikiqtaġruk.

Over the course of 2016–2021, AAOKH shared information at ~35 events that included open meetings in our partner communities, comanagement meetings (so-called "Alaska Native Organizations"), public-facing conferences that elicit community and Tribal participation (e.g., Alaska Forum on

[6] September—Amiġaiqsivik (Coastal dialect), Sikuaqtuġvik (Point Hope dialect), Amiġaiqhivik (Anaktuvuk Pass dialect). Month when caribou lose their velvet, month of early freeze-up, some duck hunting, fall whaling preparation begins. Moose hunting, still some fishing and hunting at Camp. Panmagrak (capelin, *Mallotus villosus*) come onto shores near Utqiaġvik (North Slope Borough 2019).

Fig. 3. Time series of CTD measurements of salinity, temperature, and an indicator of algal biomass (chlorophyll *a*) near the Noatak Channel at the Qikiqtaġruk waterfront, taken by observer Vincent Schaeffer during April–August 2019 (dates of measurements are noted on the *x*-axis). Observations and contributed reports from Steering Group member Noah Naylor, observer Robert (Bobby) Schaeffer, and Elder Cyrus Harris (personal communication) provided additional context about the implications of ocean physical conditions on access and availability of traditional resources and local activities.



May 13: Noah Naylor noted, "Channel opens and start of ugruk (bearded seal) hunting. [Hunting started] Very early. It seemed [it used to be] the first 2 weeks in June. Dad said he remembers the 28th as the earliest he hunted.

July 19, 2019: Bobby Schaeffer observed, "Since we had a hot June and parts of July, the waters warmed up not only up the rivers, but in the Kotzebue Sound as well. The waters got too warm in the ocean so the crab split to deeper colder waters in mid July. This was a first. The CTD [ocean measurement] measured 64 degrees with very little salinity. Crazy!"

On 14,Aug 2019, Nearby Sisualik Elder Cyrus Harris reported seeing a lot of short-tailed shearwaters that were "hungry" and following boats. He had never seen this species before.

the Environment, Alaska Tribal Conference on Environmental Management), workshops focused on CBM in the Arctic, scientific conferences, and federal and international forums (e.g., U.S. Interagency Arctic Research Policy Committee). Many of these meetings have included direct support to include observers in presentations and discussions, which creates a platform for observers to share their perspectives in their own words and identify key themes in their observing efforts that should be emphasized. We have especially targeted community-oriented meetings and Indigenous organizations that are relevant to local decision-making rather than scientific or academic products. For example, participation in comanagement meetings was seen as a way to tailor observing to discussions related to Indigenous-led management systems and food security. Although much of AAOKH's efforts focused on engaging local communities, we also continued the legacy of SIZONet's efforts to apply AAOKH observations to the broader scientific community. In particular, AAOKH served as an example of bottom-up monitoring programs in Arctic observing forums (Eicken et al. 2014; Moore and Hauser 2019; Danielson et al. 2022), specifically a mechanism for local and IK to be valued alongside instrument-based science products in policy and management activities.

In addition to maintaining a website as a stable source of online information (https://arctic-aok.org/), we adopted two primary approaches to increase the accessibility and visibility of observing activities, including biannual newsletters, called *AAOKH News*, and an AAOKH Facebook page. Each newsletter was professionally designed with simple and engaging graphics, observer photos, short summaries of recent AAOKH activities, weather and environmental conditions, student updates, and observing themes from approximately the past 6 months (Fig. 2). The newsletter allowed rapid dissemination of recent project synthesis products and updates. Newsletters also included short features highlighting observer perspectives (e.g., the "Observer Corner") and collaborative research projects or updates. Every issue included a description of the AAOKH team as well as details on how to contact them, get involved, or learn more about the project. To make the newsletter broadly accessible, including to individuals with limited connectivity, *AAOKH News* was distributed in several different ways, including online on our website, an emailed distribution list, and hardcopy newsprint mailed directly to every post office boxholder in each AAOKH community. By 2021, six issues of AAOKH News had been mailed to ~3131 boxholders in 7–8 communities (including Kali (Point Lay), Iŋaliq (Diomede), and Kiŋigin (Wales), Alaska, that have geographic, collaborative, or past ties to AAOKH).

While *AAOKH News* offered opportunities to summarize recent observing activities and program updates, it lacked the advantage of social media platforms that offer real-time interactions and sharing of observations and time-specific and relevant instrument-based science products (e.g., satellite images of ice cover, trail mapping results, oceanographic data). Since its inception in 2017, the AAOKH Facebook page has attracted nearly 2700 followers by the end of 2021. Facebook remains among the most popular social media outlets in rural and coastal Alaska, and we used the platform to share recently acquired (within hours or days) observations, relevant satellite imagery or other data, and news. Nearly all of the followers were based in Alaska (90.4%), in addition to Canada (2.9%), the United Kingdom (1%), and small followings (<1%) from several other countries. The largest followings were by residents of Utqiaġvik (15.1%), Anchorage (14.8%), Fairbanks (5.6%), and Qikiqtaġruk (4.5%). Residents of Ulġuniq, Tikiġaq, and Sitŋasuaq (Nome) each contributed ~2% of the followers, and several other rural Alaska communities had small followings (<1%). The most popular posts, in terms of "Likes" and other impressions, tended to include observations of charismatic marine wildlife species (e.g., nannut, or polar bears, *Ursus maritimus*) that are able to galvanize the public interest, unusual or novel observations (e.g., aaġlut, killer whales, *Orcinus orca*, in the Beaufort Sea), updates about health status (e.g., niqqaaġiksuaq, healthy animals) or unusual health conditions of a primary traditional food (niqipiaq), and summaries of recent important traditional activities within a community (e.g., aġviqsiuq, bowhead whaling). In general, posts with photos of wildlife or Arctic landscapes, or posts addressing current topics associated with the changing environment, tended to draw more interactions. Although observers did not usually comment on posts of their own observations, some posts were frequently commented on in ways that indicated how widespread or uncommon the reported condition may be for residents in other coastal Alaska communities. Several times a year, residents who were not affiliated with AAOKH also often directly shared photos, videos, and their own observations that might correspond to an AAOKH post. Posts also garnered additional media attention from journalists in the state or country. In addition to sharing observations and synthesis products with AAOKH communities, Indigenous organizations, and government agencies, observers also recognized the need to share observations of the changing Arctic environment with the wider general public.

> "*I think* [AAOKH summary products] *can be shared with Alaska Native organizations* [comanagement organizations], *they're excited to see things like this from students and from universities… putting something out there that they can see in the news, I think it's something that should be shared. I think it's only fitting. You know sometimes we see the weather channel and things like that. Things that are happening in the state. And I think a lot of the rural areas are waiting for something like this to show up. Instead of the regular news, something to ignite villages… To make awareness of what is going on. Especially in the Arctic. You know sometimes we see news about the Arctic in other countries, right? And here in Alaska… When are we gonna see something about Alaska that can be shared with people? Maybe those are the next things we should try to elevate. It's positive, you know. Programs like this cost money. Any program. When things like this are shared, there's many philanthropists that are interested in funding these programs that can be helpful. But they're never going to know if it's not out there…*"—Billy Adams (April[3] 2022), AAOKH observer from Utqiaġvik.

The COVID-19 pandemic introduced new limitations to our engagement strategies and relationship-building activities on local scales. The AAOKH annual meetings shifted to virtual platforms in 2020 and 2021, with toll-free calling options for those with limited bandwidth. We conducted no AAOKH-related travel in 2020 and limited travel in 2021 (with explicit mitigation strategies in line with community recommendations and mandates), despite our preference for in-person interactions for community meetings and public-facing conferences. We provided presentations and updates to many comanagement organizations and other conference venues that shifted to virtual meeting platforms in 2021. Our distributed network of observers in communities also allowed for sustained observation efforts in regions that were otherwise inaccessible to nonlocal researchers for the duration of the pandemic. Overall, communication via *AAOKH News* and Facebook facilitated our ability to maintain connections with communities across the region.

Engaging and creating opportunities for Indigenous students

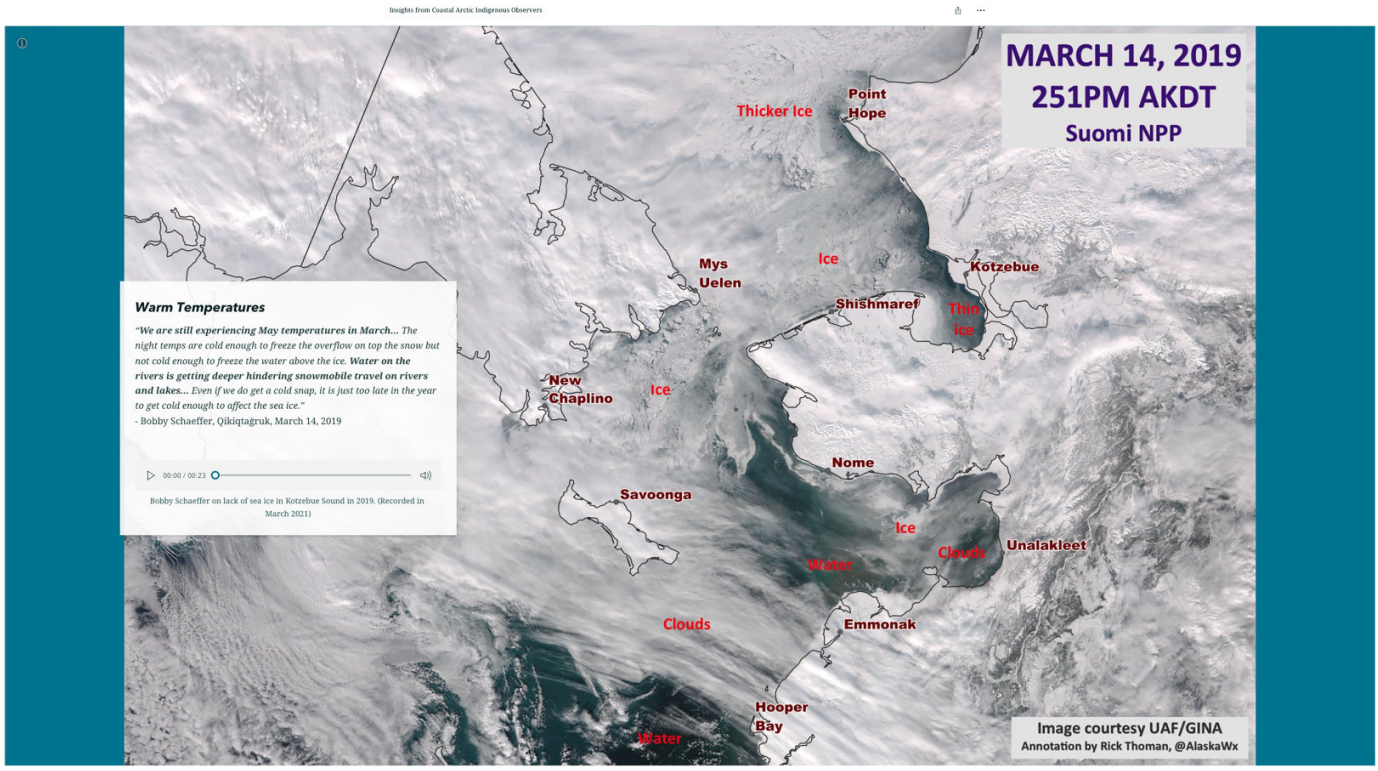
> *"You guys are doing a real good job of incorporating Native students into this program. I think it's something you should be really proud of…they have the information from their communities, they have their heritage, and they're also learning scientific research"*—Noah Naylor (March[2] 2021), AAOKH Steering Group member from Qikiqtaġruk.

Three current and recent student theses (RG, EL, and KP) were aligned with AAOKH goals to include and support Indigenous students, as described in this section. Additional education and outreach components were aimed at braiding Indigenous and western science ways of knowing to engage educators, community members, and youth in climate change learning and stewardship projects in their communities (Spellman et al. 2018). Approximately 400 youth participated in AAOKH education and outreach activities within the communities of Utqiaġvik and Qaaktuġvik during 2016–2021 (Table 1), including hands-on classroom and field activities meant to be culturally-relevant and place-based. For example, AAOKH supported full-day field trips onto the sea ice near Utqiaġvik for 8th grade students to learn about sea ice and snow properties, sea ice ecosystems, and Indigenous perspectives of ice conditions. Other activities involved hands-on demonstrations of kites that can be used to measure weather conditions and monitor sea ice and snow cover properties.

The first example of a recent student thesis focused on sharing and summarizing AAOKH observations by producing an ArcGIS StoryMap (Glenn 2022). Observations from the AAOKH network were compiled alongside supporting instrumental data to build a StoryMap using the ArcGIS online web platform. Sharing multimedia content as well as maps and geospatial data brought a story of "Insights from Coastal Arctic Indigenous Observers" to life. The goals for this StoryMap were to 1) synthesize AAOKH community-based observations and identify key observing themes; 2) communicate local narratives of Arctic environmental change and particular impacts to subsistence activities, travel access, and community infrastructure; and 3) make the research product accessible to AAOKH communities as well as the general public by using a form of digital storytelling in line with Iñupiaq ways of sharing stories. Observers were contacted individually to elaborate on, confirm, and refine the key observing themes of the StoryMap. Each discussion focused on one question: what environmental conditions are you seeing in your community that have impacts on subsistence activities, travel access, and/or community infrastructure? This question directly resulted from the key themes identified by observers during the preceding annual Steering Group meeting (in spring 2021) and from searches of the AAOKH database. The goal of this question was to identify and share Arctic environmental changes and their impacts on Arctic Indigenous communities from the perspective of AAOKH observers. Four overarching themes of the StoryMap emerged from observations made by AAOKH observers from 2018 to 2021: 1) coastal storms, flooding, and erosion; 2) changing winds (speed, direction, and frequency); 3) warmer temperatures (ocean and air); and 4) changing sea ice conditions (e.g., Fig. 4). Observations and photos with known GPS locations were embedded in a web-based map included in the StoryMap. Following the production of a draft StoryMap, review and edits were incorporated by the AAOKH team of scientists, observers, and Steering Group members, as well as science communication experts, before the StoryMap was finalized. One observer (BA) suggested to include observations that positively represent the health of subsistence resources and to emphasize that "even with environmental changes and events that we continue to experience, the resources we depend on have shown to be healthy and the populations of the animals are looking healthy". To this end, a new section on "changes in subsistence" was added to the StoryMap that described changes to subsistence activities as a result of environmental change, including observations from each community demonstrating successful subsistence harvesting activities.

Another student thesis is focused on a prominent shift occurring in the Alaska Arctic that involves changes in the species composition, timing, and abundance of traditional fish resources, including the potential establishment of species of aqalugruaq (Pacific salmon, *Oncorhynchus* spp.) new to the region. The varied story of Pacific salmon and Indigenous people in Alaska exemplifies place-based human-ecological relationships maintained over thousands of years (Carothers et al. 2019, 2021). Salmon–people–place relationships in Alaska span a spectrum from "inextricably linked" to nearly nonexistent, and the unique place-based responses to environmental changes span as broad of a continuum. The incongruence of relationships with salmon across space, and specifically across much of Alaska and the Arctic, is only recently becoming apparent as discernible changes in ecological processes are being directed by climate change. In extreme cases, some places have seen environmentally induced salmon die-off events (Westley 2020) while others are experiencing unprecedented encounters with salmon, both in number and species composition (Dunmall et al. 2021; Chila et al. 2022). The latter is an indicator of salmon habitat range expansion and potential establishment in a region that historically falls within the end of the salmon–people–place spectrum of little to no relationship, giving rise to questions and concerns about the ecological consequences of salmon in these regions. To address these changes, EL's graduate research has broad goals to: 1) better understand the habitat expansion and establishment of Pacific salmon in Arctic Alaska, 2) the nuances of how expansion is happening, and 3) the consequences of establishment when considered through a holistic lens that prioritizes ecological concerns of greatest importance to people-place systems. In association with AAOKH, questionnaire survey methods are being used to learn directly from IK holders about how changes in fish harvesting (abundance, species composition, timing, and concerns about the future of salmon) are currently occurring and what it means to individual harvesters' ways of life. The vast geographic range of participating AAOKH communities spans from the northernmost region where salmon have been established historically, Qikiqtaġruk, where there are changes in species-specific abundance (i.e., drastic increases in amaqtuuq (pink salmon, *Oncorhynchus gorbuscha*) abundance, while all other salmon species remain unchanged or in decline). On the other end of the spectrum in Qaaktuġvik, salmon have been seldom encountered historically and are now increasingly observed in non-salmon subsistence fishing efforts. The social-ecological consequences of changing numbers and species of salmon across the Arctic Alaska are unknown, but early survey results indicate localized concerns about how salmon establishment may impact the ability to maintain traditional ways of life and food security.

Fig. 4. Example of an observation from Qikiqtaġruk set alongside a satellite image of sea ice cover from the warmer temperatures section of the AAOKH StoryMap. Bobby Schaeffer's observation describes warmer temperatures affecting rivers, water, and sea ice, which impacts travel by snowmobile. Figure modified from Glenn (2022), with permission.



A third student has focused on centering Indigenous perspectives when examining changes in resource use within a changing environment, and specifically changing connections among the aġvik (bowhead whale, *Balaena mysticetus*), whale hunters in Utqiaġvik, and sea ice using a video project currently in production. In collaboration with a local Iñupiaq filmmaker and endorsed by comanagement organizations (e.g., Alaska Eskimo Whaling Commission, Barrow Whaling Captains Association, and Native Village of Barrow), the project's purpose to document the stories of the whalers experiencing modern environmental changes also highlights collaborations between Iñupiat and Western scientists during spring whaling. Video footage will include multiple aspects of whaling, such as how whaling crews break and maintain snowmachine trails to cross jumbled landfast ice to reach the flaw lead edge. Semi-directed interviews with whaling crews will be used to learn about how whaling and sea ice have changed in recent years, the roles of different crew members, and their perspectives on how whaling involves multiple generations. Western scientific research will be paired with the perspectives of hunters, including efforts to conduct mapping of the trails used by whalers and the ice thickness along trails (Druckenmiller et al. 2013).

> *"As a graduate student with AAOKH, my job is to show how we can use these observations to inform managers and researchers about what our communities' hunters and whalers have known for centuries. Within the observations, the observers themselves and the young hunters, can inform us (researchers/scientists) on what to research, how we should approach it, and understand the value of Indigenous Knowledge"*—Kimberly Kivvaq Pikok (June[7] 2022), University of Alaska Fairbanks Master of Science student from Utqiaġvik.

This project also focuses on promoting young Iñupiaq hunters and youths (ages 18–30 years) who are involved in hunting, managing, and implementing their Iñupiaq values for marine mammal resources. With a specific aim to uplift youth and hunter voices through the leadership of an Iñupiaq youth (i.e., KP), we intend to establish a renewed sense of communication in regards to policymaking, hunter concerns, and food security between scientists, researchers, community members, and young Iñupiaq hunters. This project offers the potential to support stronger relationships between multigenerational hunters as well as Tribal, federal, and state wildlife and natural resource managers charged with comanagement. Furthermore, we hope this project will serve as a guide to researchers, Indigenous youth, communities, and Tribes on how to assess and research multigenerational perspectives that relate to community wellness, knowledge, and governance given a changing climate and a new era of subsistence practices.

[7] June—Iġñivik (Coastal dialect), Iġñivik (Point Hope dialect), Iġñivik (Anaktuvuk Pass dialect). Month of fawning, caribou calves are born, seal hunting, sisuaq (beluga whale, *Delphinapterus leucas*) hunting in Wainwright and Point Lay, camping and fishing on rivers and lakes begins, Nalukataq (whaling celebration) in whaling communities (North Slope Borough 2019).

Taken together, these examples illustrate ways in which AAOKH-linked student research projects strongly align with our overarching programmatic goals and values while simultaneously supporting the career development and scholarship of each student. The StoryMap product addresses AAOKH guiding principles to share observations of environmental change in an easily accessible storytelling format, be responsive to the priorities and themes of environmental change relevant at the scale of each community, and highlight and include observers iteratively throughout the process. Intertwined social and ecological research on salmon–people–place systems reflects community concerns and priorities associated with the changing environment while simultaneously facilitating future goals to be responsive to Indigenous food security priorities. By telling the stories of Utqiaġvik whalers in the face of a changing environment, we also hope to reflect on multigenerational Iñupiaq values that can promote and inform Indigenous-led marine mammal comanagement processes in Alaska.

Discussion

AAOKH has made substantial strides in engaging Arctic Alaska coastal communities beyond the stage set by SIZONet, expanding our network of observers, and adhering to community-driven research priorities (Fig. 5). Regular communication between AAOKH observers and the academic team ensures local interests and concerns are captured in the process of tracking Arctic environmental changes. Consistent, full-text observations made from the perspective of IK holders provide a rich dataset of nuanced and local-scale documentation of Arctic Alaska environmental change not found in contemporary literature. The broad geographic region covered as well as the level of detail and depth of observations shared, including standardized variables such as air temperature and sea ice thickness, allows AAOKH observations to be directly correlated to instrumental measurements captured through remote sensing. We have also broadened community engagement during our expansion phase. Since the end of SIZONet, we have increased the visibility of the AAOKH program in communities, encouraged participation across a larger number of Iñupiaq coastal communities, and built a knowledge hub for communication and information exchange that involves multiple platforms and ways to summarize and share information at local scales. Our program scope and open funding platform created flexibility to develop new monitoring approaches as communities and observers identified opportunities to address local environmental questions.

Over the course of its evolution, from a collaboration initiated during the IPY with a narrow focus on community-based monitoring of sea-ice processes and services (i.e., the SIZONet origins) to a broader effort encompassing a range of activities, AAOKH serves as a forum that highlights and defines a set of core functions as an observatory and knowledge hub. We function at the interface between IK, community priorities and concerns, research interests, government agency roles, and the broader public. While some aspects of these roles may be unique to Iñupiat homelands in northern Alaska, many are relevant in other settings and are discussed in more depth below.

Core function one: documenting, tracking, and synthesizing rapid change in coastal environmental systems

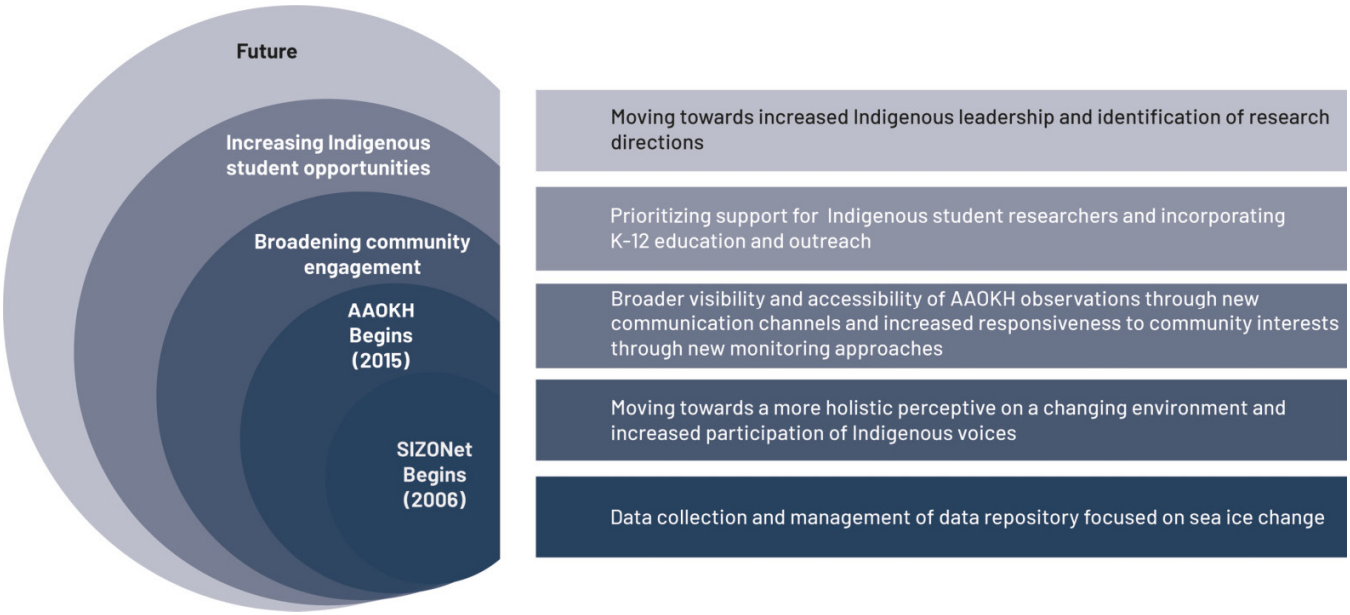
> *"It's important for people to consider how [climate change] is changing things. I think one of the most important things is tracking changes from year to year"*—Bobby Schaeffer (April[3] 2022), AAOKH observer in Qikiqtaġruk.

As emphasized by both the Indigenous members of the AAOKH Steering Group and the observers themselves, a key element of AAOKH is to document changing environmental conditions. Sustained AAOKH observations provide context for hazard assessments and communication as well as the changing uses of the environment, including subsistence harvests and over-ice or over-land travel. This information serves different functions, including keeping a record of events and processes that are not captured through other established, Tribal, agency, or university-operated observing systems. The focus on uses or services provided by the environment helps establish a link to impacts and responses at the community scale. The broadening of observations towards a more holistic approach helps identify system-wide, complex changes, which align with Indigenous ways of knowing and western scientific "ecosystem approaches" that emphasize the interconnected environment over focusing on a narrow set of processes or variables (see Yua et al. 2022). Here, we provided examples of AAOKH observations documenting a wider range of variables covering different phenomena and processes in the physical environment as well as the presence and behavior of different species of wildlife (e.g., see examples in Figs. 2–4). We were able to build on SIZONet's ability to capture observations by IK holders, such as the reflections by Leonard Apangalook, a St. Lawrence Yupik IK holder from Gambell, who linked around 30 different environmental indicators to the fall and winter freeze-up seasons (Krupnik et al. 2011).

The close connection between observations, such as those of AAOKH observers, and Indigenous uses and stewardship of Arctic lands and waters provides context for community-scale responses to rapid Arctic environmental change. Community-driven monitoring can help build a foundation at the regional and pan-Arctic scales not only for communicating observations but also for sharing ways to live with changing environments. One of the co-authors (JL) was part of a project that spanned Inuit communities in Greenland, Canada, and the US and pioneered such large-scale comparative work (Gearheard et al. 2006). Work conducted since (e.g., Ford et al. 2019; Fox et al. 2020) points the way towards broader synthesis and collaboration at the pan-Arctic scale, particularly with a focus on observations relevant in a community decision-making context.

The formal record of observations encapsulated in the combined SIZONet-AAOKH database may also serve important functions in wildlife or broader resource management and regulatory processes. Comanagement bodies (e.g., for Alaska marine mammals) are one example in which the use of Indigenous-led data and monitoring efforts could be empha-

Fig. 5. Programmatic progression diagram of the AAOKH program, from the foundation laid by SIZONet, to increasingly focus on more holistic perspectives of the changing environment, improving communication and information exchange, elevating Indigenous participation and scholarship, and future goals of increased Indigenous sovereignty over the research and data processes.



sized to inform regional decision-making (Robards et al. 2018; Moore and Hauser 2019; Breton-Honeyman et al. 2021). Observers themselves may be active in these arenas, potentially serving as a bridge between observing and policymaking. Increasingly, there is a recognized need for such interfaces or input mechanisms for IK and local observations, such as in the context of US regulatory processes (Kendall et al. 2017), emergency management and response (Eicken et al. 2011), travel hazard identification (Dammann et al. 2018; Rolph et al. 2018), and weather prediction services (Fox et al. 2020; Simonee et al. 2021). Efforts such as AAOKH may ultimately contribute to recent calls from the US federal government to apply Indigenous and Traditional Ecological Knowledge in federal decision-making (Lander and Mallory, 2021). We further explore how observations can inform policy on local scales and comanagement in the sections below.

Core function two: communicating observations from IK holders, their meaning, and implications

> "*The way [AAOKH] is now is providing a lot of information that needs to be heard*"—Billy Adams on the importance of sharing observations (March[2] 2020), AAOKH Observer in Utqiaġvik.

Communicating observations made by IK holders, and their meaning with respect to rapid change and its impacts, has been recognized and developed as a key element of AAOKH's work. The focus of AAOKH communications has been on supporting observers as they engage with their own community and across the broader northern Alaska coastal region. The value of such communications extends from providing a means for discussion and calibration of specific findings across the region to supporting education and community outreach efforts. Effective communication across and beyond the region provides a broader context for environmental shifts occurring along latitudinal or regional gradients and can also help in anticipating potentially disruptive changes (e.g., major storms with coastal flooding).

By regularly posting recent observations on our AAOKH Facebook page, we are able to center the perspectives of our network of Indigenous observers in a public forum, in addition to fulfilling our goals for localized, iterative, and rapid information exchange. For example, we posted an image of an ugruk (bearded seal) in June[7] 2019, shared by Billy Adams (Utqiaġvik observer), which showed blubber of the seal colored yellow-orange. Billy observed, "large bearded seal [had] discolored blubber, did not smell right, and hard bumps throughout the seal. Many seals harvested have been reported in this state in the past month. It is a concern we should discuss further". Facebook reported 583 engagements, 185 reactions, 290 shares, and 90 comments to this post, including comments from subsistence hunters in communities around coastal Alaska. Other commenters from the Utqiaġvik region reported similar harvests of ugruk with orange-colored blubber or other unusual conditions (e.g., hair loss). Commenters from western Alaska and Bering Sea regions, however, noted that this type of blubber has occurred more frequently in their region, and some Elders even considered it a delicacy. Preliminary veterinary investigations (R. Stimmelmayr (personal communication)) suggest that a fair number of yellow-orange ugruk blubber discolorations are likely related to diet. However, yellow, discolored blubber can also be related to underlying liver conditions. Examination of vital organs by hunters, as part of their traditional and cus-

tomary practices for assessment of seal health, will help in their decision-making process as to whether their catch is fit for human consumption (Stimmelmayr and Sheffield 2022). Many Facebook commenters also noted an interest in knowing more about this condition. This example illustrates the ability of this platform to serve as a means of catalyzing public discussion and information exchange between IK holders and community members, as well as a way to identify local interests and concerns.

Core function three: broadening education and outreach, by moving over and making space, for Indigenous scholars and leadership

> "*Probably the biggest benefit I saw was the students. That's a wonderful, wonderful program. I think [for the future] more effort, more students from the rural areas that are going to be affected by more global warming and environmental changes. Because they are going to live it. As we grow old and disappear, they're going to live it and their families are going to live it. I think the emphasis should be placed on getting more student participation. I like the way it [i.e., AAOKH] is set up, and I think we can build on it and make it even better*"—Bobby Schaeffer (March[2] 2021), AAOKH observer in Qikiqtaġruk.

The role of AAOKH as a means of fostering Indigenous scholarship has gained in importance over the duration of the project (Fig. 5), including by supporting place-based education (in particular at the K-12 level), introducing Indigenous perspectives into university teaching and research, and all the way to Indigenizing academic programs. Numerous studies have highlighted the lack of diversity and inclusion of underrepresented minorities, and Indigenous scholars and students in particular, in geosciences and STEM fields more broadly (Carter et al. 2021; Harris et al. 2021, NASEM 2020). Connecting students in these fields to community-identified research priorities and building on concepts central to many IK systems, such as interdependence and altruism, has been found to increase engagement (Carter et al. 2021), which validates the approach taken here. Intentionally creating space for Indigenous graduate students was also meant to promote their leadership and intellectual prowess in defining projects of interest to them while also being responsive to concerns and issues in AAOKH communities. Each student has distinct disciplinary training and thesis research requirements, so AAOKH is not the only component of their graduate programs, yet their reflections (Box 1) illustrate the value of building safe spaces and relationships to specifically support Indigenous students. By supporting their career development, sometimes in nontraditional ways, we hope to also create pathways for their future leadership in programs like AAOKH that are grounded in the IK of their own people and regions. As much as we aim to support our students, we too (i.e., non-Indigenous academics on the AAOKH team) have been able to learn from them about how to best support the communities we work with.

We also acknowledge that additional work is needed to build stronger K-12 educational and outreach opportunities within communities. Several observers have indicated their desire and support for their observations to be used in classrooms within their communities. We are considering new interactive data products to summarize and share data, including opportunities to develop new K-12 educational products or curricula based on AAOKH observations. The creation of new curricula may allow students to explore place-based and culturally relevant environmental changes happening in their own regions and from the perspectives of Iñupiaq Knowledge holders. This will help fulfill the wishes of observers and other IK holders to continue training and engaging the youth in IK and ways of knowing for learning about their environment, monitoring, and decision-making in their communities.

Core function four: creating an interface for scientists, agencies, and others to engage with Indigenous-led observations

> *"The [AAOKH] database could be useful for scientists coming up to the areas, or hunters that are going to a new areas, or for people who might be moving back to the area if they have been away for a while. I think it could be a tool for high school teachers and junior high students to teach"*—Carla SimsKayotuk (April[3] 2022), AAOKH observer in Qaaktuġvik.

While much of AAOKH's efforts have focused on engaging local communities, the project has also expanded upon SIZONet's aim to share observations with the broader scientific community and agency personnel. Thus, AAOKH has served as an example of bottom-up monitoring programs in the context of Arctic observing (Eicken et al. 2014; Danielson et al. 2022), and observer insights are also central components of scientific studies (e.g., Johnson and Eicken 2016; Eerkes-Medrano et al. 2017; Deemer et al. 2018). Engagement with and access by agency personnel is more difficult to gauge, yet our work to broaden community engagement (Fig. 5) has created an information infrastructure that can support knowledge exchange and inform management and policy.

In contrast to sharing observations on Facebook, our online data repository provides a more searchable interface that can be accessed by researchers, managers, educators, or the public—given their adherence to our data use agreement. A web search of the digital object identifier assigned to the observations dataset indicates that at least eight different scientific publications or reports have formally cited the observations (both AAOKH and SIZONet phases). However, undocumented use or consultation of the observations is expected to be substantially greater. With limited database analytics to verify user groups, our assumption is that this resource is primarily utilized by researchers at academic institutions for scholarly works and is currently underutilized by Tribes, comanagement organizations, or other institutions that focus on subsistence resources, community planning, or adaptation. As a result, we are further refining our data use agreement for research purposes to ensure that AAOKH observations are put into proper context and with the free, prior, and informed consent of our observers. Simultaneously, we are working to transform the functionality of our database to make it more useful and usable for locally driven purposes. The AAOKH StoryMap developed as part of RG's thesis provides an alternative data product that showcases and synthe-

Box 1. Reflections by current and recent AAOKH graduate students on how working with AAOKH has affected their personal education, career trajectories, and academic experiences.

AAOKH, in my opinion, has very much organically become an exceptional example of a community-based monitoring (CBM) program coordinated by an academic institution. I use the word "organically" because I believe that the success of the program—the level of trust and mutual regard that has been garnered between program and communities is truly rooted in the motivations and values of the current (and past?) program leader(s) to do good work. This isn't something that can necessarily be taught; or blueprinted into the design of a CBM program. As a budding scientist, being involved with such a respected program and learning from my mentor (DH) and the observers has been instrumental in developing my own identity as a researcher. Because of the longstanding trusted relationships that AAOKH has built with observers, I have been able to learn from people across the Arctic who are eager to support us students and our work through AAOKH, which is something I otherwise wouldn't have. It has given me a lot of confidence in developing my identity as western natural scientist and an Indigenous person to learn from other Indigenous people who support me and my work, because operating at this intersection, especially in the beginning, can sometimes feel very disparate and internally polarizing.

Being involved in AAOKH has been the most enriching opportunity in my graduate program. Apart from the program goals and activities themselves, I feel immeasurably grateful to have met and had the opportunity to work with other Indigenous students from rural Alaska, RG and KP, who I now consider my good friends, and to have the support of program researchers who genuinely want to support us students and our individual research interests. This of course wouldn't have been possible without the person who brought us all together, our mentor (DH), whose mentorship, support, and friendship has been invaluable in working towards research goals and in becoming a scientist myself.

— Elizabeth Mik'aq Lindley, Yup'ik

When I first started my degree program, I was unsure about engaging with Indigenous communities in an academic context. I had little understanding of what it meant to be doing research with Indigenous communities. Fortunately for me, my mentor (DH) was a great mentor in helping me to coordinate conversations with AAOKH observers, in framing my research conclusions and in navigating academia as an Iñupiaq student. I have also had the great opportunity to meet and work with other Indigenous students involved with AAOKH, and those connections have turned into lasting friendships. It has meant so much to me to feel the overwhelming support from the AAOKH science team in my academic endeavors.

In regards to working with the AAOKH observers and researchers, I was reminded of a lesson that I learned as a kid which was that everything has a story—from rocks to the mountains, to the plants and animals, to the ocean and rivers, and to us. Even though different groups of people from different cultures and careers may interpret or understand stories differently, no matter how the story is told and interpreted, each story will talk about growth, changes, extreme events, and struggles. I did not realize how looking at each living thing as their own main character in a story made it feel like a personal connection or a sense of self because we can relate to certain stages of their life. Throughout my college journey, I have been told to keep personal matters or biases away from research, but these AAOKH observations are not just observations for data purposes or words written on a screen or paper, knowing the ice and ocean conditions, understanding animal movements, and knowing the weather conditions is personal and important to our communities and hunters because this is the type of knowledge we need to know to have food on our tables, give back to the communities, and teach our children. I see the AAOKH observations as stories—there are so much within the people that write these observations and there is so much knowledge within their observations. The observers can tell the sea ice's story, the bowhead whale's story, seals, caribou, the weather, etc. just by looking at it, observing it, and feeling it. Their observations taught me that everything in nature is an open book, you just need to allow yourself to read it, understand it, watch it, and listen to it. That's how you learn their stories and how you learn to correctly tell their stories—make people want to learn more by how you tell the stories that the land and/or ocean told you. With the connections and relationships that we (observers, AAOKH researchers, and students) have, we are able to respectfully tell these stories from different perspectives, but still highlighting and uplifting the importance of our Indigenous Knowledge holders.

— Kimberly Kivvaq Pikok, Iñupiaq

Working with AAOKH as an Indigenous student from Arctic Alaska has been a very rewarding experience. I have had the privilege of working with observers and observations from communities similar to my own, who practice many of the same subsistence and community activities I participated in with my family growing up. In this way, I felt very connected to the work I was doing and the people whose observations I was reading.

The major deliverable of my work with AAOKH was an ArcGIS StoryMap which synthesizes observations from AAOKH communities. So often in popular media, Indigenous communities in Alaska are described from the perspective of people who don't live there. The rhetoric around climate change and Alaska Indigenous communities has been molded by the perspectives of outsiders who lack the understanding of what it means to be living through these changes everyday. What was very rewarding for me was to be able to prioritize and elevate the voices and the observations from AAOKH observers who describe these impacts in their own words and reflect on them in their annual reports.

Another thing that has been rewarding was to be working within an academic organization which is co-led by Indigenous people. Indigenous children are taught from a young age to listen to their Elders, especially when out on the land or ice, as they have lived many years thriving in the Arctic environment. They pass on knowledge about how to safely navigate unforgiving conditions. That wisdom is necessary to be able to safely hunt, live, and thrive in the Arctic. I believe it is also necessary to understand and mitigate climate change impacts. So to be working in an organization that is actively pursuing guidance from Indigenous people doesn't only feel rewarding, it feels right.

— Roberta Tuurraq Glenn, Iñupiaq

sizes AAOKH observing themes in a publicly accessible and summarized way. Importantly, this StoryMap also places community observations and datasets from operational agencies or other research projects into the same framework.

Despite an increasing recognition of the value of these observations in the data-sparse Arctic, sharing information regularly with other science initiatives can be challenging when there is a mismatch in expectations for data collection. Formalizing data sharing agreements in such applications would be important to ensure mutually agreeable terms for regular information exchange. Alternatively, formalizing a data sharing policy also empowers communities to choose not to participate in a research effort. AAOKH-affiliated scientists are also actively engaged in research to connect with other observing programs across Arctic regions (Johnson et al. 2015; Eicken et al. 2021), including the contribution of information on good practices for Arctic CBM and advancing relationships with other regional and pan-Arctic observing efforts (Danielsen et al. 2021, 2020). Similarly, AAOKH explores links with other communities experiencing and monitoring environmental change at the pan-Arctic scale as a part of the ELOKA network of projects. For example, we have the opportunity to examine broad-scale pan-Arctic environmental trends by engaging with other CBMs that rely on ELOKA digital platforms (Johnson et al. 2021). At the international level, AAOKH is well positioned to contribute to efforts to promote the use of community-based monitoring and Indigenous-led observations for sustained Arctic observations, specifically by supporting the development of shared Arctic variables that are of value to Arctic Indigenous communities (Starkweather et al. 2022).

Core function five: supporting community and Indigenous-led responses to environmental change

> "*Global warming is happening. It is affecting different villages in different ways. I collect observations…this is an important tool for the future"… "We can look back on these observations in years to come…[and] compare if there are any dramatic changes*"—Guy Omnik (December[8] 2020), AAOKH observer in Tikiġaq.

While currently the least developed element of AAOKH, we anticipate that the direct support of community-scale responses to rapid change, by informing short-term decision-making and long-term planning, will grow in importance. We have made strides in responding to community priorities and interests by implementing new observing protocols and maintaining data services (e.g., ocean monitoring and mapping of whaling trails), yet we also see new opportunities for AAOKH observations to be more directly applied to local decision-making, particularly in the context of Indigenous food security. Many AAOKH observations directly correspond to dimensions of Indigenous food security, as defined by ICC-Alaska (2016), as well as the comanagement of fish, birds, and wildlife in Alaska. Although the science and management of coastal marine wildlife in northern Alaska is rooted in western scientific frameworks, there is an opportunity to improve natural resource management approaches by elevating the perspectives and practices provided by IK holders (Yua et al. 2022). Incorporating Indigenous observations, such as those contributed to AAOKH, may be particularly useful for strengthening local decision-making and Indigenous sovereignty over management systems that have been dominated by western approaches. Similarly, the long-term records sustained through a program like AAOKH document phenological shifts, novel conditions or species, health, and ecology of the biophysical environment that might otherwise be missed in more conventional scientific practices that often maintain a disciplinary focus or take a reductionist monitoring approach (Eicken 2010; Moore and Hauser 2019; Tengö et al. 2021).

Iñupiaq hunters are also experts at assessing metrics of wildlife health. Examples of observations include documentation of body condition, behavior, or disease, such as color and texture of blubber or muscle (e.g., as described in the previous sub-section), unusual behavior (e.g., use of terrestrial rather than sea ice substrate by natchiq, or ringed seal), or simply "fat", "skinny", or "typical" body condition (Ostertag et al. 2018). More explicit inclusion of IK, and specifically Indigenous ecological metrics, could help tip the balance of power in comanagement frameworks to allow for more equitable, inclusive, and stronger decision-making while maintaining the health of wildlife, fish, and also the people reliant on them (Loseto et al. 2018; Raymond-Yakoubian and Daniel 2018; Peacock et al. 2020; Breton-Honeyman et al. 2021; Yua et al. 2022). Furthermore, our ability to document and understand the connections between accessibility to resources (Brinkman et al. 2016; Hauser et al. 2021) and travel safety under changing ice, ocean, and land conditions (Ford et al. 2019; Fox et al. 2020; Simonee et al. 2021) directly intersects with food security, management, and policy decisions (ICC-Alaska 2016; Heeringa et al. 2019; Brinkman et al. 2022).

An important step in our ability to directly apply AAOKH observations to local decision-making and food security issues involves modifications in our database functionality. Currently, the database format for data collection, entry, and query is heavily influenced by how it was set up during SIZONet as an observing system specifically working with observers to collect observations on sea ice and ice-related activities. Although still relevant, as SIZONet evolved into AAOKH, there was a shift in focus from observations centered on sea ice to documenting the wide-ranging environmental factors that influence daily community activities, including the accessibility and availability of subsistence resources as well as impacts to community infrastructure that supports these activities (e.g., ice cellars, access roads, and boat launches). To accommodate a broader range of observations (e.g., related to wildlife health and travel safety), we are considering the implementation of new categories to be used during data entry, which can help direct the use of observations for applications in various decision-making contexts. Our goal is to work with observers, Tribes, and comanagement organizations to develop more accessible and useful data tools and products.

[8] December—Siqiñġiḷaq (Coastal dialect), Umigraġvik (Point Hope dialect), Hiqiñġiḷaq (Anaktuvuk Pass dialect). Month of no sun, month when skylights are made of ice blocks, seal and polar bear hunting (North Slope Borough 2019).

Future directions for continued progression toward a knowledge coproduction framework

> "*…if we can keep that [trust and knowledge] going with this group…otherwise we'll have to start over and have to gain that trust again and that can take valuable time*"—Noah Naylor (March[2] 2021), AAOKH Steering Group member from Qikiqtaġruk.

The foundations of AAOKH, and SIZONet before it, were built on trust and knowledge as well as an equitable valuation of IK alongside western science. The body of observations collected so far through AAOKH and SIZONet provides a critical and unique collection of IK and first-hand perspectives, as well as an example of ways of sharing, during a time of rapid environmental change across the Arctic. However, we also acknowledge that neither project was necessarily conceived with the tenets of knowledge coproduction (Yua et al. 2022) at heart. Historical framing of coproduction research conceived of more interdisciplinary approaches to conventional science, often for actionable science that was inclusive of "stakeholder" perspectives (e.g., Bremer and Meisch 2017). We strive for a coproduction approach that embodies the concept of reciprocity as a respectful inclusion of both Iñupiaq and western ways of understanding the environment. As we turn toward future goals of sustaining AAOKH's core functions, based on our mutually beneficial relationships with observers and communities, we must also evaluate where we stand in relation to power dynamics, resource distribution, and overall equity in our research relationships. This will help us identify the additional work needed to center Indigenous voices and strengthen Indigenous self-determination over our research collaborations and approach. During our progression from SIZONet to AAOKH, we have continued to track and strengthen records of Indigenous insights on Arctic change, emphasized communication with communities, created new data and information responsive to community interests, and supported Indigenous scholarship and training opportunities. Yet an honest reflection suggests there is more to do to elevate Indigenous governance over our shared research. If we take a decolonizing approach to our ongoing and future collaborations (Roué and Nakashima 2022), the roles of Indigenous and non-Indigenous contributors need redefinition and evaluation in terms of leadership of the project, data ownership, accessibility, and capacity building of not just Indigenous youth and scholars but also non-Indigenous researchers (Pedersen et al. 2020; Wilson et al. 2020).

AAOKH currently has multiple platforms and pathways for knowledge sharing that can complicate Indigenous data sovereignty. Utilizing both an online database with use restrictions and regular sharing of observations on our Facebook page, we are assessing our abilities to provide equitable access to data while also supporting Indigenous data sovereignty and limiting misuse of information. An important pathway forward requires AAOKH to continuously work toward a culturally appropriate data-use policy (Carroll et al. 2021) to ensure proper crediting and use of AAOKH observations. We are actively working as a team, along with our ELOKA partners, on revising our data use agreements and sharing protocols. We also recognize that there are limits to understanding the usability and accessibility of our data and current platforms for sharing information without a stronger evaluative component to the AAOKH program. In addition to instituting database analytics to track access and use of the database, we will particularly seek Indigenous evaluation techniques and opportunities (Waapalaneexkweew and Dodge-Francis 2018; Firestone et al. 2019; Velez et al. 2022) as we continue the project into the future.

While much focus is often put on capacity-building for Indigenous communities and youth, part of our ongoing and future efforts must also consider ways for our non-Indigenous participants to understand the inequitable history of research in the region whilst also finding pathways to lift up Iñupiaq voices, values, and customs (Zurba et al. 2021). Examples from other Arctic regions provide models of knowledge transfer techniques that can disrupt the colonial history of Arctic research (Ljubicic et al. 2022), such as programs based on the land that serve as forums for Elders, youth, and researchers to respectfully engage in cross-cultural dialogue and uphold relational accountability (e.g., in the context of leadership, ethics, Indigenous values, and language). These may be important opportunities for experiential learning for non-Indigenous researchers and Indigenous youth alike.

As we continue to pursue a stronger coproduction of knowledge framework with future iterations of AAOKH, our goal is to support Indigenous self-determination and governance over the project, observations, and knowledge that we collaboratively generate. As one initial step toward promoting Indigenous scholarship and leadership within AAOKH, we created a new job opportunity for one of our recently graduated students (RG), who has cultural connections to AAOKH communities, to increasingly lead community engagement and project management. We believe this puts her into a position poised to increasingly lead the definition of our future research directions. Instituting reflective and evaluative components to ask who owns, benefits from, and is involved in the design and framing of the scope of our research (Tuhiwai Smith 1999) will be critical to our progress going forward.

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Copyright

Data availability

Observers retain ownership of their observations as well as provide consent for their observations to be archived and shared, upon acceptance of user agreements, on the online platform curated by the Exchange for Local Observations and Knowledge of the Arctic.

Data are available upon acceptance of a data use agreement at https://eloka-arctic.org/sizonet/, with the following citation: Observers of Coastal Arctic Alaska 2022. Local Observations from the Seasonal Ice Zone Observing Network (SIZONet) and Alaska Arctic Observatory and Knowledge Hub (AAOKH), Version 2. Edited by the AAOKH Team. Boulder, Colorado: National Snow and Ice Data Center. http://dx.doi.org/10.7265/jhws-b380.

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