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Marine mammal ecology and health: finding common ground between conventional science and indigenous knowledge to track arctic ecosystem variability

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Abstract

Marine mammals respond to, and thereby reflect, changes in Arctic ecosystems that are important both to practitioners of conventional science (CS) and to holders of indigenous knowledge (IK). Although often seen as contrasting approaches to tracking ecosystem variability, when CS and IK are combined they can provide complementary and synergistic information. Despite exceptions, ecosystem-focused CS is often spatially broad and time shallow (1000 s km, decades) while IK is comparatively narrow spatially and time deep (10 s km, centuries). In addition, differences in how information is gathered, stored, applied and communicated can confound information integration from these two knowledge systems. Over the past four decades, research partnerships between CS practitioners and IK holders have provided novel insights to an Alaskan Arctic marine ecosystem in rapid transition. We identify insights from some of those projects, as they relate to changes in sea ice, oceanography, and more broadly to marine mammal ecology and health. From those insights and the protocols of existing community-based programs, we suggest that the strong seasonal cycle of Arctic environmental events should be leveraged as a shared framework to provide common ground for communication when developing projects related to marine mammal health and ecology. Adopting a shared temporal framework would foster joint CS–IK thinking and support the development of novel and nonlinear approaches to shared questions and concerns regarding marine mammals. The overarching goal is to extend the range and depth of a common understanding of marine mammal health and ecology during a period of rapid ecosystem alteration. The current focus on CS–IK co-production of knowledge and recent inclusion of marine mammals as essential variables in global ocean observatories makes this an opportune time to find common ground for understanding and adapting to the rapid changes now underway in Arctic marine ecosystems.

1. Introduction

As top predators, marine mammals must adapt to habitat alterations resulting from biophysical processes and thereby serve as sentinels of ecosystem variability (Moore 2018). Conventional science (CS) shows that shifts in marine ecosystems can be revealed by tracking both extrinsic and intrinsic marine mammal responses to environmental perturbations now evident in the Arctic (Moore and Stabeno 2015, Moore

et al 2018a, 2018b). For example, bowhead whale (*Balaena mysticetus*) distribution in the western Beaufort Sea (140–157°W, to 72°N) was closer to shore and shifted toward Point Barrow during the fall period 1997–2014 compared to 1982–1996 (Druckenmiller *et al* 2018). This extrinsic signal was coincident with a 20–25 days/decade increase in the open-water period, an environmental shift associated with improved whale feeding opportunities nearshore driven by greater upwelling along the shelf break. A

corresponding intrinsic signal was reported in the form of improved bowhead whale body condition and a marked increase in population size for the period 1989–2011 (George *et al* 2015). Further, bowhead calf counts during aerial surveys have been comparatively high since 2012 (Clarke *et al* 2018), supporting the report of improved body condition, particularly of pregnant female whales, and leading to population growth during a period of rapid sea ice loss.

Marine mammals are fundamental to the nutrition and culture of Indigenous people across the Arctic (ICC-Alaska 2015). The scope of indigenous knowledge (IK) encompasses the health of the human-marine mammal relationship (e.g. Metcalf and Robards 2008, Ostertag *et al* 2018). Specifically, 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 (e.g. Huntington *et al* 2005, Berkes 2007, Gadamas 2013, ICC-Alaska 2015, Alessa *et al* 2016). For example, traditional knowledge interviews conducted over the past decade have provided a wealth of information on how marine mammal populations in northern and western Alaska have responded to biophysical changes in the environment (Huntington *et al* 2017). Although shifts were identified in distribution, abundance, migration, behavior and health, IK indicates that so far marine mammal populations in the region remain healthy and abundant despite changes in the coastal ecosystem. Because climate change effects are expected to continue and possibly accelerate, it is important that the ways in which hunters gather and incorporate new information into their understanding of the marine environment receive further attention (Huntington *et al* 2017). Indeed, climate-related impacts to accessibility of traditional hunting opportunities are perceived as a critical challenge to the future resilience of the Arctic Indigenous life style (Brinkman *et al* 2016).

CS and IK have complementary temporal and spatial scales. Despite exceptions, ecosystem-focused CS is often spatially broad and time shallow (1000 s km, decades) while IK is comparatively narrow spatially and time deep (10 s km, centuries; e.g. Krupnik and Jolly 2002, Huntington *et al* 2004, Lewis *et al* 2009). Certainly, some aspects of CS extend over long periods (e.g. insights from ancient DNA, paleoecology, or archaeology), but research focused on the present-day ecology and health of marine mammals are only decades-long at best (e.g. George *et al* 2015, Clarke *et al* 2018). In addition, the means of knowledge sharing among CS researchers is through peer-reviewed papers and formal presentations. Conversely, Berkes and Berkes (2009) describe how IK information (analogous to CS data) is acquired over several years of observations (similar to long-term CS sampling), then shared with other community members and across generations, which creates a collective understanding of environmental relationships and shifts. These

fundamental differences to ways of understanding and sharing complex environmental information often contribute to communication challenges that result in a large gap in information integration between CS and IK. Challenges to information integration also result from the different nature of information acquisition. While independent quantification of information is fundamental to CS, IK favors a collective-qualitative understanding of the system, which often avoids precise categorizations. Specifically, IK may apply ‘fuzzy logic’ by accumulating a large volume of information on a continuous basis that is collectively applied to adjust to the changing Arctic ecosystem (Berkes and Berkes 2009). Despite challenges to information integration, input from both CS and IK approaches can lead to an improved understanding of the natural world.

Because marine mammals often play a central role in both IK and CS ways of thinking about arctic ecosystem variability, they can act as a bridge linking these two different ways of understanding the natural world. We review several CS–IK research partnerships formed over the past ~40 years to identify insights and practices that supported a shared understanding of ongoing changes in the Alaskan Arctic marine ecosystem. We then derive a depiction of how CS and IK have worked successfully in a paired fashion in the recent past, and suggest how more synergistic collaborations might be fostered in the future through the adoption of a shared annual-cycle framework. The overarching goals of this paper are to further develop the idea of using marine mammal ecology and health indices as a means to track arctic ecosystem variability and to describe the potential role of marine mammals as a bridge for communicating and combining information based upon CS and IK.

2. Insights from research partnerships

Indigenous people have a long history of helping newcomers survive in the Arctic, as demonstrated by aid to explorers, whalers and missionaries arriving in Utqiaġvik [Barrow] since the late 1880s (Brower 1942). By the mid-1900s, many Utqiaġvik residents were often key contributors to science teams working at the Naval Arctic Research Laboratory, although their essential role as partners on various projects often went unrecognized (Norton 2001). More recent work, focused on impacts of climate change on Arctic ecosystems and Indigenous hunting practices, has aimed to recognize the key contributions that local people make to successful science projects (e.g. Wohlforth 2004). Indeed, research partnerships between CS practitioners and IK holders over the past ~40 years have sought to improve mutual understanding on topics related to sea ice, ocean biophysics, and marine mammal ecology and health (e.g. Ashjian *et al* 2010, Druckenmiller *et al* 2012, George *et al* 2015,

Harwood *et al* 2015, Loseto *et al* 2018a). Below we review just a few examples of projects on each of those topics, with a focus on identifying novel insights that resulted from CS–IK research partnerships.

2.1. Sea ice and oceanography

Sea ice is an iconic component of the Arctic environment and of keen interest to both CS researchers and IK holders. A focus on sea ice dynamics provides a link between CS and IK due to the critical role sea ice plays as a physical driver of Arctic marine ecosystem structure and function, as well as the services it provides as a platform upon which traditional activities occur (Eicken 2010). For example, Druckenmiller *et al* (2012) conducted semi-directed interviews with hunters to understand the impact of ice conditions on the spring bowhead whale hunt near Utqiagvik, AK, including choice of sea ice trail, ice camp locations and overall safety. Scientists also measured ice thickness and conditions along the trails used by hunters during four seasons (2008–2011). Three insights emerged from the study, including: (1) tracking ice conditions along ice trails revealed clear interannual variability in the thickness of the shore-fast ice, (2) documenting trail building and hunting strategies demonstrated how the community responds to variability, and (3) developing CS information resources for the community facilitated interaction with hunters and demonstrated project relevance to environmental challenges facing the community. These insights provided a foundation for the development of a framework to quantify the impacts of loss of sea ice on safety of on-ice travel and operations across a range of difference icescapes and ice uses (Dammann *et al* 2018), which remain some of the biggest challenges for Alaska Native marine mammal hunters (Huntington *et al* 2017). Motivated by the need to forecast safe sea-ice conditions at operational timescales (<10 days), insights from CS–IK sea ice partnerships were included in exploring how IK fits into a forecaster toolbox to support useful sea-ice information products (Deemer *et al* 2018).

During the ice-free season, ocean biophysics (i.e. hydrography and biological production) becomes a focus of study and observation. Ashjian *et al* (2010) investigated short-term variability in hydrography associated with changes in wind speed and direction that altered zooplankton composition in the community-identified fall whaling area northeast of Utqiagvik. Aggregations of roughly 50–100 bowhead whales were observed in early September 2005 and 2006, at locations consistent with a retrospective IK analyses of whaling activities for 1984–2004. During the two year study, euphausiids (krill) and copepods were upwelled onto the Beaufort Sea shelf during E or SE winds, then concentrated there when the winds reversed or slackened, resulting in a favorable feeding environment for the whales and a good whaling location for hunters.

This mechanistic wind-shift model became known as the ‘krill trap’. These findings were subsequently augmented with remotely-sensed data (Okkonen *et al* 2011), and together with IK provided the foundation for a community-focused video (*Arctic Currents*), depicting a year in the life of a bowhead whale (<https://uaf.edu/museum/exhibits/digital-media/arctic-currents/>). The overarching insight from this partnership was how CS–IK communication led to a refined understanding of why bowheads regularly occur near Utqiagvik in late summer and fall, a whaling season that has become increasingly important to the community as sea ice loss has sometimes put the spring hunt in jeopardy. A key measure of the success of this partnership is that the wind-shift mechanism that underlies the ‘krill trap’ is now an environmental indicator commonly used by hunters to anticipate good fall-whaling conditions.

2.2. Marine mammal ecology and health

Since the late 1970s, there have been numerous studies focused on bowhead whale population dynamics and ecology in Pacific Arctic waters. While the first two decades of work were often conducted by either CS practitioners or IK holders (Burns *et al* 1993), more recent studies often rely on CS–IK teams to investigate migration timing and seasonal habitats (e.g. Citta *et al* 2015). Long-term datasets on diet, made possible by hunters providing researchers’ access to whales for sampling, have been particularly informative regarding marine mammal responses to ecosystem variability (e.g. Harwood *et al* 2015, Ostertag *et al* 2018). Indeed, an important insight from this work is that the body condition of pagophilic (ice loving) bowhead whales improved during a period of rapid sea ice loss (George *et al* 2015). A second key insight comes from the detection of euphausiids (krill) in the stomachs of whales harvested in late summer (Kaktovik) and fall (Utqiagvik) since the mid-1970s (Lowry *et al* 2004). Zooplankton sampled from whale stomachs has been the only consistent means to demonstrate that this key-prey species has been available to whales (and other upper-trophic species) in the Beaufort Sea for decades. If not for CS–IK partnerships focused on whale diet and body condition, we might think krill were ‘new’ in the Beaufort Sea ecosystem, as a result of recent environmental changes. These data lead to a larger question regarding the role and importance of euphausiids (krill) in the Pacific Arctic marine ecosystem. Krill are key components of arctic ecosystems in the Atlantic sector, so understanding their role in the Pacific sector seems critical in this period of rapid change.

In another multi-decade example, CS and IK have been successfully integrated to understand the ecology and health of beluga (*Delphinapterus leucas*) offshore of Alaska and western Canada. In the late 1990s, traditional knowledge interviews with hunters in coastal

communities demonstrated a detailed understanding of migration timing, site fidelity, and importance of nearshore habitats used by belugas in spring, yet year-round migratory routes, offshore distribution and habitat selection were poorly understood (Huntington and the communities of Buckland E, Koyuk, Point Lay, and Shaktoolik 1999, 2004). Satellite telemetry studies, initiated in collaboration with hunters in the community of Point Lay Alaska in 1998, revealed remarkable offshore movements >700 km to nearly 80° N during summer (Suydam *et al* 2001). These long-distance trips were unexpected by researchers and hunters alike, who presumed belugas maintained coastal affinities (Huntington *et al* 2004). Subsequent telemetry studies, conducted in partnership with the hunters, have resulted in long-term datasets that have further illuminated population segregation, migration timing, behavior, and responses to shifting sea ice environments (e.g. Citta *et al* 2013, Hauser *et al* 2014, 2017, 2018). Similarly, the initiation in 1980 of standardized hunter-based sampling of belugas harvested in the Mackenzie River estuary allowed government scientists to document interannual differences in blubber thickness and evidence of an overall decline in growth rates, thought to reflect changes in the marine ecosystem (Harwood *et al* 2014). This discovery provided the foundation for recommendations to match the hunter-based sampling with isotopic and fatty acid profiling to investigate potential shifts in beluga diet, in addition to more holistic monitoring (Loseto *et al* 2018b) that includes IK-specific body condition and disease indicators (e.g. color and texture of blubber or meat, inspection of vital organs, review of surface behaviors, and qualitative metrics of body condition) co-developed through a CS–IK exchange (Ostertag *et al* 2018).

Lastly, recent CS–IK research partnerships have begun to address identified gaps (Laidre *et al* 2015) in understanding impacts of rapid sea ice loss to pagophilic ringed seal (*Pusa hispida*) and bearded seal (*Erignathus barbatus*) abundance, diet, body condition, and seasonal distribution and behavior. Although considerable ecological information could be acquired from satellite-linked telemetry data, early efforts to capture and tag ice seals involved CS practitioners conducting multi-week field campaigns that tried to anticipate predictable occurrence and behavior of seals and relied on favorable weather. In Northwest Alaska, the inclusion of local IK holders to the tagging teams conveyed their intimate understanding of seal behaviors and distribution, as well as local wind, current, and sea ice conditions, which significantly improved project success (A. Whiting, personal communication). Ultimately cooperative projects reliant on the Native Village of Kotzebue-trained hunter-taggers resulted in >80 ringed and bearded seals being tagged, often without scientists present. Information from the tagged seals provided insights for scientists and community members on the seasonal and diel

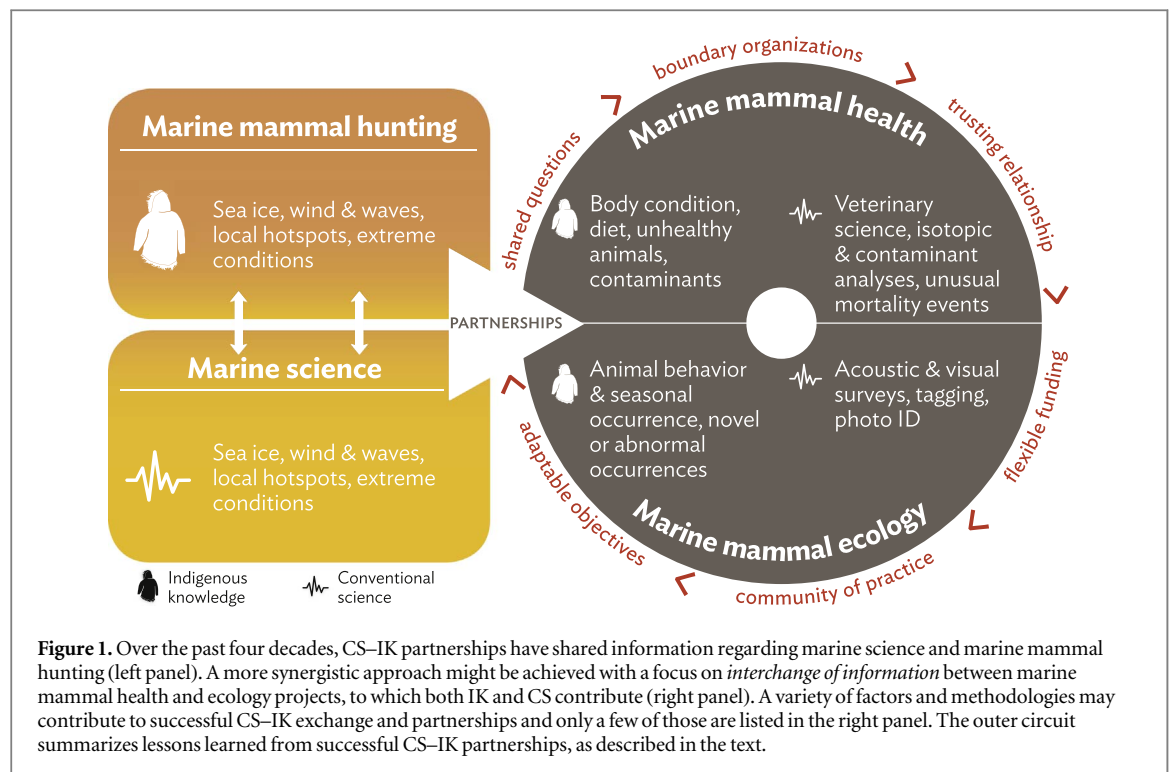
differences in dive and haul-out behavior as well as habitat selection and seasonal age-specific distribution and movements (e.g. Crawford *et al* 2012, 2018, Cameron *et al* 2018). Hunters have also been instrumental in collecting various body measurements and biological samples from subsistence-harvested seals, yielding insights in diet and body condition (Wang *et al* 2016). Hunter samples have also provided evidence that ringed and bearded seals in the Chukchi and Bering Seas have not shown declines in body condition, growth, or reproduction between historical (1975–1984) and recent (2003–2012) periods, suggesting that these ice-adapted seal populations are adapting to recent Arctic changes in the region, at least for now (Crawford *et al* 2015). IK holders have also provided more than biological samples for CS analysis. For example, Alaska Native hunters have long evaluated marine mammal body condition to determine whether harvested animals are safe for handling and consumption, in this way providing an index of marine mammal health. Hunters have been critical to reporting, collecting, and providing persistent surveillance for disease, such as the widespread unusual mortality event (UME) affecting ice seals and walrus in 2011 that raised concerns among both CS and IK communities regarding issues of food safety and overall ocean health (Moore and Gulland 2014).

3. Finding common ground to integrate CS and IK information

The case studies above leverage CS and IK approaches to improve understandings of sea ice dynamics and biophysics as it relates more broadly to hunting practices, food security and ultimately marine mammal ecology and health in the Pacific Arctic region. Building on insights from past CS–IK partnerships, a question arising is: can the two approaches be combined in a proactive way to provide common ground for a more synergistic method to track ecosystem variability using marine mammals as indicators? Without being prescriptive, our review reveals several examples of metrics that may be useful for tracking indicators of marine mammal health and ecology while also creating the space for the development of other potential key indicators (table 1). For example, CS practitioners and IK holders both have long-held interest in the interplay of atmospheric and ocean factors that lead to productivity hotspots, but until recently CS and IK approaches have operated mostly in tandem, focused on either marine science or the Indigenous practice of marine mammal hunting (figure 1: left panel). A more synergistic approach might be achieved with a focus on *interchange* between marine mammal health and ecology as key indicators of Arctic ecosystem variability, to which both CS and IK contribute (figure 1: right panel). Because Indigenous communities rely on marine mammals for food

Table 1. Example metrics developed from various CS–IK research partnerships in the Pacific Arctic that demonstrate opportunities to track indicators of marine mammal ecology and health that reflect responses to environmental variability. Other metrics may be developed through future CS–IK partnerships, community-based observing or other co-production of knowledge approaches.

Indicator	Example metric	Relevance	Species tracked	References
Body condition	Blubber thickness	Thicker blubber represents healthier whales	Beluga whale, bowhead whale, ice seals	Harwood <i>et al</i> (2014), Crawford <i>et al</i> (2015), George <i>et al</i> (2015), Ostertag <i>et al</i> (2018)
	Number of ‘rolls’ (i.e. lateral folds), roundness, appearance of backbone	‘Fat’ whales have rolls and wide backs, and are round versus long, slender whales. The backbone is apparent on skinny whales.	Beluga whale	Ostertag <i>et al</i> (2018)
Disease	Color and texture of skin, meat or blubber	Spots, discolorations, soft texture could indicate unhealthy animals.	Beluga whale	Ostertag <i>et al</i> (2018)
	Inspection of vital organs	Marks, spots, infections are often visible on organs such as the lungs, heart, or liver	Beluga whale	Ostertag <i>et al</i> (2018)
	Presence of lesions or infected skin wounds	Infected wounds or a number of scars indicate sick animals	Ice seals, walrus, beluga whale	Moore and Gulland (2014), Huntington <i>et al</i> (2017), Ostertag <i>et al</i> (2018)
	Allopecia	Hair loss was a component of a widespread unusual mortality event (UME) for Arctic pinnipeds and was used as an indicator of sick animals by hunters.	Ice seals, walrus	Moore and Gulland (2014), Huntington <i>et al</i> (2017)
Behavior	Swim speed, surfacing frequency, sluggishness	Sick animals swim slowly and may surface to breathe more frequently. Sick pinnipeds during UME events were sluggish and non-responsive.	Ice seals, walrus, beluga whale	Moore and Gulland (2014), Huntington <i>et al</i> (2017), Ostertag <i>et al</i> (2018)
Diet	Fatty acids/stable isotopes of hunter-collected samples	Biological samples can be used to track diet	Beluga whale, ice seals	Wang <i>et al</i> (2016), Loseto <i>et al</i> (2018b)
	Stomach contents of hunter-collected samples	Biological samples can be used to track diet	Bowhead whale, ice seals	Lowry <i>et al</i> (2004), Crawford <i>et al</i> (2015)
Distribution and migration	Unseasonal presence or persistence in a region, shifts in distribution per seasonal hunting locations and timing	Animals that arrive early or stay for extended durations may indicate shifts in migration timing	Beluga whale, bowhead whale, ice seals	Hauser <i>et al</i> (2017), Huntington <i>et al</i> (2014, 2017), Druckenmiller <i>et al</i> (2018)
Habitat use	Use of different habitat types, habitat segregation by sex or age class	Animals may shift types of habitat used as environmental conditions shift (e.g. sea ice type, snow depth)	Bowhead whale, bear-ded seal	Cameron <i>et al</i> (2018), Druckenmiller <i>et al</i> (2018)



and cultural wellbeing, they are often the ‘first responders’ when animals show signs of illness or stress. Furthermore, hunters together with CS partners are able to routinely obtain body measurements and samples of stomach contents, thereby tracking long-term marine mammal health status. These practices are naturally combined with various aspects of CS, including wildlife veterinary investigations, biochemical research techniques such as isotopic and contaminant analyses, and the coordination of responses to unusual mortality events. Ultimately there are parallels and divergences in both ways of understanding marine mammal ecology and health indicators, but CS–IK partnerships can extend the range, types, and relative strengths of the both paths to understanding (Berkes and Berkes 2009). We suggest that a focus on the relationships and commonalities of key indicators of marine mammal health and ecology provide an opportunity to leverage both CS and IK insights tracking Arctic ecosystem variability.

Experience shows there is no simple ‘one size fits all’ approach to finding common ground to integrate CS and IK information. The development of specific environmental indicators will depend upon identifying shared questions about variability in marine mammal health and ecology, as well as the broader marine ecosystem. Specific indicators may also vary among regions and local communities, seasons, and species (table 1). Past CS–IK partnerships have shown that Iterative processes often help define research goals and objectives, as well as foster relationships between CS practitioners and IK holders that build trust and respect for the different ways of knowing (Robards *et al* 2018). An information ‘broker’ or ‘boundary

organization’ proficient in both CS and IK practices can facilitate information exchange and support the development of ‘communities of practice’ over time (Eicken 2010, Robards *et al* 2018). Sometimes a proactive co-management organization can act as a boundary organization to provide common ground for dialogue among scientists, hunters, resource managers and the communities they serve (Adams *et al* 1993). For example, research on Alaskan beluga whale ecology and health (see section 2), has advanced through mutual identification of science priorities via the Alaska Beluga Whale Committee (ABWC), which is the co-management organization that places tribal representatives from Alaska Native coastal communities at the same table as local, state, and federal biologists and managers. At its inception, the ABWC was designed as an organization that recognized the fundamental importance of beluga whale ecology and health to both hunters and conventional scientists. Thus, decisions and recommendations by the group embody the diverse opinions and joint agreement resulting from a CS–IK partnership (Adams *et al* 1993). By identifying broad information needs relevant to scientists, hunters and resource managers, the ABWC has integrated CS and IK ways of understanding beluga health and ecology, while demonstrating the capability of this species to reflect ecosystem variability in a time of rapid change (e.g. Suydam *et al* 2001, Hauser *et al* 2017, 2018). The ABWC is only one example, among many, of possible paths towards finding common ground for integration of CS–IK information. The overarching goal is to find a framework that might achieve this on a more regular basis.

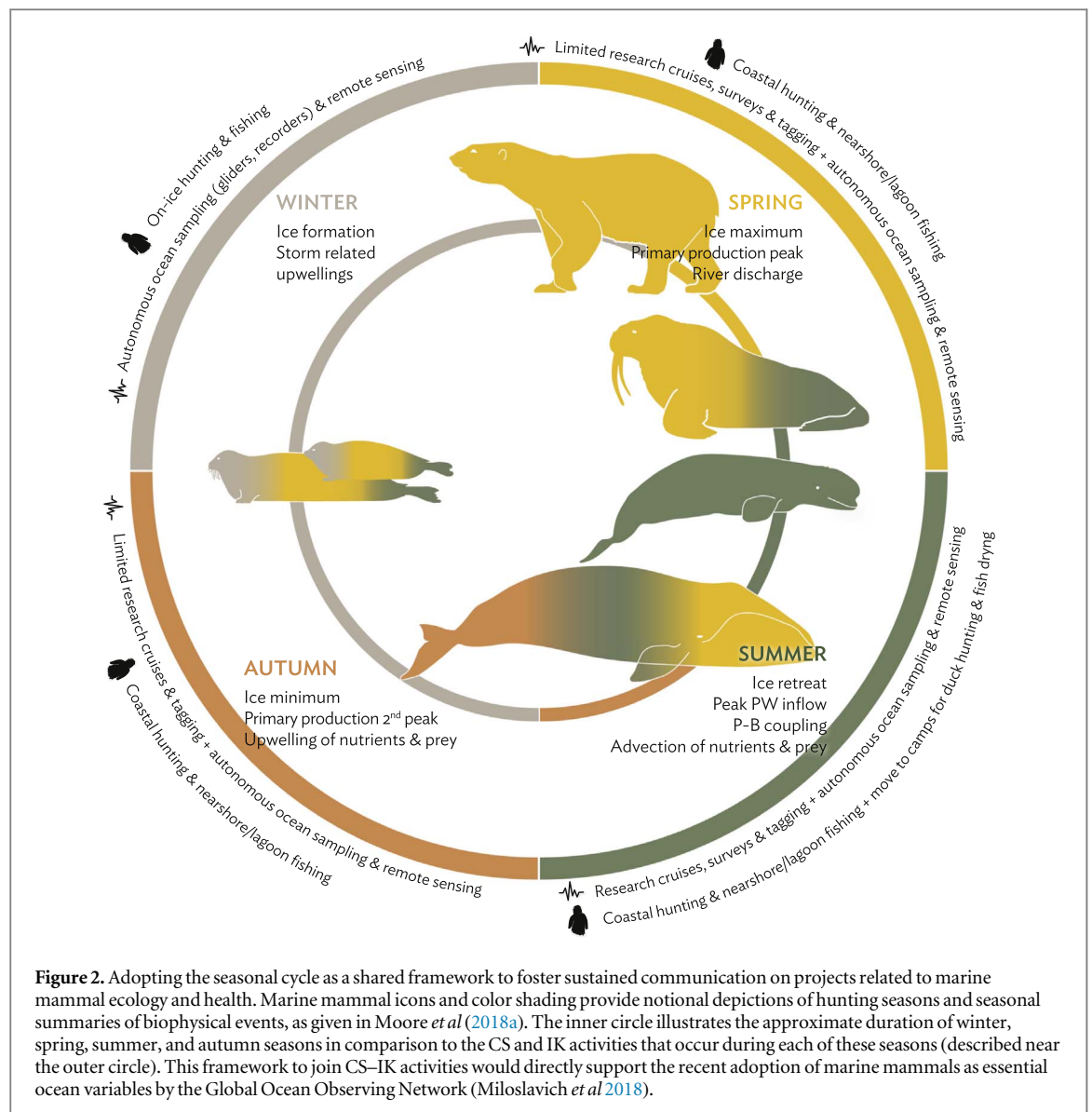
4. Future directions

Existing collaborative ocean observing initiatives provide an opportunity to develop CS–IK metrics of marine mammal ecology and health to track Arctic ecosystem variability. In the world of CS, the recent expansion of global and regional observatories aims to foster shared knowledge of ocean variability based upon tracking essential ocean variables (EOVs; Miloslavich *et al* 2018). Three expert panels are working to standardize EOV metrics in the fields of physics, biogeochemistry, and biology and ecosystems (<https://goosocean.org/eov>). Although the development of biology and ecosystem indicators is in its infancy, the routine inclusion of marine mammals as EOVs in next-generation ocean observatories will promote a multicultural approach towards a shared understanding of marine ecosystems (Crise *et al* 2018). At the community level, the Alaska Arctic Observatory and Knowledge Hub (AAOKH; <https://arctic-aok.org/>) networks and shares local environmental and ecological observations by Indigenous experts from seven coastal communities across north and north-western Alaska. The AAOKH builds on previous collaborative projects (Eicken *et al* 2014) by reporting on sea ice processes, oceanographic conditions, marine wildlife sightings, hunting activities, and factors affecting hunting opportunities. With a focus on the seasonal cycle around which many traditional activities revolve, anomalous observations stand out, such as the presence of novel species, unhealthy animals, or atypical environmental conditions. Repeated observations provide opportunities to examine spatial and temporal changes in coastal biophysics, marine mammal ecology and health across the spatially-broad seven-village network of the AAOKH. Other community-based observation programs include the Bering-region-focused Sea Ice for Walrus Outlook (SIWO; <https://arcus.org/siwo>), the Local Environmental Observer network (LEO; <https://leonetwork.org>), and programs embedded in the Exchange for Local Observations and Knowledge of the Arctic (ELOKA; <http://eloka-arctic.org/>). All of these programs provide additional examples of effective exchanges between CS and IK, but none specifically offer a shared framework to foster common ground between the two.

Expanding on methods adopted by community-based programs, and incorporating recent suggestions for facilitating communication between CS and IK (Moore *et al* 2018a, 2018b), we propose using the strong seasonal cycle of Arctic environmental events as a shared framework to foster sustained communication and integrate common indices of marine mammal health and ecology (figure 2). A seasonal cycle is common to the planning of both CS and IK activities, but the two calendars rarely converge. When CS and IK activities are combined on a seasonal-cycle frame, commonalities and differences in the two approaches

are evident. For example, although they vary with the seasons, IK activities are continuous over the calendar year. In contrast, CS activities are generally focused on the late-spring to early-autumn period, with remote sensing from satellites and autonomous instruments extending observations through winter months (outer circle). However, the length of each season is not equal, and winter is much more prolonged than the rapid spring and fall transition periods or short open-water summer season (inner circle). These disparities in season length in turn create differences in the nature of information acquisition, resulting in short periods of CS on-site sampling compared to the persistent observing associated with IK activities throughout the annual cycle. The continuous activities of Indigenous hunters throughout the year can provide place-based observation opportunities that CS cannot, or at least not without great expense and likely a limited scope. In contrast, CS often sample broad geographic regions using ships, aircraft, animal telemetry and unmanned aerial systems (UAS) during the summer season and via satellite-based remote sensing of the environment throughout the year. When these mismatches in scales and knowledge acquisition systems of IK and CS are considered, the complementarity of the two approaches to understanding marine mammal health and ecology can be better appreciated. The local and deep-time aspects of IK observations of sea ice, ocean conditions, marine mammal ecology and health complements the broad-scale CS sampling through surveys and remote sensing. Combined, both approaches have the potential to provide a more holistic and inclusive understanding of the Pacific Arctic marine ecosystem.

A key strength of the various participatory science programs is the ability to network within and across IK communities, as well as with CS. While the scale of community-based observations that encapsulate the deep-time IK in programs like AAOKH are local, data can be networked across the broad spatial range of northern Alaska. Discussions and cross-correspondence erupt with networking capabilities, fueled especially by social media tools that are widely used in many northern communities. These networks can form robust and adaptive observing arrays, similar to broad-scale CS ocean observing systems such as the Distributed Biological Observatory (Moore and Grebmeier 2018). In this case, IK networking offers bridging opportunities between coastal environmental and marine mammal observations and offshore CS ecosystem sampling and remote sensing (Moore and Kuletz 2018). The time is ripe for developing and networking observing efforts focused on marine mammal indicators, as there are many and diverse community-based observing programs across the Arctic (e.g. The Atlas of Community-based Monitoring and indigenous knowledge in a Changing Arctic; <http://arcticcbm.org/index.html>), as well as efforts to network at national, international, and pan-Arctic levels (e.g. Johnson *et al* 2018a, 2018b).



Recent advances in co-production of knowledge focus on the development of ‘actionable knowledge’ that supports the resilience of local people (Alessa *et al* 2016, Robards *et al* 2018). Successful co-production programs include capacity building for CS to empower future citizenry of coastal communities to fluidly move between both IK and scientific frames of mind. As indicators of ecosystem variability, marine mammals provide a nexus for sustained integration of CS and IK (e.g. George *et al* 2015, Loseto *et al* 2018a, 2018b). Combining these two approaches in novel and synergistic ways will foster more rapid adaptation to ecosystem shifts through coordinated decision-making that cross-weaves knowledge (e.g. Danielson *et al* 2010). Adopting a shared annual-cycle framework to support communication, especially on matters related to marine mammal ecology and health, seems a solid initial step to finding common ground to improve our understanding of an ecosystem important to all.

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