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SPECIAL FEATURE: ORIGINAL ARTICLE

Weaving Indigenous and Sustainability Sciences to Diversify Our Methods (WIS2DOM)

The role of Indigenous science and local knowledge in integrated observing systems: moving toward adaptive capacity indices and early warning systems

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Abstract Community-based observing networks (CBONs) use a set of human observers connected via a network to provide comprehensive data, through observations of a range of environmental variables. Invariably, these observers are Indigenous peoples whose intimacy with the land- and waterscape is high. Certain observers can recall events precisely, describe changes accurately, and place them in an appropriate social context. Each observer is akin to a sensor and, linked together, they form a robust and adaptive sensor array that constitutes the CBON. CBONs are able to monitor environmental changes as a consequence of changing ecological conditions (e.g., weather, sea state, sea ice, flora, and fauna) as well as anthropogenic activities (e.g., ship traffic, human behaviors, and infrastructure). Just like an instrumented array, CBONs can be tested and calibrated. However, unlike fixed instruments, they consist of intelligent actors who are much more capable of parsing information to better detect patterns (i.e., local knowledge for global understanding). CBONs rely on the inclusion of Indigenous science and local and traditional knowledge, and we advocate for their inclusion in observing networks globally. In this paper, we discuss the role of CBONs in monitoring environmental change in general, and their utility in developing a better understanding of coupled social-ecological systems and developing decision support both for local communities as well as regional management entities through adaptive capacity indices and risk assessment such as a community-based early warning system. The paper concludes that CBONs, through the practice of Indigenous science in partnership with academic/government scientists for the purpose of knowledge co-production, have the potential to greatly improve the way we monitor environmental change for the purpose of successful response and adaptation.

Keywords Adaptive capacity · Adaptive capacity indices · Arctic · Community-based early warning systems · Community-based observing networks · Indigenous knowledge · Indigenous science · Social-ecological systems

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Establishing community-based observing networks as Indigenous science

Detection and monitoring systems share several features in that they operate by acquiring, organizing, and storing data to determine patterns for the purpose of mounting appropriate responses (Balasubramaniyan et al. 1997). We articulate community-based observing networks (CBONs) as a distributed array of human sensors in communities throughout the Arctic who are able to observe their environments on a regular basis (Fig. 1). In this capacity, they are capable of detecting events that indicate that the environmental system is operating unusually (Dasgupta and Attoch-Okine 1997), that is, away from a normal, variable baseline. A common misconception among scientists is that

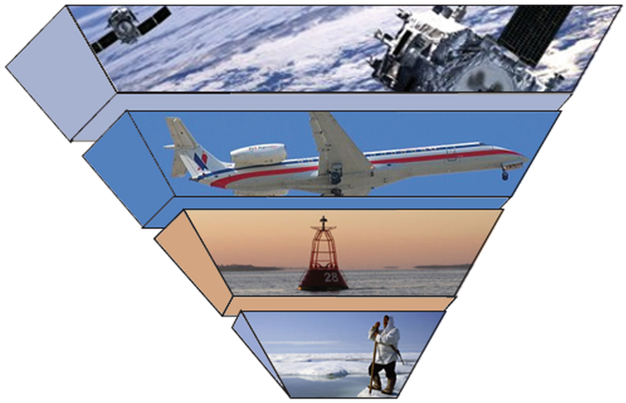

Fig. 1 Integrated suite and scales of observing networks ranging from satellite-based remote sensing, through aerial observations, to meteorological station/buoy-based platforms to community-based observing networks (CBONs)

CBONs are equivalent to citizen science (CS). While both engage humans, CBONs differ significantly from CS in several key ways: (a) they are networks of human observers with particular skills and exposure to land- and waterscapes who are able to make systematic observations, to assess trends, and to place those trends into cultural context, versus CS in which observers are taught to operate scientific instruments, but are not asked about their perceptions; (b) the data are collected in coordination with other instrumented networks and structured to augment the latter's spatiotemporal coverage (see Fig. 1); (c) CBONs are developed and designed as a partnership between academic/government and community practitioners where the variables of concern are collectively determined in the context of a specific purpose (e.g., developing an adaptive capacity index); (d) CBONs themselves are adaptive, allowing for the modification of the format or types of observations, if necessary; (e) observations occur in the context of other variables relative to historical patterns, maintained through local traditional knowledge versus CS which may operate with little context; (f) the community is a partner in the process of science, versus CS where the community or observer is contracted to carry out specific observations for flora and/or fauna counts; and (g) relative to f above, CBONs can help refine and evolve Western scientific questions.

Another refinement of terms used in the context of CBONs is that they primarily engage "traditional knowledge" (TK) which in and of itself does not entirely reflect the processes of locally based observation, interpretation, and application of findings (Johnson et al. 2015). The term "Indigenous science" more closely reflects the cumulative place-based observations of natural phenomena that includes humans and non-human others and tends to integrate and acknowledge humans as part of the natural world and its processes (Pierotti and Wildcat 2000). Such scientific knowledge is embedded in the local cultural milieu and does not distinguish between nature and culture (Berkes 1999). It also recognizes, develops, and applies appropriate technologies, while accepting their limits, to sustain resilient landscapes. We define resilient landscapes as earth surfaces and human communities which are actively designed and managed such that ecosystems, human uses (i.e., culture and economies), and the built environment act in concert to optimize energy use and maintain ecosystem services for a wide range of users, including non-human. Characteristics of Indigenous science include its development and application as a spatially localized and place-based practice, which, like hypothesis testing, uses systematic trial and error to resolve best practices or uncover relationships and its ability to compare current social-ecological dynamics to those which occurred historically (Snivley and Corsiglia 2000).

In this paper, we discuss the role of CBONs in monitoring environmental change in general and for Indigenous communities specifically, using examples from the Arctic, and their utility to better understand coupled social-ecological systems (SES) and for developing decision support for local communities through adaptive capacity indices and community-based early warning systems. SES reflect the ability to acquire, distribute, and sustain the acquisition of resources over long periods of time, through trade-offs that maintain a functional balance between social and ecological well-being (Alessa et al. 2009; Berkes et al. 2003; Folke et al. 2005). A key reason to adopt an SES perspective is to enhance *adaptive capacity* which we define as the ability of institutions, systems, and individuals to maintain and control this balance under changing environmental conditions such that they are *resilient*. Communities which lose functionality in both social and ecological systems are referred to as *vulnerable* and said to have poor adaptive capacity and may tend toward collapse or, more likely, experience deterioration in quality of life and overall function (Alessa et al. 2009). We note the caveat that CBONs are only one tool and approach, albeit valuable, in responding to environmental change and that their use and application cannot be considered in isolation from such issues as, for example, resource use and land use by industries, unsettled or dysfunctional land rights arrangements, and Indigenous community decision-making and priorities.

The arctic setting

The arctic region is recognized by numerous assessment reports (ABA 2013; AMAP 2007, 2013) as a broad region of biological productivity as well as a potentially rich source of fossil fuels and mineral resources (ABA 2013; AMAP 2007). More recently, it is also identified as a focal point for growing geopolitical interests (Huettmann 2012; Kovalev and Gainutdinova 2012; O'Rourke 2010) and industrial development (AMAP 2007; Kumpula et al. 2011). Changes in the Bering and Chukchi Seas as well as land-based development contributing to river-borne transfers into the shallow arctic basin can have direct impacts on biota, resulting in disturbances for subsistence-dependent communities and commercial fisheries (e.g., AMAP 2013; Grebmeier et al. 2006). Impacts from changes in the physical environment can flow through the lower trophic levels, thereby influencing upper trophic level species, where both indirect (bottom-up) and direct impacts (changing habitat) can occur (Hunt et al. 2002). In addition, communities increasingly rely on infrastructure and technologies which use fossil fuels, hinging the dynamics of many subsistence activities on their availability and costs (Poppel 2008). We currently have few data and little understanding on how these components are changing and what the collective, cumulative, and interactive consequences are (Kumpula et al. 2011). In other words, we know little about what the social implications of specific biophysical changes are. It is also critical to develop an "early warning system" for enhancing management approaches toward a proactive, versus reactive, set of responses to assist Indigenous communities.

Indigenous science and local traditional knowledge: key components of monitoring social-ecological change

Humans inhabiting northern regions for millennia have developed an exceptional understanding of the environment needed for their survival (Kliskey et al. 2009; Krupnik and Jolly 2002; Usher 2000). The collective memory of humans in the Arctic holds information about past environmental variability that extends beyond the knowledge acquired by Western science in recent decades, which tends to be deeply rooted in past colonial practices (Berkes 1999; Johnson and Murton 2007; Smith 2012). This knowledge makes arctic residents, and especially Indigenous peoples, capable of observing changes and trends with a comprehension of temporal patterns that no other sensors can replicate (Fig. 1). Moreover, sub-populations of arctic residents, in particular those who have had extensive land-schooling (e.g., elders, hunters), often retain long memories of environmental variability and change (Alessa et al. 2007; Seyfrit and Hamilton 1997). The knowledge held within the memory of elders has proven to be one of the most valuable sources of information for observing as it provides the base upon which future observations are made and analyzed (Galloway McLean 2010; Nakashima et al. 2012). Humans, as sensors, are a valid independent source of information that, when appropriate methods of data collection are used, are capable of providing insight into the questions of arctic system change, including questions that deal with seasonality (Krupnik and Jolly 2002).

Indigenous science methods have rarely been quantified because they are implicitly a set of holistic practices that embed the user (person) in the local SES (Mahoney et al. 2009), from which there is no separation of Indigenous identity and place (Mustonen 2012, 2014). However, in general they can be described in much the same way that the Western scientific method can: a body of knowledge is used as the foundation for a starting point (e.g., developing a hypothesis) as a process of creating order from disorder (Berkes 1999). This body of knowledge, equivalent to the peer-reviewed literature, consists of a continuous living awareness of the conditions in which the community existed in the past. This awareness spans multiple generations and is augmented by stories, dances, art, and customs, including what is taboo (Cajete 2000). It is also intrinsically embedded in Indigenous languages through which ideas and ways of knowing are transmitted (Harrison 2008). Collectively, this is referred to as traditional knowledge and oral histories. The approaches used by an individual, for example, a marine mammal hunter, to make decisions on a given day as well as for the short- and longer-term future are as sophisticated and systematic as those in Western science: data obtained through observation are weighed against the body of knowledge (traditional knowledge). The data are analyzed, and decisions are made regarding whether or not to go hunting, the time of day to go hunting, the best route to take and the likelihood of finding, for example, walrus in any given locale (MacDonald 1998; Oozeva et al. 2004). We propose that observations made through Indigenous science practitioners provide critical insight because no other data are placed in a comparative context (Fidel et al. 2014; Huntington et al. 2013a, b). Criticisms exist on the validity and precision of such data because it is generally accepted that humans perceive the world around them through highly variable and subjective filters (Humphreys 2000). However, Indigenous scientists are particularly adept at making accurate observations, while at the same time being the recipients and holders of a collective cultural body of knowledge (e.g., Berkes 1999; El-Hani and Badeira 2008; Oozeva et al. 2004). The act of residing, surviving, and thriving in a place means that the resident must "know" their environment in such a way as to repeatedly have a high likelihood of acquiring necessary resources, whether they are physical or not, on a regular basis. The consequence of failure can be serious—sickness, suffering, and death (Alessa 2009). In other words, the stakes in Indigenous science can be high to ward off unnecessary danger, and hence, it should come as no surprise that there exists a high level of precision (MacDonald 1998). Indigenous science requires something that, with few exceptions, Western science has failed to accomplish: long periods of observation in the same place and the transmission of these observations to others in that place so that they can use them practically and often, from a young age (Mustonen and Lehtinen 2013). In our opinion, Indigenous science is the original sustainability science, or more specifically social-ecological system science.

Just as biological diversity increases the adaptive capacity of ecosystems, a diversity of knowledge will likely prove essential to the adaptive capacity of communities as it provides insights into well-being and vulnerability from a cultural perspective that may otherwise be absent from modern scientific understanding (Hovelsrud et al. 2007; Turnbull 2000; Larry Mercuieff, personal communication, Dec. 2014). Indeed, peoples of the Bering Sea, for example, have exhibited high adaptive capacity for many generations by sharing information through language, song, art, dance, and prayer (Fienup-Riordan et al. 2013, Huntington et al. 2013a, Krupnik and Jolly 2002).

One priority across Indigenous communities is to better understand sources of vulnerability and ways they can become more resilient through effective adaptation strategies (Magga et al. 2011). Supporting indigenous adaptation processes is a priority of the Indigenous Peoples' Biocultural Climate Change Assessment Initiative (IPBCCA) and is also evident in the 'Anchorage Declaration' (2009), The Declaration of the Indigenous Peoples of the World to the UNFCCC COP 17 International Indigenous Peoples' Forum on Climate Change, Durban, South Africa (2011), and numerous other declarations. Importantly, in these documents, adaptation is discussed as a process coming from within indigenous cultures, not outside. To this end, Indigenous observers, as part of a CBON, are a first front in being able to detect change in the context of, and for the purpose of, appropriate response.

CBONs are collaboratively developed, so the communities have direct involvement in the design and function of the networks ensuring that the type of data collected is relevant and the methods are culturally appropriate, making CBONs more sustainable than other monitoring networks (Danielsen et al. 2005). This is especially critical since the current SES baseline that constitutes arctic communities is poorly characterized and the consequences of different types of change are relatively unknown, greatly limiting the ability of communities, industry, and agencies to develop desired, equitable, and sustainable development, mitigation, and response plans (Ford and Pearce 2012). CBONs may operate somewhat differently depending on the design and interest of individual communities, though all are essentially a network of human sensors that better allow the Arctic to be observed as an SES using Indigenous science since they simultaneously acquire data at local scales in their societal contexts (Hovelsrud et al. 2007). That is:

(a) what changes are occurring
(b) why these changes are of concern to a community
(c) what type of response is the community planning or initiating
(d) what are the consequences to/trade-offs for different outcomes of change

Such types of observations are critical for advancing knowledge of a changing arctic SES as well as for enabling communities to become more resilient in place through effective adaptation and response strategies using the idea of "security," which reflects the spectrum of trade-offs and their consequences (Alessa et al. 2008a).

Benefits to communities

We often speak of Indigenous science and monitoring environmental change from a "what can it do for advancing Western science" perspective. However, the inclusion of Indigenous science in observing networks also benefits communities. It allows them to define which observation should be made, that is, it allows them to make observations that are relevant to their daily lives (e.g., weather and ocean conditions which affect marine mammal hunting) (Tremblay et al. 2008). It ensures that Indigenous perspectives and contexts are included in the development of policies by exerting bottom-up local control, versus centralized perceptions (Fidel et al. 2014). For example, information provided by the long-standing Arctic Borderlands Ecological Knowledge Cooperative, which includes interviews with local hunters, is incorporated in the Caribou Harvest Management Plan (Russell et al. 2013) supporting fair management of a resource that communities in the area are dependent on. Another international CBON, the Community-based Observing Network for Adaptation and Security (CONAS, and its predecessor the Bering Sea Sub-Network—BSSN), documents important harvest areas in the Bering Strait region (Fidel et al. 2012) and comprises eight Alaskan and Russian Far East communities—Aleut, Central Yup'ik, Chukchi, Koryak, and Siberian Yup'ik. This information was used by local leaders in the US Coast Guards Port Access Route Study public meetings and leads to a greater appreciation of not only the extensive areas used by St. Lawrence Island communities, but the potential for conflict between hunters and commercial vessel traffic.

The Inuvialuit Harvest Study (Canada) also works to document subsistence harvests in order to better protect harvest rights and pursue compensation for harvests affected by development (IHS 2003). Lastly, the Snow-Change project in northern Eurasia that documents Indigenous observations of climate change maintains a website that functions as an information portal and capacity building resource for communities and other Arctic stakeholders (Mustonen 2002). Including Indigenous science in CBONs recognizes the role of local communities as 'first responders' and, as such, identifies what tangible resources, financial or otherwise, are needed to equip them to be effective in a range of responses to either acute (i.e., an oil spill or shipwreck) or gradual change. It recognizes subsistence ways of life as critical in the discussions of what "security" entails (e.g., climate; also see section on community-based early warning systems below). It has the potential to bring resources to communities on their own terms, in other words, resources that are truly needed rather than those which are perceived to be needed by a centralized governance structure. Recognizing Indigenous science as critical to observation networks finally acknowledges and validates that this type of information is just as valuable as Western science data. And importantly, it is one way for Indigenous communities to regain control and ownership of their knowledge that has historically been appropriated through centuries of colonization and reintroduced as anecdotes from non-Western 'others' (Smith 2012). Making these histories visible can provide a healing power to the communities (Mustonen 2012). Finally, it minimizes the disaggregation and loss of Indigenous knowledge by maintaining the role of Indigenous scientists in linking local knowledge to global science.

What do we need to observe in order to adapt?

The variables that are currently observed are primarily selected based on current Western science ecological theory: (1) stressors can be changing climate (e.g., temperature, water availability, light quality), chemical climate (e.g., carbon dioxide, methane, ozone and nitrogen deposition, black carbon, dust, aerosols), and land use (e.g., overgrazing, deforestation, agriculture); (2) effects can include social (e.g., changes in land use, population, peoples' perceptions of changes in natural resources, how risk is perceived, how decisions for societal benefit are made) and ecological (e.g., changes in animal and fish populations, plant communities, net primary productivity, fertility, rising sea level) indicators; and (3) have dynamic negative and positive feedbacks (Grebmeier et al. 2006; Hunt et al. 2002). Yet, *once perturbed, many processes do not necessarily follow linear or historic trends, become reorganized, and self-establish new states making adaptation difficult*. Expected climatic changes can and will challenge communities' current level of resilience, emphasizing the need to increase reflexive learning through continuous observation and data collection (Amundsen 2012). A stronger approach entails the development of the observing system, the data protocols, and the selection of variables by the community, that is, co-production between Indigenous science and Western science. To address this complexity, a set of diagnostic tools based on using socially relevant indicators, called adaptive capacity indices (ACIs), are proposed (see ACI section below).

Indeed, one of the most urgent needs that can be filled by CBONs as part of the suite of integrated observatories is to support efficient and effective adaptation to environmental change. In order to better address the environmental questions put forward by society, observations that are placed in a clear set of social contexts must be better integrated into our current observatory models (Ford and Pearce 2012). In northern latitudes, an integrated Arctic observing network has been of significant interest for sometime (Polar Research Board 2007). Furthermore, there are efforts underway already to advance such a network, for example, through the Interagency Artic Research Policy Committee (IARPC) and the Sustaining Arctic Observing Networks (SAON) led by the Arctic Council and the International Arctic Science Committee (IASC). The Alaska Experimental Program to Stimulate Competitive Research (EPSCoR) has also invested heavily in observing and monitoring networks with an emphasis on incorporating Indigenous science.

There are two primary challenges in linking social and environmental data together—determining appropriate scale and interoperability capability, that is, between Western and Indigenous science. This is where Indigenous science through CBONs is best applied. For example, the US Global Change Research Program's National Climate Assessment (NCA), is written to support broad regional understanding, but is not well aligned to local ecological phenomena or to the level of social context where risk is evaluated and decisions are made to sustain livelihoods (Tilmes et al. 2012). In almost all biophysical arctic observing networks, local social context is absent, making it difficult for communities and agencies to make linkages across complex management scenarios (e.g., across agency and political jurisdictions). In addition, management of indigenous community data requires special considerations (Pulsifer et al. 2012). Early and ongoing dialog (meaningful communication) with communities can address emerging issues of data management to ensure the handling of data is supportive of the language and culture in which it was gathered and benefits participating communities (Grimwood et al. 2012; Pearce et al. 2009). It is important to recognize that some information gathered to support adaptation may be sensitive, so community consent must be obtained before any information is released, often through discussions with the local tribal leadership. This means that not all information gathered in a community will be made publically available. Indigenous science, and co-production of knowledge with communities, offers a solution at the local scale (Armitage et al. 2011; Nakashima et al. 2012) and, most importantly, is absolutely necessary for the development of adaptive capacity indices (ACIs).

Adaptive capacity

A key question within arctic observing networks is whether it is possible to identify the characteristics of communities that influence their propensity or ability to adapt. The IPCC identified six broad classes of determinants of adaptive capacity in IPCC 2001 including (1) economic resources, (2) technology, (3) information and skills, (4) infrastructure, (5) institutions, and (6) equity. Then in IPCC 2007, IPCC identified eight general categories of determinants of adaptive capacity, namely (1) range of technology options to reduce emissions, (2) range of policy instruments to adopt these options, (3) the structure of critical institution and allocation of decision-making authorities, (4) availability and distribution of resources to mitigate impacts, (5) the stock of human capital including education and personal security, (6) stock of social capital including the definition of property rights, (7) access to risk-spreading processes, and (8) ability of decision-makers to manage information, including perceived credibility of information and the decision-makers themselves. These are not standalone categories, as there is overlap and relationships among them. For example, technology may be required to access certain risk-spreading measures. IPCC (2013) states with high confidence that "Adaptation planning and implementation … are contingent on societal values, objectives, and risk perceptions. Recognition of diverse interests, circumstances, social-cultural contexts, and expectations can benefit decision-making processes. Indigenous, local, and traditional knowledge systems and practices … are a major resource for adapting to climate change … Integrating such forms of knowledge with existing practices increases the effectiveness of adaptation." This recognizes the importance of community-level approaches to adaptation.

In the Bering Sea region, based on the CONAS network, relevant determinants of adaptive capacity include all of these, but they vary locally in importance and the processes in which they emerge. Economic wealth (resources), while important, is often substituted for natural wealth (resources). Through subsistence activities, including hunting, fishing, and gathering, communities are able to withstand economic hardship despite the transition to a cash economy, and maximize personal food security (Gerlach and Loring 2013). Access to technology (including communication technology) maximizes harvesting efficiency, expands the areas people can harvest from, and allows rural residents to be part of decision-making and global processes. Institutions that allow for greater equity including local voice, and power sharing, as found in some co-management agreements are critically important in the Bering Sea region (e.g., the Alaska Eskimo Whaling Commission). As such, when decision-making authority is allocated to include vulnerable populations, their adaptive capacity is increased. Traditional risk-spreading processes include food sharing which targets the most vulnerable subsets of a population (elders, single mothers). Risk spreading is also manifest in the flexibility to harvest 'new' species, use new harvest methods, and/or to change the location of a harvest, which is practiced beyond the Bering Sea and in Eurasia as well (Magga et al. 2011). Traditional information management, and credibility of that information, differs from modern/Western practices. Science that affects a community is often not deemed credible, especially if it ignores traditional knowledge and wisdom. Similarly, the decision-making processes and the decision-makers themselves are often not deemed credible when they do not consider community concerns. We have also found that additional indicators are needed: level of protection for key subsistence harvests and harvest areas, willingness to substitute one resource for another, intactness of traditional knowledge regarding land- and seascapes, and ability to preserve key cultural elements while viewing globalization as an opportunity.

Adaptive capacity indices

To improve decision-making, communities around the world are seeking tangible and systematic approaches to guide adaptation through the development of tools (Juhola et al. 2012; Valdivia et al. 2010) called adaptive capacity indices (Yohe and Tol 2002). We define ACIs as: *a systematic synthesis of key social, biological, and physical indicators that allow for targeted yet coordinated responses to occur under changing conditions for the purpose of sustaining desired livelihoods and well-being.* Further, we emphasize that ACIs must be community based. In other words, they are developed through the participation and leadership of the users in partnership with scientists and resource managers (Fig. 2).

Historically, ACIs have been approached using theory-driven indicators that combine primarily economic and ecological information to provide an adaptive management

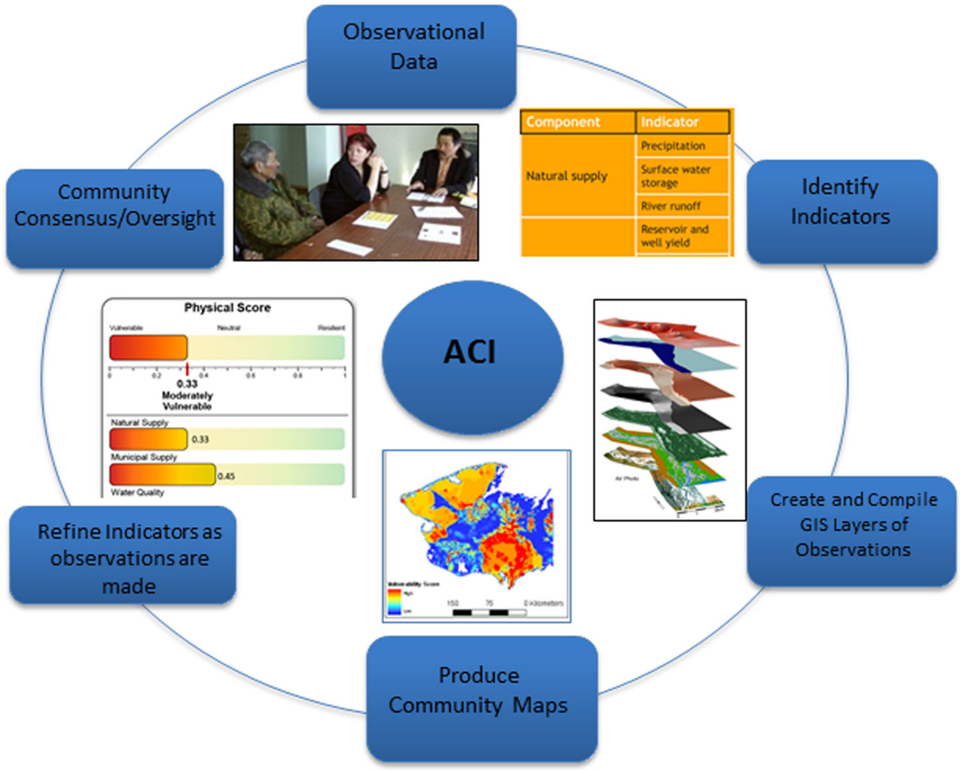

Fig. 2 Process of developing adaptive capacity indices (ACIs) through partnerships with communities on the ground and spatial visualization software such as GIS

tool (UNISDR 2005). Most ACIs worldwide are at the country-level scale and are difficult to apply to individual communities or regions seeking to develop adaptation strategies as an iterative, ongoing process (Vincent 2007). Very few, to date, have been developed from a community-engagement/partnership approach incorporating indicators that are central to livelihoods and well-being or that adhere to Indigenous science (Brooks et al. 2005). No ACIs currently exist for the Arctic. In order to incorporate observations from CBONs into ACIs and 'early warning systems,' we must ask the following questions in the context of our current observation networks with the goal of including Indigenous science through CBONs:

1. What are we observing and why? Are the scales of these observations applicable to the scales of livelihoods?
2. How are observed data accessed and used, and by whom?
3. How well do observations on the ground map to scientifically informed indicators of adaptive capacity?

Indigenous science more readily facilitates a "people-centered" approach (Karl 2002) where the community has strong buy-in into the development and management of ACIs, so responses to environmental changes across social scales can be made in sufficient time to ameliorate real or perceived environmental threats (Alessa et al. 2008a, b). The response window is designed to reduce the possibility of personal harm, erosion of well-being, damage to valued ecosystems, and loss of livelihood. It also provides communities, practitioners, and decision-makers conducting resource management with *advanced information of perceived risks that can be readily translated into prevention, mitigation, preparedness, and response actions.* Such a definition sets the stage for using ACIs to help develop arctic early warning systems (EWS, see section below). While community-based ACIs are based on community needs, they must be balanced with the inclusion of the best available science that articulates the trade-offs at various scales (Brooks et al. 2005). Trade-offs have not been historically considered in the adaptation literature in a robust sense (IOM 2013).

Frequently, when Indigenous people discuss adaptation, it is accompanied by apprehension. Historically, adaptation often meant modifying one's own ways to fit another colonizing, dominant culture (Olia Sutton, personal communication, Apr. 2014). In the documents reviewed from Indigenous-lead organizations, adaptation to climate change is discussed as coming from within their Indigenous culture. IPCCA supports 'indigenous adaptation processes,' while the Anchorage 2009 declaration demands recognition of traditional knowledge and practices in developing strategies to address climate change. Adaptation in Indigenous communities must occur on their terms in order to better preserve well-being, language, and culture. This includes an assessment of the trade-offs and values from a local, indigenous perspective. This could be accomplished by creating ACIs in part with data obtained through CBONs and that would ensure Indigenous perspectives are not ignored in regional, or national adaptation efforts (Fig. 3). By partnering with scientists, sound evidence on the impacts of climate change and desired responses may be documented, which could support advocacy for certain policies or help secure access to funds for adaptation response and planning (Gray et al. 2014). Supporting organizations, such as the Arctic Council, are integral to the development of community-based ACIs because they can facilitate active and meaningful participation of community members, for example, through the recently developed Arctic Adaptation Exchange Portal (AAEP—Arctic Council SDWG 2013). The primary goal of a local-level ACI is to support the community's decision-making regarding adaptation. While the information may be interesting to an outsider, it has the greatest usefulness within the community. Another key facet of both adaptation and ACIs is being able to respond—data from CBONs that inform ACIs can also be organized to support early warning systems as a responsive strategy to environmental change (Fig. 3).

Community-based observing as an early warning system

In the United Nations International Strategy for Disaster Reduction (UNISDR) terminology, the early warning system is the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities, and organizations threatened by hazards to take necessary preparedness measures and act appropriately in sufficient time to reduce the possibility of harms or losses. This definition encompasses the range of factors necessary to achieve timely warnings for effective response. A people-centered early warning system necessarily comprises four key elements: (1) knowledge of the risks; (2) monitoring, analysis, and forecasting of the hazards; (3) communication or dissemination of alerts and warnings; and (4) local capacities to respond to the warnings received. The expression "end-to-end warning system," also from UNISDR terminology, emphasizes that early warning systems need to span all steps from detection of critical changes to community response. Reliable early warning systems developed globally have been instrumental in saving lives and protecting assets and livelihoods. However, they have not yet been developed in the arctic for the purpose of anticipating changes that require adaptation through targeted responses.

An emphasis on identifying emerging threats as a complex suite of emergent processes in the Arctic is a growing desire for investments in observing networks, modeling, research, and decision-support tools (Bring and Destouni 2013; Polar Research Board 2007). Federal agencies annually invest billions of dollars to support current observation systems (US Department of State 2014); state, local, and private-sector entities also have established significant observing capacities (Berkes 2009). Many of these observing systems provide significant value and are meeting critical needs relevant to specific agencies but do not incorporate Indigenous science and do not serve rural communities (Johnson et al. 2015).

Focusing on the relationships between current and emerging threats requires a more concerted connection with communities on the ground. In a continual feedback loop, communities are asked to prioritize needs so as to develop indicators for ACIs that can be used to develop a community-based early warning system. The information derived from observing networks forms the basis for continual monitoring of system changes. A community-based early warning system is one that is developed, managed, and maintained by the community itself. It is based on a "people-centered" approach that empowers individuals and communities threatened by rapid and/or undesired changes to act in sufficient time and in an appropriate manner to reduce the possibility of personal harm, loss of well-being, damage to valued ecosystems, and loss of livelihood. It provides communities, practitioners, and organizations involved in resource management with advance information of risks that can be readily translated into prevention, preparedness, and response actions. Community-based early warning systems can help to reduce economic losses by allowing people to better protect their assets, livelihoods, and ways of life (Pineda 2015). The role of supporting organizations, including governmental, will be to facilitate active and meaningful participation of all community members. Ultimately, the EWS will be owned by the community for them to use to capitalize on opportunities and avoid or mitigate adverse events. The term 'early warning' is used in many fields to describe the provision of information on any given emerging undesired circumstance where that information can enable action in advance to reduce acute risks later on. Early warning systems exist for natural geophysical and biological hazards, complex socio-political emergencies, industrial hazards, personal health risks, and many other related hazards (e.g., Huggel et al. 2012) but few exist that are driven by indigenous communities for the purpose of optimizing their resilience. The significance of effective early warning systems lies in the recognition of its benefits by the members of the

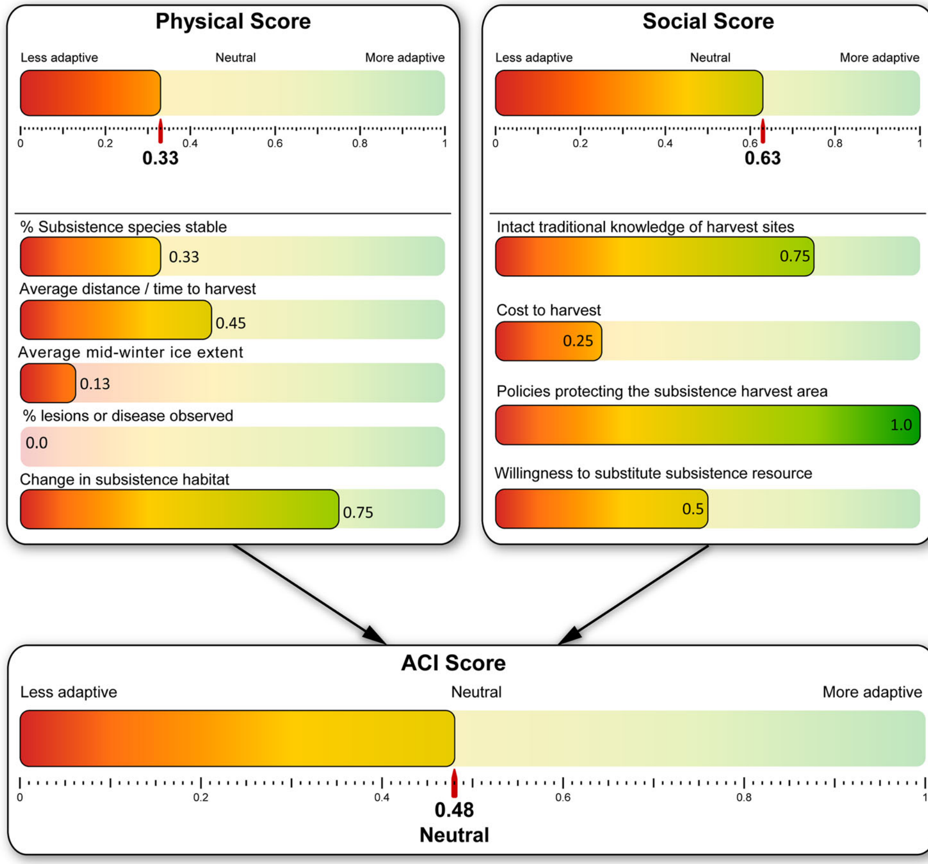

Fig. 3 An example of a results dashboard from an adaptive capacity index for freshwater for a community in western Alaska

community itself: the community must accept responsibility for their own futures. The incorporation of more Indigenous knowledge in cataloging early warning signs will increase community-level response and action (Galloway McLean 2010).

The Arctic provides a useful test bed for exploring these issues because this region is confronting more rapid environmental change than many other parts of the world (Ford and Pearce 2012) and provides a useful lens for considering and tackling the challenges associated with integration and interoperability between observation networks, ACIs and EWS. It is important to connect information on emerging threats with improved understanding of which assets and resources are most vulnerable in order to better inform adaptation planning (Pearce et al. 2011). Thus, an essential first step is to develop a shared vision of the desired early warning system, with buy-in and incorporation of Indigenous science methods and approaches. Lessons from existing collaborative management efforts suggest that diverse modes of communication, deliberation, and social interaction are important factors in knowledge co-production (Armitage et al. 2009, 2011) for successful community-based early warning systems.

Conclusion

Community-based observing networks are a way to systematically observe place-based environmental change and place it in a cultural and temporal context. CONAS, in the Bering Sea, is an example of an active CBON that is contributing to the development of ACIs and could potentially anchor a community-based early warning system. In these endeavors, Indigenous science provides an essential set of knowledge in the context of community needs and histories that extends sustainability science to social-ecological system science in order to help guide social adaptation.

We conclude that CBONs could be used as a novel approach for achieving environmental security, following the UN Millennium Project (United Nations 2009), which adopts a focus that is broadened beyond security concerns in the traditional sense, to include both short-term impacts and longer-term outcomes such as food and water security, as well as overall community well-being (United Nations 2009). Environmental security is used as an integrating concept, because it offers a more powerful and inclusive perspective for identifying vulnerabilities, planning adaptive responses, and evaluating outcomes than do ecological sustainability, conservation, or health (individually). Policy makers urgently need technical information that can guide responsible arctic policies given the political will to open shipping routes and enhance development in the north (Kelly and Ljubicic 2012). Locally and regionally scaled vulnerability assessments and adaptation plans remain constrained by a lack of high-quality, locally relevant baseline data about assets such as biota, water, and infrastructure and by a lack of decision-support tools that integrate with the best available sociological and climatic data and projections (Shaw et al. 2008). Bridging biophysical, ecological, and socioeconomic information at appropriate scales for management, decision-making and adaptation for a cross-scale analysis is paramount for sustainable Indigenous communities in the face of these environmental changes (West and Hovelsrud 2010). CBONs allow environmental change data to be used, through ACIs and even community-based early warning systems, in a timely manner by individuals and communities at risk, thus enabling them to take appropriate action.

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