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Detecting and Coping with Disruptive Shocks in Arctic Marine Systems: A Resilience Approach to Place and People

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Abstract It seems inevitable that the ongoing and rapid changes in the physical environment of the marine Arctic will push components of the region's existing social-ecological systems—small and large—beyond tipping points and into new regimes. Ongoing changes include warming, freshening, acidification, and alterations to food web structure. In anticipation we pose three distinct but interrelated challenges: (1) to explore existing connectivities within components of the marine system; (2) to seek indicators (if they exist) of approaching regime change through observation and modeling; and (3) to build functional resilience into existing systems through adaptation-oriented policy and to have in hand transformative options when tipping points are crossed and new development trajectories are required. Each of the above challenges is scale dependent, and each requires a much deeper understanding than we currently have of connectivity within existing systems and their response to external forcing. Here, we argue from a global perspective the need to understand the Arctic's role in an increasingly nonlinear world; then describe emerging evidence from new observations on the connectivity of processes and system components from the Canada Basin and subarctic seas surrounding northern North America; and finally posit an approach founded in "resilience thinking" to allow northern residents living in small coastal communities to participate in the observation, adaption and—if necessary—transformation of the social-ecological system with which they live.

Keywords Arctic Ocean · Climate change · Biogeochemical systems · Resilience · Regime shifts

INTRODUCTION

Although it has long been suspected that the high latitudes will experience the fastest and largest responses to climate forcing, the changes in the physical biogeochemical systems actually observed this past decade years have far outpaced the climate model predictions used in the 4th IPCC report of 2007. The Arctic Ocean is changing extraordinarily fast, and to fully understand why requires that we examine its two-way interconnection with its neighboring subarctic Pacific and Atlantic domains and their joint roles in global-scale hydrological and thermohaline cycles. Humans, too, are inextricably linked to the changes we are observing today, both as drivers of change through our greenhouse gas emissions and as the very populations that need to anticipate and prepare for the uncertainties that lie ahead.

The high Arctic is remote, sparsely populated and currently a minor player in the global economy. So why go there to conduct research on the dynamics of complex systems and launch experiments in adaptive management? This article first argues that by looking at and understanding the rapid and nonlinear changes that are taking place in the Arctic, we can develop powerful tools to manage and cope with emerging global-scale issues ("Why is the Arctic important" section). Results from the International Polar Year (IPY)—Canada's Three Oceans project (C3O) and the Canada/US Joint Ocean Ice Study (JOIS) are next presented as a case study to demonstrate the essential connectivities among the Arctic Ocean and subarctic oceans and to explore how changes within this coupled physical system are now impacting marine life and ecosystems ("A system in transition: the Canada Basin of the Arctic Ocean" section). These challenges to stability suggest cross-scale actions that will both aid in the advance detection of regime shifts and build resilience within Northern communities coping with rapid change ("A resilience approach to social adaptation and action" and "Detection" sections). The system is complex, the clock is ticking, and we are dangerously late out of the gate; original data across multiple scales are sorely needed now ("Outlook" section).

WHY IS THE ARCTIC IMPORTANT?

The following discussion illustrates the physical and social importance of understanding tipping points within Arctic systems. First, although the evidence is still somewhat anecdotal, a pattern seems to be emerging around the world of increased nonlinearity in complex-adaptive systems critical to human well-being. Financial, political, food, security, and energy systems appear to be experiencing rising incidence of sudden and severe shifts in core behaviors, sometimes even leading to system collapse. Such events may be revealing a specific causal architecture that could characterize the birth and progression of future global crises, in which relatively small crises that originate within particular systems or geographical regions interact and then propagate across system boundaries, ultimately expanding to involve global systems.

Second, changes to the Arctic will have serious consequences to the global economy and society. For example, a preliminary economic valuation of the cost in terms of lost climate services from the decrease of Arctic sea ice by the Pew Environment Centre estimates that albedo changes and accelerating methane emissions are equivalent to the release of approximately 3 000 million metric tonnes of CO_2 (Goodstein et al. 2010). In economic terms, they estimate costs due to climate change (warmer temperatures) in the range of $62–371 thousand million (USD) in 2010. In 2050, this number could rise to $2.4–24.1 trillion and over the next century, the climate change effects in the Arctic could cost as much as $4.9–91.2 trillion. These costs will put significant strain on global economies—even the mid-range estimates are comparable to the combined gross domestic product of the UK, Russia, and Germany. Similarly, in a report issued at the Cancún climate conference in December, 2010, Munich RE, a global reinsurance company, reported (Munich 2010) that "Aggregate losses from weather-related natural catastrophes since 1980 now total US $1 600 thousand million, insured losses increasing on average by 11% per year." Munich RE relates these business risks directly to global warming: "the growing number of weather-related catastrophes can only be explained by climate change." Given the rapid shifts occurring in the Arctic, and the likely connections between Arctic and global climate systems, these costs may be traced back, in significant part, to changes in the Arctic.

Third, the Arctic is indeed a harbinger of change—the nonlinear climate future is evident there now, and significant changes to the climate system are occurring faster than anticipated in the last IPCC (2007) report. Such change is occurring on many visible fronts: ocean warming; sea-ice retreat and thinning; permafrost thawing and greenhouse gas release; sea level rise and coastal erosion; altered wind fields and storms tracks; increased river discharge; shifting ocean fronts and ecological barriers; invasion of non-indigenous species; increased hypoxia; ocean acidification; and potential impacts on the thermohaline circulation (see Carmack and McLaughlin 2011, for key references). None of the above elements act independently; they are interacting components of a complex system.

Fourth, the Arctic is thus now a creative frontier; a potential test bed for creative responses and adaptive policies resilient to shock and change. From this emerges a global invitation: *come to the Arctic* for information, ideas, knowledge, and experiments involving the early detection of and adaptation to climate change and inevitable tipping points that follow; a place to conduct adaptive experiments to develop the critical capacity for management and responsible governance in a nonlinear natural world. For most people, the Arctic is an empty zone, and many have great trouble imagining that it could be of any great importance to global affairs. But the Arctic is one of a number of places (including the Amazon Basin) now considered to be near a climate or management-related tipping point, with global-scale consequences. Together with humankind's response, adaptive or transformative, such places will play a central role in the evolution of human civilization.

A SYSTEM IN TRANSITION: THE CANADA BASIN OF THE ARCTIC OCEAN

If the Arctic is a harbinger of climate change, then the Canada Basin can be considered as its ground zero. During the past decade the astounding the effects of the astounding decreases in both ice extent and multi-year ice, are evident throughout the underlying water column. Following Lenton et al. (2008) we consider the Beaufort Gyre of the Canada Basin as a so-called tipping element; that is, as a subset of the Earth System which exhibits a strongly nonlinear response to climate forcing. Internal to this so-defined element are the specific physical and geochemical processes that are tightly coupled as a complex-adaptive system. But the element is also driven by external forcing from the atmosphere and adjacent subarctic oceans. As shown below, the combination of internal dynamics and external forcing sets the Canada Basin as a potential candidate for regime shift.

Observations carried out during the C3O and JOIS studies are shown in Fig. 1a and a schematic of the Arctic Ocean and adjacent subarctic oceans are shown in Fig. 1b. While the Polar Vortex and much of the Arctic atmosphere are characterized by a counter-clockwise circulation, the

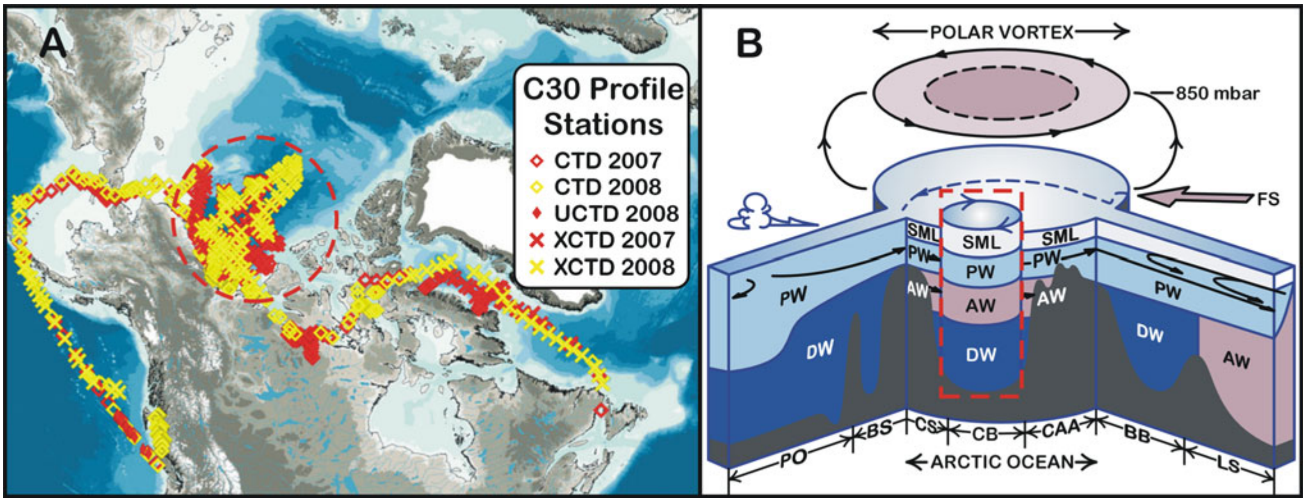

Fig. 1 **a** Map of the study area and location of stations occupied by the CCGS Louis S. St-Laurent and CCGS Sir Wilfrid Laurier in 2007 and 2008 as part of the IPY—C3O project and the Canada/USA JOIS. The term CTD denotes a station at which a Conductivity–Temperature–Depth profiler was deployed, while XCTD denotes a station at which an expendable Conductivity–Temperature–Depth probe was deployed. The location of the Canada Basin and Beaufort Gyre is marked by the *dotted circle*; and **b** schematic view of the C3O/JOIS area showing the water mass structure of the Arctic Ocean, the exchange of waters with the adjoining subarctic Pacific and subarctic Atlantic Oceans and the overlying atmosphere. *PO* Pacific Ocean, *BS* Bering sea, *CS* Chukchi sea, *CB* Canada Basin, *CAA* Canadian Arctic archipelago, *BB* Baffin bay, *LS* Labrador sea, *PW* Pacific water, *AW* Atlantic water, *SML* surface mixed layer, *DW* deep water, *FS* Fram strait. BS and CS are joined through Bering Strait. The location of the Beaufort Gyre is marked by the *red border*

mean wind field in the Canada Basin is dominated by the clockwise Beaufort High. This wind field in turn drives the clockwise Beaufort Gyre which acts to collect and stack water masses of widely diverse origins vertically, forming a layer-cake of downward increasing densities (Fig. 2). Consequently, interpretations of physical and biogeochemical change within the water column must consider external forcing and large-scale advection of water masses—and their unique physical and biogeochemical properties—from adjoining seas before drawing conclusions about complex changes internal to the system.

Rapid change of systems within the Canada Basin has been observed in the first decade of the twenty-first century (Carmack and McLaughlin 2011; Dickson 2011) (Fig. 3). Connected to the rapid retreat and thinning of sea ice (Kwok et al. 2009) the water column has warmed at depths exceeding 800 m owing to warmer waters entering from the Atlantic (McLaughlin et al. 2009) and Pacific Oceans (Woodgate et al. 2010) (Fig. 3a). Change in the velocity of ice drift is also drawing more warm Pacific water into the western portion of the Beaufort Gyre (Shimada et al. 2006). Increased ice melt combined with wind-driven surface convergence have substantially freshened the upper ocean (Proshutinsky et al. 2009). This freshening, combined with sea-ice retreat and decreased albedo, has allowed formation of a near surface temperature maximum below the freshened surface in the upper 10–20 m (Jackson et al. 2010; Toole et al. 2010) (Fig. 3b). Spin-up of the gyre, associated with greater ice drift velocities (Yang 2009) is deepening the chlorophyll maximum layer, which forms annually in the halocline atop the Pacific waters (McLaughlin and Carmack 2010) (Fig. 3c). The increase in stratification caused by upper layer freshening and ice melt constrains the upward flux of nutrients; this reduction in nutrients, nitrate in particular, has affected the food web from 2003 to 2008 as shown by a shift in phytoplankton cell size that favors the smaller picoplankton over nanoplankton (Li et al. 2009) (Fig. 3d). This transition to smaller phytoplankton cells may subsequently impact energy flow pathways through the entire food web as well as the sequestering of carbon to the deep ocean (Barber 2007); indeed, Parsons and Lalli (2002) hypothesized such a shift would favor a low energy system characterized by jellyfish blooms as opposed to a high energy food web characterized by fish and marine mammals. While it is prudent to note that our current lack of understanding of complex marine food webs allows us at best to posit of plausible scenarios, and not forecast, the stakes are sufficiently high to warrant our most serious attention.

The ecosystem has been further modified by sea-ice reduction and the significant input of sea-ice meltwater because of their influence on the carbonate system. Global ocean acidification has been exacerbated in the Canada Basin by the build-up of sea-ice meltwater. Meltwater has low values of carbonate ions that affect the solubility of calcium carbonate and the ability of marine calcifying organisms to produce calcium carbonate shells or exoskeletons. This solubility shifted in 2008 as surface water tipped from an environment that enabled the formation of shells to one in which dissolution occurs (Yamamoto-Kawai et al. 2009) (Fig. 3e). This change particularly affects

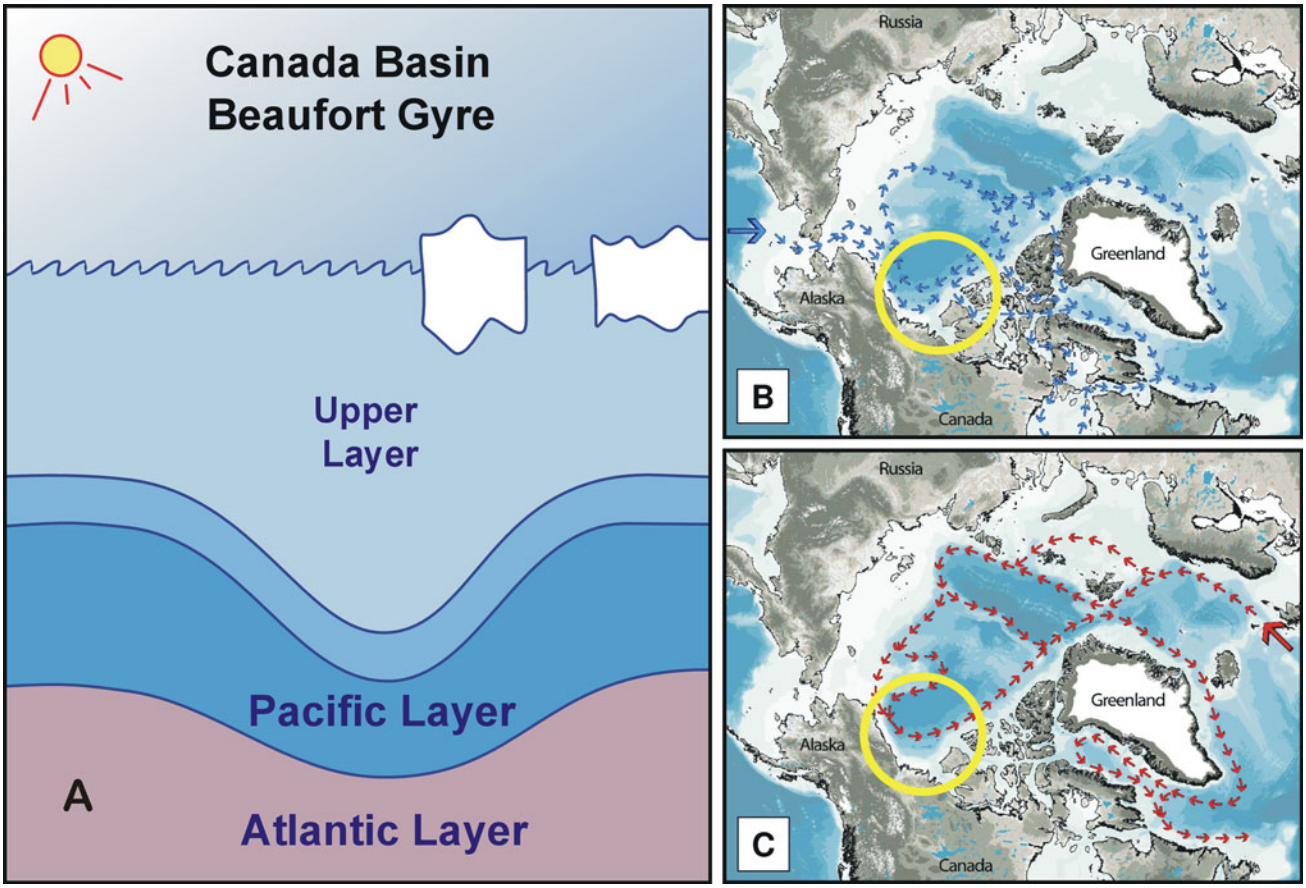

Fig. 2 **a** Schematic view of the upper 500 m of the Canada Basin and anticyclonic Beaufort Gyre showing the upper (seasonal) layer, the Pacific layer and the Atlantic layer. Maps of the study area showing **b** the inflow and circulation of Pacific-origin waters (approximately 60–220 m) and **c** the inflow and circulation of Atlantic waters (below approximately 220 m); the location of the Canada Basin is marked by the *yellow circle*

organisms such as the larvae of shell-forming pteropods like *Limacina helicina* (Fig. 4) that are concentrated in the upper 50 m. Finally, the northward retreat of the ice edge in summer and open ocean conditions now allows upwelling-favorable winds to transport nutrient-bearing Pacific-origin waters onto the continental shelf (Fig. 3f), thereby increasing primary production (cf. Carmack and Chapman 2003). The characteristics of Pacific waters are also corrosive, due to the remineralization of organic matter upstream on the Bering/Chukchi shelves. The upwelling of these waters onto the shelf may affect benthic communities of mussels and clams, and perhaps the people who rely on their harvest for subsistence.

The Arctic is not simply a passive victim of climate change. Zhang et al. (2008), for example, argue for a fundamental change in the high-latitude atmospheric circulation during the twenty-first century. Indeed, a changing Canada Basin feeds back on the global system, with potential impacts on ocean currents and global precipitation patterns. This two-way interaction is discussed by Overland et al. (2011) and is shown schematically in Fig. 5. Global warming and Arctic amplification act to reduce the sea-ice cover, freshen the surface layers, reduce albedo, and allow increased heat storage in the upper ocean (Jackson et al. 2011). This enhanced heat storage in newly sea-ice-free ocean areas is then returned to the atmosphere in the following autumn, thus modifying the large-scale wind field. As noted by Overland et al. (2011), observations from winter in 2009–2010 showed that the typical Polar Vortex was weakened over the central Arctic, resulting in enhanced meridional air mass exchange and record snow and low temperatures; a Warm Arctic-Cold Continents pattern. The resulting meridional wind component was the strongest since the beginning of the record in 1865. These amplification processes suggest that the Arctic system is sensitive to external forcing, with substantial feedbacks to lower latitudes that may intensify with further declines in sea ice (Fig. 5).

The Canada Basin is the “end of the line” for the Gulf Stream, and the return flow of Atlantic water then feeds back into the global thermohaline circulation system; so changes in water properties in the Canada Basin will also affect the global ocean. Increased heat content in both the

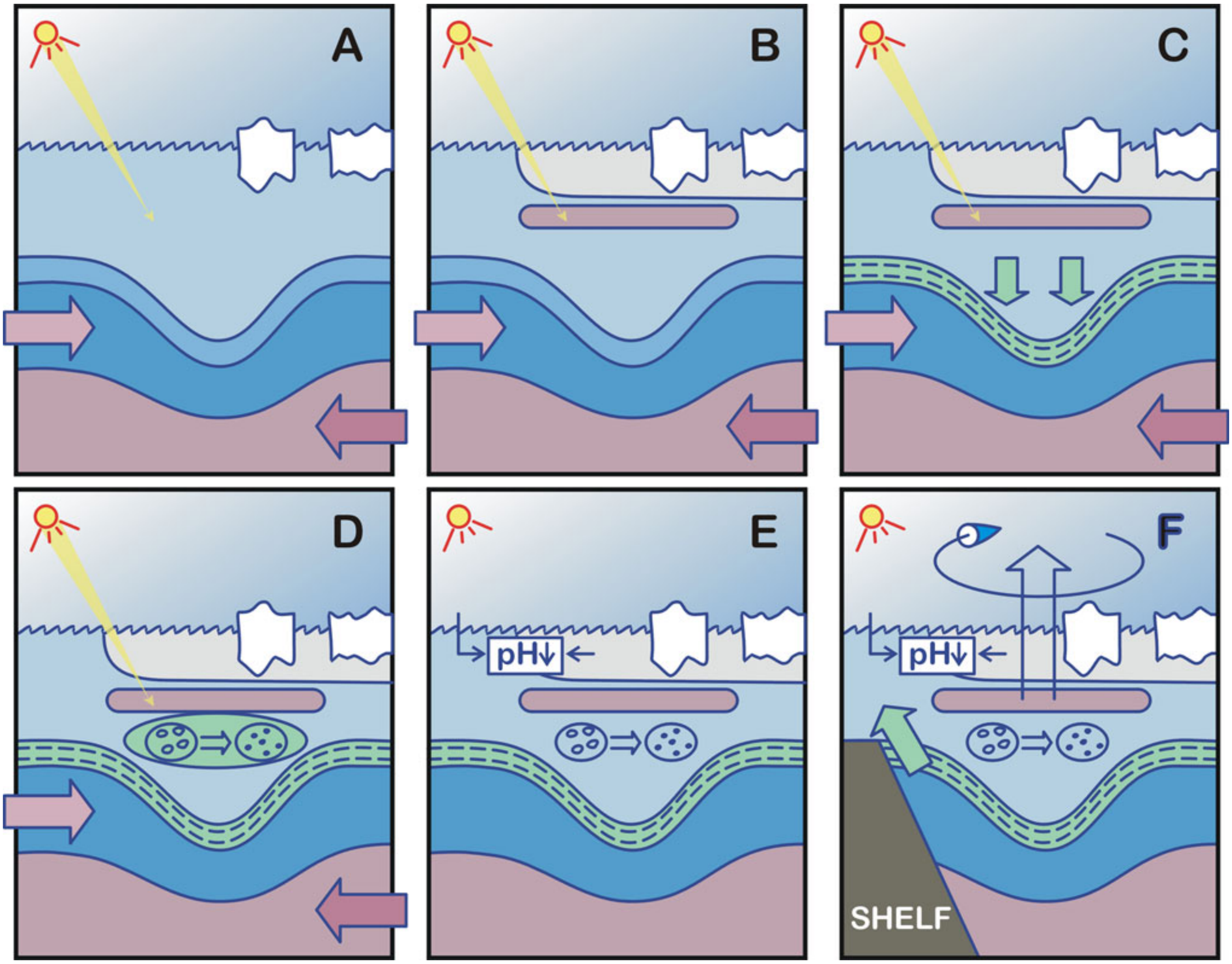

Fig. 3 Schematic views of coupled changes within the Canada Basin and Beaufort Gyre observed from 2002 to 2010: **a** warming of the upper layer via reduced ice cover and altered surface albedo, of Pacific and Atlantic layers by incoming waters for the adjoining subarctic Pacific and Atlantic; **b** increased ice melt leading to fresher surface waters and formation of a subsurface temperature maximum below the summer ice melt layer; **c** deepening of the Pacific-origin halocline and associated chlorophyll maximum layer; **d** shift in the size-spectra of phytoplankton to smaller organisms; **e** decreased pH in the upper layers related to ice melt; and **f** increased upwelling of subarctic-origin waters onto the continental shelf owing to more efficient coupling of wind/ice/ocean at the shelf break

upper and Atlantic layers will affect ice conditions in both the Canada Basin and the outflow region of the Arctic Ocean north of Greenland. It may also modify the East Greenland Current and melt sea ice. Warmer and fresher Atlantic waters could similarly affect convection in the Greenland sea and the strength of the Denmark Strait Overflow and, thereby, alter the global thermohaline circulation (cf. Proshutinsky et al. 2002).

A RESILIENCE APPROACH TO SOCIAL ADAPTATION AND ACTION

In the face of rapid change it is now, more than ever, imperative to close the gap between new knowledge and the corresponding implementation of new policy. Resilience theory offers a useful framework to understand and cope with rapid change and potential regime shifts in the Arctic (cf. Walker and Salt 2006). Resilience is taken here to mean the capacity of a system to absorb disturbance and reorganize so as to still retain the same function, structure, and feedbacks; it is the capacity to *change* in order to maintain *identity*. As such, ecosystems are recognized to be complex-adaptive systems, characterized by multi-stable states and often controlled by a small number of dynamical parameters. Resilience of a system is viewed in terms of a so-called stability domain**:** the "basin of attraction" of a system, where the dimensions are defined by the set of controlling variables that have distinct threshold levels. A regime shift or "flip" signals the change in a system state

Fig. 4 Photograph of the shell-forming pteropod *L. helicina*; shell size is approximately 5 mm (photo R. Hopcroft)

from one regime (or stability domain) to another. A threshold (tipping point) defines the level of a controlling variable where a change occurs in a critical feedback causing the system to self-organize along a different trajectory. Are the changes noted in "A system in transition: the Canada Basin of the Arctic Ocean" section pushing the Canada Basin into a new stability domain, one that will impact humans?

The change from one state to another can be abrupt, requiring immediate action by groups or societies that depend upon these ecosystems. Adaptability recognizes the capacity of components within a system to influence resilience; transformability is the capacity to transform the stability landscape itself—to become a fundamentally new system—when ecological, economic or social systems become untenable. Resilience thinking recognizes scale and connectivity, launches small but significant steps, and learns (not plans) into the future. An example of adaptation to a regime shift in the Arctic region—and the critical importance of adaptive social action—is given by Hamilton et al. (2003), who documented the response of two communities in southwestern Greenland to the collapse of cod stocks in the 1960s. In this case one community, Sisimiut, altered their technologies, and prospered through the abrupt ecological transition from cod-to-shrimp, while the other, Paamiut, maintained a traditional but fundamentally unsuccessful cod fishing effort, and thus declined. Although both communities experienced the same ecological regime shift and had similar capital and human resources, the stronger social capital (social networks and cohesion) of Sisimiut allowed a more successful adaptation to change. Yet how can we detect such rapid ecosystem transitions over the vast and poorly monitored Arctic?

The greatest capacity for adaptation and thus resilience occurs where social groups are flexible and networking across many scales, from the local to the regional where more powerful social and economic factors come into play. Local issues must be nested within a broader context of governance (Folke et al. 2002; Gunderson and Holling 2002). This is not easy; one cross-scale approach is to unite traditional knowledge and Western scientific observations (Carmack and Macdonald 2008; Fienup-Riodan and Carmack 2011). The two approaches are complementary: the strong oral traditions of indigenous peoples carry a deep experiential understanding of the world that is passed on

Fig. 5 Schematic view showing the coupling of Arctic and subarctic systems under global warming. *AA* Arctic amplification, the 850 mbar surface is taken as representative of the Polar Vortex, *WW* Westerly winds, eddy flux convergence occurs along the Westerly wind maximum *MW* is meridional winds, *Q* ocean/atmospheric heat exchange, *NSTM* near surface temperature maximum, *PW* Pacific water, *AW* Atlantic water, *NPIW* North Pacific Intermediate water, *DW* is deep water. See text for changes and feedbacks

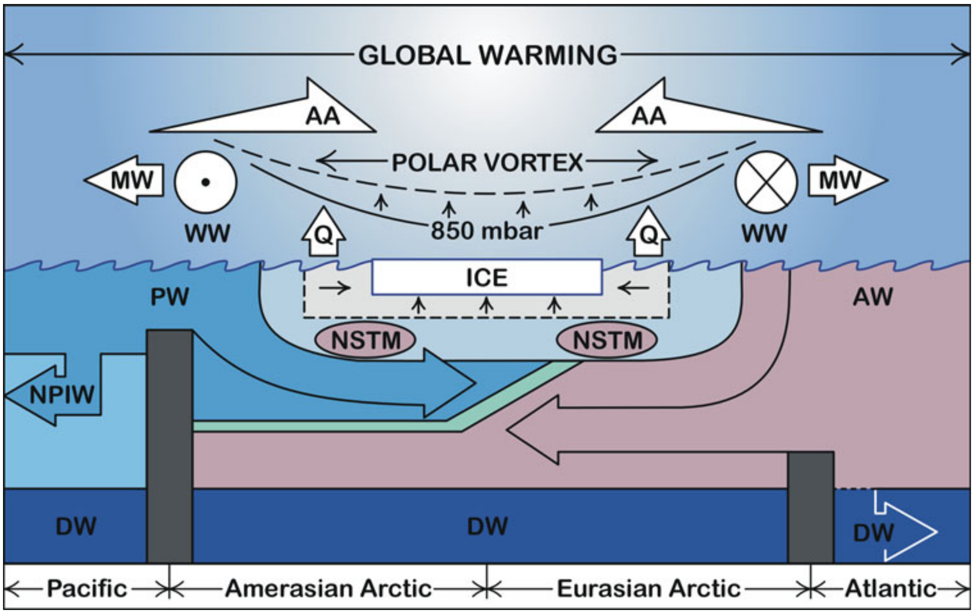

Fig. 6 Inuit hunter with captured seal (photo H. Huntington)

through narrative and demonstration, while western science advances through measurement, hypothesis testing, and modeling. Most oceanography is carried out on large spatial scales in the offshore ocean, while Northern residents are most concerned with nearshore waters of their small, coastal villages and with ice covers that impact on hunting success and safety of travel (Fig. 6).

We suggest that the ability of people living in close contact with the land and sea to give meaning to experience is a powerful and sometimes overlooked quality that local peoples bring to the study of environmental change. Whiteman and Cooper (2011) define ecological "sensemaking" as the process used to make sense of material landscape and ecological processes. They note that by tapping deep experiential knowledge, the skill of ecological sensemaking allows a hunter or traveler to interpret clues and react quickly when faced with the dangers of swiftly changing ice and ocean conditions, and to quickly know when things are not as they were or as they should be. Conversely, the inability to make sense of subtle physical and ecological changes and clues—occurring at widely varying time scales—introduces hidden and sometimes dangerous vulnerability at the local and cross-scale level.

DETECTION

Clearly there is a pressing need to identify the leading indicators and mechanisms of abrupt change and regime shift (see Dakos et al. 2008 for examples). Mård Karlsson et al. (2011) identified three types of regime shifts in Arctic terrestrial ecosystems and stressed the need to better match the scales of hydrological and ecosystem monitoring to improve regime shift detection and prediction. Evidence that indigenous peoples can provide a sensitive, early warning system of abrupt ecosystem change is given in the following two narratives, reported by Fienup-Riodan and Carmack (2011). The first was told by Peter Kattuk of Sanikiluaq, Nunavut, Canada. In winter, 2009–2010 he captured 71 seals, and 69 had shrimp in their stomachs instead of the usual capelin. Further, the seals were skinny (perhaps because shrimp are a less nutritious prey than capelin) and tended to sink when shot (perhaps because hydroelectric development in the James Bay region has freshened the upper layer salinity in winter). The key question is: Did Peter Kattuk simply observe an anomalous year, or has he experienced a regime shift that may require adaptation within his community or at the regional (Hudson Bay) scale? The second narrative was told by Adamie Thomassie, an elder of Kangirsuk, Nunavik, Canada. In winter of 2010–2011, the lakes that Adamie has fished for Arctic char since his childhood were near devoid of fish, and caribou hunting on the surrounding land was also poor. The snowmobile tracks that Adamie traveled were rough ice from freezing rain rather than snow, and the sea remained unfrozen, even as temperatures drop below −40°C. The changes that Peter Kattuk and Adamie Thomassie report are not slow changes over their lifetimes, but instead are abrupt. Are Peter and Adamie, through their ecological sensemaking, both giving early warning of major change?

The Arctic marine environment clearly faces the potential consequences of climate change and regime shift.

The C3O study has established a marine baseline around all of Canada, against which future change can be measured, and the JOIS study has shown the rapid pace that change is occurring in the Canada Basin. What is now required is a "downscaling" from the "global" scale perspective of C3O to the regional and community scale; only then can sound and appropriate operational and policy decisions be made (cf. Visbeck 2008; Dickson 2011). We thus suggest that the experiential knowledge of local people, with their deep understanding of the land and unmatched skills of on-ice travel, provide the strongest way to build a sustainable and multi-scale network to observe climate and environmental parameters of both the Western and Traditional variety.

OUTLOOK

Significant loss of Arctic sea ice and permafrost will affect ocean currents and global precipitation patterns, with direct impacts on specific industry sectors such as agriculture, energy, insurance, and all Fortune 500 companies operating in coastal areas. Increases in drought, fire, flooding, extreme weather events (hurricanes, typhoons, cyclones), and shifting rainfall patterns (including changes to the Asian monsoons) will affect food and water security worldwide. Surprisingly, however, the social and economic discussion of the potential costs of a melting Arctic to the rest of the world has received little attention in the world's elite decision-making arenas. Although the Arctic has appeared at least twice as an official session at the *World Economic Forum Annual Meeting* in Davos-Klosters, Switzerland, these sessions have primarily focused on a geopolitical discussion on how to gain access to new minerals and resources and who they belong to. The integration of a scientific foundation into the geopolitical discussion is missing. The Arctic is not simply a store-house of new resources—it has a complex and profound regulatory role in managing the global climate system (cf. Lenton et al. 2008; Serreze and Barry 2011; Overland et al. 2011). The Arctic may be home to a vast amount of newly (or soon to be) accessible fossil fuels: the development of these resources will offer tempting short term gains to some companies/countries. However, the amplification effects of continued fossil fuel development will accelerate Arctic sea-ice melt and thereby increase longer term costs to the global economic system. Unpredictable nonlinear change is now under way in the Arctic. This has global ramifications, yet this type of integrated discussion is not occurring within key sectors. There is an information gap among constituents and across scales.

As a small step to address these cross-scale challenges we have attempted to show here that the deep understanding of place acquired and passed on by indigenous peoples, both to the needs of their own communities and to Western science in general is essential. At the same time, it is clear that climate change is a global phenomenon and that deeper understandings must take into account large-scale connectivity (Carmack and McLaughlin 2011). Offshore research in the Arctic has clearly revealed huge changes in ice cover and ocean properties, with consequences to the ecosystem. If the ability of Western scientists to abstract and apply general laws is combined with the traditional knowledge and sensemaking of the Pan-arctic indigenous communities, and linked through social networks, then we have the potential to develop a foundation of environmental and climate monitoring and to serve as an "Early Warning System" to identify change, tipping points and regime shift in the twenty-first century (see Huntington 2011).

We think integrated Arctic science across disciplines, scales, and cultures are the only means by which we can track and interpret the complex shifts occurring now and in the future, within and beyond Arctic boundaries. By investing in integrated Arctic science, its people, and in cross-scale information networks, we can build the foundations of a resilient future. So are we ready to move together toward a deeper understanding of the Pan-arctic system and to make this potential integration a true asset? In the words of Holling (Pers. Comm.), "Indeed, our planet's oceans are now being monitored. If we add to this a greater understanding of the seas immediately offshore of indigenous communities, scales can be bridged and people engaged."

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