SEARCH Understanding Change Panel (UCP) Position Paper

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1. BACKGROUND: OBSERVED CHANGES IN NEED OF UNDERSTANDING

An understanding of change in the arctic system requires an explanation of the diverse array of recent and ongoing changes in its different components. These changes, as documented by the Panel on Observing Change, include a recent warming that is highly seasonal, larger over land than over the oceans, and comparable in some arctic subregions to the warming of the early 20th-century. The documented changes also include low-frequency variations of the atmospheric circulation associated with patterns such as the Arctic Oscillation and the Pacific Decadal Oscillation; an acceleration of the arctic hydrologic cycle that is suggested by some indicators but for which the observational evidence is not comprehensive; thinning and reduced extent of sea ice, especially in the past decade and in the Pacific sector; glacier retreat that is largest in the Alaskan sector; warming of permafrost and a shortening of the snow season length in many regions; pervasive reports by indigenous arctic communities of warmer and increasingly variable weather; and changes in ecosystems. While both natural variability and changes in external forcing (including greenhouse gas concentrations) must be considered in the quest for understanding such changes, the interplay between the changes in the various system components makes it necessary to consider component interactions and feedbacks, many of which have not yet been quantified. Hence this draft synthesis of our understanding of Arctic change is intended to be an evolving document. We begin with a summary of key issues relevant to understanding recent changes in specific components of the arctic system. We provide an overview of key uncertainties and needs for Understanding Change activities for SEARCH implementation, which have direct implications for priorities within Observing Change activities. In addition, we provide a brief discussion of outreach and education activities so that the knowledge gained from SEARCH implementation can be translated to the wider public and integrated into SEARCH's Responding to Change activities. We conclude with a synopsis that represents our position on attribution of recent and projected arctic changes.

2. CONSIDERATIONS RELEVANT TO UNDERSTANDING AND ATTRIBUTION

2.1. Surface Air Temperature

In investigating major warm anomalies over the 20th century, it is apparent that links exist with weather patterns that promote warm air advection from lower latitudes. Winter/spring warming over northern Europe and Siberia during the 1980s and 1990s has been shown to be driven, to a large extent, by enhanced westerly airflow associated with the positive phase of the Arctic (North Atlantic) Oscillation (AO). This positive-phase dominance of the AO also explains the cooling of eastern Canada and southern Greenland over the past 30 years. In the North American sector, much of the warming of Alaska has resulted from a phase shift during 1976-77 of the Pacific Decadal Oscillation (PDO). This shift to a positive phase of the PDO resulted in enhanced southerly airflow and warm advection into Alaska and northwestern Canada, especially in the winter and spring. Groisman et al. (1994) showed that a warming during late winter or early spring can be enhanced by snow retreat in parts of northern North America. While the past decade has seen the AO regress toward a more neutral, yet variable state, the Arctic has nevertheless continued to show a general warming trend.

2.2. Large-scale Atmospheric Circulation

The period 1970-1999 saw an increase in the intensity of major weather systems (centers of action) for subarctic regions that influence the Arctic. Mean pressures have decreased in the Icelandic and Aleutian centers, while pressures in the Siberian high have increased. A major feature of the winter Arctic Oscillation (AO) is that it is also associated with the strength of the stratospheric polar vortex, with cold stratospheric temperatures associated with its positive phase. The AO is associated with the NAO in winter, but the spatial patterns may separate in other seasons. The time history of the AO shows modest negative values from the 1950s turning to strongly negative in the mid 1960s to early 1970, then followed by a general rise. There was a period of major positive values in 1989-1995. The AO has subsequently regressed to a more neutral (albeit variable) state. Up until a few years ago the general upward trend in the AO from the 1960s through mid-1990s was considered a significant (and continuing) climate change relative to earlier periods (Feldstein 2002). Despite the return of the AO to more neutral conditions over the decade, some modeling studies suggest that external forcing, including increased greenhouse gas concentrations and stratospheric ozone loss, may favor a higher frequency of its positive state (e.g., Kuzima et al., 2005). However, the AO/NAO record is also consistent with a red noise time series model of atmospheric variability (Wunsch, 1999). Changes in the AO index indeed mirror changes in stratospheric temperatures for the previous three decades. The 1980s show a period of stratospheric warming followed by a cold strong polar vortex in the positive AO years. As many indicators of change in the Arctic, such as temperature and others discussed below, still show continuing trends, it is clear that the AO offers only a partial explanation of observed Arctic change.

While the AO is the strongest spatial mode of variability during winter in the northern hemisphere extratropics, a second mode emerges when the domain of analysis is limited to 70-90N. This mode, which corresponds to a “dipole” of sea level pressure with a strong pressure gradient over the central Arctic and winds blowing into or out of the Arctic from the North Atlantic, may affect the exchanges of water and sea ice between the Arctic and the North Atlantic (Wang et al., 2005). This mode has also shown substantial variability during the past several decades.

In summary, the multi-decadal decrease in pressure and strengthening of the Icelandic Low is consistent with the positive trend of the AO. However, the positive AO would predict an increase in pressure of the Aleutian low and a decrease in the Siberian high (Wu and Wang, 2002) in contrast to observations. Given that many Arctic changes are occurring in the Pacific sector, and are not accounted for by the spatial pattern of the AO, there is much more to be learned about climate forcing of the Arctic.

2.3. Terrestrial Processes

The arctic climate system is closely coupled with surface processes. On land, there are at least three critical coupling mechanisms (Figure 1). The first is through the snow and ice effects on albedo, the second is through effects of vegetation on the hydrological cycle and its effects on river discharge and heat exchange, and the third is through trace gas emissions (CO_2, CH_4). The first two directly affect local to regional climate, while trace gases direct influence is at the global level. These effects also create both positive and negative feedback loops. Climate warming causes an increase in the rate of microbial decomposition of soil organic matter, which directly releases CO_2 to the atmosphere, but leads to a cascade of indirect feedbacks through nutrient supply, increased plant growth, and a shift in plant community composition to woody shrubs. While the simple feedback loop between plant productivity and greenhouse-gas-induced warming is a negative feedback, the rest of the system appears to be largely dominated by positive feedback loops, enhancing the sensitivity of tundra ecosystems to climate change. The shift from open tundra dominated by sedges and mosses to shrub tundra dominated by dwarf birch (and willow) is critical. This shift changes the chemical composition of soil organic matter, the nature of carbon-nitrogen linkages, the regulation of winter snow dynamics, and the energy budget of the tundra. The shift also affects subsistence users of the tundra, since caribou depend on open tussock tundra because it provides the lichens that they depend on for winter forage and the easy movement that is makes searching for lichens energetically practical. Shrub tundra with lower lichen productivity and deeper snow presents a major challenge for caribou and people who rely on them.

Other key regulators of Arctic climate include disturbance processes such as fire, insects and land use changes that regulate movement of boreal tree line and species composition (and patchiness) of boreal forests across Eurasia and North America. At a continental scale, the integrated effect of recent changes in high latitude ecosystems influence the composition of atmospheric trace gases recorded at atmospheric monitoring stations. Long-term records of carbon dioxide at these stations suggest increases in carbon uptake in response to spring warming, but possible offsets from drought during summer. These observations have only been superficially tapped for the purpose of understanding large-scale changes in terrestrial ecosystem function.

In terms of the terrestrial water budget, the melting of permafrost is an irreversible process as the melt water generally escapes. Surface vegetation represented by tundra is showing indications of transitioning to shrubs or wetlands in some areas, as monthly summer temperatures exceed 10ºC. Tundra roughly covers the same regions as permafrost, and its area, as estimated from satellite measurements, has decreased by about 17 % over the last 25 years (Wang and Overland 2005). Counter-intuitively, increased shrubs trap snow, with this insulating effect reducing winter heat losses from the underlying soil, leading to an early snow melt (Sturm et al. 2005). As noted in the following section, there has been an overall increase in runoff from Siberian Rivers from the 1950s to the 1995s. While there is debate about the relative contributions of warmer temperatures, changes in precipitation, and the role of melting permafrost in this increase, current thinking is that precipitation changes are dominant.

An effective SEARCH initiative needs three terrestrial components: 1) a measurement program that identifies key mechanisms driving changes in the surface energy budget, runoff, diversity, and ecosystem services, 2) a scaling program that quantifies the extent of recent changes in vegetation, soils, and other land surface properties across the Arctic, and 3) a modeling component that effectively integrates the complex feedback mechanisms to provide enhanced understanding how the land, ocean, and atmospheric components of the arctic system interact to drive overall system behavior and climate.

2.4. Precipitation and Snow Cover

Variability in precipitation is influenced by storm tracks, by orography and (for summer precipitation) by surface evaporation and static stability. Under a positive AO/NAO, there is an increased northward transport of vertically integrated moisture flux between 10 W and 100 E and a decreased transport from 150ºW to 10ºW, leading to a net increase of precipitation over evaporation on the Arctic (Dickson et al., 2002). The AO-driven increase of precipitation in Scandinavia during the 1980s and 1990s is well documented and was responsible for the increase in Scandinavian glacier mass during this period. While there are other indications of increases of Arctic precipitation during the 20th century (e.g., IPCC, 2001a), the sparseness of the precipitation network and the problem of gauge undercatch call such trends into question. There are also indications of increasing discharge of the major arctic rivers (Peterson et al., 2002; ACIA, 2004), but such trends and changes in seasonality are complicated by direct human impacts on hydrology (dams, diversions).

When precipitation is deficient, the lack of moisture may be a more severe constraint for forest growth from Arctic change than gains due to increased temperature Across the western Arctic an increase in the number of forest fires is also an issue. Severe fire years occurred in Siberia and northwestern North America in 2003 and 2004, respectively. The factors responsible for extended periods of precipitation deficiency are largely unknown.

Snow cover area (SCA) in Eurasia shows large year-to-year variability, with decreases in the early 1990s and again in 2003. SCA in North America decreased from the late 1980s onward, again with much year-to-year variability. The twenty-four year trend in mean annual hemispheric snow extent is a decrease of approximately 4% per decade (Strack et al., 2004). Reasons for these trends have not been established. The relevant climate change variable for snow may not be its extent, but snow water equivalent and the timing of spring melt. Changes in snow water equivalent are poorly known due to sparse data. Snow melt onset at Barrow, Alaska was about 10 days earlier in the mid-1990s compared to the 1970s, with considerable year-to-year variability (Stone et al., 2002). Barrow is influenced by advection both from the Arctic and the North Pacific (Overland et al., 2002), so snow cover characteristics in this region are likely related to shifts in the predominant flow pattern.

2.5. Sea Ice

Based on satellite data, sea ice area at the end of summer in the Arctic (September) has declined about 17 % over the last 25 years. Regionally, this is seen as a retreat in the ice edge of 300-500 km in the Beaufort Sea or the East Siberian Sea depending on year. Of particular note are the extreme September ice minima of the past three years (Stroeve et al., 2005). Part of the general downward trend in ice extent may be attributable to altered wind fields associated with the upward trend in the AO up to the mid 1990s (Rigor et al., 2002). A large volume of thick multi-year ice is thought to have exited the Fram Strait in the 1990s, leaving the Arctic with more thin, first-year ice more prone to melt in summer. The recent extreme minima may in part represent a response to this effect. (Rigor and Wallace, 2004). More recent work (Lindsay and Zhang, 2005) indicates that while the impacts of altered wind fields on ice circulation are important, the overall downward trend is more clearly allied with general warming. There appear to be feedbacks at work in the sense that increased open water and thin ice absorb more solar energy in summer, leading to less ice growth the following winter. It has been proposed that the Arctic may be near a "tipping point" where there is a new equilibrium state between increased solar absorption in the ocean during summer and the amount of first-year sea ice that can grow during the following winter (Lindsay and Zhang 2005).

2.6. Glaciers

Glacier mass balance is determined by the difference in accumulation (primarily snowfall) and ablation. Temperature change is therefore a key issue. There has been a loss of glacier mass in North America since 1970, while there was a slight increase, probably due to increased precipitation, in Scandinavia during the same period (ACIA, 2004). Altimeter measurements indicate that the Greenland ice sheet is thinning around much of its periphery, although there are indications of thickening in the interior of the ice sheet. The net effects of these two processes are presently a subject of debate.

2.7. Oceans

As an important component of the cryosphere, the Arctic Ocean is thought to be in the vanguard of change. Accordingly, recent observations of loss of ice cover, especially in the marginal seas during summer, together with changes in ice-drift trajectories, sea-ice thickness and the distribution of fresh water in the upper ocean have engendered considerable concern that the ocean has already begun to change (Serreze et al., 2000) with what are as yet poorly understood consequences for the organic carbon cycle and the marine ecosystem. Better access to this ocean as a result of the loss of ice cover is likely to encourage further commercial development including fisheries, transport, and oil exploration—mostly in the marginal seas.

Circulation in the Arctic Ocean critically influences the region's ecosystems by exporting the excess of fresh water, nutrients, and marine organisms. There is a net flow of water (~1 Sv) from the Gulf of Alaska through the Bering Sea into the Arctic Ocean. This throughflow removes excess freshwater from the North Pacific, which carries nutrients onto the Bering shelf and becomes sea ice further north. Because of the influence that ocean circulation has on the region's ecosystems, additional research is needed to understand the processes that control ocean currents, their variability, and their role in supporting the marine life.

Typical pathways of Pacific Water into the Arctic Ocean extend northward from the Bering Strait through the Chukchi Sea via three distinct branches (western, central and coastal), then to the east and possibly north into the Beaufort Sea. Shelf-basin interactions along the outer shelves and slopes of the Chukchi and Beaufort Seas define the rates of exchange between Pacific Water and ambient arctic water masses. These processes are thought to contribute to the maintenance of the arctic cold halocline, a water column feature that through increased stratification prevents melting of the multiyear ice pack by the underlying warm Atlantic Water, which is distributed throughout the Arctic Ocean via boundary (slope) currents. In turn, Atlantic water is distributed throughout the Arctic Ocean via currents moving counterclockwise along the slope at the basin margins. The boundary between the domains of Pacific Water and Atlantic Water within the Arctic Ocean is a major feature that can change in response to arctic climate regimes, which are in part controlled by the Arctic Oscillation. Understanding long-term variability of the above phenomena and their effect on the region's ecosystems should be a priority, extending the multiyear measurements and ecosystem modeling in the western Arctic Ocean.

The northward flow of Pacific Water through the Bering Strait provides a significant linkage between the North Pacific/Bering Sea and the Arctic Ocean. The advection of nutrient-rich water from the northern Bering Sea/Gulf of Anadyr extends the high ecosystem productivity from the Bering Sea into the Arctic Ocean. The central Arctic supports bacterial and heterotrophic microzooplankton biomass similar to levels found in other pelagic regions of the world's oceans. Microzooplankton can be major bacterivores and herbivores, and they may be a significant food resource for macrozooplankton in the Arctic. A sharp decrease in zooplankton abundance in the northern Bering Sea from 1983 to 2003 has recently been documented. In turn, their food resources include both phytoplankton and bacteria, the latter possibly supported by the relatively high Arctic standing stocks of dissolved organic matter.

The Arctic Ocean also directly and indirectly supports many marine mammals such as polar bears, ring seals and bowhead whales; however, logistical constraints and political boundaries have left much of this area largely unexplored. The southern Chukchi/Beaufort Seas have been known for centuries as whale migration routes, for the abundance of other marine mammals, and for bird colonies. Some limited pelagic and benthic-related research has been conducted on the Chukchi and Beaufort Sea shelves, which are of great biological and economical importance because they sustain some of the most productive and high-diversity ecosystems in the world. There have been apparent northward shifts of marine ecosystems in both the Atlantic and Pacific sectors (Beaugrand et al., 2002; Overland and Stabeno, 2004). The native communities that settled along the northern Alaskan coasts have always depended on whale subsistence hunting as the main source of their diet (and survival). Nonetheless, there remains a lack of fundamental understanding of these regions that for centuries have been used for subsistence harvest by native communities.

3. ATTRIBUTION OF OBSERVED PHYSICAL CHANGES

3.1. Introduction and Conceptual Model

Attribution of change is difficult in that the Arctic is intimately coupled to the global climate system. Attribution receives much attention in the global context, most notably through the Intergovernmental Panel on Climate Change (e.g., IPCC, 2001a). There are three general approaches to attribution: investigation of long time series records, understanding processes, and the use of general circulation models (GCMs). For the Arctic we can divide causes of decadal and longer variability into external forcing, intrinsic (internal) variability of the atmosphere and ocean, and feedbacks/amplifications through land and oceanic cryospheric processes. External forcing can further be divided into natural (solar variability and volcanoes) and anthropogenic (CO_2 and SO_4). Most models predict that greater Arctic change lies ahead. It is unclear in what proportion observed changes are driven by natural/intrinsic variations, internal feedbacks or anthropogenic sources.

Climate change in the Arctic is complicated by feedbacks that may affect not only the Arctic but also its interactions with the global system. Among the processes involved in these feedbacks are (a) changes in albedo, going from highly reflective ice and snow surfaces to highly absorptive open ocean and uncovered vegetation, causing additional solar energy to be absorbed and accelerating the warming trend, (b) the interaction of changes in the wind field and surface heat fluxes with changes in cloud cover, (c) the potential release to the atmosphere of large stores of carbon from land and shallow coastal ocean areas, and (d) release to the North Atlantic of additional fresh water from melting sea and land ice and increased river runoff, altering the thermohaline circulation. All of these feedbacks have the potential to operate on decadal time-scales, and possibly to lead to abrupt change.

A conceptual model illustrating the three mechanisms of Arctic change is shown in Fig. 2 (after Stenchikov et al., 2002). External forcing (solar, volcanoes and CO_2) affects the absorption of radiation and is particularly effective in the sub-tropic stratosphere. Increased absorption raises the temperature and can increase the north/south temperature gradient, and thus increase the forcing to the atmospheric general circulation. An example of such forcing is the response to the Pinatubo volcanic eruption. On a yearly/global basis volcanoes such as Pinatubo have a cooling influence. However, in the winter following the eruption, there appears to have been an increase in the positive phase of the AO/NAO, with increased temperatures over northern Eurasia and negative anomalies over west Greenland (Robock and Mao, 1992). Although the polar vortex has two positive feedbacks, one through dynamic cooling of the stratosphere and ozone chemistry and one through modification of vertical wind shear and gravity wave propagation, the variability induced by the interaction between the time mean flow and transient eddies (DeWeaver and Nigam, 2000) argues for a large climate noise paradigm, i.e. intrinsic atmospheric variability affecting polar regions. Ozone loss has been both an anthropogenic influence and a dynamic response to Arctic stratospheric cooling. Decreasing trends (1979-93) in March total column ozone are in part congruent with the AO trend. The final element of the conceptual model is the positive temperature feedback from surface processes in the Arctic, i.e. loss of sea ice and tundra (Overland and Wang, 2005). Warmer temperatures influence the geopotential height field in the troposphere over the Arctic and affect northward advection of heat. While Fig. 2 is a simplified schematic, it illustrates the potential for complex interactions between the processes and feedbacks contributing to Arctic temperature change.

3.2. Changes Over the Previous Two Centuries

A surface temperature times series (Fig. 3), averaged over the Arctic and an extended winter period (after Polyakov et al., 2002), shows about a 1ºC warm anomaly during 1930s-40s, which is of the same magnitude as observed in the 1990s. There is no early century warm anomaly at mid-latitudes. One interpretation of this curve is that a low frequency oscillation which might turn negative in the 21st century. Another interpretation comes from comparing the meteorological events that contribute to the anomalies. The composite signal for the earlier period is made up of a number of individual events that vary greatly by region and season with local amplitudes of 3-4 deg C. The temperature anomaly patterns in the 1990s are Arctic-wide and are more associated with AO type sea level pressure patterns, in strong contrast to the earlier period (Overland et al., 2004). Temperature anomaly patterns in the 1990s appear unique in the 20th century (Przybylak, 2003). Some years during the 1930s were unusual in that west Greenland and Eurasia were simultaneously warm. While there is evidence that the initiation of these earlier warm periods reflects intrinsic variability, multi-year feedbacks may have had a role. There may have been a connection between stronger winds and sea ice reductions in the Barents Sea (Bengtsson et al., 2004). Cod production was strong for many years in west

Greenland, indicating an oceanographic connection, such as a change in the THC. Sea ice losses and changes from tundra to shrub vegetation may also be forcing a "memory" effect in the current Arctic system.

There is evidence from Swedish instrumental records, near the North Atlantic/west Siberia air mass boundary in winter, and Baltic Sea ice records that the 1800s were about a degree colder than the first half of the 1900s with a step transition around 1900 (Alexandersson et al., 2003; Omstedt and Chen, 2001). The late 1700s may have been slightly warmer than the following decades. The Swedish data do not have the large multi-decadal variability in the 1800s that is more broadly seen in the 1900s. Summer temperature estimates for Nome Alaska, based on tree ring density, also show modestly colder temperatures in the 1800s relative to the 1900s (D'Arrigo et al., 2004).

Figure 4 shows estimates of the magnitude of external forcing for the previous three centuries, where the signals have been normalized in terms of their radiative impact (Crowley, 2000). Volcanic impacts are large but of short duration with maximum activity in early and late 1800s and late 1900s, and minimums in the 1700s and mid-1900s. The effect of CO_2 in the late 1900s is an order of magnitude larger than the variability related to the solar signal.

3.3. Model Projections

Model projections of surface temperature for 2060-89 based on the average of five (5) models (ACIA, 2004) show the largest increases in winter after much sea ice is either gone or thin. The albedo feedback associated with retreating sea ice dominates the signal of high-latitude climate warming. Associated with this pattern of warming over the Arctic are corresponding decreases of sea level pressure and increased precipitation, implying that the validity of the model projections of Arctic change are as credible as their handling of the process of sea ice retreat. Other model intercomparisons studies suggest that the NAO/AO positive phase may intensify in the future due to increasing CO_2 concentrations (Kuzmina et al., 2005). An apparent paradox is that while the long-range projections favor changes in fall and winter over the oceans, recent Arctic change is strongest in winter and spring and larger over land. This can be partly resolved by an examination of model projections for the near future (2010-2029). For this "emerging greenhouse" period, there is large model-to-model and intra-ensemble variability in spatial patterns of warming and cooling, not unlike recent temperature trends in (Serreze and Francis, 2005). The output for these more proximate periods suggests both an AO type response, and a non-AO response especially for North America. Thus, for the next decades one can anticipate the interactions between external forcing, intrinsic variability of atmosphere and ocean, and unique Arctic feedbacks, in influencing Arctic change.

4. HUMAN DIMENSIONS OF CHANGE IN THE ARCTIC

4.1. Contribution of Human Activities to Arctic Climate Change

Regional and global human activities contribute in a variety of ways to arctic environmental change. In addition to greenhouse gas emissions (mainly carbon dioxide and methane), particulate air pollution has significantly reduced albedo of snow and ice (Hansen and Nazarenko, 2004). Arctic and boreal ecosystems store a third of earth 's soil carbon (McGuire et al., 1997. Carbon cycling resulting from socially driven land use and land cover change could create feedbacks to arctic climate. Expansion of tree line reduces albedo, creating a positive climate feedback (Chapin et al., 2000; Callaghan et al., 2002). On the other hand, increased fire frequencies and intensity in the boreal forest zone would increase albedo, producing a negative feedback (Chambers and Chapin, 2002). Large hydroelectric systems—particularly on the Ob and Yenisey—already seasonally regulate freshwater discharges to the Arctic Ocean. Climate-enabled expansion of subarctic agriculture in Russia and Canada (Cohen, 1997) could change runoff patterns and sediment discharge of large river systems in Eurasia and North America, with unknown consequences for the Arctic Ocean environment.

Identifying with greater precision the relative contribution of different human activities to arctic climate forcing and system feedbacks is needed in order to evaluate the opportunities for long-term mitigation of climate change. At some point in time, the loss of snow and ice cover, augmented with carbon and methane release from melting permafrost, extension of tree line, and other feedbacks may cause the Arctic to continue to warm even if the human contribution ceased. Establishing the conditions when this point of no return is likely to be reached might be a fundamental research question for SEARCH, since it establishes a deadline beyond which climate mitigation policies will no longer be effective in the Arctic.

4.2. Arctic Residents: Impacts and Mitigation Issues

Arctic indigenous residents are closely tied to local ecosystems, and have recently observed many ecosystem effects associated with climate change (Krupnik and Jolly, 2002). Climate change has many implications for arctic residents, including changes in access, effects of coastal erosion and permafrost melting on infrastructure, and safety of marine travel with loss of sea ice. However, arctic physical system changes affect arctic residents most strongly through the changes they cause to arctic marine and terrestrial ecosystems (Chapin et al., 2005). Inuit people living along the arctic coast of North America practice a mixed subsistence-cash economy based oriented around hunting of marine mammals. Arctic marine mammals are all highly adapted to sea ice; many species important to hunters may not survive the loss of summer sea ice, or may decline by so much that they can no longer support subsistence hunts (IPCC, 2001b). Loss of top predators such as polar bears and pinnipeds, combined with changes in primary production, and could cause Arctic Ocean ecosystems to shift between top-down to bottom-up regulation. This would leading to unpredictable ecosystem shifts. In any case, Arctic marine food webs could change to an extent that current subsistence systems are no longer viable (although new ones might emerge).

Human adaptations to ecosystem changes are difficult to predict. Research on resilience of social-ecological systems (Birkes and Folke, 1998; Walker et al., 2004) can help predict what characteristics are associated with flexible systems that can accommodate change more easily, and understand the limits to change. When local systems have reached their limits of adaptive capacity, research suggests that population movements and demographic shifts are likely to occur (Hamilton et al., 2000). A determination of these limits within the context of arctic environmental change should be an important driver of SEARCH.

5. SYNOPSIS OF CURRENT UNDERSTANDING OF ARCTIC CHANGE

A synthesis of observational evidence and our present understanding leads to the conclusion that the Arctic changes of the past several decades are attributable to a combination of circulation-driven changes, probably augmented by the effect of increased greenhouse gas concentrations and, locally, by human activities. While many modeling studies suggest that the increase in greenhouse gases may favor shifts in the primary atmospheric circulation modes, in particular a higher frequency of the positive AO mode, we find no compelling evidence that recent variations of the circulation are greenhouse-driven. Because much of the recent circulation-driven change is likely a manifestation of natural variability, there is a possibility that the recent warming trajectory could slow in the near future. In this respect, we believe that the Arctic Climate Impact Assessment has overstated the role of greenhouse warming in recent and near-term projections of Arctic change. Nevertheless, even if the recent changes are not primarily greenhouse-driven, the large changes in the upper ocean, sea ice and marine ecosystems introduce inertia and possible feedbacks, making it more difficult for natural variability of the atmospheric circulation to reverse them. The persistence of large negative sea ice anomalies and continued Arctic warming in the current neutral phase of the Arctic Oscillation illustrates this point.

In the longer term (50-100 years), the robustness of the greenhouse signal in climate model projections shifts the balance of the likely changes toward the greenhouse-driven patterns. In such scenarios, the changes will be larger in the Arctic than elsewhere. An improved understanding of the relevant feedbacks, and the incorporation of these feedbacks into models in a credible manner, will be essential for projecting realistic spatial and seasonal patterns of change. Even in the absence of a complete understanding of ongoing and projected environmental changes in the Arctic, it will be necessary to address the limits of adaptive capacity of local systems, including arctic communities, with en eye towards population movements and demographic shifts.

6. EDUCATION AND OUTREACH

Education and outreach must be a key component of SEACH, particularly in the area of understanding arctic change. The development of effective mechanisms and venues to serve stakeholders, the general public, and the needs of K-12 and higher education, promises to be a formidable task. Needs of the general public end educators can certainly be met to some degree by the every growing capabilities of the internet (for example, http://www.arctic.noaa.gov/detect), through which SEARCH findings and activities can be articulated at appropriate levels. However, more innovative approaches will also need to be developed. Stakeholders directly impacted by arctic change—arctic residents—should be active participants in the SEARCH program. The combination of indigenous knowledge and instrumental records offer exciting possibilities for a synergistic approach to increased understanding of recent and ongoing changes in the Arctic. While activities under SEARCH must be relevant to their needs and concerns of Arctic residents, SEARCH will in turn benefit from their input. Here it must be recognized that while the changing Arctic will adversely impact traditional ways of life, it may also provide opportunities. For example, opening of the northern sea route to shipping has potential economic benefits to Arctic residents, and longer growing seasons may provide new opportunities for local food sources in some arctic areas.

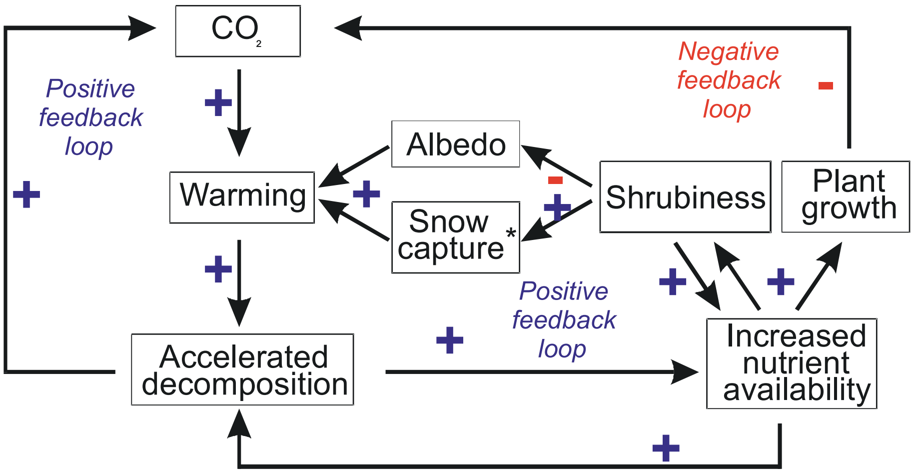
7. KEY UNKNOWNS IN THE UNDERSTANDING OF CHANGE: PRIORITIES FOR SEARCH

Based on the preceding discussion, the following emerge as priorities for SEARCH activities directed at an improved understanding of arctic change:

- A determination of the extent to which human activities have contributed to recent and ongoing environmental change in the Arctic. These activities range from the local (e.g., land use) to the regional (e.g., water management) to the global (e.g., greenhouse gas inputs to the atmosphere).
- An evaluation of the extent to which circulation-driven changes of arctic temperature and pressure are attributable to enhanced greenhouse gas concentrations, in contrast to natural variations within a chaotic fluid system. This activity will require considerations of coupling between the upper and lower atmosphere.
- Quantification of key feedbacks in the arctic system, including those involving the land surface (e.g., trace gas release, surface albedo changes), the ocean (e.g., freshwater inputs and upper-ocean stratification), and the atmosphere (e.g., changes in cloudiness and associated heat fluxes).
- A determination of the northward shifts of marine and terrestrial species.
- A determination of the limits of adaptive capacity of local systems in the Arctic, including human communities. While this issue overlaps with the charge of the Responding to Change panel, it must be considered in any attempts to evaluate the most likely evolution scenarios in the Arctic over the coming decades to a century.

Figures

Figure 1. Summary of feedbacks between Arctic terrestrial system and atmosphere:



* snow capture only causes winter warming

Figure 2. Conceptual model of arctic warming (from Stenchikov et al., 2002):

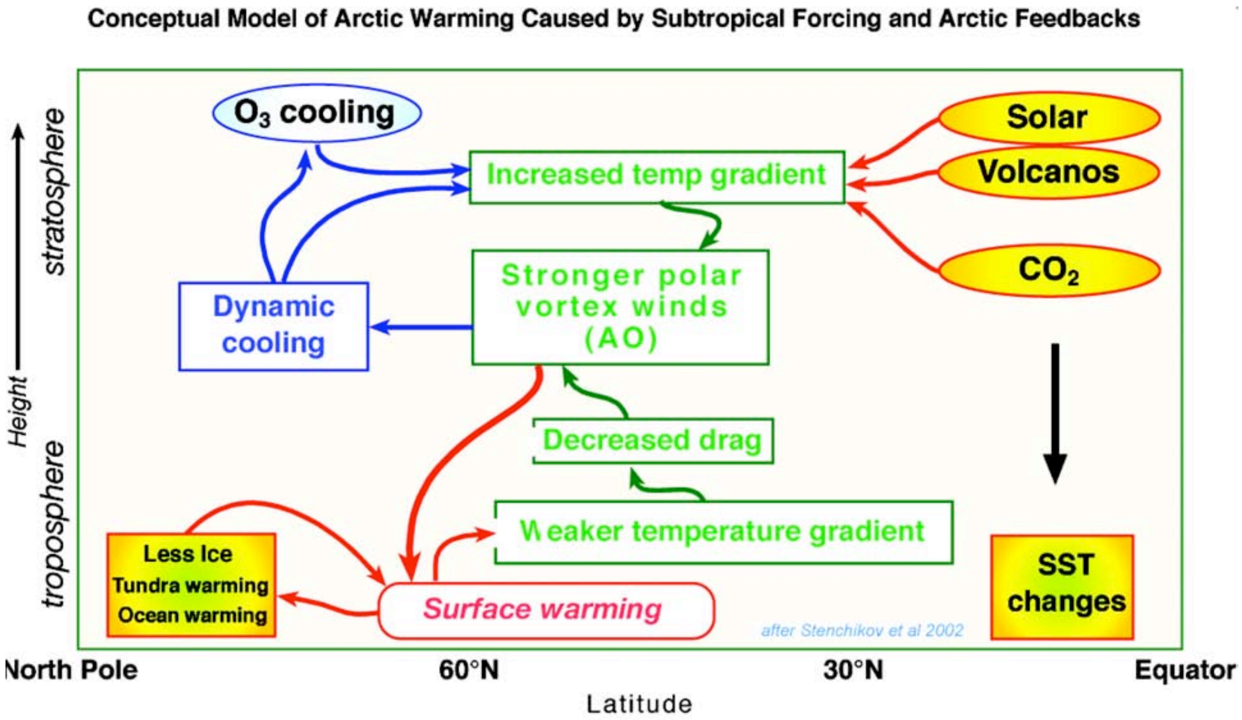


Figure 3. 20th-century Nov-March surface air temperature anomalies for arctic marine areas (red) and for mid-latitudes (black)(from Polyakov et al., 2002).

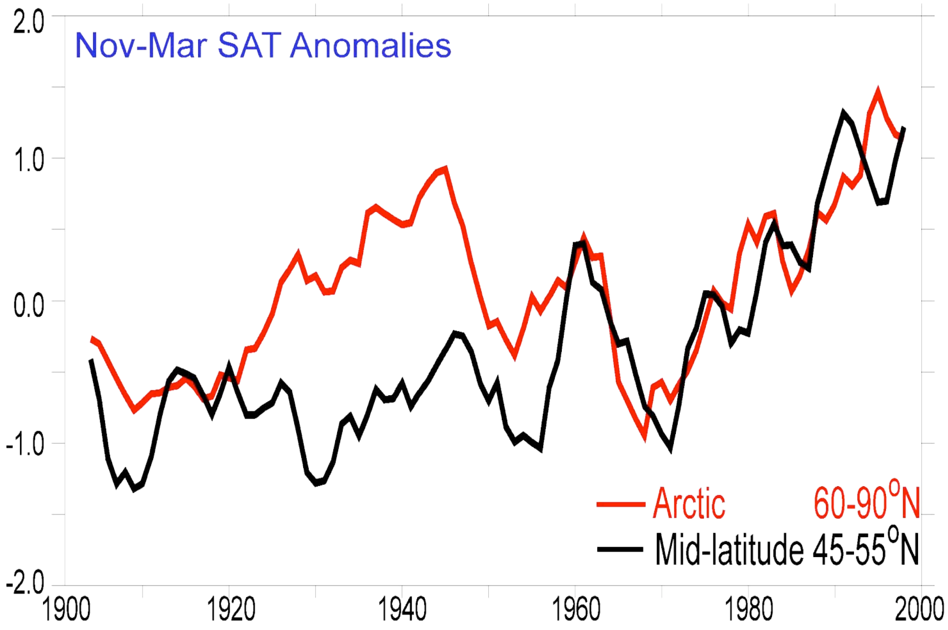
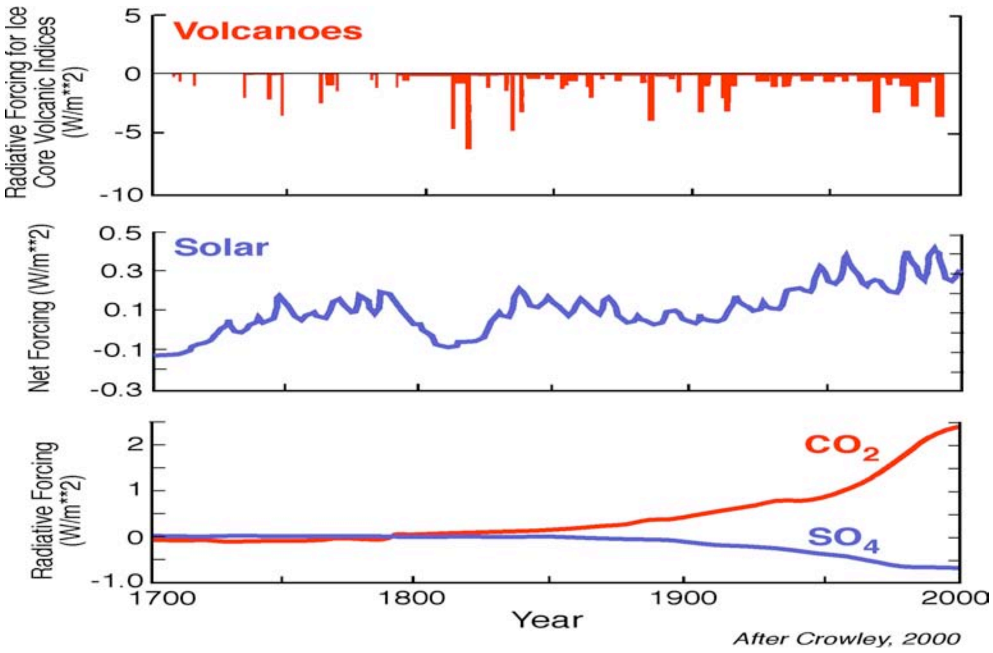


Figure 4. External climate forcing, 1700-2000.



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