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Natural Variability of Arctic Sea Ice Over the Holocene

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The area and volume of sea ice in the Arctic Ocean is decreasing, with some predicting ice-free summers by 2100 A.D. [*Johannessen et al.,* 2004]. The implications of these trends for transportation and ecosystems are profound; for example, summer shipping through the Northwest Passage could be possible, while loss of sea ice could cause stress for polar bears. Moreover, global climate may be affected through albedo feedbacks and increased sea ice production and export. With more open water, more new sea ice forms in winter, which melts and/or gets exported out of the Arctic.

The recent decrease in summer sea ice (Figure 1a) may result from radiative forcing, possibly due to increased greenhouse gas concentrations, and/or from reduced winter ice cover which allows greater atmospheric warming [*Rigor et al.,* 2002]. While several studies predict a continuous decline in ice cover, the timing, magnitude, and regional expression vary between models [e.g., *Johannessen et al.,* 2004]. For example, the Canadian Arctic Archipelago (CAA) may remain encumbered with summer ice, because multi-year ice accumulates along its coastline and invades the channels [*Agnew et al.,* 2001].

Interestingly, the Holocene sea ice history of the CAA indicates less summer sea ice 10,500–9000 years before present (B.P.), perhaps similar to current trends. All sea ice proxies point to an early Holocene ice cover minimum, but regional differences characterize later times.

A consortium of Canadian groups is using ocean cores, ice cores, and mammalian and archeological histories to build a Holocene sea ice history; preliminary results are reported here. By the end of International Polar Year activities in 2008, more will be known about the natural variability of sea ice during past times. Although sea level changed over the Holocene, tracing sea ice history across the Arctic can lead to a better assessment of the underlying dynamics that govern sea ice extent, which may help distinguish anthropogenic from natural forcing.

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Marine Mammals

The establishment of perennial Arctic sea ice cover in the late Tertiary led to the evolution of ice-adapted mammals, including the bearded seal, ring seal, walrus, polar bear, narwhal, beluga, and bowhead whale. Continued existence of this community is evidence that the sea ice cap has not disappeared during the Quaternary.

The remains of over 1200 bowheads have been recorded in the CAA, and more than 500 have been radiocarbon dated. The annual migration of bowheads follows the seasonal expansion and contraction of the sea ice front, as the animals prefer to remain close to the ice edge. As the sea ice retreats, Bering Sea as well as Davis Strait stocks of bowheads converge upon the CAA. The two are prevented from intermingling today by a persistent sea ice barrier that plugs the central part of the archipelago.

The distribution and radiocarbon ages of whale remains indicate that during at least one interval of the Holocene, Bering Sea and Davis Strait bowheads could intermingle, (Figure 1b). The Bering Sea bowhead was the first to reach the CAA about 10,000 carbon-14 (^{14}C) years ago (11,450 calendar years B.P.). Bowheads entered via the Beaufort Sea about 1000 years after submergence of the Bering Strait, and they ranged up to the fronts of receding continental ice sheets [*Dyke et al.,* 1996; *Dyke and Savelle,* 2001]. Until about 9500 ^{14}C years B.P. (10,700 calendar years B.P.), by which time the Davis Strait bowhead ranged into the eastern Northwest Passage, the Bering Sea and Davis Strait stocks were separated by a glacier ice barrier. With dissipation of this barrier, the two stocks were able to intermingle, ranging well beyond historical limits. About 8000 ^{14}C years B.P. (8900 calendar years B.P.), the Bering Sea and Davis Strait stocks were separated, as they are today. Thus, a year-round sea ice barrier must have become established at that time in the central part of the Northwest Passage.

Holocene Ice Cores

The melt layers in summit cores from Agassiz (82°N) and Penny (65°N) ice caps are records of summer warmth (Figure 2a). Some melting occurs in 90% of summers atop the Agassiz ice cap. Refreezing after infiltration forms air-bubble-free 'melt layers.' Temperature can be interpreted based on the correlation between measured summer warmth and the percentage of the annual layer thickness consisting of refrozen meltwater. However, this melt layer/temperature transfer function has a limited range as the coldest summers leave no melt record, and the warmest summers, after complete infiltration of the annual layer, generate runoff from the site. Thus a 100% melt layer does not represent maximum warmth, and temporal discontinuities may occur in long intervals of the ice core with 100% melt replacement.

The Agassiz record in Figure 2a is from a core that reached bedrock at 135 meters. With this core, the Holocene melt record is complete, extending over 10,000 years back to the large oxygen-18 (^{18}O) increase at the termination of the Younger Dryas cooling period. Oxygen-18 in ice is a paleo-thermometer that mimics the air temperature of the past. During the early Holocene, some annual layers were formed entirely by refrozen meltwater. Because runoff may then have occurred from the core site, temperature reconstructions are minima. After about 9500 years B.P., the record shows high centennial-scale variability superimposed on a progressive summer cooling (of about 2.5°C) from that warmest period until today.

The Agassiz melt record is rather invariant over the last 2000 years, except for twentieth-century warming. Here the relationship between summer temperature and melt percent (the transfer function) is at the cold (low) end of its sensitivity range. The Penny record, from a warmer location, is more sensitive for this period and shows substantial variability in intensity of summer snowmelt through the last two millenia.

Summer wind direction may also influence sea ice clearance. If sea ice is exported by wind, it need not melt in situ. Paleowind proxies in the Arctic are difficult to obtain. However, pollen records indicate variable transport of tree pollen to the Arctic throughout the Holocene [*Bourgeois et al.,* 2000]. If the northwest mainland was the source of tree pollen, then early Holocene winds were

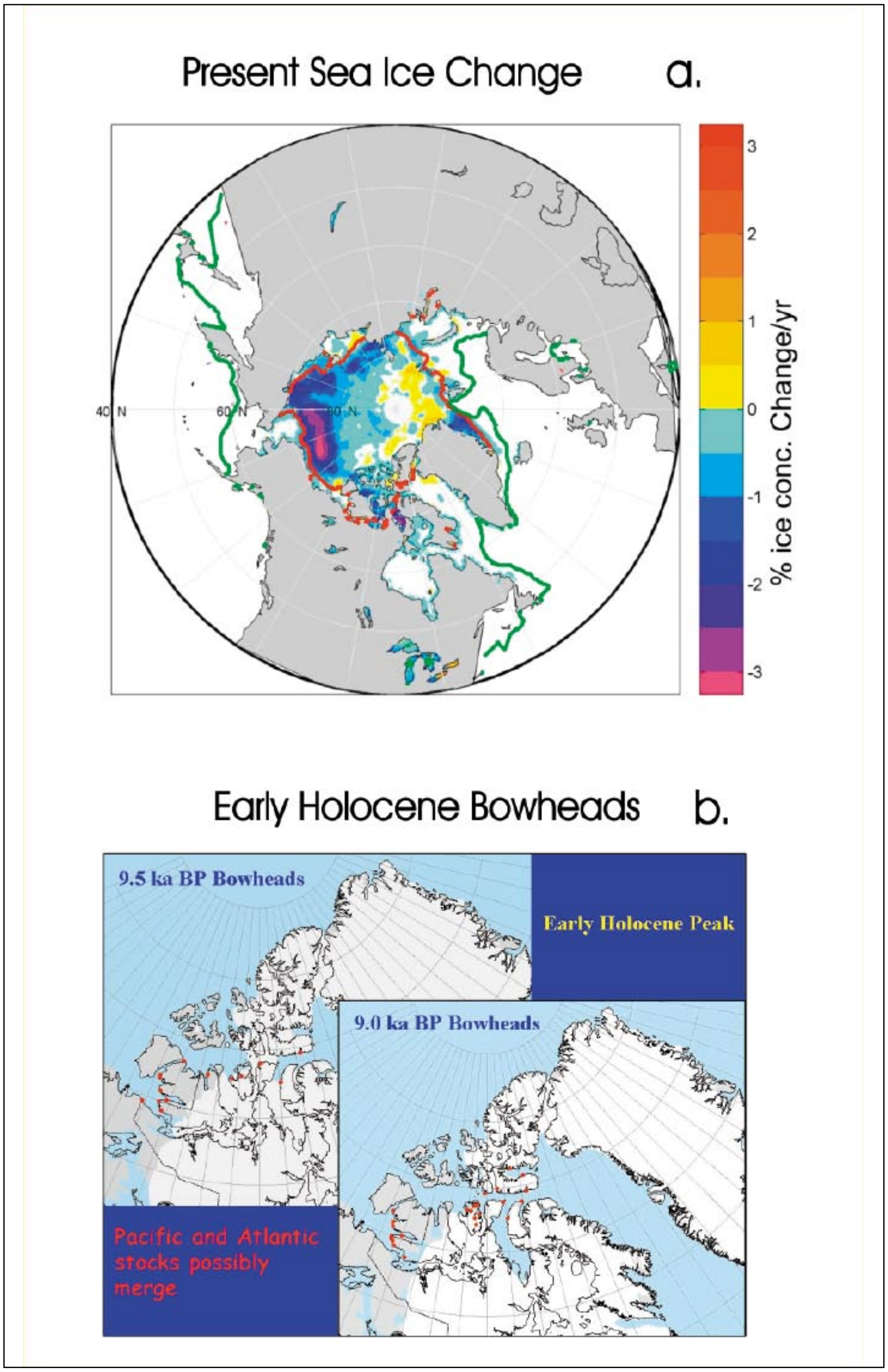

*Fig. 1. (a) September ice trends and average minimum (September, red line) and maximum (March, green line) ice extents, 1979–2003 [*Cavalieri et al., *2004]. (b) Distribution of bowhead whale bones dated 9.5 ± 0.25 and 9.0 ± 0.25 ^{14}C kiloyears B. P. White areas are ice sheets.*

more frequently from the southwest during spring and early summer.

Ocean Core Dinoflagellates and Isotopes

Dinoflagellate cyst assemblages reflect sea surface temperature, salinity, and ice cover. Inferences of sea ice cover, temperature, and salinity rely on the best analogues among modern assemblages from sites throughout northern oceans [*de Vernal et al.,* 2005]. Results from the eastern and western Arctic indicate opposite trends in sea ice cover: increasing in the east while decreasing in the west (Figure 2b). Both regions experienced successions of warm and cold intervals. Changes in regional fresh water input in conjunction with millennial-scale extraterrestrial cycles (e.g., the 1800-year lunar cycle) may explain such trends. Long sediment cores collected in 2004 and 2005 in the Beaufort Sea, the Northwest Passage, and Chukchi-Siberian seas will better define the regionalism of Holocene sea ice history.

Foraminiferal Isotopes

Neogloboquadrina pachyderma left-coiled (Npl) foraminifera grow along the pycnocline, where water density switches from cold, dilute, surface water to warmer, saline North Atlantic Water (NAW) in the Arctic Ocean. The $\delta^{18}O$ values in their shells have negative offsets from isotopic equilibrium values ranging from -1‰ (Arctic Seas) to -3‰ (Canada Basin), although temperature gradients still result in predictable isotopic shifts [*Hillaire-Marcel et al.,* 2004]. The offset could be linked to rate of sea ice formation [*Bauch et al.,* 1997]. Freezing isotopically light seawater produces ice and isotopically light brines that sink to the pycnocline. Mixing of these brines into NAW and export of surface water and sea ice to the North Atlantic maintain steady state conditions, thus resulting in an asymptotic isotopic offset value near -2.5 to 3‰ in Npl. From this view, the greater modern offsets in the western than in the eastern Arctic Ocean would reflect the differences in sea ice formation rates along the shelves.

These offsets were maintained in the Chukchi Sea during most of the Holocene (Figure 2b), with possibly larger offsets early on, which can be inferred as continuous sea ice formation and the greatest brine production in the early Holocene. The record illustrates some decoupling between surface-water conditions, as reconstructed from dinoflagellate cyst assemblages, and conditions prevailing in the NAW, as indicated by the size-dependent ^{18}O-gradients in Npl (Figure 2b). The 9000–8000 year interval depicts a large offset between small and large specimens, suggesting much warmer conditions in the NAW than in the surface water [see *Hillaire-Marcel et al.,* 2004]. However, between 7000 and 6000 years B.P., these size-dependent gradients nearly vanished, suggesting a weakening of the pycnocline. This likely resulted from a higher surface salinity and less sea ice, as also indicated by the dinoflagellate cysts.

Implications for Future Warming

The history of sea ice shows strong regionalism. Marine animals that depend on sea ice survived the early Holocene by adapting and migrating. At the height of the warmth, which was but three degrees warmer than now, the Pacific and Atlantic bowhead whales could visit each other through the Northwest Passage. Future Arctic warming is expected to be considerably warmer than this, and the free passage of biota and ships is certain.

More open water in summer means more area for freezing winter sea ice. Hence, less summer ice can increase the rate of winter brine expulsion. North Atlantic bottom-water formation rates feed back into the climate system. Since climate feedbacks are often not linear, one could expect surprises. This research suggests that hints about these surprises and their explanations may be found in the past.

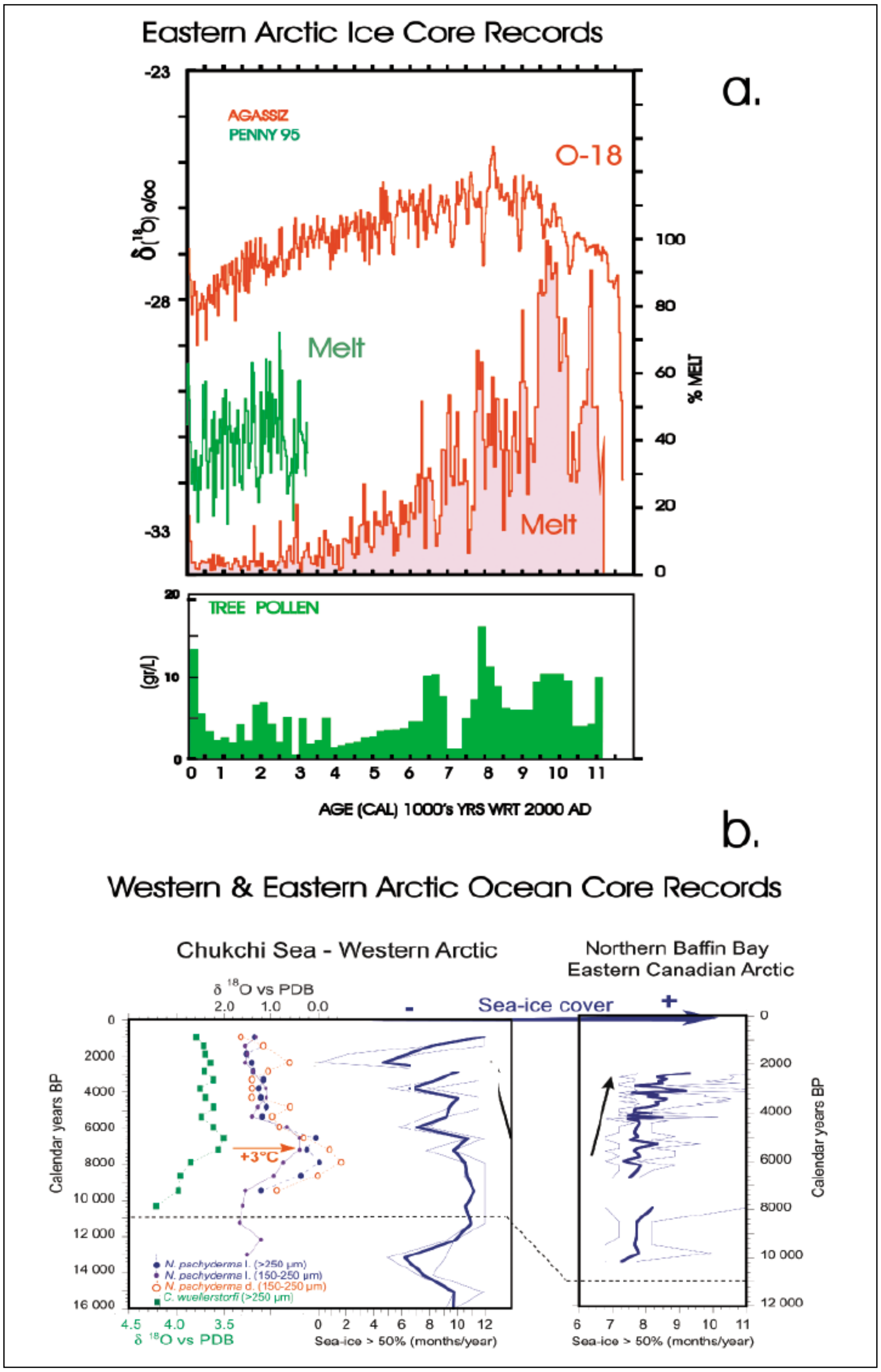

*Fig. 2. (a) Melt layer percent, Agassiz and Penny ice caps, Canadian Arctic. Ages based on annual layering and volcanic acid horizons; estimated accuracies ±5% [*Fisher et al., *1995]. (b) Opposite trends of sea ice cover in western and eastern Arctic. Chukchi core B15 is from Northwind Basin (Holocene, 10 centimeters thick) [*de Vernal et al., *2005]. Baffin Bay data are from cores P008 and P012 (10 meters of Holocene).*

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