New Record Shows Pronounced Changes in Arctic Ocean Circulation and Climate

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Does the Arctic Ocean surface circulation north of Alaska oscillate to and fro like a slow washing machine on millennial timescales? New evidence from the sediment record over the last 10,000 years suggests that it does and that in the recent past, the western Arctic Ocean was much warmer than it is today.

Similar Holocene climatic fluctuations are seen in many records worldwide; yet their origin remains enigmatic. Modeling and observational studies suggest that the Arctic may play an important role in these climate fluctuations through changes in surface albedo, modifications of oceanic thermohaline circulation, and changes in biogeochemical cycling of nutrients and radiatively important gases [PARCS, 1999]. Understanding the Arctic's role in or response to Holocene climate change is difficult because of an inadequate number of long-term Arctic records at the necessary spatial and temporal resolution [PARCS, 1999]. However, a new multi-parameter record from a thick sequence of post-glacial sediments from the upper continental slope off the Chukchi Sea shelf reveals previously unrecognized millennial-scale variability in Arctic Ocean circulation and climate. This new record, along with recently obtained sediment records from the Arctic's Eurasian margin [Stein, 2000; Duplessy et al., 2001], suggest that the Arctic's outer shelves and continental slopes hold much promise for elucidating the Arctic's link to climate change.

These new records suggest that we may have been looking in the wrong places for such paleo records. Previously, sediment coring and paleo research has focused on the ridges in the central Arctic Ocean. Very low sedimentation rates due largely to the perennial pack ice and low melt-out rates characterize most sediment records from the central Arctic Ocean. This sediment also contains sparse biogenic remains due to low productivity under the sea-ice cover. In contrast, the marginal areas of the perennial pack ice, including many of the upper continental slopes in the Arctic, are ice-free in the summer and both productivity and sediment melt-out from the pack ice are much higher than for areas under the perennial pack ice. Ice-free summer conditions also occur on the extensive shallow shelves of the Arctic, but these shelves are subject to erosion, especially during the lower sea levels of the last glacial.

As part of Phase I of the Western Arctic Shelf-Basin Interactions (SBI) program of the National Science Foundation's Office of Polar Programs, a 4-m-long sediment piston core, 92AR-P1, referred to here as P1, and a companion box core provided by the U.S. Geological Survey were examined using a multitude of environmental proxies. This core, from 201-m water depth, provides a unique record of paleoceanographic changes during the Holocene and part of the last glacial. The relatively high sedimentation rates, averaging ~22 cm/k.y., provide good temporal resolution and, together with many sediment parameters, provide new insight into environmental variations in the western Arctic. The core site is located in an apparently critical junction that records an oscillating surface circulation and ice drift [Proshutinsky and Johnson, 1997]. This circulation today...
Trans-Polar Drift that corresponds to a low-pressure system over the Beaufort Sea (AO) to a circulation dominated by the anti-cyclonic Beaufort Gyre that corresponds to a high-pressure system over the Beaufort Sea (AO), from one dominated by the Atlantic Layer are directly linked to the Arctic climate oscillation. Thus, the study site is strategically located to sensitively monitor climate-linked changes in both surface and deep-ocean conditions.

Fluctuating Ice-drift Patterns and the Arctic Oscillation

Analyses of the postglacial sediments in core P1 reveal important variations in most paleoenvironmental indicators, notably those related to the ice-drift patterns. The smectite clay percentages from volcanic terrains indicate a significant change in source every 1–2 k.y. (Figure 2). Smectite above 25% can only come from two areas of similarly high smectite, the Taymyr Peninsula (Figure 1) or south of P1, the volcanic belt in southwestern Alaska or eastern Siberia. The smectite is often highest (>25%) when elevated percentages of detrital Fe oxide grains are chemically matched either to bottom sediments on the Chukchi Sea or the Laptev Sea. Today, the surface currents flow northward across the Chukchi Sea and bifurcate around shallows, but they do not normally flow over the P1 site (Figure 1). The Fe oxide grains matched to the Chukchi Sea source were presumably transported during the Holocene to the P1 site by sea ice that entrained them either from the shallower parts of this sea (<50 m water depth) or farther south along the northward drift of sea ice through Bering Strait.

When elevated numbers of Fe oxide grains match to the Laptev Sea source, we infer transport of the smectite by sea ice drifting eastward across the East Siberia Sea (coastal current; Figure 1). At other times, transport was northward from the Bering Strait across the Chukchi Sea and also westward from northern Canada (Banks Island) as occurs most of the time today via the weak, anti-cyclonic Beaufort Gyre.

This switching between Russian and North American sources of ice-rafted detritus (IRD) seen in core P1 is the first indication of a millennial-scale net change in surface currents older than those documented for the past half-century in the western Arctic Ocean [Proshutinsky and Johnson, 1997]. The modern reversals in ice drift occur on a decadal time scale and are probably linked to the Arctic Oscillation. When a -AO dominates the Beaufort Gyre is stronger and the drift to P1 is primarily from northern Canada (Figure 1). When a +AO dominates, the Trans-Polar Drift moves closer to the P1 site, bringing with it sea ice from Russia.

Because small amounts of Fe oxide grains from both the Laptev Sea and Canadian sources occurred throughout P1, the possibility exists that there is a more frequent switching, perhaps analogous to the decadal scale reversals of surface drift in this area over the last 50 years [Proshutinsky and Johnson, 1997]. However, sediment records with much higher sedimentation rates will be needed to demonstrate such decadal-scale oscillations.

Environmental Changes

In addition to the fluctuations in surface circulation, the P1 record reveals dramatic postglacial changes in surface and benthic environmental conditions. One of the more striking trends is the substantial increase in preserved organic carbon in the earliest Holocene (Figure 3). This record suggests substantially lower organic matter input to these sediments at the Pleistocene-Holocene boundary (2.2 m depth in P1), possibly as a result of lower marine productivity that was caused by a low salinity meltwater cap, coupled with decreased, coarse, glacial IRD influx and associated terrestrial organic matter. The calcareous foraminifers are rare and decrease to nil over this interval. There is a broad peak in agglutinated foraminifera, but even these disappear near the close of this apparently low productivity interval (see the following Web site for more data: http://web.odu.edu/webroot/orgs/SCI/colsciences.nsf/pages/ocean-darbypaleo). Peaks in Fe oxide grains from both the Mackenzie River and Russian rivers such as the Ob and Yenisey occur at this time, indicating large flood events or river ice discharges (Figure 3). This influx of fresh water into the Arctic Ocean coincides with changes in average sulfate/organic carbon ratios of 0.8-0.83, suggesting lower salinities that even approach values associated with fresh water sediments (see above Web site).

Organic carbon and biogenic silica are elevated between ~7.5-8 k.y. (Figure 3), suggesting that marine productivity was higher at this time than during the preceding glacial-postglacial transition. Overlapping and immediately preceding this increased biogenic flux to the sediments, the bulk sediment molybdenum/titanium (Mo/Ti) ratio peak (Figure 3) indicates anoxic sediments and possibly some association with slightly elevated levels of manganese oxides in the sediment. This Mo/Ti enrichment is similar to what is seen in the most recent sediments. Surface temperatures (SST) also underwent considerable change. Based on plankton remains (dinocysts) preserved in core P1, during the middle Holocene the August SST fluctuated by

![Fig. 2. Smectite clay and Fe oxide grains in core P1 are matched to specific source areas using microprobe chemical fingerprinting (Darby and Bischof, 1996). The smectite peaks (>25%) occur every 1-2 k.y. and are either coincident with elevated amounts of ice-rafted Fe oxide grains (>10%) from the Taymyr Peninsula (Laptev Sea) analogous to a -AO (arrows to right) or from the Chukchi Sea (arrows to left). When the smectite and Fe oxide grains are from the Chukchi Sea, there are also elevated amounts of Fe oxide grains from northern Canada (primarily Banks Island) and the drift scenario is analogous to a +AO. The percent of sand (>63μm) drops from an average of 8% in the Pleistocene to 1% in the Holocene, coinciding with a change from glacial ice-rafted IRD to sea ice IRD. The companion box core (B3, 50 cm in length) overlaps the piston core (P1) at 20 cm depth due to loss during piston coring. The 14C dates and a large peak in detrital dolomite at 25 cm in B3 and 5 cm in P1 confirm the overlap. The depths of radiocarbon age dates are indicated by "+".](Image)
5°C and was 3–7°C warmer than it is today (Figure 3). This magnitude of change is analogous to the polar front shifting more than 20° in latitude from its current location near the Aleutian Islands (50°N) to just north of Barrow, Alaska. Benthic calcareous microfossils—foraminifers and ostracodes—only appear after the early Holocene. This contention is corroborated by the PI record of bottom water conditions varied considerably during the Holocene. The variability in the benthic water proxies is not surprising given that the PI site lies near the sharp hydrographic boundary between the cold, fresh surface waters and the relatively warm, saline waters of the Atlantic Intermediate layer. The observed BWT oscillations at PI possibly resulted from fluctuations in the extent or temperature of the Atlantic layer. The warm pulses are perhaps analogous to the recent rapid and large (1–2°C) shifts in BWT superimposed on a net cooling of around 1°C since the mid-Holocene. The variability in the benthic water proxies is not surprising given that the PI site lies near the sharp hydrographic boundary between the cold, fresh surface waters and the relatively warm, saline waters of the Atlantic Intermediate layer. The observed BWT oscillations at PI possibly resulted from fluctuations in the extent or temperature of the Atlantic layer. The warm pulses are perhaps analogous to the recent rapid and large (1–2°C) shifts in BWT superimposed on a net cooling of around 1°C since the mid-Holocene.

Thus, the surface circulation and possibly the extent of the Atlantic-derived intermediate water appear to have changed several times during the Holocene. Our records indicate that Holocene variability in the western Arctic is larger than any change observed in this area over the last century. While recently observed polar warming is dramatic, the record of change in core PI suggests that mid-Holocene temperatures may have been 5°C warmer only a few thousand years ago. In this respect, future work should be focused on higher resolution climate records from the Arctic Ocean. The study of PI provides encouragement that even higher resolution records can be recovered from the upper continental slopes of this ocean.

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References


Imaging Spectroscopy Measures Desertification in United States and Argentina

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 Much international environmental research and policy development now focuses on desertification in arid and semi-arid ecosystems of the world. These "dryland" regions, which include most of the world's shrublands, grasslands, and savannas, cover nearly 45% of the Earth's land surface and support a large fraction of the world's food production. The U.S. Senate, along with 173 other countries, recently ratified the United Nations (UN) Convention to Combat Desertification [UNEPA, 1992], a multinational effort to address this pressing human and environmental problem [Showstack, 2001].

The U.N. describes desertification as "land degradation in arid, semi-arid and dry sub-humid areas (drylands) resulting mainly from adverse human impact. It is a widespread but discrete spatial process of land degradation throughout the drylands that is quite different from the phenomenon of observed cyclic oscillations of vegetation productivity at desert fringes ("desert expansion or contraction") as revealed by satellite data and related to climate fluctuations. At present desertification directly affects about 3.6 billion hectares—70% of the total drylands, or nearly one quarter of the total land area of the
Fig. 1. Modern Arctic surface circulation (white dashed arrows) dominated by the Trans-Polar Drift (TPD) and the weaker Beaufort Gyre (BG) is shown, superimposed with competing drift patterns for a positive Arctic Oscillation (+AO) scenario (red) and a -AO (black). Core P1 is centrally located to record changes in these two major drift patterns as well as northward drift from the Bering Strait (dashed black). Important source areas during -AO and a stronger BG include the shelf off Banks Island (BI) and the Mackenzie River.