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Researchers explore Arctic freshwater's role in ocean circulation

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tions, make the acquisition of satellite data with high spatial resolution from instruments such as Landsat-7 and Ikonos a problem. Data from new instruments such as the Moderate Resolution Imaging Spectroradiometer (MODIS), which have a higher spatial resolution than AVHRR and a repeat coverage of one to two days, may be very useful for monitoring local and regional environmental conditions.

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Researchers Explore Arctic Freshwater's Role in Ocean Circulation

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A critical, but insufficiently understood, component of global change is the influence of Arctic freshwater input on water mass exchange between the Arctic Ocean and Atlantic and Pacific Oceans. Four of the Earth's 10 largest river systems, the Mackenzie, Ob, Yenisei, and Lena, contribute water to the Arctic shore (Figure 1) from a vast watershed that drains continental interiors. This river discharge flows into the world's largest contiguous continental shelf and supplies over 50% (1823 km^3) of the riverine input to the Arctic Ocean.

Another equally significant freshwater source is inflow through the Bering Strait. Much of this freshwater is transformed to sea ice on the shallow (< 150 m deep) Arctic continental shelf and comprises up to 10% of the surface waters of the Transpolar Drift Stream (Figure 1). Variations in sea ice flux from the Arctic to the North Atlantic Ocean are known to cause major changes in the thermohaline circulation. For example, the great salinity anomaly of the 1970s is a testimony to the sensitivity of the system to relatively modest changes in freshwater flux from the Arctic [*Belkin et al.*, 1998]. Even larger fluxes of freshwater occurred during the past 20 kiloyears (k.y.) from the Arctic ice sheet (for example, Heinrich events) and river sources that triggered major changes in thermohaline circulation and ventilation of the Arctic Ocean [*Andrews*, 1998].

The Arctic Ocean and fringing shelf seas, more than any other marine system, were affected by changes in bathymetry during the last glacial-deglacial cycle, which occurred from 20 k.y. to 6 k.y. ago. Ice sheet coverage and isostatic and eustatic changes in sea level led to variations of tens to hundreds of meters in the bathymetry of straits, channels, and shelves that border the Arctic Ocean. These changes in ocean basin geometry must have caused large-scale shifts in water-mass exchange between the Arctic Ocean and Atlantic and Pacific Oceans, thus affecting thermohaline circulation and Arctic halocline formation. However, the influence of altered ocean depth thresholds and Arctic freshwater inputs on documented changes in the Atlantic and Pacific Oceans remains largely unknown.

To assess the role of Arctic freshwater inputs and bathymetry variations in global hydrologic change via integrating paleo-data with watershed and ocean models, a workshop sponsored by the National Science Foundation drew 30 diverse scientists to Monterey, California, in early October 1999. This group of oceanographers, paleoceanographers, oceanographic, sea ice and watershed modelers,

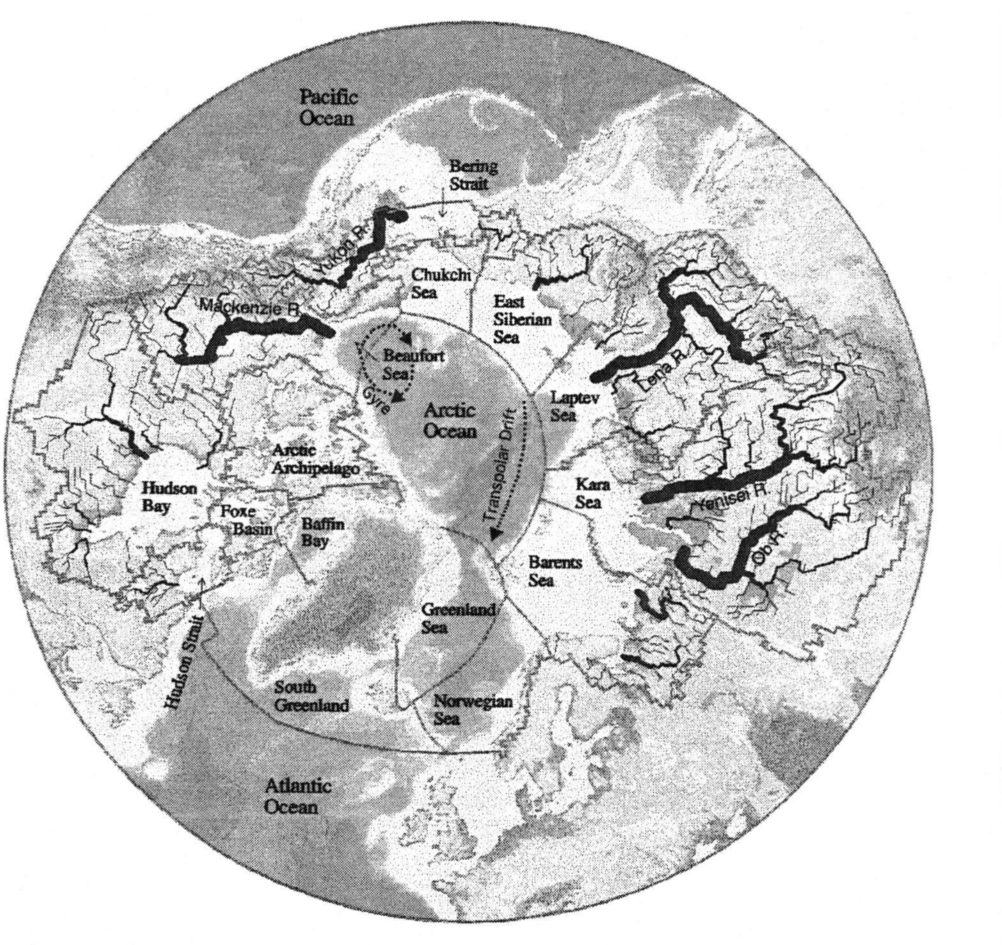

Fig. 1. The Arctic "half hemisphere" showing oceans, shelf-seas, and catchment areas for Arctic rivers. Blue line thickness of rivers represents relative river run-off (courtesy of R. Lammers and B. Peterson). Original color image appears at the back of this volume.

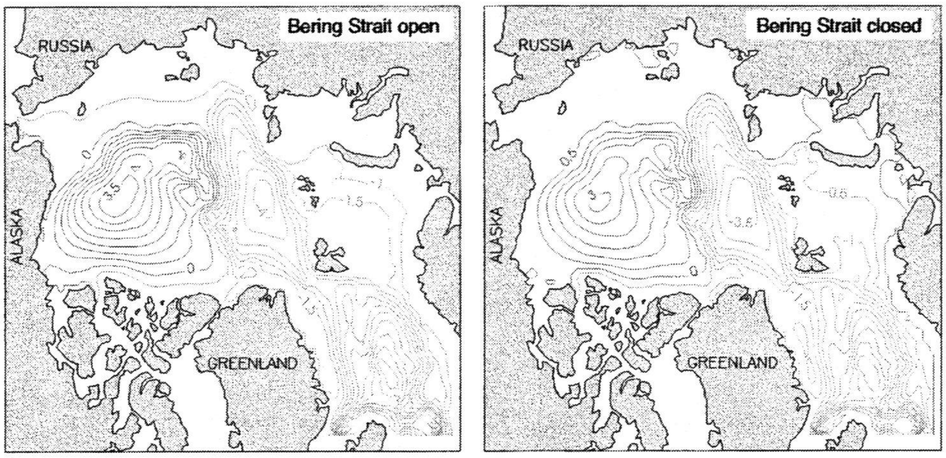

Fig. 2. Preliminary ocean mean vertically integrated mass transport stream function (Sv) with the Bering Strait open and closed, which needs to be verified with additional modeling. The clockwise circulation in the Beaufort Gyre is reduced when the Bering Strait is closed as a result of decreased inflow of freshwater into the center of the gyre. Also, there is more inflow of warm Atlantic Water through the Fram Strait and less into the Barents Sea when the Bering Strait is closed. Because Fram Strait inflow is warmer, this leads to a warming of intermediate water masses in the Arctic Ocean (courtesy of M. Steele and J. Zhang). Original color image appears at the back of this volume.

and Quaternary scientists explored the complex effects on global ocean circulation of eustatic and isostatic changes in sea level, ice sheet coverage, melt-water inputs, river discharge, and variable sea-ice dynamics in the Arctic over the past 20 k.y.

Participants highlighted recent advances in oceanographic and watershed modeling that have improved simulations of Arctic Basin ocean circulation, sea ice flux, and river discharge. Watershed models are pan-arctic with temperature, precipitation, soil type, and vegetation amongst critical boundary conditions and provide output of runoff or river discharge. Ocean circulation models are global in coverage and vary in scale from 2° x 2° to a 9-km grid with 45 ocean levels resolved. Higher resolution models (< 50-km grid) provide enhanced simulations with details of bathymetry and circulation processes. The workshop participants concluded that enhanced integration between atmosphere, watershed, and ocean models is needed to forward understanding of hydrologic paleoclimate drivers and to improve predictive capabilities. Specifically, the performance of ocean, sea ice, and watershed models needs to be further evaluated with altered boundary conditions during "extreme" climate events such as the Last Glacial Maximum, meltwater-dominated periods (for example, Younger Dryas), neoglaciation, and warm periods such as the early Holocene (ca. 9 k.y.). Evaluating model performance for these paleo periods provides needed tests of model veracity to predict future changes.

The Last Glacial Maximum is a favored period for oceanographic modeling because the limits of ice sheets, sea-ice, and sea level are relatively well known and provide extreme conditions for assessing the operation of ocean and watershed models. However, glaciation of the Barents Sea and Canadian High Arctic Island channels restricts Arctic water mass exchange. Workshop presentations indicated that with a glaciated North American continent and much of Eurasia in the rain-shadow of the European ice sheet, freshwater delivery by Arctic rivers was diminished by ~50%. The vast expanse of the Eurasian and Alaskan Arctic continental shelves remained glacier-free and was exposed during the last glaciation, when global sea level fell by ~120 m. The exposure of up to 30% of the worlds continental shelf during the last glaciation certainly shifted the loci of sea ice formation from the shelf to the Arctic Ocean and may have reduced the lateral ventilation of the Arctic Ocean.

Understanding the effect of sea level change on the shallow (50 m deep) Bering Strait is critical. The Strait remained closed during the last glaciation and only reopened 11-12 k.y. ago. However, the relative sea-level history of the Bering Strait remains poorly constrained. Available ^{14}C ages on terrestrial macrofossils from Bering Strait marine records underscore the paradox [*Elias et al.*, 1996], with apparent reconnection of the Bering Strait about 1000 years earlier than predicted by eustatic records [*Fairbanks*, 1989].

The reopening of the Bering Strait has been associated with strengthening of Younger Dryas cooling in the North Atlantic, because renewed Pacific water input displaced Arctic sea ice-bearing waters into the North Atlantic [*Duplessey et al.*, 1996]. This mechanism has been countered by global ocean modeling, which shows that opening of the Bering Strait led to a 2 Sv increase in North Atlantic inflow to the Nordic Seas [*Reason and Power*, 1994]. However, higher resolution (40 km) modeling preformed in response to the workshop indicated a more complex response of the ocean system (Figure 2). This model shows that closing of the Bering Straits weakens the Beaufort Gyre and causes a compensatory increase in meridional transfer of North Atlantic waters into the Arctic Ocean through Fram Strait at the expense of flux into the Barents Sea.

There is a clear need for additional oceanographic modeling to examine thresholds for dynamic connection between the Pacific and Arctic Oceans through the Bering Strait and compensatory effects in the North Atlantic Ocean. A number of participants highlighted that large meltwater and iceberg releases ($>10^5$ km^3) occurred during many intervals between 16 k.y. and 10 k.y. from ice sheets that fringe the North Atlantic and Arctic Oceans. This large influx of freshwater, some of which is associated with Heinrich events, generally suppressed thermohaline circulation and shifted convection loci southward. However, there were periods when freshwater stratification was not maintained and surface productivity increased dramatically with periodic incursions of North Atlantic surface waters to 80°N [*Doken and Hald*, 1996]. This complex interplay between meltwater fluxes and variable input of North Atlantic water is ripe for modeling by the oceanographic community.

Uncertainty persists as to whether the last Eurasian ice sheet partially or completely blocked discharge of the Ob and Yenisei Rivers. Recent field research indicates that an ice sheet or ice cap situated in the northern Kara Sea had terminated on Taymyr Peninsula (C. Hjort, pers. comm., 1999). Drainages in northern Siberia might have been blocked if a contiguous glacier system existed in the northern Kara and Barents Seas, creating a proglacial lake system that diverted water from the Arctic Ocean.

Sediment core records from the Laptev Sea continental slope, presented at the workshop by H. Bauch, document a prominent negative oxygen isotopic excursion (~1.5%) between ~13 k.y. and 11 k.y. that may herald the breaching of this proglacial lake. Additional marine and glacial geologic research is critical for constraining the ice sheet and fluvial dynamics of northern Siberia. Model exercises that trace the transformation of large freshwater fluxes from Eurasian rivers or proglacial impoundments are needed to ascertain effects on the Arctic halocline.

In many Arctic areas, summer temperatures of ~10 k.y. to 7 k.y. ago exceeded current conditions. This warming was particularly striking in northern Eurasia, where the tree line advanced hundreds of kilometers northward, concomitant with degradation of permafrost. Questions remain as to whether this distinct warming in the Arctic solely reflects elevated insulation values, or whether it resulted from additional amplification by increased oceanographic heat transport with glacio-isostatic deepening of North Atlantic pathways. The Barents Sea is the only continental shelf in northern Eurasia that sustained a 1-2+ km-thick ice sheet during the last glaciation [*Forman et al.*, 1999]. The glacio-isostatic response, rather than eustatic effects, dominates Holocene relative sea level in this formerly glaciated area.

Upon deglaciation at ~10 k.y., the Barents Sea, which now has a mean water depth of 230 m, was deepened by about 100 m, reflecting remnant isostatic compensation. The shelf progressively shallowed into the Holocene with ~90% of rebound completed by 6 k.y. Circulation in the Barents Sea is largely controlled by bathymetry, with North Atlantic water confined to depths of >200 m. Thus the postglacial deepening of the Barents Sea should have increased the trajectory of North Atlantic inflow into the European Arctic. Increased North Atlantic input into the Barents Sea would have changed the production of Arctic intermediate water, the outflow of Arctic water at depth, sea-surface productivity, and sea-ice distribution.

Warmer sea-surface temperatures in Nordic seas may have "locked" atmospheric circulation in a negative Arctic Oscillation configuration [*Thompson and Wallace*, 1998], thus pumping moisture and warmth into Siberia. A mode shift in the climate system is supported by the paleohydrologic inferences of Eurasian rivers—presented at the workshop by J. Syvitski—which indicate a ~25% increase in discharge for the early Holocene. During the last glaciation, the Innututian Ice Sheet extended across the islands and channels of the Canadian Archipelago and curtailed the exchange of water between the Arctic Ocean and Baffin Bay. With deglaciation, glacio-isostatic adjustment induced large bathymetric changes in the High Canadian Arctic that increased the volume of the Arctic seas. The sill depths of the inter-island channels in the Canadian Archipelago deepened by 60–160 m with deglaciation from west to east between 9.0 to 7.5 k.y. The deepening of these channels increased the surface water flux between the Arctic Ocean and Baffin Bay. Currently about 0.5–1.5 Sv flows from the Arctic Ocean through these channels, but in the early to middle Holocene the outflow would have increased substantially; the compensatory effects on North Atlantic Ocean circulation remain unknown.

The participants agreed that models of varying resolution should be employed to explore the effects of changing bathymetry and freshwater input on global change. Coarser grid global models (1° x 1°) are suitable for examining how changes in ocean basin bathymetry and closing and opening of the Bering Straits cause large-scale water mass exchange between oceans; however, finer-scale models (for example, 10–20 km grid) are needed to understand and parameterize physical processes controlled by small bathymetric features (for example, Canadian Arctic Archipelago channels) and resolve large-scale boundary currents, eddies, and tidal processes that are critical for water mass formation and exchange.

A clear conclusion of the workshop is that atmosphere, ocean, sea ice, and Arctic watershed models must be integrated to better track the exchange of water and energy. This is particularly important for future predictions because warming in the Arctic has been associated with increased terrestrial precipitation [e.g., *Cattle and Crossley*, 1995], which has clear feedbacks on the Arctic halocline and thermohaline circulation.

The workshop—Assessing Impacts of Arctic Bathymetry Changes and Freshwater Inputs on Shelf and Ocean Circulation for the Past 20,000 Years—was held October 1–2, 1999, at the Naval Postgraduate School in Monterey, California, USA.

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Innovative Software Facilitates Cyclone Tracking and Analysis

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The need for research and development of new cost-efficient methods for tracking and analyzing atmospheric cyclones is apparent. Currently, storm tracking is performed either manually or using numerical codes. The manual approach is more accurate but it requires considerable time and labor. Numerical schemes [e.g., *Murray and Simmonds*, 1991] track the cyclones from digital sea level pressure (SLP) data, linking the sequential positions of cyclone centers using different assumptions based on atmospheric dynamics. This approach is very effective computationally, but it creates a number of uncertainties and biases, especially in the Northern Hemisphere.

The software—free of charge to the user—is intended to merge the advantages of both approaches; that is, it simulates the manual tracking procedure, but makes it faster and less dependent on the operator who has a subjective view and the potential for errors. The interactive storm tracking system (ISTS) software is based on computer animation of SLP fields. It was developed as an application for Microsoft Windows 95/98/NT and behaves as any Windows application. Effective operation of the software requires a Pentium platform with 16 MB RAM running under Win-95/98/NT. The software contains the animation system, tracking engine, and visual applications for the analysis of results.

The animation system supports interactive access to the value beyond the color. It provides the opportunity to effectively animate sequential fields of digital data in a rectangular domain. Data are presented in a specially designed format that stores the physical values as 2 byte binary integers. Converters for the most recognized formats (netCDF, GRIB) may be easily prepared. The tracking algorithm first defines the cyclone centers using the user-selected approach. Then the mouse buttons are used to link the centers into the cyclone tracks. The mouse clicks automatically imply the number of cyclone centers, with the current pointer unique number appearing on the screen in the clicked point. Up to 20 different cyclones can be tracked simultaneously. By the end of each individual cyclone track, the information for the current track (coordinates, date/time, and the corresponding SLP values) is saved as an ASCII file upon request by the operator. This file can then be

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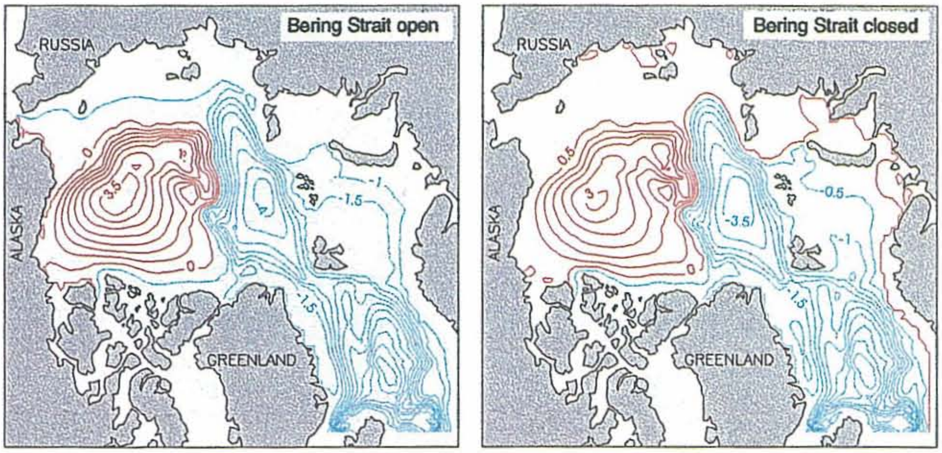
Fig. 1. The Arctic "half hemisphere" showing oceans, shelf-seas, and catchment areas for Arctic rivers. Blue line thickness of rivers represents relative river run-off (courtesy of R. Lammers and B. Peterson).



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