Witness The
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Arctic Research at Lamont-Doherty Earth Observatory

Early Years of Lamont Research in the High Arctic

Columbia University's Lamont-Doherty Earth Observatory (LDEO) entered the arena of arctic research more than four decades ago, when the Alaskan Air Command established Drifting Station A (or Alpha) on a 3 m-thick ice floe at 83° N 165° W. Station A was a U.S. contribution to the International Geophysical Year in 1957.

Lamont scientists under the general direction of Jack Oliver and field leadership of Ken Hunkins conducted a program of geophysical and oceanographic research at the station, while investigators from other institutions carried out programs of upper atmosphere, meteorological, sea-ice, and biological research. The Lamont program used many instruments and techniques that had been developed by Doc Ewing and other Lamont scientists for exploration of the open oceans, modified for use from the ice camp. Important results included the following:

- echo soundings mapped the Alpha Rise and Canada Abyssal Plain;
- measurements of currents yielded the first direct observations of the Ekman spiral, which had been predicted 50 years earlier;
- the first seismic refraction lines in the Arctic Ocean led to understanding of the upper crustal structure in the region;
- the first bottom photographs ever taken in this ocean showed the life and ice-rafted rocks on the ocean floor; and
- a new understanding of wind-driven motion of the ice pack was obtained.

Other ice camps, most led by Ken Hunkins, followed:

- Drifting Station Charlie led by George Cvijanovich;
- Fletchers Ice Island (T-3) from 1962–1974;
- the Arctic Ice Dynamics Joint Experiment (AIDJEX) ice camps in the 1970s;
- the Fram Expeditions in 1979.

The first Arctic Ocean precision depth recorder and nuclear magnetic resonance magnetometer measurements were made from Drifting Station Charlie. New instruments, such as the first satellite

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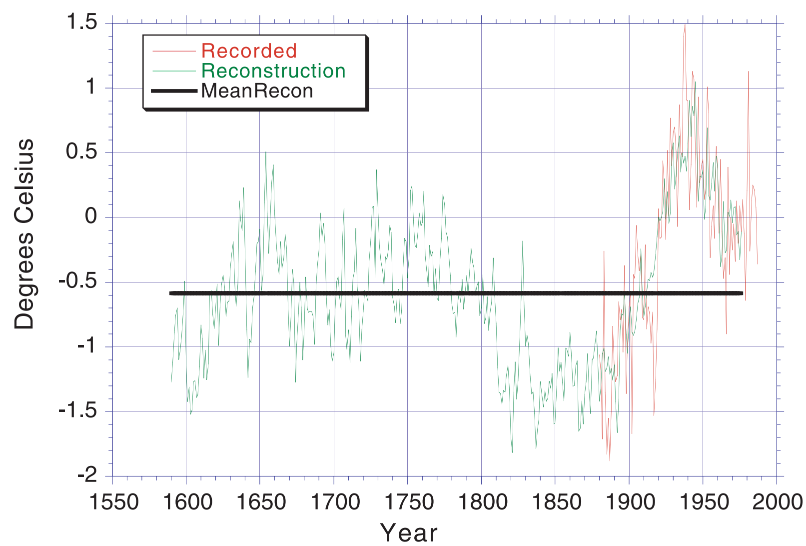

Lamont researchers have reconstructed annual temperatures for the arctic zone (65–90°N) during the past 400 years using tree-ring width data from 12 sites near circumpolar treeline and three sites at northern, elevational treeline. Ten or more trees were sampled at each site. At all the sites, annual growth is limited by temperature. The regression used principal component analysis to reduce the number of predictors and one forward lag of the series to account for carryover effects of temperature on tree growth. The regression explains 66% of the variance in temperature after adjustment for degrees of freedom lost due to the regression. The tree-ring reconstruction helps quantify the unusual warming that is reflected in other arctic investigations. This and similar reconstructions provide a long-term context for interpreting present changes in arctic regions (figure by Gordon Jacoby).

Lamont-Doherty Earth Observatory conducts a wide range of research in the Arctic and high-latitude regions of the northern hemisphere. These studies began in 1957 with support from the U.S. Air Force Cambridge Research Center and, soon thereafter, the Office of Naval Research (ONR). Support for recent and current research is provided by ONR, the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), the Department of Energy (DOE), *National Geographic*, Palisades Geophysical Institute, the Geological Survey of Canada, and the NSF Office of Polar Programs, Ocean Sciences program, Climate Dynamics program, and Earth System History program.

navigator—which was a classified system at the time—and a seismic sparker, led to extensive mapping of Arctic Ocean bathymetry and sediment layers from T-3. Simultaneous profiling of temperature, salinity, and currents at an array of four AIDJEX camps revealed 127 separate subsurface anticyclonic eddies at depths of 50-300 m. These eddies were approximately 10 km in diameter and covered nearly 25% of the Beaufort Sea. Helicopter surveys conducted from the Fram Expedition ice camps revealed anomalous diurnal tidal currents over the Yermak Plateau. The ice-camp studies were followed by the Marginal Ice Zone Experiment in 1983–84 and the Cooperative East Arctic Research Expedition in 1988–89, which gave new results on the behavior of oceanographic exchange through Fram Strait.

Paleoclimate Studies—Tree Rings

Gordon Jacoby and Rosanne D'Arrigo of the Tree-Ring Laboratory at Lamont have been collecting samples at northern treeline (70°30' N) for more than two decades. In 1989, the first reconstructions of large-scale temperature were published. Since then, Lamont scientists and others have incorporated these data in many reconstructions of northern hemisphere and arctic temperature history. Ongoing studies in Alaska and the Taimyr Peninsula, Siberia are producing new data for improved reconstructions and information about climatic and ecological changes in the Arctic. The Siberian studies, coordinated with Russian scientists, are producing millennial-length records by using living, relict, and subfossil samples from the northernmost trees on the planet.

Paleoecology

The Paleoecology Lab at LDEO has a history of research on Quaternary climate and vegetation history along the southern coastline of Alaska. Projects led by Dorothy Peteet, also at NASA's Goddard Institute for Space Studies (GISS), have used high-resolution pollen, macrofossil, and radiocarbon dating of lake and peatland sediments. Peteet has focused particular attention on migration rates of spruce, western hemlock, and mountain hemlock along the south-central Alaskan coastline from Yakutat to Kodiak Island.

Recent proposals have centered on the Bering-Steller Glacier region, where new results point to advances and retreats of this glacier throughout the Holocene. Research on Kodiak Island led to the discovery of the "Fern Gap", a Younger Dryas equivalent, pointing to the dramatic role of this abrupt climate change in the North Pacific.

More recent research on the paleoecology of the Mesa Site, on the North Slope of Alaska, shows that peat formation signals major environmental change in the Arctic. Peteet, in collaboration with A. Andreev (Institute of Geography, Moscow), has also led peatland research in Siberia and published results from the Pur-Taz region of western Siberia. In collaboration with GISS modelers Anthony Del Genio and Ken Lo, Peteet is continuing sensitivity tests of climatic forcing based on the paleoenvironmental results from the Arctic and sub-Arctic.

Ice cores contain detailed records of paleoclimate, including large and abrupt changes in atmospheric dust. Dust found in polar ice cores can vary in amount by more than two orders of magnitude. Pierre Biscaye and Francis Grousset are investigating the continental origins of the dust as indicators of past atmospheric change. Their approach has been to measure characteristics of the dust that may identify source areas. The tracers are:

- clay mineralogy, which is dependent on the climate; and
- Sr-, Nd-, and lead-isotope composition, which are related to the rock type and geologic age of the rocks from which the local sediments in the source area were derived.

In collaboration with Danish colleague Anders Svensson, Biscaye and Grousset have applied this approach to dust from the two ice cores retrieved from the Greenland summit (see *Witness* Spring 1997), which hold records of the past 110,000 years. The deserts of Eastern Asia are the source of the Summit dust. The researchers propose that if the source area of the dust has not changed significantly in size or location despite severe changes in global climate and dust flux, then variations in the amount of dust found in the cores must be the result of changes in the intensity of winds in the source area. Dust extracted from snow deposited over the past decade also seems to have been derived primarily from Eastern Asia. To further pin down the provenance of the dust and its degree of change, the researchers are continuing to analyze source-area samples from as many northern hemisphere locations as possible.

Oceanic Uptake of Carbon Dioxide (CO_2)

Since 1983, Lamont's Ocean CO_2 Group, headed by Taro Takahashi, has been collaborating with Jon Olafsson (Marine Research Institute, Reykjavik, Iceland) for field studies aimed at understanding seasonal and interannual changes in CO_2 and nutrient chemistry and in CO_2 uptake in waters of the Irminger, Iceland, and Norwegian seas.

In 1993–1995, researchers observed that the concentrations of CO_2 and nutrients were drawn down by phytoplankton blooms in mid-April through July. Concentrations of silicate, nitrate, and phosphate in surface water dropped from high winter values to nearly zero. Total CO_2 concentration was also drawn down at the end of blooms. As a result, the partial pressure of CO_2 (pCO_2) in surface water also dropped from 3% under-saturation in winter to approximately 24% under-saturation at the height of blooms.

Thus, the oceans near and north of Iceland become strong CO_2 sinks during spring through summer months. The strong drawdown of surface water pCO_2 is one of the major processes causing the high-latitude North Atlantic and its adjacent seas to be a major sink of CO_2 in the global oceans. To document interannual changes, the field study is continuing in collaboration with research groups in Iceland and other Nordic countries.

Heat Flux and Ice Studies

With the Surface Heat Budget of the Arctic (SHEBA) project (see *Witness*, this issue), Lamont has continued its long tradition of ice-camp work in the Arctic. Doug Martinson is a co-principal investigator in the upper ocean physical oceanography component of SHEBA. Martinson, Miles McPhee (McPhee Research), Tim Stanton (Naval Postgraduate School), and Jamie Morison (University of Washington) are investigating the detailed hydrographic structure of the upper 150 m of the Arctic Ocean and how it evolves seasonally from continuous CTD profiles.

Some of the early findings include:

- unusually fresh surface water, and
- unusually thin ice compared to data collected during the AIDJEX project in the 1970s.

Jay Ardai served as chief scientist of the SHEBA ice camp during some of the winter months; Jay had also played an integral role in the work of many previous ice camps, beginning with T-3.

Most recently, Martinson and Mike Steele (University of Washington) have employed in the Arctic techniques that were developed in the Antarctic for estimating ocean-ice heat fluxes. Steele and Tim Boyd (Oregon State University) documented the loss of the near-surface cold halocline layer (CHL) in the 1990s—a significant change in the upper ocean of the eastern Arctic. Martinson and Steele have shown that, without the CHL, the arctic water column looks and behaves like the Antarctic water column, with significant winter ocean heat fluxes (15–20 watts/m^2) and reduction of winter ice growth by 70–80% relative to previous years when the CHL was present. If the CHL absence continues with no compensating changes in atmospheric forcing or ice advection, the long-term stability of the perennial ice pack will be in question.

Freshwater Sources and Circulation

The Arctic receives approximately 10% of the total global river runoff. Freshwater is also supplied by sea-ice meltwater and by the relatively fresh Pacific Water (Bering Strait) inflow. Export of these large volumes of freshwater through Fram Strait and the Canadian Archipelago may influence deep water formation in the Greenland and Labrador seas, which may in turn affect global climate.

Peter Schlosser, Brenda Ekwurzel, and Gerhard Boenisch use the distribution of mass, salt, oxygen isotopes, and nutrients

- to determine sources of freshwater; and
- to estimate the respective proportions of the total volume in the surface waters of the Arctic Ocean.

Their goal is to understand the vulnerability of Arctic Ocean circulation to changes in the freshwater budget. Comparison of ^{18}O data collected in the Eurasian Basin in 1991 and 1996 indicates a shift in river-water transport from the Eurasian Basin to the Canadian Arctic.

Large-scale general circulation models for the Arctic Basin are being used by Schlosser and Bob Newton in collaboration with Wieslaw Maslowski (Naval Postgraduate School) to further understand the freshwater balance in the Arctic Ocean. These models are forced with the ECMWF re-analysis winds for the 1979–1993 time period and are fit to the temperature, salinity, and ^{18}O observations. The redistribution of fresh water indicated by the ^{18}O data has been simulated by the model.

USS Pogy, *surfaced in the Arctic Ocean, enabling a hydrocast from the adjacent ice during the SCICEX '96 expedition. Lamont principal investigators have been extensively involved in the multidisciplinary scientific projects carried out on these cruises. The late Marc Langseth chaired the scientific steering committee for the first cruise in 1993, and Jay Ardai, Dale Chayes, Bernie Coakley, and Ray Sambrotto have sailed on the two-month long submarine voyages (photo by Ray Sambrotto).*

Water Mass Formation and Circulation

Bill Smethie and Peter Schlosser have been measuring a variety of trace substances in the Greenland-Iceland-Norwegian (GIN) seas since the early 1980s and have participated in numerous icebreaker expeditions to the Arctic Ocean (*Polarstern, Louis St. Laurent, Oden, Polar Sea, Polar Star*) from the mid-1980s to the present. In collaboration with European colleagues (Reinhold Bayer, Markus Frank, Hugo Loosli, and Bernd Kromer), Smethie obtained chlorofluorocarbon (CFC) measurements, and Schlosser obtained $^3H/^3He$, ^{14}C, and ^{39}Ar measurements from much of the Eurasian Basin and parts of the Makarov and Canadian basins. In 1993, both investigators collected data from the first Scientific Ice Expedition (SCICEX) submarine cruise (see *Witness* Spring 1996), and they continue to participate in these annual cruises under the heavily ice-covered central Arctic Ocean (see *Witness,* this issue).

The early 1980s GIN seas studies showed that:

- deep convection renewed the deep Greenland Sea on a time scale of approximately 30 years; and
- the exchange rate of water between the deep GIN seas and the deep Arctic was about 1 Sv (10^6 m^3s^{-1}).

More recent studies by Schlosser, Boenisch, Doug Wallace (University of Kiel), and John Bullister (NOAA/PMEL) have revealed that renewal of the bottom water by deep convection ceased in the early 1980s, with the deep water evolving toward deep Arctic Ocean characteristics. Ocean studies by Smethie and Schlosser have shown that:

- the upper mixed layer beneath the ice cover is renewed on a time scale of 5–10 years, based on $^3H/^3He$ measurements;
- the flow pathways of the two branches (Fram Strait and Barents Sea) of Atlantic-derived intermediate water are clearly seen in the $^3H/^3He$ and CFC data. Both branches follow the bathymetry in a cyclonic flow pattern that extends along the Lomonosov Ridge and across the ridge into the Canadian Basin, reaching the central and southern Canadian Basin in 15–20 years; and
- the deep and bottom water renewal times, based on ^{14}C and ^{39}Ar data, are approximately 450 years for the Canadian Basin and 200 years for the Eurasian Basin.

Arctic Contaminants

Stephanie Pfirman, Peter Schlosser, Bob Newton, Bill Smethie, and Bob Anderson are investigating potential pathways of contaminants in the Arctic in collaboration with Roger Colony and Hajo Eicken (University of Alaska Fairbanks), Ignatius Rigor (University of Washington), and Wieslaw Maslowski (Naval Postgraduate School).

Modeling and field programs have investigated the origin and fate of drifting multiyear sea ice and its role in transporting contaminants across the Arctic Basin. The researchers are reconstructing the age, origin, and trajectory of sea ice based on tracer analysis of cores from the ice and comparison with predicted backward trajectories. Research on the potential for transport of contaminants by ocean currents includes modeling and tracer geochemistry (^{85}Kr, CFCs, ^{3}H/^{3}He, d^{18}O) to investigate likely pathways and residence times.

Both sea-ice trajectories and surface and near-surface currents show marked interannual variations forced by changes in the atmospheric circulation, which will impact the fate of entrained contaminants. For example, observations and modeling (in collaboration with Maslowski) show that fresh water and any dissolved agricultural or industrial contaminants discharged by rivers have recently been taking a more easterly path than they did before the late 1980s.

Marine Biology

Raymond Sambrotto has been working to clarify the sources and sinks of carbon in the western Arctic. Sampling for the inorganic and organic carbon pools was conducted along the Arctic Ocean Section in 1994 and on SCICEX submarine cruises. The goals are:

- to better define the size of the various carbon pools in arctic waters, and
- to clarify how this carbon is redistributed beneath arctic ice.

The unusual arctic conditions create a situation in which the flux of carbon in its deep basins may be dominated by horizontal as much as by vertical processes. Sampling from the Arctic Ocean Section provided data from the eastern side of the Canada Basin, while submarine samples provide additional data from these regions, as well as parts of the Beaufort Sea and western Canada Basin. Sampling extends into waters of intermediate depth and focuses on the upper halocline that is derived from various inputs, including river discharge and modified shelf water. Researchers are trying to identify the amount of carbon entering the halocline from the various sources, based on alkalinity and other tracers for river water.

Chris Langdon has been measuring oxygen concentrations from underway sensors on the SCICEX cruises as well as on-board Winkler titrations. Variations in oxygen are useful in sorting out the importance of locally produced *vs.* advected carbon respiration. Such distinctions are critical for understanding the Arctic's role in the carbon cycle and how this may change with a reduction of ice cover.

Marine Geology and Geophysics

Since 1995, the U.S. Navy has provided a Sturgeon Class fast attack submarine for an annual unclassified SCICEX cruise in the Arctic Ocean (see *Witness*, this issue). The quiet, stable submarine provides an ideal platform for the efficient acquisition of underway geophysical data. James Cochran and Bernard Coakley have used SCICEX geophysical data to investigate the structure of the Gakkel Ridge—the slowest-spreading section of the global mid-ocean ridge system (at 0.6–1.3 cm/yr). Analyses of SCICEX gravity and bathymetry profiles across the Gakkel Ridge clearly show that:

- the crustal thickness on the ridge must be less than 3 km; and
- extensive areas with no crust, or very thin crust, may exist.

This result places important constraints on models of melt production and migration at mid-ocean ridges. Dale Chayes, in collaboration with Margo Edwards (University of Hawaii), has led the effort to create a unique set of active sonar instruments for SCICEX missions. The Seafloor Characterization and Mapping Pods (SCAMP) includes:

- an arctic-optimized SeaMARC™-type Sidescan Swath Bathymetric Sonar;
- a swept frequency ("chirp") High Resolution Sub-bottom Profiler;
- a gravimeter; and
- a Data Acquisition and Quality Control System.

SCAMP was installed and tested on the *USS Hawkbill* during SCICEX '98. Data were collected along approximately 3,300 km of the Gakkel Ridge. Two segments totaling 250 km were mapped out to 50 km on either side of the ridge. SCICEX '99 completed mapping the western portion of the Gakkel Ridge and studied the structure of the Lomonosov Ridge.

High-Latitude Mantle Studies

Lavas that erupt at ocean-ridge spreading axes are windows into the composition of the shallow mantle. Iceland is the largest mid-ocean ridge mantle plume. Steve Goldstein and German colleagues K. Haase (University of Kiel) and C. Devey (University of Bremen) are conducting a petrological and geochemical study on the Kolbeinsey spreading ridge north of Iceland (69°–72° N) to investigate relationships between mantle flow, mixing processes, and magmatic processes forming the oceanic crust near a mantle plume. The spreading ridges near Iceland represent extremes in the global variations of water depth, crustal thickness, and major element compositions. Recently erupted glass has been sampled at a spatial resolution of 2–4 km, the highest for any mid-ocean ridge segment.

The study will generate a comprehensive set of major trace element and isotopic data (Sr, Nd, Pb, He). While chemical variations are affected by the melting and cooling of magma/rock, isotope ratios are not; they "see through" these processes and trace the spatial distribution of the source rocks that melt to form the magmas. The combination of chemical and isotopic data for samples collected with such a high spatial resolution will make this the most comprehensive regional geochemical data set available for a ridge segment, and it will be a unique resource for geophysical and geochemical modeling of melting and mantle flow.

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