The LAII Program: Land–Atmosphere–Ice Interactions

Biocomplexity in the Arctic Terrestrial System

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LAII stands for Land–Atmosphere–Ice Interactions. It, along with OAII (Ocean–Atmosphere–Ice Interactions), was one of the first components of the Arctic System Science (ARCSS) program at the National Science Foundation (NSF). The focus of LAII has been primarily on understanding the role of the terrestrial system in Arctic change.

For historical reasons, studies during the initial phases of LAII focused primarily on tundra and its role in the Arctic carbon budget, yet shrub tundra and boreal forest cover a significant percentage of the Arctic as well. Consequently, in recent years LAII research has expanded to include these ecosystems. Additionally, as we have come to recognize the unprecedented changes taking place throughout the Arctic, the geographic scope of the program has had to expand, extending from Alaska to the entire pan-Arctic. LAII focus, too, has broadened from carbon exchange to the exchange of energy and moisture, with some research now addressing the impact of the changing Arctic on animals and human society.

At the time of this writing, LAII is poised once again to evolve in response to new science questions and issues. A science plan has just been released for a new program called PACTS (Pan-Arctic Cycles, Transitions and Sustainability), which focuses on the vulnerability of Arctic systems and the costs of sustaining Arctic human, animal, and plant systems.

Aerial view of tundra and ice wedge polygons.

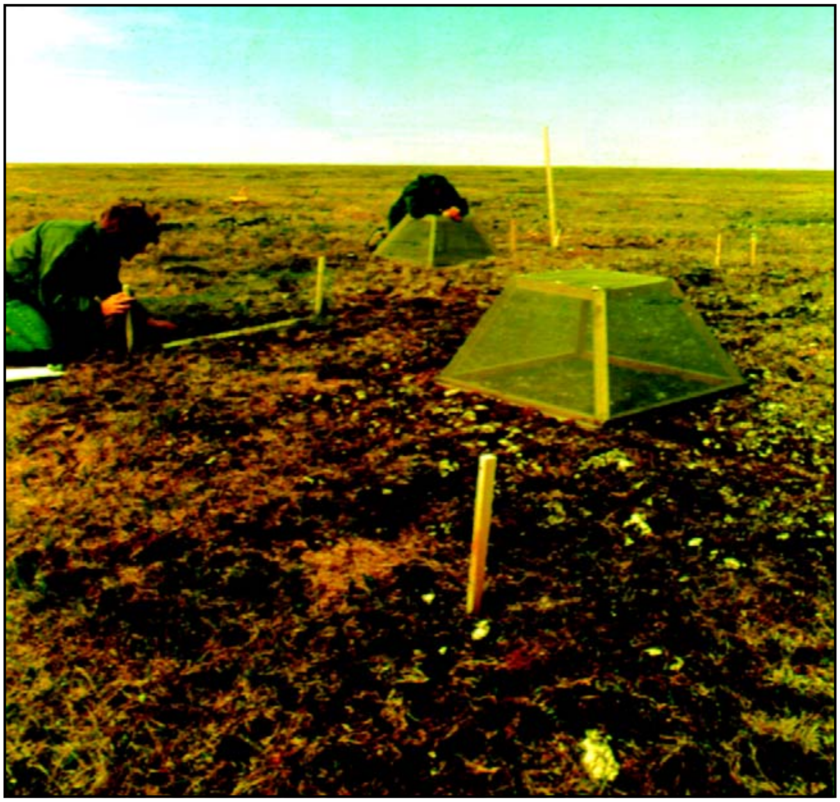
Roots of the LAII Program

Arctic tundra, covering about 6% of the land surface of the earth (about 4 million square kilometers) and 44% of the land north of the Arctic Circle, was recognized as an important land cover by the 1950s. Initial scientific interest in tundra stemmed from the fact that it survived some of the lowest temperatures and shortest growing seasons experienced by any ecosystem. Through a series of coordinated studies, it soon became apparent that tundra was linked in complex and important ways to Arctic hydrology, the thermal balance of the active layer, permafrost, and the climate through the surface energy exchange. To understand the Arctic, one had to understand the tundra. In addition, vast stores of peat underlying the tundra regions were identified as a major repository of terrestrial carbon whose fate, in some complex way, was linked to the state of the tundra and the climate.

Research was focused on several of these issues, and good progress was made. The early studies correctly identified that:

- Tundra vegetation could not be understood without also understanding the biophysical and biogeochemical linkages between the tundra and its environment and climate, and
- Changes in the tundra potentially have global effects through a number of feedbacks and linkages between the Arctic and lands farther south.

This dual focus—on change and climate and on linked biotic and abiotic systems—was well ahead of its time, predating current interest in



Tundra biome manipulation experiments near Barrow, Alaska, 1973.

linked systems and biocomplexity by about 40 years.

Excluding a few studies by individuals, the first coordinated U.S. tundra study was the U.S. IBP (International Biological Program) Tundra Biome program (1970–1974). This program set a model for subsequent programs by addressing climate, hydrology, and carbon exchange as well as the physiology and ecology of plants, microbes, and tundra fauna. It was based at the Naval Arctic Research Laboratory at Barrow, Alaska, and largely limited its focus to wet coastal tundra there.

It was followed by the RATE (Research on Arctic Tundra Environments) (1975–1978) and the R^4D (Response, Resistence, Resilience and Recovery from Disturbance) programs (1984–1987). These two programs were located farther south in drier tundra (at Atqasuk) and in the rolling foothills just north of the Brooks Range at Toolik Lake. They also had a wider focus than just tundra vegetation.

Funding for these coordinated studies varied. The Office of Naval Research funded some of the earliest studies, while the IBP was funded by NSF. NSF also funded the RATE program. R^4D was funded by the Department of Energy (DOE). In a way, all of these programs continued the trend, recognized early on, that the whole system, not just the vegetation, would need to be studied if the response of the system to disturbance or change was to be understood or predicted.

Origin and Organization of the LAII Program

The seeds for ARCSS were planted when the leaders in the U.S. Arctic global change community formulated a science initiative focus on the pan-Arctic region and climate change in 1987. When launched 1991, the ARCSS program had three components—OAII, LAII, and GISP2/PALE (the Greenland Ice Sheet Coring Program). The LAII program was developed following a workshop held in Boulder, Colorado, in 1990.

The goals of ARCSS were, and to a large extent remain, to:

- Understand the physical, geological, chemical, biological, and sociocultural processes of the Arctic system that interact with the total earth system and thus contribute to or are influenced by global change, in order to:
- Advance the scientific basis for predicting environmental change on a seasonal-to-centuries time scale and for formulating policy options in response to the anticipated impacts of global change on humans and societal support systems (http://www.nsf.gov/od/opp/arctic/system.htm).

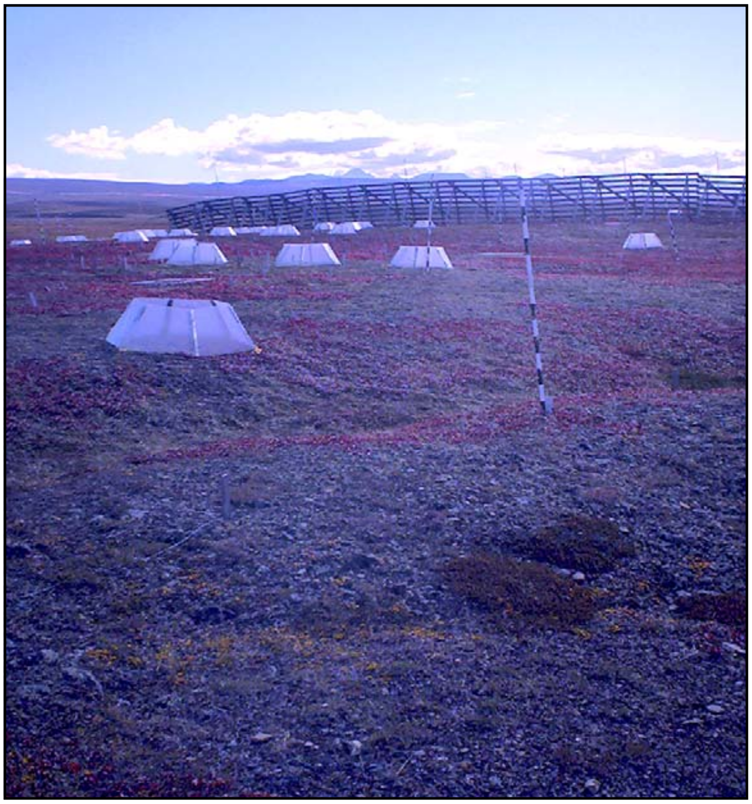
The goal of LAII has been to improve understanding of the role of interactions among land, atmosphere, and ice in the functioning of the Arctic system, with an emphasis on improving the predictability of Arctic system responses to global change. Research within LAII has been organized around four main themes:

- Detection and analysis of Arctic change;
- Circumpolar extrapolation of Arctic terrestrial climate feedbacks;
- Past and future changes in the Arctic system; and
- Sustainability of the Arctic system under global change.

The inaugural LAII initiative was called the Flux Study (1993–1998). It was followed by a second initiative called ATLAS (Arctic Transitions in the Land–Atmosphere System: 1998–2003), which is now winding down. As the Flux Study was gearing up, ITEX was also brought into the LAII program (1995). The purpose of ITEX (International Tundra Experiment) is to

A Short History of ITEX

The start of ITEX can be traced to a challenge put forward by Arthur Lachenbruch, who asked why botanists were not using plant response to monitor climate change in a fashion similar to the way permafrost was being used. From a workshop held in December 1990 emerged the basic ITEX experimental design: a standardized, simple, inexpensive phenology study that could be applied across the Arctic and that would look at organisms rather than whole systems. Small, open-top chambers would be used to passively warm tundra plants and to measure their response. Rapid progress was made, and soon the ITEX network was up and running. Shortly after its inception it became part of the UNESCO Man and the Biosphere Program's Northern Sciences Network. In the U.S., ITEX sites were located at Toolik Lake and Barrow, Alaska, as well as in the alpine tundra of Colorado. In 1995 the U.S. contribution to ITEX was brought into the LAII program as a companion to the Flux Study. Over time the first simple ITEX experimental protocol has been expanded to include more sophisticated measurements and manipulations involving whole system responses. As the Flux Study evolved into the ATLAS program, ITEX evolved into NATEX (North American Tundra Experiment), with a more extended ecosystem response as its focus. NATEX is still an integral part of the ITEX network, which, with over 20 sites in 13 countries, is one of the few truly circum-Arctic research programs.



A set of ITEX cones on the tundra near Toolik Lake, Alaska. In the background is a snow fence designed to test the effect of increased snow on the tundra.

monitor the performance of plant species and communities on a circumpolar basis in undisturbed habitats with and without environmental manipulations. The U.S. effort under ITEX (which eventually came to be called NATEX, the North America Tundra Experiment) was seen as a logical and complementary addition to the Flux Study, which also had a strong focus on tundra plants. In addition, more than a dozen projects that did not fit neatly into these two larger initiatives, but nonetheless addressed the core issues of LAII, were also brought into the program.

From its inception, LAII has been operated by the research scientists themselves in cooperation with the ARCSS program manager. A Science Steering Committee (SSC) with about 10 members works in partnership with a Science Management Office (SMO), currently at the Center for Global Change and Arctic System Research at the University of Alaska Fairbanks. The SSC and the SMO provide scientific leadership and science planning for LAII activities. During the active phases of both the Flux and ATLAS initiatives, they also developed and implemented coordinated field plans, with the assistance of the NSF Arctic logistics contract* in order to ensure full integration between projects.

The SSC has emphasized integration across the wide array of disciplines represented in LAII. This successful blending of ecology, biology, geophysics, atmospheric sciences, and glaciology has been a significant accomplishment of the program as a whole. It has come about through coordinated field studies and has been promoted by organizing special sessions at national meetings, by compiling special journal issues, by developing data CDs (through JOSS, the Joint Office for Science Support in Boulder, Colorado), and by organizing working retreats for investigators. The LAII web site (http://www.laii.uaf.edu) maintained by the SMO is an excellent source of information on these synthesis activities and the projects that make up LAII. Two television documentaries, produced in conjunction with KUAC-TV in Fairbanks, Alaska, provide good overviews of LAII research and the multidisciplinary work that has been required to achieve results.

LAII Initiatives

In the initial phase of LAII, 28 projects were funded. Thirteen projects comprised the Flux

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* Currently VECO Polar Resources

The San Diego State University Sky Arrow aircraft in Barrow, Alaska, prior to a flight to measure CO_2 and other concentrations and fluxes along a traverse line over the tundra as part of the ATLAS project. In the Flux Study, a slightly different aircraft was used.

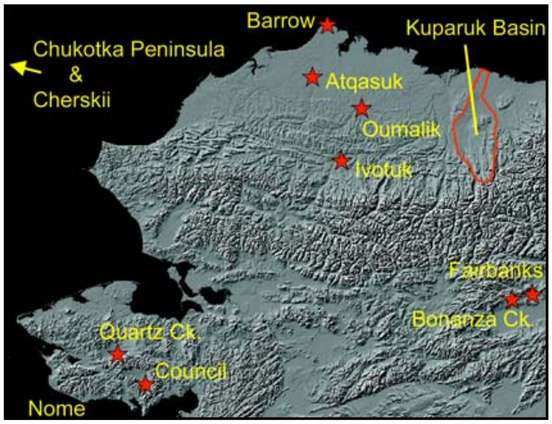
Study, all focused on the Kuparuk River Basin on the North Slope of Alaska. This 9000-square-kilometer basin (an area the size of the Netherlands) extends from the Arctic coast near Prudhoe Bay south to the Brooks Range and includes Toolik Lake Field Station, perhaps the largest U.S. Arctic research station, operated by the University of Alaska.

An eddy flux tower used to measure the weather and the flux of CO_2 and moisture from the tundra to the atmosphere.

In concert, the 13 projects investigated the variables and processes controlling the fluxes of carbon dioxide (CO_2), methane (CH_4), water, energy, and nutrients between the watershed and the atmosphere. The study emphasized spatial scaling, working from plot to watershed. Several methods of scaling up were used. For the exchange of carbon dioxide between the atmosphere and the tundra and the freshwater system, point measurements were made using chambers and eddy flux towers. The towers were moved from one vegetation type to another, remaining in residence long enough to determine the variation in flux during a range of representative growing season conditions. By the end of the project, virtually all of the main types of vegetation found on the Arctic Slope of Alaska had been sampled. Aircraft fitted with open-path infrared gas analyzers were used to make measurements along traverse lines of tens to hundreds of kilometers. For snow cover, hydrology, active layer thickness, and vegetation, spatial scaling was done using spot sampling, traverses, and satellite data. From relationships developed from the measurements, water, energy, methane, and CO_2 fluxes were extrapolated over the entire basin using maps of topography and vegetation and gridded fields of weather data. Both experimental and modeling results were summarized in a special issue of the *Journal of Geophysical Research*.

The second phase of LAII consisted of a major coordinated study called ATLAS, involving more than 25 universities, and the continuation of ITEX. Like the Flux Study, ATLAS research focused on fluxes of CO_2, water, and energy between Arctic terrestrial ecosystems and the atmosphere and oceans, but this time the goal was to understand how these fluxes varied across transition zones between ecosystems and at vegetation boundaries. Seven intensive research sites were established, with five sites located in Alaska and two sites located in the Russian Far East. Studies conducted at these sites were complementary with research being done along the network of high-latitude transects established by the International Geosphere–Biosphere Programme (IGBP) and at the two Long Term Ecological Research (LTER) sites in Alaska (Toolik Lake and Bonanza Creek).

The ATLAS program built directly on the Flux Study results. Extrapolations and models developed in the Kuparuk Basin were applied and tested on a parallel transect line running from Ivotuk to Barrow. ATLAS also employed the concept of "space for time" by making measurements at Council near Nome, Alaska. Council is warmer and moister and has more extensive coverage of shrubs than the Arctic Slope, with treeline nearby. These conditions were thought to be a reasonable analog for what the conditions on the Arctic Slope might be like if the climate continued to warm. The sites in Russia provided opportunities



Sites studied in northwestern Alaska during the Flux Study and ATLAS programs.

for comparative studies of tundra under different regimes of climate change and of processes in transitional ecosystems between tundra and boreal forest. The site on the Chukotka Peninsula has not experienced warming, unlike the sites at Council and Quartz Creek. The other Russian site (Cherskii) is in a transitional ecosystem between tundra and larch forest not represented in Alaska.

Using data from these sites, modeling efforts, including both retrospective analyses and regional and global climate model sensitivity experiments, have investigated potential future scenarios for the Arctic over the next 10–200 years. To achieve greater pan-Arctic coverage, both the Flux Study and ATLAS research have been integrated with studies from Canada (BOREAS: Boreal Ecosystem–Atmosphere Study). Some of these extrapolations were published in a special issue of *Global Change Biology* in 2000. Initial results related to the space-for-time part of ATLAS are summarized in a special issue of the *Journal of Geophysical Research* currently in press; because the program is just ending, the data are still being analyzed. Data from the Barrow–Ivotuk transect have been issued in a user-friendly CD.

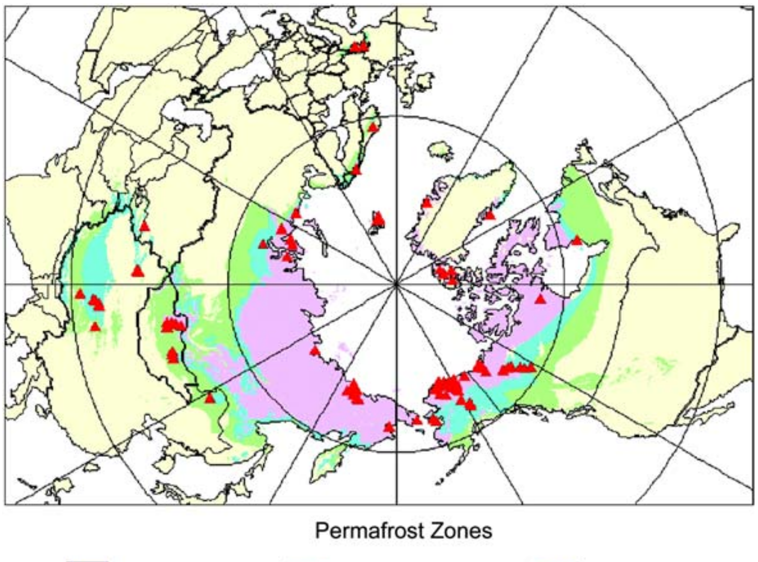
Six U.S.-funded projects made up LAII's latest contribution to ITEX. The initial results from these projects, as well as their international ITEX counterparts, have been synthesized. ITEX researchers have also led the development of global comparisons of the warming response of terrestrial ecosystems, through the development of networks like the GCTE global change and terrestrial ecosystems Network of Ecosystem Warming Studies (NEWS).

LAII has also been home to a number of independent projects. Notable among these were projects that focused on atmospheric processes and their interactions with ice and snow, projects that examined synoptic-scale climate analyses, and projects that focused on permafrost dynamics and the human dimensions of global change. A wide range of other topics were also funded. These include historical and paleo-reconstructions of climate, vegetation, biogeochemistry, and permafrost; process studies of soil heat flux, biogeochemistry, and treeline movement; circum-Arctic hydrologic analyses; studies of the sustainability of Arctic communities; and modeling and synthesis activities. One of the most notable independent projects was CALM, in which a series of circum-Arctic sites were developed for monitoring changes in active layer thickness. This network currently includes more than 100 sites in 15 countries.

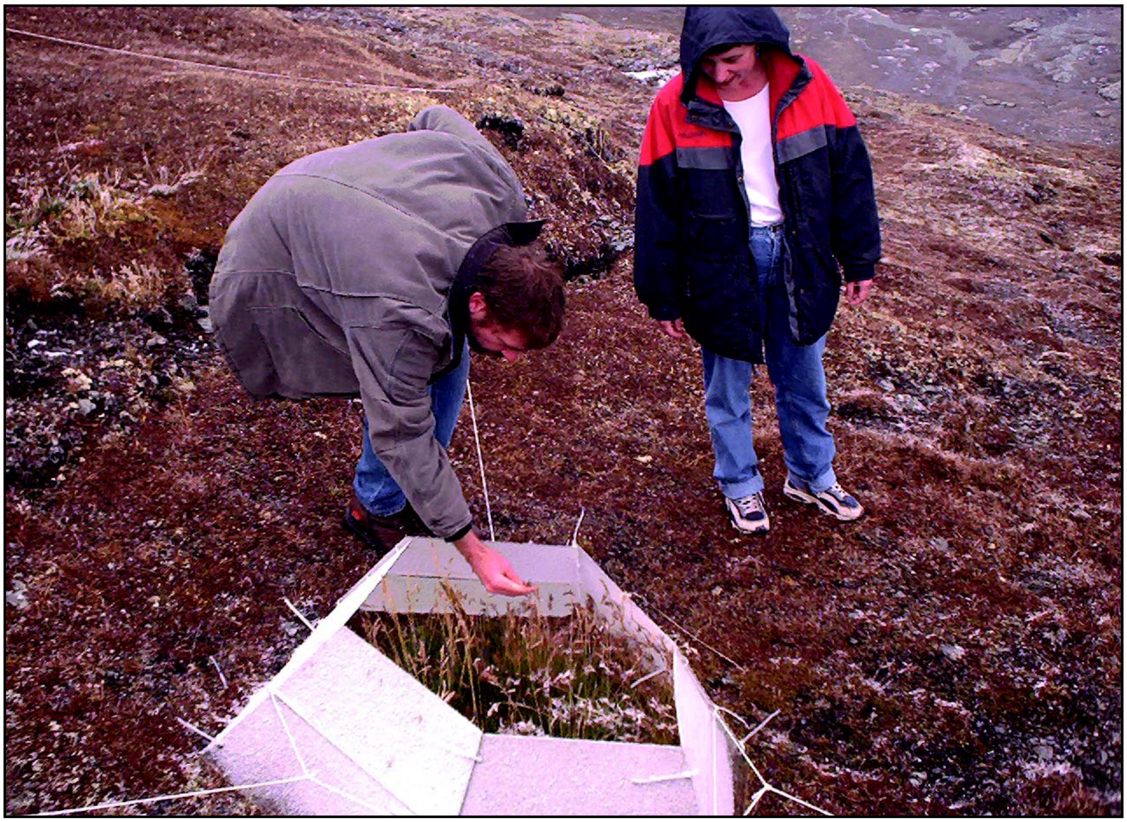
The Circumpolar Active Layer Monitoring Program

The Circumpolar Active Layer Monitoring program, known as CALM, was based on ideas developed at an international symposium held in West Siberia in 1989 and is modeled in many ways on the ITEX network. The goal of the program is to observe the long-term response of the active layer and near-surface permafrost to changes in climate. The most difficult part of implementing the program was building an alliance of active field scientists willing to both share their data and adopt a set of standardized protocols. Despite these difficulties, by 1995 the fledgling circum-Arctic network was up and running.

Under ATLAS the network has expanded rapidly with the addition of several Alaskan sites. The most significant expansion, however, occurred when NSF (through the CALM program) was able to provide funding for 23 sites in Russia. Existing or newly developed sites in Canada, China, Greenland, Kazakhstan, Mongolia, Norway (Svalbard), Sweden, Switzerland, and Antarctica were also brought into the program, making it both bipolar and circumpolar. The CALM network now includes more than 100 stations, operated by scientists from 15 countries. The program is administered at the University of Cincinnati, where a web site is maintained (http://k2.gissa.uc.edu/~kenhinke/CALM/). Only a little more than a decade into its existence, CALM has already produced a large body of scientific literature. In addition, data produced from the CALM network has proven useful in model validation. Activity under the CALM program reached its apogee in late 2002, when 35 scientists from 6 countries attended a workshop at the University of Delaware, where scientists had an opportunity to discuss progress and plan future activities. A workshop report will be issued in 2003, and a group of papers presented at the workshop is in preparation for publication in *Permafrost and Periglacial Processes*.



Location of CALM sites in the Arctic, with permafrost distribution also shown.



An ITEX cone, where warming has caused the plants within to grow more vigorously than the surrounding tundra.

Significant Findings

A decade of integrated research within LAII has substantially improved our understanding of the role of land–atmosphere–ice interactions in the Arctic system. Below are some key findings from the various components of LAII.

Flux Study and ATLAS

- The Alaskan Arctic has warmed significantly in the last 30 years, with associated warming of permafrost, expansion of shrub ranges (and treeline in some locations), and a temporary increase in CO_2 efflux.
- Winter is a more important period of biological activity than previously appreciated. Biotic processes, including shrub expansion and decomposition, have significant effects on winter processes, including snow structure and accumulation and the annual carbon budget of ecosystems.
- Observed vegetation changes can have a significant positive feedback to regional warming. These vegetation effects are, however, less strong than those exerted by land–ocean heating contrasts and the topographic constraints on air mass movements.

ITEX

- Experimental warming initially increased growth in most Arctic plants, particularly in shrubs, the growth form that has greatest impact on Arctic feedbacks to climate (through changes in carbon storage and energy exchange).
- At many sites the growth response to warming diminishes over time, suggesting long-term limitation of growth by other factors. The sustainability of the warming response may differ between the Low and High Arctic, perhaps indicating different long-term limitations of growth with latitude. Both the timing and the magnitude of the flowering response differ from the growth response to warming, suggesting different effects of climate on growth vs. reproduction and dispersal.

Independently Funded Projects

- All thaw lake basins sampled on the Alaskan North Slope are younger than 5000 years old. Ground ice and organic carbon accumulate following lake drainage events.
- The duration of lake ice cover (seasonal or multiyear) is a dominant control on the bio-

geochemistry of Arctic lakes. Paleoclimate sediment core proxies can therefore determine the duration of lake ice cover, and modern process studies and modeling can use this information to determine the climatic conditions necessary to sustain it.

- Circumpolar Active Layer Monitoring (CALM) shows that the active layer depth responds sensitively to summer climate, increasing in warm years and decreasing in cold years.
- Patterns of treeline response to twentieth century warming show that spruce began to invade tundra throughout Alaska after 1850, that the advance started earliest in central Alaska and more recently on the Seward Peninsula and in Alaska Range, and that spruce invasion of permafrost-affected tundra depends on melting of permafrost in some sites.

The Future

As our understanding of Arctic change has increased and as we have identified more and more aspects of the Arctic ecosystem that seem to be changing in unprecedented ways—ways that directly impact living things—the need to document and understand these changes has increased. Scientists can expect to be called on even more in the future to provide data and knowledge to leaders and policy makers as they grapple with the consequences of change. In particular, we need to learn through research how vulnerable the Arctic system is and what the costs might be of sustaining biotic systems and human society in the face of change.

These pressing questions, which grew directly out of LAII research, have led to the development of a new science plan, a blueprint for future research that begins where LAII research has ended. The program envisioned in the plan, called PACTS (Pan-Arctic Cycles, Transitions, and Sustainability), focuses on two critical questions that will take on increasing importance as the Arctic continues to change:

- How vulnerable are current Arctic ecosystems and food webs, and what will it require to sustain Arctic societies in the face of environmental change?
- How will changes in Arctic biogeochemical cycles and biophysical feedback processes affect both Arctic and global systems?

These may be the questions that fuel the next decade of research on the interaction of biotic and abiotic systems in the Arctic.

References

Arft, A.M., et al. (1999) Responses of tundra plant species to experimental warming: Meta-analysis of the International Tundra Experiment. *Ecological Monographs*, vol. 69, p. 491–511.

Brown, J., K.M. Hinkel, and F.E. Nelson (2000) The Circumpolar Active Layer Monitoring (CALM) program: Research designs and initial results. *Polar Geography*, vol. 24, p. 165–258.

Brown, J., P.C. Miller, L.L. Tieszen, and F.L. Bunnell (1980) *An Arctic Ecosystem: The Coastal Tundra at Barrow, Alaska*. Dowden, Hutchinson and Ross, Inc., Stroudsburg, PA.

JOSS (2002) *ATLAS Project Ivotuk Site CD*. Joint Office for Scientific Support (JOSS), CIRES, Boulder, CO.

Kane, D.L., and W.S. Reeburgh (1998) Introduction to special issue: Land–Air–Ice Interactions (LAII) Flux Study. *Journal of Geophysical Research*, vol. 103, no. D22, p. 28,913–28,915.

McGuire, A.D., M. Sturm, and F.S. Chapin III (In press) Arctic Transitions in the Land–Atmosphere System (ATLAS): Background, objectives, results, and future directions. *Journal of Geophysical Research*.

Nelson, F., J. Brown, T. Lewkowicz, and A. Taylor (1996) Active layer protocol. In *ITEX Manual* (U. Molau and P. Molgaard, ed.), Second Edition. Danish Polar Center, Copenhagen, p. 14–16.

Serreze, M.C., et al. (2000) Observational evidence of recent climate change in the northern high-latitude environment. *Climatic Change*, vol. 46, p. 159–207.