JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D2, 8166, doi:10.1029/2002JD002367, 2003

Arctic Transitions in the Land–Atmosphere System (ATLAS): Background, objectives, results, and future directions

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Received 23 March 2002; revised 21 June 2002; accepted 23 June 2002; published 25 January 2003.

[1] This paper briefly reviews the background, objectives, and results of the Arctic Transitions in the Land–Atmosphere System (ATLAS) Project to date and provides thoughts on future directions. The key goal of the ATLAS Project is to improve understanding of controls over spatial and temporal variability of terrestrial processes in the Arctic that have potential consequences for the climate system, i.e., processes that affect the exchange of water and energy with the atmosphere, the exchange of radiatively active gases with the atmosphere, and the delivery of freshwater to the Arctic Ocean. Three important conclusions have emerged from research associated with the ATLAS Project. First, associated with the observation that the Alaskan Arctic has warmed significantly in the last 30 years, permafrost is warming, shrubs are expanding, and there has been a temporary release of carbon dioxide from tundra soils. Second, the winter is a more important period of biological activity than previously appreciated. Biotic processes, including shrub expansion and decomposition, affect snow structure and accumulation and affect the annual carbon budget of tundra ecosystems. Third, 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. The papers of this special section provide additional insights related to these conclusions and to the overall goal of ATLAS. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 1615 Global Change: Biogeochemical processes (4805); 1620 Global Change: Climate Dynamics (3301); 1640 Global Change: Remote sensing; 1655 Global Change: Water cycles (1836); *KEYWORDS:* Alaska, Arctic, carbon, energy, tundra, water

Citation: McGuire, A. D., M. Sturm, and F. S. Chapin III, Arctic Transitions in the Land–Atmosphere System (ATLAS): Background, objectives, results, and future directions, *J. Geophys. Res.*, *108*(D2), 8166, doi:10.1029/2002JD002367, 2003.

1. Science Background

[2] Evidence continues to mount that warming experienced in the Northern Hemisphere during the past few decades has been affecting the structure and function of terrestrial ecosystems in high-latitude regions [*Oechel et al.*, 1993, 2000a; *Kurz and Apps*, 1999; *Osterkamp and Romanovsky*, 1999; *Barber et al.*, 2000; *Serreze et al.*, 2000; *Stocks et al.*, 2000]. It is important to understand the nature of these changes as they have implications for human livelihoods in high-latitude regions and elsewhere through effects on subsistence resources, commercial fisheries resources, infrastructure, and industrial activity (e.g., oil and gas development). It is also important to understand these changes because they may have consequences for the functioning of the Arctic System, particularly in the way that (1) water and energy are exchanged with the atmosphere, (2) radiatively active gases are exchanged with the atmosphere, and (3) freshwater is delivered to the Arctic Ocean.

[3] Responses of high-latitude ecosystems to global change have the potential to influence water and energy exchange with the atmosphere in several ways. Expansions of shrub tundra into regions now occupied by sedge tundra, and of boreal forest into regions now occupied by tundra, reduce growing season albedo and increase spring energy absorption and may enhance atmospheric warming [*Bonan et al.*, 1992; *Thomas and Rowntree*, 1992; *Foley et al.*, 1994; *McFadden et al.*, 1998; *Chapin et al.*, 2000a, 2000b]. Decreased albedo due to the extension of snow-free and ice-free periods on terrestrial and lake surfaces, and reduction in the area occupied by glaciers and continental ice sheets may

0148-0227/03/2002JD002367$09.00

also enhance atmospheric warming. Disturbance may also affect energy exchange with the atmosphere. For example, while fire disturbance often reduces albedo shortly after the fire, it also provides the opportunity for deciduous forests to develop, which will generally raise albedo. Thus, disturbance regimes (e.g., fire) that increase the proportion of nonforested lands and deciduous forests have the potential to reduce energy absorption and work against atmospheric warming [*Chapin et al.*, 2000b].

[4] Increases in the atmospheric concentrations of radiatively active gases have the potential to influence the climate through altering the Earth's near-surface energy balance [*IPCC WGI*, 2001]. High-latitude ecosystems may influence the atmospheric concentrations of carbon dioxide and methane in several ways [*Smith and Shugart*, 1993; *McGuire and Hobbie*, 1997; *McGuire et al.*, 2000a, 2000b; *Chapin et al.*, 2000b]. They contain approximately 40% of the world's soil carbon inventory that is potentially reactive in the context of near-term climate change [*McGuire et al.*, 1995; *Melillo et al.*, 1995; *McGuire and Hobbie*, 1997]. Regions affected by permafrost are especially vulnerable to climate change because of altered drainage. Thermokarst activity that leads to the expansion of lakes and wetlands may cause increased releases of methane [*Reeburgh and Whalen*, 1992; *Zimov et al.*, 1997]. Reductions in the water table of tundra ecosystems substantially enhance the release of carbon from high-latitude soils [*Oechel et al.*, 1995; *Christensen et al.*, 1998]. The replacement of tundra with boreal forest might initially decrease but eventually increase carbon storage in high latitudes [*Smith and Shugart*, 1993], with time lags and rates of change that are sensitive to the rate and variability of climate change [*Chapin and Starfield*, 1997]. Disturbance in the boreal forest region may substantially influence regional carbon exchange with the atmosphere [*Kurz and Apps*, 1999; *Dargaville et al.*, 2002]. The responses of carbon storage in high-latitude ecosystems have important implications for the rate of CO_2 accumulation in the atmosphere and international efforts to stabilize the atmospheric concentration of CO_2 [*Smith and Shugart*, 1993; *McGuire and Hobbie*, 1997; *McGuire et al.*, 2000b; *Betts*, 2000]. In particular, it is important to understand how changes in trace gas exchanges and changes in albedo of high-latitude terrestrial ecosystems influence both regional and global energy balance [*Betts*, 2000].

[5] The delivery of freshwater from the pan-Arctic landmass is of special importance since the Arctic Ocean contains only about 1% of the world's ocean water, yet receives about 11% of world river runoff [*Shiklomanov et al.*, 2000; *Forman et al.*, 2000]; the Arctic Ocean receives freshwater inputs from four of the fourteen largest river systems on Earth [*Forman et al.*, 2000]. Additionally, the Arctic Ocean is the most river influenced and land locked of all oceans and is the only ocean with a contributing land area greater than its surface area [*Ivanov*, 1976; *Vörösmarty et al.*, 2000]. Freshwater inflow contributes as much as 10% to the upper 100 meters of the water column for the entire Arctic Ocean [*Barry and Serreze*, 2000]. Changes in freshwater inputs to the Arctic Ocean have the potential to alter salinity and sea ice formation, which may have consequences for the global climate system by affecting the strength of the North Atlantic Deep Water Formation [*Aagaard and Carmack*, 1989; *Broecker*, 1997]. Modeling studies suggest that maintenance of the thermohaline circulation is sensitive to freshwater inputs to the North Atlantic [*Manabe and Stouffer*, 1995]. Also, freshwater on the Arctic continental shelf more readily forms sea ice in comparison to more saline water [*Forman et al.*, 2000]. The responses of freshwater inputs to the Arctic Ocean depend on changes in the amount and timing of precipitation, and the responses of permafrost dynamics, vegetation dynamics, and disturbance regimes to global change. For example, changes in evapotranspiration associated with permafrost and vegetation dynamics have consequences for river runoff that depend additionally on changes in precipitation inputs to terrestrial ecosystems.

[6] Changes in high-latitude terrestrial ecosystems have consequences for the climate system that may affect the rate and magnitude of changes that occur in high latitudes and elsewhere. Thus, it is important to understand how spatial and temporal variability in climate is affecting spatial and temporal variability in high-latitude terrestrial ecosystems as this understanding will provide insight that is relevant to understanding responses to climate change in the Arctic and in other regions. The Arctic Transitions in the Land–Atmosphere System (ATLAS) Project was established in 1998 under the Land–Atmosphere–Ice Interactions (LAII) component of the Arctic System Science (ARCSS) Program of the National Science Foundation to study spatial and temporal variability of terrestrial processes in the Arctic that have potential consequences for the climate system. This paper describes the objectives and design of the ATLAS Project, reviews the papers of this special section in the context of previously reported LAII research, and summarizes important results of the ATLAS Project.

2. Objectives and Design of ATLAS

[7] The ATLAS Project succeeded the LAII Flux Study [*Kane and Reeburgh*, 1998], which focused on studying processes controlling the fluxes of carbon dioxide, methane, water, energy, and nutrients between tundra ecosystems and the atmosphere and ocean in the Kuparuk River Basin in northern Alaska between 1993 and 1996. Initial results of the LAII Flux Study have been summarized by *Kane and Reeburgh* [1998]. Like the Flux Study, the ATLAS Project also has concentrated on the exchange of mass and energy between the terrestrial ecosystems in the Arctic and the atmosphere and ocean. However, ATLAS expanded its spatial scope of interest from a hydrologic basin to the Western Arctic region (i.e., Alaska and the Russian Far East) and to the circumpolar Arctic. Some efforts of ATLAS were devoted to evaluating to what extent the understanding gained from the Flux Study was or was not representative of other terrestrial ecosystems in the Arctic. In addition, ATLAS has also attempted to gain a better understanding of temporal variation in processes that are responsible for the exchange of mass and energy in terrestrial ecosystems of the Arctic. Modeling approaches were employed in ATLAS to provide the capability to examine the regional to pan-Arctic scale and the decadal to century scale implications of new understanding gained from the field studies.

[8] To accomplish the goals of ATLAS, seven intensive research sites were established, with five sites located in Alaska and two sites in the Russian Far East (Figure 1). These sites provided the capability to study processes

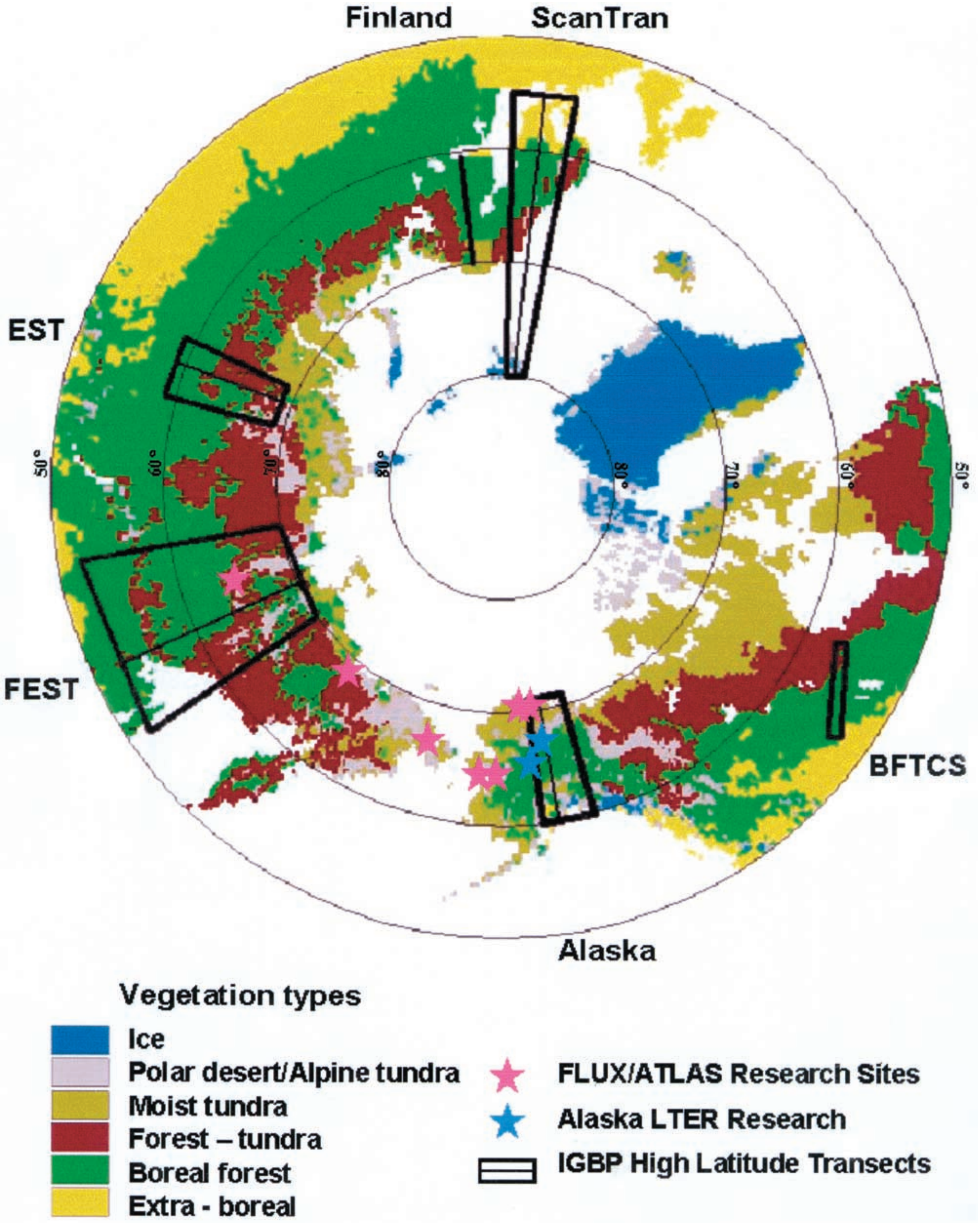

Figure 1. Polar projection vegetation map indicating the location the intensive research sites of the ATLAS Project in relation to the locations of the IGBP's high-latitude transects and the intensive research sites of the FLUX Study and of the two LTER programs in Alaska. The IGBP transects include the Alaska Transect, the Boreal Forest Transect Case Study (BFTCS), the Scandinavian Transect (ScanTran), the East Siberian Transect (EST), and the Far East Siberian Transect (FEST). While the Finland Transect is not technically an IGBP Transect, the Finland Transect has been treated as a sister transect to ScanTran [see *McGuire et al.*, 2002]. The vegetation map is courtesy of Catharine Copass.

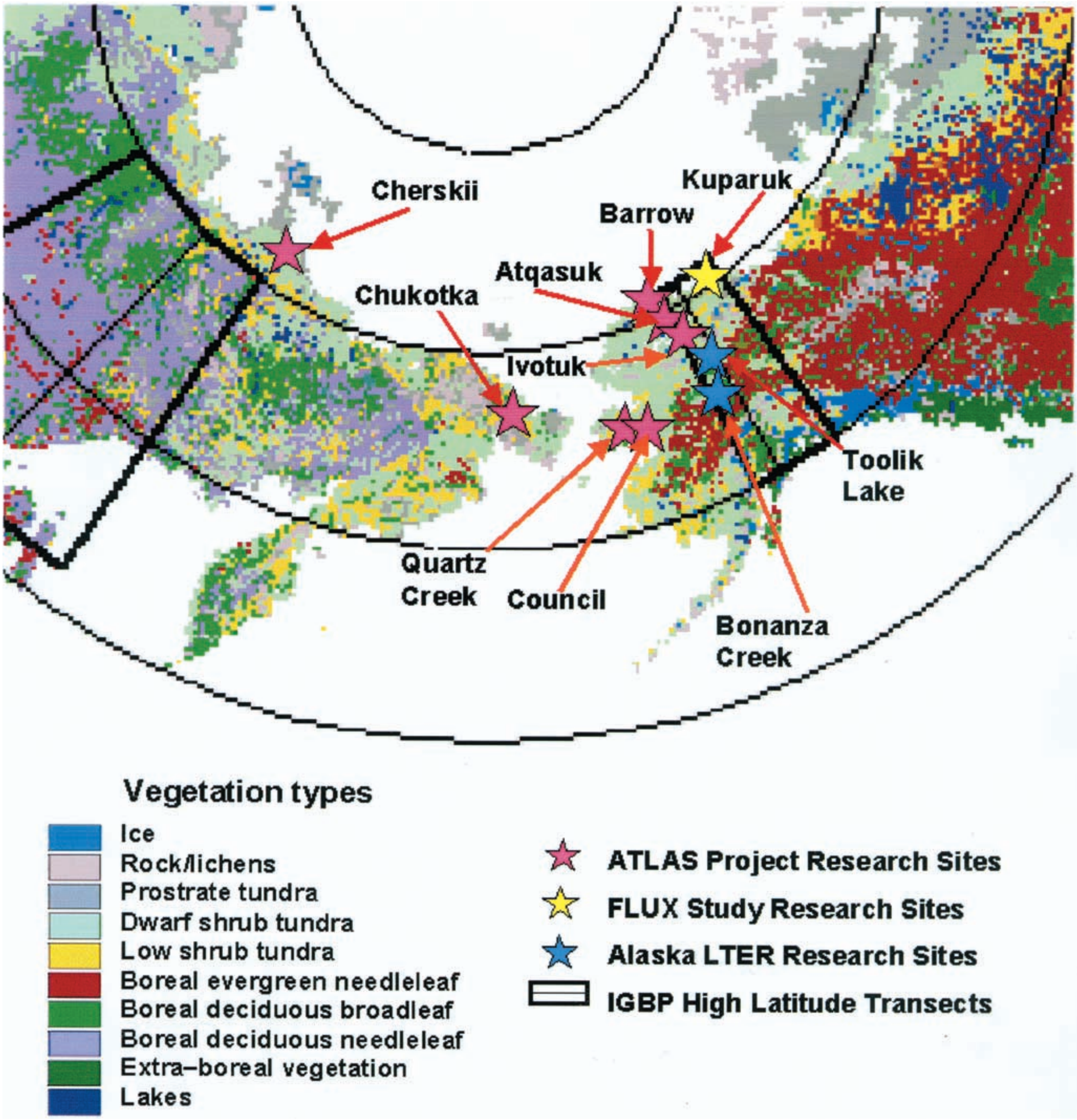

Figure 2. An inset from Figure 1 identifying the intensive research sites of the ATLAS Project (Barrow, Atqasuk, Ivotuk, Council, Quartz Creek, Cherskii, and the site on the Chukotka Peninsula), the Flux Study (the Kuparuk River Basin), and the two LTER programs in Alaska (Toolik Lake and Bonanza Creek).

influencing mass and energy exchange across the western Arctic. Studies conducted at these sites complement research being conducted along the network of high-latitude transects established by the International Geosphere–Biosphere Programme (IGBP) (Figure 1) [see also *McGuire et al.*, 2002] and by the two Long-Term Ecological Research (LTER) sites at Toolik Lake and Bonanza Creek in Alaska (Figures 1 and 2). The ATLAS sites in Alaska include sites located on a transect from Barrow to Atqasuk to Ivotuk on the North Slope and sites at Council and Quartz Creek on the Seward Peninsula. The Barrow to Ivotuk transect was specifically established to test the ability to extrapolate understanding from the Kuparuk River Basin to other parts of the Alaska North Slope, while the sites on the Seward Peninsula were established to evaluate understanding of tundra ecosystems in a warmer climate located near the boundary between tundra and boreal forest. The sites in Russia provide opportunities for comparative studies of (1) tundra under different regimes of climate change and (2) processes in transitional ecosystems between tundra and boreal forest. One of the intensive sites in Russia is located on the Chukotka Peninsula across the Bering Strait from the Seward Peninsula (Figure 2). In contrast to a similar setting at Quartz Creek on the Seward Peninsula in Alaska, which has experienced warming in recent decades, the Chukotka site occurs in a region that has not experienced warming [see *Serreze et al.*, 2000]. The other intensive site in Russia is located in Cherskii (Figure 2) and provided the opportunity to study processes in transitional ecosystems from tundra to larch forest, which contrasts with the study of processes in transitional ecosystems from tundra to spruce forest at the Council site on the Seward Peninsula.

3. Overview of Papers in This Special Section

[9] Some of the papers in this special section have examined processes in the Western Arctic, while others have examined processes in other regions of the pan-Arctic. While all of the studies focused on the Western Arctic were conducted as part of ATLAS, some of the studies that are focused on other regions [e.g., *Boike et al.*, 2003; *Nolan et al.*, 2002] represent international collaborations with ATLAS. To better compare and contrast insights relevant to the Western Arctic versus other regions, we have separated discussion of the papers of this special section with respect to whether they focused on studying processes in the Western Arctic or in other regions of the circumpolar Arctic. As we discuss each paper, we provide the background from prior research relevant to the results of each study, with an emphasis on prior results from LAII research in the Flux Study and the ATLAS Project. The background we provide specifically focuses on the contributions of each study in providing insight concerning controls over spatial and temporal variability in the exchanges of water/energy and trace gases between the land and the atmosphere, and freshwater delivery to the Arctic Ocean.

3.1. Insight From Studies Focused on the Western Arctic

[10] Both *Bonan et al.* [1992] and *Foley et al.* [1994] have conducted studies with general circulation models that indicate that the position of northern tree line has a substantial influence on global climate. Regional modeling studies focused on Alaska have shown that the expansion of shrub tundra at the expense of sedge tundra may result in substantially warmer summers over tundra, with warming effects that extend into the boreal forest of Alaska [*Lynch et al.*, 1999; *Chapin et al.*, 2000b]. While these modeling studies clearly highlight that vegetation change has the potential to influence climate, the magnitude and extent of impacts on climate will depend on the temporal and spatial patterns of land cover change in the circumpolar Arctic. Two ATLAS studies have documented that tundra ecosystems in Alaska are becoming more shrubby on the North Slope [*Sturm et al.*, 2001a] and on the Seward Peninsula [*Silapaswan et al.*, 2001] over the last several decades. The study by *Lloyd et al.* [2002] complements these two studies by documenting the response of the tree line ecotone on the Seward Peninsula in Alaska to 20th century warming. Through the use of tree rings to reconstruct the response of tree line to warming, the study by *Lloyd et al.* [2002] indicates that spruce trees located in upland tundra have established progressively farther from the forest limit since the 1880s. This has led to a conversion of shrub tundra into low-density forest–tundra within a band extending approximately 10 km from the forest limit. Modeling experiments conducted by *Lloyd et al.* [2002] suggest that fire may play a role in the expansion of tree line, and that large and nearly instantaneous responses to warming are likely at the tree line ecotone. Together, the studies by *Lloyd et al.* [2002], *Sturm et al.* [2001a], and *Silapaswan et al.* [2001] provide important information on the temporal and spatial dynamics of vegetation change in arctic Alaska over the last century. A key question raised by these studies is whether similar changes are occurring in other terrestrial regions of the pan-Arctic.

[11] Based on the results of the FLUX Study, several studies have focused on questions related to spatial and temporal extrapolation of carbon dynamics over the Kuparuk River Basin in Alaska [*Hobbie et al.*, 1998; *Clein et al.*, 2000; *McGuire et al.*, 2000b; *Oechel et al.*, 2000b; *Williams and Rastetter*, 1999; *Williams et al.*, 2000, 2001]. The study by *Le Dizes et al.* [2003] builds on these previous studies in several ways. First the uptake of carbon by the vegetation is now simulated by the aggregated canopy model (ACM), which has been developed and tested in the context of eddy covariance data available for a N-S transect across the basin [see *Williams and Rastetter*, 1999; *Williams et al.*, 2000, 2001]. Second, the dynamics of the new version of the model have been calibrated and verified (1) in the context of decadal-scale experiments that have manipulated temperature, nutrients, and light and (2) in the context of an experiment that has manipulated atmospheric carbon dioxide [see also *Hobbie et al.*, 1998; *Clein et al.*, 2000]. Third, the study has broken new ground by demonstrating how it is possible to use remotely sensed data to verify model dynamics in a retrospective fashion, and then use the model to simulate the dynamics for projected variations in climate. Fourth, the study has conducted a time series analysis and has identified that while the immediate response to year-to-year variation in temperature is the release of carbon in a warmer year, the response a year later is to increase carbon storage. This result has implications for longer-term trends in warming and is consistent with the study of *Oechel et al.* [2000a], which has documented an initial release of carbon followed by the storage of carbon among studies that have examined summer carbon dynamics of tundra ecosystems on the North Slope of Alaska over the last several decades. The result is also interesting in the context of the study by *Braswell et al.* [1997], which shows a 9-month lag in carbon storage to increasing temperature at the global scale and has evaluated lags in NDVI response with temperature for various biomes globally. Finally, *Le Dizes et al.* [2003] has evaluated nitrogen cycle issues responsible for long-term changes in carbon storage by partitioning the responses of carbon storage. This analysis has identified that the increase in vegetation carbon/nitrogen ratio (i.e., more wood) and the change in redistribution of nitrogen from the soil to plants are key factors responsible for increases in carbon storage, and has shown that the relative strength of these factors in the future depends on moisture conditions. These results are particularly important in that they are consistent with information from other ATLAS studies that tundra in Alaska is taking up more carbon in summer [*Oechel et al.*, 2000a]

and is becoming more shrubby, i.e., more woody [*Sturm et al.*, 2001a; *Silapaswan et al.*, 2001]. The results from the study by *Le Dizes et al.* [2003] demonstrate the power and value of integrating field and experimental studies of processes with process-based modeling studies in ATLAS.

[12] Processes that occur in the nongrowing season are important to understand because the nongrowing season lasts 9 or more months of the year. A number of studies that have measured the exchange of carbon dioxide between tundra ecosystems and the atmosphere during the nongrowing season have documented that substantial losses of carbon dioxide from tundra soils may occur during fall, winter, and spring months [*Kelley et al.*, 1968; *Coyne and Kelley*, 1971, 1974; *Zimov et al.*, 1993, 1996; *Oechel et al.*, 1997; *Fahnestock et al.*, 1998, 1999; *Grogan and Chapin*, 1999; *Jones et al.*, 1999]. Modeling studies have also indicated that processes that control the release of carbon dioxide from soils during the nongrowing season are relevant in the context of the global carbon cycle [*McGuire et al.*, 2000a]. While it has been documented that carbon dioxide loss from soils of tundra ecosystems is a major part of the annual carbon budget, relatively little is known about controls and how they operate in the nongrowing season. This is particularly important to understand as high-latitude ecosystems contain approximately 40% of the soil carbon stored globally in terrestrial ecosystems [*McGuire et al.*, 1995], and projections of future warming indicate that high-latitude ecosystems will experience the greatest warming in the nongrowing season [*IPCC WGI*, 2001]. The study by *Michaelson and Ping* [2003] is specifically focused on elucidating temperature controls over decomposition in the nongrowing season and on understanding how temperature responses interact with respect to how easily organic matter is decomposed by microbes, i.e., with respect to substrate quality. In laboratory incubations at $-2°C$, they found that carbon dioxide loss was correlated with water-soluble organic carbon (wsOC) levels, which is generally considered more readily decomposed by microbes in comparison to organic carbon this is not water soluble. Soils collected from permafrost had higher levels of wsOC in comparison with soils from the active layer, and levels of wsOC were not correlated with total organic carbon levels. Thus, the study by *Michaelson and Ping* [2003] highlights the importance of understanding how substrate quality interacts with soil thermal dynamics to influence the decomposition of soil organic matter during the nongrowing season. The results of the study are also relevant to the issue of understanding how the warming and melting of permafrost will influence the release of carbon dioxide from tundra soils.

[13] The active layer, i.e., the layer above permafrost that experiences seasonal thawing during the summer and freezing during the winter, is an important area of hydrological and biological activity in tundra ecosystems [*Kane et al.*, 1991]. Thus, an understanding of the controls over spatial and temporal variation in active layer thickness is important to understanding controls over spatial and temporal variability of hydrological and biological activity in tundra ecosystems. The Circumpolar Active Layer Monitoring (CALM) program was established to study the impacts of climate change in permafrost environments, and currently consists of more than 85 sites in 11 countries in the Northern Hemisphere. The study by *Hinkel and Nelson* [2003] analyzes 6 years of variability in summer thaw depth for three CALM 1 km^2 grids located on the arctic coastal plain in Alaska and for four CALM grids located in the northern foothills of the Brooks Range. For each of the grids, interannual variability in the end of season thaw depth is strongly correlated to the local growing season surface air temperature. On the coastal plain, thaw depth is greatest in thaw lake basins. Within each of the grids, spatial variation of thaw depth appears to depend on complex interactions among the local influences of vegetation, substrate properties, snow cover dynamics, and terrain.

[14] Previous research from the Flux Study and ATLAS has identified that spatial variation in the function and structure of tundra ecosystems is influenced by climate and soil parent material [*Hobbie et al.*, 1998; *Epstein et al.*, 2000, 2001; *Walker et al.*, 1998; *Walker*, 2000; *McGuire et al.*, 2000b]. While this research has documented that water, energy, and carbon dioxide exchange between tundra ecosystems and the atmosphere vary spatially, this spatial variation is not completely understood and is not well represented in large-scale models of climate and ecosystem dynamics. To better understand controls over the variability in vegetation structure and function, the study by *Walker et al.* [2003] examined aboveground phytomass, leaf area index (LAI), and the normalized difference vegetation index (NDVI) across a climate gradient in northern Alaska on acidic and nonacidic soil parent material along two transects (Barrow to Ivotuk and Prudhoe Bay to Toolik Lake). Along the summer temperature gradient spanned by the study, phytomass increased over 200% on acidic soils and approximately 50% on nonacidic soils with increasing temperature. There was a 700% increase in shrub phytomass on acidic substrates, but only a 70% increase on nonacidic substrates. While there was a doubling of LAI on acidic substrates over the summer temperature gradient, there was no response of LAI on nonacidic substrates over the gradient. However, NDVI increased on both substrates along the summer temperature gradient. The patterns elucidated by *Walker et al.* [2003] provide relationships that should be useful in specifying spatial variation in biophysical and biogeochemical parameters of tundra vegetation in climate and ecosystems models applied to the North Slope of Alaska.

3.2. Insight From Studies Focused on Other Regions of the Circumpolar Arctic

[15] The timing of the transition from the snow-covered period to the snow-free period in tundra ecosystems of the Arctic is critical to understanding energy balance, as albedo decreases substantially during this transition and energy input is quite high. There is a great deal of uncertainty in the representation of this transition in land-surface models, and the snowmelt transition can be biased to occur a month early to a month late depending on the particular land-surface model [*Lynch et al.*, 1998]. Much of this uncertainty is associated with an incomplete understanding of winter and spring ablation of snow. Processes related to winter ablation of snow have been studied in the Flux Study and in the ATLAS Project [*Holmgren et al.*, 1998; *Sturm et al.* 1997, 2001b, 2001c; *Sturm and Holmgren*, 1998; *Liston et al.*, 2002]. Processes related to spring ablation have also received attention [*Liston*, 1995; *McNamara et al.*, 1999]. The study by *Boike et al.* [2003] at a continuous permafrost

site on Spitsbergen is complementary to studies of snow processes that have been conducted by the Flux Study and the ATLAS Project. In the Spitsbergen study, an energy balance model was applied to estimate atmospheric, ground heat and snow heat fluxes for snow covered periods from autumn 1998 to winter 2000. The analysis identified that controls over snow ablation could be attributed to different processes in winter in comparison to spring, with sensible heat and rain primarily responsible for winter ablation of snow, while net radiation was primarily responsible for ablation during the spring. The analysis also suggests that the ground heat flux may be an important energy sink during winter. The importance of winter rain in the study by *Boike et al.* [2003] represents a key contrast with processes that are responsible for winter and spring ablation of snow in tundra ecosystems of the North American Arctic, but could have increased importance under some future climate scenarios.

[16] The duration of snowmelt is a crucial period in the annual water budget of arctic terrestrial ecosystems as it can account for up to 80% of annual runoff. In spring 2000, ATLAS conducted a regional-scale exercise to obtain detailed ground-based observations of snow conditions and meteorology during the snowmelt period in eleven sites across Alaska and northern Canada (Atqasuk, Barrow, Caribou-Poker Creeks, Council, Imnaviat Creek, Ivotuk, Prudhoe Bay, Sagwon Bluffs, Franklin Bluffs, Quartz Creek, and Resolute in Canada) (Hinzman et al., unpublished data). The study by *Nolan et al.* [2002] complements the ATLAS snowmelt intersite comparison by combining the use of SAR and Landsat imagery to analyze the hydrological dynamics from 1998 through 2000 of Lake El'gygytgyn, a lake in Siberia with no outlet that was formed by the impact of a meteor several million years ago. The study uses the remote sensing analyses to validate a lake-ice computer model that will then be used to extend understanding of hydrological dynamics for time periods without remote sensing data. A sediment core containing a 300,000-year record has been obtained from Lake El'gygytgyn, and the results of the lake-ice model will be used to interpret information contained in the sediment core to help reconstruct climate over the history of the lake.

[17] Freshwater runoff into the Arctic Ocean can influence its salinity and sea-ice dynamics [*McDonald et al.*, 1999; *Steele and Boyd*, 1998], which have the potential to affect the global thermohaline circulation [*Forman et al.*, 2000]. As climate warms, it is not clear how the dynamics of freshwater inputs into the Arctic Ocean will be affected. The study by *Serreze et al.* [2002] analyzes climatic control over spatial variability in runoff of the four largest rivers (Ob, Yenisey, Lena, and Mackenzie) draining into the Arctic Ocean from 1960 onward. Cold season runoff has increased through time in both the Yenisey and Lena. This pattern is most pronounced in the Yenisey, where runoff has increased sharply in the spring, decreased in the summer, but has increased for the year as a whole. While the mechanisms responsible for this pattern are not completely clear, the patterns are linked to higher air temperatures, increased winter precipitation, and strong summer drying. It is possible that the changes in runoff patterns for the Yenisey and Lena are associated with changes in active layer thickness and the thawing of permafrost.

[18] Approximately 40% of tundra in the Arctic occurs in the Canadian Arctic, but the structure and function of this area of the Arctic has been poorly represented in large-scale climate and ecosystem models. The study by *Gould et al.* [2003] has developed spatial data sets of dominant vegetation types, plant functional types, horizontal vegetation cover, aboveground plant biomass, and above and below ground annual net primary production for Canada north of the northern limit of trees. The study indicates that nearly 90% of the biomass and net primary production is concentrated in the Low Arctic, which is approximately 50% of the tundra area in the Canadian Arctic. In a similar analysis, the study of *Walker et al.* [2003] applied their relationships between phytomass and summer temperature to the circumpolar Arctic, with the result that 60% of the above ground phytomass is concentrated in the Low Arctic. The spatial data sets developed by *Gould et al.* [2003] should be useful for specifying the land surface and for evaluating simulations of ecosystem properties of the Canadian Arctic by large-scale climate and ecosystem models.

4. Summary and Future Directions

[19] Three important conclusions have emerged from previously reported research of the Flux Study and the ATLAS Project. First, associated with the observation that the Alaskan Arctic has warmed significantly in the last 30 years, permafrost is warming [*Romanovsky and Osterkamp*, 1997], shrubs are expanding [*Sturm et al.*, 2001a; *Silapaswan et al.*, 2001], and there has been a temporary release of carbon dioxide from tundra soils [*Oechel et al.*, 2000a]. Second, the winter is a more important period of biological activity than previously appreciated [*Oechel et al.*, 1997; *Fahnestock et al.*, 1999; *Sturm et al.*, 2001b]. Biotic processes, including shrub expansion and decomposition, affect snow structure and accumulation [*Sturm et al.*, 2001b] and affect the annual carbon budget of tundra ecosystems [*Fahnestock et al.*, 1999; *McGuire et al.*, 2000a]. Third, observed vegetation changes can have a significant positive feedback to regional warming [*Chapin et al.*, 2000a, 2000b; *Lynch et al.*, 1999]. These vegetation effects are, however, less strong than those exerted by land–ocean heating contrasts [*Serreze et al.*, 2001] and topographic constraints on air mass movements [*Lynch et al.*, 2001].

[20] The papers of this special section enlarge upon these conclusions and address the goal of better understanding spatial and temporal variation in land–atmosphere exchange of mass and energy across the circumpolar Arctic. Several document changes in various aspects of the land surface, including changes in tree line [*Lloyd et al.*, 2002] and large-scale hydrology [*Serreze et al.*, 2002]; the response of the active layer to summer temperature [*Hinkel and Nelson*, 2003] may be an important factor in both of these changes. *Le Dizes et al.* [2003] have identified shrub expansion as the likely factor responsible for the temporary release of soil organic carbon from tundra soils in response to warming because the response of woody growth may lag the response of decomposition to warming. Two studies add to our understanding of winter processes. The Spitsbergen study of *Boike et al.* [2003] provides an important regional contrast to studies of snow ablation in Alaska and highlights the importance of winter rain in some regions of the Arctic.

Michaelson and Ping [2003] have clarified that the response of winter decomposition to increasing winter soil temperature depends on the quality of soil organic matter. Four studies have made use of remote sensing as a tool to better understand temporal and spatial variation of processes in the Arctic [*Nolan et al.*, 2002; *Le Dizes et al.*, 2003; *Walker et al.*, 2003; *Gould et al.*, 2003]. The studies by *Walker et al.* [2003] and *Gould et al.* [2003] provide important information on how the structure and productivity of vegetation varies along summer temperature gradients in the Alaskan and Canadian Arctic, which should be useful for specifying the land surface and for evaluating simulations of ecosystem properties of tundra ecosystems in the Arctic by large-scale climate and ecosystem models.

[21] This special section and overview paper provides an update of how ATLAS and other LAII studies have contributed to our understanding of how land–atmosphere interactions of high-latitude terrestrial ecosystems may influence the climate system. Substantial synthesis in ATLAS remains to be accomplished, and a number of synthesis activities within and across projects are currently underway. These activities can be grouped into three categories. First, several parallel activities are synthesizing what has been learned about patterns of and controls over spatial and temporal variability in arctic landscapes. These include synthesis studies that are focused on active layer, vegetation, and carbon dynamics. Second, there is a major activity focused on synthesizing what has been learned across projects about winter biological and biophysical processes. Finally, there is a synthesis activity that is focused on identifying key uncertainties in arctic climate and ecosystem models. One effort related to this synthesis activity is a study that is modifying land-surface models of regional and global climate models based on what has been learned in ATLAS about how vegetation and soil structure influence water and energy exchange in transitional ecosystems between tundra and boreal forest. Sensitivity experiments will be conducted by these new models to explore how spatial and temporal variations in soil and vegetation structure influence spatial and temporal dynamics of simulated climate at regional and pan-Arctic scales.

[22] While we do not yet know the full results of the syntheses being conducted by ATLAS, we provide thoughts on what we believe will be necessary to better understand the role of high-latitude terrestrial ecosystems in the functioning of the Earth system. First, there is a need for modeling based on the current state of knowledge that is designed to identify parameters and processes to which the functioning of high-latitude terrestrial ecosystems are most sensitive. The results of these modeling studies should provide insight for the design of observation networks and process studies that will further the development and parameterization of regional and global models. A key challenge for extending our understanding of processes will be to conduct manipulations or comparisons at a spatial scale sufficient to incorporate landscape heterogeneity into understanding that would emerge from such studies. Finally, we see a need for studies that assess vulnerabilities of arctic ecosystems to determine consequences of coupled interactions between changes in the arctic and human activities. Over the past decade, LAII research has made substantial progress in improving our understanding about how land–atmosphere interactions of high-latitude terrestrial ecosystems influence the climate system, and has laid the foundation for the type of studies that are needed to extend this understanding.

[23] **Acknowledgments.** This research was supported by the Arctic System Science Program of the National Science Foundation (OPP-9732126, OPP-9732281, OPP-0095024, and OPP-9732077).

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