Summer Differences among Arctic Ecosystems in Regional Climate Forcing

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ABSTRACT

Biome differences in surface energy balance strongly affect climate. However, arctic vegetation is considered sufficiently uniform that only a single arctic land surface type is generally used in climate models. Field measurements in northern Alaska show large differences among arctic ecosystem types in summer energy absorption and partitioning. Simulations with the Arctic Regional Climate System Model demonstrate that these variations in land surface parameters and ecological processes cause variation in surface fluxes that is sufficiently large to affect the regional climate. Plausible changes in arctic vegetation in response to high-latitude warming would feed back positively to local summer warming. This local warming could extend into the boreal zone. Climate feedbacks that operate during the growing season are particularly likely to impact vegetation and ecosystem properties. These field and model results suggest that vegetation changes within a biome could be climatically important and warrant consideration in regional climate modeling.

1. Introduction

In the Arctic, significant increases of temperature and precipitation are projected as a consequence of increasing greenhouse gas concentrations (Kattenberg et al. 1996). This warming could be amplified, if carbon dioxide (CO_2) is released from the large soil carbon pools in tundra or boreal forest (Lashof 1989; Oechel et al. 1993) or if the tree line migrates northward and reduces regional albedo (Bonan et al. 1992; Rowntree 1992; Foley et al. 1994). However, these feedbacks may not strongly affect high-latitude ecological and biogeochemical processes because their effects are exerted primarily at the global scale (the CO_2 feedback), due to rapid atmospheric mixing (Fung 1993), or in early spring (the albedo feedback) (Bonan et al. 1995; Douville and Royer 1997), when plant and microbial activity are minimal. In summer the energy supply to the arctic climate system is controlled by absorbed solar radiation, whereas in winter the arctic energy budget is dominated by advection from lower latitudes. Therefore summer is the season in which we would expect local controls such as changes in land cover to affect the surface energy budget of the Arctic most strongly (McGinnis and Crane 1994).

Despite the prediction that the snow–albedo feedback should have its major effect on early spring surface temperatures, the climate record shows that high-latitude warming trends in Alaska are nearly as pronounced in June and July (0.5° and 0.2°C decade^{-1}, respectively), as during the snow melt season (0.4°–0.6°C decade^{-1}) (Hammond and Yarie 1996; Overpeck et al. 1997; Serreze et al. 2000). Does this summer warming simply

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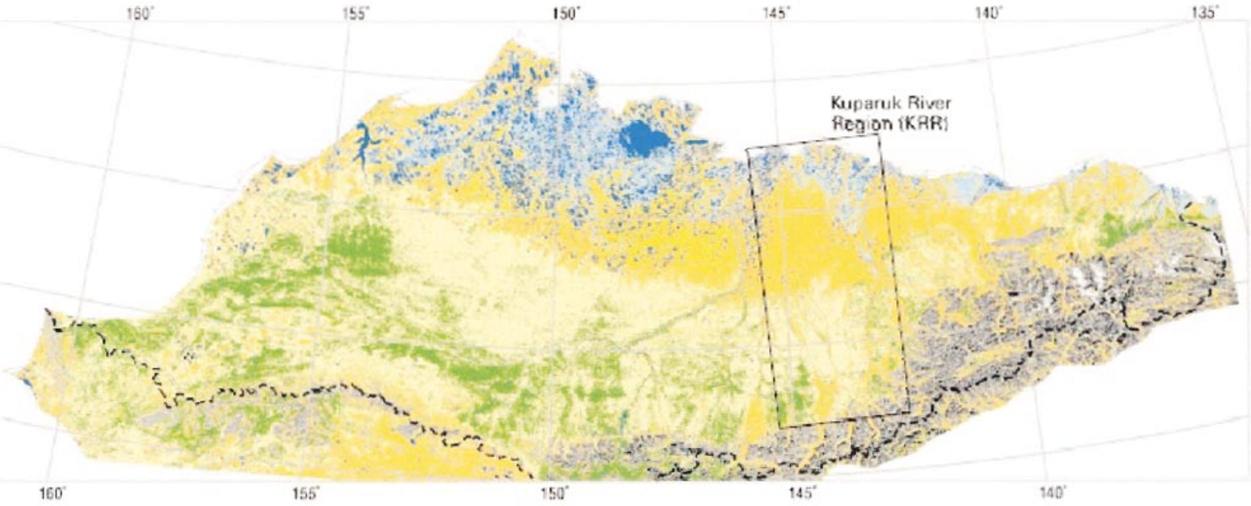

FIG. 1. Land cover classification of the North Slope of Alaska by Muller et al. (1999) based on Landsat MSS imagery. Also shown is the Kuparuk River region, where the flux measurements were made. Major vegetation types are dry tundra (brown), moist tundra (three subtypes in shades of yellow), shrub tundra (green), wet tundra (light blue), water (dark blue).

reflect inertia in the ocean–climate system, such as lags in sea surface temperatures or melting of sea ice, or could changes in high-latitude surface processes also contribute to the current summer warming in the Arctic? Although there has been some northward movement of the tree line (Payette and Filion 1985; Cooper 1986; Payette et al. 1989), this has probably converted less than 1% of the tundra zone to forest during the 30-yr period of observed warming, because of the long time lags (generally >50 yr) required for establishment and growth of tree seedlings in areas north of the arctic tree line (Chapin and Starfield 1997). Therefore, a northward shift in boreal forest is unlikely to explain the summer warming that has occurred recently. Thus it becomes important to consider whether vegetation changes *within* the arctic or boreal biomes could produce changes in surface forcing sufficient to affect the regional climate of northern land areas during summer.

Global and regional climate models are sensitive to structural differences between strongly contrasting vegetation types during periods of active plant growth (Charney et al. 1977; Graetz 1991; Bonan et al. 1995), such as the differences between forest and grassland (Shukla and Mintz 1982), desert and vegetated surfaces (Xue and Shukla 1993, 1996), or forest and tundra (Bonan et al. 1992; Foley et al. 1994; Pielke and Vidale 1995). Relative to the differences among biomes, arctic tundra is remarkably homogeneous in land surface parameters, with low values for canopy height, surface roughness, leaf area index (LAI), length of snow-free season, etc. (Wilson et al. 1987; Bonan 1996) (see below). However, direct measurements show significant differences among arctic ecosystem types in surface energy partitioning and moisture exchange (McFadden et al. 1998; Eugster et al. 2000), so that any climatically induced changes in the relative abundance of these ecosystem types might alter regional energy exchange.

In this paper we present results of field measurements showing that there is substantial variability among arctic ecosystem types in surface energy partitioning and moisture exchange during the snow-free season. We then use the Arctic Regional Climate System Model (ARCSyM) to show that the variation in land surface parameters and ecological processes that give rise to this variation in surface fluxes is sufficiently large to affect the regional climate. Finally, we show that plausible changes in arctic vegetation in response to high-latitude warming act as a positive feedback to local summer warming and that this local warming could extend into the boreal zone. These results suggest that vegetation changes within a biome could be climatically important and warrant more careful consideration in regional climate modeling.

2. Methods

a. Study region

We studied the predominant arctic ecosystem types on the northern slope of the Brooks Range in northern Alaska (Walker et al. 1998; Muller et al. 1999; Fig. 1). Their distribution follows variations in topography and soil moisture (Walker et al. 1989), with well-drained dry tundra (heath) on ridge tops, moist tundra on gentle slopes, shrub tundra on warm slopes, stream margins and river floodplains, and wet tundra in lowlands. We also studied the vegetation types that we expect to become more common with climatic warming: shrub tun-

TABLE 1. Land surface parameters of Alaskan arctic ecosystem types and the range of parameter values found in other nonarctic biomes. Parameter values for Alaskan ecosystems are representative of the sites described in this paper and were used as input parameters for the climate modeling. Parameter values for generic tundra and other biomes are values used by the NCAR LSM (Bonan 1996) and are similar to values used by other models to represent the surface parameters for tundra in global models. Here, nd indicates no data.

Parameter	Wet tundra	Moist tundra	Shrub tundra	Dry tundra	Forest tundra	Generic tundra	Other biomes
Canopy top (m)	0.2	0.2	0.7	0.1	5.0	0.5	0.5–35.0
Canopy bottom (m)	0.01	0.01	0.01	0.01	0.1	0.01	0.01–11.50
Aerodynamic roughness length (m)	0.02	0.03	0.07	0.01	0.30	0.06	0.06–2.62
Displacement height (m)	0.03	0.06	0.6	0.05	1.9	0.34	0.34–23.45
Leaf dimension (m)	0.01	0.003	0.04	0.001	0.001	0.04	0.04
Maximum LAI	0.5	0.85	1.2	0.15	2.6	3.50	0.90–5.00
Maximum SAI	0.00	0.08	0.15	0.01	0.30	2.40	0.30–2.70
Rooting depth (m)	0.3	0.3	0.3	0.2	0.4	nd	nd
Foliar N (%)	1.6	1.5	1.4	1.3	1.2	nd	nd
Albedo	0.175	0.155	0.150	0.155	0.125	nd	nd

dra, which is more common in the southern tundra zone (Alexandrova 1980), and forest tundra, which has scattered black spruce trees and is typical of vegetation at the arctic tree line. These ecosystems are representative of types that occur throughout the circumpolar Low Arctic (Bliss and Matveyeva 1992), that is, that part of the Arctic with a nearly continuous vegetation cover.

Although these ecosystems are distributed along a moisture gradient, they all have relatively high water availability within the rooting zone (Shaver et al. 1991). Each ecosystem is underlain by permafrost (permanently frozen ground), which prevents vertical drainage of water and has a surface soil layer of undecomposed organic matter with a high water-holding capacity. The water table is commonly slightly above or below the ground surface in wet tundra, near the organic-mineral interface in moist tundra, within the rooting zone of shrub tundra, and beneath the rooting zone of dry tundra. Although most roots are concentrated in the surface organic mat, maximum rooting depth in all communities extends into moist mineral soil. Maximum stomatal conductance correlates strongly with leaf nitrogen in the Arctic (Oberbauer and Oechel 1989) and globally (Schulze et al. 1994). Leaf nitrogen concentration is lowest in dry tundra (Shaver and Chapin 1991). Low leaf nitrogen concentration rather than water supply probably constrains stomatal conductance in dry tundra and other arctic ecosystems (Oberbauer and Dawson 1992). Thus, if water supply limits evapotranspiration in these ecosystems, it probably reflects the vertical distribution of rooting densities, low root temperature, and low hydraulic conductance of dry mosses, factors that are not represented in the land surface models currently used in climate simulations.

The canopy characteristics that influence land–atmosphere exchange differed substantially among the ecosystem types that we studied. Due to the presence of scattered trees, forest tundra had much larger values of all structural parameters than did nonforested tundra (Table 1). Even among nonforested sites that we studied, there was a 7–10-fold range in values for canopy height, roughness length, LAI, stem area index (SAI), and leaf dimension. Although currently not represented in land surface models, moss biomass and cover also differed among these ecosystem types (Shaver and Chapin 1991; Epstein et al. 2000). Therefore, although tundra canopies are shorter and less leafy than those of many other biomes, there is substantial variation in canopy characteristics among the tundra ecosystems that we studied.

b. Field measurements

In late June to early August of 1994–96 we measured surface energy and water vapor exchange by eddy covariance (Eugster et al. 1997; McFadden et al. 1998) in several representative stands of the major Alaskan arctic ecosystem types: wet tundra ($n = 4$ sites), moist tundra ($n = 7$ sites), shrub tundra ($n = 3$ sites), heath ($n = 1$), and forest tundra ($n = 1$ site). Measurements were made in 1994–96 during a period with both positive and negative seasonal North Atlantic oscillation (range -2.1 to 1.2) (Hurrell 1995; updated on http://goldhill.cgd.ucar.edu/cas/climind/nao_seasonal.html). These flux measurements constitute the first replicated comparison of surface energy and moisture exchange among arctic ecosystems. The sites spanned the entire latitudinal range of arctic tundra in central Alaska from a High Arctic climate at Prudhoe Bay on the arctic coast (70°17′N, 148°55′W) to a northern boreal climate at Wiseman (67°27′N, 150°05′W) in the Brooks Range. Surface fluxes were measured for 1–2 weeks at each site with the eddy covariance technique using 3-axis sonic anemometers (Applied Technologies models SWS-211/3V and SAT-211/3Vx) and closed-path infrared gas analyzers (LI-COR model 6262). We also measured net radiation [Radiation and Energy Balance Systems (REBS) model Q*7.1]; ground heat flux (REBS model HFT 3.1 heat flux plates; $n = 4$ plates per site) corrected for heat storage in the soil above the plates; and ancillary meteorological, soil, and vegetation parameters. During each observation period we used two similarly instrumented towers to measure surface fluxes simultaneously from two contrasting ecosystem types. We estimated a measurement error of 6%–9% for all energy fluxes based on an intercomparison of the two towers at the same site (Eugster et al. 1997). The energy budget–closure error averaged 16 ± 2% across sites. Albedo was measured with an Eppley albedometer at one site representative of each major vegetation type for 2–3 days at each site; midday (average minimum) albedos are reported (Betts and Ball 1997; Eugster et al. 2000).

c. *Current vegetation distribution and plausible future changes*

The relative proportions of the ecosystem types on the Alaskan North Slope (area north of the Brooks Range) were determined from a satellite-derived [Landsat multispectral scanner (MSS)] vegetation map, which field surveys showed to have an 89% accuracy (Muller et al. 1998).

We developed a scenario of future vegetation in a warmer Arctic, based on vegetation changes observed in field warming experiments (Chapin et al. 1995), vegetation distribution along climatic gradients in Alaska (Alexandrova 1980), and paleorecords of vegetation changes in response to past warming episodes in Alaska (Brubaker et al. 1995).

The change in forcing in each ecosystem type was estimated based on (1) the 10-yr average global radiation (182 ± 11 W m^{-2}; average ± standard error of the 10-yr period) and net radiation (112 ± 21 W m^{-2}) during summer (June–August) at the center of our study area (Toolik Lake Long-Term Ecological Research site, 68°38′N, 149°46′W), (2) reasonable scenarios of vegetation change, and (3) observed albedo and energy partitioning in each ecosystem.

d. *Regional climate model*

The ARCSyM is a coupled atmosphere–land–sea ice–ocean model (Lynch et al. 1995, 1999a) consisting of a hydrostatic, primitive-equation atmospheric model (Giorgi et al. 1993), the National Center for Atmospheric Research (NCAR) Land Surface Model (LSM) land surface–vegetation model (Bonan 1996), a dynamic–thermodynamic sea ice model (Lynch et al. 1995), and a high-resolution oceanic mixed layer (Bailey et al. 1997). In these simulations, ARCSyM was initialized and forced at the lateral boundaries every 6 h by observational analyses of temperature, moisture, wind, sea level pressure, and pressure heights from the European Centre for Medium-Range Weather Forecasts (ECMWF). The computational domain consisted of a horizontal grid at 20-km resolution covering northern Alaska, with 23 vertical sigma levels in the atmosphere. In order to focus on the effect of land surface properties, the sea ice and ocean were partially specified rather than freely interacting. The ocean model was replaced by a ‘‘swamp ocean,’’ which consisted of a constant heat flux and observed sea surface temperatures (Shea et al. 1992) and sea ice concentrations (derived from special sensor microwave/imager data; Weaver et al. 1987). The sea ice thickness and surface fluxes were calculated using the sea ice thermodynamics scheme [based on Parkinson and Washington (1979) with modifications following Ebert and Curry (1993)], but no ice dynamical motion or change in concentration were permitted. This strategy was chosen to minimize any model biases or responses that may arise from the nonland portions of the domain. The NCAR LSM model uses a 6-layer diffusion formulation for soil temperature and moisture that incorporates delayed infiltration. Simulations were performed for summer 1995 (April–September) that compared the standard NCAR LSM tundra specification (with grasses and shrubs—similar to most land surface model tundra characterizations) and using a tundra specification based on soil and vegetation parameters measured in wet tundra sites, as described by Lynch et al. (1999a). The model was also run in a ‘‘column mode’’ (Lynch et al. 1999b), using land surface parameters measured in the moist tundra and shrub tundra sites and with specified wind fields and moisture and temperature advection from the ECMWF analyses, to study the local impact of replacing moist tundra with shrub tundra. This model can be implemented at a specific observational site, and in tests behaves very similarly to the spatially explicit model system. Simulations with this model were performed for a representative location on the North Slope of Alaska, for the same period as the spatially explicit simulations, April–September 1995. Nominal column horizontal resolution was 20 km, with 23 levels in the vertical up to a top level at 50 hPa.

3. Results and discussion

a. *Field measurements of surface energy and moisture exchange*

Midsummer net radiation varied by 29% among the ecosystems we studied as a result of differences in albedo (Table 1). Albedo was highest in wet tundra, because of the high reflectivity of dead sedge leaves in the canopy. The low albedo of forest tundra resulted from the greater trapping of shortwave radiation in the taller, more complex canopy.

Midsummer energy partitioning also differed substantially among arctic ecosystems. Sensible heat flux was largest in forest tundra and heath (40% of net radiation), followed by shrub, moist, and wet tundra. Sensible heat flux was low (29% of net radiation) but variable in wet tundra (Table 2). Canadian subarctic forest tundra also had 20%–35% higher sensible heat flux than did wet tundra (Lafleur et al. 1992; Boudreau and Rouse 1995). Ground heat fluxes showed the opposite pattern, being lower in forest tundra (6% of net radiation) than in other tundra types (about 15% of net radiation), as was also observed in the Canadian subarctic (Lafleur et al. 1992; Boudreau and Rouse 1995). The lower ground

TABLE 2. Net daily partitioning of net radiation among fluxes of sensible (H), latent (LE), and ground heat (G), (expressed as a percent of net radiation) in Alaskan tundra ecosystems. Data are means [± standard error)], with the number of sites indicated.

Energy flux	Wet tundra	Moist tundra	Shrub tundra	Dry tundra	Forest tundra
Net radiation (W m^{-2})	115 ± 18	107 ± 11	104 ± 16	85	93
Component (% of net radiation)					
H	29.0 ± 8.0	33.0 ± 2.5	35.9 ± 6.8	40	40
LE	33.5 ± 6.6	35.6 ± 1.5	37.6 ± 2.5	31	30
G	16.0 ± 1.3	15.8 ± 1.4	15.1 ± 3.3	16	6
Number of sites	4	7	3	1	1

heat flux of forest tundra was presumably caused by both greater leaf area, which shades the ground surface, and the deeper permafrost table, which reduced the soil thermal gradient. Latent heat flux was similar in magnitude to sensible heat flux (30%–38% of net radiation) and was lower in forest and dry tundra than in other ecosystem types.

The surface fluxes we observed in replicate moist tundra ecosystems (the most common type in the region) during our 1–2-week measurement periods were similar to those measured at a single site from June to August (Vourlitis and Oechel 1997), suggesting that our measurements are representative of the growing season surface energy budget, as concluded from the comparative analyses of McFadden et al. (1998). All arctic ecosystems that we measured exhibited greater net daily ground heat flux during summer (6%–16% of net radiation) than is typical of most temperate ecosystems (generally close to zero) (Stull 1988), due to the strong thermal gradient between the ground surface and permafrost and the long hours of solar radiation (20–22 h during our study period). Boreal conifer forests typically have albedo (Betts and Ball 1997) and ground heat flux (Jarvis et al. 1997) slightly lower than the values we measured in forest tundra, but considerably lower than the values we observed in nonforested tundra. Thus, although we measured only one forest tundra site, the patterns we observed in that site are consistent with previous observations.

Moist tundra occupies over half of the North Slope of Alaska, with the remaining area approximately evenly split among shrub tundra, wet tundra, and mountains and lakes (Table 3, Fig. 1). Because moist tundra occupies the greatest area and is intermediate between shrub and wet tundra in albedo and energy partitioning, the values for this ecosystem type might be considered

TABLE 3. Current and potential future vegetation types in the Alaskan Arctic and the impact of this vegetation change on summer energy absorption and surface energy exchanges. R_{net} (net radiation), SEs reflect projected interannual variability based on annual variation SE of global radiation at Toolik Lake.

Variable	Effects of vegetation change				Area-weighted change
Current vegetation	Moist tundra	Shrub tundra	Wet tundra	Mountains and lakes	
Future vegetation	Shrub tundra	Forest tundra	Forest tundra	Mountains and lakes	
Aerial extent (% of tundra)[a]	53	19	9	19	
Changes in solar energy absorption[b]					
Δalbedo	−0.005	−0.025	−0.050	—[c]	−0.012
ΔR_{net} (W m^{-2})	0.9 ± 0.1	4.6 ± 0.1	9.2 ± 0.1	—	2.2 ± 0.1
Changes in energy balance components (W m^{-2})[d]					
Δ H	3.4 ± 0.2	4.5 ± 0.2	12.3 ± 0.6	—	3.7 ± 0.2
Δ LE	2.2 ± 0.1	−9.0 ± 0.5	−4.5 ± 0.3	—	−0.9 ± 0.1
Δ G	−1.1 ± 0.1	−10.1 ± 0.6	−11.2 ± 0.6	—	−3.5 ± 0.3
Total changes in forcing (W m^{-2})[e]					
ΔAtmospheric heating during summer	3.4 ± 0.2	4.7 ± 0.2	13.3 ± 0.2	—	3.9 ± 0.3
ΔHeat transfer from summer to winter	−1.1 ± 0.1	−10.5 ± 0.6	−12.1 ± 0.6	—	−3.7 ± 0.3

[a] Percent of Alaskan arctic tundra (Muller et al. 1999).

[b] R_{net} is calculated from −(Δalbedo) multiplied by the average global radiation (182 W m^{-2}) at Toolik Lake.

[c] No measurements for mountains and lakes, for which we assume zero change.

[d] Changes in each energy balance component (not considering the change in albedo) are calculated from the difference in measured energy partitioning (means in Table 2) of current and "future" vegetation types multiplied by the long-term average net radiation at Toolik Lake (112 W m^{-2}).

[e] Total changes in forcing are calculated from the difference in measured energy partitioning of current and "future" vegetation types multiplied by the sum of the long-term average net radiation at Toolik Lake (112 W m^{-2}) plus the change in net radiation (ΔR_{net}) due to the change in albedo. For example, atmospheric heating during summer = $(H_{\text{future}} - H_{\text{current}})\,[R_{\text{net}} - (\Delta\text{albedo} \times K)]$, where K = average global radiation.

representative for the North Slope of Alaska. Moist tundra has considerably lower values of canopy height, surface roughness, LAI, SAI, and leaf dimension than values currently assumed in most global and regional models (Table 1). This could partially explain the tendency of climate models to overestimate evapotranspiration and surface drying at high latitudes (Lynch et al. 1999b). A comparison of general circulation model results and observations also indicated a general oversimulation of evaporation over arctic terrestrial areas and suggested that the surface parameterizations should be an initial focus in diagnosing the model biases (Walsh et al. 1998).

Other arctic regions differ substantially in vegetation composition from the North Slope of Alaska. For example, the Russian and Canadian High Arctic are sparsely vegetated; central Siberia has extensive areas of shrub lands and forest tundra; and the lowlands and peat lands of northern Siberia have abundant lakes and wet tundra (Bliss and Matveyeva 1992). If the patterns of energy exchange that we measured in these ecosystem types are representative of other regions, as suggested by a recent review of the literature (McFadden et al. 1998; Eugster et al. 2000), these other areas of the circumpolar Arctic may differ substantially from northern Alaska in their energy absorption and partitioning. Even within moist tundra of northern Alaska there are substantial differences in energy partitioning associated with variation in landscape age and disturbance (Walker et al. 1998). Is this variation in energy exchange within, and among, arctic ecosystems climatically important?

b. *Scenarios of future arctic vegetation and energy exchange*

As one test of the sensitivity of regional energy exchange to variation in arctic vegetation, we estimated the change in regional energy exchange that would result from plausible future changes in vegetation in northern Alaska. These estimated changes in regional energy exchange are based on the field measurements of surface fluxes in those tundra vegetation types that are currently widespread and in those that will likely become more common in a warmer climate.

We hypothesized plausible scenarios of vegetation response to climatic warming based on field experiments, observations, and paleoreconstructions. Field manipulations that increased summer air temperature by 3°C converted moist tundra to shrub tundra within 10 yr (Chapin et al. 1995). A vegetation conversion from moist to shrub tundra also occurred during Holocene warming (Brubaker et al. 1995) and in permanent plots (Chapin et al. 1995; Sturm et al. 2000, manuscript submitted to *J. Climate*) in response to regional warming that has occurred since 1980 (Chapman and Walsh 1993; Hammond and Yarie 1996; Serreze et al. 2000). Near the southern limit of arctic tundra, shrub tundra replaces moist tundra on hill slopes (a pattern consistent with experimental and paleoecological responses to warming); forest tundra replaces shrub tundra in riparian zones; and forest tundra replaces wet-meadow tundra in lowlands (Alexandrova 1980). These vegetation transitions along latitudinal temperature gradients are similar to those that occurred during Holocene warming (Brubaker et al. 1995), suggesting that similar changes might plausibly occur in the future. Shrubs are already an important component of moist tundra, explaining why the conversion from moist to shrub tundra can occur quickly. In addition, shrubs trap snow, increasing the winter insulation and creating warmer soils and perhaps enhanced nutrient availability—a positive feedback that speeds the conversion from moist to shrub tundra (Sturm et al. 2000, manuscript submitted to *J. Climate*).

If the tundra vegetation in arctic Alaska were to change as hypothesized above, the increase in sensible heat flux (3.4 W m^{-2}) associated with replacement of moist tundra by shrub tundra would enhance the slight warming due to the increased net radiation (0.9 W m^{-2}; Table 3). Increased atmospheric heating during summer would also result from replacement of shrub tundra by forest tundra (4.7 W m^{-2}) and replacement of wet tundra by forest tundra (13.3 W m^{-2}), due to modest increases in net radiation (reduced albedo) and large increases in sensible heat flux. Each postulated vegetation change would reduce ground heat flux and, therefore, the energy stored in soils in summer and released in winter. The measurements of ground heat flux used in this calculation are independent of the sensible heat flux measurements made by eddy covariance and provide independent assessment of the extent to which vegetation change would cause heat to be released to the atmosphere in summer versus winter.

The regional consequences of energy balance feedbacks to climate associated with vegetation change can be approximated by extrapolating linearly (Boudreau and Rouse 1995) from our local measurements of relatively uniform 1-ha vegetation patches to the North Slope of Alaska. For the North Slope, the area-weighted average increase in atmospheric heating is 3.9 W m^{-2} (Table 3). This change in summer heating is due primarily to a change in energy partitioning at the surface (a 3.7 W m^{-2} increase in sensible heat flux and a 3.5 W m^{-2} decrease in ground heat flux), with only a minor additional sensible heat flux resulting from the change in albedo (Table 3). The changes in heat transport to the atmosphere due to altered evapotranspiration are relatively small (a decrease of 0.9 W m^{-2}).

The tussock-to-shrub transition, which occurred within a decade in response to an experimentally imposed 3°C increase in summer air temperature (Chapin et al. 1995), accounted for half of the projected increase in regional summer heating (3.9 W m^{-2}). Vegetation transitions requiring tree invasion would likely occur more slowly (Chapin and Starfield 1997). Even the smallest predicted vegetation-induced increase in summer at-

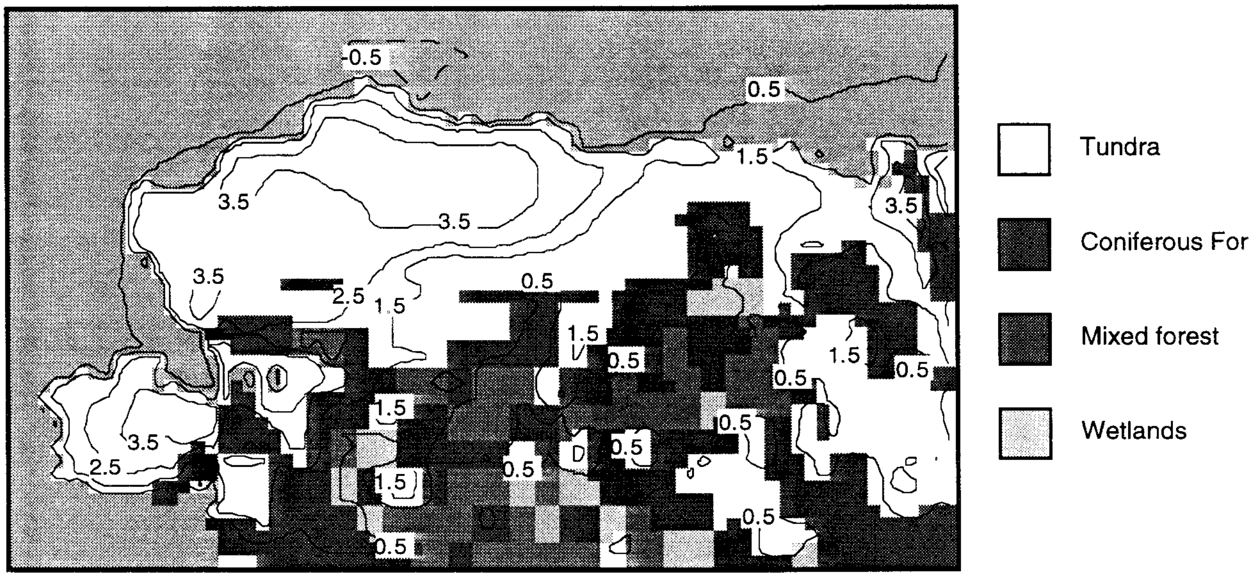

FIG. 2. Map of the difference in Jul surface temperature simulated by the regional climate model (ARCSyM) between simulations that assume 1) the standard land surface parameters used for arctic vegetation in most climate models (similar to shrub tundra) and 2) the parameters measured for wet-meadow tundra at Prudhoe Bay, AK.

mospheric heating (i.e., the transition from tussock to shrub tundra, 3.4 W m^{-2}) is similar in magnitude to the unit-area atmospheric forcing associated with the shift from glacial to interglacial periods during the Pleistocene (a 2% change in solar constant; 4.6 W m^{-2} at the top of the atmosphere; 1 W m^{-2} at the ground surface) or a doubling of atmospheric CO_2 (4.4 W m^{-2}), two forcings known to have large climatic effects (Rind and Lacis 1993; Kattenberg et al. 1996). The changes in regional forcing due to projected change in arctic vegetation would have their greatest direct impact on the summer climate of northern terrestrial regions, in contrast to changes in global forcing associated with changes in CO_2 concentration or solar constant, which would exert their effects throughout the year at a global scale. The effect of these changes in tundra vegetation on global mean temperature obviously depends on their aerial extent relative to other land surface changes occurring elsewhere on the globe.

The projected increase in summer heating of the arctic atmosphere in response to reasonable scenarios of vegetation change in the Alaskan Arctic would act as a positive feedback to enhance the probability and rate of arctic vegetation change. The associated reduction in ground heat flux could offset the projected increases in thaw depth (Kane et al. 1992) and CO_2 release (McKane et al. 1997) that have been estimated assuming constant vegetation.

c. Sensitivity of regional climate to arctic vegetation changes

We tested the sensitivity of Alaskan climate during summer to changes in arctic vegetation both locally (using the ARCSyM in column mode) and regionally (using a spatially extensive domain). We first performed two one-dimensional simulations for the summer of 1995 in which the land surface beneath the atmospheric column was parameterized as either moist tundra or shrub tundra, based on our field measurements (Table 1). Simulated near-surface temperature during summer (June–August) was 3.5°C warmer over shrub than moist tundra due to increased sensible heat flux, providing independent support of our hypothesis that a transition from moist to shrub tundra would cause local atmospheric warming. The warming simulated by ARCSyM extended throughout the planetary boundary layer (not shown). Detailed sensitivity analysis of model results and validation are presented elsewhere (Lynch et al. 1999a). Here we focus on the consequences of measured differences in input parameters to the land surface model.

The net impact and significance of arctic tundra on the changes in regional forcing that we estimate depend upon lateral energy transfers with other regions such as oceans and boreal forest. To test whether tundra surface properties would affect climate beyond the tundra, we performed two spatially explicit simulations over Alaska using ARCSyM. One simulation was initialized using the land surface parameter values we measured in wet tundra; the second simulation was parameterized using the values typically assigned to tundra in global climate models (Table 1; Lynch et al. 1995, 1999a). The ‘‘generic’’ tundra parameterization is similar to shrub tundra and resulted in July near-surface air temperatures that were 2.5°–4° and 1.0°–2.5°C higher than with the wet tundra parameterization in the western and eastern parts of the tundra zone, respectively (Fig. 2), reflecting greater sensible heat fluxes to the atmosphere from this shrublike ecosystem. This warming occurred throughout the model domain (except for a slight cooling north of Alaska) and extended south into boreal forest, as the warmer, drier air was advected southward. These impacts of tundra vegetation on boreal climate were accompanied by reductions in cloudiness and moisture advection (Lynch et al. 1999a), which have the potential for more widespread and long-term impacts.

4. Conclusions

We conclude that differences among arctic vegetation types in summer energy partitioning, and to a lesser extent in albedo, were large enough to warrant inclusion in regional and global climate modeling efforts that seek to accurately simulate high-latitude processes. These regional-scale climate effects of vegetation are crucial if simulations are to be accurate enough for use in regional management. Changes in these vegetation types in response to climate warming could act as a significant positive feedback to regional warming during the growing season and are likely to have effects that extend beyond the Arctic. Climate feedbacks that operate during the growing season are particularly likely to impact vegetation and ecosystem properties.

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