Impact of Arctic treeline on synoptic climate

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Abstract. The position of the Arctic treeline has been associated with the preferred location of Arctic fronts that demarcate the boundary between Arctic and polar air masses. It has been argued that differences in summer energy balance, particularly in sensible heating, across treeline between forest and tundra may help determine the location of these frontal zones. Our observations of the energy balance at treeline show that the daily averaged summer heating contrast between forest and tundra is on the order of magnitude less than that previously proposed and that the influence on the atmosphere is confined to a shallow layer. In addition, maximum heating contrasts occurred in spring rather than in summer when the Arctic frontal zone is best expressed. Hence energy-balance contrasts at treeline are unlikely to be the major determinant of the position of the Arctic front.

Introduction

The position of the Arctic treeline has previously been correlated with the location of Arctic fronts [Bryson, 1966; Hare and Ritchie, 1972] (from hereon termed the Arctic frontal zone). Such a co-location of the mean summer position of the Arctic frontal zone with treeline could occur because conditions to the north are too severe for trees to establish [Bryson, 1966]. However, it has also been argued that differences between forest and tundra in summer energy balance, particularly in sensible heating, may help determine the location of frontal zones [Hare and Ritchie, 1972; Pelto and Vidale, 1995]. The summer Arctic frontal zone has strong impacts on the locations of cyclogenesis, cyclone tracks, and precipitation patterns [Serreze et al., 2000]. The implication is that Arctic warming may displace the position of northern treeline northward of its present location as it did during warmer periods of the Holocene [Bryson et al., 1965; McDonald et al., 1998]. A contemporary northward advance of the Arctic treeline associated with enhanced greenhouse warming could feed back positively to climate change because of the lower albedo and higher heat fluxes from the forest compared to adjacent tundra [Lafleur and Rouse, 1995]. This is especially true in spring when masking of the snow by trees reduces albedo thus increasing energy absorption and transfer to the atmosphere [Foley et al., 1994; Rowntree, 1992; Bonan et al., 1995]. Consequently, a northward advance of the treeline could contribute to high-latitude climate change. However, there have been no direct measurements at treeline of the impacts of vegetation on atmospheric dynamics.

Methods

To assess whether differential heating between forest and tundra are sufficient to govern the position of the Arctic frontal zone, we examined sensible heat fluxes and their influence on the thermal structure of the overlying boundary layer at Council on the Seward Peninsula of Alaska. We also compared other major components of the surface energy budget, namely the radiation balance and latent and ground heat fluxes. Measurements were made in a region of tundra and adjacent white spruce forest (Picea glauca) during the 1999 summer growing season (June-August) and the 2000 spring transition season (May). This region of tundra and forest is representative of the two vegetation types that bracket the observed vegetation transitions across the northern treeline [Lafleur et al., 1992]. The tundra site was a moist lichen-dominated tussock tundra (N64°50.499' W163°41.591') 8 km northeast of the white spruce forest site (N64°54.456' W163°40.469'). The white spruce forest contained 1104 stems per hectare, with a mean diameter at breast height of 0.125 m ± 0.003 SE and a mean tree height of 6.16 m ± 0.081 SE.

Simultaneous measurements of latent (LE) and sensible (H) heat flux were made using the eddy covariance technique in a configuration identical to previous work [Eugster et al., 1997]. In addition, over ten days in June 2000, simultaneous vertical rawinsonde soundings (GPS-80, Vaisala) of boundary-layer temperature and humidity above the forest and tundra sites were made to compare the impact of these two ecosystem types on boundary-layer structure and development. These are the first simultaneous measurements of energy balance and atmospheric profiles to be made over tundra and forest ecosystems of which we are aware.

Results

The average albedo of the forest canopy (0.095) during summer was lower than that of the tundra (0.19) because of its darker color and taller more complex canopy architecture. In turn, the forest site absorbed 11 percent more...
net radiation on a daily basis (11 W m\(^{-2}\)) than the tundra (Figure 1a). The greater leaf area in the forest (2.7 m\(^2\) m\(^{-2}\) \pm 1.023 SE) versus tundra (0.52 m\(^2\) m\(^{-2}\) \pm 1.032 SE) resulted in less radiation at the ground surface and therefore less ground heat flux in the forest than the tundra. The partitioning of energy between sensible and latent heat fluxes (Bowen ratio = \(H / LE\)) did not differ consistently between forest and tundra (Figure 1a). Therefore, the greater net radiation and lower ground heat flux in the forest site resulted, on average, in a sensible heat flux contrast of 60 W m\(^{-2}\) between forest and tundra in the 2 hours either side of solar noon (Figure 1b). These differences between forest and tundra were most pronounced around solar noon (Figure 1b) but were apparent only for a short time. Due to the large spatial scales implicit when examining synoptic scale features, it is the contrast between the forest and tundra averaged over days rather than hours that will influence frontal location. Over a day the sensible heat contrast between forest and tundra averaged only 5 W m\(^{-2}\) (Figure 1a). This is only 10 percent of the differential heating cited as necessary to be manifested as a synoptic front [Pielke and Vidale, 1995]. The difference in sensible heat flux between treeline forest and tundra that we observed is consistent with previous observations of midday contrasts of 25-50 W m\(^{-2}\) during BOREAS [Onclay et al., 1997] and daily average heating contrasts over northern Canadian treeline of 12 W m\(^{-2}\) [Lafleur and Rouse, 1995; Lafleur et al., 1992]. Gradual forest-tundra transitions, which are common at the latitudinal treeline, are likely to show weaker heating gradients than between the distinct stands of forest and tundra that we measured.

The heating contrasts between tundra and forest were greater in spring (Figure 1c,d) than in summer (Figure 1a,b) due to the masking of snow by the forest canopy. The snow cover resulted in a much higher albedo over the tundra (0.68) compared to the forest (0.16) and hence 142 W m\(^{-2}\) more net radiation at the forest on a daily basis (Figure 1c). This generated an average daily sensible heating contrast of 140 W m\(^{-2}\) between the tundra and forest (Figure 1c), which is three times that suggested in previous work as being necessary to be defined as a synoptic front [Pielke and Vidale, 1995]. This period of maximum contrast lasts only 2-3 weeks in spring when incoming solar radiation is strong and the surface is still snow-covered. In addition, measurements were made during predominantly clear-sky conditions when thermal contrasts are expected to be greatest. Although spring is a time of large heating contrasts between tundra and forest, the Arctic frontal zone is not well expressed at this time. Rather, the Arctic frontal zone can be clearly distinguished from mid-latitude frontal activity, only during summer [Serrze et al., 2000], when heating contrasts between tundra and forest are small.

The heat produced from energy exchanges at the surface is mixed into the boundary layer during the day. Large-scale horizontal gradients in boundary layer temperature and depths then provide the proposed anchoring of Arctic fronts by treeline. In summer, energy exchange and boundary layer observations reveal a combination of stronger surface heating and more efficient vertical mixing at the forest. This resulted in a heating of the lower boundary layer by up to 2 °C more at the forest than tundra at solar noon (Figure 2a). However, these differences in temperature between the two sites were only clearly observed up to a height of

**Figure 1.** The seasonal daily average differences in surface energy balance components for forest and tundra during (a) summer and (c) spring and the average hourly sensible heat flux for forest and tundra during (b) summer and (d) spring. Error bars indicate standard error and time is shown in Alaska Daylight Time (ADT). Summer measurements are an average for June-August and spring measurements (May 8-13).
150 m (Figure 2a). There is a small difference in temperatures between the sites at 250-300 m, however this difference is small. Above 300m the profiles converge and therefore the influence of surface heating differences is confined to a shallow atmospheric layer. Using the Arctic Regional Climate System Model (ARCSyM) [Lynch et al., 1995] we conducted experiments over Alaska to estimate the average 00Z July temperature profiles from four pairs of adjacent tundra and forest gridcells (each 30x30 km) near the Seward Peninsula. The results from the regional climate model showed heating differences as high as 30 Wm⁻² (data not shown), but only during periods of greatest solar heating, consistent with observations. The simulations produced a higher air temperature over the forest with the influence also being confined to a shallow layer (less than 200 m) (Figure 2b). The profiles are not expected to converge completely above this height as the grid cells are spatially distinct and are separated by nearly 500 km. This means that the synoptic climate will influence the absolute magnitude of the profile but not the trend in the profiles. A direct comparison of the absolute magnitudes of both measured and modelled temperature profiles is not valid here due to differences in spatial and temporal scales. The modelled profiles represent the average July 1995 temperatures over spatial scales of greater than 100 km, whereas the measured profiles represent an eight day June 2000 average over a much smaller spatial scale. Our observations and simulations both suggest that the influence of increased surface heating has only a modest influence on the boundary layer, which is unlikely to influence frontal development. It is acknowledged that our observations were made essentially over large patches of tundra and forest, which is different from a conceptual treeline with tundra and forest immediately adjacent. However, we argue that this patchiness is representative of the true nature of vegetation at treeline.

Our results are consistent with sensitivity studies using the ARCSyM [Lynch et al., 1995]. A comparison of the control experiment described above with simulations in which either mountains were removed or forest was replaced by tundra showed that, on synoptic scales, topography had a stronger effect on frontal location than did vegetation [Lynch et al., 2000]. A historical analysis (1979-1998) of pan-Arctic temperature fields at 850 hPa showed that a maximum expression of frontal frequencies during summer was associated with deep baroclinicity and upper tropospheric wind maxima [Serreze et al., 2000]. These features occurred where large-scale heating contrasts between the cold Arctic Ocean and snow-free land combined with mountain barriers acted to focus the location of baroclinicity. These studies argue that treeline represents a response to, rather than a forcing of, the preferred location of frontal activity, conclusions that are consistent with our observations.

Conclusions

Our measurements and modeling along with the previous historical analyses [Serreze et al., 2000] suggest that heating contrasts between tundra and forest appear insufficient to generate large-scale frontal features. If warming of several degrees in the Arctic were to occur this would provide a potential for the northward movement of treeline, however, our results suggest that such a shift in treeline would not feedback to affect the position of large-scale synoptic features such as the Arctic front. Nevertheless, differences in surface energy exchanges between the forest and tundra may be important and sufficient to drive local-scale circulations that could themselves be ecologically important. In addition a 2 °C higher surface temperature over forest compared to tundra (Figure 2) could promote tree reproduction and expansion into tundra at the northern edge of the boreal forest in an environment where temperature limits reproduction, establishment, and growth of trees [Hobbie and Chapin, 1998].

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References


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