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The boreal forest and the polar front

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Abstract. The analysis presented in this paper suggests that the larger heating over the boreal forest in the spring and summer, as contrasted with weaker heating over the adjacent tundra, results in a preferred position of the polar front along the northern edge of the boreal forest. This positioning is well documented in the literature (see, for example, Bryson, 1966; Barry and Hare, 1974; Kreps and Barry, 1970). This heating results from the lower albedo of the boreal forest which is not compensated by an increase in transpiration, even with the larger leaf area index of the forest. The warmer temperatures are mixed upward by the deep boundary layer over the forest and mesoscale circulations which result from the patchiness of heating associated with the heterogeneous landscapes of the forest. Thus in contrast to previous assumptions in which the arctic front position in the summer determines the northern limit of the boreal tree line, our study suggests the boreal forest itself significantly influences the preferred position of the front. This conclusion reinforces the findings of Bonan et al. (1992) and Foley et al. (1994) on the important role of boreal forest–tundra interactions with climate.

1. Introduction

In a landmark paper, *Bryson* [1966] concluded that the boreal forest occupies the region between the mean or modal boundaries of arctic air in winter and in summer. In our paper we suggest that the average summer position of the arctic front is a result of the location of the boreal forest. In other words, this region of vegetation creates a meteorological environment that results in the preferred position of the arctic front in the summer along the boreal forest–tundra boundary. This strong influence of surface heating patterns on synoptic scale weather should not be surprising. It has been found for oceanic influences on weather (e.g., *Shvortsov and Tonkacheev* [1993] in the Atlantic Ocean and *Trenberth and Branstator* [1992] in the tropical Pacific associated with El Niños). *Otterman et al.* [1984] have also concluded that the location of the taiga-tundra ecoline exerts a significant effect on climate through snow cover albedo feedbacks. *Bonan et al.* [1992, 1995], using a general circulation model (GCM), have already found a strong influence of the boreal forest and tundra in weather and climate. *Bonan et al.* [1995], for example, found that the boreal forest warms surface air temperatures at all times of year, compared to simulations in which the forest is replaced with tundra. *Foley et al.* [1994] concluded, using a coarse-resolution GCM, that heating over a boreal forest that is farther north than its current position is as important as orbital variations in explaining the warm period of the Holocene. They suggested that vegetation feedbacks need to be considered in assessing possible future climate.

2. Hypothesis

Our hypothesis extends the concept proposed by *Foley et al.* [1994] in that in the spring and summer, the low albedo (i.e., 0.10 [*Monteith*, 1975]) within the boreal forest results in large sensible heating rates in the overlying troposphere. This heating becomes significant once the solar elevation angle in the spring becomes high enough. Tundra, in contrast, has somewhat higher albedos (e.g., 0.18–0.25 [*Oke*, 1973] and 0.15–0.20 [*de Jong*, 1973; *Bonan et al.*, 1995]). The association of the boreal forest and tundra region with weather and climate is not new. *Hare and Ritchie* [1974] discuss the surface heat budget gradient between the closed boreal forest and the tundra and illustrate an association with the July arctic front location. However, at the end of their paper, they state that they have not yet been able to establish the links between their approach and that of *Bryson* [1966] with respect to the bioclimatology of the boreal forest. We propose, in our paper, to connect these two perspectives in a unified hypothesis.

It has generally been assumed that the large solar heating of the boreal forest resulted in large latent heat fluxes rather than sensible heat fluxes. However, results from the Boreal Ecosystem-Atmosphere Study (BOREAS) of 1994 [*Baldocchi and Vogel*, 1995; P. J. Sellers et al., The Boreal Ecosystem-Atmosphere Study (BOREAS): An overview and study, submitted to *Bulletin of the American Meteorological Society*, 1995] indicate that much of the net radiative flux at the vegetation surface results in larger sensible rather than latent heat fluxes, particularly on sunny days. *Lafleur et al.* [1992] also showed that the boreal forest has greater sensible heat flux and less latent heat flux in the summer than tundra, although for their observational site near Churchill, Manitoba, the albedo differences were small (3–5% different). This conclusion regarding larger sensible heat fluxes over the forest is supported by the *Bonan et al.* [1995] model analyses. The conclusion of *Lafleur et al.* [1992] that albedo differences are small, however, must be limited to local geographic locations. Even a cursory view of the tundra–boreal forest region from aircraft or satellite shows the forest region to be darker. These lower albedos are confirmed by the data of *Monteith* [1975] and others.

This ecologically induced influence on the partitioning of surface energy should have an effect on weather and climate, as suggested by *Baldocchi and Harley* [1995], *Dirmeyer* [1994], *Koster and Suarez* [1995], *Collins and Avissar* [1994], *Lee and Shin* [1989], *Dabberdt and Davis* [1978], *Cotton and Pielke*

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Plate 1. Photograph of a smokestack in the boreal forest of Manitoba and Saskatchewan, Canada.

[1995], *Bonan et al.* [1992, 1995], and others. This influence includes a deep boundary layer, as illustrated in Plate 1, where a smoke plume rapidly mixes up to nearly 3 km above the surface. Perhaps this conclusion should not have been surprising. Since the boreal forest growth rates are slow (presumably because the tree roots are embedded in cold soil), they cannot assimilate carbon very quickly. Since carbon assimilation and transpiration are intimately related [i.e., *Sellers et al.*, 1992], transpiration rates must also be slow. Tundra also has weak transpiration; however, its higher albedo results in weaker sensible heat fluxes.

Over the boreal forest the heat is transported quickly to higher levels of the troposphere, first through boundary layer heating and then through mesoscale circulations which result from the spatial heterogeneity of the boreal forest [*Steyaert et al.*, 1995]. The deep boundary layers over the boreal forest and the excellent visibility (in the absence of forest fires) on sunny days are direct results of this deep tropospheric mixing that results from the larger sensible heat flux (see Plate 1). This heterogeneity permits spatial variations of surface sensible heat fluxes of hundreds of watts per meter squared, between lakes and adjacent patches of pine, spruce, and aspen.

The horizontal gradient in tropospheric heating between the boreal forest and the tundra results in a preferred position of the arctic front in the summer. Synoptic fronts (see, for example, *Pielke* [1995]) are defined by

$$\nabla_p(\Delta z) = R_d/g \ \ln\,[P_1/P_2]\nabla_p\bar{T}$$

and

$$\Delta \overrightarrow{V}_g = (g\,\overrightarrow{k}\,/f) \times \nabla_p(\Delta z)$$

where Δz is the thickness between the pressure surfaces P_1 and P_2, $\bar{T}$ is the mean temperature in that layer, g is the gravitational acceleration, R_d is the gas constant of dry air, and ∇_p is the east-west and north-south gradient on a pressure surface. The quantity $\Delta \overrightarrow{V}_g$ is the change in the vector geostrophic wind across the two pressure surfaces. It is appropriate to use these synoptic definitions of a front because of the long spatial scale of the boreal forest across North America and Asia. The association between the spatially varying surface heating and the preferred positioning of the synoptic front is illustrated schematically in Figure 1.

3. Results

To assess the influence of different heating rates between the boreal forest and adjacent tundra region, we can apply the *Hare and Ritchie* [1974] data, as well as case study preliminary analysis transects from the BOREAS field program obtained by the National Center for Atmospheric Research (NCAR) Electra (D. Lenschow, personal communication, 1994). Over a season, the average daily difference between the boreal forest and the tundra is of the order of 50 W m^{-2}. This value will be refined through modeling and further analysis of the Electra data. This value of heat flux would correspond to a heating rate of about 0.8°C d^{-1} if distributed throughout the 1000- to 500-mbar layer. In terms of a thickness gradient change (equation (1)), this corresponds to about 20 m d^{-1}. From (2), using a 500-km distance for the spatial gradient, the wind speed at 500 mbar would increase by 4 m s^{-1} d^{-1}. During predominantly cloud-free days during the warm season, the cumulative effect of this gradient would be of the order of 28 m s^{-1} week^{-1}.

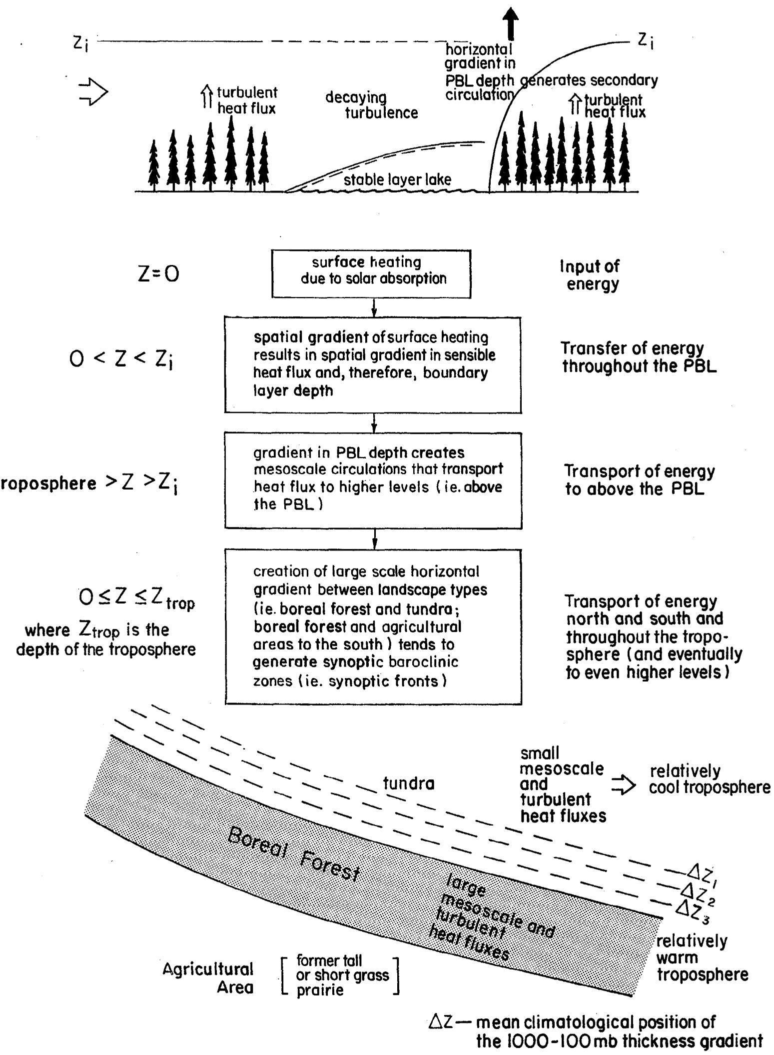

Figure 1. Conceptual model of how the surface heterogeneities influence the circulations above them through differential fluxes and their associated boundary layers.

Using U.S. National Weather Service guidance [*Pielke*, 1995], a thickness gradient of this size is defined as a synoptic front. If the differential flux were 100 W m^{-2}, the magnitude of $\nabla_p \bar{T}$, $\nabla_p(\Delta Z)$, and ΔV_g would be twice as large.

4. Conclusions

The analysis presented in this paper suggests that the larger heating over the boreal forest in the spring and summer, as contrasted with weaker heating over the adjacent tundra, results in a preferred position of the polar front along the northern edge of the boreal forest. This positioning is well documented in the literature (see, for example, *Bryson* [1966]). This heating results from the lower albedo of the boreal forest which is not compensated by an increase in transpiration, even with the larger leaf area index of the forest. The warmer temperatures are mixed upward by the deep boundary layer over the forest and mesoscale circulations which result from the patchiness of heating associated with the heterogeneous landscapes of the forest. Thus in contrast to previous assumptions in which the arctic front position in the summer determines the northern limit of the boreal tree line, our study suggests the boreal forest itself significantly influences the preferred position of the front. This conclusion reinforces the findings of *Bonan et al.* [1992] and *Foley et al.* [1994] on the important role of boreal forest–tundra interactions with climate.

This result of large heating over the boreal forest should not be surprising. Since the trees in this region grow only slowly, probably because of the cold soil temperatures, they cannot use much of the photosynthetically active radiation which they receive. Thus much of the solar radiation must go into sensible rather than latent heat flux, which results in the deep boundary layers frequently observed over the boreal region on sunny days.

This conclusion has significant implications for climate change. Since the northern portion of the boreal forest is not sexually regenerating [*Elliott-Fisk*, 1983; *Nichols*, 1976; *Pielou*, 1991], our analysis suggests that if it were burnt over, the position of the polar front in the summer would shift southward. Also, in the case of a regional warming of the climate, northward progress of the treeline would be delayed by the preferred positioning of the arctic summer polar front, which would tend to perpetuate cooler air masses over the tundra.

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