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Comparison of regional surface fluxes from boundary-layer budgets and aircraft measurements above boreal forest

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Abstract. Daytime surface sensible and latent heat fluxes (H_s and λE_s) above boreal forest, derived independently from the boundary-layer budgets of heat and water vapor and by eddy correlation from the Twin Otter aircraft, are compared. The aircraft and boundary-layer budget values of $H_s + \lambda E_s$ underestimated surface available energy by 25% and 4%, respectively, when the sum of the minor surface energy balance terms (storage and photosynthesis) was estimated as 17% of net radiation. The boundary-layer budget estimate of the regional Bowen ratio (1.05) agreed to within 15% of the aircraft measurement (0.91). Both methods clearly have value for estimating land-surface fluxes at a regional scale.

1. Introduction

Regional estimates of land surface fluxes are needed to characterize the land-atmosphere interaction and to improve the diurnal and seasonal boundary-layer cycles in large-scale atmospheric models. The atmospheric boundary layer responds to surface forcings at regional scales. Radiosonde-based budgets provide a framework for evaluating surface fluxes at regional scales [*Diak and Whipple*, 1994; *Kustas et al.*, 1995; *Barr and Strong*, 1996] and for assessing their influence on boundary-layer growth and development [*Barr and Betts*, this issue]. In this study we compare two independent estimates of the regional surface sensible and latent heat fluxes above the heterogeneous boreal forest landscape: one based on boundary-layer (BL) budgets of heat and moisture, and the other as measured from the Twin Otter flux aircraft (FT).

2. Data

This study analyzes radiosonde and aircraft data collected during the 1994 field phase of the Boreal Ecosystem-Atmosphere Study (BOREAS), during three intensive field campaigns: IFC-1, May 24 through June 16; IFC-2, July 19 through August 8; and IFC-3, August 30 through September 19.

2.1. Site Description

Figure 1 maps the BOREAS southern and northern study areas (SSA and NSA), and Table 1 summarizes their land covers. The two study areas were spatially heterogeneous and spanned the south-to-north extent of the Canadian boreal forest. The SSA was dominated by deciduous (trembling aspen) and mixed deciduous-coniferous forest in the SW and by wet coniferous (black spruce) forest in the NE. The NSA was dominated by wet coniferous and mixed forest. Both study areas had significant inclusions of dry coniferous (jack pine) forest, lake, wetland, burn, and regeneration.

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2.2. Meteorological Data

Serial upper-air soundings were released from Candle Lake (SSA) and Thompson (NSA) at approximately 1115, 1315, 1515, 1715, 1915, 2115, and 2315 UTC on most days in IFC-1 and -2. Many days in IFC-3 excluded the 1315 sounding. The field program and BL budget analysis are described by *Barr and Betts*, this issue].

Net radiation, R_n, was measured in two ways: from FT and at two BOREAS surface weather stations in each study area; the SSA old aspen and old jack pine tower flux sites, the NSA old jack pine tower flux site, and an NSA site near the Thompson zoo. The surface stations used Radiation and Energy Balance Systems (REBS) $Q*6$ net radiometers, corrected for calibration errors (E. Smith, Florida State University, personal communication, 1995). When coincident, the FT and surface R_n agreed very closely.

In assessing surface energy balance closure (equation (2), below), we used FT R_n with the FT surface fluxes and surface R_n with the BL budget fluxes. We first applied a small adjustment to the surface R_n, to extrapolate from the surface weather stations to the region. The adjustment corrected for local versus regional albedo differences. The local albedo α was measured at each weather station by Eppley pyranometers. The regional albedo α_r was measured from the FT. The mean α_r values were 0.117 (SSA) and 0.120 (NSA), and did not vary significantly with IFC. The adjusted surface value (R_n^*) was

$$R_n^* = R_n + (\alpha - \alpha_r) R_s \tag{1}$$

Equation (1) reduced the measured values by 0.3% for the SSA and by 2.8% for the NSA. Note that the value for R_n was not adjusted for local versus regional differences in skin temperature, which could potentially account for an additional but smaller correction. Hereafter all surface (BL budget) R_n values have been adjusted, but for brevity we drop the asterisk superscript.

We defined the fractional surface energy balance closure, ε_s, as

$$\varepsilon_s = (H_s + \lambda E_s)/(R_n - S) \tag{2}$$

where H_s is the surface sensible heat flux density, λE_s is the surface latent heat flux density, and S is the sum of the minor

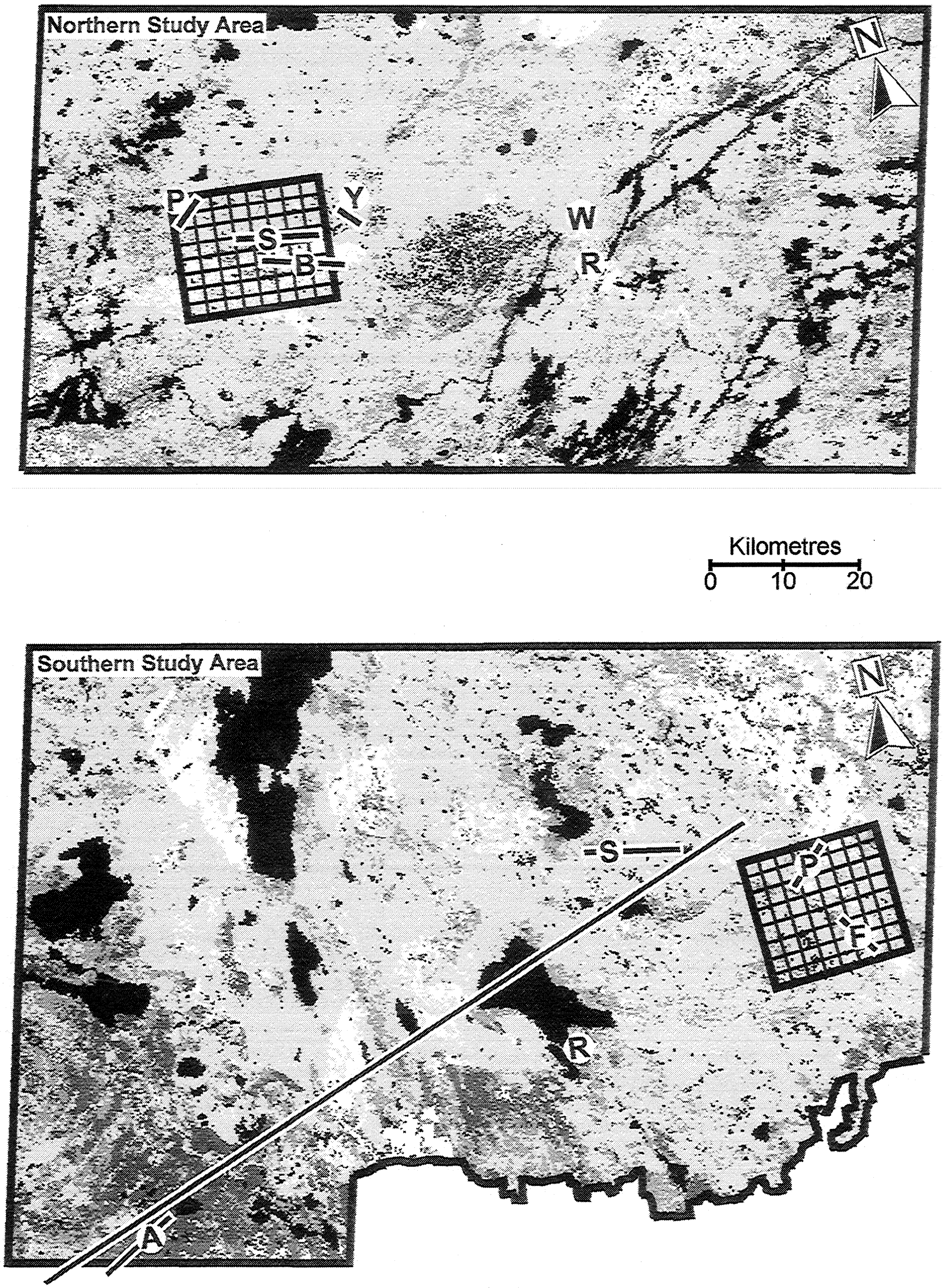

Figure 1. Boreas northern and southern study areas with land cover [*Hall et al.*, this issue] and Twin Otter flux (FT) lines. The FT grid lines were spaced every 2 km, and the long flight line in the SSA is the forest transect. Gray scale: black, lake; dark gray, deciduous forest; midgray, mixed forest; light gray, coniferous forest; white, burn and regeneration. Symbols: A, old aspen tower flux site; B, burn; F, fen tower flux site; P, old jack pine tower flux site; R, radiosonde release site; S, old black spruce tower flux site; W, Thompson zoo surface weather station; Y, young jack pine tower flux site.

energy balance terms (soil or open-water heat flux, canopy heat storage and photosynthetic energy flux). A value for ε_s of 1.0 indicates perfect agreement between the sum $H_s + \lambda E_s$ and surface available energy $R_n - S$. A key uncertainty at the regional scale is estimating S, which is primarily a measure of heat storage by the landscape, including photosynthesis. We first estimated S/R_n for each land cover class and then derived an average for the boreal forest landscape, as shown in Table 1. Our best estimate for the summer, daytime value of S at the landscape scale was as 17% of R_n for both the SSA and NSA.

We estimated S/R_n in Table 1, where possible, from measurements at BOREAS tower flux sites. Measured, daytime S/R_n values were 0.06 at the SSA old black spruce tower flux site (P. G. Jarvis, personal communication, 1995) and 0.09 at the SSA old aspen tower flux site (T. A. Black, personal communication, 1995). Where no measurements were available, we approximated S/R_n from previous studies at other sites. *Barr et al.* [1994] reported daytime S/R_n of 0.10 for mature deciduous forest, and *McCaughey and Saxton* [1988] reported the same value for mature mixed forest. We approximated the value of S/R_n for clearcuts, recent burns, and regenerating forest to be intermediate between the mature forest value and the daytime, bare soil value of 0.25 [*Novak and Black*, 1983]. For over open water our estimates for S/R_n were based on the FT fluxes, which suggested daytime S/R_n of 0.4 (fen) and 0.9 (lake). Clearly, uncertainties in S/R_n lead directly to uncertainty in ε_s.

Mean values for the surface Bowen ratio β_s,

$$\beta_s = H_s/\lambda E_s \quad (3)$$

were also calculated from mean H_s and λE_s from composites of both the FT flight legs and the BL budget.

2.3. FT Measurements

Regional measurements of H_s and λE_s were made from the National Research Council's Twin Otter flux aircraft (FT) [*Desjardins et al.*, this issue]. The eddy covariance was calculated after linearly detrending the data. *MacPherson et al.* [1992] give a detailed description of the FT eddy correlation instrumentation and methodology. The FT measured H_s and λE_s on select, fair-weather days (Table 2) throughout the SSA and NSA. Figure 1 maps the flight legs used in this analysis. Three types of flights were flown in the SSA: tower flux site flybys, an SW-NE forest transect roughly spanning the SSA, and a 16 by 16 km grid in the NE. Two flight types were flown in the NSA: tower flux site flybys and a 16 by 16 km grid. The tower flux values refer to FT flybys over the tower flux sites, not flux measurements on the towers. We averaged all flight segments with lengths between 9 and 22 km and elevations of less than 50 m above ground level (agl); 323 of 1074 flight segments did not meet these criteria and were excluded from the analysis. The mean length of the acceptable flight legs was 15 km. The mean elevation was 36 m agl. The flight legs spanned a range of surface inhomogeneities, from the nearly homogeneous tower flux site to the heterogeneous SSA forest transect.

Table 1. Percentage Land Cover of the Boreal Forest Landscape, by Study Area, With Values of the S/R_n Ratio for Each Land-Cover Element

	Percent of Total		
Land Cover Type	SSA	NSA	S/R_n
Forest, wet coniferous	47.3	45.4	0.06
Forest, dry coniferous	0.8	6.6	0.08
Forest, mixed	17.1	20.2	0.08
Forest, deciduous	9.6	4.2	0.09
Regeneration	10.4	6.2	0.15
Recent burn	0.4	0.0	0.20
Cleared/disturbed	1.1	4.1	0.20
Open water	9.6	10.3	0.90
Fen	3.7	2.9	0.30
Weighted mean			
SSA	···	···	0.17
NSA	···	···	0.17

Hall et al. [this issue].

Table 2. Twin Otter Flight Days

IFC	SSA	NSA
1	May 25–27, 29, 31; June 1, 4, 6	June 7–11, 13
2	July 20–27	July 28–29; Aug. 1–2, 4, 8
3	Sept. 8, 11–18	Aug. 31; Sept. 1–3, 6, 8, 19

3. BL Budget and FT Surface Flux Intercomparison

Two factors complicated the intercomparison of surface fluxes. First, the measurement periods were not identical. The BL budget estimates spanned the BL growth period from 1515 to 2115 UTC, whereas the FT fluxes were measured mostly between 1600 and 1900. The mean times (1815 for BL budget and 1809 for FT) were, however, nearly identical. However, because the FT measurements were mostly within 2 hours of noon, they represented periods of higher R_n (508 W m^{-2}) than the BL budget estimates (473 W m^{-2}), as shown in Table 3. Further, the FT and BL budget measurement days did not completely overlap. The BL budget estimates spanned each IFC at both study area, whereas the FT measurements spanned only half of each IFC at each study area. For this reason we made only coarse stratifications by study area or IFC and focused on comparing FT and BL budget estimates for surface energy balance closure ε_s and the surface Bowen ratio β_s, rather than the fluxes themselves.

3.1. Bulk Comparisons

Table 3 compares the net radiation R_n, surface energy balance closure ε_s, and the surface Bowen ratio β_s as measured by FT and as derived from the BL budget. The FT versus BL budget differences in R_n are discussed above. The reader is

Table 3. A Bulk Comparison of FT and BL Budget Flux Parameters, Stratified by Study Area and IFC

	FT			BL Budget		
	R_n, W m^{-2}	ε_s	β_s	R_n, W m^{-2}	ε_s	β_s
All	508	0.75	0.91	473	0.96	1.05
SSA	524	0.74	0.79	488	0.87	0.90
NSA	488	0.77	1.08	454	1.09	1.24
IFC-1	560	0.72	1.17	545	0.98	1.31
IFC-2	531	0.79	0.68	485	0.92	0.79
IFC-3	415	0.76	1.00	380	0.97	1.08

The bulk ε_s values were estimated using a landscape mean S/R_n of 0.17.

Table 4. Mean FT Flux Parameters for the Tower Flux Site Flybys

Tower Flux Site Flyby	ε_s	β_s
SSA		
Old aspen	0.81	0.60
Old black spruce	0.69	1.16
Old jack pine	0.72	1.35
Fen	0.69	0.44
NSA		
Old black spruce	0.69	1.33
Old jack pine	0.65	1.83
Young jack pine	0.66	1.46
Burn	0.80	0.80

referred to *Barr and Betts* [this issue] for a discussion of individual BL budget components.

The striking difference in the surface energy balance closure, ε_s, in Table 3 is that the sum of $H_s + \lambda E_s$ in the BL budget underestimated surface available energy $R_n - S$ by only 4%, whereas the FT $H_s + \lambda E_s$ sum underestimated $R_n - S$ by 25%. This is using our best initial landscape estimate for S/R_n of 0.17 (Table 1). The observations of *Desjardins et al.* [this issue] indicate that this value for S/R_n may be too low; some BOREAS tower flux sites were at higher elevations and had less standing water than was typical of their land covers. This is particularly true of wet coniferous forest, which dominated the landscape. This difference would cause the measured values of S/R_n at these sites (and in Table 1) to be atypically low. After adjusting our estimates of S/R_n upward for this possible difference, the highest plausible landscape value for S/R_n becomes 0.23. This correspondingly increases ε_s, but the FT fluxes are still a 19% underestimation of $R_n - S$ (and the BL budget surface fluxes become a 3% overestimate). The underestimation of daytime $H_s + \lambda E_s$ by FT eddy correlation was not unique to this aircraft or to this study. A similar underestimation of daytime flux was reported by the other BOREAS flux aircraft and at the BOREAS flux towers [*Desjardins et al.*, this issue]. The 19–25% underestimation of $R_n - S$ by FT $H_s + \lambda E_s$ is in the upper range of previous aircraft flux studies. Using flux aircraft above the FIFE (First ISLSCP Field Experiment) grassland, *MacPherson et al.* [1992] and *Kelly et al.* [1992] observed a 10–30% underestimation of $H_s + \lambda E_s$ relative to $R_n - S$; they attributed this, in part, to a loss of longwave contributions to the eddy flux. The underestimation of $H_s + \lambda E_s$ by eddy correlation may also be related to mesoscale transfer [*Sun and Mahrt*, 1994].

The striking feature of the surface Bowen ratio, β_s, comparison in Table 3 is that although the pattern of β_s by category was identical for both measurement methods, the BL budget consistently gave a β_s which is about 15% higher than the FT. For all the data $\beta_s \approx 1$, with a higher Bowen ratio in the NSA than the SSA. The difference between NSA and SSA was not the result of a difference in land cover (Table 1) but may have reflected a SSA versus NSA difference in climate or species adaptation. The Bowen ratio was highest in IFC-1, when the ground and lakes were cold, and shows a substantial midsummer depression, presumably associated with peak evapotranspiration from deciduous species.

Desjardins et al. [this issue] reported a similar low bias in FT β_s in comparison with the surface eddy correlation measurements at the BOREAS tower flux sites. They attributed the difference to their observation that many tower flux sites were better drained than was typical of their respective land covers. A second possible source of bias in the FT fluxes in this study is that they were not corrected for the eddy flux divergence between the surface and the FT flight level (36 m agl). This would bias FT β_s low because the layer from 0 to 36 m typically warmed and dried. The mean warming rate of 0.88 K h^{-1} and drying rate of -0.09 g kg^{-1} h^{-1} would increase FT β_s by about 8%. However, the BL budget β_s may have been biased high by the assumption that the eddy fluxes were negligible at the EL top [*Barr and Betts*, this issue]. We conclude that the BL budget method probably overestimates β_s and that the FT method probably underestimates β_s.

The consistency of the BL budget and FT estimates for ε_s and β_s demonstrated the effectiveness of both techniques for integrating surface fluxes across a spatially heterogeneous land surface. Both bypassed the difficulties of upscaling and can be used as ground truth for subsequent studies. The FT measurements were superior in several respects: they linked surface fluxes to specific land covers at scales of several kilometers; they characterized spatial heterogeneity at these scales; and, although biased low, they gave instantaneous flux estimates. Their weakness was in the underestimation of $R_n - S$.

3.2. Stratification of FT Measurements by Land Cover

Tables 4 and 5 group the FT measurements by land cover. The tower flux site flybys in Table 4 tied β_s most distinctly to specific land-cover elements. If we average the values in Table 4 by land cover and study areas the coniferous forest composite (old jack pine, young jack pine, and old black spruce) has the highest mean β_s (1.42), with β_s higher in the NSA (1.53) than in the SSA (1.22) and higher for old jack pine (1.67) than for old black spruce (1.24). The mean deciduous forest β_s (0.60) was less than half of the coniferous forest value. Fen had the lowest β_s (0.44), while a regenerating burn in the NSA had intermediate β_s (0.80).

The SSA forest transect was subdivided into individual flight segments based on land cover, as shown in Table 5. The forest transect traversed the NE-to-SW transition from coniferous to deciduous forest. The coniferous flight segments had mean β_s of 0.90, compared with transitional mixed forest β_s of 0.66 and deciduous β_s of 0.55. The SSA forest transect included three flight segments over lake. The near-zero H_s and λE_s but high R_n of the lake segments suggested a daytime lake value for S which approached R_n. Apparently, most of the daytime surface available energy over lake was used to warm the lake. This was substantiated by FT temperature measurements, which showed that the lake surface was on average 6°C cooler than the air at FT flight level.

Tables 4 and 5 also show the fractional surface energy bal-

Table 5. Mean FT Flux Parameters Along the SSA Forest Transect

Land Cover (Legs)	ε_s	β_s
Coniferous (2)	0.68	0.90
Coniferous/mixed (1)	0.67	0.76
Mixed/deciduous (1)	0.66	0.57
Deciduous (2)	0.71	0.55
Lake (3)	0.86	−0.01

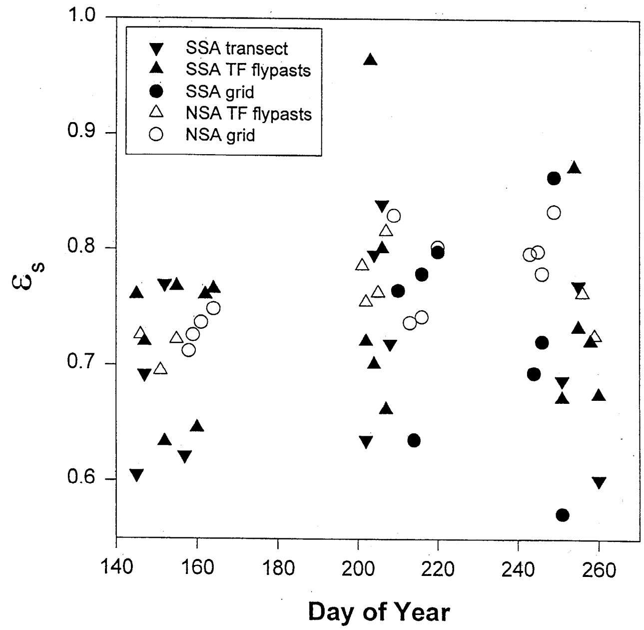

Figure 2. Daily mean fractional surface energy balance closure ε_s by the FT, stratified by flight leg and study area.

ance closure ε_s, based on individual land-cover values for S/R_n from Table 1. All ε_s values fell in the range 0.65 to 0.81, with values slightly lower for coniferous forest than for deciduous forest. The coniferous vs. deciduous ε_s difference is consistent with *Desjardins et al.*'s [this issue] claim that the wet coniferous boreal forest had a higher mean S/R_n than was measured at the SSA tower flux site (the value in Table 1). The lake ε_s value is still in question because it was based on estimate for S/R_n of 0.90. When S/R_n is high, ε_s is very sensitive to S/R_n.

Figures 2 and 3 show the seasonal variability in ε_s and β_s, for individual flight legs and separating the SSA and NSA. The grid pattern sampled a more heterogeneous area than the tower flux site flybys and gave intermediate values for β_s of 0.84 (SSA) and 1.07 (NSA), rather close to the FT study area means in Table 3.

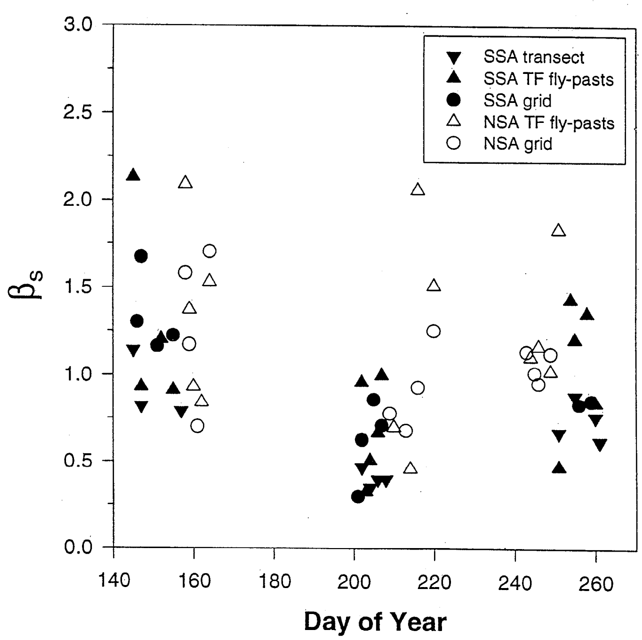

Figure 3. Daily mean FT Bowen ratio (β_s) stratified by flight leg and study area.

Table 6. Mean BL Budget Flux Parameters, Stratified by Wind Direction in the SSA

Upwind Land Cover	ε_s	β_s
Deciduous	0.87	0.70
Coniferous	0.87	1.12

3.3. Stratification of BL Budget by Wind Direction

Although the BL budget method did not tie the surface fluxes to specific land cover elements in the heterogeneous boreal forest landscape, a rough stratification of forest type by wind direction was possible in the SSA, because the sonde release site lay on the border of the SW-to-NE deciduous-to-coniferous forest transition (Figure 1). Upwind deciduous forest gave lower mean BL budget β_s (0.70) than upwind coniferous forest (1.12), with no corresponding difference in ε_s (Table 6). We were encouraged by the ability of the BL budget method to detect the SW-deciduous versus NE-coniferous β_s contrast within the SSA. In contrast to the spatially detailed FT flux measurements, the BL budget method integrates surface fluxes over a broader, but less well defined source region. Nevertheless, the BL budget and FT methods showed a similar deciduous versus coniferous β_s contrast in the SSA. The mean BL budget upwind deciduous β_s of 0.70 was 36% lower than the mean upwind coniferous β_s of 1.12 (Table 6). The corresponding FT forest transect's mean deciduous β_s of 0.55 was 39% lower than the mean coniferous β_s of 0.90 (Table 5). That the two methods gave a similar coniferous versus deciduous β_s contrast (offset by a 25% mean bias) suggests that BL budget methods may be able to detect spatial variations in land surface fluxes.

4. Conclusions

This study has demonstrated the effectiveness of both FT and BL budget methods for estimating regional-scale surface fluxes from a spatially heterogeneous landscape. Both methods reported a mean, daytime, summer Bowen ratio β_s near 1.0 for the boreal forest landscape, in sharp contrast to the summer β_s of 0.4 previously reported for both the FIFE grassland [*Smith et al.*, 1992] and the agricultural cropland of southern Saskatchewan [*Barr and Strong*, 1996]. The aircraft flux estimate of β_s is about 15% lower than that derived from the BL budget. A more significant difference was found in the surface energy balance closure: the aircraft flux estimate was low by 19–25%. Further study is needed of the surface heat storage ratio S/R_n for forest and nonforest landscape elements and of the possible sources of bias in the BL budget and FT Bowen ratios. We plan a follow-up study in which we estimate ground-truth fluxes by integrating other BOREAS flux data, including measurements by 3 other flux aircraft and 10 tower flux sites, across the complex boreal forest landscape.

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