Radiosonde boundary layer budgets above a boreal forest

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Abstract. Daytime surface sensible and latent heat fluxes were estimated above boreal forest from the boundary layer budgets of heat and water vapor. Two budgets were integrated from serial soundings in the atmospheric boundary layer: one for the mixed layer and one for the entrainment layer. Horizontal and vertical advection were derived from synoptic analyses. The surface fluxes were then calculated as a budget residual. The mean entrainment parameter $A_e$ above the boreal forest was estimated to be 0.21. The dependence of entrainment on buoyant and shear forcings agreed with earlier studies.

1. Introduction

Daytime surface fluxes of sensible and latent heat drive the growth and development of the mixed atmospheric boundary layer (BL) over land. As the mixed BL deepens, it entrains or mixes downward warmer, drier air from above. The balance between the surface fluxes and entrainment determines the rates of BL deepening, warming, and moistening (or drying).

This study analyzes radiosonde data collected during the 1994 field phase of the Boreal Ecosystem Atmosphere Study (BOREAS). One of the objectives of BOREAS was to quantify the interaction between the boreal forest and the atmospheric BL and provide data sets to test and improve global forecast and climate models. The diurnal BL cycle is difficult to simulate in large-scale models because the surface forcings are not easily estimated at regional scales and because our understanding of BL top entrainment is limited. The common parameterizations of entrainment have not been adequately evaluated for different land surface types and wind shears and over the seasonal cycle. Recently, simple BL parameterizations, which better represent entrainment, have been introduced into two global models [Beltaas and Betts, 1993; Hong and Pan, 1996]. The improved representation of the BL, when coupled to a more interactive land-surface scheme, has led to improvements in forecast skill [Beltaas et al., 1996; Hong and Pan, 1996].

Radiosonde-based budgets of heat and moisture provide a framework for evaluating surface and entrainment fluxes at the regional scale and for assessing their joint influence on BL development. Betts and Ball [1994] demonstrated good agreement between sound-based budget estimates of entrainment and direct measurements by instrumented aircraft above the Konza prairie [Betz et al., 1992]. Diak and Whipple [1994] used a simple mixed layer model, driven by sound-based measurements of BL growth, to estimate daytime surface sensible and latent heat fluxes. Kustas et al. [1995] showed how upper air budget methods could be coupled with remotely sensed net radiation and soil heat flux to estimate the surface energy balance. Betts and Barr [1996], using the same methodology as here, reevaluated entrainment over the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) grassland, and its dependence on wind shear. In this study, we estimate regional surface and entrainment fluxes from the BL budgets of heat and water vapor.

2. Data

This study analyzes data from the BOREAS southern and northern study areas (SSA and NSA), collected during the three 1994 Intensive Field Campaigns (IFC 1, May 24 to June 16; IFC 2, July 19 to August 8; and IFC 3, August 30 to September 19). A companion paper [Barr et al., this issue] shows the location and land cover of the study areas.

2.1. Upper Air Soundings

Serial upper air soundings were released from Candle Lake (53.73°N, 105.27°W, 503 m, in the SSA) and Thompson (55.75°N, 97.87°W, 206 m, in the 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 because of the later sunrise. The SSA sonde release site was a 200 m wide grassy clearing, 1.5 km south of Candle Lake. It was surrounded by 12–15 m tall mixed forest. The NSA sonde release site was at the zoo near Thompson, on the edge of town near the wooded banks of the Burntwood River.

The radiosondes measured atmospheric pressure, temperature, relative humidity, wind speed, and wind direction at a mean vertical resolution of 27 m (2.9 hPa) in the BL. The mean sonde ascent rate within the BL was 5.4 m s\(^{-1}\). Both upper air sites used Vaisala RS80 radiosondes, equipped with a capacitive bead thermistor and Humicap thin wall capacitor hygrostat. The sondes were tracked by a Digigrone II M815 receiver with NAVIAD Loran C wind finding. Sonde relative humidity (RH) was corrected for a calibration bias (see appendix). The maximum bias was found at 70% RH, where the sonde sensor underestimated RH by 5%.

2.2. Net Radiation

Net radiation $R_n$ was measured at two BOREAS surface weather stations in each study area: the SSA old aspen and old jack pine tower flux sites, and the NSA old jack pine tower flux site and a site near the Thompson airport. We applied two small adjustments to $R_n$: a correction for calibration errors and
an adjustment for local versus regional albedo differences [Barr et al., this issue].

2.3. Canadian Regional Finite Element Model Data

Estimates for horizontal and vertical advection, which cannot be determined from serial sonde ascents, were based on regional finite element (RFE) model synoptic analyses, every 3 hours. Because these estimates lacked mesoscale detail on hourly timescales, they added noise to the individual 2-hour BL budgets. However, we believe that the synoptic advection estimates were satisfactory, when averaged over periods of at least 15 days. On this long timescale, the mean horizontal advection was small.

3. Boundary Layer Development

3.1. Delineating the Boundary Layer

For each sounding, we delineated the mixed layer (ML) and entrainment layer (EL), within the atmospheric boundary layer (BL), by visual inspection (see Figure 1). The procedure, although somewhat subjective, used well defined criteria. The ML top was identified as the lowest level of an inversion in potential temperature θ, which capped a mixed layer of nearly uniform θ. It was also characterized by an abrupt drop in mixing ratio q. We also calculated the profile of saturation pressure ps [Betts, 1982], the pressure of the lifting condensation level of air parcels. The profile of ps plast, where pl is surface pressure, has a distinct local minimum at ML top. The nocturnal BL top was identified as the level that capped a strong surface inversion in θ. It was also characterized by inflections in the rate of the profiles of θ, ps plast, and horizontal wind speed. The EL top was delineated as the level where the relatively constant free atmosphere (FA) lapse rates in θ, q, and ps plast were reached (Figure 1). This EL top was somewhat more difficult to identify than the ML top. However, precise delineation of EL depth was not critical because the EL budget analysis assumed a constant value of EL depth, equal to its mean depth.

Table 1 lists the sonde analysis days. We analyzed fair-weather days only, excluding days with fewer than six soundings, more than 2 mm of precipitation, low solar irradiation (Rs/RN < 0.4, where Rs/RN is the ratio of measured daily solar irradiation to the theoretical top-of-the-atmosphere value), substantial horizontal sensible or latent heat advection in the ML, little ML growth (daily maximum BL depth <100 hPa), or significant BL decline (>40 hPa between soundings) during the normal ML growth period (1515–2115 UTC). This left 9, 13, and 10 days in the SSA during IFC 1, 2, and 3, respectively, and 10, 7, and 7 days in the NSA during IFC 1, 2, and 3, respectively.

The data were stratified by study area, IFC, time of day, wind speed and direction, and wind shear across the EL. The effect of wind direction in the SSA is shown in the companion paper [Barr et al., this issue].

3.2. Boundary Layer Development

Composite SSA and NSA sounding time series were prepared by averaging the soundings at each release time. The composites were not used in the BL budget analysis but were prepared to show ML growth over the forest. Within the ML, we first scaled individual profiles of potential temperature θ and mixing ratio q to the mean ML depth, and then averaged the profiles. Above the ML, the pressure coordinate of individual soundings was shifted to match the composite ML top. Because there was no 1315 UTC sounding in IFC 3, 1315 was excluded from the composite sounding time series.

Figures 2 and 3 show the SSA and NSA composite sounding time series. Early morning soundings had a well-developed nocturnal BL, 0.1–0.7 km in depth, which gave way to mixed layer development, typically by 1515 UTC. The ML then deepened and warmed during the day. A strong superadiabatic zone underlay the ML. The superadiabatic surface layer was deepest (13 hPa on average) at 1515 and 1715 and declined to 9 hPa at 1915 and 2115. Early morning ML growth was slow under the strong nocturnal inversion. By midmorning, ML growth had eroded the nocturnal BL. This led to a period of explosive BL growth as the ML overtook the residual of the previous day’s ML. The 1515 ML was deeper in the NSA (pressure depth of 55 hPa) than the SSA (32 hPa) because the Sun rose about 30 min earlier in the NSA. Mean daily maximum ML depth was slightly higher in the NSA (192 hPa) than the SSA (179 hPa) and in IFC 1 (208 hPa) than IFC 2 and 3 (166 and 178 hPa).

ML potential temperature θ was nearly “well mixed” at 1515, 1715, 1915, and 2115 UTC (Figures 2a and 3a). The 1515–2115 θ profiles had a characteristic weak minimum in θ near the midpoint of the ML. By 2315, the minimum θ was nearer to the surface, at 30% of the ML depth. In contrast, ML humidity structure was not “well mixed”; the mixing ratio q declined with height in the BL (Figures 7b and 3b). The mean decline in q from the top of the surface superadiabatic layer to the top of the ML was 0.3 g kg⁻¹ at 1515 UTC, 0.7 g kg⁻¹ at

<table>
<thead>
<tr>
<th>IFC</th>
<th>Southern Study Area</th>
<th>Northern Study Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>May 25–27, 31, June 1, 4, 6–7, 10</td>
<td>May 25, 27, June 2, 4, 7–10, 13, 16</td>
</tr>
<tr>
<td>2</td>
<td>July 21, 23–27, 30–31, Aug. 2–5, 8</td>
<td>July 21, 27, 29, Aug. 1, 4, 5, 8</td>
</tr>
<tr>
<td>3</td>
<td>Aug. 31, Sept. 1–2, 6–7, 11, 13, 16–17, 19</td>
<td>Aug. 30, Sept. 1–3, 7, 9, 17</td>
</tr>
</tbody>
</table>
1715 and 1915, and 0.9 g kg\(^{-1}\) at 2115. The ML \(\theta\) and \(q\) structures were consistent with other observational studies [Mahrt, 1976; Betts and Ball, 1994] and large eddy simulations [Wygnaard and Brotz, 1984].

The EL deepened slightly during the ML growth period (1515–2115 UTC), from a minimum depth of 21 hPa at 1515 to a maximum depth of 33 hPa at 1915. The 1515–2115 mean EL depth was 29 hPa. The composite sounding time series also showed a characteristic zone of cooling near the BL top, produced by overshooting thermals [Betts, 1974; Mahrt, 1979]. The BL-top cooling zone was partially obscured by subsident warming but was evident when consecutive pairs of soundings were compared.

In both composites (Figures 2a and 3a), ML \(q\) fell about 1 g kg\(^{-1}\) during the morning hours to a minimum at 1915 UTC, and then increased. The upward transport of moisture can be seen as the BL deepens into drier air above. The composite sounding time series also showed warming and some moistening in the free atmosphere above the BL. Analysis of the RFE model output showed that the free atmosphere warming was dominated by subsidence, horizontal advection, and radiative heating. Shallow cumulus clouds on some days may also transport water out of the BL.

4. Boundary Layer Budget Analysis

4.1. Budget Equations

The analysis follows Betts and Barr [1996], with the addition of horizontal and vertical advection from the RFE analyses. We have omitted the equations here. We constructed budgets for the ML and EL for each 2-hour time increment between soundings. The ML equations can be written symbolically for sensible \(H\) and latent heat \(LE\) as the sums.
Table 2. Mean Mixed-Layer Budget Estimates and Their Components, Stratified by Study Area and IFC

<table>
<thead>
<tr>
<th></th>
<th>IFC 1</th>
<th>IFC 2</th>
<th>IFC 3</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>19</td>
<td>20</td>
<td>17</td>
<td>56</td>
</tr>
<tr>
<td>$R_a$</td>
<td>545</td>
<td>485</td>
<td>380</td>
<td>473</td>
</tr>
<tr>
<td>$H_o$</td>
<td>299</td>
<td>210</td>
<td>247</td>
<td>252</td>
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<tr>
<td>$H_i$</td>
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<td>-68</td>
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<td>-91</td>
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<tr>
<td>$\lambda E_o$</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>$\lambda E_i$</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>$\epsilon_e$</td>
<td>284</td>
<td>285</td>
<td>239</td>
<td>271</td>
</tr>
<tr>
<td>$\beta_e$</td>
<td>192</td>
<td>192</td>
<td>159</td>
<td>194</td>
</tr>
</tbody>
</table>

Values are in units of W m$^{-2}$. SSA, southern study area; NSA, northern study area; IFC, Intensive Field Campaign; n, number of days, with three individual (2 hour) budget analyses per day.

$H_i = H_o + H_a + H_s$  

(1a)

$\lambda E_i = \lambda E_o + \lambda E_s$  

(1b)

The local change terms, $H_o$ and $\lambda E_o$, were derived for each time step from the time change of sonic variables, averaged though the ML. The horizontal advection terms $H_s$ and $\lambda E_s$ (small in the mean) were estimated from RFE analyses in the ML. The entrainment fluxes $H_s$ and $\lambda E_s$ came from a similar budget equation for the EL, where we also estimated vertical advection from the RFE analyses, and neglected fluxes through the EL top [see Betts and Barr, 1996]. The EL budget used a mean EL thickness of 30 hPa, equal to its mean depth. We then calculated the surface Bowen ratio $\beta_e$ as

$\beta_e = H_s/\lambda E_s$  

(2)

4.2. Surface Energy Balance Closure

The measured surface net radiation $R_a$ (with a small correction for landscape albedo) [Barr et al., this issue] was compared with the sum of the surface fluxes derived from the sonic budget. We defined a fractional surface energy balance closure $\epsilon_e$ as

$\epsilon_e = (H_s + \lambda E_s)/(R_a - S)$  

(3)

where $S$ is the sum of the minor energy balance terms (soil or open-water heat flux, canopy heat storage, and photosynthetic energy flux). A value for $\epsilon_e$ of 1.0 indicates perfect agreement between the sum $H_s + \lambda E_s$ and surface available energy $R_a - S$. A key uncertainty at the regional scale is estimating $S$, which is primarily a measure of heat storage by the landscape, including photosynthesis. Our best estimate was $S \sim 0.17R_a$ for both the SSA and NSA [Barr et al., this issue].

4.3. Budget Components

Table 2 summarizes our estimates for $H_s$ and $\lambda E_s$, and their components in (1a) and (1b) and the two derived parameters, Bowen ratio $\beta_e$ and fractional energy balance closure $\epsilon_e$. The budgets were dominated by the local change and entrainment.

For each IFC and study area, horizontal advection contributed negligibly ($\leq 10\%$) to the estimates of the surface fluxes. Because the entrainment latent heat flux exceeded the surface flux, the BL dried on average during the day, as seen in the composite figures. Our energy balance closure parameter $\epsilon_e$, gives some indication of the reliability of the budgets. For the full summer's data set, $\epsilon_e = 0.96$ (with a best estimate of the bulk landscape storage $S$ of 17% of $R_a$). The smaller data subsets have values of $\epsilon_e$, indicating errors in the energy balance, as large as 13% (for the SSA composite).

4.4. Surface Bowen Ratio

The mean surface Bowen ratio $\beta_e$ was 1.05. The surface Bowen ratio was 38% higher in the NSA than the SSA, and there was a substantial midsummer depression in $\beta_e$, presumably associated with peak evaportranspiration from deciduous species. More detailed stratifications, which reduced each analysis to less than 15 days, are not shown, as the variability increased with decreasing sample size.

This mean daytime summer $\beta_e$ near 1.0 over the heterogeneous boreal forest is in sharp contrast to, say, the FIFE grassland, for which daytime summer $\beta_e$ is $\approx 0.4$ [Smith et al., 1992].

4.5. Variation With Time of Day

Table 3 shows the time of day variation in the budget estimates for $H_s$ and $\lambda E_s$. We have less confidence in these. The time-of-day variation in $H_s$ is well behaved, but the variation in $\lambda E_s$ is not. The plausible values for $\lambda E_s$ at 1715–1915 and 1915–2115 UTC result from anomalously low mixing ratios in the 1915 soundings (Figures 2b and 3b), perhaps the result of a midday radiation error in the sonic humidity measurement. However, the 1715–1915 underestimation and 1915–2115 overestimation of $\lambda E_s$, were mutually compensating, and the daily latent heat flux totals were little affected. Previous studies [Barr and Strong, 1996; Betts et al., 1995; Teweleit, 1970] reported a similar, anomalous midday depression in $q_s$, which they attributed to radiative heating of the RH sensor. Although the manufacturer's specifications [Vaisala, 1992] indicated low

Table 3. Mean Mixed-Layer Budget Estimates, Stratified by Time of Day

<table>
<thead>
<tr>
<th>Time of Day (UTC)</th>
<th>n</th>
<th>$R_a$</th>
<th>$H_o$</th>
<th>$\lambda E_o$</th>
<th>$H_s$</th>
<th>$\lambda E_s$</th>
<th>$\epsilon_e$</th>
<th>$\beta_e$</th>
<th>$\lambda E_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1515 1715</td>
<td>56</td>
<td>430</td>
<td>130</td>
<td>177</td>
<td>-106</td>
<td>330</td>
<td>0.87</td>
<td>0.79</td>
<td>0.55</td>
</tr>
<tr>
<td>1715–1915</td>
<td>56</td>
<td>520</td>
<td>221</td>
<td>83</td>
<td>-40</td>
<td>208</td>
<td>0.71</td>
<td>0.79</td>
<td>0.09</td>
</tr>
<tr>
<td>1915 2115</td>
<td>56</td>
<td>622</td>
<td>216</td>
<td>291</td>
<td>-42</td>
<td>241</td>
<td>1.32</td>
<td>0.74</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Unit of measure is W m$^{-2}$. n, number of individual (2 hour) budget analyses.
shortwave absorptivity (0.27) and longwave emissivity (0.26) for the aluminum paint which coated the humidity sensor’s plastic cap, the possibility of a radiation error cannot be ruled out. The 1915 g depression was larger in the SSA, where solar noon was 1901, than the NSA, where solar noon was 1829 UTC.

4.6. Other Sources of Error

We have neglected daytime radiative heating of the BL; a hypothetical radiative warming rate of 0.04 K h⁻¹ over the mean BL depth of 116 hPa would account for a 13 W m⁻² overestimation of \( H'_\text{a} \).

A key assumption in the EL budget is that the fluxes are zero at EL top. In fact, EL-top fluxes can be negative for \( H' \) and positive for \( \lambda E' \), when coupled cloud layers cap the BL [Beets, 1976]. This would cause \( H' \) and \( \lambda E' \) to be underestimated (in magnitude) and \( H' \) to be biased high and \( \lambda E' \) to be biased low. Comparison with near-surface data from the Twin Otter [Barr et al., this issue] suggests that this may be so. We plan in a subsequent study to attempt stratifications based on the cumulus cloud fraction (which was typically small and, unfortunately, poorly measured) to assess this.

5. Entrainment

5.1. Entrainment Parameterizations

Entrainment is often parameterized in terms of buoyant convection, assuming that the entrainment virtual heat flux at the BL top, \( H'_\text{a} \), is a constant fraction \((-A_R)\) of the surface virtual heat flux \( H'\text{a} \) [Betts, 1973; Carson, 1973; Tennenkes, 1973]:

\[
H'_\text{a} = -A_R H'\text{a}
\]

The classical value for \( A_R \) is 0.20 [Stull, 1988], although some recent studies reported mean values for \( A_R \) of 0.36 [Betts et al., 1992] or 0.44 [Betts and Ball, 1994] above the FIFE grassland, later reduced to 0.31 for no-wind conditions in the work by Bett and Barr [1996].

When the influences of wind shear at the surface and BL top are added to (4) [Stull, 1976a, 1988, Tennenkes and Driedonks, 1981],

\[
H'_\text{a} = \gamma_1 H'\text{a} + \left( \gamma_2 \rho c_p T_0 / (g z_i) \right) u^3_z - \left( \gamma_3 \rho c_p T_0 / (g z_i) \right) (\Delta u)^3
\]

where \( \rho \) (kg m⁻³) is the density of air, \( c_p \) (J kg⁻¹ K⁻¹) is the specific heat of air, \( T_0 \) (K) is near-surface air temperature, \( g \) (m s⁻²) is the acceleration of gravity, \( z_i \) (m) is ML depth, \( u_z \) (m s⁻¹) is the friction velocity, and \( \Delta u \) (m s⁻¹) is the “jump” in mean streamwise horizontal wind speed across the EL. The parameters \( \gamma_1 \), \( \gamma_2 \), and \( \gamma_3 \) quantify the combined effects of buoyancy, surface wind shear, and EL wind shear on entrainment. Equation (5) modifies (5) of Stull [1976a], using Stull’s [1988] assumption that his variable \( d_z \), (the depth of the negative heat flux region in the upper ML) is a constant fraction \( A_R/(1+A_R) \) of ML depth. We incorporated this proportionality into parameters \( \gamma_2 \) and \( \gamma_3 \) in (5).

The value for \( u_z \), in (5) was estimated from the mean horizontal wind speed \( (u) \) in the ML, using the formulae of Betts and Barr [1996]. When radiosonde wind speeds were missing (at Thompson before June 7, 1994), \( u \) was estimated from RFE forecasts. In estimating \( u_z \), we used a momentum roughness length \( z_{0M} \) of 1.3 m and estimated \( z \) as 20% of \( z \). The estimates for \( u_z \) were sensitive to \( z/s_{0M} \). More seriously, the values of \( \gamma_2 \) and \( \gamma_3 \), in turn, were also dependent upon \( z/s_{0M} \) because of the cubic dependence of \( H'_\text{a} \) on \( u_z \) in (5). We believe that our values for \( z/s_{0M} \), if anything, have contributed to conservatively low estimates for \( \gamma_2 \) and \( \gamma_3 \).

5.2. Bulk Estimates of \( A_R \)

Table 4 shows our bulk estimates of the entrainment parameter \( A_R \) from (5), with an estimate of uncertainty in parentheses, and the mean ML wind speeds and wind shears across the EL. Our value using all data for both study areas and the whole summer is

\[
A_R = 0.21 \pm 0.05
\]

This value for \( A_R \) is higher than the two estimates of 0.08 ± 0.12 (composite analysis) and 0.11 ± 0.10 (mean of individual analyses) derived by Davis et al. [this issue] from aircraft measurements of \( H'_\text{a} \) and \( H'\text{a} \). As Davis et al. comment, their estimate for \( A_R \) has high uncertainty because \( H'_\text{a} \) is estimated by extrapolation from the BL flux profile. Two factors contribute to the uncertainty in \( A_R \): uncertainty in the BL depth and noise in the BL flux profile. Our estimate for \( A_R \) lies just within the upper uncertainty limit of the Davis et al. values.

Stratified by study area and IFC, our estimates of \( A_R \) show more variability, which we believe is largely a result of the smaller sample size. There is an increase in mean ML wind speed and EL wind shear from IFC 1 to IFC 3, and this may account in some small part for the higher \( A_R \) estimate for IFC 3 (see next section). The latest sunrise in IFC 3 also means that the 1515-2115 budget period includes more of the rapid ML growth period, when \( A_R \) may be high.

It was difficult to quantify the uncertainty in \( A_R \) (which we will denote \( \delta A_R \)). Table 4 gives values for \( \delta A_R \), which were estimated from the observed variability in \( H'\text{a} \) and \( H'\text{a} (\delta H'_\text{a} \text{ and } \delta H'_\text{a} \text{ }) \), as

\[
\delta A_R / A_R = \left( \delta H'_\text{a} / H'_\text{a} \right) + \left( \delta H'_\text{a} / H'_\text{a} \right)
\]

The values for \( \delta H'_\text{a} \) and \( \delta H'_\text{a} \) were estimated from the respective standard errors in \( H'_\text{a} \) and \( H'_\text{a} \). The variation in \( \delta A_R / A_R \) with study area and IFC resulted almost entirely from sample size differences. Considering the wide range and large uncertainty in previous estimates of \( A_R \) [Stull, 1976b, 1988; Betts, 1991], this degree of uncertainty was encouraging. We believe that the degradation in \( A_R \) with diminishing sample size re-
sulted from large random errors in individual 2-hour budgets. The large random errors resulted primarily, not from errors in the radiosonde data, but from the inability of synoptic analyses to resolve local fields of horizontal and vertical advection on a daily or hourly basis. Based on the results of this study, we estimated the minimum number of days required to estimate $A_R$ to within ±40% from sonde-based budget methods to be at least 20.

The neglect of transports out of the BL into shallow clouds in the EL budget biases $|H_{el}|$ low and $|H_{ul}|$ high, both of which lead to a low bias in $A_R$, as in the work by Betts and Barr [1996].

5.3. Variation of $A_R$ With Wind and EL Wind Shear

We assessed the effects of surface and EL wind shear on $A_R$ by stratifying the budget analyses by friction velocity $u_*$, mean ML wind speed $\langle u \rangle$, and EL wind speed jump $\Delta u$. Tables 5 and 6 show the increase of $A_R$ with increasing $\langle u \rangle$ and $\Delta u$ stratifications. For both stratifications the increase in $A_R$ was largest between the middle and high classes, consistent with the cubic response of $H_{el}$ to $\langle u \rangle$ and $\Delta u$ in (5). (Similar results were found when the data were stratified by $u_*$.) Our (5) parameter estimates were 0.16 for $\gamma_1$, 1.6 for $\gamma_2$, and 0.004 for $\gamma_3$. We cannot establish clear confidence limits for $\gamma_4$, $\gamma_5$, or $\gamma_6$. However, our estimates are consistent with earlier field and model estimates. Our estimate for $\gamma_1$ of 0.16 is a little lower than the accepted value of 0.20 [Driedonks, 1982; Stull, 1988; Moeng and Sullivan, 1994] and much lower than the value of 0.31 from the Okeo grassland [Betts and Barr, 1996]. As discussed earlier, the neglect of fluxes at the EL top is a probable cause of a low bias here. The values for $\gamma_3$ and, especially, $\gamma_6$ were less certain. Our estimate for $\gamma_2$ of 1.6 is larger than Moeng and Sullivan’s [1994] $\gamma_2$ of 1.0. It is also higher than Betts and Barr’s [1996] $\gamma_2$ of 0.8, but much lower than Driedonks’ [1982] $\gamma_2$ of 5.0 and Stull’s [1988] $\gamma_2$ of 6.0. Moeng and Sullivan’s estimate for $\gamma_2$ of 1.0, based on large eddy simulation, is perhaps the most definitive to date. Few previous studies have been able to quantify $\gamma_6$. Moeng and Sullivan [1994] commented that their entrainment parameterization was unsuited to harocline flows because it did not include EL shear. Driedonks [1982] found it difficult to obtain accurate data for $\Delta u$. Our rough estimate for $\gamma_3$ of 0.004 is lower than Stull’s [1988] recommended value of 0.0072 but is near the lower end of the $\gamma_3$ range (0.0048–0.060) given by Stull [1976a].

6. Summary and Conclusions

A budget analysis of the 1994 BOREAS radiosonde data has estimated surface fluxes and BL-top entrainment over the boreal forest. Averaged over the summer, this budget estimate of the sum of the surface fluxes, $H_b + \lambda E_b$, underestimated the surface available energy $(R_{in} - S)$ by only 4%, using an estimate of the landscape energy storage fraction, $S/R_{in}$ of 0.17. For smaller composites of the sonde data, for the two study areas (southern and northern) and three 1FCs which spanned late spring to early fall, the sonde budget estimates closed the surface energy balance to within ±15%.

The mean surface Bowen ratio $\beta$ of 1.05 for the boreal forest in summer is much higher than the value of 0.4 over the FIFE grassland [Smith et al., 1992]. The analysis is subject to large random errors, and it was necessary to average the budgets over periods of 15 days or more to produce credible flux estimates. We attributed the errors primarily to the inability of synoptic analyses to resolve local fields of horizontal and vertical advection on a daily or hourly basis.

We also assessed two parameterizations of entrainment over boreal forest. The (4) entrainment parameter $A_R$ was evaluated from sonde-based ML and EL budgets as 0.21, in close agreement with the accepted value of 0.20. Because the EL budget underestimated entrainment, when a cloud layer is coupled to the ML, the value of 0.21 placed a lower limit on $A_R$.

The value for $A_R$ increased with increasing surface and EL wind shear in a manner similar to previous studies. Stratification by friction velocity and the EL wind speed “jump” gave (5) entrainment parameter estimates of 0.16 for $\gamma_1$ (hurricane convection), 1.6 for $\gamma_2$ (surface shear), and 0.004 for $\gamma_3$ (EL shear). Additional study is needed to assess the impact of shallow clouds and to account for the anomalous near-shore depression in sonde humidity.

Appendix: Relative Humidity Calibration of the Vaisala Radiosonde for BOREAS

A1. Method

A bias in the Vaisala RS80 radiosonde relative humidity (RH) was identified on the basis of laboratory evaluation and routine field checks at the surface before launch. A single bias correction (A1) was applied to the data.

The laboratory evaluation used a General Eastern Hygro
Figure A1. Laboratory and field evaluation of Vaisala RS80 radiosonde relative humidity (RH) calibration, BOREAS 1994. The error bars denote 1 standard deviation from the mean.

M3 dew-point hygrometer, a platinum resistance thermometer, and a General Eastern relative humidity generator. Four sondes were evaluated, drawn from two different batches. The evaluation was at 21°C, and the sondes were powered with 12 V DC. Each sonde was evaluated independently on a separate day. The Vaisala RH sensor was first equilibrated at 15% RH for 60 min. The value for RH was then altered every 20 min in 10% RH steps, ascending from 15% to 85% RH, and then descending from 85% to 15% RH. The value for RH reached equilibrium within 10 min of each step change. Data were sampled and averaged for the final 3 min at each step, at sampling periods of 5 s (M3) and 1.5 s (Vaisala). Field checking was done routinely during the 1994 intensive field campaigns at Candle Lake and Thompson. The field checks used a wet and dry bulb psychrometer in a Stevenson screen, with the sonde hung below the Stevenson screen. The wet-bulb psychrometer was ventilated at Thompson and unventilated at Candle Lake. The computation of relative humidity from wet and dry bulb temperature was done using the standard Atmospheric Environment Service Tables for ventilated and unventilated wet-bulb psychrometers. In addition, a few spot checks were made with a sling psychrometer, and radiation errors were assessed by exposing the temperature and humidity sensors of five sondes to alternating 60 s periods of direct sun and shade.

A2. Results

Figure A1 summarizes the Vaisala RH bias as a function of RH for both laboratory evaluation and field checks. The laboratory evaluation (open circles and squares) of the Vaisala RH sensor showed high precision; a well-defined negative bias, which increased in magnitude from near zero at 15% RH to a maximum of −5% RH at 75% RH (70% Vaisala RH); and a hysteresis of 1% RH after exposure to higher (95%) RH. The Vaisala RH sensors were extremely precise. The standard deviation in the Vaisala RH bias was approximately equal to the RH Vaisala resolution of 1%. The differences between individual sensors were similar at all levels of RH.

The Vaisala RH bias as observed in routine field checks agreed with the laboratory evaluation in sign but was twice as large in magnitude, increasing in magnitude from −5% RH at 27% RH to −10% RH at 70% RH (Figure A1). However, the field-check data were noisy, and the observed bias in the laboratory was most often within 1 standard deviation of the mean field bias. A comparison of the biases observed at Candle Lake and Thompson showed little difference. We cannot adequately explain why the field tests show a larger mean bias. The field data cover a range of temperatures from 4°C to 30°C. Radiation errors were small and difficult to detect in the field. The field spot checking of five sondes showed an average shade-to-sun temperature increase of 0.32 ± 0.28°C and an average shade-to-sun RH decrease of −0.16 ± 1.4% RH.

With a conservative philosophy, weighing the laboratory data more heavily, we applied the correction curve (solid line in Figure A1) to the sonde data. This RH bias curve δh is given (as a decimal) by

\[ \delta h = \begin{cases} -0.1473h^3 + 0.1107h^2 & h \leq 0.9 \\ 0.4592(1 - h) & h > 0.9 \end{cases} \]  

(A1)

where h is the Vaisala RH measurement on a 0 to 1 scale. We fitted (A1) to give zero bias at 0 and 100% RH, and a maximum negative bias of 5% at 70% Vaisala RH.

The apparent bias in the Vaisala sonde is a serious one and needs further careful study.

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References

BARR AND BETTS: BOUNDARY LAYER BUDGETS ABOVE BOREAL FOREST


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