Calculation of Area-Averaged Fluxes: Application to BOREAS

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ABSTRACT

This study estimates area-averaged fluxes over the Boreal Ecosystem–Atmosphere Study (BOREAS) region using tower and aircraft data. The dependence of the area-averaged flux on various assumptions and external flow characteristics is examined.

1. Introduction

A number of field programs have been motivated by a need to estimate area-averaged fluxes. Such an averaging area could correspond to a grid area in a large-scale numerical model. Recently, a number of different approaches have been applied to the estimation of area-averaged fluxes in the Northern Hemisphere Climate Processes Land-Surface Experiment. These approaches include flux aggregation methods from aircraft (Frech and Jochum 1999), inferred regional fluxes from evolution of the mixed layer (Gryning and Batchvarova 1999), and area-averaged momentum fluxes from satellite-based land use (Hasager and Jensen 1999).

This study estimates area-averaged fluxes on a somewhat larger scale based on a network of eddy correlation tower sites and eddy correlation aircraft measurements from the Boreal Ecosystem–Atmosphere Study (BOREAS; Sellers et al. 1995). The BOREAS data provide broad spatial coverage, but construction of area-averaged fluxes still suffers from a number of problems, which include the following.

1) Numerous observational and analysis problems arise with tower and aircraft eddy correlation measurements (e.g., Mahrt 1998). Many of the problems are most severe with weak-wind nocturnal conditions.
2) Tower measurements are sometimes biased toward warmer, drier locations and tend to avoid low-lying wet areas (Desjardins et al. 1997).
3) Over heterogeneous surfaces, measurements do not sample all types of vegetation classes. Generally, bodies of water are not sampled with towers. Edges between forest stands and clearings or fields can significantly augment the area-averaged momentum flux.
4) Aircraft provide spatial coverage but usually only for midday periods. A single aircraft can sample only a subdomain of the area on a given day. Attempts to sample an entire area have led to inadequate sample size for each vegetation class.
5) Construction of area-averaged fluxes must make substitutions for missing and unreliable data or discard such periods. When area-averaged fluxes are estimated from a significant number of point measurements, data may be missing from at least one point a substantial fraction of the time.
6) Tower eddy correlation measurements must be high enough above the canopy to obtain representative measurements of the microregion (van Ulden 1978; Horst and Weil 1992). That is, the footprint of the flux measurement must be large when compared with the vegetation elements (bushes, trees) or clumping of vegetation elements. From another point of view, the flux measurements must be above the roughness sublayer (Raupach et al. 1991).

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TABLE 1. Bowen ratios and adjustment factor for sites with adequate aircraft data.

Surface type	Aircraft	Tower	Adjustment factor
Old aspen SSA	0.71	0.94	0.75
Old black spruce SSA	1.31	1.48	0.88
Old jack pine SSA	1.58	1.72	0.92

7) Aircraft measurements must be sufficiently low to avoid significant flux divergence between the surface and the aircraft level.

2. Approach

The philosophy here is to produce the most accurate estimates of the area-averaged flux even if ad hoc assumptions must be made that are specific to this experiment. We wish to avoid using models to supplement the data analysis, because the goal is to provide estimates for comparison with models.

Tower fluxes for 30-min periods were extracted from the Boreal Information System for the period 1 June 1994–30 September 1994 for the Southern Study Area (SSA). We will discuss the entire diurnal variation, but plots will be shown only for noontime values.

The area-averaged fluxes $[F_\phi]$ will be estimated according to the format

$$[F_\phi] = \sum_{i=1}^{I} \alpha_i W_i F_{\phi,i}, \qquad (1)$$

where ϕ is the vertically transported variable such as potential temperature or moisture, the brackets denote spatial aggregation, $F_{\phi,i}$ is the tower flux for the ith surface type, α_i represent corrections for the tower data for the ith surface type (section 2a), and W_i is the fractional coverage for the ith surface type (section 3).

a. Representativeness of tower data

A tower cannot be completely representative of the subarea flux because of spatial variations even within a given vegetation type. In addition, towers for wet surface types are sometimes located in the least wet locations for practical reasons. In such cases in BOREAS, the aircraft measured less sensible heat flux and greater latent heat flux when compared with the tower (Desjardins et al. 1997). As a result, the Bowen ratio for the aircraft data was smaller than the tower Bowen ratio for some of the sites. Table 1 shows the values of the Bowen ratio for the aircraft and tower data computed from the sensible and latent heat fluxes averaged over all the periods with aircraft passes over a given tower. Although aircraft fluxes may incur significant errors, we assume that the bias in the Bowen ratio is less for the aircraft fluxes than for the tower-based fluxes.

One could impose the average aircraft Bowen ratio on the tower data. However, this procedure would remove seasonal and synoptic changes in the Bowen ratio. Instead, we adjust the tower Bowen ratio downward by a fixed fraction (adjustment factor, Table 1). The tower latent and sensible heat fluxes for each observation are then adjusted (augmented latent heat flux and reduced sensible heat flux) to match the adjusted Bowen ratio while preserving the sum of the tower sensible and latent heat fluxes. The Bowen ratio adjustment is applied only to daytime periods for which the net radiation, sensible heat flux, and latent heat flux are all positive. Aircraft data were not taken during nocturnal conditions. Because the aircraft data are biased toward midday fair weather conditions with clear or partly cloudy skies, the above adjustment may be too large for conditions of overcast or low sun angle. Therefore, for net radiation values less than $R_{\text{crit}} = 500$ W m^{-2}, the adjustment is reduced by the factor $R_{\text{net}}/R_{\text{crit}}$, where R_{net} is the observed net radiation.

b. Other adjustments

The net radiation measurements are adjusted according to Hodges and Smith (1997). Such adjustments are posed in terms of a linear relationship with an offset. Relationships were constructed separately for daytime and nighttime cases, here defined in terms of positive or negative net radiation. These adjustments led to minor changes in the area-averaged fluxes, partly because the sign of the difference between the corrected and uncorrected values changes between different tower sites, leading to partial cancellation with area averaging.

c. Bodies of water

Bodies of water can contribute significantly to the area-averaged fluxes at night when cooler air from land flows over warmer water and the nocturnal fluxes are weak over land. Advection of warm daytime air over cooler water may substantially suppress fluxes over the water during the afternoon (Burba et al. 1999). Heikinheimo et al. (1999) find that fluxes over smaller sheltered lakes are smaller than those over larger lakes.

Application of the bulk aerodynamic method to estimate surface fluxes encounters numerous problems over lakes, even if suitable measurements of wind, air temperature, and lake surface temperature are available. Based on Vickers and Mahrt (1997), the airflow and wave field would not achieve equilibrium and information on wave state would be required to estimate surface fluxes over small and medium-size lakes. Furthermore, the thermal roughness length required by similarity theory in the bulk aerodynamic approach was found to behave poorly for fetch-limited flows (Mahrt et al. 1998). Currently, no rigorously tested model exists for fetch-limited flows.

To test existing approaches, Canadian Twin Otter aircraft fluxes over Candle Lake in BOREAS (Sun et al. 1997) were computed from 1-km means and then averaged over the 10-km flight track over the lake. Thirteen passes were available, accumulated over nine midday flights. As an instructive example, we apply the bulk aerodynamic formula with the widely used surface flux routine of Fairall et al. (1996), which was designed for open water conditions. Model input information includes wind, air temperature, specific humidity, and water surface temperature remotely sensed by the aircraft. This model grossly underpredicts the surface moisture flux over the lake for 11 of the 13 passes and modestly underestimates the heat flux for most of the passes. Part of the problem may be that the wind and air temperature measurements were collected at roughly 30 m above the lake surface, which is probably too high in very stable conditions.

However, we think that the main factor is the strong advection of turbulence from land, which overrides the stable cool marine layer adjacent to the water surface. In these cases, the vertical transport of turbulence energy computed from the aircraft data is generally downward in contrast to normal boundary layers. That is, the main source of turbulence is from above. The surface is then no longer the driving mechanism for the turbulence. As an apparent result, surface layer similarity theory underestimates the turbulent transport. This problem will be reported in more detail in a future manuscript.

The Priestley–Taylor coefficient, which relates the evaporation to the net radiation (Priestley and Taylor 1972; Brutsaert 1982; De Bruin 1983), was computed by assuming that $R_{\mathrm{net}} - G = H + \mathrm{LE}$, where R_{net} is the net radiation, H is the heat flux from the water surface, LE is the latent heat flux, and G is the heat flux into the water. For the current aircraft data, the Priestley–Taylor coefficient averages about 1.9, as compared with the usual value of 1.26. That is, the traditional value of the Priestley–Taylor coefficient would underpredict the evaporative flux by about 30%. Again, advection of strong turbulence from land and downward transport of turbulence toward the lake surface is suspected to be an important influence on the surface moisture flux. Data are not available for estimating the diurnal variation of the Priestley–Taylor coefficient.

Application of models to estimate the flux over the lake in periods with no aircraft data suffers from serious data input errors in addition to model errors. Because the conditions over the lake were not routinely measured, one would have to infer the input data from land observations. A more pragmatic approach is constructed by fitting the diurnal variation of the latent and sensible heat fluxes based on aircraft data (Sun et al. 1997, 1998). This approach will better approximate the lake fluxes for the current task but admittedly is somewhat ad hoc and is not general. A reasonable fit to the data is

$$H = 10\ \mathrm{W\ m^{-2}} \times \cos[\omega(\mathrm{hr} - 0400)], \qquad (2)$$

where ω is the frequency corresponding to diurnal variations [$2\pi/(24\ \mathrm{h})$] and hr is the local time. According to this formulation, the heat flux over the lake is maximum upward in the early morning (0400 local time) when the air temperature is a minimum and reaches maximum downward in the late afternoon (1600) when the air temperature is a maximum. This relationship ignores the seasonal shift of the diurnal cycle that occurs between the end of June and September.

The latent heat flux is represented as

$$\mathrm{LE} = 30\ \mathrm{W\ m^{-2}} + 10\ \mathrm{W\ m^{-2}} \cos[\omega(\mathrm{hr} - 0400)]. \qquad (3)$$

With this formulation, the latent heat flux reaches a maximum in the early morning with a value of 40 W $\mathrm{m^{-2}}$ and a minimum of 20 W $\mathrm{m^{-2}}$ in the late afternoon. For simple calculation of area-averaged net radiation, the net radiation over the water is assumed to be equal to the area-averaged value over the land region. Differences between land and water occur from different surface temperatures, different albedos, and possible less convective cloud cover over the lake. The lakes are the most uncertain part of the area averages in BOREAS. It is fortunate they occupy only 7% of the total area.

TABLE 2. Fractional coverages.

Class	Hall et al. (1997), adjusted	Desjardins et al. (1997)
Black spruce	0.51	0.58
Jack pine	0.02	0.19
Aspen	0.27	0.16
Fen	0.13	0.07
Water	0.07	0.00

d. Fractional coverage W_i

Two sets of fractional coverages are used to explore the sensitivity of the calculation to exact geographic boundaries. The primary set is based on Hall et al. (1997). To study the sensitivity to exact geographical location, we also use a set of fractional coverages from Desjardins et al. (1997) that are based on only a part of the SSA where grid flights were flown. This area contained substantially more conifer and less aspen in comparison with the entire SSA.

Based on 1994 Landsat Thematic Mapper imaging using bands 2 (red), 4 (infrared), and 5 (midinfrared), Hall et al. (1997) identified 13 classes of surface type. To proceed, we must translate these 13 classes into the categories based on the available towers, plus the water category (Table 2). We assume that all deciduous, regeneration deciduous, and medium-age deciduous are aspen, wet conifer is black spruce, dry conifer is jack pine, mixed is one-half aspen and one-half black spruce, and new generation and medium-age regeneration conifer are prorated between black spruce and jack pine. The 1994 Landsat image omitted 12% of the eastern part of the SSA. Fractional coverages for this part of the domain are estimated from Chen et al. (1999). As a final adjustment, the fractional coverage of the fen is thought to be substantially higher than the originally

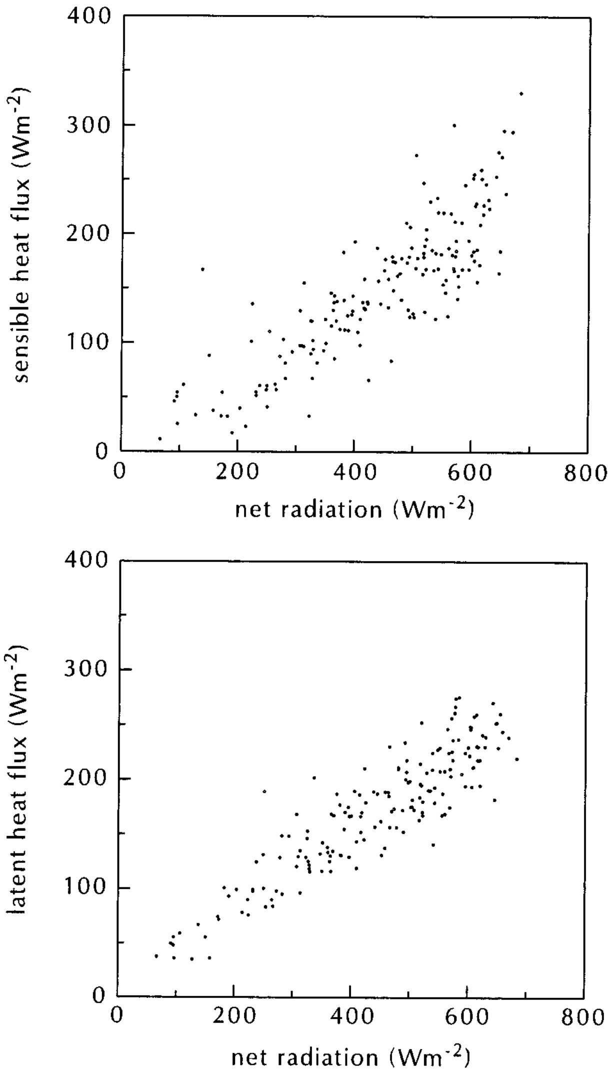

FIG. 1. Area-averaged fluxes vs area-averaged net radiation for noon local time for (top) sensible and (bottom) latent heat fluxes.

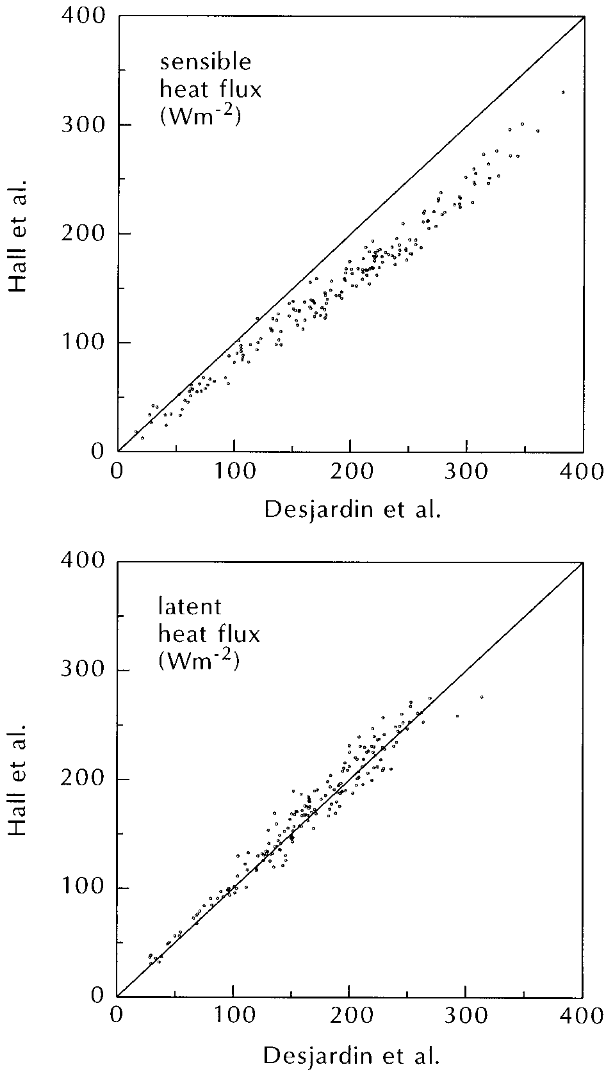

FIG. 2. Area-averaged fluxes using the adjusted fractional coverages from Hall et al. (1997) vs those using Desjardins et al. (1997) for noon local time for (top) sensible and (bottom) latent heat fluxes.

reported 8% (F. Hall 1998, personal communication). We have augmented the value to 13% and decreased the other nonwater fractional coverages in proportion. The final values of fractional coverage are listed in Table 2.

3. Area-averaged fluxes

The area-averaged fluxes are highly correlated to the net radiation, underscoring the need for models to predict correctly the cloud cover; the noontime relationship between area-averaged fluxes and net radiation is shown in Fig. 1. The relationship between area-averaged fluxes and area-averaged net radiation is a little stronger than the relationship at individual locations.

Figure 2 shows how the use of the fractional coverages from Desjardins et al. (1997) leads to significantly larger noontime sensible heat flux, about 25% larger on average. The corresponding area-averaged latent heat fluxes were typically 5%–10% smaller. This comparison underscores the fact that the exact choice of the boundary of the integration area is important, particularly when the fraction of total conifer and total deciduous change. The latent heat flux is generally larger over the deciduous forests when compared with the conifer forests.

Although the area-averaged sensible heat flux is not significantly altered by inclusion of lakes, the area-averaged latent heat flux is enhanced significantly at night. Without the effect of the lakes, the area-averaged latent heat flux ranges between about 0 and 10 W m^{-2}; the lakes augment this area-averaged value up to 3 W m^{-2}. In the daytime, the fluxes over the lake are small in comparison with those over land, and the influence of

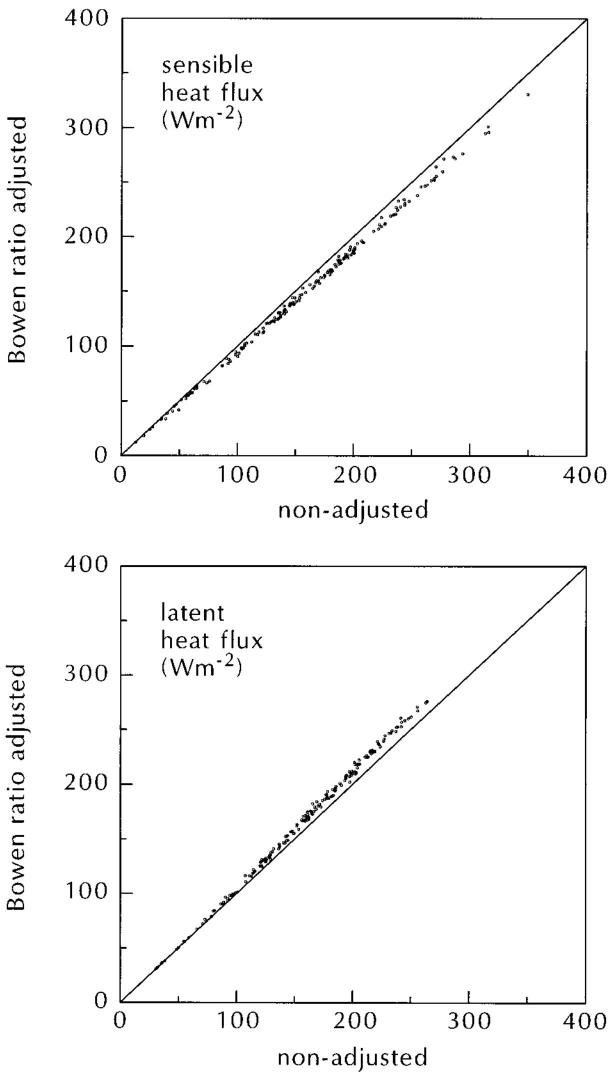

FIG. 3. Area-averaged fluxes vs fluxes calculated without applying the Bowen Ratio adjustment for noon local time for (top) sensible and (bottom) latent heat fluxes.

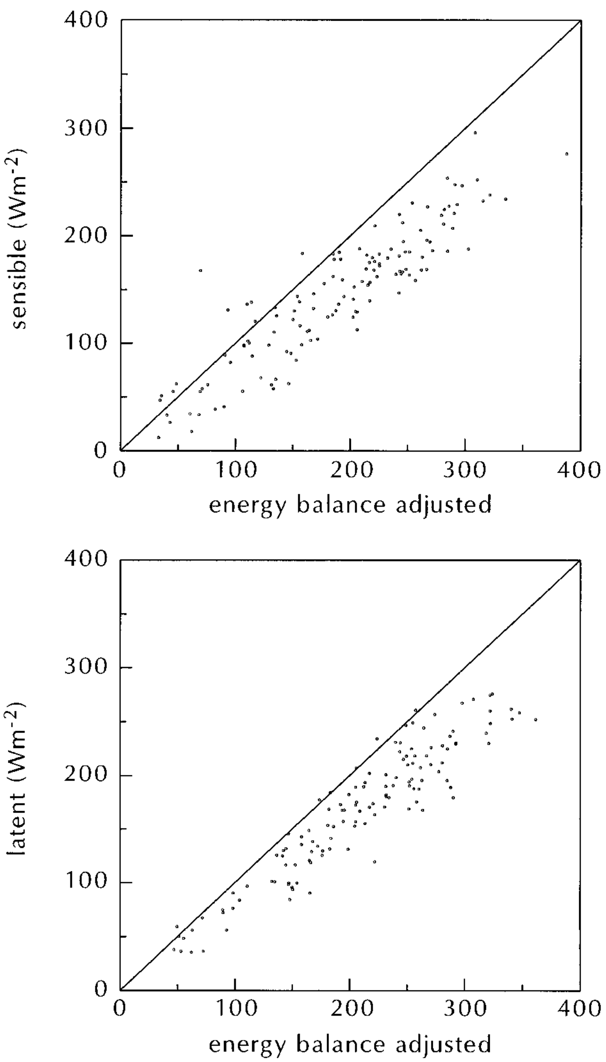

FIG. 4. Area-averaged fluxes vs those adjusted by balancing the surface energy budget.

the lakes is to reduce the area-averaged fluxes by about 6%.

Figure 3 shows that the adjustment of the Bowen ratio increases the noontime area-averaged latent heat flux by about 6% and decreases the area-averaged sensible heat flux by about 6%. This adjustment is not negligible but is small when compared with the influence of day-to-day variations of cloud cover and net radiation.

4. Surface energy budget

Some investigators maintain that flux estimates can be improved by forcing them to balance the surface energy budget. This adjustment assumes that the errors in the surface energy imbalance are due mainly to the eddy correlation estimate of the sensible and latent heat fluxes and that the estimates of the net radiation and soil heat flux are approximately correct. The usual procedure is to increase the sensible and latent heat fluxes proportionally to preserve the Bowen ratio. That is, the total of the sensible and latent heat fluxes is increased to balance the surface energy budget without modifying the Bowen ratio.

In some cases, adjustment of the fluxes to balance the surface energy budget is not justified. For example, over fens and in black spruce forests with considerable standing water, much of the solar radiation is absorbed by the water. Because this loss is not explicitly included in the surface energy budget, adjustment of the sensible and latent heat fluxes would overestimate such fluxes.

As expected, using fluxes adjusted to balance the surface energy budget increases the area-averaged fluxes. For example, area-averaged fluxes at noon increase typically by 25% (Fig. 4). Because of difficulties in assessment of errors in the surface energy budget, we recommend the above flux adjustment as a measure of uncertainty of fluxes rather than as an improved flux estimate.

5. Conclusions

The above study estimated area-averaged fluxes from tower and aircraft eddy correlation data in BOREAS. Because aircraft data are taken during only a small fraction of the total field program and tower measurements are site-specific, demanding assumptions must be made to estimate area-averaged fluxes. However, the area-average flux estimates are most sensitive to the net radiation and, therefore, sensitive to estimated cloud cover. The estimation of the fractional coverages of conifer and deciduous vegetation is also important. Various adjustments to the flux (section 2 and the appendix) were less important. Fluxes over the fetch-limited lakes are the most uncertain part of the analysis.

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APPENDIX

Corrections and Missing Data

No adjustment of the Bowen ratio was carried out for the fen site, which also did not include aircraft measurements. To reduce difficulties associated with isolated missing data, such as a single half-hour value, fluxes were computed for each hour by searching for all flux values within a 2-h window. The fluxes were then averaged by weighting according to the inverse of the difference between the desired time and the reported time. This procedure circumvented problems with some irregularities in reporting time and reduced the influence of random clouds on a given flux value. When data are not available for any of the sites, the area integration is not performed. Missing data are mostly due to rain, when data from the sonic anemometers are unreliable. The original flux data for the fen site were considered to be unacceptable for low wind speed conditions and were replaced with modeled data (Boreas Information System).

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