Estimation of area-averaged moisture flux

By L. MAHRT1*, K. KOTWICA1, JIELUN SUN2, J. I. MacPHERSON3 and R. L. DESJARDINS4

1Oregon State University, USA
2University of Colorado, Boulder, USA
3National Research Council, Canada
4Agriculture Canada, Canada

(Received 24 April 1997; revised 27 January 1998)

SUMMARY

Toward the goal of predicting area-averaged evapotranspiration, the evaporative fraction is modelled in terms of surface radiation temperature, air temperature, solar zenith angle, Normalized Difference of the Vegetation Index and albedo. Previous relationships break down when applied simultaneously to a variety of surfaces. The zenith angle is required to account for the influence of shaded ground on the remotely sensed surface radiation temperatures. The model of evaporative fraction is developed from Canadian Twin Otter aircraft data from the BOREal Ecosystem–Atmosphere Study and the California Ozone Deposition Experiment. The model consists of separate submodels for active agriculture, forested surfaces, bare soil/senescent vegetation and water surfaces. These broad land-use groups are effectively determined from remotely sensed red and near-infrared reflectances.

The area-averaged moisture flux predicted by the model compares favourably with that computed from independent data over forested surfaces. However, the model performs poorly over bare soil/senescent surfaces, and data for a wider variety of surface conditions are required before the generality of the model can be evaluated.

KEYWORDS: Land surface processes Modelling evapotranspiration

1. INTRODUCTION

The primary goals of this study are to examine spatial variations of the evaporative fraction of the surface moisture flux and its relationship to remotely sensed surface variables, and estimate regionally aggregated surface moisture fluxes. Constructing such a model requires choice of the moisture-flux quantity to be modelled, discussed in the next subsection, and choice of remotely sensed predictor variables, discussed in subsection (b).

(a) Moisture-flux ratios

Certain moisture-flux ratios, such as the evaporative fraction and Bowen ratio, are more time-invariant during the daytime compared with the moisture flux itself. When the moisture-flux ratio does not vary substantially from morning to afternoon, observations from a single satellite pass (Stewart 1996) or from aircraft observations can be used to estimate the total daytime evaporation. Aircraft platforms provide valuable spatial coverage but normally cannot provide diurnal coverage.

The evaporative fraction is usually defined as the ratio of the latent-heat flux to the available energy (net radiation minus the soil-heat flux)

$$E_t \equiv \frac{LE}{R_{net} - G}$$

where $LE$ is the latent heat flux, $R_{net}$ is the net radiation and $G$ is the heat flux to the soil. This relationship could be generalized to include canopy storage in the denominator, although this information is not normally available from field data. Excluding significant horizontal advection, the daytime evaporative fraction is generally bounded by unity but

* Corresponding author: College of Oceanic and Atmospheric Sciences, Oregan State University, Corvallis, OR 97331, USA.
can become erratic during transition periods between day and night when the denominator switches sign. The Bowen ratio may also become erratic during transition and nocturnal periods when the moisture flux is small and difficult to measure. The Bowen ratio is more variable than the evaporative fraction in semi-arid or arid conditions. For this reason, we choose the evaporative fraction as the moisture-flux ratio to be modelled.

To interpret previous observational studies, we utilize the close relationship between the evaporative fraction and the Priestley–Taylor coefficient, expressed as

\[ E_t = \alpha_e \frac{\Delta}{\Delta + \gamma} \]  

where \( \alpha_e \) is the Priestley–Taylor parameter, \( \Delta \) is the slope of the saturation vapour-pressure curve and \( \gamma \) is the psychrometric constant. The Priestley–Taylor parameter depends on stomatal conductance (De Bruin 1983) and soil moisture content. With \( \alpha_e = 1 \), Eq. (2) can be identified with the radiation term of the Penman–Montieth relationship; in which case specification of \( \alpha_e \) greater than unity could be viewed as adjustment for neglect of the aerodynamic term in the Penman–Montieth relationship.

The evaporative fraction, or related Priestley–Taylor coefficient, is found to be relatively time-independent between mid-morning and mid-afternoon over relatively unstressed grasslands and agricultural regions in the observational studies of Sugita and Burtsaert (1991), Smith et al. (1992) and Crago (1996a). Nichols and Cuenca (1993) and Kustas et al. (1994) found that the daytime averaged evaporative fraction was proportional to the mid-day evaporative fraction, which allows estimation of the daily evapotranspiration from mid-day measurements. This time-invariance of the evaporative fraction during the day appears to be due to several compensating effects (Crago 1996a, b). This compensation can be understood by noting that the evaporative fraction is proportional to the stomatal conductance and atmospheric moisture deficit (McNaughton and Spriggs 1989; Verma et al. 1992), which for some plant communities have opposite tendencies in the daytime.

These opposing tendencies can be expressed in terms of the interplay between surface evaporation, boundary-layer growth and dry-air entrainment (De Bruin 1983). After the break-up of the nocturnal surface inversions, the rapid growth of the late-morning boundary layer into the weakly stratified residual layer leads to entrainment of dry air, which often reaches the surface only partly diluted (Mahrt 1991) and increases the atmospheric moisture deficit. McNaughton and Jarvis (1991) suggest that dry-air entrainment and associated increased moisture deficit partially compensates for modest increases of stomatal control so that the evapotranspiration is less variable. For the boreal forest data analysed in this study, the evaporative fraction also shows remarkably little variation between days.

In conifer forests in the western United States with typical summer water-stressed conditions, the evaporative fraction often decreases from morning to afternoon due to a substantial decrease of stomatal conductance associated with an increase of moisture deficit beyond a critical value (e.g. Waring and Schlesinger 1985; Law and Waring 1994). However, with no soil moisture stress, the evaporative fraction for western conifers may even increase in the afternoon (e.g. McNaughton and Black 1973). Even for these cases, the evaporative fraction is much more time-invariant than the moisture flux itself.

Soil heat-flux measurements are not available for many of the surface types covered by the aircraft data sets. The heat flux into the soil, \( G \), is sometimes parametrized to be \( \alpha_G R_{\text{net}} \) in which case

\[ E_t = \frac{1}{(1 - \alpha_g)} \frac{LE}{R_{\text{net}}} \]  

where $\alpha_g$ is a specified coefficient. For the field programs in this study, $\alpha_g$ is highly variable between tower sites because of variable soil moisture and variable sheltering of the soil by the canopy and ground litter. Measurements of the spatially averaged soil heat flux are normally not available, in which case the evaporative fraction is often defined as

$$E_F \equiv \frac{LE}{R_{net}}. \quad (4)$$

Even $R_{net}$ is often not available in routine data sets, or requires evaluation of the downward long-wave radiation from temperature profiles. Therefore we will also evaluate a more practical version of the evaporative fraction (Brutsaert and Sugita 1992)

$$E_{FS} \equiv \frac{LE}{S} \quad (5)$$

where $S$ is the downward solar radiation.

(b) Remotely sensed variables

Remotely sensed variables provide spatial coverage that is not possible with other observational platforms. However, the relationship between remotely sensed variables and the physics of evapotranspiration is complex, particularly when simultaneously considering a variety of surface types.

In an effort to parametrize the surface energy budget directly, Jackson et al. (1977), Seguin and Itier (1983) and Carlson et al. (1995) model the surface evaporation with the general format

$$LE = R_{net} + A - B(T_{sfc} - T_{air})^n \quad (6)$$

where $T_{sfc}$ is the remotely sensed surface temperature and $T_{air}$ is the atmospheric temperature at some standard level. If $n = 1$, then the last term on the right-hand side is of the form of the bulk aerodynamic formulation for the surface heat flux (see references in Mahrt (1996)). With $n = 1$, $B$ is then related to the transfer coefficient for heat and wind speed (or inverse of the atmospheric resistance) and therefore depends on stability, wind speed and surface roughness. These dependencies could explain the variation of $B$ between studies, as noted by Seguin and Itier (1983) and others. When $n$ is not equal to unity, but made a function of the Normalized Difference of the Vegetation Index (NDVI) or other remotely sensed variables, the analogy of this term to the heat-flux formulation breaks down, but the statistical fit improves. The term $A$ is included by Seguin and Itier (1983) and others to improve the statistical fit, and could be viewed as compensation for neglect of soil heat flux and canopy storage of heat.

Our attempts to apply Eq. (6) to spatially averaged aircraft-measured moisture fluxes for a wide variety of surfaces and sun angles failed, partly because of the influence shaded ground surfaces had on $T_{sfc}$. Sun and Mahrt (1995) quantitatively demonstrate how shaded ground surfaces between the trees reduces the remotely measured surface radiation temperature, while the heat flux and, presumably, moisture flux are dominated by the sunny canopy top. Ogunjemiyo et al. (1997) find little relationship between spatial variations of heat flux and surface radiation temperature over the boreal forest.

If the data are confined to a given location and a narrow range of sun angles, the influence of shaded ground on $T_{sfc}$ might be partially represented by adjustments of the coefficients in Eq. (6). This influence may contribute to the variation of the coefficients in Eq. (6) between sites. For example, Lagouarde (1991) finds that $B$ increases with the surface roughness length. The rate of this increase is much greater than would be predicted
by surface similarity theory. It may be that with rough surfaces, the reduction of $T_{sc}$ by the influence of shaded surfaces requires compensating enhancement of $B$ in order to predict the correct heat flux.

The use of two source canopy models (Shuttleworth and Wallace 1985; Norman et al. 1995; Blyth 1995) with remotely sensed data offers the potential of decomposing the observed surface temperature into canopy and ground contributions. However, for the present, the required input data for canopy models are not available for the wide range of surface types included in this study and we opt for a simpler statistical approach, similar to the format of Eq. (6).

Previous studies have often shown a well-defined relationship between evaporation and remotely sensed surface radiation temperature, NDVI and albedo (Carlson et al. 1995; Pelgrum and Bastiaanssen 1996 and studies cited therein). We will also take advantage of available remotely sensed variables. For reasons discussed in subsection (a), the surface moisture flux will be modelled in terms of evaporative fraction. The evaporative fraction can be computed by dividing Eq. (6) by the net radiation. Here we use the general format of Eq. (6) with $n = 1$ to retain, albeit weak, connection to the surface energy balance. The model for evaporative fraction will include needed information on the zenith angle and available additional remotely sensed information. We write

$$EF = -b(T_{sc} - T_{air})f_1(\text{zenith angle}) + f_2(R_i)$$

where $f_1$ and $f_2$ are functions to be determined from the aircraft data (section 5), $b$ is a coefficient related to the transfer coefficient for heat, and $f_1(\text{zenith angle})$ is a correction to the air–surface temperature difference adjusting for the influence of inactive shaded surfaces on the remotely sensed surface temperature. The set of terms $R_i$ could be identified with term $A$ in Eq. (6) but essentially represents improvement in the model by including remotely sensed quantities such as NDVI and albedo (section 5).

It is not possible to isolate the relationship between a given remotely sensed variable in Eq. (7) and a specific physical influence in the surface energy balance. This is a necessary concession with models based on remotely sensed information. Furthermore, the relationship between remotely sensed variables and specific physical influences varies from one geographic region to another. For example, greater albedo corresponds to more reflected short-wave radiation and less net radiation available for sensible-heat flux and evapotranspiration. In addition, higher albedo sometimes signals less vegetation and exposure of lighter coloured soils, which in turn corresponds to less evapotranspiration (Goward et al. 1994). In general, lighter coloured semi-arid regions correspond to less evaporation compared with dark-green areas with low albedo. As a result, albedo is an important parameter in the remote-sensing algorithm for the surface energy balance developed by Bastiaanssen et al. (1998) and others. In contrast, over the boreal forest, the evaporative fraction is proportional to the albedo instead of the usual inverse proportionality. The darker conifer forests (low albedo) are characterized by greater stomatal control compared with the lighter-coloured deciduous forests. These results suggest that albedo cannot be identified with a single physical mechanism in the surface energy balance.

As a second example, Sun and Mahrt (1994), Bastiaanssen et al. (1998) and others find that the spatial variation of the evaporative fraction is closely related to the NDVI, particularly if there are substantial variations of vegetation due to land-use practice. However, within fully vegetated regions, the evaporative fraction is controlled by spatial variations of stomatal control, and the NDVI is of little use, as will be found in this study for the forested regions. These results suggest that some division into different surface types is necessary before constructing models of evaporation based on remotely sensed variables. Such a division is carried out in section 6.
The next section describes the aircraft data sets used in this study. Examination of the general behaviour of the evaporative fraction is found in sections 3 and 4.

2. DATA

This study analyses data collected by the Twin Otter research aircraft from the Canadian National Research Council during The Boreal Ecosystem–Atmosphere Study (BOREAS) (Sellers et al. 1995; MacPherson 1996; Mahrt et al. 1997). The data were collected over a variety of surfaces (Tables 1 and 2) normally between late morning and mid afternoon. During the BOREAS, the data were collected with repeated passes over fixed tracks. Each track represents different dominant species. Generally, all of the repeated passes for a given day and given track occur within a one-hour period, in which case the

| Class | Number of aircraft flights | Averaged evaporative fraction | NDVI | Albedo | Reflectance
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Red(R_{660}) Near-infrared(R_{730})</td>
</tr>
<tr>
<td>Agricultural (AG)</td>
<td>39</td>
<td>0.52</td>
<td>0.32</td>
<td>0.18</td>
<td>0.13</td>
</tr>
<tr>
<td>Bare soil/senescent</td>
<td>18</td>
<td>0.29</td>
<td>0.07</td>
<td>0.21</td>
<td>0.23</td>
</tr>
<tr>
<td>Forest</td>
<td>65</td>
<td>0.32</td>
<td>0.42</td>
<td>0.12</td>
<td>0.06</td>
</tr>
<tr>
<td>Deciduous</td>
<td>17</td>
<td>0.43</td>
<td>0.47</td>
<td>0.14</td>
<td>0.07</td>
</tr>
<tr>
<td>Conifer</td>
<td>48</td>
<td>0.28</td>
<td>0.40</td>
<td>0.11</td>
<td>0.06</td>
</tr>
<tr>
<td>All data</td>
<td>122</td>
<td>0.38</td>
<td>0.34</td>
<td>0.15</td>
<td>0.11</td>
</tr>
</tbody>
</table>

NDVI = Normalized Difference of the Vegetation Index.

| Subclass | Number of aircraft flights | Averaged evaporative fraction | NDVI | Albedo | Reflectance
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CODE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Red(R_{660}) Near-infrared(R_{730})</td>
</tr>
<tr>
<td>Agricultural (AG)</td>
<td>12</td>
<td>0.59</td>
<td>0.38</td>
<td>0.19</td>
<td>0.12</td>
</tr>
<tr>
<td>Bare soil/senescent</td>
<td>7</td>
<td>0.35</td>
<td>0.05</td>
<td>0.21</td>
<td>0.27</td>
</tr>
<tr>
<td>BOREAS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>aspen (asp)</td>
<td>10</td>
<td>0.45</td>
<td>0.53</td>
<td>0.15</td>
<td>0.06</td>
</tr>
<tr>
<td>burn</td>
<td>6</td>
<td>0.43</td>
<td>0.40</td>
<td>0.14</td>
<td>0.09</td>
</tr>
<tr>
<td>fen</td>
<td>1</td>
<td>0.37</td>
<td>0.49</td>
<td>0.13</td>
<td>0.06</td>
</tr>
<tr>
<td>bs.s</td>
<td>11</td>
<td>0.32</td>
<td>0.39</td>
<td>0.10</td>
<td>0.06</td>
</tr>
<tr>
<td>bs.n</td>
<td>12</td>
<td>0.28</td>
<td>0.43</td>
<td>0.10</td>
<td>0.06</td>
</tr>
<tr>
<td>jp.s</td>
<td>6</td>
<td>0.29</td>
<td>0.37</td>
<td>0.10</td>
<td>0.06</td>
</tr>
<tr>
<td>jp.n</td>
<td>11</td>
<td>0.23</td>
<td>0.39</td>
<td>0.12</td>
<td>0.07</td>
</tr>
<tr>
<td>yjp</td>
<td>8</td>
<td>0.26</td>
<td>0.40</td>
<td>0.12</td>
<td>0.07</td>
</tr>
<tr>
<td>AG spring</td>
<td>12</td>
<td>0.34</td>
<td>0.10</td>
<td>0.15</td>
<td>0.16</td>
</tr>
<tr>
<td>AG summer</td>
<td>15</td>
<td>0.60</td>
<td>0.46</td>
<td>0.19</td>
<td>0.10</td>
</tr>
<tr>
<td>AG autumn</td>
<td>11</td>
<td>0.25</td>
<td>0.09</td>
<td>0.20</td>
<td>0.24</td>
</tr>
</tbody>
</table>

'\(n\)' refers to the northern study area and 's' refers to the southern study area. bs refers to old black spruce, jp to old jack pine and yjp to young jack pine. Much of the burn track is populated by very young aspen. The last three rows are the agricultural track in BOREAS averaged over each season.
TABLE 1(c). SUBCLASS STATISTICS IN CODE

<table>
<thead>
<tr>
<th>Track and class</th>
<th>Number of passes</th>
<th>Length of the aircraft track (km)</th>
<th>Averaged evaporative fraction</th>
<th>NDVI</th>
<th>Albedo</th>
<th>Reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton (a1–a2) AG</td>
<td>8</td>
<td>7</td>
<td>0.58</td>
<td>0.47</td>
<td>0.19</td>
<td>0.10 0.47</td>
</tr>
<tr>
<td>Cotton (a1–a2) AG</td>
<td>6</td>
<td>7</td>
<td>0.53</td>
<td>0.49</td>
<td>0.20</td>
<td>0.10 0.49</td>
</tr>
<tr>
<td>Cotton (a3–a4) AG</td>
<td>8</td>
<td>6</td>
<td>0.55</td>
<td>0.39</td>
<td>0.18</td>
<td>0.12 0.46</td>
</tr>
<tr>
<td>Orchard/sen. Soil/sen.</td>
<td>8</td>
<td>2</td>
<td>0.34</td>
<td>0.13</td>
<td>0.19</td>
<td>0.22 0.47</td>
</tr>
<tr>
<td>Grape AG</td>
<td>6</td>
<td>2</td>
<td>0.50</td>
<td>0.28</td>
<td>0.18</td>
<td>0.14 0.41</td>
</tr>
<tr>
<td>FLIGHTS 13/19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil/Soil/sen.</td>
<td>16</td>
<td>5</td>
<td>0.34</td>
<td>-0.04</td>
<td>0.18</td>
<td>0.25 0.38</td>
</tr>
<tr>
<td>Mixed AG</td>
<td>16</td>
<td>7</td>
<td>0.57</td>
<td>0.18</td>
<td>0.18</td>
<td>0.17 0.40</td>
</tr>
<tr>
<td>Cotton AG</td>
<td>16</td>
<td>4</td>
<td>0.61</td>
<td>0.51</td>
<td>0.19</td>
<td>0.09 0.48</td>
</tr>
<tr>
<td>Cotton AG</td>
<td>16</td>
<td>4</td>
<td>0.63</td>
<td>0.42</td>
<td>0.19</td>
<td>0.12 0.46</td>
</tr>
<tr>
<td>Cotton AG</td>
<td>16</td>
<td>3</td>
<td>0.65</td>
<td>0.38</td>
<td>0.19</td>
<td>0.12 0.44</td>
</tr>
<tr>
<td>Senescent Soil/sen.</td>
<td>16</td>
<td>3</td>
<td>0.23</td>
<td>0.01</td>
<td>0.22</td>
<td>0.31 0.52</td>
</tr>
<tr>
<td>Mixed Soil/sen.</td>
<td>16</td>
<td>5</td>
<td>0.50</td>
<td>0.28</td>
<td>0.20</td>
<td>0.16 0.47</td>
</tr>
</tbody>
</table>

al–a4 refer to anchor points in CODE (MacPherson 1992).

TABLE 2. WITHIN-CLASS AND DAY-TO-DAY VARIANCE

<table>
<thead>
<tr>
<th>Class</th>
<th>Within-class</th>
<th>Day-to-day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural</td>
<td>0.94</td>
<td>0.73</td>
</tr>
<tr>
<td>Forest:</td>
<td>2.32</td>
<td>0.03</td>
</tr>
<tr>
<td>Deciduous</td>
<td>0.62</td>
<td>0.29</td>
</tr>
<tr>
<td>Conifer</td>
<td>1.89</td>
<td>0.01</td>
</tr>
<tr>
<td>All data</td>
<td>9.01</td>
<td>0.09</td>
</tr>
</tbody>
</table>

One hundred times the variance of the evaporative fraction is shown for the different classes of the aircraft BOREAS data where the seasonal means of the evaporative fraction for each class have been removed.

latent- and sensible-heat fluxes and air temperature are approximately constant during the repeated passes.

Thirty eight passes over an agricultural area south of the boreal forest are also analysed. Typically one pass was flown in the late morning at the beginning of the flight mission and one pass in the early or mid-afternoon period at the end of the flight mission. Although the flight track over the agricultural area was approximately 20 km, repeated passes were not flown and some of the flux values do not satisfy the sampling criteria of Vickers and Mahrt (1997a). In the late-spring period, much of the area is bare soil and emerging crops. In mid summer most of the area is covered with green crops dominated by canola and summer wheat. For the late-summer period, most of the crop was senescent or harvested.

This study also analyses Canadian Twin Otter aircraft data from the San Joaquin Valley of California taken during the California Ozone Deposition Experiment (CODE) (MacPherson 1992; Mahrt et al. 1994; Pederson et al. 1995). The CODE data analysed here include two flight days, 23 July 1991 and 30 July 1991. Each flight consisted of eight passes over a 30 km track above 5–10 km segments of well organized cool irrigated surfaces and warm dry unirrigated surfaces (see Fig. 3 from Mahrt et al. (1994)). Consequently, the track was divided into seven segments, and fluxes were averaged over the eight repeated
passes for each segment of the flight. Since the two days are only seven days apart with clear skies and nearly the same surface conditions, the segment values are averaged over the two flights to provide one value for each segment for use in the plots in section 3. For the regression analyses in subsequent sections, segment averages for individual days are used. In addition, the CODE data include a variety of other tracks which were sampled for only one flight day for each track (Table 1(c)). These tracks are described by MacPherson (1992). All of the aircraft tracks in both the CODE and BOREAS were flown at about 35 m above the surface. Use of the 35 m air temperature in Eq. (7) generally leads to a greater temperature difference than would occur with use of the standard 10 m air temperature. Therefore, the value of \( b \) computed from aircraft data will be smaller than that corresponding to use of 10 m air temperature.

In addition to the aircraft data already described, we employ grid-pattern flights from the BOREAS and CODE (section 6) as independent data to test the model for area-averaged moisture flux. Although tower data from the BOREAS and CODE were mentioned in the introduction, they will not be used in this study which evaluates the area-averaged moisture flux.

The vegetation is classified here in terms of the influence of the surface on the evaporative fraction. The model performance is always improved by forming more detailed vegetation classes and breaking the classes into separate seasons. For practical modelling of the evaporative fraction the classes are limited to water surfaces, bare soil and senescent vegetation, active agricultural land use, and forests and no seasonal subdivisions are applied. These classifications are formally constructed in section 6 using red and near-infrared reflectance. To document within-class variability in this section, the data are subdivided into subclasses (Tables 1(b) and (c)). When computing ratios for each class or subclass, the numerator and denominator are averaged first and then the ratio is computed, since averaging ratios is statistically unstable.

The ground surface will be classified in terms of the reflected red radiation centred on 660 \( \mu \text{m} \) \( (G_{660}) \) and the reflected near-red radiation centred on 730 \( \mu \text{m} \) \( (G_{730}) \), both from the Skye Industries Vegetation Greenness Indicator mounted on the Twin Otter aircraft. Unfortunately, the measurement of downward radiation in these narrow-band channels malfunctioned on several flights and seemed to suffer from errors associated with correction for aircraft attitude angles. Therefore, we will compute pseudo reflectances by normalizing with the more reliable downward solar radiation \( S \) and then scale the result based on comparison over surfaces of known reflectance values. The resulting estimated reflectances are of the form:

\[
R_{660} = \alpha_{660} \frac{G_{660}}{S}
\]
\[
R_{730} = \alpha_{730} \frac{G_{730}}{S}
\]

where \( \alpha_{660} \) and \( \alpha_{730} \) are the scaling parameters that account for the use of total downward solar radiation instead of the narrow-band values corresponding to \( G_{660} \) and \( G_{730} \). The values of \( \alpha_{660} \) and \( \alpha_{730} \) are found to be approximately 15 and 25, respectively. The values of near-infrared reflectance for the deciduous forests are roughly 40% greater than the conifer-forest values, in agreement with Goward et al. (1994). The values of the near-infrared reflectances reported here are smaller than those of Goward et al., partly because the 730 \( \mu \text{m} \) channel used here is still in the region of sharp increase of reflectance with increasing wavelength, and the channel width varies between instruments. The NDVI is less sensitive to differences between instruments and is computed here from the upwelling components in the 660 and 730 \( \mu \text{m} \) channels.
3. Dependence on remotely sensed variables

Before constructing specific models, the general relationship between evaporative fraction and remotely sensed variables will be examined. The broad-class averaged evaporative fraction varies between about 0.28 for the conifer and soil-senescent classes and 0.52 for the agricultural class (Table 1(a)). The evaporative fraction varies substantially within the bare soil-senescent class due to variations of soil moisture and inadvertent inclusion of some active vegetation within the averaging regions. The evaporation fraction varies significantly between subclasses within a given class (Tables 1(b) and (c)). The remotely sensed variables will help represent this within-class variation. These data also capture the sharp decrease of the evaporative fraction in the BOREAS agricultural region from 0.60 in summer to 0.25 in early autumn (Table 1(b)).

For a given class, the daytime evaporative fraction increases systematically with the seasonal increase of NDVI (Fig. 1(a)). For the agricultural class, the NDVI predicts much of the variation of the evaporative fraction between tracks (Fig. 1(b)). The NDVI is less useful for the forest classes where the within-class variations of the NDVI are small. Even though the conifer class is characterized by large NDVI, it is characterized by low evaporative fraction due to significant stomatal control. The black spruce is limited by nutrient availability while the sandy soils of the jack-pine regions are sometimes water limited. The view of the aircraft radiometer also includes considerable coverage of moss and lichens between the trees. The moss and lichen surfaces have about the same NDVI as the trees. However, the moisture flux from the moss and lichen surfaces decreases rapidly as the moss dries out during fair-weather periods, yielding much less moisture flux than from the trees. In any event, the variation of average evaporative fraction between the conifer tracks (Table 1(b)) is not related to variations of NDVI.

One might appeal to surface temperature as an indicator of evaporative fraction since the surfaces which transpire more are cooler. Unfortunately, the field-of-view of the remotely sensed surface temperature includes sunlit and shaded canopy and ground surfaces. Shaded ground surfaces may contribute little to the total evapotranspiration, but strongly influence the remotely sensed surface temperature. We return to this problem for surface evapotranspiration in section 5.

Surface albedo is often available in field data sets and geographic information systems. The relationship between the evaporative fraction and the surface albedo is not systematic for the surface types included in the present study (Fig. 2) although it will be found to be of supplemental use for the forest class (section 5). The evaporative fraction is smaller over the dark-green conifer forests with smaller albedo, and larger over the deciduous forest and agricultural areas with larger albedo. This contrasts with the usual relationship between evaporation and albedo (see the introduction). The evaporative fraction for the present data is small again for the largest observed values of albedo, here associated mainly with senescent vegetation. The relationship between evaporative fraction and albedo is complex, and albedo, alone, is not a reliable indicator of evaporative fraction.

The red reflectance is a much better predictor of evaporative fraction within each class (Fig. 3). With transpiring vegetation, more of the red radiation is absorbed by chlorophyll and less is reflected for most types of chlorophyll. Reflected red radiation has been previously found to be a particularly good discriminator between different parts of the boreal forest (Hall et al. 1995; Mahrt et al. 1997). However, for general application, the red reflectance is normally less available and more vulnerable to atmospheric correction problems.
Figure 1. (a) Evaporative fraction averaged over all of the flights for each interval of the Normalized Difference of the Vegetation Index (NDVI) for the four classes of data (see Table 1(a)). (b) Evaporative fraction for each flight as a function of the NDVI. Location abbreviations are listed in Tables 1(b) and (c).
Figure 2. Evaporative fraction averaged over all of the flights for each interval of the albedo for the four classes of data (see Table 1(a)).

Figure 3. Evaporative fraction averaged over all of the flights for each interval of the red reflectance $R_{660}$ for the four classes of data (see Table 1(a)).
4. Day-to-Day Versus Within-Class Variations

The day-to-day variations of the evaporative fraction at a given location (flight track) show quite different relationships to external parameters compared with the spatial variation of the evaporative fraction within a given class of surface type. Because the selected vegetation classes are broad, the spatial variation within a given class is greater than the day-to-day variations at a given location. This within-class spatial variation is better represented by non-thermal channels in the visible and near-infrared, while day-to-day variations are more related to the surface–air temperature difference.

The relative importance of day-to-day variations and within-class spatial variations is examined in this section by decomposing the evaporative fraction as

\[
(E_F)_{i,k} = \langle E_F \rangle + [E_F]_{i}^{IFC} + E_{F(i,k)}'
\]

where \(\langle E_F \rangle\) is the evaporative fraction averaged over all of the tracks and flight days within a given class such that

\[
\langle E_F \rangle \equiv \frac{1}{I} \sum_{i=1}^{I} \frac{1}{K} \sum_{k=1}^{K} (E_F)_{i,k}
\]

where \(K\) is the number of flights for the \(i\)th track and \(I\) is the number of tracks.

\([E_F]_{i}^{IFC}\) is the deviation of the seasonal average of \(E_F(i,k)\) from the overall mean for the \(i\)th track. \([E_F]_{i}^{IFC}\) has been computed by dividing the data into three seasons: late spring, mid-summer and late summer/early autumn. These three seasons correspond to three intensive field campaigns (IFCs) in the BOREAS. \([E_F]_{i}^{IFC}\) is computed as

\[
[E_F]_{i}^{IFC} \equiv \frac{1}{KC} \sum_{k=1}^{KC} (E_F)_{i,k} - \langle E_F \rangle
\]

where \(KC\) is the number of flights for a given track and season.

\(E_{F(i,k)}'\) is the residual of the evaporative fraction defined by Eq. (10); that is, the deviation after removing the overall average \(\langle E_F \rangle\) and track averages \([E_F]_{i}^{IFC}\) for a given season. The within-class variance of the seasonally averaged evaporative fraction is computed as

\[
\frac{1}{3} \sum_{IFC=1}^{3} \frac{1}{I} \sum_{i=1}^{I} ([E_F]_{i}^{IFC})^2
\]

and the day-to-day variation for a given class is computed as

\[
\frac{1}{I} \sum_{i=1}^{I} \frac{1}{K} \sum_{k=1}^{K} (E_{F(i,k)}')^2.
\]

The inner sum in Eq. (14) computes the day-to-day variation for a given track and the outer sum averages this day-to-day variance over all of the tracks.

The CODE data are available for only one or two days for each track and are omitted from the analysis of Eqs. (13)–(14). For the BOREAS agricultural data, we use daily (flight) averages which normally consist of one or two passes per day. The relative importance of within-class variations compared with day-to-day variations at a given location obviously depends on the degree of homogeneity within a given class. For example, breaking the forest class into deciduous and conifer classes reduces the within-class variation by about half (Table 2).
With seasonal means removed \((E'_{ij,k})\) for the BOREAS data (Table 1(b)), the day-to-day variance for a given track (Eq. (14)) is always smaller than the within-class spatial variation (Eq. (13)), as shown in Table 2. For the conifer forests, the day-to-day variation at a given location is quite small while the variation between the conifer tracks is large. The agricultural class contains more within-season variation because of crop growth. When seasonal means are not removed, the day-to-day variance is the same order of magnitude as the within-class variance between tracks, indicating that the seasonal change in evaporative fraction is much larger than the day-to-day variation for these data.

The day-to-day variation of the evaporative fraction is expected to be related to variations of stomatal control which in turn are related to air temperature, vapour-pressure deficit, soil moisture, solar radiation and soil nutrients. Relationships between the evaporative fraction and some of these variables could be isolated for special subclasses of data but no general relationship could be found.

For some of the locations in the BOREAS, the evaporative fraction averages are 10–15% greater for partly cloudy conditions compared with sunny conditions, although the scatter is large. Sugita and Brutsaert (1991) and Crago (1996a) also found modest increases of evaporative fraction with intermittent cloud passage. However, the variance explained by the above model for evaporative fraction does not increase significantly when limiting the data to sunny days only.

For the aspen track, a little more than 25% of the day-to-day variance of the evaporative fraction is explained by the variation of surface friction velocity (correlation coefficient = 0.51) which is the single most important variable for the aspen. Apparently, on windy days, mixing between the air above the canopy and subcanopy air increases, leading to significant flux of moisture from the transpiring understory (witch hazel). On days with weaker friction velocity, the fluxes are due primarily to buoyancy-driven motions originating from the canopy top which leads to more heat flux and less total evapotranspiration.

5. MODELS FOR DIFFERENT VEGETATION CLASSES

In this section the evaporative fraction will be modelled in terms of remotely sensed surface parameters separately for the different classes of vegetation cover (section 2). The overall modelling plan is sketched in Fig. 4. The models for evaporative fraction will assume that air temperature and surface net radiation (or solar radiation) are known in addition to the remotely sensed variables.

(a) **Surface temperature**

The present data include a variety of surface types and a wide range of solar zenith angles and fractional coverage of shaded surfaces. Consequently, surface radiation temperature is poorly correlated with both the heat flux and the evaporative fraction. Since the heat flux is mainly related to the sunny ground and canopy surfaces, the area-averaged surface radiation temperature, \(T_{sfc}\), will be decomposed as a weighted average of the sunlit surface temperature, \(T_{sul}\), and shaded surface temperature, \(T_{sh}\), such that

\[
T_{sfc} = f_{sh}T_{sh} + (1 - f_{sh})T_{sun}
\]  

where \(f_{sh}\) is the fraction of shaded ground surface as seen by a downward-pointing radiometer. The error in Eq. (15) due to linearly averaging temperature instead of radiance (fourth power of the temperature) is less than the estimated 1 degC equivalent error in the radiometer (Mahrt et al. 1997). Rearranging Eq. (15) to obtain an expression for \(T_{sun}\) gives

\[
T_{sun} = T_{sfc} + \frac{f_{sh}}{(1 - f_{sh})}(T_{sfc} - T_{sh}).
\]
Equation (16) contains the expected limit where the area-averaged surface temperature approaches that of the sunny surface as the fractional coverage of shaded ground vanishes. In the other limit, where the fraction of shaded ground approaches unity, both \((1 - f_{sh})\) and \((T_{sfc} - T_{sh})\) vanish since the area-averaged surface radiation temperature approaches that of the shaded ground surface.

From a different point of view, the temperature of the sunny surface is formulated in the appendix in terms of the measured average surface temperature and the standard deviation of the surface temperature, \(\sigma_{sfc}\), such that

\[
T_{sun} = T_{sfc} + \frac{\sigma_{sfc}}{\sqrt{(1 - f_{sh})/f_{sh}}}. \tag{17}
\]
The advantage of this approach is that $\sigma_{T_{\text{sc}}}$ can be estimated from high-resolution measurements of surface radiation temperature, if available.

Ignoring variable spacing between the trees, the fraction of shaded ground surface varies as (appendix, Eq. (A.9))

$$f_{\text{sh}} = \frac{h}{L_T} \tan(Z) \quad (18)$$

up to the maximum value of $L_g/L_T$ where $h$ is the height of the trees, $L_T$ is the total distance between tree centres, $L_g$ is the width of ground surface between the trees seen from above and $Z$ is the solar zenith angle.

Based on data for mature black spruce collected by Chen and Cihlar (1996), the fraction of the shaded ground surface is approximately linearly proportional to the zenith angle and of the form

$$f_{\text{sh}} = 0.5Z \quad (19)$$

up to a maximum value of 0.65 at 70°, where $Z$ in Eq. (19) is expressed in radians. This implies that $L_g/L_T$ applied in Eq. (18) should be 0.65 for old black spruce.

The above relationships offer several possibilities for modelling $T_{\text{sun}}$. With the existing data, it was not possible to distinguish clearly between the performance of the above two formulations of zenith angle, $Z$. Use of Eq. (17) improved the prediction of evaporative fraction compared with using the averaged surface radiation temperature. However, case-study analyses indicated that the radiometer could not adequately resolve sunny and shaded areas, and consequently underestimated $\sigma_{T_{\text{sc}}}$ when compared with ground-based measurements.

A relatively simple formulation for $T_{\text{sun}}$ can be constructed by assuming $f_{\text{sh}} \ll 1$ and adopting Eq. (19), in which case Eq. (16) can be expressed as

$$T_{\text{sun}} = T_{\text{sc}} + CZ \quad (20)$$

where $C$ is an undetermined coefficient. We modify the model for evaporative fraction (Eq. (7)) by replacing the measured surface radiation temperature $T_{\text{sc}}$ with $T_{\text{sun}}$ (Eq. (20)), in which case Eq. (7) becomes

$$E_F = a - b(T_{\text{sc}} - T_{\text{air}}) - cZ + d_i R_i \quad (21)$$

where $cZ$ is the correction for the influence of shade on $T_{\text{sc}}$ and $d_i$ are the coefficients of additional remotely sensed terms. The shade-correction term augments the predicted heat flux and reduces the predicted evaporative fraction. The constant $a$ improves the performance of regression models based on Eq. (21). For instructional purposes, the additional remotely sensed variables, $R_i$, are omitted in the next subsection but restored in subsection (c).

(b) Application to different classes

Equation (21) with $R_i = 0$ is applied to each of the three classes of land surfaces: bare soil and senescent vegetation, agricultural land use, and forests. For supplementary calculations, the forest class is further broken into conifer and deciduous subclasses. Water surfaces will be considered later in this section. This division into vegetation classes simplifies the formulation of evaporative fraction since its relationship to surface variables is quite different for different classes of land surfaces. Trying to model the evaporative fraction simultaneously for all of the data leads to larger errors.

Determining the coefficients in Eq. (21) using regression analysis indicates that inclusion of the solar zenith angle significantly increases the variance explained for the
The first 4 columns represent: (1) the class name (number of aircraft flights), (2) variance explained by the evaporative-fraction model Eq. (21) based on surface temperature difference without the zenith-angle term, (3) variance explained by Eq. (21) based on the surface temperature difference and zenith-angle term, and (4) variance explained by Eq. (21) based on the three-variable model with surface temperature difference, zenith angle and the best predictor between the Normalized Difference of the Vegetation Index (NDVI) and albedo. Values in parentheses are the variance explained for the corresponding model where evaporation is scaled by the downward solar radiation (Eq. (5)) instead of net radiation. The best predictor between NDVI and albedo, listed in the 5th column, is always the same between use of net radiation or downward solar radiation. The last two columns contain the significance level for the three-variable model and the significance of adding the third variable to the two-variable model. A significance level of 100% implies greater than 99.9%.

The top line identifies the term in the regression equation.
The modelled evaporative fraction (Table 3) versus the observed evaporative fraction for the data listed in Table 1. Triangles are forest cases, diamonds are bare soil/senescent cases and pluses are agricultural cases. Each point is one flight for a given site.

\( R_i \) in Eq. (21) to albedo and NDVI which would be more readily available in routine applications.

The albedo discriminates between the conifer (low albedo, low evaporative fraction) and deciduous classes (higher albedo, higher evaporative fraction) and was also of some use for simultaneously modelling all of the data (Table 3). However, this dependence is opposite to the usual negative relationship between albedo and evaporative fraction where active vegetation corresponds to low albedo and high \( E_F \) and more arid regions correspond to high albedo and low \( E_F \). NDVI in Eq. (21) is useful for the agricultural class where evapotranspiration is related to the amount of crop cover and the soil/senescent class where some active vegetation may have been included within the averaging area. Adding NDVI or albedo to the conifer class did not significantly increase the variance explained and is omitted for this submodel.

The performance of the models is shown in Fig. 5. The separate models for the soil/senescent vegetation, agricultural crops and forest classes, collectively explain 74% of the variance of the observed evaporative fraction as opposed to 64% when one model is used for all of the classes combined. The model results in Fig. 5 show no overall bias since the coefficients were computed from the data themselves. The model will be tested against independent data in section 6.

\( d \) Use of downward solar radiation

Replacing the net radiation with the downward solar radiation reduces the amount of required input information. The model for the evaporative fraction scaled by the downward solar radiation instead of net radiation \( (E_{F_i}, \text{Eq. (5)}) \) generally performs as well as the model for \( E_F \) based on net radiation (Tables 3–4).
TABLE 4. THREE-VARIABLE EVAPORATIVE-FRACTION MODELS

<table>
<thead>
<tr>
<th></th>
<th>Forest</th>
<th>Agricultural</th>
<th>Bare soil/senescent</th>
<th>Total</th>
<th>Grid flights</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_F$</td>
<td>0.61</td>
<td>0.65</td>
<td>0.26</td>
<td>0.64</td>
<td>0.63</td>
</tr>
<tr>
<td>$E_{F_S}$</td>
<td>0.58</td>
<td>0.71</td>
<td>0.25</td>
<td>0.66</td>
<td>0.70</td>
</tr>
</tbody>
</table>

The evaporative fraction is normalized by net radiation (first line) and downward solar radiation (second line) for the forest, agricultural and bare soil/senescent classes, combined class (total) and the grid flights. Numbers are fraction of variance explained.

(e) Water surfaces

For water surfaces, the evaporation will be modelled with the bulk formula written as

$$\overline{w} \overline{q'} = C_q V (T_{sfc} - T_{air}).$$

Over the water, $C_q$ is usually specified to vary with stability according to Monin–Obukhov similarity theory. While the surface drag coefficient increases with wind speed due to increasing wave-form drag and wave breaking, the dependence of the exchange coefficients for heat and moisture on wind speed is less obvious (e.g. Makin and Mastenbroek (1996) and references therein). Furthermore, Monin–Obukhov similarity theory may be unreliable over lakes and coastal zones where advection and internal boundary-layer development are common. Favouring simplicity, we specify the exchange coefficient to be constant with a value of $1.5 \times 10^{-3}$, typical of inland water (Vickers and Mahrt 1997b).

6. Regionally averaged moisture flux

In this section we use remotely sensed information to classify the surface according to the categories chosen in section 2 and individually modelled in section 5. Since the vegetation classification does not have to be conducted routinely or operationally, we included the red and near-infrared channels as potential discriminators in addition to NDVI and albedo. In fact, the red and near-infrared reflectances jointly provide superior discrimination between vegetation types (Fig. 6). The lake data points with larger red and near-infrared reflectances correspond to shallow lakes with abundant algae.

The submodel for the forest data is tested by applying it to independent Twin Otter data from grid flights, described by Ogunjemiyo et al. (1997) which were primarily over conifer forest. These data were not used previously in this study to construct the model. Each of the grid patterns consists of nine 16 km flight legs running east–west and nine 16 km legs running north–south. The pattern is flown twice per day. The classification scheme in Fig. 6 is applied to 4 km sublegs. Based on this classification scheme, all the sublegs are classified as the forest class. The forest model is then used to predict the evaporative fraction for each subleg which is converted to the moisture flux using the observed net radiation, as schematically shown in Fig. 4. The moisture-flux values are averaged over the 36 sublegs and averaged over the two passes to predict the area-averaged moisture flux. The predicted moisture flux is well correlated with the observed area-averaged moisture flux and shows no significant bias (Fig. 7). For the grid data, using the model for evapotranspiration scaled with the downward solar radiation performs as well as the model for the evapotranspiration scaled by net radiation (Table 4).

For the single CODE grid flight over mixed irrigated and nonirrigated farmland, consisting of mostly cotton and safflower (Mitic et al. 1995), the spatially averaged evaporative fraction is 0.57 while the model predicts 0.54, which corresponds to 328 W m$^{-2}$ and
Figure 6. Vegetation classification based on red and near-infrared reflectances. Each point is one flight for a given site.

Figure 7. The area-averaged modelled evaporative fraction versus the observed area-averaged evaporative fraction for the independent grid area.
310 W m$^{-2}$, respectively. Cancellation of errors from different surface types contributes to the relatively good comparisons.

7. Conclusions

Previous studies often show a well-defined relationship between evaporation and remotely sensed surface radiation temperature, NDVI and albedo. However, when simultaneously considering the variety of surface types in the present study, this relationship becomes more obscure without including information on the solar zenith angle. The zenith angle helps account for the contamination of the remotely sensed surface radiation temperature by that shaded ground surface which does not contribute to the surface heat flux.

The relationship of the evaporative fraction to these remotely sensed variables changes substantially between different surface types. The spatial variations within a given class of surface types are much larger than day-to-day variations at a given location. In fact, for the boreal forest, the day-to-day variation of the evaporative fraction at a given location is remarkably small. Modelling the area-averaged moisture flux is facilitated by partitioning the surface into the broad classes of bare soil/senescent vegetation, active agricultural areas, forests, and water surfaces. This classification is implemented in terms of remotely sensed red and near-infrared reflectances which are superior to albedo and NDVI as discriminators of surface conditions for prediction of the evaporative fraction. Regression models for the evaporative fraction based on remotely sensed surface temperature, albedo and NDVI are developed for each broad surface class. Red reflectance is a superior indicator compared with albedo and NDVI, since chlorophyll absorbs red-band radiation. Red reflectance was not used in the model of evaporative fraction since it would be less available for future application of the model. The performance of the model can be improved using more surface classes, although simplicity is emphasized here. For the present data sets, the occurrence of cloud cover did not significantly reduce the variance explained by the model for evaporative fraction.

To estimate the area-averaged moisture flux, the evaporative fraction is predicted with the class models and then converted to evapotranspiration given observations of net radiation (Fig. 4). This output is combined with the prediction of surface moisture flux over the water surfaces to form the area-averaged evapotranspiration. Models based on evaporative fraction normalized by downward solar radiation perform as well as those normalized by net radiation, suggesting that the input information can be simplified without reducing model accuracy.

Applying the model to independent aircraft data from grid-flight patterns successfully predicts the area-averaged surface moisture flux. However, the generality of the above approach is not known and has to be extended to even lower sun angles, native semi-arid conditions, tropical rain forests, and snow-covered surfaces. More data and soil-moisture information are required for the bare soil/senescent-vegetation class where the present model does not perform well.

Acknowledgements

The comments of the reviewers are greatly appreciated. This work is supported by the National Aeronautics and Space Administration grant NAG 5-2300, grant ATM-9310576 from the Physical Meteorology Program of the National Science Foundation, and grant DAAH04-9610037 from the US Army Research Office. Kyle Kotwica was supported by ASSERT grant F49620-93-1-0497 from the Air Force Office of Scientific Research.
APPENDIX

(a) Spatial variability of surface radiation temperature

One could estimate the difference between the shaded ground temperature and the sunny surface temperature in terms of the standard deviation of the observed surface radiation temperature. Unfortunately, the measured surface radiation temperature corresponds to averaging over an area of about 5–10 m and therefore includes both shaded and sunny surfaces within the averaging area. To infer the standard deviation of the surface temperature at higher resolution, the standard deviation of surface temperature is plotted as a function of averaging length from the existing data and then extrapolated to zero averaging length. This extrapolation augments the standard deviation of the surface radiation temperature by only a few tenths of a degree.

If each measurement of the surface temperature is either a purely sunny surface or a shaded surface, then the averaged surface temperature is just the weighted sum of the sunny and shaded surface temperatures such that

\[
\bar{T}_{sfc} = f_{sh}T_{sh} + f_{sun}T_{sun}.
\]

The variance of the surface temperature is just the weighted sum of the square of the deviation from the mean surface radiation so that

\[
\sigma_{sfc} = \left[ f_{sh}(T_{sh} - \bar{T}_{sfc})^2 + f_{sun}(T_{sun} - \bar{T}_{sfc})^2 \right]^{1/2}.
\]

Substituting Eq. (A.1) into Eq. (A.2) and rearranging

\[
\sigma_{sfc} = \left[ f_{sh}(1 - f_{sh})(T_{sun} - T_{sh})^2 \right]^{1/2}
\]

or

\[
T_{sun} - T_{sh} = \frac{\sigma_{sfc}}{\sqrt{f_{sh}(1 - f_{sh})}}
\]

in which case

\[
\delta T \equiv T_{sfc} - T_{sh} = (1 - f_{sh})\frac{\sigma_{sfc}}{\sqrt{f_{sh}(1 - f_{sh})}}.
\]

Substituting this expression for \( \delta T \) into Eq. (16), we obtain

\[
T_{sun} = T_{sfc} + \frac{\sigma_{sfc}}{\sqrt{(1 - f_{sh})/f_{sh}}}
\]

where the fraction of shaded ground surface, \( f_{sh} \), is modelled in terms of Eq. (19). For a given value of \( \sigma_{sfc} \), the temperature excess of the sunny surface, \( T_{sun} - T_{sfc} \), is larger with larger fractional coverage of shaded ground. This result is used in section 5.

(b) Surface radiation temperature of forests

Consider the following geometry where the trees are assumed to be regularly spaced cylinders:

\[
h \equiv \text{tree height}
\]
\[
L_c \equiv \text{tree width}
\]
\[
L_g \equiv \text{spacing between trees}
\]
\[
L_T \equiv L_c + L_g
\]
\[
Z \equiv \text{sun zenith angle}.
\]
Therefore $L_T$ is the total distance between trunk centres. The width of the shaded ground between the trees as seen from above is

$$L_{sh} = \min(h \tan(Z), L_g)$$

(A.7)

while the width of the sunny ground is

$$L_s = \max(L_g - L_{sh}, 0).$$

(A.8)

The fractional coverage of the shaded ground surface seen from above is then

$$f_{sh} = \min \left( \frac{h \tan(Z)}{L_T}, \frac{L_g}{L_T} \right)$$

(A.9)

which is used in section 5.

REFERENCES


1997b Fetch limited drag coefficients. *Boundary-Layer Meteorol.*, 85, 53–79