Measuring Canopy Structure and the Kinematics of Subcanopy Flows in Two Forests

RALF M. STAEBLER* AND DAVID R. FITZJARRALD

Atmospheric Sciences Research Center, University at Albany, State University of New York, Albany, New York

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ABSTRACT

A better understanding of forest subcanopy flows is needed to evaluate their role in the horizontal movement of scalars, particularly in complex terrain. This paper describes detailed measurements of the canopy structure and its variability in both the horizontal and vertical directions at a deciduous forest in complex terrain (the Harvard Forest, Petersham, Massachusetts). The effects of the trunks and subcanopy shrubs on the flow field at each of six subcanopy array locations are quantified. The dynamics of the subcanopy flow are examined with pragmatic methods that can be implemented on a small scale with limited resources to estimate the stress divergence, buoyancy, and pressure gradient forces that drive the flow. The subcanopy flow at the Harvard Forest was driven by mechanisms other than vertical stress divergence 75% of the time. Nocturnal flows were driven predominantly by the negative buoyancy of a relatively cool layer near the forest floor. The direction of the resulting drainage flows followed the azimuth of the longest forest-floor slope. Similar results were found at a much flatter site at Borden, Ontario, Canada. There was no clear evidence of flow reversals in the subcanopy in the lee of ridges or hills at the Harvard Forest even in high wind conditions, contrary to some model predictions.

1. Introduction

The goals of this paper are to describe, classify, and characterize the flow fields inside and above a forest in complex terrain and to investigate the dynamical forces that control them. A detailed description of the canopy structure in both vertical and horizontal dimensions was made and was used to help to interpret data from a small subcanopy sensor array. Application of the results ranges from understanding horizontal transport of carbon dioxide (CO$_2$) (Staebler and Fitzjarrald 2004) to the dispersion of pollen and spores and the investigation of disease vectors in forest canopies (Moore 1987; Aylor 1999).

The assumptions of horizontal homogeneity generally applied by those making flux measurements over forests are often violated in the real world to a degree that could produce significant errors (e.g., Baldocchi et al. 2001). Although there is a substantial body of work in the literature on the vertical structure of flows in homogeneous forests, little research has been published on the kinematics of subcanopy flows in inhomogeneous forests in complex terrain. Wilson and Meyers (2001) studied the spatial coherence of CO$_2$ fluxes using three sonic anemometers alternately separated horizontally or vertically in the subcanopy but made no reference to the mean wind field. A study of advection of CO$_2$ in Belgium showed evidence of drainage flows on what was assumed to be a two-dimensional forested slope but did not provide any additional information on wind fields (Aubinet et al. 2003).

These studies did not address questions of dynamic forcing and were limited to relatively short periods (less than a season) or relatively small spatial extent [25 m in Wilson and Meyers (2001) and 50 m in Aubinet et al. (2003)]. Relatively homogeneous terrains were selected to simplify interpretation. In contrast, the study presented here spans four years, three seasons, and an area of 80 m by 80 m around an active “AmeriFlux” (Baldocchi et al. 2001) tower site (the Harvard Forest, Petersham, Massachusetts), in relatively complex terrain typical of much of the world.

Flows in horizontally homogeneous forests have been observed for several decades (Kaimal and Finnigan 1994, chapter 3; Fitzjarrald and Moore 1995). Within the canopy, profiles of mean and turbulent moments exhibit a rough similarity, scaling with normal-
The induced pressure gradients can become more important than momentum mixed from above or induced by large-scale pressure gradients. This behavior is especially true when there is a shallow nocturnal ground inversion in forests with an appreciable leaf area index (LAI). The large vegetation density above can effectively isolate lower canopy layers from momentum penetrating from above.

Topographically induced circulations have a preferred direction and can lead to motions that appear in long-term averages. Smith et al. (1972), Lee et al. (1994), and Pyles et al. (2004) investigated directional wind shear in the subcanopy. Although it is generally agreed that the Coriolis effect inside the canopy is small in comparison with other terms in the momentum equation (Smith et al. 1972; Lee et al. 1994), horizontal pressure gradients may play a role near the ground where the Reynolds stress divergence approaches zero. Pyles et al. (2004) found significant departures from modeled shear in the lowest 15% of the canopy and hypothesized that this behavior resulted from local mountain-valley breeze, though they lacked measurements of mesoscale pressure gradient forcing. The presence of a pressure gradient that changes in the vertical direction, either induced by the Bernoulli effect of flow over hills or through a surface-layer density anomaly, is the most likely source of subcanopy directional shear. Mesoscale pressure gradients will contribute to this term but will, as compared with forcing that is coupled to the landscape, not directionally bias long-term averages of subcanopy dynamics.

Most previous studies of subcanopy air motions focus on the consequences of downward momentum mixing; here we also examine the role of local momentum sources. In contrast to the familiar plane surface-layer case, characteristic scales in subcanopy motions are not well understood, and this lack of understanding leads to arbitrary assumptions in modeling. Many of these motions result from drainage flows, but how cooler air created by radiative flux divergence at the canopy top gets to the forest floor to foster these flows must depend on the observed vertical and horizontal canopy structure, details that rarely accompany subcanopy flow measurements.

The approach in this paper is to describe the physical or structural environment of the forest, followed by a description of the meteorological conditions to which the forest is exposed. A method is described to characterize canopy structure and subcanopy flow fields that can be applied at other sites. Although this work cannot provide an all-inclusive analysis of the connections between canopy structure and the forest microclimate, it
promotes a deeper awareness of the role of the physical structure (Parker et al. 2004a).

2. Theory

The momentum equation along a slope describes flows both above and below the canopy:

\[
\frac{\partial u_i}{\partial t} + u_i \frac{\partial u_i}{\partial x_j} = -\frac{\partial \tau_{ij}}{\partial x_j} + \frac{\theta_v}{\rho} \frac{\partial h}{\partial x_i} - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + F_{D,i},
\]

where \( h \) represents the topographic elevation, \( \tau \) is the stress tensor, \( \overline{\theta_v} \) is the mean virtual potential air temperature, and \( \theta_v^* \) is the local departure from it. The right-handed coordinate system is defined by \( i = 1 \) being parallel to the slope and \( i = 3 \) being perpendicular to the slope. A repeated index indicates summation. Term 5 describes the horizontal pressure gradient; \( F_{D,i} \) represents the sum of all drag forces, assumed to be zero above the canopy. The Boussinesq approximation has been applied, and Coriolis and molecular dissipation effects are neglected.

Reynolds stress divergence (term 3) describes coupling with the flows aloft, which depends strongly on the canopy vegetation density. This term has been discussed in the introduction. Term 4 describes the buoyancy forcing, which will cause relatively colder (warmer) air to flow downhill (uphill). This term defines katabatic flows in which the forcing is local; that is, both slope and temperature inversions are collocated in the measured layer. Drainage flows, on the other hand, can also refer to flows for which the negative buoyancy was generated some distance from the point of interest and is then advected there through the momentum advection term 2 (Fitzjarrald 1984). The direction from which these buoyancy flows will emanate is often not obvious in complex terrain; different scales of motion can affect the local flow under different conditions (Mahrt et al. 2001).

The theory of drainage flows for simple geometries has been discussed comprehensively in the literature (Prandtl 1942; Fleagle 1950; Mahrt 1982; Fitzjarrald 1984). Equilibrium between advection of momentum along the slope and the vertical stress divergence, as well as between horizontal heat advection and vertical heat divergence, yields the classical steady katabatic, nose-shaped wind profile. To date, there is little information in the published literature on the depth of drainage flows inside canopies, where the unknown frictional effects of trunks, branches, and leaves complicate the situation. The simplest parameterizations with constant mixing length or eddy diffusivity (e.g., Prandtl 1942) are probably not applicable there. Moreover, characteristic scales needed to specify the eddy diffusivity, as for second-order closure models (e.g., Poggi et al. 2004) or large-eddy simulations (e.g., Fitzmaurice et al. 2004), have not yet been observationally validated. Most previous studies have concentrated on neutral conditions, with little modeling of the light wind conditions that are typical of the nocturnal subcanopy.

Term 5 (pressure perturbation) may be important in the vicinity of hills, as recent modeling and wind tunnel studies of canopies on hills have shown. Finnigan and Belcher (2004) used a linear hill flow model based on Hunt et al. (1988), which they modified by covering the hill with a homogeneous canopy. The results for steady-state conditions under neutral stratification indicate a region of reversed flow on the lee side. In the upper canopy, there is an approximate balance between the pressure gradient perturbation and the vertical transport of momentum; deeper in the canopy, the pressure gradient perturbation balances the drag forces. By balancing the pressure forcing term with the stress divergence, a level in the canopy on the lee side of a ridge can be estimated at which the wind speed drops to zero. If the canopy is deeper than this level, flow separation and a region of reversed flow should be expected. This level is estimated to be about 10 m at the Harvard Forest, and, because the canopy has a depth of about 20 m, flow reversal is predicted in the lower half.

Upon generation, these subcanopy flows are then modified by the immediate local topography and by obstacle effects of the vegetation. The drag force (term 6) is often parameterized as \( F_D = -(C_D)(CAD)|u||u| \), where \( C_D \) represents a drag coefficient and CAD is the canopy area density (Kaimal and Finnigan 1994, p. 95).

To understand the flows in and above a forest in complex terrain, detailed measurements were conducted at the Harvard Forest using sonic anemometers at several levels from the ground up to just above canopy top along with an acoustic sounder to measure winds aloft. These data are contrasted with similar data obtained at a topographically distinct yet ecologically similar forest at Borden, Ontario, Canada. The data collected in these studies represent the most comprehensive set of subcanopy flow observations covering a time frame of several months to date and provide additional insights into subcanopy dynamics. Although these measurements still fall short of completely describing subcanopy flows, they allow the testing of several hypotheses:

1) Subcanopy wind reductions resulting from understory obstructions can be quantitatively related to observed spatial distributions of subcanopy vegetation.
2) Subcanopy winds are homogeneous over a horizontal spatial scale of about 5 canopy heights, despite the presence of significant variations in canopy density.

3) Stress divergence does not usually determine the nocturnal flow in the understory.

4) Thermal stratification inside the forest is usually stable.

5) Buoyant forcing determines the subcanopy flow direction and intensity for a significant fraction of the time.

6) Divergences measured directly in the understory are consistent with the observed mean vertical wind speed.

3. Sites and methods

a. Topography

Data from two sites are described in this paper: the Harvard Forest (42°32’N, 72°11’W, 340 m MSL), and the Borden Forest Research Station, operated by the Meteorological Service of Canada [Canadian Forces Base (CFB) Borden; 44°19’N, 79°56’W, 215 m MSL]. The former is a mixed deciduous forest dominated by red oak, red maple, and hemlock (with an average tree height of 20 m, an LAI of about 3.4, a stem density of about 660 ha⁻¹, and a growing season of typically 150 days) and is 60-80 yr old (Moore et al. 1996). The latter is mixed deciduous forest dominated by red maple and trembling aspen (with an average tree height of about 22 m, an LAI of 4.1, a stem density of about 980 ha⁻¹, and a growing season of 150 days) and is 80-100 yr old (Lee et al. 1999).

The scales that most affect the flow fields at these sites are best seen by inspecting the topographical elevation sections as depicted in Figs. 1 and 2. For the dominant westerly wind direction, the main feature is the rise to the ridge on which the Harvard Forest is located; the main slope is about 2 km west of the tower, and the height difference is 120 m (a slope of 12%). The peak of the ridge, about 20 m above the tower location, is about 400 m from the tower. In the northerly direc-
tion, Prospect Hill is the main feature, with a peak 80 m above the tower base and a slope of 20%. The most consistently downsloping direction is toward the southeast, ending in the Swift River valley.

In comparison, slopes at Borden are much smaller (~0.5% in the southwest–northeast direction) but possibly not negligible (Fig. 2). No features are present that would cause significant pressure or flow perturbations.

b. Methods

To monitor the wind speeds in the subcanopy at the Harvard Forest, a network of sonic anemometers was deployed in an area of 80 m by 80 m, 1.8 m above the ground (Fig. 3). A 5-m tower at the center of the network was instrumented for detailed profiles of temperature, humidity, and CO$_2$ to supplement the profiles on the main flux tower, 11 m to the south. SPAS/2Y two-axis sonic anemometers (Applied Technologies, Inc.) with a resolution of 0.01 m s$^{-1}$ were used on the periphery of the network, and a Gill HS (Gill Instruments, Ltd.) three-axis sonic anemometer operated at the center. In the vertical direction, three-axis sonic anemometer data were available at 29, 17, and 8 m (SATI, Applied Technologies, Inc.) on the main tower, and two-axis data were available at 5 and 3 m on the 5-m tower (CATI/2, Applied Technologies, Inc.). The measurements discussed in this paper cover the periods from 27 July to 18 November 1999, from 23 August to 4 December 2000, from 1 October to 1 December 2001, and from 19 April to 4 December 2002. Details on the continuous measurements at the Harvard Forest, as well as on the subcanopy measurements, can be found elsewhere [Moore et al. (1996) for the former; Staebler and Fitzjarrald (2004) and Staebler (2003) for the latter].

Vertical profiles of the CAD were obtained using the methods of Parker et al. (2004b) by walking six parallel transects covering the network with an upward-looking laser range finder (LD90–3100HS; Riegl Laser Measurement Systems GmbH). To relate the horizontal obstruction effects experienced by the flow field to the
physical obstacles, the same laser was used to obtain horizontal scans. A turntable mounted on a tripod was designed on which the laser was mounted in addition to an electronic compass (EZ Compass 3; Advanced Orientation Systems, Inc.), recording the orientation. Both laser and compass data were streamed serially to a laptop computer for collection, at 170 and 5 Hz, respectively.

Measurements of the wind fields up to levels of typically 500 m above ground were conducted at both sites with Doppler sodar instruments (PA-1; REMTECH, Inc.). This instrument provides half-hour data on 30 levels of echo strengths (related to the local temperature structure function $C_T^2$, a measure of the amplitude of temperature fluctuations in the air), wind speeds, and wind directions. The manufacturer claims vertical and horizontal wind speed accuracies of 0.05 and 0.2 m s$^{-1}$, respectively, and a directional accuracy of 3°.

Information on the continuous measurement program at Borden can be found in Lee et al. (1999). To monitor the understory flows, a model TR-90AH 3D sonic anemometer (Kaijo-Denki) was installed in June of 1999 at 1.4 m above ground; a second one was added in July of 2000, and a third (CSAT, Campbell Scientific, Inc.) was added in July of 2001, within a radius of 54 m of the main tower. Data were collected continuously until December of 2002.

4. Observations

a. Canopy structure

The average vertical CAD profiles at the Harvard Forest, obtained from the horizontal transects, illustrate significant spatial variability (Fig. 4). Transect 1 is distinctly bottom heavy, primarily because of the dense, low hemlock found along this transect. The transects that are oriented toward the southwest, especially transects 4 and 5 for which the forest is dominated by maple and oak, exhibit more evenly distributed canopy elements. On average, 90% of all canopy area is found below 20 m, but some canopy elements are found as high as 25 m. To quantify the obstacle effect on the subcanopy wind measurements, the empirical concept of “transmission factors” (Fujita and Waki-moto 1982) was applied to each of the subcanopy anemometers (Fig. 3). Winds were binned into 30° wind direction sectors, and the average wind speed for each sector for each anemometer was determined. The maximum wind speed in the network for this sector was then declared the reference (relatively un-
obstructed) wind speed $U(\phi)$, so that for each location

$$u(\phi, x) = \text{TF}(\phi, x)U(\phi),$$

(2)

where $u$ is the wind speed for wind direction sector $\phi$ at location $x$, and TF is the transmission factor. To obtain a hypothetical wind field that is unaffected by these localized differences, winds can then be corrected for the obstruction effect by dividing by the appropriate TF.

To relate the size of obstacles to a transmission factor, Fujita and Wakimoto (1982) stated that only the angular size of the object was of importance, and they expressed $\text{TF} = e^{-k\beta}$, where $\beta$ is the vertical angular size of an obstacle and $k$ is an empirically determined coefficient. The approach using vertical angular sizes of obstacles is inappropriate inside a forest. Instead, we apply horizontal angular sizes, weighted by distance to the obstacles. Inside this type of forest, every direction is obstructed within less than 50 m. Because it is reasonable to assume that nearer objects should be weighted more heavily, and because the angular size of any object is given by $d/r$ [where $d$ is the width of the object (e.g., the diameter of a trunk) and $r$ is the distance], the approach taken was to add the inverse of the laser distances $r$ (which are all equally spaced in direction $\theta$) for a given sector to give an obstruction parameter,

$$N_{\Delta\theta} = \sum_{\Delta\theta} 1/r.$$  

(3)

To convert this obstruction parameter to a pseudo TF', we calculate

$$\text{TF}'(\Delta\theta) = 1 - \frac{N(\Delta\theta)}{N_{\text{max}}(\Delta\theta)},$$

(4)

where $N_{\text{max}}$ is the maximum obstruction parameter found in the network in sector $(\Delta\theta)$.

The effect of wind speed on the obstacle effects was tested by recalculating the wind-based transmission factors for wind speeds above and below 0.2 m s$^{-1}$ (the subcanopy median). Higher wind speeds generally resulted in better agreement between the two methods.

In close proximity to obstacles, some measure of the deflection of the flow around the obstacles is needed. Significant and systematic deflections are observed at the different anemometer locations (Fig. 5). A small part of these deflections is due to flow distortion by the instruments themselves (Kaimal et al. 1990), but this was found to be typically less than 5° when all instruments were collocated. Most of the deflection seen in Fig. 5b is therefore due to understory obstacle effects. Given typical wind speeds of 0.2 m s$^{-1}$ and trunk diameters of 0.1 m (i.e., Reynolds number $Re \approx 1500$ for kinematic viscosity $\nu \approx 1.5 \times 10^{-5}$ m$^2$ s$^{-1}$), laminar flow is still plausible in many cases. Deflection angles would be expected to peak on the sides of the largest obstruction densities (lowest transmission factor), that is, to line up with the maximum rate of change of the transmission factor. There are some indications of this behavior—for example, near 50° and 180° at the north anemometer location or 150° and 240° at the east location. Overall, the correlation between the wind-based TF (Fig. 5c) and optically determined TF' (Fig. 5d) is not convincing. We speculate that the sensitivity of the optical method to obstacles that are too small to affect the wind is at fault and that a laser with a smaller beamwidth would perform better; verifying these speculations is left for continuing work.

b. Subcanopy meteorology at the Harvard Forest

Median profiles of temperature and wind speed (Figs. 6 and 7) indicate that stable stratification is the norm in the bottom 8 m of this forest except during leafless periods with bare ground, when a combination of the soil’s thermal inertia and direct insolation keep the ground warmer than the air above it (Fig. 6). The daytime profiles during summer indicate radiative warming of the foliated canopy space while the lack of sunlight reaching the floor (typically < 10%) results in colder air near the ground. The nocturnal profile in the summer also clearly shows the effect of the foliage in preventing mixing with the air aloft, with the temperature approaching the above-canopy value more slowly than in winter. In summary, conditions for negative buoyancy near the ground, conducive to drainage flows, exist 83% of the time (92% of the time at night and 65% during daytime).

The wind speed profiles (Fig. 7) display exponential behavior inside the canopy, as parameterized by Cionco (1985), only in the leafless state, when the CAD profile is relatively straight (see below). During foliated periods, the wind speed increases only by about 60% from 1.8 m to the top of the canopy, as compared with a factor of more than 3 in winter. The ratio of the wind speed at 1.8 m to the wind speed at 29 m stays almost constant throughout the year. The foliated profiles also provide an example of the difficulties of making representative wind speed measurements inside a canopy: the lower values of the wind speed at 20 m are due to a slightly greater proximity of canopy elements to the tower at this level, as verified during the transects described in section 3b. It is clear that the Cionco (1985)
approach only applies to horizontally and vertically simple canopy structures.

c. Subcanopy flows

Subcanopy flows are generated through a balance of the four driving forces given in Eq. (1). Away from the very close proximity of obstacles, drag has little effect on the direction of the flow, and it is disregarded in the subsequent analysis. The transmission factors projected and measured in section 4a are local manifestations of drag in the immediate surroundings of the anemometers and have been considered (see below).

The drag term and its spatial variability were estimated with $F_D = -(C_D)(CAD)u|u|$, using the detailed measurements of canopy profiles described in section 4a (Fig. 8). If $C_D$ is assumed to be 0.15, a value typical for mixed deciduous forests (Lee 1997), the magnitude of the drag term (typically 0.01 m s$^{-2}$ in the summer) dominates over all of the other terms in the momentum budget (typically 0.004 m s$^{-2}$; see below). This result is not surprising, considering the resulting strong vertical attenuation of winds in forests (Fig. 7). This drag decreases significantly in winter, allowing better penetration of the wind into the canopy. The values shown here should be regarded only as order-of-magnitude estimates; $C_D$ values appropriate to highly turbulent conditions may not always be adequate to describe the situation in weak subcanopy flows.

In over 12 000 half-hour averages collected during the studies from 1999 to 2002, only 25% show alignment between the wind vector at 29 m and that at 1.8 m within an angle of ±30°. The data show no bias of the directional shear from above the forest to the subcanopy toward counterclockwise rotation, indicating
that the influence of mesoscale pressure gradients on the subcanopy flows at the Harvard Forest is negligible in comparison with local factors. The fractions for alignment within $\pm 30^\circ$ between the 3D anemometer at 1.8 m and other anemometers horizontally displaced by 40–60 m are typically around 60%, whereas the wind vectors directly above the 3D anemometer at 3 and 5 m were aligned to this degree 76% and 72% of the time, respectively. Those at 8 and 17 m on the main tower nearby are aligned with the 1.8-m wind vectors 30% and 27% of the time, respectively. These results illustrate that the airflow in the subcanopy is frequently not driven simply by momentum transfer from above.

To determine the relative importance of the three driving forces on the flow near the ground, each was parameterized as follows. The vertical stress divergence was calculated from the momentum flux gradient between 8.2 m and the ground (where it goes to zero). The buoyancy term was calculated using the potential temperature at 2.5 m minus the average temperature between 15 and 28 m. A representative 4.5° topographic slope was used.

Estimating the Bernoulli pressure gradient term involved some assumptions. The linear theory (Hunt et al. 1988; Finnigan and Belcher 2004) predicts the maximum pressure gradient for a series of sinusoidal 2D hills halfway downhill on the lee side with a maximum magnitude of $\frac{\partial p}{\partial x} \sim \rho U_0^2 \frac{H}{2L} \left( \pi / (2L) \right)^2$, where $U_0$ is a reference wind speed inside the “middle layer,” estimated to be around 800 m above ground given the topography at the Harvard Forest. This wind speed was extrapolated from measurements at 30 m using a relationship established from periods of measurements at both levels, with the 800-m data derived from radar wind profiler measurements 9.5 km to the west-northwest [courtesy of the National Oceanic and Atmospheric Administration (NOAA)]. The characteristic height scale $H$ and length scale $L$ for the hill were determined from Fig. 1 and were allowed to vary ac-

![Figure 6. Median potential temperature profiles at the Harvard Forest for over 12,000 half-hours from 1999 to 2002. Here $\theta'$ represents the difference (K) relative to the temperature at 30 m. The horizontal bars denote the interquartile range. The foliated period corresponds to yeardays 160–260, and the leafless period corresponds to yeardays 1–120 and 300–365. Day is defined as 0900–1700 EST, and night is defined as 2000–0400 EST.]
According to wind direction. The fractions to be used in the following analysis can then be summarized thus:

\[ \frac{t}{a}/H_{11005}/H_{20879}/H_{11128}/H_{9270}/H_{11128}/H_{20879}, \]

\[ \frac{p}{a}/H_{11005}/H_{20879}/H_{11128}/H_{9267}/H_{11128}/H_{20879}, \]

\[ \frac{b}{a}/H_{11005}/H_{11408}/H_{20849}/H_{20850}/H_{329}, \]

where \( tfrac, pfrac, \) and \( bfrac \) stand for stress divergence, pressure gradient, and buoyant fractions, respectively. The ratio of \( bfrac \) to \( tfrac \) can be thought of as a Richardson number, indicative of the stability regime of the flow. As expected, these calculations suggest a stronger role played by stress divergence during the day and by buoyancy at night (Fig. 9). The pressure term, which is based on the assumptions discussed above and may be overestimated, appears to be relatively invariant but may be as important as the other two terms. On average, the \( bfrac \) is 52% (26%), \( pfrac \) is 33% (35%), and \( tfrac \) is 15% (38%) during the night (day).

The seasonal cycle of these forcing terms showed that the stress divergence term appears to be most significant in the subcanopy during daytime in late winter/early spring and then again in the autumn (Fig. 10). During these periods the forest is leafless and momentum can penetrate more easily through the canopy. A secondary minimum in the winter is due to the seasonal variation in synoptic wind speeds, which are diminished in winter because of the frequent occurrence of stable systems with smaller synoptic pressure gradients. Nights are dominated by buoyant forcing throughout the year but especially during the spring, during which season the temperature gradients close to the ground are strongest because of the cold ground and the warming air aloft. The fraction of nights with friction velocity \( u_* < 0.2 \text{ m s}^{-1} \) is almost constant throughout the year, ranging from a minimum of 29% in May to a maximum of 34% in July.

To determine the effect of these different forces on...
the subcanopy flow, different flow characteristics must be isolated. Flows generated by the buoyancy term are expected to come from the direction of the dominant slope, although it is not obvious at the Harvard Forest (see Fig. 1) what this direction might be. To investigate the existence of a preferred subcanopy wind direction under strongly buoyant conditions, wind roses were plotted for increasing fractions of the buoyant term (Fig. 11). These show that northwest and north flows increase as negative buoyancy becomes dominant. On average, 37% of all subcanopy winds come from the northwest and 25% come from the north when bfrac is greater than 80%, as compared with 13% and 22%, respectively, when bfrac is less than 20%. This trend is consistent from year to year and applies at all points in the anemometer network.

Rather than the topography in the immediate vicinity of the tower, which slopes down toward the northeast, or the steepness of the most significant slopes within a few kilometers, the deciding factor on the direction of drainage flows appears to be the combined length of uphill plus downhill slope along an axis. This argument is strengthened by results at Borden (section 4e). In physical terms this can be explained by the continuous
addition of momentum to the flow over a longer distance, if the air close to the ground continues to be cooled.

If the predictions in Finnigan and Belcher (2004) apply to the slopes at the Harvard Forest, there should be observable flow reversals near the ground when a sufficiently strong wind aloft flows over the elevated ground to the west and north before reaching the tower site. Cases with low buoyant forcing (<10%) were separated out and split by the fraction of the pressure gradient term (Fig. 12). There was some indication that the relative fraction of reversed flows increases as the pressure gradient fraction increases. However, there was no clear separation between alignment (stress dominated) and reversals (pressure dominated), and the whole spectrum of angles was observed, even at the extremes when the angles should have congregated either near 0° or 180°. The linear theory also predicts a speed up of the flow aloft, resulting from the Bernoulli effect, of about 5% at heights of about 150 m above ground for this topography. Combining local sodar wind profile measurements with radar profiler measurements 10 km to the west-northwest suggested a speed up of 20%–60% at these heights—that is, significantly more than predicted.

d. Subcanopy flow divergence

In this section we focus on two questions: 1) Can we measure the mass divergence with a small network of sonic anemometers? 2) Is the divergence constant with height, thus allowing for measurements at a single level? The continuity equation for incompressible flow gives

\[
\int_0^S (\nabla_{\text{hor}} \cdot \mathbf{u}) \, dz = -\mathbf{w}(h).
\]

Lee (1998) and Finnigan (1999) asserted that \( \partial \mathbf{w} / \partial z = \mathbf{w}_\nu / h \), that is, that \( \mathbf{w} \) increases linearly with height, even in the subcanopy, such that \( h (\nabla_{\text{hor}} \cdot \mathbf{u}) = -\pi(h) \). This assertion is tested with data from the Harvard Forest.

The uncertainty in the divergence measurement comprises instrumental, random (meteorological), and systematic, obstacle-related components. Errors resulting from instrumental and alignment uncertainties were estimated during an 8-day test period, during which all sonic anemometers were placed within 4 m of each other. Divergences were calculated as if the instruments were deployed in the network. This component includes errors resulting from instrumental interference with the wind (e.g., transducer-shadowing effects). During the test period, the apparent average divergence was \((4 \pm 2) \times 10^{-5} \text{ m s}^{-1}\), well below measured divergences (see below), indicating that the measurement of divergence is not limited by instrumental uncertainties.

To see whether the flow deflections at each subcanopy anemometer location (Fig. 5) played a significant role in the calculated divergence, wind vectors
were corrected for these deflections (section 4a) and the divergence was recalculated. No systematic difference was found between these two sets of divergences, but the noise on the corrected divergences (variance from half-hour to half-hour) increased by about 30%. Applying this correction did not improve the correlation between divergences and vertical mass flow (see below).

To test the consistency of the data and whether the divergence is constant with height, one relates the divergences to the vertical mass flow. After removal of the directional dependence (i.e., the streamline component) of $\nabla$ using the technique of Lee (1998), the vertical velocities at 29, 17, and 8 m were compared with the divergence in the subcanopy. As an example, we examine a 10-day period in 2001 with an unusually pronounced diurnal cycle in the divergence (Fig. 13). Although $\nabla$ (8 m) appears anticorrelated with the divergence on days 317, 318, 319, 322, and 323 and has the correct magnitude, the relationship breaks down on the other days. No correlation is observed with the anemometers at 17 and 29 m except on day 322. Signals at 5 and 1.8 m are difficult to interpret, most likely because mean vertical components at these levels approach the instrumental limits.

In the 10-day period shown, the correlation between the divergence and $\nabla$ (8 m) suggests that the assertion of constant divergence with height may hold up to 8 m but that vertical mean motions above this height are decoupled (except on yearday 322). This example does

Fig. 11. Wind roses as a function of the fraction of the buoyant term in the sum of the forces, based on statistics for all data. (bottom right) Wind roses laid over a topographic map centered at the Harvard Forest flux tower. The solid (dashed) radials indicate the distance to the nearest hilltop (valley), that is, the nearest significant topographic inflection point. The horizontal scale is in meters, and the contour spacing is 16 m. [Reprinted from Staebler and Fitzjarrald (2004, their Fig. 9), copyright 2004, with permission from Elsevier.]
not represent the norm, however. Just as often, the divergence is positively correlated with $\pi$ at the various levels, which can only be explained by the flows below 1.8 m being decoupled from those above. The most consistent pattern that was observed was that all periods with persistent subcanopy flows from 90° to 180° were associated with positive divergence. This pattern may be due to a response to the local topography.

**Fig. 12.** Histograms (number of occurrence, for half-hourly averages with buoyant forcing fractions < 10%) of the angle between the wind directions at 29 and 1.8 m [$\Delta(wd) = |wd(29 m) - wd(1.8 m)|$] as a function of the pressure gradient fraction.

**Fig. 13.** The horizontal divergence at 1.8 m in comparison with $\pi/h$ at all available levels, for a 10-day period in Nov 2001 (yeardays 314–324). Shown are half-hour means (s$^{-1}$), smoothed with a 6-h running mean.
From these directions, deflection of the flow along the topographic contour lines results in an increased divergence.

The divergence measured at 1.8 m shows no clear correlation with the measured vertical velocity. A better correlation can be found when vertical velocities at the various levels are compared, with correlation coefficient squared \( r^2 = 0.27 \) and 0.14 for the fits of \( \vec{v} \) at 17 and 8 m, respectively, against \( \vec{v} \) at 29 m. The slopes for the least squares fit \([0.45 \pm 0.02 \text{ (mean \pm standard error)} \] and \( 0.23 \pm 0.01 \), respectively\) were somewhat less than the ratios of the heights (17/29 and 8/29), however, which means that \( h(\nabla_{\text{hor}} \cdot \vec{u}) = -\vec{v}(h) \) may be an oversimplification or that the divergence may increase with height. Given the scatter on the relationship, however, the assertion of linear increase of \( \vec{w} \) with height cannot be statistically disproved.

Although this discussion sheds some light on subcanopy kinetics, the measurements provide an incomplete picture. Given the complexities of the vertical and horizontal distributions of canopy elements, the possibility of persistent midcanopy circulations cannot be excluded. In response to the first question posed, it appears that measuring the subcanopy divergence is not limited by instrumental capabilities, but the consistency of the measured divergences could not be confirmed through comparison with the mean vertical velocities. In response to the second question, we infer that divergence at this site is not constant with height, although this possibility cannot be excluded statistically. For future field studies, we recommend measuring the divergences at several vertical levels and on varying horizontal scales, which could be done with a network of canopy towers, instrumented at several key levels.

e. Comparison with Borden

The topography at Borden (Fig. 2) does not include any large slopes that would, at first sight, suggest the development of sustained slope flows. Borden was initially meant to serve as a control site at which subcanopy flows would be correlated well with the wind aloft because of the relatively flat terrain. The dominant mesoscale signature at Borden is the lake-breeze effect that results from the proximity to Georgian Bay, 20 km to the northwest.

As at the Harvard Forest, temperature profiles at Borden (Fig. 14) are stable in most cases except during daytime in the winter, when solar radiation can pen-

![Fig. 14. As in Fig. 6, but for Borden, 2002.](image-url)
etrate easily to the ground. This condition may be conducive to gravity flows, although the local slopes are relatively small. Measurements demonstrated that even at Borden the subcanopy flows were usually decoupled. A strong dominance of flows from the south and southwest was evident and coincides with a small (0.5%) but steady slope extending from 1.5 km at the south-southwest to more than 4 km at the north-northwest (Fig. 2).

The dynamic forcing components were calculated as described in Eq. (7), except that no topographic pressure forcing term was included. Flows aloft are predominantly from the northwest at Borden. In the subcanopy, flows from the south and south-southwest dominate the wind roses (Fig. 15) even when the buoyant fraction is small (69% of the time), but the dominance increases even more (to 88%) as the buoyant fraction becomes dominant. As at the Harvard Forest, it is not the steepest slope that produces local drainage flows, but the slope with the largest horizontal extent.

On average, subcanopy flows are aligned with flows aloft to better than 30° only 24% of the time. For wind directions aloft between 90° and 270° the fraction is 39%, and for the northern sector (between 270° and 90°) it is 7%. For the northern sector the flows oppose each other (within 180° ± 30°) 28% of the time. The decoupling of the subcanopy flows from the flow aloft appears to be even more complete at Borden than at the Harvard Forest. The best explanation for this is Borden’s higher CAD and more evenly distributed upper canopy. Therefore, even at Borden, considered to be one of the flattest AmeriFlux sites, subcanopy flows are generally driven through forces other than simple downward transport of momentum.

![Fig. 15. Borden wind roses at 1.5 m as a function of the fraction of the buoyant forcing term. Data are for 2001. (bottom right) The slope rose, indicating the length of uninterrupted up (solid) or down (dashed) slope in each direction. The horizontal scale is in meters, and the contour spacing is 10 m.](image-url)
5. Summary and conclusions

The canopy structure and the wind fields inside and above two forests in complex terrain were surveyed. Direct observations at the Harvard Forest showed that the canopy structure was highly variable, both spatially and seasonally. The average canopy profile was bimodal, resulting from the combination of areas of bottom-heavy (coniferous/mixed) and top-heavy (deciduous) foliage distributions. The winter canopy density profile was relatively straight, with a resulting wind profile that is explained well by a simple exponential approximation (Cionco 1985). To relate wind profiles to the more complicated summer canopy profiles requires a more sophisticated approach.

Measurements of horizontal obstructions made using a laser range finder quantified effects of subcanopy obstructions on the wind fields. Significant interseasonal differences, both in directionality and magnitude, were observed. No clear correlation between optically determined obstruction maps and the wind-derived transmission factors was found (hypothesis 1). This issue may only be resolved using a laser system that is either less sensitive to very small obstacles or has a finer resolution (i.e., a smaller beamwidth).

The observed canopy structure suggests strong spatial variability in the drag exerted on the flow, as well as the exchange of momentum, energy, and trace gases throughout the canopy space, which is commonly treated as a continuous porous medium. Observations of differences at the various network end points, however, indicated a relatively uniform wind field with only minor flow deflections or attenuations (hypothesis 2).

Inside the forest, the drag term dominates the momentum equation, especially in summer, with values that are typically $\sim 0.01 \text{ m s}^{-2}$ as compared with $\sim 0.004 \text{ m s}^{-2}$ for the stress divergence, buoyancy, and pressure gradient terms. Thermal stratification conditions conducive to drainage flows exist in the subcanopy on 92% of all nights, and the buoyancy forcing dominates 58% of the time (hypothesis 3). Staebler and Fitzjarrald (2004) found that a large fraction of these nights are associated with anomalously low above-canopy CO$_2$ fluxes, coincident with significant horizontal transport of CO$_2$ in the subcanopy.

The pressure gradient term, crudely estimated using a linearized theory of flow over hills (Finnigan and Belcher 2004), did not have any significant diurnal variations, on average, and accounted for about 30% of the forcing on the subcanopy flows. Combining local sodar wind profile measurements with radar profiler measurements 10 km to the west-northwest suggested a Bernoulli speed up of 20%–60% at heights of approximately 150 m above ground, as compared with the $\sim 5\%$ predicted by linear theory.

The stress divergence dominated the daytime flows in the early spring and in the autumn when the canopy was leafless and exposed to seasonally higher synoptic wind speeds. The buoyant term dominated the nights throughout the year but especially during spring when the ground was still cold and the air above it was warming, creating a stronger surface inversion (hypotheses 4 and 5). Daytime stratification is generally stable inside the forest during the summer, whereas winter profiles show the effects of solar radiation heating the ground in the absence of foliage.

Subcanopy flows from the northwest significantly increased as the buoyancy term fraction increased, indicating drainage flows from this direction. At both the Harvard Forest and Borden, the deciding factor on the direction of drainage flows appeared to be the length of the slope, not the slope angle. Even at the relatively flat Borden site, drainage flows were shown to be an important feature. There may be no “ideal” sites.

Divergences calculated from a subcanopy array of sonic anemometers often showed a diurnal cycle, suggesting convergence at this site near the ground during daytime hours. These divergences could not be reconciled with measured vertical mass flow measurements, however (hypothesis 6). These vertical mass flow measurements, at levels of 8, 17, and 29 m above the forest floor, were generally consistent with each other, although the increase of $\overline{\nabla} \cdot \mathbf{w}$ with height appeared to be less than proportional to the height.

There clearly is a need for further measurements to determine why $\overline{\nabla} \cdot \mathbf{w}$ and the divergence are not easily reconciled. The recommended course of action is to measure the divergence at several vertical levels, with towers at the end points of the network, in addition to $\overline{\nabla} \cdot \mathbf{w}$ at these points. It would also be helpful to vary the size of the network or to have nested arrays to provide more information on the relevant scales on which local $\overline{\nabla} \cdot \mathbf{w}$ and divergence can be related.

The method developed in this work is suited to obtaining a more thorough description of both the canopy structure and the wind fields with limited resources. The applicability of the guidelines presented here, such as determining the relevant slopes for drainage flows, should be tested at other sites. Any attempt to establish generally applicable models to describe subcanopy flows will depend on further testing.

Further model development is needed to describe subcanopy flows, taking into consideration topography, the canopy density, and air density anomalies near the surface. As more information becomes available on
these structural parameters, for example, from satellite measurements (e.g., Blair et al. 1999), it will become feasible to develop an appropriate model to provide estimates of subcanopy flows at many sites and of how these flows may transport scalars such as CO$_2$, pollutants, pollen, and spores.

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