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Reply to comment by Finnigan on "On micrometeorological observations of surface-air exchange over tall vegetation"

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I thank Dr. Finnigan for his correspondence and his insightful analysis of the assumptions involved in Lee (1998). Before responding to his comment, it is useful to state the objective of Lee's analysis which is to examine the role of a non-zero mean vertical velocity or flow divergence/convergence in determination of surface-atmosphere exchange rates by the eddy covariance technique. Adequate upwind fetch with a horizontally homogeneous source distribution is assumed and (weakly) 2D air motions leading to flow convergence/divergence occur at length scales much larger than the tower footprint. Because this debate is motivated by a need for conservation of mass in surface-air exchange measurements, which is unfortunately not apparent in some field studies, arguments will need to be both practical and theoretically sound.

The main point of dispute is the assumption about horizontal advection (assumption 'b'). This assumption and assumptions 'a' and 'c', critiqued by Finnigan, are made in almost all observational studies of surface-air exchange. This emphasizes the need to examine them critically. Lee (1998) separates total advection into horizontal and vertical (or mass flow) components and postulates that vertical advection is generally the dominant one at sites where the usual flux observational criteria are met. However, it is understood that horizontal advection is not always much smaller than vertical advection. For example, horizontal advection is not negligible near the boundary where there is an abrupt change in the surface source strength (poor fetch; e.g., Mahrt et al., 1994; Sun et al., 1998), or at places where a large horizontal gradient of the scalar concentration exists in response to heteorogeneous surface source distributions (Raupach et al., 1992).

Finnigan uses thought experiments and the results of a linear analysis of neutrally stratified flow over hills (Raupach et al., 1992) to illustrate how the concentration field might respond to flow convergence/divergence. The mechanisms he has identified offer valuable guidance for future observational and modeling studies of the advection problem. There are, however, a number of points in need of clarification from the perspective of real atmospheric flows:

(1) The experimental goal is to quantify the surface flux, $(\overline{w'c'})_0$ by measurements of the eddy flux, $(\overline{w'c'})_r$ at height z_r above the surface. (As with Finnigan, the canopy source is ignored here for simplicity.) Any systematic deviation of the latter from the former represents a bias that must be handled properly. It is important to remind the reader that the measurement height is usually within the lowest portion of the 2D

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flows (e.g., much lower than the vortex center of Fig. F1, where prefix F denotes figure or equation numbers in Finnigan, and within the inner layer of Raupach et al. (1992)), where the vertical concentration gradient is at a maximum. Hence discussion should be limited to this layer.

(2) One way to interpret the hypothetical circulation pattern in Fig. F1 is to use it as a model for land-sea breezes. As with any other thermal circulations, their location is quite predictable because they are locked to a particular pattern of landscape heterogeneity. Vertical advection exists at the vertical stagnation streamlines, which can extend as far as 20 km inland. The vortex center is located approximately above the shoreline (surface source discontinuity). Directly below the vortex center, a horizontal concentration gradient will develop due to the source discontinuity and convection of isoconcentration lines. Obviously, sites very close to the shoreline are not ideal for flux monitoring. By obeying the conventional site selection criteria (e.g., 1 : 100 instrument height to fetch ratio) one may be able to minimize horizontal advection but not vertical advection.

(3) The patterns depicted in Figs. F1 and F2 bear some resemblance to flow in the convective atmospheric boundary layer. A great number of experimental studies have experienced difficulty in achieving energy balance closure when the site is under the influence of stationary cell-like convection. The evidence in Lee (1998) shows that vertical advection (or mass flow) is a major cause of the problem. Horizontal advection is unlikely to play a dominant role because of the low ambient wind speed. If the convection cells propagate past the flux tower at a reasonable speed so that both updraft and downdraft motions are adequately sampled, then the mean vertical velocity should vanish and no mass flow effect will be detected. Under strong ambient wind conditions, we can easily achieve energy balance closure and obtain well-behaved fluxes of other scalars (e.g., CO_2) in the field, which suggests (1) that horizontal advection is not important, and (2) that mass flow correction is not significant either, possibly because strong mechanical turbulence prevents the cell-like convection from taking shape and greatly reduces the vertical concentration gradient.

(4) It is difficult to draw general conclusions from the study by Raupach et al. (1992), for three reasons: (a) The focus of Raupach et al. (1992) is the effects of low hills upon scalar fields. Their results are not cast in a form to allow a quantitative comparison of the two advection terms. (b) Large variations in the surface source strength, primarily due to variations in the incident solar radiation along a curved slope, are included in their computations, leading to non-negligible horizontal (along-slope) advection. The slope in the model domain is quite steep (elevation gain of 100 m within 500 m distance) from the viewpoint of selecting sites for surface-air exchange studies. (c) It is important to be aware of the approximations and assumptions in linear analyses of the Jackson and Hunt's type, as discussed by Jackson and Hunt (1975) and Raupach et al. (1992). One limitation is the inviscid assumption (i.e., zero eddy diffusion) for the outer layer. Another limitation is that the linear theory is valid only in the range $10^4 < L/z_o < 10^7$, where L is the characteristic length of the hill and z_o is the surface roughness. Given a typical value of 1.5 m for z_o for forest vegetation (the primary focus of Lee), this requires $L > 15$ km. Obviously at such a large spatial scale, thermal effects can no longer be ignored and full-scale investigations with mesoscale models are needed.

(5) The question about whether inclusion of vertical advection can improve NEE assessment is an important one. (Along a line of reasoning similar to Finnigan, concern should also be expressed about whether addition of the air storage (term 1 on RHS of Eq. F2.7) to the eddy flux, a standard practice adopted by all research groups, can improve energy and carbon budgets, because the time rate of change in the concentration can result from advection.) A full answer to the question cannot be provided by examination of the flow field alone because direct comparison of the advection terms requires realistic simulations of both the flow and concentration fields. There is experimental evidence in Lee (1998) to support the postulation that, at sites far away from the surface source discontinuity, inclusion of vertical advection can improve the energy budget. Further tests of the postulation are now possible with data obtained at a single tower since horizontal advection can be estimated as the residue from the mass/temperature conservation and energy balance equations, assuming that all other terms in the equations can be measured with sufficient accuracy.

Finnigan raises the possibility that the scalar concentration field may adjust to flow convergence/divergence so that 'double-counting' may be introduced into the NEE assessment if only correction for the mass flow is made. There is little evidence from numerical studies of mesoscale flows (Taylor et al., 1998; Pinty et al., 1989; Pielke et al., 1991; Schilling, 1991; Segal et al., 1991) to suggest such an adjustment effect. These studies show that a detectable horizontal scalar concentration (temperature in most instances) gradient is limited to the vicinity of the surface source discontinuity. Further away where the flow convergence/divergence rate is largest (and hence the adjustment effect should be largest), little, if any at all, horizontal gradient can be found.

Let us now turn attention to the averaging procedure. Lee's vertical integration recognizes the fact that all micrometeorological observations are made at a single point. In Finnigan's procedure, the mass conservation is integrated over a control volume lying within the tower footprint. It is an accepted view that tower-based observations are representative of horizontal averages over the upwind footprint. Spatial and temporal integrations are hailed as a major advantage of micrometeorological techniques over other techniques (Baldocchi et al., 1988; Dabberdt et al., 1993). Since the tower footprint is much smaller than the 2D motions, the vertical integration should be a good approximation that allows us to capture the two major terms (storage and mass flow) contributing to the vertical flux in a practical way. However, the mismatch in footprints of the mean vertical velocity, the profile of scalar concentration and the eddy flux will introduce uncertainties. This is an unavoidable stochastic aspect of the micrometeorological techniques and contributes to the reasons why accuracy of the techniques is limited, a point brought out clearly by Finnigan's analysis.

In conclusion, the critique of Finnigan significantly advances the adevection debate but it does not invalidate Lee's original analysis. Further, two particularly important points emerge from this debate, namely: (1) careful site selection cannot guarantee an absence of advection because flow convergence/divergence can occur at scales much larger than the scale of micrometeorology; (2) Advection can bias long-term flux observations because diurnal variations in the mean vertical velocity can be systematic. It is our hope that the analyses by Finnigan (1999) and Lee (1998) will stimulate more numerical and experimental investigations of the advection problem.

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References

Baldocchi, D.D., Hicks, B.B., Meyers, T.P., 1988. Measuring biosphere-atmosphere exchange of biologically related gases with micrometeorological methods. Ecology 69, 1331–1340.

Dabberdt, W.F., Lenschow, D.H., Horst, T.W., Zimmerman, P.R., Oncley, S.P., Delany, A.C., 1993. Atmosphere-surface exchange measurements. Science 260, 1472–1481.

Finnigan, J.J., 1999. A comment on the paper by Lee (1998): 'On micrometeorological observations of surface-air exchange over tall vegetation'. Agric. For. Meteorol., this issue.

Jackson, P.S., Hunt, J.C.R., 1975. Turbulent wind flow over a low hill. Q. J. R. Meteorol. Soc. 101, 929–995.

Lee, X., 1998. On micrometeorological observations of surface-air exchange over tall vegetation. Agric. For. Meteorol. 91, 39–49.

Mahrt, L., Sun, J., Vickers, D., MacPherson, J.I., Dejardins, R.L., 1994. Observations of fluxes and inland breezes over a heterogeneous surface. J. Atmos. Sci. 51, 2484–2499.

Pielke, R.A., Dalu, G.A., Snook, J.S., Lee, T.J., Kittel, T.G., 1991. Nonlinear influence of mesoscale land use on weather and climate. J. Climate 4, 1053–1069.

Pinty, J.-P., Mascart, P., Richard, E., Rosset, R., 1989. An investigation of mesoscale flows induced by vegetation inhomogeneities using an evapotranspiration model calibrated against HAPEX-MOBILHY data. J. Appl. Meteorol. 28, 976–992.

Raupach, M.R., Weng, W.S., Carruthers, D.J., Hunt, J.C.R., 1992. Temperature and humidity fields and fluxes over low hills. Q. J. R. Meteorol. Soc. 118, 191–225.

Schilling, V.K., 1991. A parameterization for modelling the meteorological effects of tall forests – a case study of a large clearing. Bound.-Layer Meteorol. 55, 283–304.

Segal, M., Garratt, J.R., Pielke, R.A., Ye, Z., 1991. Scaling and numerical model evaluation of snow-cover effects on the generation and modification of daytime mesoscale circulations. J. Atmos. Sci. 48, 1024–1042.

Sun, J., Desjardins, R., Mahrt, L., MacPherson, I., 1998. Transport of carbon dioxide, water vapor, and ozone by turbulence, and ozone by turbulence and local circulations. J. Geophys. Res. 103D, 25873–25885.

Taylor, C., Harding, R.J., PielkeSr., R.A., Vidale, P.L., Walko, R.L., Pomeroy, J.W., 1998. Snow breezes in the boreal forest. J. Geophys. Res. 103D, 23087–23101.