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AN INTRODUCTION TO FLUX MEASUREMENTS IN DIFFICULT CONDITIONS

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Abstract. The origins of the aerodynamic techniques now widely used at sites around the world to measure continuous biosphere–atmosphere exchange of carbon and energy are briefly reviewed. A survey of the current state of this approach concludes that the technique often fails when standard analysis routines are applied to data from single towers in complex flows. In the daytime, problems are signaled by failure to close the surface energy balance because turbulent energy fluxes are routinely underestimated. Complex flows are more prevalent at night when they lead to failure to measure all the respired CO_2. At such times, the aerodynamic methodology is commonly supplemented by biological models. A set of papers from a workshop on "Flux Measurements in Difficult Conditions" held at the National Center for Atmospheric Research (NCAR) in January 2006 are introduced next. Two papers review the causes and magnitude of these flow-based problems. Four papers describe intensive field experiments that detail the mechanisms that cause problematic complex flows. These experiments show, inter alia, that the technique of replacing nighttime eddy flux measurements by biological models can also be systematically biased. Finally, two model studies are used both to illustrate the physics behind these complex flows and to motivate an approach to systematic correction of single-tower results.

Preamble

There is disturbing recent evidence that the terrestrial and oceanic sinks for CO_2 are weakening. Together with increasing world economic activity and the increased carbon intensity of this activity, this is leading to trajectories of greenhouse gas concentrations in the atmosphere that are now tracking the upper limit of the Intergovernmental Panel on Climate Change (IPCC) range of scenarios (Canadell et al. 2007). These findings add extra urgency to the work of terrestrial ecologists concerned with the carbon cycle, who for at least 20 years have focused on the location and dynamics of the terrestrial carbon sink and its likely future trajectory in a greenhouse world. While the behavior of the carbon cycle on the continental scale can be quantified by large-scale atmospheric inversion techniques, understanding of its detailed dynamics on land relies on measurements of high temporal resolution at a spectrum of representative biomes. This has been the driving force behind the growth of the FLUXNET.

The FLUXNET (Baldocchi et al. 2001) is an international network of over 450 towers used to measure the exchanges of carbon dioxide, water vapor, and energy between the biosphere and the atmosphere. It employs methods based on direct measurement of the turbulent or "eddy" flux of these quantities using fast-response instruments. At the spatial scales represented by tower measurements, the vertical exchange between ecosystems and the atmosphere has three components: the turbulent or eddy flux, the mean or advective flux, and molecular diffusion. Molecular diffusion is negligible except very close to leaf and soil surfaces and is often included in the specification of the source or sink strength. In the ideal steady, horizontally homogeneous flows for which the approach was first developed, only the eddy flux is important and so this term is often used to describe tower-based exchange measurements even when advective fluxes are important. A more accurate and inclusive term is the *aerodynamic* approach and that is what we will use throughout this paper.

These methods allow the daily cycle of ecosystem exchange to be tracked for years in succession but only over "tower patches," each a few hectares in size. However, the explosive growth in the FLUXNET in the last few years means integration of hundreds of sites spanning biome and climate space is going a long way to redressing this shortcoming. One consequence, though, of this rapid growth in the FLUXNET has been the need to cope with complex flows at the towers as few sites are located in the ideal flat homogeneous terrain of the textbooks. Complex flows can lead to systematic distortion of the results obtained from these towers unless standard analysis routines can be corrected. Understanding the basis for such corrections was the motivation for a workshop on "Flux Measurements in Difficult Conditions" that was held 26–28 January 2006

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in Boulder, Colorado, USA, and is the theme of this Invited Feature in *Ecological Applications*.

A Short History

It was in the early 1960s that researchers interested in measuring the exchange of energy and biologically important trace gases between plants and the atmosphere first began to employ aerodynamic methods on a regular basis (e.g., Penman and Long 1960). The basic idea was that by measuring the turbulent flux of heat, water vapor, CO_2, or momentum at some distance above a plant canopy, scientists could avoid the crippling sampling problems they faced when aggregating measurements on individual leaves or from small patches of soil. Instead, they realized, the spatial averaging inherent in atmospheric turbulence meant that a single measurement of the turbulent flux could provide the average biosphere–atmosphere exchange from an area of canopy equivalent to what we now call the instrument footprint. The problem was that direct measurement of the eddy flux of any of the properties they were interested in was difficult to impossible.

An indirect alternative was available, however. This was to assume the turbulent fluxes were proportional to the more readily measured gradients of mean concentrations. This analogy with molecular diffusion was already well developed in fluid dynamics. In micrometeorology, it was combined with assumptions of similarity between transfer of momentum and scalars (e.g., Lemon and Wright 1969) or just between the different scalars, the so-called Bowen ratio approach, (e.g., Brown and Covey 1966) to provide the first aerodynamic methods of surface exchange measurement. Unfortunately, despite their widespread adoption, problems with these "gradient–diffusion" approaches were soon apparent (Raupach 1979) and the search continued for ways to measure the turbulent fluxes directly.

Practical methods started with three-dimensional propeller anemometers and fast-response temperature sensors, but, by the late 1960s, sonic anemometers with their much smaller measuring volume and much greater frequency response were becoming the instruments of choice. Early, continuous-wave sonics, however, were prone to serious drift of their mean levels and required constant attention to maintain in operation. As a result, their use was confined to intensive field campaigns. Analogous problems bedeviled the first rapid-response "open path" scalar sensors, which appeared in the 1970s and which relied on absorption of an infrared beam by H_2O or CO_2 molecules, but their promise was such that, by the mid 1980s, the future of surface-exchange measurements was clear. Continuous improvements in the accuracy and reliability of open path and closed path scalar sensors and especially of sonic anemometers continued through the 1980s, and by the end of the decade eddy flux systems were being used for continuous diurnal measurements of momentum, energy, and trace gasses in major campaigns like HAPEX and BOREAS (Andre et al. 1988, Sellers et al. 2002).

In its early incarnations, this aerodynamic methodology was confined to steady conditions at sites chosen for their horizontal homogeneity. Under these conditions, the vertical turbulent flux fairly close to the surface could be equated to the surface–atmosphere exchange. Experiments conducted in "campaign mode" allowed weeks of data to be rifled to find periods corresponding to such canonical conditions as in the famous Kansas and Minnesota experiments (Kaimal and Wyngaard 1990). As the technique was extended to track exchange with the biosphere over the diurnal cycle, it was necessary to cope with non-stationarity of the eddy flux. This was manifested as changes in the total concentration of scalar in the air layer between the sensor and the surface, which meant that the vertical eddy flux at the sensor no longer equaled the surface exchange. This was particularly important when measuring over tall canopies such as the northern forests that were the focus of BOREAS. Measuring this "storage" term by an array of concentration sensors on the tower then became an essential complement to the eddy flux sensor even at horizontally homogeneous sites.

Over the last decade, the aerodynamic technique has become widely regarded among ecologists as a "turnkey" system and is being adopted worldwide to make continuous measurements of land–atmosphere exchange from a wide range of biomes. Currently there are more than 450 sites registered on the FLUXNET database (*available online*).[2] Clearly, the investment in this technology is enormous whether measured in dollars or in personnel. The motivation for this massive effort is the need to understand and quantify the terrestrial carbon and water cycles and their likely future under climate change. These tower-based measurements provide one of the three pillars upon which rests our understanding of the atmospheric pathway in the terrestrial carbon cycle. The others are large scale concentration inversions and biomass assays. Ideally, we would like these three methods, which operate naturally on different time and space scales, to be independent so that we can use them to triangulate gaps in our understanding. At the moment, however, we cannot separate biomass assays and models from aerodynamic measurements.

The State of Eddy Flux Measurement

Given the widespread adoption of the aerodynamic approach, we could be forgiven for assuming that any serious problems in the technique were well understood and had either been eliminated or that correction procedures were readily available. This is far from the case! To explore this statement, it is useful to divide the kinds of problem encountered at the average flux tower

[2] ⟨http://www.fluxnet.ornl.gov/fluxnet/index.cfm⟩

site into three groups: instrumental, operational, and flow based. Instrumental problems include such matters as relative placement of sonic anemometer and scalar sensors, frequency losses when drawing air to closed path sensors down long tubes, and the "Webb, Pearman, Leuning" (henceforth, WPL) corrections required for open path sensors (Webb et al. 1980, Fuehrer and Freihe 2002, Massman and Lee 2002, Leuning 2004). Operational problems are exemplified by the need for gap filling when data records are incomplete either because of scheduled interruptions for calibration or unplanned outages like rain or lightning strike. Flow-based problems are more fundamental as they go to the heart of the aerodynamic approach. They result from those departures from horizontal homogeneity and stationarity that mean that the surface exchange cannot be equated to the sum of eddy flux and storage terms.

All three types of problem were comprehensively discussed in a workshop held by Ameriflux in Corvallis, Oregon, USA in 2002 and whose proceedings were subsequently published as Lee et al. (2004*b*). At that workshop, the key questions in the first two groups were clearly set out and, if they were not all answered, a program for the community to address them was clear. In contrast, although the workshop exposed the third set of problems to the light, the path toward solving them was not clear nor was the severity of the problems universally accepted. This remains the case today despite the fact that the focus of the FLUXNET community has moved on. Annual meetings of the main FLUXNET subgroups, Ameriflux, Carbo-EuroFlux, and Asia Flux have concentrated on biological and ecological interpretations of measurements from groups of sites rather than on fundamental questions of technique. This has been possible because sites where aerodynamic measurements are complemented by extensive biological measurements, sometimes termed "super sites," can combine the two and avoid using questionable data from the flux tower, at least when such data are recognized. Such fusion of data from the different sources is now becoming very sophisticated with advanced data assimilation approaches being employed by leading researchers (e.g., Braswell et al. 2005, Williams et al. 2005, Sacks et al. 2006).

Unfortunately, most of the sites in the FLUXNET, particularly the new ones that are responsible for its recent explosive growth, do rely almost exclusively on the eddy flux measurements so that solving the kind of flow-based problems discussed at Corvallis remains of fundamental importance. Even at sites where obviously unphysical data can be replaced by biological models carefully calibrated to the site, the possibility of systematic bias in the tower data cannot be ignored. Two key indicators signal the possibility of such bias: the inability to close the daytime energy balance and the underestimation of nighttime respiration. Both of these problems are endemic at tower sites in forest canopies and, as we shall see below, both are ultimately a result of flow fields that contradict the assumption of horizontal homogeneity implicit in the standard analysis framework.

Recognizing that the attention of most in the FLUXNET community had moved on from these rather fundamental questions of technique at just the time when it was experiencing its most rapid growth, a workshop on "Flux Measurement in Difficult Conditions" was convened at the National Center for Atmospheric Research (NCAR), in Boulder, Colorado, in January 2006. This workshop was sponsored by NCAR and the Integrated Land Ecosystem Atmospheric Processes Study (iLEAPS) program of the International Geosphere Biosphere Program (IGBP). A brief description of the workshop can be found in Finnigan et al. (2006). This Invited Feature of *Ecological Applications* contains a selection of papers developed from presentations at the workshop and is intended to highlight the nature and importance of problems with flux measurements caused by complex flows and to set out a research agenda to address them.

The papers that follow fall into three groups. First are two reviews that set out both the evidence for and the significance of the two main symptoms of flow-induced errors. Foken surveys the magnitude and causes of lack of energy balance closure while Aubinet analyzes the problems of measurement in nocturnal stable conditions and the underestimation of the flux of respired CO_2. Next come three papers that quantify these problems at three contrasting forest sites: a European deciduous forest (Kutsch et al.), a subalpine conifer forest (Yi et al.), and a tropical rain forest (de Araujo et al.). A fourth experimental study by Detto et al. discusses in detail the kind of problem typically encountered at a complex site. Following this, we look at the help that modeling can provide, both through insights into the processes at work in complex flow conditions and by providing a basis for corrections. First, Belcher et al. use analytic approaches to derive general rules to describe flows through forest edges and over hills under a wide range of atmospheric conditions and finally, Sogachev et al. model the flow and CO_2 transport into and out of forest edges and nonuniform tall canopies.

Energy Balance Closure

The energy balance of a canopy–soil layer below some measurement height h is conventionally written as

$$R_n - G - P = H + \lambda E \tag{1}$$

where R_n is the net radiation passing through a horizontal plane at the sensor height, h, G is the flux of heat into storage in the plant and soil (plus the small amount stored in the air layer below h), P is the radiation used up in photosynthesis (P is typically $\sim 0.01 R_n$ and is usually neglected in the energy balance), H is the eddy flux of sensible heat, and λE the eddy flux

of latent heat away from the surface with E the flux of water vapor and λ the latent heat of vaporization.

As Foken (2008) discusses, at most sites where the energy balance is measured, the right-hand side of Eq. 1 is typically 25% smaller than the left-hand side. Once problems with instrumentation and experimental design are eliminated, this discrepancy can only be caused by systematic overestimation of $R_n - G$ or underestimation of $H + \lambda E$. While some very recent reanalysis of the energy balance (Haverd et al. 2007) has suggested that at tall forest sites the contribution to G from biomass storage may be more important than has been realized hitherto, Foken shows that, overall, the problem must almost certainly lie in an underestimation of the turbulent energy flux terms. By comparing data from a series of sites, he is able to suggest three possible causes for this: failure to count the contribution from low-frequency turbulent eddies; large-scale circulations locked into the landscape by contrasts in the surface energy balance (the so-called "inland sea breezes"), and advection. While it is difficult to see why local circulations would always lead to an underestimation of $H + \lambda E$ and the same could be said about advection, the fact that in heterogeneous landscapes most towers are placed on hill tops rather than in valleys may induce a systematic bias in such processes.

The failure to count the contribution from low-frequency eddies is now well attested as one cause of lack of closure (Finnigan et al. 2003, Malhi et al. 2004). Indeed, the fact that very low-frequency motions can be "active" in scalar and momentum transfer from near the surface has recently been recognized in several other contexts in boundary layer studies (McKeon and Sreenivasen 2007) and is prompting a re-evaluation of the universality of Monin-Obukhov scaling formulae (Hogstrom et al. 2002). The problem is exacerbated when measurements are made above a porous canopy well above the solid surface. An immediate problem for eddy flux measurements is that the period of "eddies" that contribute significantly to $H + \lambda E$ can be up to four hours (Finnigan et al. 2003), which not only compromises our ability to resolve the diurnal cycle but also blurs the distinction between the eddy motions, which we treat statistically as "turbulence," and the mean flow field, whose role in producing advective fluxes we treat deterministically.

Since failure to close the energy balance closure is a diagnostic of methodological failure, we must recognize as Foken points out, that underestimation of $H + \lambda E$ resulting from such errors signals a comparable underestimation of the daytime assimilation flux.

Nighttime CO_2 Fluxes

The underestimation of total exchange fluxes under nighttime stable conditions is the largest single obstacle to routine calculation of daily and seasonal source–sink strengths at FLUXNET sites. Recognition of the general failure of flux towers to measure realistic respiration fluxes prompted the introduction of the u_* filter (Goulden et al. 1996). Low values of the friction velocity, u_*, above the canopy are taken as an indication that the aerodynamic method is unreliable and respiration is calculated instead using biological models. These models are calibrated against chamber measurements or times when u_* is high and the aerodynamic method is believed to be working, a procedure with obvious circularity and one that has recently been shown to lead to real bias (Kutsch et al. 2008, Yi et al. 2008). Given that underestimation of respiration can lead to unrealistically high values of net ecosystem exchange (NEE), this is a serious and fundamental problem of the aerodynamic approach. It is most serious in tropical forests where growth continues all year and nights are long. There, it is too obvious to be ignored (Goulden et al. 2006). The degree of bias in temperate forests, however, where results may be wrong but not unrealistic, is unknown.

In this Invited Feature, the various factors contributing to underestimation of respiration are reviewed by Aubinet (2008), who concludes that three processes are to blame: intermittency, advection, and drainage flows; the two latter being intimately coupled in nighttime stable conditions.

Intermittency is a defining feature of very stable conditions in the atmospheric boundary layer (Finnigan 1998). Very stable conditions are characterized by gradient Richardson numbers that are, on average, much larger than one but which can be temporarily reduced to less than the critical value of around 0.25 by features like Kelvin Helmholtz waves, whose origins lie well above the surface, or by oscillations in the nocturnal jet. (A value of gradient Richardson number, Ri of $\sim$0.25 is taken as the limit of sustained turbulence. For $\mathrm{Ri} < 0.25$, turbulence gains energy from the mean shear faster than it loses it to damping by buoyant forces. For $\mathrm{Ri} > 0.25$, buoyant damping dominates and turbulence collapses.) In complex topography, these processes may also be modulated by interaction with hills and valleys. These features can produce patches of active turbulence, which are localized in time and space, thereby violating any assumptions of stationarity or homogeneity that are included in the data analysis process. Even in horizontally homogeneous conditions, the sub-canopy airspace may be vented by spatially random, localized events that are not captured by the tower or that, if they were captured, would bias the results. At this moment, we do not have any basis for calculating long-term biases in tower budgets that might be induced by such intermittent transfer events but it is a study that is long overdue.

Before proceeding to discuss advection, it is perhaps useful to clarify the problem advective fluxes pose. The mass balance for an arbitrary scalar of density c in an averaging volume of length $2L$, width $2L$, and height h equal to the sensor height can be written as follows:

$$\int_{-L}^{L}\int_{-L}^{L}\int_{0}^{h}\left(\underset{1}{\frac{\overline{\partial c}}{\partial t}}+\underset{2}{\bar{u}\frac{\partial \bar{c}}{\partial x}}+\underset{3}{\bar{v}\frac{\partial \bar{c}}{\partial y}}+\underset{4}{\bar{w}\frac{\partial \bar{c}}{\partial z}}+\underset{5}{\frac{\partial \overline{u'c'}}{\partial x}}+\underset{6}{\frac{\partial \overline{v'c'}}{\partial y}}+\underset{7}{\frac{\partial \overline{w'c'}}{\partial z}}\right)dz\,dy\,dx=\underset{8}{\iint_{S(h)} J_c\,dS}. \quad (2)$$

The x coordinate is aligned with the mean wind, $\bar{u}$, at the flux tower; y is the crosswind and z the vertical (surface normal) direction with corresponding mean velocity components $\bar{v}$ and $\bar{w}$; u', v', and w' are the turbulent fluctuations around these mean values; while $\bar{c}$ and c' are the corresponding scalar quantities. The overbar denotes a time and space average so that local variations of quantities in the complex geometry of the inter-canopy airspace are smoothed out (Finnigan 1985, Raupach et al. 1986). The right-hand side of Eq. 2 represents the total flux of scalar c from the plant and soil surfaces into the inter-canopy airspace. It consists of the integral of the local flux density, $J_c(x, y, z)$ across the surface $S(h)$, which comprises all the plant–air and plant–soil interfaces contained in the averaging volume $4L^2h$.

Note that the "advective" flux terms (terms 2, 3, and 4 of Eq. 2) are written in the conventional form, e.g., as

$$\bar{u}\frac{\partial \bar{c}}{\partial x}.$$

Recently, Kowalski and Serrano-Ortiz (2007) have argued that these mean flux divergence terms should be written in the *flux* form, e.g., as

$$\frac{\partial \bar{u}\bar{c}}{\partial x}$$

in order to avoid problems with the "WPL" terms for trace gases at low concentration, such as CO_2 (Webb et al. 1980, Fuehrer and Freihe 2002). While the flux form is correct, in most circumstances, the difference between the two forms should be very small. However, adopting the flux form for field measurements, where the vertical and horizontal advection terms are evaluated separately from profiles on different towers, leads to substantial practical problems, so here we will continue to use the conventional form.

The fundamental problem posed by advection at most flux sites where only a single tower is deployed, is that measuring horizontal advection (terms 2 and 3 of Eq. 2) requires us to measure horizontal gradients of mean wind speed and concentration. This is impossible from a single tower. Furthermore, while the vertical advection term (term 4 of Eq. 2) can, in principle, be measured on a single tower, in practice this is very difficult to do because the measured vertical velocity, $\bar{w}$ is extremely sensitive to the choice of coordinate alignment (Finnigan 2004*a*, Lee et al. 2004*a*) and it multiplies the large vertical scalar gradient, $\partial\bar{c}/\partial z$, amplifying any error. To make matters worse, vertical advection is of little use on its own as it is often of opposite sign to the horizontal advection and, therefore, partly cancelled by it. The horizontal divergence of the eddy flux (terms 5 and 6 of Eq. 2) is usually assumed on scaling grounds to be smaller than the advective flux divergence and is often ignored (Finnigan 2004*b*).

Advection can occur both in daytime and nighttime, if the canopy source–sink is spatially heterogeneous or is located on hilly country. The most striking differences are between night and daytime conditions. In particular, it is clear that sites in gentle terrain, while they suffer little advection during the day when turbulence is strong, can be severely affected by advection caused by drainage flows at night. An idea of the relative magnitudes of daytime and nighttime advection at a complex terrain site is given by the measurements of Feigenwinter et al. (2004) or Marcolla et al. (2005), who found that at midday, advective fluxes were about 10% of the eddy flux but by two or three hours after sundown they became the dominant term in the mass balance, Eq. 2, being about four times larger than the eddy flux plus storage (terms 1 and 4 of Eq. 2).

Advective distortion of the computed biosphere–atmosphere flux during the day is likely to be more important for CO_2 than for heat or water vapor because the complicated within-canopy flow field can interact with the contrast between the upper canopy assimilation sink and the soil respiration source (Katul et al. 2006). Such model calculations warn us that even moderate topography or canopy heterogeneity, while having little effect on the true net ecosystem exchange (NEE), can lead to large localized advective contributions to the total mass balance, Eq. 2. In *Models and Measurements*, we discuss models of flow and transport that can be used to test a site for its propensity for advective fluxes and their magnitude relative to the eddy flux.

As a guide to experimentalists who wish to identify anomalous nighttime data, Aubinet (2008) has classified nighttime advective flows into five categories according to whether the windfield is converging (accelerating), diverging, or horizontally homogeneous and whether the canopy source–sink strength is increasing or decreasing in the windward direction. He has linked the convergence or divergence of the windfield to categories of stable flows proposed by Mahrt (1982). Using this scheme, he has been able to classify published advection experiments providing a useful illustrative guide to understanding and interpreting such flows.

There is steadily accumulating evidence that nighttime advection caused by drainage flows is the root cause of the failure to capture the respiration flux in stable conditions at night. Cold air anomalies have been observed to be co-located with low points in the landscape at such times (Goulden et al. 2006). Nighttime flows within the canopy are always downslope once they have become established (e.g., Aubinet et al. 2003,

Marcolla et al. 2005, Staebler and Fitzjarrald 2005). The velocity profiles of the within-canopy flows take on the characteristic wall jet shape of gravity currents (Prandtl 1942, Watanabe 1994). These drainage flows appear sometime after the collapse of the turbulence within the canopy soon after sundown. This collapse has two effects. First it accelerates the cooling of the within-canopy air layer as radiative heat loss cannot be redressed by an efficient downward turbulent heat flux. Second, as turbulent momentum exchange into the canopy falls, the canopy air layer becomes dynamically uncoupled from that above. This is typically signaled by horizontal shear at the canopy top, the airflow above going in the synoptically forced direction and that within the canopy flowing downslope (e.g., Marcolla et al. 2005, Staebler and Fitzjarrald 2005).

As well as dynamically uncoupling the canopy layer from the boundary layer above, collapse of the turbulence means that respired CO_2 no longer diffuses vertically past the eddy flux sensor. Instead, it accumulates in the sub canopy airspace and is registered as a storage term (1 of Eq. 2) or is advected sideways as a drainage current develops, which occurs as the cool air layer in the canopy moves downslope under the influence of gravity. We will say more in *Models and Measurements* about the physical mechanisms that control this process but first it is instructive to consider what we have learned from the four detailed field experiments reported in this special issue.

Yi et al. (2008) measured all the terms in Eq. 2 using up to four profile and flux towers at the Niwot Ridge Ameriflux site, an elevated (3050 m above sea level) subalpine conifer forest on the flank of a mountain ridge. They were able to compute the full mass balance for six years in succession. As already noted at other sites, the rule on stable nights was turbulence collapse, followed by decoupling and downslope flow in the canopy whatever the direction of the above-canopy flow. There were also large systematic differences between the six-year NEE calculated from all the terms in Eq. 2 and NEE calculated by the "biological" method, where periods with low u_* were replaced by model results calibrated at times of higher u_*. The reason was that even when u_* was relatively high at the level of the sonic anemometer above the canopy, advection in the canopy was still significant. As a result, filling the nighttime, low u_* gaps using the biological model overestimated NEE by 65%.

Kutsch et al. (2008) compared direct measurements of advection with a biological model calibrated to their Carbo Euroflux site, at Hainich, Thuringia, Germany. The site is a deciduous forest in moderately complex terrain. They also found decoupled flow at night and that nighttime (low u_*) advection was much stronger than during the day and was directed increasingly downslope as u_* fell. Also, like Yi et al., they found that advection still continued within the forest at night even though u_* values on the tower above the canopy were high and that this was liable to give rise to a bias when the u_* filter method was employed.

The third experimental study by de Araujo et al. (2008) concentrated on measuring the CO_2 concentration field in a tropical rain forest near Manaus, Brazil, through the wet and dry seasons. Advection was not measured directly in this case but could be qualitatively inferred. The area studied was much larger than the tower patch scale measurements of the two previous experiments. The most striking finding was the non-locality of the exchange in this plateau–slope–valley topography. CO_2 drained from the plateau during the night and accumulated in the valleys, from which it was not flushed until mid-morning. Clearly, accounting for the regional exchange at this site requires an analysis framework which recognizes the great complexity of the regional flow field.

The final field experiment focused not on the carbon balance but on the complexity of the flow field that develops behind a forest edge and exemplifies the kind of problem faced when trying to get representative flux measurements in forest clearings. Using an array of three-dimensional sonic anemometers, Detto et al. (2008) were able to show that when the canopy is sufficiently dense, the flow downwind of the forest alternates between either flowing through the canopy into the clearing or flowing over the rear edge of the canopy, separating, and forming recirculating eddies in the lee of the trees. The first situation is that assumed in models like those of Belcher et al. (2008) and Sogachev et al. (2008) and generates negative vertical velocities just above the canopy while the second produces recirculating eddies in the separated flow region similar to those seen behind solid backward-facing steps.

Simple models based on the development of internal boundary layers after roughness changes are often used to calculate how far downwind a tower must be placed for flow to have adjusted to a new surface (Kaimal and Finnigan 1994). Very dense canopies tend to have lower effective roughness than more open ones because a canopy's capacity to absorb momentum peaks at some intermediate density Seginer (1974). These results show, however, that the large eddies that develop behind a dense canopy can delay the adjustment of the flow to the smoother surface for a considerable distance compared to what a naïve calculation based on a simple comparison of roughness lengths would indicate.

A conclusion common to these four studies and to all the others that have measured advection in the field directly is that even with many towers and instruments deployed, the estimation of the advective flux is subject to large errors. Experience is telling us that it is impossible to employ direct measurement of advection as a routine procedure at sites with complex flow fields. If direct measurement were the only option available, this would be a conclusion that cast major doubt on the program to use eddy flux towers to understand the terrestrial carbon sink as most sites seem to be plagued

by complex flows at night, if not by day. There is, however, an alternative path. A great deal of knowledge of the way complex canopy flows behave can be encapsulated in mathematical models. These models automatically satisfy conservation laws of mass, energy, and momentum and, over the last few years, considerable strides have been taken in merging advances in understanding of the mechanics and modeling of canopy turbulence with that of flow over topography and over complex surfaces.

Models and Measurements

A detailed discussion of the role of mathematical modeling in surface flux measurement can be found in Finnigan (2004*b*). Here we restrict ourselves to brief remarks on three areas of application: (1) assessing the advection at a given site; (2) planning measurement strategies; and (3) data assimilation.

The models we are talking about are analytic or numerical solutions of Eq. 2 together with the momentum and continuity equations that determine the windfield that drives Eq. 2. When the models are used in the predictive mode implied by areas 1 and 2 in our list, we also need to specify the source distribution, $J_c(x, y, z)$, which may require solutions for the radiation field. The model described by Katul et al. (2006) provides one such example. Ideally, these models would be able to cope with arbitrary terrain, complex foliage distributions and a range of diabatic stabilities. They would resolve the flow both vertically through the canopy and boundary layer and horizontally. Their basic physics and parameterizations would be validated against extensive data sets. They would be simple to apply to any given site and should not require extensive calibration to individual sites. At the moment, no such models exist.

What is available is a limited number of models that calculate the windfield around rather simple two-dimensional topography or roughness changes and an even smaller number that also calculate scalar flow and transport. The models range in complexity from large eddy simulation (LES) models that are too computationally expensive to be applied generally (e.g., Patton et al. 1998), to very simple closure models that can be solved analytically (e.g., Finnigan and Belcher 2004). In between lie numerical solutions that can cope with more sophisticated turbulence closures and source distributions (e.g., Sogachev et al. 2002, 2008, Ross and Vosper 2005). It is fair to say that few of these models have been extensively validated. This is not surprising as there exist no appropriate data against which to compare them. In the field, we have a few limited data sets for flow around forest edges (e.g., Kruijt et al. 1995, Irvine et al. 1997) most of which report only the windfield, while there are no experiments yet available that track the development of the flow through a canopy on a hill. Results from wind tunnels are not much more useful. Again, there are windfield data around forest edges but no scalar data (Morse et al. 2002) and only one detailed experiment reporting the wind and turbulence in a tall canopy on a two-dimensional ridge (Finnigan and Brunet 1995).

Leaving aside for the moment the state of the modeling and validation effort, we can ask what we would use models for, if they were available. The first two purposes: assessing a given site for its propensity to advection and planning the measurement strategy at a site, including such things as tower placement or identifying wind directions that are likely to be problematic, are in many ways complementary. Data assimilation, the third purpose, requires more explanation and we will postpone this until we have discussed the two model studies reported in this issue. They represent two different approaches to simulating the complex flows found at tower sites.

Belcher et al. (2008) use analytic models with simple mixing length turbulence closures to investigate the mean wind and scalar fields around forest edges and over low two-dimensional hills. They also address the question of stable stratification and drainage flows on hills. The power of the analytic approach is illustrated by the way these models are able to clarify the physical processes underlying many of the observations we have already discussed and also to derive scaling arguments that can be used both to aid experimental design and, with appropriate caveats, give a first assessment of the likely size of advective fluxes. Starting with an analytic treatment of neutrally stratified flow into and out of forest edges, they derive length scales for the adjustment of the mean wind and scalar fields. These length scales are given in terms of fundamental canopy properties like leaf area distribution and drag coefficients and show for example that towers located too close to the forest boundaries will be subject to significant vertical advection. More fundamentally, they show that the scalar field adjusts to changes in canopy properties much more slowly than the windfield, placing stringent requirements on the homogeneity required of a site before scalar advection can be ignored a priori.

Neutrally stratified flow over a hill covered with a tall canopy is complicated because the perturbation pressure field generated by the presence of the hill penetrates the foliage easily whereas the turbulent shear stress that transfers momentum into the canopy from the boundary layer above is rapidly absorbed by the foliage. As a result, the airflow divides into an upper canopy layer, well coupled to the boundary layer, and a lower canopy layer, whose dynamics are set by a balance between foliage drag and pressure forces (Finnigan and Belcher 2004). The interaction between these upper and lower canopy flows produces strong vertical velocities out of the canopy behind the hill crest. When scalars are added, this translates into large advective fluxes, even on low hills. The situation is most severe for CO_2 during daylight, when the differing upper and lower canopy dynamics interact with assimilation in the upper canopy and respiration at the ground to maximize the advective flux.

Finally, Belcher et al. extend the analytic model to stable flow. First they show that the tenfold difference in adjustment lengths for momentum and heat in the canopy ensures that turbulence collapses in the canopy after sundown even though fully developed but stably stratified turbulence may continue all night in the boundary layer above. They go on to demonstrate that the resulting within-canopy momentum balance depends on the slope length but not its steepness, providing a possible explanation for the prevalence of nighttime advective drainage flows at sites where advection is negligible by day.

In contrast to the highly simplified analytic approach just described, Sogachev et al. (2008) investigate the flow around a forest edge using a so-called $k - \varepsilon$ turbulence closure. Unlike the methods of Belcher et al., theirs was able to accommodate complex vertical variations in the foliage density and in the source–sink of CO_2. In ways that are somewhat analogous to the way that different upper and lower canopy dynamics interact with the ground source and canopy sink of CO_2 on a hill to produce complex advective fluxes, the much slower adjustment of the air layers in the trunk space of their canopy as compared to the crown space led to complex patterns of advective and eddy fluxes. Their results showed the importance of the relative strengths of the ground source and canopy sink in producing "wavelike" patterns in the eddy flux extending a considerable distance downwind of the edge. The model of Sogachev et al. has been applied already to several different examples of complex terrain and is probably the most advanced of the candidate models available for assessing advection or planning measurements at a given site.

The third way to use models to aid measurements is through data assimilation. This is a technique that is highly developed in fields like astronomy and meteorology and has been largely responsible for continuing improvements in the reliability of numerical weather predictions. Data assimilation techniques are ultimately based on a Bayesian view of the relationship between models and experimental data. Prior knowledge is encapsulated in the model structure and is updated by the observations. This approach allows us to assign different confidence levels to the measurements and the model. More practically, it means that we can force the data to be compatible with a flow and transport model that explicitly includes advection and stability effects, always assuming that we have such a model. To put this statement in perspective, current single tower data analysis routines are *implicit* data assimilation schemes, where we force our data to be compatible with a one-dimensional flow and transport model that does not include advection. As we have seen, direct measurement of advection is costly and inaccurate. Data assimilation into appropriate three-dimensional flow and transport models is a much more efficient and objective way of supplying the extra information required to close advective mass balances.

A final comment is necessary before closing this discussion of the use of models. We have concentrated on small scale models that resolve the details of complex flows at the tower patch scale. In some cases, where the larger scale flow field is itself complex, such models may need to be embedded in larger scale boundary layer or mesoscale models. The flow fields around the Manaus site described by de Araújo et al. (2008) would typify such a situation.

Summary and Directions for Further Work

We have provided evidence for some systemic problems in aerodynamic flux measurements and noted that these are signaled by failure to measure properly the daytime energy budget and nighttime respiration flux. The nighttime problem is the more serious as it precludes computing daily NEE without supplementing the tower measurements with biological process models calibrated to the site. More worrying is the fact that careful assessment of this procedure at several sites shows that it can be subject to serious bias because of the failure of the u_* filter approach to signal the absence of advection in the canopy space. Furthermore, even though daytime measurements are generally more reliable, failure to close the energy budget because sensible and latent heat fluxes are undercounted is prima facie evidence that assimilation fluxes will be undercounted too. All this has meant that the powerful ability of the aerodynamic approach to resolve carbon and energy dynamics sub-diurnally can only really be realized at "super sites" where extensive cross calibration with other types of measurement is possible. The majority of sites in the rapidly growing FLUXNET network cannot command these resources.

One path to correcting tower measurements for these problems, all of which ultimately are a result of complex flow fields that are advective or intermittent in time or space, is to add information using appropriate models. Such flow and transport models can aid in experimental design and site selection as well as being the basis for correction procedures. In this sense, the advection classification scheme introduced by Aubinet (2008) can be viewed as a simple phenomenological model to aid experimental design and interpretation. The most efficient way to employ flow and transport models, however, would be to use them as vehicles for data assimilation, when they could be employed for routine correction once they were calibrated for a given site. At a more fundamental level, as we see in the papers presented in this invited feature, such models can illuminate the basic physics behind many of the surprising observations that have come out of the FLUXNET. Unfortunately, we do not yet have models suitable for general application nor do we have the data sets necessary to validate them. Both of these facts are a challenge to the flux measuring community.

What could we expect if we were able to apply ideal models to the range of sites now represented in

FLUXNET? First it is likely that we would identify a group of sites where the flow fields were so complex for so much of the time that obtaining reliable surface exchange measurements will never be possible. Two groups of sites might fall into this category. The first would obviously be those towers located in extremely complex terrain where three dimensional eddy and advective flux divergence fields are so complicated that, even with the best flow model, the number of measurements that would be needed would be prohibitive. The second group is less obvious. It would comprise those sites where spatial and temporal intermittency of transport is too large for us to have confidence that we can assemble enough realizations of exchange to reduce the error in ensemble NEE to a useful level.

Surprisingly, this group might include sites where the terrain is reasonably level at scales significantly larger than the tower footprint but where winds are typically light with strong convection. In such cases, the direction of nighttime drainage flows or daytime convective currents can be quite unpredictable so that intermittent localized vertical convection rather than turbulent diffusion at sub-canopy scale is the primary means of exchange between the canopy and boundary layer. Such conditions pose the question of how long it would be necessary to sample at a single tower to measure a representative ensemble of such events, even when their spatial location is random. Even more difficult to handle is the situation where relatively small differences in surface cover and energy balance tend to bias convective events to particular spots in the landscape. A proper analysis of these questions is long overdue.

The third and, we hope, the largest group of sites would be those where the topography interacts with the climatology in such a way as to produce predictable daytime and nighttime flow fields. In such conditions, we can, in principle, correct for advection using the model-based approaches we have outlined. For example, if we can understand and model the direction of nighttime drainage currents with confidence, then data assimilation into a properly calibrated model should provide a robust routine correction. An example where understanding the dynamics of the onset of drainage currents has already motivated an alternative methodology for computing nighttime respiration is given by van Gorsel et al. (2007). They exploit the fact that there is a period of one to two hours between sunset, when assimilation stops, and the time when the canopy air layer has cooled sufficiently to initiate a drainage current. Within this period, the respiration is well represented by the sum of eddy flux and storage, with storage the dominant term.

Conclusion

I hope that it has become clear in this short review that, while there are some systemic problems still remaining that undermine our confidence in results from many FLUXNET towers, there are straightforward ways to address these problems. It will require both experimental and theoretical effort to understand and model complex flows to the degree that we can correct for their impact on tower measurements, but the agenda is clear. The aim in most cases will be to remove bias from the tower results and often this will be at the expense of increased scatter or reduced ability to resolve the diurnal cycle but increased scatter can be addressed by increasing the sizes of our ensembles whereas biased results are actively misleading and can in turn bias the ecological models in which they are interpreted.

Evidence of anthropogenic climate change is now unequivocal and the largest imponderables in predicting and preparing for its future course lie in estimating future emissions and the dynamics of oceanic and terrestrial sinks. At present, the vast amount of information on the mechanism of the land sink that is latent in the terrestrial flux tower network can only be accessed with confidence at a very restricted number of sites, where the aerodynamic measurements can be reinforced with other data. While the effort required to produce correction procedures so that daily NEE can be obtained from a majority of sites may be large, the return on such effort is potentially enormous. I hope that the papers that follow in this feature will serve as an encouragement and exhortation to a community effort toward this end.

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