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NIGHTTIME TURBULENCE STATISTICS AND TRACE GAS EXCHANGE IN A MIXED DECIDUOUS FOREST

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1. INTRODUCTION

Turbulence statistics were measured at eight levels in and above a mixed northern hardwood forest at the AmeriFlux site of the University of Michigan Biological Station (UMBS~Flux) in northern lower Michigan (USA, 45°35' N, 84°42' W) during a 15 day period in July and August 1999.

These measurements are used to address the concern that, at night, turbulence intensity is often small and turbulent fluxes as measured by eddy covariance become ill defined. Moreover, advection or drainage flows due to horizontal heterogeneity or topography at various scales may export material released at the forest floor from the ecosystem horizontally, without being accounted for above the canopy (e.g., Lee, 1998; Finnigan, 1999, Baldocchi *et al.*, 2000).

Our data show that vertical velocity statistics follow established similarity relations above canopy, and in the canopy layer the attenuation of turbulence is closely related to the profile of vegetation area density, but with distinct differences between day and night. We examine the role of turbulence in the nocturnal exchange of trace gases from the forest floor through the canopy by evaluating the CO_2 conservation equation in the canopy-air layer. The importance of advective transport out of a finite "footprint volume" may be examined from imbalances in the 1-D equation and their magnitude is discussed in terms of the soil level emission fluxes and the turbulence activity within and above the canopy. It is shown that advective or drainage effects can be important, even at sites that appear to be flat and homogeneous.

2. SITE AND MEASUREMENTS

The UMBS~Flux site lies in a secondary successional hardwood forest, with aspen, maple, oak and birch species dominating the canopy, and a dense understory of young white pine. The mean canopy height is 22-23 m. This particular forest architecture results in a bimodal vegetation area distribution profile (Figure 1). This vegetation area profile and a maximum total vegetation area index (VAI) of 3.9 was measured with LAI-2000 sensors (LiCor, Lincoln, NE). The minimal fetch, to Douglas Lake in the north, is 1 km. The terrain is a gently sloping plain up from this lake (~ 30 m over 1 km) that continues for another 1 km to the south, where it drops abruptly in a steep escarpment towards the southwest.

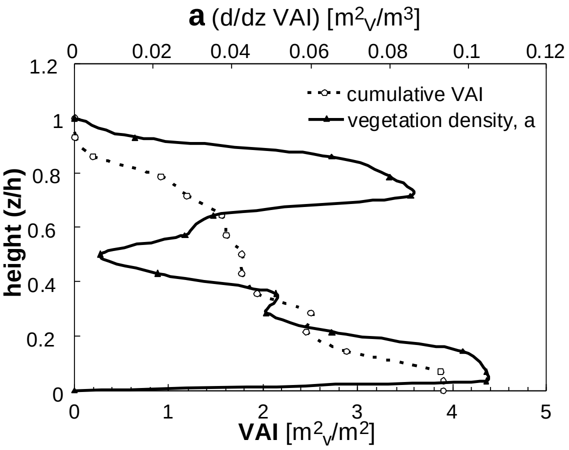

Figure 1: Vertical profile of cumulative vegetation area index (VAI) and vegetation density (a) at UMBS~Flux.

The main instrument tower of this AmeriFlux site is a 46 m self supported steel structure with a triangular base of 5.1 m that tapers to 1.8 m at 30 m and above. Eddy covariance systems (CSAT, Campbell Scientific, Logan, UT) are operated continuously at 46 m and 34 m. Sample gas is delivered to closed-path infrared gas analyzers (IRGAs, LI-6262, LiCor) in a shelter near the tower base by Teflon tubes (4.8 mm inner diameter).

In July 1999 a 24.4 m canopy tower (triangular 0.35 m on a side) was constructed about 30 m to the SW of the AmeriFlux tower, in a patch of forest that is considered typical in canopy and understory density by visual estimation. The tower exceeds the canopy by about 2 m, but required no trees or major branches to be cut in its construction. Thus, it can be used to measure turbulence and concentration profiles that approach typical canopy layer conditions for this site. A three dimensional sonic anemometer (CSAT) was installed at the mean canopy height (h = 22 m), and vertical velocity fluctuations were measured using 1-D sonic anemometers (CA-27T, Campbell Sci.) at five levels in the canopy layer (at 16, 11, 7, 3.5, and 1 m). These instruments were sampled at 5 Hz. In addition, forest floor, bole, and leaf CO_2 emissions were measured with portable flux chambers (LI-6400, LiCor), on a clear night (YD 207/99-208/99). CO_2 storage in the canopy layer was evaluated from a switched manifold that cycled sample air from eight logarithmically spaced levels of

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Teflon tubes to a LI-6262 IRGA every 15 min. CO_2 storage increments were evaluated at hourly intervals.

Here, we report on an intensive measurement period from YD 199/1999-214/1999 (July 18 – August 2, 1999). This period was characterized by warm sunny weather and clear, relatively calm nights.

3. THE CO_2 BUDGET

The carbon dioxide budget for a volume beneath a flux measurement above the forest canopy, whose trace in the forest is given by the flux footprint, can be written

$$\int_0^{z_r}\left[\frac{\partial C}{\partial t}+\frac{\partial F_C}{\partial z}+\overline{w}\,\frac{\partial \overline{C}}{\partial z}+u\,\frac{\partial C}{\partial x}\right]dz=\int_0^{z_r}P_{CO_2}\,dz \qquad (1)$$

where the first term on the left is the time rate of CO_2 concentration change, the second term is the vertical turbulent flux divergence, the third and fourth terms represent advection in the vertical and horizontal respectively. The horizontal advection term is not Reynolds decomposed and thus includes both mean advection and horizontal turbulent transport (and x is any horizontal direction). The right hand side represents all sources and sinks of CO_2 in the volume. All terms are integrated from the forest floor up to the eddy covariance sensor height, z_r. If the second term only includes turbulent transport, it reduces to just the flux at height z_r. This is the net vertical ecosystem exchange measured by an eddy covariance system above the canopy, F_{CO2}. The first term is the storage change flux and can be determined by the time rate of change of interpolated concentration profile measurements, ΔS_{CO2}. The right hand side is governed by the ecophysiological behavior of the forest and is the quantity that is commonly desired in forest CO_2 exchange projects. At night, in the absence of photosynthesis, this term reduces to the respiratory production of the forest floor, the tree boles and the foliage. In principle, these components can be measured using flux chambers, but need to be scaled up to the ecosystem, usually based on very small sample sizes with enormous internal inconsistencies. Here, measurements with portable closed chambers on nine forest floor collars, and numerous trunk-collars (for bole respiration) are combined with measurements of leaf respiration on the five most dominant species, to form an estimate of total nighttime ecosystem respiration, R_{Ctot}. The advection terms can only have a net effect over time scales of one hour or more in the presence of horizontal heterogeneity and are extremely difficult to measure. This they are usually unaccounted for or assumed to be small in tower based CO_2 exchange studies. If treated as a residual, they are necessarily superimposed by the ensemble of errors in all other terms. Thus, in the framework of the present analysis, the balance equation becomes

$$\Delta S_{CO_2}+F_{CO_2}=R_{C_{tot}}-\text{advection}+\text{errors} \qquad (2)$$

It is a common assumption that storage change becomes unimportant if the canopy volume is well ventilated and that the ecosystem respiration is primarily controlled by soil temperature (T_s, e.g., Schmid *et al.*, 2000a). If it is additionally assumed that advection effects cancel when averaged over long time periods (involving all wind directions), the *expected ecosystem respiration* can be modeled in an exponential relationship as

$$R_{C_{tot}}=a_1\exp\left(a_2\cdot T_s\right) \qquad (3)$$

where $a_{1,2}$ vary with soil moisture and are determined by regression based on measurements of F_{CO2} during well ventilated periods. Because of the practical difficulty of obtaining continuous coverage of respiration measurements, the nighttime CO_2 budget will be compared to the expected ecosystem respiration determined by relations of type (3).

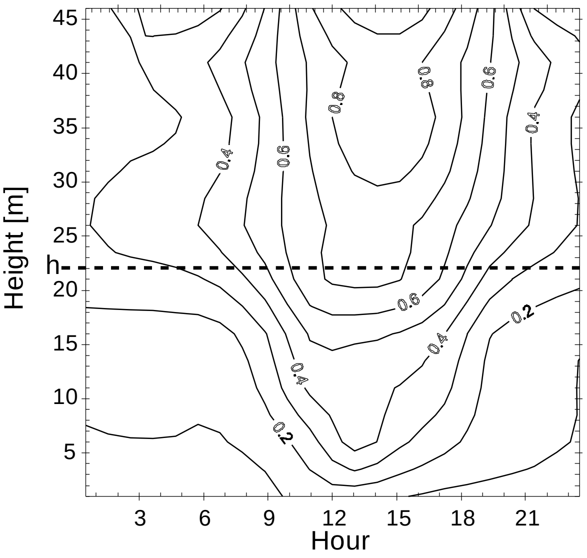

Figure 2: Mean daily variations of vertical velocity standard deviations (σ_w) in and above the forest canopy. Contour values are σ_w in [ms^{-1}]. The horizontal dashed line indicates the mean canopy height.

4. RESULTS

The measurements of vertical velocity fluctuations during the observation period are summarized in Figure 2. The values of the contour lines are labeled in m·s^{-1}. Above the canopy, the magnitude of the standard deviation of vertical velocity, σ_w, remains nearly constant with height throughout the day. It reaches a maximum in early afternoon that is roughly twice the value of the nighttime minimum. Below canopy, vertical fluctuations are very small at night, exhibiting a strong gradient at canopy height. At the onset of convection in the early morning, stronger vertical fluctuations are starting to penetrate into the canopy even before the values aloft start to increase significantly. By mid afternoon, the below canopy σ_w have grown to almost four times their nighttime level. Detailed profiles of $\sigma_w/u_*(h)$ (not shown here) demonstrate that the σ_w profiles closely follow the structure of the cumulative VAI profiles (Figure 1). Gradients are strongest at the two levels where the vegetation density is highest, in the crown layer and in the undergrowth. As expected, this effect of vertical decoupling is more pronounced at night than during the day and reaches its strongest expression at the mean canopy height.

Figure 3 shows the mean daily variations of the eddy flux of CO_2 measured at 46 m, friction velocity at 46 and 22 m (= *h*), and the CO_2 storage flux of the canopy layer. Positive F_{CO2} indicates that the forest is a net source and vice-versa. Positive storage change, ΔS_{CO2}, on the other hand reflects accumulation of CO_2 in the canopy layer, and negative ΔS_{CO2} indicates that CO_2 is either consumed by photosynthesis, or flushed out of the canopy layer.

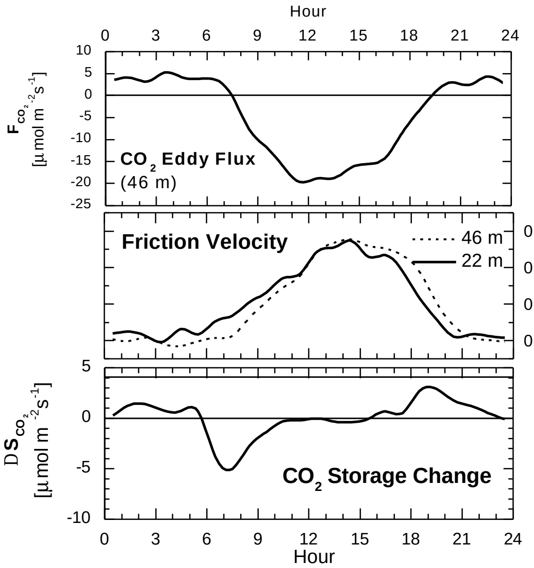

Figure 3: Mean daily variations of measured CO_2 exchange at 46 m, friction velocity, and CO_2 storage change in the canopy layer over the 15 day period.

At night, friction velocity is low. The measured eddy flux fluctuates around 5 µmol m^{-2} s^{-1}, but the canopy layer is accumulating carbon at a little less than half that rate. near 06:00 h, several things seem to happen: u_* at canopy height starts to increase, CO_2 is being flushed out of the canopy at a rate roughly equal to the F_{CO2} from the night hours before. The fact that F_{CO2} does not increase dramatically, but remains about the same could indicate that either photosynthesis is already effective, or that the extra CO_2 removed from storage is advected away. During the day, storage change is very small, largely attributable to the high u_*. CO_2 exchange is dominated by photosynthesis. In the early evening, u_* at canopy height is starting to decrease again (followed a little later by the 46 m level) and the storage change responds by CO_2 accumulation. This initial pulse of storage change quickly abates. Two potential mechanisms are: the onset of evening cooling reduces respiration, or drainage flows remove CO_2 laterally. More detailed analysis of temperatures and the expected respiration will shed light on this.

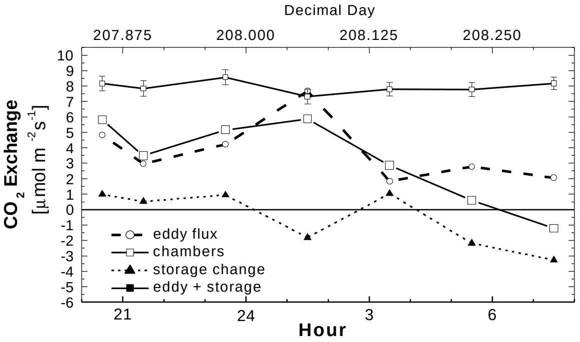

Figure 4: CO_2 exchange budget terms during the night from YD 207/99-208/99. Fluxes measured by eddy-covariance at 46 m, and chamber measurements of forest floor and leaf respiration that are scaled to the ecosystem are compared to storage change in the canopy air layer.

Manual respiration measurements, using the portable closed chamber, were performed during one night (July 26, 1999). The measurements from all collars have been averaged to two hourly values and are plotted together with the eddy flux measurements and the storage change calculations in Figure 4. The night of July 26 was warm and thus it is not surprising that the respiration rate declined only slightly through the night. The standard difference between the nine forest floor collars is indicated by the error bars in the graph. Storage change remained small during this period and fluctuates slightly in a seemingly random manner. However, these small fluctuations in storage change do not seem to be due to measurement uncertainties, because they are mirrored quite well by corresponding fluctuations in the eddy flux signal. The slight storage deficit at about 01:30 h is reflected in a boost of positive eddy flux. Following (2), the storage change and the eddy flux should add up to the ecosystem respiration, in the absence of advection or errors. As indicated by the eddy + storage curve in Figure 4, the short lived fluctuations in the eddy flux and the storage change partially cancel each other, so that the course of the sum-curve is both smoother and closer to the scaled up chamber flux values than the eddy flux curve. However, a substantial residual, attributable to advection (drainage) or cumulative errors, remains between the eddy+storage and the chamber flux curve. The uncertainties, particularly in the chamber flux curve, are considerable. Since the largest errors may be systematic (but unknown), the small error bars on the chamber flux curve may give a false sense of precision. On the other hand, the qualitative agreement in the temporal evolution of these curves indicates that they do resolve even slight fluctuations in a physical process that affects all terms of the budget equation.

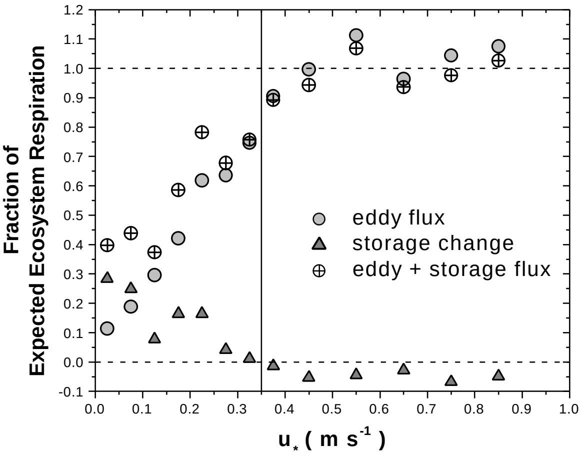

Figure 5: The importance of nighttime hourly CO_2 storage change vs. u_*. The flux values are scaled by the expected ecosystem respiration determined by the relationship in eq. (3) for $u_* \geq 0.35$ ms^{-1}.

To examine the importance of u_* as a surrogate for the mixing power of turbulence and the coupling of the canopy layer with the surface layer above, the measured eddy fluxes and the storage change were plotted against u_* (at 46 m) in Figure 5, as fractions of the expected ecosystem respiration (3), following Goulden *et al.*, 1996. As expected, the importance of storage change increases sharply with weakening turbulence. The fraction of the expected ecosystem respiration that is measured by eddy co-variance (at 46 m) decreases and becomes insignificant at very low values of above-canopy u_*. The finding that the eddy-flux fraction levels out at unity and the u_*-dependence disappears at high u_* levels, is not surprising because the determination of the expected ecosystem respiration precludes this as an assumption. However, the reduction of the storage term to near zero at about the same threshold of $u_* \geq 0.35$ m s^{-1}, confirms the validity of this assumption. Figure 5 shows clearly that the decline of the measured portion of R_{Ctot} in the eddy covariance toward low u_* is compensated only partially by the storage term. Thus, the inclusion of the storage term to correct fluxes measured by eddy covariance is not sufficient at low turbulence levels. It appears that vertical or horizontal advection effects, due to thermally induced drainage flow for example, become significant during low-wind nights. Unless advective transport can be measured accurately, rejection of low-wind nighttime measurements and replacement by respiration models such as (3) are essential in estimations of annual carbon sequestration. Schmid *et al.* (2000b) show that neglect of this bias (e.g. by filling data gaps with ensemble average fluxes) leads to an overestimation of carbon sequestration by about 1 t C ha^{-1} yr^{-1} at the UMBS~Flux site.

5. CONCLUSIONS

- In nighttime calm conditions, measured eddy-covariance fluxes commonly misrepresent the ecosystem CO_2 respiration.
- CO_2 storage change in the canopy air volume is significant at hourly time scales, but is not sufficient to close the CO_2 budget in a one-dimensional framework.
- Despite considerable remaining uncertainties, there is strong evidence that three-dimensional advective effects are significantly affecting estimates of carbon sequestration even at seemingly flat and homogeneous sites.

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