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Advective Flux in Relation to Net Ecosystem CO2 Exchange at the Niwot Ridge Ameriflux Site
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The overall aim of our project was to study the influence of complex mountain topography on the carbon budget of the local subalpine forest ecosystem. The results of the research are summarized in a series of abstracts below:

1. In a modeling exercise, we asked the question, how much CO_2 is assimilated by ecosystems in complex mountainous terrain in the Western U.S. Using two ecosystem biogeochemistry models, Century and Biome-BGC, we showed that over 50% of the annual carbon sequestration in the Western US occurs in ecosystems between 1000 and 1500 m in elevation (Schimel et al. 2002). This means that most of the carbon is assimilated in ecosystems with montane terrain. Traditionally, humans have used the landscapes in simpler terrain for agricultural exploitation. This has left the most productive natural ecosystems to the complex terrain, where it is most difficult to make good measurements of surface-atmosphere CO_2 exchange by the eddy covariance method.

2. Using three years of continuous observations at the Niwot Ridge Ameriflux site in the Front Range of Colorado, we have studied the effects of local topography and canopy structure on turbulent flux measurements. The study site is located in mountainous terrain within a subalpine, coniferous forest with an average canopy height (h_c) of 11.4 m. Displacement height and roughness length were derived from wind profiles and determined to be d = 7.8 ± 1.6 m (0.67 h_c) and z_o = 1.71 ± 0.80 (0.15 h_c), respectively. Despite a relatively short fetch (400 m) of consistent sloping terrain (5-7°) before dropping sharply (10-13°) to the east (downslope) of the tower, footprint analysis models, energy budget closure and direct tests for vertical divergence of sensible heat flux at different heights above the canopy revealed that the fetch was adequate for consistent turbulent flux measurements and supported the conclusion that forest structure and composition was homogeneous within the fetch. Adequacy of the eastern fetch appears to be helped by the dominance of buoyancy-forced flows during easterly winds, which tends to shrink the fetch in the horizontal direction. Within the canopy, turbulent intensities (i_x) for the horizontal winds (u and v) reached maxima between z/h_c = 0.09-0.26, whereas turbulent intensity for the vertical wind peaked at z/h_c = 0.53 and third-moment statistical analysis (for skewness) revealed the dominance of canopy-scale sweep-ejection motions in the vertical turbulence. Near-ground maxima in i_u and i_v may reflect frequent drainage flows which interact with tree boles, stems and canopy elements to create air flow wakes and eddies. The effects of the canopy on the spectral structure of surface-layer and within-canopy turbulence were in accordance with Monin-Obukhov theory for the former, and indicated the existence of spectral "shortcuts" in the latter. The spectral peaks and changes within the canopy were similar to those noted in previous studies in non-mountainous terrain, suggesting that the observed canopy influences are highly local and not dependent on larger-scale topography. Eulerian length scales (Λ_x) at a measurement height of 1.87 h_c were determined to be Λ_w ~ 0.7-1.2 h_c and Λ_u ~ 9.6-14 h_c, which are similar to measurements made in forests on simpler terrain. Three different methods of coordinate rotation (double-coordinate rotation, triple-coordinate rotation, and planar-fit rotation; denoted as DR, TR and PF, respectively) were investigated to determine possible advantages and

disadvantages for analysis in complex terrain. These yielded eddy fluxes that were in excellent agreement; however, significant variability in rotation angles at low wind speeds were encountered with the commonly-used DR and TR methods, as opposed to the PF method. During stably stratified nocturnal periods, a second maximum in the vertical profiles of wind speed and length scale was found below ~ 6 m. The development of this secondary maximum coincided with a decrease in the measured vertical turbulent eddy flux measured above the canopy. These observations support the frequent occurrence of nighttime drainage flows, which can result in horizontal advective flux. These nighttime stable periods also indicated a bias toward positive, non-zero mean vertical wind speed (determined from half-hour averages), suggesting the presence of a flow convergence below the measurement sensors. This is likely caused by subtle topographic variation within the vicinity of the tower. Overall, the results revealed that daytime turbulent fluxes at this mountainous site could be measured and validated with consistency comparable to sites on simpler terrain. However, the existence of drainage flows along paths of topographic convergence, if coupled to horizontal scalar gradients, may significantly complicate nighttime turbulent flux measurements during periods of high atmospheric stability, and make it difficult to correct nighttime fluxes using common methods of gap filling. The result of this study were published in Turnipseed et al. 2003.

3. The location of the Niwot Ridge Ameriflux site within the Rocky Mountains subjects it to airflows which are common in mountainous terrain; notably, the formation of valley/mountain flows and mountain lee-side waves. In this study, we examined the effects of these mesoscale flows on local flux measurements. The major effect of valley/mountain flows was statistical nonstationarities caused by a lee-side convergence zone in which upslope and downslope flows met at the tower site, and alternated within single averaging periods. Using analyses of the standard deviation of wind direction, periods of lee-side convergence were identified for 26% of the half-hour flux measurement periods during June-August, 2001. Stationarity was violated in 25% and 36% of those periods when momentum fluxes or sensible heat fluxes were analyzed, respectively; this means that overall, stationarity was violated due to mountain/valley flows in < 10% of the summertime measurement periods that were analyzed. On relatively stable, summer nights, but with some measurable westerly wind (friction velocity, $u^* < 0.4$ m s^{-1}), we observed evidence for small mountain waves (wavelength, λ ~ 3.9 km), with embedded canopy waves (λ ~ 45 m). Turbulence intensity (as measured by the standard deviation of the vertical wind speed, σ_w), temperature (T) and CO_2 concentration varied systematically during the waves, exhibiting periodicities that appeared congruent with the period of the wave (with the highest σ_w, lowest T, and highest CO_2 concentration occurring during wave peaks). Large spectral peaks for sensible heat, H_2O and CO_2 fluxes were observed at frequencies of 0.05 Hz (20 s) and 0.0008 Hz (20 min). Integration of the co-spectra indicated that between 25-50% of the total scalar fluxes, was accounted for within the low frequency wave. During periods of high westerly winds, typically in winter, we observed large mountain gravity waves, with crests that formed east of the tower site. During these periods, the flux tower was in a region of downslope "shooting flow", which created high turbulence, but did not detrimentally affect local flux measurements based on valid turbulence statistics and nearly-complete energy budget closure. Periodically, we found evidence for re-circulating, rotor winds in the simultaneous time series of wind data from the Ameriflux tower site and a second meteorological site, situated 8 km to the west. Only 14% of the half-hour time periods that we examined for a four-month period in the winter of 2000-2001 showed large differences in wind direction (> 50°) between the two locations, indicating the

possible existence of rotor winds. The influence of rotor winds on local flux measurements would be expected to be variable, depending on the diameter of the rotor and the location of its center relative to the flux tower. Overall, the results from this study demonstrate that the potential exists for significant influences of mesoscale wind flow patterns on local flux measurements. However, most of the influences are relatively rare among the half-hour measurement series we screened. Given the rarity of the influences, and the potential to identify their occurrence through examination of normal turbulence statistical parameters, it should be possible to flag questionable periods and apply corrections or eliminate time periods when justified. The results of this study were published in Turnipseed et a. 2004.

4. Mean horizontal advective CO_2 flux (Fc_{mha}) has been considered to be a substantial component of net ecosystem CO_2 exchange (NEE) during nighttime stable conditions at many measurement sites, especially those with complex terrain. We developed and deployed an experimental design to measure Fc_{mha} in a subalpine forest in complex terrain in Colorado. Nocturnal katabatic winds (drainage flows) are prevalent at this site, occurring during 66% of nocturnal hours. Typically ranging 0.5-1.0 ms^{-1} through the canopy, these winds are associated with thermal inversions and substantial vertical and horizontal CO_2 concentration gradients. Vertical CO_2 concentration differences in mid-summer varied most in the subcanopy, decreasing ~30ppm with height (from 1m to 10m). While the downslope minus upslope CO_2 concentration differences measured 110-150m apart exhibited a wide range (-9 to +25 ppm), downslope concentrations were typically higher. Much of the range in horizontal concentration differences and, consequently $Fc_{mha,}$ appears to be the result of short duration mixing events of within canopy air. These disturbances appear to alter the horizontal concentration fields that develop under near steady-state periods. In the course of the 2001 and 2002 growing seasons during drainage flow, half-hour nocturnal Fc_{mha} averaged ~7.4 +/- 6.8 $\mu mol\ m^{-2}s^{-1}$ when mixing was weak (friction velocity $u_* < 0.3\ ms^{-1}$ at 33m) and wind direction shear with height was low ($<90^o$ from 10 to 1m). During upslope conditions, Fc_{mha} was ~3.9 +/- 6 $\mu mol\ m^{-2}s^{-1}$. While these averages closely bracket averages from concurrent soil surface chamber measurements (~4-6 $\mu mol\ m^{-2}s^{-1}$), they are considerably higher than the average derived from eddy covariance measurements (~2 +/- 3 $\mu mol\ m^{-2}s^{-1}$), measured above canopy when mixing was considered adequate ($u_* > 0.3\ ms^{-1}$). For more than 54% of all nighttime observations, mixing of air within and above canopy is too weak ($u_* < 0.3\ ms^{-1}$) for reliable eddy covariance measurements (Fc_{ec}) of NEE. Rather than use gap filling models for such periods, we suggest that Fc_{mha} measurements be added to Fc_{ec}. These results have been submitted for publication to the journal Agricultural and Forest Meteorology and are in the stage of peer review.

References

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