J9.2 A NOVEL APPROACH COMBINING CANOPY FLOW ANALYSIS AND STABLE ISOTOPES TO UNDERSTAND AND QUANTIFY TURBULENT CARBON EXCHANGE IN FORESTS

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1 INTRODUCTION

Micrometeorological tools have found broad application in ecosystems carbon cycle research for the study of ecosystem scale carbon dioxide and water exchange with a notable success for the eddy covariance (EC) method. However, these studies would benefit from additional information on the source and sink component fluxes of carbon dioxide and water vapor as well as the driving processes behind the atmospheric exchange, beyond the net flux measurements provided by the EC methodology.

We present a novel, cross-disciplinary approach for identifying the sources of component fluxes at an ecosystem scale by combining analysis of the turbulent transport, the determination of the flux source through conditional flux analysis and tracer information from natural abundance stable isotope analysis of the carbon dioxide. The approach provides a direct method for determination of component fluxes of carbon dioxide and water and aims to reduce uncertainty of flux estimates of (daytime) ecosystem respiration in forest ecosystems.

The approach is based on identifiable changes in the correlation structure of carbon dioxide and water vapor concentrations in the canopy air during updraft events. A recently developed conditional sampling approach (Scanlon and Albertson, 2001; Thomas et al., 2008) and a state-of-the-art wavelet analysis tool (Thomas and Foken, 2007) are both applied to high-frequency observations of the two trace gases and velocities. The two methods are combined to evaluate the hypothesis that short-term excursions from similarity theory predictions of the correlation structure between carbon dioxide and water vapor are associated with the vertical transport through coherent structures. Although these short-term excursions have been demonstrated to carry the quantifiable fingerprint of sub-canopy ecosystem respiration primarily from the forest floor, questions on the exact transport mechanisms and the variability of this signal were left unanswered.

In addition to the analysis of the canopy flow to refine the conditional sampling approach we explore the use of concurrent high time resolution measurements of the natural abundance stable isotope ratios δ^{13}C and δ^{18}O of carbon dioxide to explain the variability of the conditionally sampled signal. The working hypothesis is that the stable isotope signatures can be traced back to different sinks and sources of water vapor and carbon dioxide in the canopy (Dawson et al., 2002; Buchmann et al., 2002; Bowling et al., 2008), and subsequently be integrated into the conditional sampling scheme to directly quantify ecosystem-scale photosynthesis and respiration fluxes. Such a method would provide perspective on bridging trace gas exchange observed at plant level with that at the ecosystem level and help reduce uncertainty of flux estimates of ecosystem respiration by indirect model parameterization approaches.

2 METHODOLOGY

The analysis of flux regression and vertical flow was made in two complementary steps. First, a conditional sampling of the correlation between carbon dioxide and water vapor concentrations in relation to the direction of the vertical wind speed provided information on the occurrences of sub-canopy respiration flux events. Second, a more detailed time line of the flow, the related turbulence scales and consequent duration of organized upward motion ("ejection") follows from detection and conditional sampling of coherent structures by wavelet analysis. These coherent structures are assumed to be capable of moving air parcels through the canopy without full turbulent mixing and are therefore useful to help refine the flow characteristics of the conditional sampling.

2.1 Respiration events

The identification of respiration events is based on analysis of the correlation between concurring perturbations of the carbon dioxide ($c\prime$) and water vapor ($q\prime$)

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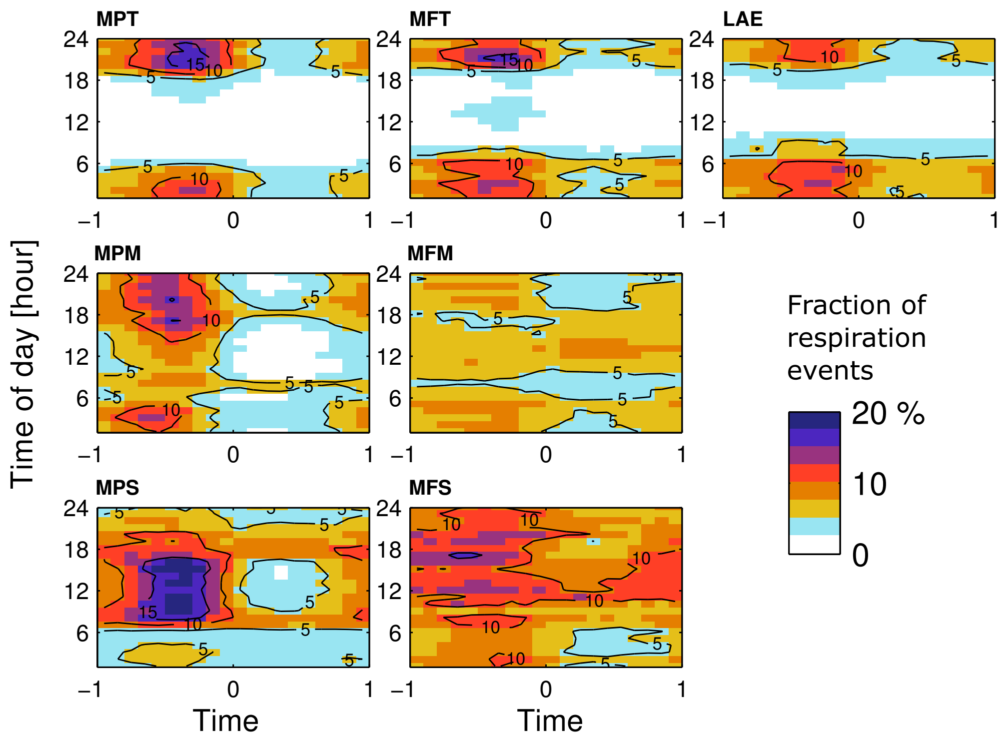

Figure 1: Ensemble average of the fraction of respiration events for each hour of day against the time scale of the coherent structures, which represent periods of a combined "ejection" and "sweep" phases and a normalized duration. The ensemble average period is one month for MP and MF and two months for LAE.

concentrations and the vertical wind speed (w). Air from sub-canopy source is postulated to contain above average amounts of carbon dioxide and water vapor and therefore can be identified by $w\prime > 0$, $c\prime > 0$, $q\prime > 0$. An additional hyperbola function $c\prime q\prime \cdot (\sigma_c \sigma_q)^{-1} > H$ (with H=¼) helps limit the classification of values for which $c\prime > 0$ and $q\prime > 0$ but which do not significantly deviate from the daytime negative correlation between carbon dioxide and water vapor (Thomas et al., 2008).

2.2 Coherent structures

Coherent structures (CS) represent the occurrence of an alternate "ejection" and "sweep" phase motion and can be recognized in scalar time series by sharp gradients. Here we use the virtual temperature (T) to detect coherent structures. The T time series were averaged (from 20 to 2 Hz, to reduce computation time), normalized and extended ("zero padded" on both ends) before a number of subsequent wavelet analyses could be applied (Thomas and Foken, 2005). First, application of a Bi-orthogonal wavelet (BIOR5.5) provided a fast low-pass filter for event durations longer than 6.2 s, limiting the inclusion of small size turbulent eddies. Second, a Morlet wavelet (MORL) was used to compute wavelet variance spectra for scales limited to event durations of approximately 5 to 240 s. Third, from the first identified variance maximum the dominant event duration (D_e) was determined and a Mexican Hat (MEXH) wavelet was applied to localize these events in time (Farge, 1992; Collineau and Brunet, 1993b,a; Thomas and Foken, 2005, 2007). For each half hour, the event time and duration of the detected CS were used for computation of conditional sampled averages.

2.3 Research sites

The data used in this ongoing study were collected at three research sites representing forests of different canopy architectures; a sparse ponderosa pine (MP), a dense Douglas fir (MF) and a heterogeneous mixed vegetation (LAE), covering June 2006, July 2007 and June–July 2008, respectively. The MP and MF sites are located in central (44.45° N, 121.56° W) and western (44.65° N, 123.55° W) Oregon, USA, respectively, where the MP site is characterized by an intense summer drought period (Thomas et al., 2008). The LAE site is located on the south facing slope of the Laegeren mountain (47.48° N, 8.36° E) in northern Switzerland (Eugster et al., 2007; Etzold et al., 2010).

Time series of wind speed (w), carbon dioxide (c)

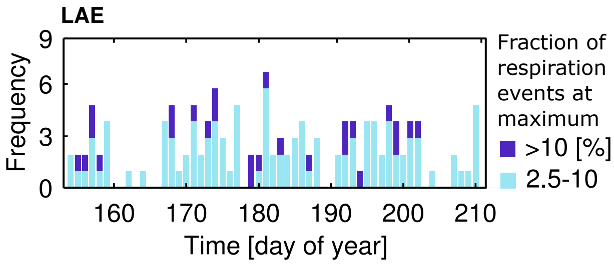

Figure 2: Frequency of occurance of daytime (9am–6pm) hours for which respiration events cover more than 2.5% of the data at the observed maximum in the "ejection" phase of the coherent structures, shown per day for the period June–July 2008.

and water vapor concentration (q) and virtual temperature (T) were collected using sonic anemometers (at MP and MF model CSAT-3, Campbell Sci., Logan, UT, USA; at LAE model Solent HS, Gill Instruments Ltd., Lymington, UK) and open-path infrared gas analyzers (Li 7500, Licor Inc, Lincoln, NB, USA). At MP and MF, three sets of instruments were installed for simultaneous below (MFS, MPS), within (MFM, MPM) and above the canopy (MFT, MPT), respectively. In addition, at LAE air was sampled at the sonic anemometer and drawn to a climatized cabin below the instrument tower for continuous measurement of the stable isotope ratios of δ^{13}C and δ^{18}O of CO_2 in air using a laser absorption spectroscope (QCLAS-ISO, Aerodyne Research, Inc., Billerica, MA, USA) configured for concurrent analysis at 10 Hz, with a precision of about 0.2 ‰ $Hz^{-1/2}$ based on Alan Variance plots. Calibration procedures were applied hourly using three CO_2-in-air gas mixtures of known isotopic composition of which one is used for a stepped dilution to determine concentration dependencies. More technical details can be found in Nelson et al. (2008), Tuzson et al. (2008) and Barthel et al. (2010). Data assessment consisted of a de-spiking routine according to Vickers and Mahrt (1997), a cross instrument time offset correction by optimizing for maximum covariances and a rotation of the wind vectors.

3 RESULTS & DISCUSSION

A higher fraction of sub-canopy source respiration events was shown in the "ejection" phase (first half) of the detected coherent structures, which clearly reveals the connection between the organised motion through coherent structures and the identifiable patterns in the regression between water vapor and carbon dioxide pertubations (Fig. 1). The appearance of a daytime maximum contribution at approximately the center of

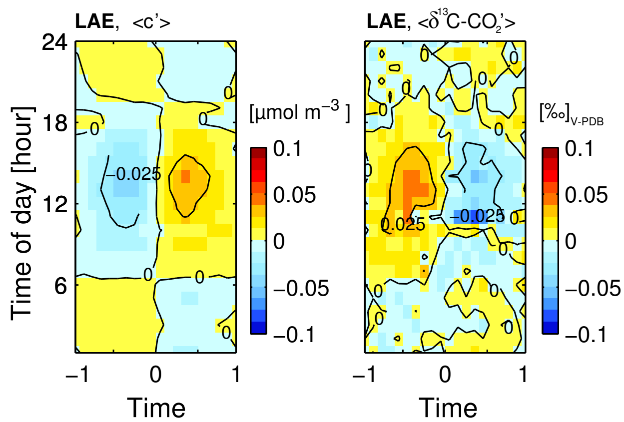

Figure 3: Ensemble average of pertubations relative to the mean of the coherent structure of (left) the carbon dioxide concentration $\langle c\prime \rangle$ and (right) the stable isotope ratios of carbon dioxide $\langle \delta^{13}C\text{-}CO_2\prime \rangle$, expressed in [$\mu$mol m^{-3}] and [‰], respectively.

the "ejection" phase is most clear for the below canopy (MPS, MFS) and the within canopy (MPM) data, which follows the findings of Thomas et al. (2008) for these particular sites. In contrast, for the above canopy measurements the daytime fraction of respiration events in the ensemble mean was generally small (Fig. 1). However, for individual days and daytime half hours the fraction of respiration events can be larger, though the occurrences are intermittent in space and time (Fig. 2). This may be attributed to full turbulent mixing causing the sub-canopy respiration events to become unidentifiable, or insufficient separation of sources and sinks caused by overcast weather, or intermittent turbulence causing variation in the mean carbon dioxide concentration. Nevertheless, the results show there is a link between the physical transport by coherent structures from within the canopy and sub-canopy respiration events.

A pattern can be recognized for the daytime ensemble averages of carbon dioxide perturbations relative to the mean of the coherent structure ($\langle c\prime \rangle$), showing negative values in the "ejection" phase of the coherent structures, followed by positive values in the "sweep" phase (Fig. 3). This can be explained by a dominance of the photosynthetic uptake flux and represents the passing of coherent structures in time, where a phase of upward moving air depleted in carbon dioxide by canopy photosynthetic uptake is followed by an exchange of air from above that is relatively enriched in carbon dioxide. This is confirmed by the δ^{13}C values, which shows a relatively $^{13}CO_2$ enriched signal in the daytime "ejection" phase, indicating the effects of isotopic discrimination against $^{13}CO_2$

by photosynthetic uptake of carbon dioxide (Fig. 3). However, if we combine the conditional sampling of sub-canopy respiration events and coherent structures the patterns in ensemble averaged concentrations or stable isotope ratios of carbon dioxide are less clear. This shows that conditional sampling analysis should be performed on a per case and half-hour basis.

The stable isotope signals generally show the inverse of the values for pertubations of carbon dioxide concentration indicating the difference in source–sink relationships between vegetation and atmosphere. It is that difference specifically that will help determine the origin of the flux and the processes that affected the carbon dioxide composition. Furthermore, this information can in turn be used to further refine the conditional sampling scheme to detect sources and sinks within and below the canopy.

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REFERENCES

Barthel, M., P. Sturm, L. Gentsch, and A. Knohl, 2010: Technical note: A combined soil/canopy chamber system for tracing δ^{13}C in soil respiration after a $\delta^{13}CO_2$ canopy pulse labelling. *Biogeosciences Discussions*, **7**, 1603–1631, doi:10.5194/bgd-7-1603-2010.

Bowling, D. R., D. E. Pataki, and J. T. Randerson, 2008: Carbon isotopes in terrestrial ecosystem pools and CO_2 fluxes. *New Phytologist*, **178**, 24–40, doi:10.1111/j.1469-8137.2007.02342.x.

Buchmann, N., J. R. Brooks, and J. R. Ehleringer, 2002: Predicting daytime carbon isotope ratios of atmospheric CO_2 within forest canopies. *Functional Ecology*, **16**, 49–57.

Collineau, S. and Y. Brunet, 1993a: Detection of turbulent coherent motions in a forest canopy .1. wavelet analysis. *Boundary-Layer Meteorology*, **65**, 357–379, doi:10.1007/BF00707033.

— 1993b: Detection of turbulent coherent motions in a forest canopy .2. time-scales and conditional averages. *Boundary-Layer Meteorology*, **66**, 49–73, doi:10.1007/BF00705459.

Dawson, T. E., S. Mambelli, A. H. Plamboeck, P. H. Templer, and K. P. Tu, 2002: Stable isotopes in plant ecology. *Annual Review of Ecology and Systematics*, **33**, 507–559, doi:10.1146/annurev.ecolsys.33.020602.095451.

Etzold, S., N. Buchmann, and W. Eugster, 2010: Contribution of advection to the carbon budget measured by eddy covariance at a steep mountain slope forest in Switzerland. *Biogeosciences Discussions*, **7**, 1633–1673, doi:10.5194/bgd-7-1633-2010.

Eugster, W., K. Zeyer, M. Zeeman, P. Michna, A. Zingg, N. Buchmann, and L. Emmenegger, 2007: Methodical study of nitrous oxide eddy covariance measurements using quantum cascade laser spectrometery over a Swiss forest. *Biogeosciences*, **4**, 927–939.

Farge, M., 1992: Wavelet transforms and their applications to turbulence. *Annual Review of Fluid Mechanics*, **24**, 395–458, doi:10.1146/annurev.fl.24.010192.002143.

Nelson, D. D., J. B. Mcmanus, S. C. Herndon, M. S. Zahniser, B. Tuzson, and L. Emmenegger, 2008: New method for isotopic ratio measurements of atmospheric carbon dioxide using a 4.3 mu m pulsed quantum cascade laser.

Scanlon, T. M. and J. D. Albertson, 2001: Turbulent transport of carbon dioxide and water vapor within a vegetation canopy during unstable conditions: Identification of episodes using wavelet analysis. *Journal of Geophysical Research-Atmospheres*, **106**, 7251–7262.

Thomas, C. and T. Foken, 2005: Detection of long-term coherent exchange over spruce forest using wavelet analysis. *Theoretical And Applied Climatology*, **80**, 91–104.

— 2007: Flux contribution of coherent structures and its implications for the exchange of energy and matter in a tall spruce canopy. *Boundary-Layer Meteorology*, **123**, 317–337.

Thomas, C., J. Martin, M. Goeckede, M. Siqueira, T. Foken, B. Law, H. Loescher, and G. Katul, 2008: Estimating daytime subcanopy respiration from conditional sampling methods applied to multi–scalar high frequency turbulence time series. *Agricultural and Forest Meteorologyb*, **148**, 1210–1229, doi:10.1016/j.agrformet.2008.03.002.

Tuzson, B., J. Mohn, M. J. Zeeman, R. A. Werner, W. Eugster, M. S. Zahniser, D. D. Nelson, J. B. McManus, and L. Emmenegger, 2008: High precision and continuous field measurements of δ^{13}C and δ^{18}O in carbon dioxide with a cryogenic free QCLAS. *Applied Physics B. Lasers and Optics*, **92**, 451–458, doi:10.1007/s00340-008-3085-4.

Vickers, D. and L. Mahrt, 1997: Quality control and flux sampling problems for tower and aircraft data. *Journal of Atmospheric and Oceanic Technology*, **14**, 512–526.