On the Anomalous Behaviour of Scalar Flux–Variance Similarity Functions Within the Canopy Sub-layer of a Dense Alpine Forest

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Abstract Within the canopy sub-layer (CSL), variability in scalar sources and sinks are known to affect flux–variance (FV) similarity relationships for water vapour (q) and carbon dioxide (C) concentrations, yet large-scale processes may continue to play a significant role. High frequency time series data for temperature (T), q and C , collected within the CSL of an uneven-aged mixed coniferous forest in Lavarone, Italy, are used to investigate these processes within the context of FV similarity. This dataset suggests that MOST scaling describes the FV similarity function of T even though the observations are collected in the CSL, consistent with other studies. However, the measured FV similarity functions for q and C appear to have higher values than their temperature counterpart. Two hypotheses are proposed to explain the measured anomalous behaviour in the FV similarity functions for q and C when referenced to T . Respired CO_2 from the forest floor leads to large positive excursions in the C time series at the canopy top thereby contributing significantly to both C variance increase and C vertical flux decrease—both leading to an anomalous increase in the

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FV similarity function. For q , transport of dry air from the outer-layer significantly increases both the variance and the water vapour flux. However, the expected flux increase is much smaller than the variance increase so that the net effect remains an increase in the measured FV similarity function for water vapour above its T counterpart. The hypothesis here is that identifying these events in the temporal and/or in the frequency domain and filtering them from the C and q time series partially recovers a scalar flow field that appears to follow FV similarity theory scaling. Methods for identifying both types of events in the time and frequency domains and their subsequent effects on the FV similarity functions and corollary flow variables, such as the relative transport efficiencies, are also explored.

Keywords Canopy turbulence · Carbon dioxide transport · Flux–variance similarity · Forest floor respiration · Outer-layer modulations · Scalar dissimilarity

1 Introduction

Flux–profile and flux–variance (FV) similarity theory and scaling behaviour of scalar variance remains critical for developing and testing footprint and plume dispersion models. However, little is known about such scaling within the roughness sub-layer of forested canopies, at least when compared to the atmospheric surface layer (ASL).

Over the past two decades, a large number of studies have shown that flux–profile and FV similarity functions for scalars such as temperature (T) and water vapour concentration (q) mainly differ due to source inhomogeneity at the ground (Thom et al. 1975; Garratt 1978; Raupach 1979; Raupach et al. 1979; Padro 1993; Kustas et al. 1994; Katul et al. 1995; Bink 1996; Bink and Meesters 1999; Andreas et al. 1998; Mölder et al. 1999; Lyons et al. 2001). However, even over a homogeneous surface, several studies did not find FV functions for T to be identical to those for q (De Bruin et al. 1993). Other studies suggested that some of the observed differences between FV similarity functions for T and q may be attributed to the active role of temperature in the turbulent kinetic energy (TKE) budget (Katul and Hsieh 1999). De Bruin et al. (1993) observed that when surface evaporation was sufficiently low, top-down processes related to entrainment were such that the local standard deviation of q was no longer related to the local surface flux (Mahrt 1991a, b; Roth and Oke 1995; Asanuma et al. 2007). Similar conclusions were reported for the marine surface layer (Mahrt 1991a; Sempreviva and Gryning 2000; Katul et al. 2008). Hence, this led a number of authors to conclude that higher-order statistics similarity relationships (such as the FV similarity functions) measured in the ASL are sensitive to modulations from non-local effects such as large-eddy convection and/or entrainment from the ‘free atmosphere’. These non-local (hereafter referred to as ‘outer-layer’) modulations are likely to affect significantly the scalar variances, but less so vertical fluxes (Hogstrom 1990; Roth and Oke 1995; McNaughton and Laubach 1998; Hogstrom et al. 2002; McNaughton and Brunet 2002; Cullen et al. 2007). During daytime conditions, convective structures populate the outer layer (defined here as that part of the atmospheric boundary layer that extends well above the ASL but just below the capping inversion). These convective structures transport to the surface dry and cold air from the upper mixed layer (as observed in Roth and Oke 1995) or dry and warm air entrained from above the capping inversion. While much attention has thus far centered on the TKE budget and FV similarity functions for T and q (Hogstrom et al. 1989; Leclerc et al. 1990; Lamaud and Irvine 2006), there is growing interest in exploring FV similarity relationships for carbon dioxide concentration (C), in addition to T and q . Contemporary applications utilizing FV similarity functions for C include, (1) evaluating components of the turbulent

CO₂ flux budget near the canopy top for testing higher-order turbulent closure models (Juang et al. 2006), (2) developing alternative gap-filling methods for estimating annual carbon budgets (Choi et al. 2004), (3) comparing turbulent transport efficiencies between CO₂ and other scalars such as T and q to inspect similarities in the transfer pathways near the ground.

This last application received significant attention in both vegetated and urban canopy sub-layer (CSL) experiments. Several studies revealed that the standard relationships of Monin-Obukhov similarity theory (MOST) require correction factors when used inside the CSL (Thom et al. 1975; Garratt 1978, 1980, 1983; Mölder et al. 1999). In fact in the CSL, variability in C , q , and T sources and sinks within the canopy are likely to influence FV similarity relationships as well as other second-order flow statistics. For example, when only leaf stomata control the mass transfer, the turbulent transport efficiency of C and q should be comparable in magnitude, and departures from this inequality may be used to assess respiratory contributions (Williams et al. 2007; Thomas et al. 2008). In urban environments, linkages between differences in car and house emissions of C and release of q by urban vegetation were captured by differences in transport efficiencies (Moriwaki and Kanda 2006). Still, non-local modulations originating from the outer layer may continue to play a significant role in scalar dissimilarity above both urban and vegetated canopies (De Bruin et al. 1993; Roth and Oke 1995; de Arellano et al. 2004; Moene et al. 2006; Górska et al. 2006). Recently, Moene et al. (2006) explored the influence of surface heterogeneity and of entrainment effects on the deviation from MOST for temperature, humidity and carbon dioxide concentration using observations made over a savannah landscape in Ghana (West Africa). They confirmed MOST scaling during wet soil moisture conditions and deviations from MOST scaling during dry soil moisture conditions, and attributed these departures to entrainment processes from the outer layer, consistent with Detto et al. (2008) for a semi-arid ecosystem in Sardinia (Italy). Roth and Oke (1995) attributed the scalar dissimilarity above an urban area, in part, to the influence of convective structures that extended well above the surface layer and originated in the outer layer or above the capping inversion.

Hence, further investigation on FV similarities within the CSL for these three scalars (T , q , and C) appears warranted to assess how the FV similarity functions are modified and whether large-scale processes within the outer-layer continue to play a significant role in scalar similarity relationships within the CSL. In this context, large-scale processes refer to processes originating from the outer layer or above the capping inversion with integral length scales much larger than the local mixing length within the ASL.

As a case study, the FV similarity functions (and corollary statistics such as the transport efficiencies and scalar correlations) for T , q and C are considered within the CSL above an alpine-forested site in Lavarone Italy, away from any major industrial or urban centre. The unique attributes of the site and the study period include, (1) cloud free conditions during much of the daytime, (2) sufficiently water stressed conditions so that latent heat fluxes (LE) were much smaller than their sensible heat flux (H) counterpart (enhancing dry convective conditions previously reported to produce outer-layer modulations in the ASL), and (3) source-sink relationships for CO₂ and water vapour are significantly different in this stand. The main q sources and C sinks reside in the foliage and are controlled by leaf stomata. For C , however, there is an additional source due to forest floor respiration introducing significant dissimilarity in the C versus q sources and sinks. The forest floor evaporation for this dense and water stressed canopy is negligible compared to the latent heat flux from the canopy top. Hence, by using all three scalars here, the main turbulent mechanisms contributing to the anomalous behaviour in FV similarity functions within the CSL are investigated. Two

hypotheses are proposed to explain the measured anomalous behaviour in the FV similarity functions for q and C when referenced to T . Respired CO_2 from the forest floor is shown to lead to large positive excursions in the C time series at the canopy top. This respiration contribution significantly amplifies the FV similarity functions during daytime conditions by reducing the net vertical carbon dioxide flux (i.e. smaller negative value) and by increasing the C variance. On the other hand, for unstable conditions, outer-layer modulations to the CSL can affect the FV similarity function for q . Transport of dry air from the outer layer significantly increases both the q variance and the latent heat flux consistent with other canopy turbulence studies (including urban). However, the expected flux increase is much smaller than the variance increase (De Bruin et al. 1993) so that the net effect remains an increase in the measured FV similarity function for water vapour above its classical behaviour.

Therefore, identifying these ‘anomalous’ events in the temporal and/or in the frequency domain and filtering them from the C and q time series might partially recover a scalar flow field that follows classical FV similarity theory. It should be noted that the analysis here does not consider the full range of possibilities known to induce anomalous scaling in FV similarity functions such as advective conditions (Kroon and De Bruin 1995; McNaughton and Laubach 2000; Assouline et al. 2008). However, the interplay between outer-layer processes and dissimilarity in canopy scalar sources and sinks, the focus here, remains a logical first step in any basic inquiry on FV similarity functions for carbon dioxide concentration within the CSL.

Unless otherwise stated, the following nomenclature is used: the longitudinal, lateral, and vertical coordinates are x , y , and z , respectively, and the instantaneous velocity components along these three directions are u , v , and w , respectively. An overbar indicates time averaging and a prime denotes a fluctuation from the time average. Because the analysis is conducted for the scalar statistics collected above the canopy, no spatial averaging is necessary.

2 Theory

Based on MOST for a stationary and planar homogeneous flow without subsidence, any dimensionless turbulence statistic depends on the atmospheric stability parameter, $\zeta = \frac{z-d}{L}$, where z is the height above the ground, d is the zero-plane displacement, and L is the Obukhov length given by

$$L = -\frac{u_*^3 \bar{T}}{\kappa g \overline{w'T'}}, \quad (1)$$

where $\overline{w'T'}$ is the mean kinematic sensible heat flux, $\bar{T}$ is the mean air temperature, $\kappa = 0.4$ is von Karman’s constant, g is the gravitational acceleration, and u_* is the friction velocity given by

$$u_* = \left(\overline{u'w'^2} + \overline{v'w'^2} \right)^{1/4} \quad (2)$$

where u' , w' , and v' are the turbulent fluctuations in the longitudinal, vertical, and lateral velocities, respectively. The turbulent standard deviation of any scalar s , σ_s , can be expressed as a function of ζ (Tillman 1972; Businger 1973)

$$\frac{\sigma_s}{|s_*|} = \phi_s(-\zeta) \quad (3)$$

where $s_* = \overline{w's'}/u_*$ is a scalar concentration scale. The function $\phi_s(-\zeta)$ must satisfy two limits (De Bruin 1982; De Bruin et al. 1993, 1994; Albertson et al. 1995; Wesson et al. 2001):

- (1) In the neutral case, $-\zeta \rightarrow 0$ and $\phi_s(-\zeta)$ approaches a constant.
- (2) In the free convection limit, $-\zeta \rightarrow \infty$ and σ_s/s_* should become independent of u_* .

These two limits can be satisfied with an expression of the form

$$\frac{\sigma_s}{s_*} = C_1(1 - C_2\zeta)^{-1/3}, \quad (4)$$

where C_1 and C_2 are similarity constants.

For free convection conditions (e.g. $-\zeta > 5$), Eq. 4 is well approximated by

$$\frac{\sigma_s}{s_*} \approx C_3(-\zeta)^{-1/3} \quad (5)$$

where $C_3 \approx 0.99$ (corrected for $\kappa = 0.4$) originally determined elsewhere (Wyngaard et al. 1971) and verified over a semi-arid area in the region called ‘La Crau’ in southern France (Kohsiek et al. 1993), over a uniform and flat and dry lakebed (Albertson et al. 1995), and for several canopies (Wesson et al. 2001). Although the $\phi_s(-\zeta)$ function was experimentally shown to be the same for T , q , and C over a uniform wheat field (Ohtaki 1985), De Bruin et al. (1999) studied the correlation coefficient between T and q over a dry vineyard in Spain and concluded that if non-local effects are of the same order as local effects, T and q will be dissimilar.

The functions $\phi_s(-\zeta)$ for two scalars (e.g. q and C) can be related to their transport efficiency ratios by

$$\frac{\sigma_c}{|c_*|} \frac{|q_*|}{\sigma_q} = \frac{\phi_c(-\zeta)}{\phi_q(-\zeta)} = \frac{\sigma_c \overline{w'q'}/u_*}{\sigma_q \overline{w'c'}/u_*} = \frac{R_{wq}}{R_{wc}}, \quad (6)$$

where $R_{ws} = \overline{w's'}/(\sigma_w\sigma_s)$ is the correlation coefficient between vertical velocity and an arbitrary scalar concentration. If expression (5) is used to represent the FV similarity functions, then the ratio of the transport efficiency of the two scalars becomes the inverse ratio of the FV similarity constants.

3 Experiment

Much of the experimental set-up is described elsewhere (Marcolla et al. 2003; Cava et al. 2006), and only salient features most pertinent to the study objectives are repeated here for completeness. The experimental site is an uneven-aged mixed coniferous forest in Lavarone, Italy (45.96° N, 11.28° E; 1,300 m above sea level). This site is part of a long-term CO₂ flux monitoring initiative known as CarboEuroflux (Valentini et al. 2000). The canopy is about 28–30 m tall ($= h_c$) and is primarily composed of *Abies alba* (70%), *Fagus sylvatica* (15%), and *Picea abies* (15%), with a maximum leaf area index of 9.6 m² m⁻² when expressed as half of the total leaf area per unit ground.

The data used for the analysis were collected as part of a summertime intensive measurement campaign performed in 2000 (from August 10 to September 8). The micrometeorological tower was situated on a gently rolling plateau, selected to ensure homogeneous vegetation within at least 1 km distance in all directions, except for a 45° sector in the south and south-west for which the vegetation extended uniformly some 300 m from the tower. The tower was equipped with five eddy-covariance flux instruments situated at 33, 25, 17.5, 11, 4 m from the forest floor. The turbulent velocity and sonic anemometer temperature were sampled at 20 Hz for the highest and the lowest levels by Gill R3 ultrasonic anemometers (Gill Instrument,

Lymington, UK.). The water vapour and carbon dioxide concentration were sampled only at these two levels by the same data acquisition system using a LiCor 7500 open-path fast response infrared gas analyzer (IRGA) (LiCor Inc., Lincoln, NE, USA). Hence, the analysis here uses time series data collected at these two levels.

Half-hourly mean values of the main turbulence statistics were computed for each level following two coordinate rotations to ensure the mean lateral and vertical velocities were zero. These two rotations were needed because the interest here is not in the total mass transport but in how turbulent fluxes relate to turbulent scalar variances. The Webb–Pearman–Leuning correction (Webb et al. 1980; Detto and Katul 2007) was used to separate ‘natural’ fluctuations from fluctuations induced by ‘external’ effects (i.e. air temperature and water vapour concentration fluctuations) in the measured carbon dioxide and water vapour concentrations.

The analysis was performed on 19 days during daytime conditions (between 0900 and 1500 local time) resulting in 228 30-minute runs, while those exhibiting clear non-stationarity were discarded. The atmospheric stability conditions were classified based on $\zeta = \frac{z-d}{L}$, where $d \approx 0.75h_c$ is the zero-plane displacement height for momentum and L is measured at the canopy top. For some analyses (see Sect. 4.2), atmospheric stability conditions were not treated as a ‘continuum’ but clustered according to three classes: near neutral ($-0.1 < \zeta < 0$); mildly unstable ($-0.8 < \zeta < -0.1$); and unstable ($\zeta < -0.8$).

4 Results

The similarity between scalars and flux–variance MOST scaling is first tested above the top of the forested canopy ($z = 32$ m), and possible causes of dissimilarity are investigated using quadrant analysis and conditional sampling methods. Observations of scalar patterns collected near the forest floor ($z = 4$ m) are used as additional or ‘satellite’ signals for further confirmation that some events are not statistical artefacts but are large-scale and coherent.

4.1 Flux–Variance Analysis

The dimensionless standard deviations for temperature, water vapour, and carbon dioxide concentrations measured above the top of the forest ($z = 32$ m) are plotted against $-\zeta$, shown in Fig. 1. Overall, the temperature data follow a typical MOST FV scaling described by Eq. 4 when $C_1 = 2.3 \pm 0.1$ and $C_2 = 9.5 \pm 0.5$ (the correlation coefficient $R = 0.76$). These coefficients compared well with coefficients derived for the ASL ($C_1 = 2$, $C_2 = 9.5$, as in Kaimal and Finnigan 1994). The error estimate of the model coefficients was derived from Monte-Carlo simulations by randomizing these two coefficients and only accepting combinations in which R does not decrease with respect to its optimized value ($R = 0.76$). The measured FV similarity functions for the other two scalars exhibit significant scatter.

A number of studies, reviewed in the Appendix, have pointed out to the possible spurious functional relationship between measured σ_s/s_* and measured ζ because u_* appears in the dependent variable (through s_*) and the independent variable (through L). The validity of the derived relationships has been tested (see Appendix) to assess the impact of such spurious correlations arising from the fact that u_* variability affects both dependent and independent variables.

Sensible heat generally appeared to be transported more efficiently than carbon dioxide or water vapour (Fig. 2), in agreement with Katul et al. (1995), Roth and Oke (1995), Katul and Hsieh (1999), Lamaud and Irvine (2006), Moriwaki and Kanda (2006). However, the interest here lies in the variability in the correlation coefficients of water vapour and carbon

Fig. 1 Dimensionless standard deviation of (a) temperature (T), (b) water vapour concentration (q) and (c) CO_2 concentration (C), sampled above the canopy top ($z = 32$ m), versus the stability parameter $-\zeta$. Black stars refer to raw measurements, and grey full circles refer to data with ‘anomalous events’ filtered out from the q and C time series. The black dashed lines represent the experimental similarity functions $\sigma_s/s_* = C_1(1 - C_2\zeta)^{-1/3}$, where $C_2 = 9.5$ for all of the three scalars, whereas $C_1 = 2.3, 3.4$ and 2.8 for T, q , and C , respectively. The black dotted lines represent the similarity functions for free convection regime $\sigma_s/s_* = C_3(\zeta)^{-1/3}$ where $C_3 = C_1C_2^{-1/3}$

dioxide (Fig. 3); it appears that the mode of this correlation is lower than unity (in absolute value) and the scatter is as significant as that of heat to water vapour comparisons.

In situations similar to those under investigation, the different behaviour of the T and q scalars may be partially explained by the active role of temperature in the transport (Katul and Hsieh 1999). However, this argument fails to explain the dissimilarity between q and C , especially given the fact the q is generally low and can be treated as a passive scalar. To explore the time scales at which these dissimilarities originate, the scalar spectra (for variances) and cospectra are considered next.

4.2 Spectra and Cospectra

Spectral and cospectral analysis is used to explore the main mechanisms (i.e. phenomena and associated scales) affecting variances and vertical fluxes of these three scalars for different stability regimes. To minimize statistical uncertainty due to possible intermittent contributions by large-scale motions comparable to the boundary-layer depth, the spectra and cospectra are computed using 5-h (from 1,000 to 1,500) windows for the three stability classes discussed in Sect. 3. To reduce the number of data points involved in the fast Fourier transform computation, the sampling frequency was reduced from 20 Hz to 2 Hz. The contribution of these high frequencies to both variances and fluxes were found to be small (<10%). The ensemble averaged spectra and cospectra for the three atmospheric stability classes are, respectively, plotted in Figs. 4 and 5.

Fig. 2 Relative efficiency of (a) T and q , (b) T and C , and (c) q and C above the canopy top ($z = 32$ m) versus the stability parameter $-\zeta$. Black stars and grey full circles are defined in Fig. 1

The spectral energy allows detection of scales that cause deviations of normalized variances from their ASL states (Fig. 4). The spectrum of the vertical velocity component (computed for reference) peaks at a scale consistent with the shear production length scale near the canopy top (Raupach et al. 1996; Finnigan 2000; Poggi et al. 2004), and appears insensitive to atmospheric stability variations consistent with other studies (Brunet and Irvine 2000). The spectrum of T exhibits similar behaviour to the w spectrum for near-neutral conditions, but as unstable atmospheric stability conditions are approached, more of the spectral energy contribution resides at lower frequencies. In the case of C , energy remains mainly concentrated at canopy scales, but the effect of increased atmospheric stability is more pronounced in ‘distributing’ energy across lower frequencies (when compared to w , for example). The water vapour variance exhibits the strongest dependence on atmospheric stability and, in particular, under convective conditions much of the energy resides in the low-frequency range consistent with boundary-layer scale eddies.

The cospectra (Fig. 5) show that canopy scales dominate the mass and momentum transport, with boundary-layer eddies contributing much less to scalar fluxes when compared to their variance counterpart (i.e. they appear much less active in mass transport). However, their contribution increases as the flow becomes more convective, mainly for T and q . Contributions from scales commensurate with the boundary-layer height appear not to modify much the CO_2 fluxes probably because carbon dioxide transport at the top of the atmospheric boundary layer is not appreciable given that the Lavarone site is remote from any major industrial or urban centre.

Fig. 3 Same as Fig. 2 but for the correlation coefficient between (a) T and q , (b) T and C , and (c) q and C . Black stars and grey full circles are defined in Fig. 1

The analysis here demonstrates that large scales originating from the outer-layer, comparable in size with the atmospheric boundary-layer (ABL) depth, do contribute to CSL fluxes and variances, but this contribution is asymmetric with regards to the three scalars (especially q). Hence, the FV similarity may be ‘modified’ from their ASL scaling by such large-scale phenomena (especially q), though the persistent contribution of canopy-scale eddies to carbon dioxide transfer appears suggestive of other alternatives, such as forest source/sink dissimilarity within the canopy (Williams et al. 2007). Two hypotheses are proposed here to explain the anomalous behaviour of FV similarity functions for q and C in the CSL when compared to T :

1. For CO_2 , the respiration from the forest floor, often identified by ejection events leading to large positive excursions in the C time series at the canopy top, contributes significantly to both CO_2 variance and flux. This contribution tends to amplify departure from the ASL similarity scaling because ejected air parcels reaching the canopy top reduce the CO_2 flux (i.e. smaller negative value) and increase the CO_2 variance (thereby increasing the FV similarity function).
2. For q , transport of dry air from the outer-layer significantly increases the variance and the flux. However, as evidenced by spectra and cospectra, the flux increase is much smaller than the variance increase so that the net effect remains an increase in the measured FV similarity function above that predicted by MOST scaling.

Hence, the identification of these events and their filtering from the C and q series may partially recover a scalar flow field that follows MOST similarity scaling. Methods for identifying

Fig. 4 Ensemble averaged spectra of (a) vertical velocity component (w), (b) T , (c) C and (d) q , sampled above the canopy top ($z = 32$ m), versus normalised frequency ($f h_c / U$). Different symbols refer to the three stability classes defined in Sect. 3: diamonds (near-neutral), stars (mildly unstable), and circles (unstable)

both types of events and their subsequent effects on the FV similarity functions are explored next.

4.3 Identification of Events Causing Anomalous FV Scaling

A reference case is shown in Fig. 6 for near-neutral conditions ($\zeta = -0.1$) that demonstrates typical canopy turbulence features, i.e. organized ramps, unperturbed by any significant contribution from the forest floor respiration or any large-scale motion (such as outer-layer modulations). Quadrant analyses of data sampled above the canopy top for this reference case are shown in Fig. 7. The canonical features (e.g. spread along the main quadrant-forming axes) are used in the subsequent analysis as a ‘reference’ for identification of anomalous events. In the quadrant analysis, heat is used as a ‘reference’ scalar because its measured FV similarity function in the CSL is consistent with MOST scaling (Fig. 1). The time series during this reference period, collected near the forest floor, are shown in Fig. 6. In the detection of the anomalous events, the comparison of the scalar time series sampled at these two levels is used as an independent check that anomalous perturbations are not statistical artifacts but coherent events detected at both levels.

4.3.1 Identification of Respiration Events

Figure 8 shows a sample time series collected near the canopy top and at the lowest level. The canopy-top level exhibits large excursions in CO_2 concentration during ejection events

Fig. 5 Same as Fig. 4 but for the ensemble averaged cospectra of (a) momentum flux ($\overline{u'w'}$), (b) sensible heat flux ($\overline{w'T'}$), (c) CO₂ flux ($\overline{w'C'}$) and (d) water vapour flux ($\overline{w'q'}$)

(associated with forest floor CO₂ respiration). The corresponding C series collected at the lowest level clearly identifies respiration activity originating from the forest floor. Note the inverse ramp behaviour at the canopy top during these respiration events, connected with a change in the sign of the local flux (i.e. positive CO₂ flux during these events). Hence, it is clear that such intense inverted ramps affect both the variance and the CO₂ flux. The inverse ramp duration appears comparable to the other canopy ramps in the time series. For the other two scalars, these ejection events do not ‘imprint’ any particular ramp-like feature and do not appreciably contribute to the scalar variance. Hence, the dissimilarity in the FV functions of CO₂ when compared to q or T may be partially explained by these respiration-ejection events, and it can also be hypothesized that the same process may affect the q time series in a similar way in open canopies with a wet forest floor (for example, after a rain event).

The signature of such ramps in the quadrant analysis is illustrated in Fig. 9, which shows the major anomalous behaviour in quadrant 1 when compared to its counterpart for the reference case (Fig. 7). Clearly, this anomalous behaviour is connected with an ejection (or updraft) phase ($w' > 0$). To characterize statistically this anomalous behaviour of CO₂ fluctuations, these events have been automatically identified by a ‘quadrant edge-detection’ method, and Fig. 9 shows an example of how this method identifies ‘anomalous’ fluctuations. The temporal occurrence of events residing above the line connecting the edges of quadrant 1 for updraft motions (i.e. see the grey line connecting points $T' = 0$ and maximum C' and $C' = 0$ and maximum T') is first identified. By discarding these events, the quadrant analysis collapses back to the reference series in Fig. 7. The grey line in Fig. 9 highlights the detected anomalous

Fig. 6 Example time series of normalised (a) T' , (c) q' , and (e) C' , sampled above the canopy top ($z = 32$ m), for near-neutral conditions ($-\zeta = 0.1$). The same variables sampled near the forest floor ($z = 4$ m) are also shown in (b), (d) and (f), respectively. The sample time series were collected on August 16, 1430–1450 local time. Above the canopy top the values of sensible heat flux, latent heat flux, and CO_2 flux were 717 W m^{-2} , 248 W m^{-2} , and $-1.16 \text{ mg m}^{-2} \text{ s}^{-1}$, respectively; while near the forest floor they were 8 W m^{-2} , 13 W m^{-2} , and $0.18 \text{ mg m}^{-2} \text{ s}^{-1}$, respectively

ramps by this method and it is suggestive of good detection skills, while Fig. 10 shows the histogram of the duration of the detected ramps via this scheme both in seconds and in terms of reduced frequency (fh_c/U). Note that the duration of the ramps appears consistent with canopy scales, indirectly confirming the adequacy of this edge-detection method.

Furthermore, the impact of these anomalous respiration events on both the CO_2 concentration standard deviation and vertical flux are explored for each 30-min run. Figure 11 shows that, as the frequency of occurrence of these events increases, the measured FV similarity function increases proportionately above its ASL value. When these events are filtered out and the fluxes and variances are re-computed, the resulting FV similarity functions appear less scattered and resemble in scaling the FV similarity functions for the ASL (as shown in Fig. 1c, grey points).

4.3.2 Identification of Outer-Layer Modulation Events

Figure 12 shows an example of a large and intense ramp in the q' signal in which a dry air event swept the canopy top and penetrated down to the forest floor. The excursions in humidity here are large and negative, and the duration of this anomalous ramp is about 6 minutes. This duration is much larger than expected for canopy turbulence and indicates that the anomalous ramp in the water vapour fluctuations must be related to outer-layer processes. Time series traces of T' and q' reported for an urban canopy (Roth and Oke 1995) show similar ‘anomalous’ ramps with the same signs and with comparable sizes, and

Fig. 7 Quadrant analysis of normalised C' versus T' , conditioned on the basis of occurrence of (a) ejection events or updrafts ($w' > 0$), and of (c) sweeping events or downdrafts ($w' < 0$). The same analysis for q' versus T' is shown in (b) and (d). Data are relative to the time series collected above the canopy top shown in Fig. 6

Roth and Oke (1995) attributed the ramps to the passage of large rising thermals followed by cold and dry downdrafts from the outer layer. In this urban canopy study, the anomalous ramp duration ranged from 4 min to 6 min, or 800 m to 1,200 m spatial scale, using a mean wind speed near the ground of about 3.5 m s^{-1} . For the Lavarone site, this anomalous ramp duration is about 6 min and with a mean wind speed of 2 m s^{-1} leads to a length scale of about 720 m. Roth and Oke (1995) also provided a phenomenological explanation for their anomalous ramp using a conceptual diagram, which has been extended in Fig. 13 to include C ; variations in fluxes, concentrations, and two-scalar correlations are shown as well. In Fig. 13, dry and cold air originating from the outer layer is swept down and contributes to strong positive correlations between T and q in the CSL near the canopy top. However, the strength of this correlation is larger than the correlation originating from within the canopy via ejection events. The weaker correlation between T and q near the surface is mainly due to the dissimilarity in sources and sinks of q and T (Williams et al. 2007), so these anomalous events from the outer layer tend to strengthen the correlations between T and q while dissimilarity in sources and sinks within the canopy tend to weaken this correlation. Furthermore, the anomalous event affects both the vertical flux and variance of q , but less so for T (consistent with the spectra and cospectra already reported in Figs. 4 and 5). For C , the signature of the anomalous ramp is also evident, but the magnitude of the C excursions induced by this ramp is comparable to the background turbulence. The covariance between

Fig. 8 Example time series of normalised (a) T' , (c) q' , and (e) C' , sampled above the canopy top ($z = 32$ m), showing large positive excursions in C' due to ejection events connected with forest floor respiration. The same variables sampled near the forest floor ($z = 4$ m) are shown in (b), (d) and (f), respectively for reference. The sample time series were collected on August 24, 1210–1230 local time. The atmospheric stability was ($-\zeta = 0.5$). Above the canopy top the values of sensible heat flux, latent heat flux, and CO_2 flux were, respectively, 677 W m^{-2} , 216 W m^{-2} , and $0.07 \text{ mg m}^{-2} \text{ s}^{-1}$; while near the forest floor they were, respectively, -7 W m^{-2} , 34 W m^{-2} , and $0.35 \text{ mg m}^{-2} \text{ s}^{-1}$. The grey line in (e) shows the result of the quadrant edge-detection method for discriminating respiration events when applied to the selected period (cf Fig. 9a)

Fig. 9 Quadrant analysis of normalised C' versus T' , conditioned on the basis of occurrence of (a) ejection events or updrafts ($w' > 0$) and of (b) sweeping events or downdrafts ($w' < 0$). Data are relative to the time series collected at the top of the canopy shown in Fig. 8. The grey line in (a) shows the result of the quadrant edge-detection method for discriminating respiration event, applied to the selected period (cf Fig. 8e)

Fig. 10 Histogram of (a) the time scale duration and of (b) the normalised frequency (fh_c/U) corresponding to these respiration events discriminated by the quadrant edge-detection method

Fig. 11 Scatter plot of (a) reduction (%) in σ_C , (b) increase (%) in the $w'C'$ and (c) reduction (%) in $\sigma_C / w'C'$, after discarding the anomalous events related to the forest floor respiration versus their time of occurrence (%) in the 30-min time series

Fig. 12 Example time series of normalised (a) T' , (c) q' , and (e) C' , sampled above the canopy top ($z = 32$ m), showing large excursions in q' due to a downdraft event connected with large-scale outer-layer modulations. The same variables sampled near the forest floor ($z = 4$ m) are shown in (b), (d) and (f), respectively. The sample time series were collected on August 20, 1210–1230 local time. The atmospheric stability was $-\zeta = 0.3$. Above the canopy top the values of sensible heat flux, latent heat flux, and CO_2 fluxes were, respectively, 677 W m^{-2} , 203 W m^{-2} , and $-0.51 \text{ mg m}^{-2} \text{ s}^{-1}$; while near the forest floor they were, respectively, -11 W m^{-2} , 18 W m^{-2} , and $0.27 \text{ mg m}^{-2} \text{ s}^{-1}$

C and q becomes more negative due to these anomalous sweeps, but the overall contribution to the vertical CO_2 fluxes and the CO_2 variance is not appreciable. The contribution of this anomalous ramp to correlations between C and q remains clearly discernable, as shown in Fig. 13. In short, these anomalous ramps affect the correlation between C and q and the FV similarity function for q but not the FV similarity function for C .

Quadrant analysis (Fig. 14) further confirms that this main event is a large-scale sweep (in quadrant 3) detected at both levels. Because the smaller canopy ramps are superimposed on this event, its signature also appears in the ejection phases. This ejection contribution becomes problematic for any automatic detection in the time domain (via quadrants) because of the superposition of canopy ramps. Hence, for these cases, a frequency cut-off has been chosen that takes advantage of the time-scale separation (4–6 min for the anomalous ramps versus tens of seconds for canopy turbulence). The reduced frequency cut-off ($fh_c/U = 0.1$) was chosen based on the shape of the vertical velocity spectrum (Fig. 4) and the momentum flux cospectrum (Fig. 5). These two figures suggest that canopy turbulence does not significantly affect variances and momentum fluxes when the reduced frequency is smaller than 0.1. Hence, when the q spectra and cospectra are ‘high-pass filtered’ on the basis of this reduced frequency cut-off, the resulting FV similarity function resembles in scaling the FV similarity functions for the ASL (see Fig. 1b, grey points). Furthermore, the scatter in the FV similarity functions derived from the filtered series is significantly reduced.

Fig. 13 Top panel: Conceptual diagram of the boundary layer dynamics above a vegetation canopy, showing how the outer-layer modulation might affect the scalar fluctuations in the CSL (revised from Fig. 8 of Roth and Oke 1995). The expected mean scalar concentration profiles here are shown for illustrating the mechanism and are not measured above the site. Bottom panels: time series of normalized scalar concentration, fluxes, and two-scalar correlations during a ramp-like event shown in Fig. 12

4.3.3 Recovery of ASL-Based Transport Efficiencies

After filtering respiratory events and outer-layer modulations in both the q and C series, the derived FV similarity functions (grey points in Fig. 1b, c) are not identical to MOST functions, though they follow MOST scaling (including a $C_2 = 9.5 \pm 0.5$ for all three scalars). The main differences from MOST functions are in the C_1 coefficients, with the derived C_1 appearing higher when compared to heat ($C_1 = 3.4 \pm 0.2$ with $R = 0.53$ for q and $C_1 = 2.8 \pm 0.2$ with $R = 0.48$ for C). Note that the R values before the filtering operation were negligible with 0.09 for q and 0.002 for C . Again, the Appendix discusses the possible spurious correlations for these filtered series as well.

From Eq. 6, the differences in these similarity coefficients are indicative of differences in transport efficiencies. For the filtered series, the relative transport efficiencies do not approach

Fig. 14 Quadrant analysis of normalised q' versus T' , conditioned on the basis of occurrence of (a) ejection events or updrafts ($w' > 0$), and of (c) sweeping events or downdrafts ($w' < 0$) for data sampled above the canopy top ($z = 32 \text{ m}$). The same analysis for data sampled near the forest floor ($z = 4 \text{ m}$) is also shown in (b) and (d), respectively, for reference. Data are relative to the time series shown in Fig. 12

unity as expected for the ASL (see Fig. 2, grey points), but this is not surprising for the CSL. Roughly, heat remains more efficiently transported than water vapour (≈ 1.8 times) and CO_2 (≈ 1.2 times). In fact even in the ASL, heat is usually transported more efficiently because of other factors such as the active role of buoyancy in turbulent kinetic energy production. Furthermore, CO_2 appears more efficiently transported than water vapour (≈ 1.4 times).

It should be emphasized that these measurements are in the CSL and are influenced by a number of inhomogeneities; hence perfect similarity between heat, water vapour, and CO_2 cannot be expected in this layer. What is important to note from the analysis is that the anomalous events identified earlier introduce scatter much larger than factors of 1.2 or 1.5, as evidenced in Fig. 1.

5 Discussion and Conclusions

Historically, disagreements between MOST predictions and measured FV similarity functions proved to be successful in ‘fingerprinting’ novel dynamics within the ASL. Examples of this success include studies that documented the role of atmospheric boundary-layer height variations on measured σ_u/u_* collected within the ASL (Panofsky and Dutton 1984;

Hogstrom 1990; De Bruin et al. 1993). Such studies provided early evidence that inactive eddy motion, originating from the outer layer, can affect ASL flow variables such as σ_u . Inactive eddy motion was also shown to modify the root-mean-squared turbulent pressure fluctuations within the ASL (Katul et al. 1996). McNaughton and Brunet (2002) even argued that interactions between such inactive and active eddy motions responsible for momentum transfer are also possible within the ASL and proposed a simplified mechanism for its onset. Likewise, a large number of studies (Wesley 1988; Weaver 1990; Padro 1993; Andreas et al. 1998) have shown how source-sink in-homogeneity at the ground induces departure between measured FV similarity functions and predictions from MOST.

The next logical extension is whether FV similarity analysis can be used to identify the main mechanisms modulating the CSL. While lacking the ‘niceties’ of MOST formulations as a reference model for an idealized flow state, the FV similarity functions for scalars in the CSL may provide important clues about the role of outer-layer modulations and source-sink dissimilarity in describing CSL turbulence. Mainly, the basic premise is that such complex mechanisms do not affect proportionally the scalar fluxes and their variances.

Our analysis showed that within the CSL of a dense vegetated canopy, both outer-layer processes and heterogeneities in sources and sinks within the canopy volume affect FV similarity functions. Spectral and cospectral analysis suggested that scalar variances were much more sensitive to these two mechanisms than scalar fluxes. For water vapour, the outer-layer contribution to scalar fluxes can be significant when the latent heat flux is small compared to the sensible heat flux in agreement with recent studies (Lamaud and Irvine 2006). Because of the observed positive correlation between T and q (transport of dry and cold air), it can be hypothesised that the effect of air directly entrained from the free atmosphere is less significant than the effect of air transported from other zones within the outer layer (as observed in Roth and Oke 1995). Moreover, in the alpine forest studied here, where no major industry or urban centre is present, the contribution of outer-layer modulations to CO_2 appears small compared to the intermittent accumulation-ejection cycle of CO_2 inside the canopy volume. In fact, respired CO_2 from the forest floor was shown to lead to large positive excursions in the C time series at the canopy top thereby contributing significantly to both CO_2 variance and vertical flux. The same process may affect the q time series in a similar way in more open canopies and in the presence of a wet forest floor (for example, after a rain event).

The data analysis here showed that if these large-scale outer-layer modulations and ejection-accumulation events are ‘filtered out’ from the water vapour and CO_2 concentration time series, respectively, MOST scaling is approximately recovered.

Finally, other important processes that can produce anomalous scaling in FV similarity functions, such as advection, were not considered. It is difficult to explore these processes via single tower measurements, though some theoretical and experimental attempts are presented in Assouline et al. (2008) for heat and water vapour above small reservoirs. Recent studies (Feigenwinter et al. 2004; Aubinet et al. 2005; Sun et al. 2007) found that advection may be significant even during daytime especially with low intensity turbulence. However, the main concern refers to nocturnal conditions when an underestimation of CO_2 fluxes using the eddy-covariance technique frequently occurs because non-turbulent transport processes, not taken into account by the eddy-covariance system, become significant. Under these conditions, quantifying and understanding advective transport processes may be important for the improvement of flux measurements. It is possible that departures from MOST scaling for FV may provide additional clues as to when CO_2 advection is important. However, Feigenwinter et al. 2004, Aubinet et al. 2005, Sun et al. 2007 do not discuss the role of advection on FV similarity functions (only on CO_2 fluxes via the mean scalar continuity).

The broader implications of these findings are three-fold. The first pertains to the surface energy balance studies and energy balance closure. If outer-layer modulation can be significant and detected in the water vapour concentration series, then it can also affect eddy-covariance water vapour turbulent flux measurements in the CSL. However, net radiation measurements are insensitive to such outer-layer modulations. Whether this mechanism alone may explain the lack of surface energy balance closure is subject to some debate (Steinfeld et al. 2007). For example, the performed analysis showed that during a 6-min sweeping event of dry and cold air from the outer layer, the local latent heat flux actually increased (not decreased). The contributions to sensible heat flux by such events may vary as well. Here, their contribution to sensible heat was not very significant when compared to fluxes originating from within the canopy.

The second pertains to the use of the energy balance closure for latent heat flux to ‘correct’ or ‘adjust’ net ecosystem CO₂ exchange (NEE) (Twine et al. 2000). Clearly, this approach lacks any theoretical basis given the spectral and cospectral dissimilarities of these two scalars in the CSL. While the measured FV similarity functions for CO₂ and water vapour appeared higher than for heat, the mechanisms producing this increase were different. For water vapour, the increase was connected to the entrainment of dry air, while for CO₂ it was mainly connected with contributions from an ejection-accumulation cycle of respired CO₂. These two mechanisms differ in their contribution to the spectra and cospectra of water vapour and CO₂ concentrations.

The third pertains to the inference of respiration events on NEE measurements within the CSL. It is clear that the main reason for the measured FV similarity function for CO₂ appearing systematically larger than predictions by MOST is connected with the role of respiration (at this stand). This study demonstrated that when CO₂ actually follows MOST scaling, the respiration contribution to NEE above the canopy is small. Hence, it is conceivable that a combination of conditional sampling schemes, quadrant analysis, and FV similarity functions may offer a promising method to extract daytime respiration from NEE time series above the canopy, at least for some limited observations. Given the existence of a large FluxNet database (Baldocchi et al. 2001) already collected over the past decade, the latter implication awaits systematic investigation.

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Appendix: Verification of Spurious Correlations

An inherent problem in assessing MOST scaling, originally pointed out by Hicks (1978, 1981), is related to ‘virtual’ or ‘spurious’ correlations arising because measured u_* affects both the dependent and independent states being analysed. De Bruin (1982) and De Bruin et al. (1993) discussed this problem in the context of the FV method and showed that the $-1/3$ power-law dependence between σ_s/s_* and ζ may be merely an artefact of the grouping variables. In fact, s_* contains u_* and L contains u_*^3 . They concluded that the only way to show that spurious correlation effects are not important is to compare the estimated fluxes

Fig. 15 Dimensionless standard deviation as a function of $-\zeta$ for (a) T , (b) q and (c) C , produced by randomising the friction velocities. Symbols and lines are the same of Fig. 1

with independent flux measurements. More recent studies by [Andreas and Hicks \(2002\)](#) and [Hartogensis and de Bruin \(2005\)](#) deal with other MOST relationships.

To check whether the FV similarity relationships here reflect the statistics of the common variables rather than the fundamentals of turbulent scaling, the original datasets have been compared with data produced by randomising the friction velocities but retained the same sensible heat, scalar variance and fluxes (Fig. 15). In particular each 30-min measured value of u_* was replaced by a u_* drawn from a random-normal distribution having a ‘global’ mean and variance equal to the overall data mean and variance (i.e. when combining all the selected 30-min measured u_*). In this way, u_* entering into the calculations of s_* and $w'T'$ has no relationship to the true u_* measured during those conditions when σ_S and $w'T'$ were selected. Figure 15 shows that using a randomised u_* , the modelled FV similarity follows a $-1/3$ power law over the entire range of stability conditions. It is noteworthy that towards the near-neutral regime (where mechanical effects are more important than buoyancy), the randomised quantities erroneously follow the $-1/3$ power law, but the measured quantities follow the predicted similarity functions. As a consequence, the correlations are not ‘spurious’ in the near-neutral regimes.

To explore the nature of the correlations obtained in the convection regime, fluxes measured with eddy-correlation technique (correspondent to $(-\frac{z-d}{L}) > 0.2$) have been compared to modelled fluxes obtained by using the obtained similarity functions for free convection ($\frac{\sigma_S}{s_*} = C_3 (-\zeta)^{-1/3}$ where $C_3 = C_1 C_2^{-1/3}$) and thus have eliminated entirely the dependence from u_* :

Fig. 16 Turbulent fluxes of (a) T , (b) q and (c) C , measured directly using eddy-correlation technique versus the correspondent fluxes modelled by using equation (7), which is independent of u_* . Symbols are the same as in Fig. 1. For reference the 1:1 lines are also shown (dashed lines)

$$\overline{w's'} = \left(\overline{w'T'} \right)^{1/3} \frac{\sigma_s}{C_3} \left[\frac{(z-d)kg}{\overline{T}} \right]^{1/3} \quad (7)$$

Figure 16 shows good agreement between measured and modelled fluxes, in particular for the data with ‘anomalous events’ filtered out from the q and C time series (see linear correlation coefficients). On the basis of this result, it can be concluded that the correlations obtained towards the convection regime are not statistical artefacts.

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