Atmos. Chem. Phys. Discuss., 12, 6363–6418, 2012
www.atmos-chem-phys-discuss.net/12/6363/2012/
doi:10.5194/acpd-12-6363-2012

Atmospheric Chemistry and Physics Discussions

Momentum and scalar transport within a vegetation canopy following atmospheric stability and seasonal canopy changes: the CHATS experiment

S. Dupont[1] **and E. G. Patton**[2]

[1]INRA, UR1263 EPHYSE, 33140 Villenave d'Ornon, France
[2]National Center for Atmospheric Research, Boulder, CO, USA

Received: 18 January 2012 – Accepted: 22 February 2012 – Published: 29 February 2012

Correspondence to: S. Dupont (sdupont@bordeaux.inra.fr)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Momentum and scalar (heat and water vapor) transfer between a walnut canopy and the overlying atmosphere are investigated for two seasonal periods (before and after leaf-out), and for five thermal stability regimes (free and forced convection, near-neutral condition, transition to stable, and stable). Quadrant and octant analyses of momentum and scalar fluxes followed by space-time autocorrelations of observations from the Canopy Horizontal Array Turbulence Study's (CHATS) thirty meter tower help characterize the motions exchanging momentum, heat, and moisture between the canopy layers and aloft.

During sufficiently windy conditions, i.e. in forced convection, near-neutral and transition to stable regimes, momentum and scalars are generally transported by sweep and ejection motions associated with the well-known canopy-top "shear-driven" coherent eddy structures. During extreme stability conditions (both unstable and stable), the role of these "shear-driven" structures in transporting scalars decreases, inducing notable dissimilarity between momentum and scalar transport.

In unstable conditions, "shear-driven" coherent structures are progressively replaced by "buoyantly-driven" structures, known as thermal plumes; which appear very efficient at transporting scalars, especially upward thermal plumes above the canopy. Within the canopy, downward thermal plumes become more efficient at transporting scalars than upward thermal plumes if scalar sources are located in the upper canopy as the heat source. We explain these features by suggesting that: (i) downward plumes within the canopy correspond to large downward plumes coming from above, and (ii) upward plumes within the canopy are local small plumes induced by canopy heat sources where passive scalars are first injected if there sources are at the same location than heat sources. Above the canopy, these small upward thermal plumes aggregate to form larger scale upward thermal plumes. Furthermore, scalar quantities carried by downward plumes are not modified when penetrating the canopy and crossing upper scalar sources. Consequently, scalars appear to be preferentially injected into upward

thermal plumes as opposed to in downward thermal plumes.

In stable conditions, intermittent downward and upward motions probably related to elevated shear layers are responsible for canopy-top heat and water vapor transport through the initiation of turbulent instabilities, but this transport remains small. During the foliated period, lower-canopy heat and water vapor transport occurs through thermal plumes associated with a subcanopy unstable layer.

1 Introduction

Forests play an important role in biosphere-atmosphere exchanges of momentum, energy, water vapor, carbon dioxide and other trace gases. Understanding these exchanges is important for many environmental applications as well as for weather and climate forecasting. Conditional analysis of momentum and scalar fields (temperature, water vapor, trace gases) have shown that canopy-atmosphere exchange largely occurs through intermittent ventilation of the canopy air space by coherent eddy structures (Gao et al., 1989; Lu and Fitzjarrald, 1994). More precisely, quadrant analysis has shown that momentum fluxes are largely explained by strong sweeps and weak ejections associated with these coherent eddy structures (Finnigan, 2000; Poggi et al., 2004). Time-traces of scalar fields reveal ramp patterns which result from these coherent structures (e.g., Gao et al., 1989; Paw U et al., 1992; Finnigan et al., 2009). Under near-neutral conditions, observations confirm this similarity between momentum and scalar transport over a range of vegetated surface types (Coppin et al., 1986; Chen, 1990). With departure from neutral stability conditions, the mechanisms responsible for momentum and scalar transport seem to differ due to modification of the coherent eddy structure topology (Chen, 1990; Li and Bou-Zeid, 2011). Across all stability classes, scalar-scalar transport dissimilarity has also been observed within the atmospheric boundary layer (ABL) and over vegetation which has been attributed to differences of distribution of scalar sources and sinks (Williams et al., 2007) and to the scalar gradient across the top of the ABL's entrainment zone (Moene et al., 2006).

ACPD
12, 6363–6418, 2012

Coherent eddy structures apparently play a crucial role in momentum and scalar transport. Over homogeneous vegetation canopies, coherent eddy structures have been investigated for years using outdoor and wind-tunnel measurements (e.g., Paw U et al., 1992; Collineau and Brunet, 1993a,b; Turner et al., 1994; Qiu et al., 1995; Shaw et al., 1995; Brunet and Irvine, 2000; Ghisalberti and Nepf, 2002) as well as numerical experiments (Shaw and Schumann, 1992; Kanda and Hino, 1994; Patton et al., 2001; Su et al., 2000; Watanabe, 2004; Dupont and Brunet, 2008; Finnigan et al., 2009). These efforts have contributed substantially to our understanding of canopy-scale organized motions, but most of the analysis has been limited to near-neutral stability conditions. It is thought that these coherent structures scale with vorticity thickness and that the average (or "characteristic") structure can be described as the superposition of two hairpin vortices with strong sweeps (gusts) and weak ejections (bursts) between the hairpin legs (Finnigan et al., 2009). In contrast to "buoyantly-driven" motions (thermal plumes) in free convection, these "shear-driven" structures are generated by processes similar to those occurring in a plane-mixing layer flow (Raupach et al., 1996), where Brunet and Irvine (2000) attempted to extend Raupach et al.'s (1996) mixing-layer analogy to non-neutral atmospheric conditions using a broader data set.

Recent studies indicate that these "shear-driven" coherent eddy structures may not be the sole structure type participating in canopy exchange. Dupont and Patton (2012) observed that both seasonally driven canopy morphology evolution and departures from neutral stability can weaken the plane mixing-layer analogy of canopy flow, which can even vanish completely in the weak-wind free convective and strongly stable regimes. Dupont and Patton (2012) speculated that with increasing instability, the "shear-driven" coherent eddy structures may initially coexist with and ultimately be replaced by thermal plumes. This speculation is consistent with Li and Bou-Zeid's (2011) recent study over natural surfaces (a lake and a vineyard), who also suggested that with increasing instability the transport dissimilarity between momentum and scalars could be explained through modification of the near-neutral surface atmospheric boundary layer's hairpin vortices and hairpin packets and their evolution

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD

12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

into upward- and downward-moving thermal plumes. In sparse canopies, Poggi et al. (2004) and Kobayashi and Hiyama (2011) suggested that mixing-layer type structures might also coexist with traditional atmospheric surface layer (ASL) turbulence. In canopies with large and sparse trunk spaces, the mixing-layer's shear-driven structures may also coexist with well-defined wake structures which develop in the lee of tree stems (Cava and Katul, 2008; Launiainen et al., 2007; Dupont et al., 2012), but with length scales similar to the scale of the individual canopy elements. In stable atmospheric stability conditions, an unstable layer can develop in the lower canopy (Shaw et al., 1988; Jacobs et al., 1994; Dupont and Patton, 2012), generating the potential development of both intermittent, small "shear-driven" type coherent eddy structures at the canopy top and thermal plumes lower in the canopy. Consequently, with seasonal canopy changes and with the diurnal evolution of atmospheric stability, the mechanisms responsible for turbulent momentum and scalar exchange between the canopy and the atmosphere may vary.

The goal of the present paper is to: (1) further investigate the sensitivity of momentum and scalar transport over a deciduous forest to the thermal stability and to the seasonal changes of the forest, (2) to establish whether heat, water vapor and momentum are transported similarly, and (3) to characterize the turbulent structures accomplishing momentum and scalar transport. To that purpose, we use measurements performed from the 30 m profile tower of the Canopy Horizontal Array Turbulence Study (CHATS) (Patton et al., 2011). The CHATS experiment took place in Spring 2007 over a 10 m tall deciduous walnut orchard in California (USA) prior to and following leaf-out. The 30 m tall tower was densely instrumented with turbulence sensors, including sonic anemometers for sampling turbulent wind and temperature fields, and krypton hygrometers for water vapor. Compared to previous studies (e.g., Coppin et al., 1986; Chen, 1990; Li and Bou-Zeid, 2011), we investigate momentum and scalar transport: (1) within and above the vegetation, (2) across two different seasonal periods (with and without leaves) for which scalar source/sink distributions vary accordingly, and (3) across five atmospheric stability regimes (free and forced convection, near-neutral,

ACPD
12, 6363–6418, 2012

transition to stable and stable).

In a previous study (Dupont and Patton, 2012), statistical profiles of micrometeorological fields from the first to the fourth moment were analyzed in great detail following the five above stability regimes and the two seasonal periods. In this current manuscript, after recalling the main experimental setup and the main canopy-induced micrometeorological characteristics (Sect. 2), we present an investigation of momentum, heat and water vapor transport through quadrant and octant analyses (Sects. 3 and 4). The organized turbulent structures are then analyzed through space-time autocorrelations in Sect. 5. Finally, in Sect. 6, we discuss the general behavior of turbulent exchange within the CHATS walnut orchard as impacted by canopy morphology and atmospheric stability.

2 Method

2.1 Experiment

The CHATS experiment took place in Spring 2007 in one of Cilker Orchard's walnut (*Juglans regia*) blocks in Dixon, California (Fig. 1a). The orchard block was located on a flat terrain with less than a 1 m elevation difference across the entire $(1.6\,\text{km})^2$ orchard block and was surrounded by blocks of different walnut varieties and almonds. The campaign consisted of two intensive measurement periods: one from 15 March to 13 April focusing on the walnut trees before leaf-out (Fig. 1c) and another from 13 May to 12 June focusing on the walnut trees after leaf-out (Fig. 1d). These two periods will be hereafter referred as (i) the periods without leaves and with leaves, or (ii) the defoliated and foliated periods, or (iii) the no-leaves and with-leaves periods, respectively.

The trees were planted in a nearly-square pattern such that they were about 6.9 m apart in the N–S direction, and 7.3 m in the W–E direction. The trees were all about 25 yr old with an average height h of about ten meters. Before leaf-out, the cumulative

ACPD
12, 6363–6418, 2012

S. Dupont and E. G. Patton

PAI (Plant Area Index) was about 0.7, while following leaf-out the PAI increased to about 2.5. Figure 1b shows the average vertical profiles of normalized plant area density (PAD, square meter of frontal plant area per cubic meter of air) averaged over the no-leaves and with-leaves periods.

The in-situ instrumentation during CHATS was located in two main arrangements: a thirty meter vertical tower and a horizontal array. For this manuscript, we focus solely on data from the 30 m tower (Fig. 2). The tower was located near the northern-most border of the section (Fig. 1a) to provide a fetch of about 150 canopy heights when focusing on southerly winds.

Turbulent velocity components and air temperature fluctuations were measured simultaneously at 6 levels within the canopy (1.5, 3.0, 4.5, 6.0, 7.5, 9.0 m), one at canopy top (10.0 m), and 6 levels above canopy (11.0, 12.5, 14.0, 18.0, 23.0, 29.0 m) using thirteen Campbell Scientific CSAT3 sonic anemometers sampling at 60 Hz. Twelve NCAR-Vaisala Hygrothermometers (TRH) operating at 2 Hz sampled air temperature and relative humidity profiles at the same heights as the CSAT3's but with the exception of the 12.5 m level. Campbell Scientific KH2O Krypton hygrometers sampling at 20 Hz measured water vapor density fluctuations at 6 levels (1.5, 4.5, 7.5, 10.0, 14.0, and 23.0 m). All instruments on the tower were intercalibrated at the NCAR calibration facility prior to and following the experiment. Turbulence measurements were quality controlled following standard procedures (Dupont and Patton, 2012).

The integration time for all statistics was chosen as 30 min for unstable and near-neutral conditions and as 5 min for stable conditions. This lower integration time for stable conditions was used to reduce the contribution from non-turbulent motions. At all heights the recorded wind velocity components were rotated horizontally so that u represents the horizontal component along the mean wind direction x deduced at canopy top, v the horizontal component along the transverse direction y, and w the vertical component along the direction z. Statistical variables were classified following five thermal stability regimes defined at the canopy top following the procedure described in Dupont and Patton (2012): free convection (referred hereafter as FrC),

ACPD
12, 6363–6418, 2012

S. Dupont and E. G. Patton

forced convection (FoC), near-neutral (NN), transition to stable (TS) and stable (S). Only southerly winds are considered in order to have the maximum fetch at the tower.

For a more complete description of the CHATS experiment, we refer the reader to Patton et al. (2011).

2.2 Flux partitioning

In order to characterize the turbulent structures responsible for transporting momentum, heat and water vapor, quadrant and octant analyses are performed.

2.2.1 Quadrant analysis

Quadrant analysis decomposes fluxes into quadrants based upon the sign of the fluctuating quantities contributing to the co-variance (e.g., Willmarth and Lu, 1972). We use a parameter I_k to define the quadrants, such that for any quadrant k:, $I_k = 1$ when the flux falls into quadrant k, and $I_k = 0$ when it does not. Thus for momentum flux in quadrant 1, $I_1 = 1$ when $u' > 0$ and $w' > 0$, and $I_1 = 0$ otherwise. The criteria defining each of the four quadrants are presented in Table 1. For simplicity when discussing the quadrants, we will refer to them as Q1, Q2, Q3 and Q4.

Time averages of momentum or scalar fluxes occurring in each quadrant k are calculated using:

$$\langle u'w' \rangle_k = \frac{1}{N} \sum_{t=1}^{N} u'w'I_k \,, \tag{1}$$

and

$$\langle w'\phi' \rangle_k = \frac{1}{N} \sum_{t=1}^{N} w'\phi'I_k \,, \tag{2}$$

respectively. Where, $\langle\,\rangle$ denotes the 30-min time average for unstable (FrC and FoC) and near-neutral conditions and the 5-min time average for stable conditions (TS and

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD

12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

S), the prime $'$ depicts the deviation from the average value, ϕ is either the air temperature t or the air specific humidity q.

For momentum flux, Q2 and Q4 correspond to ejection ($u' < 0$ and $w' > 0$) and sweep ($u' > 0$ and $w' < 0$) motions, respectively. In the literature, scalar Q1 and Q3 fluxes have also been referred to as ejection and sweep motions during unstable conditions (e.g., Chen, 1990; Katul et al., 1997; Li and Bou-Zeid, 2011). However, organized motions associated with momentum fluxes are not necessarily the same as those transporting scalars (Böhm et al., 2010), especially in unstable conditions. Therefore in order to eliminate ambiguity, we will hereafter use the terms *sweep* and *ejection motions* only for momentum quadrant events, i.e. fast momentum fluid transported downward and slow momentum fluid transported upward, respectively. For scalar fluxes under unstable conditions, Q1 and Q3 events will be referred to as upward and downward plumes.

The magnitude fractions of the momentum and scalar fluxes within quadrant k are computed as:

$$F_k^{\tau_{uw}} = \left|\langle u'w'\rangle_k\right| \Big/ \sum_k \left|\langle u'w'\rangle_k\right| \quad (3)$$

$$F_k^{\tau_{w\phi}} = \left|\langle w'\phi'\rangle_k\right| \Big/ \sum_k \left|\langle w'\phi'\rangle_k\right| \quad (4)$$

The reader is therefore cautioned that the magnitude fractions are presented as the absolute value of the flux in a particular quadrant normalized by the sum of the absolute value of the flux across all four quadrants. This choice permits intercomparison across all stability regimes, however it should be noted that this choice eliminates the sign of the flux and forces the sum over all four quadrants to a value of one.

2.2.2 Octant analysis

In an octant analysis, the quadrant decomposition of the momentum flux is further decomposed following the sign of the temperature or water vapor fluctuations in order to

ACPD
12, 6363–6418, 2012

establish whether temperature and water vapor are transported similarly as momentum. The same approach was used by Böhm et al. (2010) and van Gorsel et al. (2010). Hence, the momentum flux in quadrant k ($\langle u'w'\rangle_k$) can be decomposed as:

$$\langle u'w'\rangle_k = \langle u'w'\rangle_k^{\phi^+} + \langle u'w'\rangle_k^{\phi^-} \tag{5}$$

where ϕ is either t or q, and $^{\phi^+}$ or $^{\phi^-}$ refers to whether the instantaneous momentum flux coincides with positive or negative ϕ fluctuations.

The magnitude fractions of momentum flux in quadrant k coincident with positive and negative ϕ fluctuations are calculated using:

$$F_k^{\tau_{uw}|\phi^+} = \left|\langle u'w'\rangle_k^{\phi^+}\right| \Big/ \sum_k \left|\langle u'w'\rangle_k\right| \tag{6}$$

and

$$F_k^{\tau_{uw}|\phi^-} = \left|\langle u'w'\rangle_k^{\phi^-}\right| \Big/ \sum_k \left|\langle u'w'\rangle_k\right| . \tag{7}$$

2.3 Correlation coefficients between fluxes

An other method to investigate the similarity between momentum, heat and water vapor fluxes is to look at the correlation coefficients between momentum and scalar fluxes, $r_{uw,w\phi}$, and between heat and water vapor fluxes, $r_{wt,wq}$, which Li and Bou-Zeid (2011) defined as:

$$r_{uw,w\phi} = \frac{\left\langle \left(u'w' - \langle u'w'\rangle\right)\left(w'\phi' - \langle w'\phi'\rangle\right)\right\rangle}{\sigma_{uw}\,\sigma_{w\phi}} \tag{8}$$

$$r_{wt,wq} = \frac{\left\langle \left(w't' - \langle w't'\rangle\right)\left(w'q' - \langle w'q'\rangle\right)\right\rangle}{\sigma_{wt}\,\sigma_{wq}} \tag{9}$$

ACPD
12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

where ϕ is either the air temperature t or the air specific humidity q, σ_{uw} and $\sigma_{w\phi}$ are the standard deviation of $u'w'$ and $w'\phi'$, respectively.

2.4 Space-time autocorrelations

In order to characterize the space and time scales of the structures associated with individual quadrant events, space-time autocorrelation analysis of streamwise and vertical wind velocity components, temperature and water vapor are performed using:

$$R^k_{\varphi\varphi}(T,z) = \frac{\langle \varphi'(0,Z)\,\varphi'(T,z)\rangle_k}{\sqrt{\langle \varphi'(0,Z)^2\rangle_k\,\langle \varphi'(T,z)^2\rangle_k}} \qquad (10)$$

where, φ refers to one of u, w, t or q. Although Eq. (10) can apply generally to any quadrant analysis, our discussion in Sect. 5 will only investigate autocorrelation analyses broken down by heat flux quadrants. Therefore k refers to the heat flux quadrant under consideration (as defined in Table 1 for heat flux). The reference point for the correlation is located at the height Z and at time $T = 0$.

2.5 Main micrometeorological characteristics

The within- and above-canopy micrometeorological response to atmospheric stability and seasonal canopy morphology variation was thoroughly analyzed and previously discussed in Dupont and Patton (2012). To permit interpretation of the analysis presented herein within the context of those findings, it is helpful to present the main features here. Figure 3a,b compares profiles of mean normalized streamwise wind velocity ($\langle u\rangle$), air temperature ($\langle t\rangle$), water vapor ($\langle q\rangle$), momentum flux ($\langle u'w'\rangle$), heat flux ($\langle w't'\rangle$), and water vapor flux ($\langle w'q'\rangle$) across the five stability regimes, where Fig. 3a,b presents the findings during the period without- and with-leaves, respectively. Variables are normalized by a reference value located at canopy top (10 m).

In near-neutral stability conditions, the turbulent wind exhibits the following universal characteristics during the foliated period (Fig. 3b): (i) strong wind shear at canopy top

ACPD
12, 6363–6418, 2012

associated with an inflection point in the mean horizontal velocity, (ii) rapid decrease of momentum flux with descent into the canopy, and (iii) positive and negative Sk_u and Sk_w at canopy top, respectively (see Dupont and Patton, 2012). During the period without leaves (Fig. 3a), these same features are present but less exacerbated due to the lower canopy density: the inflection point occurs at around 6 m height and the magnitude of the skewness maxima reduces (see Dupont and Patton, 2012). It was observed in Dupont and Patton (2012) that the resemblance of the canopy flow with plane mixing-layer flow is stronger during the foliated period than during the defoliated period.

In unstable atmospheric conditions (FoC and FrC), a negative temperature gradient of less than 1 K is observed between canopy-top and above, and within-canopy air always appears more humid than above-canopy air, especially during the foliated period. In near-neutral conditions, wind statistics profiles show similar features with or without leaves on the trees. However with increasingly unstable conditions, the wind shear decreases at the inflection point, the gustiness of the flow increases, and wind skewness maximums decrease in magnitude (see Dupont and Patton, 2012, for these latter two findings). Heat and water vapor flux profiles suggest that heat and water vapor sources are distributed similarly during the foliated period (i.e. mostly through the upper canopy and to a lesser extent at the ground), but that during the unfoliated period heat and moisture sources differ (i.e. small and at the ground for water vapor, and large and both at the ground and through the upper canopy for the heat, amplitude not shown). Within-canopy scalar skewness appears dependent on the source location (see Dupont and Patton, 2012).

During stable atmospheric conditions (TS and S), a positive temperature gradient of about 3 K generally develops between the canopy and aloft. During the foliated time frame, temperature and heat flux profiles indicate a well-defined unstable layer in the lower canopy. With increasingly stable conditions, wind statistics exhibit similar tendencies as with increasingly unstable conditions.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD
12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

From these micrometeorological characteristics, Dupont and Patton (2012) concluded that: (i) “shear-driven” or mixing-layer type coherent structures located at canopy top are strongest in near-neutral conditions and with leaves on the trees, (ii) with increasingly unstable conditions, “buoyantly-driven” coherent structures may become important and coexist with or replace mixing-layer type structures, (iii) in stable conditions as well as when the trees are foliated, small and intermittent “shear-driven” structures or Kelvin-Helmholtz instabilities may be present at canopy top, which coexist with “buoyantly-driven” coherent structures in the lower canopy layers during the foliated period, and (iv) the vertical distribution of scalar sources influences micrometeorological characteristics and therefore may impact turbulent exchange and structure. In the next sections, we will further investigate these points by analyzing momentum and scalar transport and associated turbulent structures.

3 Momentum transport

Quadrant analysis (e.g., Willmarth and Lu, 1972) provides information on the motions responsible for momentum transport. Figure 4 presents the fraction of $\langle u'w' \rangle$ in each quadrant, as defined in Eq. (3), according to variations in atmospheric stability and to canopy morphology.

Consistent with current understanding (e.g., Finnigan, 1979; Shaw et al., 1983), in near-neutral conditions (NN) momentum flux in the upper canopy occurs through a combination of ejections and sweeps, but the majority of momentum transport occurs via sweeping motions (Fig. 4). During the foliated period, sweeps and ejections transport about 60 % and 25 % of the momentum flux in the upper canopy, compared with 55 % and 25 % during the period with no-leaves. Furthermore, sweeps dominate momentum transport through the entire canopy during the period with no-leaves, but during the foliated period sweeps only dominate transport in the canopy's foliated region, i.e. above $z/h \sim 0.4$ or $z \sim 4$ m; suggesting that the “shear-driven” coherent eddy structures do not penetrate as deeply (i.e. have a smaller vorticity thickness) when the

ACPD
12, 6363–6418, 2012

canopy is foliated. Above the canopy, momentum transfer still occurs largely through sweeps and ejections, but ejections dominate above $z/h \sim 1.4$; suggesting a transition of the flow regime from a dominance of the canopy-induced "shear-driven" coherent eddy structures to that of traditional rough-wall boundary layers whose mean wind profile varies logarithmically with height and whose momentum transport has been shown to be dominated by ejections (e.g., Adrian, 2007). This general feature is in agreement with previous observations over vegetated canopies (Raupach et al., 1996; Finnigan, 2000; Poggi et al., 2004; Dupont and Brunet, 2008) and confirms that under near-neutral conditions momentum transfer at canopy top primarily occurs through the penetration of the canopy by fast, downward-moving gusts. We note that Finnigan et al. (2009) proposed these "shear-driven" coherent eddy structures to be comprised of a linked pair of hairpin vortices; i.e. a combination of an ejection-producing head-up and a sweep-producing head-down, with the head-down vortex dominating at canopy-top due to rapid straining and preferential vorticity amplification associated with downward deflections.

With departures from neutral stability (i.e. in the TS and FoC regimes), the momentum flux distribution closely mimics the NN regime, but with a reduced overall contribution from sweep and ejection motions and compensating larger contributions from inward and outward interactions. In FoC and during the foliated period, the contribution from ejections reduces to a similar magnitude as the inward and outward interaction contributions within the canopy. These two regimes reveal an intermediate behavior between the NN regimes and the two other extreme stability regimes (S and FrC).

In free convection (FrC), the momentum flux is small and its partitioning is nearly equal across the four quadrants; with only 15 % differences between quadrants within the canopy. In the upper canopy, downward motions dominate momentum transfer during both seasonal periods, with a slight bias toward inward interactions while ejections contribute the least. During the foliated period, upward motions contribute most to near-surface momentum transfer, but not overwhelmingly so.

ACPD
12, 6363–6418, 2012

S. Dupont and E. G. Patton

In stable conditions (S), sweeps contribute slightly more to upper-canopy momentum transport than the other quadrants during the period with no-leaves and the other quadrants contribute nearly equally. However during the foliated period, the distribution is more complex due to the development of the lower-canopy unstable layer. Hence in the upper canopy, downward motions dominate slightly, while ejections control slightly momentum transport in the lower canopy with inward interactions contributing the least. These differences between quadrants are less than 10 % throughout the canopy.

In conclusion, the classic "shear-driven" coherent eddy structures (1) appear well defined in the NN regime, (2) are still present in FoC and TS but weaker for transporting momentum, and (3) are negligible in FrC and S regimes. This result confirms Dupont and Patton's (2012) observations where they showed via analysis of momentum flux correlation coefficients that "shear-driven" coherent eddy structures transport momentum most efficiently during near-neutral conditions.

4 Scalar transport

The linkages between turbulent structures and scalar transport are analyzed in this section. To determine whether the same sweep/ejection events dominating momentum also transport temperature and water vapor, we now extend Sect. 3's quadrant analysis of momentum fluxes using octant analysis (Sect. 4.1). When scalar fluxes are not associated with the same momentum-derived quadrant events, we then use a quadrant analysis of heat and water vapor fluxes to identify the type of events transporting scalars (Sect. 4.2). Finally, flux correlation analysis permits analysis of the similarity between momentum, heat and water vapor flux similarity (Sect. 4.3).

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD

12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

4.1 Momentum flux partitioning and the connection with scalar transport

4.1.1 Temperature

As described in Sect. 2.2.2, octant analysis helps identify whether momentum quadrant events transport positive or negative scalar perturbations. For both leaf-states, Figs. 5 and 6 present octant analyses for temperature fluctuations, where positive and negative fluctuations are denoted by t^+ and t^-, respectively.

Because heat fluxes are negligible during NN, one should expect that momentum quadrant events during NN should transport t^+ and t^- equally. This expectation is well-observed during the foliated period (Fig. 6), but Fig. 5 shows that ejections transport more t^- than t^+ (and the opposite for sweep motions) during the period without leaves. We attribute this discrepancy to the larger number of 30-min periods within the stable side of the NN regime than in the unstable side (see Fig. 4 of Dupont and Patton, 2012).

During TS and across both seasonal periods (Figs. 5 and 6), ejection motions generally transport more t^- from the upper canopy up to 29 m, while sweeping motions transport more t^+ within the canopy peaking at about $z = 6$ m. These findings are consistent with the fact that temperature generally increases with height in stable conditions. The maximum at $z = 6$ m also implies that sweep motions transport warm air most efficiently at this height. Inward and outward interactions (Q3 and Q1) transport t^+ and t^- equally, except: (i) in the upper canopy during the no-leaves period with a slight higher proportion of t^+ for slow downward motions (Q3), and (ii) in the lower canopy during the foliated period where fast upward and slow downward motions transport more t^+ and t^-, respectively.

For the period without leaves (Fig. 5), the momentum fluxes in the four quadrants are similar between the weakly stable (TS) and strongly stable (S) regimes, although ejections and sweeps more equally transport t^+ and t^- in strongly stable conditions (S). However during the foliated period and in the lower canopy, downward motions (Q3 and Q4) transport more t^- and upward motions (Q1 and Q2) more t^+ in both regimes (TS and S). This results from radiative cooling of the upper canopy air by the

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD

12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

leaves (which are of low heat capacity) such that downward(upward) motions in the lower canopy layers import relatively cool (warm) air. In stable regime (S), downward motions efficiently transport t^+ at canopy top, while above the canopy upward motions transport slightly more t^-.

In unstable forced convection (FoC), ejection and sweep motions transport more t^+ and t^-, respectively (Figs. 5 and 6). As was found for TS, sweeps transport heat most effectively at about 6 m, but in FoC conditions the sweeps transport cooler air (t^-) into the canopy layers, which is consistent with the fact that under unstable conditions the vertical gradient of temperature is negative. An important interpretation of this result is that the presence of heat sources throughout the upper canopy does not change the sign of the temperature fluctuations transported by sweep motions penetrating the canopy. The efficiency of ejections at transporting heat decreases rapidly with depth into the canopy, although in FoC ejections now typically transport t^+ instead of t^- as was shown for TS. During period with no-leaves, inward and outward interaction motions transport t^+ and t^- equally, except in the lower canopy for the slow downward motions which transport slightly more t^-, which is likely related to large atmospheric boundary layer (ABL) scale downward motions penetrating deep within the canopy. During the foliated period, outward and inward interaction motions appear more efficient in transporting t^+ and t^-, respectively, and are almost as efficient as ejection and sweep motions. This feature is even more pronounced in the free-convection regime (FrC) across both seasonal periods, where upward motions (Q1 and Q2) transport more t^+ and downward motions (Q3 and Q4) more t^- within and above the canopy. The FrC data also shows that within the upper canopy, downwelling motions transport t^- more effectively than upward motions transport t^+, a feature that is somewhat exacerbated when there are leaves on the trees. We suspect that this feature during the FrC regime results from the fact that upwelling motions are largely connected with small-scale convective plumes that are in their infancy developing from canopy-imposed heat sources (either the woody matter or the leaves), while downwelling motions are associated with large ABL-scale convective cells which are able to penetrate through the upper canopy bringing much cooler air from aloft.

4.1.2 Water vapor

Generally speaking, the octant analysis for water vapor fluctuations (Figs. 7 and 8) exhibits only few differences compared to that just discussed for temperature fluctuations. For all stability regimes, upward motions more likely transport q^+ and downward motions more likely q^-; which results from the generally negative vertical gradient of water vapor in the lower atmosphere. As was found for heat, negative water vapor fluctuations carried by downward motions are not impacted by crossing water vapor sources in the upper canopy. As mentioned in Sect. 2.5, the source location for heat largely remains distributed through the canopy for both seasonal periods. However, water vapor sources occur mostly at the ground during the period without leaves, and when the leaves are on the trees water vapor sources are largely distributed through the upper canopy. The upper canopy source during the with-leaves period generally increases the efficiency of upward motions at transporting q^+ above the canopy and increases the efficiency of downward motions at transporting q^- in the upper canopy. This result is consistent with Dupont and Patton's (2012) correlation coefficient analysis which suggested increased water vapor transport efficiency when emitted through the upper canopy than at the ground. Note that this source-location influence on water vapor transport efficiency also has implications for residence times of other trace gases since surface emitted species are apparently transported less efficiently within the canopy layers than species emitted in a distributed fashion through the canopy depth, suggesting longer within-canopy residence times for surface-emitted species.

It follows from this octant analysis that sweeps and ejections, i.e. "shear-driven" coherent eddy structures, play a major role in transporting scalars in the FoC, NN and TS regimes, while in FrC and S regimes upward and downward motions seem more important. The efficiency of scalar transport by organized structures is even more important if the source is located in the upper canopy. Furthermore, scalars carried by downward motions do not seem impacted by crossing scalar sources. More precisely, downward

ACPD
12, 6363–6418, 2012

motions appear more efficient at transporting dry and cool air within the canopy in unstable conditions, even well below the main water vapor and heat sources. This feature indicates important information on scalar sources, which will be discussed further in Sect. 6.

4.2 Quadrant analysis of scalar fluxes

In free convection (FrC) and stable (S) conditions, Fig. 4 showed that sweeps and ejections do not contribute significantly more to momentum transfer than inward and outward interactions. We now investigate whether direct quadrant analysis of scalar fields reveal similar results; Figs. 9 and 10 show a quadrant analysis of heat and water vapor fluxes, respectively, for both seasonal periods and all stability conditions.

4.2.1 Above the canopy

Above the canopy, the turbulent heat flux in stable conditions (S) mostly occurs through upward motions carrying cool air (Q4) and secondly by downward motions carrying warm air (Q2). While in unstable conditions (FrC), the turbulent heat flux occurs through upward motions carrying warm air (Q1) and then secondly by downward motions carrying cool air (Q3). However analysis of the number of events within each quadrant (not shown), the opposite is true: (i) warm downward motions are more frequent than cool upward motions in stable conditions, and (ii) cool downward motions are more frequent than warm upward motions during unstable conditions. The dominance of warm upward motions at transporting heat increases with increasingly unstable conditions while differences in the amplitude between warm downward and cool upward motions decreases slightly with increasingly stable conditions. We attribute the relative increase of Q1 vs. Q3 in unstable conditions compared to the more similar magnitudes of Q4 vs. Q2 in stable conditions to fact that under unstable conditions, convective plumes impart vertical asymmetry in the buoyancy forcing, where updrafts confined to narrow regions efficiently transporting locally-sourced heat upward in the direction of

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD
12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

the buoyancy forcing and downdrafts are spatially much broader and weaker and transport heat entrained from above the ABL less-efficiently downward against the buoyancy forcing (e.g., Wyngaard and Brost, 1984; Schmidt and Schumann, 1989). This fact that convective plumes transport scalars upward more efficiently than downward is also consistent with a variety of previously reported observations above natural and urban surfaces (e.g., Maitani and Ohtaki, 1987; Chen, 1990; Moriwaki and Kanda, 2006; Li and Bou-Zeid, 2011).

Turbulent water vapor fluxes above the canopy are similarly explained by humid upward motions (Q1) and dry downward motions (Q3) across all stability regimes (Fig. 10), where the dominance of Q1 and Q3 events is generally more pronounced during the foliated period. During the defoliated period, the partitioning of the water vapor flux across quadrants does not vary much with height above the canopy compared to during the foliated period. We purport that these seasonal differences in the partitioning across quadrants result from the different water vapor source locations during the two periods (i.e. at the ground for the defoliated period, and distributed through the canopy for the foliated period).

4.2.2 Within the canopy

During both seasonal periods, a switch occurs between the quadrant events responsible for heat transport above the canopy and within; where this switch occurs both with regards to transport efficiency (Fig. 9) and to the frequency of occurrence (not shown). For example, counter to the above-canopy findings just discussed, cool downward plumes (Q3 events) dominate within-canopy heat transport in unstable conditions (FrC and FoC) peaking at around $z = 6$ m for the defoliated period and shifting up to $z = 7$ m in the presence of the leaves. Similarly, the frequency of cool downward plumes (Q3) decreases while that of warm upward plumes (Q1) increases, to even become larger than cool downward plumes (not shown). Water vapor fluxes exhibit a similar switch near canopy-top (i.e. dry downward plumes (Q3) become more efficient than humid upward plumes (Q1) at transporting water vapor, Fig. 10). However,

ACPD
12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

this switch only occurs during the foliated period, while during the defoliated period, moist upward plumes (Q1) remain more efficient (or equally efficient) and less frequent than dry downward plumes (Q3) at transporting water vapor. This different behavior for within-canopy water vapor transport (i) with season and (ii) between heat and water vapor during the defoliated period, can only be related to the difference of source distribution of water vapor between both seasonal periods and to the difference of source distribution between heat and water vapor during period without leaves, respectively.

As mentioned previously, warm/moist downward motions (Q4) dominate above-canopy heat and water vapor transport in stable conditions (TS and S), but the importance of these Q4 motions rapidly diminishes with depth into the canopy where cool/dry upward motions (Q2) become the main mechanism for transporting heat and water vapor. In the lower canopy, warm upward (Q1) motions dominate near-surface transport during unstable conditions, a finding which is similar to that found above the canopy during unstable conditions. In stable conditions (S), warm upward (Q1) and cool downward (Q3) motions also dominate the heat flux. Unstable air in this layer explains this behavior. During TS however, leaves substantially modify the mechanisms transporting heat and moisture in the lower canopy; warm upward (Q1) and cool downward (Q3) motions dominate subcanopy transport when the leaves are present, but when the leaves are absent subcanopy heat transport largely occurs through upward cool (Q2) motions. We know from Fig. 4 that during the defoliated period in TS conditions, sweeps events dominate momentum exchange in the lower canopy. During the defoliated period, heat transport in the lower canopy occurs largely through warm downward (Q2) motions, while during the foliated period the leaves absorb and re-emit a portion of the surface-emitted radiation back toward the surface keeping the surface relatively warm. Therefore leaves in the upper canopy which are exposed to the sky cool faster than the surface generating an unstable layer in the lower canopy. Hence during the foliated period, heat and water vapor transport in the lower canopy occurs through thermal plumes confined within the canopy extending to between (4, 7) m height during (TS, S) conditions, respectively.

ACPD
12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

To recapitulate, in free convection (FrC) above-canopy heat and water vapor transport largely occurs through a combination of warm/humid upward (Q1) and cool/dry downward (Q3) motions, providing evidence of convective plumes. While in stable conditions (TS and S), cool/humid upward motions and warm/dry downward motions generally account for their transport. In contrast to these above-canopy findings associated with unstable conditions, upward and downward motions switch their importance within the canopy in response to the canopy-imposed scalar source. This switch likely relates to the active role of heat inducing small local thermal plumes at the heat source location which also transport water vapor emitted at the same location. This idea will be discussed further in Sect. 6.

4.3 Dissimilarity between momentum, heat and water vapor transport

Li and Bou-Zeid (2011) recently used correlation coefficients between momentum and scalar fluxes (or scalar-scalar fluxes) to investigate transport similarity/dissimilarity in the atmospheric surface layer above a lake and a vineyard. To investigate the influence of stability and canopy morphology on transport similarity, Fig. 11 presents correlation coefficients between momentum flux and scalar (heat and water vapor) fluxes, $r_{uw,wt}$ and $r_{uw,wq}$, as well as the correlation coefficient between the two scalar fluxes, $r_{wt,wq}$, for both seasonal periods and for the five stability regimes (Eqs. 8 and 9).

Generally speaking, Fig. 11 confirms that the absolute correlations between momentum and scalar fluxes decrease with departures from neutral stability. Absolute correlations between momentum and water vapor fluxes increase during the foliated period for the non-extreme regimes (FoC and TS) because momentum sinks and water vapor sources both largely occur through the canopy, while during the defoliated period water vapor solely comes from the ground. Similarly, $r_{wt,wq}$ increases during the foliated period due to the general co-location of their sources. For all stability regimes, correlations between momentum and scalar fluxes decrease in the lower canopy tending toward zero at the ground.

ACPD
12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

5 Characterization of main turbulent structures

The analysis presented in the previous sections showed that heat and water vapor are generally transported: (1) by warm upward and cool downward thermal plumes in free convection, (2) by sweep and ejection motions in near-neutral conditions, and (3) by warm downward and cool upward motions at canopy top and by warm upward and cool downward thermal plumes in the lower canopy during stable conditions. Since canopy-top sweep and ejection motions during near-neutral conditions have already been discussed in the literature (e.g., Shaw et al., 1983), we now use space-time autocorrelation analysis to illuminate coherent motion characteristics during the two extreme stability regimes (FrC and S).

5.1 Warm upward and cool downward thermal plumes during free convection

Space-time autocorrelations (Eq. 10) provide information regarding the distance/time over which samples at a fixed location and time are correlated with samples at earlier or later times and other heights on the tower during a particular heat flux quadrant event. For both seasonal periods, Figs. 12–14 present contours of the average space-time autocorrelations of u, w, t and q during free convective conditions (FrC), where events associated with warm upward and cool downward plumes (i.e. Q1 and Q3 for heat flux) are calculated and presented separately. For all three figures, the time reference point is $T = 0$ min, and the space reference point varies for each figure such: $Z = 23$ m (Fig. 12), $Z = 10$ m (canopy top, Fig. 13), and $Z = 4.5$ m (Fig. 14). For simplicity, we will hereafter refer to space-time autocorrelations from Eq. (10) as R_{uu}, R_{ww}, R_{tt} and R_{qq} for autocorrelations of u, w, t and q, respectively, and will delineate them according to their association with either warm upward or cool downward plumes. In these figures, negative times correspond to times before the structure detection (downwind condition) and positive times to times after the structure detection (upwind condition). Note that the time coordinate for R_{ww} spans a shorter duration than the other autocorrelations.

With the reference point located above the canopy at $Z = 23$ m (Fig. 12), autocorrela-

ACPD
12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

tion contours indicate that warm upward motions are more connected to regions within the canopy than are cool downward motions, especially during the foliated period and for R_{ww}, R_{tt} and R_{qq}. The correlations are generally quite low within the canopy, except for R_{qq} during the period with no-leaves, where the within-canopy R_{qq} correlations remain quite large over a relatively longer time frame than do the autocorrelations for other variables. Scalar correlation contours (i.e. R_{tt} and R_{qq}) also generally extend upwind for cool-downward plumes and downwind for warm-upward plumes.

With respect to their size and shape, autocorrelations referenced to canopy-top (Fig. 13) reveal distinct differences between the two seasonal periods compared to those referenced above the canopy. R_{uu} and R_{ww} contours appear smaller during the foliated period resulting from the higher canopy density, where (1) the higher canopy density limits downward penetration of the cool-downward motions into the canopy, and (2) the leaves' active contribution to initiating small warm-upward plumes. For both seasonal periods, R_{ww} contours exhibit very limited correlation in time with relatively stronger correlation in the vertical. R_{uu} contours reveal substantially more correlation than R_{ww}, but with notably shorter correlation in time and height for warm-upward motions compared to cool-downward motions; where these R_{uu} correlations during cool-downward motions tilt distinctly downwind. R_{uu} correlations extend well into the canopy for both upward and downward plumes during the defoliated period. R_{tt} and R_{qq} contours also exhibit a downwind tilt; where their correlations generally extend downwind within and above the canopy for warm-upward motions plumes, and extend mostly upwind within the canopy for cool-downward motions. For R_{tt} and R_{qq}, cool-downward plumes are generally correlated over larger depths than are warm-upward motions. As observed for R_{qq} referenced to $Z = 23$ m, R_{qq} generally exhibits correlation over longer times and greater depths during the defoliated period compared to the foliated period.

Autocorrelations using a within canopy reference point ($Z = 4.5$ m, Fig. 14), R_{uu} contours vertically extend over a significantly shorter distance during the foliated period than during the defoliated period, while the opposite is true for R_{ww}. R_{tt} and R_{qq} correlations reveal quite similar shape and size as correlations referenced to canopy top,

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD

12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

with the exception that they are more tilted and the former are more confined within the canopy. Compared to correlations referenced to canopy top, R_{qq} correlations during the period with no-leaves remain significant when referenced to $Z = 4.5$ m; revealing similar correlation magnitude over slightly shorter times and heights for warm-upward motions, but extending over even larger times/heights for cool-downward motions.

Therefore, cool-downward plumes at canopy top seem to come from well above the canopy for both seasonal periods, with the correlated areas of u and t extending up to $z = 29$ m. Correlated areas of t for warm-upward plumes at canopy top extend mostly within the canopy and less above, particularly during the period with-leaves; where, this behavior is even more pronounced for correlated area referenced to $z = 4.5$ m. These features indicate that: (1) large upward plumes located above the canopy, typical of the convective boundary layer, might not form at canopy top but above, and (2) downward plumes from the convective boundary layer generally penetrate the canopy, but with some resistance when there are leaves on the trees, which induces a time lag between the presence of the plumes at canopy top and at the ground. The correlated areas of u and w for warm-upward plumes referenced to canopy top show no time lag, and the downwind correlated area for scalars extends to regions both above and within the canopy. While cool-downward plumes at canopy top are clearly related to the downwelling legs of large ABL-scale convective plumes, the origin of warm-upward plumes at canopy top remains ambiguous. We will discuss this further in Sect. 6.

5.2 Warm-downward and cool-upward motions at canopy top during stable conditions

Contours of R_{uu}, R_{ww}, R_{tt} and R_{qq} in the stable regime (S) for warm downward and cool upward motions referenced to time zero ($T = 0$ min) and to canopy top ($Z = 10$ m) are presented in Fig. 15 for both seasonal periods. These correlations correspond to $R^2_{\varphi\varphi}$ and $R^4_{\varphi\varphi}$ in Eq. (10).

Generally speaking, warm downward motions appear to come from well above the canopy, which is especially visible in contours of R_{tt} and R_{qq} that exhibit an elliptical

ACPD
12, 6363–6418, 2012

shape with a downwind tilt. These motions do not penetrate deeply within the canopy, especially during the foliated period, due to (1) the higher density of the canopy, (2) the stratified layer which develops at canopy top, and (3) to the presence of the unstable layer in the lower canopy. On the other hand, autocorrelation contours of R_{ww} for cool upward motions mostly extend within the canopy. Contours of R_{tt} and R_{qq} remain confined within the upper canopy during the foliated period while contours of R_{uu} and R_{ww} go up to the ground and extend slightly above the canopy but mostly on the upwind side. Contours R_{ww} and R_{uu} have a slight upwind tilt.

These observations indicate that instabilities observed at the canopy top in stable regime may be initiated by downward motions from aloft carrying warm air. In response, cool upward motions develop but may not be as well defined as the warm-downward motions. During the foliated period, upward motions also result from upward thermal plumes developing in the lower canopy. Upward plumes also induce canopy-top instabilities (i.e. waves) that do not contribute to scalar transport; which explains why contours of R_{uu} and R_{ww} for cool upward motions extend deeper within the canopy than those of R_{tt} and R_{qq}.

5.3 Warm-upward and cool-downward plumes in the lower foliated canopy during stable conditions

Contours of R_{uu}, R_{ww}, R_{tt} and R_{qq} in the stable regime (S) for warm-downward and cool-upward motions referenced to time zero ($T = 0$ min) and to canopy top ($Z = 4.5$ m) are presented in Fig. 16 for both seasonal periods. These correlations correspond to $R^1_{\varphi\varphi}$ and $R^3_{\varphi\varphi}$ in Eq. (10).

Correlated areas generally remain confined to the lower canopy (below ∼ 6 m), especially for scalars, indicating a decoupling between the lower- and upper-canopy regions. Contours of R_{uu} and R_{ww} extend slightly above the canopy but mostly on the upwind side suggesting that thermal plumes within the canopy may destabilize the flow above acting to generate Kelvin-Helmholtz structures; subtly recoupling the lower and upper canopy layers. Contours of R_{uu} and R_{ww} are almost circular while contours of R_{tt} and

ACPD
12, 6363–6418, 2012

R_{qq} extend more-so upwind for upward plumes and downwind for downward plumes.

6 Discussion

Momentum and scalar (i.e. heat and water vapor) transfer between an orchard canopy and the overlying atmosphere has been investigated for two seasonal periods, trees without and with leaves, and for five thermal stability regimes: free and forced convection, near-neutral condition, transition to stable and stable. From quadrant and octant analysis of momentum and scalar fluxes, as well as from space-time auto-correlations of wind velocity components and scalars, we are able to identify some characteristics of the turbulent structures that transport such quantities following the atmosphere stability and the seasonal period. Such characteristics are summarized in Fig. 17 and discussed in the following sub-sections.

6.1 Free convection regime

In this regime, the scalar transport (heat and water vapor) occurs mostly through thermal plumes. Due to low mean wind speeds, shear-driven organized turbulent structures do not exist for transporting momentum. Warm/humid upward thermal plumes appear more efficient and less frequent than cool/dry downward thermal plumes at above-canopy heat and water vapor transport. Upward plumes are narrower and more intense than surrounding downward plumes, as indicated by the positive skewnesses of the temperature, water vapor and vertical wind velocity (Dupont and Patton, 2012); a typical feature of convective boundary layers.

Scalar autocorrelations, and to a lesser extent wind velocity autocorrelations, have shown that downward plumes at canopy-top come from well above the canopy while upward plumes originate mostly from within the canopy and not above; this feature being especially true during the foliated period. Upward plumes within the canopy were also shown to become less efficient but more frequent at transporting heat than

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD
12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

downward plumes. In order to explain these different features, we speculate that large upward plumes of the convective boundary layer do not form at the canopy top but somewhere above the canopy. These large upward thermal plumes likely result from aggregation of local, small, upward thermal plumes induced by canopy-imposed heat sources that actively participate in turbulence; a process which has been previously documented by Gates and Benedict (1963) over broad-leaved and coniferous trees. Hence, we suggest that heat sources imposed by the canopy elements (especially during the foliated period) generate small scale plumes that coalesce well above the canopy into large upward thermal plumes. During the period with no-leaves when the heat source from the ground overwhelms than that from the upper canopy, large upward plumes may develop closer to the ground; an idea which is supported by the large vertical extent of the correlations within and above the-canopy for upward plumes. This mechanism explains the frequency increase and lower intensity of upward thermal plumes within the canopy compared to above.

Downward plumes within the canopy likely correspond to the downwelling legs of large ABL-scale convective boundary layer plumes penetrating within the canopy. Their penetration attenuates through momentum absorption as these large-scale motions encounter the canopy elements, generating a time lag between their presence at the canopy top and at the ground. Downward plumes appear (1) more efficient at scalar transport, and (2) less frequent than within-canopy upward plumes; a consequence of directly comparing against upward plumes. Upward plumes exhibit different characteristics throughout and above the canopy, while downward plumes remain the same fluid motion within the canopy as found above canopy, albeit with less vigor as they feel the influence of the canopy and the surface below.

During the foliated period, water vapor sources/sinks are similar to those for heat, occurring mostly in the upper canopy where local thermal plumes develop. Consequently, water vapor should be directly injected into these local upward thermal plumes, and be transported initially by these plumes; a feature suggesting that heat and water vapor should be transported similarly during the foliated period. However, Dupont and Pat-

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD

12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

ton (2012) showed larger correlation coefficients for heat transfer than for water vapor transfer, suggesting that heat is transported more efficiently by organized structures than water vapor. We explain this discrepancy by (1) the active role heat plays in generating the local upward thermal plumes, (2) the possible local dissimilarity between heat and water vapor source distribution, and (3) the time response for stomata to open/close (few minutes according to Jones, 1992) could generate a phase shift between water vapor release and thermal plume development; all combining to reduce the efficiency of local upward thermal plumes at transporting water vapor.

During the period with no-leaves, water vapor sources occur solely at the ground while heat sources occur both at the ground and through the canopy. Water vapor should therefore be transported by thermal plumes developing at the ground, followed by being transported by larger upward plumes. Local upward thermal plumes induced by upper-canopy heat sources may not transport much water vapor, since water vapor is released at the surface and not directly within in these plumes. When water vapor is emitted solely at the surface (i.e. when there are no leaves on the trees), within-canopy upward plumes transport more water vapor over relatively shorter duration than do within-canopy downward plumes; with this same characteristic found above the canopy. However, when the scalar is imparted to the flow in a distributed fashion through the canopy (e.g. water vapor in the foliated period, or temperature during either period), downward motions dominate within-canopy transport eventhough upward motions still contribute more to above-canopy scalar transport. Therefore, in free convective conditions (light winds) the scalar source location and that scalar's active role in generating vertical motions (active vs. passive scalar) explains the reduced correlation coefficient between heat and water vapor fluxes during the period with no-leaves. Heat and water vapor are therefore transported differently during this period.

The release of heat and water vapor by vegetation is not continuous and depends on numerous environmental factors. Scalar sources should increase with the gradient between the surface and the surrounding air as well as with increasing wind velocity via the exchange coefficient. Therefore, downward thermal plumes carrying depleted

ACPD
12, 6363–6418, 2012

S. Dupont and E. G. Patton

scalar concentrations should enhance the scalar source. When these plumes pass through the scalar source region, the scalar quantity transported by the plumes should therefore change. However, the CHATS observations show that scalars carried by downward plumes are not modified when passing through the elevated scalar source region (Sect. 5.1). The only explanation for this discrepancy could be a time delay between the plume's passage and the plant's response, a feature which is well known for water vapor (through stomatal time response; Jones, 1992) but not for heat. Hence why we suggest that scalars are generally emitted into local upward plumes. This process is certainly only true when scalar sources are collocated with heat sources. This finding may impact scalar source modeling within large-eddy simulations (LESs) since upward and downward thermal plumes are explicitly resolved by these models.

6.2 Near-neutral regime

Dupont and Patton (2012) found that the plane mixing-layer analogy explains turbulent flow within and above the CHATS canopy better during the foliated period than during the defoliated period. Resulting from defoliated canopy's sparseness, sweep and ejection motions responsible for transporting momentum and scalar constituents may be a combination of mixing-layer type coherent structures developing below canopy top superposed with surface boundary-layer type structures. Although, the mixing-layer structures dominating exchange during the foliated period transport these quantities more efficiently.

6.3 Stable regime

In this regime, the micrometeorology and associated turbulent exchange within the canopy differ substantially across seasonal periods due to the well-defined unstable layer in the lower canopy during the foliated period. During the no-leaves period, turbulent exchanges appear similar to that of stable surface boundary layers, but with potential development of either Kelvin-Helmholtz instabilities or gravity waves in the upper

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD

12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

canopy; although, not fully developing into mixing-layer type coherent structures like those in the near-neutral regime likely as a result of the canopy-top gradient Richardson number exceeding the critical value of 0.25. Initiation of these instabilities could be related to intermittent warm and dry downward motions associated with residual elevated shear layers or low level jets (Mahrt, 1999). These instabilities could then propagate into the canopy airspace, as recently observed by van Gorsel et al. (2011) over open canopies.

During the foliated period, turbulent exchanges in the lower CHATS canopy occur mostly through thermal plumes. Upward thermal plumes act to perturb the flow at canopy top, generating instabilities or gravity waves; intermittent downward motions from above can act similarly. Hence, during the foliated period, two types of turbulent structures may coexist within the canopy, small and intermittent "shear-driven" coherent eddy structures at canopy top and "buoyantly-driven" coherent structures in the lower canopy. Both structures may stay confined in their region of development, inducing a decoupling between the lower and the upper canopy.

6.4 Intermediate stability regimes

The forced convection regime (FoC) should be seen as an intermediate regime between the near-neutral (NN) and free convection (FrC) regimes with the possible superposition of: (i) "shear-driven" structures, mixing-layer type structures developing in the upper canopy and surface boundary-layer type structures if the canopy is sparse, and (ii) "buoyantly-driven" structures, or thermal plumes. With increasingly unstable conditions, it is not clear whether there is a clear superposition of different structure types, or if "shear-driven" structures become progressively "buoyantly-driven" structures. Hommema and Adrian (2003) observed from smoke visualization that in an unstable surface boundary layer turbulent structures lift off the surface. They postulated that these structure correspond to the superposition of a "shear-driven" structure and a buoyant upward motion.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD

12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

In the transition to stable regime (TS), an unstable layer progressively develops in the lower canopy during the foliated period and plane mixing-layer type structures becomes smaller, less frequent and look more like Kelvin-Helmholtz type structures; a result of decreased ambient turbulence levels.

7 Concluding remarks

CHATS data analysis suggests that the canopy's seasonal state plays a vital role in determining the turbulent transport processes coupling the canopy layers with the overlying atmosphere. In near-neutral stability (NN), traditional mixing-layer type structures dominate turbulent scalar transport when there are leaves on the trees. While in the absence of leaves, canopy exchange appears to occur through a combination of these mixing-layer structures superposed with surface layer type structures.

Eventhough the vegetation imposes heat sources during both seasonal periods, the low heat capacity of the leaves compared to the branches/trunks dramatically modifies the vertical temperature distribution across stability ranges. With departure from near-neutral conditions, the sweep and ejection motions associated with mixing-layer type turbulent structures no longer dominate canopy exchange. Rather, turbulent scalar exchange occurs through thermal plumes during unstable conditions. During stable conditions, elevated radiational cooling of the exposed leaves in the upper canopy generates downwelling thermal plumes in the lower canopy; a feature not present during the defoliated period, and which is of critical importance in controlling within-canopy chemical processing of biogenic or surface-emitted reactive species.

Some turbulent exchange processes remain ambiguous and require further study: (i) in unstable conditions, the link between local thermal plumes generated by the vegetation elements and large scale convective plumes above the canopy, (ii) the coupling between these locally generated thermal plumes and scalar source strength/location, and (iii) in stable conditions, the origin and development of intermittent instabilities in the upper canopy.

Acknowledgements. This work was conducted at the National Center for Atmospheric Research (NCAR), Boulder, CO, USA. Sylvain Dupont was supported by the Institut National de Recherche Agronomique (INRA) through its long term mission program, and by the program "PEDO COTESOF" of the Agence Nationale de la Recherche (ANR). Edward Patton was supported by NCAR's Bio-hydro-atmosphere interactions of Energy, Aerosols, Carbon, H_2O, Organics & Nitrogen (BEACHON) project and by the Army Research Office (Grant No.: W911NF-09-1-0572) under subcontract from the University of Colorado, Boulder. We would like to thank: (i) Drs. M. Böhm, S. P. Burns, B. A. Gardiner, J. J. Finnigan, I. N. Harman, T. W. Horst, R. H. Shaw, P. P. Sullivan, J. C. Weil, and E. van Gorsel for helpful discussions, (ii) the Cilker family for their interest and willingness to allow CHATS to take place at Cilker Orchards, and (iii) the individuals and sponsors who collaborated on bringing CHATS to fruition, with special thanks to the NCAR EOL staff who worked tirelessly to ensure the quality and success of the campaign. NCAR is sponsored in part by the National Science Foundation.

References

Adrian, R. J.: Hairpin vortex organization in wall turbulence, Phys. Fluids, 19, 041301, doi:10.1063/1.2717527, 2007. 6376

Böhm, M., Harman, I., Van Gorsel, E., Finnigan, J., Raupach, M., Vogt, R., and Christen, A.: Identification of processes governing within-canopy momentum and scalar transfer from vegetation canopies to urban landscapes, in: Proc. of the Amer. Meteorol. Soc. 19th Symp. on Bound.-Layers and Turb., Abstract J5.3, 1–6 August 2010, Keystone, CO, USA, 2010. 6371, 6372

Brunet, Y. and Irvine, M. R.: The control of coherent eddies in vegetation canopies: streamwise structure spacing, canopy shear scale and atmospheric stability, Bound.-Lay. Meteorol., 94, 139–163, 2000. 6366

Cava, D. and Katul, G.: Spectral short-circuiting and wake production within the canopy trunk space of an alpine hardwood forest, Bound.-Lay. Meteorol., 126, 415–431, 2008. 6367

Chen, F. Z.: Turbulent characteristics over a rough natural surface. 2. Responses of profiles to turbulence, Bound.-Lay. Meteorol., 52, 301–311, doi:10.1007/BF00122092, 1990. 6365, 6367, 6371, 6382

ACPD

12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

Collineau, S. and Brunet, Y.: Detection of turbulent coherent motions in a forest canopy. 1. Wavelet analysis, Bound.-Lay. Meteorol., 65, 357–379, 1993a. 6366
Collineau, S. and Brunet, Y.: Detection of turbulent coherent motions in a forest canopy. 2. Time-scales and conditional averages, Bound.-Lay. Meteorol., 66, 49–73, 1993b. 6366
Coppin, P. A., Raupach, M. R., and Legg, B. J.: Experiments on scalar dispersion within a model-plant canopy. 2. An elevated plane source, Bound.-Lay. Meteorol., 35, 167–191, doi:10.1007/BF00117307, 1986. 6365, 6367
Dupont, S. and Brunet, Y.: Influence of foliar density profile on canopy flow: a large-eddy simulation study, Agr. Forest Meteorol., 148, 976–990, 2008. 6366, 6376
Dupont, S. and Patton, E. G.: Influence of thermal stability and seasonal canopy changes on micrometeorology within and above an orchard canopy: the CHATS experiment, Agric. Forest Meteorol., 157, 11–29, 2012. 6366, 6367, 6368, 6369, 6373, 6374, 6375, 6377, 6378, 6380, 6389, 6390, 6392
Dupont, S., Irvine, M. R., Bonnefond, J.-M., Lamaud, E., and Brunet, Y.: Turbulent structures within a pine forest with a large and sparse trunk space: stand and edge conditions, Bound.-Lay. Meteorol., doi:10.1007/s10546-012-9695-8, 2012. 6367
Finnigan, J. J.: Turbulence in waving wheat. II. Structure of momentum transfer, Boundary-Lay. Meteorol., 16, 213–236, 1979. 6375
Finnigan, J. J.: Turbulence in plant canopies, Annu. Rev. Fluid Mech., 32, 519–571, 2000. 6365, 6376
Finnigan, J. J., Shaw, R. H., and Patton, E. G.: Turbulence structure above a vegetation canopy, J. Fluid Mech., 637, 387–424, 2009. 6365, 6366, 6376
Gao, W., Shaw, R. H., and Paw U, K. T.: Observation of organised structures in turbulent flow within and above a forest canopy, Bound.-Lay. Meteorol., 47, 349–377, 1989. 6365
Gates, D. and Benedict, C.: Convection phenomena from plant in still air, Am. J. Bot., 50, 563–573, 1963. 6390
Ghisalberti, M. and Nepf, H. M.: Mixing layers and coherent structures in vegetated aquatic flows, J. Geophys. Res.-Oceans, 107, 3011, doi:10.1029/2001JC000871, 2002. 6366
van Gorsel, E., Böhm, M., Harman, I., Finnigan, J., Christen, A., and Vogt, R.: Effects of diabatic stability on turbulent biosphere-atmosphere exchange processes for momentum and scalars, in: Proc. of the Amer. Meteorol. Soc. 19th Symp. on Bound.-Layers and Turb., Abstract J8.6, 1–6 August 2010, Keystone, CO, USA, 2010. 6372
van Gorsel, E., Harman, I. N., Finnigan, J. J., and Leuning, R.: Decoupling of air flow above

ACPD
12, 6363–6418, 2012

and in plant canopies and gravity waves affect micrometeorological estimates of net scalar exchange, Agr. Forest Meteorol., 151, 927–933, 2011. 6393
Hommema, S. E. and Adrian, R. J.: Packet structure of surface eddies in the atmospheric boundary layer, Bound.-Lay. Meteorol., 106, 147–170, doi:10.1023/A:1020868132429, 2003. 6393
Jacobs, A. F. G., Van Boxel, J. H., and El-Kilani, M. M.: Nighttime free convection characteristics within a plant canopy, Bound.-Lay. Meteorol., 71, 375–391, 1994. 6367
Jones, H.: Plants and microclimate, a quantitative approach to environmental plant physiology, 2nd edition, Cambridge University Press, New York, NY 10011-4211, USA, 1992. 6391, 6392
Kanda, M. and Hino, M.: Organized structures in developing turbulent-flow within and above a plant canopy using a large-eddy simulation, Bound.-Lay. Meteorol., 68, 237–257, 1994. 6366
Katul, G., Kuhn, G., Schieldge, J., and Hsieh, C. I.: The ejection-sweep character of scalar fluxes in the unstable surface layer, Bound.-Lay. Meteorol., 83, 1–26, doi:10.1023/A:1000293516830, 1997. 6371
Kobayashi, N. and Hiyama, T.: Stability dependence of canopy flows over a flat larch forest, Bound.-Lay. Meteorol., 139, 97–120, doi:10.1007/s10546-010-9572-2, 2011. 6367
Launiainen, S., Vesala, T., Mölder, M., Mammarella, I., Smolander, S., Rannik, U., Kolari, P., Hari, P., Lindroth, A., and Katul, G. G.: Vertical variability and effect of stability on turbulence characteristcis down to the floor of a pine forest, Tellus B, 59, 919–936, 2007. 6367
Li, D. and Bou-Zeid, E.: Coherent structures and the dissimilarity of turbulent transport of momentum and scalars in the unstable atmopsheric surface layer, Bound.-Lay. Meteorol., 140, 243–262, doi:10.1007/s10546-011-9613-5, 2011. 6365, 6366, 6367, 6371, 6372, 6382, 6384
Lu, C. H. and Fitzjarrald, D. R.: Seasonal and diurnal variations of coherent structures over a deciduous forest, Bound.-Lay. Meteorol., 69, 43–69, 1994. 6365
Mahrt, L.: Stratified atmopsheric boundary layers, Bound.-Layer Meteorol., 90, 375–396, 1999. 6393
Maitani, T. and Ohtaki, E.: Turbulent transport processes of momentum and sensible heat in the surface-layer over a paddy field, Bound.-Lay. Meteorol., 40, 283–293, doi:10.1007/BF00117452, 1987. 6382
Moene, A. F., Michels, B. I., and Holtslag, A. A. M.: Scaling variances of scalars in a convective

ACPD
12, 6363–6418, 2012

boundary layer under different entrainment regimes, Bound.-Lay. Meteorol., 120, 257–274, doi:10.1007/s10546-006-9053-9, 2006. 6365

Moriwaki, R. and Kanda, M.: Local and global similarity in turbulent transfer of heat, water vapour, and CO_2 in the dynamic convective sublayer over a suburban area, Bound.-Lay. Meteorol., 120, 163–179, doi:10.1007/s10546-005-9034-4, 2006. 6382

Patton, E. G., Davis, K. J., Barth, M. C., and Sullivan, P. P.: Decaying scalars emitted by a forest canopy: a numerical study, Boundary-Lay. Meteorol., 100, 91–129, 2001. 6366

Patton, E. G., Horst, T. W., Sullivan, P. P., Lenschow, D. H., Oncley, S. P., Brown, O. J., Burns, S. P., Guenther, A. B., Held, A., Karl, T., Mayor, S. D., Rizzo, L. V., Spuler, S. M., Sun, J., Turnipseed, A., Allwine, E. J., Edburg, S. L., Lamb, B. K., Avissar, R., Calhoun, R. J., Kleissl, J., Massman, W. J., Paw U, K. T., and Weil, J. C.: The canopy horizontal array turbulence study, B. Am. Meteorol. Soc., 92, 593–611, 2011. 6367, 6370, 6401, 6402

Paw U, K. T., Brunet, Y., Collineau, S., Shaw, R. H., Maitini, T., Qiu, J., and Hipps, L.: On coherent structures in turbulence above and within agricultural plant canopies, Agr. Forest Meteorol., 61, 55–68, 1992. 6365, 6366

Poggi, D., Porporato, A., Ridolfi, L., Albertson, J. D., and Katul, G. G.: The effect of vegetation density on canopy sub-layer turbulence, Bound.-Lay. Meteorol., 111, 565–587, 2004. 6365, 6367, 6376

Qiu, J., Paw U, K. T., and Shaw, R. H.: Pseudo-wavelet analysis of turbulence patterns in three vegetation layers, Bound.-Lay. Meteorol., 72, 177–204, 1995. 6366

Raupach, M. R., Finnigan, J. J., and Brunet, Y.: Coherent eddies and turbulence in vegetation canopies: the mixing-layer analogy, Bound.-Lay. Meteorol., 78, 351–382, 1996. 6366, 6376

Schmidt, H. and Schumann, U.: Coherent structure of the convective boundary layer derived from large-eddy simulation, J. Fluid Mech., 200, 511–562, 1989. 6382

Shaw, R. H. and Schumann, U.: Large-eddy simulation of turbulent flow above and within a forest, Bound.-Lay. Meteorol., 61, 47–64, doi:10.1007/BF02033994, 1992. 6366

Shaw, R. H., Tavangar, J., and Ward, D. P.: Structure of the Reynolds stress in a canopy layer, J. Clim. Appl. Meteorol., 22, 1922–1931, 1983. 6375, 6385

Shaw, R. H., den Hartog, G., and Neumann, H. H.: Influence of foliar density and thermal-stability on profiles of Reynolds stress and turbulence intensity in a deciduous forest, Bound.-Lay. Meteorol., 45, 391–409, doi:10.1007/BF00124010, 1988. 6367

Shaw, R. H., Brunet, Y., Finnigan, J. J., and Raupach, M. R.: A wind tunnel study of air flow in waving wheat: two-point velocity statistics, Bound.-Lay. Meteorol., 76, 349–376, 1995. 6366

Su, H. B., Shaw, R. H., and Paw U, K. T.: Two-point correlation analysis of neutrally stratified flow within and above a forest from large-eddy simulation, Bound.-Lay. Meteorol., 94, 423–460, 2000. 6366

Turner, B. J., Leclerc, M. Y., Gauthier, M., Moore, K. E., and Fitzjarrald, D. R.: Identification of turbulence structures above a forest canopy using a wavelet transform, J. Geophys. Res.-Atmos., 99, 1919–1926, 1994. 6366

Watanabe, T.: Large-eddy simulation of coherent turbulence structures associated with scalar ramps over plant canopies, Bound.-Layer Meteorol., 112, 307–341, 2004. 6366

Williams, C. A., Scanlon, T. M., and Albertson, J. D.: Influence of surface heterogeneity on scalar dissimilarity in the roughness sublayer, Bound.-Layer Meteorol., 122, 149–165, doi:10.1007/s10546-006-9097-x, 2007. 6365

Willmarth, W. W. and Lu, S. S.: Structure of the Reynolds stress near the wall, J. Fluid Mech., 55, 65–92, 1972. 6370, 6375

Wyngaard, J. C. and Brost, R. A.: Top-down and bottom-up diffusion of a scalar in the convective boundary layer, J. Atmos. Sci., 41, 102–112, 1984. 6382

Table 1. Description of quadrant events for momentum ($\langle u'w' \rangle$), heat ($\langle w't' \rangle$) and water vapor ($\langle w'q' \rangle$) fluxes and their associated event names. For any variable x: x^+ signifies $x' > 0$, and x^- signifies $x' < 0$.

Flux	Quadrant 1 (Q1)	Quadrant 2 (Q2)	Quadrant 3 (Q3)	Quadrant 4 (Q4)
$\langle u'w' \rangle$	u^+w^+ outward interaction	u^-w^+ ejection motion	u^-w^- inward interaction	u^+w^- sweep motion
$\langle w't' \rangle$	w^+t^+ warm upward plume	w^-t^+ warm downward motion	w^-t^- cool downward plume	w^+t^- cool upward motion
$\langle w'q' \rangle$	w^+q^+ humid upward plume	w^-q^+ humid downward motion	w^-q^- dry downward plume	w^+q^- dry upward motion

ACPD
12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

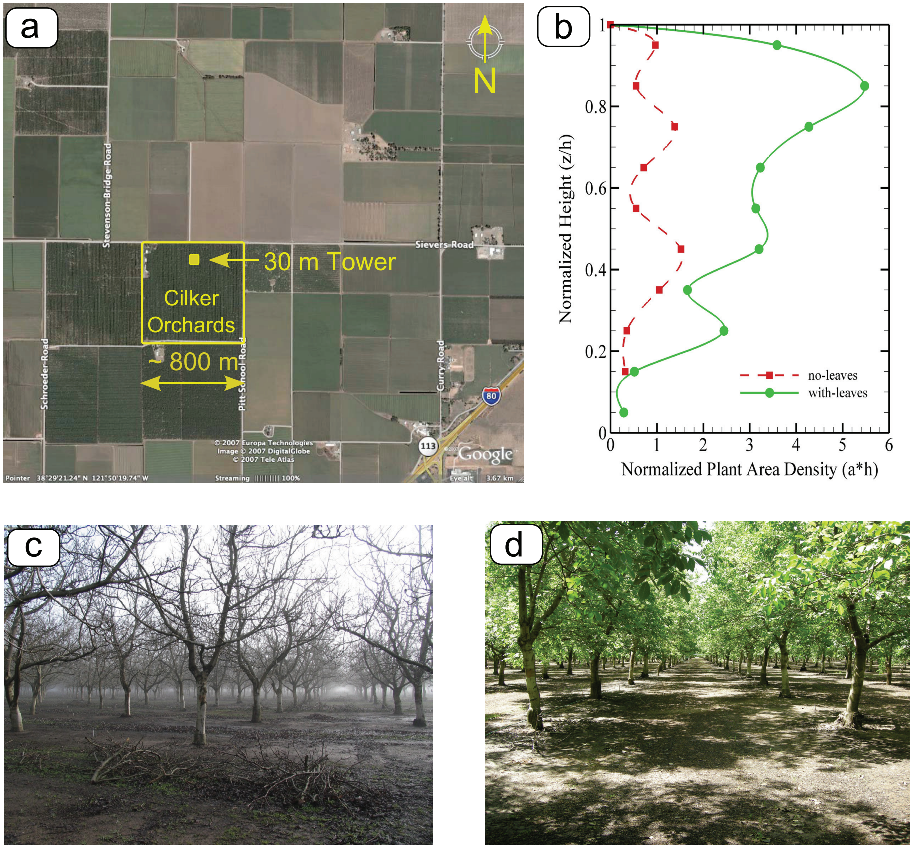

Fig. 1. **(a)** Image from Google Earth depicting the 800 × 800 m Cilker Orchards and showing the location of the 30 m tower. **(b)** Plant area density profiles measured during CHATS before and after leaf-out. Photos showing the orchard: **(c)** before leaf-out, and **(d)** after leaf-out, respectively. Figure adapted from Patton et al. (2011).

ACPD
12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

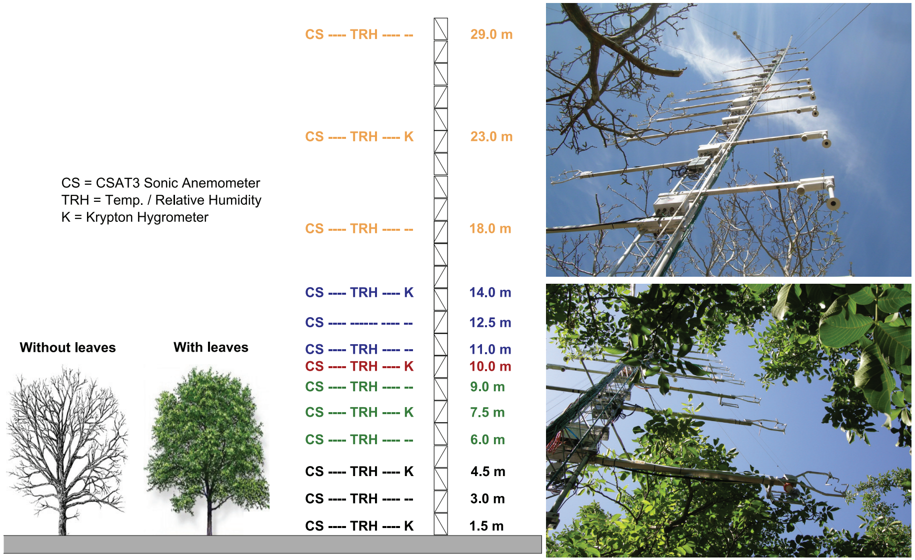

Fig. 2. Left: thirty meter tower with the instrument locations during CHATS. Right: pictures of the thirty meter tower from below; above: no-leaves, below: with-leaves. Adapted from Patton et al. (2011).

ACPD
12, 6363–6418, 2012

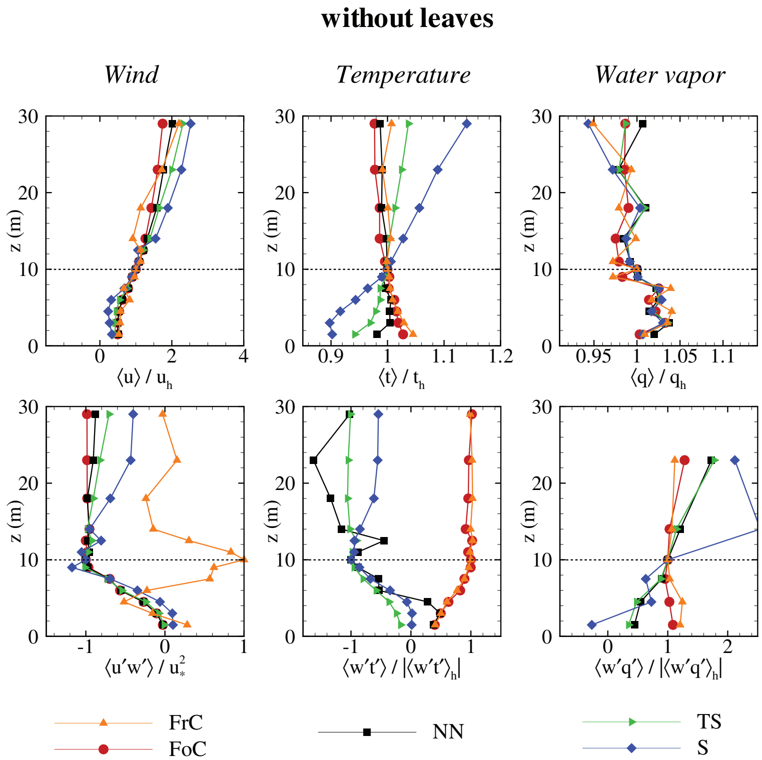

Fig. 3a. Vertical profiles of mean streamwise wind velocity ($\langle u \rangle$), air temperature ($\langle t \rangle$), air specific humidity ($\langle q \rangle$), momentum flux ($\langle u'w' \rangle$), heat flux ($\langle w't' \rangle$), and water vapor flux ($\langle w'q' \rangle$) for all stability regimes and for the period with no-leaves. All variables are normalized by canopy-top ($z = 10$ m) reference values. The dashed line indicates the canopy top. Recall that the FrC, FoC and NN regimes use 30-min averages, while the TS and S regimes use 5-min averages.

ACPD
12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

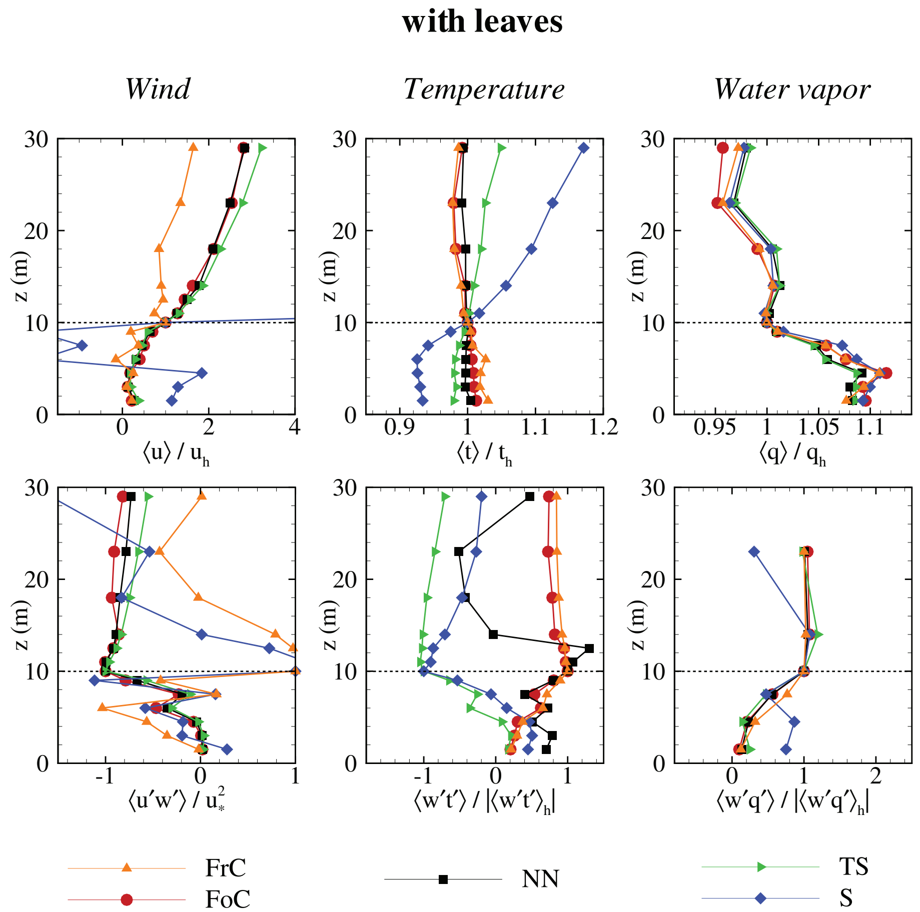

Fig. 3b. Similar to Fig. 3a, but for the period with leaves.

ACPD
12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

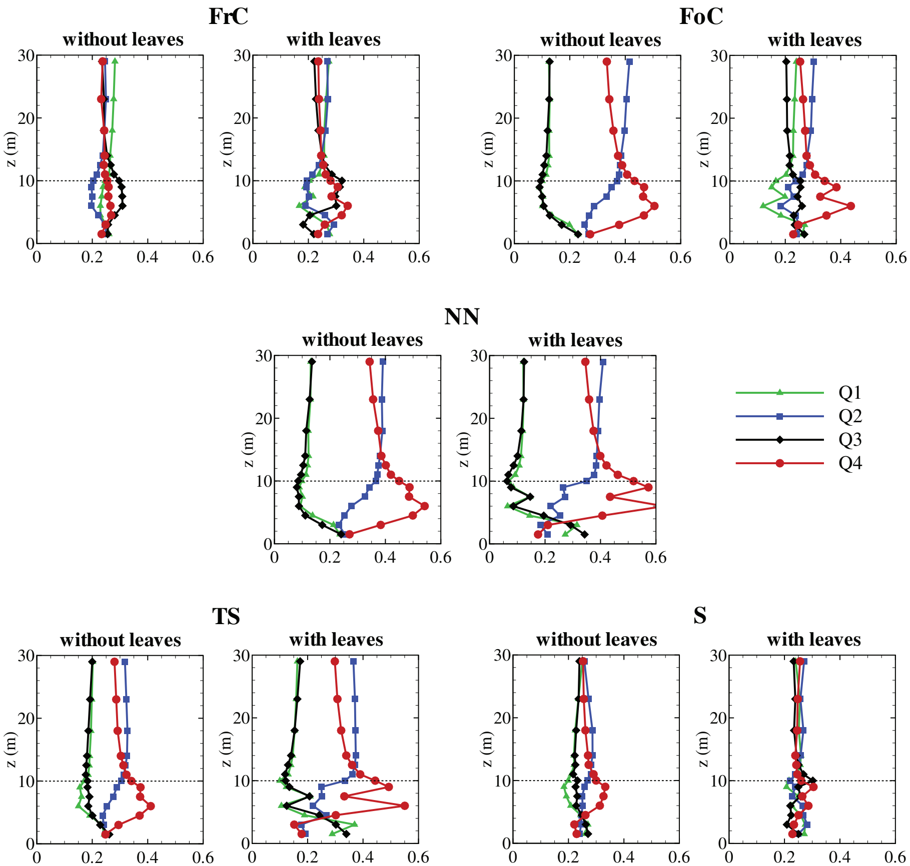

Fig. 4. Fraction of the momentum flux $\langle u'w' \rangle$ in each momentum quadrant as defined in Eq. (3) across the five stability regimes and two seasonal periods. Quadrants are defined in Table 1. The dashed line indicates the canopy top.

ACPD
12, 6363–6418, 2012

S. Dupont and E. G. Patton

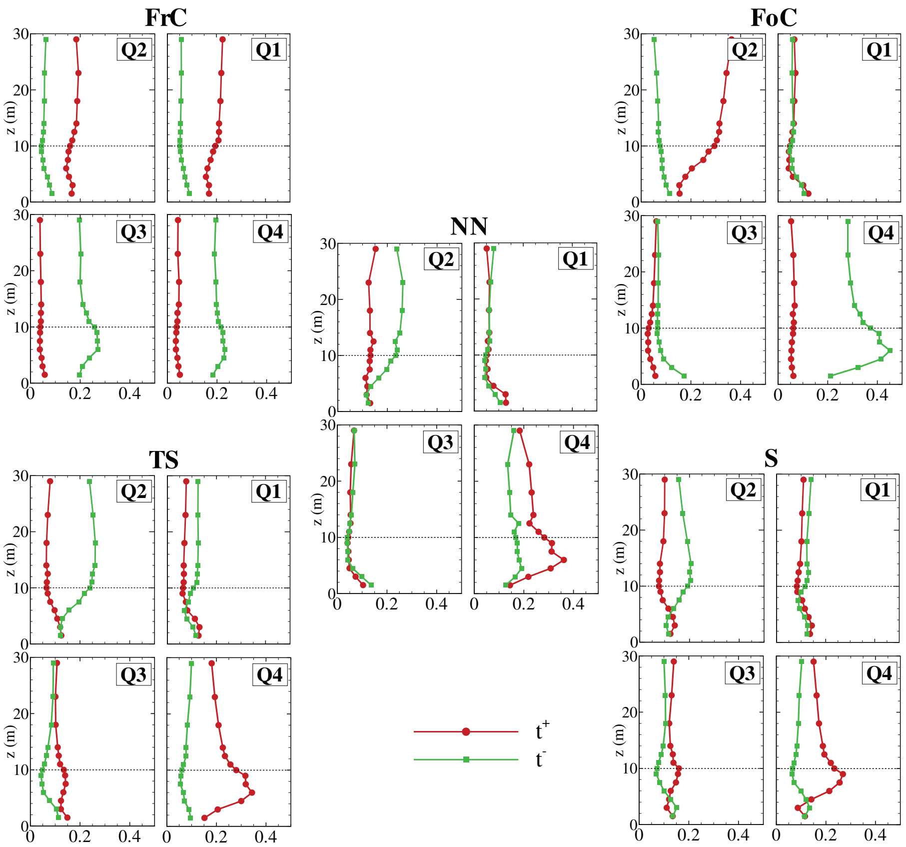

Fig. 5. Partition of the momentum flux quadrants associated with positive or negative temperature fluctuations, as defined in Eqs. (6) and (7). All stability regimes are presented for the period with no-leaves. The quadrants are defined in Table 1. The dashed line indicates the canopy top.

ACPD
12, 6363–6418, 2012

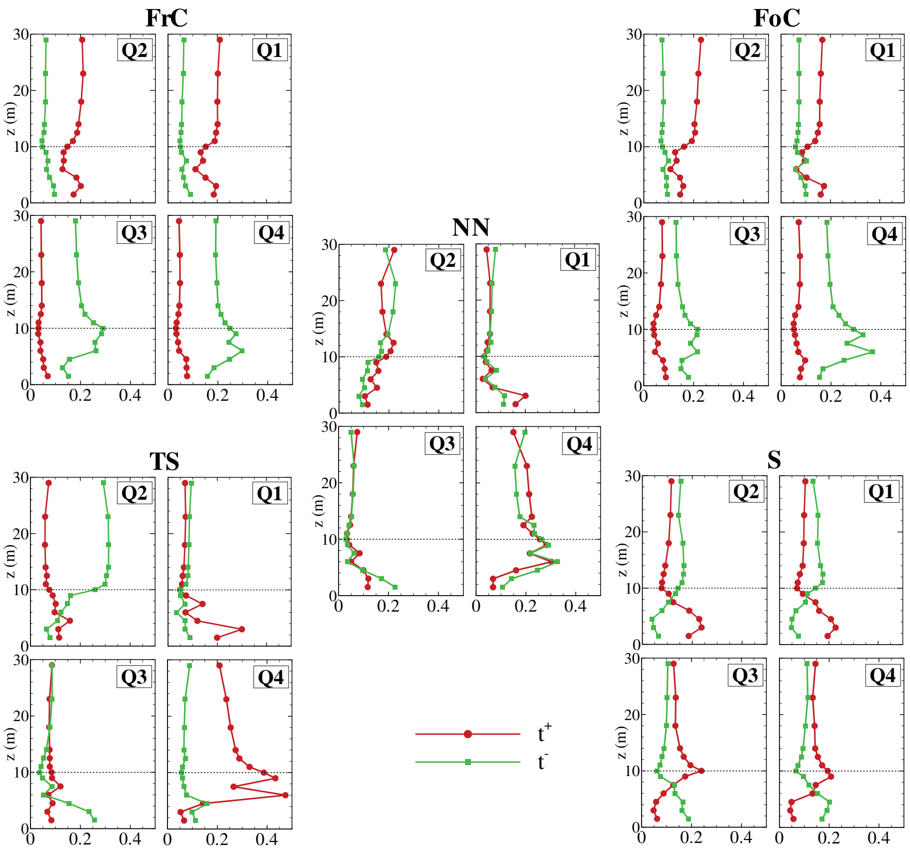

Fig. 6. Same as Fig. 5, but for the period with-leaves.

ACPD
12, 6363–6418, 2012

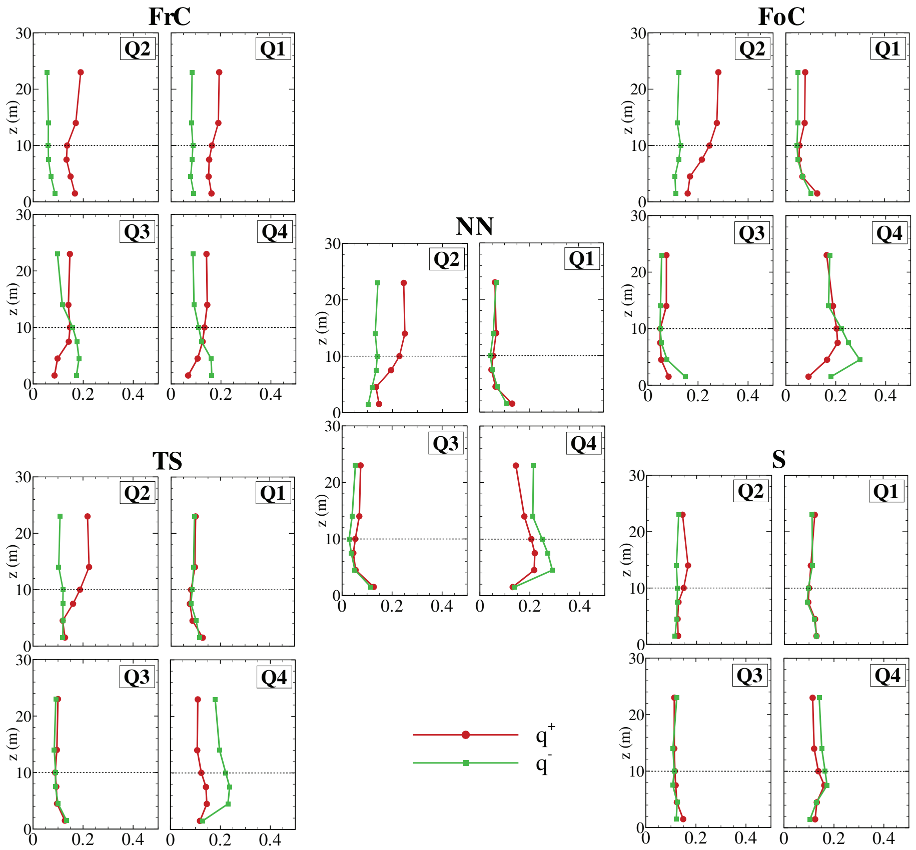

Fig. 7. Same as Fig. 5, but for water vapor fluctuations during the period without-leaves.

ACPD
12, 6363–6418, 2012

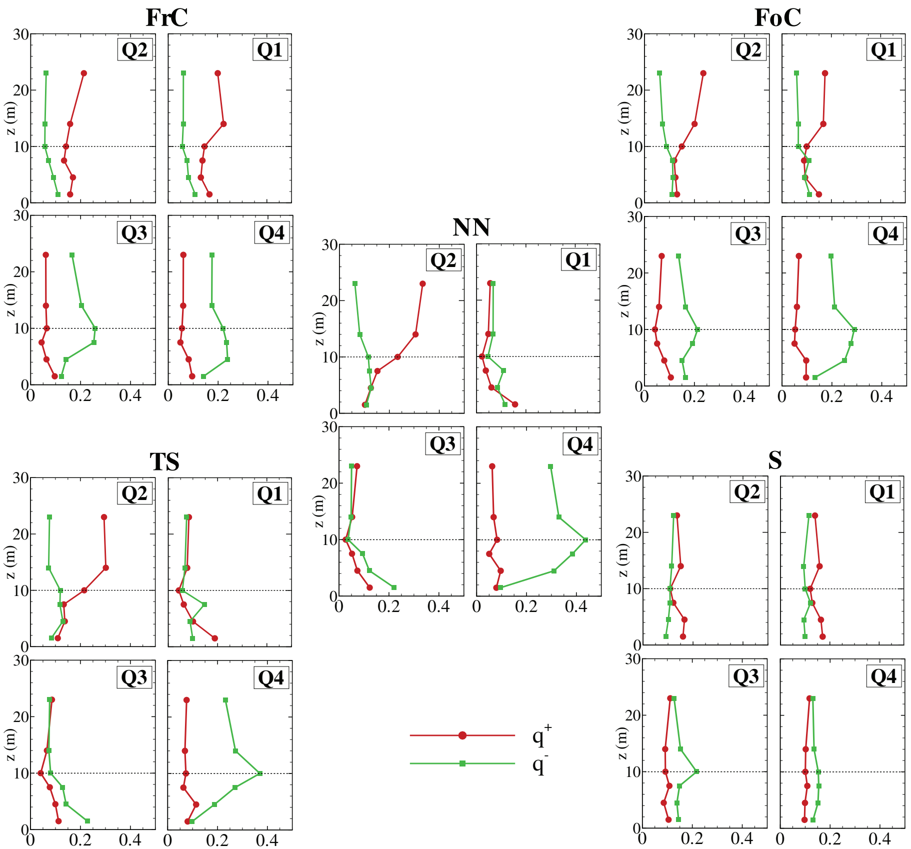

Fig. 8. Same as Fig. 6, but for water vapor fluctuations during the period with-leaves.

ACPD
12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

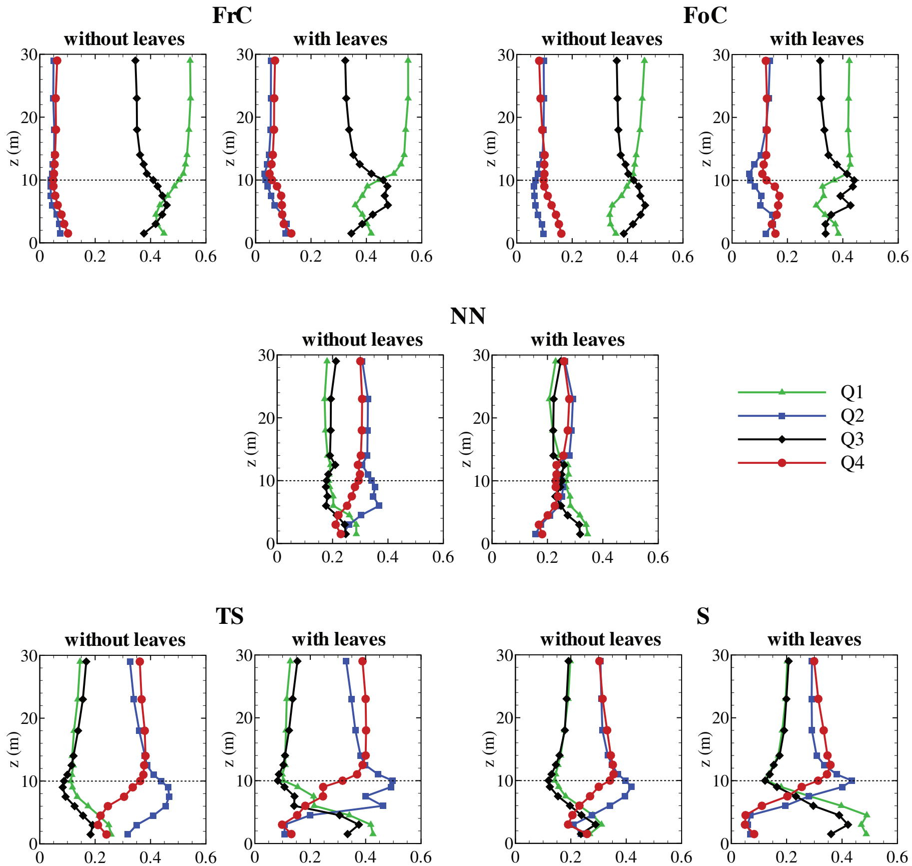

Fig. 9. Fraction of the heat flux $\langle w't' \rangle$ within in each quadrant as defined in Eq. (3) for all five stability regimes and the two seasonal periods. The quadrants are defined in Table 1. The dashed line indicates the canopy top.

ACPD
12, 6363–6418, 2012

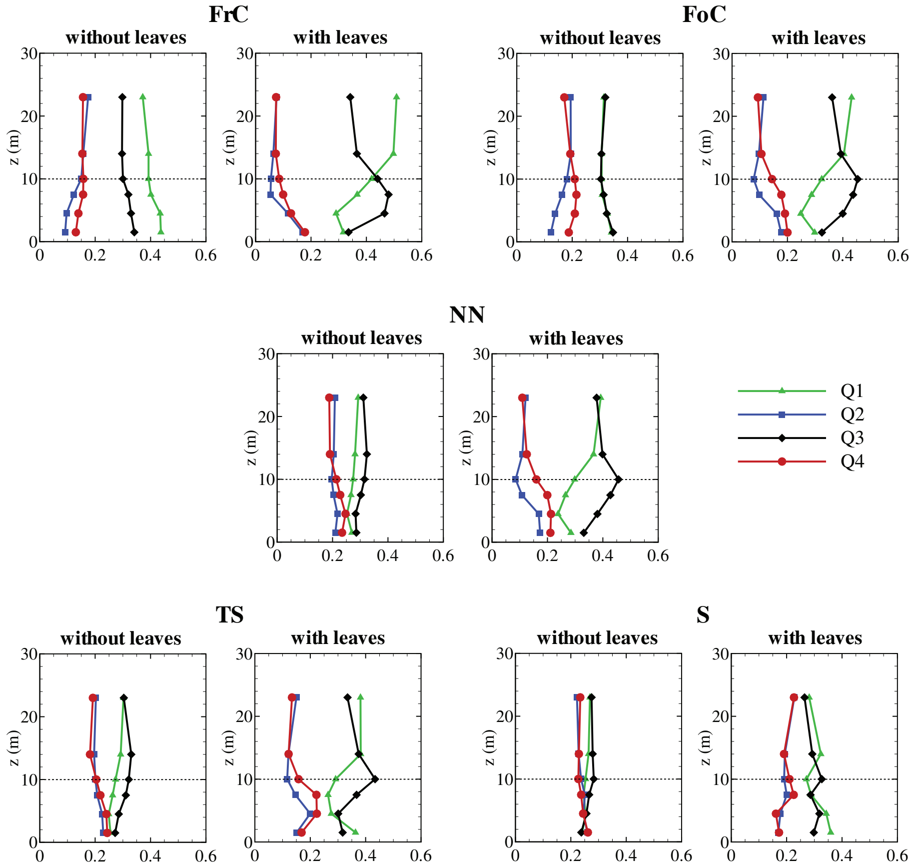

Fig. 10. Fraction of the water vapor flux $\langle w'q' \rangle$ in each quadrant as defined in Eq. (3) for all five stability regimes and the two seasonal periods. The quadrants are defined in Table 1. The dashed line indicates the canopy top.

ACPD
12, 6363–6418, 2012

S. Dupont and E. G. Patton

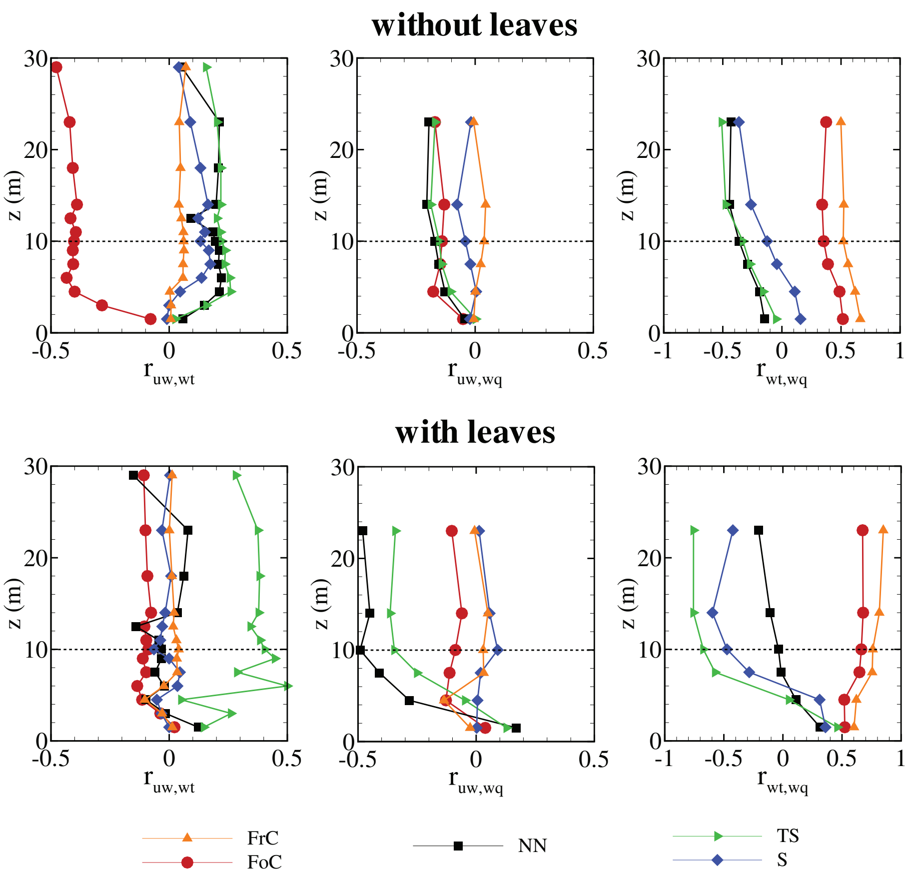

Fig. 11. Vertical profiles of mean correlation coefficients between momentum and heat fluxes ($r_{uw,wt}$), momentum and water vapor fluxes ($r_{uw,wq}$), and heat and water vapor fluxes ($r_{wt,wq}$), for all five stability regimes and for both seasonal periods. The dashed line indicates the canopy top.

ACPD
12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

ACPD

12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

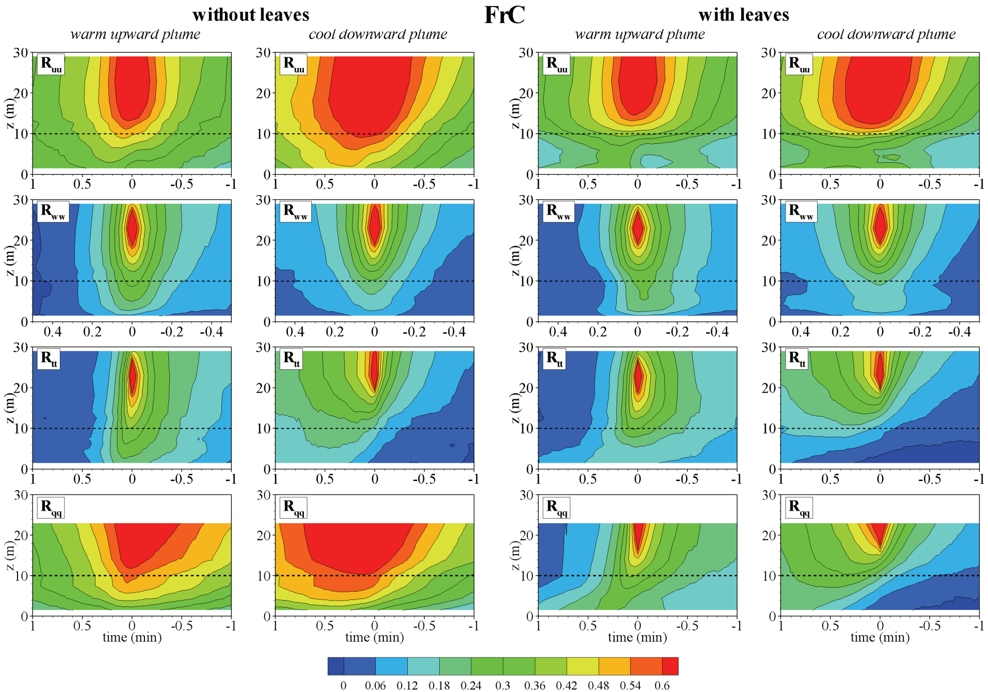

Fig. 12. Autocorrelation contours of u (R_{uu}), w (R_{ww}), t (R_{tt}) and q (R_{qq}) associated with warm upward and cool downward plumes referenced to $Z = 23$ m and $T = 0$ min, for free convection (FrC) and for both seasonal periods. The autocorrelations correspond to $R^1_{\varphi\varphi}$ and $R^3_{\varphi\varphi}$ in Eq. (10), where φ is either u, w, t or q. Negative times correspond to times before the structure detection (downwind condition) and positive times to times after the structure detection (upwind condition). The dashed line indicates the canopy top.

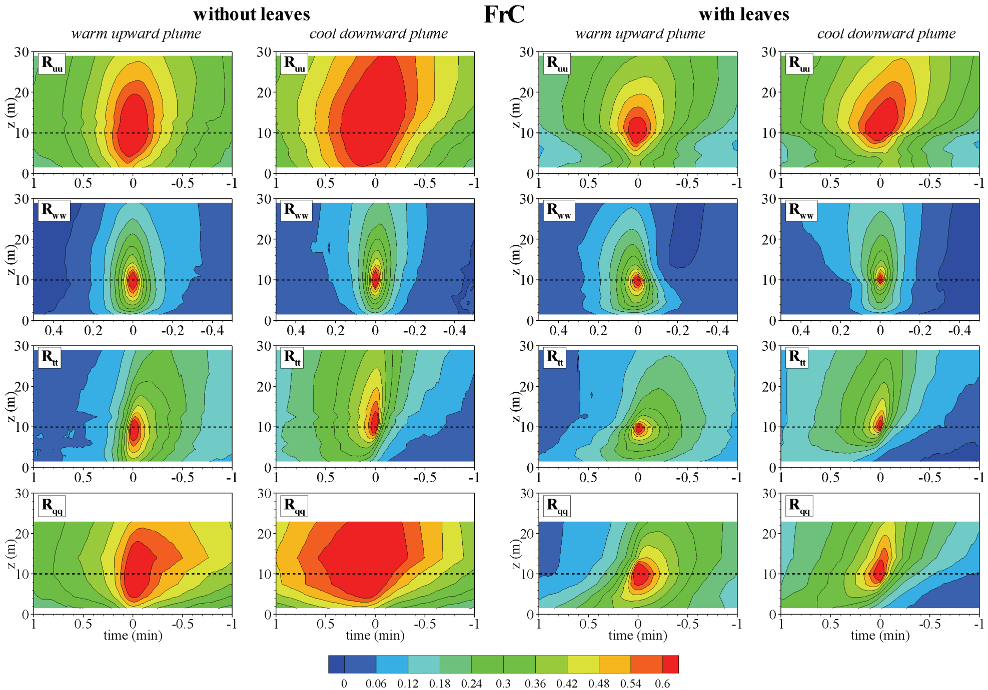

Fig. 13. Same as Fig. 12 but for autocorrelations referenced to canopy top ($Z = 10$ m).

ACPD
12, 6363–6418, 2012

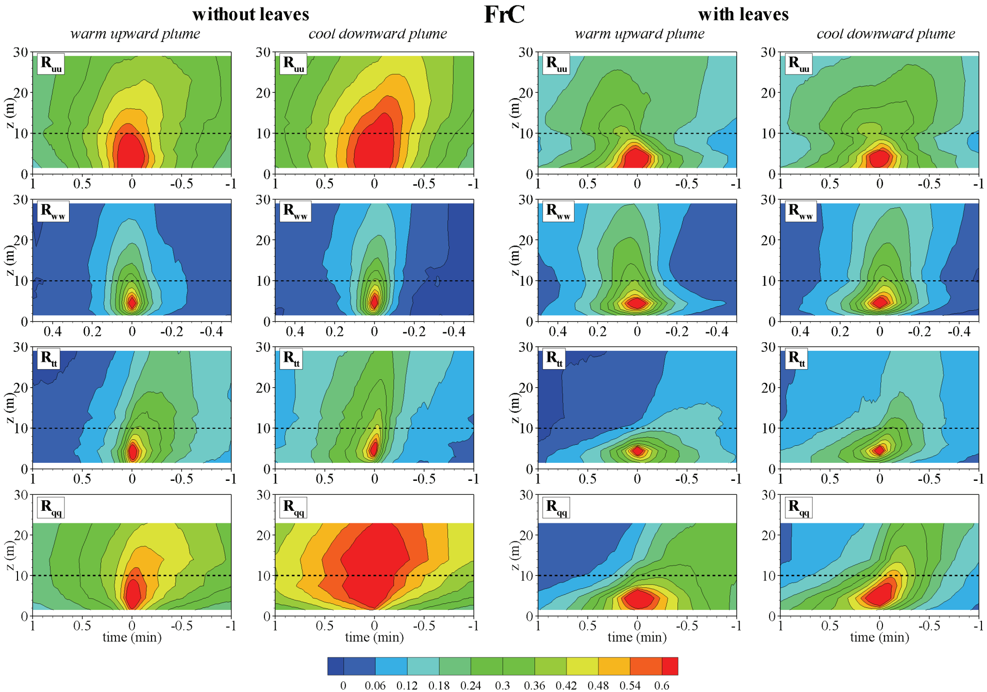

Fig. 14. Same as Fig. 12 but for autocorrelations referenced to $Z = 4.5$ m.

ACPD
12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

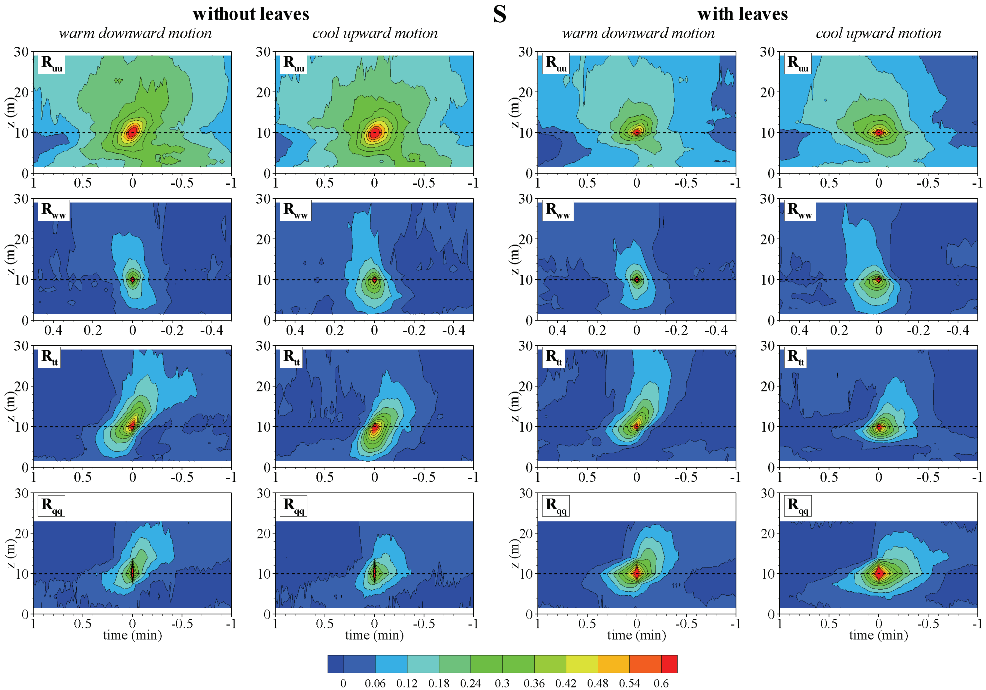

Fig. 15. Autocorrelation contours of u (R_{uu}), w (R_{ww}), t (R_{tt}) and q (R_{qq}) associated with warm downward and cool upward motions referenced to canopy top ($Z = 10$ m) and $T = 0$ min, for the stable regime (S) and for both seasonal periods. The autocorrelations correspond to $R^2_{\varphi\varphi}$ and $R^4_{\varphi\varphi}$ in Eq. (10), where φ is either u, w, t or q. Negative times correspond to times before the structure detection (downwind condition) and positive times to times after the structure detection (upwind condition). The dashed line indicates the canopy top.

ACPD
12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

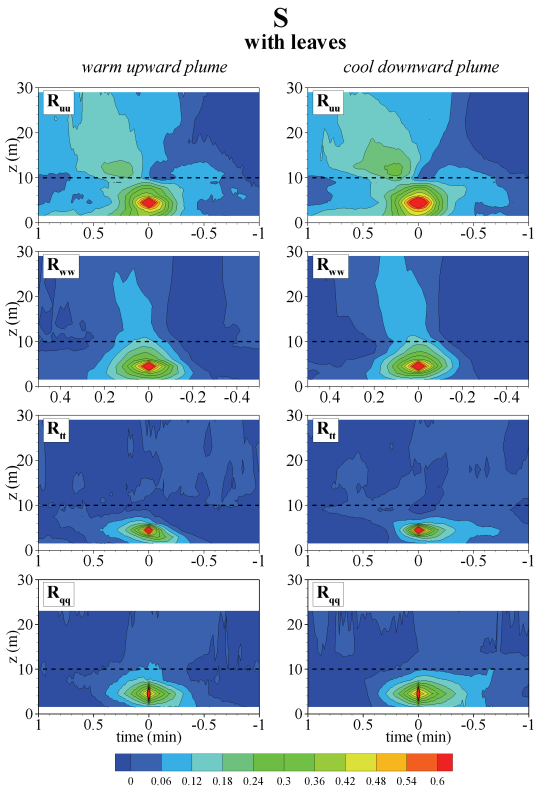

Fig. 16. Autocorrelation contours of u (R_{uu}), w (R_{ww}), t (R_{tt}) and q (R_{qq}) associated with warm upward and cool downward motions referenced to canopy top ($Z = 4.5$ m) and $T = 0$ min, for the stable regime (S) and for the period with leaves. The autocorrelations correspond to $R^1_{\varphi\varphi}$ and $R^3_{\varphi\varphi}$ in Eq. (10), where φ is either u, w, t or q. Negative times correspond to times before the structure detection (downwind condition) and positive times to times after the structure detection (upwind condition). The dashed line indicates the canopy top.

ACPD
12, 6363–6418, 2012

Stability and seasonal influences on canopy transport

S. Dupont and E. G. Patton

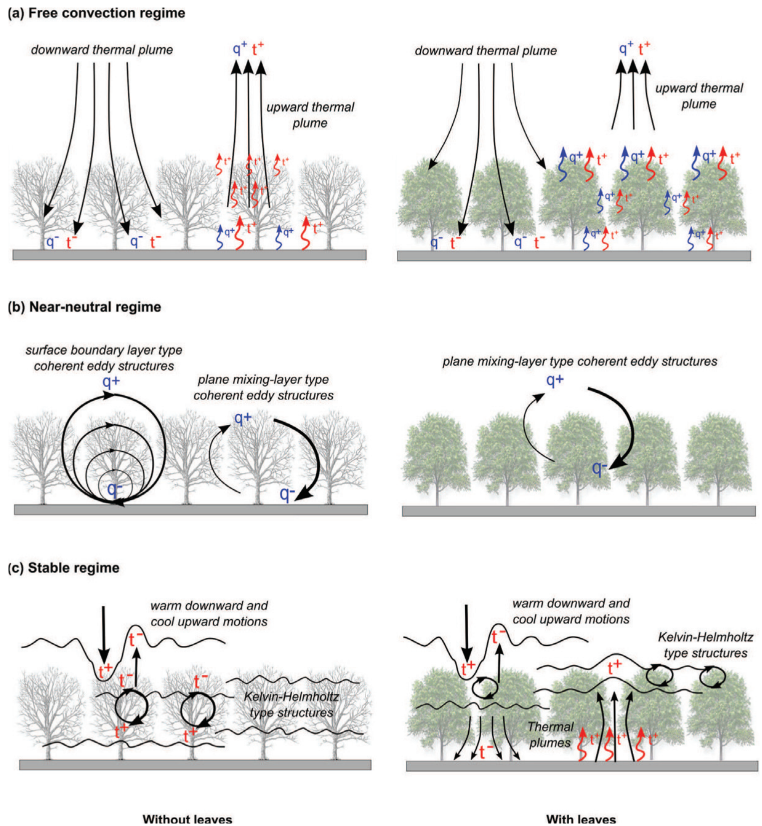

Fig. 17. Idealized representation of the turbulent structures transporting momentum and scalars (temperature and water vapor) and their main characteristics during: **(a)** free convection, **(b)** near-neutral, and **(c)** stable regimes for both seasonal periods (without and with leaves).

ACPD
12, 6363–6418, 2012