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Intermittency of water vapor fluxes from vineyards during light wind and convective conditions

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Abstract

Vineyards in many semi-arid regions globally face limited water resources. Monitoring évapotranspiration (ET) of vineyards is critical for water resource management, but remains difficult due to the complex biophysics of the surfaces. Both measurement and modeling approaches for estimating turbulent water vapor transport rely on implicit assumptions that exchanges occur in a reasonably regular fashion over the time scales generally used for averaging. However, heterogeneous vegetation in semi-arid climates, such as many vineyards, presents inherent factors, including canopy row/row space structure and frequent periods of light wind, unstable conditions, that can create episodic transport characteristics. Eddy covariance data were collected above and within the canopy of two vineyards in the Central Valley of California during the Grape Remote sensing Atmospheric Profile & Evapotranspiration experiment (GRAPEX). The goal was to document and quantify the existence of intermittent turbulence transport of water vapor, and associated episodic canopy venting. These effects were found to correlate with periods light winds and highly unstable/convective conditions. Power and cross-spectra for intermittent periods documented enhancement of low-frequency water vapor exchange events compared to more steady periods, and diminished time scale correlation between humidity within the canopy and above the canopy. Analyses show that intermittent cases can necessitate longer flux-averaging periods (up to 2 h) than more steady conditions. Episodic exchange events were isolated and summed to determine their relative contribution to the overall water vapor flux. Since light wind, unstable conditions are relatively common in many arid vineyard regions, these findings have implications for mechanistic ET models that rely on time-averaged vertical gradients, which implies reasonably steady transport.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Introduction

A large portion of global vineyard cultivation occurs in semi-arid regions where water is limited, and uncertainty of water resources is growing, while water use by the crop is high (Kool et al. 2016). In addition, it is recognized that modest water stress during certain points in the growing season can improve grape and wine quality (Robinson 2006). Given these factors, there is a need for daily, field-scale estimates of evapotranspiration (ET) to more precisely manage vineyard irrigation and water use. Transport of water vapor away from plant canopies occurs chiefly through turbulence and in turn turbulent water vapor transport can be measured. The most commonly deployed micrometeorological method to quantify ET is eddy covariance. However, measurement methods typically represent values for a small area, involve expensive equipment, and require expertise to interpret findings. Though there exist several well-developed eddy covariance flux networks globally, these networks are unable to retrieve continuous, spatial estimates of ET over large heterogeneous landscapes.

Increasing success has been made estimating ET from vegetated surfaces through combining remote sensing information with soil-vegetation-atmosphere transfer models that are able to simulate turbulent exchange. The USDA Agricultural Research Service (ARS) has developed an ET modeling system known as ALEXI/DisALEXI (Atmospheric Land EXchange Inverse/Disaggregation ALEXI) utilizing the Two-Source Energy Balance model (TSEB) land surface scheme (Norman et al. 1995) to estimate turbulent fluxes using satellite measured land surface temperature (Semmens et al. 2016). The TSEB approach computes energy exchanges by partitioning a surface between soil and vegetation components and then solving for energy balance along a set of temperature gradients between these components, a canopy air temperature, and the air temperature of the surface layer above (Anderson et al. 2005). This modeling system has successfully been validated over a number of homogeneous natural and agricultural landscapes, and shows significant promise in providing field-scale estimates of ET for more heterogeneous surfaces such as vineyards. However, unknown factors remain regarding the particular complexities involved in vineyard ET processes and how well these complexities are handled by the TSEB approach. The Grape Remote Sensing Atmospheric Profile and Evapotranspiration experiment (GRAPEX) seeks to validate ALEXI/ DisALEXI performance for vineyard surfaces and to generate new knowledge of energy balance and transport processes in vineyards. The study reported here emerges from these general goals of the GRAPEX investigations.

Measurement and modeling methods used to estimate evapotranspiration through turbulent exchange, such as TSEB, rely on assumptions of how transport by turbulence is behaving over specific lengths of time. In the eddy covariance method, flux-averaging periods of 30–60-min increments are typically used near the surface (Foken et al. 2012) to capture a sufficient sample of all fluctuations contributing to the flux. Remotely sensed ET/energy balance models connect vertical transport to time-averaged vertical gradients with the assumption that the remotely sensed land surface temperature, collected instantaneously, can represent a suitable time-averaged value in flux-gradient formulations (Kustas et al. 2002). Thus, there is an implicit assumption that turbulence fluxes will have a reasonably steady behavior over the averaging period, in order for the averaged vertical gradients to be directly

proportional to the fluxes. This includes a premise that a sufficient number of transport events occur during the averaging period whose separations in time are small enough relative to the averaging period to be considered pseudo-homogeneous. In other words, here steady behavior refers to the case where the distribution of scalar transport in time is fairly consistent, and variations occur at a high enough frequency as compared to the averaging period length. However, it is known that a number of factors can cause turbulence in plant canopies to deviate from this ideal (Finnigan 2000), and indeed some degree of non-steady, intermittent behavior, at various time and space scales, can often be expected.

Intermittent behavior in boundary turbulence may arise from global processes external to the surface layer, such as large-scale eddies that are irregularly distributed in time and space (Mahrt 1989) or from large convective thermal plume structures in the planetary boundary layer (Li and Bou-Zeid 2011). But, it may also originate as local, small-scale intermittency caused by shear-gradient effects related to complexities in foliage and canopy structure of the local surface (Lee 2011). Much of the previous work on intermittent boundary layer turbulence has been concentrated on nocturnal stable stratification where global intermittency appears as distinct episodes of activity separated by relatively longer quiescent periods with little activity (Mahrt 1998; Poulos et al. 2001; Ansorge and Mellado 2014). For daytime conditions with neutral or unstable stability, studies have focused on the presence of coherent motions such as ejections and sweeps within the wind field. This behavior often manifests as ramp-like signatures in scalar time series, where the slow accumulation of a scalar near the surface is followed by a sudden drop as near surface air is vented. The relative importance of ejections and sweeps on momentum and heat transport from plant canopies has been extensively studied (Shaw et al. 1983; Katul et al. 1997; Finnigan 2000) and it has become clear that fluxes from heterogeneous canopies can be significantly influenced by coherent turbulent events (Gao et al. 1989; Paw U et al. 1992).

Despite the importance of episodic behavior, defining intermittency quantitatively has remained difficult (Vassili-cos 2010), since it is describing properties more profound than variability, or even harmonics. It is associated with high amplitude variability and the uneven clustering of events, and methods such as telegraphic approximation have been applied to relate individual properties such as clustering to sources of intermittent variability such as foliage and atmospheric stability (Cava and Katul 2009). However, these individual properties are unable to completely capture the range of behaviors that can be considered intermittent, since inter-mittency arises from the interplay between coherent spatial structures in the wind field, heterogeneity in the surface, and thermal stratification (Lee 2011). For example, as the boundary layer becomes increasingly convective, ejection-sweep features become altered by the large influence of buoyancy effects, and transition from eddy structures toward primarily large, low-frequency thermal plume structures (Li and Bou-Zeid 2011). Given this complex interplay, intermittency may manifest in momentum and scalar time series in a variety of ways beyond simple ramp-like features.

In the case of vineyards in semi-arid climates, both the physical vineyard structure and the local atmospheric conditions serve as confounding factors that could complicate turbulence and the resulting transport processes that govern vineyard ET. The canopy is organized in the sense that there are rows, but the spatial variability of the foliage extensions into the

interspace presents a complicated pattern to the wind field, while depending on vineyard management, the foliage of the canopy crown can be quite heterogeneous as well. Shear across the overall surface is therefore relatively non-uniform, as portions of eddies dissipate energy unevenly across the canopy row spacing and individual roughness elements in the crown. The partially open canopy, where substantial radiation reaches the soil surface, suggests that local buoyancy will be important in altering eddy morphology (Lee 2009). Chahine et al. (2014) conducted large eddy simulations of vineyards and compared them to 3-D anemometry measurements to examine wind direction/row structure interactions on local-scale transport. They found that cross-row flow behaved similarly to that of a more uniform canopy, while along-row flow showed increased spatial variability, increased intermittency of turbulence, and resulted in larger fluxes of momentum. Further, the growing season of warm, semi-arid climates often features strong, persistent synoptic high pressure and resulting subsidence (Peixoto and Oort 1992). This can result in small horizontal winds, even during the day, and the large radiation often induces unstable, convective conditions near the surface, leading to infrequent, large convective structures. If intermittent, episodic exchange events were pronounced in conditions frequent to semi-arid vineyard settings, this could have important implications for measurement and modeling methods by lengthening the necessary flux-averaging period and calling into question flux-gradient assumptions in model formulations. Because light wind, unstable conditions that may favor intermittent behavior are somewhat common in many winegrowing regions, there is a need to address these concerns in light of their possible impact on efforts to monitor vineyard ET.

Two general questions emerge. First, how large is the intermittent behavior of water vapor flux or ET from vineyards during light wind and strongly convective conditions? Second, how are moisture transport processes altered during intermittency in ways that have implications for eddy covariance methodology, and for ET models? In this study, we examine the intermittent behavior of water vapor exchanges in vineyards. The specific objectives are: (1) to document the relative importance of lower frequency and episodic exchange events during periods of light wind and large convection and (2) to quantify how intermittency in the water vapor exchanges affects key properties of turbulent water vapor transport and the required averaging period for eddy covariance fluxes.

Materials and methods

Site description

The sites for this study were part of the USDA-ARS Grape Remote Sensing Atmospheric Profile and Evapotranspiration experiment (GRAPEX), consisting of two drip-irrigated vineyards closely located in California's Central Valley near Lodi, CA (38.29 N, 121.12 W, 38.4 m elev.). The two sites were each relatively flat blocks of *V. vinifera* (Pinot Noir), with one that was 7 years old (north block, site #1) and the other 4 years old (south block, site #2) at the beginning of the 2014 growing season. Figure 1 depicts the study area location and layout of the two study vineyard blocks. The area experiences a semi-arid Mediterranean climate, typical of many areas in California, with precipitation almost entirely confined to the cool season and very little if any during the growing season. Daytime conditions during the growing season typically consisted of high maximum air temperature (35–40+ °C) and

mostly clear skies with high net radiation ($> 500\text{--}600 \text{ W m}^{-2}$). Winds were often light before noon ($< 1\text{--}2 \text{ m s}^{-1}$), strengthening gradually during the day, and often peaking in the mid to late afternoon ($\sim 2\text{--}4 \text{ m s}^{-1}$), though periods of light winds could be observed throughout the day.

Vines at both sites were grown on identical quadrilateral cordon fixed trellis systems with rows oriented east-west. The rows were spaced at $\sim 3.35 \text{ m}$ with individual vines spaced along the row at $\sim 1.52 \text{ m}$ increments and maximum canopy height during the growing season typically $\sim 2.5 \text{ m}$. Late into the growing season, vine growth extended the canopy laterally into the row interspace. This growth was partially governed by the vineyard management, but resulted in a complex spatial pattern of foliage. The inter-row surface within the vineyards consisted of a grass cover crop that typically senesced early in the growing season as spring precipitation ended. Directly below the vine canopy in each row was a strip of bare soil that was moistened routinely by the above ground drip irrigation. The elevated canopy/trellis structure included a significant open space between the bottom of the canopy crown and the soil surface below of $\sim 0.7 \text{ m}$ in height occupied nearly exclusively by the narrow trellis posts and drip irrigation line.

Instrumentation

Data presented here were collected during intensive observation periods (IOPs) of several days each conducted 3–4 times throughout the 2014, 2015, and 2016 growing seasons resulting in a total of 39 days of measurements from each of the two sites. Surface fluxes and environmental conditions were measured at two towers, one at each site, placed near the eastern edge of the respective vineyard block so as to enjoy maximum footprint from the dominantly westerly winds (Fig. 1), achieving a typical fetch of $\sim 400 \text{ m}$. Fluctuations of 3-D wind velocities and water vapor above the canopy were measured on each tower using an IRGASON, combining a 3-D sonic anemometer (CSAT-A, Campbell Scientific Inc., Logan, UT¹) and open path infrared gas analyzer (EC-150, Campbell Scientific Inc., Logan, UT). These instruments were mounted facing due west at a height of 5 m agl . Net radiation was measured from the tower at 6.5 m agl using a four-component net-radiometer (CNR-1, Kipp & Zonen, Delft, The Netherlands). Soil heat flux was calculated using a diagonal transect of five equidistant (0.92 m) soil heat flux plates immediately south of each tower that extended from beneath one canopy row and across the row space to beneath the next canopy row. The plates were placed at 0.08 m depth (HFT- 3, Radiation Energy Balance Systems, Bellevue, WA) with two thermocouples near each plate at 0.02 and 0.06 m depth and soil moisture probes (HydraProbe, Stevens Water Monitoring Systems, Portland, OR) at 5 cm depth. An additional open-path IRGA (LI-7500A, LI-COR Biosciences, Inc., Lincoln, NE) was placed in the row space between canopies immediately north of each tower at a height of 1.5 m agl (Fig. 1). The term within canopy here describes these IRGA measurements from the inter-row space below the canopy top, but outside the true canopy crown. The within-canopy IRGAs were sampled by each tower's datalogger such that they were synchronized with the other tower instrumentation. Data were sampled by a CR3000 datalogger (Campbell Scientific Inc., Logan, UT, USA) at a sampling rate of 20 Hz except for two IOPs during 2016 where the sampling rate was lowered 10 Hz due to technical constraints. A more detailed description of site and instrumentation details is presented by Kustas et al. (2018).

Analyses

Fast response measurements of velocity and water vapor were quality controlled, including removing periods of bad or missing data, spike detection, and replacement when possible. Periods of interest were selected from the daytime hours (7:00–19:00 LST) of the 39 IOP days at both sites for further analysis. Time series of the vertical wind component (U_z , m s^{-1}), water vapor density (ρ_v , g m^{-3}), and instantaneous vertical water vapor transport ($U'_z * \rho'_v$, $\text{g m}^{-2} \text{s}^{-1}$) were plotted and visually surveyed to initially qualitatively isolate periods of high amplitude fluctuations that appeared episodic and unequally spaced in time. Likewise, periods of relatively frequent and more evenly spaced fluctuations were also identified. A quantitative procedure for this discrimination was also employed, as discussed later. Selected periods were restricted to predominately along-row flow, i.e., from the west, to eliminate complicating effects on turbulence of changes in wind direction with row orientation (Alfieri et al. 2018). The result was two sets of periods, one of 100 individual hours classified as intermittent and one of 100 individual hours classified as steady. These data sets were used to statistically compare the differences between the two behaviors in terms of fluxes and atmospheric conditions including mean winds, stability, and vapor pressure deficit.

Custom computer scripts were used to calculate hourly turbulent fluxes of sensible heat (H) and latent heat (λE) from the 5 m fast response data for all selected periods. Corrections applied during flux computations included a simple 2-D coordinate rotation, detrending, frequency corrections (Massman 2000), density corrections (Webb et al. 1980), as well as other corrections and computations to the raw covariances. Soil heat flux (G) was calculated as an addition of the term for the heat flow across the heat flux plates (G_p) and the term for storage in the soil layer above the heat flux plates (G_s) as $G = G_p + G_s$ (Campbell and Norman 1998). In addition to these fluxes, the friction velocity u_* and the stability parameter z/L were calculated at $z = 5$ m for each hour, where L is the Monin-Obukhov length scale (Stull 1988).

Time series of U_z and ρ_v for the 100 periods within each set were compared to time series of mean hourly horizontal wind (U_{horiz}) and z/L . Through this approach, the concurrent timing of changes in mean wind and stability with the onset and duration of intermittent behavior was examined. To quantify the time scales of fluctuations in humidity and the vertical flux of moisture, particularly in the low frequencies, a further subset was isolated from each of the 100-h sets consisting of 10 representative 2-h periods for each, where the classified behavior, either intermittent or steady, persisted through two consecutive hours. These two subsets were used to capture the influence of potential low-frequency behavior during spectral analysis and analysis of flux-averaging periods explained below.

In-house code written to perform discrete Fourier transforms was used to detrend the data, apply a Hann window, assemble power spectra and cross-spectra for the sub-selected periods, and apply a smoothing routine to the raw spectra. Cross-spectra for vertical velocity and water vapor density (U_z, ρ_v) were computed from the 5 m eddy covariance instruments and averaged for each set, producing an average water vapor flux cross-spectra for each behavior. Further, to quantify the relationships of humidity fluctuations between the surface layer above the canopy and the canopy sub-layer, power spectra and cross-spectra were created for the two 10-period subsets from water vapor density measurements both above

and within the canopy. In this way, the time scales of humidity changes of the individual layers, via p_v power spectra at each height, as well as the coherent humidity changes between the layers, via the ρ_v above, ρ_v within cross-spectra, could be addressed.

Keeping in mind the interest in flux measurement and modeling, the impact of intermittent versus steady behavior on flux averaging was investigated. For eddy covariance measurements, the flux-averaging time period must be long enough to account for all eddy length and time scales that significantly contribute to the fluxes (Finnigan et al. 2003). Near the surface, for many atmospheric conditions, 30–60-min averaging periods are sufficient to capture all of the contributing eddy sizes to the turbulent fluxes. However, given that intermittency may cause turbulence to become dominated by low-frequency events, longer averaging period length may be necessary to account for all processes contributing to the flux during intermittency. Cross-spectra of vertical velocity and scalars can be used to quantify the importance of low-frequency fluctuations and determine if all significant scales are being captured by determining the lowest spectral peaks that are distinctly separate from the red noise at the lowest end of the spectrum associated with non-stationary effects.

Additionally, energy balance requires that the turbulent fluxes must balance with the sources and sinks of energy in the system:

$$\lambda E + H = R_{\text{net}} - G - P - S \quad (1)$$

where R_{net} is the net radiation, S is the storage of energy by vegetation above the surface, and P is the energy used for photosynthesis (Campbell and Norman 1998). S and P are considered negligible in this case, and are neglected. Energy balance closure is therefore:

$$\frac{\lambda E + H}{R_{\text{net}} - G} \quad (2)$$

where a value of unity would be a perfect accounting for all energy. Since errors degrade covariances, actual values for (2) are generally less than 1. Twine et al. (2000) present an approach to forcing the values to one, and conserving energy. Here we are concerned with the appropriate length of the flux-averaging period, which can be determined by calculating flux values for increasingly larger time lengths until the energy balance closure ratio approaches a maximum value. As with cross-spectra, caution must be taken as increasing averaging period may be associated with non-stationary effects. Here turbulent fluxes were calculated for the 10 2-h periods from the intermittent and steadier period subsets using averaging periods of 15, 30, 60, 90, and 120 min. Energy balance closure was then computed for each averaging period length.

The discrimination between steady versus intermittent periods was initially qualitative. A simple quantitative approach to make the separation would be more objective and desirable and so we decided to quantify the intermit-tency of water vapor exchanges through the construction of simple metrics. Doing so is problematic, however, as inter-mittency not only

exhibits low-frequency turbulence events, which can be addressed via spectral methods, but also events that are both irregular and also possibly coherent. This represents not only a difference in the time scales responsible for the flux compared to more steady behavior, but also a variability in the time distribution of events at each time scale.

A first way to quantify the differing exchange behavior of the intermittent and steadier periods was to examine time series of instantaneous vertical water vapor transport ($U'_z * \rho'_v$) and document the temporal distribution of water vapor exchanges. Time series of the multiplied squared perturbations ($U'^2_z * \rho'^2_v$) were created as well (not shown) to better assess the distribution of absolute exchange activity in time and these were examined for coherent and intermittent patterns. The distribution of $U'_z * \rho'_v$ values during and between distinctly coherent events was used to determine positive and negative thresholds to isolate events that appeared to be significant from the quiescent periods between them (Fig. 2). The more active instantaneous fluxes that occurred outside the thresholds could then be summed and divided by the sum of all instantaneous flux values for the period, yielding a ratio of active to total flux.

$$\text{Flux Ratio} = \frac{\sum \text{gm}^{-2}\text{s}^{-1}(\text{ points exceeding threshold })}{\sum \text{gm}^{-2}\text{s}^{-1}(\text{ entire period })} \quad (3)$$

Likewise, the sum of active time length over the total period length was calculated to yield the ratio of time of active flux divided by total time.

$$\text{Time Ratio} = \frac{\sum s(\text{ points exceeding threshold })}{\sum s(\text{ entire period })} \quad (4)$$

Then, the ratio of (3) over (4), a unitless flux/time ratio, is a metric of the degree of intermittency in the flux, where larger values of flux ratio divided by smaller values of time ratio denote more intermittency.

A second approach was constructed as follows. Since turbulence kinetic energy (TKE) is such a fundamental property of the intensity of turbulence, we first computed the time series of TKE values. Then, the standard deviation of TKE was determined using several windows of different lengths (20, 600, 1200, 2400, 3600 and 4800 consecutive points or occurrences). At the 20 Hz sampling rate, these translated to 1, 30, 60, 120, 180 and 240 s. For each window, the standard deviation of TKE was determined for each location, then averaged with the window's passage over the entire time series. As expected, the standard deviation values grew larger as the window was expanded, reaching their maximum no later than the 4800 value. The ratio of the maximum value of standard deviation to the minimum value (always at the shortest window) defines the strength of episodic behavior. Figure 3 shows the results of the ratio for a number of the cases previously identified as steady or intermittent. The results clearly show a rather clean differentiation at a ratio value of about 2.6. The

results of this quantitative approach did reverse several of the earlier classifications of steady versus intermittent based on the qualitative criteria. This approach then quantitatively defines steady versus intermittent in this study.

Results and discussion

Here we report results from comparative analyses between periods demonstrating episodic, intermittent behavior and those displaying relatively steadier behavior. We focus first on connecting time series of velocity and humidity to time variations in atmospheric conditions and present summary statistics for observed conditions during the two time period types. Next, we discuss power and cross-spectra results to examine the dominant time scales of exchanges and humidity fluctuations above and within the canopy, with particular emphasis on the influence of low-frequency variability. Then, we describe efforts to quantify differences between the two behaviors that arise from the temporal distributions of flux events, including the impact on flux-averaging periods.

Time series and atmospheric conditions

Across the three growing seasons, the vast majority of IOP days had dry conditions and dominant west winds ideal for the purposes of this study. Surveying time series of U_z and ρ_v at both sites, and from both above and within the canopy, presented a range of behaviors between what could be qualitatively classified as intermittent or steady. However, distinctly intermittent periods and distinctly steadier periods of 1–4 h in length were frequently observed for nearly all IOP days. Examples of these distinct periods are illustrated in Fig. 4 for two periods during the afternoon of DOY 191 of 2015 from site #1. Figure 4a demonstrates a 40-min section of behavior identified as intermittent, where time series for humidity and vertical velocity show a patchy distribution of relatively high amplitude fluctuations separated by durations of quiescent activity. Figure 4b is a 40-min example of steady behavior, occurring about an hour after the example in Fig. 4a. Here, fluctuations are considerably more consistent in both amplitude and distribution in time. Figure 4c, d present $U'_z * \rho'_v$ time series during the same two periods. Here the contrast between the two periods is even more evident with the first period exhibiting strong, low-frequency clustering in time not apparent in the second period. By surveying periods in this manner, the 100 representative hours of each behavior type were initially isolated into two sets for comparison in the subsequent analyses.

A first effort was made to establish general relationships between the occurrence of the contrasting behaviors and atmospheric conditions. Figure 5a presents humidity, above and within the canopy, and the above canopy vertical wind component again for DOY 191 of 2015 from site #1, but for a longer period from 09:30 LST to 18:30 LST. During the late morning hours, time series become increasingly transient, displaying a patchy distribution of large variations interspersed with smaller, more consistent values. Around 15:00 LST, there was a relatively rapid transition to a period of steadier activity where U_z and ρ_v fluctuations occurred more uniformly at higher frequencies. This type of distinct transition between periods of intermittent and more steady behavior was found to occur frequently and served as a convenient cutoff between the two behaviors for period selection.

Figure 5b depicts U_{horiz} and z/L for the same daytime period. Here mean U_{horiz} decreased from higher morning values to values below 1.5 m s^{-1} during the 11:00 to 14:00 LST time period, before increasing to $\sim 2.9 \text{ m s}^{-1}$ by 16:00 LST. Values of z/L became increasingly negative during this light wind period before becoming less negative, while winds increased into the afternoon. This example expresses a pattern common to nearly all of the intermittent periods where they initiated at the onset of light winds and more unstable conditions. Conversely, periods classified as steady were most often associated with transitions to higher mean winds and lower instability.

These associations between wind velocity, stability, and behavior are quantitatively summarized through comparative statistics for key variables from the 100 intermittent and 100 steady hour sets (Table 1). Fluxes of net radiation, sensible heat, and latent heat are consistently higher for the intermittent periods than for the more steady periods. This can largely be explained by the fact that hours classified as intermittent occurred most often during the midday, with greater than 68% of the periods having fallen between the hours of 10:00 and 14:00 LST. Most of the steady periods, however, took place later in the afternoon (after 13:00 LST), with a smaller portion associated with the hours before mid-morning (before 10:00 LST), and few during midday. Energy balance closure was higher for steady hours (0.89), compared to intermittent hours (0.85). Intermittent hours also had larger variability in closure values as denoted by the difference in standard deviations. As expected, mean horizontal wind and friction velocity were notably lower for the intermittent cases, which were also associated with higher instability as indicated by their lower mean z/L . This mean value of z/L for the intermittent periods is not especially large (-0.33), though it was variable with a standard deviation near the magnitude of the mean. Of the intermittent periods, 16 had z/L values of -1 or below, while the lowest value for a steady period was -0.41 . In tandem with light winds, the behavior of time series seemed to be quite sensitive to small changes in instability. Vapor pressure deficit was more or less consistent between the period sets, a notable consistency in the mean humidity and evaporative demand despite the increased amplitude of fluctuations present during intermit-tency compared to steady behavior.

Spectra

Given the differences noted above in the characteristics of the two behavior classifications, spectra were calculated to estimate the structure of turbulence and time scales of transport for the two sets of conditions. Cross-spectra of vertical motion and water vapor density (U_z , ρ_v) consistently exhibited differing time scales of exchange between intermittent and more steady periods. In Fig. 6 cross-spectra have been averaged for the 10 representative intermittent and 10 representative steadier 2-h subset periods. The two composites are similar in the high frequencies as expected. The values grew larger as frequencies became lower for the intermittent cases, indicating more flux contribution from low-frequency events. Note the log scales here. The peak value for the intermittent composite translates to time scales of an hour or more, suggesting longer averaging periods than typically used would be necessary to recover accurate flux values. The energy balance closure analysis described later further addressed this issue.

Noting both the increased variability in the amplitude and clustering of humidity fluctuations and the dominance of low-frequency exchanges during intermittent periods, it becomes of interest to examine how this might be affecting the time scales of humidity variations within the canopy as compared to the air above canopy. Utilizing the synchronized IRGAs at 5 m and 1.5 m, ρ_v power spectra were calculated separately for above-canopy and within-canopy subsets of 10 intermittent and 10 steady 2-h periods. Figure 7 illustrates selected examples of these, comparing ρ_v power spectra for two periods on DOY 163 of 2016 from site #1. These spectra correspond to consecutive periods, one with more steady behavior from 15:00–17:00 LST and mean winds $\sim 2.6 \text{ m s}^{-1}$ (Fig. 7a), which was followed by a drop in mean winds to $\sim 1.3 \text{ m s}^{-1}$ and a quick transition to an intermittent period that extended from 17:00–19:00 LST (Fig. 7b). Spectra from the steadier period correlate strongly between the two heights, showing shared peaks across a range of frequencies, suggesting that the exchanges at the two heights are well-coupled. For the intermittent period in Fig. 7b, the above canopy spectrum displays a relatively smooth curve in this same range of frequencies. Yet, the spectrum within the canopy is somewhat reduced at the higher frequencies and some of the lower frequencies, and more variable at the lowest frequencies, suggesting the canopy is acting as a filter to various scales of transport. Similar findings were observed for the 9 other periods in each subset.

To further examine differences in the relationship between the above- and within-canopy layers, cross-spectra of water vapor density measurements from above and within the canopy (ρ_v above, ρ_v within) were also computed for the two 10-period subsets. Figure 8 depicts selected examples of these corresponding to an intermittent period and more steady period both from DOY 152 of 2015 from site #2; depicted in semi-log form to emphasize the differences in the low frequencies. The results further exhibit a strong enhancement of low-frequency signal during periods of intermittency. These contrasting patterns in covariance between the two behaviors were apparent in comparing all 10 periods in the two subsets.

Fluxes

Considering the impact of enhanced low-frequency variability in water vapor exchange during intermittency, a next step was to address how intermittency affects the temporal distribution of transport and in turn the characteristics of the overall water vapor flux. As previously noted in Fig. 4c, d, distinct differences in the temporal distribution of the water vapor transport can be identified by examining the time series of $U'_z * \rho'_v$. Intermittent periods were marked by patchy distributions of larger, infrequent exchanges, separated by less active sections of the time series, indicating that the flux is being confined to relatively short amounts of time. Steady periods, however, were characterized by smaller, more numerous events that were more consistently spaced at higher frequencies.

To better quantify these temporal distributions, $U'_z * \rho'_v$ and $U'^2_z * \rho'^2_v$ time series, were used to isolate the dominant exchanges in the $U'_z * \rho'_v$ series, using the threshold approach depicted in Fig. 2, for both sets of periods of interest. The proportion of the water vapor transport that occurred above or below the thresholds, and the time over which this proportion occurred, were summed for the periods from the intermittent and more steady period subsets. Table 2

lists the results for a portion of the periods analyzed from both sites. Striking differences were observed between the two types of condition. On average during steadier periods 97–99% of the water vapor flux occurred in 75–85% of the total time length for each 2-h period. During intermittent periods, however, 85–95% of the water vapor flux occurred in only 28–39% of the total time. Resulting ratios of flux per time for intermittent periods consistently yielded much higher values than those of steadier periods, often more than double, forming two distinct groups of values between the sets. As shown previously, hours from the intermittent set were nearly always associated with lower values of mean U_{horiz} and larger negative values of z/L , and in turn we see this relationship with flux time ratio.

Calculations of energy balance closure for various flux- averaging period lengths revealed marked differences between intermittent and steady periods. Figure 9 shows a comparison of these calculations between the two subsets of 10 2-h periods. For the steadier periods, energy balance closure increases with increasing averaging period through 30 min, peaking at 60 min and then decreasing for periods of 90 min or more. This indicates that a 30–60-min period would be ideal for averaging the fluxes. However, for the intermittent periods, the closure value failed to converge to a maximum value near unity until at least 120 min. Of course, there is always an issue of possible non-stationarity in longer averaging periods. However, in such a case, the flux estimates would be expected to become more variable rather than converge upon a higher value. Sun et al. (2006) and others have also reported a need for similar longer averaging periods for fluxes under conditions with enhanced low-frequency convection. They highlight one location where the averaging period should be 60–120 min, very similar to the case we denote here. Given the low-frequency peaks in intermittent spectra and cross-spectra that correspond to time scales of 40 min to greater than hour, it seems reasonable that an averaging period of 90 min or more would indeed be necessary to capture all of the processes contributing to the overall flux. Of note is the clear difference in the variability of closure values for the intermittent periods versus the more steady periods.

Discussion and conclusions

Through the comparisons of both time series and the summary statistics of key variables between intermittent and steady period sets, this study was able to delineate a strong connection between periods of light winds and unstable, convective stratification and the presence of intermittent turbulence transport. Intermittent behavior was most common during periods with mean winds of $1.5\text{--}2.5\text{ m s}^{-1}$ or less, while steady behavior was nearly always associated with larger mean horizontal winds of $> 2\text{ m s}^{-1}$. Further, intermittent periods were associated with buoyancy dominated periods indicated by larger negative values of z/L and high sensible heat flux. Neither the occurrence of light winds nor highly unstable stratification alone guaranteed the appearance of intermittent behavior, but overall, a clear association was quantified between light wind, convective periods and exchange behavior that is dominated by episodic, transient events.

Spectral analyses demonstrated that variations in water vapor density were often dominated by lower frequencies during light winds and highly unstable stratification. This suggests the importance of large, infrequent eddies or thermal structures in transporting water vapor

under these conditions. This is not completely unexpected due to the nature of the initial classification of steady versus intermittent periods which focused on selecting periods with large amplitude variability with irregular distributions in time. However, this importance of low-frequency events was most pronounced within the canopy, suggesting the physical presence of the vineyard canopy acted as a low pass filter to transport processes. The large peak in the lowest frequencies for the within-canopy spectra, such as Fig. 7b, suggests that only eddies or convective structures with large enough spatial scales and kinetic energy are able to penetrate the canopy and properly vent the canopy airspace during these periods. The broadness of the large, low-frequency peaks in crossspectra from intermittent periods, such as in Fig. 8, points to the importance of the irregular intervals between events during intermittency. Once fluctuations become more steady, the dominance of low frequencies diminishes and spectral curves are marked by a more regular distribution across a range of frequencies. The sharper low-frequency peaks in the canopy likely reflect distinct eddy sizes controlled by mechanical turbulence associated with canopy structure.

The analysis of flux-averaging period lengths demonstrates that substantially longer averaging periods may be necessary to calculate fluxes from eddy covariance during intermittent conditions. Assessing ET of vineyards in semiarid regions may require reconsideration of appropriate time scales when conditions favorable for low-frequency, episodic transport, i.e. lighter winds and large instability, are present. Unlike more steady conditions, episodic transport resulted in a large proportion of the flux happening in a relatively short proportion of the time. As suggested by flux/time ratios, the large majority of water vapor flux could occur in under one-third or less of a given time period. In such cases, a small number of large transport events can drastically affect average fluxes and this effect must be considered when modeling or making measurements. This also suggests that loading and venting of the canopy is less regular during intermittency affecting the moment to moment microclimate within the canopy. We could expect that this more dynamic environment within the canopy sub-layer would have possible implications for stomatal response on short-time scales, and could potentially produce unexpected behavior in vertical gradients.

Given the proximity of the two sites and similar environmental conditions, considerable differences were not observed in the behavior of exchanges between the two sites. Due to the vine age difference between the two sites, the canopy extent into the row space of the older northern block (site #1) was generally somewhat larger than the southern block (site #2). Future work to more thoroughly compare turbulence characteristics and exchange behavior between the two sites for given periods may prove beneficial in further determining any influence of vineyard structure.

Despite the importance of intermittent behavior in turbulence transport, unequivocal, objective identification remains tricky. Initial selection of periods for analysis was qualitative. However, it is clear throughout the analyses presented that periods classified as intermittent behave considerably differently than those of more steady transport. The flux/time ratios proved useful as both a quantitative metric for verifying intermittency and a method to compute differences in the amount of time fluxes occur over for a given period. The standard window technique provided an even clearer definition, with a distinct cutoff

value of 2.6, for discriminating transient and non-transient activity. This allowed quantitative determination of the intermittent and steady period sets.

It is apparent that the behavior of turbulence transport of water vapor or ET in vineyards, is often fundamentally altered during light wind, convective conditions; conditions that are not unusual in many semi-arid regions. In addition, the large transport in short periods associated with intermittent conditions, suggests that they may not conform very well to assumptions required to connect fluxes to average gradients typically used in models. Of particular note is the favored timing of intermittency at these sites during the late morning to midday, times when most satellite retrievals used in remote-sensing based modeling approaches occur. Measurements made through the near instantaneous snapshot of these retrievals could prove vulnerable to effects from large-scale, low-frequency variability in fluxes. The effects of these transient conditions on the ability of schemes in models to simulate transport deserve more attention. Future work is planned to document the performance of the TSEB model ET estimates during conditions of transient versus more idealized transport to investigate how the differing behavior affects a gradient-driven model.

The temporal details of how turbulence transport occurs in vineyards appear to be important, and so how ET is occurring in time does matter. Hence, a better understanding of transient exchanges of ET under these conditions is worthy of further investigation.

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Fig. 1.

Locations of the two GRAPEX sites. The northern vineyard block (site #1) is outlined in red, while the southern block (site #2) is outlined in blue. Tower locations, and collocated within canopy instruments, are marked with yellow dots. Photographs of the tower and within canopy instrumentation from site #1 are also shown. (Color figure online)

Fig. 2.

Time series of instantaneous vertical water vapor transport at $z = 5$ m during period 8:00–10:00 LST on DOY 152 of 2015 at site #1. Positive and negative thresholds for the period are shown. (Color figure online)

Fig. 3.

Ratio of max/min standard deviation of TKE in set of windows for various cases identified as steady or intermittent. A demarcation is apparent at the value 2.6. (Color figure online)

Fig. 4. Time series of the $z = 5$ m (blue) and $z = 1.5$ m (green) water tuations. Also, time series of the instantaneous water vapor transport, vapor density (ρ_v), and 5 m vertical wind (U_z) for two 40-min periods on DOY 191 of 2015. **a** Intermittent fluctuations; **b** more steady fluctuations. Also, time series of the instantaneous water vapor transport, for intermittent case (**c**); steady case (**d**). (Color figure online)

Fig. 5.

a Time series of the 5 m (above canopy, in blue) and 1.5 m (within canopy, in green) water vapor density, and 5 m vertical wind component for 9-h period on DOY 191 of 2015 at site #1. **b** Hourly mean horizontal wind and stability parameter (z/L) for the same period. (Color figure online)

Fig. 6.

Log-log plot of crossspectra of vertical wind (U_z) and water vapor density (ρ_v) above the canopy ($z = 5$ m). Spectra are depicted as points for 10 individual 2-h intervals (red) and 10 steady 2-h periods (blue). Composite average spectra for both sets of 10 intervals are shown with solid lines. (Color figure online)

Fig. 7. Power spectra of water vapor density (ρ_v) above canopy (5 m) and within canopy (1.5 m) for two consecutive 2-h periods on DOY 163 of 2016. **a** Steady case from 15:00–17:00 LST and **b** Intermittent case from 17:00–19:00 LST

Fig. 8. Semi-log plot of crossspectra of water vapor density (ρ_v) above canopy (5 m) and within canopy (1.5 m) for an intermittent and steady period at site #2

Fig. 9. Comparison of energy balance closure for 10 intermittent (red) and 10 steady (blue) 2-h periods. Fluxes were calculated for five averaging periods of increasing length. Boxes outline the middle 50% of the distribution, and lines depict trends for the mean closure values for intermittent and steady periods, respectively. (Color figure online)

Table 1

Means, standard deviations, T-statistics, and p values of key variables for intermittent and steady periods

		R_{net} , W m^{-2}	H , W m^{-2}	λE , W m^{-2}	Closure	VPD, kPa	U_{horiz} , m s^{-1}	u^* , m s^{-1}	z/L
Intermittent periods	Mean	562	192	311	0.85	2.041	2.13	0.33	-0.327
	σ	110	90	85	0.09	0.794	0.40	0.07	0.325
Steady periods	Mean	324	82	222	0.89	2.216	2.72	0.40	-0.071
	σ	188	91	101	0.06	0.823	0.70	0.11	0.115
T-statistic		8.79	6.54	6.30	-4.22	0.28	-9.12	-7.55	-8.55
p value		2.64E-15	5.41E-10	1.96E-09	4.03E-05	0.78	3.43E-16	3.84E-12	5.03E-14

The critical T-statistic for a $p = 0.001$ is |3.39|, for significance of differences between means of each period

Table 2

Proportion of the water vapor flux outside the thresholds, proportion of time this flux occurred for each period, and resulting flux/time ratios for five intermittent and five steady periods

Year	DOY	Time	Site	Proportion flux	Proportion time	Ratio flux/time	z/L	U_{horiz} m s ⁻¹	λE , W m ⁻²
Intermittent periods									
2014	181	1200–1400	1	0.91	0.33	2.78	– 0.399	1.70	319.5
2015	152	0800–1000	1	0.88	0.29	3.02	– 0.709	1.05	153.7
2015	152	1000–1200	1	0.94	0.39	2.38	– 0.542	1.40	200.3
2016	123	1100–1300	2	0.91	0.34	2.67	– 0.891	1.00	234.4
2016	162	0900–1100	2	0.90	0.31	2.90	– 0.174	1.85	255.2
Steady periods									
2014	216	0800–1000	1	0.97	0.81	1.24	– 0.090	2.27	116.3
2015	152	1500–1700	1	0.99	0.82	1.21	– 0.086	2.75	185.3
2015	152	1700–1900	1	0.97	0.75	1.30	0.006	3.20	87.1
2015	191	1500–1700	1	0.99	0.84	1.18	– 0.068	2.80	210.5
2016	123	1600–1800	2	0.99	0.80	1.23	0.012	2.10	180.4

Also, the 5 m hourly mean horizontal wind, stability parameter z/L , and latent heat flux values from eddy covariance measurements