**UNDERSTANDING TURBULENT KINETIC ENERGY (TKE) STATIONARITY WITHIN A FOREST
CANOPY.**

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Abstract

Year round measurements of turbulence were taken at heights, above, below, and in the live crown in an old-growth forest in Howland, ME. A technique to determine the stationarity of turbulence kinetic energy (TKE) is presented and used as a classifier of the turbulence intermittency in the nocturnal boundary layer. The results show that both the length of a stationary TKE signal and the scale of intermittency vary with canopy depth. TKE remains stationary for longer periods above the canopy, and shorter periods are observed in the open space below the live crown. Neutral stability conditions exhibit the highest intermittency at all heights. Additionally a new intermittency factor is introduced which allows for characterizing turbulent regimes. The results have broader implications for understanding and identifying turbulent statistics in the stable boundary layer.

1. Introduction

Forests play a large and vital role in global carbon and water budgets. Therefore, a fundamental understanding of the mechanisms that control energy and mass exchange between the atmosphere and forested ecosystems is of key importance. While much work has focused on the coupling of the turbulence above and below canopies during unstable daytime conditions (e.g. Vickers and Thomas 2013), less is known about stable nighttime conditions in these environments (Aubinet 2008; Mahrt 2010; Mahrt et al. 1998). Additionally, much of our current understanding of scalar fluxes is grounded in long-term eddy covariance measurement methods (Baldocchi 2003). These methods, however, are less reliable at night during stable stratification (Aubinet 2008). Understanding forest-atmosphere exchanges at night is important for practical

applications such as turbulence and wind modeling (Finnigan et al. 2009), eddy covariance quality control techniques, and quantification of ecosystem exchange (Baldocchi 2003).

One area of particular interest is the subject of intermittency in the stable boundary layer (SBL) (examples include: Liang et al. 2014; Salmond 2005; Sun et al. 2012; Sun et al. 2013; Sun et al. 2004; Van de Wiel et al. 2002a; Van de Wiel et al. 2002b). Possible sources of intermittency have been identified as density currents (Sun et al. 2002), mesoscale wind gusts penetration downward into the stable surface layer (Sun et al., 2004), low-level jets (Prabha et al. 2007), turbulence-wave interaction (Mahrt, 2014), and flow interaction with complex topography (Cava, et al., 2005). Many of these studies have focused on the possible sources of intermittency, or on classifying intermittency regimes. More recently, a broader theoretical understanding of the persistence of the mean flow and conditions necessary to sustain turbulence, and turbulent mixing, has started to take shape (e.g. Van de Wiel et al. 2012). The addition of a forest canopy, an environment where flow is regularly disturbed by vegetation elements and canopy gaps, complicates the previously proposed intermittent classification schemes. Recently, Vickers and Thomas (2013) have made a detailed evaluation of the various terms in the turbulent kinetic energy (TKE) tendency equation, and concluded that subcanopy turbulence is driven by shear generation above the canopy, further confirming previous work (e.g. Dwyer et al., 1997; Leclerc et al., 1990; Lesnik, 1974; Meyers and Baldocchi, 1991, and others). This is a strong indication of a coupling between the two layers (Belcher et al., 2012; Lee, 2000; Mahrt et al., 2000). However, in stable conditions evidence of decoupling has been reported, particularly associated with wind shears (Alekseychik et al. 2013).

At the core of micrometeorological measurements is the direct measurement of turbulence with sonic anemometers. To determine fluxes of heat, momentum and other scalars, it

is assumed that the first-, and sometimes second-, order statistics of the turbulent field are stationary. This assumption, however, which is fundamental to our understanding of turbulence, is often not valid. If it is valid, it only holds for short periods of time, generally assumed to be 30 minutes or less. This is particularly true in the weak wind conditions which can dominate stable conditions (Cullen et al. 2007). It is also known that the assumption of stationarity does not always hold true in the atmospheric surface layer (ASL). To address these issues, several different tests for stationarity have been developed and used to quality control data (Foken and Wichura 1996; Mahrt 1998). More recently Cava et al. (2014) have proposed a combined stationarity index for this purpose and concluded that stable conditions have the most ambiguity in determining stationarity.

Work by Nappo et al. (2010) has shown the potential of durations of turbulence stationarity as a classifier of the turbulence regimes in the stable boundary layer. In other words, how long a time series stays time-invariant is a classifier of overall levels of turbulence. In a homogeneous environment (Nappo et al. 2010) a correlation exists between the duration of stationarity and the kurtosis of heat flux within the stable surface layer, but a poor association is evident between the two above the surface layer. Therefore, the examination of how long turbulent variables remain stationary can enhance our full understanding of how these changes affect measured fluxes in different surface environments. Furthermore, identifying how long a variable stays stationary can help separate the events which happen at mixed scales. We present here the application of this technique to a non-homogeneous forest environment to quantify stationarity of turbulence regimes at different levels within the canopy, and second identify potential couplings of non-stationarity and intermittency in this environment. In addition we propose a new intermittency factor as a method of classifying nocturnal turbulence regimes.

2. Methods

Data were collected at the Howland Research Forest in Howland, Maine, which consists mostly of an old growth Spruce/Fir forest. Mean canopy height in the study plot is 20.6 meters. The site is part of the AMERIFLUX network, site US-Ho2. Detailed canopy information can be found in Hollinger et al. (1999) and Xiao et al. (2004). Three CSAT3 sonic anemometers (Campbell Scientific, Inc. Logan, UT) were installed on the Howland West tower: one just above the canopy top (21.4 m), one at the center of the live crown (15.1 m) and one just below the live crown (8.0 m). These heights were chosen to correspond to a simultaneous study examining tree sway dynamics (Granucci et al. 2013). Anemometers were monitored with a Campbell Scientific CR9000X datalogger at a rate of 10Hz. Nocturnal data from August 2009 to December 2010 are analyzed here. In all, the data set represents ~2000 hours of nighttime data over 215 nights. 30 minute average wind speeds at the 21.4 meter height range from 0.15 to 3.97 m/s. 49% of data immediately above the canopy showed calm to weak winds, defined as less than 1.0 m/s. If this definition is expanded to 2.0 m/s 91% of the data is considered calm conditions. TKE time series were constructed for nocturnal data, beginning one hour after sunset and ending one hour prior to sunrise. This period was generally assumed to be stable and free of effects of the transition from convective to stable and vice versa. Discussion of the actual stability conditions sampled during this time period is presented below.

a. Duration of Stationarity

Stationary periods were computed to examine the energy penetration into the canopy of this site during stable boundary layers. The duration of stationary periods of TKE was calculated at each of the three sonic anemometer locations following the techniques of Nappo et al. (2010),

using a “double mass balance” method. To do this, changes are identified between the slopes of two different time series, S_q and S_q^p . S_q is the cumulative sum of some variable, q :

$$S_q(t_i) = \sum_{j=1}^i q(t_j) \quad [1]$$

with slopes between consecutive points ψ :

$$\psi_i = \frac{S_q(t_{i-1}) - S_q(t_i)}{t_{i-1} - t_i} \quad [2]$$

S_q^p is a linearly extrapolated series computed as a straight line with a slope equal to the that between points t_n and t_{n+1} where j is the starting point of the subseries:

$$S_q^p(t_i) = S_q(t_{i-1}) + \frac{S_q(t_j) - S_q(t_{j-1})}{t_j - t_{j-1}} (t_i - t_j) \quad [3]$$

A significant change in slope of the cumulative variable S_q implies a change in the mean value of that variable. Thus, the duration of stationarity, d , or how long the record of a variable has a constant mean, is defined when the absolute value of the difference of the measured and extrapolated TKE slope exceeds some value $\sigma_{\psi i}$. $\sigma_{\psi i}$ is calculated as the standard deviation of the individual slopes in the time period being tested:

$$\sigma_{\psi i} = \sqrt{\frac{1}{i-j} \sum_{t=i}^j (\psi_i - \mu)^2} \quad [4]$$

where, μ is the mean of ψ values between i and j . In this way, every significant change in slope represents a change in “weak” first-order stationarity.

The process works as follows. Starting with $i=3$ and $j=2$. The values of $S_q(t_i)$, $S_q^p(t_i)$, ψ_i , and $\sigma_{\psi i}$ are computed for increasing values of j . If the difference $S_q^p - S_q$ exceeds $\sigma_{\psi i}$ the duration $d = j-i$, and the process restarts with $i=j$ and $j=i-1$. This algorithm is implemented in Python version 2.7 and code is available from the authors upon request.

For this study, q represents turbulence kinetic energy, e , defined as:

$$\bar{e} = \frac{1}{2}(\overline{u'u'} + \overline{v'v'} + \overline{w'w'}) \quad [5]$$

128 where the ' indicates the turbulent component of each vector wind component and the overbar
 129 represents a time average. Figure 1 shows an example of the cumulative TKE (S_e) for the night
 130 of September 3-4, 2009. Values are normalized to a cumulative sum of unity for display
 131 purposes because the value of TKE is much less in the mid- and lower- canopy regions. The
 132 inset graph shows a subset of data and the changes in slope identifying the duration of
 133 stationarity, along with the lines for S_e^p . When utilizing this technique it is important to
 134 recognize that the shortest possible duration of stationarity is the variable time series resolution,
 135 defined here as the integral times scale after (Nappo et al., 2010). This is because in [3], t_i-t_j
 136 cannot be smaller than the time resolution of the variable of interest. Therefore, in the following
 137 discussion, the integral time scale is equivalent to the initial averaging time represented by the
 138 overbar in [5]. This definition varies from some uses and is used to represent the time-scale over
 139 which the integration is occurring.

Figure 1: Normalized cumulative TKE for the night of September 3-4 2009, for a 100 second averaging time. Values are normalized to 1 for display purposes. The solid line is the above canopy measurement. The dashed line is the mid-canopy measurement. And the dotted line is the below canopy measurement. The inset graph represents the first 700 seconds of the data period with dotted vertical lines indicating the durations found by the change in slope method discussed above. In this case the durations are 200s, 100s, 200s, 100s, and 100s. The solid gray lines represent the predicted time series S_e^p , for each duration.

b. Stationarity Fraction

To compare different turbulent regimes we introduce a stationarity fraction factor, S_{FRAC} , computed as

$$S_{FRAC} = \frac{n}{\frac{T}{t_i}} \quad [6]$$

Where n is the number of periods of stationarity, T is the total length of the record in seconds, and t_i is the integral time scale as discussed above. n is computed as how many periods of stationarity, d , of S_e are identified during a data record as discussed above, and is representative of how often the mean TKE changes its magnitude. That is, each change in slope marks the end of a stationary period and the start of a new “run” of a stationary signal. S_{FRAC} is a dimensionless value which represents how often during a measurement period turbulence levels change. By definition, S_{FRAC} values can range from 0 to 1. A value of 1 would indicate the entire record length was non-stationary, and therefore highly intermittent, because no two consecutive time periods had the same first order statistics. A value of 0 would indicate the entire record length was stationary and no intermittency was experienced. Neither extreme is expected to occur, as some level of turbulence will always be present. The stationarity fraction is a linear function of the number of stationary subsets found in a given data record. But it is an exponentially decreasing function of the mean duration for the data record because as the mean duration, $\bar{d}$, increases, the number of possible periods decreases at an exponential rate. For example, in a 3600 second data record there can be 36 one hundred second periods, 18 two hundred second periods, 12 three hundred second periods, 9 four hundred second periods and so on. S_{FRAC} can be found for any length data record, T .

It is important to note here the meaning of intermittency in the context of this work. Classically, intermittency means flow that experiences turbulence at some times and not at

others. Strictly using this definition, however, does not work well in the boundary layer environment because some level of turbulence, defined as a deviation from the mean, will always be present. Therefore in this environment, the flow always experiences turbulence. Thus, we define intermittency as a change in first order turbulence statistics. This is an extension of the definitions used in current boundary layer research, such that the turbulent “bursts” and (e.g. Doran 2004) intervening periods are identified when there are changes in the first order statistics. By computing, d (and subsequently n), using a criteria of one standard deviation as discussed above, intermittency is thus a measure of how often the turbulence level changes in the data record.

S_{FRAC} is similar to the intermittency factor defined by Howell and Sun (1999). But it is more universal since it does not consider the overall value of turbulent activity, but rather how often turbulent activity changes. Thus it allows a comparison of intermittency between two data records with different overall turbulent levels. In this way S_{FRAC} is more akin to the turbulent event fraction of Doran (2004), but further avoids the need to introduce an arbitrary turbulence threshold value. A choice of integral time scale, however, is still necessary, although this could be considered more universal values. Additionally, the threshold used to determine slope changes, $\sigma_{\psi i}$, could also be changed to some multiple (e.g $2\sigma_{\psi i}$ or higher), which would define a turbulent burst as a larger change in statistics.

3. Results

a. Descriptive Long Term Statistics

Durations were calculated for each nocturnal period, and a nightly mean duration ($\bar{d}$) was computed for each night, where:

$$\bar{d} = \frac{\sum_{i=0}^{i=n} d}{n} \quad [7]$$

and d , and n are as defined previously. Durations were computed for integral times scales (t_i) ranging from 10 seconds to 5 minutes. This range was chosen to represent values extending from shorter than the co-spectral gap (Vickers and Mahrt 2003) to a reference averaging time commonly used in nocturnal canopy studies (e.g. Dupont and Patton 2012).

The dependence on of mean duration with choice of t_i is shown in Figure 2. Mean duration increases linearly with t_i , although the rate of increase varies with canopy height with a slope of 3.5 above the canopy, 3.2 within the canopy, and 2.7 below it. The linear increase is expected because of the restriction that d cannot be smaller than t_i . The differences in the rate of increase is discussed in section 4. Figure 2 also shows that in general, when $t_i > 60$ seconds, the duration of TKE stationarity decreased with canopy depth. That is, the longest periods of stationarity were seen above the canopy. This persistence decreases at the mid-canopy level, and the shortest durations are seen below the canopy. When $t_i < 60$ s the mean duration at the above canopy and mid-canopy levels are approximately equal. In terms of total range (not shown), with $t_i > 60$ s mean nightly duration ranges from approximately $2t_i$ to $10t_i$, with $t_i < 60$ s the minimum nightly duration remains at $\sim 2t_i$ for all height levels, but the maximum value shows no relationship with t_i (not shown). Figure 2 also shows the variability seen across all 215 nights is greatest at the mid-canopy level.

Figure 2: Dependence of mean nightly duration (i.e. average length of a stationary data run) on choice of averaging time. Solid line is above canopy, dashed line is mid-canopy, and dotted line is below canopy. Light gray lines indicate one standard deviation around the nightly means.

When looking at the length of durations, the number of nights where any single value of d was 30 minutes or longer increases nearly linearly with the chosen integral time scale, until $t_i=240$ seconds, with $t_i>240$ seconds no additional long periods are identified (not shown). Also, the integral time scale increases, so does the probability of finding a stationary data run that lasts for 30 minutes or longer, but the specific relationship varies with height. For shorter integral time scales (< 180 seconds) the highest probability of TKE remaining stationary for more than 30 minutes is at the mid-canopy level. The least number of nights with longer periods of persistence is seen below the canopy. This is consistent with the shorter $\bar{d}$ observed below canopy as shown in Figure 2.

Figure 3 shows the mean S_{FRAC} for all 215 nights with increasing integral time scales. The above canopy mean nightly S_{FRAC} does not vary with choice of integral time scale. The mid-canopy mean nightly S_{FRAC} increases from 0.22 to 0.35 with increasing t_i . The below-canopy mean nightly S_{FRAC} increases from 0.28 to 0.4 with increasing t_i . At both the mid- and below-canopy heights the rate of increase slows when t_i is longer than 120 seconds. S_{FRAC} is greatest above canopy for short time scales and greatest below canopy for longer time scales.

Figure 3: Average Nightly S_{FRAC} versus integral time scale for all 215 nights. Solid line is above canopy, dashed line is mid-canopy, and dotted line is below canopy.

Figure 4 shows nightly values of $\bar{d}$ and S_{FRAC} computed using $t_i=100$ s for all 215 nights as a function of friction velocity, u^* . The value of $t_i=100$ s was chosen for two reasons: it marks a transition as shown in Figure 3, and it is consistent with other work, as this is a commonly used time to filter submesoscale motions in flux analysis (e.g. Klipp and Mahrt, 2004 and others). Similar relationships were seen for other values of t_i . For all measurements the u^* value is computed from the top sonic. Figure 4 also shows the results of calculating $\bar{d}$ and S_{FRAC} above

the canopy for each hour of data rather each full night. The same relationship and thresholds are observed for hourly data record lengths as for nightly data. The nightly stationarity fraction ranges in values from a minimum of 0.063 observed mid canopy on September 2, 2010 to a maximum of 0.53 observed mid-canopy on January 8, 2010. A weak linear function exists between S_{FRAC} and u^* at the above and mid canopy heights (slope = 0.12 and 0.10, $r^2=0.22$ and 0.14 respectively). Below the canopy, a linear regression shows no correlation ($r^2=0.00001$) and a slope of -0.003 showing no trend exists below the canopy. Fitting a line with both u^* and $S_{FRAC}=0$, results in a nearly identical line for all three heights with a slope of ~ 0.6 and r^2 values ranges from 0.4 to 0.5. When comparing the nightly S_{FRAC} with height within the canopy, the strongest correlation is seen between above- and mid- canopy levels with a linear regression having an $r^2=0.7$. The correlation is weaker when comparing mid- to below-canopy ($r^2=0.53$) and weakest between the above- and below-canopy measurements ($r^2=0.37$).

Figure 4: Nightly mean duration, $\bar{d}$, versus mean friction velocity, u^* , (left) and nightly stationarity fraction, S_{frac} , versus mean friction velocity (right) for measurements above canopy (diamonds), at mid-(circles) and below (triangles)- canopy heights. One point for each night is shown. The grey symbols are computed hourly, rather than nightly for above canopy measurements from the entire dataset (2000 hours).

An example of typical distributions of d in a single night for a t_i of 100 seconds is shown in Figure 5. It demonstrates that the number of periods with short durations dominates. At each height there are some periods where TKE stays stationary for 5 minutes or more, but relatively few times where TKE remains stationary for 15 minutes or more. This general pattern of each night being dominated by short periods of stationarity and a decrease of the occurrence frequency of longer periods of stationarity is consistently observed for all nights and all values of t_i .

Figure 5: Typical distributions of durations for the night of September 3-4 2009. Total data record length is 31919 seconds (8 hours and 52 minutes) and durations were computed with a base averaging time of 100 seconds. Upper panel is above canopy, middle is mid-canopy and bottom is below canopy.

Since the intermittency measure of S_{FRAC} can be computed for any initial length data record, a value was computed for each 30 minute data record. Figure 6 shows the variation of S_{FRAC} over the course of each night. In general, intermittency is highest in first 30 minutes of the nocturnal boundary layer and decreases rapidly in the first three hours. The values level off for the remainder of each night, with the value staying highest below the canopy, indicating more intermittency at the below-canopy level through each nocturnal period as stability increases over the course of each nocturnal period.

Figure 6: Intermittency (S_{frac}) over time for a 30 minute data runs starting 1 hour after sunset. The solid line is above canopy, dashed is mid-canopy, and dotted is below-canopy. The shading indicates one standard deviation of the mean of all 215 nights.

b. Stability Dependence

Because all measurements are in the canopy roughness sublayer (CRSL) the most commonly used measure of stability, the Bulk Richardson number, could not be computed reliably. Instead the local stability parameter, ζ , is used as an indicator of stability conditions. ζ is computed as $(z-d)/L$, where d is the displacement height estimated as $0.66h$, where h is the average canopy height. ζ was computed at the top sonic, and each 30 minute measurement period was classified as unstable ($\zeta < -0.1$), neutral ($-0.1 < \zeta < 0.1$) or stable ($\zeta > 0.1$). The overall stability regime is best characterized by the forcing conditions at the top of the canopy even if below canopy layers are decoupled from the upper canopy mechanical turbulence. As expected, the majority of the data was considered stable (3058 half hour periods, 75%), although 922 half hour periods (22%) were identified as unstable with the majority of ζ values ranging from -0.1 to -5000. 125 half hour periods were identified as neutral (3%). Most of the unstable periods occurred in the Fall and Winter months. In almost all cases, once unstable conditions were identified, the data remained unstable for the rest of the night. Often this occurred after 3 AM. There were some nights where no stable conditions were identified at all. These atypical nights will be the subject of future investigations. When neutral conditions were identified they tended to remain so for only 2-3 hours before returning to either stable or unstable conditions. Figure 7 shows histograms of the 30 minute stationarity factor above the canopy for each stability group, similar distributions were found at mid- and below- canopy levels with the mean shifting slightly as presented above. Stability itself is not an indicator of changing stationary conditions, but the mean S_{FRAC} in stable conditions is higher than in unstable conditions and it is highest in neutral conditions. An ANOVA and paired T-tests indicate that the differences observed between different stability conditions are all statistically significant.

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Figure 7: Relative frequency of above canopy intermittency factors for different stability conditions. Unstable has a mean

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S_{frac} of 0.3, Neutral has a mean S_{frac} of 0.5 and Stable has a S_{frac} of 0.34.

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c. Case Study

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In this section we present results in detail for the night of September 3-4, 2009. The

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cumulative TKE curve and distributions of d for this time period were shown in Figure 1 and

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Figure 5 respectively. This night represents a typical low wind speed observational period with

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8.5 hours of continuous measurements. The average above canopy wind speed was 0.9 ms^{-1}

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ranging from 0.2 ms^{-1} to 1.7 ms^{-1} . Stability was classified using the local stability parameter ξ ,

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computed at the top of the canopy. The entire night is stable with $\xi \gg 0.1$, indicating a fully

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developed stable boundary layer. Figure 8 and Figure 9 show TKE measured at the beginning

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and end of the night along with the corresponding durations of stationarity. These two periods

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were chosen to represent a high intermittency period as indicated by an above canopy 30 minute

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S_{FRAC} of 0.78 and a low intermittency period as indicated by an above canopy S_{FRAC} of 0.11

317 respectively. The effects of canopy elements on the intermittency characteristics are seen in
318 these figures. As momentum is transported down through the canopy, the mid-canopy shows the
319 highest S_{FRAC} during the low intermittency period and the lowest S_{FRAC} during the high
320 intermittency period. This suggests when conditions are stationary above the canopy, energy is
321 transported downwards, causing more disruption in the first order statistics. Intermittent
322 conditions above the canopy also indicate intermittent conditions within and below the canopy.
323 For comparison, the method was applied to this night with a threshold of $2\sigma_{\psi i}$. As would be
324 expected, the results show a longer duration and a lower S_{FRAC} . But, the relationship between the
325 three heights and overall change of S_{FRAC} over the course of the night stay the same.

Figure 8: TKE for the first 30 minutes measured on September 3rd, 2009. Grey and white segments indicate where changes in the slope of, S_e , were identified. Top panel – above canopy, Middle panel – mid-canopy level, Bottom panel – below live crown.

Figure 9: As for figure 8 for the 30 minutes from 4:08 AM to 4:38 AM on September 4th, 2009.

4. Discussion

Overall, in the nocturnal canopy roughness sublayer, TKE can remain stationary for periods ranging from the averaging time scale to periods upwards of one hour, although the latter is rare. As shown in Figure 2, with respect to height in the canopy, for integral times greater than one minute the longest periods of stationarity were seen just above the canopy, where interaction of winds and roughness elements provides the most opportunity for mechanical generation of turbulence. This decreases at the mid-canopy level where the sheltering effect of branches and needles reduce the wind energy. The shortest durations are seen below the canopy where wind speeds tend to be more light and variable. Above the canopy, it is most likely that TKE remains stationary for a period of twice the chosen averaging time. While in and below the canopy space, it is most likely that TKE will only remain stationary for the chosen averaging time. When an averaging time of less than one minute is used, the top and mid canopies levels have the same mean duration characteristics. This indicates that even when using extremely short averaging times, the assumption of stationarity can be violated when computing traditional 30 minute fluxes. Despite this, every night had at least 1 period (most often more) of TKE stationarity lasting for 15 minutes or longer, and these long periods are most likely to occur at the above canopy level.

As seen in Figure 4, a wide range of conditions are possible in the nocturnal CRSL. At this site, TKE is most likely to remain stationary for some portion of the night when u^* values are less than 0.5 ms^{-1} . Above the canopy, when u^* exceeds this value, S_{FRAC} is linearly correlated with a slope of 0.38. For u^* conditions less than 0.5 ms^{-1} the slope of the line increases to 1.16 and the strength of the relationship, as indicated by a linear regression fit statistic, is reduced. No simple relationship with mean wind speed exists for either the mean duration of stationary runs

or the stationarity fraction. Although, in general, as wind speed increases mean duration decreases and intermittency increases. There is a continual increase in intermittency, as measured by S_{FRAC} , with an increase in the variance and standard deviation of wind. When compared with higher order statistics (not shown), there is an increase in S_{FRAC} with decreasing skewness and kurtosis of horizontal wind speed until a threshold value of $S_{FRAC}=0.2$, above which, S_{FRAC} remains constant with kurtosis and skewness of horizontal wind speed, at all heights. This means that a period with a positively skewed windspeed distribution is more highly intermittent with regards to turbulence than a non-skewed windspeed distribution. This indicates that turbulence intermittency is related to higher order statistics. Furthermore, no long-term relationship was observed with either wind direction or season, indicating that the causes for intermittent turbulent events is either localized or isolated in time. This is in agreement with other studies, but given the length of this data set it is worth noting.

When comparing intermittency between the three measurement locations, it is observed that the occurrence of intermittent conditions above the canopy is a poor predictor of intermittent conditions within or below canopy. But intermittent conditions at mid-canopy and below canopy levels are highly correlated, meaning that when intermittent turbulence exists at mid –canopy it also exists below canopy and vice versa. The highest variability is seen at the mid-canopy level. Further analysis is needed to identify the potential causes of the observed bursts in TKE.

When applied to longer term eddy covariance data sets, this method could help identify and remove non-stationary records of varying time durations as opposed to current methods which eliminate an entire average period if it is flagged as non-stationary. Thus preserving a larger portion of the original dataset and improving the accuracy of measured fluxes. As an example, the night of September 3-4 2009 was used with the stationarity tests of (Foken and Wichura

378 (1996) as presented in Cava et al. (2014). This test assesses the variability of shorter periods
379 within each 30 minute sample by computing a ratio of the variability of the 5 minute fluxes to the
380 mean 30 minute fluxes. If the ratio is less than the threshold of 30% then the time series is
381 considered to be strongly stationary. For this night, using a reference flux of $w'T$, all above
382 canopy 30 minute runs would be identified as stationary, but 5 of 17 the mid-canopy runs (29%)
383 and 15 of 17 below-canopy runs (88%) of the below canopy runs would fail the stationary test.
384 When loosening the RN threshold to the more operational threshold (Cava et al, 2014) of 50%,
385 an additional 2 runs are considered stationary at mid-canopy and an additional 3 runs are
386 considered stationary below canopy. Figure 10 shows the result of calculating vertical heat flux
387 using the traditional technique with 5 minute subintervals and using the duration, d , as a
388 changing sub-interval time. The major differences are seen early in the evening (corresponding
389 to the highly intermittent shown in Figure 8) where a stronger downward heat flux is found and
390 late at night (corresponding to the low intermittency period shown in Figure 9) when a less
391 intense downward heat transfer is seen.

Figure 10: Vertical heat flux above canopy for night of Sept 3-4. Solid line is traditional 30 minute computation with 5 minute subintervals and dashed line is a 30 minute value using a variable sub-interval period equal to the duration of stationarity.

5. Conclusions

We have presented a technique for measuring intermittency in the stable boundary layer, when intermittency is considered a change in the statistics. The results presented here have been based on turbulence kinetic energy, but the technique could be applied to any non-negative variable. This technique has value for the future understanding of stable boundary layers. Specifically, we conclude that at night in CRSL the assumption of stationarity is only true for periods < 1000 seconds and really can only be assumed reliably for periods < 200 s. Additionally, intermittency is highest at the beginning of a nocturnal period. Here we attempted to eliminate the transitional periods between day and night by removing the first hour after sunset from the analysis, however a change in intermittency is still observed as the stable boundary layer grows

(Figure 5). This indicates that in a forested environment the effects of the residual layer persist at until at least two hours after sunset, and that the highest potential for intermittency exists in periods transitioning from one stability regime to another. Finally, it is possible to have data runs of stationary TKE that last longer than one hour, although they are rare. The actual duration of stationarity, however, is dependent on the initial Reynolds averaging time which has broader implications for flux calculations at night and within canopies.

Given the length of the study period and the wide variation in conditions observed, these general observations can be useful for parameterizing models of CRSL dispersion, vertical flux and advection of scalars. Furthermore, these methods can provide some additional detail on fluxes within the canopy, while still maintaining the underlying assumption of stationarity. Additionally this technique has the potential to provide measures of energy penetration into the canopy.

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7. References

- Alekseychik, P., I. Mammarella, S. Launiainen, Ü. Rannik, and T. Vesala, 2013: Evolution of the nocturnal decoupled layer in a pine forest canopy. *Agricultural and Forest Meteorology*, **174**, 15-27.
- Aubinet, M., 2008: Eddy covariance CO₂ flux measurements in nocturnal conditions: An analysis of the problem. *Ecological Applications*, **18**, 1368-1378.
- Baldocchi, D. D., 2003: Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. *Global Change Biology*, **9**, 479-492.
- Belcher, S.E., Harman, I.N. and Finnigan, J.J., 2012. The Wind in the Willows: Flows in Forest Canopies in Complex Terrain. *Annual Review of Fluid Mechanics*, **44**, 479-504.
- Cava, D., Schipa, S. and Giostra, U., 2005. Investigation of Low-Frequency Perturbations Induced by a Steep Obstacle. *Boundary-Layer Meteorology*, **115**, 27-45.
- Cava, D., A. Donato, and D. Contini, 2014: Combined stationarity index for the estimation of turbulent fluxes of scalars and particles in the atmospheric surface layer. *Agricultural and Forest Meteorology*, **194**, 88-103.
- Cullen, N., K. Steffen, and P. Blanken, 2007: Nonstationarity of turbulent heat fluxes at Summit, Greenland. *Boundary-Layer Meteorology*, **122**, 439-455.
- Doran, J., 2004: Characteristics of Intermittent Turbulent Temperature Fluxes in Stable Conditions. *Boundary-Layer Meteorology*, **112**, 241-255.
- Dupont, S., and E. G. Patton, 2012: Influence of stability and seasonal canopy changes on micrometeorology within and above an orchard canopy: The CHATS experiment. *Agricultural and Forest Meteorology*, **157**, 11-29.

447 Dwyer, M.J., Patton, E.G. and Shaw, R.H., 1997. Turbulent kinetic energy budgets from a large-
 448 eddy simulation of airflow above and within a forest canopy. *Boundary-Layer*
 449 *Meteorology*, **84**, 23-43.

450 Finnigan, J. J., R. H. Shaw, and E. G. Patton, 2009: Turbulence structure above a vegetation
 451 canopy. *Journal of Fluid Mechanics*, **637**, 387-424.

452 Foken, T., Wichura, B., 1996. Tools for quality assessment of surface-based flux measurements.
 453 *Agricultural and Forest Meteorology* **78**, 83-105.

454 Foken, T., and B. Wichura, 1996: Tools for quality assessment of surface-based flux
 455 measurements. *Agricultural and Forest Meteorology*, **78**, 83-105.

456 Granucci, D., M. Rudnicki, A. Hiscox, D. Miller, and H.-B. Su, 2013: Quantifying the effects
 457 of freezing on tree sway frequencies. *Agricultural and Forest Meteorology*, **168**, 10-14.

458 Hollinger, D. Y., S. M. Goltz, E. A. Davidson, J. T. Lee, K. Tu, and H. T. Valentine, 1999:
 459 Seasonal patterns and environmental control of carbon dioxide and water vapour
 460 exchange in an ecotonal boreal forest. *Global Change Biology*, **5**, 891-902.

461 Howell, J. F., and J. Sun, 1999: Surface-Layer Fluxes in Stable Conditions. *Boundary-Layer*
 462 *Meteorology*, **90**, 495-520.

463 Klipp, C.L. and Mahrt, L., 2004. Flux-gradient relationship, self-correlation and
 464 intermittency in the stable boundary layer. *Quarterly Journal of the Royal*
 465 *Meteorological Society*, 130(601): 2087-2103.

466 Leclerc, M.Y., Shaw, R.H., Hartog, G.D. and Neumann, H.H., 1990. The Influence of
 467 Atmospheric Stability on the Budgets of the Reynolds Stress and Turbulent Kinetic
 468 Energy within and above a Deciduous Forest. *Journal of Applied Meteorology*, **29**,
 469 916-933.

470 Lee, X., 2000. Air motion within and above forest vegetation in non-ideal conditions. *Forest*
471 *Ecol Manag*, **135**, 3-18.

472 Lesnik, G., 1974. Results of measurement of turbulent energy balance components in a layer of
473 vegetation. *Izv. Atmos. Oceanic Phys*, **10**, 652-655.

474 Liang, J., L. Zhang, Y. Wang, X. Cao, Q. Zhang, H. Wang, and B. Zhang, 2014: Turbulence
475 regimes and the validity of similarity theory in the stable boundary layer over complex
476 terrain of the Loess Plateau, China. *Journal of Geophysical Research: Atmospheres*, **119**,
477 2014JD021510.

478 Mahrt, L., 1998: Flux sampling errors for aircraft and towers. *Journal of Atmospheric and*
479 *Oceanic technology*, **15**, 416-429.

480 Mahrt, L., 2010: Computing turbulent fluxes near the surface: Needed improvements.
481 *Agricultural and Forest Meteorology*, **150**, 501-509.

482 Mahrt, L., 2014. Stably Stratified Atmospheric Boundary Layers. *Annual Review of Fluid*
483 *Mechanics*, **46**, 23-45.

484 Mahrt, L., S. Jielun, W. Blumen, T. Delany, and S. Oncley, 1998: Nocturnal Boundary-Layer
485 Regimes. *Boundary-Layer Meteorology*, **88**, 255-278.

486 Mahrt, L., Lee, X., Black, A., Neumann, H. and Staebler, R., 2000. Nocturnal mixing in a forest
487 subcanopy. *Agricultural and Forest Meteorology*, **101**, 67-78.

488 Meyers, T.P. and Baldocchi, D.D., 1991. The budgets of turbulent kinetic energy and Reynolds
489 stress within and above a deciduous forest. *Agricultural and Forest Meteorology*, **53**,
490 207-222.

491 Nappo, C., A. Hiscox, and D. Miller, 2010: A Note on Turbulence Stationarity and Wind
 492 Persistence Within the Stable Planetary Boundary Layer. *Boundary-Layer Meteorology*,
 493 **136**, 165-174.

494 Prabha, T. V., M. Y. Leclerc, A. Karipot, and D. Y. Hollinger, 2007: Low-Frequency Effects on
 495 Eddy Covariance Fluxes under the Influence of a Low-Level Jet. *J. Appl. Meteorol.*
 496 *Climatol.*, **46**, 338-352.

497 Salmond, J., 2005: Wavelet analysis of intermittent turbulence in a very stable nocturnal
 498 boundary layer: implications for the vertical mixing of ozone. *Boundary-Layer*
 499 *Meteorology*, **114**, 463-488.

500 Sun, J., L. Mahrt, R. M. Banta, and Y. L. Pichugina, 2012: Turbulence Regimes and Turbulence
 501 Intermittency in the Stable Boundary Layer during CASES-99. *Journal of the*
 502 *Atmospheric Sciences*, **69**, 338-351.

503 Sun, J., D. H. Lenschow, L. Mahrt, and C. Nappo, 2013: The Relationships among Wind,
 504 Horizontal Pressure Gradient, and Turbulent Momentum Transport during CASES-99.
 505 *Journal of the Atmospheric Sciences*, **70**, 3397-3414.

506 Sun, J., and Coauthors, 2002: Intermittent Turbulence Associated with a Density Current Passage
 507 in the Stable Boundary Layer. *Boundary-Layer Meteorology*, **105**, 199-219.

508 Sun, J., and Coauthors, 2004: Atmospheric Disturbances that Generate Intermittent Turbulence
 509 in Nocturnal Boundary Layers. *Boundary-Layer Meteorology*, **110**, 255-279.

510 Van de Wiel, B. J. H., A. F. Moene, R. J. Ronda, H. A. R. De Bruin, and A. A. M. Holtslag,
 511 2002a: Intermittent Turbulence and Oscillations in the Stable Boundary Layer over Land.
 512 Part II: A System Dynamics Approach. *Journal of the Atmospheric Sciences*, **59**, 2567-
 513 2581.

514 Van de Wiel, B. J. H., R. J. Ronda, A. F. Moene, H. A. R. De Bruin, and A. A. M. Holtslag,
 515 2002b: Intermittent Turbulence and Oscillations in the Stable Boundary Layer over Land.
 516 Part I: A Bulk Model. *Journal of the Atmospheric Sciences*, **59**, 942-958.
 517 Van de Wiel, B. J. H., and Coauthors, 2012: The minimum wind speed for sustainable turbulence
 518 in the nocturnal boundary layer. *Journal of the Atmospheric Sciences*, **69**, 3116-3127.
 519 Vickers, D., and L. Mahrt, 2003: The cospectral gap and turbulent flux calculations. *Journal of*
 520 *Atmospheric and Oceanic Technology*, **20**, 660-672.
 521 Vickers, D., and C. K. Thomas, 2013: Some aspects of the turbulence kinetic energy and fluxes
 522 above and beneath a tall open pine forest canopy. *Agricultural and Forest Meteorology*,
 523 **181**, 143-151.
 524 Xiao, X., D. Hollinger, J. Aber, M. Goltz, E. A. Davidson, Q. Zhang, and B. Moore Iii, 2004:
 525 Satellite-based modeling of gross primary production in an evergreen needleleaf forest.
 526 *Remote Sensing of Environment*, **89**, 519-534.
 527
 528