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Effects of thinning a forest stand on sub-canopy turbulence

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ABSTRACT

The density of a forest canopy affects the degree of influence of vegetation on the mean and turbulence flow fields. Thinning a forest *in situ* is difficult and expensive therefore many studies investigating the effects of changing canopy density have been done in wind tunnels or with modeling. Here, we analyze data collected at 0.13 h, 0.83 h, and 1.13 h (canopy height; h = 21 m) as the surrounding loblolly pine stand was progressively thinned three times. The first thinning removed the understory and the two subsequent thinnings removed whole trees leading to a 60% reduction in the overall stand density. As the forest was thinned, turbulence and wind speed near the surface (0.13 h) increased and became more connected with above the canopy (1.13 h). The variation of the three-dimensional wind components increased for 0.13 h when the understory was thinned. Turbulence at 0.83 h and 1.13 h increased when whole trees were removed (2nd and 3rd thinning). An increase in the peak spectral power of the 0.13 h vertical velocity indicated an increase in the influence of larger eddies surviving through the canopy, but these did not affect the vertical turbulence or momentum transfer.

1. Introduction

The density of a forest stand impacts the local flow and thermal fields leading to complex interactions between canopy geometry, turbulent transport and biophysical effects (Albertson et al., 2001; Starkenburg et al., 2015). An increase (decrease) in the stand density increases (decreases) the amount of turbulence damping and momentum absorption (Pujol et al., 2013). For the densest canopies, the majority of momentum absorption occurs in upper parts of the canopy where the majority of the foliage resides, limiting the impact of the underlying surface roughness on the flow (Huang et al., 2013; Yue et al., 2007). As the stand density decreases, the flow transitions from the mixed layer analogy (Raupach et al., 1996) toward a more classical boundary layer with isolated roughness elements (Pietri et al., 2009; Poggi et al., 2004). However, the way this transition occurs and how sparse the canopy needs to be for this transition to occur is unknown.

Changing turbulence with canopy density creates a direct connection between the within-canopy turbulence, stand density, and depth into the canopy (Burns et al., 2011; Chamecki, 2013; Green et al., 1995; Russell et al., 2016). Measurements of the *in situ* vertical turbulence profile have been used to study leaf-on/leaf-off cycles (Lee et al., 2011; Staebler and Fitzjarrald, 2005) and from the effects of changing stand densities via comparisons of different forests with different canopy densities (Finnigan, 2000). However, studies with *in situ* measurements where the surrounding stand density is changed are rare outside of wind tunnels (Green et al., 1995; Thistle et al., 2011).

The change from a perturbed mixing layer (dense canopy) to a wall-bounded boundary layer with irregularly placed obstacles (Pietri et al., 2009; Poggi et al., 2004) is often investigated using the standard deviation, skewness, and kurtosis within the canopy. Above the canopy, these statistics are not as strongly affected (Finnigan, 2000; Novak et al., 2000; Poggi et al., 2004). For different canopy types and densities, these values show that the vertical profile of turbulence above the canopy under neutral stability converges when normalized by friction velocity (u_*) measured at the canopy top (h_c) (Finnigan, 2000; Raupach et al., 1996). Within the canopy, there is a wider variation within the turbulence and wind profiles based off the canopy type, density, and surrounding conditions. The variation in the turbulence statistics with increasing stand density can explain some of the variability in the within-canopy portions of the “family portraits” (Novak et al., 2000).

Changes in the stand density modulate the turbulent structures affecting the scalar and momentum transfer through the canopy (Poggi et al., 2004). Stability is the other major factor driving the structure of turbulence structures in the sub-canopy (Dupont and Patton, 2012a,b; Patton et al., 2016; Su et al., 2004; Thomas et al., 2013). Even at the lowest stand densities considered in the cited literature, the turbulence

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profile is consistent with a canopy-influenced profile (Novak et al., 2000; Pietri et al., 2009). By staggering the alignment of the canopy within a wind-tunnel, Pietri et al. (2009) concluded that a staggered canopy reduces the canopy's porosity and enhances tree-wake interactions. This creates a more even foliage layer to absorb momentum and separate the within-canopy layer from the atmosphere above. Unlike row crops and aligned forests, a more even distribution of the vegetation does not have the same wind direction dependence (Chahine et al., 2014).

To the best of our knowledge from a literature search, two datasets have been compiled from *in situ* measurements of a thinned forest (excluding leaf-on/leaf-off comparisons). Green et al. (1995) presented results for three plots (0.8 ha each) thinned at different densities within a larger forest. Their results showed that tree spacing and canopy density are major factors in modifying canopy turbulence; in sparser canopies, more wind can penetrate the canopy due to local variations in the canopy density producing a spatially variable wind field. Edburg et al. (2010) described aspects of canopy flow and dispersion for a circular, 1.13 ha (60 m radius) progressively thinned loblolly pine forest finding that the lower canopy density increases the wind speed and turbulence within the canopy accelerating plume dilution while decreasing plume meandering. Thistle et al. (2011) showed that the more open canopy allows for more interaction between the sub-canopy and free atmosphere enhancing mixing and the possibility of coupling with the loss of the understory. The understory increases the number of roughness elements near the surface with which the flow can interact. Effects of the overstory on the flow have been described (Bai et al., 2012, 2015; Lee et al., 2011) more thoroughly than the effects of the understory (Blanken, 1998).

In this work, we investigate the effect of changing forest density on turbulence structure using the data introduced in Edburg et al. (2010) and Thistle et al. (2011) to describe how changing the density through the understory differs from removal of whole trees. The data set presented here is unique as the data were collected within the same forest stand without moving the instruments while the stand was successively thinned (Thistle et al., 2011). Previous work using these data has focused mainly on impacts of the stand thinning on tracer dispersion. The objective for this work is to investigate the effects of a decrease in canopy density on the evolution of the mean turbulence structure and connection between within and above canopy measurements as canopy density decreases.

2. Data and methods

2.1. Data site

Measurements were recorded at 10-Hz at three heights on the same tower (0.13 h, 0.83 h, and 1.13 h; where $h = 21$ m was the average stand height) using Vx Probe sonic anemometers (Applied Technologies, Inc., Longmont, CO) in a loblolly pine forest near Winnfield, Louisiana USA (Winn Ranger District, Kisatchie National Forest; 31° 53′ 23.3″ N, 92°50′ 39.9″ W, Fig. 1). Data were collected in the morning to early afternoon from May 14 to May 28, 2004 coinciding with the tracer releases (Thistle et al., 2011). Over the study period, the forest was thinned three times (Table 1) at a radius of 60 m leading to a total thinned area of 1.13 ha (Thistle et al., 2011). Whether the fetch was long enough for the flow to reach a new equilibrium with the changed canopy density is unknown. The first thinning (T1) removed the understory which consisted of brush and red maple saplings, some of which extended up into the upper canopy. During the other two thinning periods (T2, T3), whole trees were removed by a heavy tractor with a grapple able to manipulate the removed trees. The measurement tower was not disturbed during this process so the sonic anemometers maintained a consistent set-up. Mean meteorological data were collected from the nearest airport station at Natchitoches, LA (KIER) located approximately 30 km southwest of the measurement site. For more details regarding the experimental set-up and tracer-dispersion results see Thistle et al. (2011).

The sonic anemometer data used here were collected between 12:00 UTC and 20:00 UTC. Data were pre-processed by despiking (Vickers and Mahrt, 1997) and checked against the instrument measurement limits. No coordination rotations were performed to preserve the effect of changing canopy geometry on the 3-dimensional flow components. Hereafter, u, v, w, and V refer to the longitudinal, lateral, vertical, and mean streamwise winds ($V = [u^2 + v^2]^{1/2}$), respectively. Data were block averaged for the entirety of each thinning period. The statistics in Section 3.1 were calculated from the 100 s averages. Following convention, 30-min averages were used to calculate the stability metrics presented in Section 3.2.

A RemTech PA0 SODAR (Remtech, Inc., Velizy France) was located approximately 2 km west of the tower site in a clearing (Fig. 1) and operated from May 15–27, 2004. The SODAR measured 15 min mean horizontal wind speed and direction at 20 m increments from 20 to 600 m over the same period as the sonic anemometer collected data. Only data collected from 20 to 400 m above ground level were used due to the sparse data above 400 m.

2.2. Global wavelet transform

Overall, 177 half-hour periods were measured. Of these, 15 were incomplete half-hours leaving a total of 162 full half-hour data blocks. Mean global wavelet spectra were calculated from 30-min blocks for each thinning and height. The 10 Hz data were block averaged to 1 Hz before the wavelet transform was calculated using a Morlet mother wavelet (Terradellas et al., 2001, 2005; Torrence and Compo, 1998). Spectral powers were normalized by the respective components' standard deviation (σ_x) (where x represents the u, v, and w components). The frequency was normalized by the mean streamwise wind speed (V) at each height and the height of the canopy (h_c). Hereafter, normalized frequencies are referred to as "n" ($n = fh_c/V$) and the natural frequencies as "f". Reported slopes were determined between the peak spectral energy and the spectral energy 1.5 decades times the frequency of the peak spectral energy except for T1 at 1.13 h. The peak for T1 at 1.13 h occurred before the roll-off so the peak before the roll-off was used as the starting point.

3. Results

3.1. Synoptic conditions

A cold front moved through the northern and western portion of Louisiana between May 14 and May 15, stalling out over the eastern portion of the state on the border with Mississippi on May 16 (Fig. 2). By 7 am Eastern Standard Time on May 17, the front had passed out of the region, leaving the measurement site under the influence of a high-pressure system. No other surface-based synoptic feature passed through the region during the measurement period. The high-pressure system kept the low-level SODAR-based wind direction consistent for the rest of the study period (Fig. 3).

The wind direction shifted from approximately 135 ° to between 225 and 315 ° between May 16 and May 17, one day before the transition from UT to T1. This kept the SODAR upwind of the measurement site from May 17 onward. T2 and T3 had similar mean wind speed profiles after increases from UT to T1 to T2. Approximating $u_* = kz\frac{\partial u}{\partial z}$, where k is the von Karman constant (0.4), z is the measurement height, and $\frac{\partial u}{\partial z}$ is the vertical wind speed gradient, an estimate for the friction velocity (u_*) can be determined for each thinning within the canopy roughness layer. The canopy roughness layer is estimated to range between 2 and 5 times the canopy height (40–100 m here) (Hammerle et al., 2007; Thomas, 2011). With an inflection point observed in the SODAR data, we used the wind speeds between 60 and 200 m from the