MEASURED AND NUMERICALLY SIMULATED BURSTING FREQUENCY OF FLOW WITHIN AND ABOVE A SUCCESSIVELY THINNED FOREST

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ABSTRACT

Intermittent coherent structures play a key role in the transport of momentum and scalars between a forest canopy and the atmosphere. Two features of coherent structures are bursts and sweeps. Transport of high speed momentum towards the canopy is defined as a sweep, wheras, transport of low speed momentum away from the canopy is defined as a burst. Capturing the time frequency of bursts is important in describing the exchange of scalars and momentum between a forest canopy and the atmosphere. We applied a single point burst detection algorithm to measured and simulated flow through a successively thinned loblolly pine canopy. Measurements were conducted in four canopies with varying leaf area density and basal area. A large-eddy simulation was used to simulate the flow within and above the two of the four canopies. Source terms were added to the momentum and sub-grid turbulent kinetic energy transport equations to represent the effect of the forest canopy. Results from a dense and an open canopy are presented. The LES under predicts the turbulent kinetic energy and time between bursts for the open canopy. This may be attributed to the sub-grid scale turbulent kinetic energy source term and the domain size.

INTRODUCTION

Coherent structures are defined here as organized motion that are spatially and temporally intermittent, and efficiently transport momentum and scalars. Coherent motion has been an important theme in turbulence research dating back to the 1950's (Robinson 1991). Coherent structures have been visualized, detected, and simulated in various wall bounded flows (Willmarth and Lu 1972). Coherent structures have also been detected in geophysical flows, such as flow through plant canopies (Baldocchi and Meyers 1988). It has been estimated that coherent structures are responsible for up to 75% of the scalar transport between a forest canopy and the atmosphere (Gao et al. 1989). Two features of coherent structures are bursts and sweeps. Transport of high speed momentum towards the roughness is called a *sweep*, whereas transport of low speed momentum away from the roughness is called a *burst*. Plotting the fluctuating velocity in the flow direction (u') verses the fluctuating velocity in the vertical direction (w') revels a quadrant analysis, where quadrant two is the burst quadrant, and quadrant four is the sweep quadrant.

Coherent structures can be detected using flow visualization, conditional sampling, and numerical simulations (Robinson 1991). Conditional sampling can be performed using one or more measurements of instantaneous velocities. Examples of single point and multiple point methods are the Q2 method of (Lu and Willmarth 1973), and the VITA method of (Blackwelder and Kaplan 1976) respectively. Wavelet analysis has also been used to detect coherent structures in wall bounded flows (Thomas and Foken 2005).

Numerical simulation techniques that reproduce coherent structures are large-eddy simulation (LES) and direct numerical simulation (DNS). The Navier-Stokes equations are solved for all turbulent scales in DNS. In LES the Navier-Stokes equations are spatially filtered; the resolved (or large) scales are solved, and the sub-grid scales are modeled. Numerical simulations have many advantages over field measurements including: 1) the practitioner has control over all input parameters to test conditions that might not occur in the field; 2) numerical simulations have a higher spatial resolution over a discrete domain size which allows investigations of the spatial limitations of measurements; and 3) numerical simulations are monetarily less expensive than large scale field experiments.

We present mean velocity, turbulent kinetic energy, and the mean time between bursts (T_B) using the Q2 method for measured and numerically simulated flow over a successively thinned loblolly pine canopy.

METHODS

Data

Data was collected during a 2004 tracer gas experiment on the Winn Ranger District of the Kisatchie National Forest located near Winnfield, Louisiana, USA. The objective of the experiment was to determine the effect of stand density on pheromone dispersion. The experimental design included tower based measurements of turbulence. Three dimensional sonic anemometers were position at 2.6, 16.6, and 22.8 m above the ground and measured velocity at 10 Hz. The measuring volume of a sonic anemometer is approximately 10 cm^3. The forest stand was successively thinned to represent control strategies used by forest managers to combat the southern pine beetle. Four trials were run in an un-thinned canopy, then the understory was removed and three trials were run in a canopy with a basal area of about 140 ft^2, three trials were then run with the canopy thinned to a basal area of 100 ft^2, and finally four trials were run with the basal area reduced to 70 ft^2. The average height of the canopy was 20 m. Canopy characteristics through the thinning trials are shown in Table 1. For a complete experimental design description see Thistle et al. 2005. Data from daytime periods for the un-thinned and 3rd thinned canopies were selected for analysis. Data records were broken up into half hour blocks; each block was processed using a program that removed spikes greater than five standard deviations and performed a coordinate rotation such that the mean lateral and vertical velocities were set to zero.

Data from a LES of flow within and above two horizontally homogenous forest canopies representing the un-thinned and 3rd thinning canopies was also used in this study. The LES domain simulated was 45 x 30 m in the horizontal directions and 45 m in the vertical direction. Grid size cells ranged from 0.5 m within the canopy to 1.2 m at the top of the domain. The simulation had a time step of 0.5 s, and represented one 30 min time period. A porosity model based of leaf area density was used to represent the effects of canopy elements on momentum following Shaw and Schumann 1992. The effects of canopy elements on turbulent kinetic energy was included following Shaw and Patton 2003. A heat flux of 125 W/m^2 was supplied at the top of the canopy and exponentially decreased through the canopy to the ground with an extinction coefficient of 0.6. Resolved velocities were exported from a vertical line of cells located in the center of the domain at each time step.

Analysis

The Q2 method was used to calculate the mean time between bursts. This method was selected based off the results of Tubergen and Tiederman 1993. An *event* is detected when

$$|u'w'| \geq H \times (u_{rms} w_{rms}) \qquad (1)$$

where u is the horizontal velocity, w is the vertical velocity, the superscript " ' " indicates a departure from the mean, the subscript "rms" indicates a root-mean squared value, and H is a threshold parameter. The threshold parameter, H, is used to separate the noise from true bursts events. Nearly constant bursting frequencies have been calculated for a threshold value varying of $0.25 < H < 1.4$ for flow over wheat stubble (Wells 1998). Multiple detections occurring from the same event are separated from independent events using a time frequency parameter. Time fractions were calculated as the ratio of the number of events to the total number of events for a threshold parameter of zero. note: check this definition of time fraction

RESULTS AND DISSCUSSION

Vertical profiles of measured and simulated mean wind speed and turbulent kinetic energy are shown in Figure 1 and 2. Simulated velocity and turbulent kinetic energy compares with the un-thinned canopy, however the simulation does not show as large of an increase of velocity and turbulent kinetic energy as the measurements.

Measured and simulated time between bursts and time fractions are shown in Figure 3 - 5. Time between bursts for the simulation were shorter than measurements. Measured time fraction decreases with thinning in the upper canopy, but does not change significantly in the understory of the canopy. The simulated time fractions do not significantly change with thinning or height.

The pheromone dispersion data set from the Winnfield field study is unique because whole trees were removed between experiments. This treatment altered both basal and leaf area, unlike deciduous forests where only leaf area is altered between seasons. Measured mean statistics of velocity and turbulent kinetic energy increase with thinning. This is as expected due to less drag imposed on the mean flow by the forest elements. However, the simulation does not capture the change of turbulent kinetic energy with thinning. Furthermore, the simulation does capture the change of time fraction of bursts and sweeps with thinning. These may be due to the insensitivity of the sub-grid scale turbulent kinetic energy source term to thinning. Basal area was reduced by half in this experiment, and is not directly included in the source term. The simulated time between bursts is lower then measurements. This may be attributed to the relatively small domain size (45x30x45 m) as compared to the processes occurring in a typical atmospheric boundary layer.

CONCLUSIONS

Intermittent coherent structures act to efficiently transport momentum and scalars in wall bounded turbulent flows. We have presented measured and simulated mean turbulence statistics, time fractions, and time between bursts for a successively thinned loblolly pine canopy. The field experiment was unique because whole trees were removed between experiments. Measured results were compared to a large-eddy simulation of a horizontally homogenous forest canopy for two canopy structures. The simulation does not capture the change in turbulent kinetic energy and time fraction with thinning as measured. This is attributed to the sub-grid scale sink terms. The simulated time between burst is lower that measured, and is attributed to the relatively small domain size. Future work involve altering the sub-grid scale turbulent kinetic energy sink terms, running in a larger domain, and performing a sensitivity analysis. Wavelet analysis may also be used to detect the dominate time scales of the coherent structures. This may eliminate any error caused by the selection of the hole size, and time frequency parameter when using the Tiederman method .

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TABLES AND FIGURES

Table 1: Leaf area index (LAI) for each thinning scenario.

Thinning Scenario	LAI (m^2m^{-2})	Ratio Thinned/Unthinned
Unthinned	3.71	1.00
1st Thinning, 140 ft^2 basal area, (13.0m^2)	2.63	.70
2nd Thinning, 100 ft^2 basal area, (9.3m^2)	1.98	.53
3rd Thinning, 70 ft^2 basal area, (6.5m^2)	1.47	.39

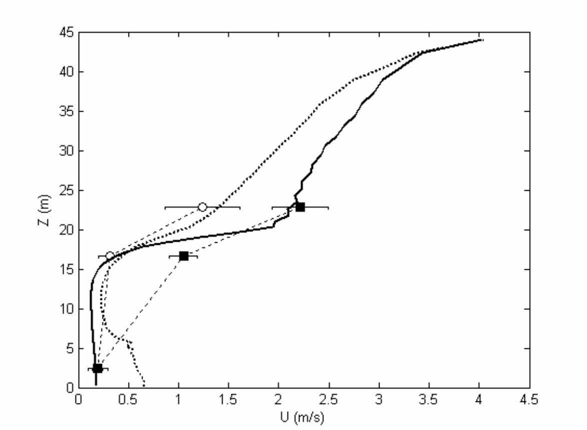

Figure 1: Measured and simulated mean wind speed for un-thinned and 3rd thinning canopies. Measurements are shown by solid circles (un-thinned) and solid squares (3rd-thinning). Error bars represent the standard deviation of the means. Simulation results are shown by solid line (un-thinned), and dotted line (3rd-thinning).

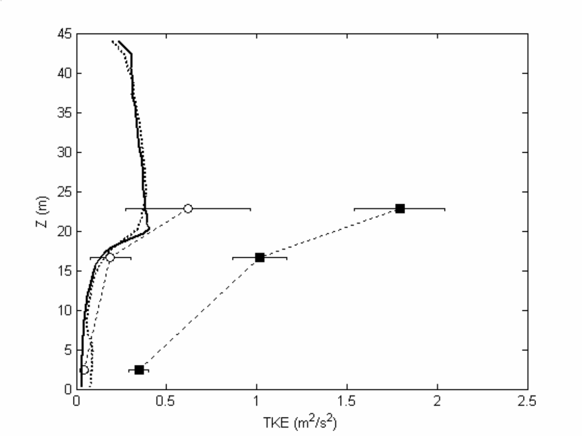

Figure 2: Same as figure one for turbulent kinetic energy.

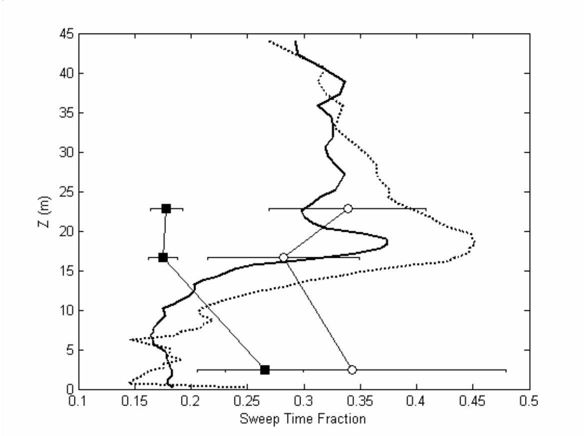

Figure 5: Same as figure one for sweep time fraction.

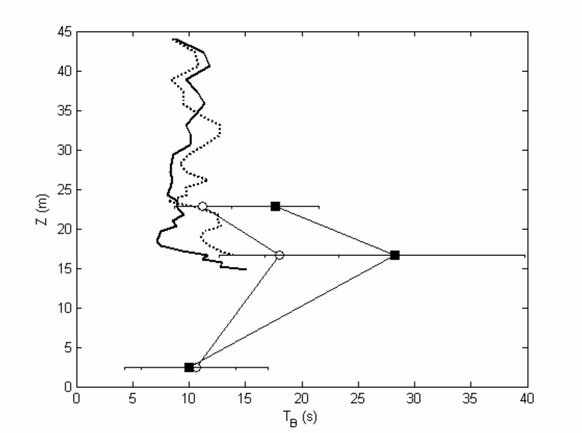

Figure 3: Same as figure one for time between bursts.

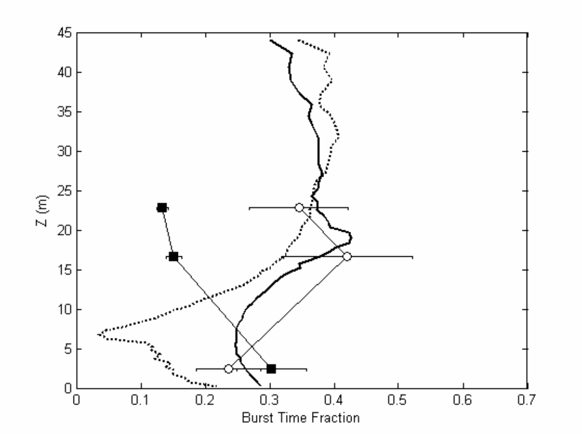

Figure 4: Same as figure one for burst time fraction.