Correlation between sonic anemometers at three heights within a mixed temperate forest

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Correlation coefficients were determined for the horizontal and vertical components from three sonic anemometers in a mixed temperate forest. It was found that the vertical structure of the canopy is important for two point correlations within the canopy. This was especially noticed for horizontal motion due to differences in structure between the upper and lower parts of the canopy, which affected the correlations between these parts. This suggests that there is a decoupling trend between these parts of the canopy. Typically the anemometers with smaller vertical height separations were shown to have stronger correlations than the larger height separations.

Understanding atmospheric structure and turbulence directly above and within a forest canopy is important for learning how gases and pollutants move within a forest. Much work has been conducted using single point statistics including a model wheat canopy wind tunnel study by Brunet et al.¹ However, it has been suggested that single point statistics tend to underestimate the correlation in flow between positions in the canopy, especially in the vertical component.² For this reason, analysis has been conducted using two point statistics by Shaw et al.² in a model wheat canopy wind tunnel, by Baldocchi and Meyers³ in a deciduous forest and in a rainforest by Kruijt et al.⁴

Through previous work, it has been determined that there is a substantial breakdown of eddies from the time they enter the canopy, at the top, to when they reach the forest floor.⁴ Using power and coherence spectral analysis, Kruijt et al.⁴ were able to show a decoupling trend between the upper and lower canopy. However, this was for a rainforest canopy which typically has a greater mass of tree foliage. In a deciduous forest, which is more applicable to this study, a similar trend was found by Baldocchi and Meyers.³ They determined that in the top 20% of the canopy, where approximately 70% of tree foliage exists, there was greater turbulence and stronger shear when compared to the lower canopy.³

This paper studies two point correlations between sonic anemometers in a mixed temperate forest. Three anemometers were set up at three vertical heights within the forest and then two point correlations were determined for both the horizontal and vertical components.

METHODS

Site Description

The experimental measurements were taken at Canadian Forces Base Borden (44° 16' 18" N, 79° 54' 45" W), located in Southern Ontario. The site is an Environment Canada Atmospheric Research Station in a heavily forested region at the north end of the base. The site contains a 45 m tower with small trailers at its base to house the meteorological instruments, as well as a shorter 2 m tower to the southeast, used for making understory measurements. The measurement fetch is small to the north, disturbed by a road and farmland. However, the remaining area is a concentrated forest, excluding access roads. The prevailing wind at this location is from the westerly direction. This provides an upwind fetch of approximately 1300 m during stable conditions and about 150 m during unstable conditions at a tower height of 33 m.⁵

The forest canopy is approximately 20 – 25 m in height and is composed of mainly aspen, red maple and ash trees to the south of the tower and coniferous trees to the north. At the time of the study the vegetation was in full leaf, providing a relatively dense upper canopy. Roughly 90% of the tree foliage, in the canopy, was between the 13 and 25 m anemometers. The understory vegetation consisted of short (roughly 1 m in height) ferns and small shrubs as well as saplings at various heights.

Experimental Setup

The experiment operated from 10 June until 11 September 2009. Three CSAT three-dimensional sonic anemometers

(Model CSAT3, Campbell Scientific Inc, Logan UT) were deployed on site. Two anemometers were located on the main 45 m tower, at 13 and 25 m; the third anemometer was positioned at the top of a secondary non-permanent 2 m tower, approximately 20 m north-east of the main tower. The two anemometers on the main tower were attached with approximately 2 m booms extending horizontally outward from the tower. The boom at a height of 13 m extended to the east with the anemometer directed towards the east. At 25 m, a boom extended to the south and the anemometer was positioned in a southerly direction. The 2 m anemometer on the secondary tower was directed towards the south. The measurements of sonic wind speed were taken at 10 Hz and stored on a computer in a trailer at the base of the main tower.

Data Analysis

The analysis of this data was completed using *Matlab* software (R2006a, The MathWorks, Inc.). Each sonic anemometer measured the three sonic wind speed components; horizontal (u), stream wise (v) and vertical (w), along with sonic temperature (T) at each height. The mean, standard deviation, covariance (equation 1) and horizontal wind speed (equation 2); were calculated from the 10 Hz output data and compiled into half hour averages. In equations 1 and 2 the over-bar denotes the mean wind speed and the prime denotes the perturbation from the mean.

$$[1] \quad cov_{uw} = \overline{u'w'}$$

$$[2] \quad S = \sqrt{\overline{u'^2} + \overline{v'^2}}$$

Correlation coefficients were then calculated for each half hour using equation 3, where σ represents the standard deviation for the component indicated by the subscript. The correlation coefficients were determined for total combined horizontal motion, which includes both u and v components together (denoted S), and also for the vertical component w . The correlation coefficients calculated for S are as follows; R_{S2S2} , R_{S2S13} , R_{S2S25} and R_{S13S25} ; while for w they are R_{w2w2} , R_{w2w13} , R_{w2w25} and R_{w13w25} ; where 2, 13, and 25 are the anemometer heights. Plots were generated for the correlations in time series and also for mean correlations at each height separation.

$$[3] \quad R_{uw} = \frac{cov_{uw}}{\sigma_u \sigma_w}$$

These correlation coefficients were only determined for times when the cup wind speed at a height of 25 m was greater than 2.5 m/s. Additionally, times with standard deviations greater than 2 were omitted from the calculations because it was assumed that during these periods the instrument was malfunctioning.

Finally a t-test was completed for the time series of

R_{S2S2} , R_{S2S13} and R_{S2S25} . It was used to determine if there was a significant difference in the mean RS for each height separation. It was also used to determine if the mean at each height separation was significantly different than zero.

Figure 1: Correlation Coefficients for the Time Series of Combined Horizontal Components.

(a) Correlation for 2 and 13 m Anemometer

(b) Correlation for 2 and 25 m Anemometer

(c) Correlation for 13 and 25 m Anemometer

Figure 2: Correlation Coefficients for the Time Series of Vertical Spatial Correlation.

(a) Correlation between the 2 and 13 m Anemometer

(b) Correlation between the 2 and 25 m Anemometer

(c) Correlation between the 13 and 25 m Anemometer

RESULTS

Figure 1 shows the time series for the correlation of the combined horizontal wind components (RS_{ij}) between the three anemometer heights (2 m, 13 m, and 25 m). In **Figure 1a**, the correlation is given between the anemometers at heights of 2 and 13 m. The mean value over the entire measurement period was 0.22 ± 0.098 . At the 2 and 25 m heights, given in **Figure 1b**, a mean correlated value of 0.13 ± 0.097 was found. **Figure 1c**, shows the correlation between the 13 and 25 m heights with a mean of 0.16 ± 0.087 . In **Figure 2**, the time series for the vertical spatial correlation is shown. In **Figure 2a**, at heights of 2 and 13 m, the mean correlation value was 0.04 ± 0.072 ; whereas, in **Figure 2b**, at the 2 and 25 m heights, a correlation of 0.03 ± 0.039 was found. **Figure 2c** shows at 13 and 25 m heights, a correlation of 0.50 ± 0.035 was determined.

The single mean correlation value from each time series given in **Figure 1** was plotted in **Figure 3a** against the vertical separation between the three anemometers. A fourth correlation point was then created with a zero height separation giving a mean correlation coefficient of 1. In **Figure 3b** mean values from each of the three vertical correlation time series shown in **Figure 2** were plotted against the vertical anemometer height separation. Again a fourth correlation of 1 was added to show when there is no height separation between anemometers.

All the t-tests showed significant differences between the mean RS values at different height separations with $p \leq 0.01$.

Figure 3: Mean Correlation Coefficients Against Anemometer Height Separation.

- (a) The plot for the Combined Horizontal Components
(b) The plot for the Combined Vertical Spatial Correlation

DISCUSSION

Horizontal Component Correlations

The correlations for the horizontal components are more consistent when compared to the vertical component. However, none of the three height separations appear to be dramatically more correlated than another. The strongest correlation is between the 2 and 13 m anemometers. At this

level in the forest the horizontal motion is expected to be the most consistent compared with higher heights in the canopy where there is greater tree foliage. This is based on work completed by Kruijt et al,⁴ where it was shown that strong vertical decoupling between the top and bottom part of the canopy exists. This decoupling would affect the horizontal correlations if the vertical separation of the anemometers spans across these two levels. The correlation could potentially be reduced as a result of having the 2 m anemometer horizontally separated by 20 m from the taller tower. The correlations between 2 and 25 m, along with the 13 and 25 m anemometers, are less significant compared with the 2 and 13 m correlation. This could be caused by the larger, more consistent, horizontal wind speed above the canopy at 25 m. Once entering the canopy, the horizontal wind speed decreases significantly with interruptions from tree branches and leaves. **Figure 1** shows that there is a large standard deviation for all three plots. This indicates that some points are well correlated and others are poorly correlated, suggesting there is high variability in the horizontal motion throughout the canopy.

The information gained from the t-tests suggests that the mean correlations for each height separation differ significantly from each other. This supports the hypothesis that there is strong decoupling between the upper and lower canopy. In addition, each mean was significantly different from zero, indicating that decoupling is not complete, but small correlations exist in the horizontal winds at different heights.

Vertical Spatial Correlation

When considering only the vertical wind component, the correlation between 13 and 25 m was greatest compared with the other height separations. It was expected that this correlation would be greater than the others, since a sweep of air is less disturbed when it first enters the canopy. As that sweep continues its downward motion it will become more disorganized with tree foliage interference, therefore vertical motions at the lower anemometers are less correlated with each other. For the 2 and 25 m correlation the low value could potentially be due to the 23 m height separation in which an eddy entering the canopy will break apart over that distance and the motion therefore becomes more disorganized. In Kruijt et al⁴ they found that strong sweeps of air entering the canopy would be unable to travel much below half the canopy height. This could explain the poor correlation for the 23 m height separation. It should be noted however, that the Kruijt et al⁴ measurements were made in a tropical rainforest and therefore the top portion of the canopy will be much denser than the forest used for our measurements. A similar trend is found in Shaw et al² where the correlation decreases with vertical separation. This is apparent in results obtained in this study as the 12 m height separation is very well correlated compared to the 23 m separation. However, the 11 m separation, for 2 and 13 m anemometer heights, has a poor correlation which contradicts

these findings. It is not surprising that there is this contradiction because once the eddy has broken apart it would not be expected to re-organize. Therefore it does not matter how close the anemometers are to each other a strong correlation should not be observed at this level in the canopy. This difference could be explained by recognizing that this study made measurements in an actual forest, whereas in Shaw et al² their measurements were taken in a model wheat canopy. More analysis including power and coherence spectra should be conducted to further investigate these results.

SUMMARY

It was found that having a large height separation between the anemometers resulted in them being poorly correlated both for the horizontal and vertical components. This indicates that the further vertical distance an eddy travels through the canopy the more disorganized it becomes. This work seems to echo work done by others which suggested that the canopy structure is an important factor in understanding air movement through the forest. For horizontal motion, the results imply that at different heights within the canopy the motion is more organized or consistent than at other levels. The information gathered also tends to support the idea suggested in earlier work about the decoupling nature of the canopy. This concept will be influenced by the structure of the canopy and density of tree foliage.

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