INTERNAL REPORT 74

EDDY SIZES ABOVE A FOREST CANOPY

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ABSTRACT

Sixteen propeller anemometers were placed 29 meters above a 45-year-old (approximately) Douglas-fir stand. Correlations between paired anemometers, when viewed as a function of distance between them, showed that eddies up to 5 meters in diameter were common, and indicated that larger eddies up to 9 meters across occur. Partial correlation coefficients between anemometers indicated that eddies are simply connected in cross section. Morning and nighttime data were excluded from analysis because the air was too calm. Results are related to the use of the eddy correlation method of determining atmospheric fluxes and the lack of preferential locations for updrafts or downdrafts above a tree crown.

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INTRODUCTION

Energy is transferred by the atmosphere from the source at the earth's surface to the sink in the upper troposhere by parcels of varying size. In the molecular boundary layer, which is less than 1 mm thick, individual molecules transport the energy by conduction and diffusion. Above this layer is a zone of microscale turbulence where eddies, moving at random, transport energy upward in a manner analogus to individual molecules in the layer below. This microscale level extends upward for the lowest few tens of meters of the atmosphere. Above it the motions have a larger scale typified in the lowest kilometer by cumulus convection and above that by cyclonic storms. The purpose of the experiment reported in this paper was to measure the size of the eddies of the turbulent layer at the top of the forest canopy, and to determine if there is a preferential location for rising and descending eddies.

The size and frequency of these eddies is determined in part by motions in the adjoining layers and the stability of the atmosphere. In particular, the eddies are more frequent when there is more activity in the layer immediately above. The roughness of the surface and the density of the vegetation also affect the dimensions of these motions.

MATERIALS AND METHODS

Experimental Site

The experiment was conducted on the lower portion of the Cedar River watershed near Seattle, Washington. The stand was 45-year-old Douglas-fir naturally regenerated after logging. Average tree spacing was 5.8 m. There were 572 trees per hectare, mostly Douglas-fir (*Pseudotsuga menziesii*) but with a few western hemlock (*Tsuga heterophylla*) and bigleaf maple (*Acer macrophyllum)*. The average diameter at breast height was 19.0 cm, and average tree height was 27.5 m. The soil was classified as a Barneston gravelly loamy sand originating from glacial outwash laid down at the end of the Vashon period.

The stand is located on relatively level ground in a broad valley in the foothills west of the main Cascade Range. Upslope mountain winds are noticeable almost every afternoon. The experiment was conducted on 12-14 September 1973. The days were clear or with high clouds except for some morning fog. Horizontal winds averaged about 4 knots.

Experimental Design

Three 2 x 4 (61 x 122 cm) boards were placed between five metal towers. One board was 30.0 m and the other 29.4 m above the ground. Attached to the boards were 16 propeller anemometers (Figure 1, Table 1) to measure the vertical windspeed. The anemometers consisted of Y. M. Young propellers on generator-type transmitters, similar to that described by Buffo (1972). The anemometer signals were recorded at 10-min intervals for two days.

Data Analysis

The data analysis consisted of finding the linear correlation coefficient between all pairs of anemometers, and the partial correlation coefficients for all pairs on the same or colinear boards, with the effects of all anemometers in between removed. For example, the partial correlation coefficient between anemometers numbers 4 and 14 was computed given the effect of numbers 5, 6, and 13 on each, but no partial correlation was computed between, say, numbers 7 and 5.

The data for the two days was grouped into 12 periods about three hours long in order to obtain uniformity of weather conditions. These periods are detailed in Table 2.

RESULTS

The correlation and partial correlation coefficients for each time period were grouped by distance into sample distributions. That is, the coefficients for all anemometer pairs less than 2 m apart were regarded as samples from an underlying distribution for all points in space less than 2 m apart. Similarly, another group comprised all pairs 2-3 m apart, and so on up to pairs greater than 9 m apart. These grouping and their sizes are shown in Tables 3 and 4 for correlation coefficients and partial correlation coefficients, respectively. A combination Student's t binomial significance tests was run to determine if the mean of the underlying distribution was significantly greater than zero. The test is described in the appendix.

Table 5 shows for each period the average magnitude of the wind (direction disregarded) and the standard deviation for all the observations for all the anemometers during that period. The former statistic is a measure of the strength of the wind field while the latter increases as the motions become more turbulent. On the basis of this information the data from all periods except numbers 1, 7, and 8 (the afternoon periods) were excluded from further analysis. During these morning and nighttime hours the atmosphere was simply too calm to provide enough eddies for a statistical analysis. In still periods when most of the observations were zero, one fairly large gust was enough to establish a "strong" linear relationship between all anemometers hit by it.

Tables 6 and 7 summarize the results of the experiment. Entries in these tables are the means of the observed correlation and partial correlation coefficients, respectively. Asterisks denote sample distributions that indicate at the 0.05 significance level that the underlying distribution does not mean zero.

Referring to Table 6, a high correlation between two anemometers indicates that they are often sampling the same eddy. These figures indicate that eddies with diameters up to at least 5 m are common and that eddies up to 9 m across also occur. Note the drop in average correlation between the 4- to 5-m and 5- to 6-m classes.

The partial correlation coefficient measures the correlation remaining between two variables after the effect of one or several intervening variables has been taken out. In this experiment, therefore, partial correlation coefficients give information concerning the shape of eddies. If eddies are round, at least simply connected, any effect a gust has on two extreme anemometers will also be observed by anemometers between them. Thus, when the effect of the interjacent anemometers is taken out of the correlation between those on the ends, a small partial correlation results. This was precisely the case observed. Table 7 shows no patterns of partial correlations significantly different from zero. Thus, at the level where these observations were taken, no evidence of the trees, breaking up air parcels could be found. Figures 2 and 3 show in graphical form the information of Tables 6 and 7.

DISCUSSION

Knowledge of eddy size is important if the eddy correlation method is to be used for determining fluxes within the canopy. In that method two instruments with different time constants measure the same atmospheric variable. The difference between simultaneous readings of fast and slow response instruments gives the eddy fluctuation which can be related to the overall flux of the quantity being measured (Rose 1966). The results of this experiment indicate that eddy correlation instruments should not be placed closer than 9 m at the top of the forest canopy if double samplings of the same eddy are to be avoided.

The data from this experiment were also used to make two other inferences concerning the use of the eddy correlation method above a forest canopy. First, vertical wind gusts were related to position with respect to tree crowns to see if updrafts appeared preferentially above the lighted side of the crown while downdrafts occurred over shaded portions. No patterns could be ascertained, thus indicating such a factor may not have to be considered in placing an eddy correlation instrument at this height. Second, the average vertical velocity (direction counted) of the wind was computed for each time period, as shown in Table 8. In the development of the eddy correlation formula the assumption is made that the net vertical wind velocity is zero for the period under consideration. Table 8 shows that while this is approximately true for the morning and nighttime periods, it is not necessarily valid for afternoons when radiation heating of the ground and canopy may cause a net upward flux of mass. Certainly the net upward velocity of 0.36 cm/sec for the whole experimental period is within the experimental error and could be explained by the mounting of the anemometers, being out of plumb.

SUMMARY AND CONCLUSIONS

This study has shown that fairly large and round eddies exist at the top of the forest canopy. It has also provided information relevant to the use of the eddy correlation method in the forests. Specifically: (1) eddy correlation instruments should not be closer than 9 m to avoid duplicate sampling of the same eddy; (2) placement of these instruments with respect to lighted or shaded portions of the tree crowns is probably not an important factor at this height; and (3) care must be taken in using a formula based on the assumption of zero net vertical mass flux in the afternoon periods. This last point is especially important to note because the afternoons, being periods of greater turbulence, would otherwise be very desirable times for sampling.

APPENDIX--SIGNIFICANCE TEST USED

If the correlation between two vectors is zero then the statistic

$$t = \frac{\hat{\beta} \quad n - 2}{1 - \hat{\beta}^2}$$

has a Student's t distribution with $n - 2$ degrees of freedom (Graybill 1961), where $\hat{\beta}$ is the sample correlation, and n the number of paired observations. Now if N significance tests are made at the α level using this statistic, then the number of rejections (R) of the null hypothesis ($\rho = o$) has a binomial distribution with parameter α provided that the underlying correlation does not indeed equal zero. Thus the observed statistic R may be tested using a one-sided binomial test with significance level α.

In this case all the sample correlations for each distance group for each time period were tested for being greater than zero, using a t test with $\alpha = 0.05$. The number of these tests in which Ho was rejected became the statistic R. For example, for a certain time period, 12 of the 15 sample correlations in the 3- to 4-m distance group may have had t statistics greater than the critical value. Therefore R would be 12 and a binomial test with $N = 15$ and $\rho = \alpha$ would indicate that the null hypothesis $\rho = 0$ should be rejected.

Note that while Tables 6 and 7 have means of the sample correlation coefficients as their entries, the means themselves were not used in the significance test.

REFERENCES

Buffo, John M. 1972. Characteristics of velocity components near and at the edge of a forest. M.S. thesis. Univ. of Wash.

Graybill, Franklin A. 1961. An Introduction to Linear Statistical Models. McGraw Hill.

Rose, C. W. Agricultural Physics. 1966. Pergamon Press, Oxford.

Table 1. Distances between anemometers (meters).

An.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	X															
2	1.52	X														
3	3.05	1.52	X													
4	4.46	2.93	1.41	X												
5	5.82	4.29	2.77	1.37	X											
6	7.70	5.82	4.29	2.87	1.51	X										
7	4.51	3.28	2.39	2.23	2.88	4.06	X									
8	4.09	2.67	1.50	1.31	2.30	3.67	0.99	X								
9	3.87	2.36	0.88	0.66	2.03	3.53	1.98	0.99	X							
10	3.90	2.40	1.08	1.02	2.18	3.62	2.95	1.96	0.99	X						
11	4.18	2.82	1.85	1.88	2.68	3.94	3.91	2.92	1.96	0.99	X					
12	4.67	3.50	2.78	2.79	3.39	4.44	4.88	3.91	2.92	1.96	0.98	X				
13	9.25	4.75	6.22	4.80	3.45	1.93	3.35	5.52	5.44	5.52	5.75	6.10	X			
14	10.18	8.66	7.14	5.73	4.38	2.86	6.66	6.45	6.36	6.43	6.63	6.91	0.93	X		
15	11.07	9.55	8.03	6.63	5.28	3.76	7.52	7.32	7.26	7.34	7.54	7.82	1.83	0.90	X	
16	12.01	10.46	8.94	7.54	6.17	4.67	3.38	8.22	8.18	8.23	8.36	8.61	2.74	1.82	0.91	X

An. = Anemometer number

Table 2. A listing of the groupings of data into time periods.

Period	Time
1	16:40 → 19:20
2	19:30 → 22:20
3	22:30 → 1:20
4	1:30 → 3:50
5	4:10 → 7:00
6	7:10 → 10:00
7	10:10 → 16:50[a]
8	17:00 → 19:50
9	20:00 → 22:50
10	23:00 → 1:50
11	2:00 → 4:50
12	5:00 → 7:50

[a]Data from 11:30 → 15:30 missing.

Table 3. Distance groupings of the anemometer locations for correlation coefficients.

Group no.	Distance (m)	Number of anemometer pairs
1	0.7 → 2.0	24
2	2.0 → 3.0	25
3	3.0 → 4.0	15
4	4.0 → 5.0	13
5	5.0 → 6.0	8
6	6.0 → 7.0	10
7	7.0 → 8.0	10
8	8.0 → 9.0	9
9	9.0 +	6
		120

Table 4. Distance groupings of the anemometer locations for the partial correlation coefficients.

Group no.	Distance (m)	Number of anemometer pairs
1	0.7 → 2.0	2
2	2.0 → 3.0	12
3	3.0 → 4.0	5
4	4.0 → 5.0	7
5	5.0 → 6.0	4
6	6.0 → 7.0	3
7	7.0 → 8.0	4
8	8.0 → 9.0	3
9	9.0 +	6
		46

Table 5. Relative strength and turbulence of the wind field during each time period.

Period	Standard deviation (cm/sec)	Average magnitude (cm/sec)
1	13.982	7.490
2	0.740	0.168
3	3.112	1.241
4	5.589	1.721
5	1.125	0.340
6	4.381	1.469
7	21.977	12.390
8	9.195	4.190
9	0.538	0.124
10	7.964	3.004
11	7.499	2.372
12	2.897	0.525

Table 6. Mean correlation by time period and distance grouping.

Time period[a]	Distance groupings (meters)								
	1	2	3	4	5	6	7	8	9
1	0.595*	0.593*	0.387*	0.375*	0.020	-0.116	-0.122	-0.276	-0.012
7	0.774*	0.720*	0.561*	0.531*	0.466*	0.555*	0.404	0.543*	0.219
8	0.271*	0.508*	0.396*	0.358*	0.264	0.184	0.219	0.080	0.010
Mean	0.546*	0.606*	0.448*	0.421*	0.250*	0.208*	0.167	0.116*	0.072

[a]See Table 2 for time periods represented by these numbers.

Asterisks (*) indicate at the 0.05 significance level that the underlying distribution does not have a zero mean.

Table 7. Mean partial correlation coefficient by time period and distance groupings.

Time period[a]	Distance groupings (meters)								
	1	2	3	4	5	6	7	8	9
1	0.007	0.114	0.011	0.064	0.109	-0.001	-0.179	0.224	0.040
7	0.783*	0.122	-0.271	0.079	0.194	-0.001	-0.307	0.419*	0.136
8	0.028	0.076*	0.120	-0.038	-0.344*	-0.497	0.133	0.131	0.089
Mean	0.257	0.104	-0.047	0.035	-0.014	-0.166	-0.118	0.258	0.088

[a]See Table 2 for time periods represented by these numbers.

Asterisks(*) indicate at the 0.05 significance level that the underlying distribution does not have a zero mean.

Table 8. Average wind velocity for each time period.

Period number	Length of period (hr:min)		Average velocity (cm/sec[a])
1	2:50		2.04[a]
2	3:00		0.10
3	3:00		-0.11
4	2:20		-0.72
5	2:50		-0.04
6	2:50		-0.84
7	6:40		1.52
8	2:50		2.17
9	2:50		0.01
10	2:50		-0.27
11	2:50		-0.01
12	2:50		0.42
		Mean	0.36

[a]Positive indicates a net upward velocity, negative indicates downward.

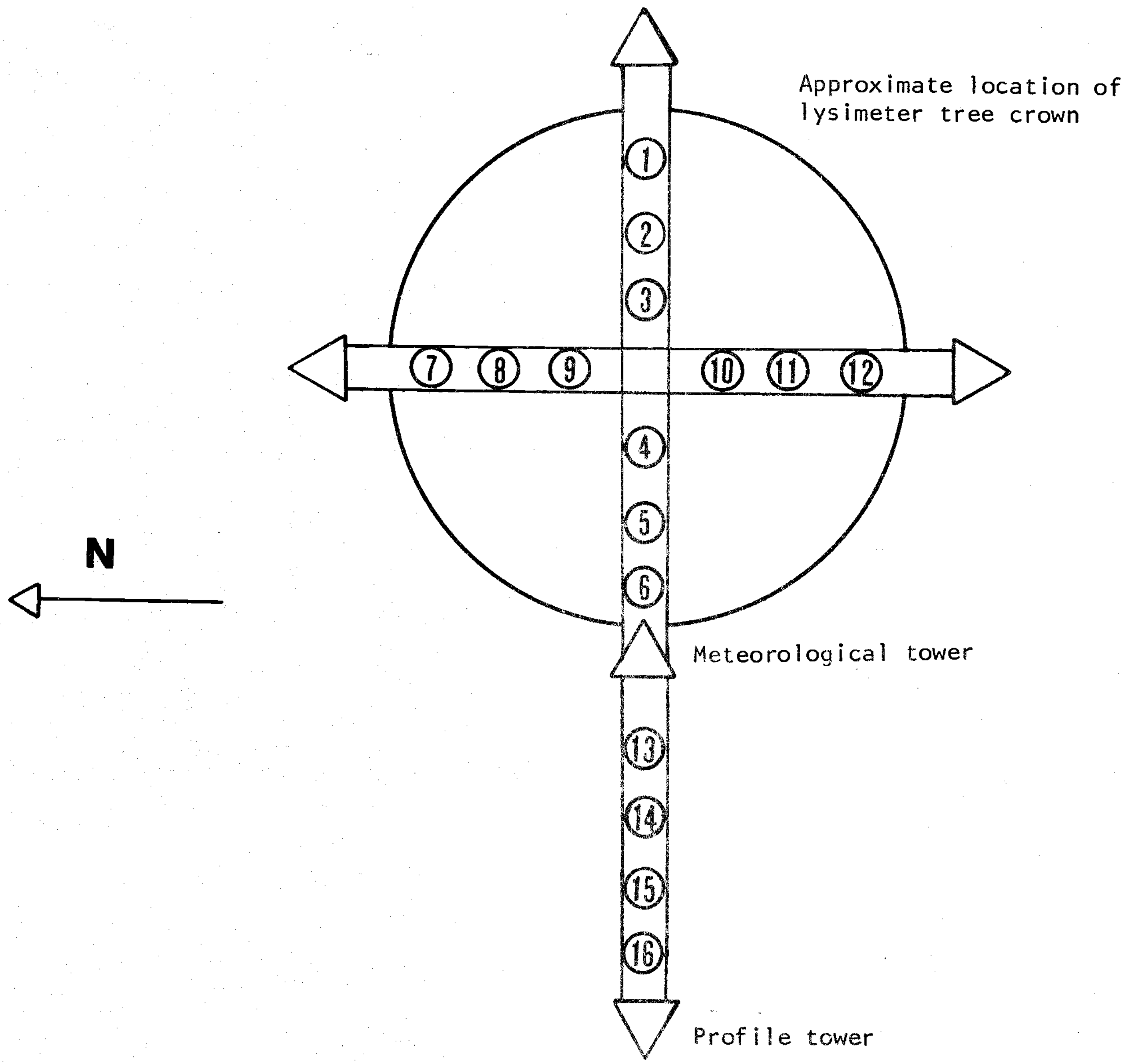

Figure 1. Placement of anemometers.

△ = triangular metal tower

○ = anemometer with designated number

▭ = 2 x 4 board

Figure 2. Correlation between anemometers vs distance between them

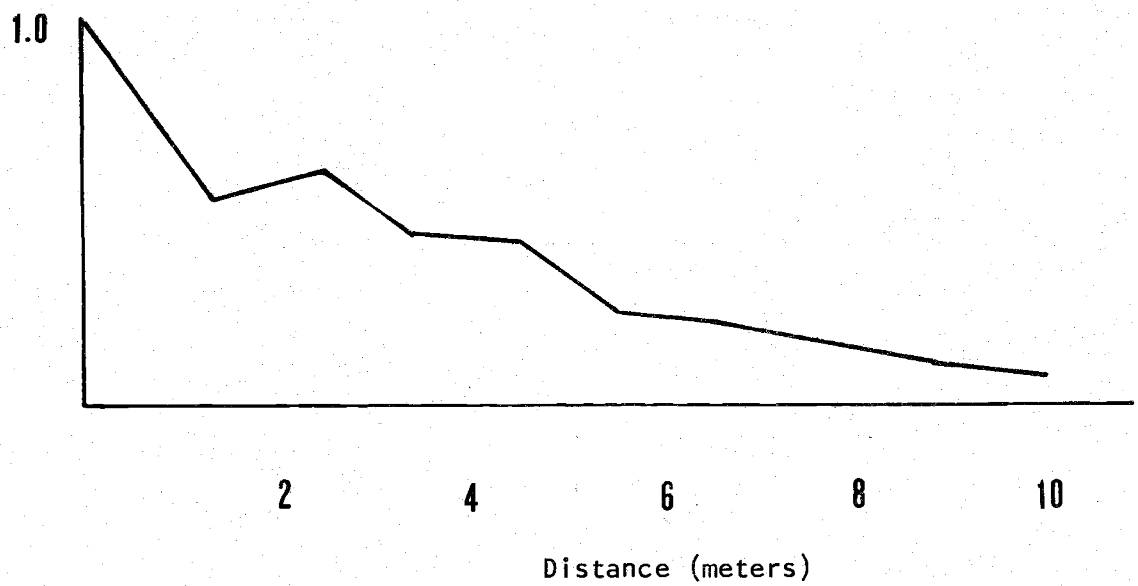

Figure 3. Partial correlation between anemometers vs distance between them