AD-A169 491 FIELD STUDY OF WIND THROUGH AND OVER A FOREST EDGE(U) 1/1
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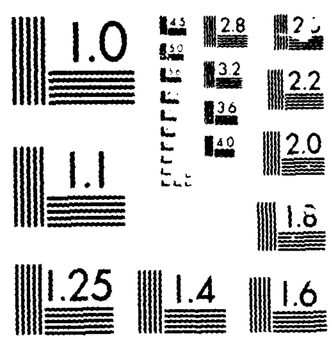
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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER ARO 21156.4-GS	2. GOVT ACCESSION NO. N/A	3. RECIPIENT'S CATALOG NUMBER N/A
4. TITLE (and Subtitle) Field Study of Wind Through and Over a Forest Edge		5. TYPE OF REPORT & PERIOD COVERED Final Report Jan.2,1984 - Jan.1,1986
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) D. R. Miller and J. D. Lin		8. CONTRACT OR GRANT NUMBER(s) DAAG-29-84-K-0017
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Connecticut Storrs, CT 06268		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Research Office Post Office Box 12211 Research Triangle Park, NC 27709		12. REPORT DATE April 7, 1986
		13. NUMBER OF PAGES 36
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

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18. SUPPLEMENTARY NOTES

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Forest Meteorology, Forest Edge, Turbulence, Micrometeorology, Canopy Flow.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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ARO 21156.4-GS

Final Report on U. S. Army Research Office
Grant Number DDAG-29-84-K-0017
Report Documentation Page
Project Title: Field Study of Wind Through and Over a Forest

20. Abstract

Three-dimensional miniature wind sensors that are stationary and have a high frequency response were developed and used to measure the wind structure inside and outside a forest edge. Extensive data sets were taken at different distances from the edge with the sensors arranged vertically through the canopy on movable towers both inside and outside the edge. Horizontally spaced sensors showed the flow inside the forest was correlated spatially at spacing less than 4m. More persistent autocorrelations at higher wind speeds demonstrated that larger eddies penetrated the canopy at higher wind speeds. Measurements above the canopy demonstrated a decay of Reynolds stress with decreasing height in the roughness sublayer. Velocity spectra demonstrated that mechanical turbulence is generated by the canopy at frequencies of about 1 hz. Comparisons of in-forest profiles with the wind blowing into and out of the forest showed the effects of the edge on the turbulent intensities, streamwise and cross stream Reynolds stresses. The flow through the edge intensified the turbulences below and above the forest canopy. Conditional sampling analyses demonstrated the sweeping and ejection mechanism of large scale momentum transfer is modified by the edge. Measurements outside the edge show the evolution of intermittent stagnation eddies against the edge.

FIELD STUDY OF WIND THROUGH AND OVER A FOREST EDGE

FINAL REPORT

D. R. MILLER AND J. D. LIN

APRIL 7, 1986

U. S. ARMY RESEARCH OFFICE

GRANT NUMBER DAAG-29-84-K-0017

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PROBLEM STATEMENT

Air flow in the forest environment governs the transport and deposition of aerosols, particulates and gases. The turbulent characteristics of fully developed flow in extensive forest and agriculture crop canopies have been intensively studied and partially described. This project was initiated to extend these studies to the forest edge, where the assumptions of a horizontally homogeneous canopy and adequate fetch are not met. Air flow over and inside forest edges has not been studied because it is inherently three-dimensional in nature and highly variable in both space and time. The problem involves studying the turbulent flow through and over an inhomogeneous porous medium that is in motion. In addition to the lack of theoretical study of the problem, no field measurements had been previously made in this environment due to the lack of available sensors capable of measuring the three wind components inside a forest canopy. This study has focused on field measurements to determine the spatial and temporal variability of the turbulence characteristics under various atmospheric conditions.

The major objective of the two year project is to gather an extensive set of field measurements with vertical and horizontal arrays of turbulent flow sensors. The field measurements are used to define the basic variability of the three-dimensional. They will also provide a set of field measurements to test numerical models and theories of turbulent flow in the edge environment. A secondary objective of the two year project is to calibrate and field test the prototype three-dimensional wind sensors being developed for use in the forest environment.

SUMMARY OF RESULTS

Data Sampling and Reduction System

A high speed, portable data recording, reduction and analysis system was assembled, and tested. A complete description is available in Lin and Miller (1985).

Sensor Development

Turbulent flow measurements in forest canopies require sensors that are stationary, have a high frequency response, are small enough to distinguish the eddies shedding off canopy elements and not interfere with the flow, and are capable of measuring three-dimensional flow at very low wind speeds. Two prototype sensors were developed and tested.

The first was a dual-triple-split hot film sensor. Its specifications, characteristics and calibration are described in Lin and Miller (1985). When calibrated in the laboratory this instrument seemed very promising but when used in the field the constant temperature anemometer bridges (DANTEC INC), which control the sensors, demonstrated considerable drift as a function of the ambient temperature. Therefore this instrument could not be used in the field until a method to control the temperature of the bridges can be established. This sensor has not been used in the field for any of the final data runs.

The second sensor system, we have named VECTOR, which was developed to measure the instantaneous wind vector, used an auxiliary electronic wind direction sensor (WOES) with a tri-diagonal hot film probe mounted on the same holder. Miller and Lin (1985) described the sensor and Miller and Lin (1986, in preparation) give the calibration and use procedures. This sensor (manufactured by TSI Inc. to our specifications) has proved to be stable and accurate in the field environment and four of them were acquired and used in the field sampling program in 1985.

Quantification of The Forest Canopy Element Distribution

Since the flow is controlled to a large extent by the forest canopy, a method to quantify the canopy as a porous medium was devised. Miller and Lin (1985) and Wang and Miller (1986) describe the point drop and photographic techniques developed and used to measure the three-dimensional spatial distributions of leaf area in the forest.

Characteristics of Turbulent Flow In The Forest Environment

Three basic investigations were conducted to characterize the turbulent flow in the forest edge. We studied the vertical wind structure with the wind blowing from the forest and with the wind blowing into the forest both inside and outside of the forest edge. The third involved a study of the horizontal variability of the flow at different levels inside and in front of the forest edge over short distances.

a. The horizontal variability within the canopy

Data sets were taken with three-dimensional sensors mounted horizontally in a rake and arrayed parallel and perpendicular to the edge. The rake experiment included data runs at four different levels in the canopy repeated with the sensors at two different spacings. Cross correlations of wind components from the arrayed sensors showed that the three-sensor array was capable of revealing the spatial characteristics of turbulence if properly spaced. However more sensors are highly desirable. Figure 1 is an example of this anaysis. It graphs the u component correlation as a function of distance between the sensors. When the sensors were further apart than about 4 meters the flow was essentially uncorrelated. This length spacing is reasonable since the canopy element spacing analysis (Wang and Miller, 1985) indicated that the characteristic spacing of tree crowns in the stand was about 6 meters.

Autocorrelations from single sensors are being used to estimate the time scale of passing eddys at the sensor location. These autocorrelations of individual wind components (u, v, w) demosnstrated correlations at lags up to three to five seconds in most data sets. Figure 2 shows autocorrelations from two different runs from one of the sensors in the rake array below the canopy. The wind velocity above the canopy during run 1 was about 2 m/sec and about .5 m/sec during run 2. The graphs demosnstrate increased persistence at the higher wind speeds at 1 and 2 seconds but the 5 second limit on correlated lags is independent of wind speed. Thus the integral scale, or eddy size is larger at higher wind speeds.

The data from this experiment is currently still being analyzed to test Taylor's hypothesis for mean velocities using the the spatial length scales from the cross-correlations and the time scales from the autocorrelations.

b. Flow characteristics inside the forest edge

The three-dimensional wind sensors were arrayed vertically on a movable tower and vertical profiles were measured at several positions inside the forest edge.

Data taken when the wind was blowing out of the forest edge from the extensive forest fetch was used to characterize the "roughness sublayer" or "transition layer" above the mean height of the forest canopy and below the surface layer (the constant u* layer). In this layer individual tree crown wakes have not yet been averaged outa The existence of this layer is demonstrated in the profiles of $\overline{u'w'}$ in Figure 3b by the decay of the Reynolds Stress ,$\overline{u'w'}$, with decreasing height in this layer. This is the first set of field measurements in forests that confirm the existance of the roughness sublayer observed in the wind tunnel results of others. Velocity spectra in this roughness sublayer show characteristic peaks at .1 - .5 hz, a flat area about 1 hz and a peak about 2 - 3 hz. These were first measured in 1984 with X-hot film probes and described in Lin and Miller (1985). Measurements in 1985 with the three-dimensional VECTOR probes showed the same characteristics. Apparently the interruption of the Kolmogrov inertial subrange (-5/3 slope) at 1 hz by a peak or shift to higher frequencies is characteristic of this site and is due to the generation of additional mechanical turbulence at this frequency by the canopy roughness. Thus in the roughness sublayer the turbulence generation takes place at frequencies typical of the length scales between tree crowns; in this case approximately 1 hz or six meters according to the Fourier analysis of the canopy surface.

The forest fetch profiles allow the characterization of the flow inside the forest in the equilibrium region, away from edge effects, where the assumption of horizontal homogeneity has been made in past studies. Table 1 and Figures 3a,b,c are examples of the mean wind speed, Reynolds stresses, and turbulent intensity profiles calculated from a three minute run. All the values are scaled by $\overline{u}$ at 23m. The mean profile of $\overline{u}$ demonstrates that counter gradient momentum flux is occurring in the lower canopy with the minimum wind speed in the dense upper canopy and the secondary maxima below the canopy.

The turbulence intensity profiles, $\overline{u'^2}/\overline{u}^2$, demonstrate that the turbulent intensities in this forest environment are very large. They are the same order of magnitude as the mean wind in the roughness sublayer and inside the canopy they sometimes exceed the mean wind u. This has major implications for the transport of airborne materials.

Conditional sampling of the Reynolds stresses at the various levels demonstrates (Figures 4a-c) the sweeping and ejection mechanism of large-scale momentum transport as previously reported by Lin and Miller (1985).

The three dimensional sensors allow us to separate the turbulence data into the mean wind and cross wind components by rotating the u direction into the mean vector direction for each measurement. Figure 3c shows that the turbulence intensity in the cross stream direction is nearly the same order of magnitude as in the streamwise direction. But the momentum flux or Reynolds stress in the cross-stream direction oscillates near zero. Conditional sampling of these cross stream stresses (Figure 5a-c) shows much lower sweeping-ejection components than interaction components than in the streamwise stresses.

Comparisons of the vertical profiles with the wind blowing into the edge (Table 2 and Figures 6 a-c) to those with the forest fetch show that the Reynolds stresses and turbulence intensities below the canopy are increased significantly by wind penetrating the edge in the trunk space. The Reynolds stresses and turbulence intensities are also increased above the canopy by the wind blowing over the edge. Conditional sampling showed a larger fraction of sweeping and less ejection than in the forest fetch condition.

c. <u>Flow characteristics outside the edge</u>

The profiles measured outside the edge are being used to examine the intermittent structure of the flow through the edge. The measurements have shown the intermittent evolution of stagnation eddies against the forest edge. Figures 8 a,b are a time series of the u' and w' wind components at a distance of .5 h from the edge and a height of 11m. The data shown are one-second averages from a run at a sampling rate of 20 hz. The data in both graphs show building up and breaking down of these eddies at regular 45-second intervals. The u' peaks simultaneously with a strong upward w' at the end of each cycle. This gusting forward and upward is the breakdown of the eddy and release of air over the top of the forest edge. These measurements together with the smoke plume observations by Bergen (1975) and Miller (1980) demonstrate that the stagnation eddy periods are dependent on the forest edge height. Bergen reported a period of 20 seconds at a 7 m forest edge. This study shows a 45 sec period at a 14 m forest edge and Miller (1980) reported a 60 second period at a 20 m edge.

The time series of the profiles measured at different distances from the edge require elaborate conditional sampling to completely define the spatial and temporal intermittant structure of these eddies. This is currently being undertaken.

z (m)	z/H	$\overline{u}/\overline{u}_{top}$	$\overline{u'v'}/\overline{u}^2$	$-\overline{u'w'}/\overline{u}^2$	$-\overline{v'w'}/\overline{u}^2$	$\overline{u'^2}/\overline{u}^2$	$\overline{v'^2}/\overline{u}^2$	$\overline{w'^2}/\overline{u}^2$
25	1.72	1.000	0.044	0.448	0.011	0.002	0.017	0.001
17.5	1.21	0.551	0.006	0.153	-0.025	0.229	0.094	0.204
15.5	1.06	0.571	0.133	0.091	0.041	0.331	0.204	0.258
13.0	0.89	0.154	-0.003	0.015	-0.005	0.019	0.013	0.025
11.0	0.76	0.259	-0.025	0.018	0.014	0.051	0.053	0.082
7.5	0.52	0.260	0.001	0.009	-0.009	0.015	0.023	0.019
5.5	0.38	0.300	0.040	0.002	-0.001	0.004	0.008	0.007

Table 1. Profile data inside the forest edge with the wind from the forest fetch. $\overline{u}_{top} \approx 4.4$ m sec^{-1}

z (m)	z/H	$\bar{u}/\bar{u}_{top}$	$\overline{u'v'}/\bar{u}^2$	$-\overline{u'w'}/\bar{u}^2$	$-\overline{v'w'}/\bar{u}^2$	$\overline{u'^2}/\bar{u}^2$	$\overline{v'^2}/\bar{u}^2$	$\overline{w'^2}/\bar{u}^2$
25	1.72	1.000	0.011	0.016	-0.024	0.051	0.088	0.036
17.5	1.21	0.328	0.030	0.030	0.071	0.035	0.066	0.086
15.5	1.06	0.263	0.068	0.013	0.065	0.221	0.080	0.136
13.0	0.89	0.098	0.007	0.008	0.010	0.011	0.014	0.013
11.0	0.76	0.143	-0.012	0.006	0.006	0.025	0.024	0.023
7.5	0.52	0.22	0.049	0.007	0.078	0.060	0.094	0.100
5.5	0.38	0.29	0.002	0.022	0.007	0.039	0.019	0.029

Table 2. Profile data inside the forest edge with the wind through the edge from the corn field fetch. $u \approx 4$ m sec^{-1}

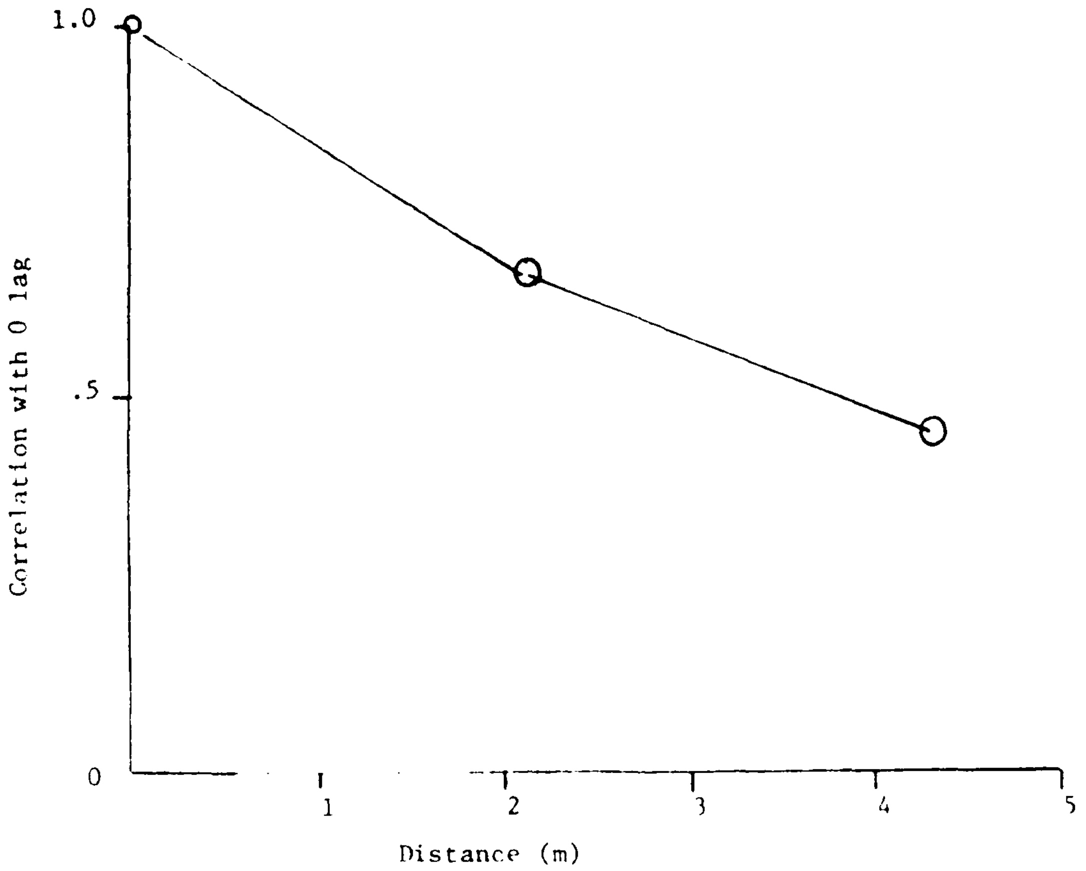

Figure 1. Cross-correlation between simultaneous measurements of u as a function of measurement separation distance.

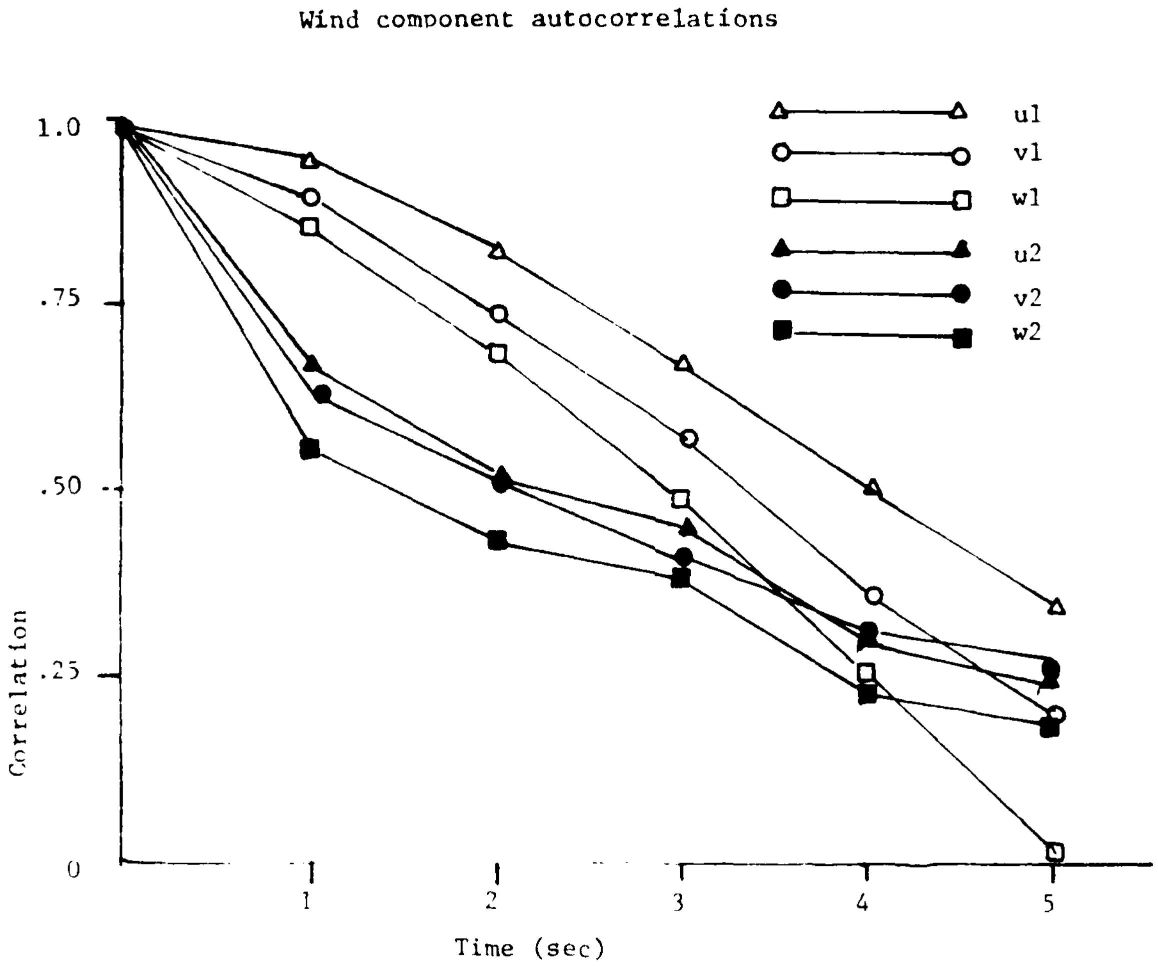

Figure 2. Autocorrelations of u, v, w components from two different runs below the forest canopy.

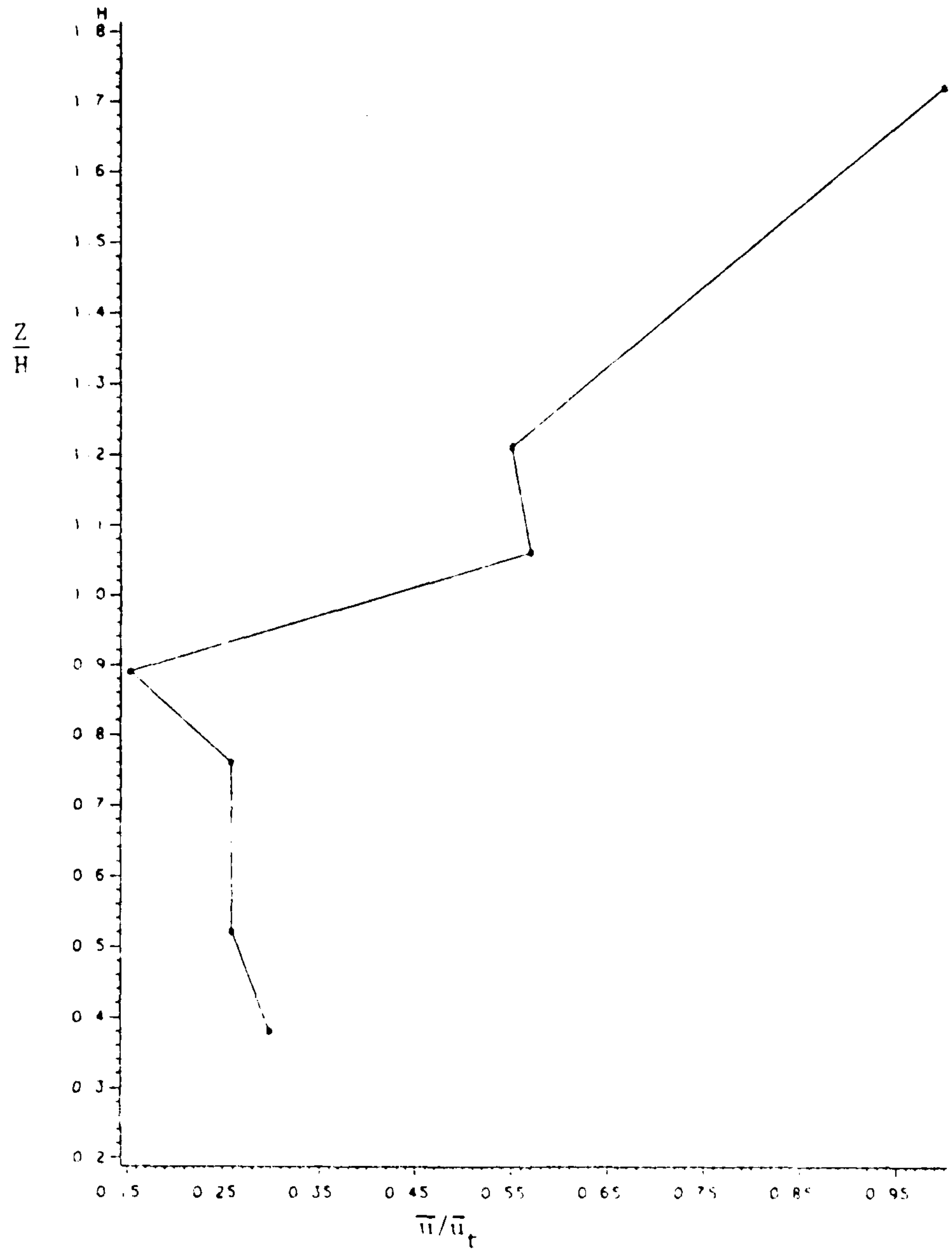

Figure 3a. Mean wind speed profile (3 minute average) in the forest equilibrium region.

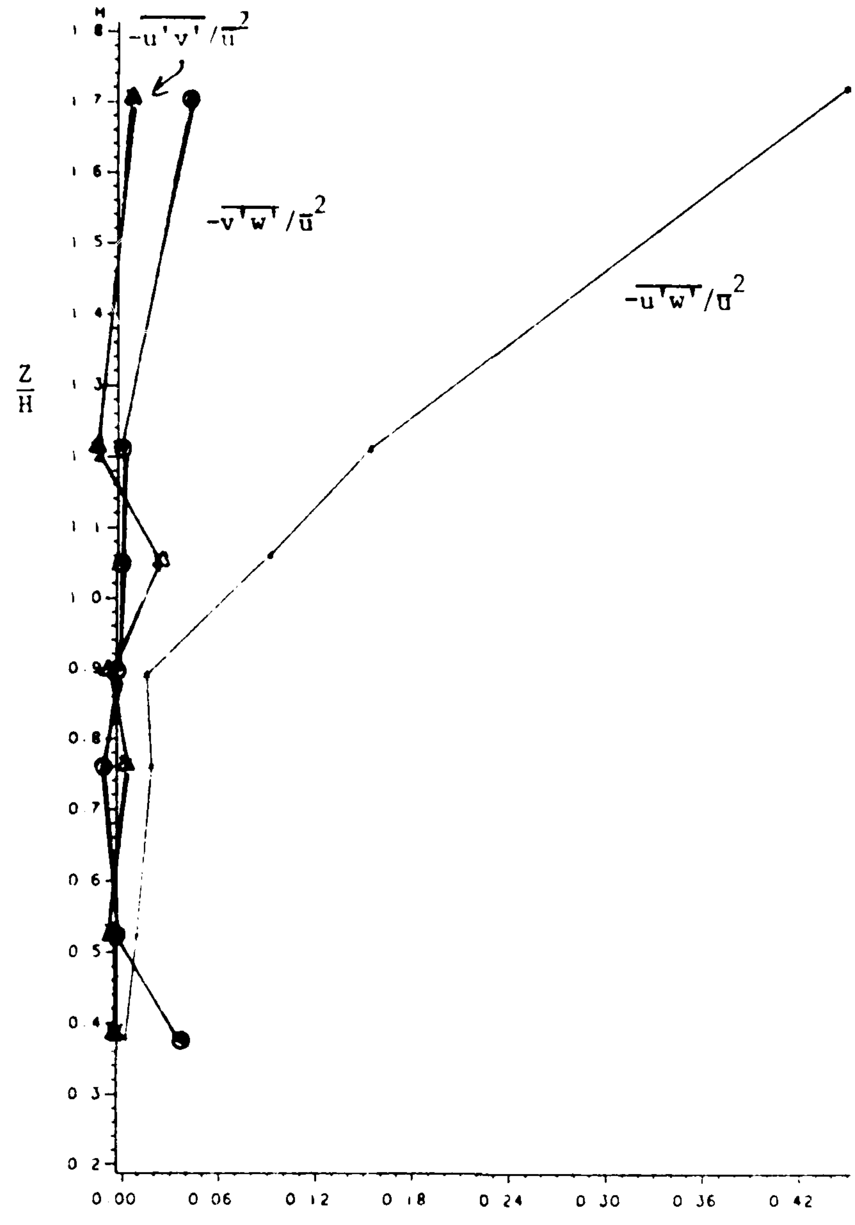

Figure 3b. Profiles of Reynolds stress in the streamwise, cross-stream and horizontal plane directions from the run in figure 3a.

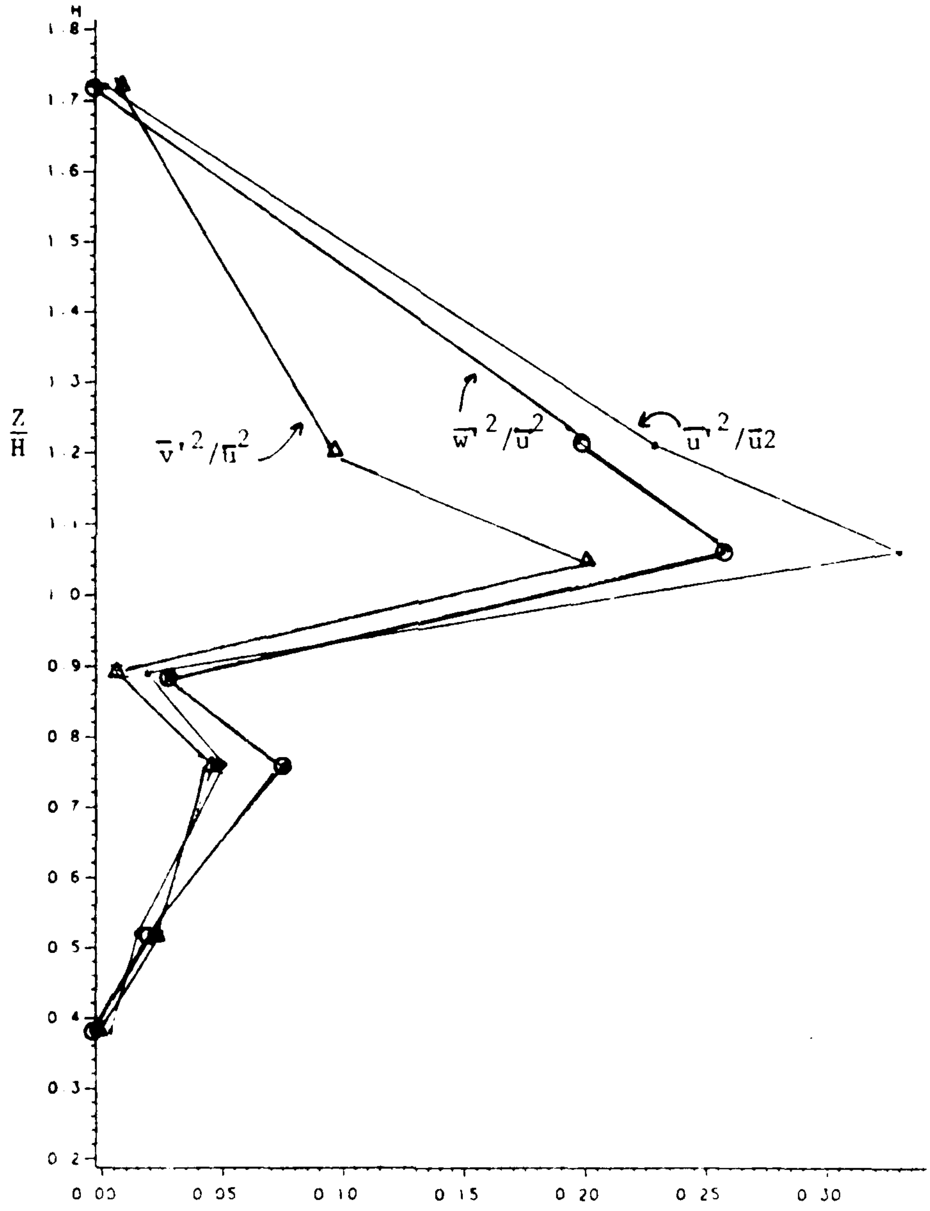

Figure 3c. Profiles of turbulent intensities from the run in figure 3a.

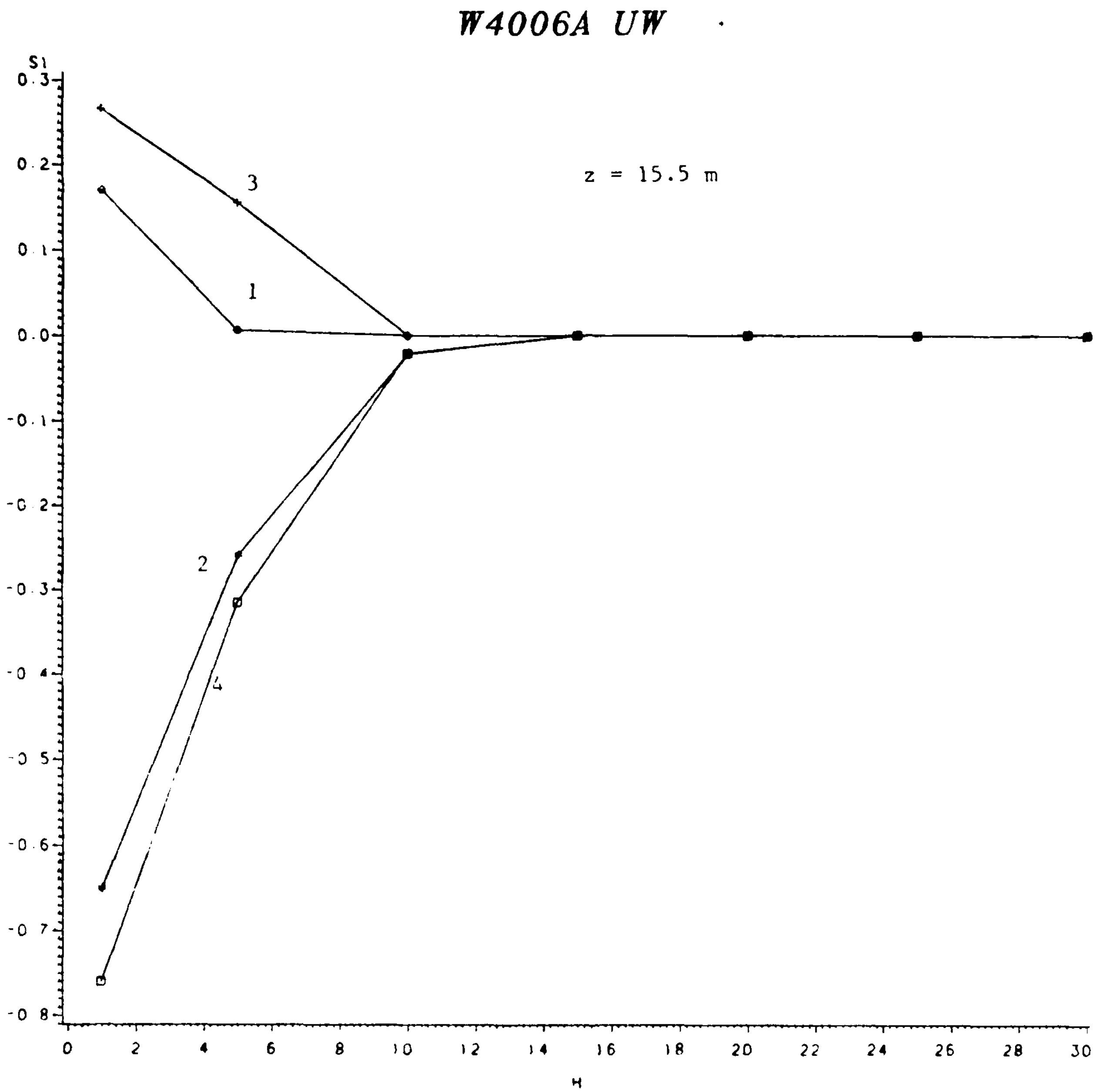

Figure 4a. Conditional analysis of Reynolds stress above the canopy in the equilibrium flow region.

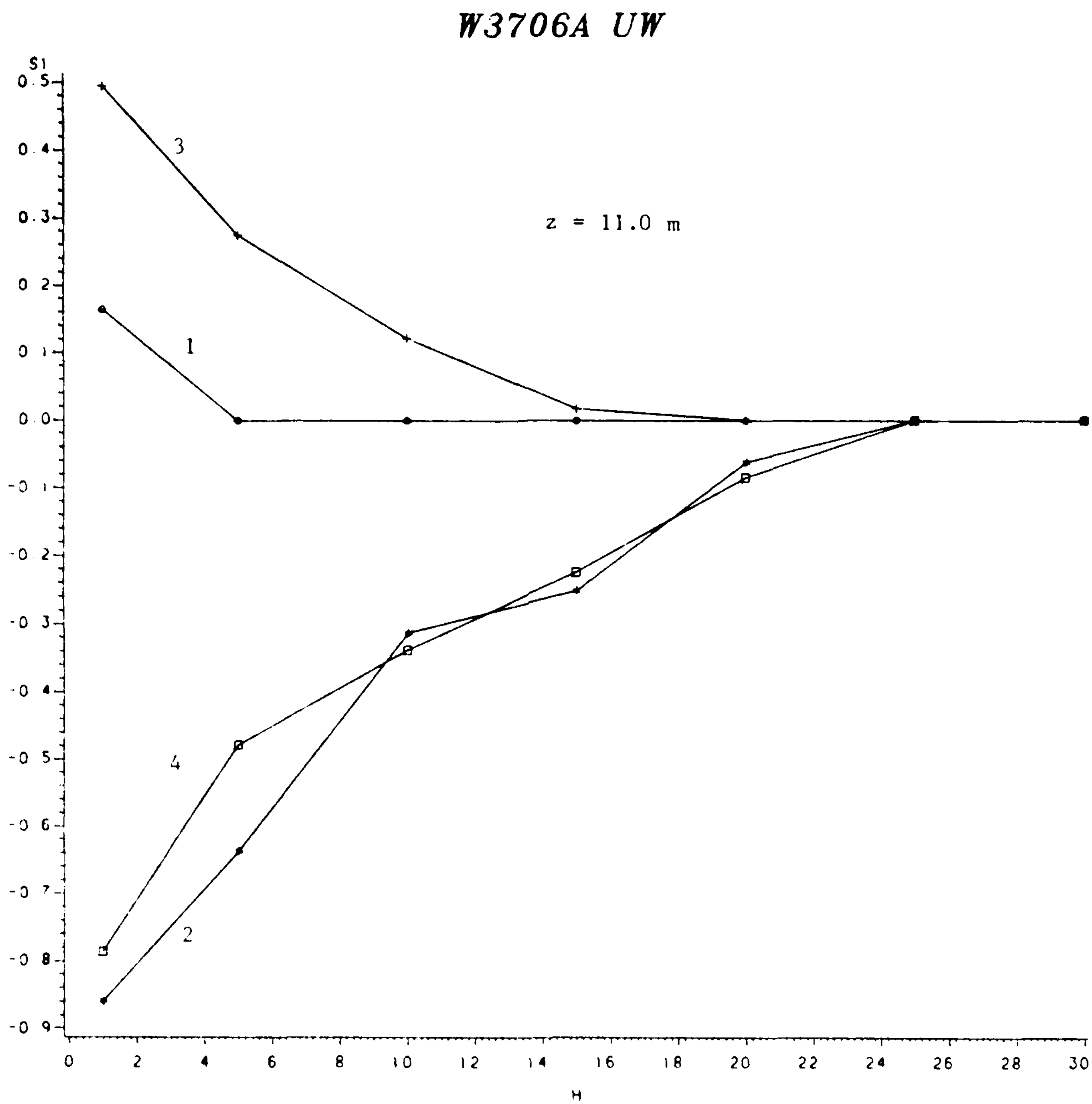

Figure 4b. Conditional sampling analysis of Reynolds stress within the canopy in the equilibrium flow region.

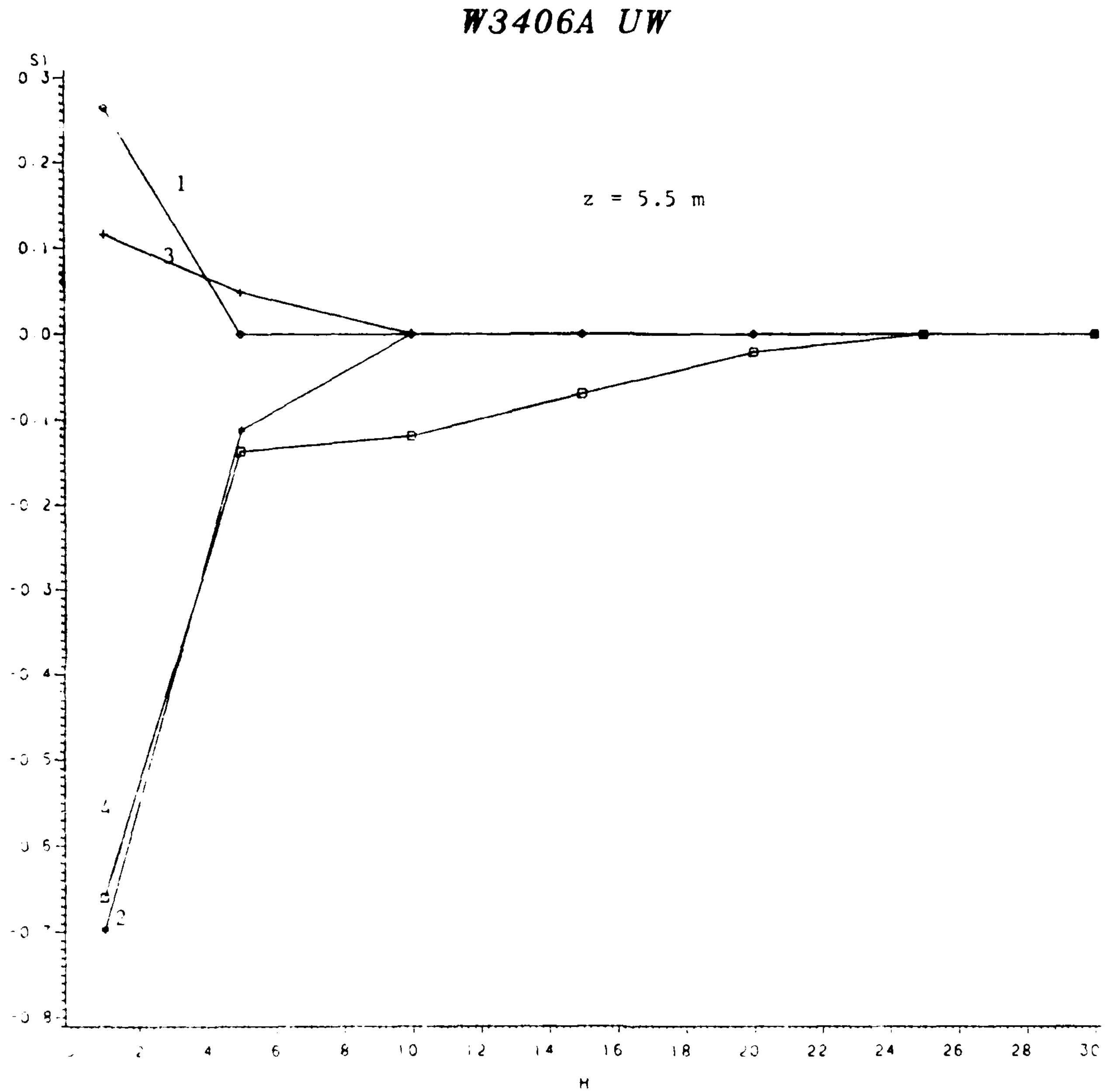

Figure 4c. Conditional sampling analysis of Reynolds stress below the canopy in the equilibrium flow region.

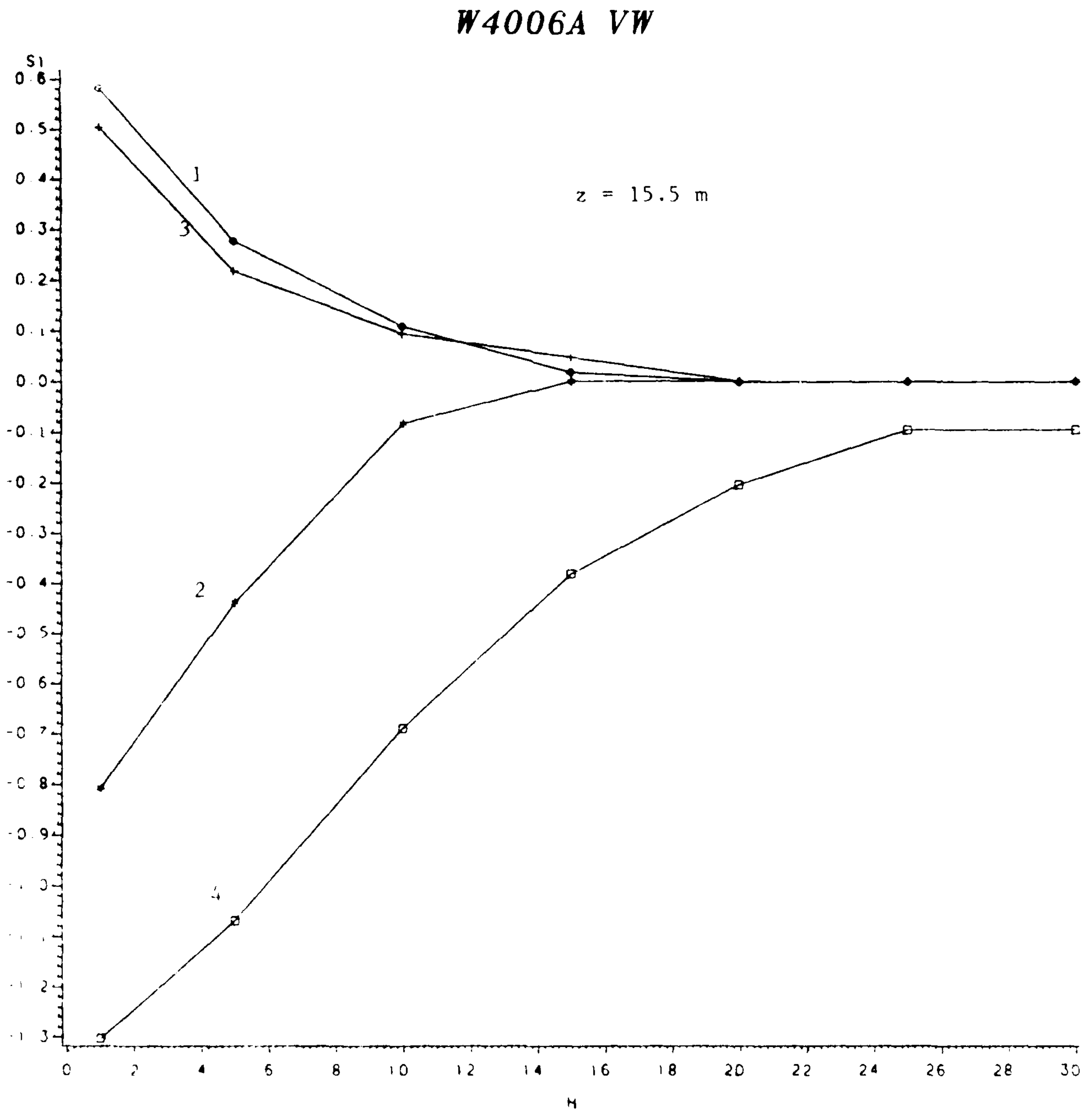

Figure 5a. As Figure 4 for the cross-stream stress.

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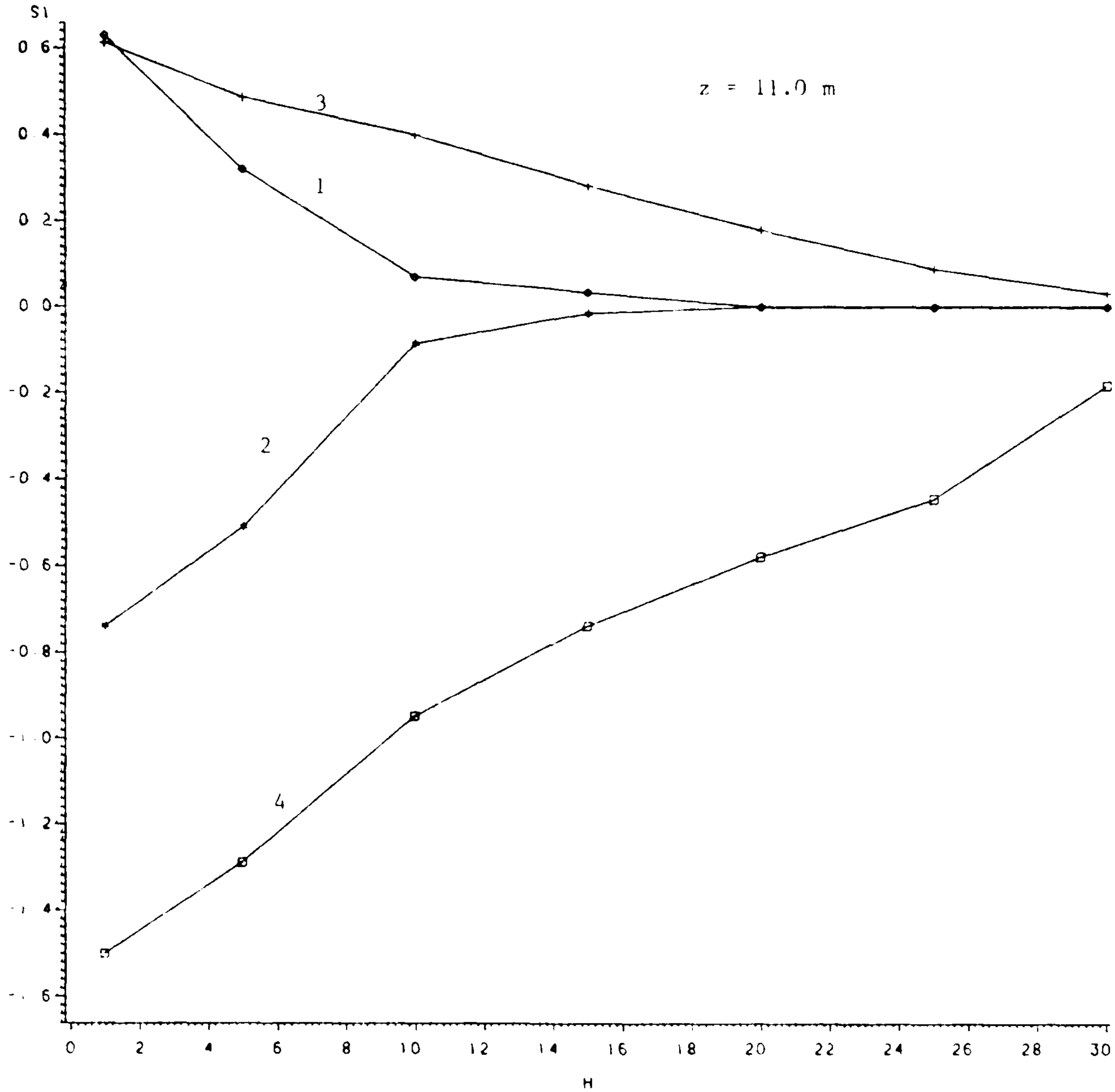

Figure 5b. As Figure 4b for the cross-stream stress.

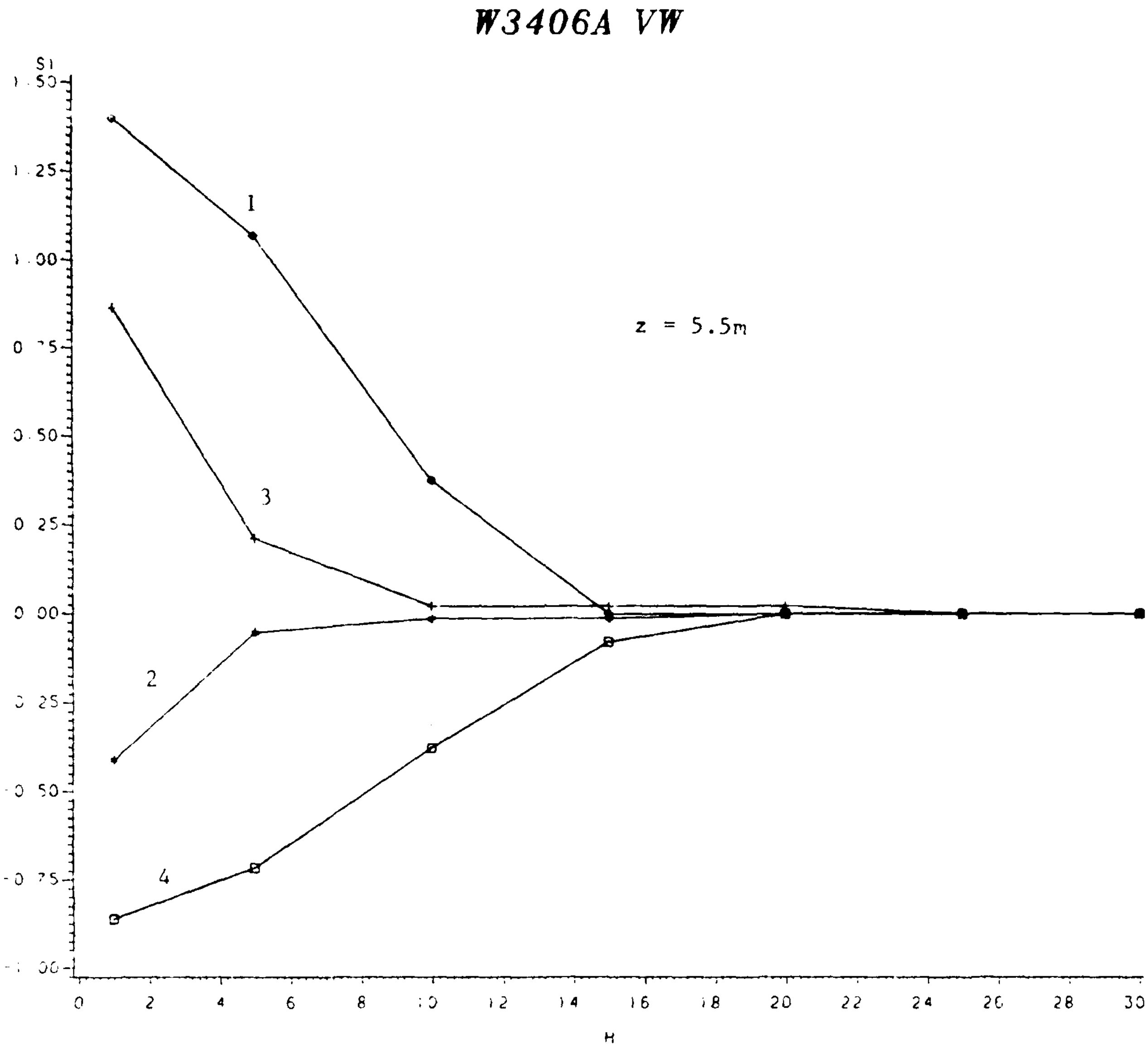

Figure 5c. As Figure 4c for the cross-stream stress.

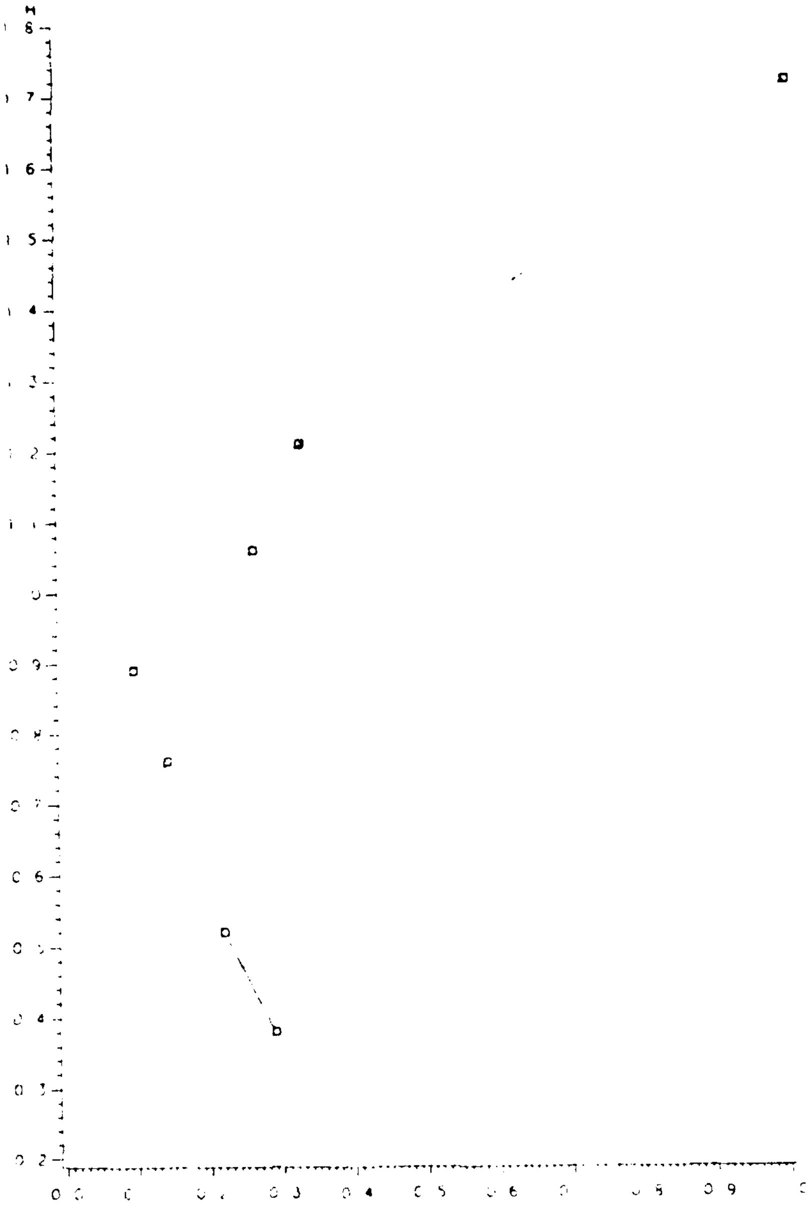

Figure 6a. Means wind speed profile (3 minute average) in the forest with the wind blowing through the edge.

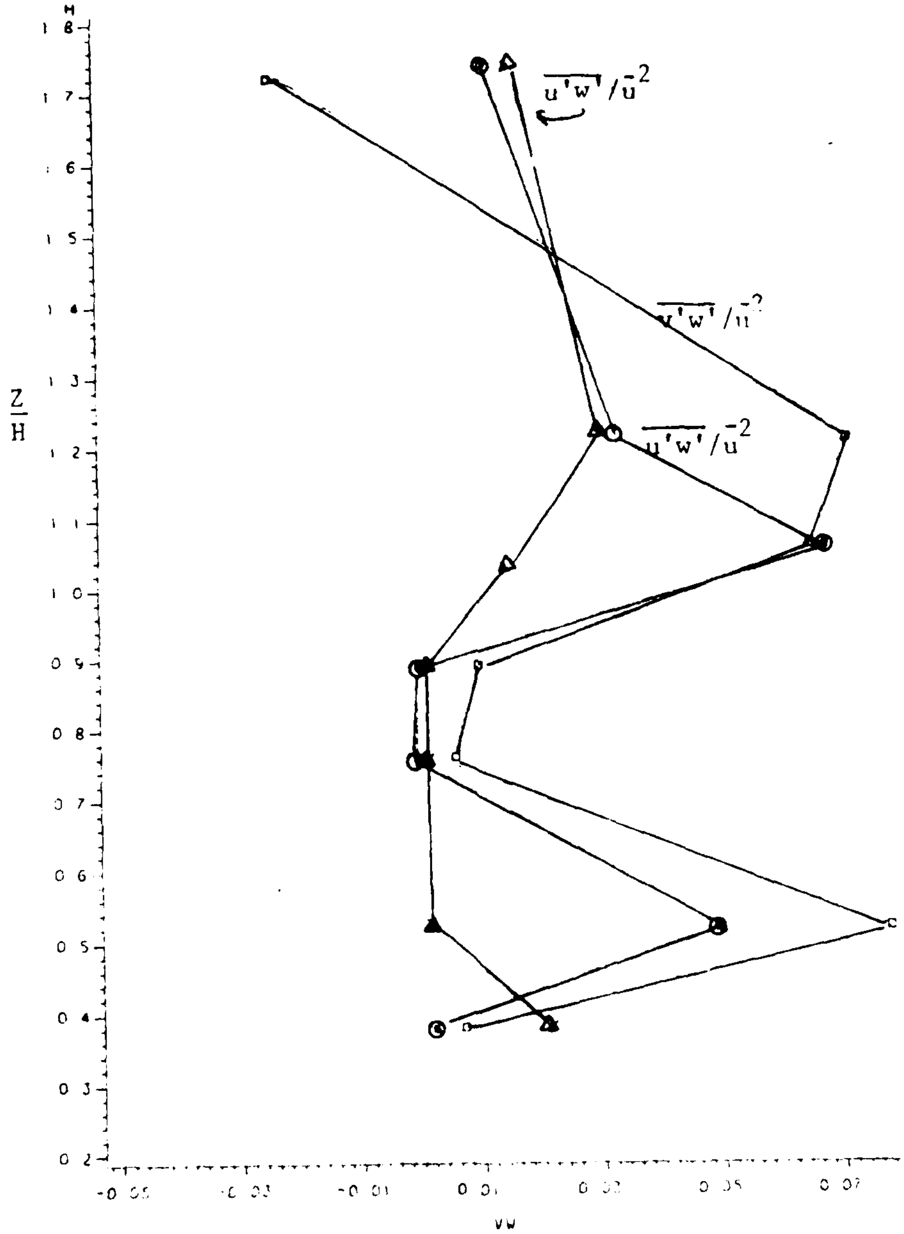

Figure 6b. Profiles of Reynolds stress in the streamwise, cross-stream and horizontal plane directions from the run in Figure 6a.

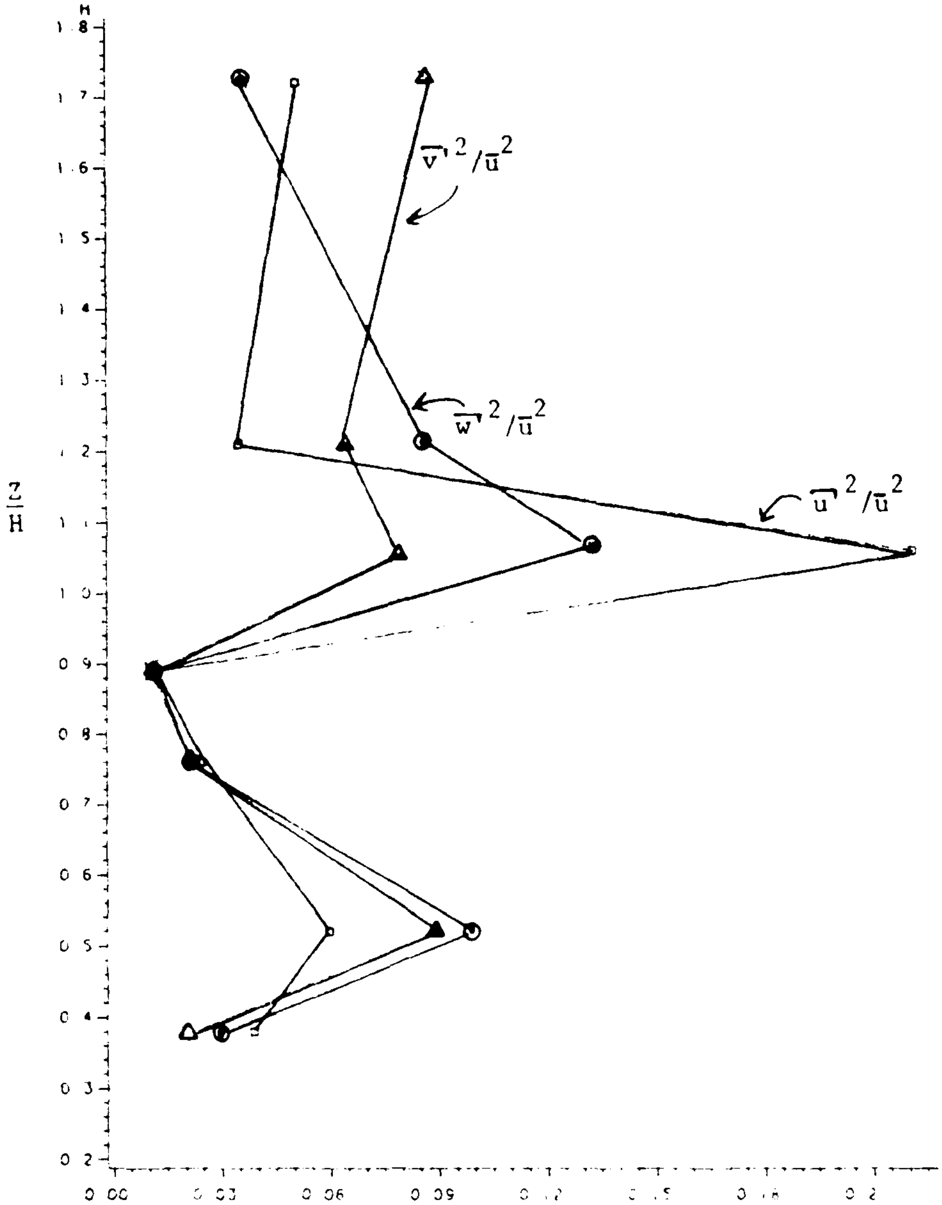

Figure 6c. Profiles of turbulent intensities from the run in Figure 6a.

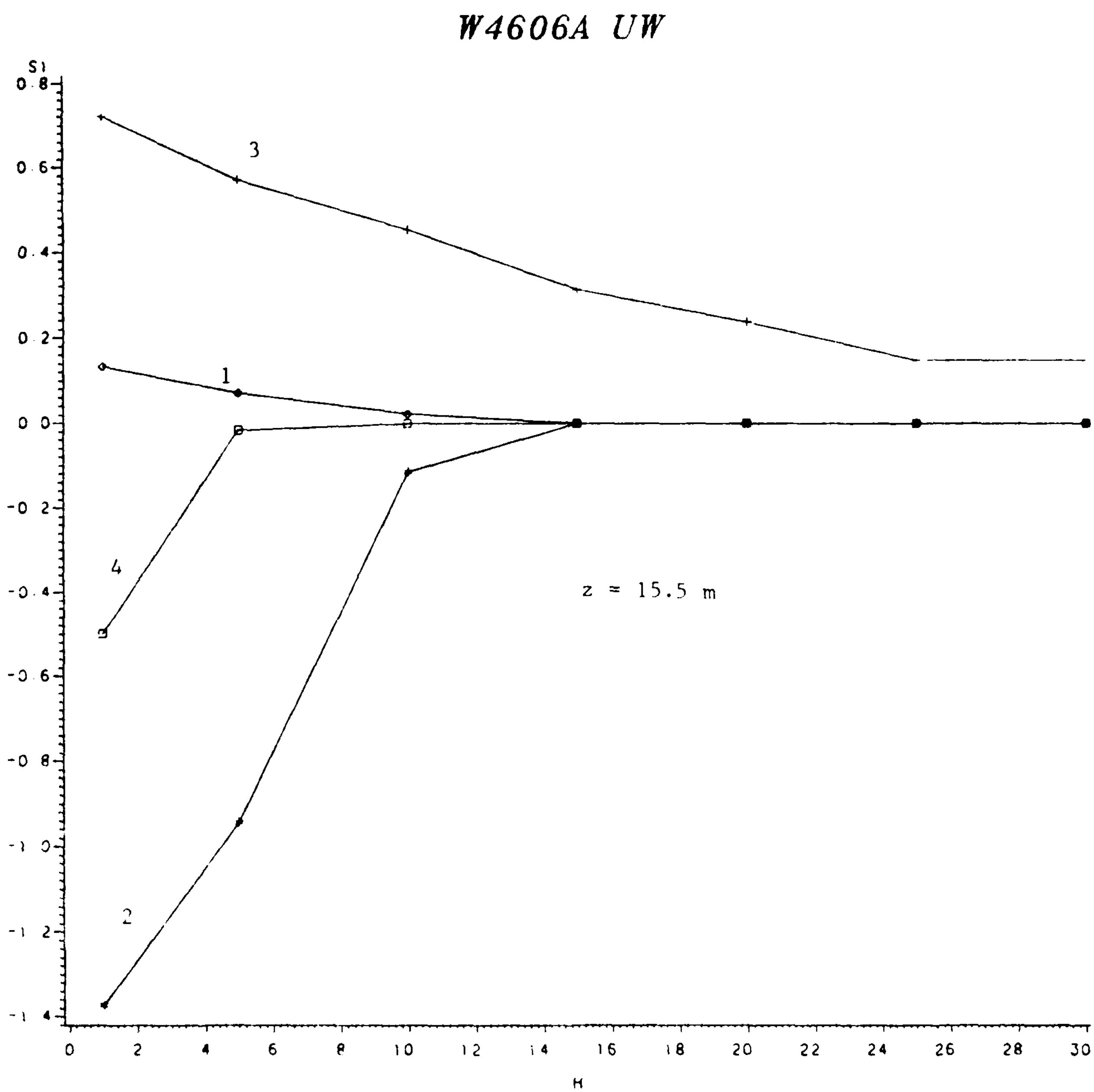

Figure 7a. Conditional sampling analysis of Reynolds stress above the canopy from the run in Figure 6a.

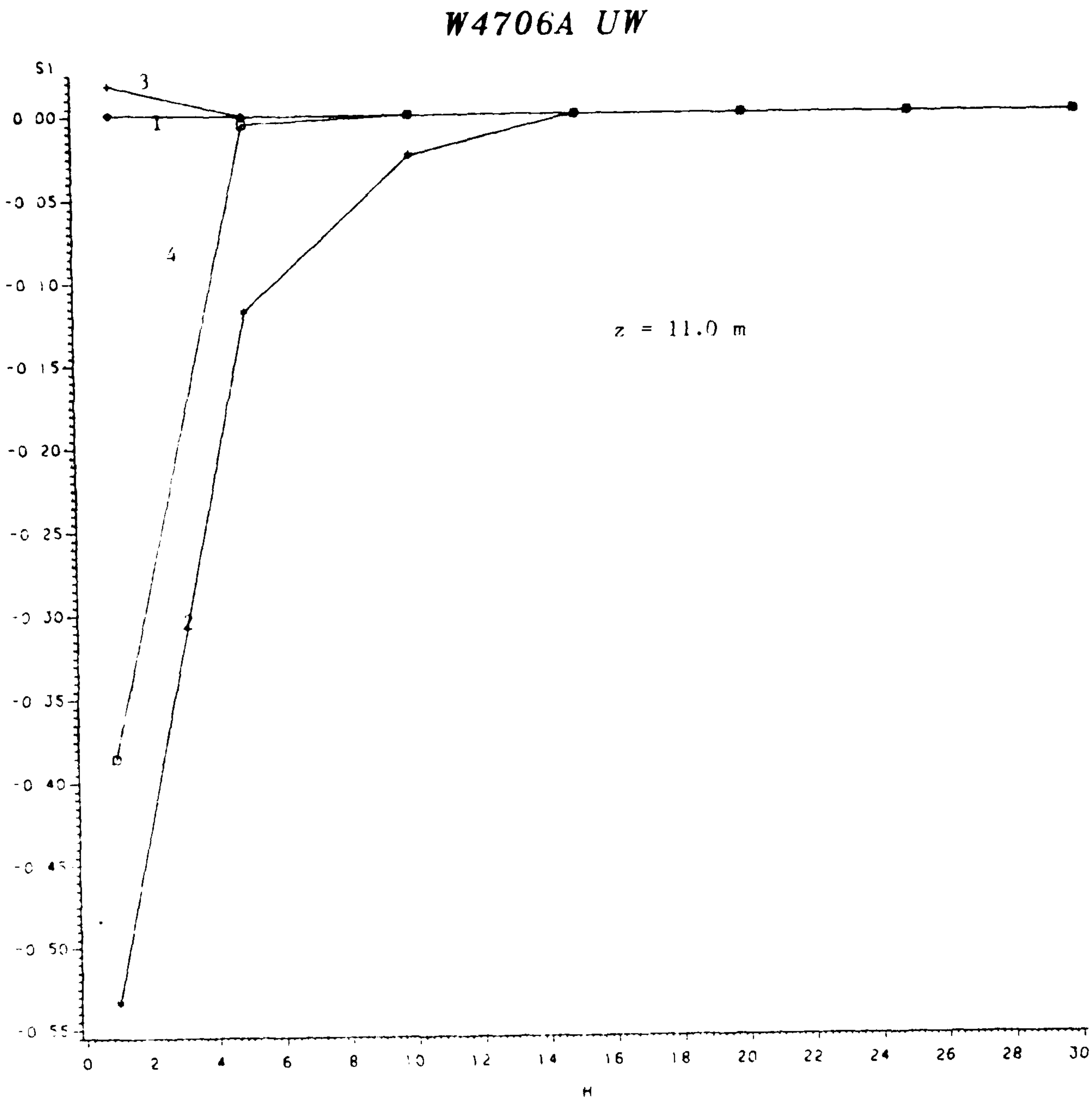

Figure 7b. Conditional sampling analysis of Reynolds stress within the canopy from the run in Figure 6a.

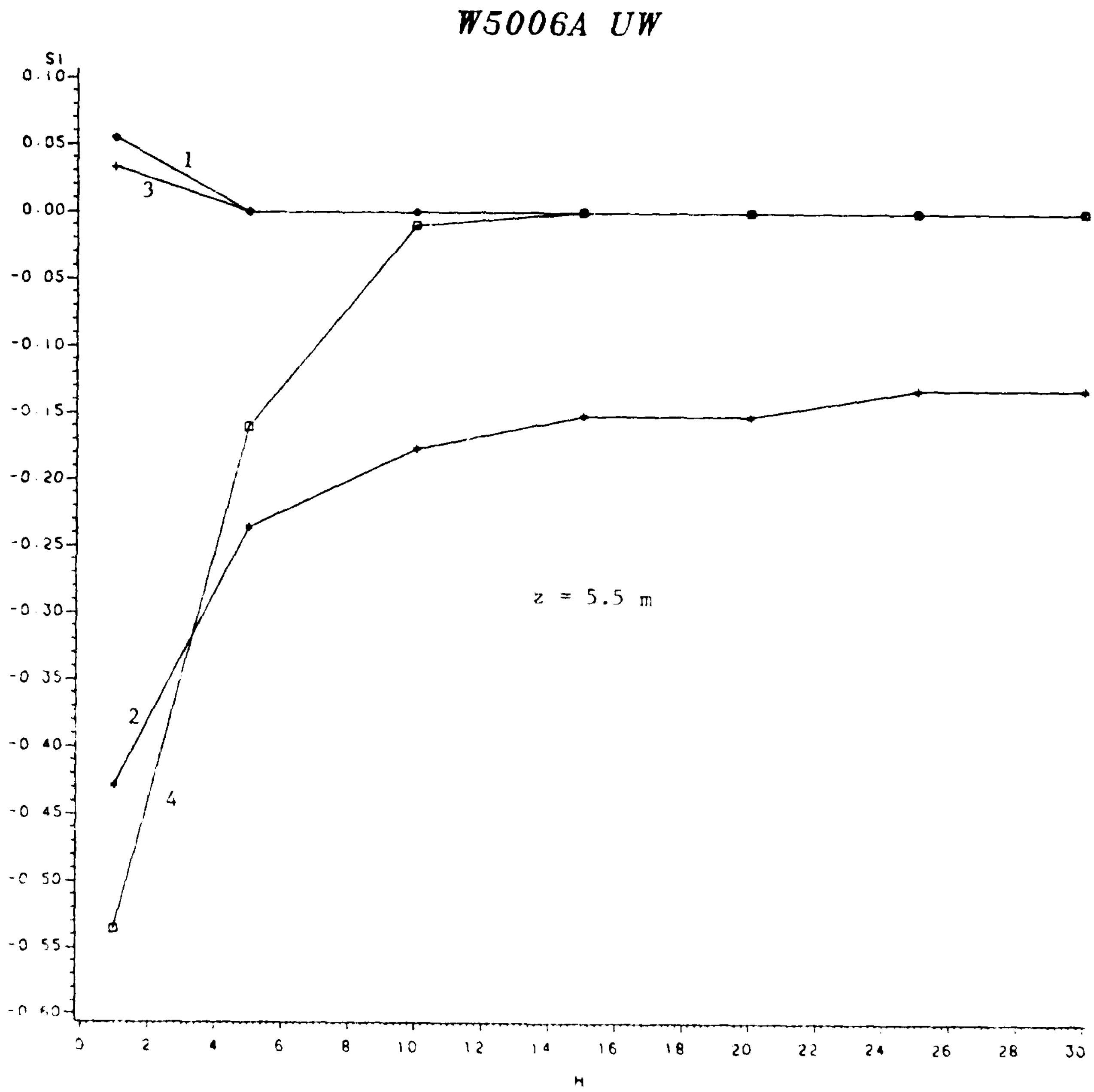

Figure 7c. Conditional sampling analysis of Reynolds stress below the canopy in the run shown in Figure 6a.

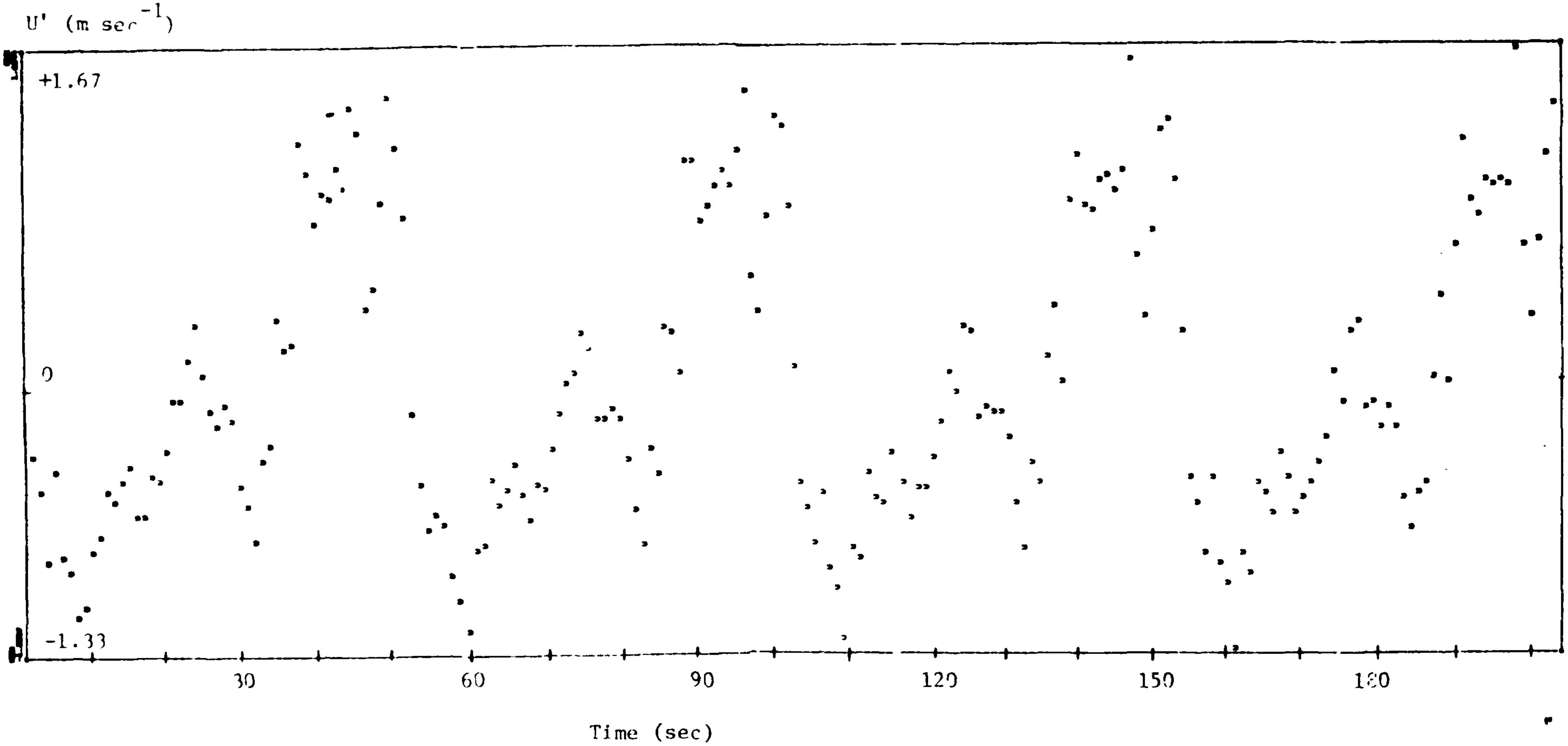

Figure 8a. 200 second time series of u' outside the forest edge.

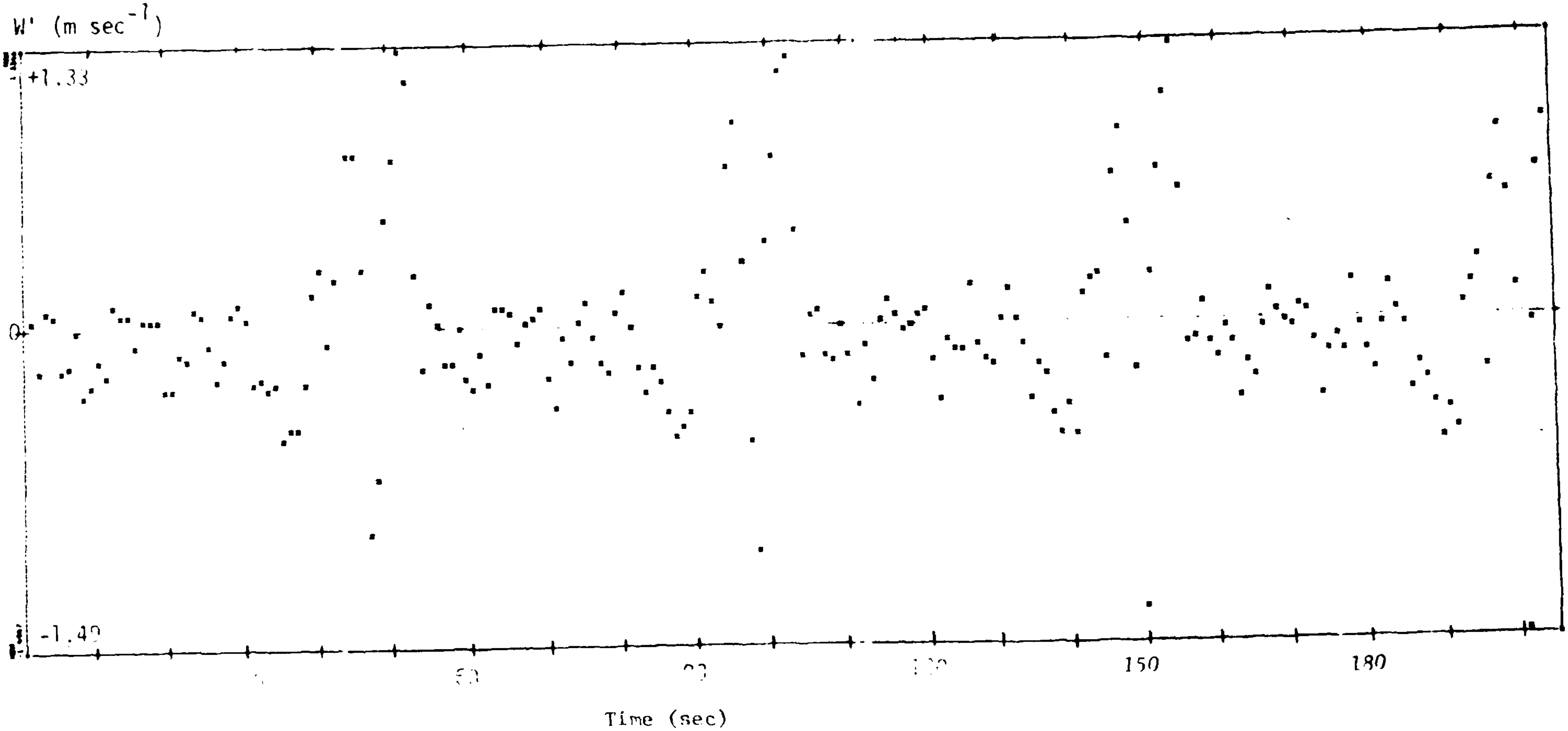

Figure 8b. 200 second time series of w' outside the forest edge.

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Lin, J. D. and D. R. Miller. 1985. A Preliminary Field Study of Turbulent Flow Over and Inside a Forest Edge. Interim technical report to the U.S. Army Research Office on grant # DDAG-29-84-K-0017. Depts. of RNR and CE, University of Connecticut. 61p.

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Lin, J. D., D. R. Miller and Z. J. Li. 1986. Calibration of a Dual-Triple-Split Hot Film sensor for three-dimensional turbulent flow measurements.

Miller, D. R. and J. D. Lin. 1986. Calibration and use of a combination triple film and miniature electronic wind octant sensor for measurement of the three dimensional instantaneous wind vector inside forest canopies.

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