FEASIBILITY STUDY OF AIRCRAFT MEASUREMENT OF CO2 EXCHANGE

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Abstract

Agriculture Canada, in collaboration with McGill University and the National Aeronautical Establishment's Flight Research Laboratory, has made the first measurement of carbon dioxide exchange using an airborne eddy flux system. The instrumentation system is briefly described. The 1980 flight program is outlined and the analysis and results discussed in detail. The data suggest that several passes over a given surface can provide representative average values of CO2 exchange.

Résumé

Agriculture Canada, en collaboration avec l'université McGill et l'Établissement National Aéronautique, a mesuré pour la première fois les échanges du dioxide de carbon entre le couvert végétal et l'atmosphère à l'aide d'instruments installés à bord d'un avion. Une description des instruments ainsi que des méthodes de calcul pour déterminer le flux de CO2 par la technique 'eddy correlation' sont inclus. Après l'étude du programme de vol ainsi que des résultats obtenus, il nous est permis de croire qu'une valeur moyenne et représentative du flux de CO2 peut être obtenue.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

AGR-OPA - Agriculture Canada Open-path CO_2 Analyzer

BIO-CO2 - Bedford Institute of Oceanography Open-path CO_2 Analyzer

ESRI - Engineering and Statistical Research Institute

N.A.E. - National Aeronautical Establishment

SAS - Statistical Analysis System

CO2 - carbon dioxide

C.V. - Coefficient of Variability (root mean square divided by the mean and expressed as a percentage)

DELTAW - change in wind direction

Dir - Wind direction

f - frequency (per second)

ha - hectare

h m s - Greenwich Mean Time in hours, minutes, seconds

hr - hour

IR - Infrared

m - meters (except when used with h m s)

mv - millivolts

p - probability of obtaining a higher correlation

ppm - parts per million by volume

r - Pearson-product moment simple linear correlation coefficient

RMS - root mean square (standard deviation)

S(f) - spectral or cospectral density

S.E. - standard error of a mean (RMS divided by the square root of the number of observations)

TAS - true airspeed in meters per second

U - horizontal gust velocity

w - vertical gust velocity

w' - fluctuation of w about its mean

c - mass mixing ratio of CO_2 in air

c' - fluctuation of c about its mean

ρ - density of air

ρ' - fluctuation of ρ about its mean

z - observation altitude

SKC - skewness of uncorrected CO_2 signal

CHAPTER 1 INTRODUCTION

1.0 Introduction

The burning of fossil fuels and wood, cultivation of soils, reclamation of large forested regions and the drainage of marshes and bogs are among the practices that contribute to the rising levels of carbon dioxide in the atmosphere. Only part of the released CO2 is recycled by the production of standing biomass and by the slow sedimentation of organic matter on land and in the oceans. Based on climatological models, there is much speculation as to the long-term effects of rising atmospheric CO2 concentration; however, realistic dynamic models require the continuous updating of input parameters.

Recent developments in atmospheric turbulence research from aircraft, combined with the micrometeorologist's interest in using CO2 exchange as an indicator of biomass production, have provided the tools necessary for the development of a system that can monitor, rapidly and on a large scale, the major sources and sinks of CO2. Agriculture Canada, in collaboration with the National Aeronautical Establishment (N.A.E.), has taken the initiative in developing such a system under the Crop Information Program. The system consists of N.A.E.'s Twin Otter Atmospheric Research Aircraft and a fast-response CO2 analyser, designed and built as the result of cooperation between the Engineering and Statistical Research and Land Resource Research institutes of the Department of Agriculture.

The feasibility study described in this thesis was the first attempt at using an airborne instrumentation system to estimate CO_2 exchange over various natural surfaces by the eddy correlation technique. The study involved:

(i) Preliminary testing and calibration of the aforementioned CO_2 analyzer and of a CO_2 sensor obtained on loan from the Bedford Institute of Oceanography.

(ii) Planning of a flight program in the Ottawa Region.

(iii) Evaluating instrument performance.

(iv) Analyzing aerially obtained estimates of CO_2 exchange and related data in order to determine the system's ability to detect differences in magnitudes of CO_2 exchange.

The envisioned uses of the airborne system are:

(i) Assessment of actual growth rates of crops and forests relative to potential production for possible evaluation of management practices and for yield forecasting.

(ii) Rapid evaluation of the extent of damages to economically important plant species caused by hail, drought, pests, floods or fire with possible application to crop insurance.

(iii) Mapping of large-scale CO_2 source-sink distributions for use in climatological modelling.

Since the eddy correlation technique may be used to measure the exchange of other atmospheric constituents, given appropriate instrumentation, an airborne system could also be used to monitor the transfer of various pollutants.

1.1 Scope

This feasibility study combined the efforts of staff of Agriculture Canada and of the National Aeronautical Establishment with that of the Department of Agricultural Chemistry and Physics under a contractual arrangement. The role of the author was to assist in calibrating the CO2 sensors, in planning of the flight program and, primarily, to analyze the data obtained in 1980. A large part of the work consisted in becoming familiar with the McGill Computer System and with the Statistical Analysis System package, as well as in developing programs for computation of variables and plotting.

CHAPTER 2 LITERATURE REVIEW

2.0 Introduction

In studying the effects of the physical environment on crop growth, it is important to obtain some measure of the growth rate of the crop. In field studies, the technique used to determine the growth rate should not affect the natural growing environment. One approach to determining the photosynthetic potential of a crop is to measure the rate of exchange of CO_2 between the crop canopy and the atmosphere. This idea is based on the fact that about 45% of the dry weight of a crop may be directly attributed to the uptake of carbon dioxide (Goncz, 1968). Three experimental techniques for estimating CO_2 exchange in the field have been used, all of which were originally developed in connection with the measurement of fluxes of other quantities. Based on theoretical work by Taylor, von Karman, Prandtl, Schmidt and others, Thornthwaite and Holzman (1939) developed an aerodynamic method for estimating evaporation from land and water surfaces. As this method requires knowing the wind profile and water vapour concentration gradient, observations must be made simultaneously at two or more heights. It is assumed that the shearing stress is constant with height within the boundary layer, that the wind profile is logarithmic and that the eddy diffusivity of water vapor is equal to that of momentum. In using this method for estimating CO_2 flux, one measures the gradient in CO_2 concentration instead of that of water vapour, and the diffusivity of CO_2 is assumed equal to that of momentum (Lemon, 1960).

Using the energy balance approach, Bowen (1926) developed another method for estimating evaporation. This technique (called the Bowen ratio method) requires knowledge of all energy flux components, i.e. measurements of net radiation, soil heat flux and a series of measurements at different heights of temperature and water vapour concentration. For CO_2 flux, one measures CO_2 concentration instead of water vapour and assumes that the transfer coefficients of sensible heat and CO_2 are equal (Monteith, 1973).

The above two methods have been used for measuring CO_2 exchange over a wide variety of crops (e.g. rice - Inoue *et al*., 1965; sugar beet - Monteith and Szeicz, 1960; barley - Biscoe *et al*., 1975), and have compared favourably in some cases (see e.g. Biscoe *et al*., 1975). However, both methods have been open to theoretical criticism. For example, Dyer and Hicks (1970) found that the relationship between the diffusivities of sensible heat and momentum is dependent on atmospheric stability and cannot be assumed equal under unstable conditions. Although some of the difficulties may be overcome with the help of empirically-based relations, the emphasis in boundary-layer research has shifted to studies based on eddy correlation theory.

The eddy correlation technique is based on the assumption that in the presence of a vertical gradient of a transferable quantity in turbulent flow over a source or sink of that quantity, there exists a correlation between the vertical flow component and the magnitude of the quantity. For example, in turbulent flow over a photosynthesizing crop, the air flowing vertically away from the crop contains, on the average, less CO_2 than the air replacing it from above. The flux is determined as the average cross product of vertical wind fluctuations and of changes in CO_2 concentration. The main practical result of these considerations is that in the hypothesized constant flux layer, measurements need only be made at one height; however, fast-response instrumentation is required in order to follow the most rapid fluctuations that might contribute to the flux.

Although the advantages of this technique had long been recognized, the lack of appropriate instrumentation delayed its first use until 1950. Swinbank (1951) was the first to use it in the field. With hot-wire anemometers and thermocouples, he was able to measure momentum and sensible heat flux over grassland. He noted that this technique could be "modified to apply to the eddy transfer of other properties in the lower atmosphere". Dyer (1961) developed an eddy correlation-based instrument, the evapotron, to measure sensible and latent heat flux. Desjardins (1968) used the eddy correlation technique to measure the flux of CO_2 over corn. The eddy flux of ozone over corn has been measured by Wesely _et al_. (1978). Jones and Smith (1977) used the eddy correlation technique to measure the flux of CO_2 over the ocean. There has also been interest in using this technique for measuring deposition of SO_2 in connection with the acid-rain problem (pers. comm. Desjardins).

It should be pointed out that the basic simplicity of the eddy correlation technique does not preclude inherent limitations. These limitations pertain mainly to instrument response and site requirements as discussed by Desjardins (1974) and by Garratt (1975). Nevertheless, the eddy correlation technique has added a new dimension to the study of turbulent transfer and turbulence structure in the lower atmosphere, as evidenced by recent studies (e.g. McBean, 1970; Grossman and Bean, 1973). Its main advantage is its versatility: it may be used under most atmospheric conditions, it is ideal for aircraft measurements because observations at only one height are needed, the data lend themselves to frequency analysis which allows the study of turbulence with respect to length and space scales as well as in time.

2.1. Previous Ground-Based Studies

In a short study of the feasibility of measuring CO_2 flux by the eddy correlation technique, Goncz (1968) pointed out that the requirement of rapid measurement of fluctuations in CO_2 concentration could best be fulfilled by sensors based on infrared absorption. Desjardins (1972) first measured CO2 flux using a modified Beckman IR analyzer that consisted basically of an outer chamber containing an IR source, measuring cells, optical filters and detectors. The design of this and similar instruments necessitates the use of vacuum pumps and intake tubing for flow rate adjustment. This may lead to damped fluctuations and reduced frequency response which further results in phase distortion between vertical wind observations and concentration data. Both of these effects result in underestimation of fluxes.

The work of Desjardins and others has led to the development of a new concept in the design of gas analyzers; the open path design. The design is such that the time constant of the instrument is limited only by the electronic components since the light path from source to detector is exposed to the natural airflow, thus obviating the use of pumps and tubing. Two such instruments were used in this project; the AGR-OPA described by Brach _et al._ (1981), and the BIO-CO2 described by Jones _et al._ (1978). Since these instruments measure the volume concentration of CO2, a correction for air density fluctuations must be applied. Jones and Smith (1978) pointed out that these fluctuations are due mainly to temperature fluctuations and that corrected fluxes are up to 30% lower than uncorrected ones. The correction may be greater if the boundary condition of no flux of dry air at the surface is assumed (Smith and Jones, 1979). It is evident that in measuring CO2 flux with open path analyzers, one must also measure temperature or obtain an estimate of sensible heat flux. Effects due to humidity and pressure fluctuations are usually an order of magnitude lower than those due to temperature changes and may be neglected.

In a recent study of CO2 exchange over the ocean, Sethuraman (1981) noted that there was a relationship between mean CO2 concentration and wind direction at a site in Long Beach, New York. This points to the need for assessing experimental sites with respect to surrounding sources and sinks of CO2 since low frequency changes in the mean have a direct bearing on the variability of flux estimates when the sampling time is very short, as would be the case in aircraft monitoring of small areas. This point is partly supported by Ohtaki's (1980) finding of significant power in the low end of the CO2 spectrum (over rice paddies) although no attempt was made to relate this with changes in wind direction. A study at Barrow, Alaska by Halter and Peterson (1981) also showed that changes in mean CO2 concentration could be attributed to variations in the origin of air masses flowing over the site.

2.2 Aircraft Studies

Bunker (1955) developed a method for computing the horizontal and vertical components of turbulence from the outputs of an anemometer, a vertical accelerometer and a gyroscope mounted on an airplane. Although his system was sensitive to fluctuations restricted in scale from 20 to 350 m, he was able to measure turbulent stress with some reliability. Technical improvements to aircraft systems, including the use of inertial navigation systems and Doppler radar have extended the sensitivity range to from a few meters to several kilometers, depending on the flying speed, length of flight and frequency response of the sensors (see e.g. Reinking, 1977).

Detailed descriptions of aircraft-mounted gust analysis systems are available. The NAE Twin Otter Atmospheric Research Aircraft used in this study is described by MacPherson et al. (1981). A less costly alternative is discussed in a report on flux measurement using an instrumented powered glider (Milford et al., 1979).

Perhaps the most complete and descriptive report on an investigation by aircraft of boundary layer exchange processes and turbulence structure is that by Grossman and Bean (1973). The motivation for and objectives of the study are clearly defined and followed by a straight- forward analysis of the dependence of turbulence statistics and spectra on height and stability. One of the more interesting aspects of this study was the comparison of alongwind and crosswind spectra and the conclusion that crosswind estimates tend to be less variable than alongwind estimates. The latter finding could be useful in situations where fetch requirements cannot be satisfied by alongwind runs but could be on crosswind runs, even if a crosswind run would be shorter.

In an investigation of the time and space variations of water vapour flux over Lake Ontario, McBean and Paterson (1975) demonstrated the use of Nemoto's equation for downwind displacement in the comparison of aircraft data with fixed-point observations. They found a 10 - 20% increased correlation between the two data sets after applying the advection correction.

The development of fast-response gas analyzers and airborne gust analysis systems has extended the uses of aircraft in atmospheric research. Besides the present CO2 study, measurements of ozone flux have been made (Lenschow _et al_., 1980) and the NAE Twin Otter is presently being used in pollution studies.

2.3 Spectral Analysis

Spectral analysis is a mathematical tool which has found its way into many fields of research, including engineering, physics, medicine and economics. It is basically a combination of harmonic analysis and statistics. In boundary layer studies it provides a versatile representation of turbulence structure and a basis for the study of transfer processes. The general theory and some applications are thoroughly described by Jenkins and Watts (1968). The application of spectral analysis in turbulence studies is treated by Lumley and Panofsky (1964) in a synthesis of theory and experimental results obtained prior to 1964. McBean (1970) discusses the use of spectral correlation coefficients in comparing the transfer mechanisms of heat and momentum. He notes that the use of these coefficients is often neglected in the literature whereas they can be used to compare transfer mechanisms in different frequency ranges.

The extensive use of spectral analysis in atmospheric studies is due mainly to the development of rapid computers and spectral analysis packages which easily handle the large number of computations involved in transforming data from the time to the frequency domain. When the number of observations in a typical eddy correlation data set is a power of 2, the Fast Fourier Transform Technique may be used. This technique is described by Brigham and Morrow (1967) who show that for large data sets, its use drastically reduces the number of computations involved.

Besides allowing a physical interpretation of measurements, spectral analysis is useful in assessing instrument performance and the technique of digital filtering and smoothing may be used to improve spectral estimates and to remove noise effects during analysis. McCulloch (1965) designed a computer method for determining coefficients for filters with preselected frequency response. This may be useful in overcoming the problem of contaminated data.

CHAPTER 3 THE EDDY CORRELATION TECHNIQUE

3.0 Introduction

This method of measuring fluxes in a turbulent boundary layer is based on a Reynolds separation of flow components into mean and fluctuating parts. It takes into account the fine structure of turbulent flow and is thus more closely related to the physical cause of turbulent transfer than are other methods. Before outlining the assumptions and equations of the eddy correlation technique, it is worthwhile constructing a simple visualization of the nature of flux measurement in turbulent flow conditions in the field. In order to avoid the use of too many general terms, the case of CO_2 flux over a crop is considered, as follows:

We are interested in measuring the rate of uptake of CO_2 by a crop in the field. This defines the crop as a CO_2 sink. The source is the atmosphere. In order for the crop to continue taking up CO_2, the atmospheric CO_2 must move toward the crop. In the unrealistic case of absolutely still air, transfer would take place by molecular diffusion, augmented by free convection. Usually however, the air above the crop is in turbulent motion and the transfer is due to the vertical exchange of 'large' volumes of air, a much more efficient process than molecular diffusion.

A simple picture of turbulent flow is that of an assortment of air parcels of different sizes moving in the direction of the horizontal wind and making random excursions in the vertical and in the direction horizontally perpendicular to the mean flow. The air parcels are commonly called 'eddies' and it is important that they be thought of as having lifetimes. In other words, at some point in time the turbulent flow region above the crop may be thought of as a set of closed volumes, each identifiable with respect to some transferable property, in this case with respect to CO2 concentration. An eddy's properties are assumed to remain constant for a finite length of time after which it loses its individuality by mixing with other eddies.

If we now consider a horizontal plane above the crop, in a given time interval some eddies pass through it from above and some pass through it from below due to their random excursions from the mean horizontal flow. If there is more CO2 on the average in the downward crossing eddies during the time interval, we would say that there is a net downward exchange (or flux) of CO2. In order to determine the direction and magnitude of the flux, we would need to know the CO2 content of each eddy and its direction and rate of motion in the vertical in a given time interval. Finally, if horizontal homogeneity may be assumed, these observations could be made at any point within the constant flux layer.

3.1 Equations

The basic relation for flux, according to the above considerations, is:

$$F=\overline{\rho wc} \qquad (1)$$

where, F is the flux (mass/area/time)

w is the vertical wind component

ρ is the density of air

c is the mass mixing ratio of CO_2, the overbar represents averaging with respect to time (distance for aircraft)

In practice, it is usually easier to measure fluctuations than to measure absolute values when the magnitude of the variable being observed is changing rapidly, thus it would be convenient if (1) could be reduced to a form such that the only required measurements would be of the fluctuations of the variables involved. This can be achieved by introducing Reynolds averaging and assumptions outlined below. Reynolds separation yields:

$$F=\overline{(\overline{w}+w')(\overline{\rho}+\rho')(\overline{c}+c')} \qquad (2)$$

where the overbars represent means and the primes denote fluctuations from the respective means. $\overline{w'}, \overline{\rho'}, \overline{c'}$ are all equal to 0 by definition.

Upon expansion we have a sum of eight terms which reduces to the sum,

$$F= (\overline{w}\overline{\rho}\overline{c}) + \overline{w}\overline{\rho'c'} + \overline{w'c'}\overline{\rho} + \overline{w'\rho'c} \text{ \_\_\_\_\_\_\_\_ (3)}$$

(since $\overline{w'}, \overline{\rho'}, \overline{c'}=0$)

Bakan (1978) points out that the assumption of constant flux follows from the continuity equation of a fluid as long as horizontal homogeneity has been assumed. This assumption is expressed as;

$$\frac{\partial}{\partial z}\overline{\rho w}=0 \text{ \_\_\_\_\_\_\_\_ (4)}$$

which, upon integration from height z=0 to the measuring height, z_*, gives

$$(\overline{\rho w})_{z_*} - (\overline{\rho w})_0 =0 \text{ \_\_\_\_\_\_\_\_ (5)}$$

Since the assumption of no vertical wind at the boundary is valid;

$$(\overline{\rho w})_{z_*}=0 \text{ \_\_\_\_\_\_\_\_ (6)}$$

which may be written as,

$$\overline{\rho}\overline{w} + \overline{\rho' w'}=0 \text{ \_\_\_\_\_\_\_\_ (7)}$$

By factoring with c terms in (3);

$$F= \overline{w}\overline{\rho'c'} + \overline{w'c'}\overline{\rho} \text{ \_\_\_\_\_\_\_\_ (8)}$$

and since $\overline{w}$ and $\overline{\rho'c'}$ are both small,

$$F=\overline{\rho}\overline{w'c'} \text{ \_\_\_\_\_\_\_\_ (9)}$$

an equation involving fluctuating terms and average density which may be closely estimated.

3.2 Eddy Correlation Using Open Path Analyzers

The above derivation is based on the assumption that one can measure fluctuations in the mass mixing ratio of CO_2; however, open path analyzers measure the volume concentration ρc. Let $a=\rho c$, then:

$$F = \overline{w\rho c} = \overline{wa}$$
$$= \overline{(\bar{w}+w')(\bar{a}+a')} = \bar{w}\bar{a} + \overline{w'\bar{a}} + \overline{\bar{w}a'} + \overline{w'a'}$$
$$= \bar{w}\bar{a} + \overline{w'a'} \qquad (10)$$

At this point it is assumed that $\bar{w}=0$ so that only the fluctuations enter the flux calculations. This corresponds to reducing (3) to:

$$F = \bar{\rho}(\overline{w'c'}) + \bar{c}(\overline{w'\rho'})$$ by the same assumption.

Thus, to arrive at expression (9), the term $\bar{c}(\overline{w'\rho'})$ must be subtracted from $\overline{w'a'}$. The term $\bar{c}(\overline{w'\rho'})$ is equivalent to

$$\frac{\bar{c}\bar{\rho}}{\bar{T}}\overline{w'T'} - \frac{\bar{c}\bar{\rho}}{\bar{p}}\overline{w'p'}$$ (where p is pressure and T is temperature)

(Bakan, 1978)

The term on the right is usually an order of magnitude smaller than that on the left and is neglected, thus the measured flux must be corrected by an expression involving the sensible heat flux which must therefore also be measured.

3.3 Eddy Correlation in Practice

Although the above ideas are fairly simple, there are several problems encountered in practice when using the eddy correlation technique. First of all we have made the assumption that the CO_2 flux estimates we have observed are somehow only due to the activity of the crop in the field we are flying over or that in which our instruments are set up. This would be possible only if no other sources or sinks of CO_2 other than the particular crop and the atmosphere would have an effect on the CO_2 concentration in the air moving over the crop past our sensors. Theoretically, this is equivalent to the assumption that the field is of infinite size. In practice, one tries to ensure that observations are made within the field's boundary layer, a region of turbulent flow above the crop whose characteristics are determined mainly by the nature of that field's surface and are thus related to the activity of that crop. The boundary layer results from the interaction of the advecting air and the aerodynamic characteristics of the canopy structure as well as the field's energy transfer characteristics (e.g. the distribution of heat sources and sinks). It is generally assumed that a downwind displacement of at least 100 times the measuring height will satisfy that condition (Pasquill, 1972).

It is also assumed that the system we are investigating is in steady-state in the statistical sense. This is the same as the assumption of stationarity with respect to the measured variables. Because the inputs to the system are constantly changing, the assumption of stationarity can only be valid for a limited time interval. This is perhaps one of the major problems in assessing flux estimates: if the sampling interval is too long, the assumption of stationarity is not valid, but if it is too short, the variability of the flux estimates may be too high and the estimates will be of no predictive or comparative value. This problem is particularly important in this study since there can be little control over the sampling interval on flights over small experimental sites because of the limitations imposed by minimum flying speeds and altitudes.

CHAPTER 4 THE EXPERIMENT

4.0 Introduction

This chapter summarizes the work done from the fall of 1979 to the fall of 1980. As this was a cooperative project, suitable references are given for documented work done by others. Undocumented technical details may be obtained from the organizations involved (they are mentioned in the text). This chapter includes pre-flight and post-flight testing of the two analyzers, special tests on the analyzers done in flight, selection of flight paths, summaries of actual project flights in 1980 and the preliminary analysis from the 1980 flights. A more detailed analysis is presented in a separate section in preparation for the conclusions of this first phase of the feasibility study.

4.1 Equipment

4.1.1 AGR Open-path CO2 Analyzer (AGR-OPA)

This analyzer was developed by the Engineering and Statistical Research Institute (ESRI) and the Land Resource Research Institutes of the Department of Agriculture. Its technical specifications are described by Brach et al. (1981). The instrument is based on the differential absorption by CO_2 at 4.3 and 4.7 micrometers. It has a frequency response of 10 Hz and a sensitivity of 4.1 mv/ppm. The advantage of this instrument is that, due to the open-path design, the time constant is determined only by electronic characteristics. Natural fluctuations in CO_2 concentration are not damped as they are in systems which sample through aspiration tubes; however, a certain amount of averaging is to be expected over the 0.75 meter separation between source and mirror, from which the infrared beam is reflected, for a total path length of 1.5 meters.

4.1.2 BIO Open-path CO2 Analyzer (BIO-CO2)

This instrument, a prototype developed by Barringer Research Limited (Toronto) was loaned by E.P.Jones and S.Smith, Atlantic Oceanographic Lab, Bedford Institute, Dartmouth, Nova Scotia. It is also of the open-path type and is described by Jones et al. (1978) who had modified it for use in measuring small magnitude CO_2 fluxes over the ocean. It gives a reliable response to beyond 10 Hz and has noise levels equivalent to 0.3 ppm. Its shorter path length (0.1 meter) gives it a resolution beyond that necessary for aircraft monitoring of CO_2 exchange when used at its most sensitive range. At the range used, the sensitivity is the same as that of the AGR-OPA. Use of the more sensitive range is obviated because instrumental drift would force continuous offsetting of the instrument.

4.1.3 Twin Otter Instrumentation

The Twin Otter was chosen for its safety at low altitudes and low airspeeds. Its instrumentation, which is described in MacPherson et al. (1981), consists of a nose-mounted gust boom for measuring the three components of air movement relative to the aircraft, a three-axis Doppler radar, accelerometers and rate and attitude gyros. Temperature, dew point, altitude (pressure and radio altimeter) and geographical position are also measured. Three on-board microprocessors compute the parameters in real-time.

N.A.E. made special modifications to the Twin Otter cabin roof for mounting the CO_2 sensors such that the open-paths would protrude through the aircraft's observation dome. A mounting structure to support the electronics compartments of the sensors was erected inside the cabin; however, space limitations prevented the mounting of both sensors at the same time.

4.2 Wind Tunnel Test of AGR-OPA

Since this instrument was not originally designed for the purpose of airborne monitoring of CO2, it was tested in the NRC wind tunnel to ensure its capability of withstanding flight conditions. The analyzer was mounted on a rotating platform in the wind tunnel and its output recorded at four airspeeds and two orientations. Although the analyzer's structure was strong enough to withstand projected flight speeds, there was a considerable increase in noise amplitude at the higher speeds. Visual analysis of the signal showed that the noise amplitude rose from an equivalent of 2.5 ppm at 40 m/s to 6 ppm at 55 m/s with a frequency of 0.7 to 0.8 Hz. After adjustment of the instrument by ESRI, the noise at 40 m/s was reduced in amplitude to an equivalent of 0.8 ppm.

4.3 Calibration of AGR-OPA

The calibration of the AGR-OPA was originally performed by the technicians at ESRI. This work included a calibration for sensitivity to CO2 and one to determine the effects of water vapor which would be a function of the IR absorption by water molecules at the filter wavelengths. The author recalibrated the instrument in July, 1980, before the instrument was to be given to NAE for mounting on the Twin Otter. The calibration procedure and details follow:

a) Base perimeter of calibration cap is cleaned and sealed with silicone grease to prevent leaking for readings taken at atmospheric pressure.

b) With the calibration cap on the analyzer,the chamber is vacuumed and then flushed with an inert gas (N_2). Since the vacuum pump cannot give a complete vacuum, this procedure is repeated three times to ensure that the remaining CO_2 concentration at atmospheric pressure is less than 0.01 ppm.

c) Each time the chamber is filled with nitrogen, a reading is taken as a zero ppm reference. The stability of the zero across flushings is used as an indication that the remaining CO_2 is negligible.

d) The tank is flushed one more time and then filled to atmospheric pressure with a mixture of CO_2 and N_2 of known CO_2 concentration. A reading is taken at this point.

e) Steps b) to d) are repeated using other standard mixtures.

Since a run with a given standard took about two hours to perform (due to vacuuming time), it was necessary to correct for zero drift. This was done by taking the difference, D_i, between the zero reading and that at atmospheric for each standard separately. These differences were then used for interstandard comparisons. The differences between pairs of D_i ($i=1,\ldots, 5$), where i denotes the standard, were thus the output equivalents to the difference in concentration for each pair of standards. The results of these comparisons are presented in Table 4.1 . As can be seen, the calculated sensitivities were quite variable. This was assumed to be due to incorrect labeling or analysis of the commercial standards, particularly for tanks 4 and 5. The average sensitivity resulting from comparisons not involving tanks 4 and 5 was 4.1 mv/ppm (comparisons I, II, V). This was assumed to be the correct sensitivity of the instrument. From this it was deduced that tanks 4 and 5 both had concentrations of 360 ppm (corrected to 348 ppm for incomplete vaccuuming of flushing gas). Using this concentration for tanks 4 and 5, comparisons III,VI and VIII, involving tank 4, yielded sensitivities of 4.114, 4.097 and 4.1 mv/ppm, respectively. Comparisons IV,VII,IX involving tank 5 yielded sensitivities of 4.1, 4.08 and 4.16 mv/ppm, respectively, using the corrected concentration. In order to validate the above investigation, tanks 4 and 5 were both checked on a Uras2 analyzer and gave the same reading. That the actual concentration of CO_2 was in fact higher than that stated by the supplier agrees with a study by Bate et al.(1969) on commercial standards. Thus the accepted sensitivity of the instrument was 4.1 mv/ppm.

4.4 BIO-CO_2 Wind Tunnel Test

The BIO-CO_2 was received from the Bedford Institute of Oceanography in July, 1980. It was immediately tested in the

Table 4.1: Intertank Comparisons for Calibration of AGR-OPA.

Comparison	Tank	Label Concentrations (ppm)	Corrected Concentrations (ppm)	Difference (mv)	Estimated Sensitivity (mv/ppm)
I	2 1	301.00 280.75	287.96 270.46	73	4.171
II	3 2	347.00 301.00	333.10 287.96	183	4.054
III	4 3	355.00 347.00	343.20 333.10	63	6.240 (3.91)
IV	3 1	347.00 280.75	333.10 270.46	256	4.089
V	4 1	355.00 280.75	343.20 270.46	319	4.385 (4.05)
VI	4 2	355.00 301.00	343.20 287.96	246	4.450 (4.02)
VII	5 1	351.40 280.75	340.86 270.46	323	4.590 (4.10)
VIII	5 2	351.40 (360) 301.00	349.20 287.96	250	(4.08)
IX	5 3	351.40 (360) 347.00	349.20 333.10	67	(4.16)
X	5 4	351.40 (360) 355.00 (360)	Same response on URAS-2 analyzer.		

(360) is the assumed concentration of tanks four and five. Figures computed with this concentration are between parentheses.

NRC wind tunnel. Visible vibrations at 40 m/s brought an abrupt end to this testing. NAE offered to construct an aerodynamic casing for the protruding nose of the instrument in order to reduce the vibrations. This was done and a test flight followed by an x-ray stress test showed that the analyzer was indeed flightworthy (all done by NAE). This instrument could not be calibrated to our satisfaction before the August test flights because of time restrictions and because of the structural characteristics of this analyzer. It was assumed that the sensitivity published by Jones *et al.* (1978), was correct.

4.5 Testing Effects of Aircraft Inputs

The sometime erratic behaviour of the BIO-CO2 on the first two flights using this instrument was investigated. A special test flight was performed to determine the effects of changes in aircraft orientation on the BIO-CO2. It was found that the BIO-CO2 was particularly sensitive to yawing disturbances and somewhat affected by pitch changes. A similar test performed on the AGR-OPA showed no effect due to aircraft inputs. (MacPherson, 1980).

4.6 Selection of Flight Paths

4.6.1 Preparation

Due to budget restrictions and prior commitments of N.A.E. it was necessary that project flights be carried out at the end of the growing season and in the Ottawa Region. This area is not ideal for testing of the instrumentation system for various reasons:

1) There are few large homogeneous stretches of particular kinds of vegetation.

2) Flat terrain tends to run East to west along the Rideau and the St.Lawrence valleys whereas power lines run North to South. This forced changes in altitude along some flight tracks.

3) Cultivated land is made up of small fields usually bordered or interrupted by forested areas. This makes it difficult to satisfy the criterion of adequate fetch required in boundary layer work.

Through the cooperation of Mr. George Jackson of the Ontario Ministry of Agriculture and Food and two field survey crews in Kemptville and Alexandria, we were able to determine what areas would best satisfy the fetch and homogeneity requirements of the eddy correlation technique. They provided us with Agricultural Land Use Systems Maps for the

Ottawa region. These were the results of field to field surveys conducted during the summers of 1979 and 1980, in the following townships: Winchester, Finch, Cambridge, Caledonia, Russell, Cumberland, Clarence, No. Plantagenet, So. Plantagenet, West Hawkesbury.

Fields were grouped into Agricultural Systems. For example, areas consisting of at least 75% corn with a mixture of hay, small grain and pasture, were designated "monoculture. Hay systems are predominantly hay fields with some small grain and a maximum of 30% corn field area. Forested, reforested, bog and built up areas were also mapped. A reconnaissance flight was undertaken on July 8, 1980, in a Cessna piloted by Dr. Hueckel of Macdonald College. We were able to verify the information provided by the maps and to find the larger corn fields in the region.

4.6.2 Flight Paths

Five different flight paths were attempted during the time the aircraft was available. These paths were flown first with the BIO-CO2 and then with the AGR-OPA (see Table 5.2) at altitudes averaging about 40 m. The paths were;

A) Long, straight flights over a mixture of vegetation types, including the Alfred Spruce Bog.

B) Repeated passes across a large corn field located just to the East side of Russell Airport; three passes were made at each of three altitudes.

C) Repeated passes over the Larose forest; one round trip at each of three altitudes.

D) Repeated passes over Lac Deschênes at different speeds to assess the background noise of the instruments and to determine the effect of airspeed on the CO2 analyzers.

E) An investigation of CO2 levels around Ottawa. These runs included one at each of three altitudes upwind of the city, three more runs downwind and two runs over the city. Passes over the city were at the minimum allowable altitude of 500m.

Flights of type A) were flown in order to determine the ease or difficulty with which one could relate flux values to local land use. For ease of flying, they were set out as straight paths; however, there were many forced changes in altitude on these paths because of power lines. These might have been avoided if they had been shown on navigational maps.

Flight types B), C) and D) were essentially "calibrating" tests. Corn and forest are two types of vegetation which have received attention in fixed-point studies of CO2 exchange, are plentiful in the immediate vicinity of Ottawa, and would be expected to exhibit differences in rates of CO2 uptake that the system could detect. Our intention was to determine the credibility of our flux measurements by comparing them to typical values for CO2 exchange over forest and corn. Exchange over Lac Deschênes could reasonably be expected to be at least an order of magnitude smaller than the flux over forest and corn.

CHAPTER 5 ANALYSIS

5.0 Data Provided by N.A.E.

The author was provided with the following:

(i) Analog traces of output from the CO_2 analyzers with analog representations of computed vertical winds. Time and event marks were also provided.

(ii) Flight track plots for each of the nine flights.

(iii) Printed output of one-second averages of recorded parameters including means and RMS values for gust data and CO_2 data for each event period (run or flight segment).

(iv) Stereo cassette voice tapes including intercom comments made by the flight crew with voice-synthesized time every minute.

(v) 9-track tapes containing the flight data.

The data provided on the tapes issue from Track 2 of the Twin Otter's Nagra recording system. All sensor signals are sampled at a rate of 16 per second, low-pass filtered with cutoff at 5 Hz to prevent aliasing (McPherson *et al.*,1981), and gust data are then computed on-board in real time. A list of the parameters provided on the tape is presented in Table 5.1. Application of bias and scaling factors, according to the equation provided at the bottom of that table, yields the ranges of the parameters in the supplied units.

5.1 Programs Used in Analysis

A Fortran program, written by the author,was used to read the tape data and to compute fluxes. The program also modified the tape data as outlined in the following paragraphs.

Since the CO2 analyzers used produce a signal proportional to the number of CO2 molecules per unit volume, changes in air density must be accounted for. A correction was applied to the 1980 data by adjusting the CO2 signal for temperature fluctuations using the equivalence of 1 ppm CO2 equal to 1 degree Kelvin, using the ideal gas law and assuming a background CO2 concentration of 300 ppm. The initial temperature for a given run was used as a reference. The first CO2 value was unchanged. Subsequent values depended on the difference between the corresponding temperature and the reference temperataure. If the difference indicated a temperature increase (decrease in density), the CO2 concentration was increased according to the above. A CO2 flux based on the uncorrected CO2 signal was also computed.

Table 5.1: List of Variables and Bias and Scaling Factors

CHANNEL	PARAMETER	UNITS	BIAS	SCALE	RANGE
0	synch GMT				
1	event		0	1	
2 *	GMT	hrs	0	1	
3 *	GMT	min	0	1	
4 *	GMT	sec	0	1	
5	LAT	deg	0	1	
6	LAT	min	300	10	
7	LONG	deg	0	1	
8	LONG	min	300	10	
9	RANGE	n mi	511	10	0-102
10	BEARING	deg	360	2	0-360
11	HEADING	deg	360	2	0-360
12 *	WIND DIR	deg	360	2	0-360
13 *	WIND SPD	m/s	511	10	0-102
14	PRESS(st)	mb	530	1	20-1640
15 *	TAS	m/s	511	10	0-102
16 *	R ALT	m	511	1	
17	AN 2 (CO2)	volts	0	51.1	+/-10
18 *	Uge	m/s	0	10	+/-50
19 *	Vge	m/s	0	10	+/-50
20 *	Wge	m/s	0	10	+/-50
21 *	TEMP	deg C	0	10	+/-50
22	unused constant voltage signal				
23	DEW PT	deg C	0	10	+/-50
24 *	AN 1 (CO2)	volts	0	51.1	+/-20
25	Ug	m/s	0	10	+/-50
26	Vg	m/s	0	10	+/-50
27	Wg	m/s	0	10	+/-50
28	Umix	m/s	511	10	0-102
29	Vmix	m/s	0	10	+/-50
30	Wmix	m/s	0	10	+/-50
31	unused constant voltage signal				

* used in analysis
NOTE: conversion from bits: eng. units =(volts + bias)/scale

(This table was adapted from MacPherson, 1980)

The flux program also advanced the CO_2 signal by two data slices (2/16 second) in order to account for the physical separation (8 meters) between the CO_2 sensor and the gust probe. A true airspeed of 60 m/s was assumed.

The horizontal gust component, which was required for computation of the momentum flux, was supplied in earth-fixed axes (ie. North-South). The lateral component was also in earth-fixed axes (East-West). The flux program changed the horizontal component from earth-fixed axes to axes representing the direction of the corresponding gust according to the formula;

$$U=(Uge^2 + Vge^2)^{1/2}$$ where Uge and Vge were the supplied gust components

Another program, written in Fortran, was used to plot the time histories of fluxes for each run. The computation of run statistics, spectral and cospectral coefficients, correlations, and plotting of spectra and cospectra were all done using the SAS (Statistical Analysis System) facility which is available on the McGill computer system.

Although the SAS procedures used were expensive, considerable programming time was saved by their use. SAS is a very flexible application package which offers the following:

(i) A variety of procedures for statistical data analysis.

(ii) Procedures for subsetting and regrouping data sets.

(iii) Programming language for transformation of data, creation of new variables and deletion of unwanted data.

5.2 Review of Test Flights

The following review of the 1980 test flights is made in order to clarify the reasons for basing the evaluation of the airborne instrumentation system on the data sets described in section 5.3. A general summary of the nine test flights is presented in Table 5.2.

Flight AG-01 was a reconnaissance flight at a large corn field just East of Russell Airport (slightly North of Embrun). Since this had previously been chosen as an experimental site for its size, it remained to find a safe approach and depart flight line. Thus, only three runs were made on that day. True air speed was 71-77m/s, yielding an extremely noisy CO2 signal. The computed fluxes on the three runs were, -25.5, -77.1, and -10.6 kg CO2 per ha per hr. These fluxes were based on detrended signals of CO2 and vertical wind . An attempt at rereading this data in order to calculate the fluxes with mean removed only, met with failure. The tape had apparently deteriorated and the data

Table 5.2: Flight Summary – Agriculture CO2 Project – 1980

Flight	Date 1980	CO2 Analyzer	GMT Takeoff	GMT Land	Weather	Temp (Deg C)	Wind Dir/ms^{-1}	Comments
AG-01	08/11	BIO-CO2	1525	1558	2/10 cumulus some cirrus	23	ENE/3 over field	Runs flown at high speed (70 m/s) therefore CO2 signal very noisy.
AG-02	08/13	BIO-CO2	1616	1726	4/10 cumulus 1/10 alto cu 1/10 cirrus	21	Light and variable	Runs flown at high speed again so CO2 signal noisy. Unexpected power lines forced altitude change.
AG-03	08/18	BIO-CO2	1804	1933	1/10 cumulus 6/10 alto cu	26	ESE/4	Analyzer steadier, noisy at start of runs then quieting down.
AG-04	08/20	BIO-CO2	1954	2055	2/10 cumulus	24	N/A (data not usable)	Rate gyro power supply failure; wind and gust data unusable.
AG-05	08/22	BIO-CO2	1409	1502	1/10 cumulus 2/10 cirrus	21	E/2 stronger at east end	Long runs over variable terrain; changes in altitude, few long homogeneous stretches.
AG-06	08/28	AGR-OPA	1512	1621	2/10 cumulus 1/10 cirrus	19	E/3 over water ENE/5 at 1000 ft	Analyzer fairly steady. Noise increases with speed.
AG-07	08/28	AGR-OPA	1859	2035	1/10 cumulus	22	NE/2	Analyzer noisier; died on last run.
AG-08	09/04	AGR-OPA	1519	1611	clear, hazy	19	ESE/3-5	Analyzer very noisy.
AG-09	09/08	AGR-OPA	1456	1547	clear, good turbulence	17	NW/5-8	Analyzer noise and spikes.

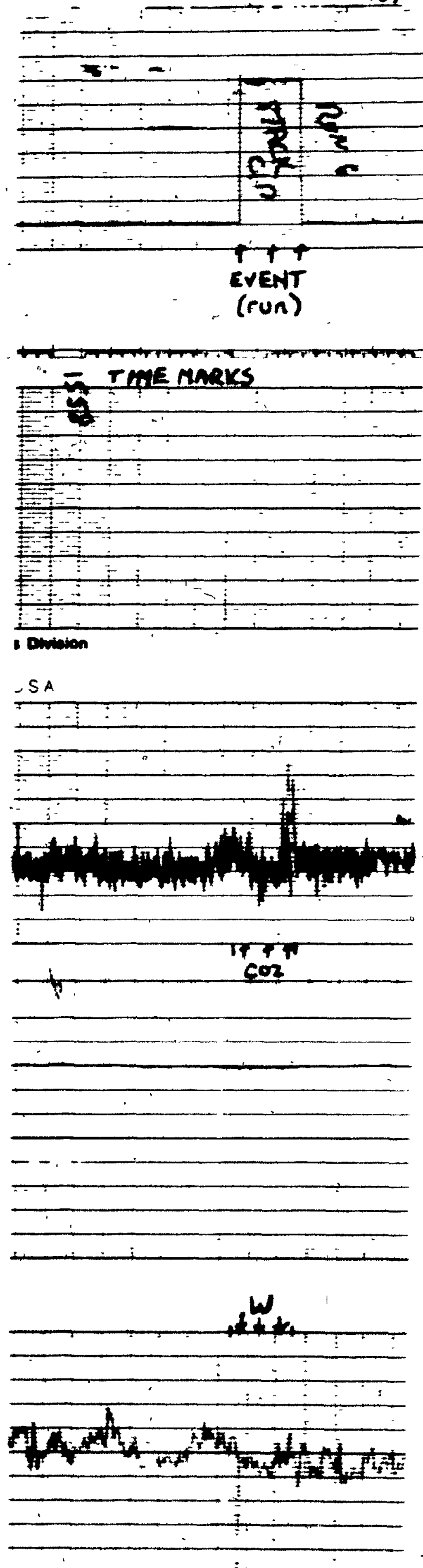
were not recoverable.

Flights AG-02, AG-05, AG-08, and AG-09 were TYPE A, long straight legs over agricultural and marginal land. The CO2 signal was very noisy on AG-02 and AG-08, and all of these flights included forced changes in altitude due to power lines. These cross-country type flights never included extended runs over homogeneous vegetation. This would make calculated fluxes difficult to interpret. Moreover, there were no repeated runs over any part of the flight path so that no measure of error could be obtained.

Failure of the power supply to one of the rate gyros during AG-04, resulted in artificial gust data. Fluxes could not be calculated for that flight. Unfortunately, the runs were over Lac Deschenes and were to provide data over water for a noise versus speed analysis on the BIO-CO2 sensor. The absence of this test results in an imbalance of the overall analysis since the noise analysis could only be performed on the AGR-OPA.

In order to ensure that the AGR-OPA was indeed sensitive to changes in CO2 and was not producing a signal dependent only on airspeed, one pass (lasting approx. 22 seconds) was flown through an industrial smokestack plume. The signal is shown in figure 5.1. A flux of +233.0 KgCO2/ha/hr was obtained for this segment, indicating that the factory was indeed a source of CO2.

Figure 5.1 Chart recorder traces of CO2 and vertical wind over industrial smokestack. Voltage scale not noted.



Having considered the overall quality of data and experimental technique in terms of the objectives of the CO_2 project and of the constraints imposed by eddy correlation theory, several criteria were set for purposes of initial data reduction. These were:

(i) Flight segments which were not repeated (replicated) should not enter enter the analysis. This criterion is understandable in that mean fluxes of repeated runs exhibit substantial variability as will be seen later.

(ii) Runs for which the CO_2 and/or vertical wind signal were particularly noisy (RMS values exceeding the norm by a factor of three or more) or unrealistic should be excluded since fluxes calculated from 'bad' data cannot be treated with any degree of confidence without applying smoothing and filtering techniques. However, these techniques are applicable when either the true signal is well-known or when the frequency range of noise can be defined.

(iii) Runs of less than 20 seconds over homogeneous vegetation should not be considered. This criterion was established as a result of inspection of cumulative flux plots which all showed large fluctuations in the cumulative mean flux over the first 10 to 20 seconds of the runs.

The above decisions effectively meant that of the nine test flights made, AG-01, AG-02, AG-04, AG-05, AG-08 and AG-09 would not enter the final analysis. Some runs from the remaining flights were also left out of the overall analysis as per criterion (ii).

The final data were grouped according to instrument used, then subsetted with respect to surface type. This yielded a corn data set for each instrument, a water set for the AGR-OPA, and a forest data set for each instrument. Thus, five data sets are considered in the analysis. While processing the data, it was found that too much computer space was needed to compute spectra and cospectra for the forest data sets. They were each split into two sets of nine runs.

5.3 Description of Data Sets Analyzed

The following data sets were chosen for evaluation of the potential of the airborne system to determine rates of exchange of CO2 between the atmosphere and terrestrial surfaces.

DS1 - Flight AG-06; Aug. 28, 1980 (AGR-OPA) Corn Field north of Embrun:

This flight consisted of nine runs over a corn field. Three runs were made at each of three altitudes. The purpose of these runs was to attempt to establish the variability of the measured fluxes at a given altitude and to establish an optimum measuring height, if such a thing exists within the supposed boundary layer. Some results are presented in Table 5.3.

DS2 - Flight AG-03; Aug.18,1980 (BIO-CO2) Corn Field north of Embrun:

Same purpose as AG-06, but with BIO sensor. Results are presented in Table 5.4.

DS3 - Flight AG-07; Aug.28,1980 (AGR-OPA) Larose Forest:

Flights of three minute duration at three different altitudes over the same path. Each three-minute flight is divided into three one- minute runs (segments) for analysis, making a total of eighteen runs. Results are presented in Tables 5.5a,b.

DS4 - Flight AG-03; Aug.18, 1980 (BIO-CO2) Larose Forest:

Same as DS3 but with BIO-CO2 and only two altitudes investigated. (appx. 50m and appx. 65m). Results are shown in Tables 5.6a,b.

DS5 - Flight AG-06; Aug.28,1980 (AGR-OPA) Lac Deschenes:

Three runs of approximately three-minute duration, one at each of three airspeeds (53, 64, 74 m/s) were made in order to evaluate the effect of airspeed on sensor output. The runs during which the CO2 sensor was stable were to provide a 'calibration' for the instrumentation system since the lake is no more than a weak source or sink of CO2 in comparison to vegetated land surfaces. Results from these runs are presented in Table 5.7.

From these data sets, five runs were deleted. Run 3 from DS4 was deleted because spikes were found on the analog traces of all signals. These were caused by an electronic malfunction of the recording system according to J.I.McPherson of N.A.E.. Runs 1 and 16 from that data set were also deleted because the CO2 sensor had drifted offscale during those runs and required offsetting. The offset was reflected in RMS values three times the norm for the BIO-CO2 signal. Runs 1 and 7 from DS2 were deleted for the same reason.

5.4 Overview of Analysis

There were several difficulties encountered in analyzing the 1980 data. There were certain factors, known to have bearing on photosynthetic activity, that the instrumentation system could not measure. Soil moisture conditions and insolation are the most obvious of these. Runs over a given surface were not properly randomized with respect to altitude, as will be seen later. Two factors that could be related to the magnitude of the CO2 flux estimates are confounded. These are: day and CO2 sensor used. Differences in CO2 exchange estimates could be due to differences in meteorological and soil conditions on the two days or could be due to instrument sensitivity or frequency response. In an attempt to arrive at a fair evaluation of the airborne system

Table 5.3: Results from AG-07. Embrun Corn Field.

Run No.	Start Time h m s	Duration s	Alt. m	TAS m/s	CO2 Flux Kg/ha/h	CO2 Flux Corrected Kg/ha/h	Sensible Heat Flux W/m2	Momentum Flux N/m2	Mean Wind m/s
1	19 12 46	29	25	58	-29.4	-27.8	28	-.152	3.4
2	19 16 24	25	22	57	-02.4	-02.4	1	-.218	1.8
3	19 20 17	22	22	59	-21.8	-20.5	24	.016	3.3
4	19 24 28	28	29	58	-50.4	-48.1	42	-.053	3.0
5	19 28 04	28	29	59	-20.7	-19.8	15	-.029	3.6
6	19 31 52	28	30	59	-48.8	-44.9	7	-.024	3.4
7	19 35 44	28	39	58	-50.8	-47.1	66	.022	3.5
8	19 39 20	28	41	57	-37.2	-33.8	60	.049	3.7
9	19 42 57	27	40	60	-62.6	-58.2	79	.001	3.3

Table 5.4: Results from AG-03. Embrun Corn Field.

Run No.	Start Time h m s	Duration s	Alt. m	TAS m/s	CO2 Flux Kg/ha/h	CO2 Flux Corrected Kg/ha/h	Sensible Heat Flux W/m^2	Momentum Flux N/m^2	Mean Wind m/s
1	18 14 55	38	44	61	+10.7	+11.6	16	-.174	3.0
2	18 17 45	29	44	61	-31.7	-27.8	66	.261	3.1
3	18 20 09	29	43	59	-08.9	-05.9	53	.020	2.6
4	18 22 48	30	25	61	-29.7	-23.6	110	-.384	2.0
5	18 25 40	26	25	64	-08.7	-07.2	27	-.276	1.8
6	18 28 34	26	25	63	-09.4	-07.4	36	-.193	3.1
7	18 31 33	33	33	61	+55.5	+57.5	36	-.118	3.2
8	18 34 43	28	33	60	-11.0	-10.3	14	-.193	3.0
9	18 37 47	27	33	60	-02.1	-01.8	4	-.108	1.9

Table 5.5a: Results from AG-07. Larose Forest (west to east).

Run No.	Start Time h m s	Duration s	Alt. m	TAS m/s	CO_2 Flux Kg/ha/h	CO_2 Flux Corrected Kg/ha/h	Sensible Heat Flux W/m^2	Momentum Flux N/m^2	Mean Wind m/s
1	19 48 33	60	42	58	-22.1	-19.7	43	.113	2.0
2	19 49 33	60	38	57	-09.3	-07.8	27	-.010	1.6
3	19 50 33	60	40	58	-11.6	-08.0	64	-.055	1.6
4	20 00 52	60	53	57	-00.7	-00.5	5	-.080	2.5
5	20 01 52	60	57	56	-24.9	-21.9	55	-.133	1.9
6	20 02 52	60	54	59	-21.9	-20.7	22	-.121	1.4
7	20 13 46	60	68	57	-31.3	-28.2	56	.040	1.1
8	20 14 46	60	66	58	-09.3	-05.4	69	-.101	2.4
9	20 15 46	60	66	57	-19.5	-18.0	27	-.093	1.8

Table 5.5b: Results from AG-07. Larose Forest (east to west).

Run No.	Start Time h m s	Duration s	Alt. m	TAS m/s	CO2 Flux Kg/ha/h	CO2 Flux Corrected Kg/ha/h	Sensible Heat Flux W/m2	Momentum Flux N/m2	Mean Wind m/s
10	19 55 27	60	43	58	-13.4	-11.8	29	-.070	1.9
11	19 56 27	60	40	58	-11.1	-07.6	64	-.081	2.7
12	19 57 28	60	38	57	-16.1	-15.9	5	-.026	2.0
13	20 08 13	60	52	58	-16.5	-13.8	49	.037	1.3
14	20 09 13	60	55	56	-17.5	-15.6	34	-.081	2.5
15	20 10 13	60	51	56	-17.9	-15.8	38	-.031	1.4
16	20 20 19	60	72	58	-17.7	-14.7	52	-.204	2.4
17	20 21 19	60	65	57	-08.9	-07.3	28	.006	3.0
18	20 22 19	60	62	58	-26.8	-23.8	53	.004	1.6

Table 5.6a: Results from AG-03. Larose Forest (west to east).

Run No.	Start Time h m s	Duration s	Alt. m	TAS m/s	CO_2 Flux Kg/ha/h	CO_2 Flux Corrected Kg/ha/h	Sensible Heat Flux W/m^2	Momentum Flux N/m^2	Mean Wind m/s
1	18 47 18	60	52	62	-38.7	-32.4	114	-.312	5.4
2	18 48 18	60	48	57	-14.1	-10.6	64	-.230	3.5
3	18 49 18	60	54	59	-41.0	-245.1	-3642	3.660	3.5
4	18 58 13	60	63	59	-00.6	-00.4	4	-.099	3.9
5	18 59 13	60	65	59	-12.6	-07.6	89	-.219	4.5
6	19 00 13	60	65	60	-12.1	-07.0	91	-.253	4.0
7	19 14 03	60	48	60	-05.9	-05.5	8	-.315	4.0
8	19 15 03	60	54	60	-13.2	-05.7	135	-.399	4.2
9	19 16 03	60	53	61	-18.0	-09.3	154	-.428	4.5

Table 5.6b: Results from AG-03. Larose Forest (east to west).

Run No.	Start Time h m s	Duration s	Alt. m	TAS m/s	CO2 Flux Kg/ha/h	CO2 Flux Corrected Kg/ha/h	Sensible Heat Flux W/m^2	Momentum Flux N/m^2	Mean Wind m/s
10	18 52 10	60	52	59	-28.6	-19.8	157	-.327	4.4
11	18 53 10	60	52	60	-10.6	-03.3	131	-.346	5.0
12	18 54 10	60	52	61	-06.0	+00.1	109	-.321	4.0
13	19 02 56	60	64	57	-17.7	-12.3	97	-.448	4.8
14	19 03 56	60	65	61	-35.2	-25.4	175	-.742	4.4
15	19 04 56	60	67	60	-03.8	+01.2	89	-.131	4.3
16	19 09 01	60	64	62	-10.1	-04.5	100	-.253	4.5
17	19 10 01	60	65	58	-14.4	-05.8	154	-.721	4.3
18	19 11 01	60	64	57	-02.6	-00.6	36	-.150	4.0

Table 5.7: Results from AG-07. Lac Deschenes.

Run No.	Start Time h m s	Duration s	Alt. m	TAS m/s	CO2 Flux Kg/ha/h	CO2 Flux Corrected Kg/ha/h	Sensible Heat Flux W/m^2	Momentum Flux N/m^2	Mean Wind m/s
1	15 25 43	60	31	53	-00.1	+00.2	25	.017	2.8
2	15 26 43	60	28	53	-17.4	-17.1	18	-.168	3.1
3	15 27 43	60	29	53	+04.7	+04.9	15	.001	3.2
4	15 29 40	60	29	64	+43.0	+43.7	13	.112	4.3
5	15 30 40	60	28	64	-147.4	-144.5	25	-.744	4.4
6	15 31 40	50	26	64	+44.2	+40.1	33	-.254	4.4
7	15 40 00	60	27	74	+04.2	+03.9	29	.597	3.3
8	15 41 00	60	29	73	-03.8	-09.9	58	-.126	3.3
9	15 42 00	40	28	74	-04.6	-03.6	11	-.022	3.3

through interpretation of the given data, the following analyses and graphical representations were made:

(i) Analysis of the effects of true airspeed on noise levels of the AGR-OPA in order to determine whether this could affect estimates of CO2 flux.

(ii) Correlation analysis on the BIO-CO2 data to determine whether true airspeed, sensor noise and CO2 flux could be related.

(iii) Computation of means, RMS values and skewness for use in setting criteria for the deletion of runs from the analysis and to be used in correlation analysis to aid interpretation of the data. The Pearson-product-moment simple linear correlation coefficient was used and the 0.10 level of significance was assumed. (RMS and skewness values used in correlation analysis are presented in Appendix B).

(iv) Testing of differences between mean CO2 fluxes using the Student's t-test for independent samples. The 0.05 level of significance was assumed.

(v) Plotting of cumulative fluxes to show the time history of fluxes in order to provide an indication of the validity of the steady-state assumption for each run. Plots of accumulating changes in wind direction were superimposed on the cumulative flux plots because it was suspected that changes in wind direction could have bearing on the sensed fluxes. A sustained change in wind direction could be representative of a change in mean air flow and/or CO2 concentration.

(vi) Plotting of average spectra and cospectra to help in the interpretation of data. These plots indicated the important scales of transfer and were used mainly for general comparisons with information gleaned from the literature.

The dependent axes on the cumulative flux plots for momentum flux, sensible heat flux and CO2 flux presented in Appendix C, are represented by the function;

$$\sum_{i=1}^{n} \frac{\left(A_i' \ w_i'\right)}{n}$$

where,

A_i' represents a fluctuation

in U for momentum flux,

in T for sensible heat flux, and

in temperature corrected CO2 for CO2 flux

Logarithm of wavelength was chosen for the independent axis of the spectral and cospectral plots since a direct relation to space scale is easily made. Frequency-weighted normalized densities were used for the dependent axes because they show the relative contribution to variance (spectra) or transfer (cospectra) in the logarithmic x-axis intervals, as can be shown by integrating with respect to natural logarithm of frequency. These plots are presented in Appendix D.

It should be noted that the spectral density estimates computed by SAS procedure SPECTRA were obtained through application of a weighted moving average, with symmetrical weights in the ratio 1:2:3:2:1, on the periodogram. This function acts as a low-pass filter, attenuating high frequency oscillations (eddies). The frequency response function for symmetrically weighted moving averages is given in Panofsky and Brier (1958).

CHAPTER 6 RESULTS AND DISCUSSION

6.0 Noise-Airspeed-Flux Relationships

Nine runs over Lac Deschenes, at three different airspeeds and at the same altitude, showed that noise levels of the AGR-OPA increased with true airspeed. The main problem was to determine whether the higher noise levels could contribute to estimates of CO_2 flux. The average spectra of the uncorrected CO_2 signal at three airspeeds (fig. 6.1) showed that noise levels were related to a frequency corresponding to a space scale of about 1.55 (log meter) as represented by the peaks at that scale. Higher frequency noise may have been present but would not show up in the spectra due to the filtering applied to the raw data by N.A.E and to the smoothing of spectral estimates discussed in the preceding section. The vertical wind spectra for these runs are peaked at longer wavelengths (fig. 6.2). The noise would therefore not be expected to contribute significantly to the estimated flux as demonstrated by the low relative contribution to the area under the cospectrum at the 1.55 scale (fig. 6.3). The frequency domain interpretation is supported by the low correlation between CO_2 flux and true airspeed for the runs at Lac Deschenes ($r=-0.40, p=0.28$). The CO_2 fluxes over corn and forest were not related to the airspeed-dependent RMS of CO_2 (see Appendix A). Finally, significant differences between mean

FIGURE 6.1

AVERAGE SPECTRA OF CO2 AT THREE AIRSPEEDS OVER LAC DESCHÊNES

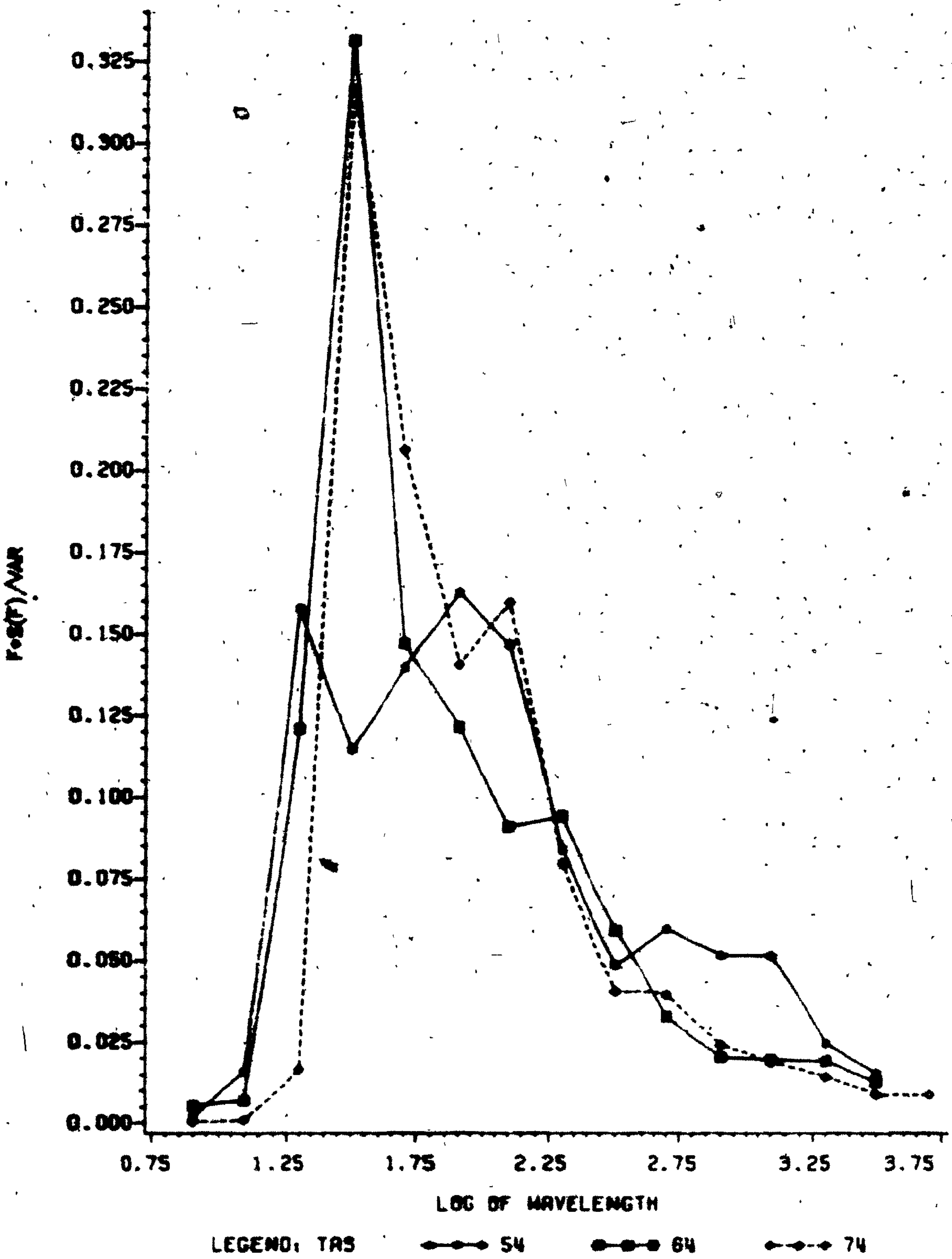


FIGURE 6.2

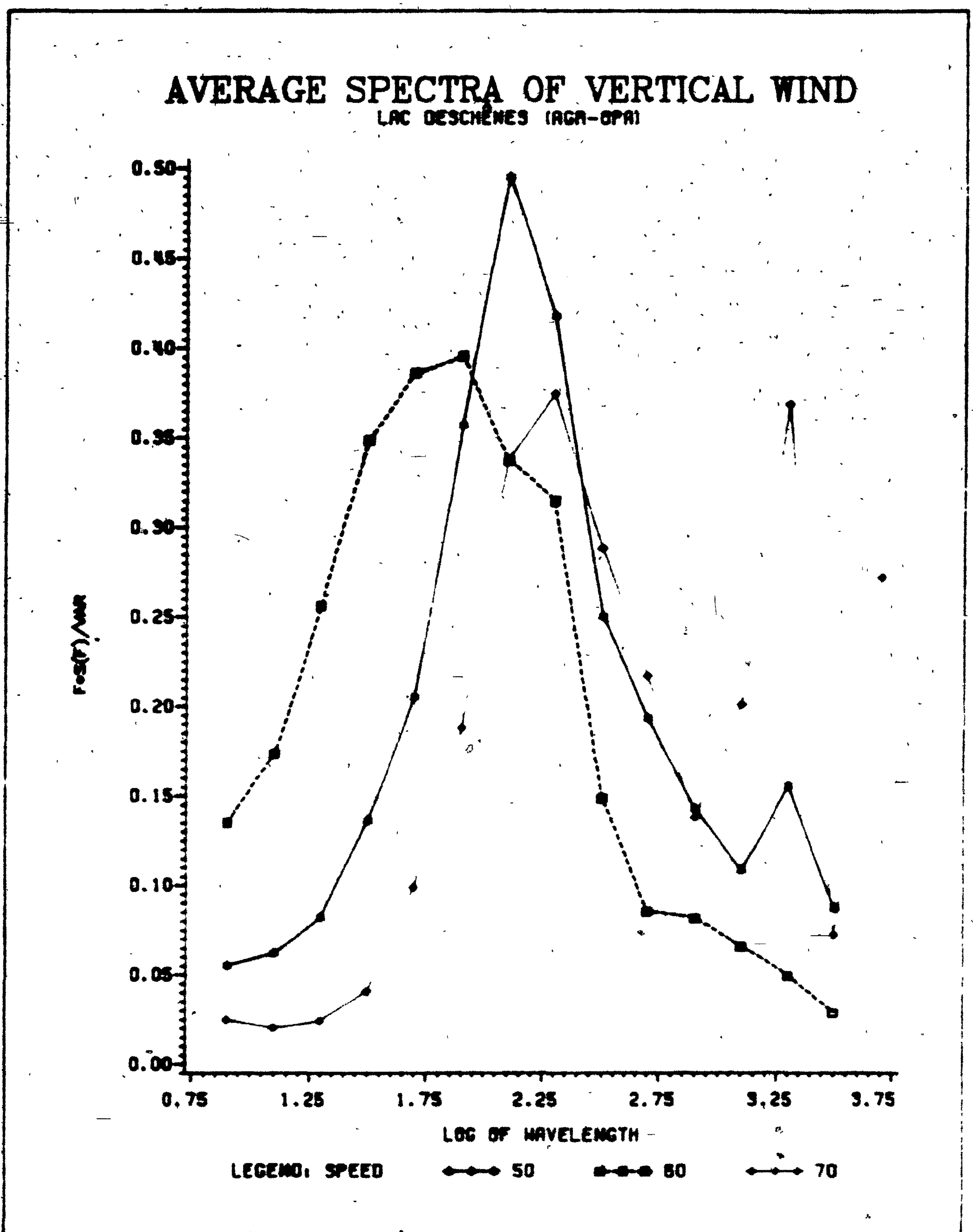
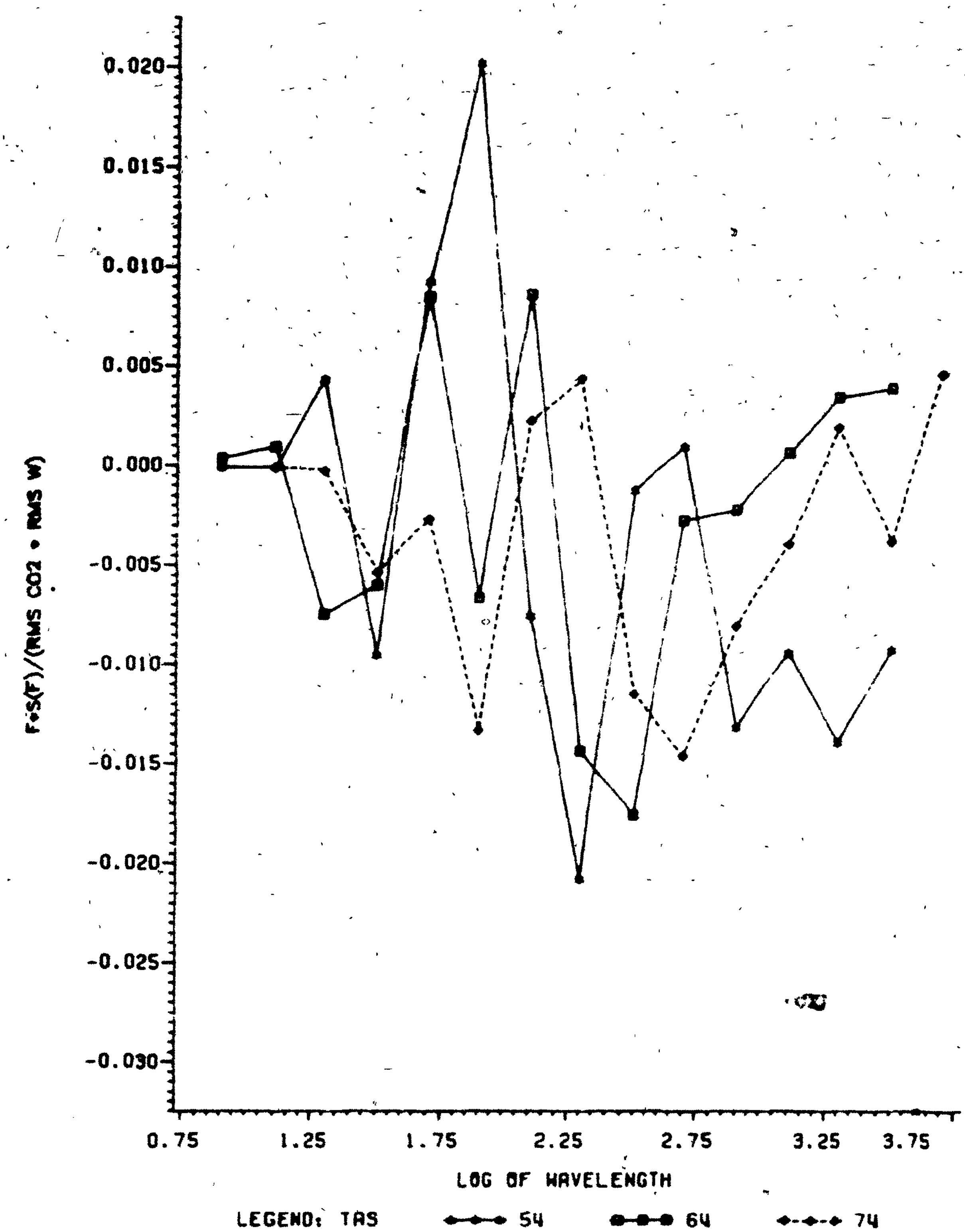

AVERAGE SPECTRA OF VERTICAL WIND
LAC DESCHÊNES (AGA-OPA)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
F*S(F)/VAR
0.75
1.25
1.75
2.25
2.75
3.25
3.75
LOG OF WAVELENGTH
LEGEND: SPEED
50
60
70

FIGURE 6.3

AVERAGE COSPECTRA FOR CO2 TRANSFER OVER LAC DESCHÊNES



CO_2 fluxes (both corrected and uncorrected) were found between corn, forest and water on the same day with the AGR-OPA (see section 6.1).

On the basis of the above information, one would conclude that estimates of CO_2 flux are not related to true airspeed for the AGR-OPA. Since it was not possible to conduct a similar set of runs over the lake with the BIO-CO_2, results from corn and forest runs with that instrument were used to evaluate the effects of airspeed.

The range of true airspeeds over corn was 59-64 m/s and over the forest was 57-62 m/s. In both sets, RMS of the CO_2 signal was highly correlated with true airspeed (corn: $r=0.96$, $p=0.0005$; forest: $r=0.43$, $p=0.087$), but CO_2 flux was not related to either true airspeed or RMS of CO_2.

The data seem to imply that CO_2 flux was not related to airspeed-dependent noise of the open-path sensors. Further assessment of data can therefore be made on the basis of differences between surfaces; however, it cannot be established whether the CO_2 fluxes obtained are independent of the instrument used since the CO_2 sensors were not flown at the same time.

6.1 Comparison of Mean CO_2 Fluxes

A summary of mean CO_2 fluxes, both corrected and uncorrected, and of mean heat fluxes is presented in Table

6.1 . F-tests on the variances of CO_2 fluxes and corrected CO_2 fluxes were performed to investigate differences in variability between fluxes measured over different surfaces and as prerequisite to testing differences between mean CO_2 fluxes using the student's t-test for two independent samples. Results are presented in Table 6.2.

Significant differences were found between mean uncorrected CO_2 fluxes over corn, forest and water on the 28th of August. No differences was detected between corn and forest on the 18th. The corrected mean CO_2 fluxes yielded the same results except in the case when surfaces were compared between days. The corrected fluxes showed differences between days for corn and for forest.

It may be interesting to note that the coefficients of variability (C.V.) for CO_2 flux and temperature-corrected CO_2 flux are lower on the 28th of August than on the 18th, while the C.V.'s for sensible heat flux are about the same on both days. Since the C.V. may be used as an indication of relative error between experiments, some interesting questions could be raised. For example, is the relative error of measurement of CO_2 flux due to a difference in daily conditions or due to the CO_2 sensor used? If it is due to daily conditions, why does sensible heat flux demonstrate about the same variability between days?

The comparison of mean CO_2 fluxes seems to indicate that conditions were better suited for photosynthetic activity on

Table 6.1: Summary of Mean Fluxes.

	No. of Runs	CO2 Flux (Uncorrected) Kg/ha/h			CO2 Flux (Corrected) Kg/ha/h			Sensible Heat Flux W/m^2		
AGR-OPA		Mean	S.E.	C.V.	Mean	S.E.	C.V.	Mean	S.E.	C.V.
Corn	9	-36.01	±6.35	53%	-35.83	±6.38	53%	36	8.93	74%
Forest	18	-16.44	±1.77	46%	-14.25	±1.70	50%	40	3.94	42%
Water	9	-04.41	±2.25	147%	-03.01	±2.25	224%	25	1.87	22%
BIO-CO2										
Corn	7	-14.50	±4.32	79%	-12,03	±3.71	81%	44	12.78	77%
Forest	15	-13.03	±2.43	72%	-07.47	±1.91	99%	99	13.61	53%

S.E. = Standard error

C.V. = Coefficient of variability

Table 6.2: Comparison of Mean CO2 Fluxes.

Comparison		CO2 Flux Uncorrected				CO2 Flux Corrected			
Date	Surface	F	Prob>F	t	t tabulated (.05)	F	Prob>F	t	t tabulated (.05)
08/28 08/28	Corn Forest	6.4065*	.0007	2.967*	2.110 t 2.306	5.9980*	.0009	3.162*	2.110 $<$ t $<$ 2.306
08/28 08/28	Corn Water	8.6140*	.0032	4.705*	2.262	6.8525*	.0067	4.858*	2.262
08/28 08/28	Forest Water	1.3446	.2879	4.077*	2.060	1.1423	.4237	3.897*	2.060
08/18 08/18	Corn Forest	1.4760	.2561	0.300	2.086	1.7609	.1794	1.215	2.086
08/28 08/18	Corn Corn	2.7820	.1146	2.629*	2.145	3.2318	.0851	2.848*	2.145
08/28 08/18	Forest Forest	1.5600	.1904	1.156	2.038	1.0541	.4529	2.659*	2.038

* Denotes significance at the 0.05 level.

the 28th of August than on the 18th. NRC weather summaries reported 1.8 and 2.8 mm of rainfall on the 26th and 27th of August, respectively, with total radiations of 4.7 and 8.1 MegaJoules per square meter. Radiation was 23.3 MJ/sq.m on the 28th with no precipitation. Precipitation from the 14th to the 18th of August was 9.0, 0.4, 0.0, 0.0, 0.2 mm, respectively, and radiations were 7.1, 13.9, 23.6, 24.4, and 18.1 MJ/sq.m. The high sensible heat flux over the forest on the 18th, coupled with the above information, would seem to indicate that conditions were dry on the 18th, and, with lower insolation on that day, could account for the lower CO_2 flux estimates obtained.

6.2 Analysis of Correlation

In an attempt at further evaluation of the 1980 data, simple linear correlation coefficients were computed between pairs of variables that were expected to provide more insight. Correlation matrices were produced for the chosen variables in various groupings;

(i) 49 runs over corn and forest on the 18th and 28th of August.

(ii) 9 runs over corn on the 28th of August.

(iii) 7 runs over corn on the 18th of August.

(iv) 18 runs over forest on the 28th of August.

(v) 15 runs over forest on the 18th of August.

(vi) 9 runs over water on the 28th of August.

The corresponding tables are presented in Appendix A. Significance was assumed at the 0.10 level. It should be noted that the sign of the correlation coefficient indicates the direction of the relationship and that this is relative to the signs of the variables involved. For example, a strong relationship between CO2 flux (more negative indicates higher rate of transfer toward the crop) and sensible heat flux (more positive indicates more transfer away from the crop), would be represented by a large negative coefficient of correlation.

It is stated at the outset that this type of analysis is exploratory and meant to raise questions as well as to lend support to some of the conclusions which have been drawn. One must also consider the fact that the experiment was not suitably randomized with respect to the variables involved and many correlations arise that would perhaps not otherwise exist.

For example, the correlation matrix for all 49 runs (Table A.1) shows a strong correlation between heat flux and altitude ($r=0.375$, $p=0.008$). A closer look at the actual data reveals that sensible heat flux over the forest (high altitude runs) on the 18th of August was much higher than in the other run groupings. Coupled with the fact that insolation during the 44 m runs was higher than during the preceding lower-altitude, producing a trend towards higher heat flux with altitude on the August 28th corn series, the spurious correlation is accounted for. In other words, without proper randomization and parametrization of variables, simple correlation analysis may lead to wrong conclusions. Some correlations which were found to be relevant to the data are outlined in the following paragraphs.

The CO_2 flux, uncorrected for temperature fluctuations, was highly correlated with sensible heat flux, over corn ($r=-0.84$, $p=0.0176$) and over forest ($r=-0.756$, $p=0.0011$) on the 18th of August, and over corn ($r=-0.62$, $p=0.0745$) on the 28th of August. For the August 28th forest runs, the coefficient was negative, but not significant ($r=-0.295$, $p=0.2355$). It is interesting to note that the CO_2 flux based on the corrected signal is always less related to sensible heat flux, indicating that the CO_2 sensor is in fact affected by temperature fluctuations in a manner related to the sensible heat flux. This point requires further investigation: if the CO_2 sensor signal is corrected for temperature fluctuations and if the magnitude of this correction is related to sensible heat flux, then applying a further correction for sensible heat flux, as suggested by Smith and Jones (1979) would be somewhat superfluous. It is also interesting to imagine that a CO_2 flux could be obtained if the open-path sensor were not corrected for temperature fluctuations, if a heat flux existed where there were no source or sink of CO_2.

Both the corrected and uncorrected CO_2 fluxes were inversely related to RMS of vertical wind over corn and forest on both days. Probabilities for the correlations ranged from 0.0143 to 0.0823. Sensible heat flux was also related to RMS w (positive coefficients) with probabilities ranging from 0.0009 to 0.0520. This seems to imply a relationship between the flow regime and transfer efficiency; however, one should not neglect the fact that insolation was variable and would have an effect on CO_2 and sensible heat exchange, as well as on the flow field by creating changes in the effects of buoyancy.

On the 28th of August, RMS of w increased with altitude over both corn ($r=0.966$, $p=0.0001$) and forest ($r=0.671$, $p=0.0023$) and RMS T decreased with altitude (corn; $r=-0.705$, $p=0.0039$: forest; $r=-0.747$, $p=0.0004$). Neither relationship held on the 18th of August. According to the discussion of the height variation of RMS w given in Lumley and Panofsky (1964), these results would be indicative of differences in atmospheric stability on the two days. Unfortunately, it is not possible to compute atmospheric stability with any degree of confidence from the provided data since the momentum fluxes are questionable, particularly those obtained over corn on both days (many of the momentum fluxes were positive instead of negative).

The momentum flux based on the gust-axes horizontal component was inversely related to RMS w (r=-0.574, p=.0001) and to mean wind (r=-0.523, p=0.0001) over all the runs, as one would expect (more momentum transfer and turbulence intensity with higher mean wind). The data show, however, a substantial number of cases where the momentum flux estimates were positive (indicating transfer away from the surface). The percentage of momentum fluxes which were positive over corn was 33%. Over forest the percentage was 31%. It would be difficult to draw any conclusions from such a small data set and the matter was brought to the attention of J.I.McPherson who suggested that the horizontal component would perhaps be better referenced to a mean wind direction. It would be interesting to compare momentum flux calculations based on a mean wind direction with those based on gust direction. One would expect that the similarity of the two would depend on the variability of wind direction.

6.3 Discussion of Cumulative Flux Plots

The cumulative flux plots, with cumulative changes in wind direction, were meant to show the time history of fluxes and to determine how much influence changes in wind direction would have on flux estimates. The plots for each run are presented in Appendix C. Perhaps the most striking feature is the initial variability of each trace which is due to the fact that the first few points are based on a small number of observations. The end points represent the final flux estimates. The plots of cumulative changes in wind direction are superimposed on the cumulative momentum flux traces and may be distinguished by their highly fluctuating nature. The right hand axis labelled 'DIRECTION' is in degrees and is associated with the changes in wind direction. From the point of view of presentation, it would have been better to plot these cumulatives from about ten seconds until the end of each run in order to be able to standardize the axes.

The most significant aspects of these plots are that few of the traces are smooth or have zero slope and that jumps in the cumulatives can often be associated with sharp changes in wind direction. A cumulative with zero slope would be indicative of stationarity (or steady-state).

These plots for runs 1 through 7 for the August 28th corn runs at Embrun display upward trends for the CO2 cumulatives and corresponding downward trends for those of sensible heat flux. This would be consistent with observations by the flight crew of shade at the end of the corn field on these runs and of sunny conditions on runs 8 and 9. Insolation was described as hazy to shady for the corn runs on the 18th of August. The CO2 cumulatives for those runs do not show the same upward trend. It would appear that the corn crop reacted rapidly to changes in insolation due to changes in cloud cover.

Two clear examples of the effects of changes in wind direction can be seen on the plots for run 4 over corn on the 28th of August and on the plots for run 7 over corn on the 18th. These effects could be representative of the spatial inhomogeneity of the experimental site itself or may indicate inadequate fetch in some directions whereby non-representative air could reach the sensors. It is interesting to note that the cumulative fluxes of sensible heat often mirror those of CO2, not only with respect to trends, but also with respect to sharp changes in wind direction.

Similar effects can be seen on the cumulatives for the forest runs on both days, although the forest runs tend to be somewhat smoother on the whole. The smoother behaviour can be partly attributed to the greater number of observations on which the final fluxes are based (usually double those over corn) due to the length of these runs; however, a substantial number of cases reflect inhomogeneity and non-stationarity.

It would appear that the assumptions on which the eddy correlation technique is based were rarely satisfied for the days and sites described in this feasibility study. It would nevertheless be reasonable to expect that given a sufficient number of runs over a crop, a representative mean flux could be obtained as suggested by the comparisons made in the previous section and in a manner analogous to the description of average density versus field size in a half-tone reproduction given in Lumley and Panofsky (1964, pp. 39-41). The question is: given a certain degree of variability or inhomogeneity, on what space scale should a flux estimate be based and how many such estimates yield a reasonable estimate of daily production?

6.4 Discussion of Spectra and Cospectra

The following points summarize an inspection of spectral and cospectral plots included in Appendix D.

1) The CO2-w cospectra showed that most of the transfer occurs at scales of about 50 to 500 meters. According to the equation for 'typical eddy size' l=kz, where l is typical eddy size at height z and k is von Karman's constant ($\approx$ 0.4), one would expect more activity at wavelengths shorter than the minimum observed. Assuming an observation altitude of 30 meters, typical eddy size would be about 12 meters. Assuming a true airspeed of 60 meters per second, the 5Hz cutoff low-pass filtering by N.A.E. would seriously attenuate contributions of 'typical' scale. The frequency response of the weighting function applied to the spectra is about 0.37 at a wavelength equivalent of 20 meters. These combined effects would account for the apparently strange behaviour at the high frequency end of the spectra and cospectra.

2) Although the average spectra of CO2 for the runs made with the AGR-OPA all showed the same noise-related

peak at log wavelength of 1.55, none of the CO_2-w cospectra showed significant contributions to CO_2 transfer in that vicinity.

3) The CO_2-w and T-w cospectra were mirror images in most run groupings, indicating that the same eddies are responsible for the transfers of sensible heat and of carbon dioxide. Exceptions were found in the forest runs of August 18th (BIO-CO2). In that group, the T-w cospectra are shifted to longer wavelengths.

4) The vertical wind spectra all show strong peaks at a scale of about 100 meters, as do the CO_2-w and T-w cospectra. The apparent dominance of vertical wind fluctuations over the transfer of CO_2 and sensible heat is consistent with eddy correlation theory.

5) The temperature and horizontal velocity spectra are nearly identical over the forest, whereas the temperature spectra over corn on the 28th of August are more like the vertical wind spectra and appear as a compromise between horizontal and vertical spectra over corn on the 18th of August.

Observations 1) through 4), all factors considered, show that some reasonable results have been obtained in this first year of experimental flights. One might easily speculate about the significance of the other observation; however, the author feels that such speculation would be beyond the scope of this study and beyond the potential of such a limited data set to give any great insights. More detailed investigations of the nature of transfer processes over natural surfaces are nevertheless to be expected as long as this project continues.

CHAPTER 7 SUMMARY AND CONCLUSIONS

The 1980 data show that it is possible to measure CO2 exchange rates using an airborne instrumentation system. Flux estimates were generally negative over vegetated surfaces, indicating that the CO2 transfer was toward photosynthesizing vegetation. Average fluxes over corn, forest and water obtained on the 28th of August were significantly different, as expected. The high variability and overlap of fluxes over the different surfaces are not presently explainable; however, the high variability exhibited in the sensible heat fluxes (except over Lac Deschenes), would imply that much of the variability is environmental.

Some variability could be attributed to problems related to the CO2 sensors. The RMS fluctuations of CO2 were much higher for the AGR-OPA, but the BIO-CO2 seemed to be affected by changes in aircraft attitude. Cumulative fluxes plotted with changes in wind direction showed that changes in the direction of air flow can often affect flux estimates. This factor is impossible to control and its effects are more serious when inadequate fetch is combined with inhomogeneity of the area immediately surrounding the experimental site, not to mention inhomogeneity of the site itself. It is unfortunate that the time available for the experimental flights was so limited and that test flights had to be conducted at a time of reduced photosynthetic activity.

More useful information may also have been obtained if the study had been conducted over surfaces where fetch and homogeneity requirements could be met. Previous airborne eddy correlation flux measurements have shown that the variability of flux measurements is related to the orientation of flights with respect to the mean flow. The site and time limitations that this particular study was faced with did not allow similar investigations.

The exchange of carbon dioxide is of interest on a global scale to climatologists, at a regional scale to agrometeorologists, at the single field crop scale to micrometeorologists and at the single plant scale to plant physiologists. The variability of estimates of CO_2 exchange depends on the technique of measurement with regard to the scale of interest. The number of factors affecting exchange estimates may also vary with the scale of interest. The problem to be addressed is, therefore, to define the scale of applicability of aerially determined flux estimates.

It is felt that the 1980 CO_2 data are inadequate to provide the required information. In order to properly define the variability of airborne CO_2 flux estimates in terms of a reasonable scale of investigation, the following are necessary:

1) Instrumentation should be refined. Noise levels could

perhaps be reduced by aerodynamic design improvements on the parts of the analyzers that protrude from the aircraft.

2) Given the best possible experimental conditions, the variability of CO_2 exchange in time and space should be investigated in much greater detail. Studies should first be made over larger and more homogeneous stretches of terrain, as might be encountered in the prairies, in order to sparate the variability due to instruments from that due to technique of measurement, including environmental parameters.

3) Sources of variability such as wind direction, orientation of flight, mean wind conditions and type of cloud cover (patchiness) must be better understood. In other words, the applicability of the eddy correlation technique in a non-steady state environment should be investigated. This may mean the development of a methodology for monitoring absolute values of crop response in a time-scale comparable to that on which eddy correlation estimates are based.

4) A ground-referencing system, including support measurements such as radiation and wind direction and capable of taking observations at various altitudes, must be included in future work. It is also suggested that the reference system be able to retrieve and record data in the same manner as the aircraft system.

Data sets could then be subjected to the same types of analysis.

5) It is already known that CO2 exchange rates over vegetation vary seasonally and diurnally. It would therefore be reasonable to test the airborne system at various times during the year, and, on any given day, at times that would reflect the diurnal change.

6) If investigations are to be made at different altitudes, the altitudes of runs should be randomized with respect to time since the estimate is also influenced by the diurnal trend and by changes in general meteorological conditions.

7) The reference system should also be used to determine boundary layer depth some time before and after the test flights. More experience may eventually provide criteria for determining an adequate observation altitude under different atmospheric conditions.

8) More attention must be paid to the consequences of data modification techniques. Various forms of analysis were attempted that, due to a limited budget, could not be properly refined. For example, the smoothing function applied to spectra attenuated frequencies of interest but different ones could not be used for the given reason.

In conclusion, it can be said that the feasibility of using airborne eddy flux systems to estimate biomass productivity is indicated. Perhaps the most important lesson learned during this study was that flight programs should be designed for ease of interpretation of data. Proper randomization of runs, adequate support data and a flight program covering most of the growing season would allow a full evaluation of the potential of the airborne instrumentation system to obtain useful estimates of CO2 exchange.

LITERATURE CITED

Bakan, S.: 1978, 'Note on the eddy correlation method for CO2 flux measurement', Boundary Layer Meteor. 14; 597-600.

Bate, G.C., D'Aaoust, A. and Canvin, D.T.: 1969, 'Calibration of infrared CO2 gas analyzers', Plant Physiol. 44; 1122-1126.

Biscoe, P.V., Clark, J.A., Gregson, K., McGowan, M., Monteith, J.L., and Scott, R.K.: 1975, 'Barley and its environment. I. Theory and practice', J. App. Ecol. 12; 227-257.

Bowen, I.S.: 1926, 'The ratio of heat-losses by conduction and by evaporation from any water surface', Phys. Rev. 27; 779-787.

Brach, E.J., Desjardins, R.L. and St.Amour, G.T.: 1981 'Open path CO2 analyser', J. Phys. E: Sci. Instrum. 14; 1415-1419.

Bunker, A.F.: 1955, 'Turbulence and shearing stresses measured over the North Atlantic Ocean by an airplane-acceleration technique', J. Meteor. 12; 445-455.

Brigham, E.O. and Morrow, R.E.: 1967, 'The Fast Fourier Transform', IEEE Spectrum 4; 67-70.

Desjardins, R.L.; 1968, 'Short-term fluctuations of CO2 and wind near the surface of a corn crop', Ann. Prog. Rep. of Microclimate Investigations, Ithaca, N.Y.; 193-206.

Desjardins, R.L.: 1972, 'A study of carbon dioxide and sensible heat fluxes using the eddy correlation technique', Ph.D. thesis, Cornell University; 175 pp.

Desjardins, R.L.: 1974, 'A technique to measure CO2 exchange under field conditions', Int. J. Biometeor. 18; 76-83.

Dyer, A.J.: 1961, 'Measurements of evaporation and heat transfer in the lower atmosphere by an automatic eddy correlation technique', Q.J. Roy. Meteor. Soc. 87; 401-412.

Dyer, A.J. and Hicks, B.B.: 1970, 'Flux-gradient relationships in the constant flux layer', Q.J. Roy. Meteor. Soc. 96; 715-721.

Garratt, J.R.: 1975, 'Limitations of the eddy correlation technique for the determination of turbulent fluxes near the surface' Boundary Layer Meteor. 8; 255-269.

Goncz, J.H.: 1968, 'Feasibility of CO2 flux measurements by eddy correlation technique', C.S.I.R.O., Division of Land Research, Canberra, Australia, Technical Memorandum 68/2; 7pp.

Grossman,R.L. and Bean,B.R.: 1973, 'An aircraft investigation of turbulence in the lower layers of a marine boundary layer', N.O.A.A. Technical Report ERL 291-WMPO 4; 166 pp.

Halter,B.C. and Peterson,J.I.: 1981, 'On the variability of atmospheric carbon dioxide concentration at Barrow, Alaska during summer', Atm. Env. 15; 1391-1399.

Inoue,E., Mihara,Y. and Tsuboi,Y.: 1965, 'Agrometeorological studies on rice growth in Japan', Agr. Meteor. 2; 85-107.

Jenkins,G.M. and Watts,D.G.: 1968, 'Spectral Analysis and its Applications'. Holden-Day, San Francisco; 525 pp.

Jones,E.P. and Smith,S.D.: 1977, 'A first measurement of sea-air CO2 flux by eddy correlation', J. Geophys. Res. 82; 5990-5992.

Jones,E.P. and Smith,S.D.: 1978, 'The air-density correction to eddy flux measurements', Boundary Layer Meteor. 15; 357-360.

Jones,E.P., Zwick,H. and Ward,T.V.: 1978, 'A fast response atmospheric CO2 sensor for eddy correlation flux measurement', Atm. Env. 12; 845-851.

Lemon,E.R.: 1960, 'Photosynthesis under field conditions. II. An aerodynamic method for determining the turbulent exchange between the atmosphere and a corn field', Agron. J. 52, 697-703.

Lenschow,D.H., Delany,A.C., Stankov,B.B. and Stedman,D.H.: 1980, 'Airborne measurements of the vertical flux of ozone in the boundary layer', Boundary Layer Meteor. 19; 249-265.

Lumley,J.L. and Panofsky,H.A.: 1964, 'The Structure of Atmospheric Turbulence', Interscience Publishers, John Wiley and Sons, Inc., USA: 239 pp.

MacPherson,J.I.: 1980, 'Flight experiments to measure the flux of carbon dioxide above various ecosystems', N.A.E. Laboratory Technical Report LTR-FR-74; 35pp.

MacPherson,J.I., Morgan,J.M. and Lum,K.: 1981, 'The N.A.E. Twin Otter Atmospheric Research Aircraft', N.A.E. Laboratory Technical Report LTR-FR-80; 21 pp.

McBean,G.A.: 1970, 'The turbulent transfer mechanisms in the atmospheric surface layer', Ph.D. thesis, University of British Columbia; 119 pp.

McBean,G.A. and Paterson,R.D.: 1975, 'Variations of the turbulent fluxes of momentum, heat and moisture over Lake Ontario', J. Phys. Oceanog. 5; 523-531.

McCulloch,J.A.W.: 1965, 'A computer program for the design of symmetrical digital filters', Meteorological Branch Circular 4230, Tec. 568 D.O.T., Toronto; 30 pp.

Milford,J.R., Abdulla,S. and Mansfield,D.A.: 1979, 'Eddy flux measurements using an instrumented powered glider', Q.J. Roy. Meteor. Soc. 105; 673-693.

Monteith,J.L.: 1973, 'Principles of Environmental Physics', American Elsevier Publishing Co., Inc., New York; 241 pp.

Monteith,J.L. and Szeicz,G.: 1960, 'The carbon dioxide flux over a field of sugar beets', Q.J. Roy. Meteor. Soc. 86; 205-214.

Ohtaki,E.: 1980, 'Turbulent transport of carbon dioxide over a paddy field', Boundary Layer Meteor. 19; 315-336.

Panofsky,H.A. and Brier,G.W.: 1958, 'Some Applications of Statistics to Meteorology', University Park, Pennsylvania; 224 pp.

Pasquill,F.: 1972, 'Some aspects of boundary layer description', Q.J. Roy. Meteor. Soc. 98; 469-494.

Reinking,R.F.: 1977, 'Direct measurement of evapotranspiration over large areas using an airborne gust probe system', 13th American Meteorological Society

Conference on Agriculture and Forest Meteorology, Purdue University, West Lafayette, Indiana.

Sethuraman, S.: 1981, 'Carbon dioxide fluxes over the Atlantic Ocean estimated from measurements at Tiana Beach, Long Island, New York', Boundary Layer Meteor. 20; 19-26.

Smith, S.D. and Jones, E.P.: 1979, 'Dry-air boundary conditions for correction of eddy flux measurements', Boundary Layer Meteor. 17; 375-379.

Swinbank, W.C.: 1951, 'The measurement of vertical transport of heat and water vapour by eddies in the lower atmosphere', J. Meteor. 8; 135-145.

Thorthwaite, C.W. and Holzman, B.: 1939, 'The determination of evaporation from land and water surfaces', U.S. Monthly Weather Rev. 67;4-11.

Wesely, M.L., Eastman, J.A., Cook, D.R. and Hicks, B.B.: 1978, 'Daytime variation of ozone fluxes to maize', Boundary Layer Meteor. 15; 361-373.

Zelitch, I.: 1971, 'Photosynthesis, Photorespiration and Plant Productivity', Academic Press, Inc., New York and London; 347 pp.

APPENDIX A: Correlation Tables.

APPENDIX A.1

Correlation Coefficients: All Runs over Corn and Forest.

CO2 Flux	CO2 Flux (Corr)	Heat Flux	Momentum Flux	RMS CO2	RMS W	RMS T	RMS U	Mean Wind	TAS	Z	SKC	
	0.984*	-0.164	-0.184	-0.453*	-0.111	-0.002	0.277*	-0.024	0.025	0.206	0.004	CO2 Flux
		0.013	-0.308*	-0.549*	0.026	0.114	0.353*	0.082	0.082	0.275*	-0.027	CO2 Flux (Corr)
			-0.661*	-0.486*	0.764*	0.616*	0.415*	0.540*	0.269*	0.375*	-0.143	Heat Flux
				0.533*	-0.574*	-0.452*	-0.659*	-0.523*	-0.322*	-0.234	0.213	Momentum Flux
					-0.549*	-0.107	-0.405*	-0.448*	-0.440*	-0.398*	0.419*	RMS CO2
						0.305*	0.490*	0.528*	0.178	0.562*	-0.179	RMS W
							0.304*	0.352*	0.017	0.159	0.159	RMS T
								0.361*	0.224	0.167	0.061	RMS U
									0.300*	0.200	-0.473*	Mean Wind
										-0.285*	-0.175	TAS
											-0.138	Z

* Denotes significance at the 0.10 level.

APPENDIX A.2

Correlation Coefficients: Nine Runs over Corn, August 28, 1980 (Agr-OPA).

CO_2 Flux	CO_2 Flux (Corr)	Heat Flux	Momentum Flux	RMS CO_2	RMS W	RMS T	RMS U	Mean Wind	TAS	Z	SKC	
	0.999*	-0.621*	-0.591*	0.030	-0.786*	0.289	0.656*	-0.524	-0.452	-0.753*	0.826*	CO_2 Flux
		-0.616*	-0.580	0.049	-0.774*	0.285	0.655*	-0.518	-0.457	-0.741*	0.832*	CO_2 Flux (Corr)
			0.316	-0.046	0.889*	-0.573	-0.219	0.178	-0.046	0.586*	-0.315	Heat Flux
				0.125	0.664*	-0.595*	-0.846*	0.778*	0.376	0.664*	-0.460	Momentum Flux
					0.143	0.273	0.332	-0.010	-0.488	0.018	0.133	RMS CO_2
						-0.591*	-0.508	0.440	0.105	0.966*	-0.468	RMS W
							0.562	-0.574	-0.125	-0.705*	0.227	RMS T
								-0.746*	-0.607*	-0.590*	0.646*	RMS U
									0.380	0.525	-0.692*	Mean Wind
										0.114	-0.327	TAS
											-0.522	Z

* Denotes significance at the 0.10 level.

APPENDIX A.3

Correlation Coefficients: Seven Runs over Corn, August 18, 1980 (BIO-CO2).

CO2 Flux	CO2 Flux (Corr)	Heat Flux	Momentum Flux	RMS CO2	RMS W	RMS T	RMS U	Mean Wind	TAS	Z	SKC	
	0.994*	-0.841*	-0.216	-0.154	-0.843*	-0.644	-0.489	-0.219	0.004	-0.174	-0.704*	CO2 Flux
		-0.776*	-0.262	-0.173	-0.809*	-0.572	-0.495	-0.261	-0.005	-0.200	-0.722*	CO2 Flux (Corr)
			-0.054	0.031	0.848*	0.873*	0.369	-0.019	-0.046	0.011	0.490	Heat Flux
				-0.349	0.470	-0.242	-0.529	0.529	-0.367	0.904*	-0.197	Momentum Flux
					-0.175	0.363	0.753*	-0.233	0.964*	-0.657	0.636	RMS CO2
						0.648	0.005	0.219	-0.255	0.510	0.269	RMS W
							0.458	-0.116	0.364	-0.255	0.463	RMS T
								-0.086	0.643	-0.720*	0.926*	RMS U
									-0.159	0.424	0.144	Mean Wind
										-0.676*	0.499	TAS
											-0.433	Z

* Denotes significance at the 0.10 level.

APPENDIX A.4

Correlation Coefficients: Eighteen Runs over Larose Forest, August 28, 1980 (AGR-OPA).

CO2 Flux	CO2 Flux (Corr)	Heat Flux	Momentum Flux	RMS CO2	RMS W	RMS T	RMS U	Mean Wind	TAS	Z	SKC	
	0.988*	-0.295	-0.188	0.121	-0.513*	0.124	-0.150	0.578*	0.028	-0.297	0.194	CO2 Flux
		-0.147	-0.200	0.143	-0.421*	0.140	-0.124	0.585*	0.066	-0.275	0.235	CO2 Flux (Corr)
			-0.039	0.088	0.711*	0.073	0.195	-0.085	0.212	0.222	0.186	Heat Flux
				0.074	-0.159	0.101	-0.342	-0.304	-0.009	-0.301	0.131	Momentum Flux
					-0.427*	0.797*	0.354	-0.095	0.446*	-0.715*	0.687*	RMS CO2
						-0.357	0.250	-0.070	-0.002	0.671*	-0.136	RMS W
							0.008	-0.066	0.268	-0.747*	0.560*	RMS T
								0.197	0.260	0.145	0.340	RMS U
									-0.097	0.094	0.108	Mean Wind
										-0.113	0.037	TAS
											-0.459*	Z

* Denotes significance at the 0.10 level.

APPENDIX A.5

Correlation Coefficients: Fifteen Runs over Larose Forest, August 18, 1980 (BIO-CO2).

	CO2 Flux	CO2 Flux (Corr)	Heat Flux	Momentum Flux	RMS CO2	RMS W	RMS T	RMS U	Mean Wind	TAS	Z	SKC
CO2 Flux		0.963*	-0.756*	0.697*	-0.084	-0.575*	-0.535*	-0.463*	-0.345	-0.152	0.028	-0.173
CO2 Flux (Corr)			-0.553*	0.594*	-0.230	-0.527*	-0.329	-0.494*	-0.218	-0.046	0.042	-0.164
Heat Flux				-0.720*	-0.299	0.510*	0.849*	0.229	0.537*	0.348	0.018	0.126
Momentum Flux					0.071	-0.746*	-0.538*	-0.605*	-0.368	-0.179	-0.066	-0.239
RMS CO2						-0.219	-0.455*	-0.221	-0.080	-0.290	0.124	-0.360
RMS W							0.219	0.716*	0.086	0.266	-0.235	0.551*
RMS T								0.165	0.575*	0.263	0.105	0.025
RMS U									-0.044	-0.036	-0.356	0.422
Mean Wind										0.183	0.184	-0.418
TAS											-0.172	0.446*
Z												-0.088

* Denotes significance at the 0.10 level.

APPENDIX A.6

Correlation Coefficients: Nine Runs over Lac Deschenes, August 28, 1980 (AGR-OPA).

CO2 Flux	CO2 Flux (Corr)	Heat Flux	Momentum Flux	RMS CO2	RMS W	RMS T	RMS U	Mean Wind	TAS	Z	SKC	
	0.994*	0.257*	-0.251	-0.337	0.416	0.019	0.656*	-0.051	-0.402	0.258	-0.113	CO2 Flux
		0.363	-0.252	0.281	0.390	0.112	0.704*	-0.051	-0.346	0.244	-0.092	CO2 Flux (Corr)
			-0.095	0.389	-0.089	0.303*	0.608*	-0.014	0.372	-0.057	0.156	Heat Flux
				0.418	-0.599*	-0.142	0.273	-0.460	0.238	0.036	-0.063	Momentum Flux
					-0.237	0.483	0.213	-0.147	0.914*	-0.315	0.623*	RMS CO2
						-0.231	0.102	0.790*	0.059	-0.223	0.234	RMS W
							0.409	-0.201	0.419	0.206	0.270	RMS T
								-0.068	0.151	0.163	0.149	RMS U
									0.222	-0.513	0.337	Mean Wind
										-0.431	0.673*	TAS
											-0.647*	Z

* Denotes significance at the 0.10 level.

APPENDIX B: Tables of Values for Root Mean Square and Skewness.

APPENDIX B.1

August 28, 1980, Embrun Corn. Values for Root Mean Square and Skewness.

Run No.	RMS CO_2 (raw)	Skewness CO_2	RMS W	Skewness W	RMS T	Skewness T	RMS U	Skewness U
1	3.06	-0.56	0.42	0.15	0.17	1.36	1.19	0.19
2	3.09	1.21	0.39	-0.27	0.18	1.73	1.44	-0.04
3	3.30	0.40	0.42	-0.41	0.17	0.99	0.83	0.09
4	2.97	-0.84	0.51	-0.09	0.16	1.88	0.78	0.04
5	2.22	-0.16	0.42	0.25	0.13	1.73	0.55	-0.25
6	3.31	-0.80	0.48	0.63	0.18	1.39	0.66	-0.02
7	2.79	-0.75	0.62	0.04	0.15	1.48	0.59	0.13
8	3.81	-0.14	0.63	-0.10	0.13	0.97	0.84	0.14
9	2.71	-0.40	0.65	0.17	0.14	1.12	0.66	0.09

APPENDIX B.2

August 18, 1980, Embrun Corn. Values for Root Mean Square and Skewness.

Run No.	RMS CO2 (raw)	Skewness CO2	RMS W	Skewness W	RMS T	Skewness T	RMS U	Skewness U
1	3.11	-1.18	0.51	0.66	0.14	-0.38	0.97	-0.13
2	1.03	0.79	0.71	0.59	0.12	0.83	1.00	-0.28
3	0.35	-3.13	0.62	0.10	0.12	0.07	0.76	-0.92
4	1.02	1.21	0.65	0.07	0.18	0.13	1.14	-0.14
5	1.56	-0.61	0.46	0.30	0.13	0.11	1.04	0.55
6	1.21	0.39	0.47	0.07	0.12	-0.04	1.06	0.19
7	5.58	-0.51	0.55	0.15	0.10	0.67	0.92	-0.09
8	0.72	-0.71	0.44	0.22	0.06	0.09	0.99	-0.62
9	0.76	-1.49	0.42	0.29	0.04	0.14	0.91	-0.58

APPENDIX B.3

August 28, 1980, Larose Forest. Values for Root Mean Square and Skewness.

Run No.	RMS CO2 (raw)	Skewness CO2	RMS W	Skewness W	RMS T	Skewness T	RMS U	Skewness U
1	2.64	1.61	0.52	0.40	0.25	0.77	1.03	-0.12
2	2.46	2.86	0.41	0.48	0.21	1.59	0.56	0.39
3	2.86	2.18	0.49	0.42	0.31	0.64	0.81	-0.56
4	2.00	-0.39	0.38	0.51	0.17	1.57	0.73	-0.57
5	2.16	1.67	0.71	-0.05	0.20	0.19	1.09	0.31
6	2.61	1.19	0.51	0.23	0.21	0.83	1.30	0.35
7	1.95	-0.19	0.62	0.15	0.13	0.85	0.61	0.36
8	1.89	0.01	0.72	0.10	0.15	0.71	0.67	-0.14
9	1.84	-0.11	0.65	-0.10	0.10	0.95	0.87	0.19
10	2.50	-0.15	0.36	0.40	0.15	1.02	0.83	-0.79
11	2.66	2.38	0.57	0.10	0.21	0.14	1.24	0.11
12	2.19	-0.17	0.31	0.07	0.22	0.93	0.54	-0.19
13	1.92	-0.08	0.59	0.44	0.12	0.58	0.81	0.67
14	1.87	-0.14	0.58	0.11	0.15	0.69	0.77	-0.17
15	2.18	0.76	0.54	0.63	0.11	1.57	1.05	-0.06
16	2.10	-0.09	0.63	0.42	0.12	0.80	1.15	0.02
17	2.07	2.05	0.51	0.23	0.11	0.96	1.03	-0.85
18	2.00	-0.24	0.76	0.18	0.14	0.66	0.81	0.15

APPENDIX B.4

August 18, 1980, Larose Forest. Values for Root Mean Square and Skewness.

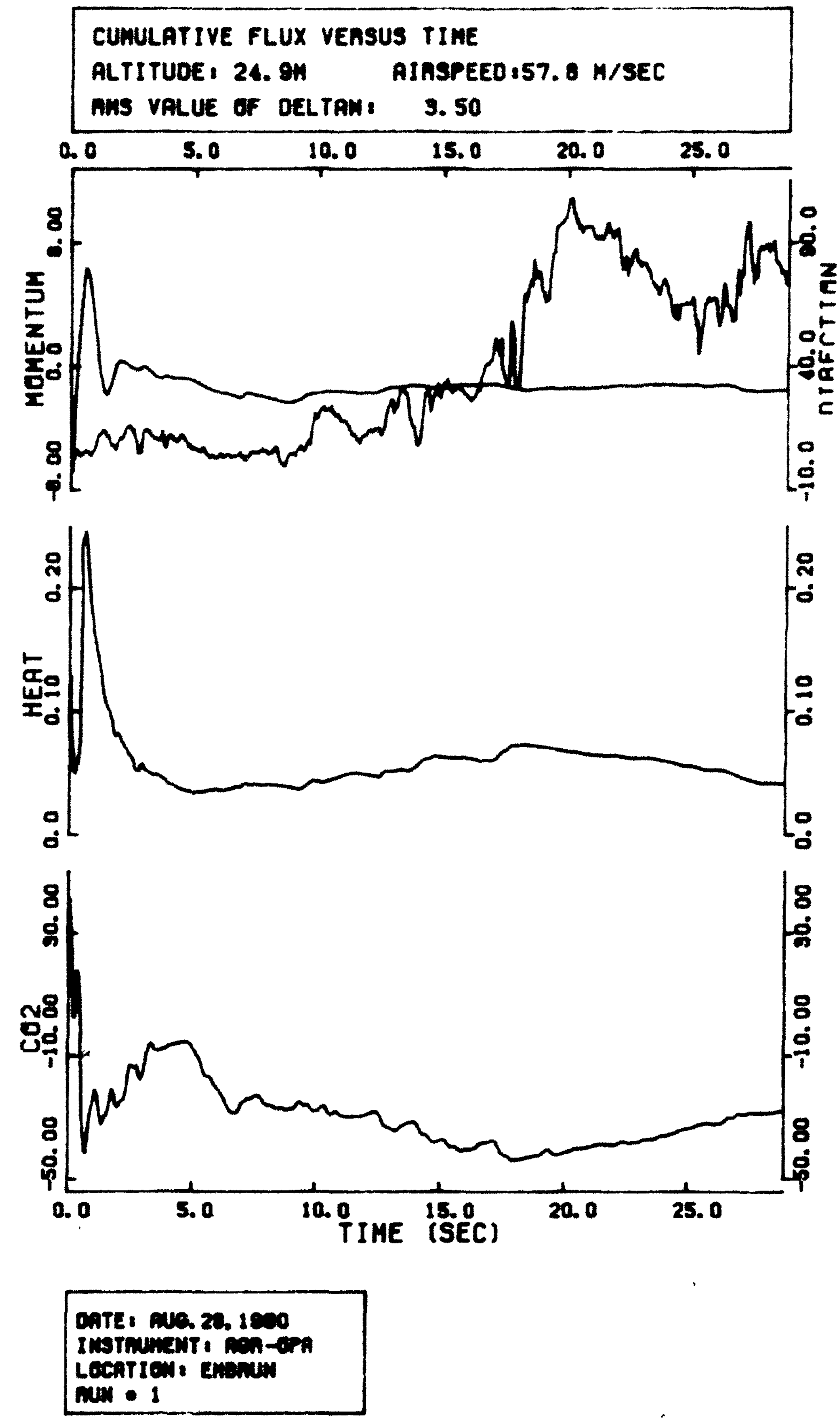
Run No.	RMS CO2 (raw)	Skewness CO2	RMS W	Skewness W	RMS T	Skewness T	RMS U	Skewness U
1	3.75	-1.92	0.72	[illegible].53	0.24	0.51	1.08	-0.21
2	0.79	-0.4[illegible]	0.7[illegible]	0.36	0.16	0.19	1.27	0.65
3	5.18	0.01	[illegible].37	1[illegible].90	3.00	-19.00	3.60	2.48
4	1.81	-1.39	0.58	-0.42	0.08	0.99	0.89	-0.51
5	0.59	-1.08	0.74	0.65	0.22	1.12	1.08	0.09
6	0.63	-0.44	0.72	0.12	0.23	0.29	1.18	0.40
7	0.82	0.07	0.91	-6.20	0.14	0.32	1.44	0.63
8	0.56	-0.14	1.02	-4.14	0.19	0.74	1.21	0.31
9	0.71	0.05	0.77	0.26	0.29	0.91	1.29	-0.15
10	1.15	-1.26	0.81	0.21	0.39	0.27	1.20	0.56
11	0.47	-1.83	0.74	0.48	0.24	0.56	1.17	0.39
12	0.47	-1.26	0.69	0.53	0.24	1.20	1.10	0.58
13	1.30	-2.88	0.68	0.42	0.23	1.09	1.15	0.62
14	0.85	0.46	1.00	0.16	0.24	0.13	1.40	-0.05
15	0.53	-0.42	0.60	0.71	0.24	1.17	0.82	0.38
16	3.04	-2.38	0.55	0.57	0.27	1.65	1.00	0.29
17	0.74	-0.46	0.93	0.30	0.28	0.63	1.33	0.14
18	0.55	-0.81	0.66	-0.03	0.18	0.01	1.30	0.30

APPENDIX B.5

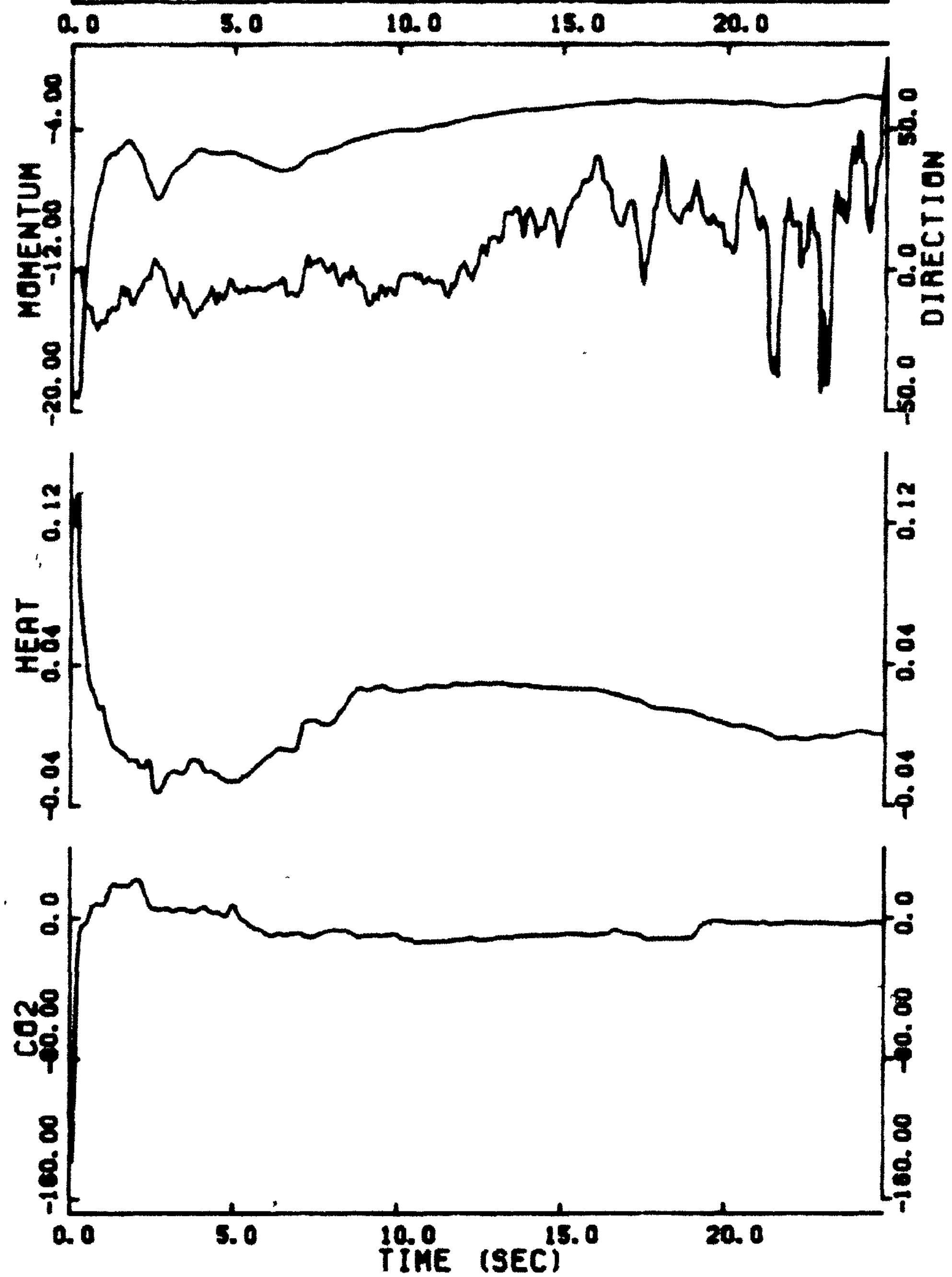
August 28, 1980, Lac Deschenes. Values for Root Mean Square and Skewness.

Run No.	RMS CO2 (raw)	Skewness CO2	RMS W	Skewness W	RMS T	Skewness T	RMS U	Skewness U
1	1.68	-4.71	0.41	-0.04	0.10	1.20	1.35	0.34
2	2.09	-0.47	0.64	-6.40	0.09	0.00	1.39	-0.30
3	1.32	-1.88	0.51	-0.33	0.09	0.49	1.31	-0.41
4	2.22	-0.96	1.21	-9.70	0.08	0.47	1.55	-0.16
5	2.03	-0.27	2.01	-16.00	0.10	0.82	1.41	0.46
6	2.18	-1.27	0.83	-8.60	0.09	0.41	1.11	-0.54
7	4.07	-0.08	0.68	-0.37	0.08	0.78	1.78	0.23
8	3.88	0.07	0.52	-0.14	0.27	-26.00	1.90	14.60
9	3.90	-0.01	0.46	-0.10	0.12	0.11	0.77	0.48

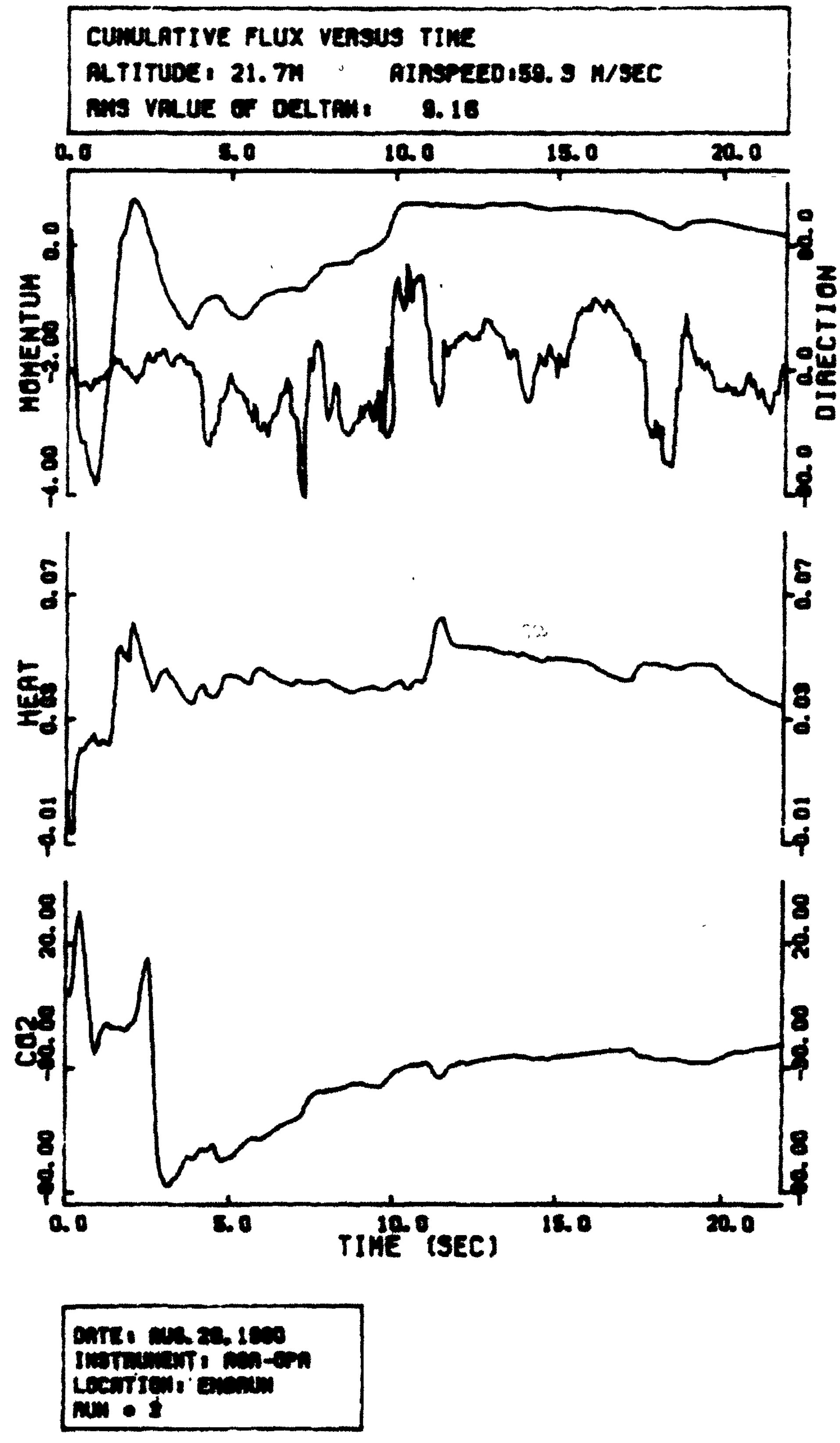
APPENDIX C: Plots of Cumulative Fluxes of CO_2, Sensible Heat and Momentum for Individual Runs.


CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 24.9M AIRSPEED:57.8 M/SEC
RMS VALUE OF DELTAN: 3.50
0.0 5.0 10.0 15.0 20.0 25.0
MOMENTUM
8.00
0.0
-8.00
90.0
40.0
-10.0
HEAT
0.20
0.10
0.0
CO2
30.00
-10.00
-50.00
TIME (SEC)
DATE: AUG.28,1980
INSTRUMENT: AGA-GPA
LOCATION: EMBRUN
RUN # 1

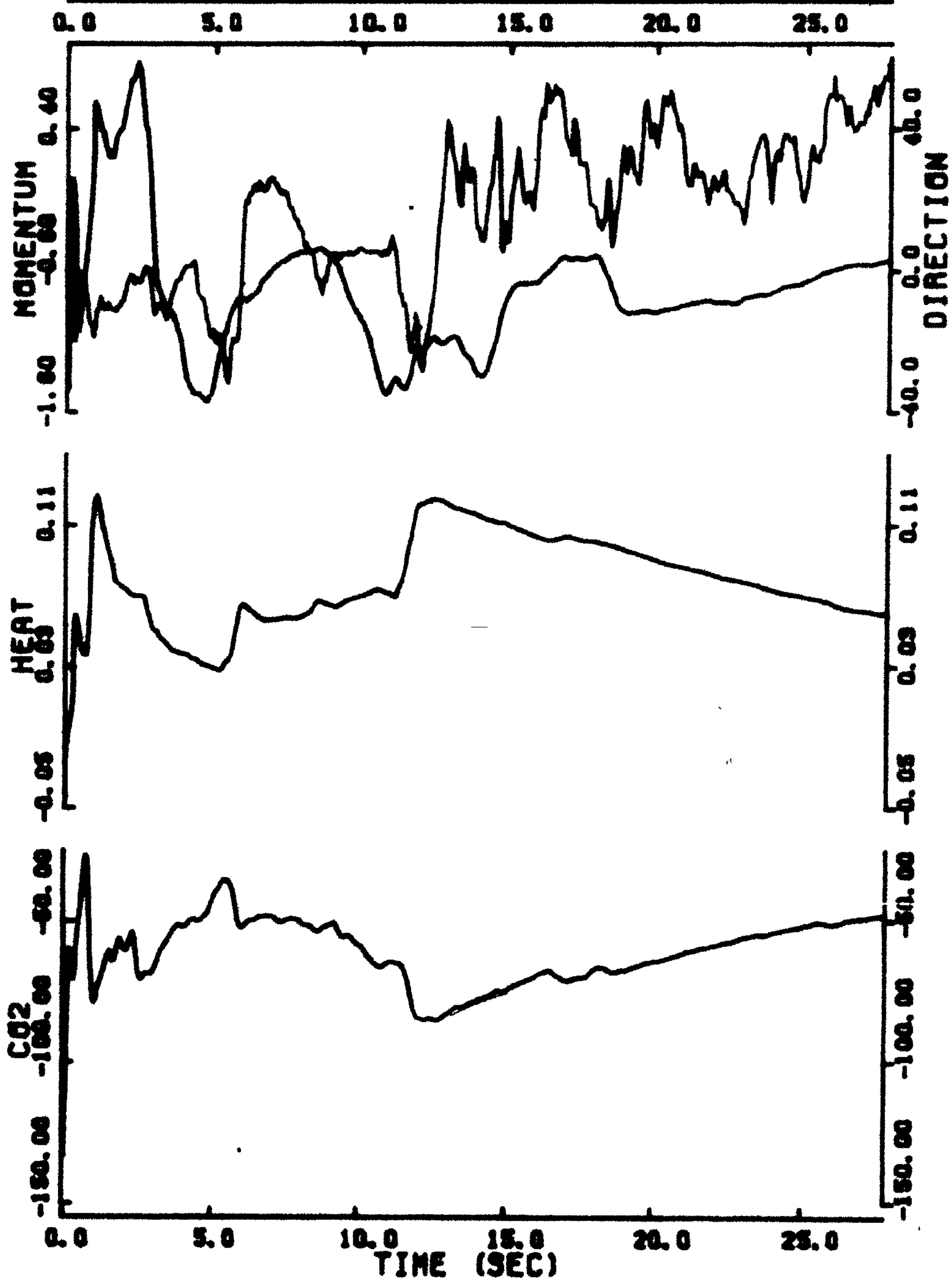
CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 22.0M AIRSPEED:57.6 M/SEC
RMS VALUE OF DELTAM: 5.48



DATE: AUG. 28, 1980
INSTRUMENT: AGA-GPA
LOCATION: EMBRUN
RUN # 2


CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 21.7M
RMS VALUE OF DELTAN:
MOMENTUM
DIRECTION
HEAT
CO2
0.0
5.0
10.0
15.0
20.0
TIME (SEC)
DATE:
INSTRUMENT:
LOCATION:
RUN

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 28.9M AIRSPEED:58.1 M/SEC
RMS VALUE OF DELTAW: 3.93



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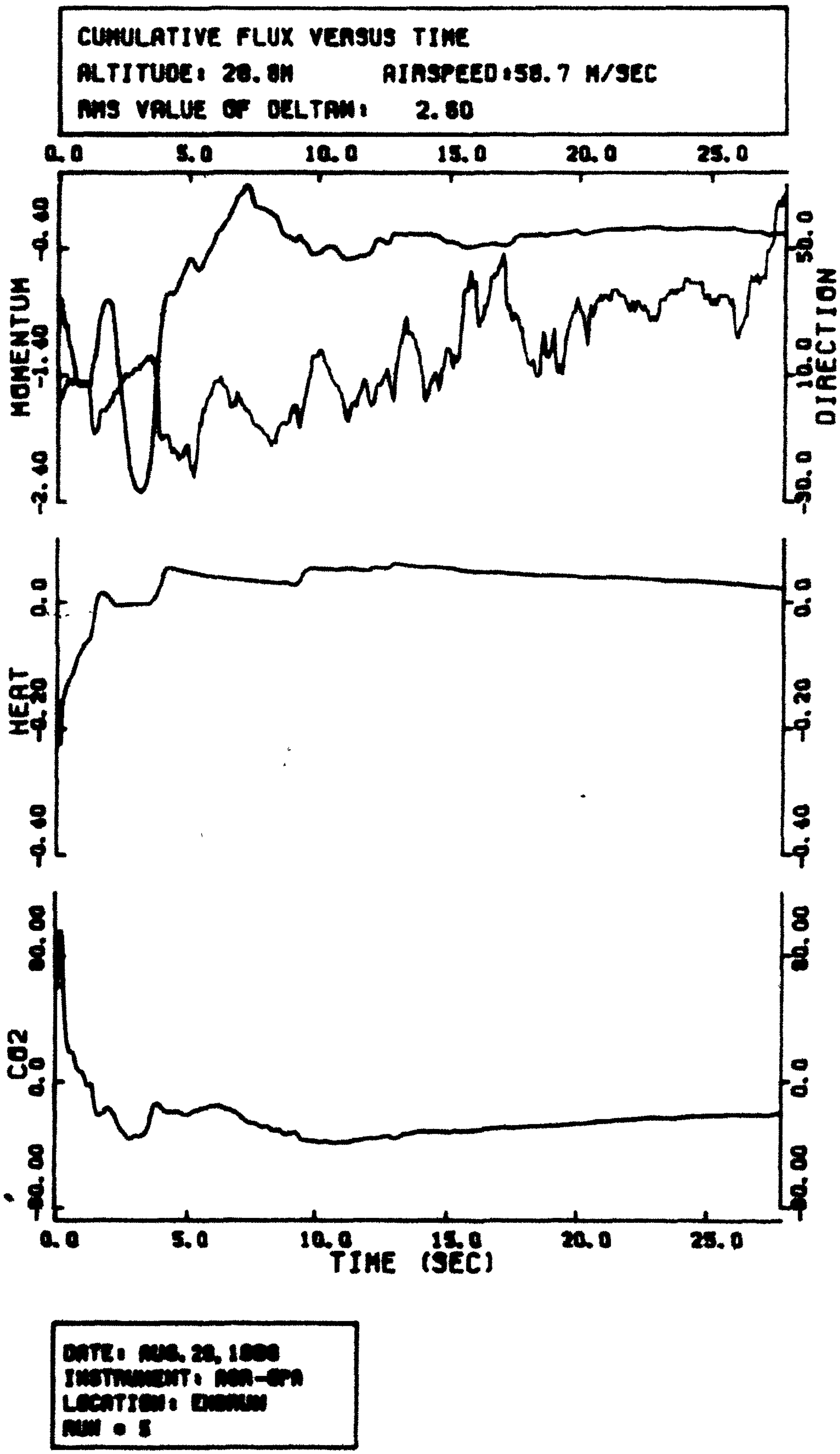
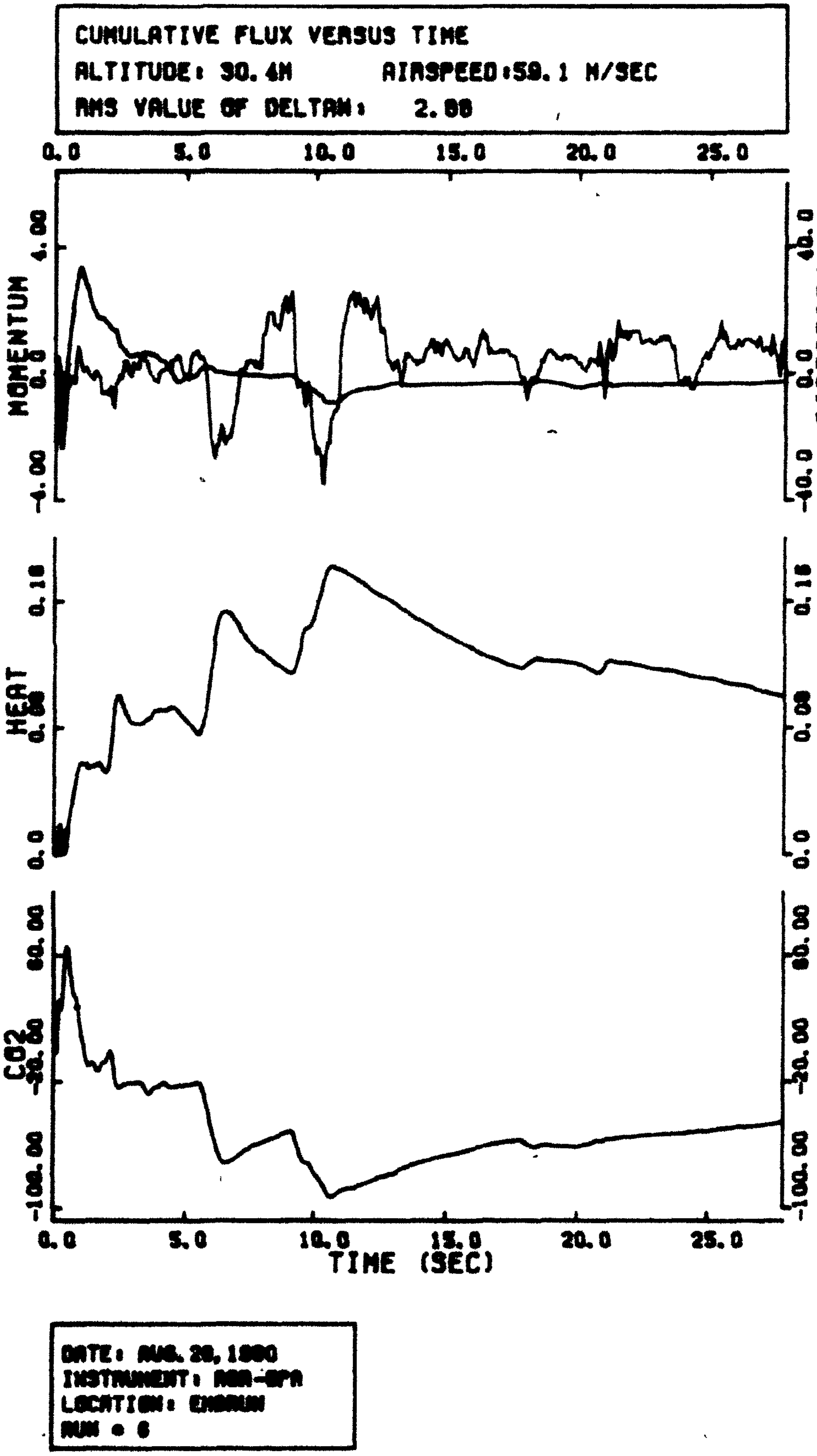
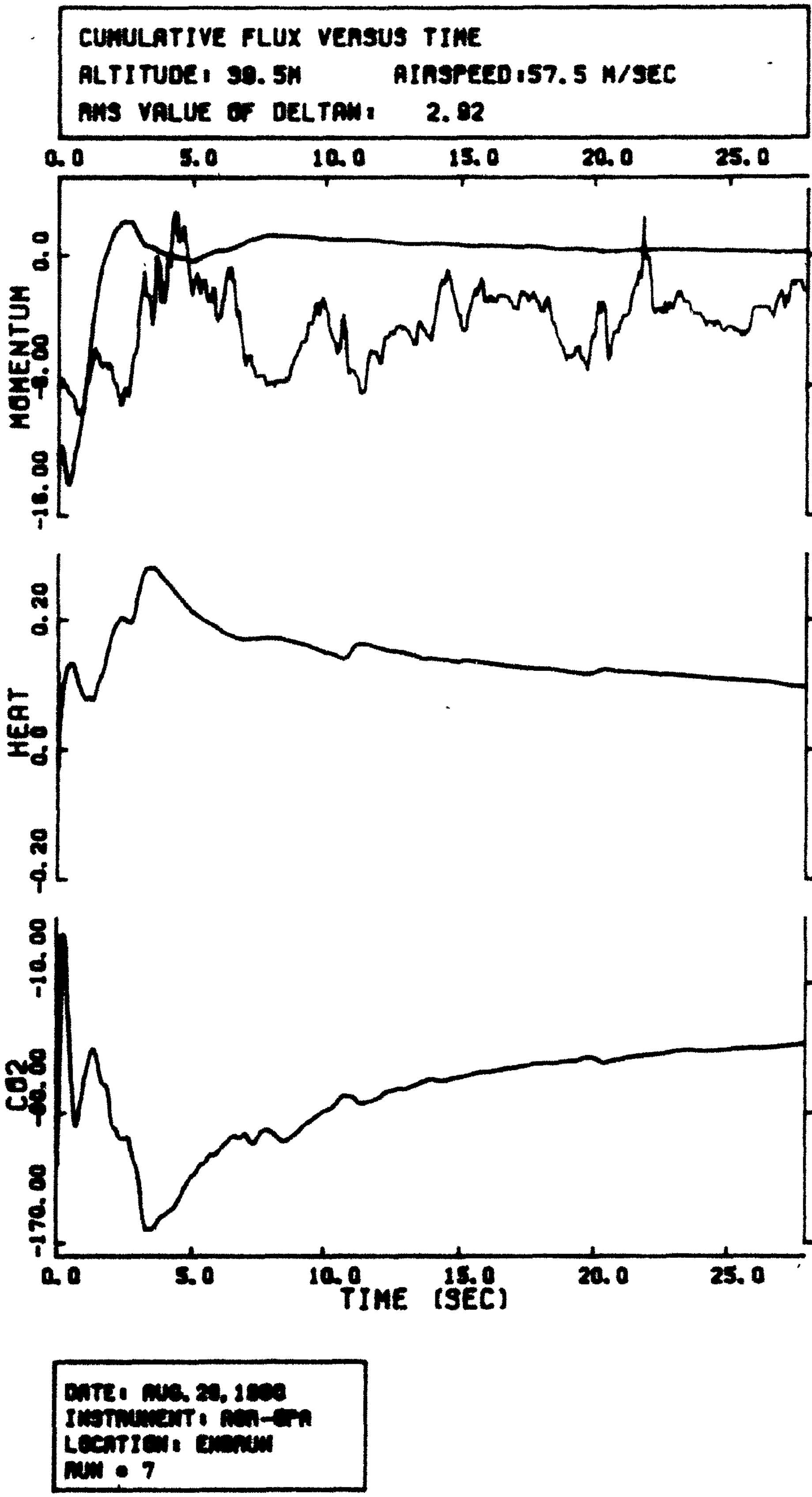
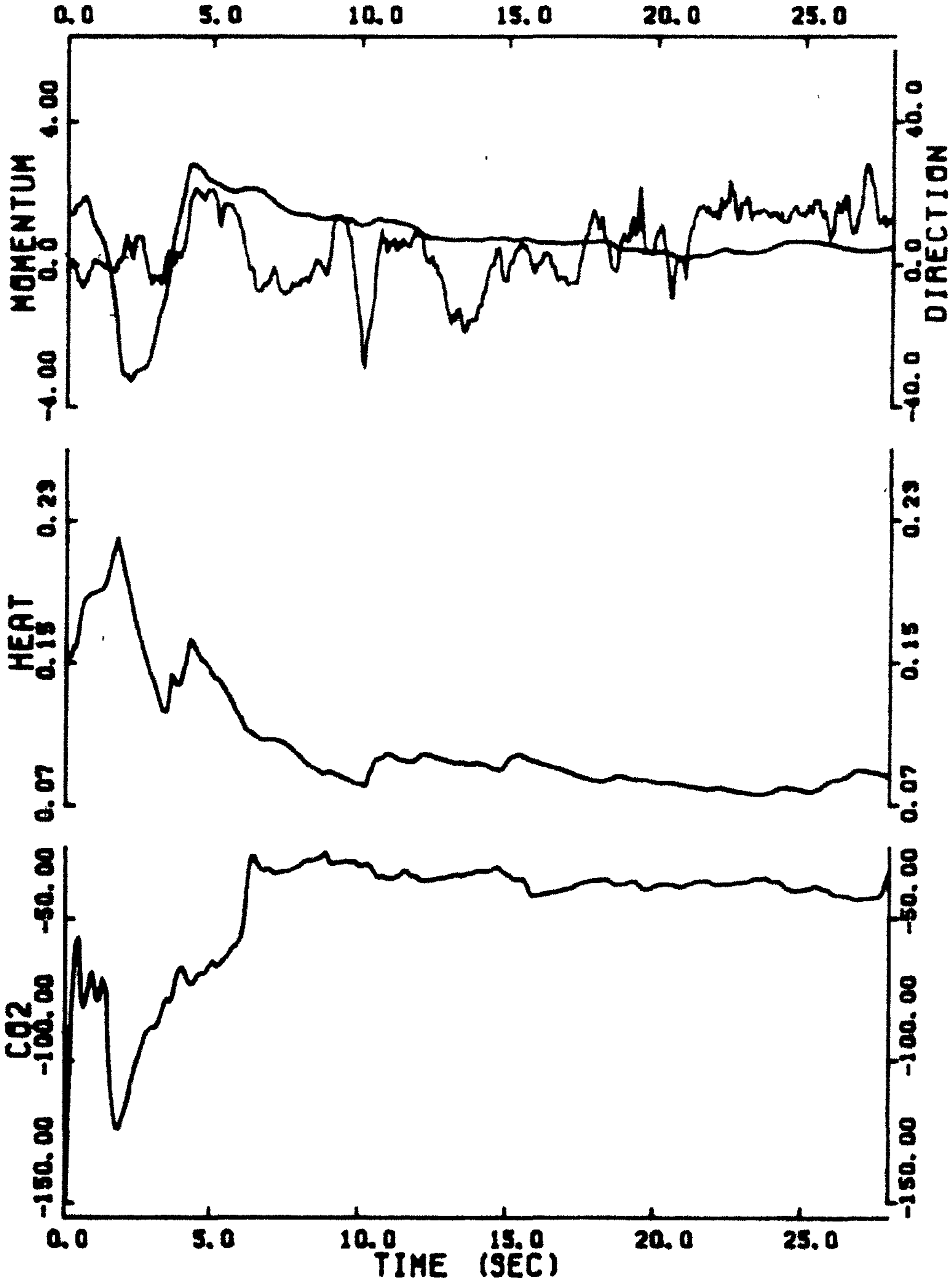
LOCATION: [illegible]
RUN = 4


CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 28.8M
AIRSPEED:58.7 M/SEC
RMS VALUE OF DELTAM: 2.80
MOMENTUM
DIRECTION
HEAT
CO2
TIME (SEC)
0.0
5.0
10.0
15.0
20.0
25.0
-0.40
-1.40
-2.40
50.0
10.0
-30.0
0.0
-0.20
-0.40
RUN = 5

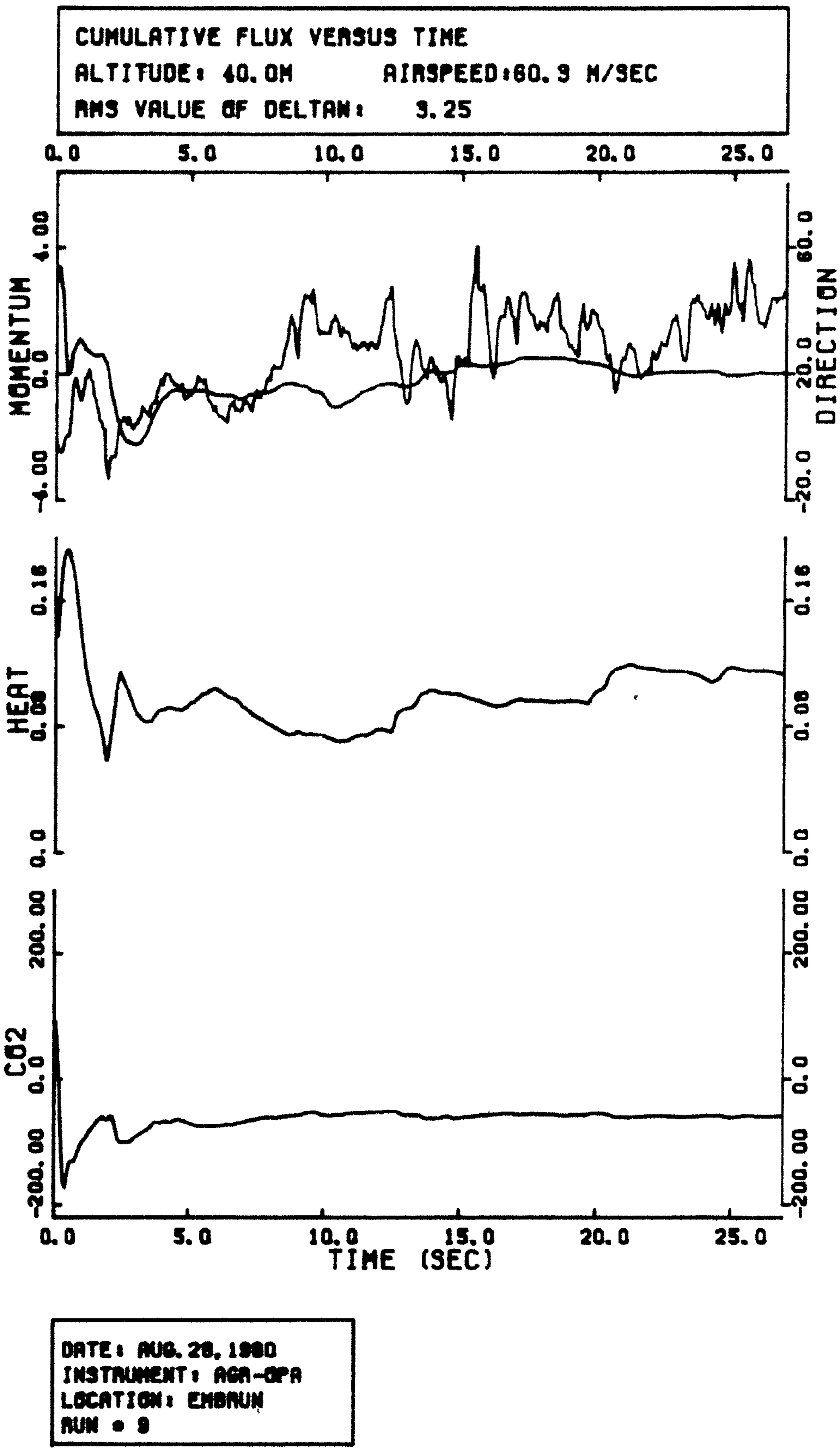

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 30.4M
AIRSPEED:59.1 M/SEC
RMS VALUE OF DELTAW: 2.88
MOMENTUM
DIRECTION
HEAT
CO2
TIME (SEC)
DATE:
INSTRUMENT:
LOCATION:
RUN

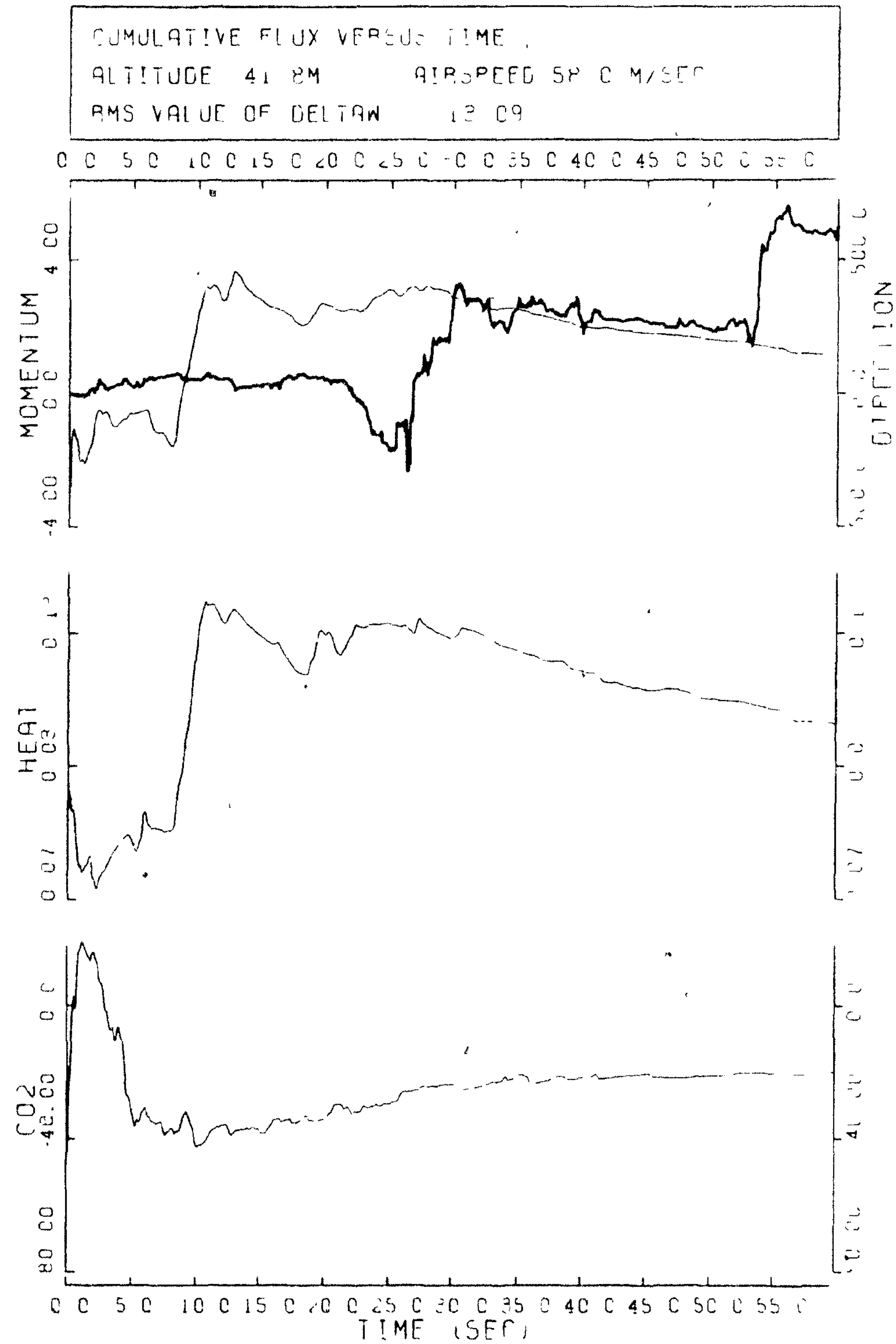

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 30.5M AIRSPEED:57.5 M/SEC
RMS VALUE OF DELTAW: 2.92
0.0 5.0 10.0 15.0 20.0 25.0
MOMENTUM
DIRECTION
0.0
-8.00
-16.00
40.0
0.0
-40.0
HEAT
0.20
0.0
-0.20
CO2
-10.00
-90.00
-170.00
TIME (SEC)
DATE: AUG. 28, 1988
INSTRUMENT: AGA-EPA
LOCATION: ENDAUN
RUN = 7

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 40.7M AIRSPEED:57.4 M/SEC
RMS VALUE OF DELTAN: 2.47

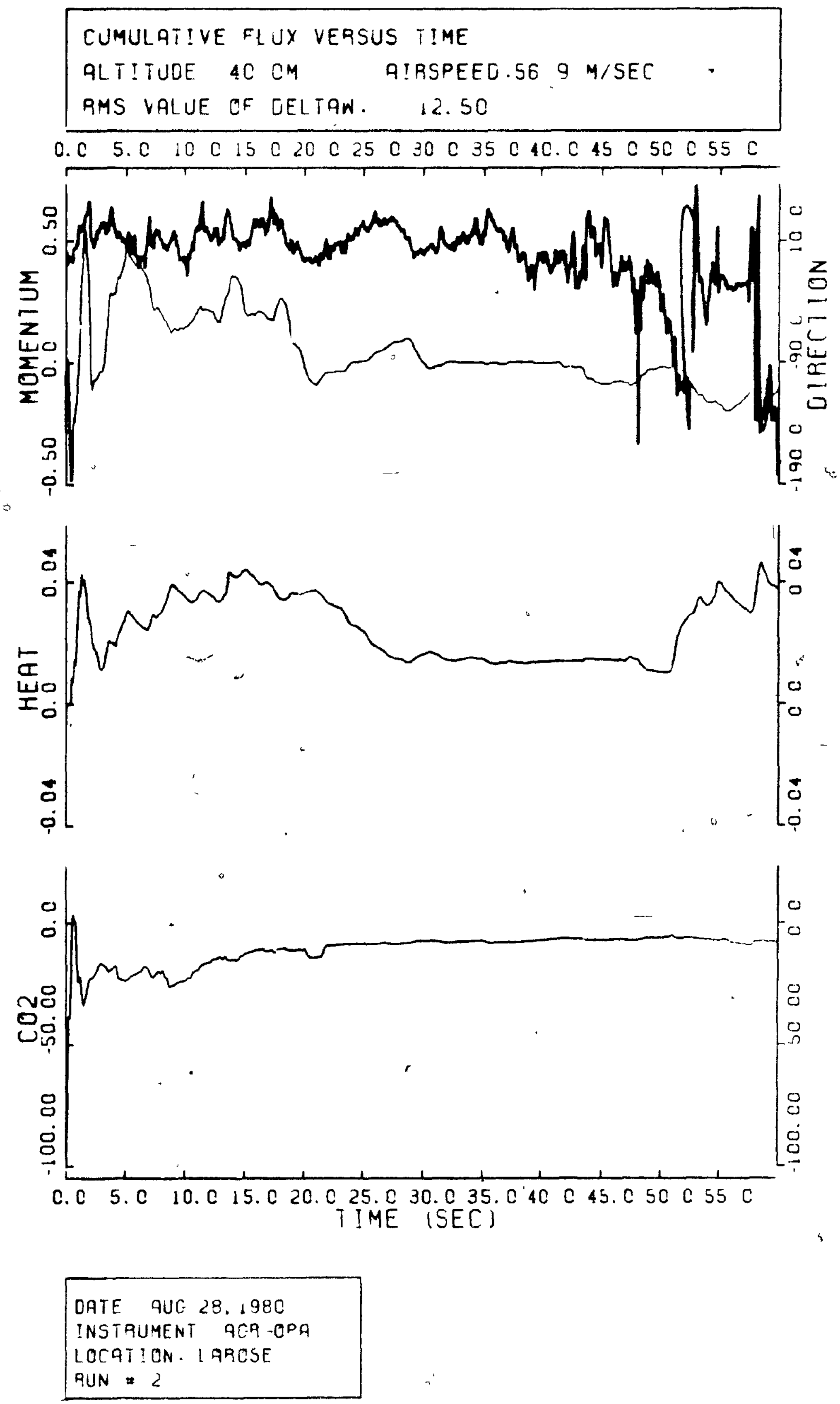


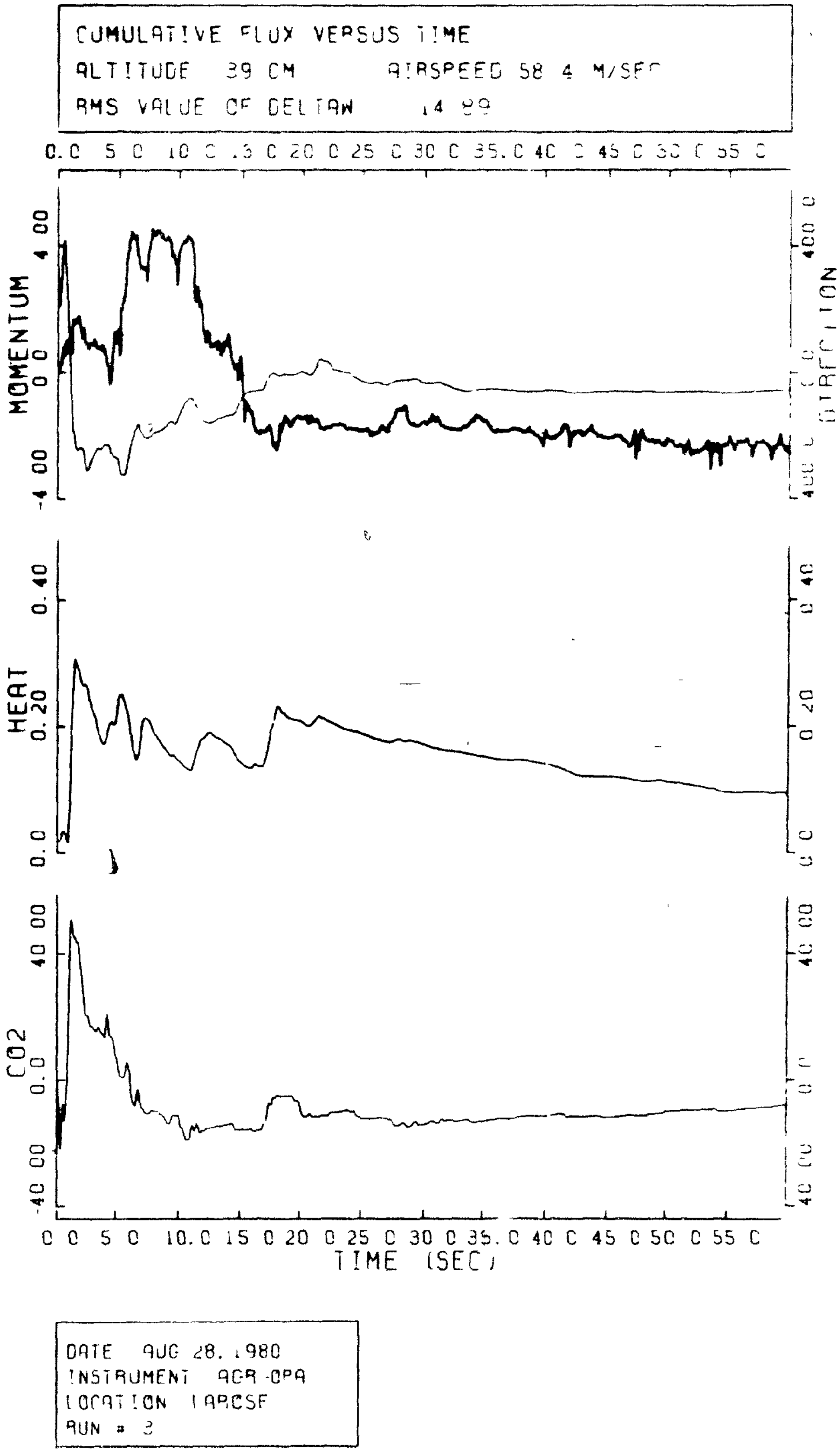
DATE: AUG.28,1980
INSTRUMENT: AGA-GPA
LOCATION: EMBRUN
RUN # 8

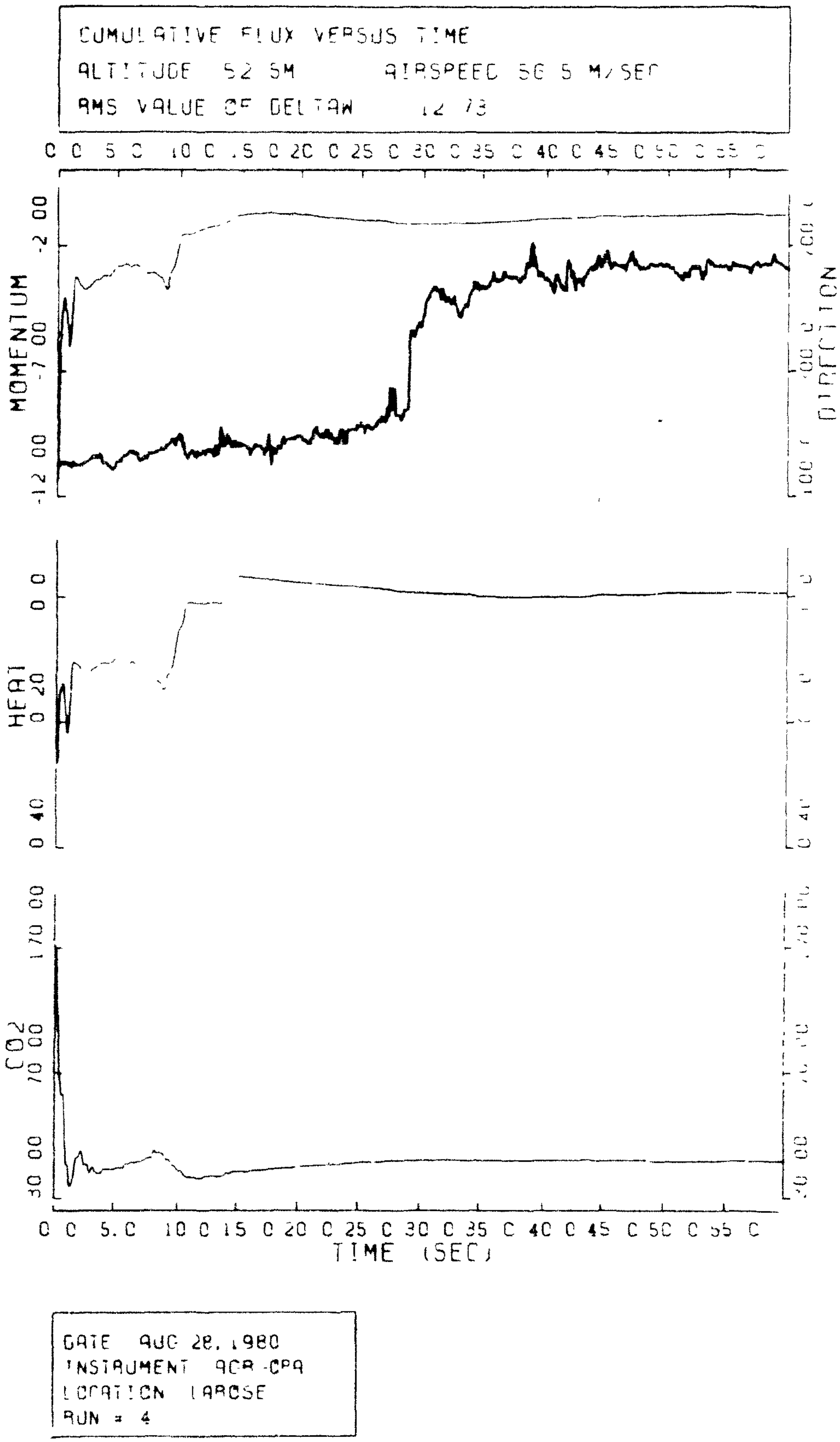

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 40.0M AIRSPEED:60.9 M/SEC
RMS VALUE OF DELTAW: 3.25
0.0 5.0 10.0 15.0 20.0 25.0
MOMENTUM
4.00
0.0
-4.00
DIRECTION
60.0
20.0
-20.0
HEAT
0.16
0.08
0.0
CO2
200.00
0.0
-200.00
TIME (SEC)
DATE: AUG.28,1980
INSTRUMENT: AGA-OPA
LOCATION: EMBRUN
RUN # 9



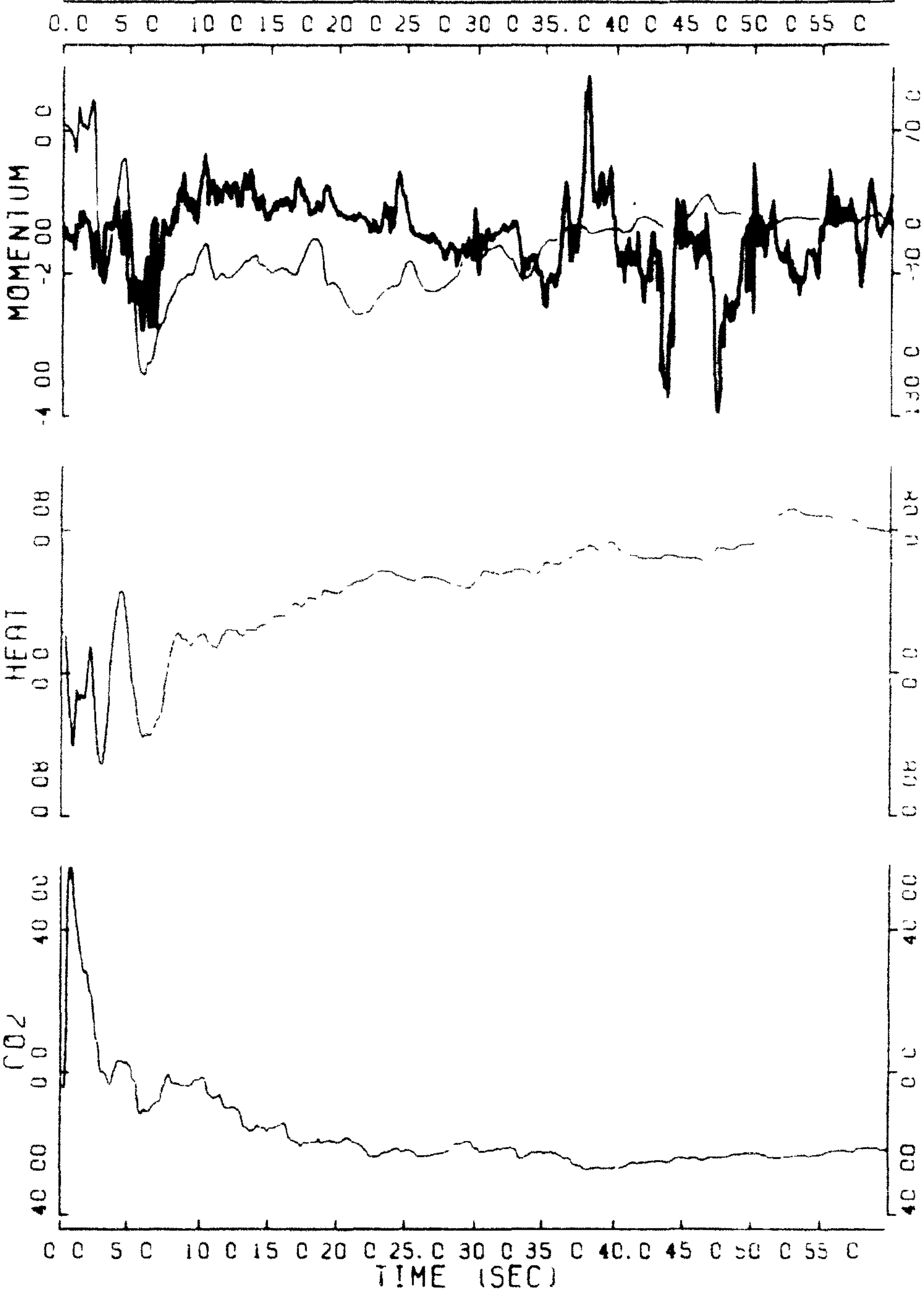
DATE AUG. 28 1980
INSTRUMENT
LOCATION
RUN #


CUMULATIVE FLUX VERSUS TIME
ALTITUDE 40 CM AIRSPEED.56 9 M/SEC
RMS VALUE OF DELTAW. 12.50
MOMENTUM
DIRECTION
HEAT
CO2
TIME (SEC)
DATE AUG 28, 1980
INSTRUMENT ACR-OPA
LOCATION. LAROSE
RUN # 2


CUMULATIVE FLUX VERSUS TIME
ALTITUDE 39 CM AIRSPEED 58 4 M/SEC
RMS VALUE OF DELTAW 14 89
MOMENTUM
DIRECTION
HEAT
CO2
TIME (SEC)
DATE AUG 28, 1980
INSTRUMENT ACR-OPA
LOCATION LARCSF
RUN # 3

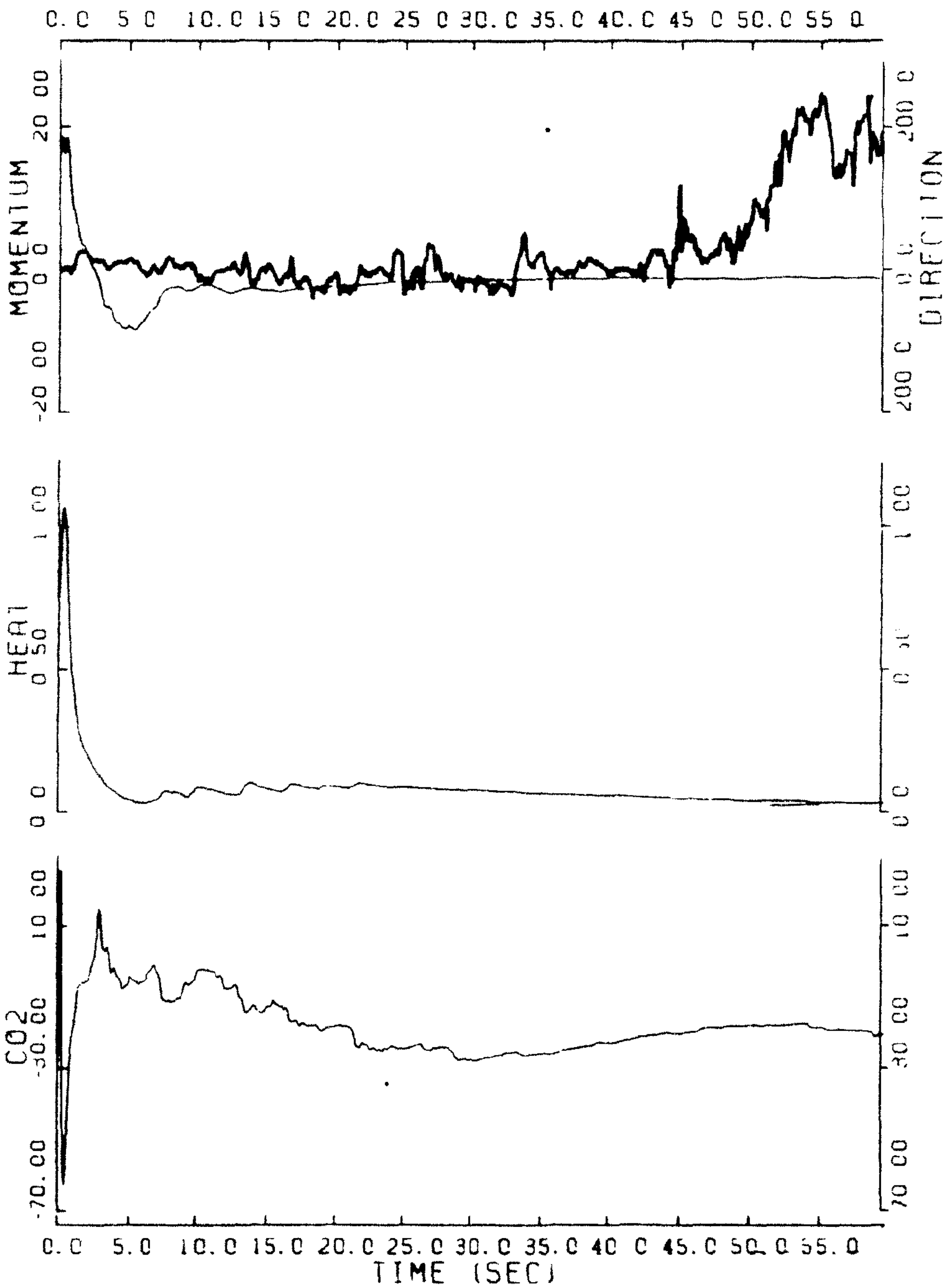

CUMULATIVE FLUX VERSUS TIME
ALTITUDE
AIRSPEED
RMS VALUE OF DELTAW
MOMENTUM
DIRECTION
HEAT
CO2
TIME (SEC)
DATE AUG 28, 1980
INSTRUMENT
LOCATION
RUN = 4

CUMULATIVE FLUX VERSUS TIME
ALTITUDE 56 9M   AIRSPEED 56 2 M/SEC
RMS VALUE OF DELTAW · 9.21

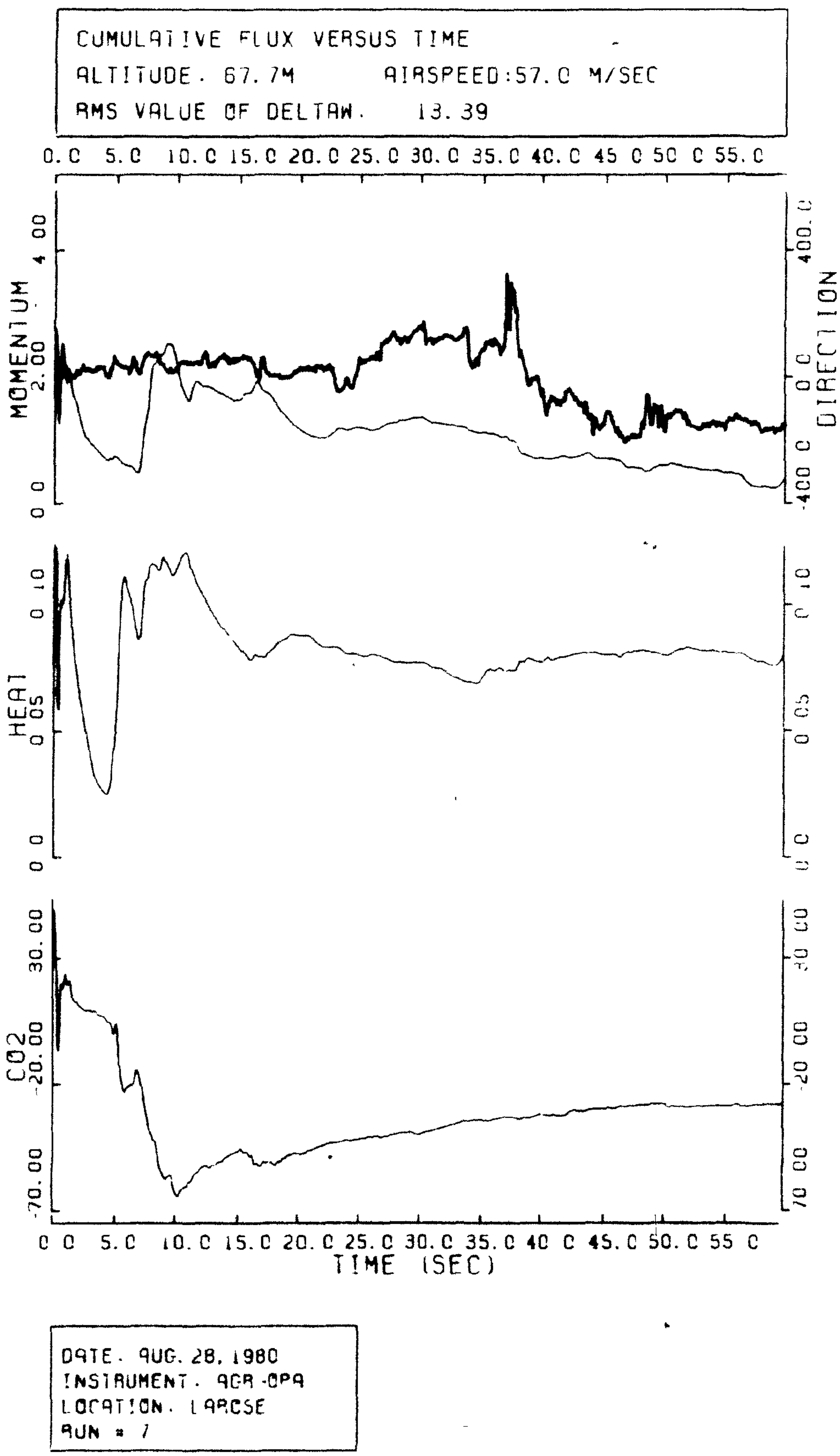


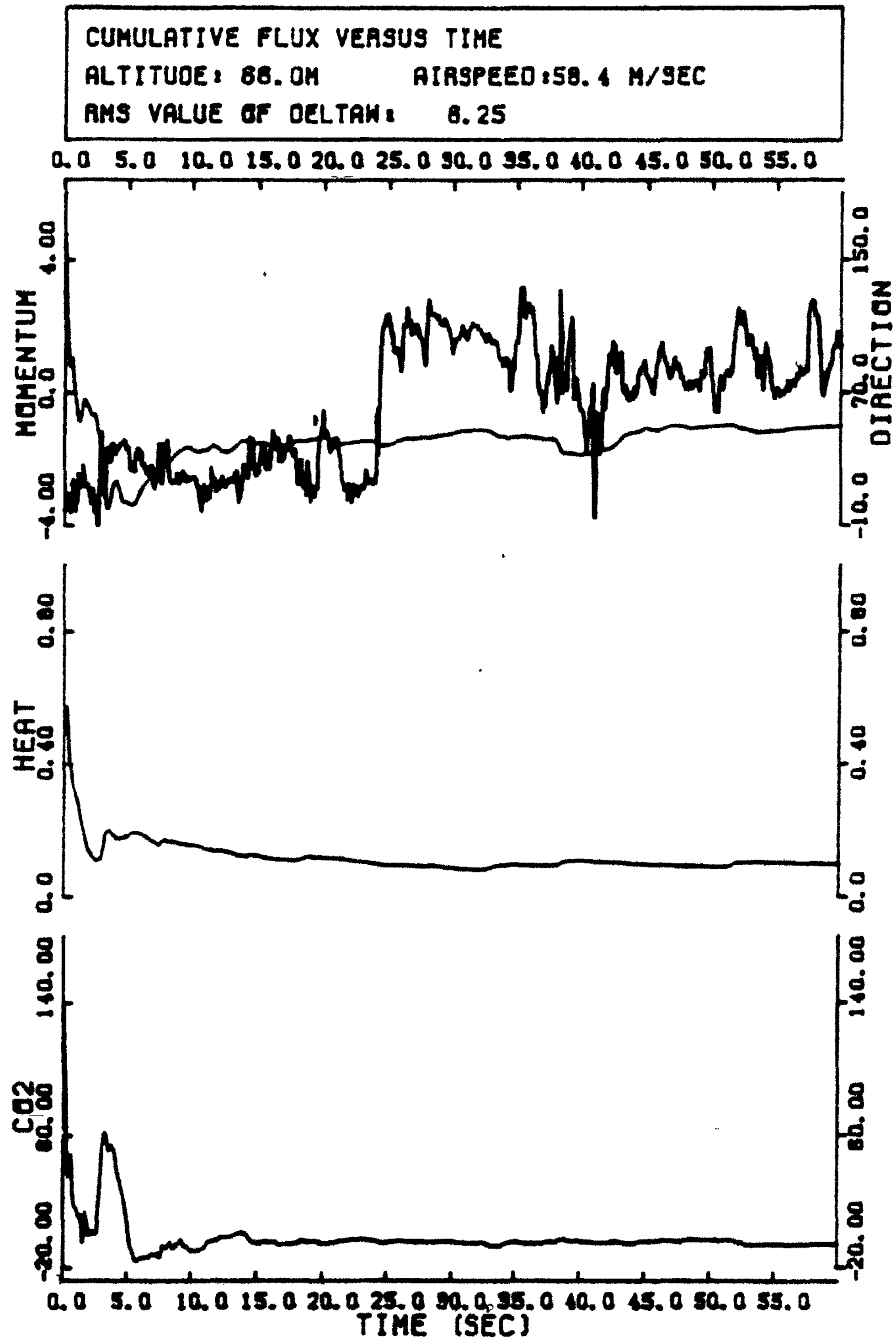
DATE AUG 28, 1980
INSTRUMENT AGA-CPA
LOCATION. LAROSE
RUN = 5

CUMULATIVE FLUX VERSUS TIME
ALTITUDE 54 4M AIRSPEED 58.8 M/SEC
RMS VALUE OF DELTAW. 8.49

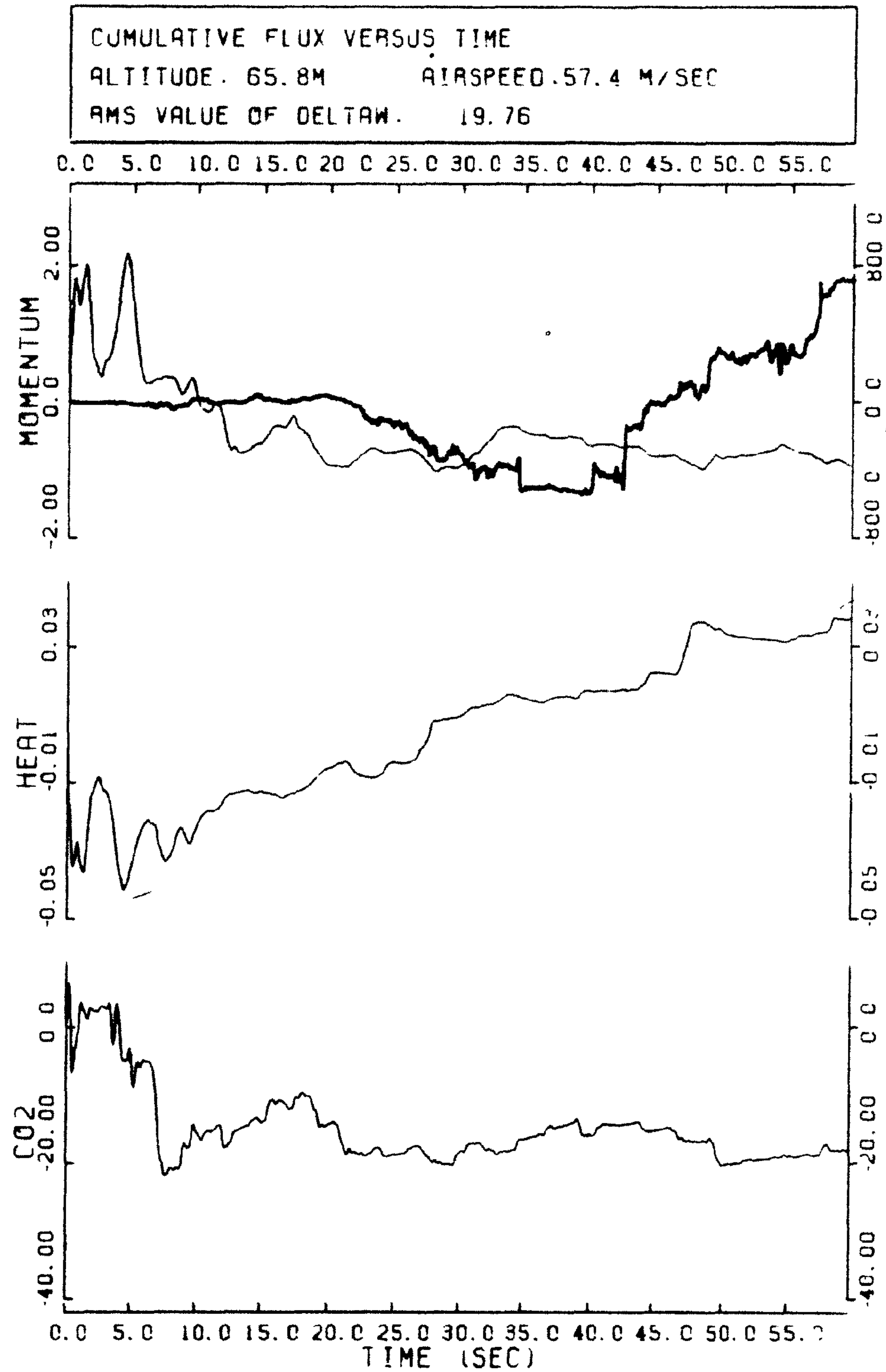


DATE AUG. 28, 1980
INSTRUMENT AGA-CPA
LOCATION. LAROSE
RUN # 6

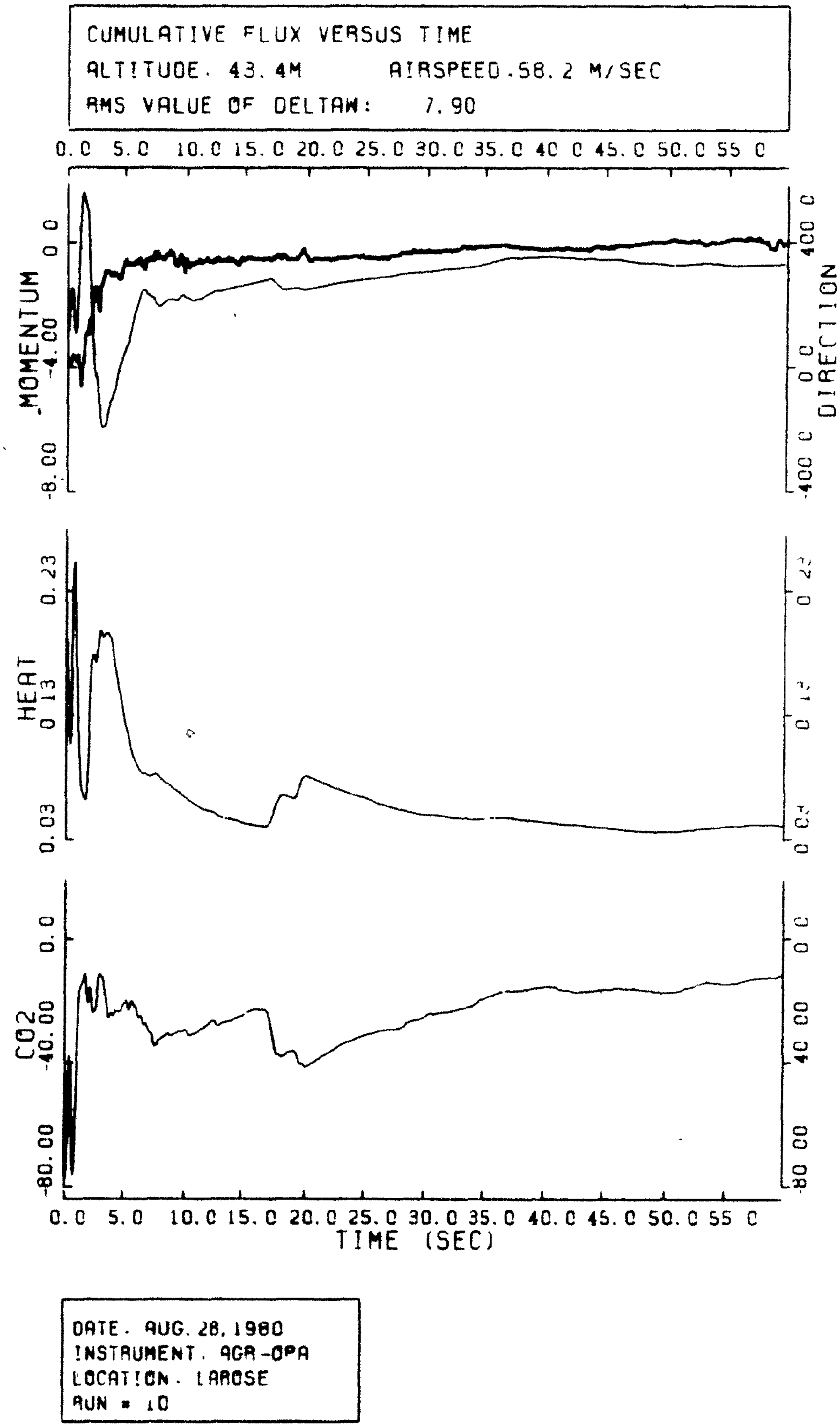

CUMULATIVE FLUX VERSUS TIME
ALTITUDE. 67.7M AIRSPEED:57.0 M/SEC
RMS VALUE OF DELTAW. 13.39
0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0 55.0
MOMENTUM
DIRECTION
HEAT
CO2
TIME (SEC)
DATE. AUG. 28, 1980
INSTRUMENT. ACR-OPA
LOCATION. LARCSE
RUN # 7

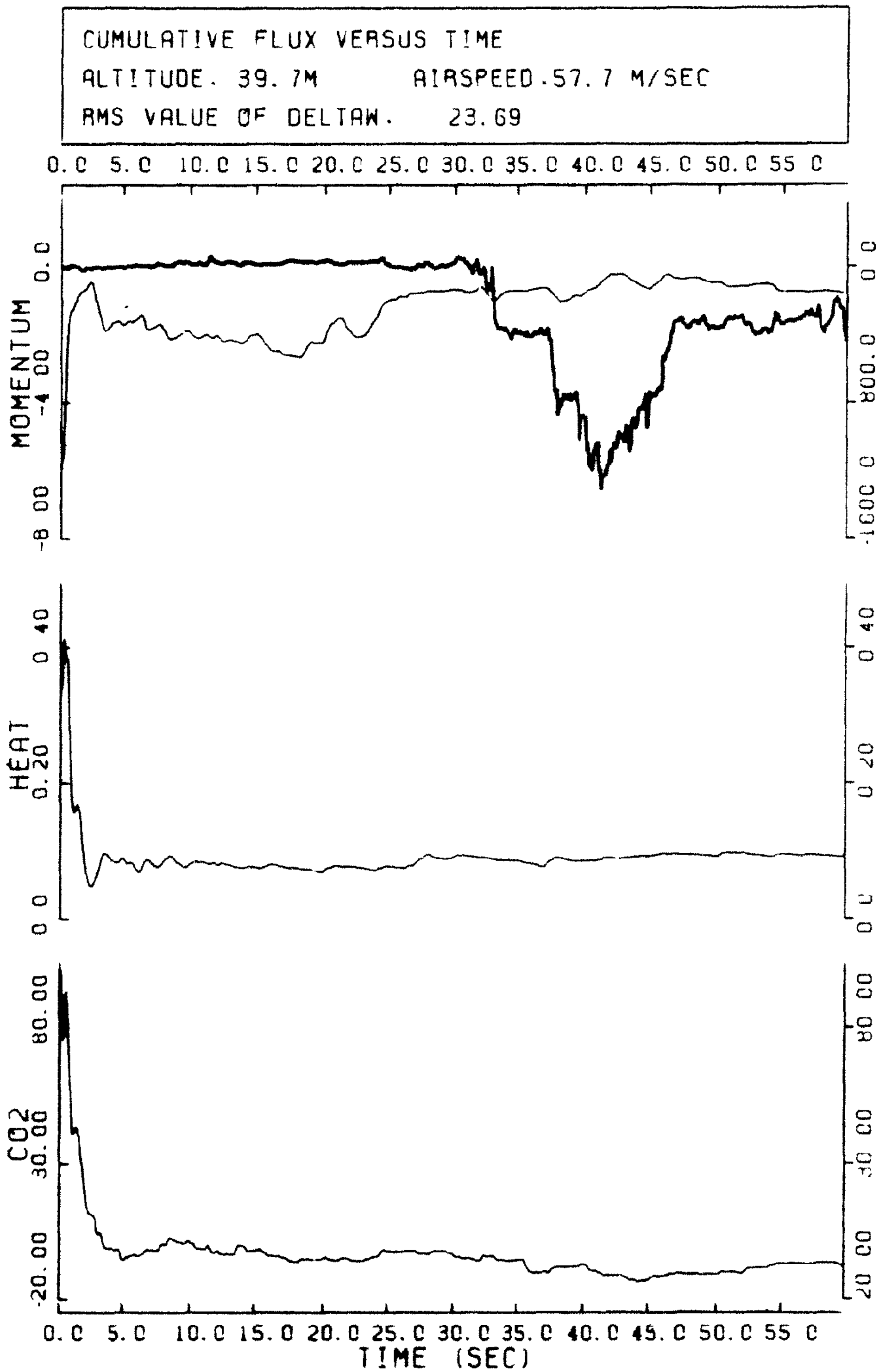


DATE: AUG. 28, 1980
INSTRUMENT: AGA-OPA
LOCATION: LAROSE
RUN # 8

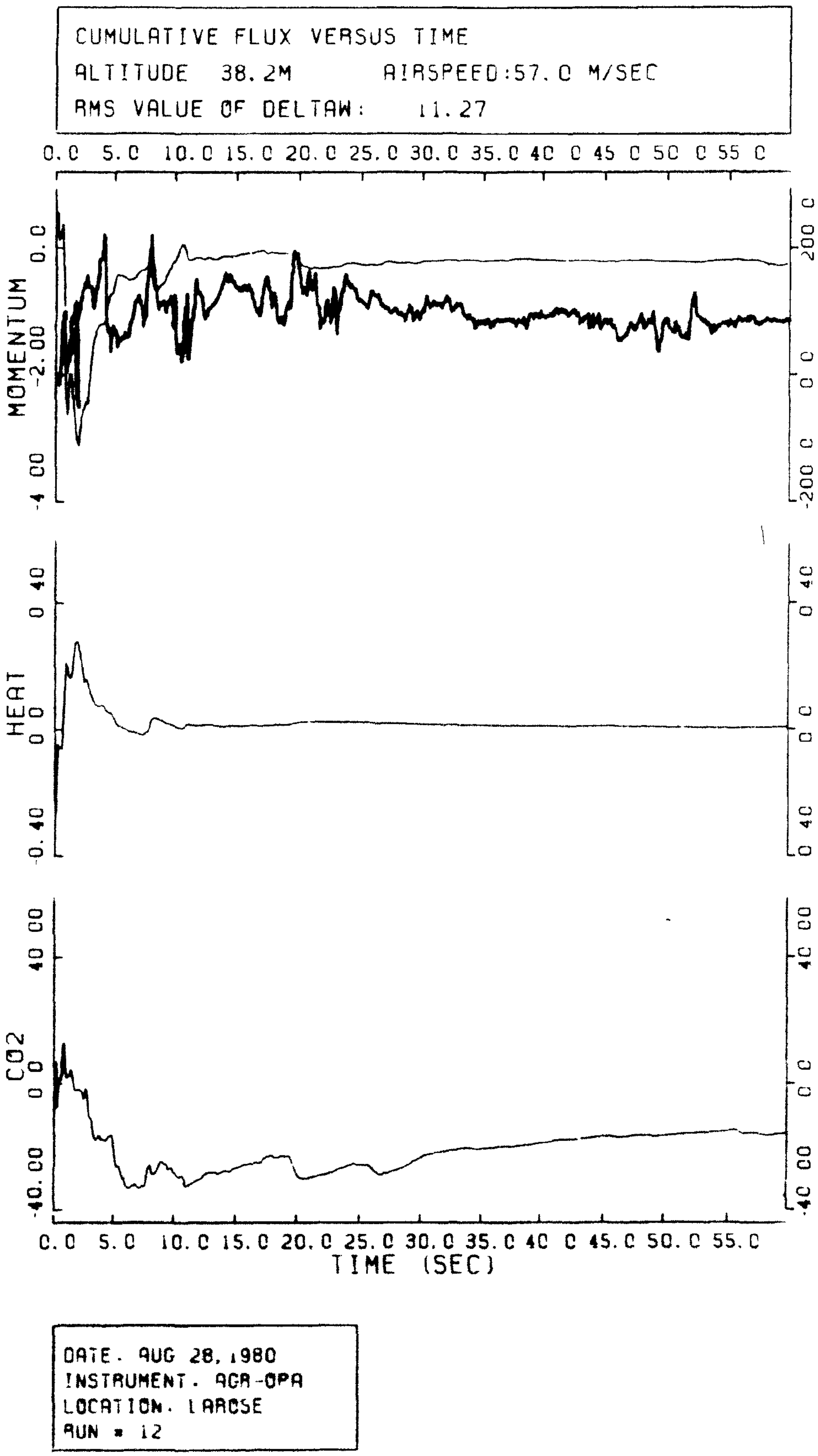


DATE. AUG. 28, 1980
INSTRUMENT. AGA-OPA
LOCATION. LAROSE
RUN = 9

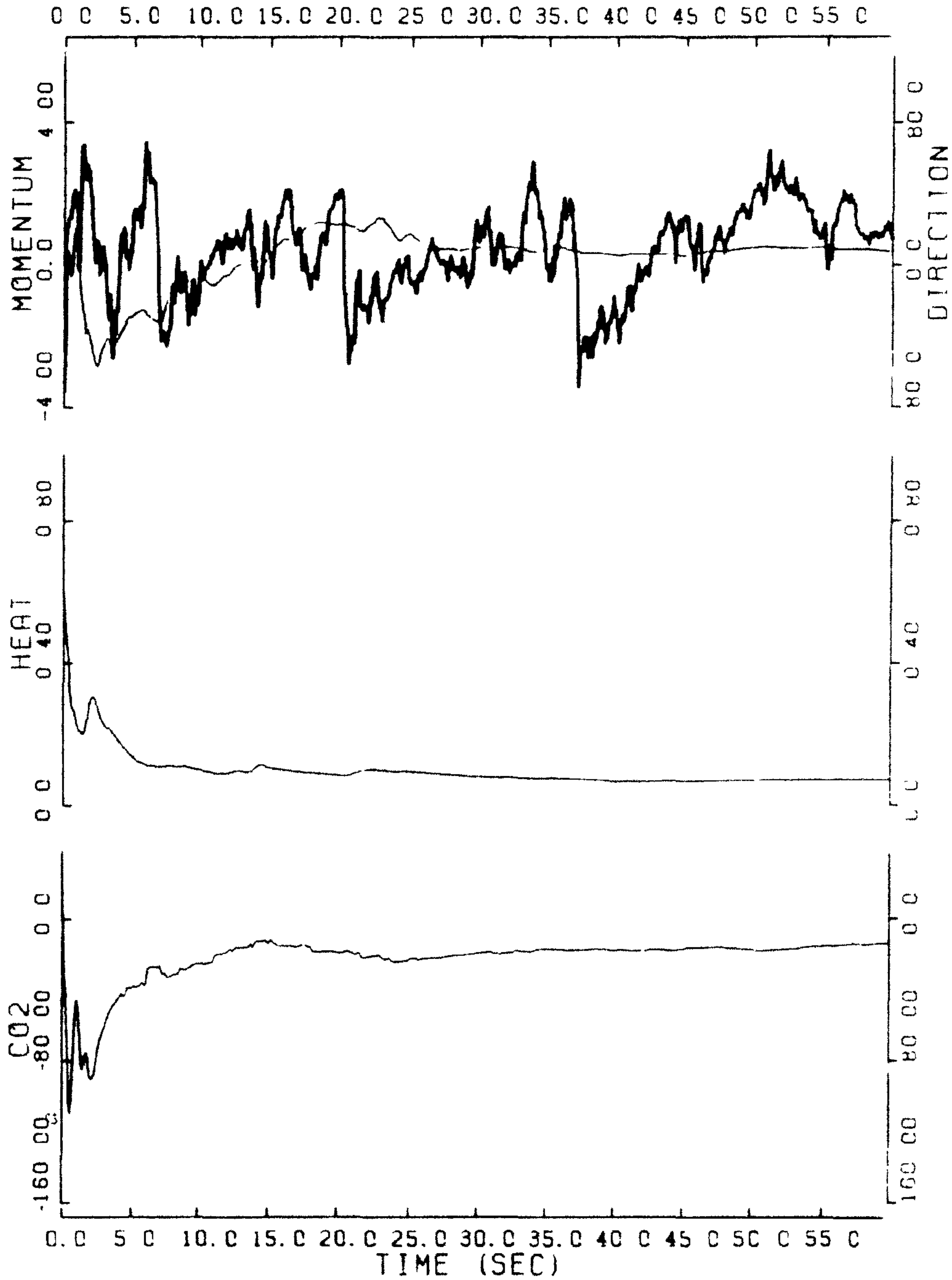

CUMULATIVE FLUX VERSUS TIME
ALTITUDE. 43.4M AIRSPEED.58.2 M/SEC
RMS VALUE OF DELTAW: 7.90
MOMENTUM
DIRECTION
HEAT
CO2
TIME (SEC)
DATE. AUG. 28, 1980
INSTRUMENT. AGA-OPA
LOCATION. LAROSE
RUN # 10



DATE. AUG. 28, 1980
INSTRUMENT. AGA-OPA
LOCATION. LAROSE
RUN # 11

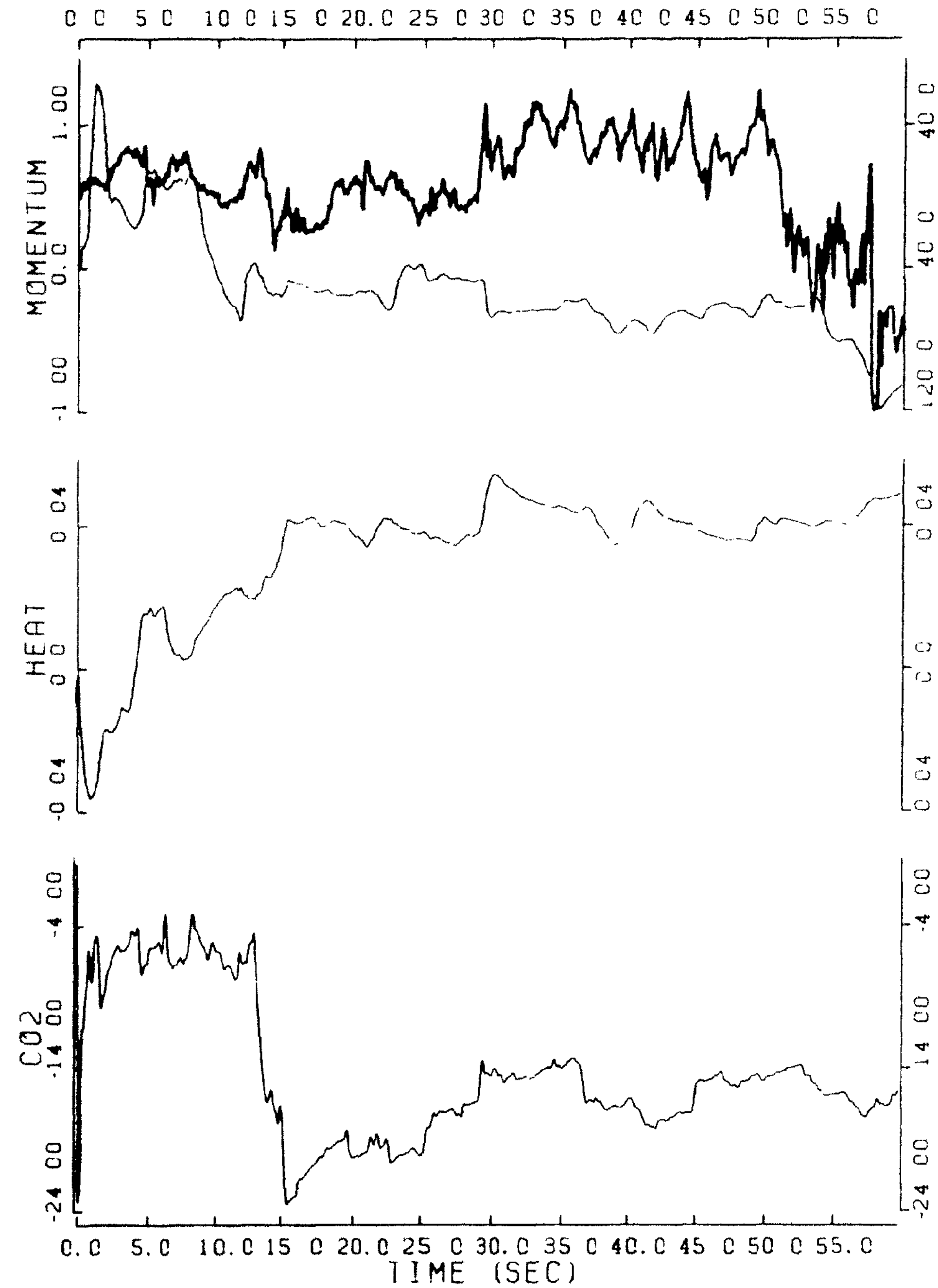

CUMULATIVE FLUX VERSUS TIME
ALTITUDE 38.2M AIRSPEED:57.0 M/SEC
RMS VALUE OF DELTAW: 11.27
MOMENTUM
DIRECTION
HEAT
CO2
TIME (SEC)
DATE. AUG 28, 1980
INSTRUMENT. AGA-OPA
LOCATION. LARCSE
RUN # 12

CUMULATIVE FLUX VERSUS TIME
ALTITUDE. 52.2M AIRSPEED.57.0 M/SEC
RMS VALUE OF DELTAW. 5.88

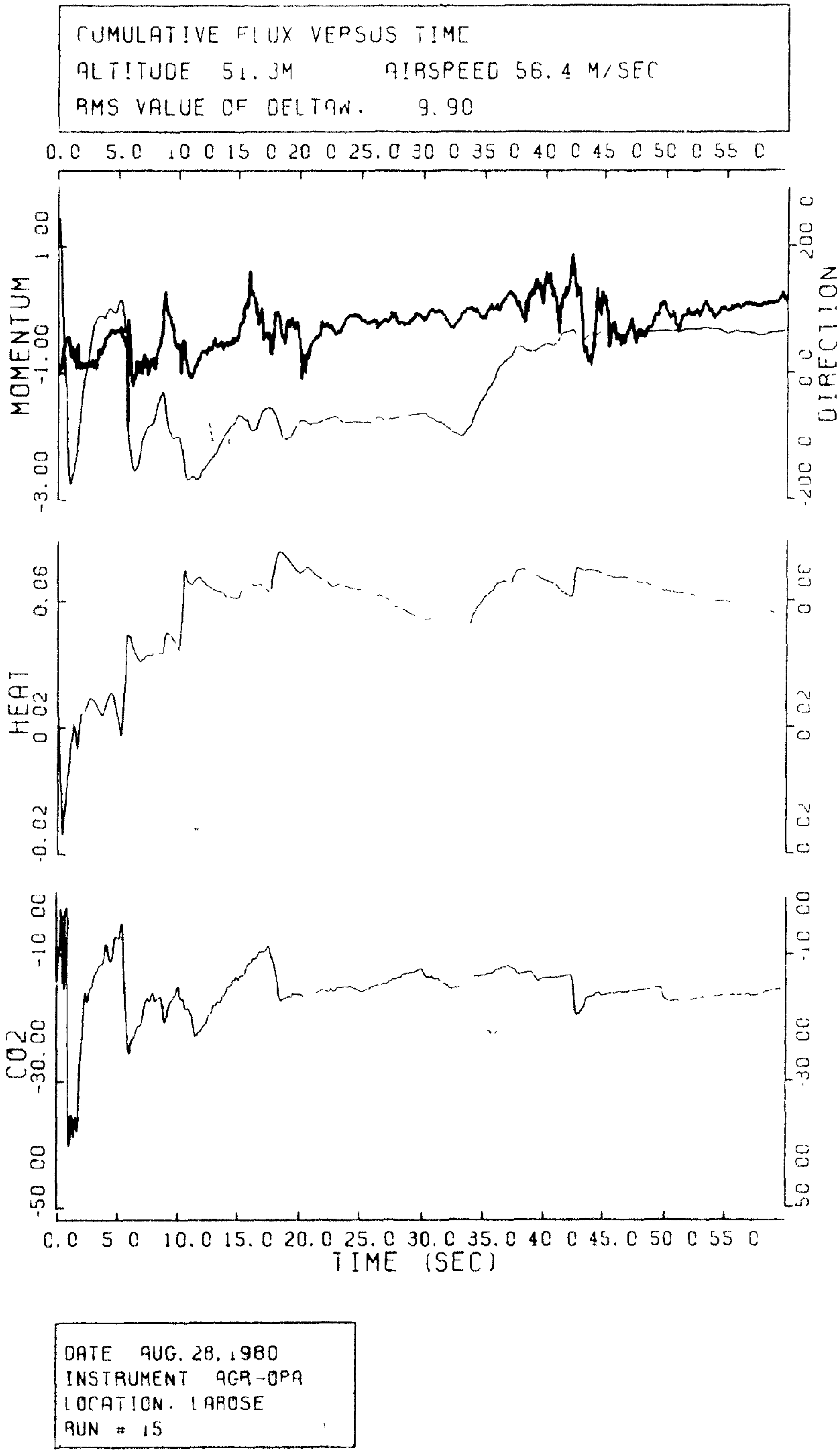


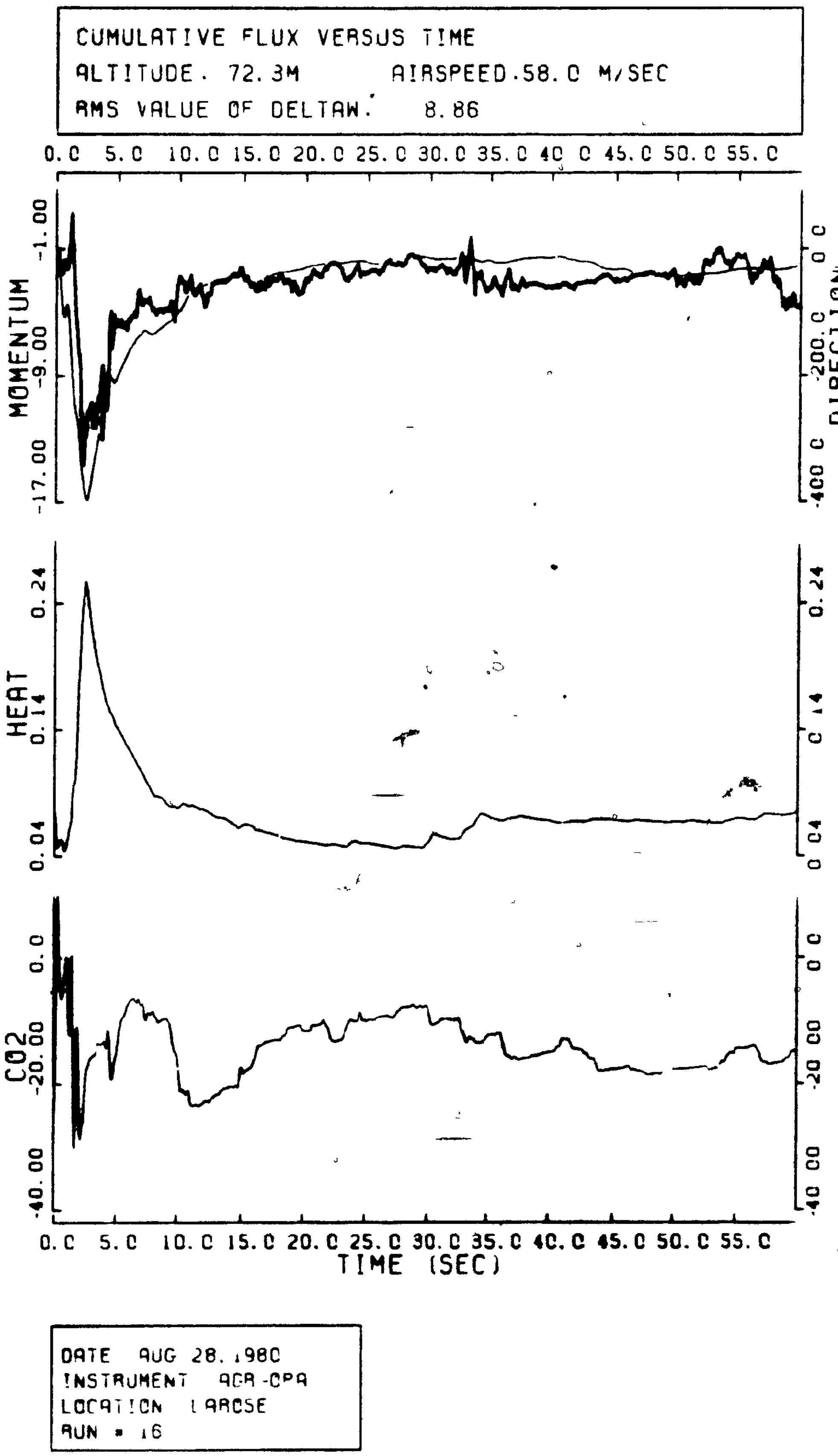
DATE. AUG. 28, 1980
INSTRUMENT. ACR-OPA
LOCATION. LAROSE
RUN * 13

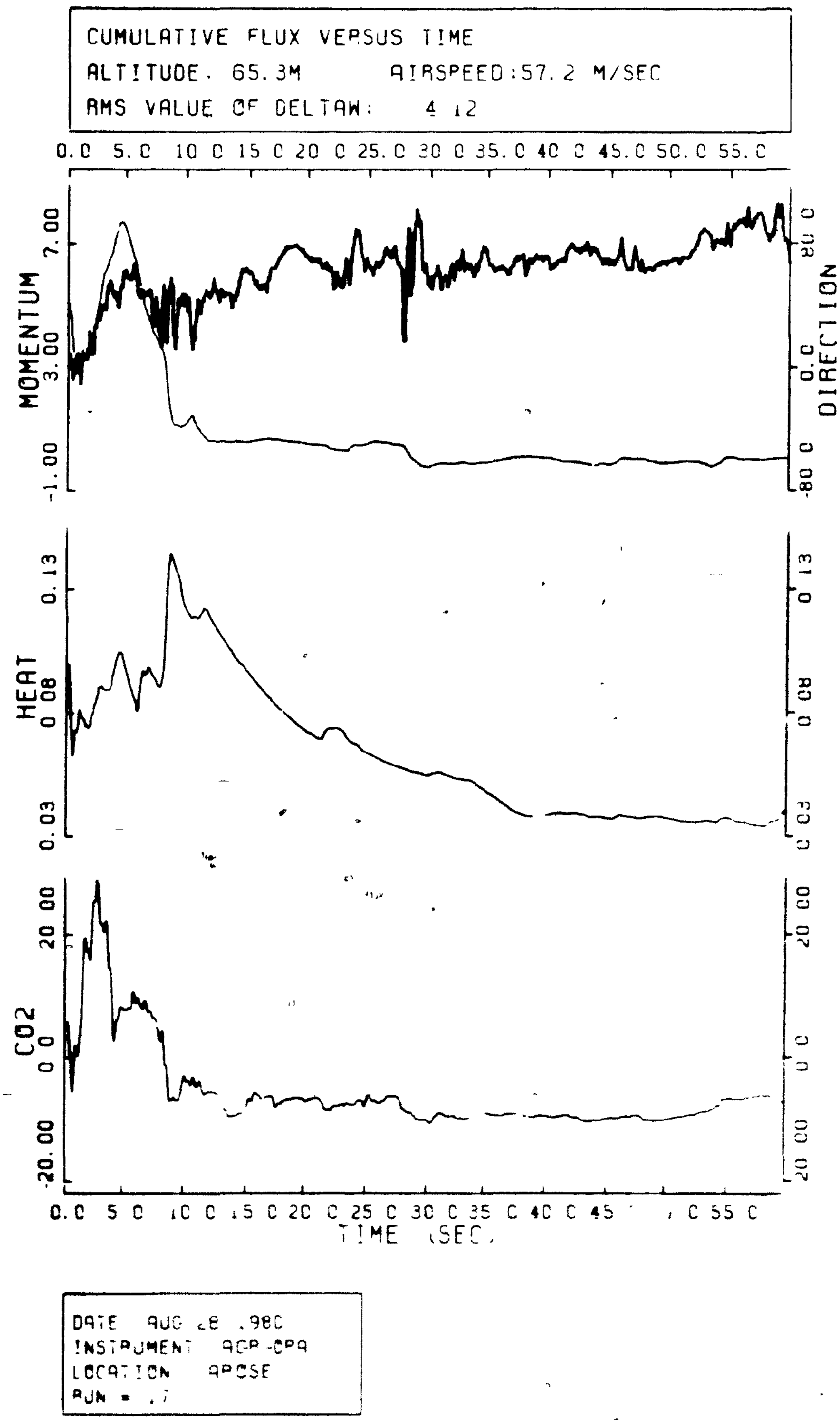
CUMULATIVE FLUX VERSUS TIME
ALTITUDE 54 7M AIRSPEED 55 6 M/SEC
RMS VALUE OF DELTAW. 5.59

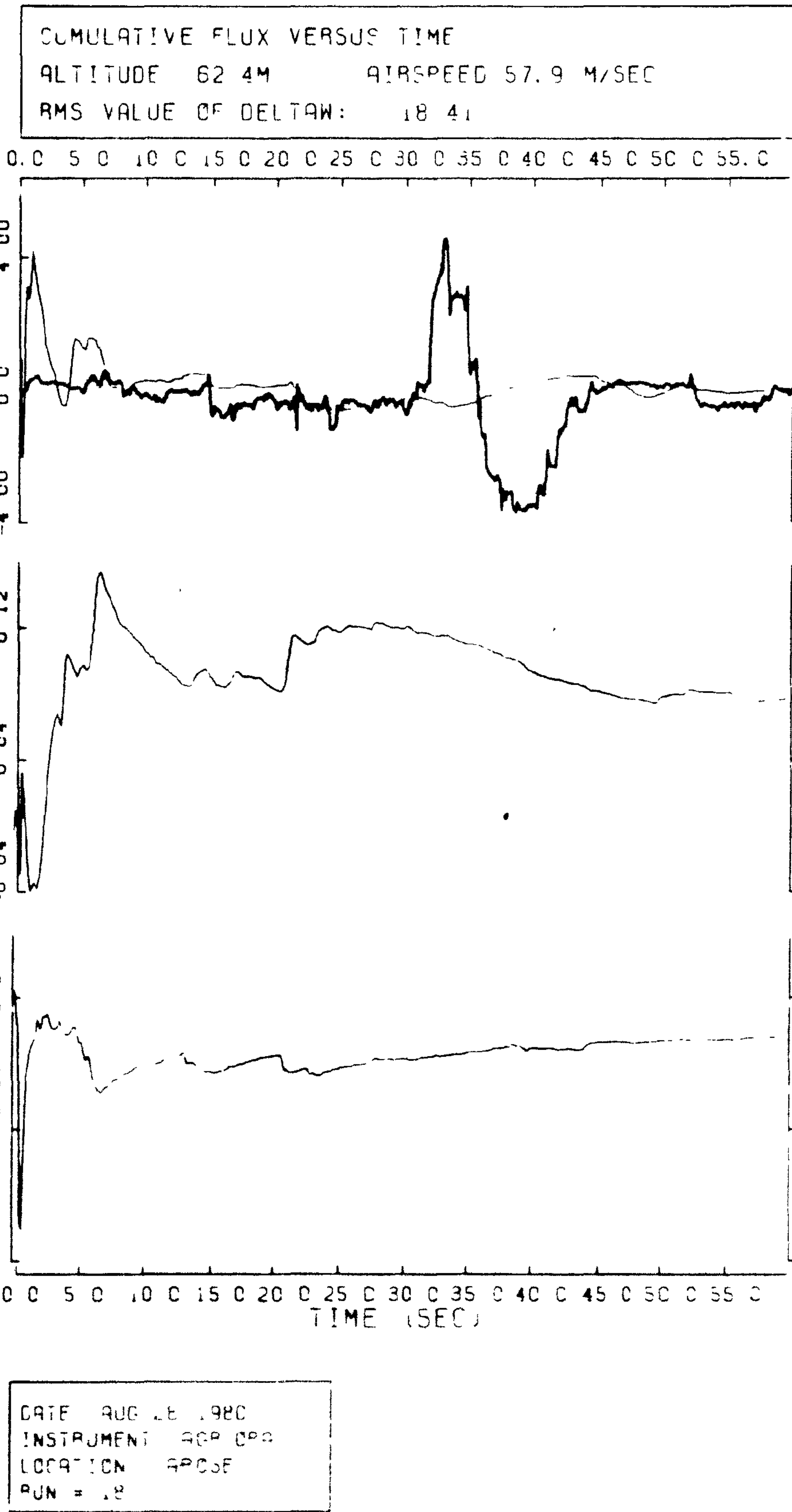


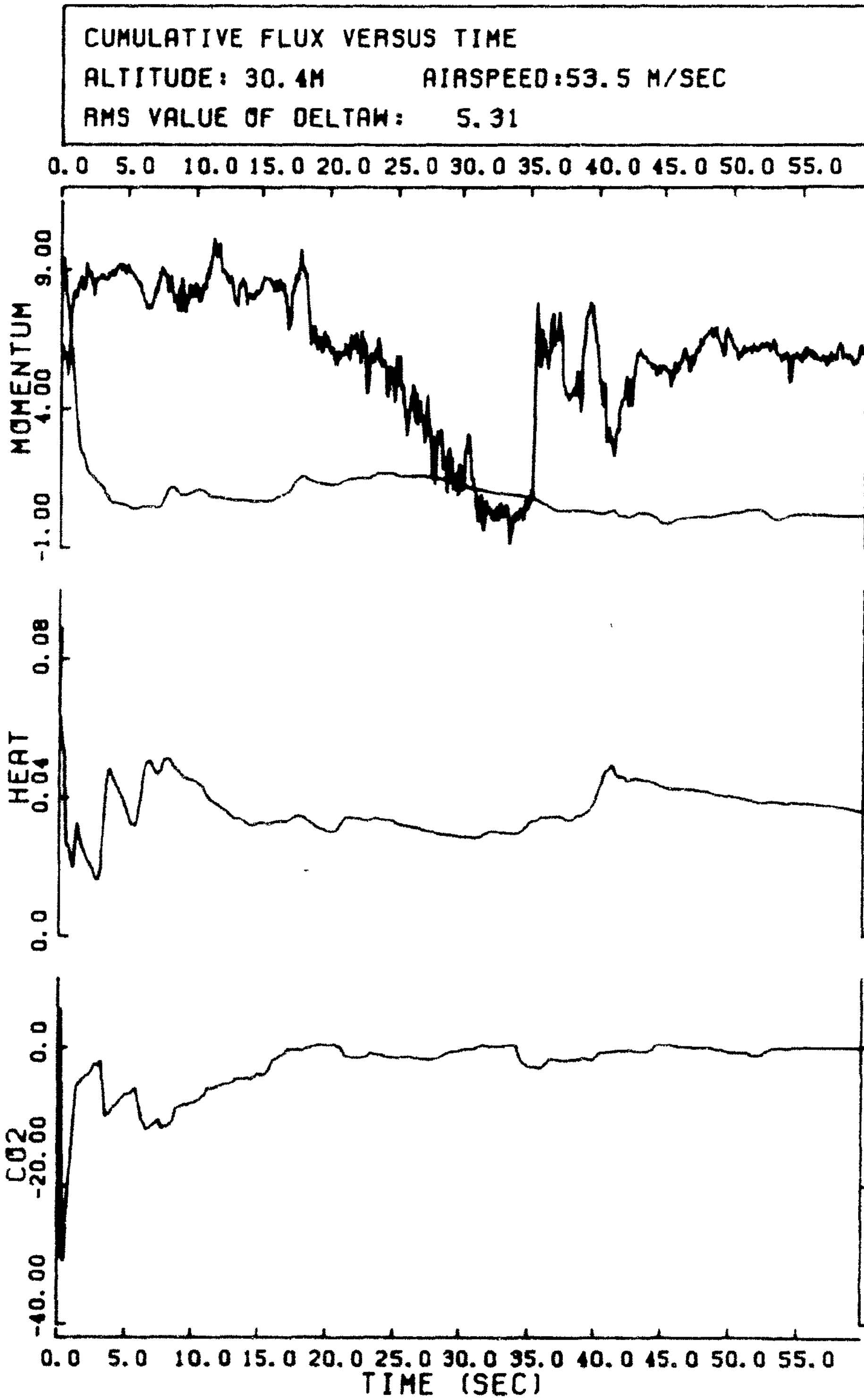
DATE AUG 28,1980
INSTRUMENT AGR-CPA
LOCATION. LAROSE
RUN # 14


CUMULATIVE FLUX VERSUS TIME
ALTITUDE 51.3M
AIRSPEED 56.4 M/SEC
RMS VALUE OF DELTAW. 9.90
0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0 55.0
MOMENTUM
1.00
-1.00
-3.00
DIRECTION
200.0
0.0
-200.0
HEAT
0.06
0.02
-0.02
CO2
-10.00
-30.00
-50.00
TIME (SEC)
DATE AUG. 28, 1980
INSTRUMENT AGR-OPA
LOCATION. LAROSE
RUN # 15


CUMULATIVE FLUX VERSUS TIME
ALTITUDE. 72.3M AIRSPEED.58.0 M/SEC
RMS VALUE OF DELTAW. 8.86
0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0 55.0
MOMENTUM
-1.00
-9.00
-17.00
DIRECTION
0.0
-200.0
-400.0
HEAT
0.24
0.14
0.04
CO2
0.0
-20.00
-40.00
TIME (SEC)
DATE AUG 28, 1980
INSTRUMENT AGA-CPA
LOCATION LAROSE
RUN # 16

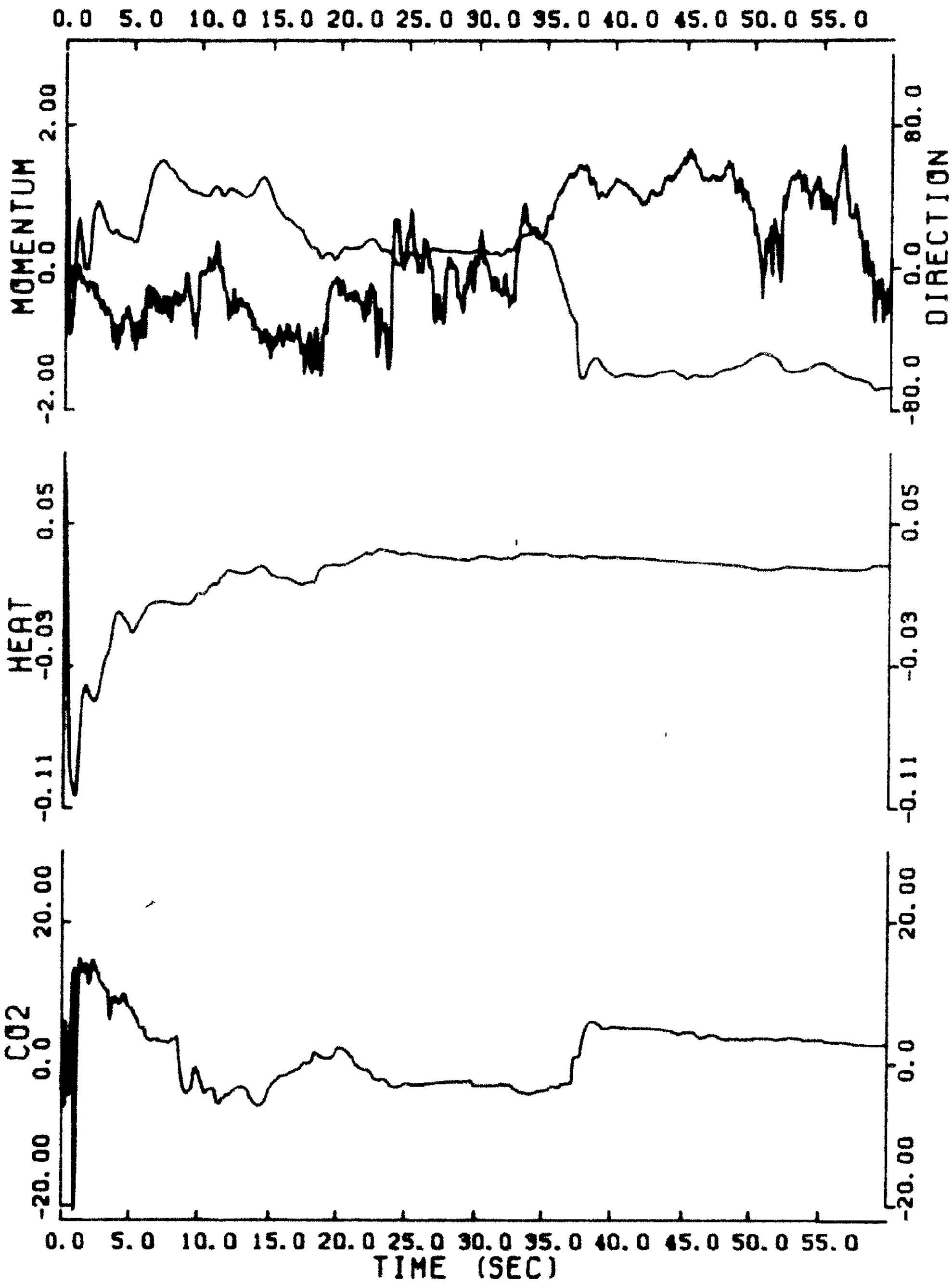

CUMULATIVE FLUX VERSUS TIME
ALTITUDE. 65.3M AIRSPEED:57.2 M/SEC
RMS VALUE OF DELTAW: 4.12
MOMENTUM
DIRECTION
HEAT
CO2
TIME (SEC)
DATE AUG 28 1980
INSTRUMENT AGR-CPA
LOCATION ARCSE
RUN = 17


CUMULATIVE FLUX VERSUS TIME
ALTITUDE 62 4M
AIRSPEED 57.9 M/SEC
RMS VALUE OF DELTAW: 18 41
MOMENTUM
DIRECTION
HEAT
CO2
TIME (SEC)

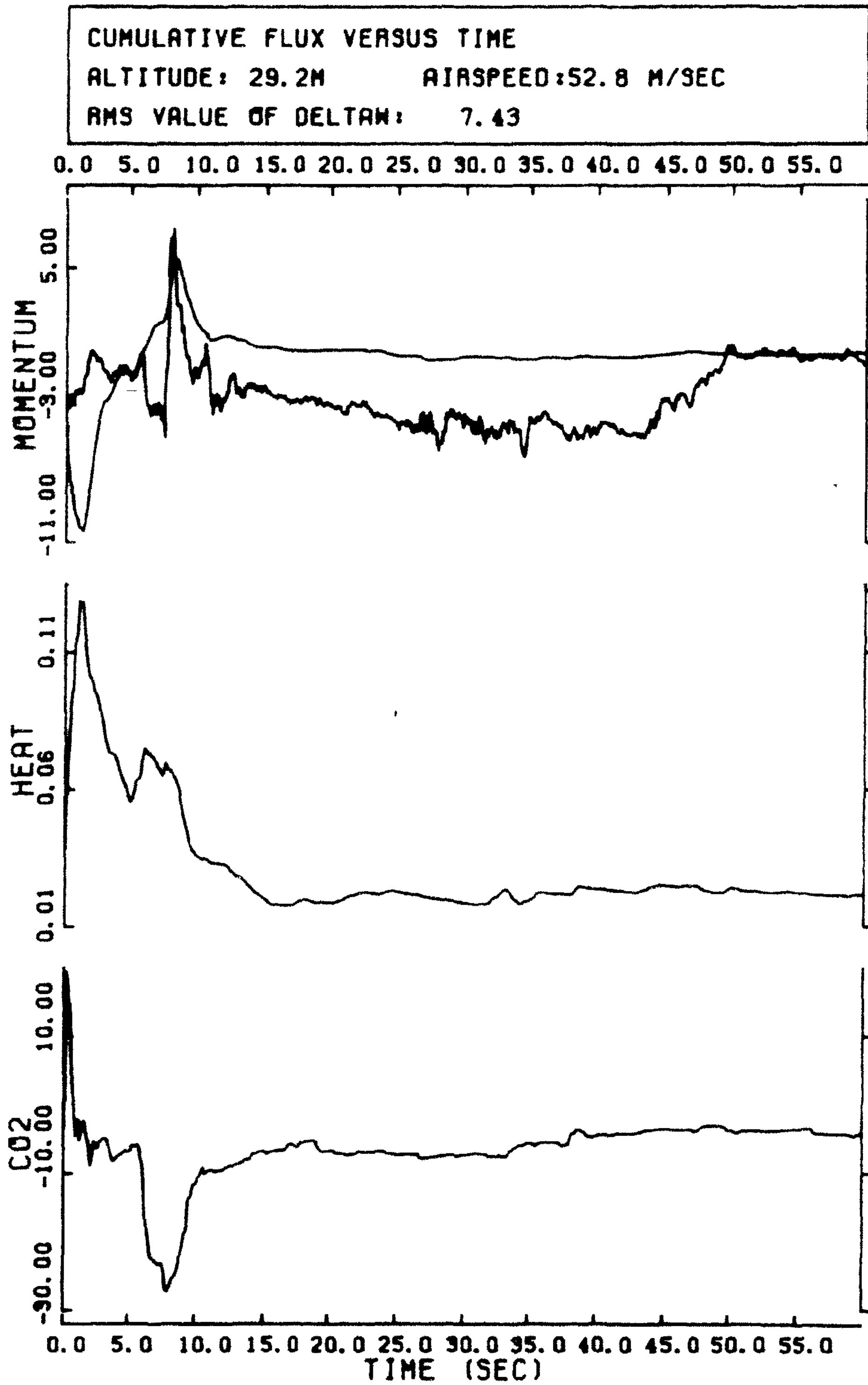


DATE: AUG. 28, 1980
INSTRUMENT: AGA-OPA
LOCATION: LAC DESCHENES
RUN # 1

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 28.1M AIRSPEED:53.3 M/SEC
RMS VALUE OF DELTAW: 5.23

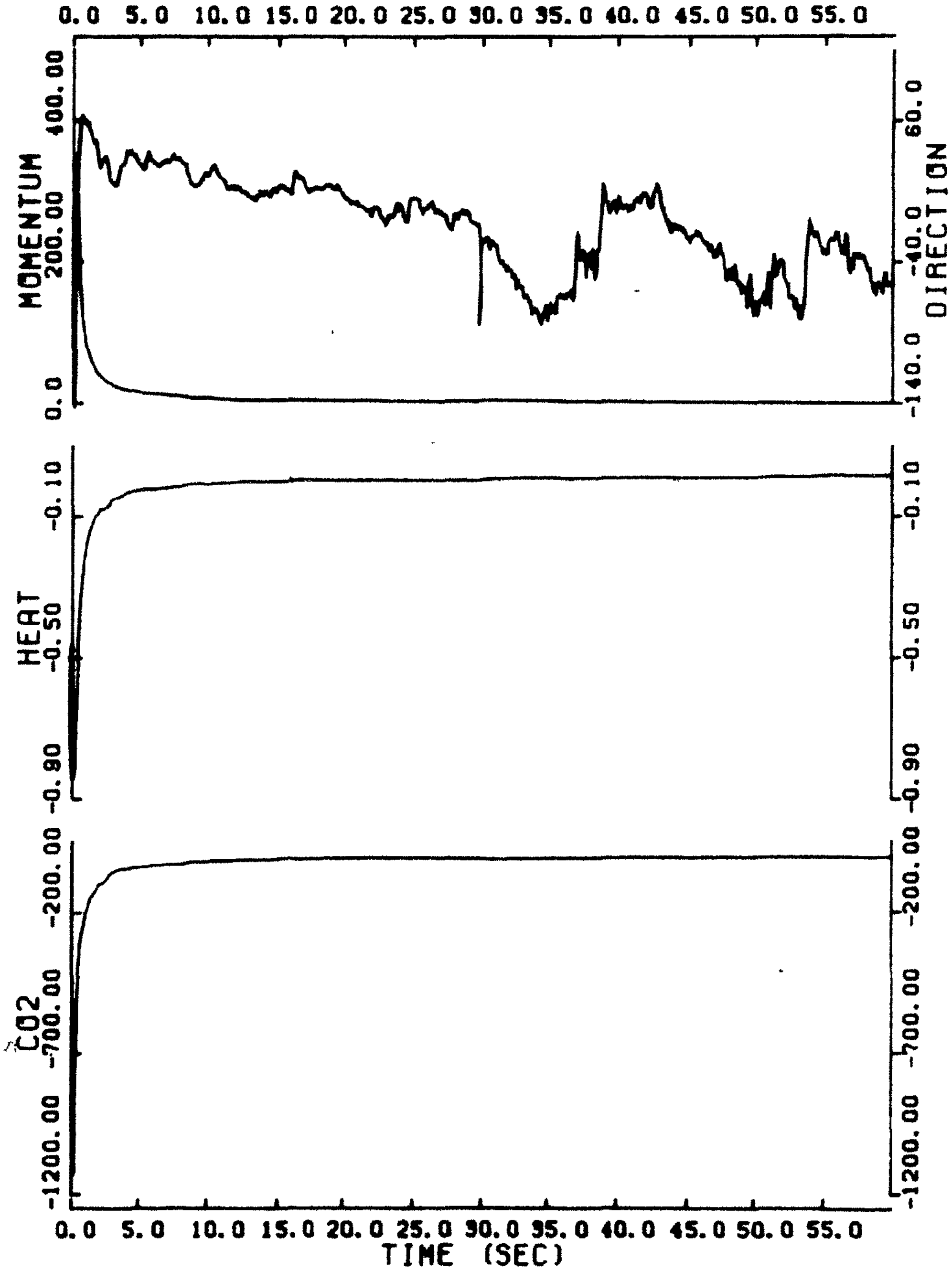


DATE: AUG. 28, 1980
INSTRUMENT: AGA-OPA
LOCATION: LAC DESCHENES
RUN # 2



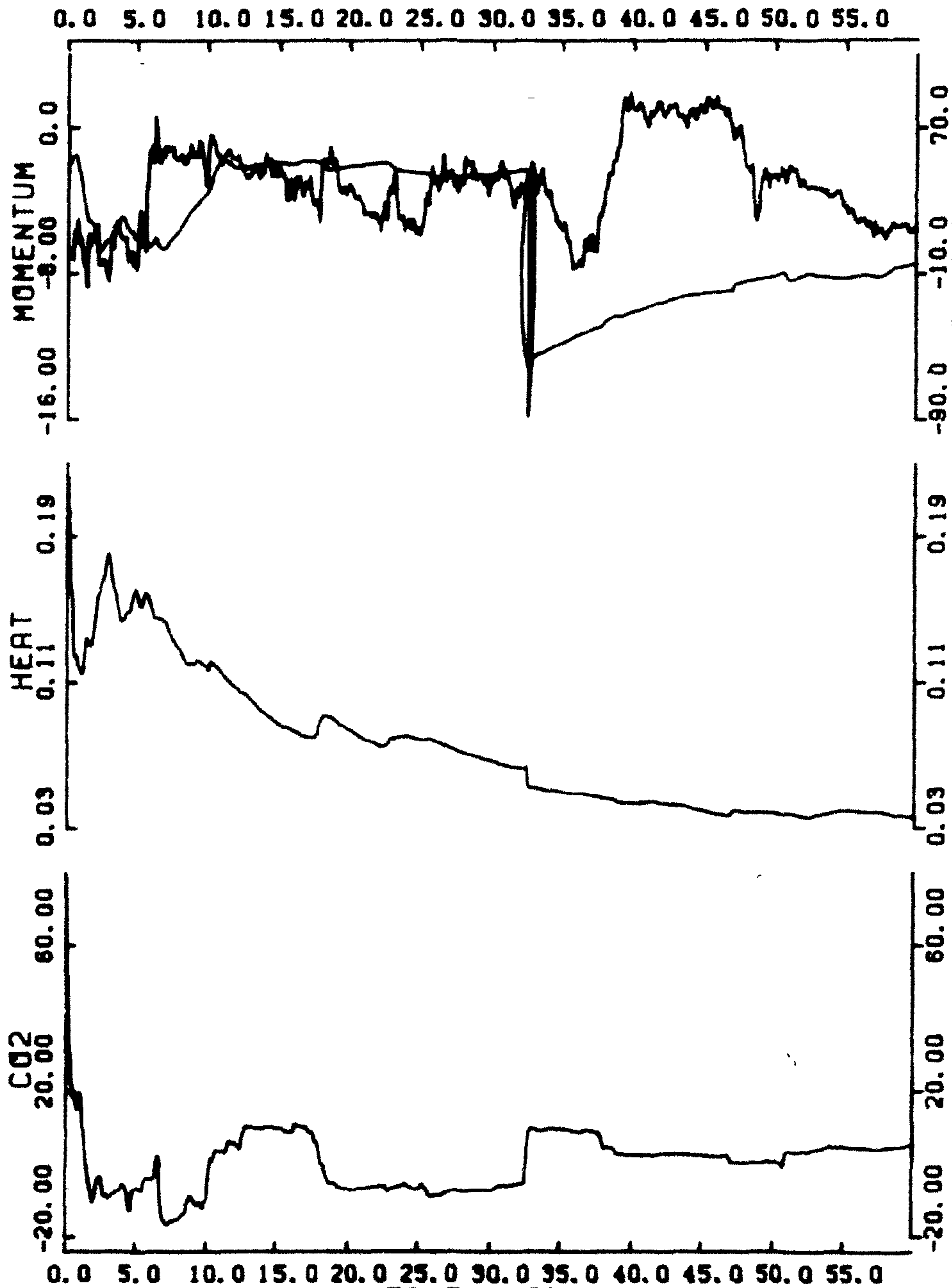
DATE: AUG.28, 1980
INSTRUMENT: AGA-OPA
LOCATION: LAC DESCHENES
RUN # 3

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 28.6M AIRSPEED:63.9 M/SEC
RMS VALUE OF DELTAW: 7.19

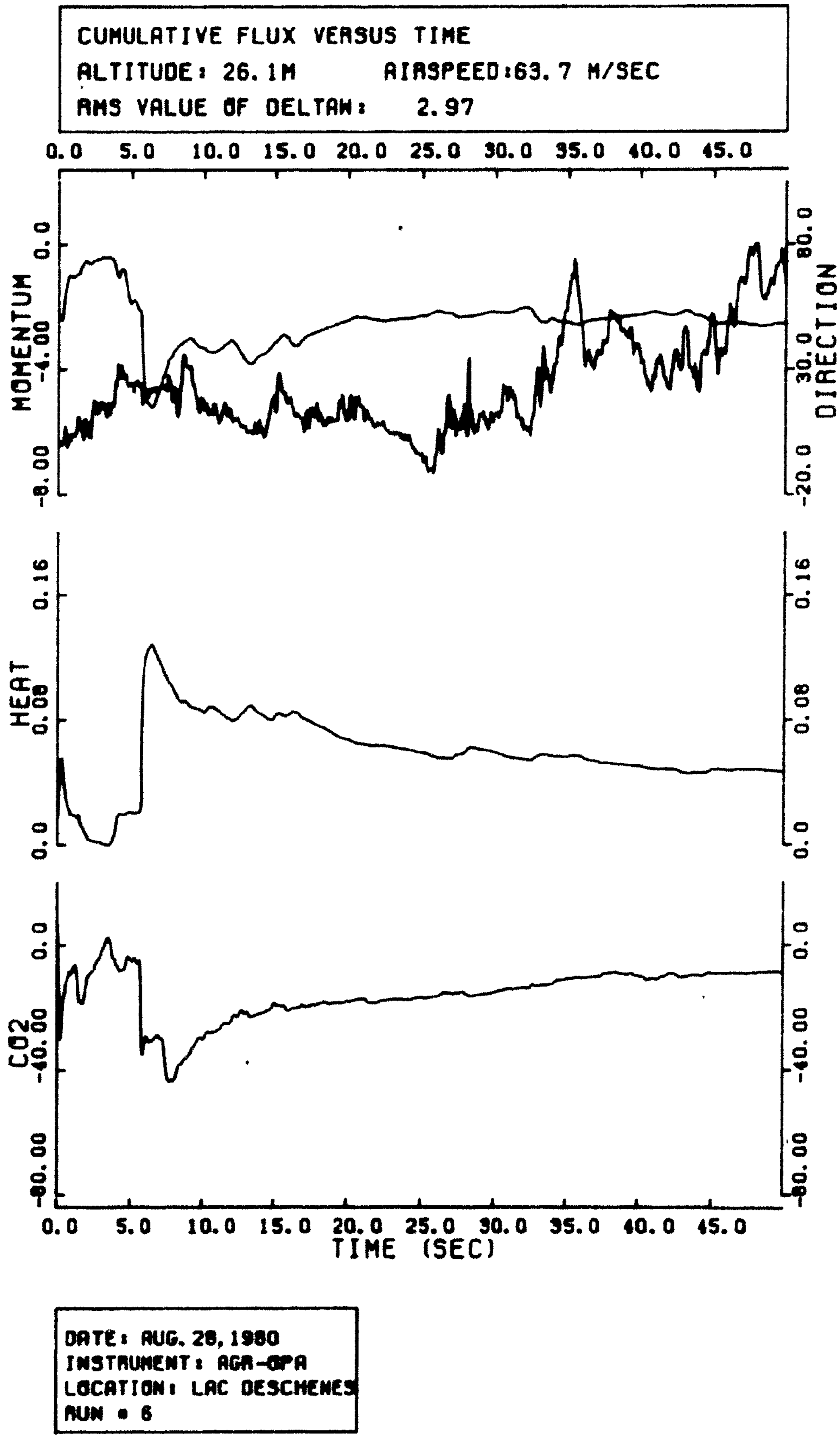


DATE: AUG.28, 1980
INSTRUMENT: AGA-OPA
LOCATION: LAC DESCHENES
RUN # 4

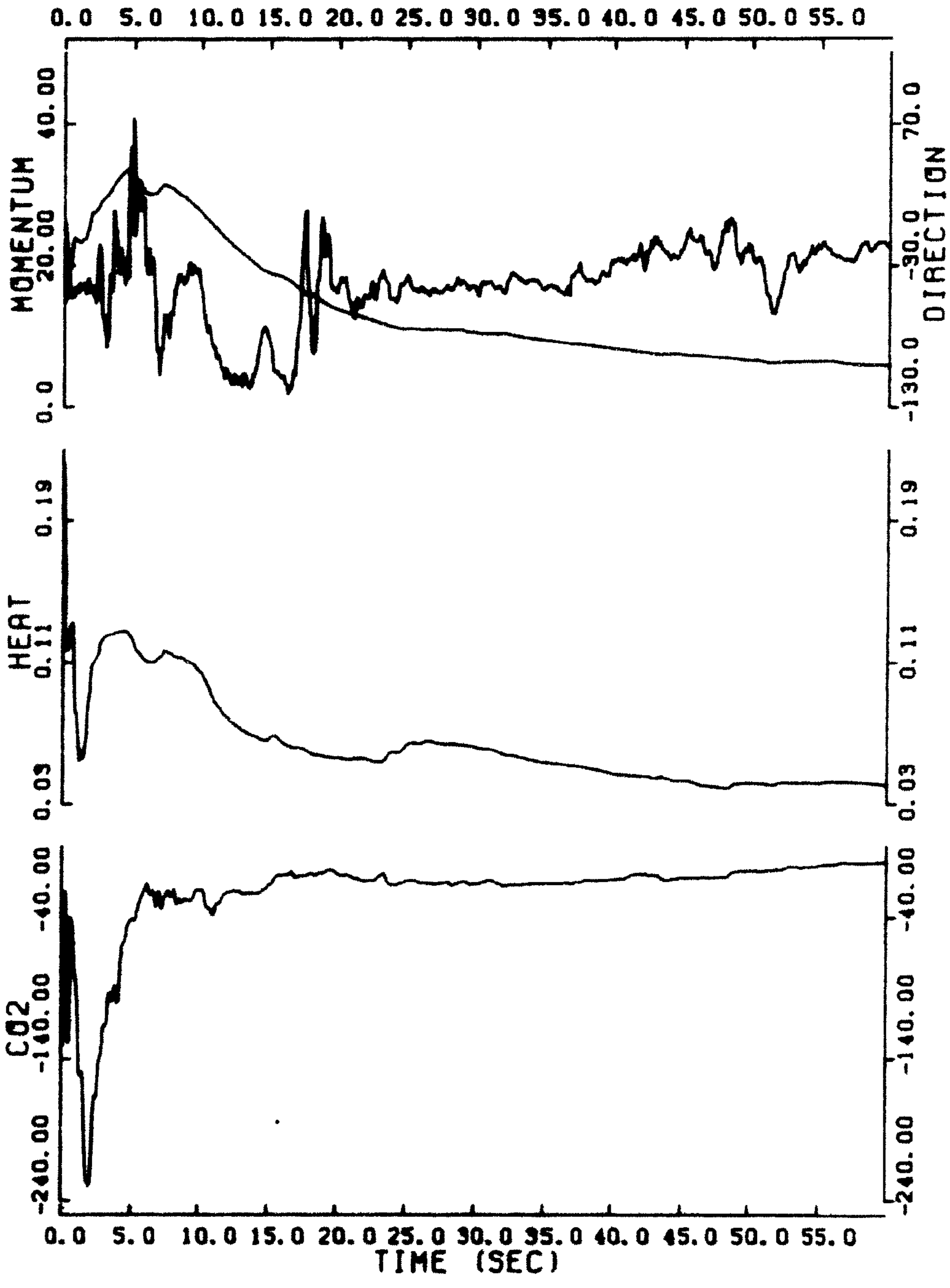
CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 28.3M AIRSPEED:64.3 M/SEC
RMS VALUE OF DELTAW: 5.96



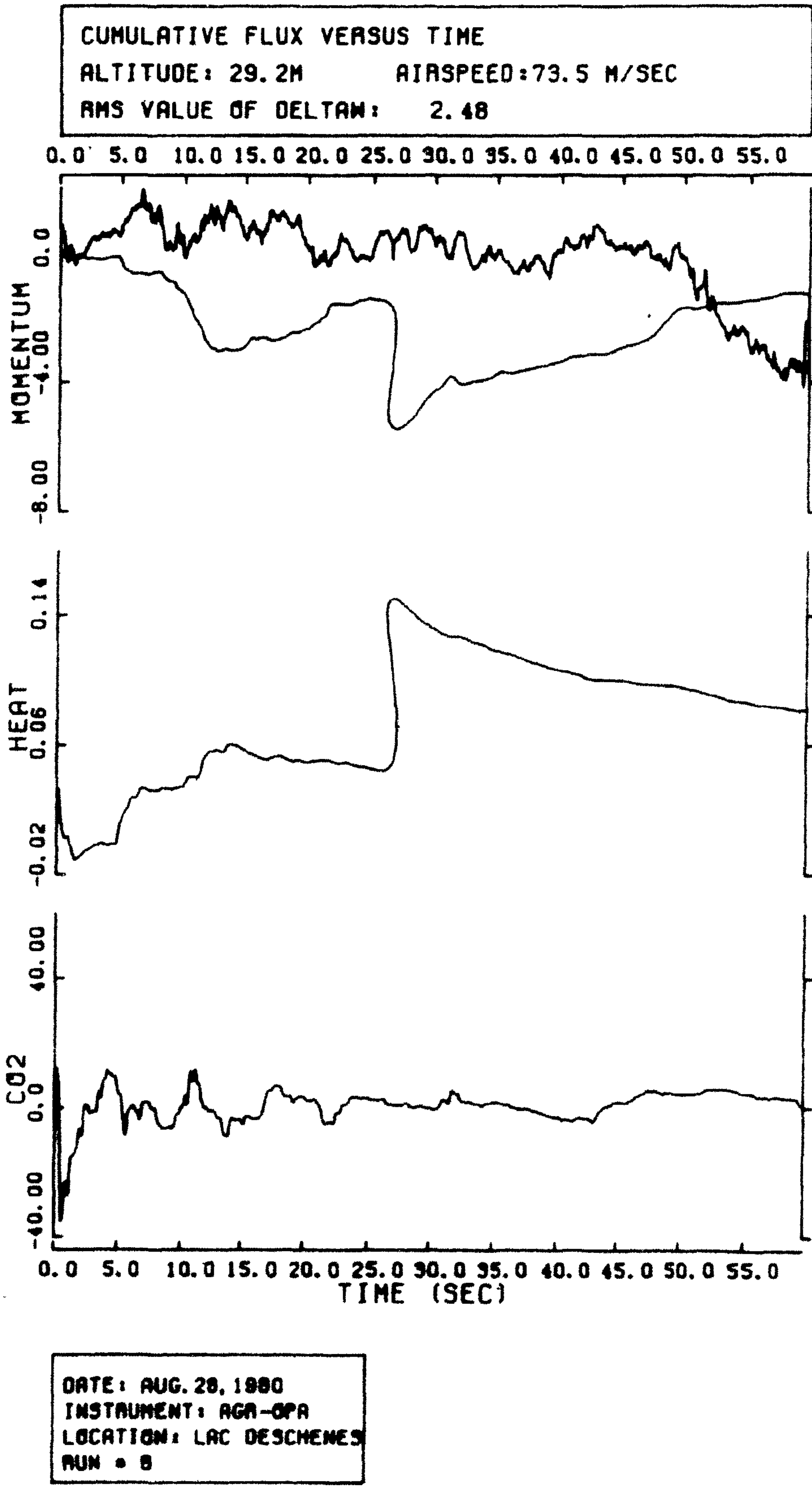
DATE: AUG. 28, 1980
INSTRUMENT: AGA-OPA
LOCATION: LAC DESCHENES
RUN # 5

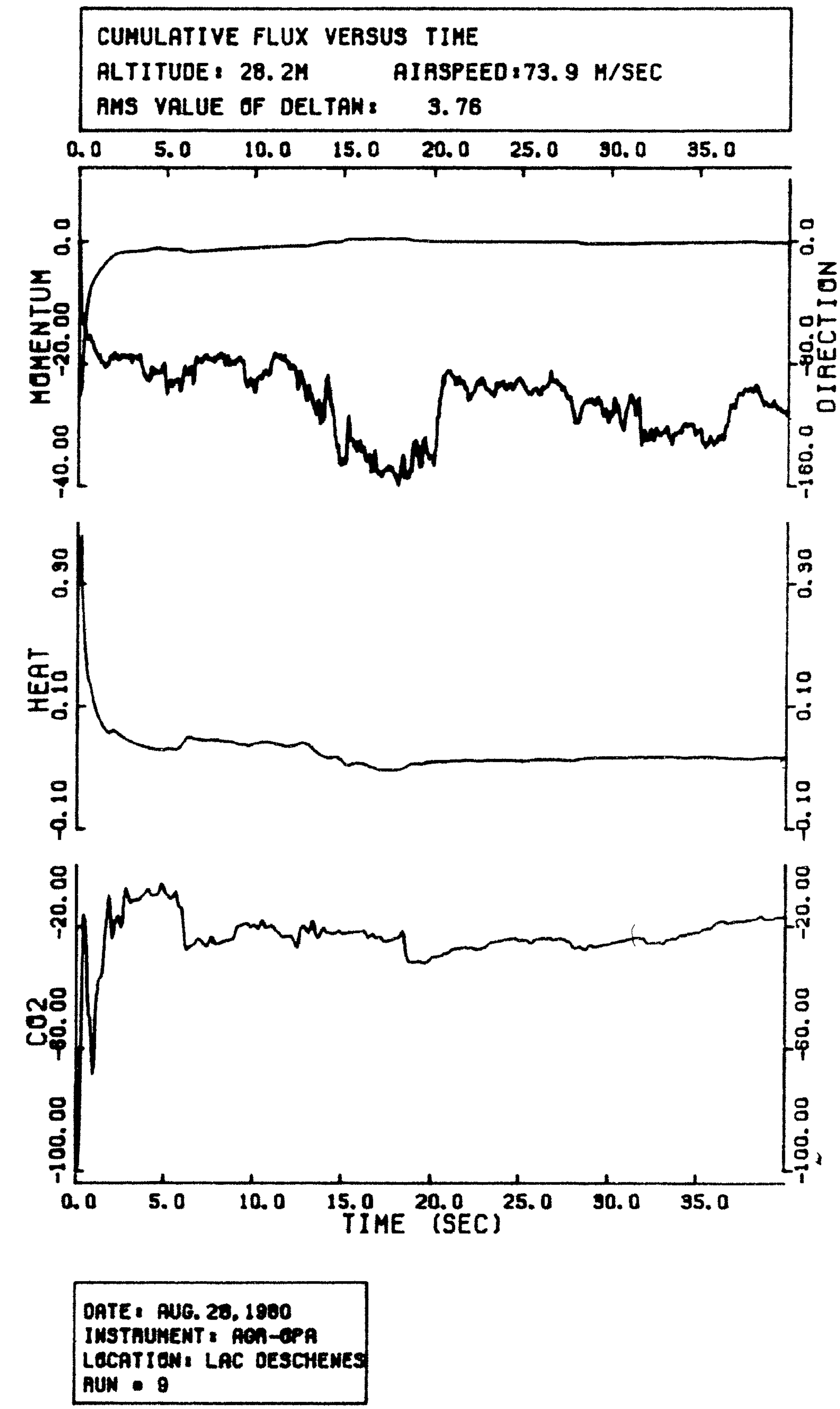

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 26.1M AIRSPEED:63.7 M/SEC
RMS VALUE OF DELTAW: 2.97
0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0
MOMENTUM
0.0
-4.00
-8.00
DIRECTION
80.0
30.0
-20.0
HEAT
0.16
0.08
0.0
CO2
0.0
-40.00
-80.00
TIME (SEC)
DATE: AUG. 28, 1980
INSTRUMENT: AGA-OPA
LOCATION: LAC DESCHENES
RUN # 6

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 27.4M AIRSPEED:74.3 M/SEC
RMS VALUE OF DELTAW: 5.95

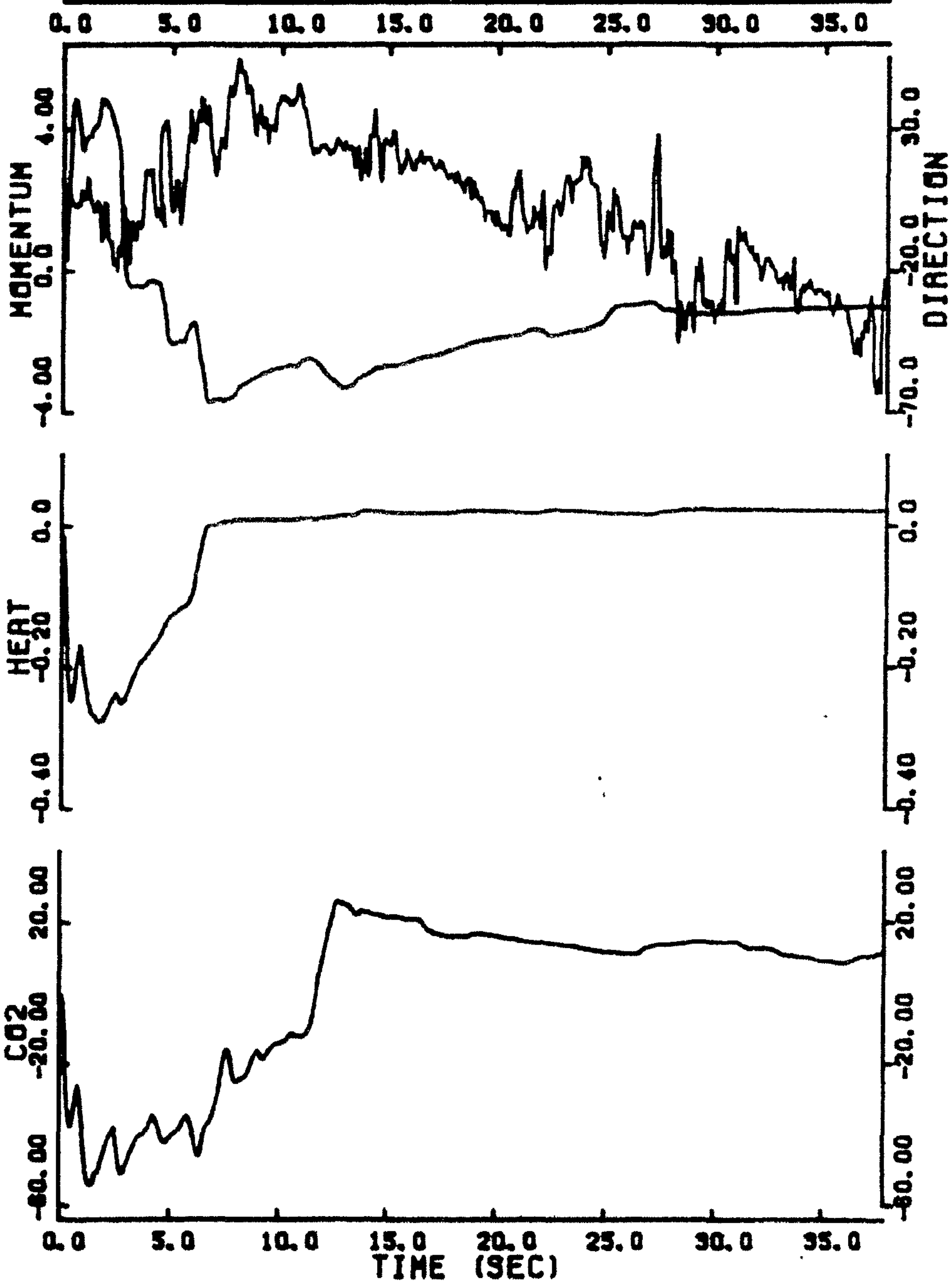


DATE: AUG. 28, 1980
INSTRUMENT: AGA-OPA
LOCATION: LAC DESCHENES
RUN # 7

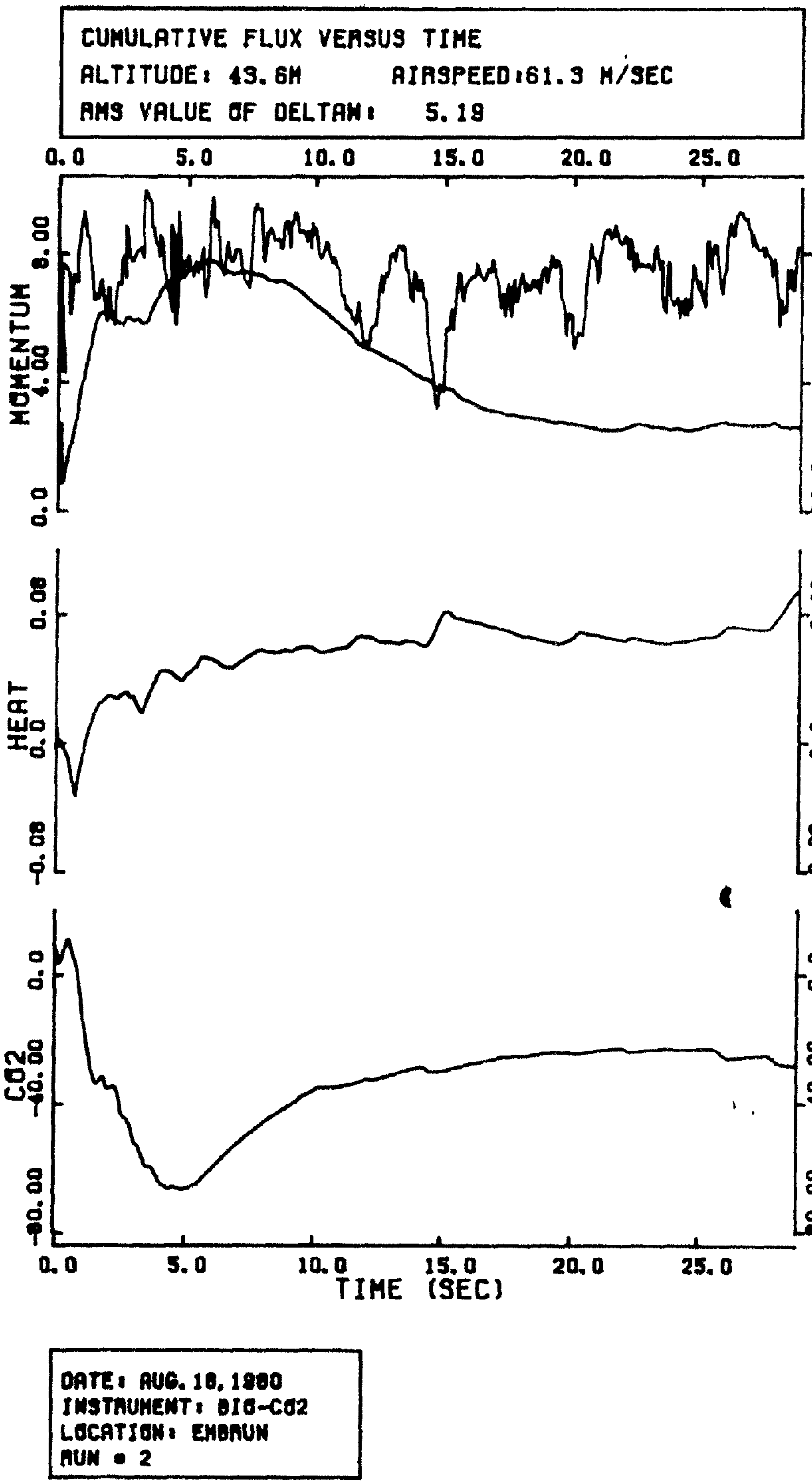

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 29.2M AIRSPEED:73.5 M/SEC
RMS VALUE OF DELTAW: 2.48
0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0 55.0
MOMENTUM
0.0
-4.00
-8.00
DIRECTION
0.0
-80.0
-160.0
HEAT
0.14
0.06
-0.02
CO2
40.00
0.0
-40.00
TIME (SEC)
DATE: AUG.28,1980
INSTRUMENT: AGA-OPA
LOCATION: LAC DESCHENES
RUN # 8

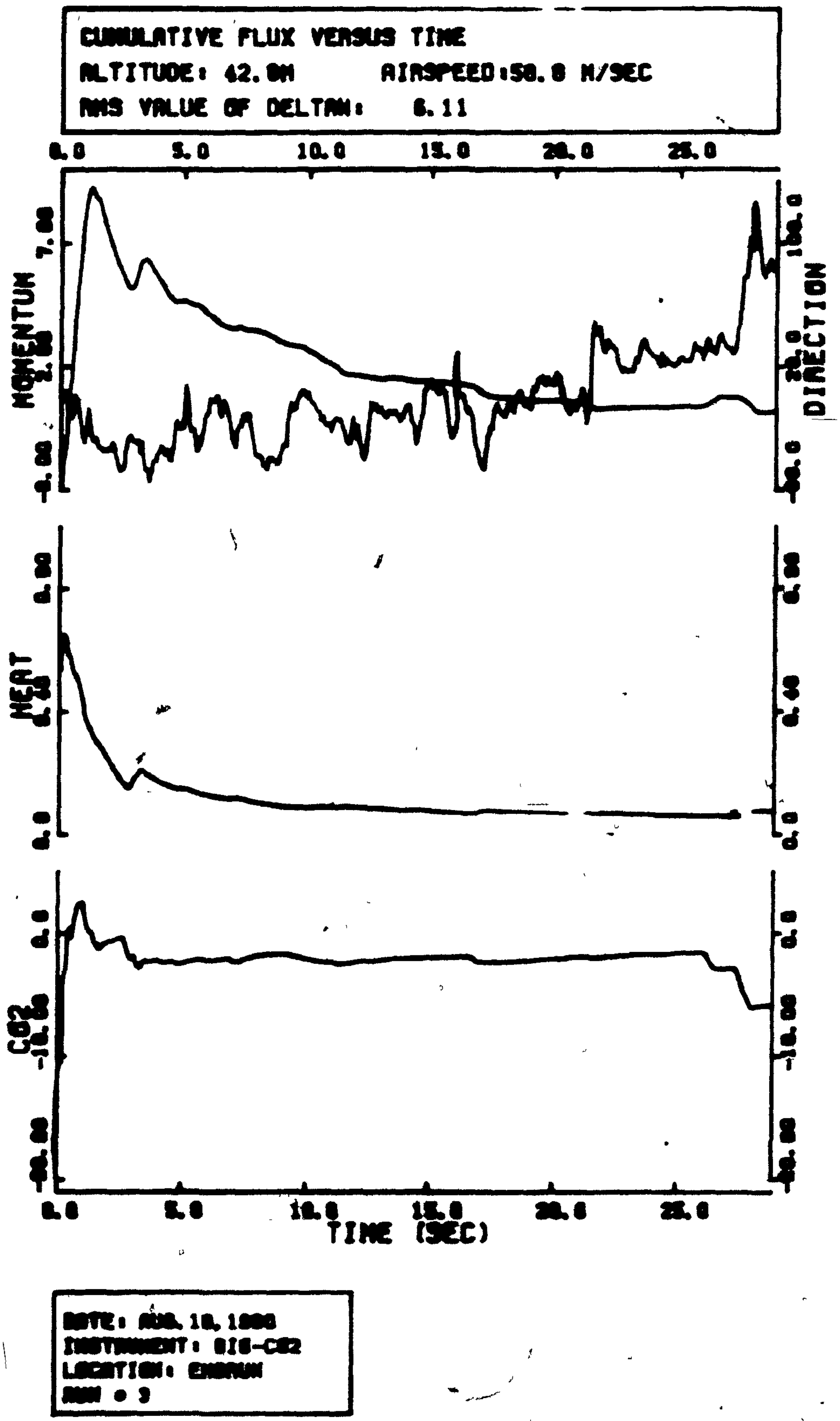

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 28.2M AIRSPEED:73.9 M/SEC
RMS VALUE OF DELTAN: 3.76
0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0
MOMENTUM
0.0
-20.00
-40.00
DIRECTION
0.0
-80.0
-160.0
HEAT
0.30
0.10
-0.10
CO2
-20.00
-60.00
-100.00
TIME (SEC)
DATE: AUG.28,1980
INSTRUMENT: AGA-GPA
LOCATION: LAC DESCHENES
RUN = 9

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 43.6M AIRSPEED:61.3 M/SEC
RMS VALUE OF DELTAH: 4.88

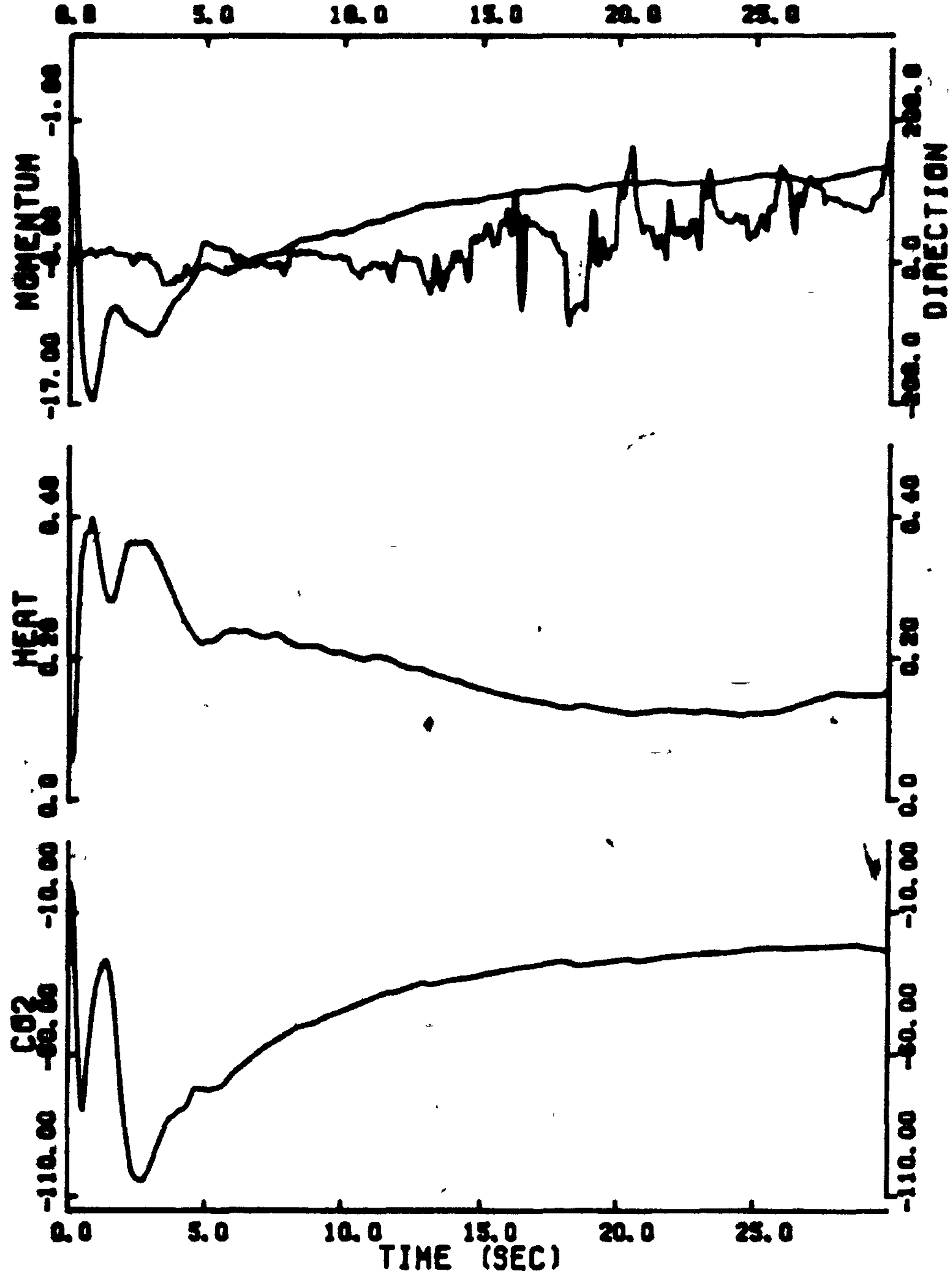


DATE: AUG.18,1980
INSTRUMENT: BIG-CO2
LOCATION: EMBRUN
RUN = 1


CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 43.6M AIRSPEED:61.3 M/SEC
RMS VALUE OF DELTAN: 5.19
0.0 5.0 10.0 15.0 20.0 25.0
MOMENTUM
8.00
4.00
0.0
DIRECTION
0.0
-40.0
-80.0
HEAT
0.08
0.0
-0.08
CO2
0.0
-40.00
-80.00
TIME (SEC)
DATE: AUG.18,1980
INSTRUMENT: BIG-CO2
LOCATION: EMBRUN
RUN # 2

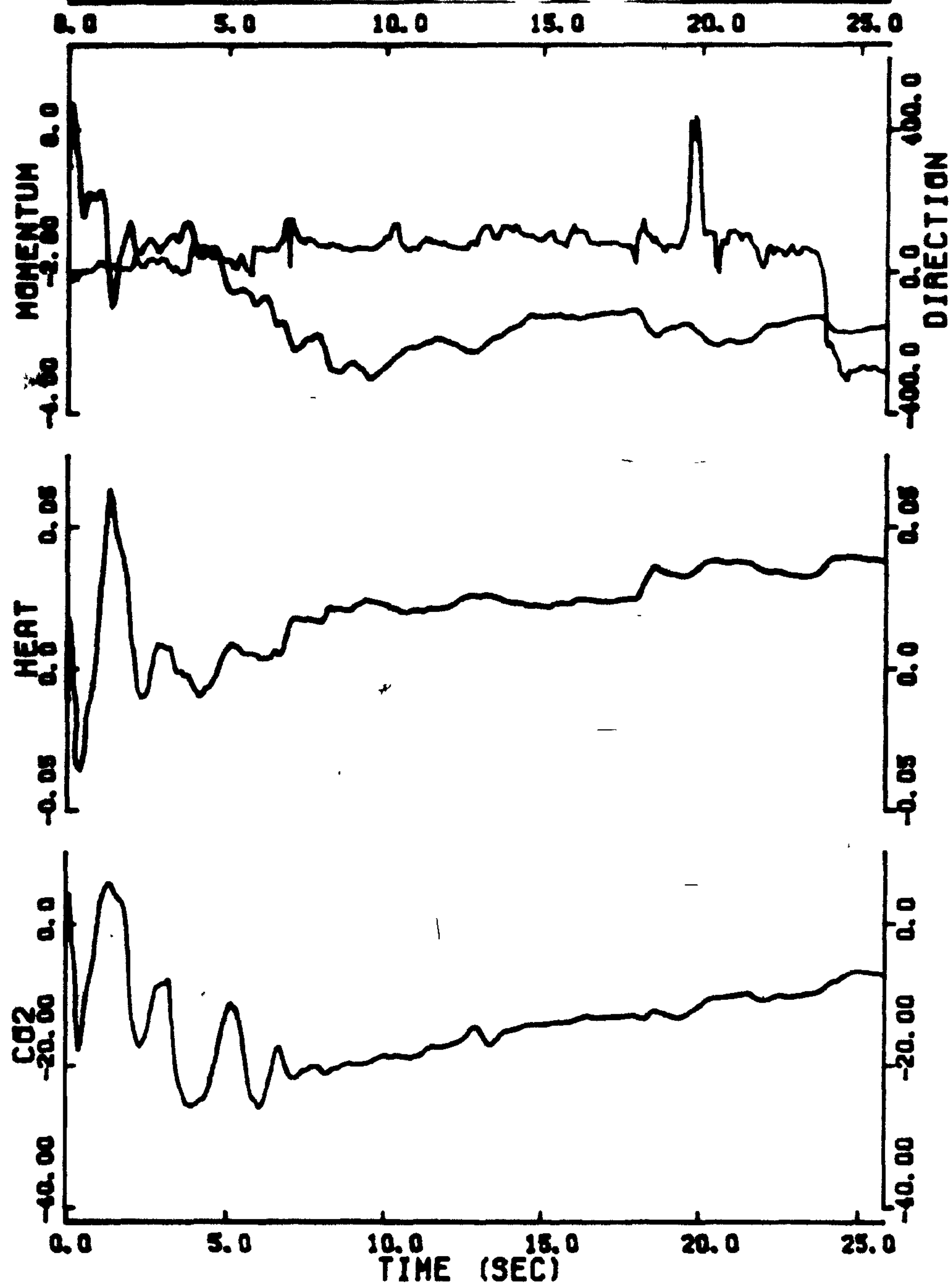

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 42.0M
AIRSPEED:50.0 M/SEC
RMS VALUE OF DELTAN: 6.11
0.0
5.0
10.0
15.0
20.0
25.0
MOMENTUM
DIRECTION
HEAT
CO2
TIME (SEC)
DATE:
INSTRUMENT:
LOCATION:
RUN = 3

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 25.4M AIRSPEED:61.4 M/SEC
RMS VALUE OF DELTAW: 13.06

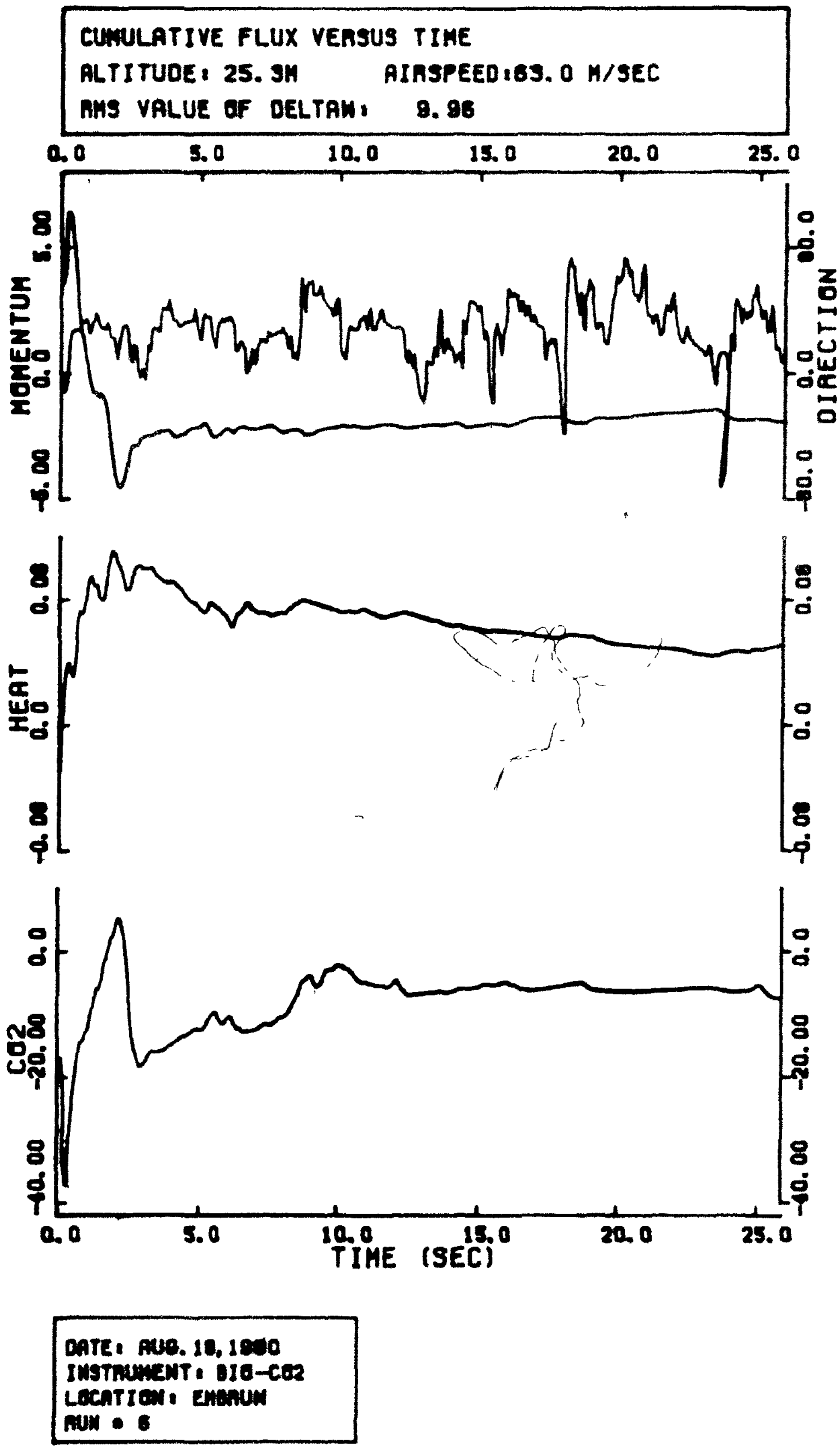


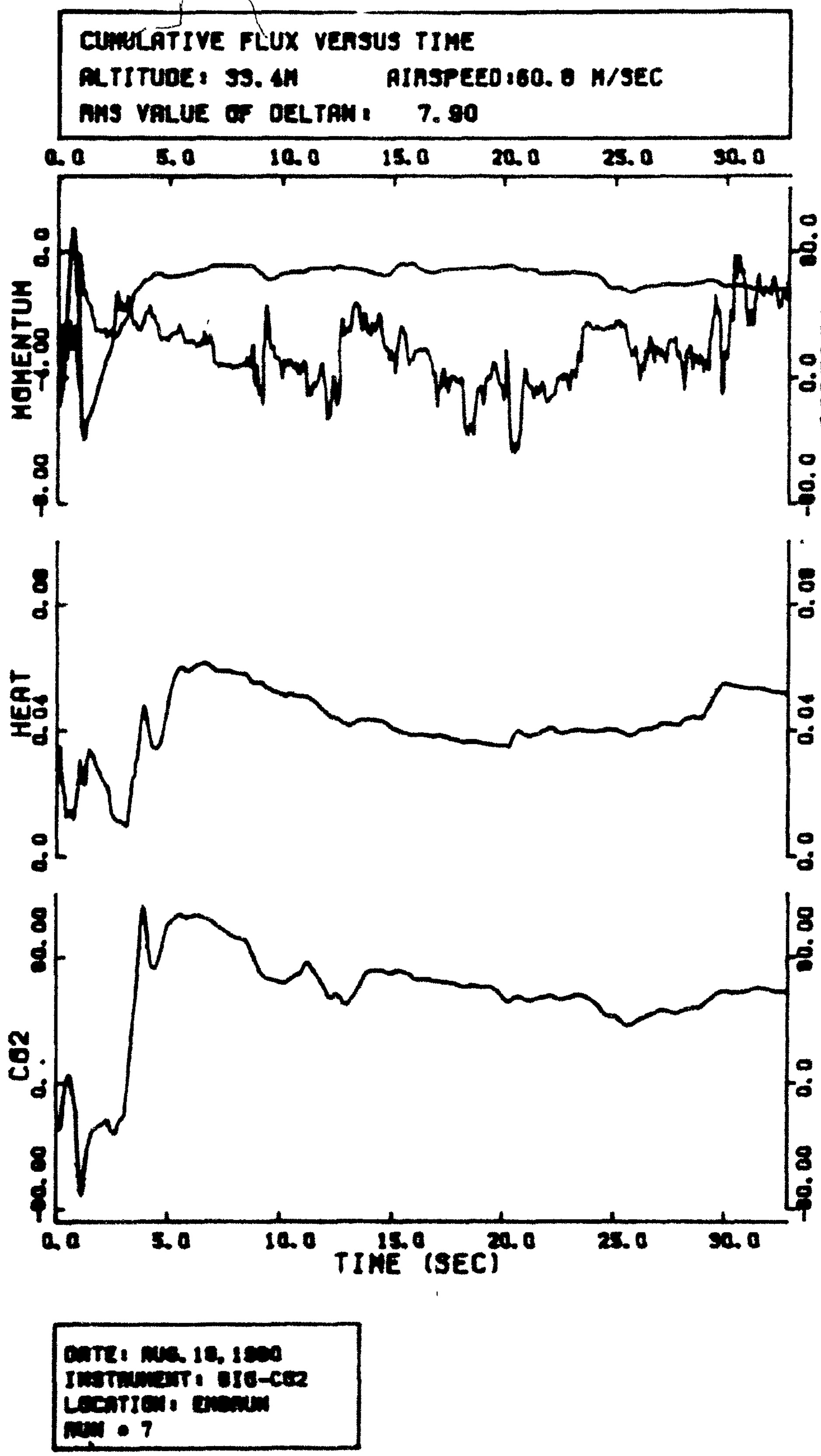
DATE: AUG.18,1980
INSTRUMENT: BIG-CO2
LOCATION: EMBRUN
RUN # 4

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 24.8M AIRSPEED:64.2 M/SEC
RMS VALUE OF DELTAM: 21.99

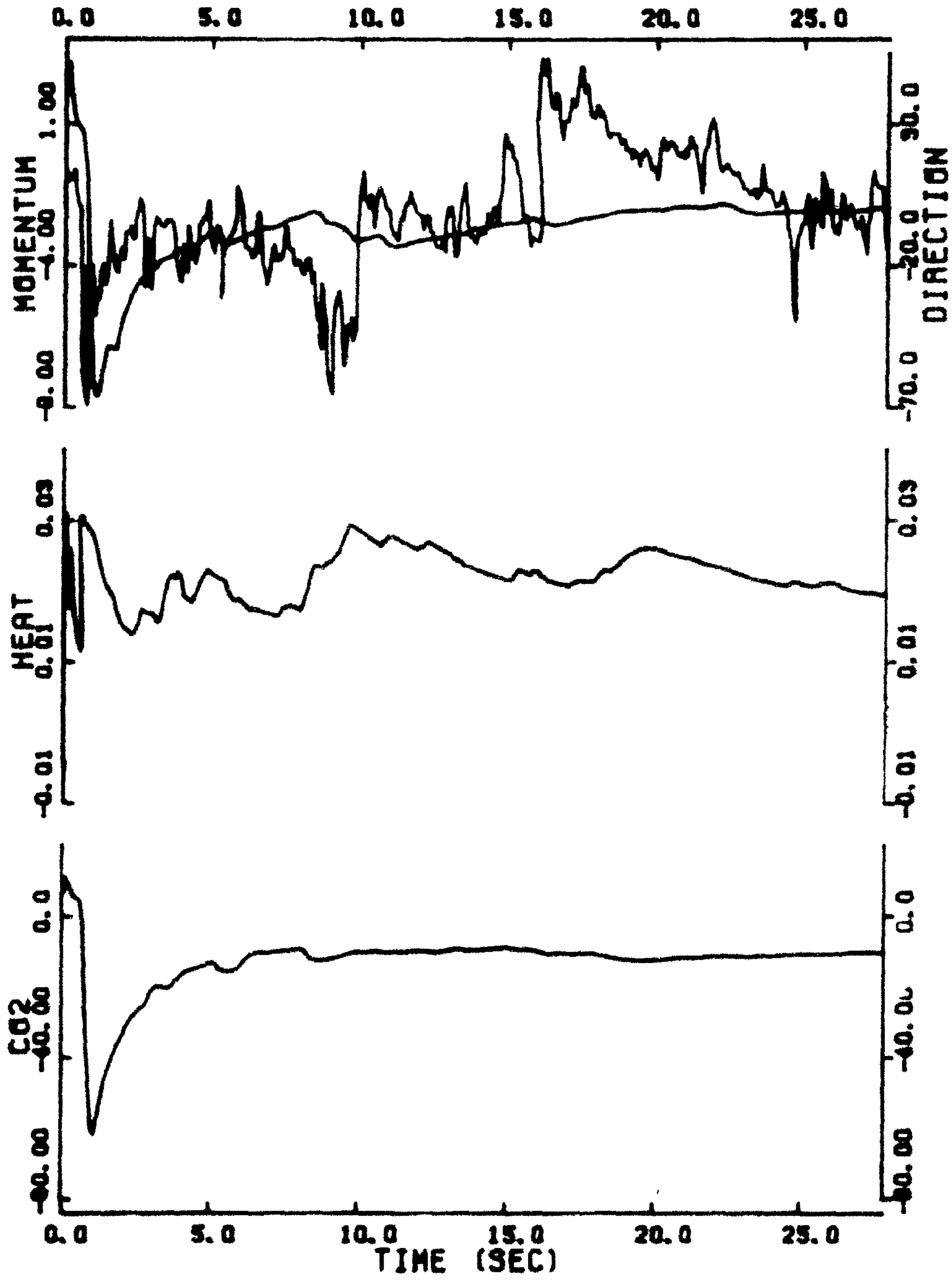


DATE: AUG. 18, 1980
INSTRUMENT: BIG-CO2
LOCATION: EMBRUN
RUN # 5

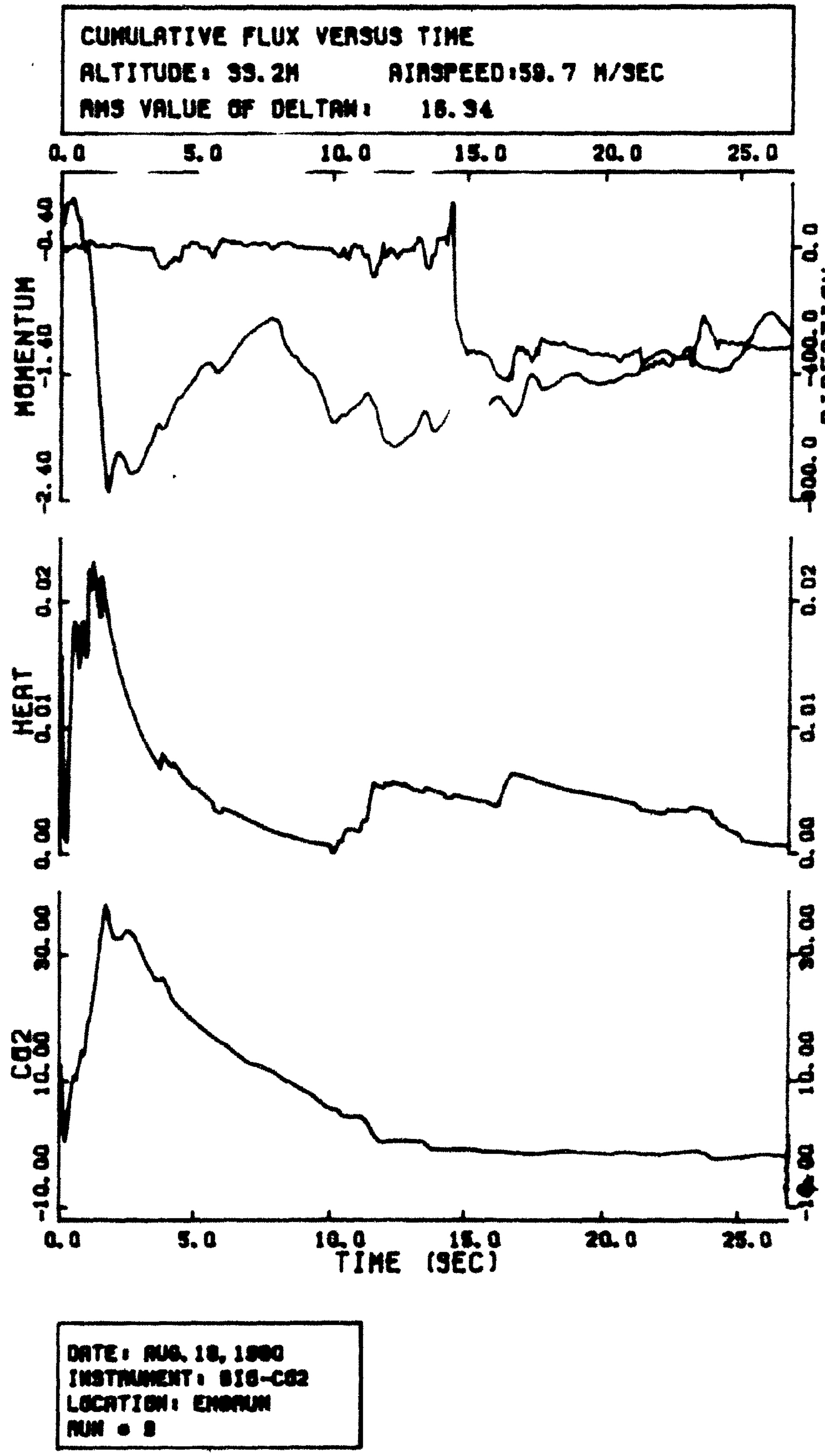

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 25.3M AIRSPEED:63.0 M/SEC
RMS VALUE OF DELTAW: 9.96
0.0 5.0 10.0 15.0 20.0 25.0
MOMENTUM
5.00
0.0
-5.00
DIRECTION
80.0
0.0
-80.0
HEAT
0.08
0.0
-0.08
CO2
0.0
-20.00
-40.00
TIME (SEC)
DATE: AUG.18,1980
INSTRUMENT: BIG-CO2
LOCATION: EMBRUN
RUN # 6

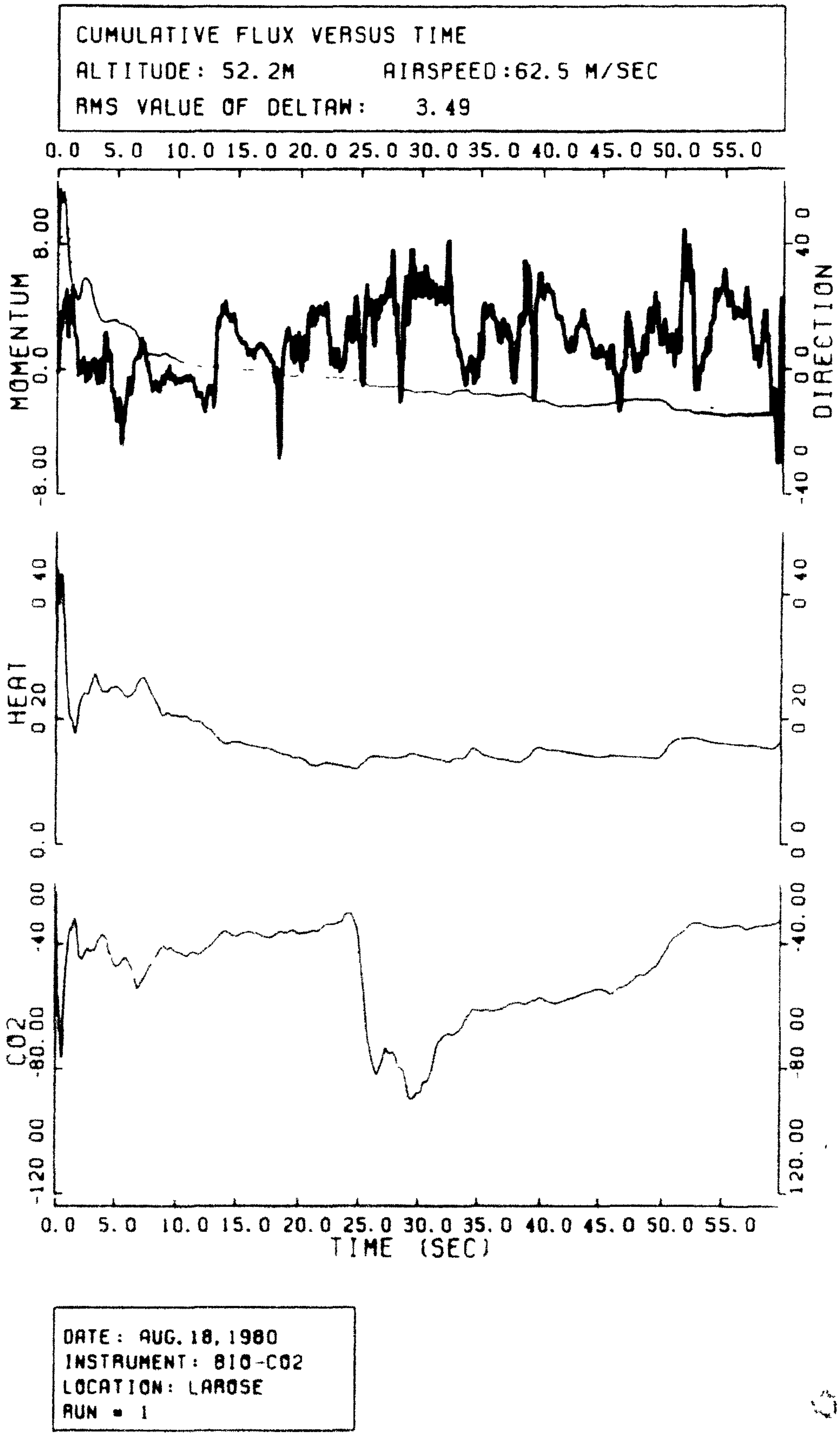

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 33.4M AIRSPEED:60.8 M/SEC
RMS VALUE OF DELTAN: 7.90
MOMENTUM
DIRECTION
HEAT
CO2
TIME (SEC)
DATE: AUG. 18, 1980
INSTRUMENT: BIG-CO2
LOCATION: ENBAUM
RUN # 7

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 32.6M   AIRSPEED:58.8 M/SEC
RMS VALUE OF DELTAM: 7.07

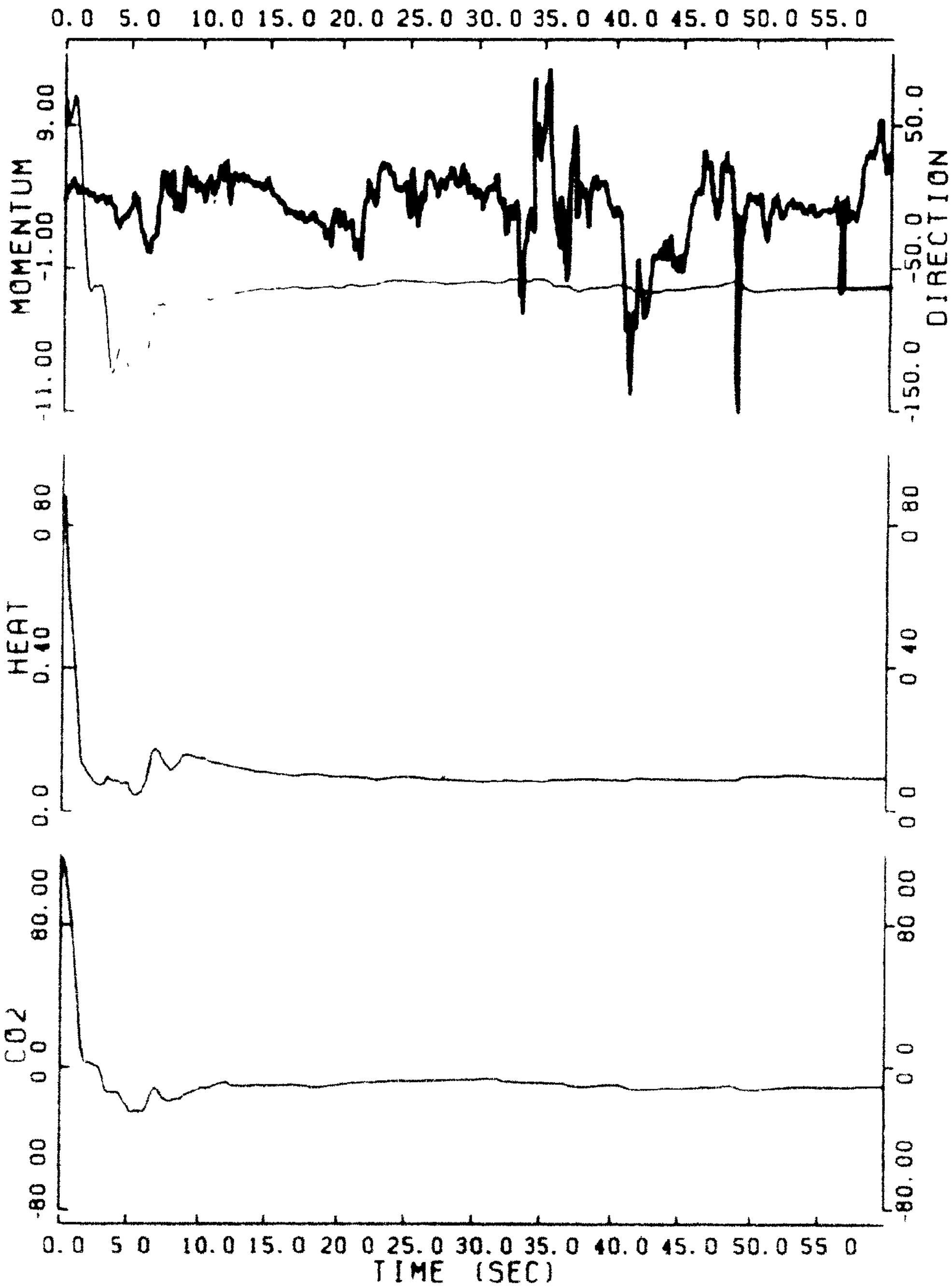


DATE: AUG. 18, 1980
INSTRUMENT: BIG-CO2
LOCATION: EMBRUN
RUN # 8


CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 39.2M AIRSPEED:59.7 M/SEC
RMS VALUE OF DELTAM: 16.34
MOMENTUM
DIRECTION
HEAT
CO2
TIME (SEC)
0.0
5.0
10.0
15.0
20.0
25.0
DATE: AUG.18,1980
INSTRUMENT: BIG-CO2
LOCATION: ENGAUN
RUN = 8

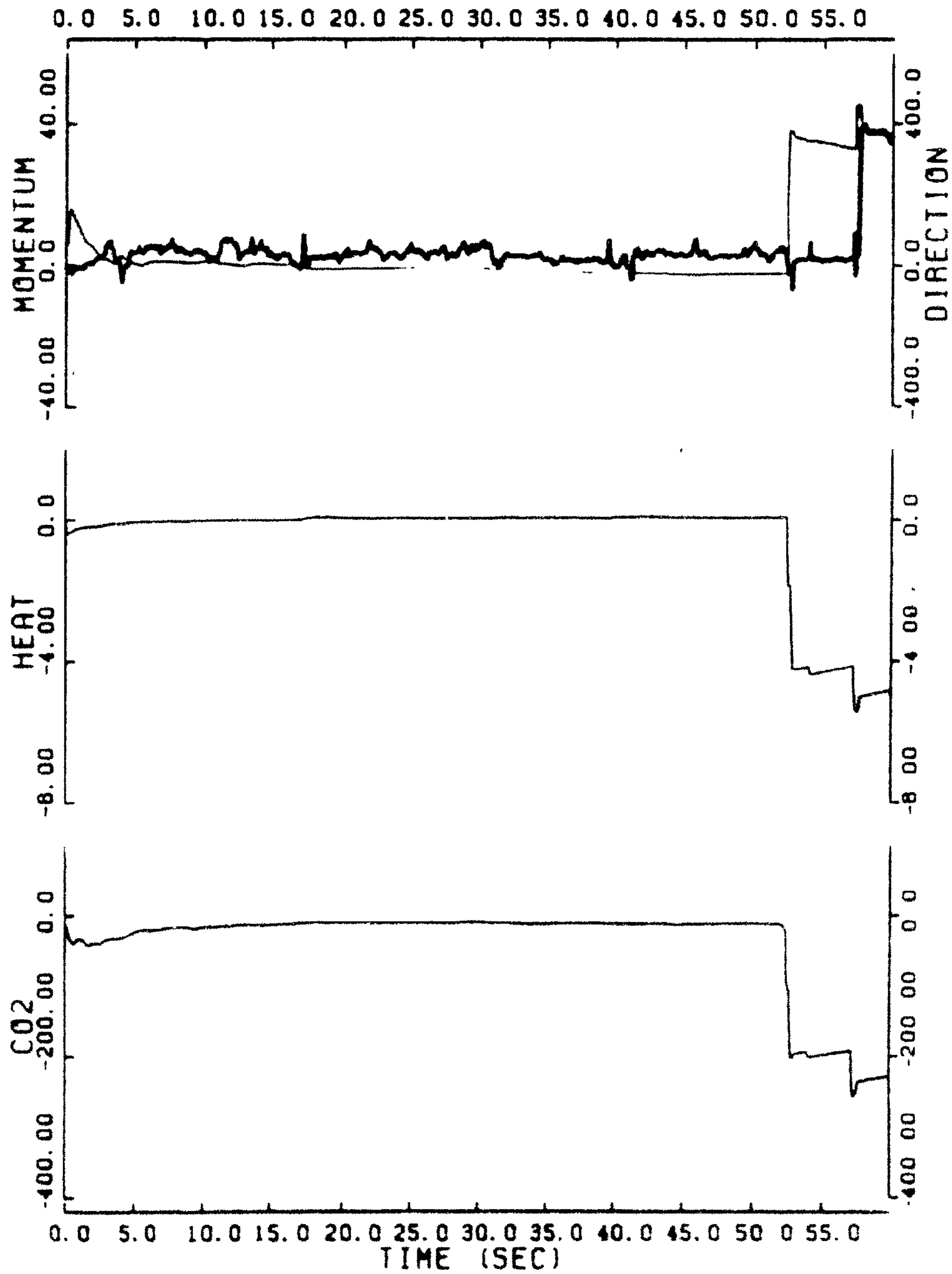

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 52.2M AIRSPEED:62.5 M/SEC
RMS VALUE OF DELTAW: 3.49
0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0 55.0
MOMENTUM
8.00
0.0
-8.00
DIRECTION
40 0
0 0
-40 0
HEAT
0 40
0 20
0.0
CO2
-40.00
-80.00
-120.00
TIME (SEC)
DATE: AUG.18,1980
INSTRUMENT: BIO-CO2
LOCATION: LAROSE
RUN = 1

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 47.6M AIRSPEED: 57.3 M/SEC
RMS VALUE OF DELTAW: 8.45



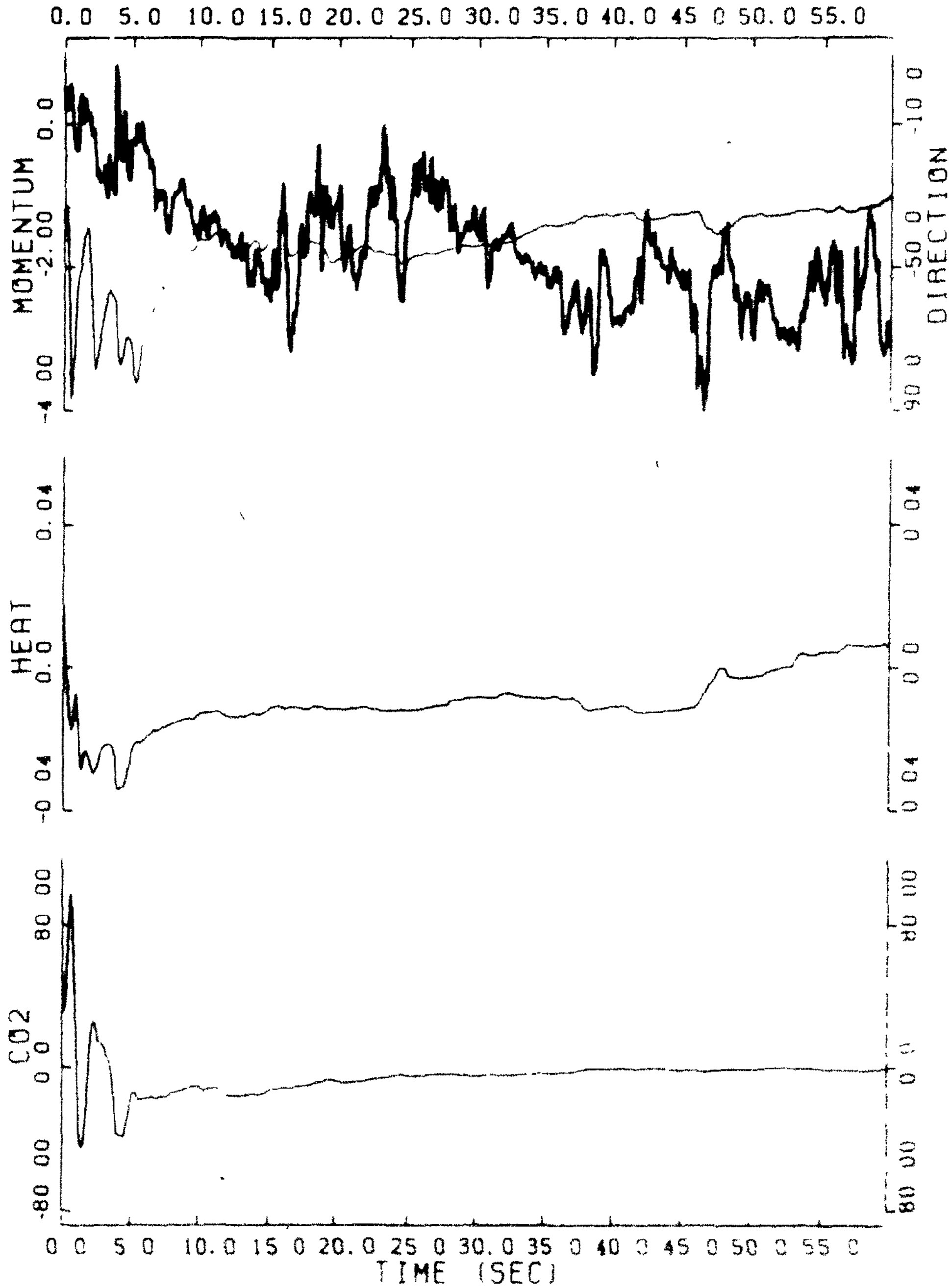
DATE. AUG. 18, 1980
INSTRUMENT. BIO-CO2
LOCATION. LAROSE
RUN = 2

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 54.3M AIRSPEED:58.8 M/SEC
RMS VALUE OF DELTAW: 12.10

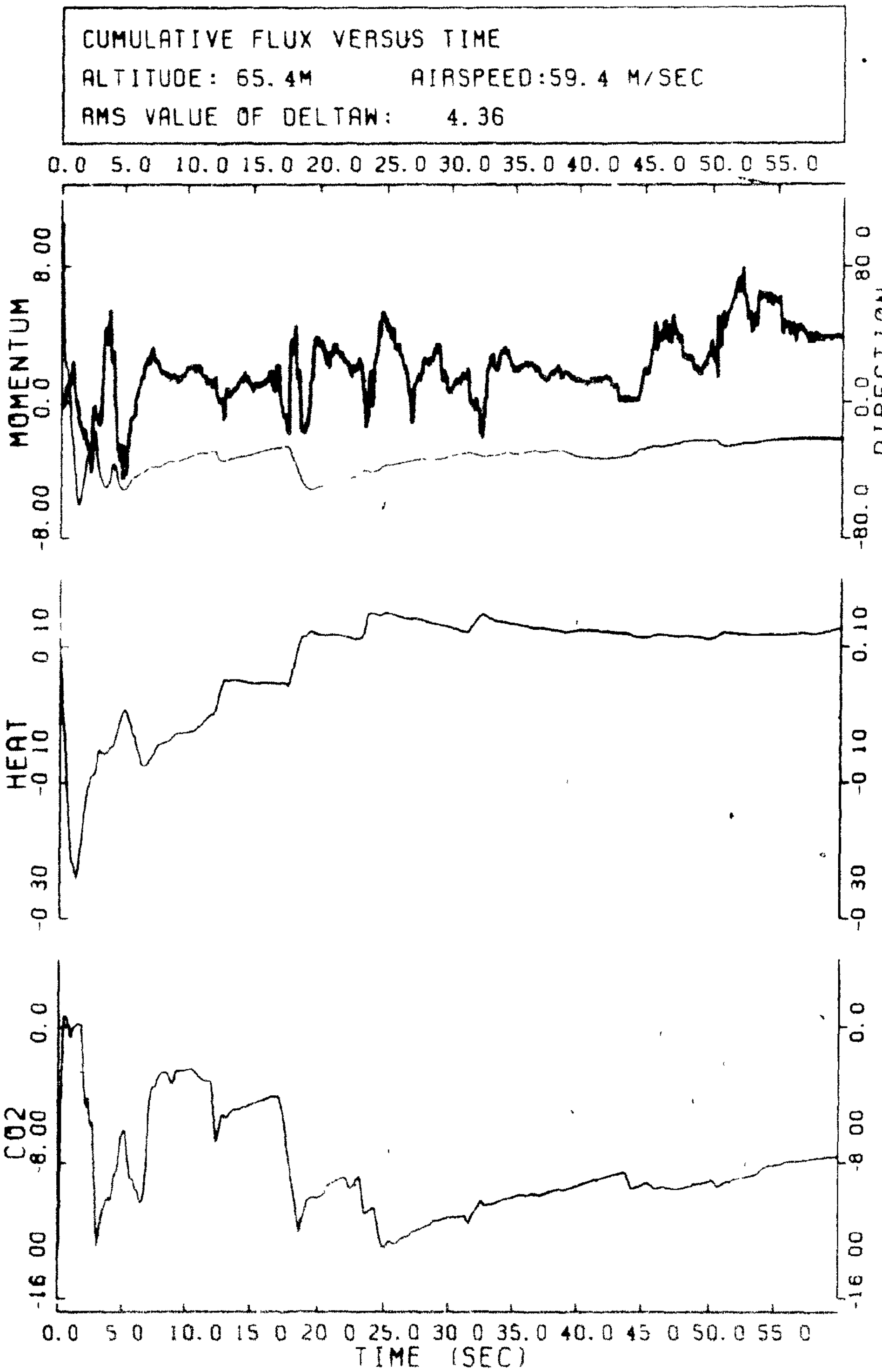


DATE: AUG. 18, 1980
INSTRUMENT: BIO-CO2
LOCATION: LAROSE
RUN # 3

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 62.7M AIRSPEED: 59.2 M/SEC
RMS VALUE OF DELTAW: 3.52

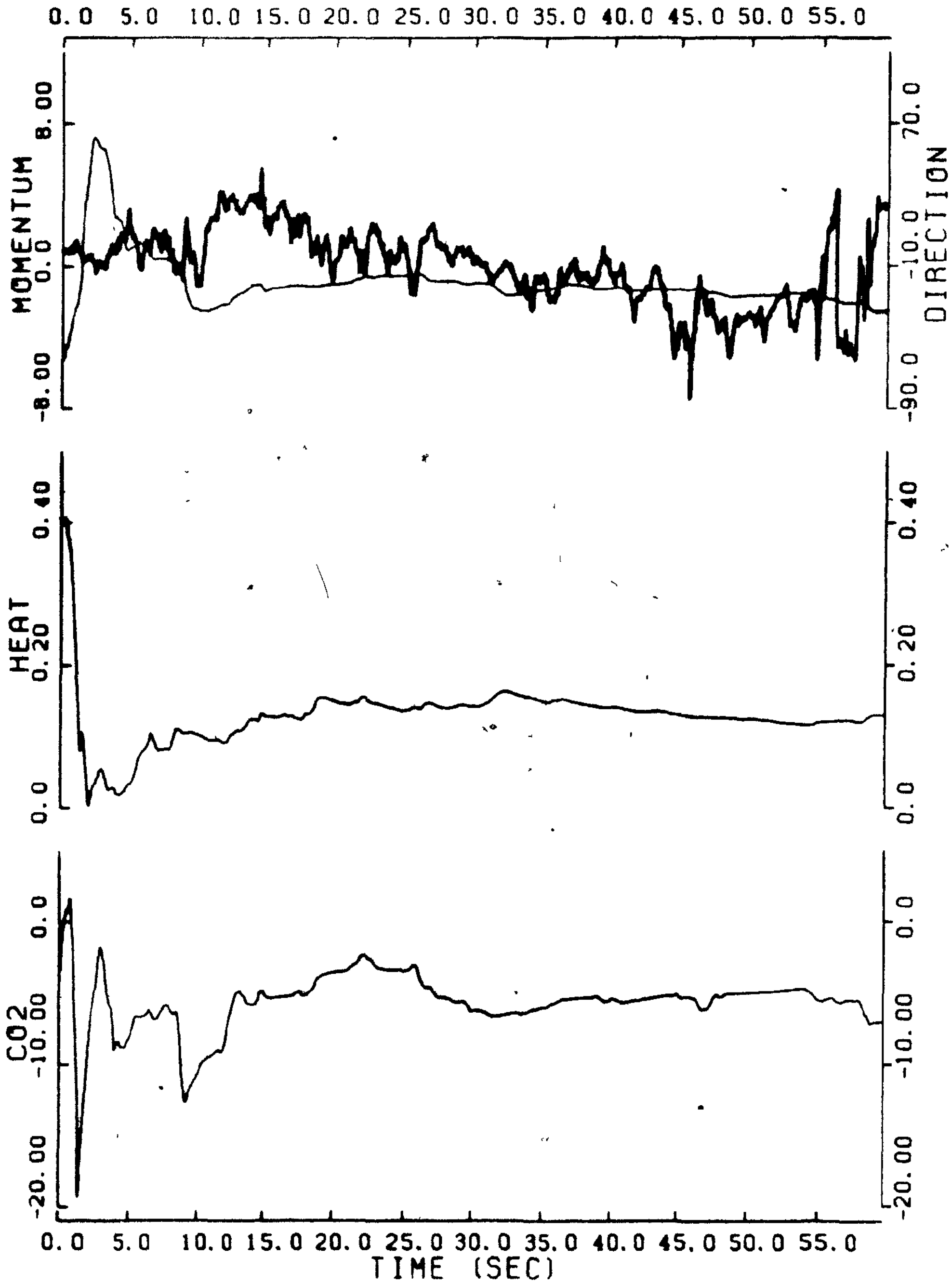


DATE: AUG 18, 1980
INSTRUMENT: BIO-CO2
LOCATION: LAROSE
RUN = 4



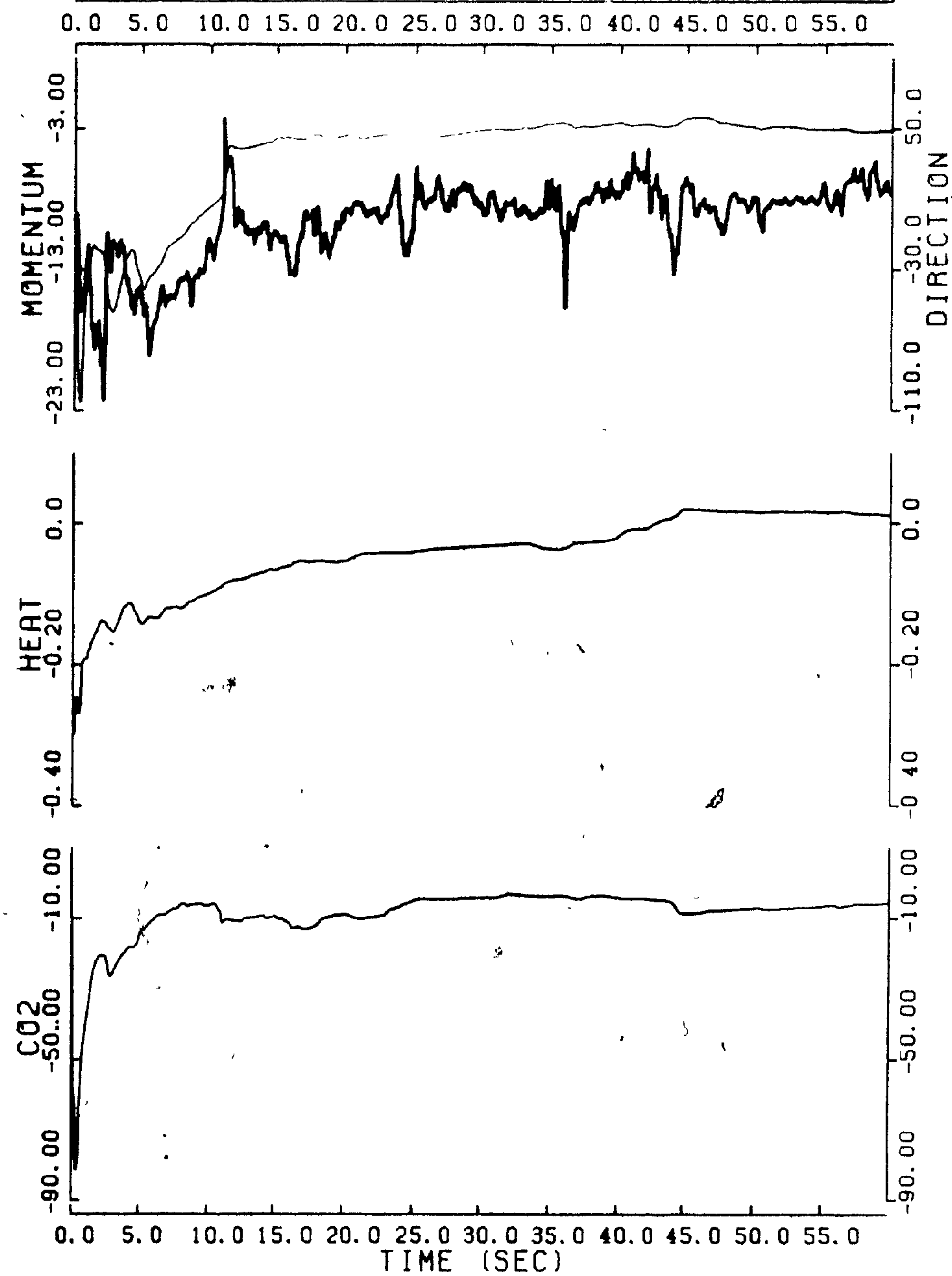
DATE AUG 18, 1980
INSTRUMENT BIO-CO2
LOCATION. LAROSE
RUN • 5

[illegible]VE FLUX VERSUS TIME
ALTITUDE: 64.7M   AIRSPEED:60.2 M/SEC
RMS VALUE OF DELTAW: 4.70



DATE: AUG. 18, 1980
INSTRUMENT: BIO-CO2
LOCATION. LAROSE
RUN = 6

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 48.3M AIRSPEED:59.6 M/SEC
RMS VALUE OF DELTAW: 4.70

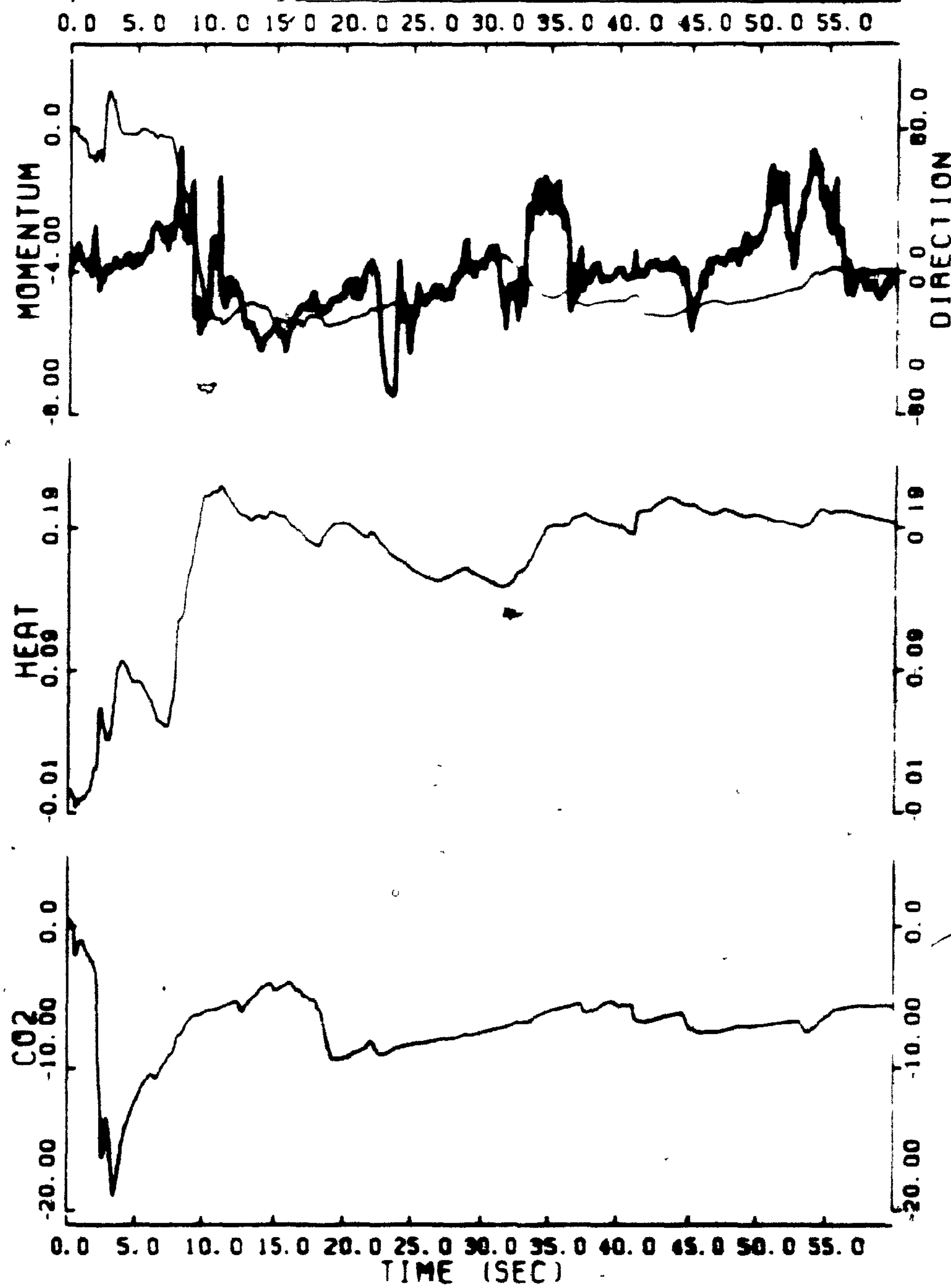


DATE: AUG.18,1980
INSTRUMENT: BIO-CO2
LOCATION: LAROSE
RUN # 7

UX VERSUS TIME

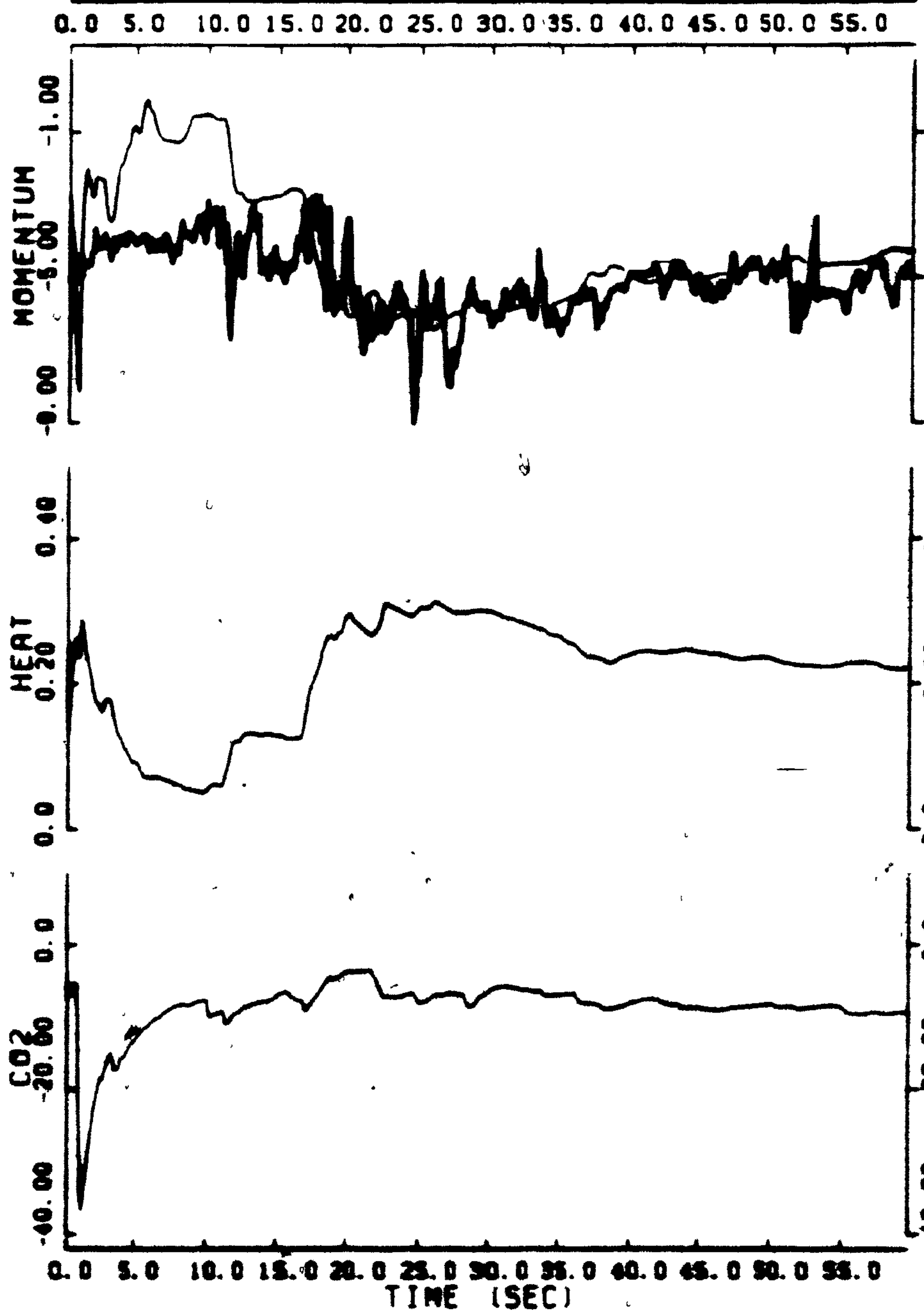
ALTITUDE: 54.4M 60.2 M/SEC

RMS VALUE OF DELTAW: 5.55

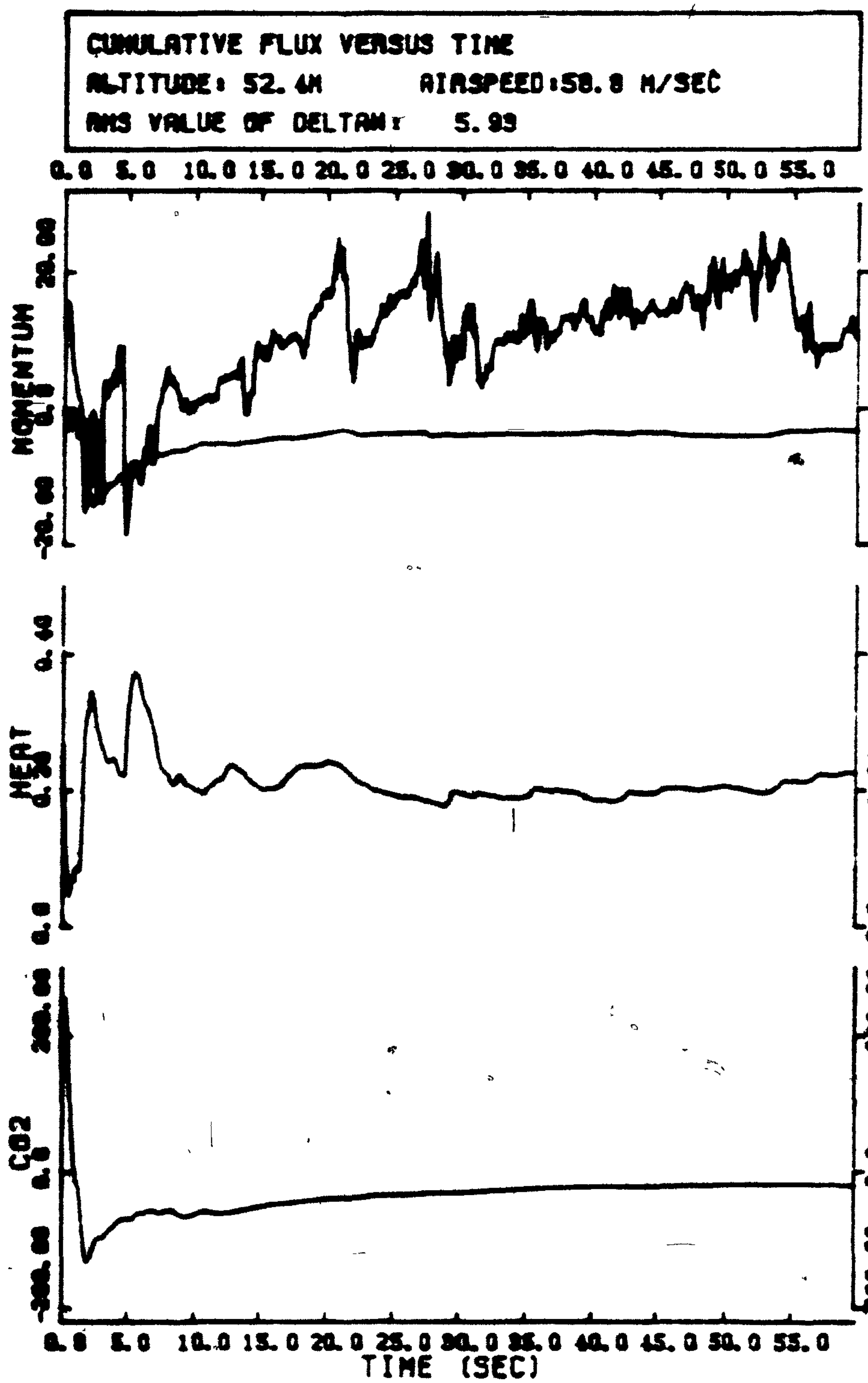


DATE: AUG. 18, 1980
INSTRUMENT. BIO-CO2
LOCATION. LAROSE
RUN = 8

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 52.5M AIRSPEED:61.1 M/SEC
RMS VALUE OF DELTAW: 5.43

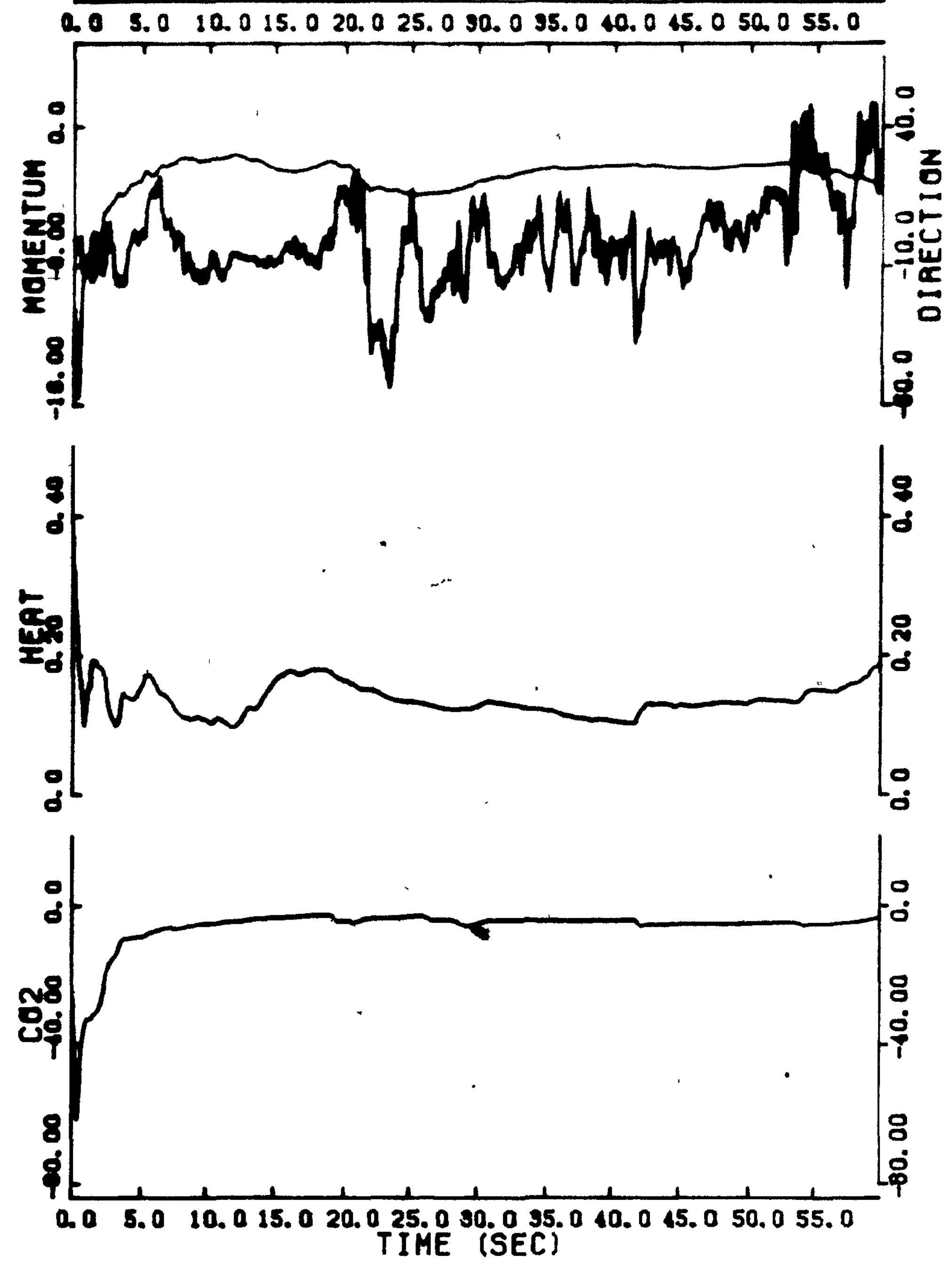


DATE: AUG. 18, 1980
INSTRUMENT: BIO-CO2
LOCATION: LAROSE
RUN = 9



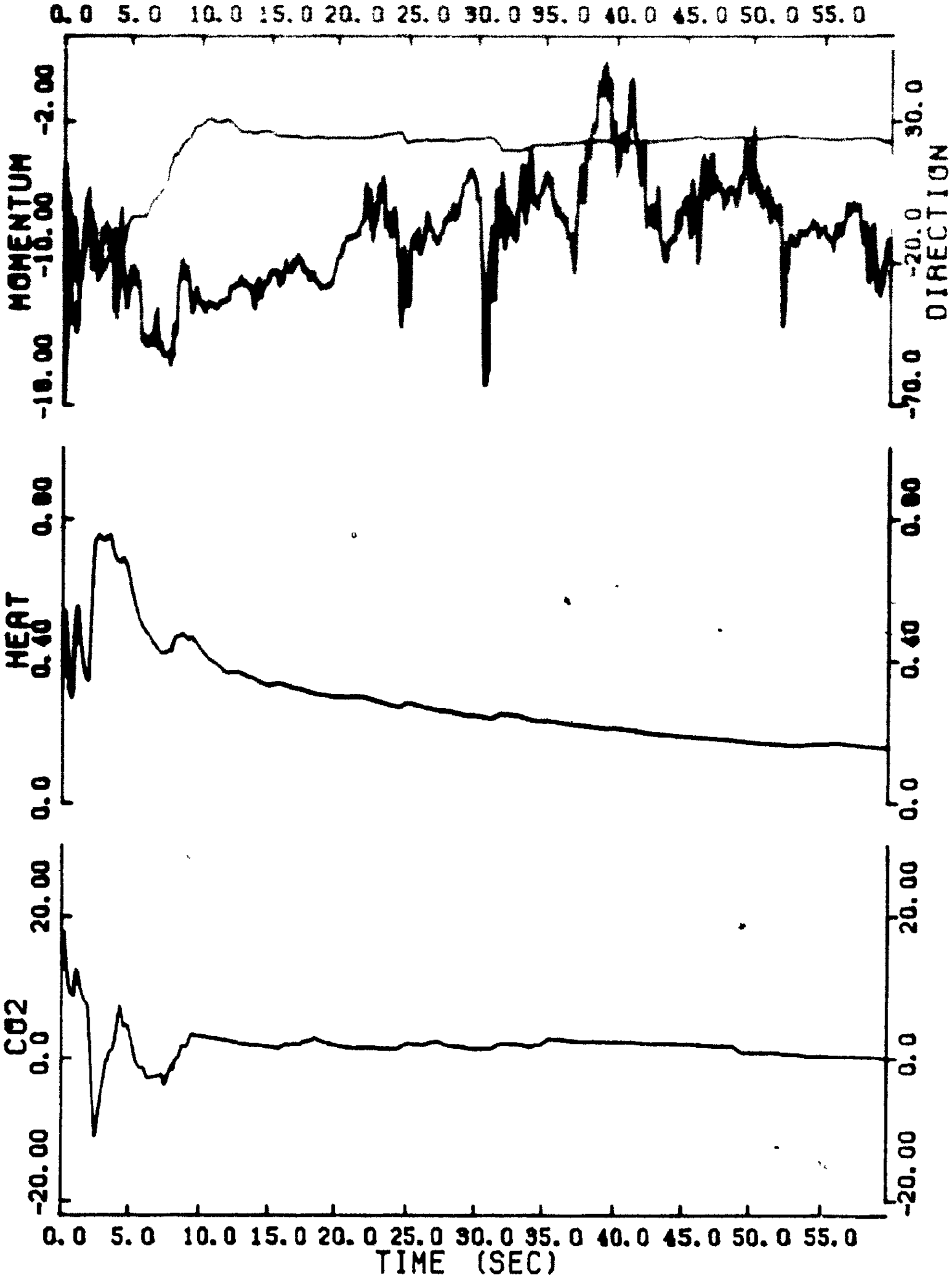
DATE: AUG. 18. 1980
INSTRUMENT: BIG-CO2
LOCATION: LAROSE
RUN = 10

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 52.0M AIRSPEED:60.4 M/SEC
RMS VALUE OF DELTAW: 9.97

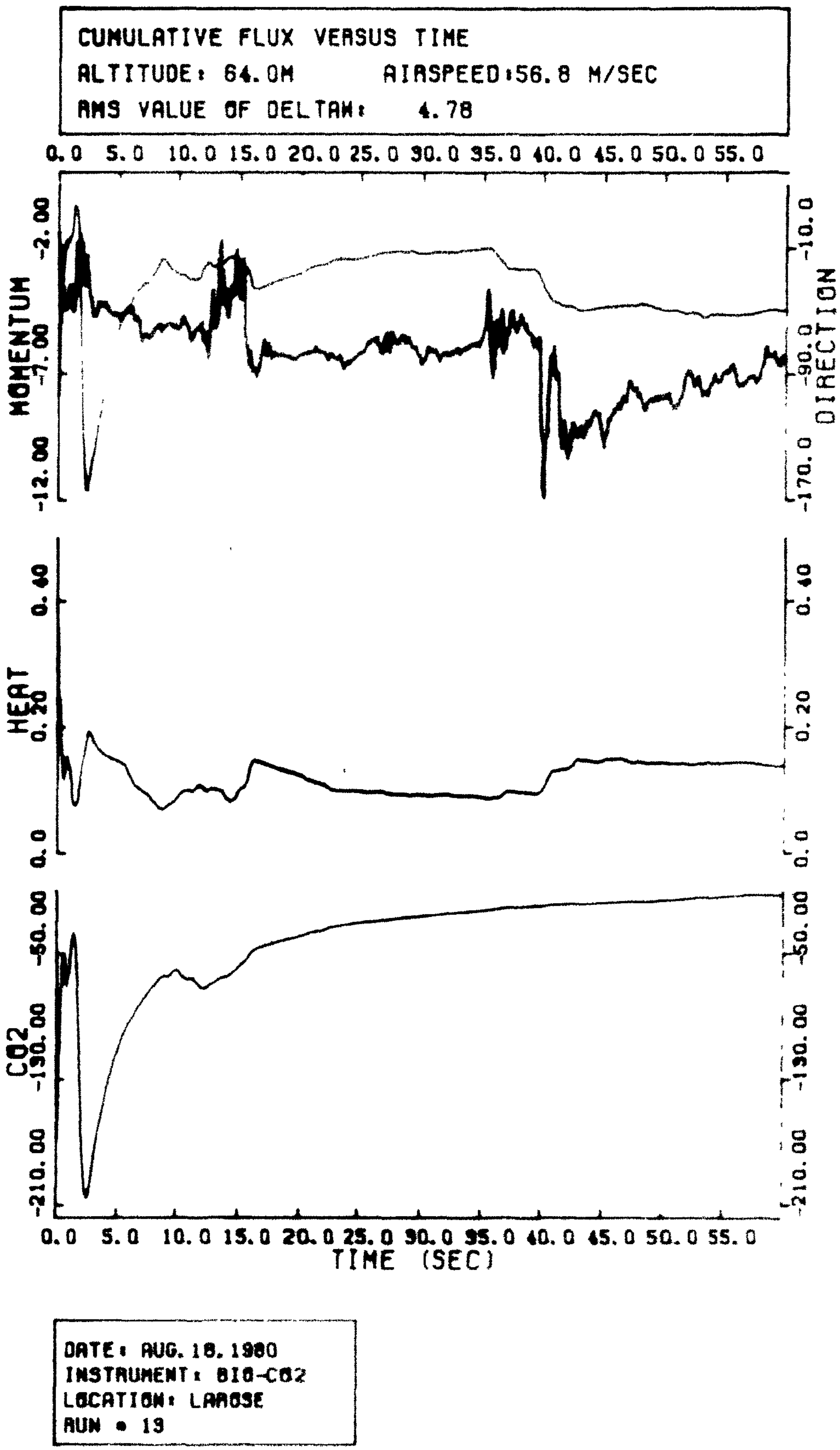


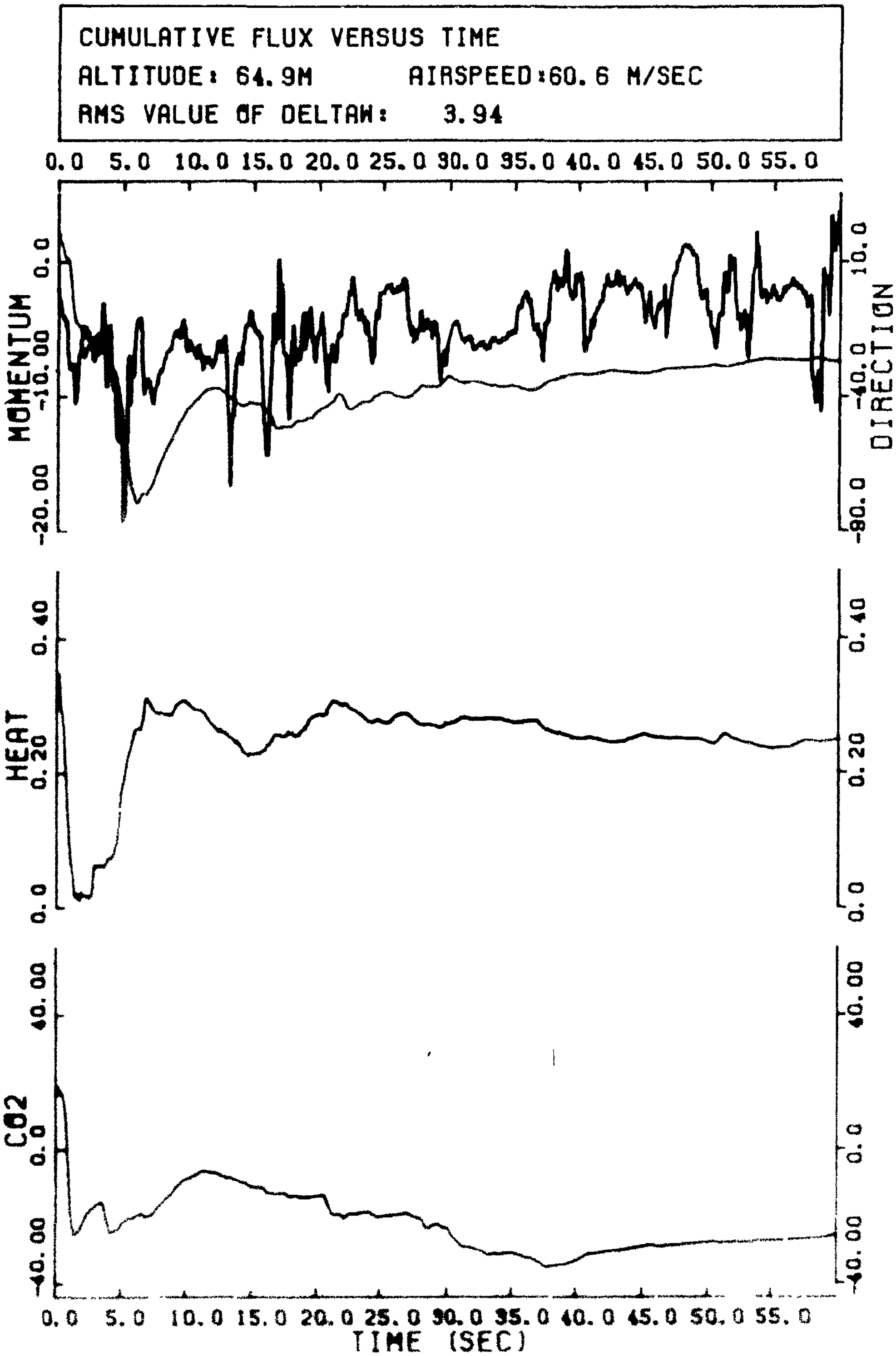
DATE: AUG. 18, 1980
INSTRUMENT: BIO-CO2
LOCATION: LAROSE
RUN # 11

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 51.5M AIRSPEED:60.7 M/SEC
RMS VALUE OF DELTAW: 4.52

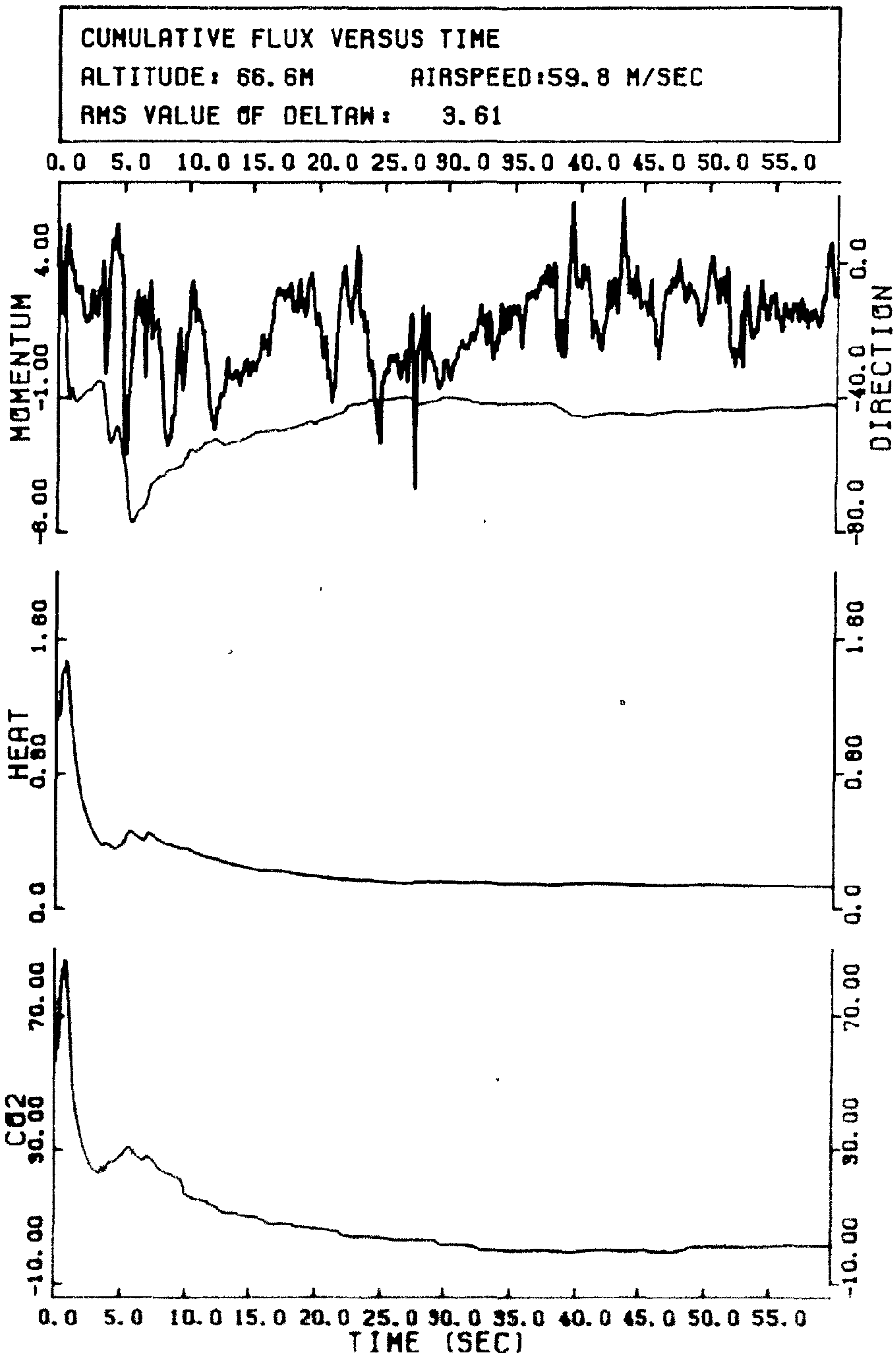


DATE: AUG. 18, 1980
INSTRUMENT: BIO-CO2
LOCATION: LAROSE
RUN # 12

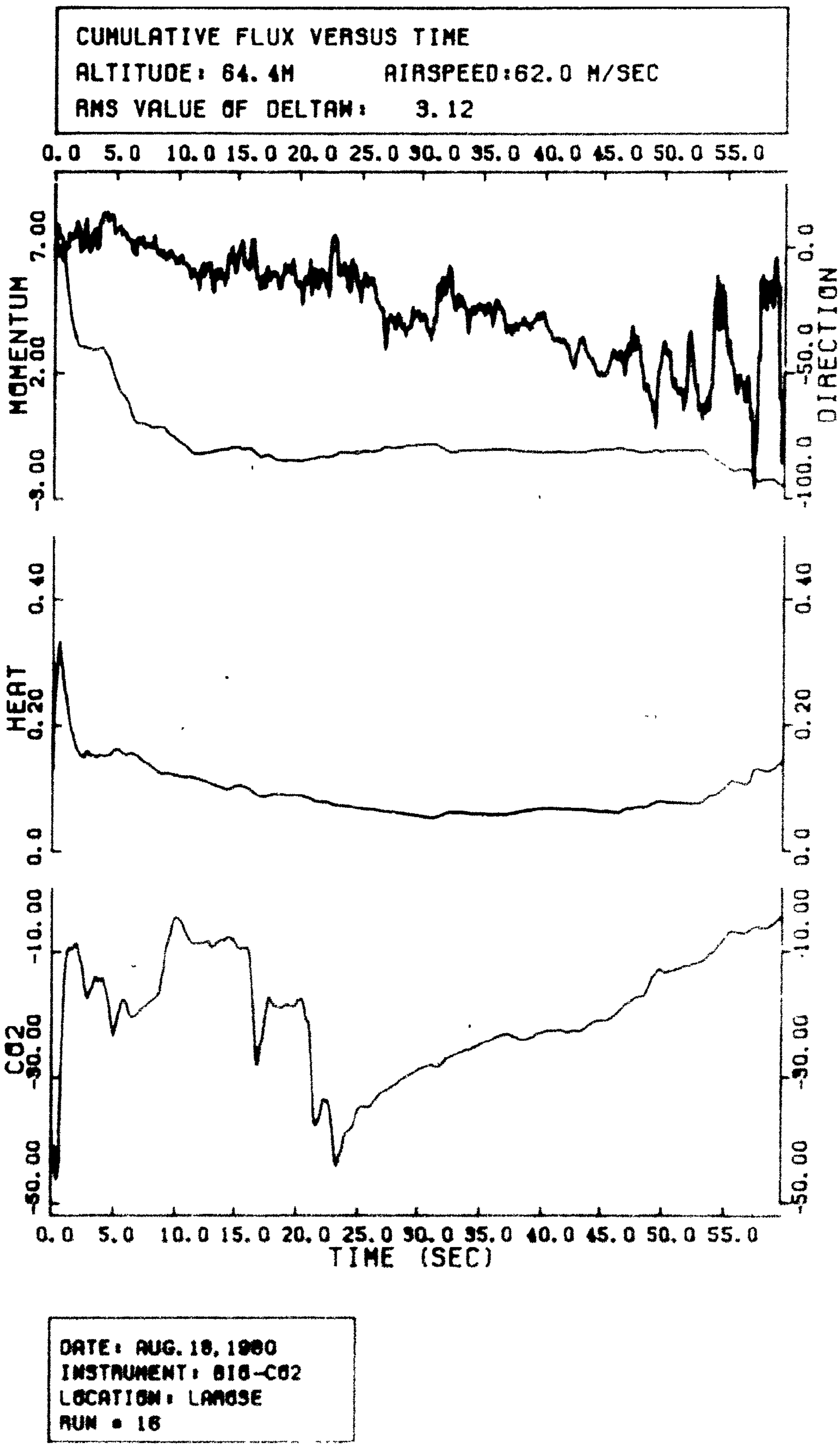

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 64.0M AIRSPEED:56.8 M/SEC
RMS VALUE OF DELTAM: 4.78
0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0 55.0
MOMENTUM
-2.00
-7.00
-12.00
DIRECTION
-10.0
-90.0
-170.0
HEAT
0.40
0.20
0.0
CO2
-50.00
-130.00
-210.00
TIME (SEC)
DATE: AUG. 18, 1980
INSTRUMENT: BIO-CO2
LOCATION: LAROSE
RUN # 13



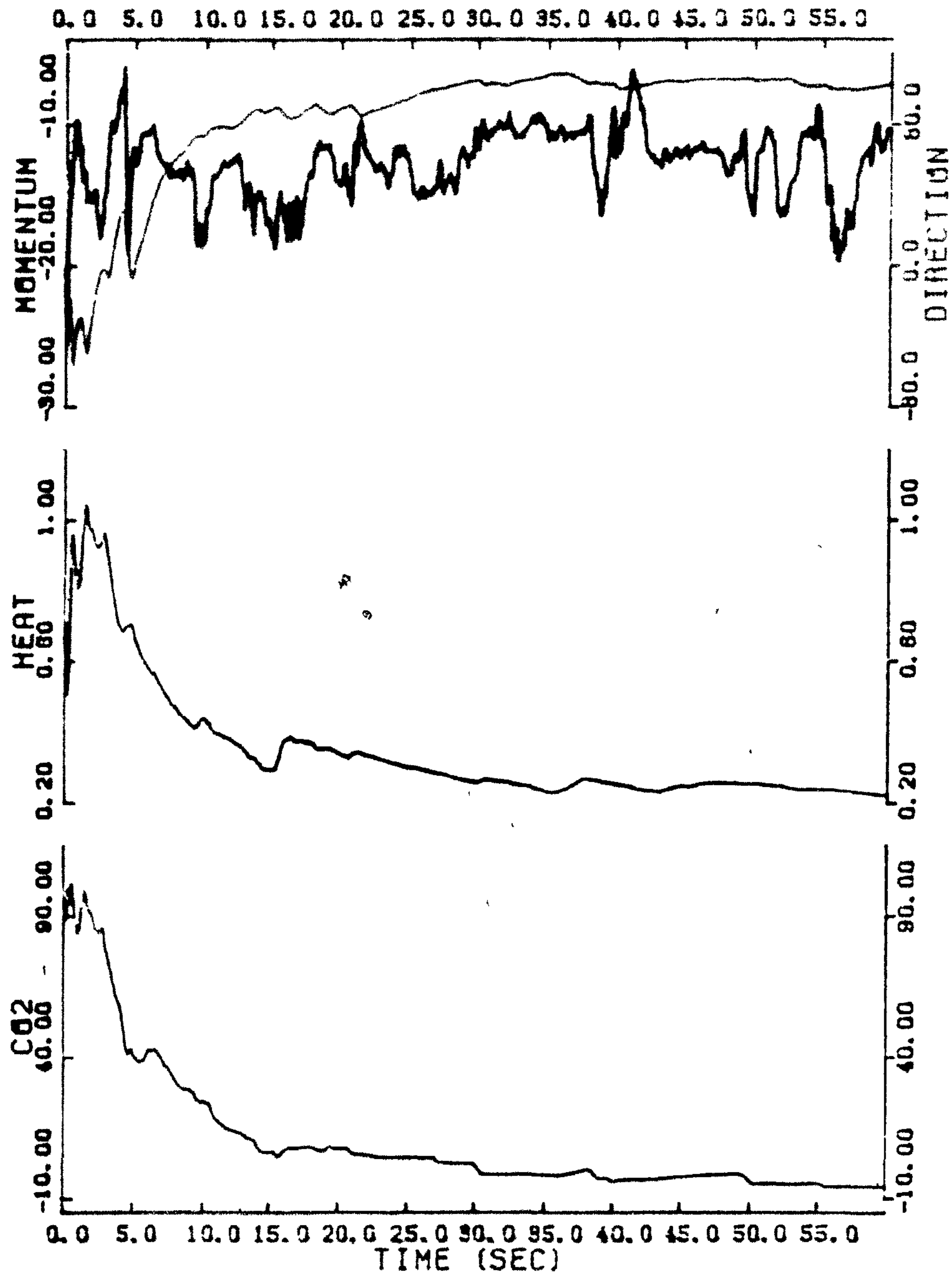
DATE: AUG. 18, 1980
INSTRUMENT: BIG-CO2
LOCATION: LAROSE
RUN # 14



DATE: AUG. 18, 1980
INSTRUMENT: BIG-CO2
LOCATION: LAROSE
RUN = 15

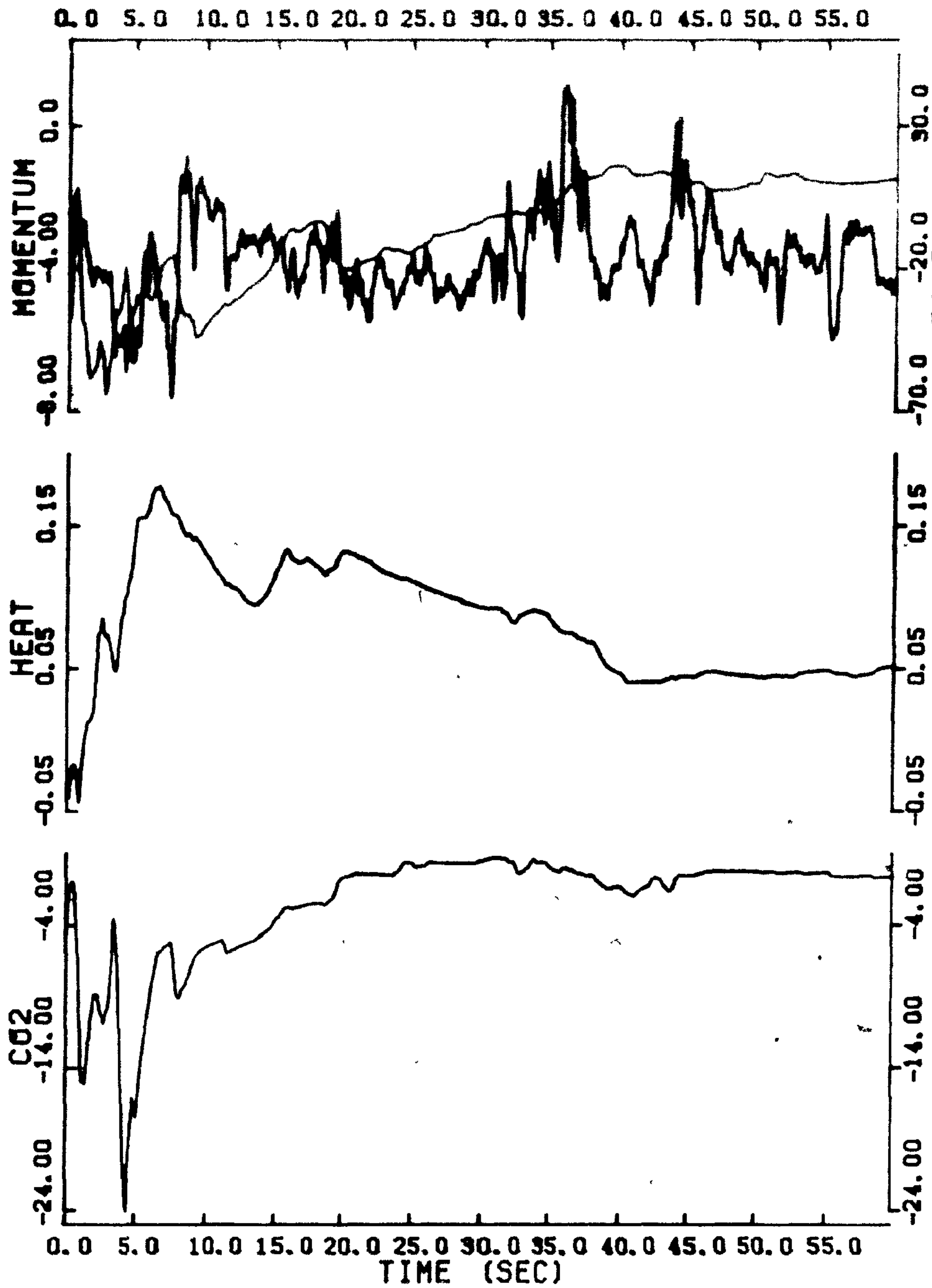

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 64.4M AIRSPEED:62.0 M/SEC
RMS VALUE OF DELTAW: 3.12
0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0 55.0
MOMENTUM
7.00
2.00
-3.00
DIRECTION
0.0
-50.0
-100.0
HEAT
0.40
0.20
0.0
CO2
-10.00
-30.00
-50.00
TIME (SEC)
DATE: AUG.18,1980
INSTRUMENT: BIG-CO2
LOCATION: LAROSE
RUN # 16

CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 65.2M AIRSPEED:57.8 M/SEC
RMS VALUE OF DELTAW: 4.80



DATE: AUG. 18, 1980
INSTRUMENT: BIG-CO2
LOCATION: LARGSE
RUN # 17

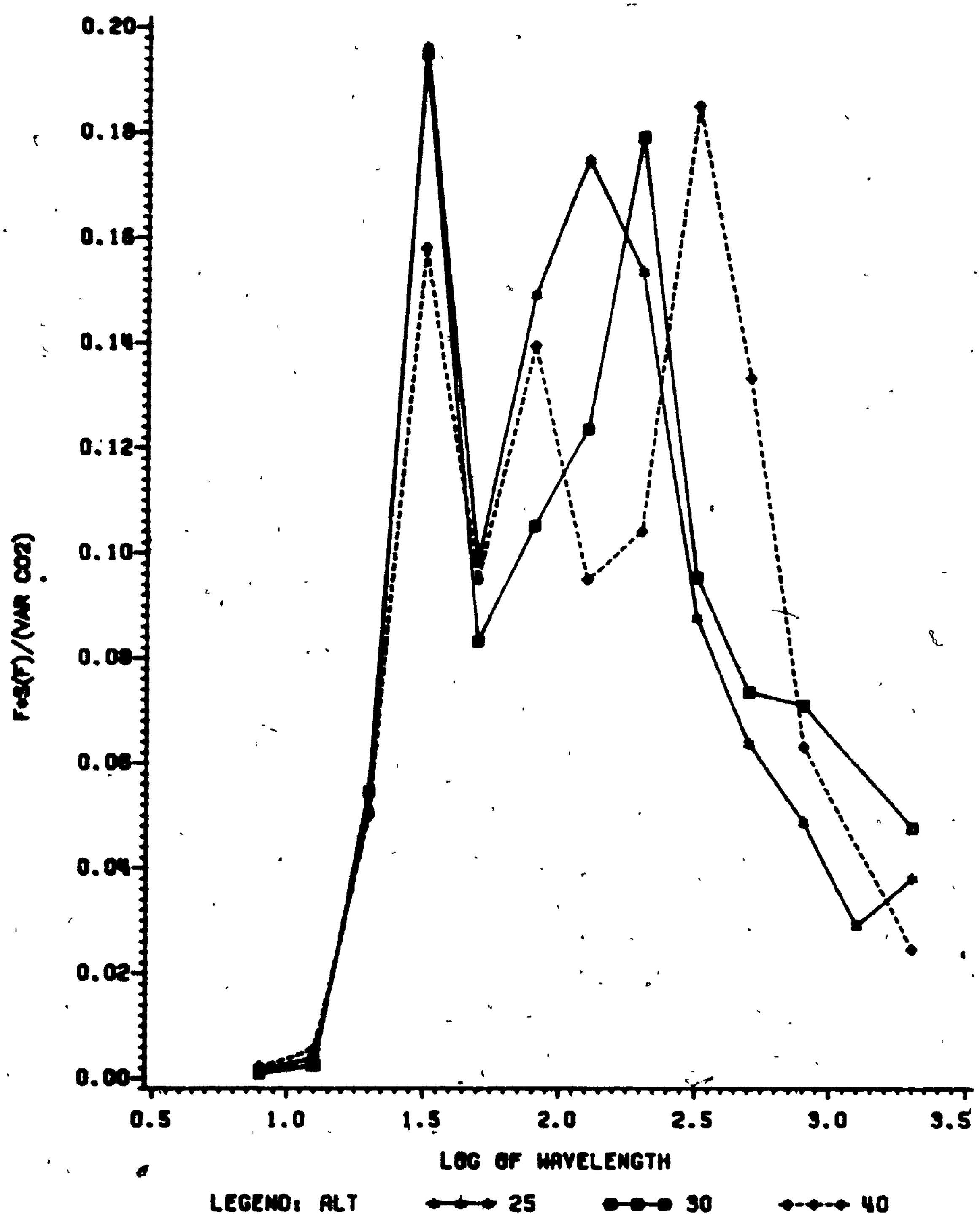
CUMULATIVE FLUX VERSUS TIME
ALTITUDE: 63.8M AIRSPEED:56.8 M/SEC
RMS VALUE OF DELTAW: 4.26



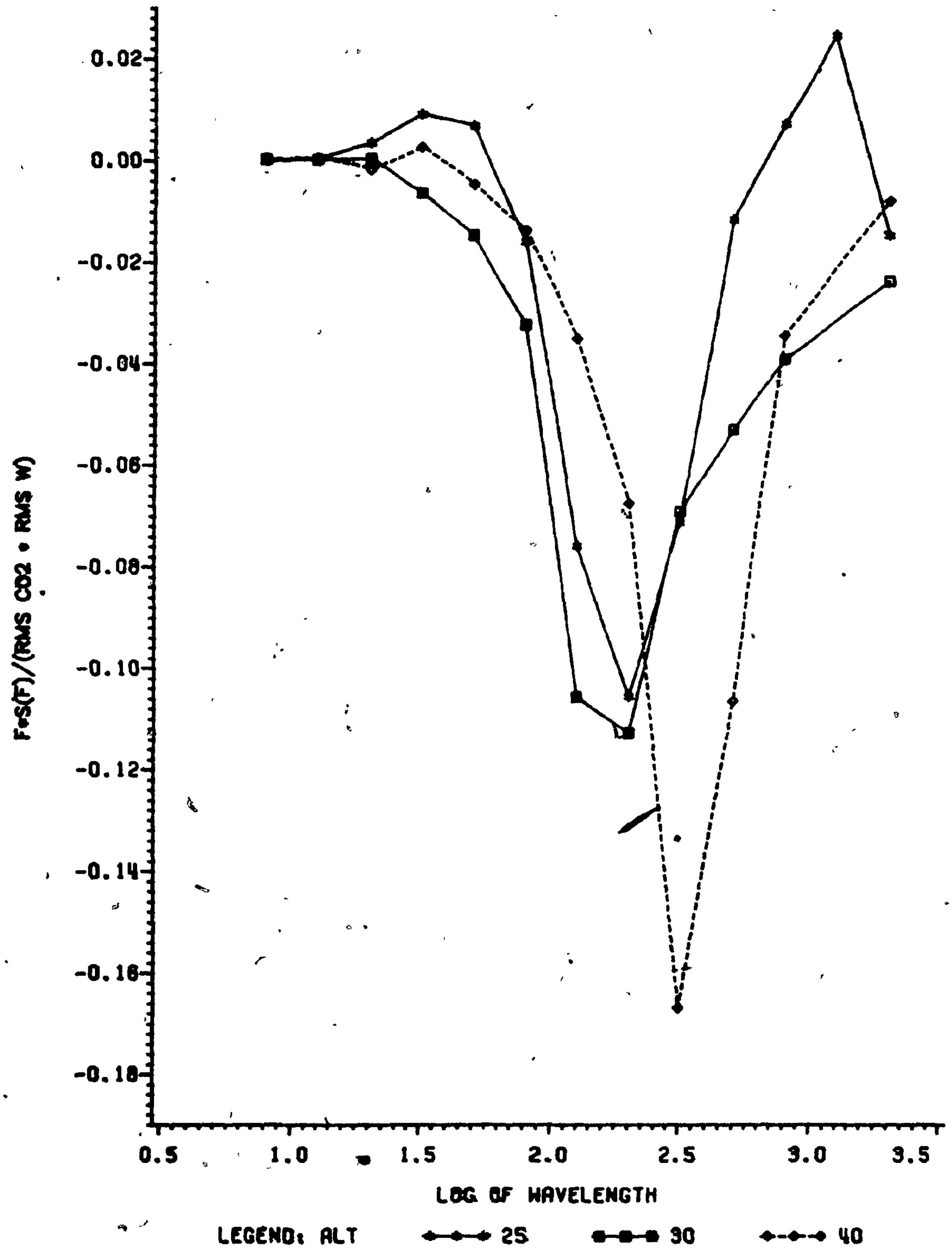
DATE: AUG. 18, 1980
INSTRUMENT: BIO-CO2
LOCATION: LAROSE
RUN # 18

APPENDIX D: Plots of Average Spectra and Cospectra.

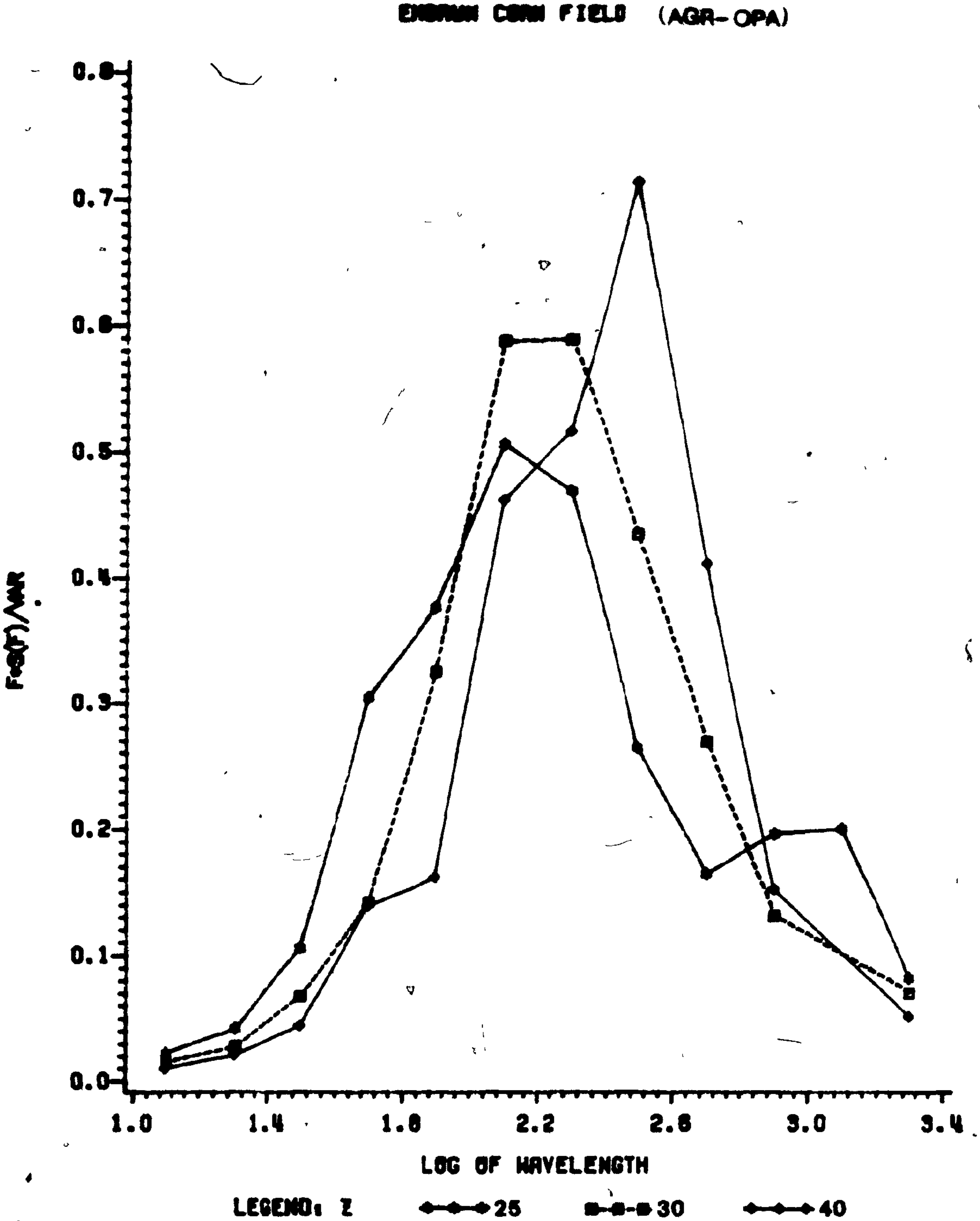
AVERAGE SPECTRA OF CO2 AT THREE ALTITUDES OVER EMERSON CORN FIELD (AGR—OPA)



AVERAGE COSPECTRA FOR CO2 TRANSFER OVER EMBRUN CORN FIELD (AGR-OPA)

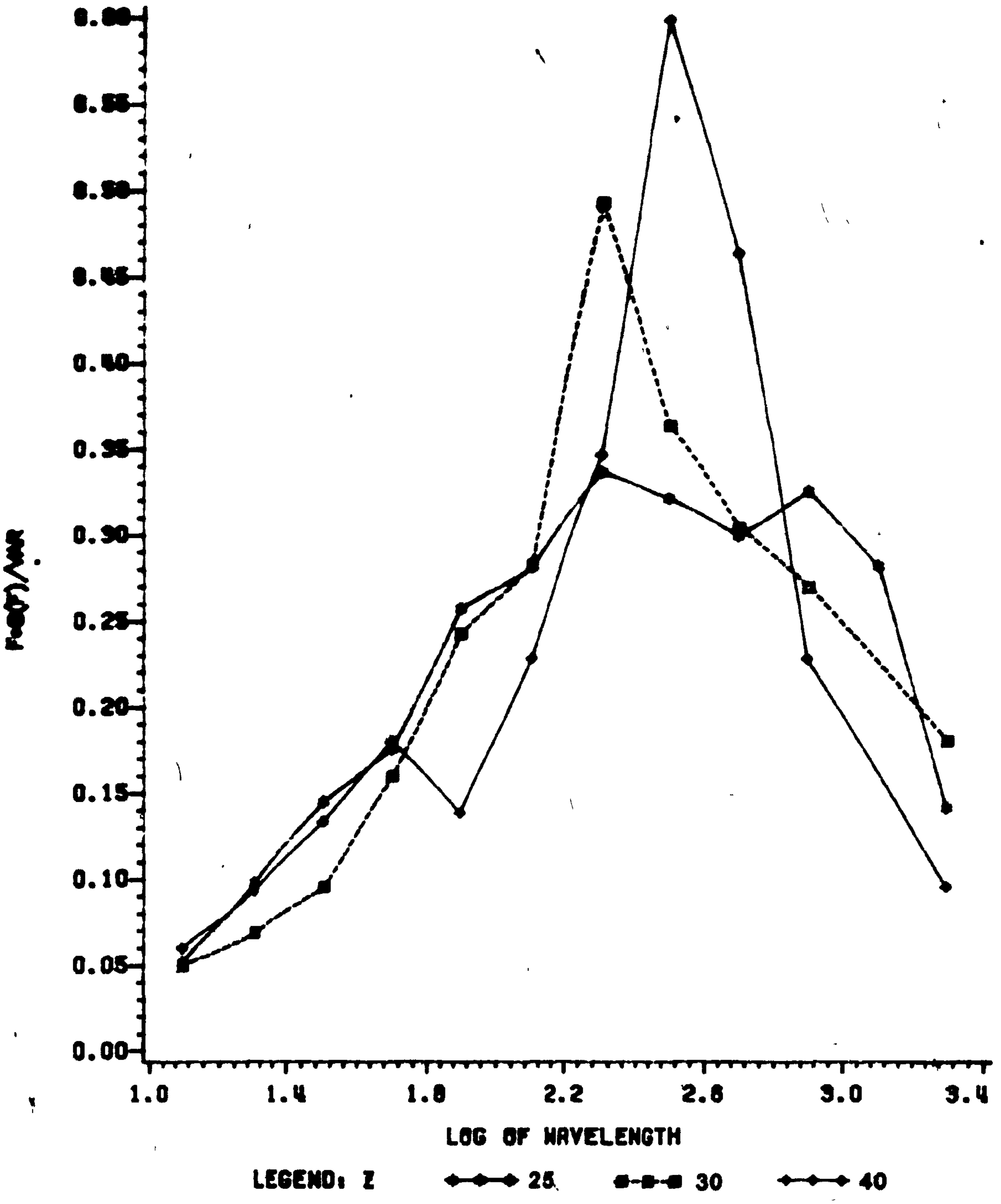


AVERAGE SPECTRA OF VERTICAL WIND



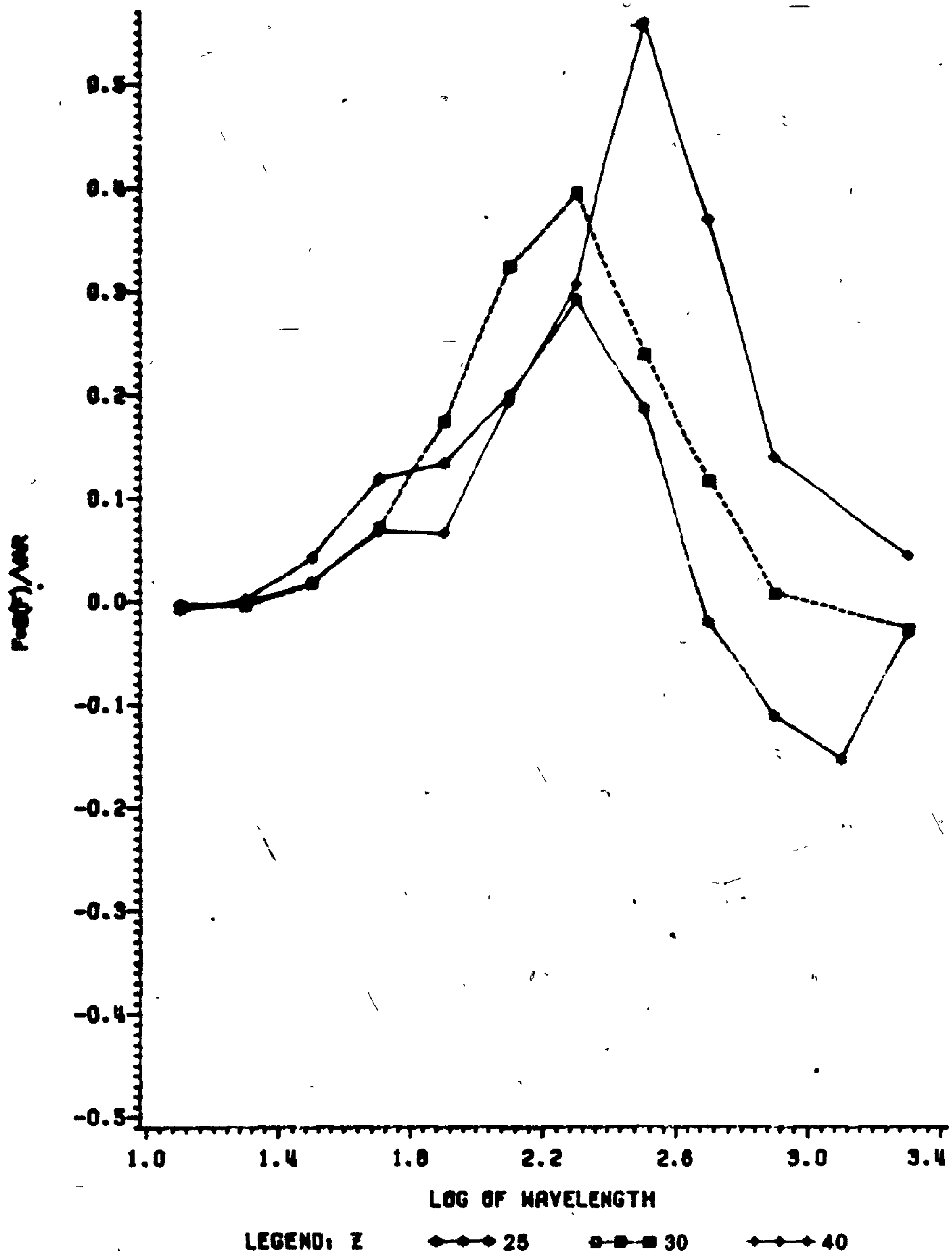
AVERAGE SPECTRA OF TEMPERATURE

[illegible] CORN FIELD (AGR—OPA)



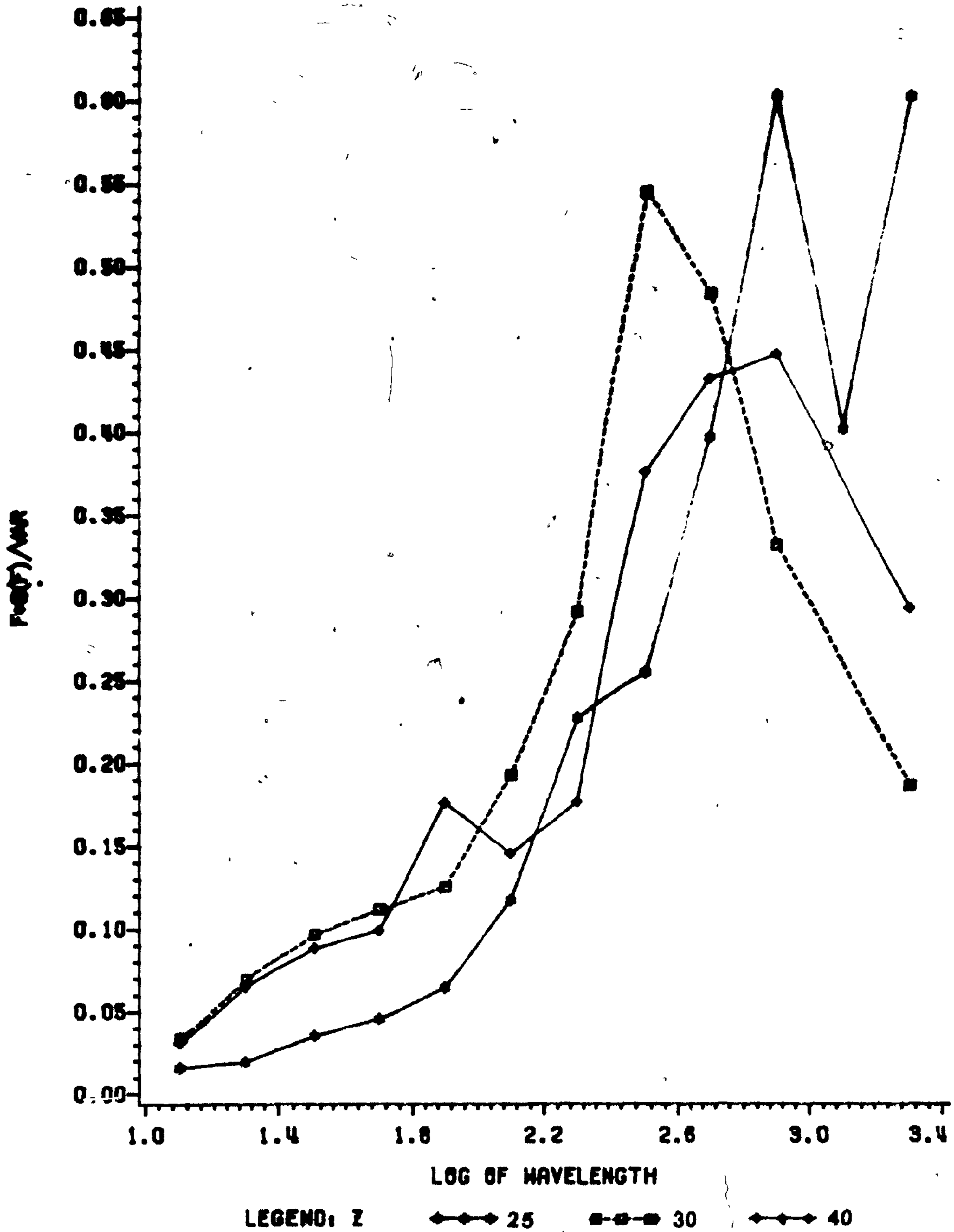
AVERAGE COSPECTRA OF TEMPERATURE AND VERTICAL WIND

CORN FIELD (AGR-OPA)

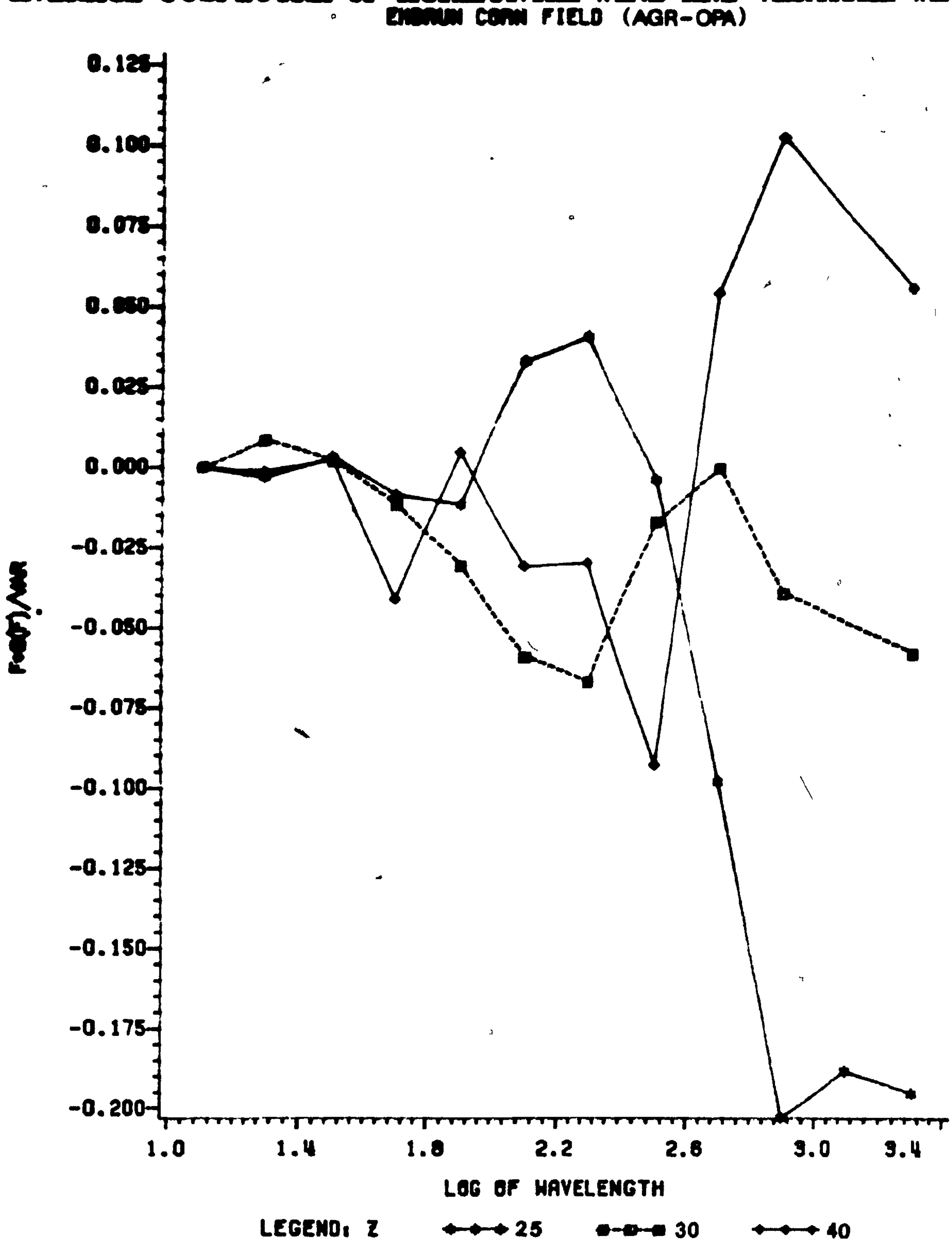


AVERAGE SPECTRA OF HORIZONTAL WIND

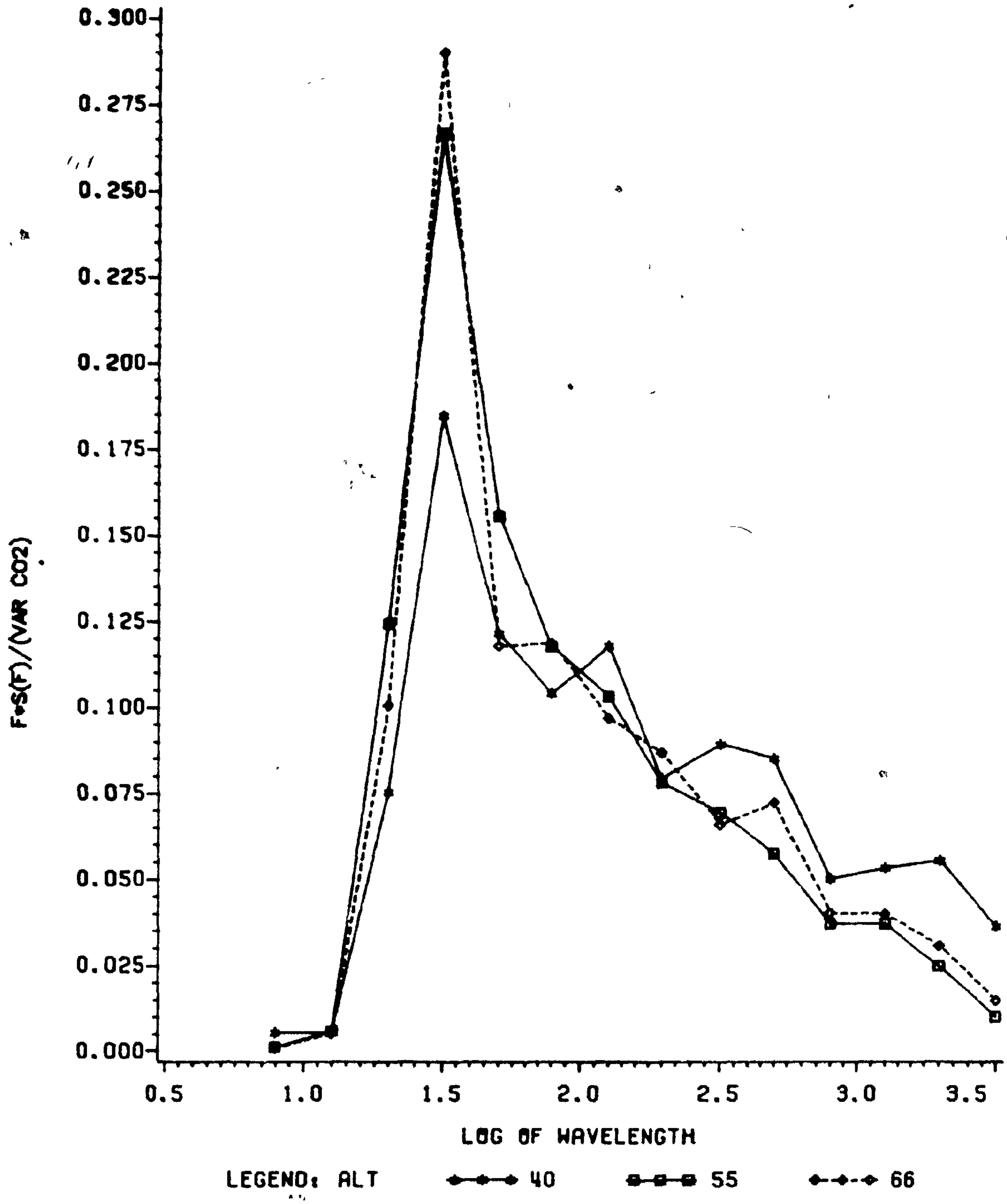
EMBRUN CORN FIELD (AGR-OPA)



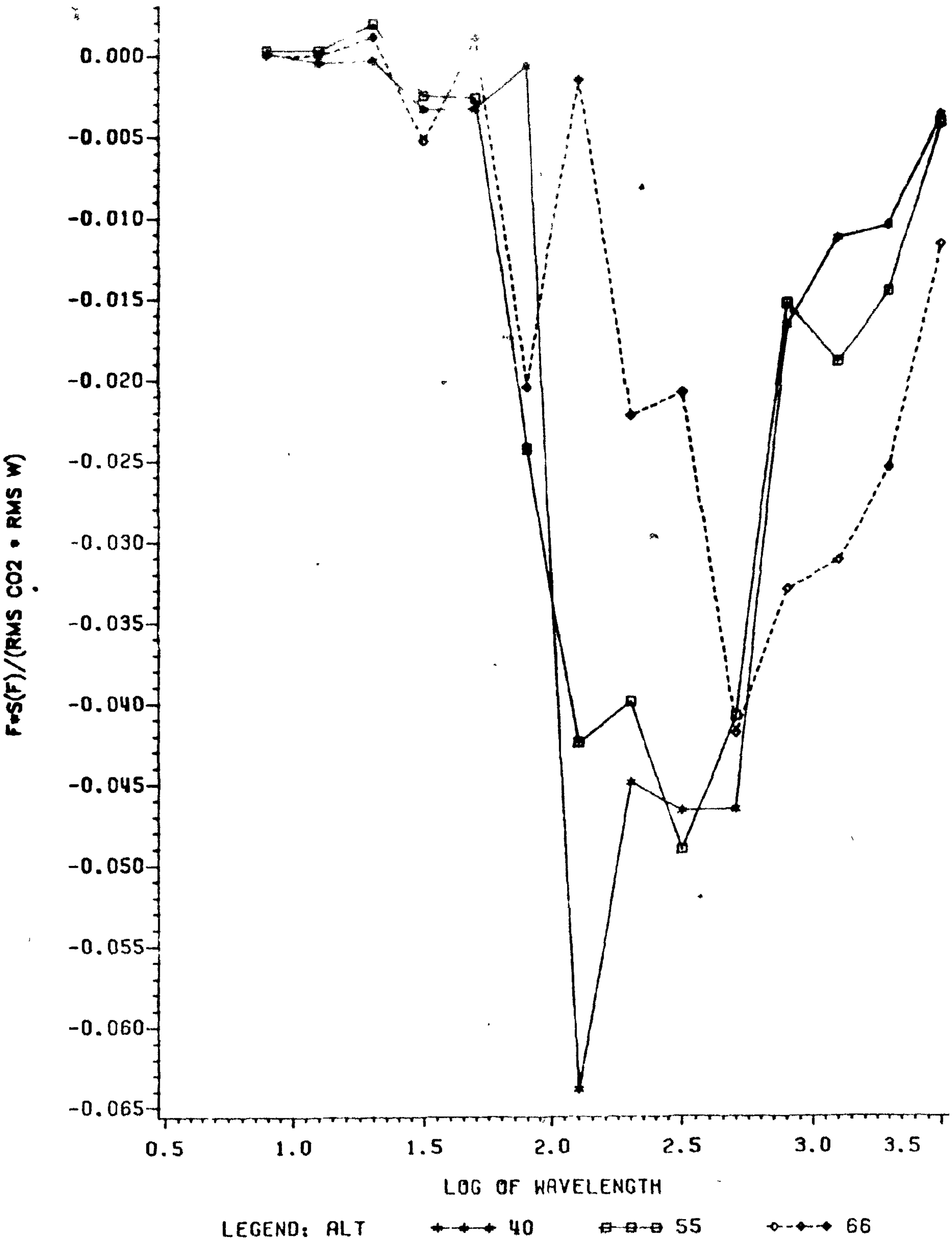
AVERAGE COSPECTRA OF HORIZONTAL WIND AND VERTICAL WIND

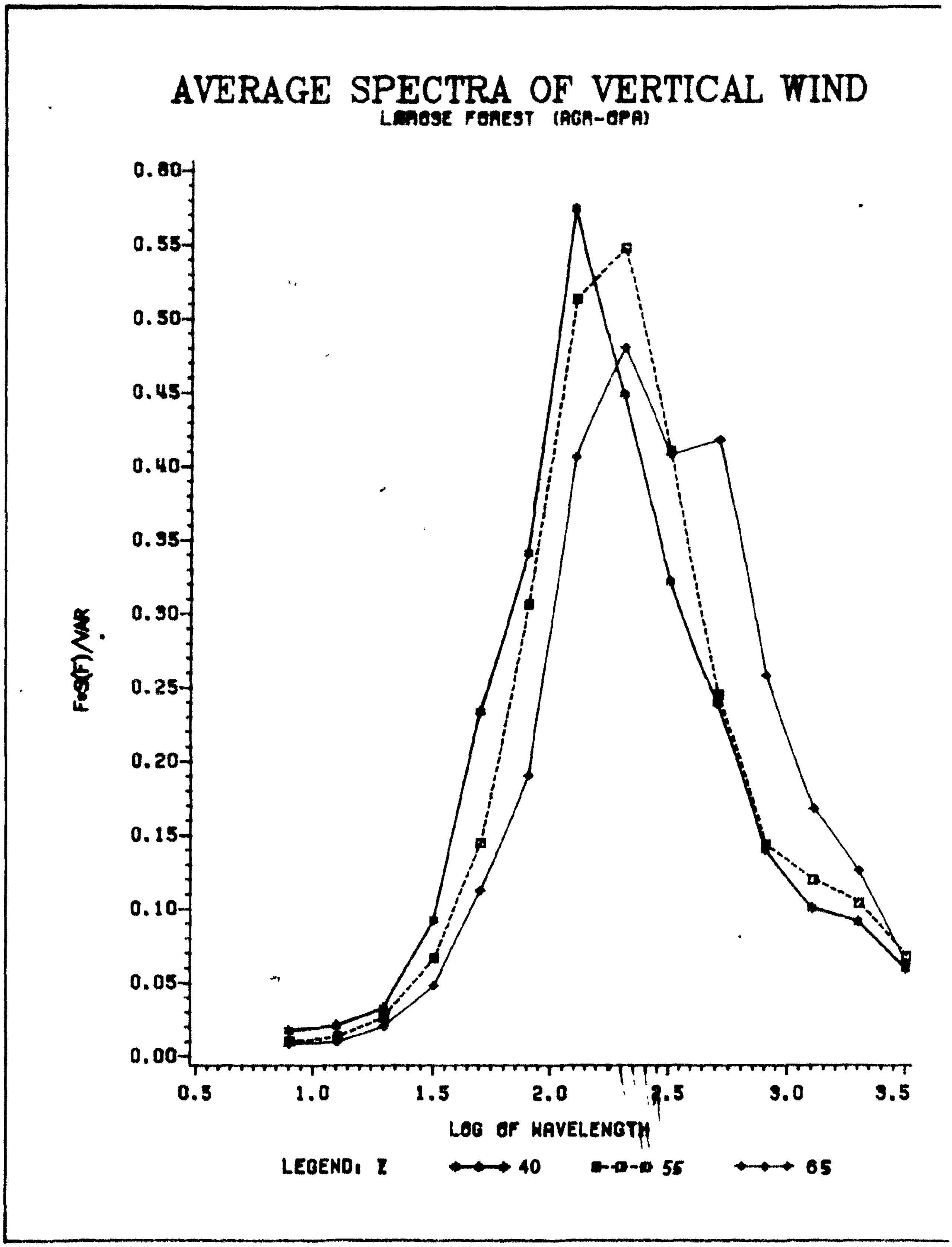


AVERAGE SPECTRA OF CO2 AT THREE ALTITUDES OVER LAROSE FOREST (AGR-OPA)

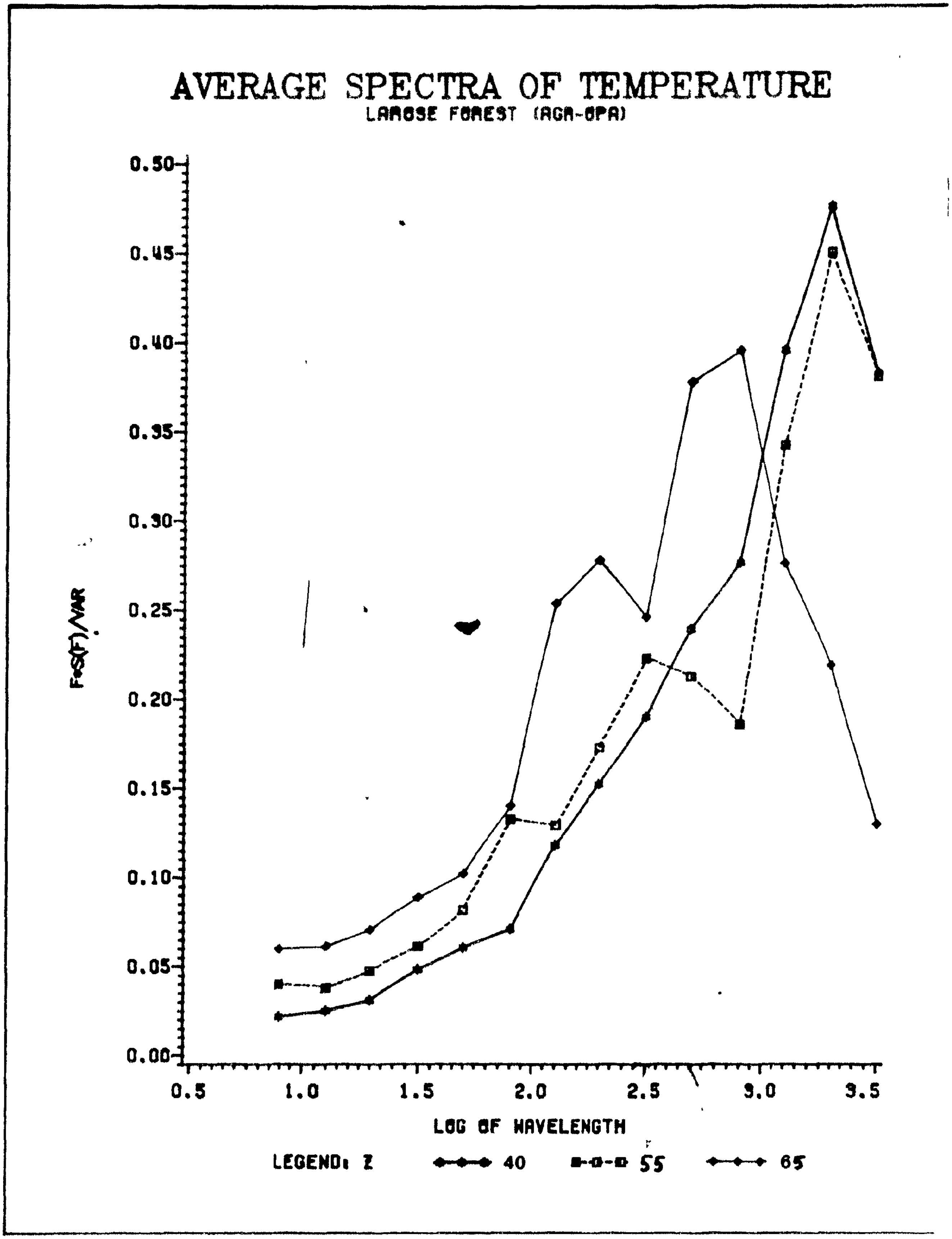


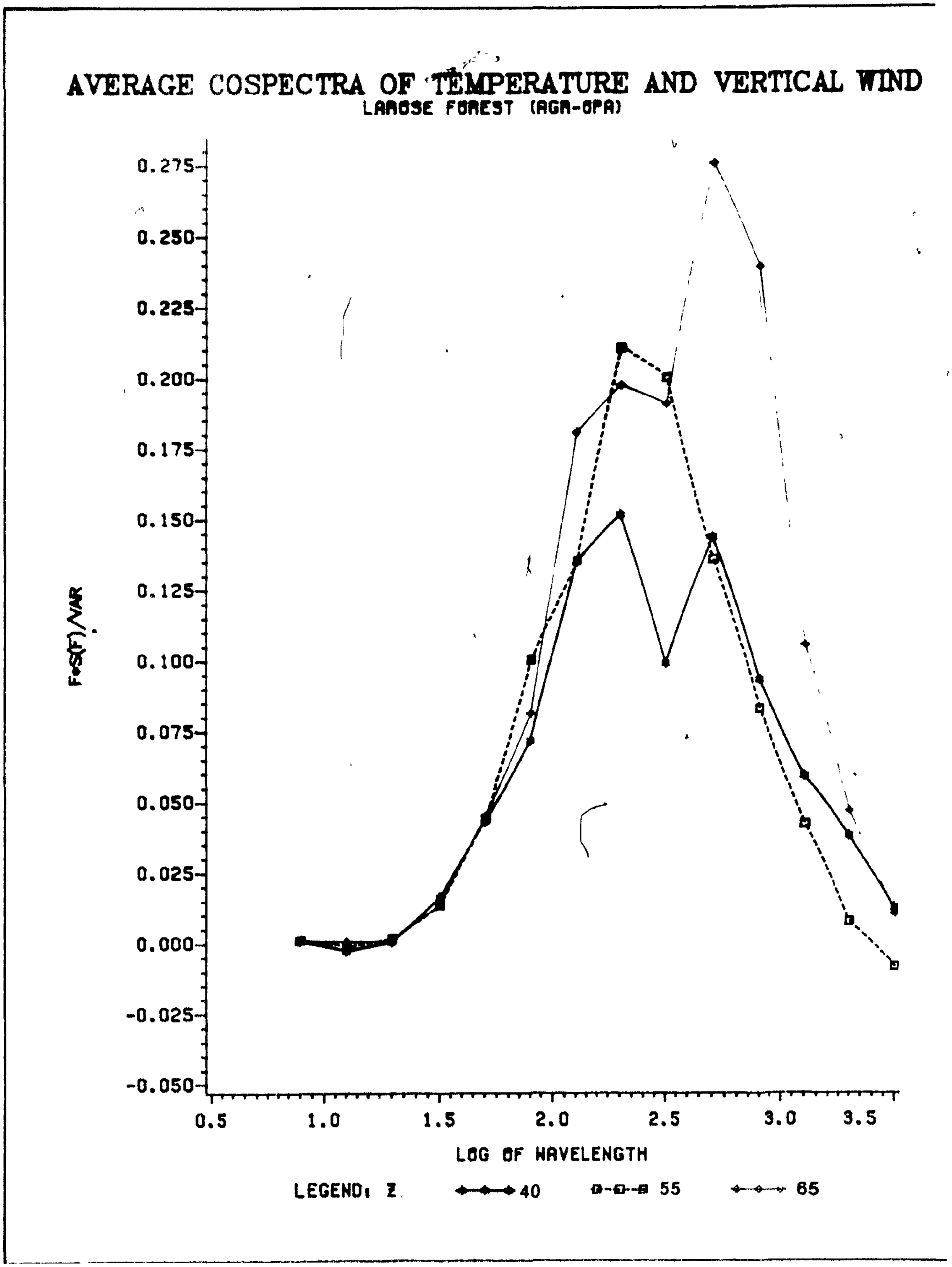
AVERAGE COSPECTRA FOR CO2 TRANSFER OVER LAROSE FOREST (AGR-OPA)

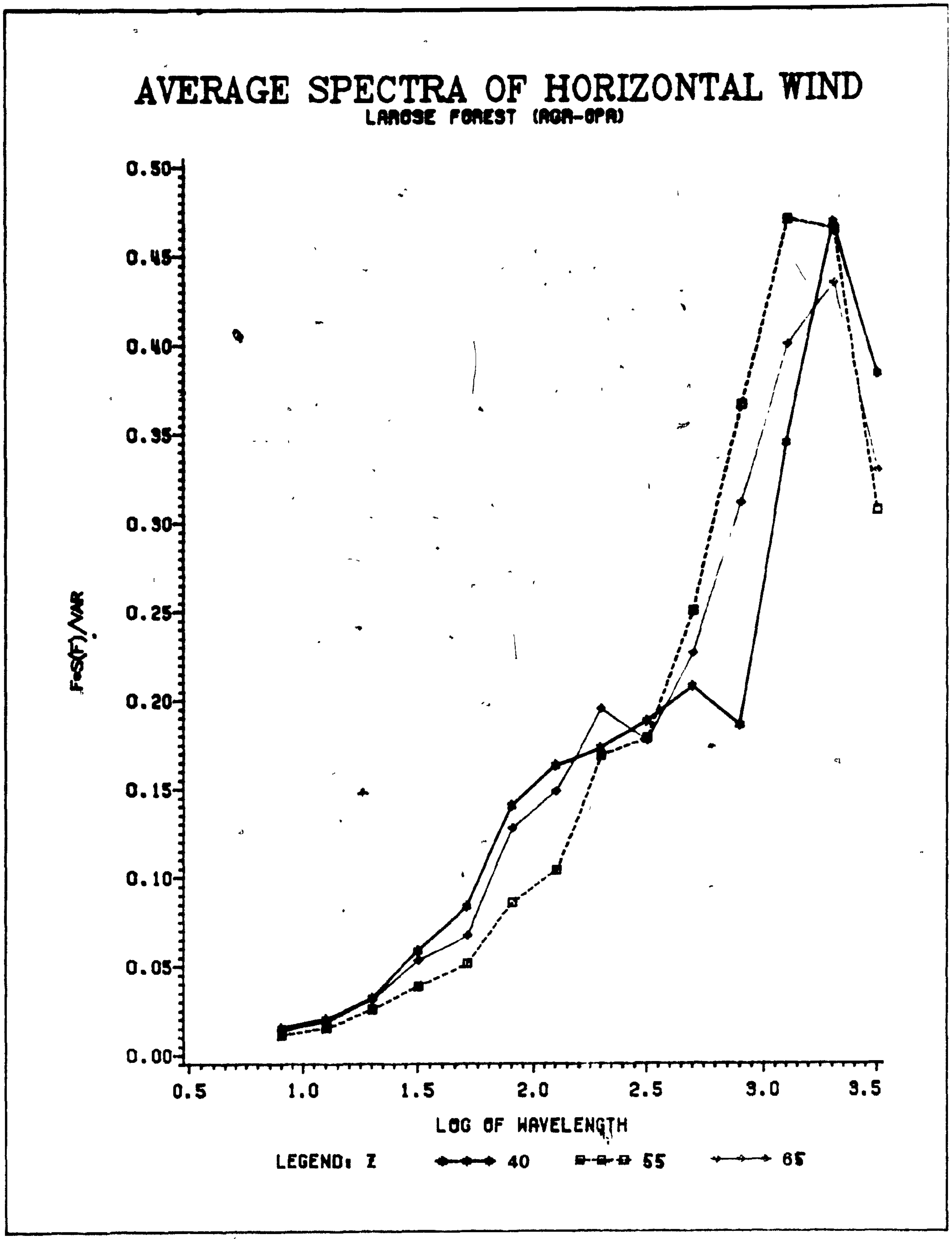


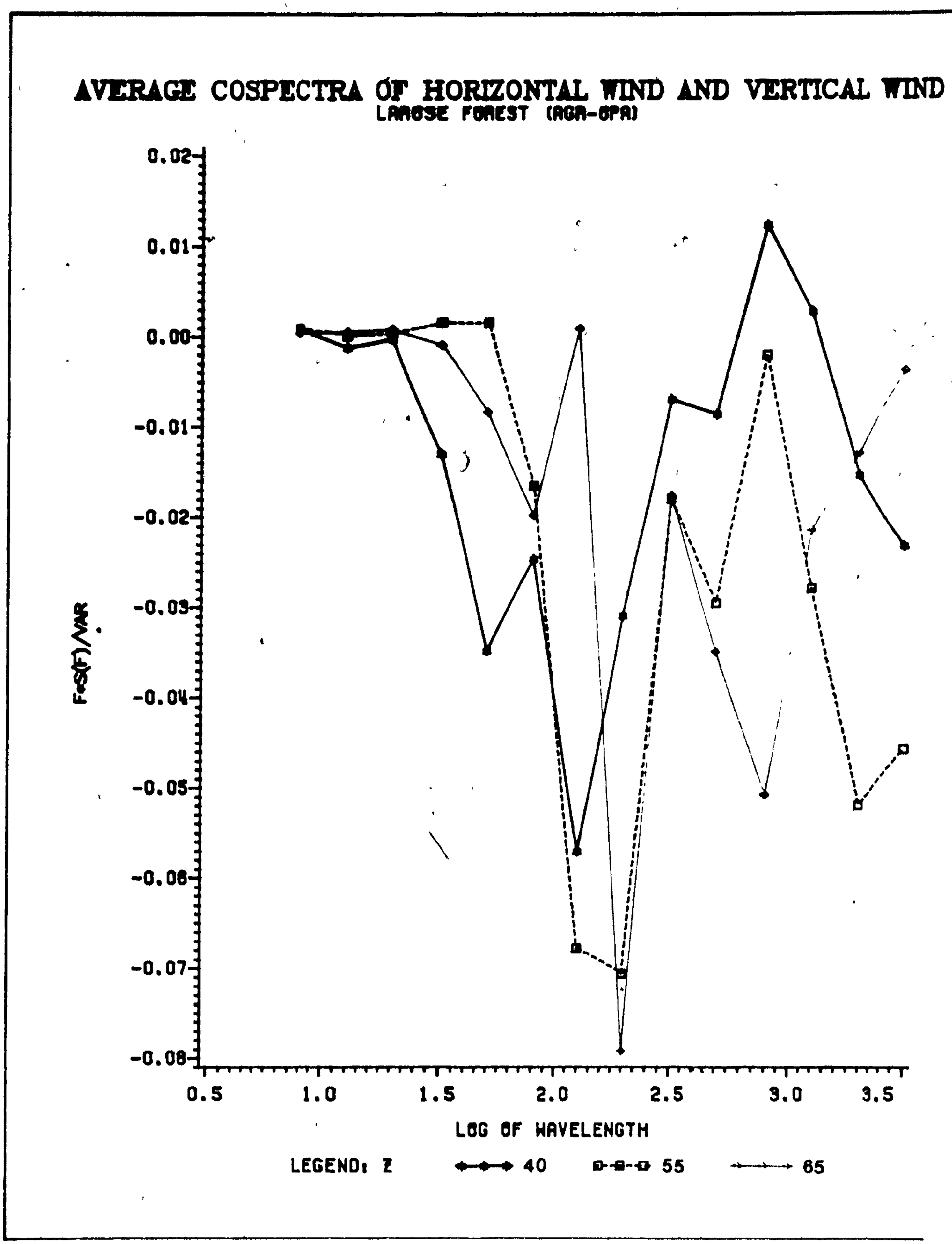


AVERAGE SPECTRA OF VERTICAL WIND
LAROSE FOREST (AGA-OPA)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
F*S(F)/VAR
0.5
1.0
1.5
2.0
2.5
3.0
3.5
LOG OF WAVELENGTH
LEGEND: Z
40
55
65

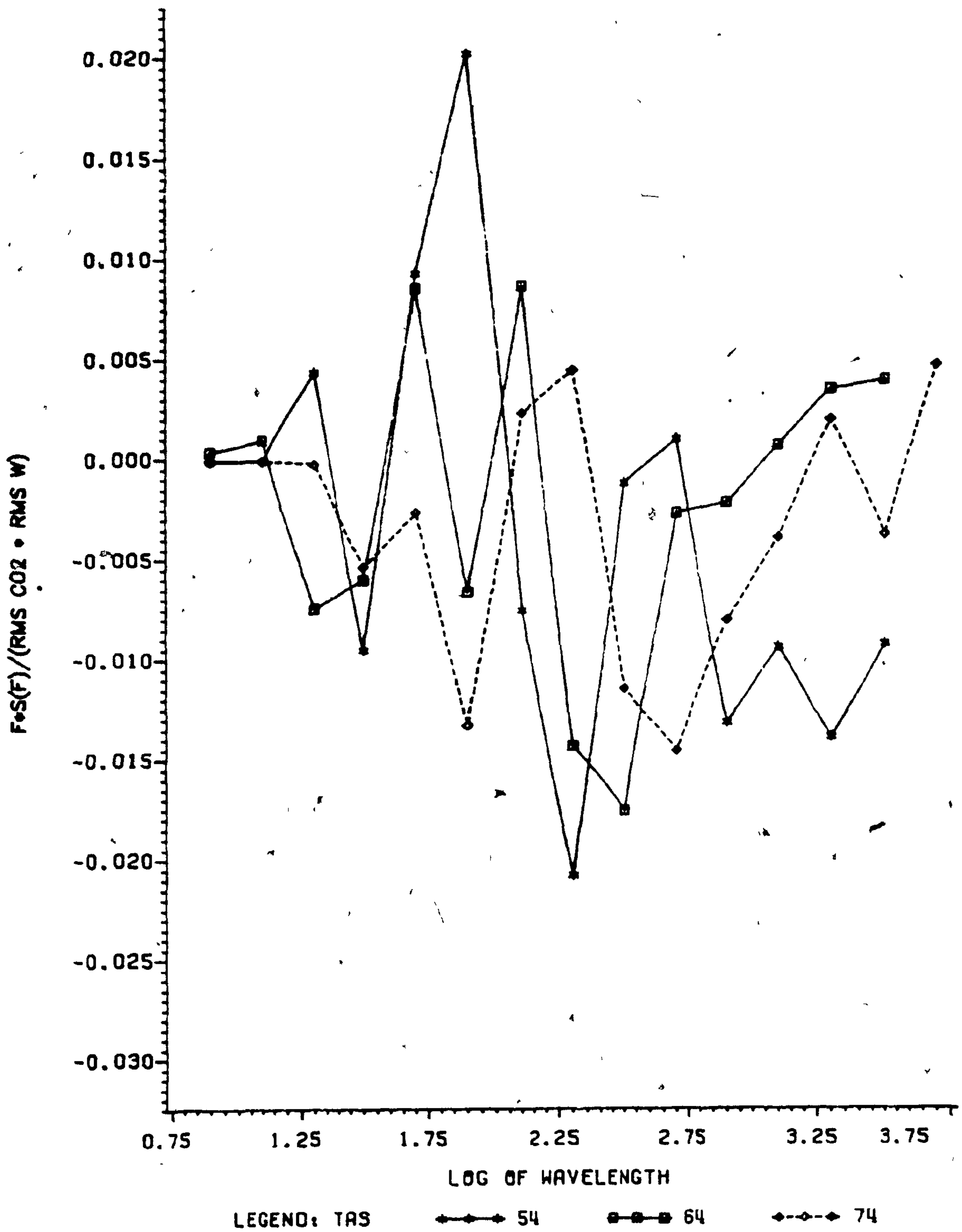

AVERAGE SPECTRA OF TEMPERATURE
LAROSE FOREST (AGA-OPA)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
F*S(F)/VAR
0.5
1.0
1.5
2.0
2.5
3.0
3.5
LOG OF WAVELENGTH
LEGEND: Z
40
55
65

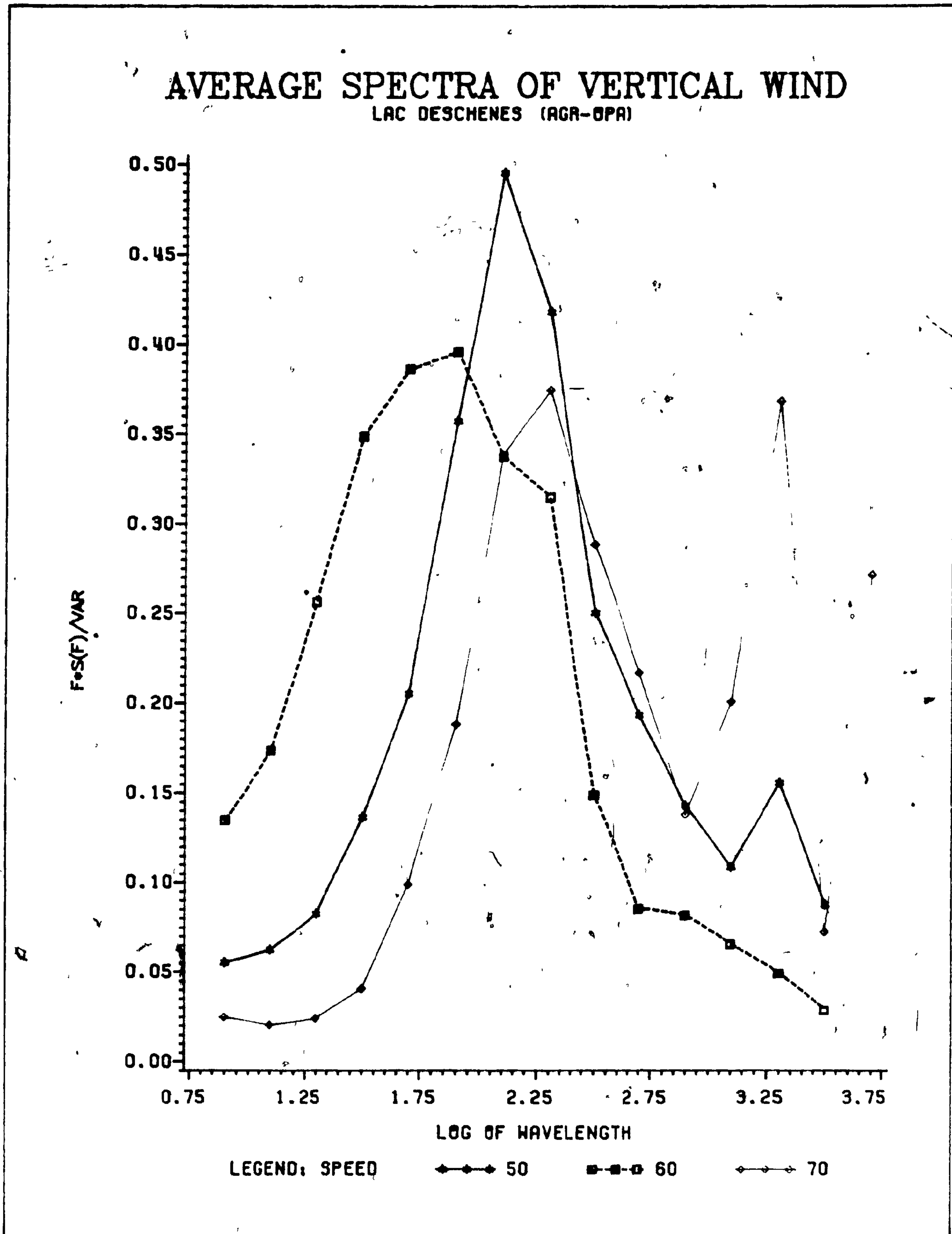

AVERAGE COSPECTRA OF TEMPERATURE AND VERTICAL WIND
LAROSE FOREST (AGA-OPA)
0.275
0.250
0.225
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
-0.025
-0.050
F*S(F)/VAR
0.5
1.0
1.5
2.0
2.5
3.0
3.5
LOG OF WAVELENGTH
LEGEND: Z
40
55
65

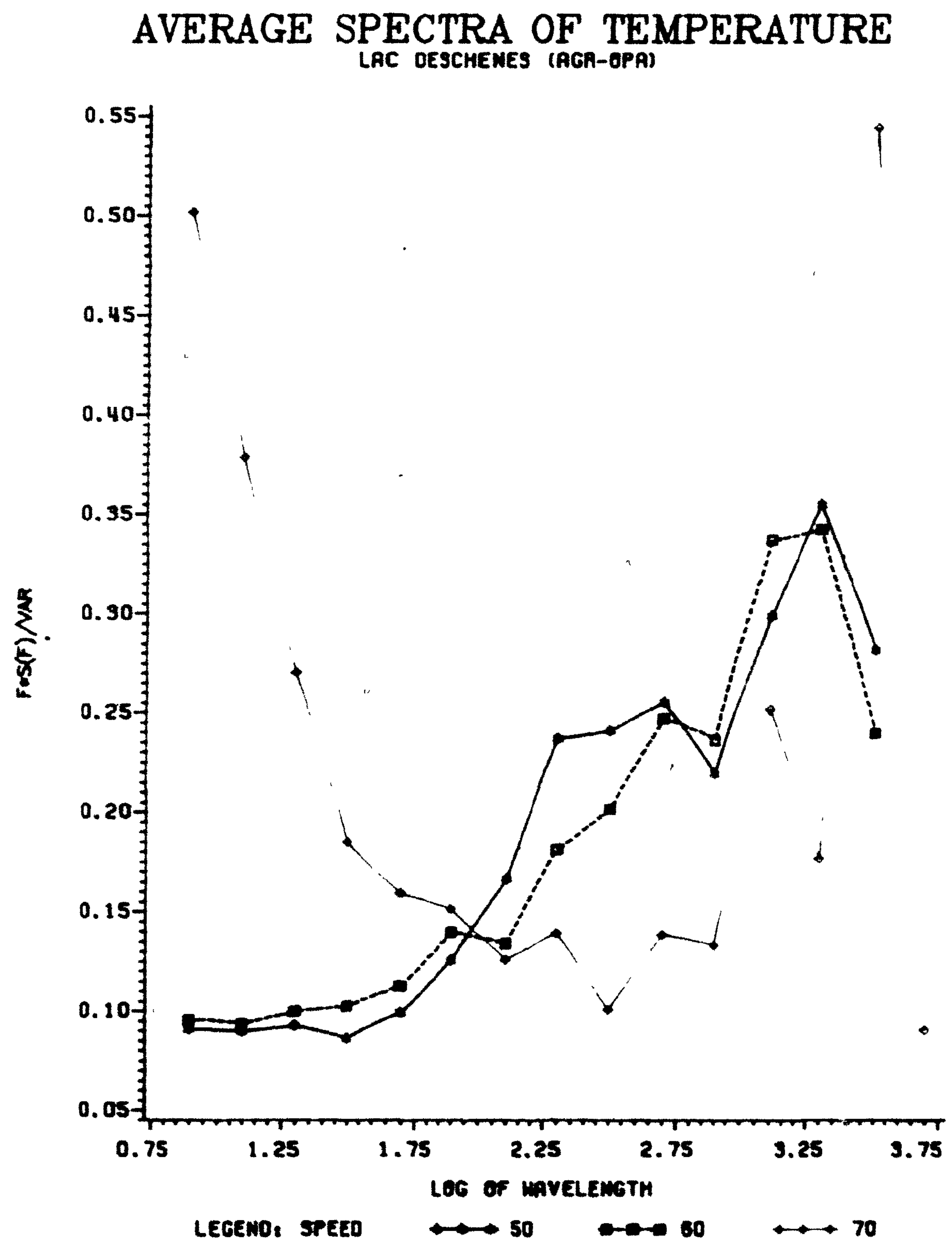

AVERAGE SPECTRA OF HORIZONTAL WIND
LAROSE FOREST (AGA-OPA)
F*S(F)/VAR
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.5
1.0
1.5
2.0
2.5
3.0
3.5
LOG OF WAVELENGTH
LEGEND: Z
40
55
65

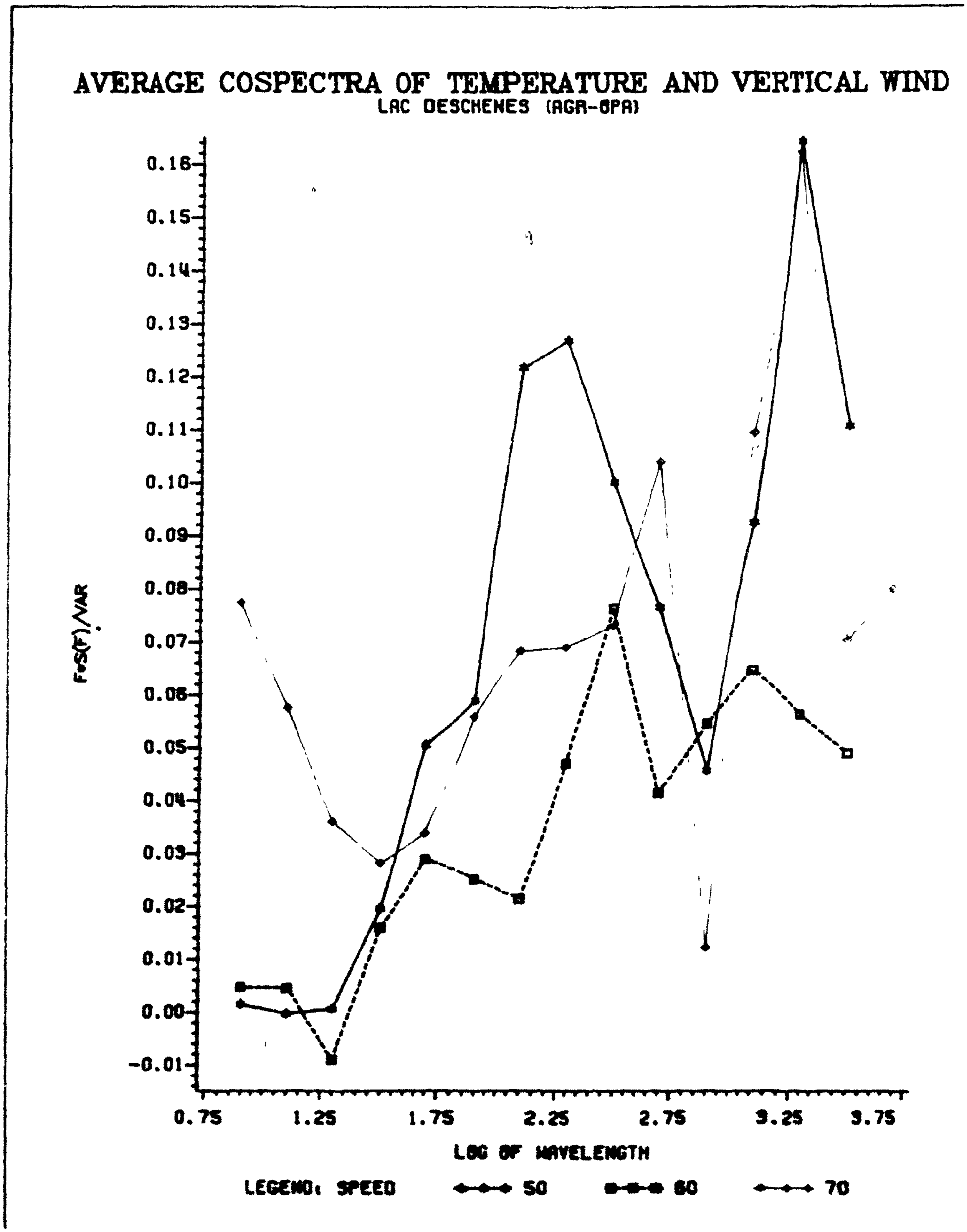

AVERAGE COSPECTRA OF HORIZONTAL WIND AND VERTICAL WIND
LAROSE FOREST (AGA-OPA)
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
F*S(F)/VAR
0.5
1.0
1.5
2.0
2.5
3.0
3.5
LOG OF WAVELENGTH
LEGEND: Z
40
55
65

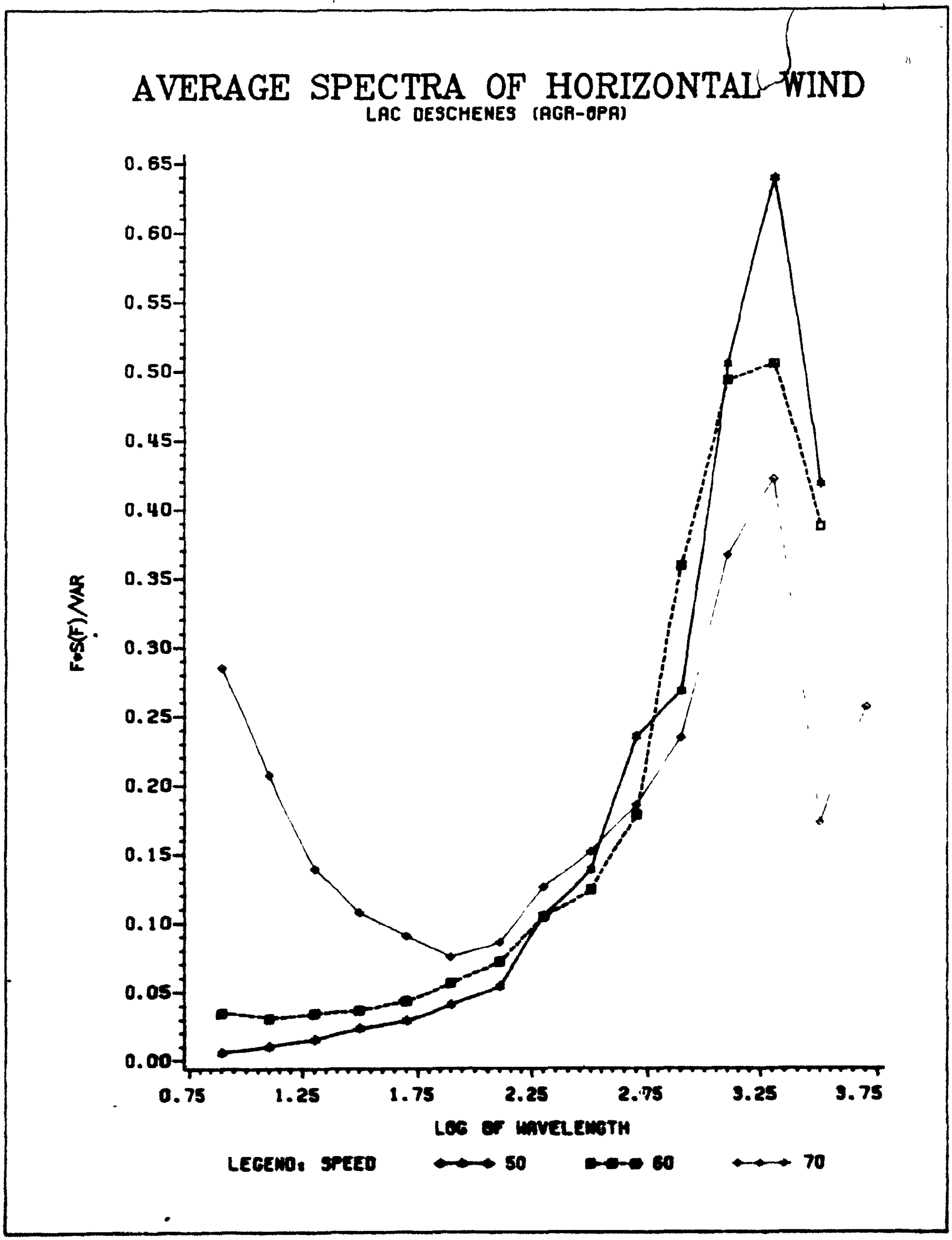
AVERAGE COSPECTRA FOR CO2 TRANSFER OVER LAC DESCHENES



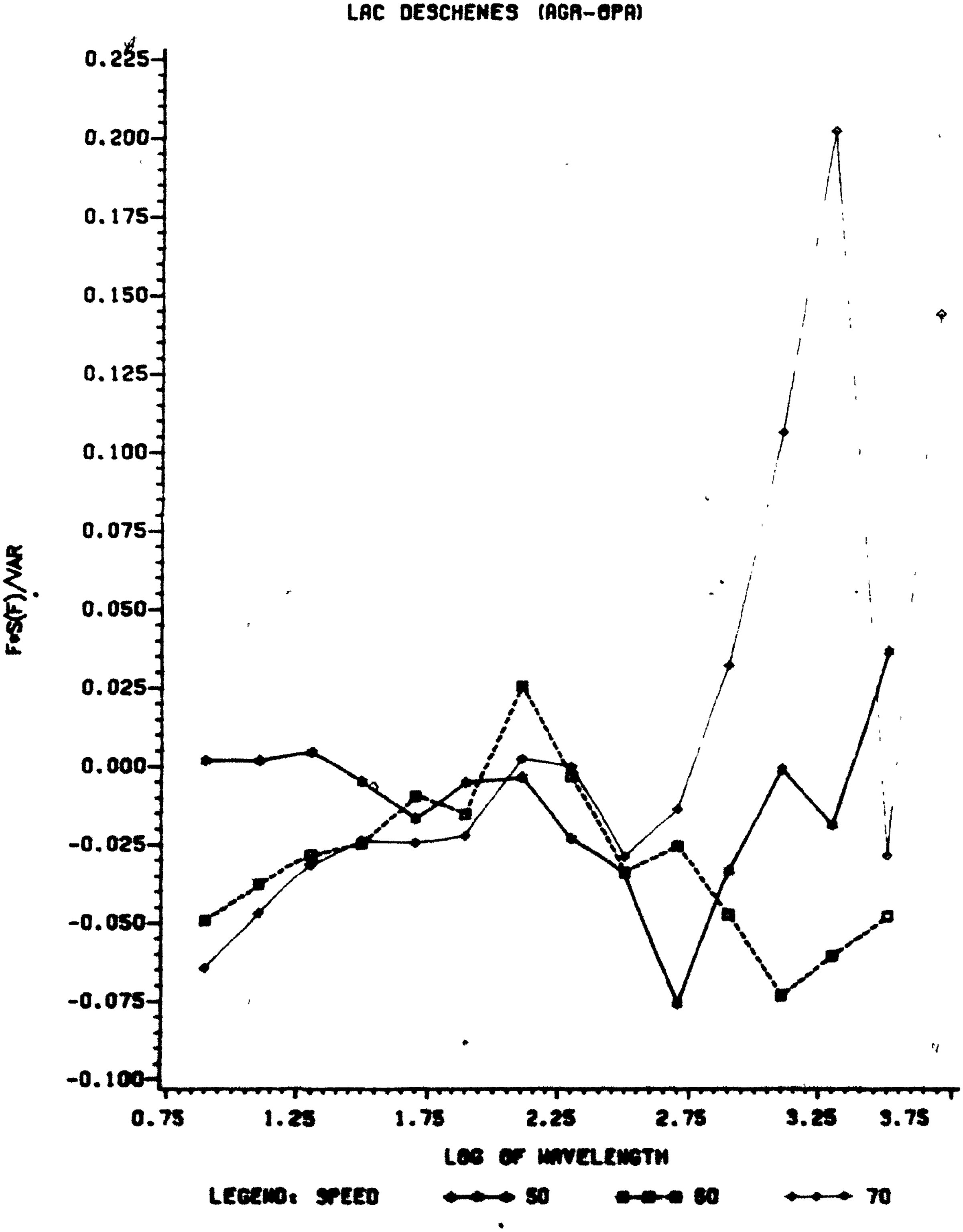

AVERAGE SPECTRA OF VERTICAL WIND
LAC DESCHENES (AGR-OPA)
F•S(F)/VAR
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.75
1.25
1.75
2.25
2.75
3.25
3.75
LOG OF WAVELENGTH
LEGEND: SPEED
50
60
70


AVERAGE SPECTRA OF TEMPERATURE
LAC DESCHENES (AGA-8PA)
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
F*S(F)/VAR
0.75
1.25
1.75
2.25
2.75
3.25
3.75
LOG OF WAVELENGTH
LEGEND: SPEED
50
60
70

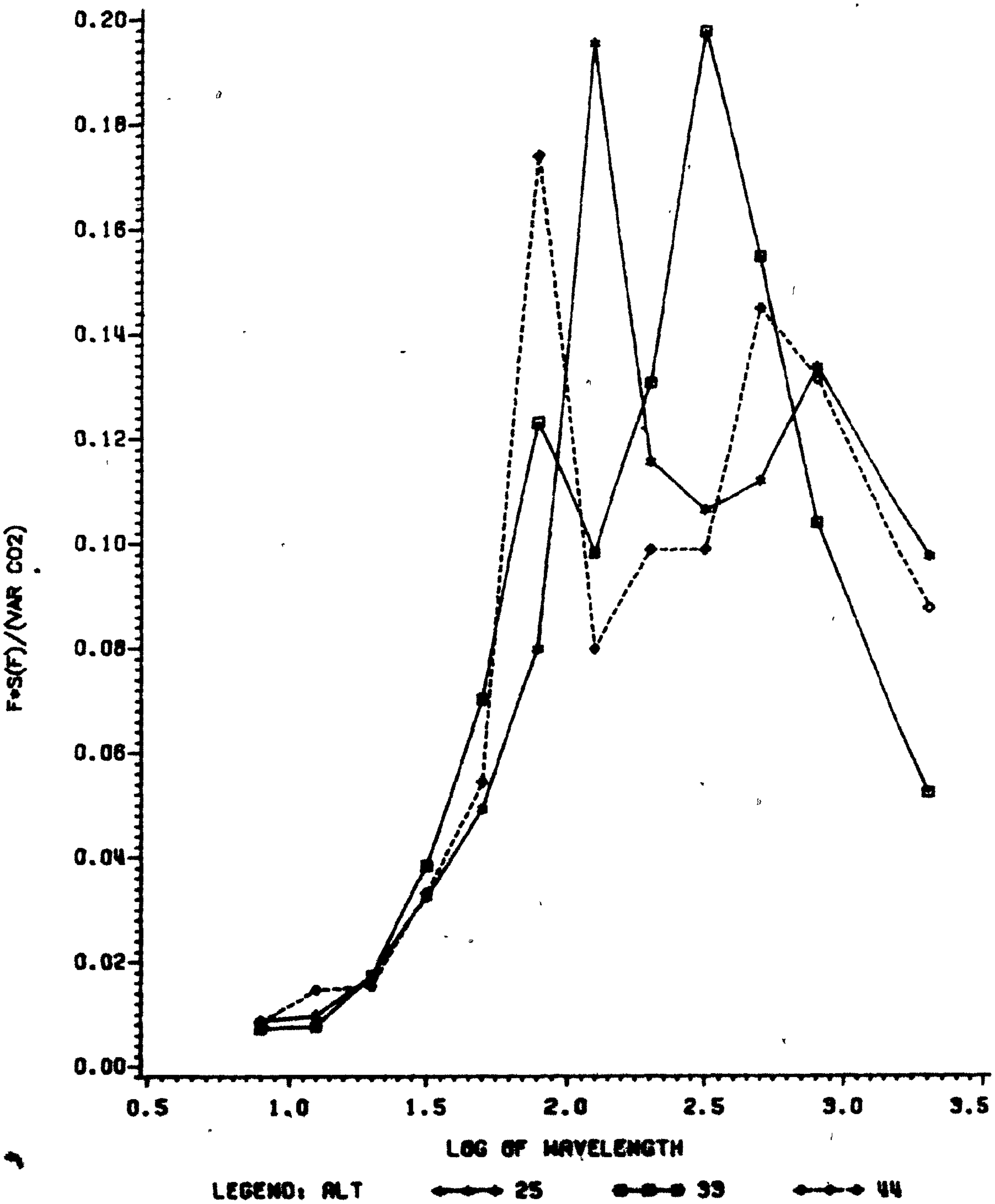

AVERAGE COSPECTRA OF TEMPERATURE AND VERTICAL WIND
LAC DESCHENES (AGR-OPA)
F*S(F)/VAR
0.16
0.15
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
-0.01
0.75
1.25
1.75
2.25
2.75
3.25
3.75
LOG OF WAVELENGTH
LEGEND: SPEED
50
60
70


AVERAGE SPECTRA OF HORIZONTAL WIND
LAC DESCHENES (AGR-OPA)
F*S(F)/VAR
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.75
1.25
1.75
2.25
2.75
3.25
3.75
LOG OF WAVELENGTH
LEGEND: SPEED
50
60
70

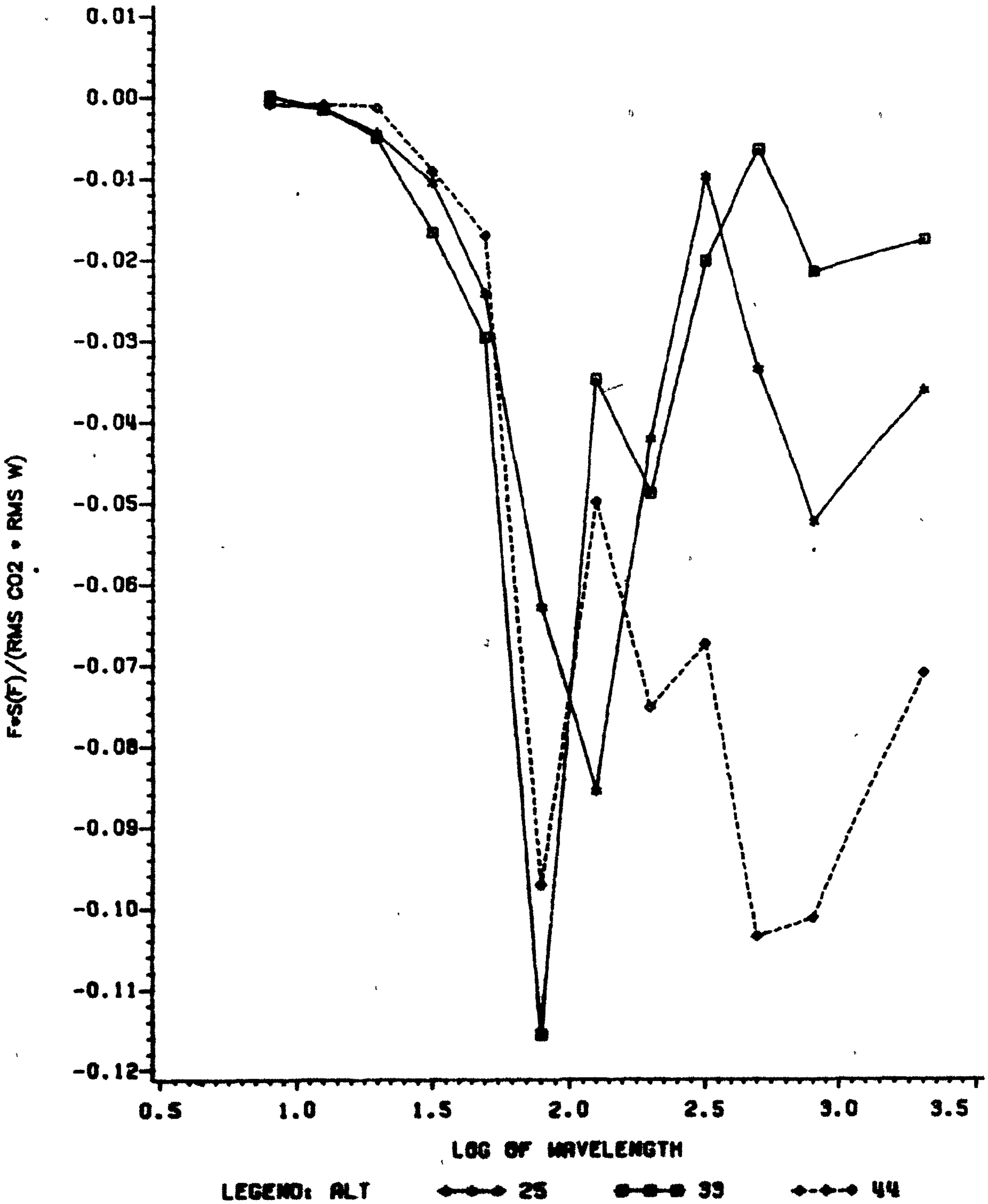
AVERAGE COSPECTRA OF HORIZONTAL WIND AND VERTICAL WIND



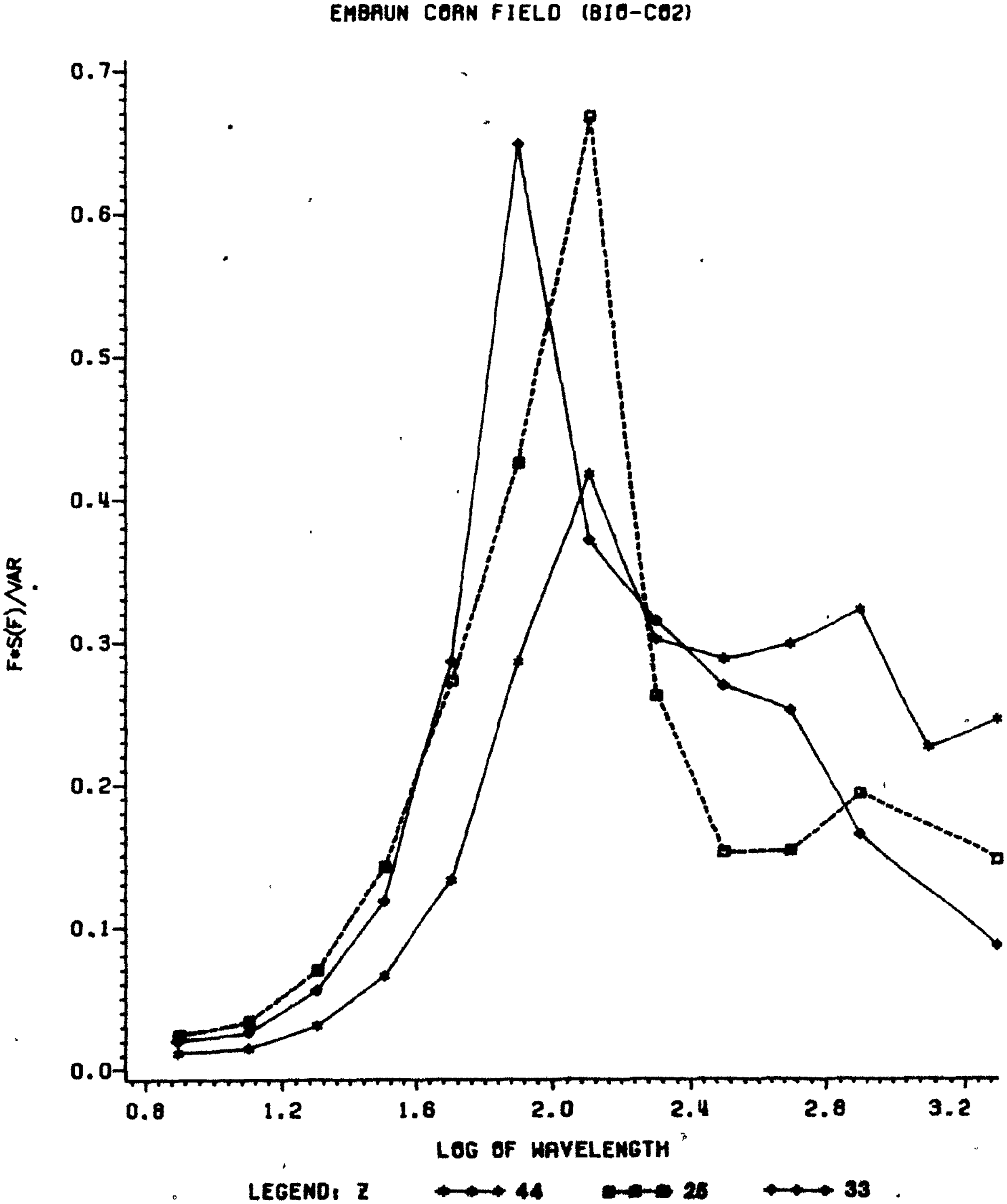
AVERAGE SPECTRA OF CO2 AT THREE ALTITUDES OVER EMBRUN CORN FIELD (BIO-CO2)



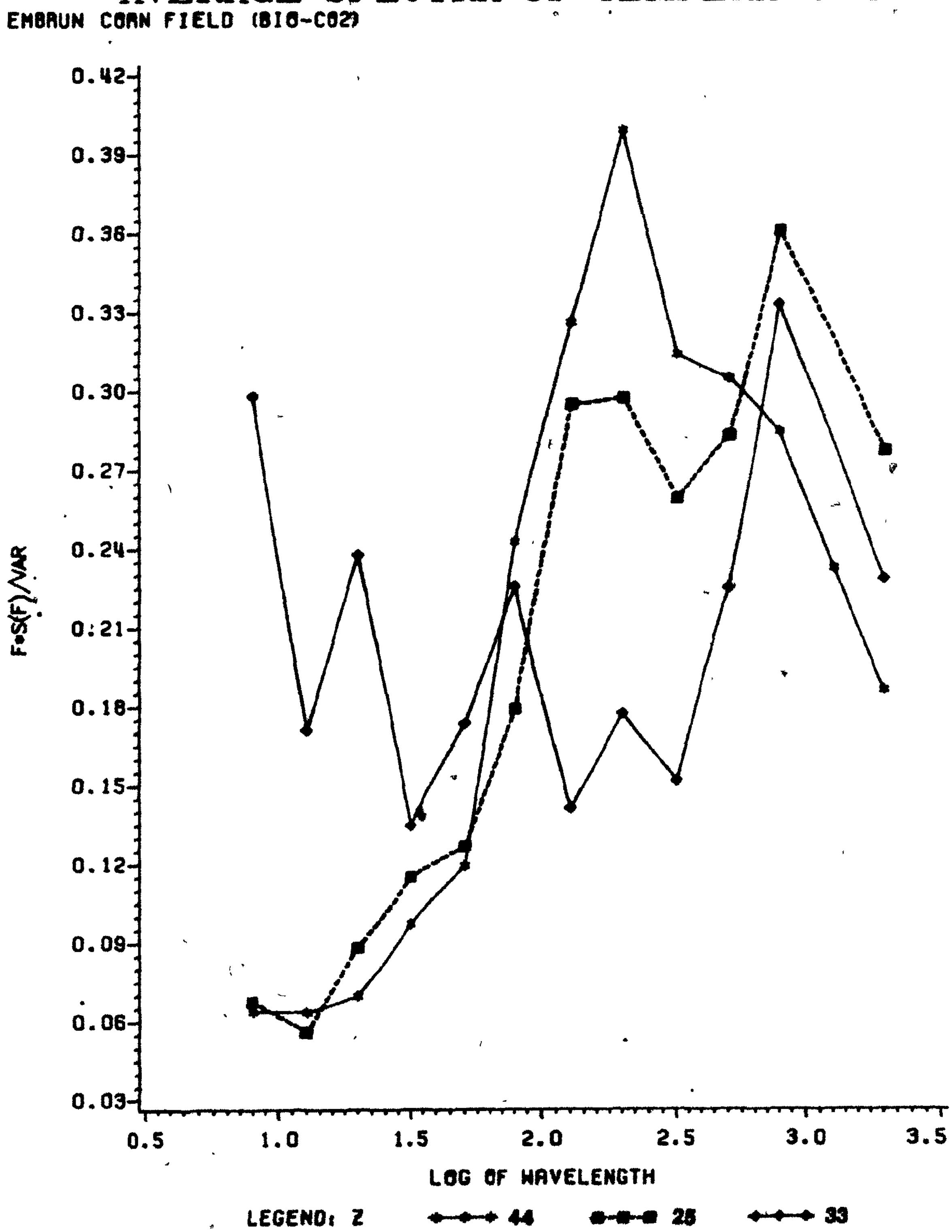
AVERAGE COSPECTRA FOR CO2 TRANSFER OVER EMBRUN CORN FIELD (BIO—CO2)



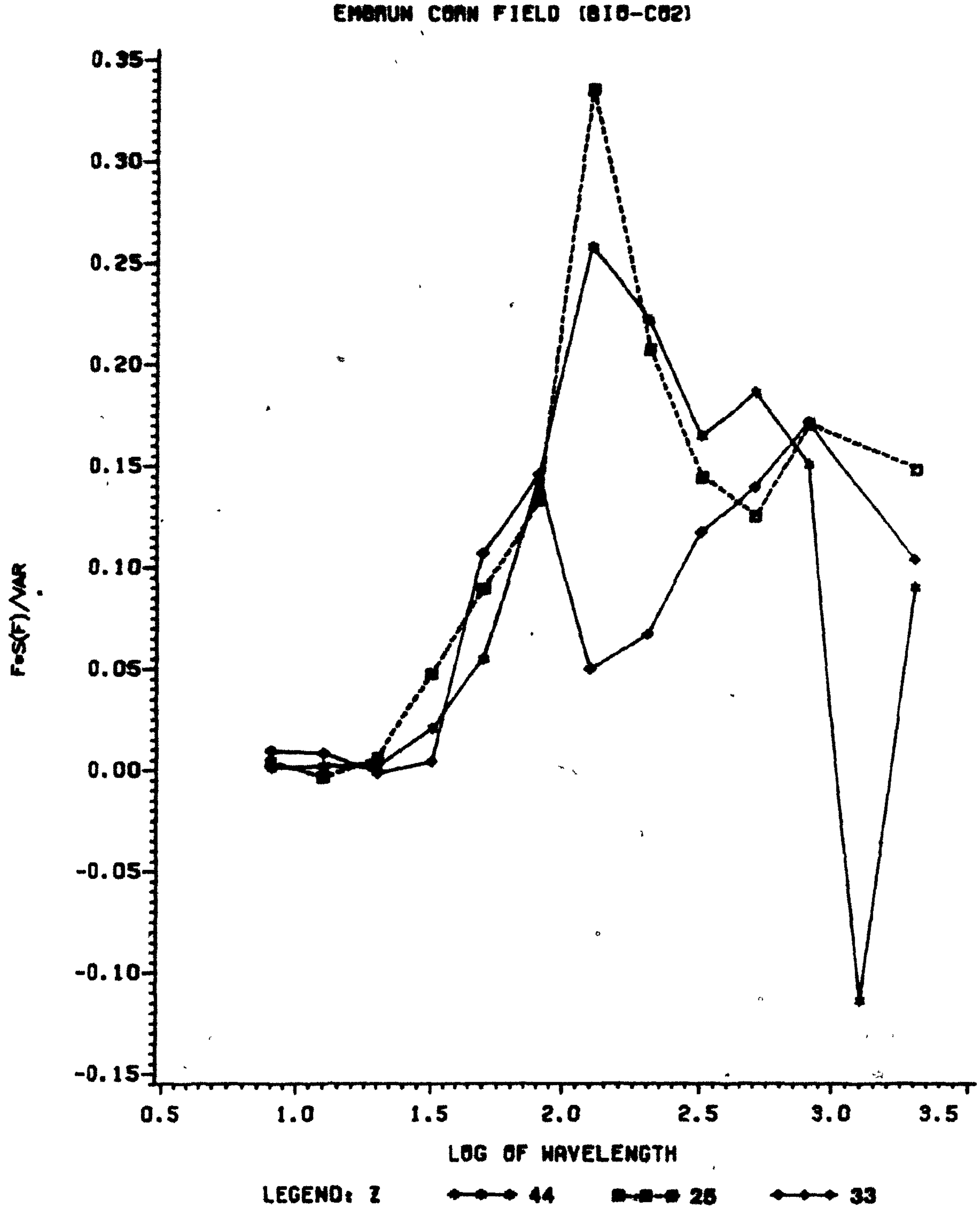
AVERAGE SPECTRA OF VERTICAL WIND



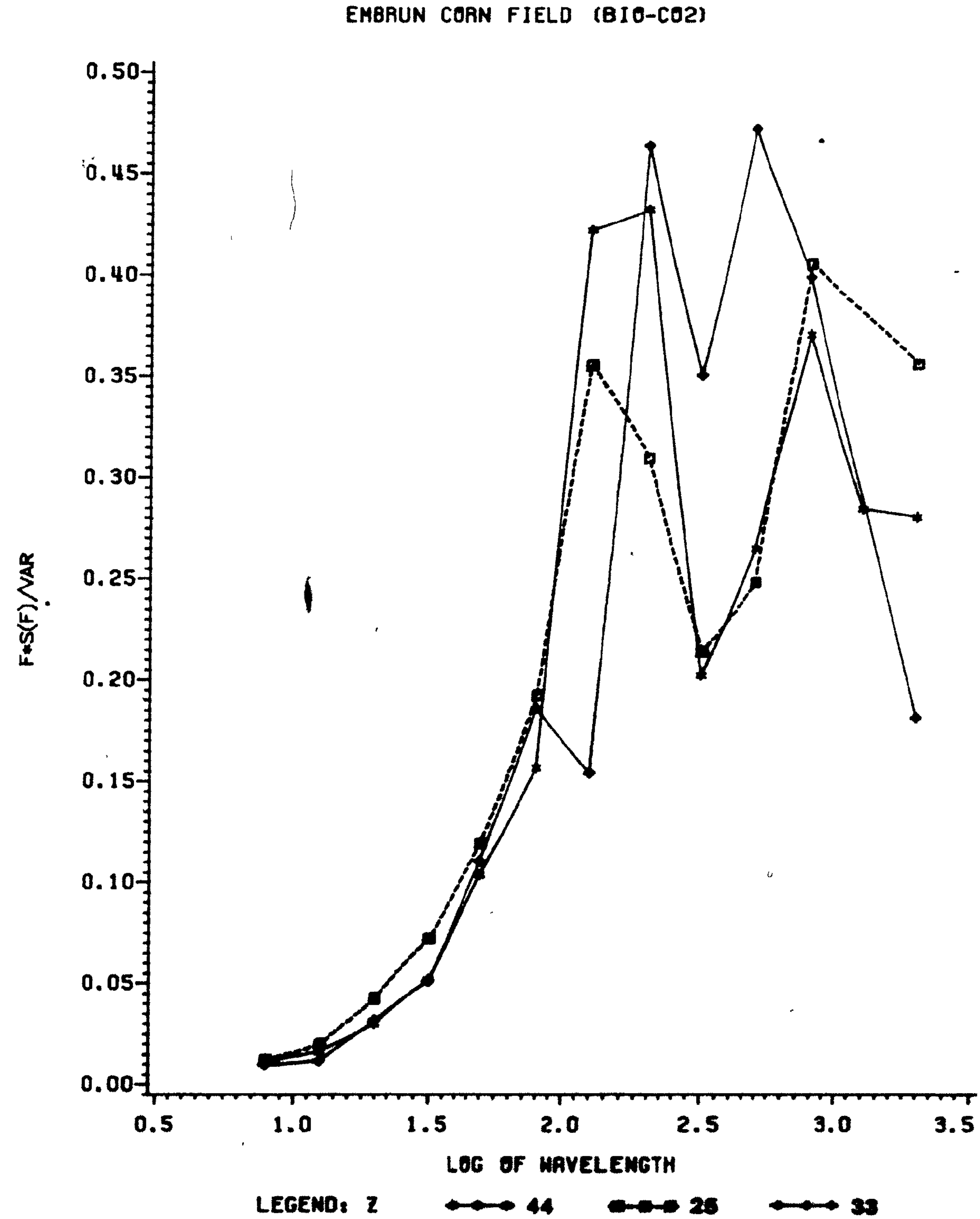
AVERAGE SPECTRA OF TEMPERATURE



AVERAGE COSPECTRA OF TEMPERATURE AND VERTICAL WIND

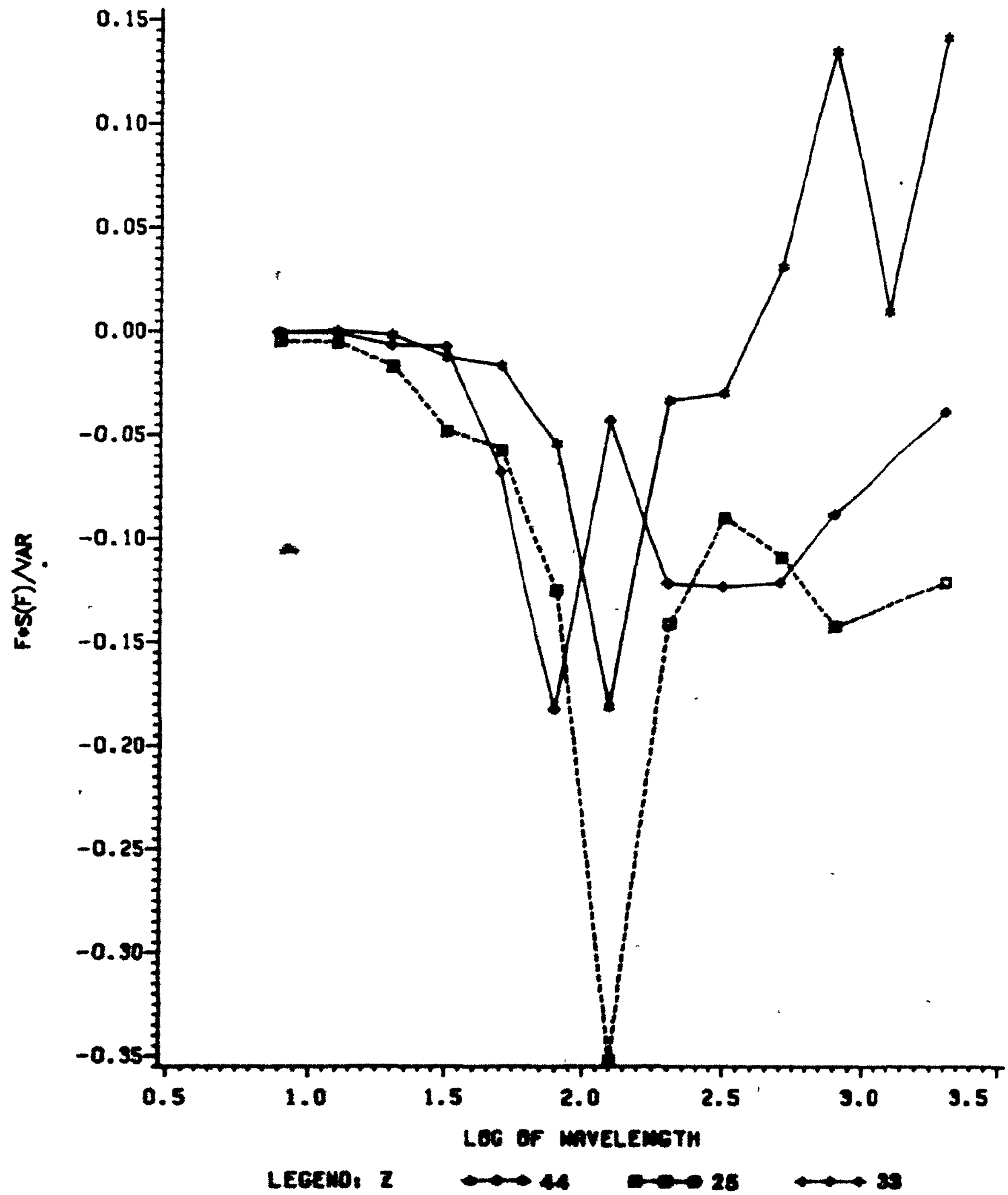


AVERAGE SPECTRA OF HORIZONTAL WIND

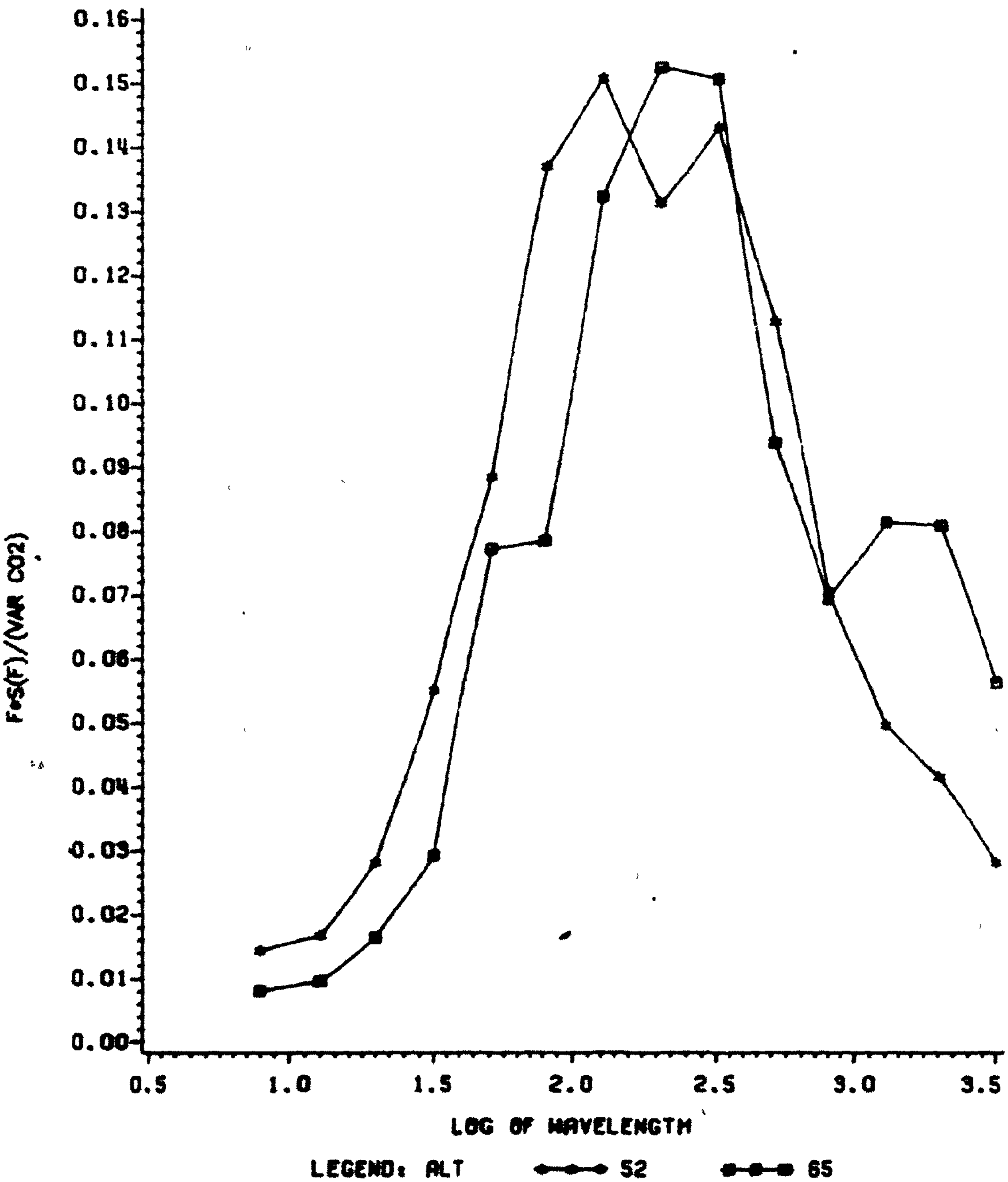


AVERAGE COSPECTRA OF HORIZONTAL WIND AND VERTICAL WIND

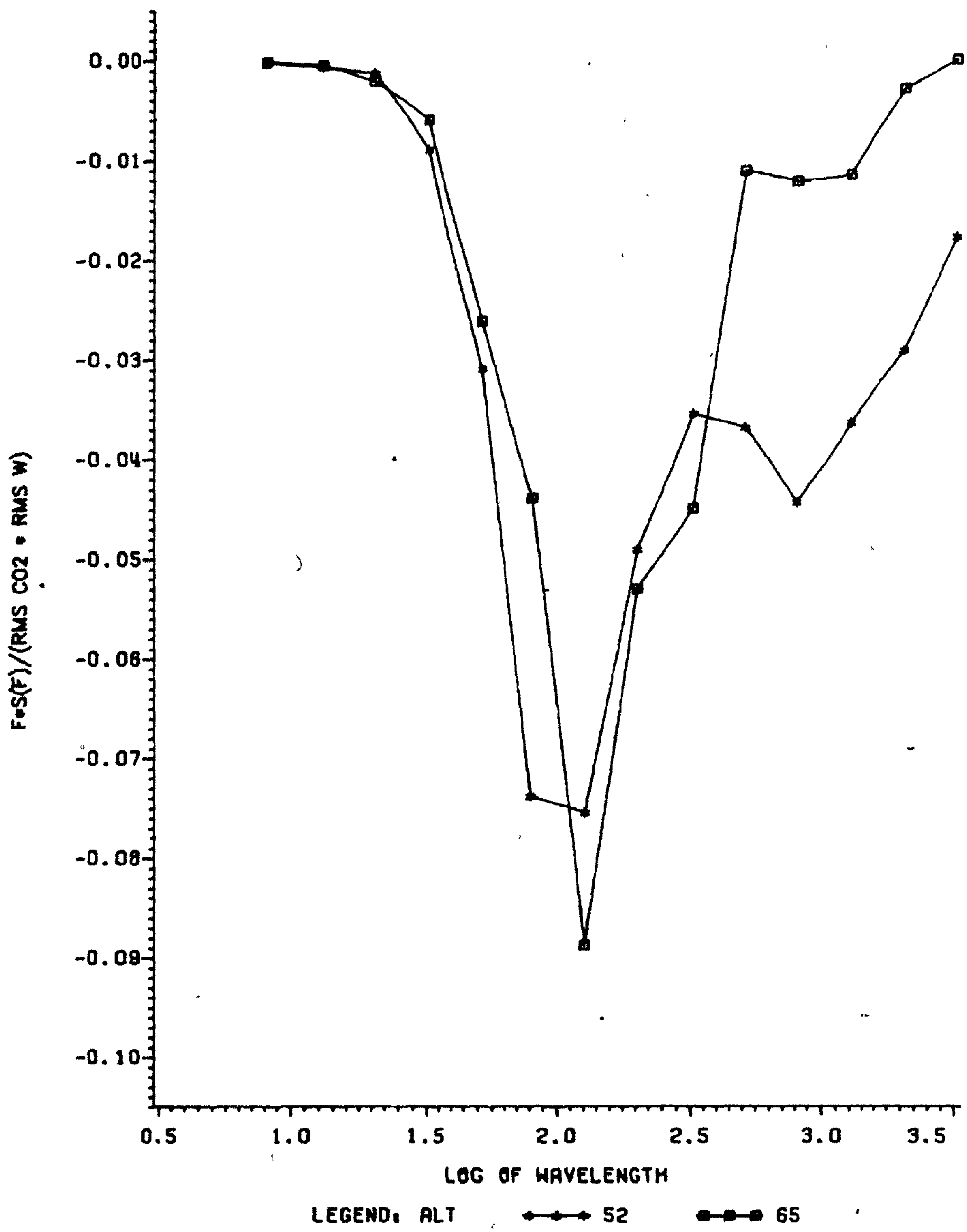
EMBRUN CORN FIELD (BIO-CO2)

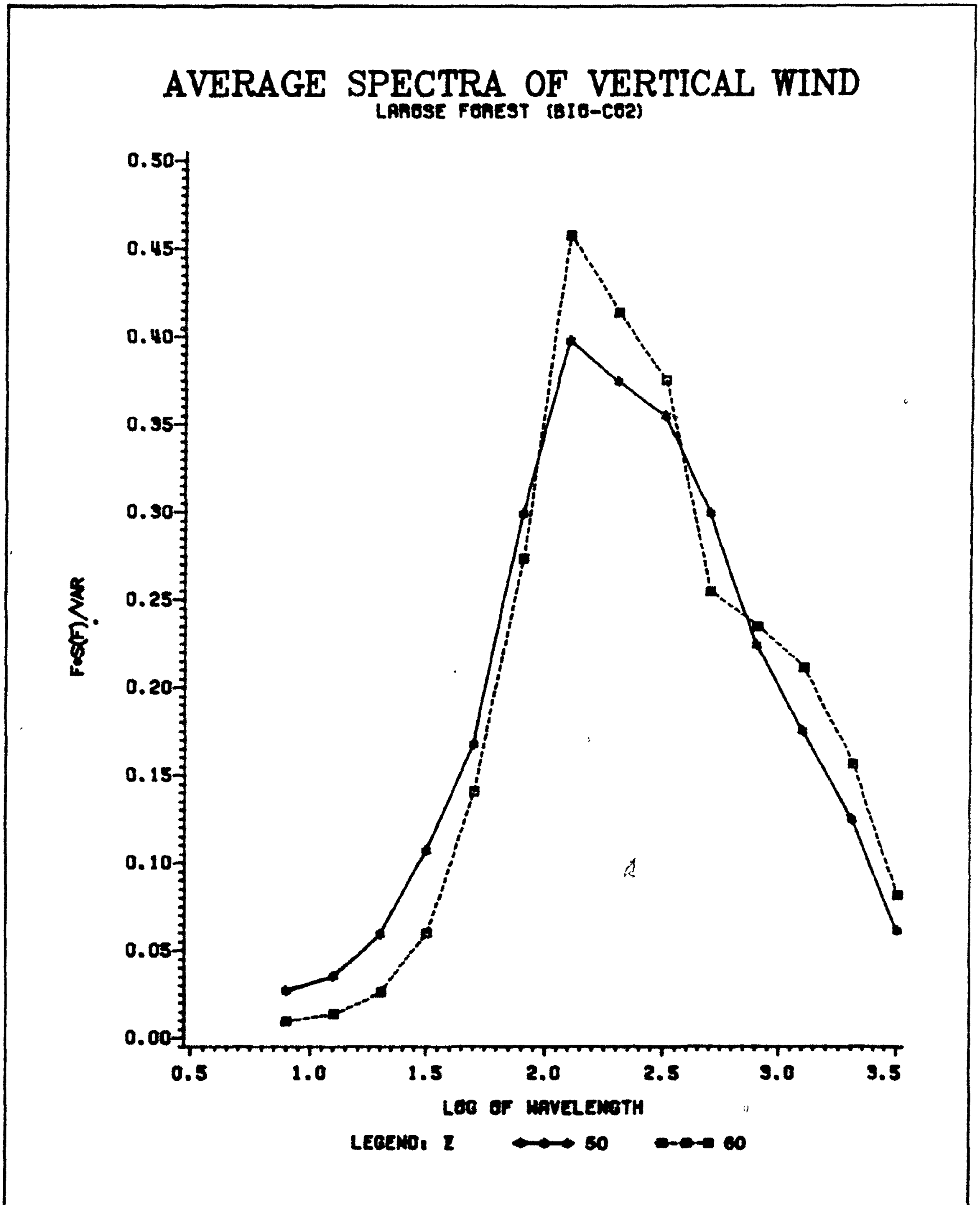


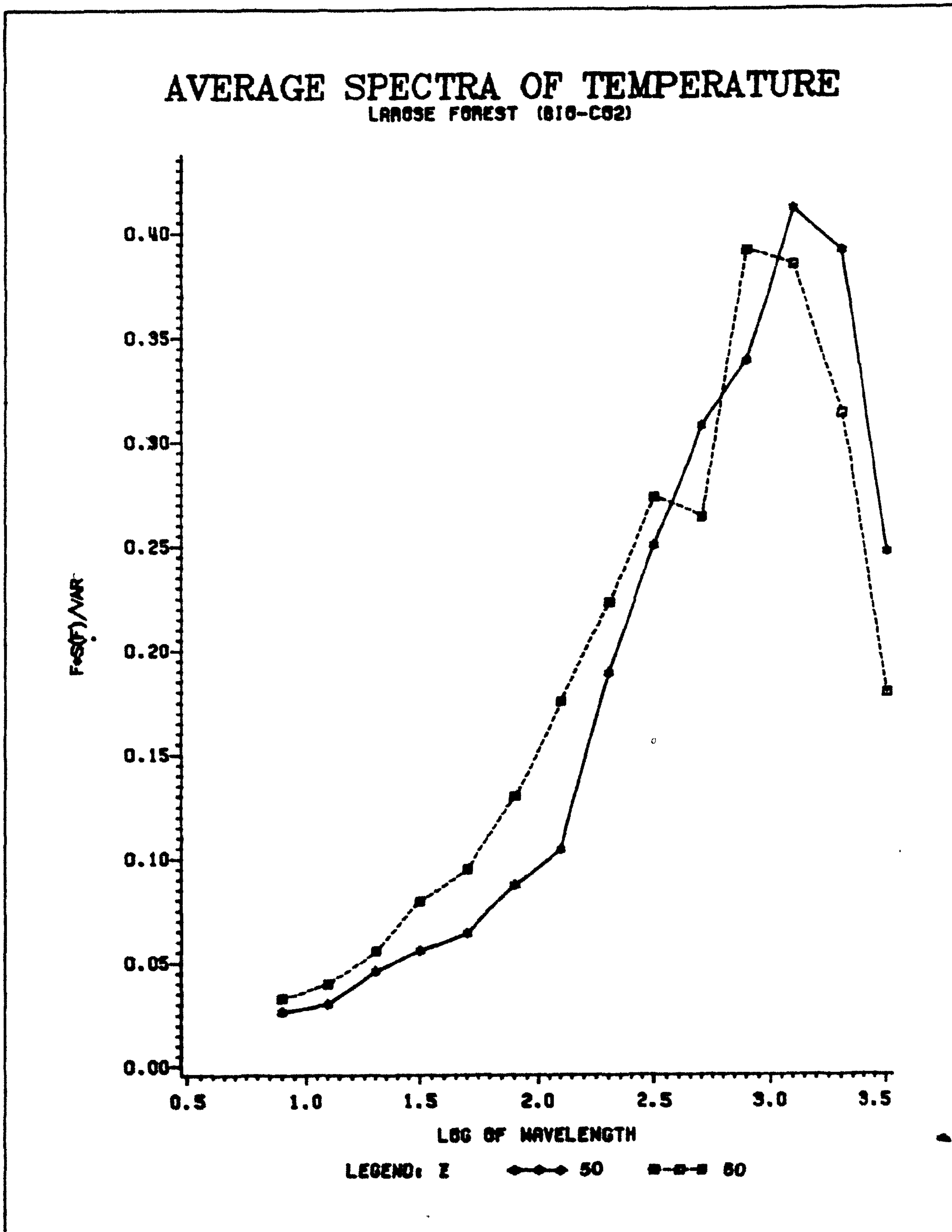
AVERAGE SPECTRA OF CO2 AT TWO ALTITUDES OVER LAROSE FOREST (BIO-CO2)

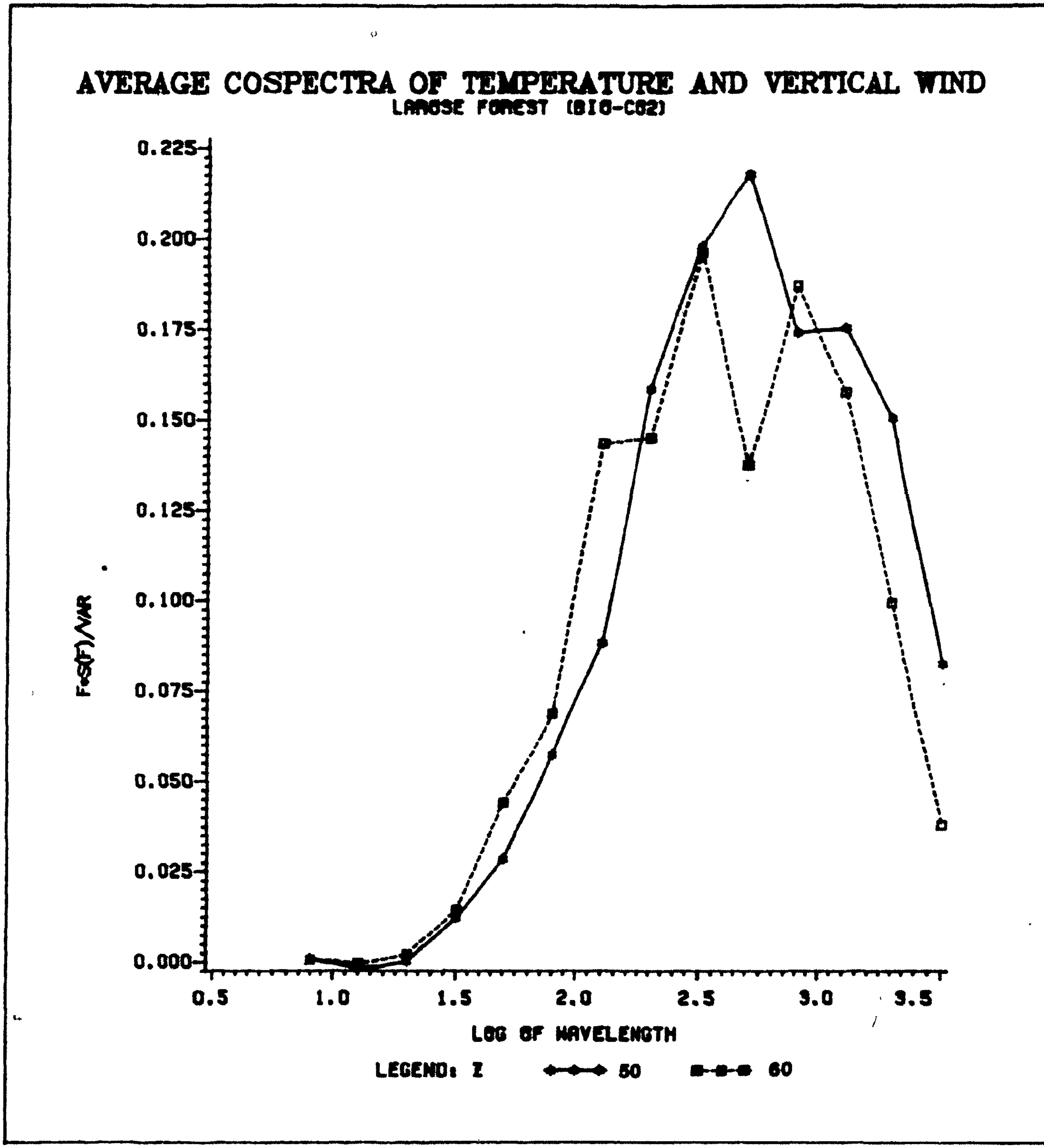


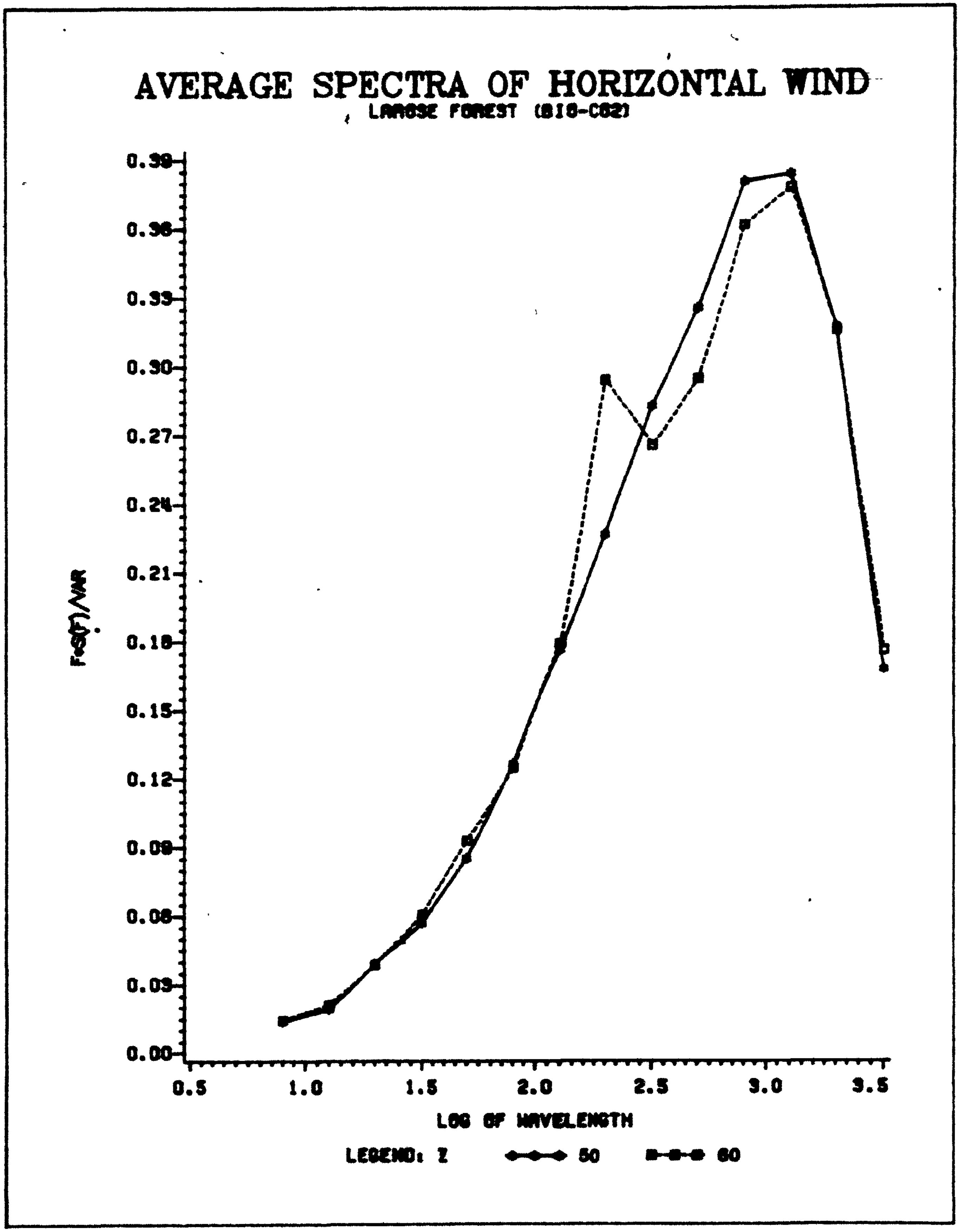
AVERAGE COSPECTRA FOR CO2 TRANSFER OVER LAROSE FOREST (BIO—CO2)

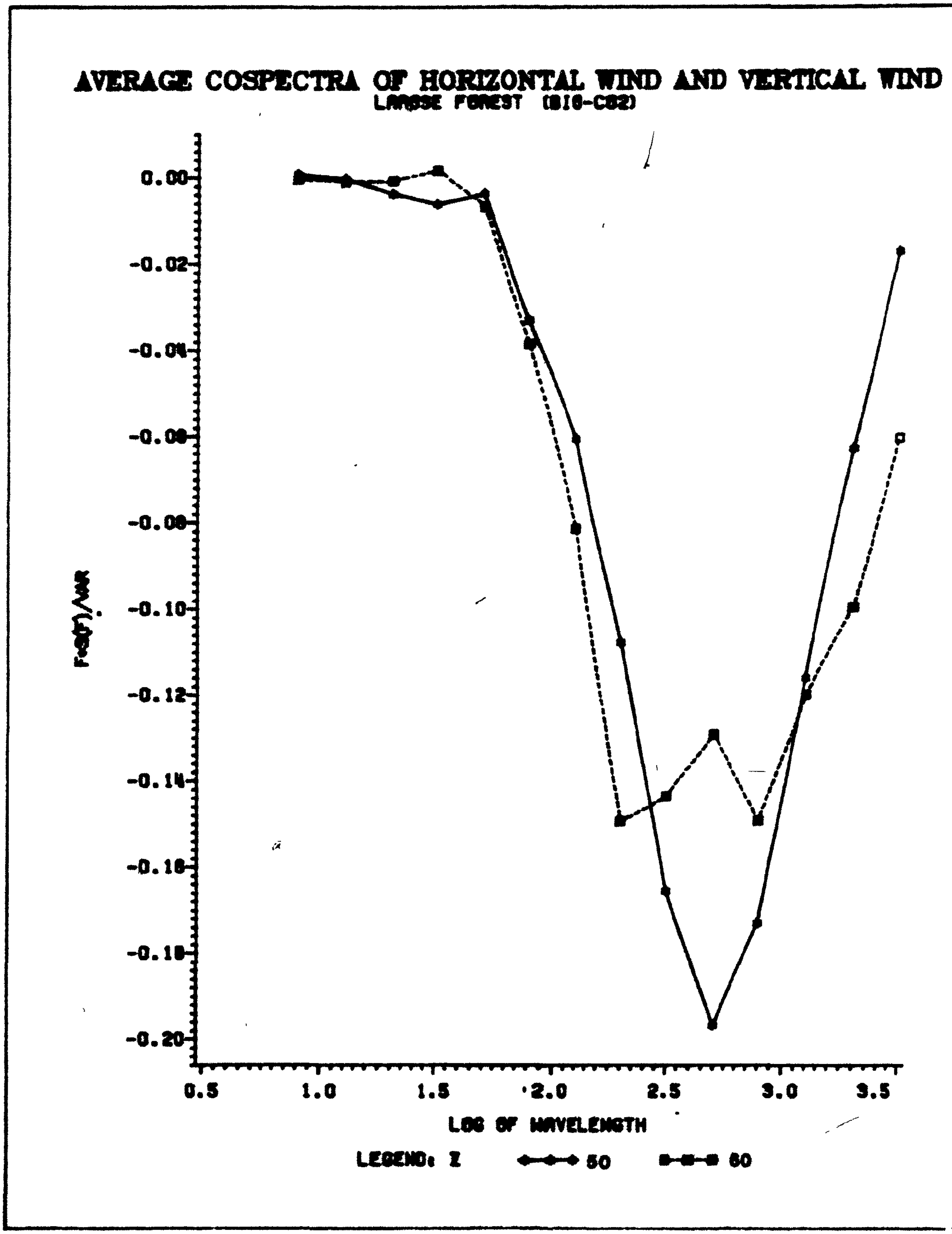



AVERAGE SPECTRA OF VERTICAL WIND
LAROSE FOREST (BIO-CO2)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
F*S(F)/VAR
0.5
1.0
1.5
2.0
2.5
3.0
3.5
LOG OF WAVELENGTH
LEGEND: Z
50
60


AVERAGE SPECTRA OF TEMPERATURE
LARGE FOREST (BIO-C02)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
F*S(F)/VAR
0.5
1.0
1.5
2.0
2.5
3.0
3.5
LOG OF WAVELENGTH
LEGEND: Z
50
60


AVERAGE COSPECTRA OF TEMPERATURE AND VERTICAL WIND
LAROSE FOREST (BIO-CO2)
0.225
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
F*S(F)/VAR
0.5
1.0
1.5
2.0
2.5
3.0
3.5
LOG OF WAVELENGTH
LEGEND: Z
50
60


AVERAGE SPECTRA OF HORIZONTAL WIND
LAROSE FOREST (BIO-CO2)
0.39
0.36
0.33
0.30
0.27
0.24
0.21
0.18
0.15
0.12
0.09
0.06
0.03
0.00
F*S(F)/VAR
0.5
1.0
1.5
2.0
2.5
3.0
3.5
LOG OF WAVELENGTH
LEGEND: Z
50
60



AVERAGE COSPECTRA OF HORIZONTAL WIND AND VERTICAL WIND
LAROSE FOREST (BIG-CO2)
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
-0.16
-0.18
-0.20
F*S(F)/VAR
0.5
1.0
1.5
2.0
2.5
3.0
3.5
LOG OF WAVELENGTH
LEGEND: Z
50
60

APPENDIX E: Publication

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