CIR TDN 6. 1969

The high-frequency fluctuation of the wind in the first kilometre of the atmosphere

by

C.J. Readings and R. Rayment
Meteorological Research Unit, Cardington, Bedfordshire, England

Abstract

This paper describes some preliminary experiments carried out at Cardington during 1968 to measure the fluctuations of wind inclination in the frequency range 0.1 - 3 Hertz. The measurements were made at heights up to about 1 km using a tethered balloon. The results illustrate the intermittency of atmospheric turbulence and show the way in which the implied average rate of dissipation of turbulent kinetic energy varies with height under different daytime stability conditions - including overhead inversions. The results are broadly consistent with a buoyancy production which is roughly constant with height in the convective layer and is the dominant contribution at the greater heights, and a mechanical production which falls off roughly as 1/z.

Introduction

In an attempt to improve our comprehension of the vertical transfer processes and the way turbulent energy is generated and dissipated over land, a detailed study has been started over relatively flat open country at Cardington (England), using a tethered balloon.

During 1968 some preliminary ascents were made in which the high frequency fluctuations of the wind were measured at various heights up to about 1 km. From these measurements the way in which the rate of dissipation of turbulent energy ϵ varied with height was determined under different stability conditions - including overhead inversions.

Calculation of ϵ

Within the inertial subrange the contribution to the variance of the vertical component (w) of the wind arising from fluctuations whose wave-numbers lie between

/k

G.2309/LG/5/69/90

k and (k + dk), is a function of k and ϵ only i.e.:-

$$S_w(k)\,dk = C_w\,\epsilon^{\frac{2}{3}}\,k^{-5/3}\,dk$$

where C_w is a constant.

Hence if the fluctuations in the vertical component are passed through a rectangular filter which only transmits frequencies lying in the range $n_1 \leq n \leq n_2$, the variance of the velocity fluctuations will appear to be:-

$$\sigma_w^2(n_1, n_2) = \int_{n_1}^{n_2} S_w(n)\,dn = \int_{k_1}^{k_2} S_w(k)\,dk = \left(\frac{3C_w}{2}\right)\left(\frac{\epsilon\,\bar{u}}{n_2}\right)^{\frac{2}{3}}\left[\left(\frac{n_2}{n_1}\right)^{\frac{2}{3}} - 1\right] \quad \ldots (1)$$

provided both n_1 and n_2 are in the inertial subrange. In deriving this expression it has been assumed that $n = k\bar{u}$ where $\bar{u}$ is the mean horizontal velocity of the wind.

In practice the instantaneous inclination of the wind to the horizontal (ϕ) was measured - not the actual vertical component. However, accepting $\sigma_w^2 = \bar{u}^2\sigma_\phi^2$ as a reasonable approximation for the normally small values of $\sigma\phi$, equation (1) may be transformed to:-

$$\epsilon = 1.84\,\sigma_\phi^3\,(n_1, n_2)\,\bar{u}^2\,n_2 \quad \ldots (2)$$

for the set of filters described by Jones [1963] which have $(n_2/n_1) = 6$. [In this expression allowance has been made for the actual non-rectangular shape of the filter in which n_1 and n_2 are the half-power cut-off points] Hence by measuring the output of any of the filter units which transmit in the inertial subrange it was possible to evaluate ϵ.

Experimental procedure

During the 1968 series of midday ascents the temperature (T), wind speed (V) and wind inclination (ϕ) were measured at various heights for periods of five minutes duration.

The sensors were mounted on a carrier which consisted essentially of an arm with a vane at one end and an inclinometer at the other [See FIG 1a]. This arm was attached at its balance point to the flying cable of a tethered balloon in such a fashion that it was free to rotate - so enabling the vane to keep the instrument facing into wind.

/ The

The inclinometer was mounted on a platform which was pivotted so that it could swing freely in the vertical plane. However these movements were damped by an air piston - so keeping the platform horizontal with a minimum of oscillation. The actual inclinometer consisted of an adjustable metal support arm with a hot-wire yawmeter attached to its upper end. In each "V" the component wires were inclined at 120° and the planes of the two "V"'s were inclined at 80°. By using this combination of two "V"'s it was then possible to maintain a linear relation between the wind inclination and the output over a range of ±40° with direction changes of up to ±30°. Measurements were thereby made to an accuracy better than 5% [Jones, 1961]

A modified photo-electric anemometer was mounted on its side so that the plane of the cup rotor was maintained in the prevailing wind direction. This instrument gave a hundred and twenty pulses per revolution and with the aid of a ratemeter it was possible to measure the instantaneous wind speed to an accuracy of 0.05 m/sec.

The temperature was measured with a resistance element consisting of 180 cms of 25μ platinum wire wound non-inductively on a plastic former. As a range of ±7°C could be covered for one set of components, a potentiometer had to be provided to enable a setting to be made, before an ascent, in accordance with the anticipated mean temperature.

The outputs from these sensors were relayed from the carrier to earth by cable telemetry and displayed on pen-chart recorders as is shown in FIG 1b. In addition the inclination signal was split and passed through two of Jones' filter units which had peak transmissions at 1.29 Hz (Band 1) and 0.216 Hz (Band 2). The outputs from these units were displayed on a pen-chart recorder and also sampled once a second by a data logger which punched the values on paper tape. At the same time it also sampled and punched the instantaneous wind inclination (ø) and speed (V).

The tapes were processed on the Ferranti Mercury computer at CDEE Porton Down. Various quantities were calculated including ϵ and $\bar{u}$ for each

/ of

of the five-minute sampling periods. However the mean temperature was obtained by reading the appropriate pen-chart record. *

Validity of the inertial subrange

By applying equation (2) to the outputs of both filter units it was possible to derive two estimates of the rate of dissipation of turbulent energy ϵ. The extent to which these agreed is illustrated by FIG 2 which shows the way in which the mean values of ϵ vary with height for two different stability classes [ϵ_1 is the value derived by applying equation (2) to the Band 1 output and ϵ_2 the corresponding value obtained from the Band 2 output - the figure will be explained later] Although these two values are in broad agreement, there is a tendency for ϵ_2 to be smaller than ϵ_1 near the ground. However this is to be expected as at low heights part of Band 2 probably lies outside the inertial subrange. The discrepancy between these two values is greater in FIG 2a than in FIG 2b. This has no physical significance being caused by an electrical smoothing circuit which affected the output of Band 1 more than that of Band 2. Thus it would seem reasonable to conclude that the experimental values so far obtained do not disagree significantly with the prediction for the inertial subrange.

/ The

* See Appendix A for a listing of the daily data.

The intermittent nature of turbulence

The values of ϵ derived from the five-minute recordings made at the same height but on different days in broadly similar conditions were found to vary by up to a factor of eight about their mean value. Furthermore consecutive five-minute recordings made at one particular height in stationary synoptic conditions showed a similar spread. Thus the former variations could not have been due to gross changes in the synoptic conditions. In addition the variability cannot be explained by instrumental inaccuracy since this at worst gives an error in ϵ of about $\pm 10\%$. Further, sampling errors should be very small as each five-minute value of ϵ is based on three hundred values. Thus the variability must be a real reflection of intermittency in the high-frequency intensity of turbulence.

At any height the frequency distribution of the individual ϵ's was extremely skew.[1] Thus the atmosphere may be pictured as consisting of a series of regions in most of which the turbulent kinetic energy is dissipated very slowly - interspaced by others in which quite the reverse is true.

The variation of ϵ with height

The balance equation for turbulent kinetic energy may be written:-

$$\frac{D\bar{E}}{Dt} = -\left(\overline{u'w'}\frac{\partial\bar{u}}{\partial z} + \overline{v'w'}\frac{\partial\bar{v}}{\partial z}\right) + \frac{g}{T}\overline{w'T'} - \epsilon + F_D \qquad \ldots (3)$$

(Rate of change per unit mass) (Mechanical Production Term) (Buoyant Production Term) (Divergence Term)

[$\bar{E}$ is the turbulent kinetic energy per unit mass; (u,v,w) are the wind's components; T is the absolute temperature; t is the time and F_D is essentially the vertical divergence of the vertical flux of $\bar{E}$] This equation would lead one to expect that the variation of ϵ with height would depend on the relative magnitudes of the mechanical and buoyant production terms. However the basic intermittency of ϵ rules out the possibility of investigating this question by using the results of a single ascent. Thus it becomes imperative first to classify the occasions and then to combine the data in each class to give a

/ mean

1. See FIG. A which illustrates the distribution of ϵ at 610m.

mean profile of ϵ. The records confirmed the general expectation that the value of ϵ at 600m would be found to increase with the net radiation.[2] So the ascents were divided into two classes according to whether the mean net radiation during a traverse was less or greater than $12\frac{1}{2}$ mw/cm^2. This classification split the data into summer and winter sets. For the summer measurements cumulus cloud was present whereas for the winter set shallow cumulus was reported for only two runs. Thus the higher radiation class may be considered to correspond to convective conditions, when the buoyancy term would be important, and the lower radiation class to almost entirely non-convective conditions when the converse would be true. The fact that heat-balance considerations require that the net radiation be roughly correlated with the turbulent heat flux supports this classification.

FIG 2 shows the way the mean value of ϵ varies with height for both classes, together with the mean wind and temperature profiles. The greater uniformity of the higher radiation curves [FIG 2a] may be merely a reflection of the rather greater amount of data therein, as can be seen from Table 1. Even so the total amount of data is not very great and this precludes a more detailed classification of the results.

In neutral conditions when, apart from divergence, the principle terms in the balance equation are ϵ and mechanical production, ϵ would be expected to fall off as z^{-1} in the constant flux layer. It can be seen from FIG 2b that the experimental curves for low radiation roughly agree with this supposition (Departures from z^{-1} probably being due to lack of data and possible variation with height of the momentum flux).

The value of ϵ_1 close to the ground tends to be the same for both classes. This seems consistent with the expectation that near the ground the mechanical production term is dominant even though the buoyancy production term becomes dominant higher up in the atmosphere. Taking a value of roughly 70 cm^{2}sec^{-3} at a height of 37m, and assuming $\epsilon = u_*^3/0.4z$ as a rough approximation, the

/ implied

2. See FIG. B and Table 3.
The radiation values used refer to the mean net radiation over the whole period of a run, and the values of ϵ are averaged in each radiation class.

implied value of the friction velocity u_* is about $\frac{1}{2}$ m.sec^{-1}. This is entirely consistent with the wind speeds and with the relatively smooth nature of the site. The high radiation curves of ϵ [i.e. FIG 2a] show much slower fall with height and differ from the corresponding low radiation curves by an amount which is almost constant with height at heights above 100m. Since the mechanical production evidently decreases with height the implication is that the foregoing constant difference is associated with the difference in the resultant of the buoyancy production and divergence terms. If the former were completely responsible this would imply a heat flux of about 8 mw/cm^2 which was almost independent of height above 100 m. Such a value is in rough agreement with empirical estimates from the net radiation. Below 100 m the difference between the two curves decreases. This is presumably a consequence of the complex effect of instability on the mechanical production term. [see FIG. C]

A further insight to this problem may be obtained by attempting to standardise the mean curves - intermittency making it impossible to attempt this with the individual ascents. Thus if it is accepted that the buoyancy contribution is independent of height and that the mechanical term at about 1 km is negligible compared to both its value at the ground and the buoyancy term (if present), then a normalized ϵ, which should correspond to the sum of the mechanical and divergence terms, may be defined as follows,

$$\bar{\epsilon}_N = \frac{\bar{\epsilon}_z - \bar{\epsilon}_{TOP}}{\bar{\epsilon}_{BOTTOM} - \bar{\epsilon}_{TOP}}$$

(where $\bar{\epsilon}_z$ is the mean value of ϵ at a height of z metres). If the divergence term and the effect of instablity on the mechanical production terms are negligible the normalized curves should be the same. The extent to which this was realised in practice is illustrated by FIG 3a which shows how $\bar{\epsilon}_N$ (based on the Band 1 curves) varied with height. It can be seen that although the two curves are brought into closer agreement they do not quite coincide.

/ Variation

Variation of ϵ with $\bar{u}$

When the individual five-minute values of ϵ were plotted against the mean wind speed no significant dependence would be detected at the greater heights. Furthermore the dependence of ϵ on $\bar{u}$ was not clearly discernable even near the ground - probably due to the intermittent nature of turbulence.[3]

Variation of $\bar{\epsilon}$ with height through an inversion

None of the ascents discussed so far have included instances where the probe passed through a temperature inversion. However this did occur on several occasions and FIG 3b is a summary of the results to date. It can be seen. that all heights have been referred to the base or the top of the inversion.

The rapid fall in the value of ϵ with height above the inversion base is the expected effect due to buoyant suppression of turbulent fluctuations. The apparent slight increase in $\bar{\epsilon}$ just below the base is rather interesting and may reflect an increase in the level of turbulence arising from the dissipation of thermals, but the small amount of data (see Table 2) is obviously inadequate to establish the point. Just above the base of an inversion one might expect to detect a bouyant subrange where $S_w(k)$ would be proportional to k^{-b} where $b > 5/3$ [e.g. Lumley and Panofsky, 1964]. However the approximate agreement between ϵ_1 and ϵ_2 does not support this - in fact the slight discrepancy between them would imply that $b < 5/3$. There results, admittedly from a rather small amount of data, disagree with Myrup's [1968] observations and more work would be needed to resolve this discrepancy.

Future work

These results have emphasized the intermittent nature of turbulence and hence the necessity of acquiring a representative specification of ϵ. Only then would it be possible to classify the results more comprehensively - so facilitating the investigation of the relative importance of the buoyant and mechanical production terms as well as the divergence. (In addition

3. See FIG. D where the five minute values of ϵ at / this 762m and 76m are plotted against their respective 5 min mean horizontal wind values.

this may also clarify the question of how the heat flux varies with height.) The more detailed classification of the ascents will also be facilitated by a more comprehensive series of ancillary measurements now being made at the ground. These include mean wind and temperature profiles from which estimates of the production terms near the ground can be derived. However, a check on the various assumptions and a more discerning appraisal of the balance equation will require measurements of the vertical fluxes of momentum and heat at different heights, and this also is planned in the long-term research programme at Cardington.

Acknowledgements

The authors would like to acknowledge their indebtedness to all the staff of the Meteorological Research Unit at Cardington especially Mr. H.E. Butler and Mr. J.T.L. Hadingham. The authors would also like to record their gratitude to Dr. F. Pasquill for many fruitful discussions and to Miss S.A. Matthews for handling the computing. The paper is published by permission of the Director-General of the Meteorological Office.

References

Jones, J.I.P. (1961), The measurement of turbulence near the ground, Porton Technical Paper No. 786.

Jones, J.I.P. (1963), A band pass filter technique for recording atmospheric turbulence, Brit. J. Appl. Phys., 14, 95-101.

Myrup, L.O. (1968), Atmospheric measurements of the buoyant subrange of turbulence, J. Atmos. Sci. 25, 1160-1164.

Table 1 - The number of five-minute recordings made at each height

Height in metres	High radiation data	Low radiation data
37	22	14
76	27	16
152	28	15
305	31	17
457	31	14
610	28	13
762	26	13
914	12	6

Table 2 - The number of five-minute recordings made at each height relative to the inversion base

Height relative to base	Number of recordings
300 m below base	10
150 m below base	13
Base	22
	21
Top	13
150 m above top	7
300 m above top	3

Table 3 - Number of five-minute recordings of ϵ at 600m in different radiation classes.

Radiation Class ($mw\ cm^{-2}$)	No.
0-10	13
10-20	9
20-30	9
30-40	9
40-50	11

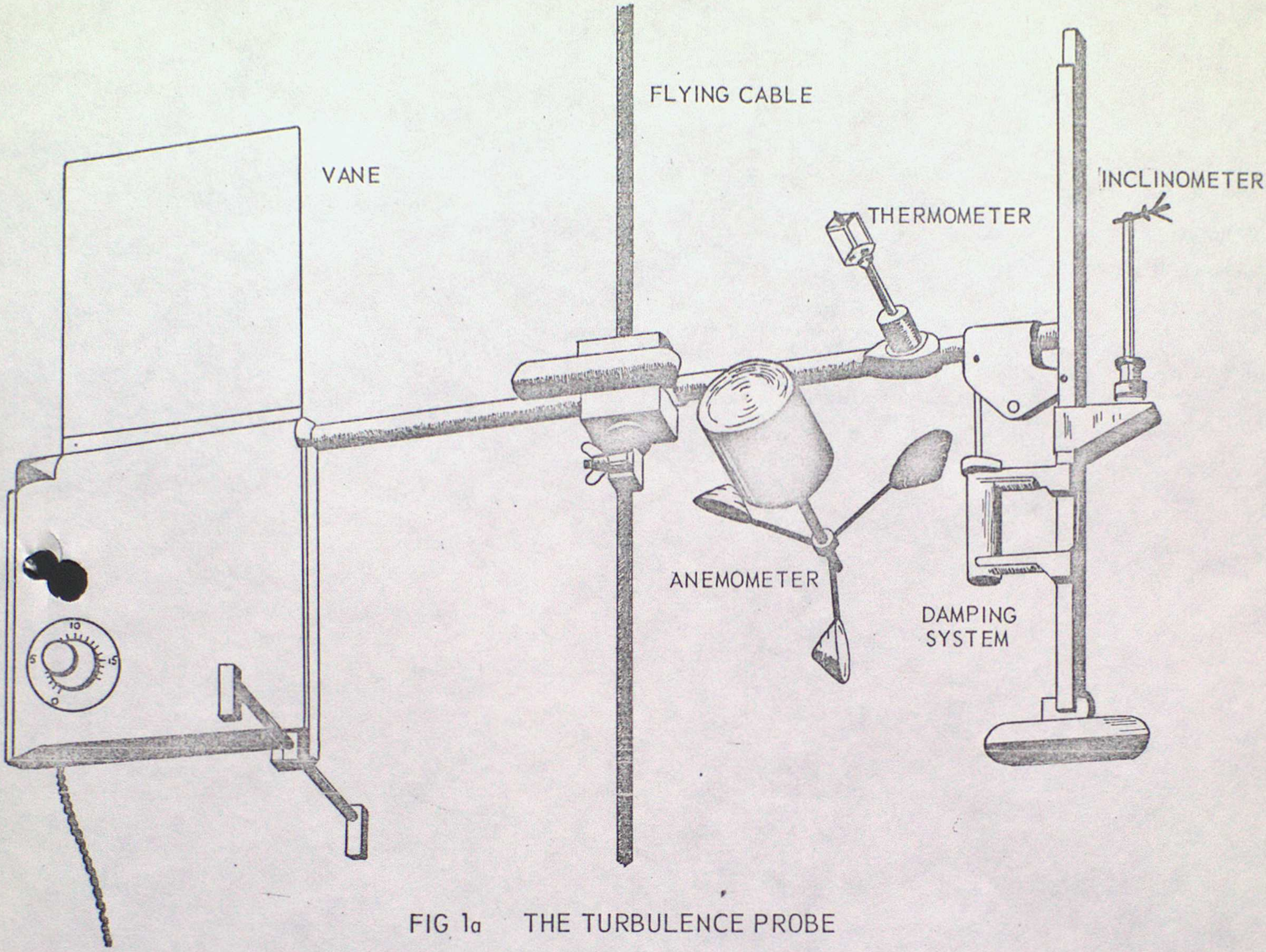

FIG 1a THE TURBULENCE PROBE

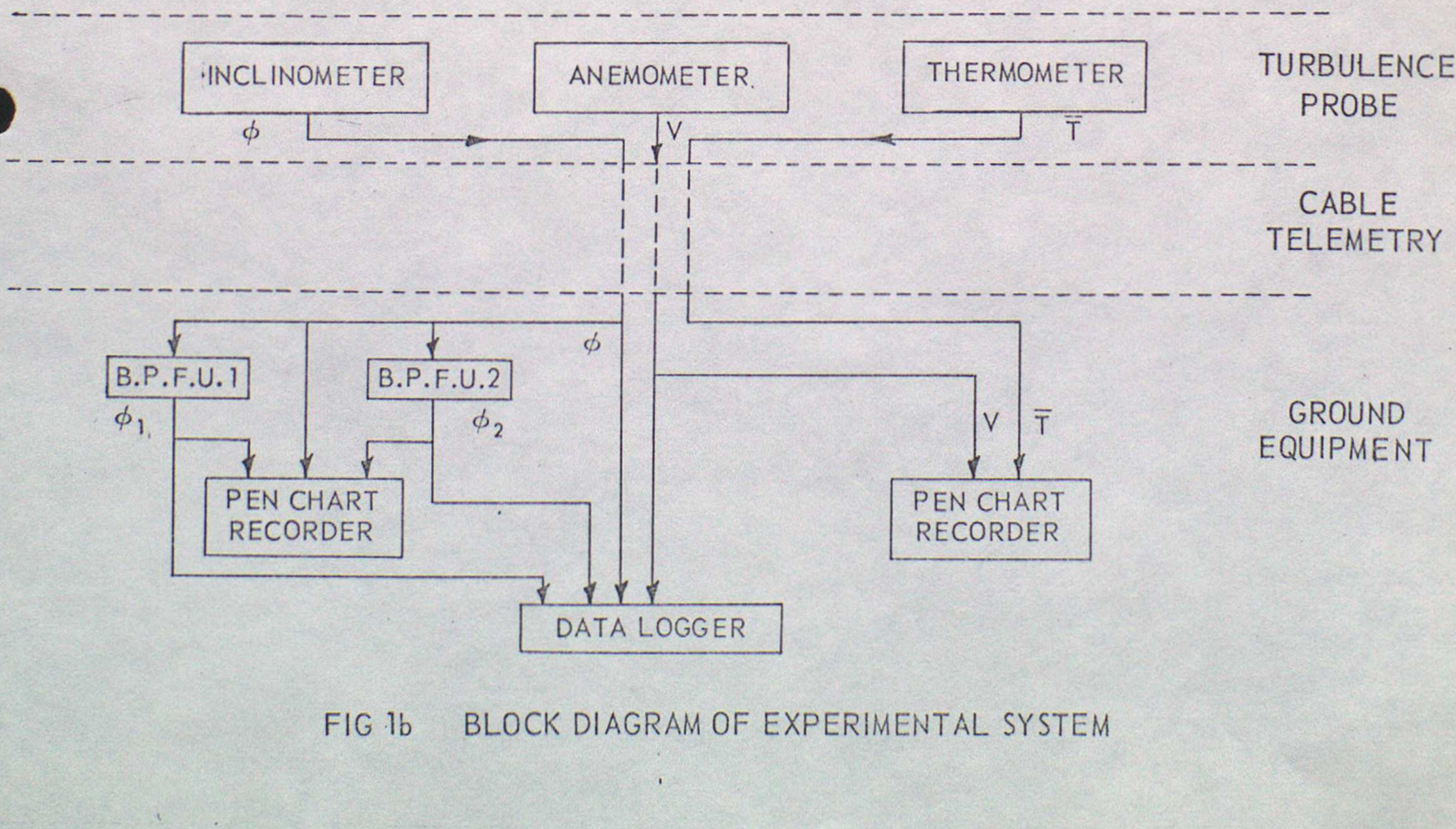

FIG 1b BLOCK DIAGRAM OF EXPERIMENTAL SYSTEM

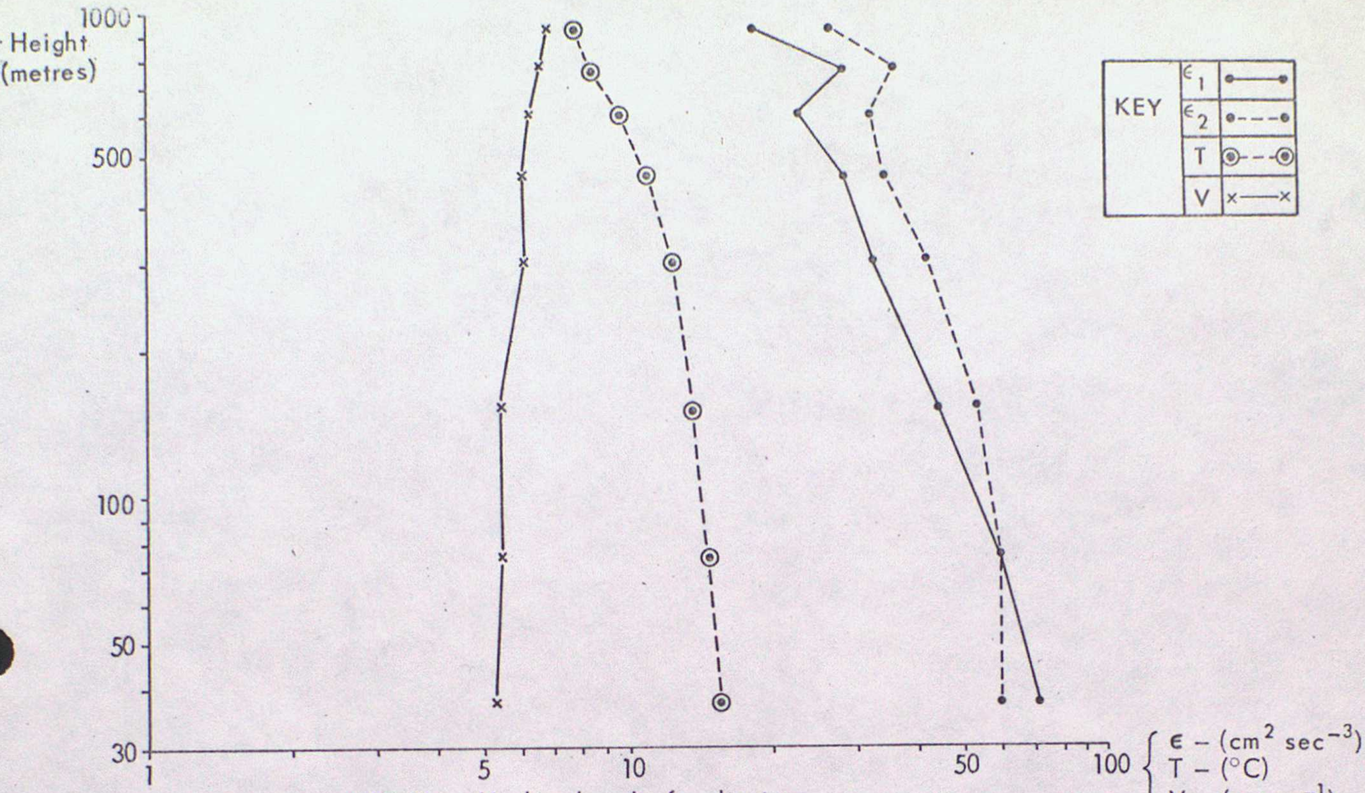

FIG 2a Higher level of radiation

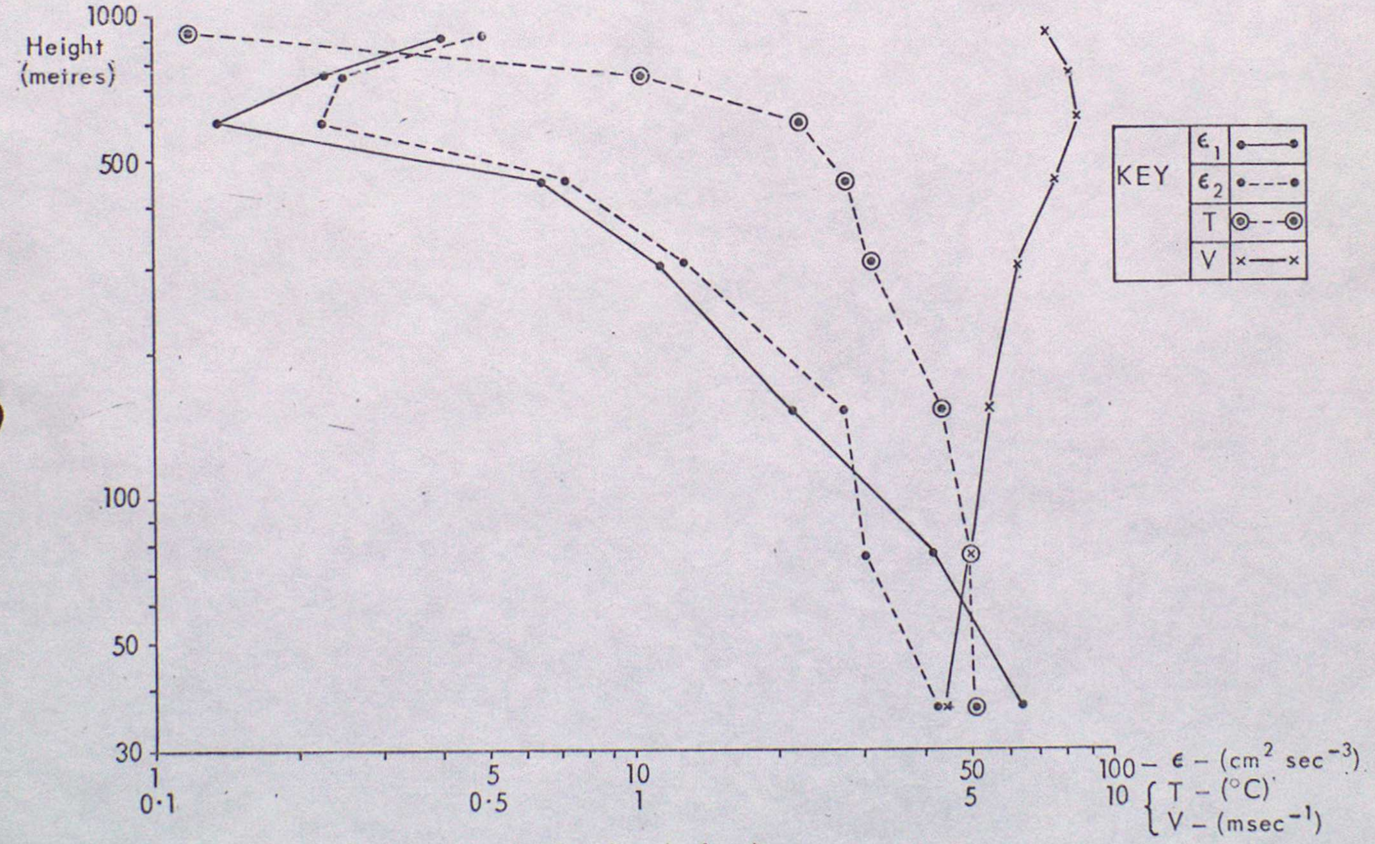

FIG 2b Lower level of radiation

VARIATION OF THE RATE OF DISSIPATION (ϵ) WITH HEIGHT

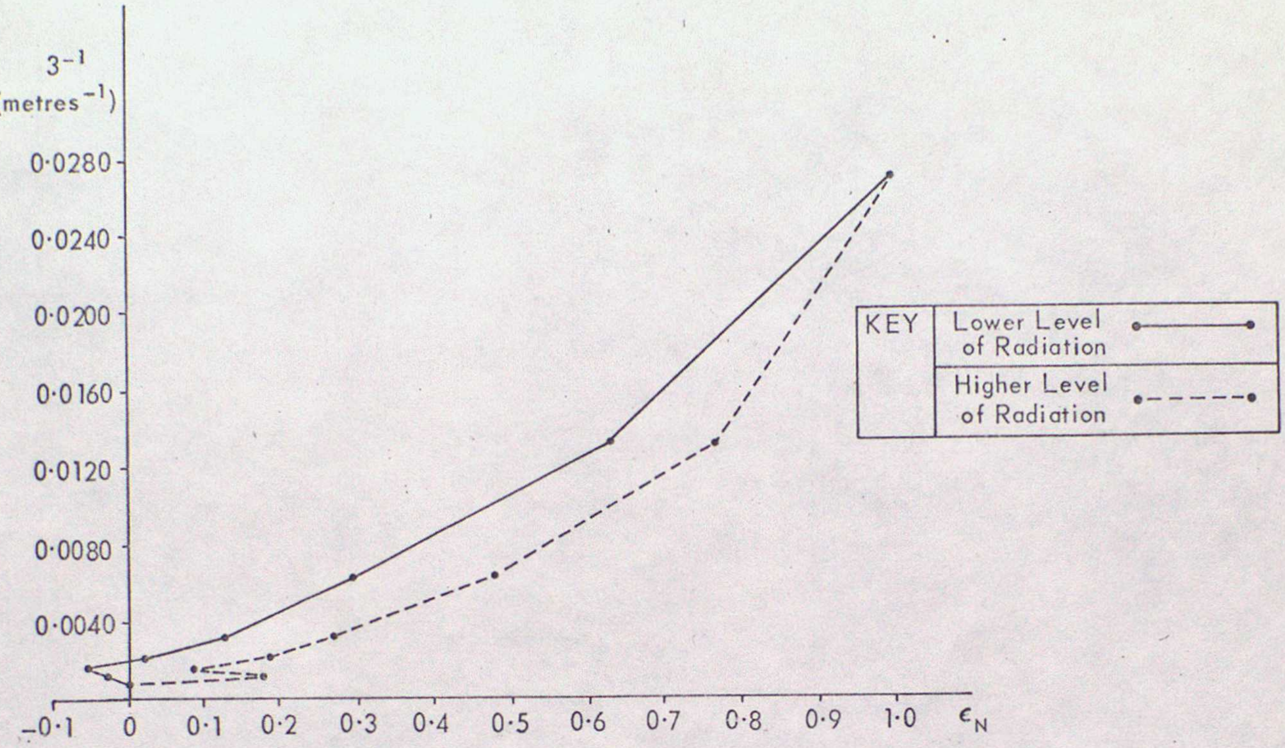

FIG 3a Variation of the normalized rate of dissipation with height

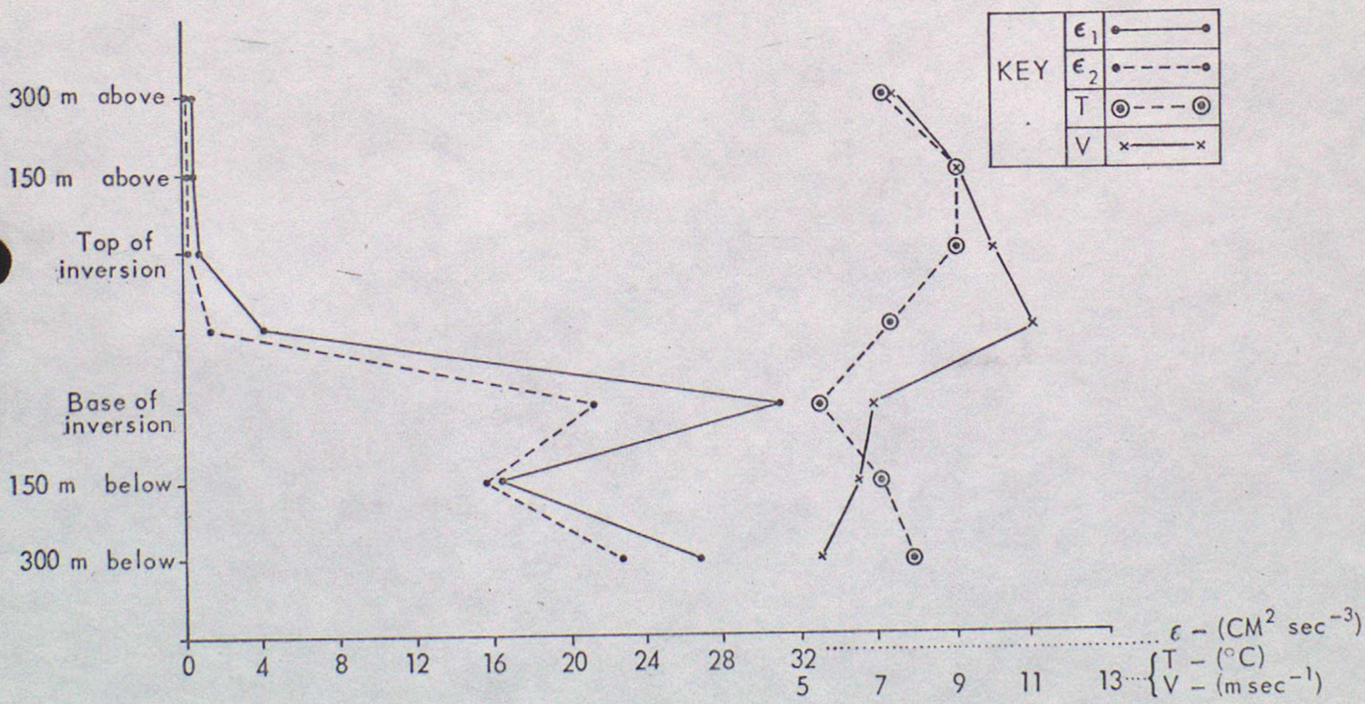

FIG 3b Variation of the rate of dissipation through an inversion

Tabulation of the results

The computed data for each run is presented in this appendix. These normally consisted of an ascent and a descent.

The first line gives the date, starting time of ascent, finishing time of descent (where applicable) in GMT, and a rough wind direction.

The second line gives the weather (generally only cloud conditions) and $\overline{R_N}$ which is the mean net radiation, during the whole run, in mw cm^{-2}.

For later surveys the next block gives mean winds (m sec^{-1}), measured on a tubular mast, and mean temperatures (^{o}C), measured on a wooden tower. The means for ascent and descent periods are listed separately where $\overline{u}_1$, $\overline{u}_2$ and $\overline{u}_3$ refer to heights of 14 ft, 28 ft and 55 ft respectively and $\overline{T}_2$ and $\overline{T}_3$ refer to the last two heights.

The main body of data is then tabulated where:-

Ht(m) - Height in metres as obtained from the amount of cable payed out.

D - Descent.

A - Ascent

$\overline{T}$ - Mean five minute temperature in ^{o}C.

$\overline{u}$ - Mean five minute wind speed in m sec^{-1}.

σ_{ϕ_1} - Standard deviation of the inclination output from filter unit 1, in 10^{-2} radians.

σ_{ϕ_2} - As σ_{ϕ_1} but for filter unit 2.

ϵ_1 - Rate of dissipation of turbulent kinetic energy in cm^2 sec^{-3} derived from the output of filter unit 1.

ϵ_2 - As ϵ_1 but relating to filter unit 2.

f_1 - Form factor of the inclination output from filter unit 1.

f_2 - As f_1 but for filter unit 2.

It should be noted that before 26/8/68 all the results had an assumed form factor of 1.25 which was used to calculate the tabulated σ_ϕ's and ϵ's. Form factors were computed from the original data thereafter and an average of these, for the five minute periods, was used to correct the earlier data before analysis.