A technique for investigation of the low level eddy structure of the atmosphere

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Summary

Wind measurements have been made using a set of sensitive anemometers and automatic recording equipment. This produces a record on punched paper tape, in a form suitable for computer processing. Simultaneous use of a number of anemometers makes it possible to partially resolve the fine structure of atmospheric flow at low levels. Numerical filtering techniques are employed to reduce the effects of unresolved eddies and to extend the investigation to variation of eddy structure with frequency.

Equipment and experimental details

The purpose of the equipment is to produce a record of the simultaneous variations of wind speed and direction at several points. Wind speed is measured with a special type of cup anemometer of high sensitivity and rapid frequency response, full details of which are given elsewhere (Jones 1965). This anemometer gives a voltage output linearly proportioned to the wind speed. A separate wind vane is connected to a resolver which splits the voltage output from the anemometer into two components corresponding to two wind components at right angles to each other. The anemometer is set up to produce these components in the required directions, and is varied according to the experiment.

Several anemometers are used simultaneously, each with their own resolver, so that with 10 anemometers it is necessary to record 20 voltage signals. A data logger is used to record each voltage; this apparatus comprises a digital voltmeter, which displays the value of the input voltage as a series of decimal digits, and a punch unit which records these digits as holes punched in paper tape. Each of the 20 voltage signals corresponding to each wind component is connected in turn to the digital voltmeter and its value recorded.

When all the signals have been measured the cycle is repeated. This is continued for as long as required. The sampling rate is variable over a wide range, from 12 channels per second to 1 channel every 30 minutes. The paper tapes are then used as data tapes for various computer programmes, and although occasional punch faults occur, these are automatically detected by the computer.

The experimental site is situated on Salisbury Plain, and consists of gently undulating downland covered with short grass. The sampling and recording equipment is installed in the Meteorology Laboratory and connected to the site by underground cables. These cables are terminated in junction boxes placed at convient points over the site so that the anemometers can easily be arranged in any pattern, regardless of the wind direction. At their other end the cables terminate in a plug-board which also contains connections to the data logging equipment, pen recorders, band-pass filters and amplifiers.

To study the structure of eddies, a single line of anemometers has been set up across the direction of the mean wind, so that a sample of all the anemometers provided a cross-section of the wind flow across the line. These cross-sections were obtained repeatedly at short time intervals and for considerable lenghts of time, giving information on the width and duration of individual disturbances within the mean flow. Moreover, since the mean wind was considerably higher than the fluctuations produced by disturbances, the series of time cross-sections could be regarded as successive space cross-sections whose spacing depended on the sampling rate and mean wind speed. This assumed that individual eddies are not formed and dissipated so fast that their shape alters substantially in the short time they take to pass over the array.

This was checked independently by a separate experiment to observe the passage of fluctuations and anemometers arranged in a line parallel to the wind, rather than across it, so that variation of correlation coefficient with distance could be measured.

Figure 1 illustrates diagrammatically the method of setting up the anemometers to study eddy structure. The arrowed circles represent eddies superimposed on the mean wind. The measurements were made at a height of 2 metres because a number of masts of this height were readily available.

Only a limited size range of eddies can be studied in a particular experiment. Resolution is limited by the number of anemometers available and by the maximum speed of the tape punch. Turbulence features which are of size comparable to the separation of anemometers in the array will not be resolved in space, and events which happen too fast will not be resolved in time. Their presence will produce only «noise» on the output.

Eddies which are very large compared to the dimensions of the array are observed as a slowly varying component in the mean wind, tending to distort the output. Therefore the data was subjected to numerical filtering, firstly to remove the noise and secondly to split the turbulence into several broad frequency bands. The techniques used have also been applied to numerical weather forecasting (Wallington 1962) and rely on the weighted averaging of adjacent values in the time series of obervations, according to the equation.

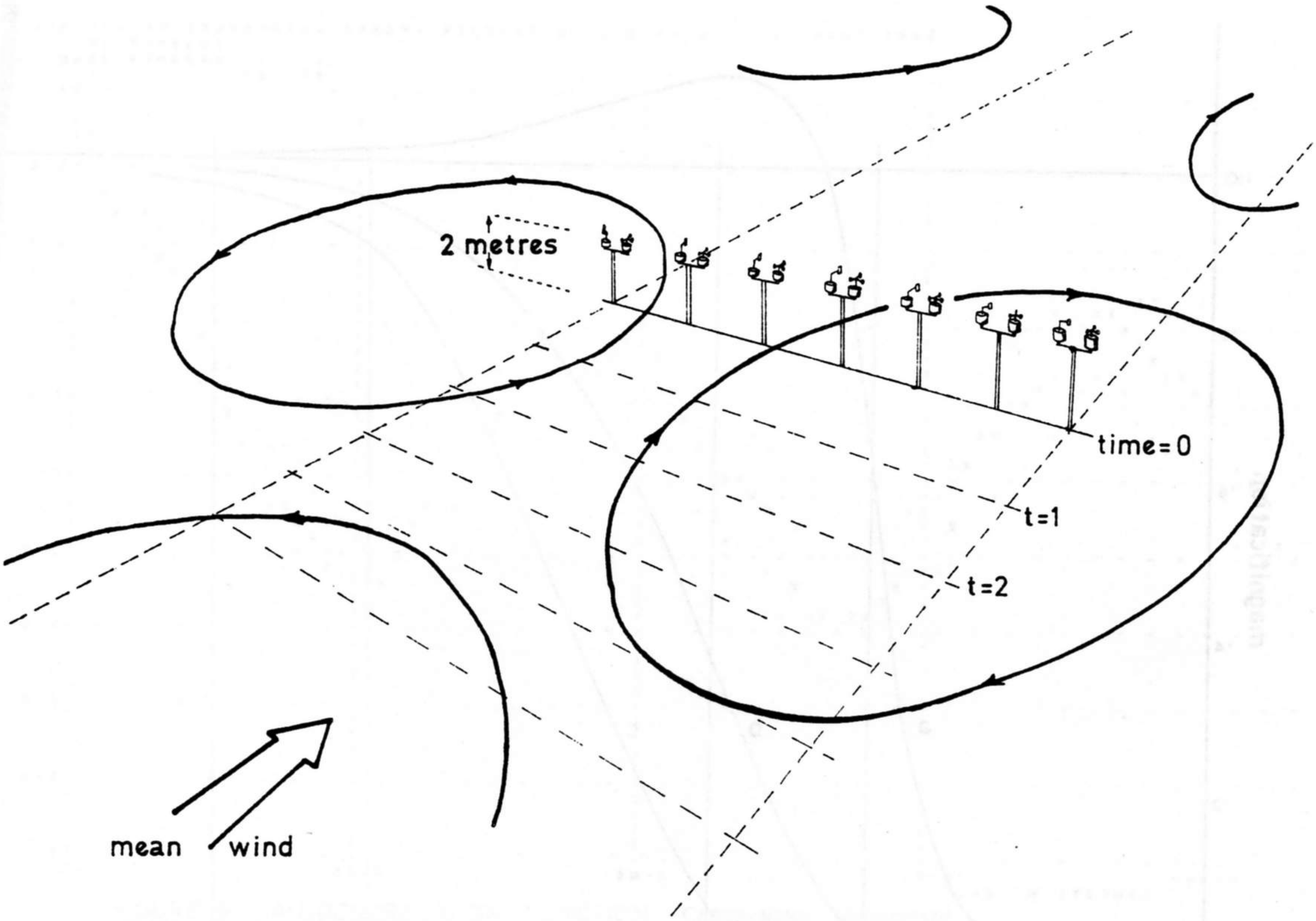

FIGURE 1. ANEMOMETER ARRAY

$x'_t = x_t + \frac{\alpha}{2}\left(x_{t+1} + x_{t-1} - 2x_t\right)$ where x_t is the value of x at time t and x_{t-1} and x_{t+1} are the values for the preceding and following measurements. This has the effect of removing high frequencies, and is analogous to electrical low pass filtering. The coefficient α is a constant and is chosen to provide the required frequency response. Substraction of the effects of two different low-pass filters gives the effect of a band-pass filter. Typical response curves are shown in Figure 2. The magnification describes the extent to which the amplitude of a sine wave of given frequency would be decreased, and the ratio of wavelength to gridlength shows how the magnification varies with the effective eddy size. The three curves in Figure 2 show the filters which have been used. The left hand curve (a) shows the filter used to decrease the noise on the output. It can be seen that eddies of less than 2 to 3 times the size of the anemometer spacing are almost completely eliminated, while those greater than about 6 times the spacing are almost unaltered. The other two filters were used to study different frequency bands. Fairly wide band-widths are used since too narrow a band-pass superimposes the band-pass characteristic heavily on the filtered winds. Preliminary electrical smoothing was also applied separately to each channel, to reduce the noise and also to decrease the danger of aliasing when sampling at rates which are lower than the anemometer response time.

The final results are presented as a two-dimensional array of wind vectors, these being drawn by hand from information supplied by the computer. The arrow represents the wind direction and the arrow shaft length is proportional to the wind speed. The scaling is chosen separately for each pattern to display details most clearly. Figure 3 shows the original unfiltered record from a set of 7 anemometers spaced across wind at 3 metre intervals, and shows that the wind was fairly steady with relatively small fluctuations superimposed on it. The mean wind was 4 metres per second. Figure 4a shows the effect of substantial smoothing of the original record, using the central response curve (b) of Figure 2 and subtracting the mean wind. Wind speeds in this eddy were about 2 metres per second. Figure 4b shows the result of subtracting filter (e) from filter (a) to give band-pass filtering, when the output is less coherent but several small eddies can still be seen. Wind speed in this band was about 1 metre per second.

Figure 5 shows the energy spectrum derived from this record of the across-wind component at a single anemometer, with a large peak corresponding to the eddies of

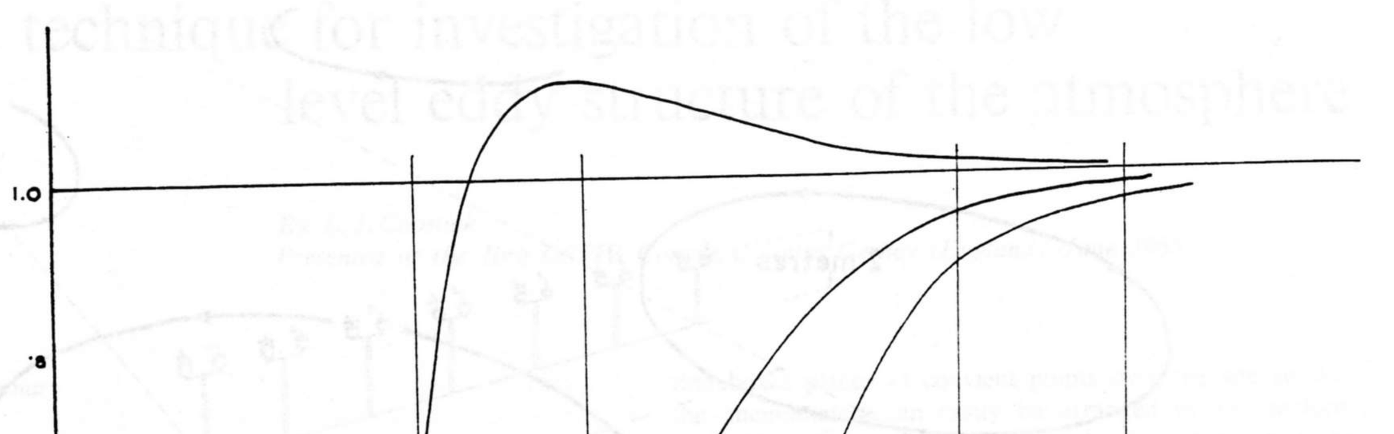

FIGURE 2. FILTER CHARACTERISTICS

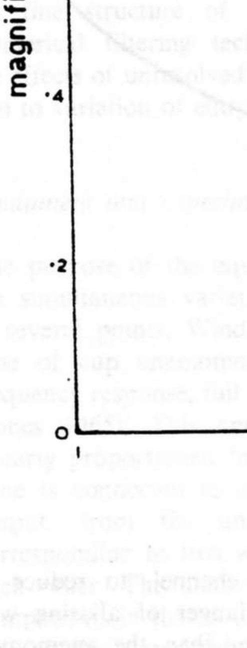

FIGURE 3.

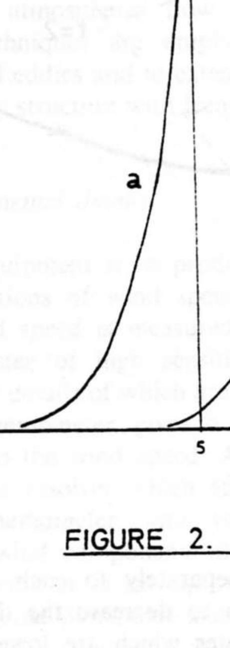

FIGURE 4a.

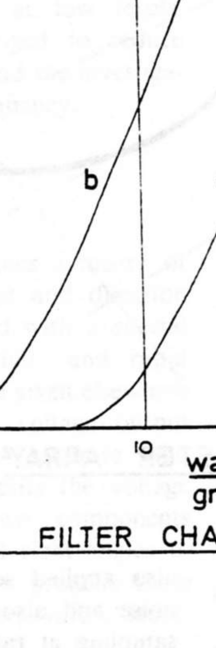

FIGURE 4b.

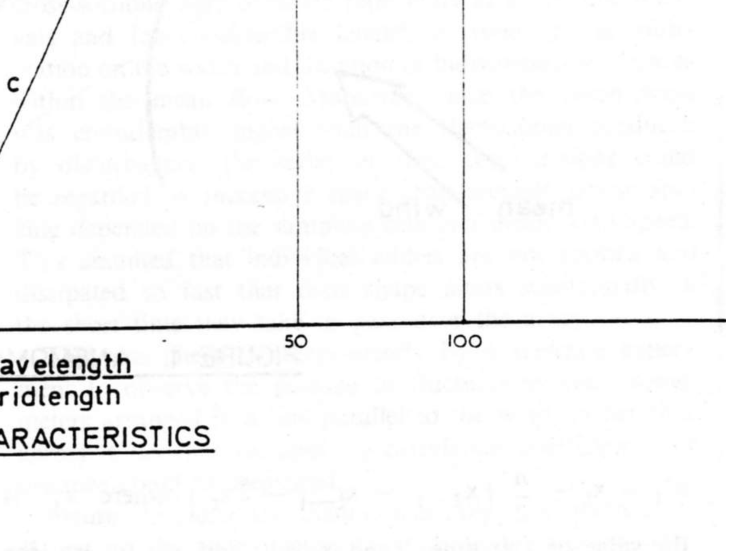

FIGURE 5. ENERGY SPECTRUM.
cross-wind component

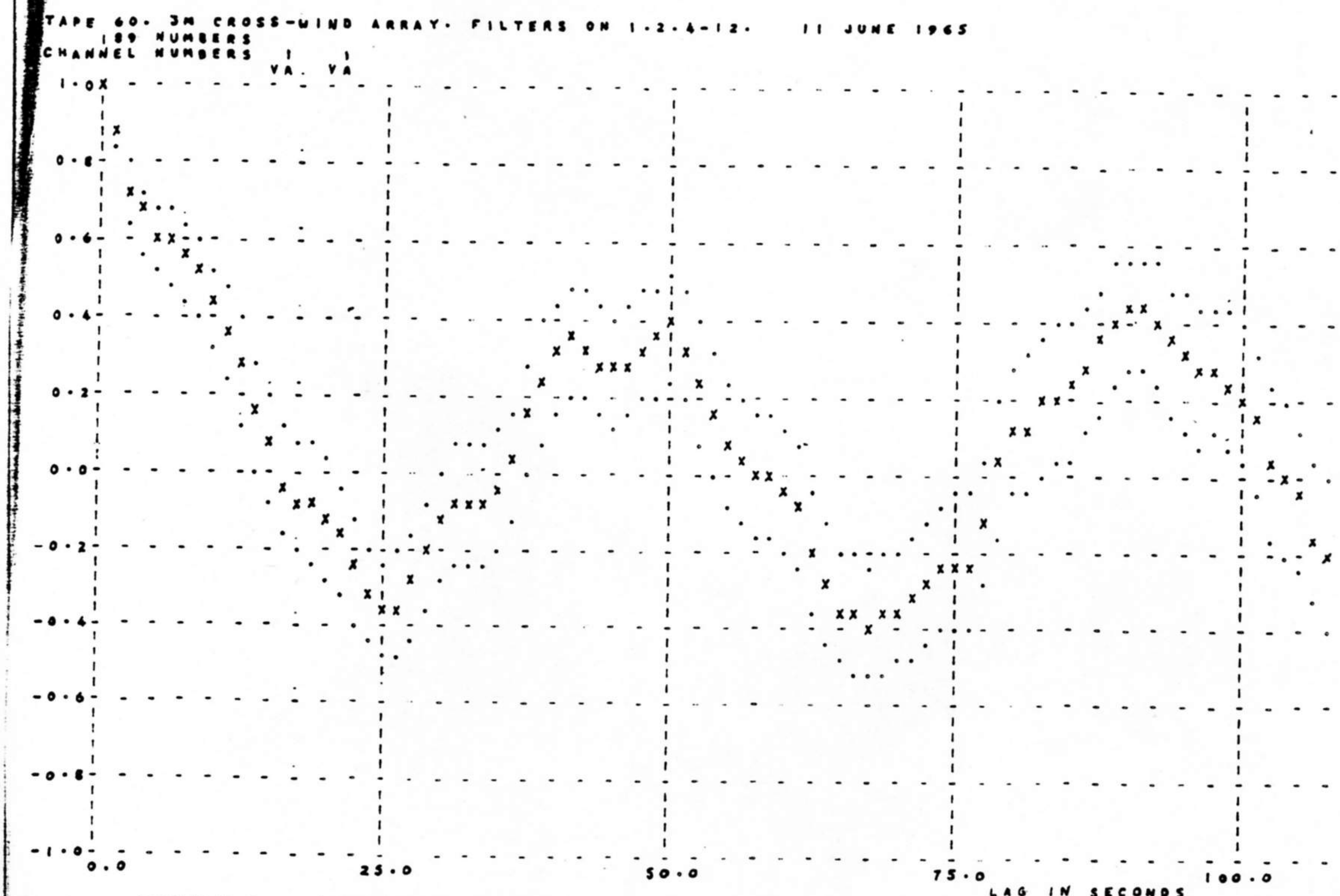

FIGURE 6. AUTOCORRELATION FUNCTION. Cross-wind component.

the size shown in Figure 4a. The total sampling time in this case was only 5 minutes which means that the spectrum shape is highly sensitive to individual events rather than long-term properties of the atmospherie flow.

Figure 6 shows the autocorrelation function for the same data and since a negative correlation coefficient corresponds to a reversal of wind direction the function can be interpreted as showing that the average time for an eddy to pass was about 25 seconds giving a diameter of about 100 metres. The classical exponential correlogram is, of course, seldom observed for such short sampling periods.

Although this technique cannot at present be used to investigate turbulence structure below distances of about 1 metre and frequencies above 1 cycle per second, other evidence has been obtained which indicates that discrete vortices exist with diameters of the order of centimetres (Sakagami 1964).

It has been found that the patterns obtained are more coherent with light winds and neutral or stable conditions. This is more likely to be due to experimental difficulties than to any physical effect, owing to the limited frequency response of the system and the fact that higher winds tend to increase the observed frequencies at a fixed point.

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