OBSERVATIONS OF TURBULENCE DOWNWIND OF A FOREST-HEATH INTERFACE

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Abstract. The growth of the equilibrium layer downwind of a forest – heath interface has been observed using eddy correlation measurements made in real time. The atmosphere adjusts more quickly to the transition from heath to forest than to the transition from forest to heath.

1. Introduction

The ideal micrometeorological site is an infinite horizontal plane of uniform vegetation, and micrometeorologists have often gone to great lengths to work at sites which approach this ideal. However, when micrometeorological techniques are applied to hydrological or agricultural research, there is less likely to be the same freedom to select sites. The choice of site will often need to be a compromise between the requirement to work within a particular area and the need to minimise measurement errors. The purpose of this study was to observe what these errors might be for the case of turbulence measurements made downwind of an interface between forest and heath (and *vice versa*).

Although the response of the atmospheric boundary layer to changing surface conditions has received much attention, this has largely been directed at the growth of the envelope containing the internal boundary layer. Relatively little work has been carried out on the growth of the equilibrium layer, within which measurements can be taken as being representative of the surface. Munro and Oke (1975) have observed the development of the equilibrium wind profile, but there have been few measurements of turbulent fluxes in the developing surface layer. With the growth in the use of eddy correlation systems for routine flux measurement it is important that the site requirements of such instrumentation become better established. This paper describes observations of the development of the equilibrium layer downwind of a change in vegetation which is not uncommon and yet is likely to be one of the largest encountered in an agricultural landscape.

2. The Site

The experimental site was in an area of flat topography comprised of Berner's Heath, which is about one square kilometre and the adjacent area of The King's Forest, which is a part of Thetford Forest in East Anglia.

The vegetation on the heath is predominately heather (*Calluna vulgaris*) approximately

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0.25 m in height and covering 75% of the ground. Interspaced with the heather are patches of short grass. The forest stand adjacent to the heath is a mixture of Scots pine (*Pinus sylvestris*) and European Larch (*Larix decidua*), with two rows of pine planted for each row of larch. After a distance of 80 m, this stand gives way to a plantation of Corsican pine (*Pinus nigra* var. *maritima*), which extends for several kilometres. The larch were taller than the Scots pine having, at the time of the study, a mean height of 11.0 m, compared to 9.2 m for the Scots pine. The mean height of the stand was thus 9.8 m. This stand, which had been brashed, had a density of approximately 4400 stems per ha. The Corsican pine had a mean height of 9.7 m and a density of approximately 3600 stems per ha. This stand had not been brashed. The two forest stands were separated by a break, 8 m wide.

3. Instrumentation

Measurements were taken with Mk 1 Hydra eddy correlation devices, each of which consists of a sonic anemometer (Shuttleworth *et al.*, 1982) an infra-red hygrometer (Moore, 1983), a fine-wire thermocouple and a pair of Gill propellor anemometers mounted at right angles in the horizontal plane. One of these instruments is shown in Figure 1. The signals from the sensors are analysed in real time by a battery-powered microprocessor system. Hourly average values of the cross- and auto-correlation terms are recorded (Lloyd *et al.*, 1984). The fluctuations are computed as deviations from moving averages calculated using a low-pass digital filter. In this study, a time constant of 375 s was used in the digital filter. Some further details of these instruments and their use are given by Shuttleworth *et al.* (1984). In the version of the microprocessor program used in this study, the wind velocity and its variance at right angles to the direction of the mean wind were not recorded.

4. Method

Hydra instruments were located at two reference positions, one with a large fetch over the upwind surface and the other with the maximum feasible fetch over the downwind surface. For the heath-forest direction, these positions were at the centre of the heath, 550 m from the interface, and at 400 m from the interface into the forest. A third instrument was deployed at intermediate positions 50, 120, or 200 m into the forest. During this first part of the experiment it was not possible to use the same instruments continuously at the reference positions, nor to use the same instrument moved between the central positions. For the forest-heath direction, the upwind reference position was located over the forest at 25 m from the interface, and the downwind reference was over the heath at 700 m from the interface. The third instrument was deployed over the heath at 50, 100, 200, 400, and also at 700 m from the interface. During this second part of the experiment, it was possible to keep the same Hydras at the reference positions and the same Hydra moving amongst the central positions. This should reduce the effect of persistent systematic errors when looking at relative changes across the heath. The

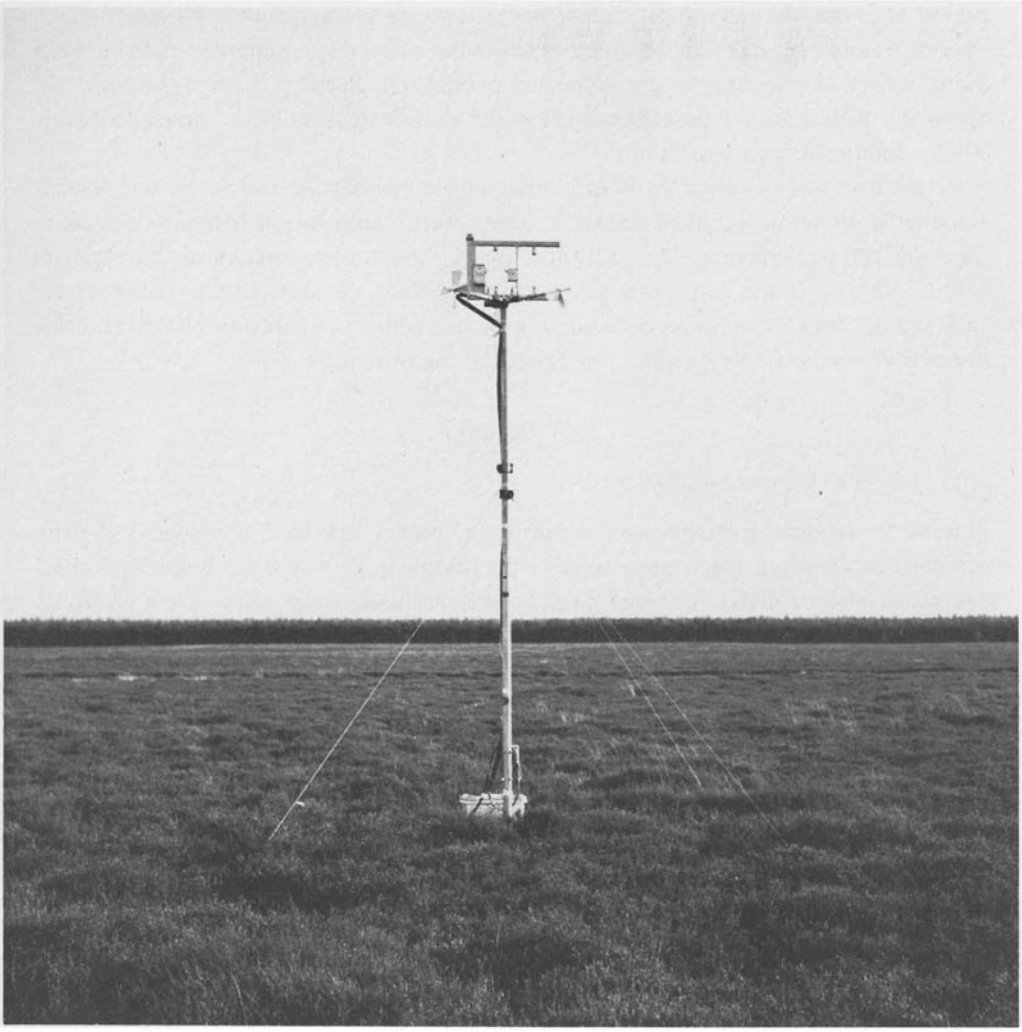

Fig. 1. The Mk 1 Hydra eddy correlation device mounted at a height of 3.5 m over Berner's Heath.

instruments were left running unattended, with hours of suitable wind direction identified from the wind vane of an automatic weather station (Didcot Instrument Co., Abingdon) located at the centre of the heath. The wind direction was considered acceptable when the hourly average was within plus or minus 45 deg of the line of instruments, which was at right angles to the interface.

When deployed over the forest, the instruments were mounted at a height of 13.5 m on masts on top of 10 m high scaffolding towers. Over the heath, the instruments were mounted at a height of 3.5 m above ground as shown in Figure 1.

The heath-forest measurements were made during the winter of 1982–1983 and the forest-heath measurements the following winter. There were several gales during both periods of observations, which caused some damage to the propellor anemometers. Propellors and bearings were replaced as and when necessary; no data were used when the propellor anemometers were suspected of being damaged. To avoid the region of nonlinear calibration for the Gill propellors, no data were used when the mean hourly wind velocity was less than 1 m s^{-1}.

It was necessary to remove off-set errors in the standard deviation of the vertical velocity fluctuations, σ_w, measurements. These were found by linear regressions of σ_w on the friction velocity, u_*, for each instrument. Sonic anemometers of this type are prone to errors in the measurement of σ_w, (Shuttleworth *et al.*, 1982). These errors, typically 0.05 m s^{-1}, are a result of random noise, which not being correlated with the horizontal wind velocity, u, does not affect the measurement of u_*.

5. Results

5.1. THE HEATH-FOREST TRANSITION

This study has been restricted to the primary variables: the friction velocity, u_*; the standard deviation of the vertical velocity fluctuations, σ_w; the mean horizontal wind velocity in the direction of the mean wind, u; and the standard deviation of u, σ_u. Various ratios of these variables have also been studied. Figure 2(a) shows the change in the primary variables when the wind was blowing from the heath to the forest. Each measurement has been normalised by the appropriate measurement made simultaneously at the upwind reference position. Figure 2(b) shows the change in the derived ratios: σ_w/u_*, σ_u/u_*, σ_u/u, and u_*/u. Those points which are not significantly different (at the 5% level) from the values measured at the farthest distance into the forest are indicated on the figure.

It can be seen from Figure 2 that the friction velocity, u_*, adjusts quickly to the new surface. σ_w reacts more slowly, but by the 120 m position follows u_*. σ_u also adjusts quickly, but there is evidence of an initial speeding up of the wind at the 50 m position. However, by the 120 m position, the wind velocity is close to its value at the farthest position. For the derived variables, σ_w/u_* is close to unity from 120 m onwards, whereas σ_u/u_* is approximately 0.7 from 50 m onwards. As there is no consistent change in u beyond 120 m, there is no consistent change in σ_u/u or u_*/u after this distance.

As these observations were taken during the winter months, there were few occasions with appreciable sensible heat flux. This together with the high values of u_* found over the forest combined to give near-neutral conditions for 82% of the 60 data points collected. Near-neutral has been taken here as being when $|z/L| < 0.04$, where L is the Monin–Obukov scale length and z is the height above the estimated zero plane, taken as 0.75 of the vegetation height. In view of this, no attempt has been made to try and differentiate between the classes of stable, near-neutral and unstable conditions.

5.2. THE FOREST-HEATH TRANSITION

The change in the primary variables for the periods when the wind was blowing from the forest to the heath are shown in Figure 3(a). The data are presented as before,

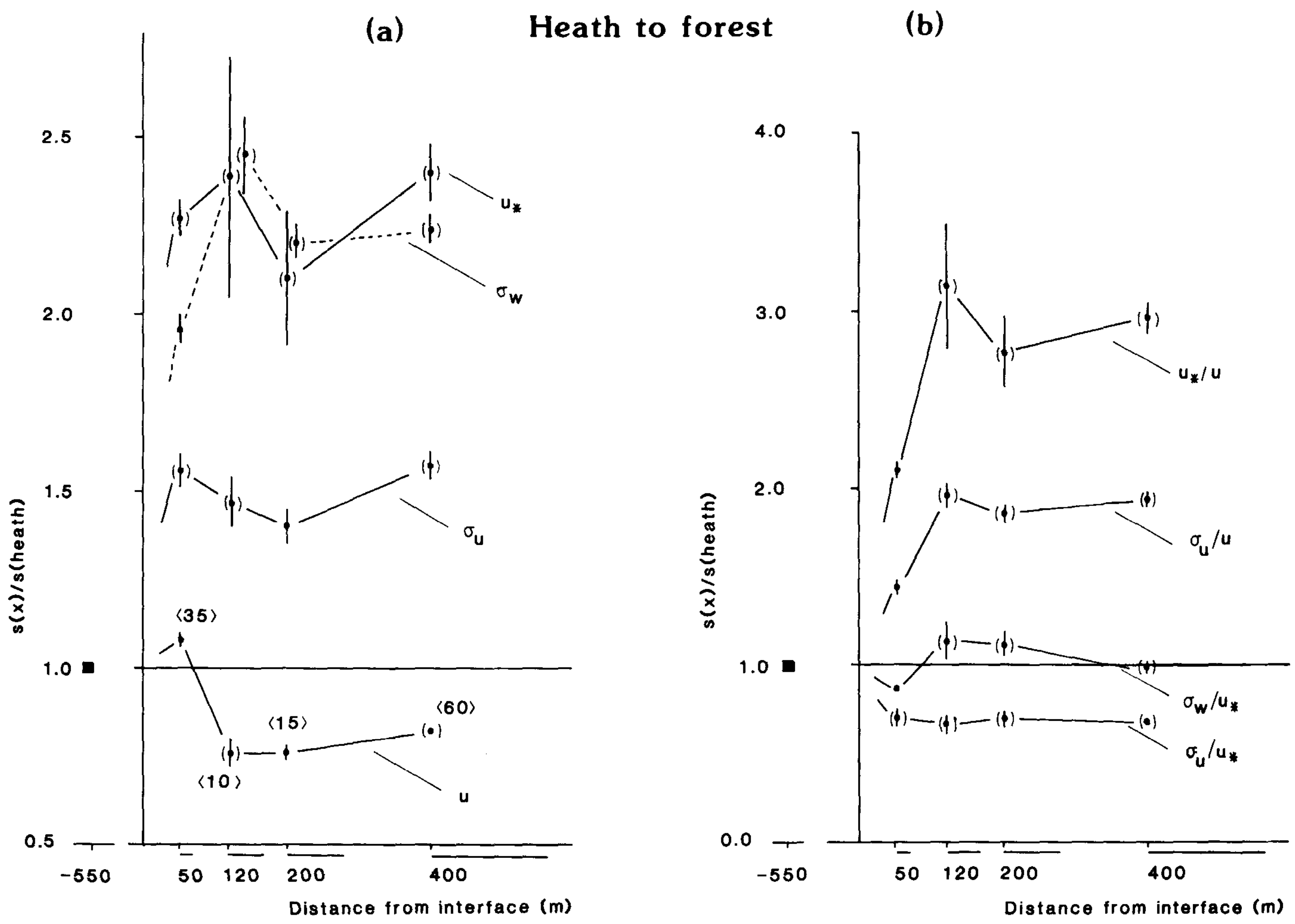

Fig. 2a–b. The variation of (a) the primary variables and (b) the derived variables with distance from the interface with the heath. Each measurement has been normalised by the measurement made simultaneously over the heath. The error bars denote the standard deviation of the mean ratio; values of 0.01 or less are not shown. Brackets indicate points which are not significantly different (at the 5% level) from those made at the farthest position from the interface. The lines below the distance axis show the range of fetch for the plus or minus 45° acceptance angle. The figures in angled brackets are the number of points included.

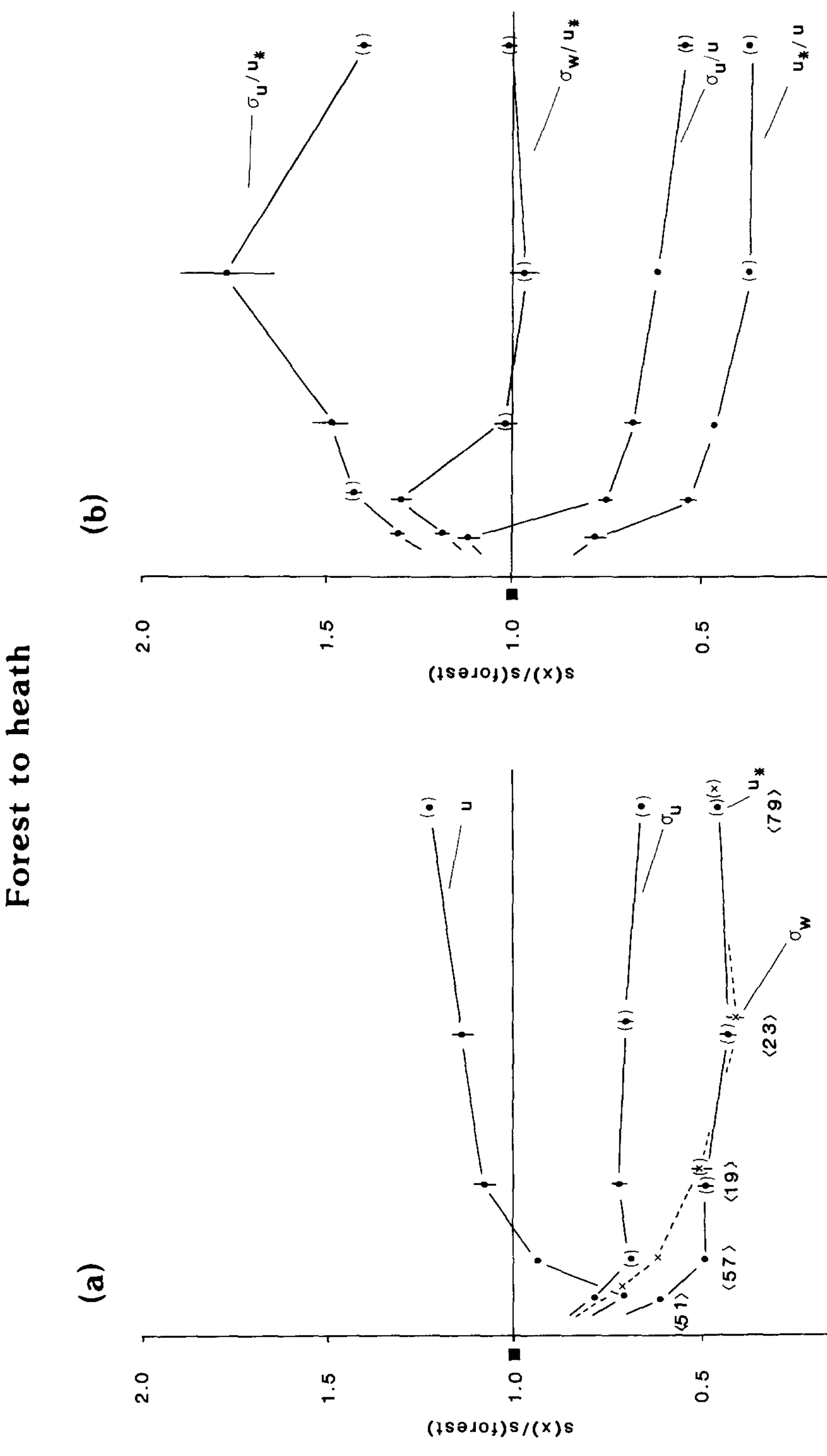

Fig. 3(a–b). The variation of (a) the primary variables and (b) the derived variables with distance from the interface with the forest. Each measurement has been normalised by the measurement made simultaneously over the forest. Other details are as for Figure 2.

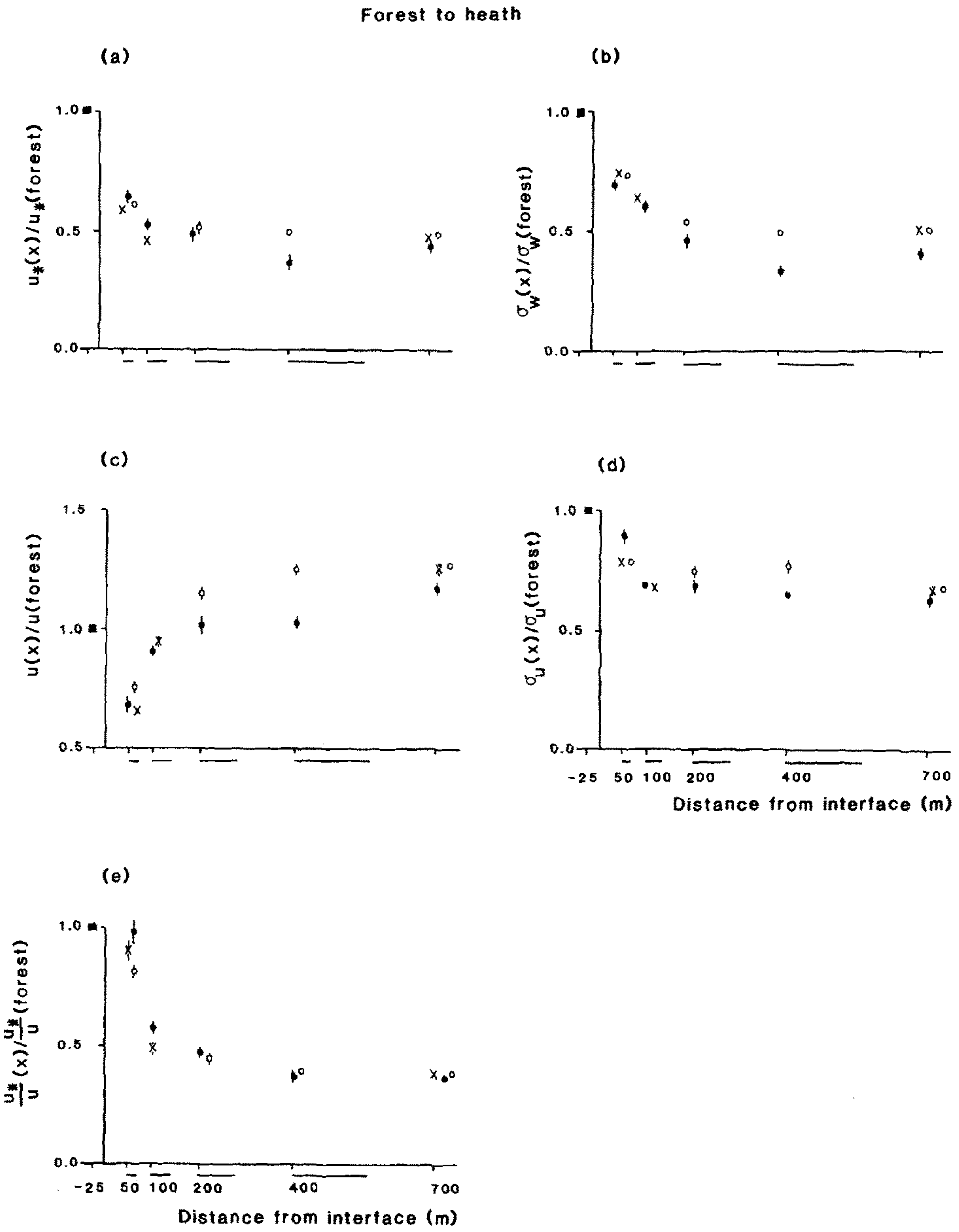

Fig. 4(a–e). The variation of (a) u_*, (b) σ_w, (c) u, (d) σ_u, and (e) u_*/u with distance from the interface with the forest, for ● stable, × near-neutral and ○ unstable conditions. Each measurement has been normalised by the measurement made simultaneously over the forest. Error bars denote the standard deviation of the mean ratio, values of 0.01 or less are not shown. The lines below the distance axis show the range of fetch for the plus or minus 45° acceptance angle. Classes containing three or less points have not been plotted.

normalised by the measurements made at the upwind reference position. In general, u_* falls rapidly over the first 100 m, so that the value at 100 m from the interface is close to the value at 700 m; σ_u behaves similarly. σ_w falls less rapidly but by 200 m is also close to its 700 m value. The measured horizontal wind velocity initially falls to a lower value than that measured over the forest and then rises steadily across the heath.

The change in the derived variables is shown in Figure 3(b). The ratio σ_w/u_*, after increasing to about 1.3 times its forest value, falls to a value close to its initial (and final) value by 200 m; on the other hand, σ_u/u_* increases to a maximum at 400 m, and then falls to a value about 50% greater than its value measured over the forest. However, the error bars on the 400 m average indicate a greater uncertainty on this observation than on the others. σ_u/u falls consistently as u increases across the heath, but u_*/u falls until 400 m and is then virtually constant to 700 m.

Although there are insufficient data to consider a detailed variation with atmospheric stability, the data have been divided into three broad classes of stable, near-neutral and unstable. Near-neutral conditions have been defined to be when z/L, as measured at the 700 m position, was within the range -0.04 to $+0.04$. The results are shown in Figure 4 for u_*, σ_w, u, σ_u, and u_*/u. Classes containing three or less points have not been plotted.

5.3. THE ROUGHNESS LENGTH OF THE HEATH

The roughness length, z_0, of the heath was determined from the slope of a line drawn through a plot of u_* versus u, for data collected during near-neutral conditions. The data used were obtained during earlier equipment trials using a three-dimensional Kaijo–Denki sonic anemometer. Use of this method requires a value to be assumed for the zero-plane displacement, d, but provided that the measurement height is large compared with d, the derivation is insensitive to the value of d used. If it is assumed that d is equal to three quarters of the vegetation height, z_0 equals 0.028 m.

6. Discussion

6.1. ERRORS

Although there is the possibility that some errors, such as those due to high-frequency loss and sensor separation, may be greater over the heath, the errors due to sensor defects, such as errors in cosine response, should not be site-specific and should cancel out in the normalisation. In considering systematic errors, it should be remembered that each of these sets of data was collected over a period of four months. The data for each position were extracted from brief periods, typically of a few days duration, when the wind was blowing from the required direction. It follows that there may be different systematic errors at the various positions. These errors may be caused by drift in the electronics of the analogue-to-digital converter, the sonic anemometer, or the amplifiers for the Gill anemometers. Wear in the bearings of these anemometers may also give changes in the static and dynamic coefficients of friction for these instruments, which will affect their stalling and start-up speeds and the slope of their calibrations. Levelling errors are also site-specific systematic errors. Pond (1968) has estimated that levelling errors can result in the shearing stress being under-measured by 10% per degree of tilt into the wind. The instruments here were thought to be levelled to within half a degree, which could result in a fractional error in u_* of about 2.5%. Changes in the calibration coefficients between calibrations are observed to be typically 2% for the sonic anemometers and about half this for the Gills and analogue-to-digital converters. The combined effect of these errors, if added quadratically amounts to some $\pm 4\%$. The effect of these errors may thus be of about the same size as the variability given by the error bars. For the heath-forest direction, where the measurements at each position were made with different instruments, these errors are likely to be greater than for the forest-heath direction, where the same instrument was used at each position. However, errors in the derived variables have the potential to be less than in the primary variables. For the dimensionless velocity ratios, errors in the calibration of the analogue-to-digital converters should cancel and errors in the individual instrument calibration slopes may also cancel completely as in σ_u/u or be reduced to their square root, as for σ_u/u_*.

6.2. THE HEATH-FOREST RESULTS

Within the limitations imposed by the imperfect site in this direction, the data in Figure 2(a) lead to the conclusion that for measurements made at a height of 13.5 m above ground over a 10 m high forest, there is no detectable difference between the values of u_*, σ_w, σ_u, or u when measured at 120 or 200 m from the edge of the forest, compared with those measured 400 m from the edge. This conclusion is reinforced by the absence of change in the ratios σ_w/u_*, σ_u/u_*, σ_u/u, and u_*/u, which are likely to be more accurately measured than the primary variables. As can be seen from Figure 2(b), in no case is there any statistically significant difference between these ratios, when measured at 120 or 200 m from the edge of the forest in comparison with those measured at 400 m from the edge.

Although the roughness parameters of the forest were not measured, the zero-plane displacement is unlikely to be outside the range 0.6 to 0.9 of the mean tree height reported by Jarvis *et al.* (1976), in a review of fourteen coniferous forest studies. With this range of values, a fetch of 120 m would, in the present case, be equivalent to a fetch : height ratio of between 16 and 27.

6.3. THE FOREST-HEATH RESULTS

The first conclusion which would be drawn from Figure 3(a) is that for measurements made at a height of 3.5 m above the heath, there is on average no detectable difference between the values of u_*, σ_w, and σ_u, when measured at 200 or 400 m from the interface with the forest, compared to those made at 700 m from the interface. There is, however, a significant linear increase in wind velocity between 200 and 700 m from the interface. The wind velocity relative to that measured over the forest increases on average from 1.08 at 200 m to 1.23 at 700 m from the edge. For a typical windspeed of 3 m s^{-1} over the forest, this would be an increase of 0.45 m s^{-1} between 200 and 700 m, equivalent to a rate of 0.9 m s^{-1} per km.

If the data are split into stable, near-neutral and unstable classes as in Figure 4, although there is more scatter, the rates of adjustment of the turbulent variables are surprisingly similar. The increase in wind velocity between 400 and 700 m is, however, not observed during unstable conditions.

The ratio u_*/u introduces a smoothing effect on the data by removing some systematic error. For all the data, regardless of stability, Figure 3(b) shows this ratio decreasing for the first 400 m, but then remaining virtually constant. Separating the data into stable and unstable conditions, Figure 4(e), reveals a similar pattern. The ratio u_*/u has completed some 85% of its total change at 200 m from the interface. Thus although there is no detectable difference between the values of the primary turbulence variables at 200 and 700 m from the interface, the measurements at 200 m cannot be said to be representative of the surface. That state would appear to exist only for unstable conditions for distances greater than 400 m from the interface. There is insufficient data to draw any conclusion about near-neutral conditions, but under stable conditions, the wind velocity is still increasing between 400 and 700 m, so although u_*/u is constant, there is still the likelihood of vertical flux divergence. The usual criterion for an adequate fetch is that 90% of the change has been completed. Using this definition and interpolating between 200 and 400 m for the unstable class gives an adequate fetch at approximately 250 m. For stable conditions, it is not possible to be so definite. u_*/u between 400 and 700 m is virtually constant so that a value of z_0 derived at 400 m would be the same as that derived at 700 m, i.e., the flow appears to be in equilibrium with the surface. However, u and u_* both increase with distance from the interface, suggesting a state of quasi-equilibrium. It would probably be stretching the data too far to make any more than the general comment that for stable conditions, a fetch of at least 700 m may be required.

Taking the zero-plane displacement as 0.75 of the vegetation height and z_0 as 0.028 m, the measurements were made at a height of $118z_0$. A fetch of 250 m is equivalent to a fetch : height ratio of 71. The fetch : height ratio 200 : 1, frequently suggested for a rough to smooth change, would give a fetch requirement of 700 m.

7. Concluding Remarks

Panofsky *et al.* (1982) have shown that low-frequency turbulence may adjust to new surfaces more slowly than higher frequencies. As lower frequency eddies are more prevalent in the horizontal component of the wind, σ_u might be expected to adjust more slowly than σ_w. There is no evidence of this in the present data, although without the ability to perform spectral analysis, it is not possible to identify how the different frequencies of turbulence develop. Some doubt must, therefore, remain as to how changes in the bulk mean values of the variables represent the changes in any particular band of the spectrum of turbulence. In addition, the flow displacement at the interface will create edge effects, causing the mean flow to be non-horizontal. With the present measurements, it is not possible to determine how far these effects persist. The changes in the mean windspeed resulting from edge effects cannot be separated from those resulting from the change in measurement height and surface roughness. Within these limitations, the data presented here confirm the previous findings of Munro and Oke (1975). Those authors suggested that simple fetch : height ratios such as 100 : 1 or 200 : 1 should not be used for assessing the site requirements of micrometeorological measurements over crops. These ratios generally give over-conservative estimates of the distances required.

For eddy correlation instrumentation used as it has been here, it would appear that a fetch of greater than 400 m will rarely be necessary; under most circumstances, considerably shorter fetches could be used without an unacceptable loss of accuracy.

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