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AN ANALYSIS OF WANGARA MICROMETEOROLOGY:
SURFACE STRESS, SENSIBLE HEAT, EVAPORATION, AND DEWFALL

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Abstract

Eddy fluxes and gradients reported for the Wangara experiment and earlier investigations of flux-gradient relations are used to derive values of the sensible heat flux and friction velocity appropriate to the general area of the Wangara experiment rather than to the considerably smoother central site. Friction velocities appear to be considerably greater than those developed in previous studies of the Wangara data set. Sensible heat fluxes are similar during daytime, but differ greatly from other estimates for night. Dewfall evaluations indicate a total of about 9 mm during the experiment; condensation occurred at rates that sometimes approached but rarely exceeded the theoretical maximum rate of about 0.07 mm/hr. Maximum dewfall occurred under clear skies (less than 40% cloud cover), and in moderate winds.

Introduction

More than a decade has passed since Clarke et al. (1971) conducted their Wangara study of the evolution of the planetary boundary layer. In the interim, there have been several other intensive studies (e.g. Minnesota; Izumi and Caughey, 1976), but it has not been until the recent publication of observations made during the Koorin experiment (Clarke and Brook, 1979) that the unique status of the Wangara experiment has been challenged. Comparison between Wangara and Koorin is enlightening, since not only does it show the intent to obtain sets of data of equivalent quality in different latitudes (and hence with different values of the Coriolis parameter), but also underlines the technological advances that were made during the decade between the two experiments. In particular, the Koorin observations are supported by a unique body of intensive micrometeorological data, including direct measurements of eddy fluxes at two locations selected to be representative of the area as a whole. Data of similar quality was not obtained during the Wangara experiment.

The purpose here is to present a set of heat and momentum fluxes inferred from the relatively sparse Wangara micrometeorological data. Although there have been other attempts to derive fluxes (e.g. Melgarejo and Deardorff, 1975; Yamada, 1976; Lo, 1978), none has considered the entire data set, and none has extended the observations made at the very smooth central site to the Wangara area as a whole. Although the Wangara central site was carefully chosen to be uniform in roughness, there were variations in surface on the mesoscale. The central site was quite bare in comparison with most of the surrounding countryside. Thus, data obtained at the Wangara central site are quite likely to be incompatible with PBL data unless they are modified to compensate for the nature of the surface over which they were made ($z_o \cong 1.2$ mm, see Clarke et al., 1971). A second emphasis of the analysis given here is to investigate dewfall, which was a significant factor during many nights of the Wangara experiment. Some of the results obtained here have been presented earlier in a summary of the impact of the Wangara experiment (Hess et al., 1981).

Profile Data

The importance of good measurements of the surface fluxes in planetary boundary layer studies was clearly recognized in designing the Wangara experiment. An initial decision was made to capitalize upon the eddy-correlation methods that were then under development, as much as possible. However because these techniques were relatively untested at that time, considerable emphasis was also placed on the collection of high-quality wind gradient information, both at the very smooth central site (Station 5) and at another site (Station 4) which was selected to be more representative of the rougher surfaces in the Wangara area. Identical wind gradient equipment was set up at each of these sites, with the exception that at the rougher site (Station 4, the western pibal station) no measurements were made below 1 m height so that the direct influence of upwind roughness elements was avoided. The wind profile mast at Station 4 was located near the edge of an extensive area of cottonbush which was judged to be representative of about 25% of the area as a whole. The remaining part of the surrounding countryside was semi-arid grazing land, of which the surface at Station 5 was fairly typical. Figure 8 of Clarke et al. (1971) demonstrates the effects on Wangara wind profiles of the local surfaces; while no wind-direction variation was evident in the roughness length data obtained at the central site, profiles from Station 4 were strongly affected by the presence of cottonbush to the west and by the lack of it to the east. The intent was to utilize profile data obtained at Station 4 in a comparison between momentum fluxes over cottonbush and over the pasture, and in this way to derive spatial averages appropriate for application in PBL studies.

The need to address the question of spatially averaged sensible heat fluxes was appreciated but manpower constraints and technical difficulties did not permit direct investigation. As in the case of the momentum fluxes, the aim was to support the thermal covariance data at Station 5 with temperature gradient observations, and after successful comparison between these two methods it was intended to move one or the other system to the second (rougher) site. As will be seen later, problems arose with both systems.

The temperature gradient apparatus used at Wangara was a relatively simple instrument which amplified, rectified, and integrated output signals derived from 400 Hz AC transformer bridges with aspirated resistance thermometers in the active arms. In order to maximize signal levels, thermometers were deployed over height intervals of 1 - 2 m and 1 - 4 m, from which inferred values of the 2 - 4 m temperature difference were derived by subtraction and tabulated in the Wangara data set. In retrospect, it seems that the 1 - 2 m data were affected by noise which has contaminated all of the published temperature differences. However, the original 1 - 4 m temperature differences, which can be recovered from the published data, suffered much lower noise levels and have formed the basis of some detailed studies of the micrometeorology of Wangara (e.g. Hicks, 1976).

Covariances

Momentum fluxes were evaluated by a covariance analyzer (Hicks, 1969; see Figure 2 of Clarke et al., 1971), from signals derived from a vertical propeller anemometer for measurement of the vertical wind velocity and a similar, vane-oriented anemometer for the horizontal component. Sensible heat fluxes were measured by a modified "Fluxatron" (Dyer et al., 1967), which evaluated covariances from temperature signals obtained from a small bead thermistor and vertical velocity signals from an independent propeller anemometer.

During the first part of the Wangara experiment, eddy correlation sensors were mounted at a height of 4 m. Early in the second part of the experiment, the sensors were moved to about 10 m height (as is seen in Figure 2 of Clarke et al., 1971) in answer to the detection of sensor response inadequacies in preliminary analyses of early results. After six days, logistical problems did not permit continued operation of the eddy-correlation devices at 10 m height. The Reynolds stress determination obtained during the six days of measurement at 10 m height confirmed contemporary methods for evaluating friction velocities from an empirically-determined friction coefficient, provided the covariances were above 1 d cm^{-2} (Hicks, 1969). Figure 1 plots the measured 10 m Reynolds stresses against estimates derived from an empirical friction coefficient applied to wind speeds at 50 cm height at Station 5. As was usual practice at the time of original analysis, the value of the von Karman constant was taken to be 0.40. Dashed lines in Figure 1 represent expectations had the von Karman constant been either 0.35 (the upper line) or 0.45 (the lower). Figure 1 provides adequate support for the friction coefficient method, and the value $k = 0.40$ was used in most subsequent analyses until further tests indicated that $k = 0.41$ might be preferred (see Dyer and Hicks, 1970; Hicks, 1976). There appears to be no convincing evidence for choosing between $k = 0.40$

or 0.41 on the basis of the Wangara data set as illustrated in Figure 1, but the assumption that k = 0.35 or some similarly low value appears to be inappropriate.

The roll-off at lower stresses was attributed to poor integration at low signal levels, but might also have been due to some remaining sensor performance inadequacy even though the data were obtained at 10 m height. A subsequent examination of the response characteristics of the velocity sensors used in the Wangara experiment suggests that these flux losses should not have exceeded a few percent.

Flux-Gradient Analyses

In a detailed analysis of the Wangara surface layer data, Hicks (1976) found that the dimensionless wind gradients ϕ_M agreed well with the relations summarized by Dyer (1974), although some modification of the usual log-linear formulation for stable stratification seemed desirable.

Assuming that the flux-gradient relations for both momentum and heat are known, it is then relatively easy to evaluate sensible heat fluxes from the available wind and temperature gradient information (the latter over the interval 1 - 4 m, as indicated above). Figure 2 illustrates the agreement between deduced values and direct measurements of sensible heat, for the six days for which 10 m eddy fluxes are available. Also shown are average differences between measured and inferred heat fluxes.

The excellent agreement between measured and deduced sensible heat fluxes can be considered to be support for the Dyer (1974) flux-gradient relations, which can then be applied to the remainder of the daytime Wangara data with considerable confidence. Evaluation of fluxes from gradients measured at night has been examined elsewhere (Hicks, 1976).

Surface Heat Budget, Station 5

The discussion given above is intended to provide a basis for computing surface heat budgets for the Wangara area. This is of considerable importance, since it is clearly incorrect to assume that the surface was dry and not evaporating, even though this assumption might prove to be a sufficient first approximation in some circumstances. In fact, a total of about 2 cm of rainfall and a considerable quantity of dewfall was reported during the experiment.

Routine observations of net radiation, R_n, and of the ground heat transfer, G, are listed in the Wangara report. Radiation values were obtained by use of a ventilated, polyethylene-shielded net radiometer, and ground heat fluxes were measured by a network of flux plates located close to the surface in order to minimize storage terms. Thus, there is a good and nearly continuous record of the quantity R_n-G, which can be equated to the sum of sensible, H, and latent, $L_w E$, heat fluxes (where L_W is the latent heat of vaporization of water and E is the evaporation rate).

Smoothed values of the components of the surface heat budget have been derived from the published Wangara data and are presented in Table 1. From the 1 - 4 m temperature differences and from wind speed differences over the same height interval, values of the gradient Richardson number Ri have been derived. Dimensionless gradients ϕ_M and ϕ_H have then been evaluated, as recommended by Dyer (1974) in unstable conditions, and by Hicks (1976) in stable. Subsequently, values of the friction velocity u_* and of H have been deduced by manipulation of the stability-corrected flux-gradient relations.

In this analysis, the effect of water vapor buoyancy on stability has been neglected. It will be seen later that this assumption is borne out by the data themselves. In this regard, it should be remembered that the correction to the thermal stability amounts to about 7% when the latent heat flux equals the sensible.

Flux-gradient relations have not been applied to data obtained during the transition periods near dusk and dawn; the unstable formulations have been applied to data obtained in the period 1000 - 1600 hrs and stable relationships to the period 2000 - 0600 hrs. Further, in order to avoid circumstances that do not fit the general flux-gradient format, only occasions in which the reported wind speeds increased monotonically with height have been considered. The analysis assumes that the diffusivities of sensible heat and momentum are equal in stable conditions, as recommended by Dyer (1974) and as inferred by the more detailed analysis of Wangara data presented earlier (Hicks, 1976).

The above procedures provide estimates of the sensible heat flux on about 60% of occasions. Much of the missing data corresponds to transition cases, but some also results from incomplete data sets. To complete the sensible heat flux data set, the following interpolations have been applied:

(a) Between occasions during which none of the heat budget components change sign, values of H have been estimated by linear interpolation of the inferred latent heat flux, $L_W E = R_n - G - H$. This method is adopted because $L_W E$ is usually far more conservative than H, when both are positive.

(b) At night, the sensible heat fluxes have been interpolated linearly.

(c) During transition periods, a graphical method has been used. In the morning, the nocturnal sensible heat fluxes have been extrapolated until the residual latent heat flux matches the value indicated by extrapolation of $L_W E$ for later in the morning. In the evening case, the reverse procedure has been applied.

The sensible heat fluxes derived as a result of these procedures are quite scattered. To derive a smoother record that is more representative of the entire Wangara area, a three-point running average has been applied. The resulting estimates of H are tabulated in Table 1, together with values of R_n - G drawn directly from the Wangara data set.

Average Friction Velocities

The Wangara experiment was designed with the need in mind to evaluate spatially-averaged and suitably smoothed momentum fluxes for use in studies of PBL behavior. It is obvious that these momentum fluxes will be greater than values derived from Station 5 data alone. Clarke and Hess (1974) evaluated friction velocities at Stations 4 and 5 and combined them arithmetically, after weighting the smoother site by a factor of three to account for the average roughness distribution of the Wangara area. They point out, however, that the drag coefficient method is likely to be subject to considerable error, especially in conditions of light winds and at night when stability effects can dominate. The analysis by Hicks (1976) addresses the question of nocturnal flux-gradient relations, and stability-corrected friction velocities for Station 5 were produced as part of the investigation. The following discussion is intended to extend these earlier studies of the Wangara data, to develop a complete set of stability-corrected friction velocities appropriate for the smooth site, and to estimate spatially-averaged values on the basis of a comparison between simultaneous observations at Stations 4 and 5.

The rougher surface at Station 4 was judged to be representative of about 25% of the surface in the Hay area, with the remainder being considerably smoother, much like the surface at Station 5. Clarke and Hess (1974) weighted friction velocities deduced from these two sites accordingly. Here, and alternative scheme will be employed, in order to take into consideration the strong wind direction dependence of Station 4 data (see Figure 8 of Clarke et al., 1971). Figure 3 presents a comparison between stability-corrected friction velocities, evaluated from simultaneous wind profiles at Station 4 and 5, in conditions in which reported wind directions were between 220° and 250° (so that the fetch at Station 4 was across conttonbush). In evaluating appropriate stability corrections, sensible heat fluxes determined at Station 5 were assumed to be equally applicable at Station 4.

The curve drawn through the averages and standard errors plotted in Figure 3 has been used to estimate spatially averaged friction velocities from the more complete (and wind direction independent) data set obtained in Hicks (1976); friction velocities have been evaluated from wind and temperature gradient data at Station 5. Simultaneous values appropriate for a cottonbush surface have then been estimated from Figure 3. These two values have been combined, assuming the 3:1 weighting recommended by Clarke and Hess (1974), in order to derive spatial averages. The resulting evaluations have been smoothed, partly to reduce the magnitude of run-to-run scatter but also in response to the desire to obtain data that are representative of the Wangara spatial scale (~60 km). For this purpose, a three-point running mean has been applied to the data, with 1 : 2 : 1 weighting. The infrequent missing values have been interpolated linearly. Table 1 also lists the friction velocities obtained in this way.

Dewfall

Figure 4 shows the accumulated change in soil water indicated by the heat fluxes of Table 1, augmented by the precipitation observations reported by Clarke et al. (1971). Data are presented as four-hour averages, and are derived directly from the smoothed evaporation rates calculated as $(R_n - G - H)/L_W$, which are sometimes negative at night, indicating dewfall.

Strong daytime evaporation and slow nocturnal dewfall are clearly evident features of Figure 4, as are also the three main periods of isolated rainfall (on days 10, 17, and 35/36). Following each of these rainfall occasions, a period of stronger evaporation is evident, at an average rate that appears to be dependent on the amount of precipitation which preceded it. It is also apparent that the amount of water deposited as dewfall was largest following days with high evaporation rates, probably because these quantities are both directly related to the availability of water. The diagram suggests that the ground accumulated water during the experiment, to the extent of about 3 mm, however little confidence can be associated with this because of the need to extrapolate through the mid-experiment break (as indicated by the dashed line in the diagram).

Table 2 lists the quantities of dewfall that are indicated at Station 5 by the present analysis, for every night for which sufficient information is available. The average amount is 0.22 mm, with an associated standard deviation of 0.19 mm.

Figure 5 shows evidence for a dependence of dewfall on the friction velocity. The positive relation suggested is counter to the expectation that greatest dew deposition should occur in light winds (a classical interpretation, see Monteith, 1963). However, Frankenberger (1955) reports dewfall increasing with wind speed over short grass; the line dotted in Figure 5 is a free-hand interpretation of the Frankenberger result, assuming a roughness length of 0.5 cm for his pasture and an average duration of dewfall of 10 hours.

Monteith (1963) predicts that the rate of dewfall should not exceed about 0.07 mm/hr. The Wangara data support this result. Inspection of Figure 4, where a line with slope of 0.07 mm/hr is drawn for comparison, indicates that only rarely do any of the Wangara data approach this limit. The period from Day 11 to Day 15 appears to have had a high frequency of near-maximum dewfall rates. As mentioned above, Figure 3 also shows that the greatest dewfalls tend to occur after days of greatest evaporation, which is not surprising since these occasions will be the most humid. Thus, dewfall appears to play the role of a natural moisture redistribution mechanism, by which water deposited in highly localized precipitation events is spread over a substantially wider region during the following days. The Wangara report indicates a total of 20 mm of precipitation during the experiment; dewfall appears to have contributed a further 9 mm at the central site.

The Station 5 dewfall data support the cloud-cover dependence that would be anticipated intuitively. Figure 6 demonstrates that maximum dewfall occurs with less than 40% cloud cover. Under complete cloud cover, the average dewfall appears to be about 25% of the clear-sky value.

Comparisons with Other Wangara Analyses

Table 3 summarizes comparisons between the fluxes derived here and values published by Melgarejo and Deardorff (1975), Yamada (1976), and Lo (1978). The first two of these three sets of values made use of similar flux-gradient relations to those used here, but the last utilized wind gradients alone and hence should be expected to display greater scatter. Values tabulated are the results of linear correlation analyses, performed separately for stable and unstable conditions. Thus, perfect agreement would be demonstrated by equality of average values and values of the correlation coefficient r and regression slope b both equal to 1.00. Inspection of the listed results indicates that substantial discrepancies exist in the case of evaluations of stably stratified heat fluxes; the exceedingly small correlation coefficients are direct indications that none of these data sets bear much resemblance to that derived here. The cause is not obvious, but could be due to either reliance upon the noisy temperature gradient information, use of inappropriate flux gradient relations, or the smoothing of the present evaluations. Heat fluxes derived in unstable conditions appear to bear a much stronger resemblance, with near-identity in the case of the Yamada (1976) analysis.

None of the previous analyses appear to have taken spatial inhomogeneities into account when evaluating friction velocities; in every case the data more closely resemble the central site evaluations than the spatial averages. Relatively high correlation coefficients are found in all of the data sets, which is not suprising since all of the friction velocities are evaluated from low-level winds and there is thus not much room for error. Table 3 shows that the Yamada (1976) data provide the best correlation with the present friction velocities in both stable and unstable conditions.

Conclusions

Wind and temperature gradients measured during the Wangara experiment provide evaluations of sensible heat and momentum fluxes that agree well with determinations made by eddy correlation at the central site, provided a von Karman constant of about 0.4 is used. Comparison between friction velocities at the relatively smooth central site, Station 4, result in spatially averaged friction velocities that are considerably greater than the values that have been deduced by other workers. At night, there is little resemblance between the heat fluxes obtained here and values derived elsewhere, and friction velocities appear to be more different than in daytime.

When combined with observations of net radiation and ground heat transfer, the present nocturnal heat fluxes provide estimates of surface condensation that approach but do not exceed the limit of 0.07 mm/hr proposed by Monteith (1963). The average dewfall amounted to about 0.22 mm per night, so that during the course of the experiment about 9 mm of dewfall occurred. In comparison, 20 mm of rainfall was reported. Evaporation dissipated about 26 mm of this 29 mm total.

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TABLE 1

Average surface heat budget components and friction velocities for the Wangara area. Heat fluxes H and R_n - G are in Wm^{-2}. Friction velocities u_* are in cm s^{-1}.

	Day 1			Day 2			Day 3		
EST	H	R_n-G	u_*	H	R_n-G	u_*	H	R_n-G	u_*
100				-14	-29	20.5	-35	-41	29.2
200				-15	-29	20.4	-37	-42	25.5
300		-29		-15	-30	21.4	-39	-44	22.6
400		-26		-15	-31	22.7	-30	-39	20.0
500		-23	10.1	-13	-31	24.C	-23	-34	16.6
600		-21	10.1	-15	-32	26.4	-18	-29	13.2
700		-11	11.9	-13	-29	30.0	-12	-19	13.0
800		24	15.4	-6	-8	32.3	0	12	18.6
900		75	19.1	7	39	34.7	16	62	26.1
1000	23	121	19.4	21	88	41.1	45	119	33.5
1100	55	150	18.4	29	108	48.9	76	159	39.1
1200	88	165	20.9	35	102	53.0	100	177	43.1
1300	96	163	23.3	29	79	52.7	98	168	44.9
1400	76	138	28.9	19	53	51.0	79	142	45.2
1500	43	94	29.7	2	21	49.9	45	98	45.2
1600	10	35	26.8	-12	-10	46.4	4	35	41.0
1700	-12	-11	20.3	-22	-28	41.5	-26	-14	30.2
1800	-25	-41	14.4	-29	-40	39.8	-41	-44	21.6
1900	-24	-40	11.8	-32	-43	38.7	-40	-43	21.3
2000	-23	-37	11.0	-31	-43	33.9	-44	-33	24.6
2100	-20	-35	13.1	-29	-44	29.8	-35	-24	23.9
2200	-16	-33	17.4	-24	-40	29.6	-28	-15	21.6
2300	-14	-32	20.2	-25	-40	31.9	-25	-27	23.0
2400	-13	-30	21.1	-24	-36	32.1	-29	-35	27.2

	Day 4			Day 5			Day 6		
EST	H	R_n-G	u_*	H	R_n-G	u_*	H	R_n-G	u_*
100	-37	-40	24.8	-5	-7	2.6	-103	-102	1.8
200	-28	-35	17.6	-5	-5	5.2	-72	-71	1.9
300	-25	-35	18.1	-2	-6	10.4	-48	-43	1.8
400	-18	-37	24.8	-1	-5	12.3	-20	-19	2.5
500	-24	-39	27.7	-6	-9	10.5	-23	-22	3.4
600	-26	-34	22.4	-9	-12	8.5	-20	-23	3.2
700	-19	-22	14.8	-10	-7	9.0	-13	-11	2.6
800	-6	21	15.7	-4	12	11.4	5	25	4.7
900	21	85	22.8	2	36	14.0	42	76	11.7
1000	47	150	27.5	37	90	16.4	67	128	16.7
1100	91	188	28.7	72	143	19.7	105	165	16.0
1200	113	196	29.9	102	186	24.3	117	180	12.7
1300	112	175	30.7	84	190	26.9	147	172	11.5
1400	75	125	30.1	70	162	26.8	127	148	10.9
1500	39	75	29.5	47	119	26.7	101	107	10.7
1600	12	29	27.9	27	54	24.1	40	61	11.4
1700	-2	5	22.4	-1	11	19.0	5	7	10.4
1800	-11	-14	14.0	-15	-14	10.6	-16	-21	8.5
1900	-12	-15	7.0	-19	-18	3.6	-18	-34	7.0
2000	-8	-12	4.4	-20	-19	1.6	-42	-32	5.5
2100	-8	-10	3.7	-22	-21	1.9	-48	-32	6.7
2200	-8	-9	3.9	-19	-18	1.9	-48	-29	9.5
2300	-6	-10	4.5	-48	-47	1.7	-34	-28	10.1
2400	-7	-9	3.7	-76	-75	1.7	-35	-29	13.3

	Day 7			Day 8			Day 9		
EST	H	R_n-G	u_*	H	R_n-G	u_*	H	R_n-G	u_*
100	-37	-29	15.4	-50	-24	4.7	-19	-19	5.7
200	-38	-28	9.7	-48	-22	4.8	-25	-25	6.8
300	-26	-22	5.5	-35	-21	5.6	-26	-26	4.6
400	-19	-18	7.5	-28	-20	5.3	-19	-20	1.9
500	1	-15	9.8	-26	-18	5.1	-16	-17	1.6
600	1	-15	9.4	-25	-19	6.2	-14	-15	2.3
700	1	-8	11.0	-17	-11	8.5	-7	-4	4.8
800	1	27	18.3	1	23	12.1	10	33	9.8
900	26	81	25.1	33	73	18.7	58	81	12.4
1000	58	133	29.5	65	128	25.4	93	136	11.4
1200	98	167	29.6	130	195	30.8	122	187	12.2
1300	91	161	28.3	142	187	30.3	149	182	13.3
1400	77	147	25.8	106	136	29.8	136	145	14.3
1500	49	102	23.2	54	69	30.2	114	96	12.9
1600	11	43	18.5	6	16	30.9	49	19	10.7
1700	22	-8	8.5	-10	-6	26.9	-11	-33	8.1
1800	-41	-33	3.9	-15	-15	19.3	-33	-59	5.5
1900	-41	-33	3.8	-15	-15	14.7	-43	-49	5.0
2000	-37	-29	3.6	-15	-15	12.9	-26	-32	4.8
2100	-35	-27	3.4	-16	-13	9.6	-24	-30	3.3
2200	-33	-25	3.7	-13	-11	6.2	-17	-29	3.3
2300	-34	-26	5.4	-10	-7	4.6	-18	-30	5.1
2400	-45	-25	6.1	-9	-9	4.6	-15	-25	5.2

	Day 10			Day 11			Day 12		
EST	H	R_n-G	u_*	H	R_n-G	u_*	H	R_n-G	u_*
100	-16	-21	4.7	-5	-7	7.7	-8	-36	18.6
200	-16	-16	6.9	-3	-8	8.9	-7	-36	18.8
300	-10	-10	10.3	-2	-6	11.5	-6	-35	19.7
400	-10	-11	12.9	1	-2	14.6	-5	-33	20.4
500	-4	-10	14.7	2	1	16.5	-4	-32	21.2
600	-6	-8	13.6	6	5	18.1	-5	-33	21.7
700	-3	-1	12.3	11	10	22.5	-1	-19	21.2
800	-1	18	14.8	19	25	28.5	5	29	22.0
900	7	46	19.8	27	70	32.0	17	101	26.3
1000	13	70	22.7	47	150	34.7	32	165	30.7
1100	15	70	22.5	79	227	37.4	62	198	32.0
1200	10	56	20.7	104	282	36.8	91	217	32.0
1300	5	40	18.1	105	272	35.4	94	221	32.7
1400	3	31	14.4	83	230	34.2	80	197	32.5
1500	0	22	11.2	59	151	32.7	50	143	31.1
1600	-1	9	9.2	37	70	31.4	27	61	27.9
1700	-2	1	8.8	20	11	28.8	-1	1	20.5
1800	-2	-4	9.6	1	-29	25.7	-15	-35	13.0
1900	-2	-4	9.3	-8	-38	23.2	-14	-34	11.9
2000	-3	-5	8.6	-10	-42	21.1	-10	-31	13.6
2100	-3	-5	7.6	-7	-36	18.8	-7	-32	15.4
2200	-4	-5	6.9	-7	-35	16.7	-6	-32	16.2
2300	-5	-5	7.6	9	-35	16.8	-6	-32	15.4
2400	-6	-6	8.9	-8	-36	18.3	-7	-31	16.6

	Day 13			Day 14			Day 15		
EST	H	R_n-G	u_*	H	R_n-G	u_*	H	R_n-G	u_*
100	-8	-31	18.2	-21	-28	11.6	-21	-39	14.8
200	-18	-31	16.5	-16	-28	13.8	-23	-44	20.5
300	-18	-29	12.6	-15	-28	13.8	-16	-41	21.3
400	-17	-27	10.1	-24	-28	10.1	-12	-32	23.0
500	-7	-26	10.6	-30	-30	9.8	-7	-20	25.8
600	-6	-25	12.3	-32	-29	13.7	-2	-9	22.0
700	0	-14	14.9	-21	-19	14.3	2	3	14.4
800	12	28	19.7	-9	19	16.0	6	41	15.3
900	38	88	26.1	13	80	22.6	13	92	24.7
1000	69	148	32.8	41	143	29.1	38	169	33.3
1100	98	186	36.8	76	191	29.7	71	231	36.4
1200	111	204	36.6	95	192	27.0	103	274	38.0
1300	116	203	32.4	109	182	24.2	99	252	39.1
1400	112	177	30.5	98	151	22.0	80	198	38.8
1500	86	126	31.5	74	117	20.7	49	123	39.5
1600	38	53	29.1	35	58	17.1	34	65	41.0
1700	-8	-4	21.6	1	3	9.6	3	2	40.2
1800	-30	-32	10.2	-12	-26	5.2	-13	-32	32.7
1900	-31	-33	4.6	-15	-29	6.4	-23	-42	24.8
2000	-31	-29	6.0	-22	-26	8.1	-14	-27	24.1
2100	-28	-27	7.3	-22	-26	5.9	-8	-18	24.3
2200	-29	-25	7.3	-21	-25	4.4	-10	-20	21.7
2300	-27	-25	7.8	-10	-24	4.8	-11	-30	20.4
2400	-27	-27	9.3	-8	-31	7.1	-17	-46	19.8

	Day 16			Day 17			Day 18		
EST	H	R_n-G	u_*	H	R_n-G	u_*	H	R_n-G	u_*
100	-19	-47	17.2	-27	-31	4.2	12	-1	43.1
200	-24	-44	13.0	-28	-32	5.1	3	-10	42.5
300	-20	-36	10.5	-32	-33	9.0	5	-10	41.9
400	-17	-35	11.4	-28	-27	13.6	-7	-20	40.4
500	-13	-35	14.0	-17	-16	14.5	-15	-28	35.7
600	-16	-35	14.6	-5	-7	15.7	-28	-41	30.5
700	-10	-23	15.9	2	1	18.9	-21	-20	28.6
800	1	22	18.8	5	15	20.7	-7	33	32.0
900	37	88	20.8	10	48	22.1	24	120	36.8
1000	74	155	22.8	11	68	23.8	60	205	39.1
1100	106	190	24.4	27	113	28.3	96	265	40.3
1200	109	187	23.3	31	128	33.5	112	268	40.2
1300	94	143	21.6	36	133	31.9	108	232	38.9
1400	68	95	21.2	22	101	27.0	87	179	38.5
1500	39	48	21.3	16	72	25.3	61	127	37.9
1600	17	24	20.3	10	50	24.7	35	66	35.9
1700	-7	-10	17.6	4	25	22.7	8	4	30.3
1800	-15	-20	14.5	-2	1	23.8	-7	-34	22.3
1900	-24	-28	13.9	-2	-9	28.5	-14	-44	18.5
2000	-23	-27	11.7	-7	-20	30.5	-13	-42	18.2
2100	-36	-40	6.7	-3	-11	31.5	-12	-41	18.1
2200	-38	-42	4.4	-1	-7	34.3	-12	-43	18.6
2300	-38	-42	4.4	14	8	37.6	-11	-44	20.2
2400	-31	-35	4.3	13	2	41.2	-9	-46	20.4

	Day 19			Day 20			Day 21/25		
EST	H	R_n-G	u_*	H	R_n-G	u_*	H	R_n-G	u_*
100	-7	-43	18.5	6	-20	5.1	-6	-18	29.4
200	-6	-40	17.3	10	-16	4.1	-12	-20	29.4
300	-6	-35	16.7	8	-18	3.1	-10	-21	29.0
400	-5	-31	15.6	10	-13	3.5	-10	-25	27.7
500	-3	-28	15.8	5	-14	4.3	-8	-23	26.8
600	-2	-29	16.2	5	-6	4.0	-10	-22	26.7
700	4	-14	16.1	5	3	3.9	-8	-17	26.4
800	13	-29	17.4	6	20	7.3	3	21	27.9
900	28	96	17.7	7	44	15.8	16	64	32.7
1000	49	159	18.0	19	83	22.0	22	93	35.3
1100	86	199	20.3	60	142	25.2	19	83	32.9
1200	115	201	22.0	106	199	27.6	15	74	30.1
1300	150	217	22.5	119	205	28.6			
1400	119	153	21.6	94	164	26.2			
1500	82	104	20.2	46	89	22.1			
1600	29	24	20.2	19	35	19.0	62	75	34.1
1700	12	3	18.5	-2	-4	14.9	16	11	27.2
1800	3	-17	11.9	-5	-16	9.8	-22	-29	17.6
1900	-5	-31	6.7	-6	-17	9.1	-33	-35	10.5
2000	2	-24	4.2	-6	-15	14.9	-25	-28	9.1
2100	10	-17	2.5	-10	-16	20.1	-18	-21	8.6
2200	10	-17	2.3	-12	-17	21.8	-13	-13	9.6
2300	8	-19	3.8	-8	-20	42.6	-12	-10	9.2
2400	6	-20	5.3	-7	-22	28.3	-11	-9	7.2

	Day 26			Day 27			Day 28		
EST	H	R_n-G	u_*	H	R_n-G	u_*	H	R_n-G	u_*
100	-8	-9	5.7	-8	-21	20.4	-13	-44	23.0
200	-4	-7	3.7	-6	-20	21.1	-13	-44	21.7
300	-7	-10	3.1	-4	-16	26.1	-21	-43	21.2
400	-14	-10	3.8	-8	-11	27.1	-27	-40	19.3
500	-16	-11	4.9	-4	-3	24.8	-24	-35	17.3
600	-12	-8	6.6	-2	0	29.1	-14	-33	18.1
700	-3	-2	8.5	9	2	33.6	4	-10	21.1
800	4	12	12.9	15	5	31.6	23	-35	25.5
900	15	46	20.5	24	27	27.7	51	100	31.6
1000	24	75	26.9	33	84	24.7	94	146	36.9
1100	32	89	30.3	46	150	29.0	144	184	39.2
1200	50	99	29.8	60	186	40.9	163	170	39.1
1300	50	81	27.8	55	168	48.8	152	155	37.6
1400	44	65	27.8	67	141	52.6	139	125	38.4
1500	19	22	25.3	53	96	56.7	111	96	40.6
1600	6	3	17.6	48	58	57.5	76	53	38.0
1700	-6	-13	7.6	10	2	52.1	12	-2	29.8
1800	-12	-18	4.0	-9	-28	41.9	-13	-25	20.8
1900	-12	-18	6.1	-20	-46	34.6	-27	-35	13.9
2000	-13	-16	9.3	-19	-47	31.3	-25	-33	10.3
2100	-14	-15	9.6	-15	-44	27.6	-23	-32	10.0
2200	-14	-15	11.7	-10	-44	27.2	-22	-31	12.0
2300	-11	-18	18.4	-10	-43	28.6	-19	-26	15.2
2400	-10	-20	21.5	-10	-44	26.4	-22	-25	18.5

	Day 29			Day 30			Day 31		
EST	H	R_n-G	u_*	H	R_n-G	u_*	H	R_n-G	u_*
100	-20	-22	19.5	-7	-23	19.1	-10	-40	25.0
200	-23	-28	11.0	0	-16	16.5	-10	-40	23.9
300	-14	-23	9.5	2	-14	15.4	-10	-40	21.6
400	-9	-18	10.9	0	-9	18.5	-10	-39	20.9
500	-2	-13	16.4	-3	-11	20.1	-8	-37	20.8
600	0	-11	20.6	1	-8	19.7	-6	-34	19.5
700	6	-2	23.5	15	0	20.6	-2	-7	20.0
800	28	19	27.6	37	47	23.8	12	46	24.4
900	63	67	31.0	79	103	28.2	56	119	31.3
1000	113	124	31.0	133	160	34.5	114	179	35.8
1100	142	184	30.7	127	163	41.9	176	218	36.2
1200	188	205	31.5	119	200	50.5	218	187	34.7
1300	203	195	34.6	93	191	57.6	214	127	32.6
1400	187	149	44.6	115	193	56.1	177	41	31.3
1500	128	92	48.3	99	128	50.4	121	38	31.7
1600	64	38	34.3	64	74	46.3	79	30	33.2
1700	21	-6	20.2	23	15	39.8	33	19	30.6
1800	-7	-28	15.9	0	-22	29.9	-2	-25	22.6
1900	-25	-42	18.8	-10	-39	24.1	-18	-43	13.5
2000	-23	-44	21.1	-11	-38	25.8	-12	-37	7.2
2100	-25	-49	21.7	-13	-40	28.7	-8	-33	6.2
2200	-19	-47	23.0	-13	-40	30.9	-13	-33	6.6
2300	-17	-40	24.2	-12	-41	34.3	-13	-33	7.8
2400	-12	-31	24.8	-10	-41	30.7	-12	-33	11.0

	Day 32			Day 33			Day 34		
EST	H	R_n-G	u_*	H	R_n-G	u_*	H	R_n-G	u_*
100	-8	-35	12.5	-27	-34	7.7	-29	-33	7.8
200	-7	-35	9.6	-7	-34	11.0	-29	-33	7.8
300	-5	-36	6.4	0	-32	11.2	-38	-22	7.0
400	-1	-29	4.4	-1	-30	8.1	-42	-22	6.2
500	-2	-27	4.2	-2	-28	3.8	-36	-20	9.3
600	-3	-28	4.9	0	-23	2.5	-36	-31	18.5
700	0	-6	6.7	7	-1	5.4	-21	-1	24.2
800	0	40	14.0	54	47	11.2	22	51	25.6
900	46	111	22.4	125	107	17.0	73	140	28.2
1000	93	168	26.8	175	164	18.1	122	197	33.6
1100	144	227	26.7	209	202	17.7	151	241	36.8
1200	167	251	24.1	229	218	17.4	174	250	36.5
1300	188	255	21.9	247	220	17.4	181	249	35.3
1400	176	222	21.4	231	197	19.1	175	223	35.2
1500	142	168	23.7	175	153	20.9	149	167	35.4
1600	77	101	26.3	103	72	21.6	95	92	34.9
1700	19	21	23.3	23	1	17.4	27	12	29.5
1800	-9	-21	17.0	-33	-41	8.8	-18	-33	19.9
1900	-20	-41	11.8	-52	-46	6.3	-33	-47	12.0
2000	-21	-36	9.8	-50	-43	6.1	-30	-41	10.9
2100	-10	-36	8.9	-39	-39	5.4	-47	-38	10.7
2200	-8	-34	7.9	-46	-35	5.1	-40	-31	10.4
2300	-26	-32	5.7	-47	-33	5.6	-31	-24	14.1
2400	-30	-32	5.0	-44	-33	7.0	-11	-25	19.8

	Day 35			Day 36			Day 37		
EST	H	R_n-G	u_*	H	R_n-G	u_*	H	R_n-G	u_*
100	-20	-34	24.2	-15	-22	44.0	-13	-40	11.7
200	-22	-47	29.3	-15	-21	42.6	-8	-24	10.7
300	-13	-54	33.7	-13	-12	40.2	-7	-15	12.6
400	-17	-58	37.1	-13	-8	38.4	-7	-14	14.9
500	-25	-55	37.1	-13	-1	32.2	-10	-18	15.5
600	-36	-50	30.9	-13	2	26.4	-10	-13	15.7
700	-18	-16	27.9	-10	6	28.4	-8	3	14.6
800	11	42	35.4	-3	68	33.7	-5	22	14,0
900	64	123	46.6	12	131	36.9	1	57	16.5
1000	117	194	52.2	17	167	35.3	7	88	19.7
1100	154	257	52.4	35	167	30.7	11	102	22.6
1200	181	285	50.7	60	207	29.3	12	100	25.9
1300	177	253	48.5	72	227	29.0	8	96	28.1
1400	145	172	46.4	63	220	27.1	6	98	27.3
1500	83	81	44.3	51	186	26.2	2	94	26.2
1600	33	23	41.1	46	139	24.8	0	69	25.4
1700	6	1	32.5	31	70	20.9	-4	36	24.2
1800	-7	-1	21.3	4	-16	17.8	-7	1	21.4
1900	-13	-1	16.9	-10	-43	17.9	-9	-11	16.3
2000	-13	-3	23.1	-10	-39	18.2	-9	-14	15.7
2100	-13	-10	33.2	-9	-41	17.6	-8	-16	19.4
2200	-11	-24	36.9	-11	-39	15.3	-9	-26	20.9
2300	-11	-30	38.0	-14	-42	12.7	-9	-32	22.0
2400	-13	-34	41.7	-15	-41	12.3	-13	-36	22.9

EST	Day 38 H	Day 38 R_n-G	Day 38 u_*	Day 39 H	Day 39 R_n-G	Day 39 u_*	Day 40 H	Day 40 R_n-G	Day 40 u_*
100	-12	-31	23.8	-8	-35	23.8	-30	-21	3.3
200	-11	-37	24.7	-10	-44	22.0	-30	-21	3.5
300	-8	-42	25.1	-11	-43	19.9	-22	-23	2.8
400	-6	-48	25.8	-10	-42	19.2	-22	-25	2.3
500	-7	-47	24.6	-8	-40	18.0	-22	-30	2.6
600	-7	-43	21.6	-7	-36	15.8	-22	-23	2.7
700	-4	-4	22.5	-1	-2	17.4	-18	-3	2.7
800	7	68	29.8	10	66	22.5	-11	36	4.7
900	39	168	37.3	45	156	24.5	-4	59	8.1
1000	77	256	41.6	65	199	21.2	48	130	10.8
1100	93	287	44.3	75	207	16.9	92	198	14.7
1200	100	312	44.5	77	200	15.1	133	263	18.4
1300	74	242	43.2	69	185	16.9	120	246	19.2
1400	60	185	43.8	62	128	17.3	111	229	18.0
1500	28	95	41.7	44	47	16.5	83	179	18.8
1600	13	67	39.2	31	2	15.8	50	118	19.1
1700	0	36	36.6	11	-17	10.7	5	34	14.8
1800	-5	9	28.5	-13	-20	4.2	-23	-14	6.8
1900	-7	-10	22.2	-22	-35	2.4	-38	-28	3.3
2000	-5	-14	23.4	-22	-32	2.6	-38	-28	3.4
2100	-3	-15	26.3	-16	-31	2.2	-31	-21	5.1
2200	-4	-20	26.7	-16	-31	1.9	-24	-151	7.0
2300	-5	-21	24.7	-16	-29	1.9	-20	-13	8.8
2400	-8	-31	23.6	-30	-25	2.5	-25	-11	10.3

	Day 41			Day 42			Day 43		
EST	H	R_n-G	u_*	H	R_n-G	u_*	H	R_n-G	u_*
100	-21	-9	8.5	-29	-26	2.9			14.5
200	-21	-9	8.9	-29	-26	3.2			20.4
300	-19	-11	17.5	-29	-26	3.2	-41	-40	25.8
400	-23	-13	23.0	-25	-22	3.5	-30	-42	29.9
500	-19	-15	20.6	-25	-22	4.9	-22	-36	33.6
600	-14	-19	17.3	-23	-20	6.7	-16	-25	34.3
700	-6	-12	20.4	-16	0	9.0	-5	3	34.3
800	2	29	25.0	2	49	11.8	10	30	35.9
900	40	98	28.1	22	109	15.1	15	59	35.3
1000	91	189	28.2	72	181	19.9	23	81	34.2
1100	122	215	27.9	118	215	23.1	16	78	29.9
1200	131	224	30.6	159		22.4	15	72	24.8
1300	109	1591	32.7	176		22.0	4	57	26.4
1400	99	163	31.5	187		24.1	2	60	28.7
1500	72	111	30.9	158		24.4	0	51	27.0
1600	50	91	32.4			19.6	-2	31	29.9
1700	9	13	28.4			11.7	-4	9	29.7
1800	-20	-17	17.3			8.7	-5	-2	20.8
1900	-41	-38	5.9			9.7	-6	-11	18.3
2000	-39	-36	3.0			10.7	-6	-22	23.7
2100	-36	-33	2.8			10.9	-7	-37	21.3
2200	-32	-28	2.9			10.3	-7	-38	31.6
2300	-30	-26	2.5			10.2	-7	-38	31.6
2400	-29	-25	2.3			11.2	-6	-33	44.2

Day 44			
EST	H	R_n-G	u_*
100	-6	-34	42.9
200	-7	-42	37.3
300	-5	-47	36.0
400	-5	-48	38.6
500	-4	-48	39.3
600	-6	-41	37.6
700	-1	0	37.8
800	8	79	41.5
900	49	182	47.8
1000	98	246	52.0
1100	159	300	53.3
1200	188	317	53.5

TABLE 2
Average nocturnal dewfall (in mm) evaluated at Station 5 as R_n-G-H.

Day	Dewfall
1	0.32
2	0.20
3	0.06
4	0.04
5	0.00
6	0.12
7	0.00
8	0.00
9	0.16
10	0.03
11	0.57
12	0.37
13	0.05
14	0.17
15	0.34
16	0.06
17	0.12
18	0.58
19	0.44
20	0.19
25	0.04
26	0.12
27	0.50
28	0.27
29	0.54
30	0.51
31	0.44
32	0.61
33	0.00
34	0.27
35	0.14
36	0.31
37	0.31
38	0.28
39	0.13
40	0.00
41	0.00

TABLE 3

Results of a regression analysis of Wangara surface-layer flux evaluations reported by (a) Melgarejo and Deardorff (1975), (b) Yamada (1976), and (c) Lo (1978) on values derived here. Two sets of friction velocities are employed, u_* (5) are values appropriate for the smooth central site, $\overline{u}_*$ represent estimates of spacial averages.

		Number of Values	Present Average	Published Average	r	b
(a)	Stable					
	H	58	-19.2	-10.6	0.05	0.03
	$u_*(5)$	61	11.5	10.1	0.86	0.65
	$\overline{u}_*$	61	13.3	10.1	0.87	0.61
	Unstable					
	H	16	109.7	117.9	0.87	0.98
	$u_*(5)$	17	27.0	25.1	0.99	0.98
	$\overline{u}_*$	16	27.9	24.6	0.98	0.94
(b)	Stable					
	H	127	-15.0	-12.3	-0.04	-0.03
	$u_*(5)$	130	14.3	12.3	0.98	0.81
	$\overline{u}_*$	130	15.9	12.3	0.97	0.79
	Unstable					
	H	69	111.6	109.1	0.96	0.96
	$u_*(5)$	69	29.5	25.5	1.00	0.80
	$\overline{u}_*$	69	31.5	25.5	0.99	0.89
(c)	Stable					
	H	29	-17.7	-11.8	0.30	0.11
	$u_*(5)$	29	16.7	12.7	0.90	0.63
	$\overline{u}_*$	29	14.9	12.7	0.91	0.71
	Unstable					
	H	10	100.8	103.0	0.90	1.07
	u_*	10	31.7	28.8	0.98	0.97
	$\overline{u}_*$	10	33.1	28.8	0.93	0.90

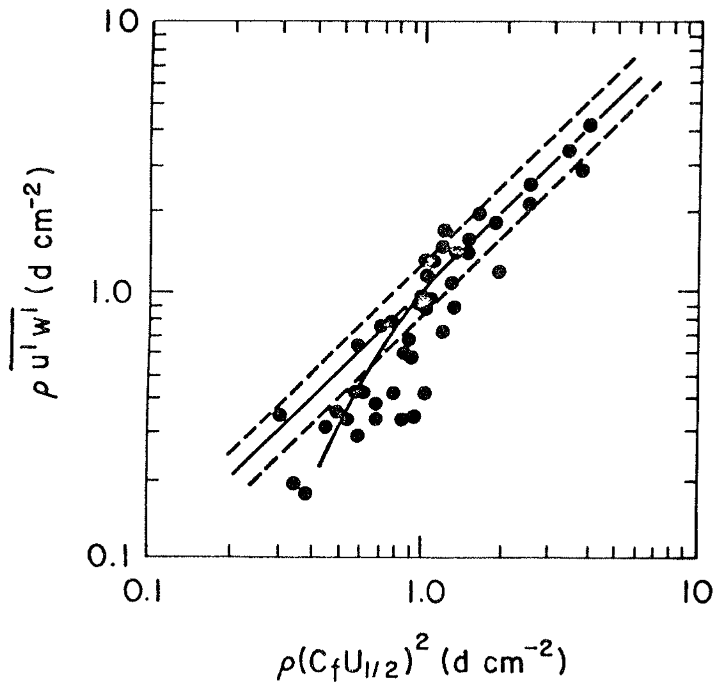

Figure 1: Comparison between Reynolds stresses measured by eddy correlation at 10 meters height and values derived from analysis of simultaneous wind data, assuming k = 0.40 (Hicks, 1969). If k were 0.35 (0.45), then data would have fallen along the upper (lower) broken line. Note the roll-off at low values.

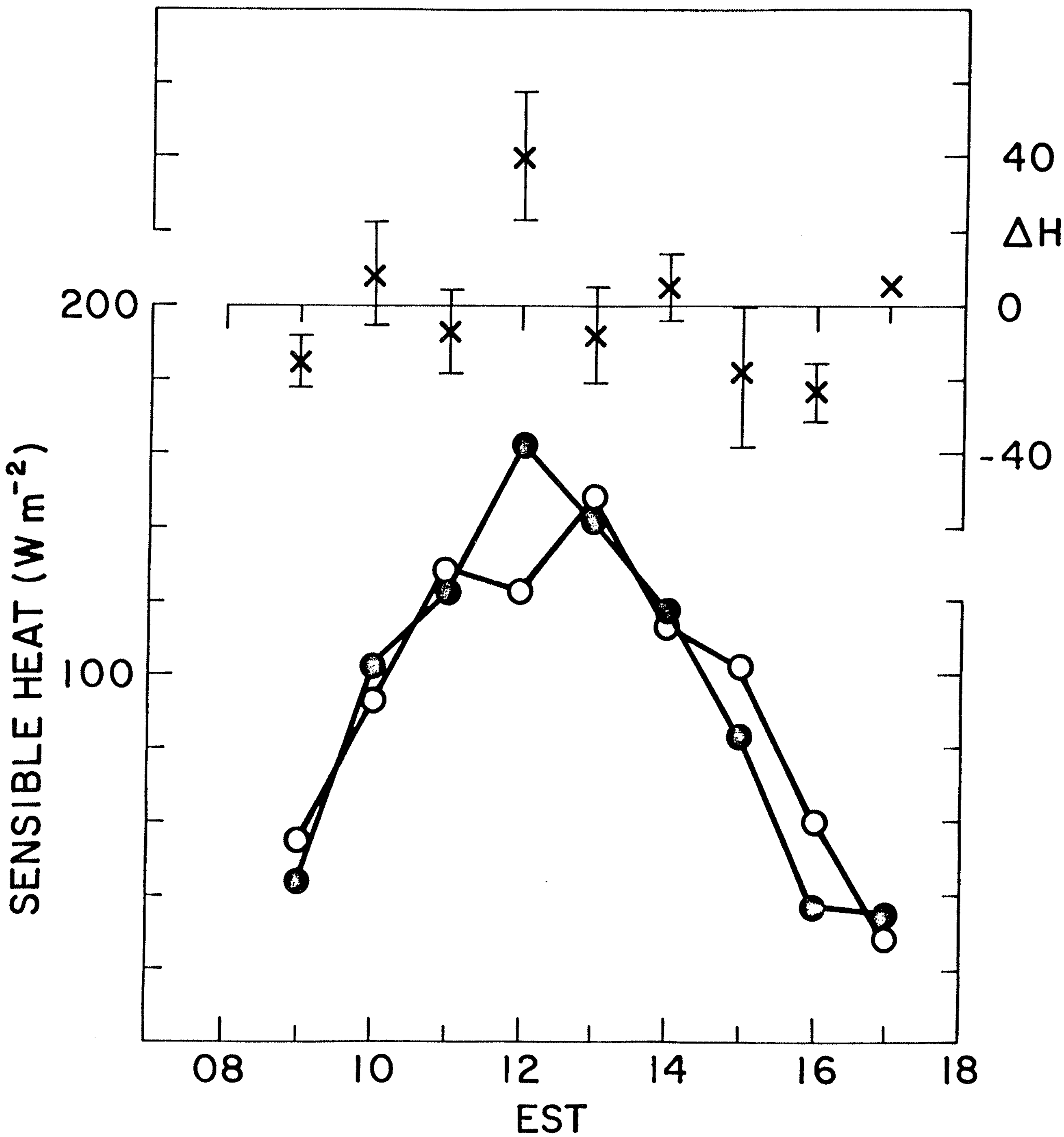

Figure 2: Average diurnal cycles of sensible heat covariances by eddy correlation at 10 m (solid circles) and values derived from 1-4 m temperature gradients (open circles). Crosses and standard error bars plotted at the top of the diagram show the average differences between the two estimates.

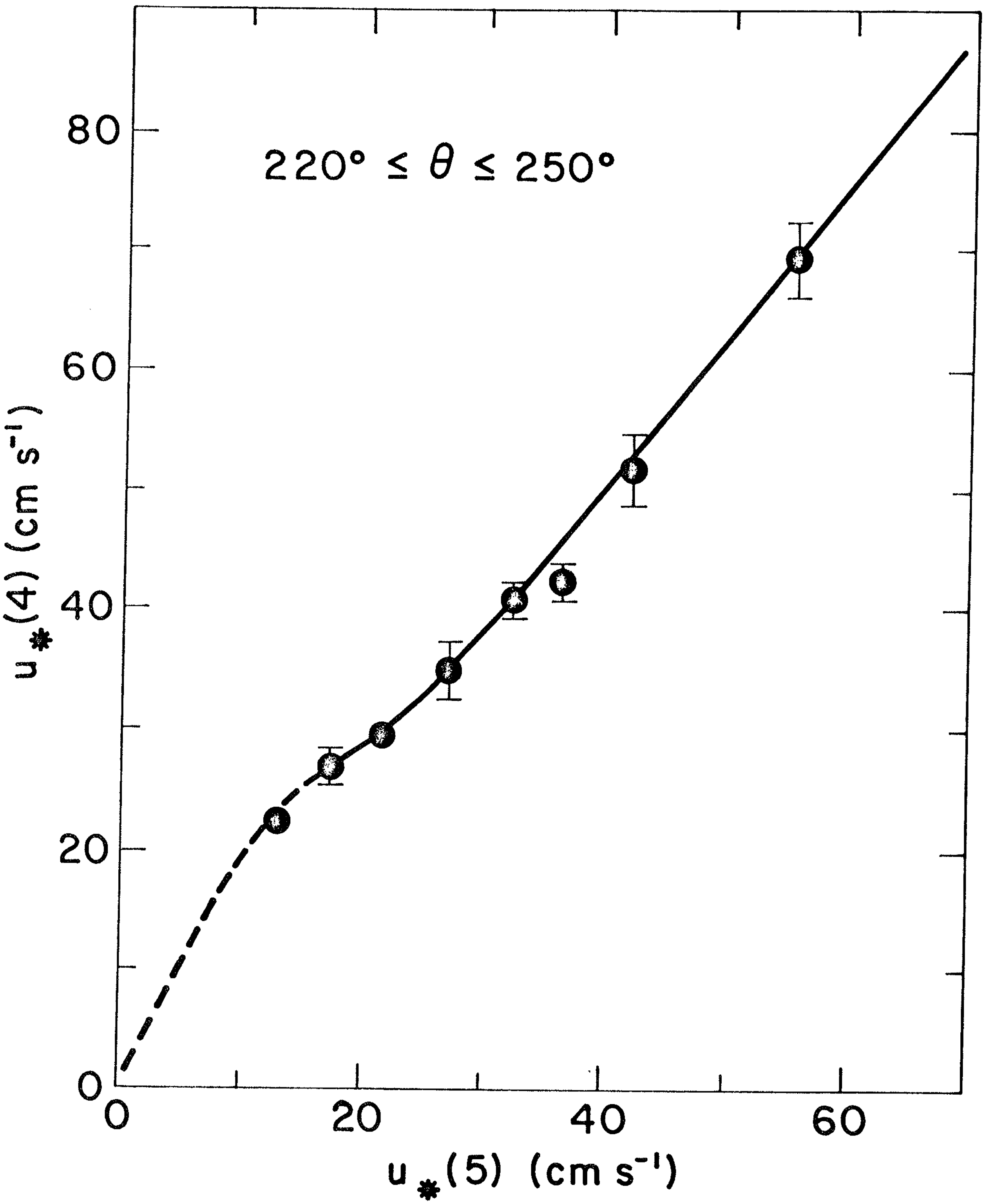

Figure 3: Simultaneous friction velocities at stations 4 and 5, on occasions when winds were from the cottonbush fetch at station 4. Bars represent ± one standard error.

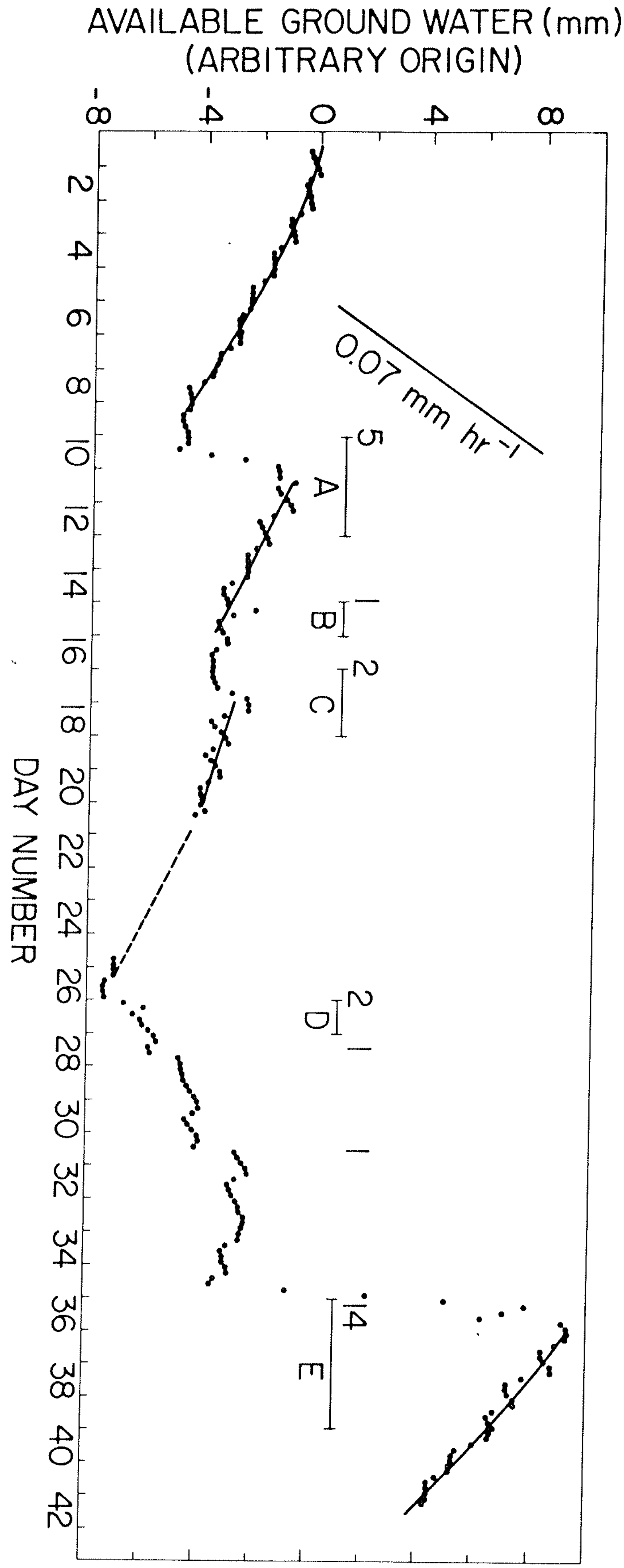

Figure 4: Changes in ground water inferred from Wangara heat fluxes. Periods A, B, C, D, and E were times when the surface at station 5 was visibly moist (see Clarke _et al_., 1971; Appendix 1). Numbers associated with each such occasion indicate the quantity (mm) of rainfall.

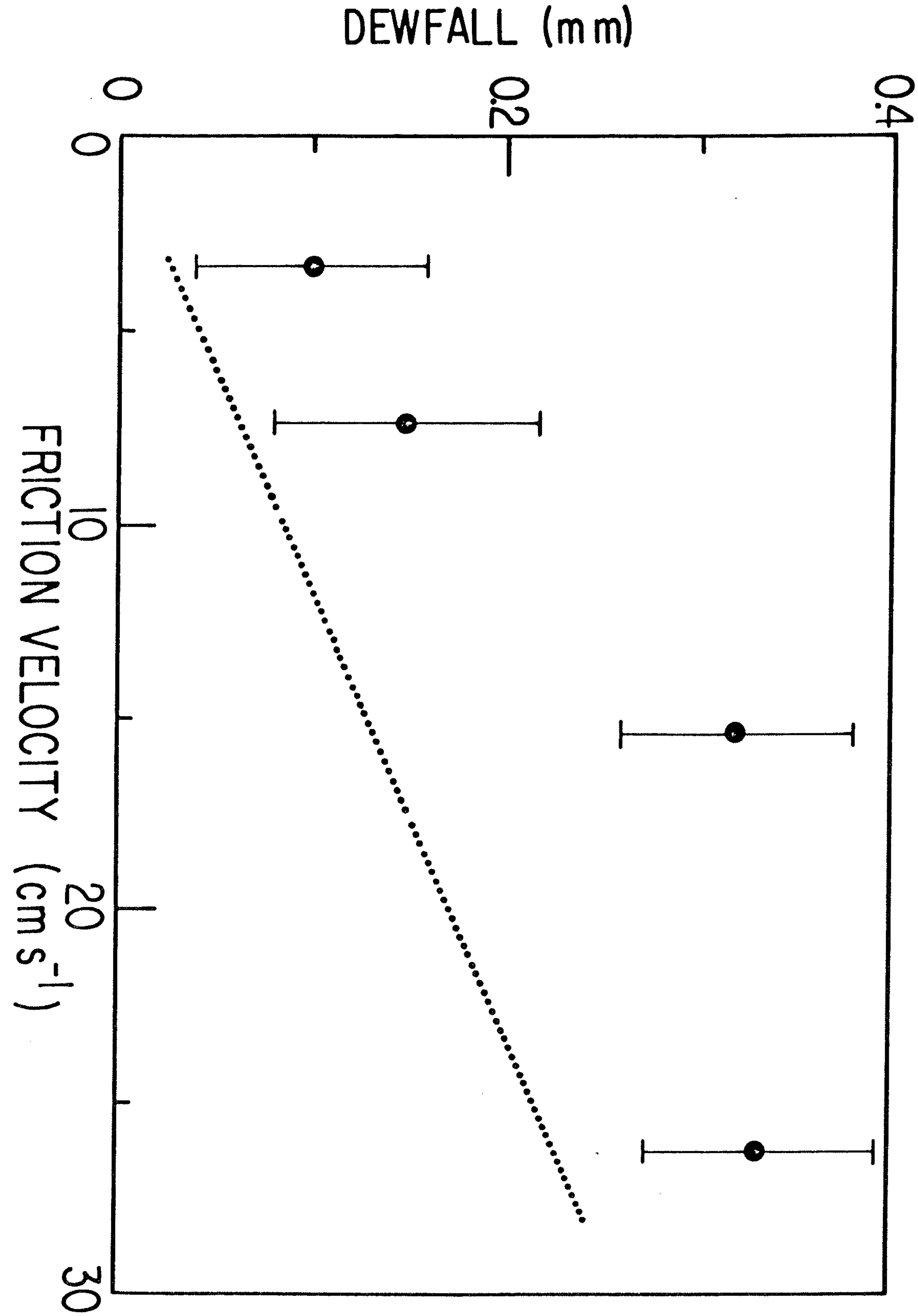

Figure 5: Relationship between dewfall and wind speed, characterized here by the friction velocity. The dotted line represents the result of Frankenberger (1955).

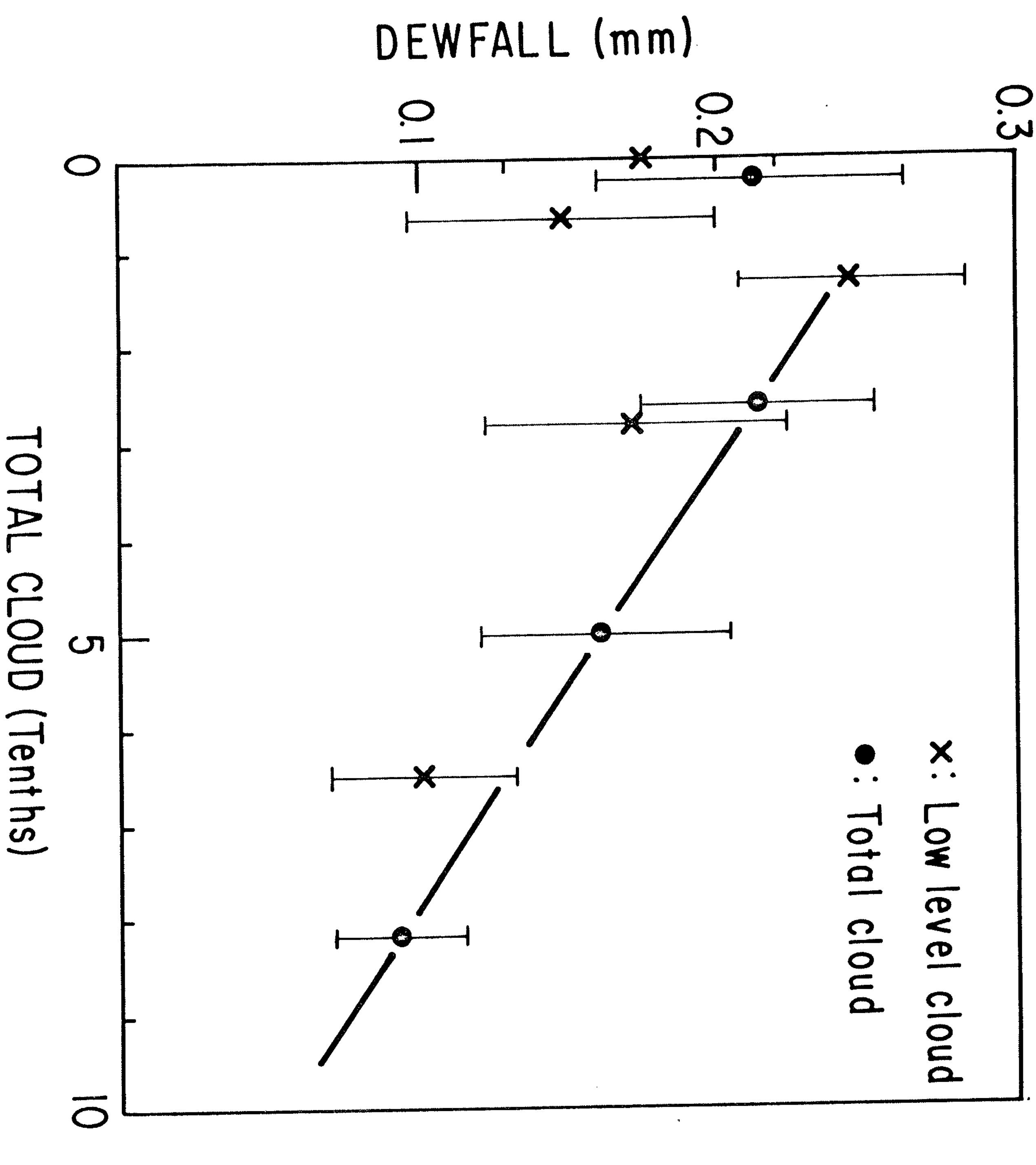

Figure 6: Station 5 dewfall as a function of average cloud cover. Bars indicate standard errors.