THE LIMITATIONS ON STRESS PARAMETERIZATION IMPOSED BY INTERMITTENCY IN TURBULENT FLOW*

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Abstract. The indirect dissipation technique is used to estimate 1-min averages of friction velocity u_* in the surface layer over the tropical ocean. These estimates are compared to estimates of u_* obtained using a drag coefficient and the relative difference between the two is examined in relation to stability and averaging time. Plumes and downdrafts are found to be responsible for an anomalous behavior of the drag coefficient estimates. Certain factors relating to plume properties, derived using conditional sampling as described in Khalsa (1980), are shown to be related to the variance between the two estimates of friction velocity. An investigation into the effects of increasing the averaging time reveals that plume spacing, which is dependent on stability, and the mean wind speed determine the minimum time for smoothing the influence of plumes and downdrafts.

1. Introduction

Surface fluxes of momentum, sensible heat, water vapor and other atmospheric constituents are commonly parameterized using bulk differences of the respective properties. In recent years more complex models of transfer mechanisms have appeared (for example, Kondo, 1975; Arya, 1977; Liu, 1978) but the results are usually stated in terms of bulk parameterization formulae with the details of the model contained in the transfer coefficients.

The range of application of simple bulk parameterization formulae is quite broad. Most global circulation models employ such formulae to obtain surface fluxes (Bhumralkar, 1976). Heat balance studies of large oceanic areas rely on bulk parameterization techniques (Bunker, 1976). Air-sea exchanges during the passage of convective disturbances have been discussed using bulk aerodynamic formulae (GATE, 1977).

Since G. I. Taylor first proposed a velocity-square law for surface stress (Taylor, 1916), there have been innumerable investigations testing this and the formulae for bulk parameterization of sensible and latent heat fluxes. These investigations indicate that these formulae are functionally correct but the data on the whole imply an uncertainty of around 25% in the transfer coefficients for stress (Garratt, 1976) and for sensible and latent heat fluxes (Friehe and Schmitt, 1976).

Verification of the bulk parameterization formulae requires an independent measurement of the fluxes. This paper describes an experiment in which estimates of stress from the indirect dissipation technique are compared with bulk aerodynamic estimates and the nature and origin of the difference between the two for short averaging times is explored. The work is an extension of a previous investigation reported in Khalsa and Businger (1977). An enlarged data set, a refined

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methodology and new techniques are used to demonstrate and analyse the influence of intermittency on the use of the bulk aerodynamics method. More quantitative measures of how these effects are reduced by lengthening the averaging interval are presented.

2. Instrumentation and Data Reduction

The data sets used in this and the previous investigation were obtained during the GARP Atlantic Tropical Experiment (GATE) in August and September of 1974. The instruments and their calibrations have been described in detail in Khalsa (1978).

A cup anemometer and dry and wet aspirated thermistors provided measurements of mean wind speed, air temperature and humidity. Turbulent fluctuations of these quantities were measured with hot film anemometers and dry and wet thermocouple temperature sensors. All instruments were mounted on a 9 m boom extending off the bow of the *USCGC Dallas*.

The linearized outputs of the hot film anemometers were processed in real time to give the high-frequency variance of the horizontal wind velocity at two heights. These signals were integrated and then recorded on magnetic tape along with the signals from the other instruments.

From the high-frequency variance of wind speed, the dissipation rate of the turbulent kinetic energy was obtained using the well-known equation for the energy spectrum in the inertial subrange. Then, a simplified form of the turbulent kinetic energy budget was used to estimate friction velocity, u_*, which gave stress $\tau = \rho u_*^2$, where ρ is the density of air. This is the indirect dissipation technique for estimating stress. The theory underlying these equations and the limitations and uncertainties involved in the technique are discussed fully in Khalsa (1978).

Of major concern is the validity of the simplified turbulent kinetic energy budget when the averaging interval is short. While the profile and eddy correlation methods of obtaining u_* become uncertain for short averaging times due to sampling error, dissipation rate can be accurately established with a short sample of the high-frequency variance. The uncertainty lies in converting dissipation rate to u_*. A definitive experiment studying the short-term kinetic energy budget has yet to be performed. In Khalsa and Businger (1977), scaling arguments and sample calculations were presented to support the assumption that certain terms in the complete turbulent kinetic energy budget which were omitted in the data reduction were not significant for short averaging periods.

3. Limitations of the Bulk Aerodynamic Method

The bulk aerodynamic formulae for stress, τ, sensible heat flux, H, and water vapor flux, E, may be written

$$\bar{\tau}/\rho = C_D \bar{U}^2 \tag{1}$$

$$\bar{H}/\rho\, c_p = -C_H \bar{U} \Delta\bar{\theta} \tag{2}$$

$$\bar{E}/\rho = -C_E \bar{U} \Delta\bar{q} \tag{3}$$

where ρ and c_p are the density and specific heat at constant pressure of air, respectively, U, θ, and q are wind speed, potential temperature, and specific humidity, respectively, and Δ stands for the value at the reference height, customarily taken as 10 m, less the value at the surface. The bulk transfer coefficients, C_D, C_H, and C_E must be determined by experiment.

Uncertainties in the transfer coefficients, which determine the uncertainty involved in the use of (1), (2), and (3), have a number of potential sources. Garatt (1976) attributes much of the scatter found in his review of the transfer coefficient for stress to insufficiently long averaging periods and instrumental errors in the measurements of stress.

An increase in C_D, the drag coefficient, with wind speed is widely acknowledged although there is no universally accepted form for this dependency. The variation of C_D with static stability has been treated theoretically by Deardorff (1968). The parameterization of stress in the marine boundary layer may depend on other factors not commonly accounted for in bulk formulations such as fetch, sea state and stationarity of the wind.

The optimal averaging period to use with (1), (2), and (3) is determined by factors such as the magnitude and frequency of the fluctuations in the bulk parameters. The long- and short-term limits are, however, evident. If the averaging period is too long, i.e., of the order of months, weeks, or, depending on wind conditions, even days, contributions to the stress from periods containing episodes of high wind speed will be underestimated due to the non-linearity of (1). Over short averaging periods, random, uncorrelated fluctuations in the bulk quantities and fluxes induced by small-scale eddies, will render the equations invalid.

Reasonable results have been obtained using 3-min averages of bulk quantities to estimate surface fluxes during transient disturbances (GATE, 1977). However, Khalsa and Businger (1977) were the first to attempt to check such short-term flux estimates against estimates using some other method. It is the purpose of this paper to elaborate on this issue.

4. Methodology

The data set which formed the basis of the current investigation consisted of twenty-two runs each of 45-min duration. One-minute averages of wind speed, U, detrended virtual temperature, T'_V, and high-frequency variance of wind speed, $\sigma^2_{\Delta k}$, were computed. When longer averaging periods were desired, $\sigma^2_{\Delta k}$ was averaged before conversion to dissipation rate, ε, because the relationship between these quantities was non-linear.

The static stability, represented by the ratio of measurement height z to the Obukhov length, L, enters into the determination of u_*^2 from ε. Because the measurements necessary for a direct evaluation of z/L were not made, the air-sea transfer model of Liu (1978) was adopted. Since this model employs bulk parameterization techniques, it would have been inappropriate to apply it with 1-min averages. Instead, the mean value for z/L was determined for each run and this quantity was used as a constant in the computation of u_*^2 from the kinetic energy budget. This is expected to introduce an error into the analysis, but the magnitude can only be ascertained by further experimentation. If the production of turbulent kinetic energy by buoyancy and shear vary together, their ratio, which determines L, may be much less variable than ε, making the use of a constant z/L viable.

As a first step in the analysis, short-term drag coefficients were computed by dividing the square of the short-term, dissipation-derived friction velocity, $u_*^2(\varepsilon)_i$, by the square of the run-averaged wind speed, $\bar{U}$: $C_{Di} = u_*^2(\varepsilon)_i/\bar{U}^2$. The run-averaged wind speed was used so that the mean drag coefficient for a run would equal the mean $u_*^2(\varepsilon)_i$ divided by the square of the mean wind speed: $\bar{C}_D = \overline{u_*^2(\varepsilon)}/\bar{U}^2$. Each C_{Di} computed in this way was adjusted to neutral stability and 10 m reference height to give $C_{DN}(10)$.

Comparisons were to be made between dissipation-derived stress, $u_*^2(\varepsilon)$, and stress estimated using a drag coefficient, $u_*^2(C_D)$. To obtain the latter, the run-averaged C_{DN} was multiplied by the square of the short-term wind speed: $u_*^2(C_D)_i = \bar{C}_{DN}\,U_i^2$. The run-averaged C_{DN} was used instead of one C_D for all runs so that the two methods of estimating stress would give approximately the same mean value for a run. As a result, only the deviations between stress estimates with periods shorter than 45 min are considered. The run-averaged drag coefficients were later checked for dependency on various parameters relating to the mean conditions for the runs.

Since a drag coefficient which was corrected for neutral stability and 10 m height was used to compute $u_*^2(C_D)$, the dissipation-determined friction velocity was also adjusted before a comparison was made. This was accomplished by multiplying the corrected short-term drag coefficient by the square of the run-averaged wind speed: $u_{*N}^2(\varepsilon)_i = C_{DNi}\,\bar{U}^2$. The run-averaged wind speed was appropriate since this was the factor used in deriving C_{Di} from the unadjusted $u_*^2(\varepsilon)_i$.

It will be noted that the mean value of $u_*^2(C_D)$ is larger than $u_*^2(\varepsilon)$ by a factor of $\overline{U^2}/\bar{U}^2$ or $1+(\sigma_U/U)^2$. The mean value of $(\sigma_U/U)^2$ for all runs was 0.02 so the difference will be considered insignificant.

The two estimates of friction velocity were differenced and divided by the run mean $u_*^2(\varepsilon)$, i.e.,

$$\Delta u_*^2/\bar{u}_*^2 = \frac{u_*^2(\varepsilon) - u_*^2(C_D)}{\bar{u}_*^2}. \tag{4}$$

The index i and the neutral designation N on C_D have been dropped for convenience.

The standard deviations of (4) will be the measure used to evaluate how much the stress estimates differ within a given run, i.e.,

$$S_\Delta = \overline{\left[\frac{u_*^2(\varepsilon) - u_*^2(C_D)}{\bar{u}_*^2}\right]^2}^{1/2}. \tag{5}$$

5. Results

5.1. Comparison of Short-Term Stress Estimates

In Khalsa and Businger (1977), it was reported that fluctuations in the short-term drag coefficient were found in some cases to be inversely related to fluctuations in wind speed. The causes of this were events which had high dissipation-determined friction velocities associated with low wind speeds and also events in which the inverse occured.

In the present study the relationship between these two variables is quantified with the computation of a correlation coefficient, $r(C_D, U)$, for each run. Values of $r(C_D, U)$ ranged from -0.7 to 0.8 with a tendency for the more negative values to occur under near-neutral conditions. Two large positive values of $r(C_D, U)$ came from runs in which there were large transitions in mean wind speed. In these runs the change in C_D in going from a lower to a higher wind speed regime resulted in a positive correlation of C_D with U while the short-term fluctuations still showed signs of being negatively correlated.

The variation of the relative difference in dissipation and drag coefficient stress estimates, $\Delta u_*^2/\bar{u}_*^2$, with wind speed was also investigated. Time series of these two quantities along with virtual temperature were plotted. A correlation coefficient between $\Delta u_*^2/\bar{u}_*^2$ and U^2, referred to as $r(\Delta, U^2)$, was also computed for each run. The value of $r(\Delta, U^2)$ will be -1 if a perfect negative correlation exists between $u_*^2(\varepsilon)$ and $u_*^2(C_D)$. If these two estimates of friction velocity are related through a positive constant of proportionality, then $r(\Delta, U^2)$ can be either positive or negative depending on whether the constant is greater or less than one. If the two variables are completely uncorrelated, $r(\Delta, U^2)$ can range from 0 to -1 depending on how much $u_*^2(\varepsilon)$ contributes to the variance of $\Delta u_*^2/\bar{u}_*^2$. A means of distinguishing the type of correlation that determined the value of $r(\Delta, U^2)$ will be explored in the next section.

The range of $r(\Delta, U^2)$ was 0.03 to -0.81 with approximately 40% of the runs having a value more negative than -0.55. The root-mean-square value of $\Delta u_*^2/\bar{u}_*^2$, S_Δ, varied from 0.2 to 0.5 and had a mean value of 0.36 for the 22 runs investigated. Two runs representing the range of $r(\Delta, U^2)$ will serve as examples.

During run 48b the wind speed was steady at approximately 7 m s^{-1} and the stability was near-neutral. The value of S_Δ was 0.34 and $r(\Delta, U^2)$ was -0.71. The negative correlation between $\Delta u_*^2/\bar{u}_*^2$ and U^2 is quite evident in the time series plot of Figure 1. The 1-min averages on this plot show that the fluctuations responsible for a negative $r(\Delta, U^2)$ had time scales of the order of minutes. A positive correlation between $\Delta u_*^2/\bar{u}_*^2$ and T_v' is also evident.

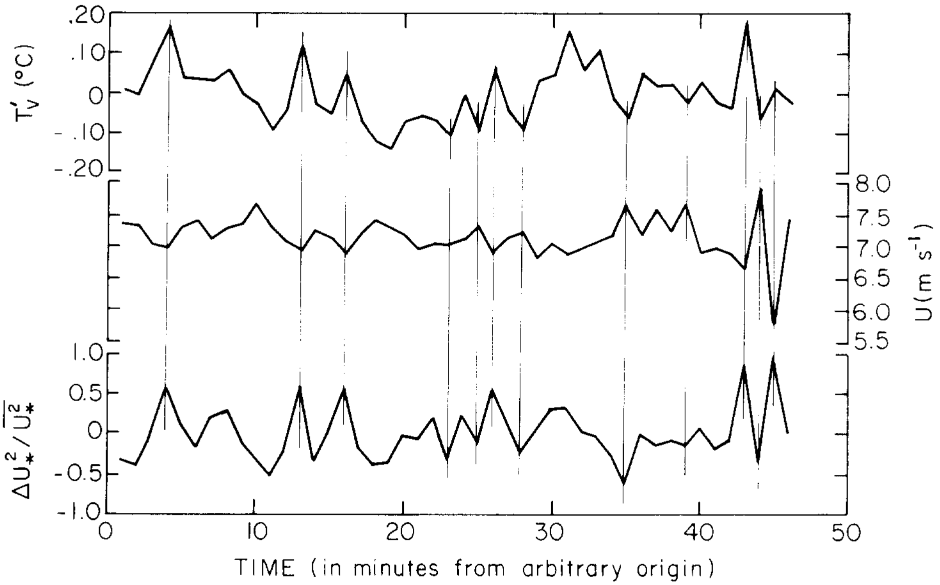

Fig. 1. Time series of $\Delta u_*^2/\bar{u}_*^2$, U and T_v' for run 48b. Vertical lines denote correlations discussed in text.

Run 42a occurred during light winds and unstable conditions. The time series in Figure 2 shows almost no correlation of $\Delta u_*^2/\bar{u}_*^2$ with U^2 as reflected by a $r(\Delta, U^2)$ of -0.17. What is quite obvious, however, is a strong correlation of $\Delta u_*^2/\bar{u}_*^2$ with T_v'. This correlation was observed on almost all plots regardless of stability. The value of S_Δ for this run was 0.32.

A possible instrumental cause for the correlation between $\Delta u_*^2/\bar{u}_*^2$ and T_v' must be considered. The sensitivity of the hot film sensors to fluctuations in ambient temperature, T, had been assumed to be negligible at the operating temperatures used. If there was in fact such a temperature dependency, a positive fluctuation in T would register as a lower cooling rate which would be interpreted as a lower wind speed. While the high-frequency information which determined $\sigma_{\Delta k}^2$ and therefore $u_*^2(\varepsilon)$ was insensitive to fluctuations in wind speed with periods greater than about 1 s, the calibration curve for the combined anemometer-linearizer system was a function of U. However, the possible magnitude of this effect is much too low to explain the observed correlation. Also, the change in slope of the calibration curve as U increased required that the correlation between $\Delta u_*^2/\bar{u}_*^2$ and T be smaller for higher wind speed runs. This was not observed.

It was argued by Khalsa and Businger (1977) that surface-layer convective elements were responsible for the anomalous behavior in short-term estimates of C_D. Time series of high-frequency temperature data had revealed signatures characteristic of plumes in regions where $u_*^2(\varepsilon)$ was large, wind speed was low and virtual temperature was high. In that earlier paper, plumes were assumed to be the only coherent features responsible for the anomalous behavior of C_D estimates.

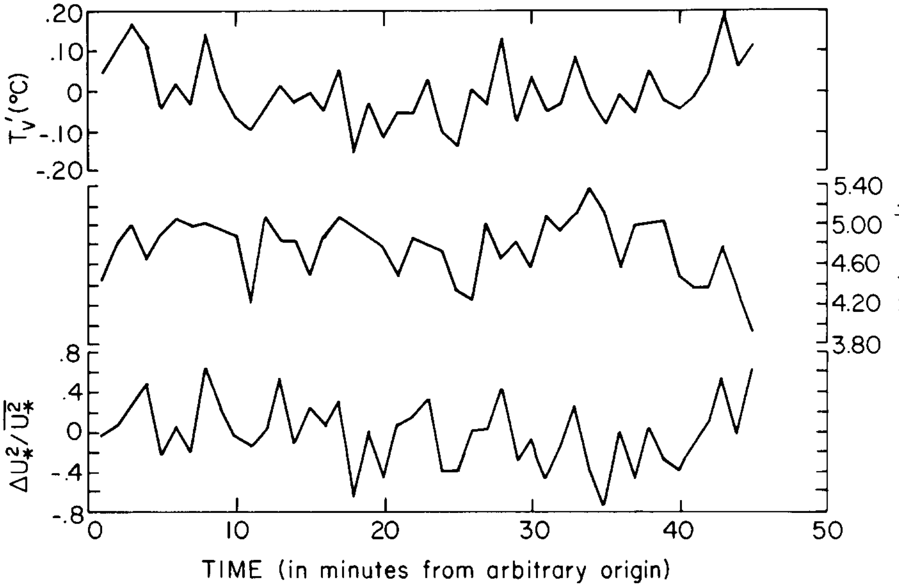

Fig. 2. Times series for run 42a (see Fig. 1). Note high degree of correlation between top and bottom signals.

However, in Figure 1 it is evident that events having low $u_*^2(\varepsilon)$, high wind speed and low virtual temperature contribute also. It is now believed that coherent downdrafts on the same scale as the plumes are responsible for these latter type of events. Thus a field of plumes and downdrafts was largely responsible for the discrepancies between dissipation and bulk aerodynamic estimates of stress.

In the interior of a plume, warm and moist air of low momentum is transported upward. Originating from a region of high shear and being accelerated by buoyancy and pressure forces, this air is highly turbulent. Downdrafts contain cool, dry and quiescent air of high momentum. The quiescent air results in a low value of $u_*^2(\varepsilon)$ although downward-moving, high-momentum air should result in an increased momentum flux and thus a large u_*^2. Thus the dissipation technique underestimates momentum flux in downdrafts and may overestimate it inside of plumes.

As instability increases the correlation between $\Delta u_*^2/\bar{u}_*^2$ and U disappears. This may be a result of decreasing wind shear for a fixed stress as instability increases. A smaller shear results in a smaller difference in momentum for a given vertical displacement of air. The fact that $\Delta u_*^2/\bar{u}_*^2$ correlated with T_v' for all runs suggests that plumes and downdrafts continue to exert an influence on $u_*^2(\varepsilon)$ although they no longer produce pronounced effects in wind speed. Conditional sampling techniques described in Khalsa (1980) have yielded results in support of these hypotheses.

5.2. Stress Scattergrams

To illustrate how plumes and downdrafts contribute to the differences in the two methods of estimating stress, the graphical representation shown in Figure 3 was

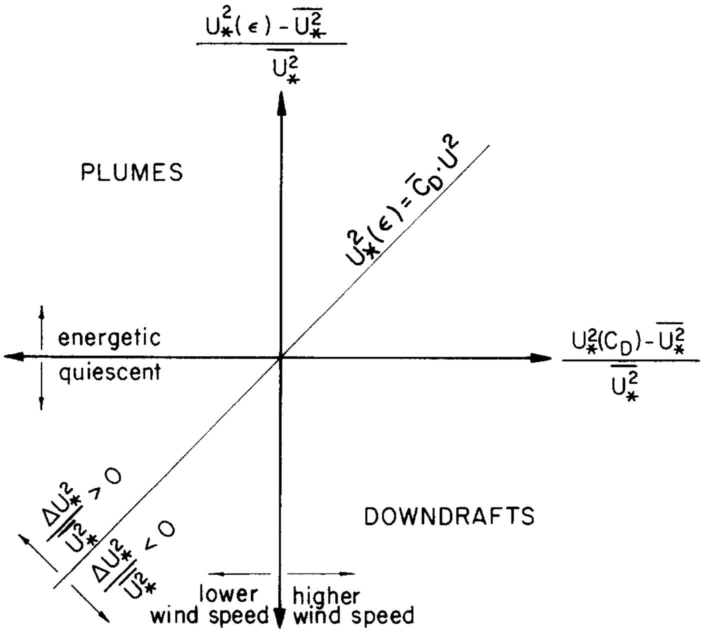

Fig. 3. Interpretation of normalized stress scatter diagram.

devised. The advantage of plotting friction velocity estimate pairs in this way is that the normal distance of any point from a line of unit slope passing through the origin is proportional to $|\Delta u_*^2/\bar{u}_*^2|$ or the contribution of the point to S_Δ. Furthermore, the sense of $u_*^2(\varepsilon)$ and $u_*^2(C_D)$ relative to the mean can be used to assign physical interpretations to the quadrants. The second quadrant, which corresponds to lower wind speeds and greater turbulence intensity, can be identified with plume. The fourth quadrant, with higher than average wind speed and lower turbulence levels, may be assumed to correspond to downdrafts.

Since all fluctuations are considered about their means, this assignment of plume and downdraft quadrants assumes that a balance exists between the two. By conservation of mass, this balance is expected to exist in the mean. If for some period, there is an excess of downdraft air, ambient air could produce points somewhere in the plume quadrant.

On a scatter diagram with axes as given in Figure 3, uncorrelated fluctuations between $u_*^2(\varepsilon)$ and U^2 will produce a cluster of points about the origin. Random noise in a $u_*^2(\varepsilon) = \bar{C}_D U^2$ relationship will appear as a cluster about a line of unity slope. An inverse relationship between $u_*^2(\varepsilon)$ and $C_D U^2$ will appear as a line with slope -1. Such a plot is thus a means of distinguishing the causes for the sign and magnitude of the correlation between $\Delta u_*^2/\bar{u}_*^2$ and U^2.

Scatter diagrams of the normalized friction velocities for the two runs previously discussed appear in Figures 4 and 5. In Figure 4 it is seen that run 48b has a substantial fraction of points lying in the plume and downdraft quadrants. Thus the

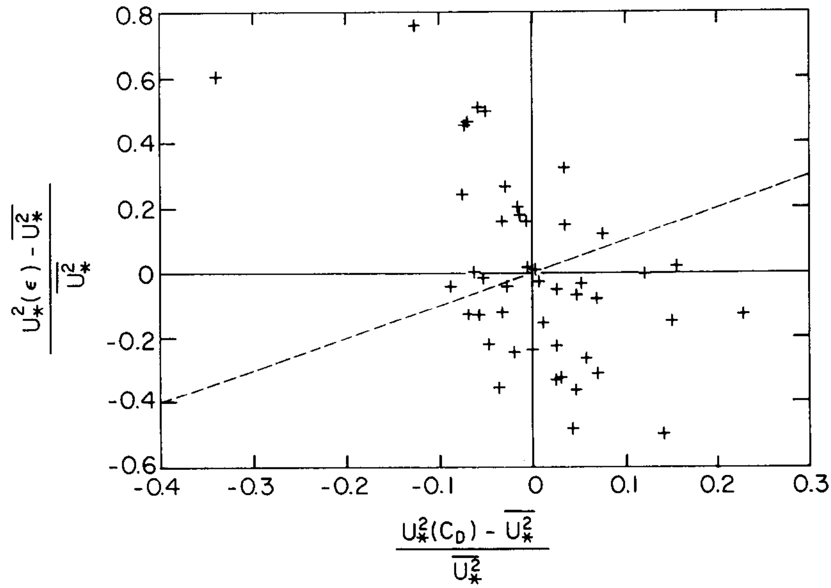

Fig. 4. Scatter diagram of normalized stress estimates for run 48b.

large negative correlation that was found between $\Delta u_*^2/\bar{u}_*^2$ and U^2 is the result of a negative correlation between $u_*^2(\varepsilon)$ and $u_*^2(C_D)$. The points farthest from the line of unit slope are in the plume quadrant implying that plume events contribute most to S_Δ. In the downdraft quadrant, the spread of points is greater and deviations from the

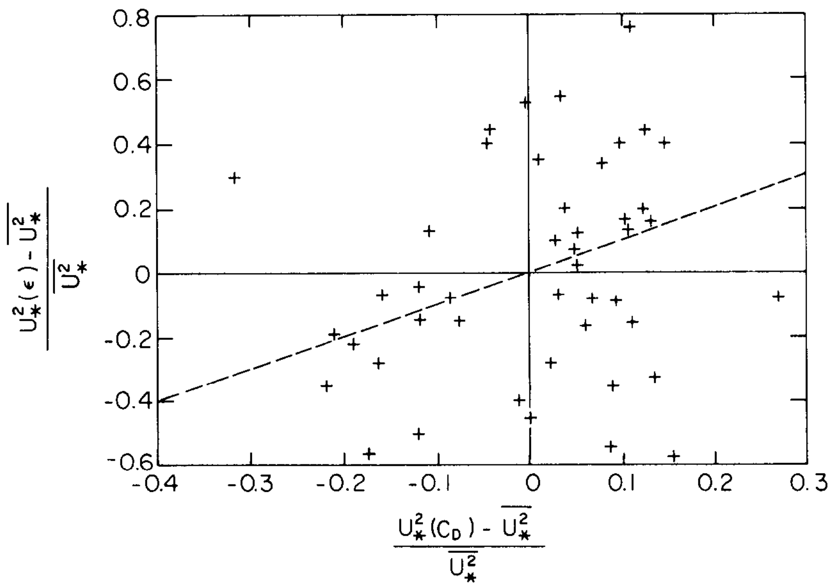

Fig. 5. Scatter diagram of normalized stress estimates for run 42a.

line of unit slope appear to be associated more with positive excursions in wind speed than with negative deviations in $u_*^2(\varepsilon)$.

Run 42a had relatively fewer points in quadrants 2 and 4 although the points which did occur contributed over half of the root-mean-square deviation in the stress estimates. A large degree of randomness and a large spread in $u_*^2(\varepsilon)$ are seen to be responsible for the small negative $r(\Delta, U^2)$.

Although $\Delta u_*^2/\bar{u}_*^2$ and U^2 were uncorrelated for this run, there was a high degree of correlation between $\Delta u_*^2/\bar{u}_*^2$ and T_v'. Thus plumes and downdrafts may have still been influencing the stress estimates. The vertical deviations from the line of unit slope in quadrants 1 and 3 could have been due to plumes and downdrafts but the associated wind speeds were not indicative of these states and therefore the points do not necessarily fall in quadrants 2 and 4.

One additional observation to be made is that there is a greater spread in the dissipation-derived friction velocity than in the estimate based on wind speed. Due to short averaging times, the intermittent nature of dissipation produced a large scatter in $u_*^2(\varepsilon)$ while the small-scale fluctuations in U did not produce as large a variance in $u_*^2(C_D)$. Instantaneous measurements of $u'w'$ through a plume indicate that stress is quite intermittent in the unstable surface layer (Kaimal and Businger, 1970). It is likely that part of the non-correlation of stress and wind speed at short time scales is associated with the dissimilarity in the probability distributions of these two quantities.

5.3. Intermittency Statistics and Stress Estimates

Plumes and downdrafts induce large, localized fluctuations in the surface-layer turbulence level. In Khalsa and Businger (1977), this type of intermittency was investigated using conditional sampling. Further work along these lines is reported in a companion paper (Khalsa, 1980).

Average values of dissipation rate ε, wind speed U, and detrended virtual temperature T_v' for each plume and non-plume interval were determined with the conditional sampling technique described in Khalsa and Businger (1977). The means of these averages for all plume and non-plume events were computed and from these the relative differences in ε, U and T_v' were produced for each run. These results confirmed that plumes were more dissipative, of lower wind speed for near-neutral conditions and more buoyant than non-plume air.

Having quantitative measures of plume properties, checks could be made for correlations of these measures with statistics relating to stress parameterization. For example, the root-mean-square difference of $\Delta u_*^2/\bar{u}_*^2$ or S_Δ was approximately equal for the two runs examined in Section 5.1 although in other respects the runs were quite dissimilar. Perhaps the plumes and downdrafts which caused the discrepancy in stress estimates had similar qualities. The relative difference between dissipation rates for plume and non-plume events, $\Delta\varepsilon/\bar{\varepsilon}$, could in part be a measure of the influence of intermittency. For runs 48b and 42a, $\Delta\varepsilon/\bar{\varepsilon}$ was approximately equal. Furthermore, the correlation coefficient between S_Δ and $\Delta\varepsilon/\bar{\varepsilon}$ was 0.7. The

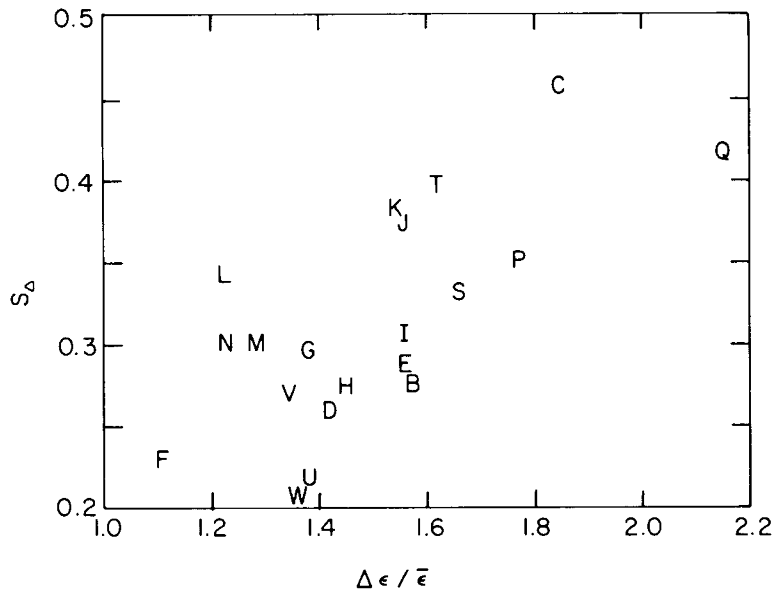

Fig. 6. Root-mean-square difference in normalized stress estimates versus normalized difference in dissipation between on and off states.

twenty runs which produced this correlation are shown in the scatter diagram in Figure 6.

It is significant to note that the fraction of time occupied by the plume state, called the intermittency factor γ, did not correlate with $S\Delta$. Thus it is not the prevalence of plumes which determined how divergent the stress estimates were but rather the intensity of the plumes with respect to their environment.

5.4. Variation of Averaging Time

The events which contributed most to the difference in dissipation and drag coefficient estimates of stress had time scales of the order of minutes as seen in Figures 1 and 2. To determine the length of averaging period necessary to smooth these events, three groups of runs were selected for study. These groups, described in Table I, were the only three in the data set which had at least 135 min of continuous data.

TABLE I

Runs used in averaging-time analysis

Run ID	Conditions
A 50b, 51a, 51b	undisturbed, steady southwesterly flow, near neutral
B 43a, 43b, 44a, 44b	disturbed, large gust at start of 44a
C 59b, 60a, 60b	disturbed, 3 hr period before gust and heavy rain

For these groups, averaging intervals of 1, 5 and 15 min were examined. For each averaging interval, the dissipation rate ε, the friction velocity derived from ε, $u_*^2(\varepsilon)$, and C_D were computed. The mean C_D and U for the group was then used to find $u_*^2(C_D)$ for each interval. The root-mean-square difference in the friction velocity estimates, normalized by the mean stress is given by S_Δ. The size, spacing and intensity of the events which produced a discrepancy between $u_*^2(\varepsilon)$ and $u_*^2(C_D)$ will determine the degree of reduction in S_Δ as the averaging interval increases. The results are presented in Table II.

TABLE II

The results of an averaging-time investigation. Run groups are defined in Table I and symbols are defined in text. The number of samples used to determine S_Δ appears to the right of the given value

Group:	A	B	C
$\bar{S}_\Delta$ (1 min)	0.336 (45)	0.312 (45)	0.251 (45)
S_Δ (5 min)	0.254 (27)	0.250 (36)	0.137 (27)
S_Δ (15 min)	0.094 (9)	0.196 (12)	0.080 (9)
U (m s^{-1})	7.54	5.98	8.57
$\sigma u/\bar{U}$ (1 min)	0.060	0.359	0.058
$\sigma u/\bar{U}$ (5 min)	0.060	0.359	0.058
$\sigma u/\bar{U}$ (15 min)	0.054	0.353	0.052
z/L	−0.07	−0.50	−0.12

The value of S_Δ (1 min) was fairly constant from run to run within a group and also for shorter segments of the runs. It is evident that group A had the largest $\bar{S}_\Delta$ (1 min) and was also the most nearly neutral, i.e., z/L was closest to zero. Group C had the smallest $\bar{S}_\Delta$ (1 min) and had the highest mean wind speed.

In the second row of Table II it is seen that 5-min averaging reduced S_Δ by about 20% for groups A and B. Group C saw a reduction of around 45% from the 1-min value. The explanation for this difference lies in the nature of the fluctuations responsible. In the runs of group C the events contributing to a large $\Delta u_*^2/\bar{u}_*^2$ had time scales of around 3 to 4 min. In contrast, while the runs of groups A and B also had fluctuations on this time scale, it was the lower frequency fluctuations with time scales greater than 5 min which were most important.

The sharp reduction in S_Δ in going from 1-min to 5-min averages for group C was the result of a greater advection speed for plumes. Group C differed from group A, which also had a moderately large mean wind speed, in being more unstable. It is shown in Khalsa (1980) that as instability increases, plumes are smaller but more numerous. These two factors, higher wind speed and smaller plume size, combined to make the time scale for the disturbance by plumes and downdrafts less than or approximately equal to 5 min.

When 15-min averages were used, it can be seen from Table II that both groups A and C experienced a 70% decrease in S_Δ over the respective 1-min averages. This suggests that the dominant influence of plumes and downdrafts had been smoothed by 15-min averaging.

Fifteen-minute averaging for group B reduced S_Δ by only 20% over 5-min averaging. Presumably plume influence had been smoothed and it was the large change in wind speed which occurred in the middle of the run that became the determining factor for S_Δ. At this time scale the data suggests that the normalized variance of the wind speed $\sigma_u/\bar{U}$, correlates well with S_Δ including the period for which a gust is largely responsible for the magnitude of $\sigma_u/\bar{U}$.

The question of minimum averaging time for the application of the bulk aerodynamic method with respect to plume influence has been discussed by Gaynor and Mandics (1978). Surface fluxes were computed with simple bulk formulae on occasions when sounder returns revealed distinct plumes extending to heights of 300 to 400 m. These plumes tended to aggregate into plume families. When 3-min averaging was used, Gaynor and Mandics noted that minima in the surface fluxes computed with bulk aerodynamic formulae occurred beneath vigorous plume families. They concluded that the minimum averaging time necessary for the bulk method to produce valid flux estimates is controlled by the period of plume families. The period indicated by the sounder records was about 10 min so they suggested that 30-min averages provided an adequate sample under the conditions of their measurements.

6. Summary and Conclusions

It has been found that in the unstable surface layer, fluctuations in the short-term drag coefficient, as determined by the dissipation method, are primarily due to the presence of plumes and their counterparts, downdrafts. The effect is anomalous in that the fluctuations in C_D are negatively correlated with wind speed. Plume- and downdraft-induced fluctuations also contribute substantialty to the normalized root-mean-square difference between the dissipation and drag coefficient estimates of stress, S_Δ. The correlation between C_D and U, or between S_Δ and U was mildly dependent on stability. This dependency was assumed to arise from the effect of decreasing shear in the wind profile as instability increased.

In the more unstable cases where S_Δ was no longer correlated with U, there was still a high correlation with detrended virtual temperature T_v'. Thus, T_v' remained a good indicator of plume and downdraft influence. However, a check for a relationship between the variance of T_v' and S_Δ^2 produced no correlation. The magnitude of the fluctuations in T_v' were apparently unrelated to those of $\Delta u_*^2/\bar{u}_*^2$ although the two signals were similar in form.

The average intensity of plumes over the background was determined by conditional sampling. This parameter was found to be correlated with S_Δ. The difference in dissipation-derived and bulk aerodynamic estimates of stress was determined more by plume intensity that the aerial coverage of plumes.

The minimum averaging time necessary to smooth the influence of plumes and downdrafts was dependent on the advection time scale of these events. This time scale was determined by the wind speed and the size of the plumes which was a function of the stability of the air.

One-minute averaging produced root-mean-square differences between the dissipation-derived and drag coefficient estimates of stress which ranged from 20 to 50%. Five-minute averages resulted in a reduction of 20% except when the plume time scale was large, in which case S_Δ was reduced by over twice this amount. Fifteen-minute averages eliminated most plume and downdraft influence, reducing S_Δ by 70% of its 1-min value.

In the case of a gust, the discrepancy in stress estimates for 15-min averages depended on the details of the adjustment in wind speed and stress. At this time scale, it is possible that S_Δ could be parameterized with the normalized variance of the wind speed.

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