Comments on "Bulk Parameterization of Air-Sea Exchanges of Heat and Water Vapor Including the Molecular Constraints at the Interface"[1]

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Liu *et al.* (1979) derive a rather complete set of bulk parameterizations on momentum, heat and water vapor fluxes above the air-sea interface. Familiar formulas are used to describe vertical transfer above the interfacial sublayers and are probably satisfactory to describe field data; effects of atmospheric stability can be taken directly into account when the actual surface temperature rather than the bulk water temperature is employed to estimate the air-sea temperature difference. Parameterizations of transfer processes in the interfacial sublayers, however, are much more controversial. Field data are sparse and are not always consistent with information obtained by use of wind-water facilities in the laboratory. Thus, the surface-renewal theory applied by Liu *et al.* (henceforth referred to as LKB) have yet to be tested fully. The purpose here is to use field data to evaluate some of the predictions by LKB on the behavior of the interfacial sublayers.

Most often, field data on vertical fluxes are collected in wind speeds that are moderate, because in light winds the atmospheric fluxes are difficult to measure or estimate accurately, and in strong winds rough seas often hamper field operations. At the low end of the wind speed range, near 2–3 m s^{-1} at a height of 10 m, capillary waves have just formed and at the high end, near 10 m s^{-1}, breaking waves and water spray have begun. This range of wind speeds is included in the considerations by LKB and is the range addressed here.

An important parameter that is needed to describe the interface is the aerodynamic surface roughness length scale z_0, often considered a function of fetch as well as wind speed. Fig. 1 shows the estimates of z_0 used by LKB, which are derived from work by Kondo (1975) for the open sea. These estimates are slightly larger than those often assumed by use of Charnock's relationship, $z_0 = \alpha u_*^2/g$, where u_* is the friction velocity and g the acceleration due to gravity. The numerical coefficient α might be expected to depend slightly on fetch and wave development; the value 0.016 is chosen for illustration in Fig. 1. In a review of available data, Garratt (1977) finds that $\alpha = 0.014$ provides the best empirical fit for open ocean. At a cooling pond where fetches were ~0.5 km, the coefficient found is ~0.008 (Hicks *et al.*, 1977). On the other hand, Amorocho and DeVries (1980) contend that α is not constant but that z_0 is approximately constant for the wind speeds of concern here. While the analysis by LKB is self-consistent with regard to values of z_0 used, alternative assumptions should be kept in mind when LKB's results are examined.

The surface-renewal theory applied by Brutsaert (1975) and LKB appears to produce results concerning the aqueous sublayer that are quite consistent with laboratory measurements. Field data, on the other hand, provide less agreement, as shown in Fig. 8 of LKB. Fig. 2 shows data on the aqueous sublayer sampled in a recent study at a cooling pond [for experimental details see Wesely (1979)], which are very similar to the data given by LKB. With these two data sets, a wide range of conditions is considered, roughly corresponding to wind speeds of 2.5–10 m s^{-1} at a height of 10 m. The slope of $S\ \mathrm{Pr}^{-1/2}$ versus Rr, where S is the transfer parameter defined by LKB, Pr the Prandtl number for the aqueous sublayer, and Rr the roughness Reynolds number, appears to be considerably less than the value of 0.25 predicted for Rr > 1. The slope for all the data points is nearly zero, which indicates that Rr is not an important parameter, and that smooth flow might be assumed in order to derive an empirical expression for the behavior of S and similar parameters. This is the type of approach taken earlier (Saunders, 1967; Wesely, 1979).

A possible explanation of the appearance of nearly smooth flow concerns a phenomenon not directly considered in the surface-renewal theory—the effects of somewhat intermittent flow in the atmospheric surface layer. A much larger variation in short-term wind speeds usually occurs in the atmosphere as compared to those in laboratory simulations. Let us assume, for example, that Rr in the aqueous sublayer responds rapidly to short-term windspeed variations. Whenever $\mathrm{Rr} \geqslant 1.0$, fully rough flow exists (according to LKB's analysis of laboratory data), causing S to be proportional to $\mathrm{Rr}^{1/4}$. Since Rr is equal to $z_0 u_*/\nu$, where ν is the kinematic viscosity, and z_0 nearly proportional to u_*^2 is assumed for both sets of data in Fig. 2,

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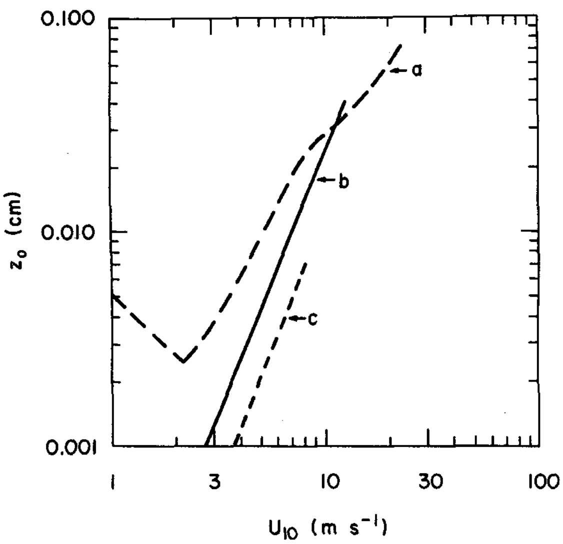

FIG. 1. Estimates of surface roughness over water derived from (a) Liu *et al.*'s (1979) adaption of work by Kondo (1975), (b) Charnock's relation $z_0 = \alpha u_*^2/g$ with $\alpha = 0.016$, and (c) the relation $z_0 = 0.008u_*^2/g$ fit to data from a cooling pond (Hicks *et al.*, 1977).

S should be proportional to $u_*^{3/4}$ for rough flow. When $\mathrm{Rr} \leqslant 1.0$, smooth flow is said to exist, so that S is a relatively large, constant value. When the value of u_* averaged over at least 10 min indicates that Rr is near unity, the case of smooth flow would dominate numerically in the computations of S.

An alternative explanation is that z_0 is constant, so that S is proportional to $u_*^{1/4}$. For the data in Fig. 2, this would correspond to S being proportional to $\mathrm{Rr}^{1/12}$, which would provide an acceptable fit to the data. However, individual field and laboratory studies usually do not find z_0 constant over the entire range of wind speeds considered here.

Another computation using surface renewal theory concerns values of the surface roughness lengths for heat, z_T, and for water vapor, z_Q, at the lower boundary of the atmospheric surface layer. By matching the mean values and slopes found from surface-renewal equations with those obtained for fully turbulent flow aloft, values of these surface roughness length scales can be found. Fig. 3 recasts the data and predictions of LKB in a form frequently used, which is $\ln(z_0/z_T)$ vs Rr on a logarithmic scale. The range of field and laboratory data indicated is derived from Garratt and Hicks (1973) and addresses both heat and water vapor. It appears that the result of LKB does not fit the observations very well. As shown in Fig. 3, the formula $z_T = \kappa/(ku_*)$, where κ is the thermal diffusivity and k the von Kármán constant, fits the data slightly better than LKB's prediction. This expression is derived with the assumption that eddy and molecular diffusivities are additive (e.g., Sheppard, 1958), an assumption that cannot be fully defended by theoretical argument except in the case where the flow is smooth.

It is worthwhile to check LKB's procedures in order to determine if the reasons for the relative success of Sheppard's expression can be elucidated. When the slopes of the temperature profiles given by LKB are matched at height z_x, the resulting relationship is

$$z_x = \kappa(\alpha_H k u_*)^{-1} \exp(z_* u_*/\kappa S), \qquad (1)$$

which provides a fixed value of $z_* u_*(\kappa S)^{-1}$ if κ, α_H, k and S are fixed. When the temperature magnitudes are also matched, the resulting expression for z_T is

$$z_T = C\kappa(ku_*)^{-1}, \qquad (2)$$

where

$$C = \alpha_H^{-1} \exp[-\alpha_H kS + \kappa S(z_x u_*)^{-1} + z_x u_*(\kappa S)^{-1}], \qquad (3)$$

which is constant when $z_x u_*(\kappa S)^{-1}$ and $\alpha_H kS$ are fixed. For example, with the values of $S = 12$ and $\kappa = 0.21\ \mathrm{cm^2\ s^{-1}}$, which are typical near 20°C, and of $(\alpha_H k)^{-1} = 2.2$, which is recommended by LKB, $z_x u_*(\kappa S)^{-1}$ is equal to 0.23 and $C \approx 0.4$. Hence, the lower curve in Fig. 3 should be increased by adding $\sim\ln(1/0.4) = 0.91$ for all Rr. This produces an even better description of the data and corresponds to smooth flow if S is held constant. Another consideration is that C is only weakly dependent on the values of S, κ, α_H, and k chosen, so that whether or not smooth flow is assumed, the relation $z_T = \kappa/u_*$ appears to be approximately correct. The analysis by LKB seem to produce different results.

In summary, field data on the aqueous sublayer give the appearance of nearly smooth flow for wind speeds of 2.5–10 m s^{-1}, even though the flow is probably not actually smooth. Also, application of

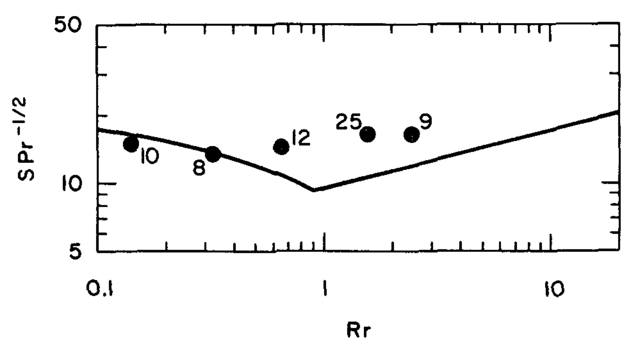

FIG. 2. Values of $S\ \mathrm{Pr}^{-1/2}$ measured for the aqueous sublayer at a cooling pond (Wesely, 1979) and compared to the model results (solid line) from Liu *et al.* (1979). The numerical value by each point is the number of contributing 10 min data-collection periods.

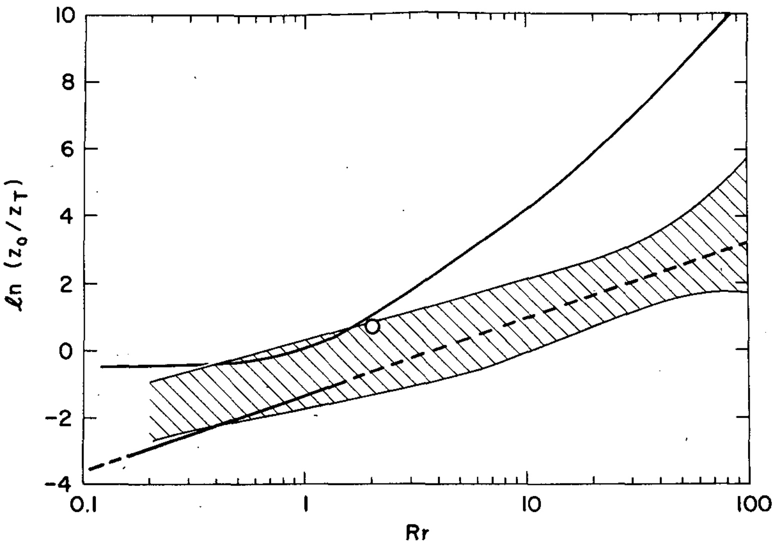

FIG. 3. Plots of $\ln(z_0/z_T)$ versus Rr, with the shaded area corresponding to the range of data points evaluated by Garratt and Hicks (1973). The upper solid line is calculated from the model suggested by Liu *et al.* (1979) and the open circle is from their experimental data. The remaining straight line results from the expression $z_T = \kappa/(ku_*)$, with the solid portion representing that supported by Hicks *et al.* (1977).

the surface-renewal theory to determination of roughness length scales for temperature and water vapor in the gas phase results in a good description of available data, especially when smooth flow is assumed. The major factor not considered directly by surface-renewal theory in its present stage of development is the great variability in wind speeds in the atmospheric surface layer. For the aqueous sublayer, considerations on the continuity of tangential stress at the interface, and on currents induced in the water by large eddies may be required also (Saunders, 1973).

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