NOTES AND CORRESPONDECE

Scaling Reasoning and Field Data on the Sea Surface Roughness Lengths for Scalars

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ABSTRACT

The heat and mass transfer over the sea is considered in terms of the sea surface roughness lengths for scalars, z_{0T} for potential temperature θ, and z_{0q} for specific humidity q, or alternatively, in terms of the roughness-layer scalar increments, $\delta\theta$ and δq. A new scaling reasoning is proposed in support of the familiar square root dependence of the above increments on the roughness Reynolds number, $\mathrm{Re}_{0u} = z_{0u}u_*/\nu$, where z_{0u} is the sea surface aerodynamic roughness length, u_* is the friction velocity, and ν is the molecular viscosity of the air. Scaling predictions are validated using data from measurements made by the National Oceanic and Atmospheric Administration's Environmental Technology Laboratory aboard the R/V *Moana Wave* in the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment in 1992–93 and the R/P *FLIP* in the San Clemente Ocean Probing Experiment in September 1993. Data presented as the dimensionless scalar increments (or the ratios z_{0u}/z_{0T} and z_{0u}/z_{0q}) versus Re_{0u} show a good agreement with theoretical predictions, especially at $\mathrm{Re}_{0u} > 2$ (over stormy sea). The resulting roughness-length formulations are recommended for practical use in climate and mesoscale air–sea interaction models.

1. Introduction

In the classical theory of the logarithmic turbulent boundary layer, the aerodynamic roughness length of the underlying surface, z_{0u}, is specified as a level, at which the mean velocity, u, extrapolates to zero when plotted versus the logarithm of the height, z. Then the velocity profile reads

$$u(z) = \frac{u_*}{k}\ln\frac{z}{z_{0u}}. \tag{1}$$

Here, $k \approx 0.4$ is the von Kármán constant for momentum, $u_* \equiv (\tau_s)^{1/2}$ is the friction velocity, and τ_s is the surface value of the downward momentum flux per unit of mass.

Similarly, the roughness lengths for scalars, z_{0T} for potential temperature, θ, and z_{0q} for humidity, q, are specified by extrapolating the logarithmic portions of the mean profiles down to the intersections with the surface values, θ_s and q_s, respectively. In particular, the temperature profile reads

$$\theta(z) = \theta_s + \frac{\theta_*}{k_T}\ln\frac{z}{z_{0T}}, \tag{2}$$

where $k_T \approx 0.4$ is the von Kármán constant for temperature (e.g., Kader and Yaglom 1990), and $\theta_* \equiv -F_{\theta s}/u_*$ is the temperature scale based on the potential temperature flux at the surface, $F_{\theta s}$, and the friction velocity, u_*.

The roughness lengths z_{0u}, z_{0T}, and z_{0q} appear as constants of integration in equations of the type $\partial u/\partial z = u_*/kz$. However, these equations lose physical sense at $z = 0$. Thus the roughness lengths are conventional parameters with the dimension of length introduced to avoid consideration of the profiles in the immediate vicinity of the surface. They depend on geometrical features of the surface, friction velocity, molecular viscosity, and molecular diffusivity.

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In meteorological literature, an alternative temperature profile formulation is often used, namely,

$$\theta(z) = \theta_0 + \frac{\theta_*}{k_T} \ln\frac{z}{z_{0u}}, \quad (3)$$

where θ_0 is the so-called aerodynamic surface temperature, that is, the potential temperature extrapolated logarithmically downward to the level $z = z_{0u}$.

Equations (1)–(3) hold true in the height interval $(z_{0u}, z_{0T}) \ll z \ll |L|$, where $L = -u_*^3/F_{bs}$ is the Monin–Obukhov length characterizing the effect of stratification on the shape of the mean profiles, and F_{bs} is the buoyancy flux at the surface. As pointed out above, these equations are not applicable close to the roughness elements. Therefore θ_0 is a conventional parameter with the dimension of temperature, which does not coincide with the actual temperature at the level $z = z_{0u}$. Moreover, the roughness lengths for momentum, z_{0u}, and for scalars, z_{0T} and z_{0q}, are generally different. As a result, the "roughness-layer temperature increment," defined as

$$\delta\theta \equiv \theta_s - \theta_0 = \frac{\theta_*}{k_T} \ln\frac{z_{0u}}{z_{0T}}, \quad (4)$$

is generally nonzero. Clearly, with a knowledge of z_{0u} and $\delta\theta$, Eq. (4) allows us to specify the temperature roughness length, z_{0T}.

Besides immediate use of the roughness lengths, z_{0u}, z_{0T}, and z_{0q}, and the logarithmic profiles (or the Monin–Obukhov-type profiles) the near-surface turbulent fluxes of momentum, $\tau_s \equiv u_*^2$; potential temperature, $F_{\theta s} \equiv -u_*\theta_*$; and humidity, $F_{qs} \equiv -u_* q_*$; are often described in terms of the drag coefficient, C_D, and the heat and mass transfer coefficients, C_H and C_M,

$$C_D \equiv \frac{\tau_s}{u_{10}^2}, \qquad C_H \equiv -\frac{F_{\theta s}}{u_{10}\Delta\theta}, \qquad C_M \equiv -\frac{F_{qs}}{u_{10}\Delta q}. \quad (5)$$

Here, $u_{10} = u|_{z=10m}$, $\Delta\theta = \theta|_{z=10m} - \theta_s$, and $\Delta q = q|_{z=10m} - q_s$ are given by Eqs. (1)–(3) or, accounting for the stratification, by the Monin–Obukhov-type equations. In any case, given the shape of the profiles, the drag and heat–mass transfer coefficients carry the same information as the roughness lengths.

In the current literature, much less attention is paid to the heat–mass transfer and the sea surface roughness lengths for scalars, z_{0T} and z_{0q}, than to the resistance and the aerodynamic roughness length, z_{0u} (see summaries in Zilitinkevich 1970; Kitaigorodskii 1970; Liu et al. 1979; Brutsaert 1982; Bortkovskii 1983; Geernaert 1990; Garratt 1992; De Cosmo et al. 1996). In this paper, scaling reasoning and new data are employed to express the roughness-layer temperature and humidity increments, $\delta\theta$ and δq, and eventually the roughness lengths z_{0T} and z_{0q} through the roughness-layer governing parameters. On this basis, practical recommendations are given for the calculation of the heat and mass transfer in operational air–sea interaction models.

2. Roughness-layer scaling

In the well-developed turbulence layer (at $z \gg z_{0u}$), the friction velocity u_* is the basic velocity scale characterizing the turbulent transport properties of the flow. Hence, $\theta_* = -F_{\theta s}/u_*$ is the natural temperature scale. Similarly, the humidity scale is $q_* = -F_{qs}/u_*$.

In the vicinity of a rough surface, the heat–mass transfer and the momentum transfer are controlled by essentially different mechanisms. Here, the mean profiles depend on the shape and the size of the roughness elements and also on the molecular viscosity and conductivity/diffusivity. The momentum flux, τ_s, generally consists of two parts, the major pressure part, τ_{sp}, and the minor molecular viscosity part, $\tau_{s\nu}$. On the contrary, the heat–mass transfer at the very surface is completely due to molecular conductivity/diffusivity within viscous sublayers adjacent to the roughness elements. Hence, the velocity scale for the scalar transport is $(\tau_{s\nu})^{1/2}$ rather than $u_* = (\tau_s)^{1/2}$. Next, the basic length scale in the roughness layer is z_{0u} rather than z, and the mean velocity scale is u_* rather than $u(z)$. As a result, the velocity gradient is measured by u_*/z_{0u}, which is why the contribution to the momentum flux due to viscosity, ν, is estimated as

$$\tau_{s\nu} \propto \nu u_*/z_{0u}. \quad (6)$$

Consequently, the temperature scale in the roughness layer is

$$\theta_{*\nu} = F_{\theta s}/\sqrt{\tau_{s\nu}} \propto \theta_* \sqrt{\mathrm{Re}_{0u}}, \quad (7)$$

where Re_{0u} is the roughness Reynolds number employing z_{0u} as the length scale,

$$\mathrm{Re}_{0u} \equiv z_{0u} u_*/\nu, \quad (8)$$

and $\theta_* = -F_{\theta s}/u_*$ is the conventional temperature scale inherent to the well-developed turbulence layer.

Assuming that the roughness-layer temperature increment $\delta\theta$ is measured by $\theta_{*\nu}$, it becomes

$$\delta\theta = (A_\theta/k_T)\theta_*\sqrt{\mathrm{Re}_{0u}},$$
$$z_{0T} = z_{0u} \exp(-A_\theta\sqrt{z_{0u}u_*/\nu}). \quad (9)$$

Here, A_θ is a dimensionless factor depending on properties of the roughness elements (over the water surface, on the shape and phase velocity of surface waves). Clearly, A_θ depends also on the Prandtl number, $\mathrm{Pr} = \nu/\chi_\theta$, where χ_θ is the heat conductivity. However, for the air $\mathrm{Pr} \approx 0.7$ is practically constant, which is why the above dependence is unimportant.

Similarly, the roughness-layer humidity increment δq and the roughness length for humidity z_{oq} are

$$\delta q = (A_q/k_q)q_*\sqrt{\mathrm{Re}_{0u}},$$
$$z_{0q} = z_{0u} \exp(-A_q\sqrt{z_{0u}u_*/\nu}). \quad (10)$$

Here, $k_q \approx k_T$ is the von Kármán constant for humidity, and A_q is the same type dimensionless factor as A_θ but dependent on the Schmidt number $\mathrm{Sc} = \nu/\chi_q$, where

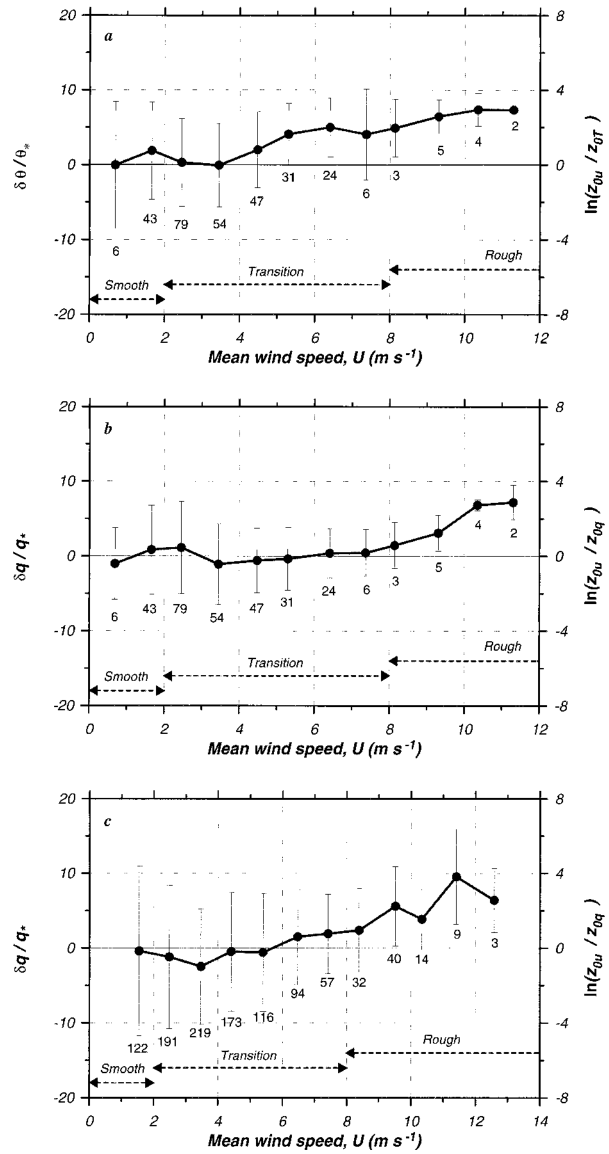

FIG. 1. Averaged dimensionless increments in temperature, $\delta\theta/\theta_*$, and humidity, $\delta q/q_*$, at the sea surface vs the wind speed, u: (a) $\delta\theta/\theta_*$ from SCOPE, (b) $\delta q/q_*$ from SCOPE, (c) $\delta q/q_*$, from TOGA COARE. Averaging is applied in wind-speed bins with 1 m s^{-1} width. Standard error bars are shown. The numbers below each bar represent the number of points averaged.

χ_q is the molecular diffusivity. For the air, the dependence of A_q on Sc is unimportant, as Sc $\approx$ 0.6 is practically constant.

Generally the square root dependence of the near-surface scalar increments on the roughness Reynolds number, similar to Eqs. (9) and (10), has been known since the 1960s. Owen and Thomson (1963) derived an expression for $\delta\theta/\theta_*$, which coincides with Eq. (9) except for the use of the roughness Reynolds number $\mathrm{Re}_{h0} \equiv h_0 u_*/\nu$ based on the typical height of the roughness elements, h_0. To make it more convenient to compare data from a number of laboratory experiments with different roughness elements, Zilitinkevich (1970) has employed the roughness Reynolds number Re_{0u}, Eq. (8), and has given a summary of laboratory data (his Fig. 1.5) suggesting the empirical formula $\delta\theta/\theta_* \propto \mathrm{Re}_{0u}^{0.45}$, which in fact is very close to $\mathrm{Re}_{0u}^{1/2}$. Yaglom and Kader (1974) have given additional theoretical arguments and laboratory data in support of the dependence $\delta\theta/\theta_* \propto \mathrm{Re}_{h0}^{1/2}$ for solid surfaces. More recently Hummelshøj et al. (1992) have employed the concept of Brownian diffusion to derive the same type of dependence for the particle dry deposition processes at the sea surface.

Mölder (1998) carried out a comprehensive experimental investigation of the heat transfer over vegetated land surfaces and disclosed essential deviations from the dependence $\delta\theta/\theta_* \propto \mathrm{Re}_{0u}^{1/2}$ in a number of cases. However, Jensen and Hummelshøj (1995) have shown that a similar type of dependence becomes consistent with data over spruce forest provided that the leaf scale rather than the total canopy height scale is substituted for h_0 in the familiar expression for the roughness Reynolds number.

Worthy of notice is a recent heat transfer model developed by Makin (1998, 1999) employing the eddy viscosity/conductivity in the wave boundary layer (see also Chalikov and Makin 1991; Chalikov and Belevich 1993).

The derivation given above (see also Zilitinkevich 1997) motivates the choice of the aerodynamic roughness length z_{0u} rather than h_0 as the basic roughness-element length scale, and, consequently, the use of the roughness Reynolds number Re_{0u}, Eq. (8), rather than Re_{h0}. This is especially convenient (and physically grounded) over the sea surface where h_0 is more difficult to specify than z_{0u}. Moreover, the above derivation clarifies the nature of the dimensionless factors A_θ and A_q and suggests a constructive approach to empirical validation of Eqs. (9) and (10). In this paper the simplest assumption is made, namely, the factors A_θ and A_q for the sea surface are treated as constants. In future work, it is reasonable to examine dependencies of the above factors on bulk parameters characterizing the wave field, such as the wave slope, the wave–wind angle, and the wave age, c_0/u_*, where c_0 is the phase speed of the dominant wave (see physical reasoning in Kitaigorodskii 1970).

Equations (9) and (10) are valid provided that the sea surface is aerodynamically rough, that is, the weather is windy and the roughness Reynolds number, Re_{0u}, given by Eq. (8) is high enough.

In calm weather, except for the cases with swell, the roughness Reynolds numbers are relatively low. Then actual surface roughness elements (ripples) are smaller than the thickness of the viscous sublayer (measured by ν/u_*); and that is why the sea surface is aerodynamically smooth. For $\mathrm{Re}_{0u} < 0.1$, the classical formulation for the effective roughness lengths and the near-surface temperature and humidity increments reads

$$z_{0u} \approx 0.1\nu/u_*, \qquad z_{0T} \approx 0.2\nu/u_*,$$

$$z_{0q} \approx 0.3\nu/u_*, \quad \text{and} \tag{11}$$

$$\delta\theta/\theta_* \approx -2, \qquad \delta q/q_* \approx -3. \tag{12}$$

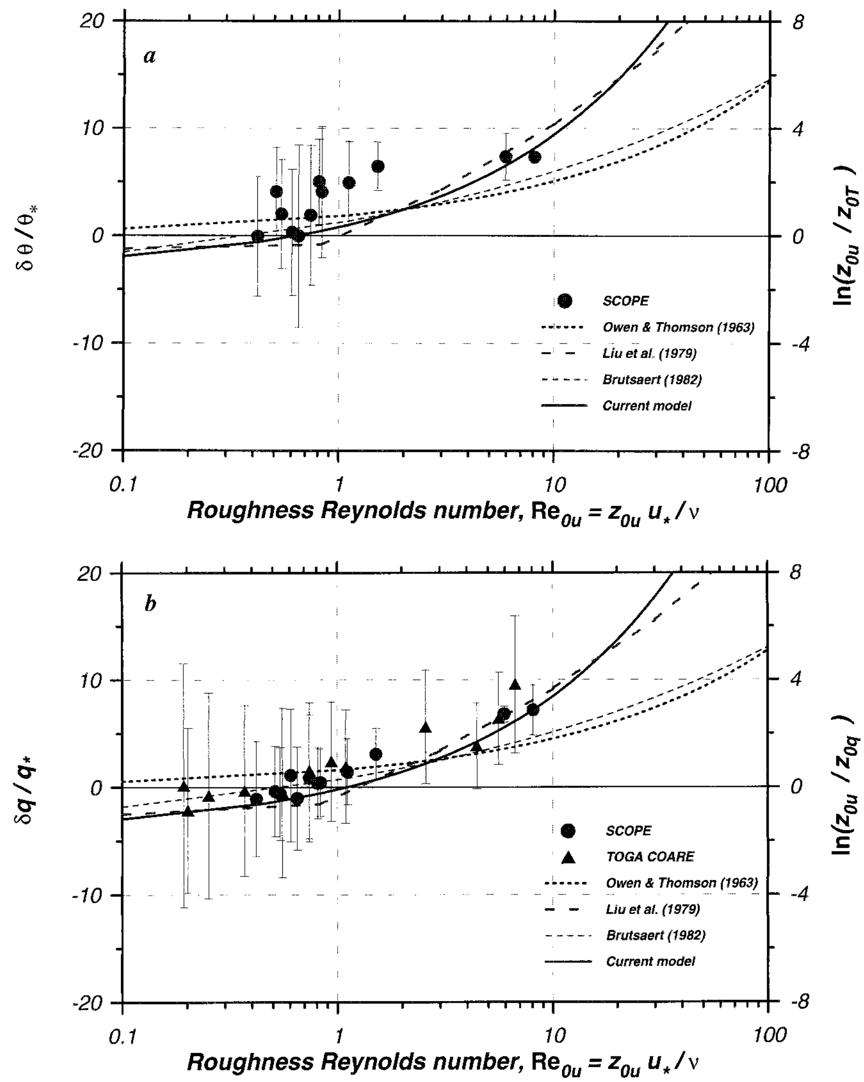

FIG. 2. Averaged dimensionless increments in temperature, $\delta\theta/\theta_*$, and in humidity, $\delta q/q_*$, at the sea surface vs the roughness Reynolds number, Re_{0u}: (a) $\delta\theta/\theta_*$ from SCOPE, (b) $\delta q/q_*$ from SCOPE and TOGA COARE. Averaging procedure is the same as in Fig. 1. The solid lines are after Eqs. (13) and (14). Other lines represent previous models. The line presented here for the Owen and Thomson (1963) model is derived from the equation $\delta\theta/\theta_* = 0.52\mathrm{Pr}^{0.8}\,\mathrm{Re}_{h0}^{0.45}$, where $\mathrm{Re}_{h0} \equiv h_0 u_*/\nu = 30\mathrm{Re}_{0u}$ (i.e., $z_{0u} = h_0/30$), Pr = 0.7 for temperature (a), and Sc = 0.6 for humidity (b). Liu et al. line is computed based on the data in Table 1 (Liu et al. 1979, p. 1727). Brutsaert (1982) model is described by Eq. (4.27) for temperature (a) and Eq. (4.28) for humidity (b) in Garratt (1992, p. 102) respectively.

See, for example, section 4.4 in Brutsaert (1982) and chapter 4 in Garratt (1992). Concerning regimes with swell, see Smedman et al. (1999).

In the following section, experimental data are employed to specify the factors A_θ and A_q and to recommend a practically useful interpolation linking the rough sea of Eqs. (9)–(10) with the smooth sea of Eqs. (11)–(12).

3. Empirical validation

Experimental data used in this paper are taken from measurements made aboard the R/V *Moana Wave* in the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) in 1992–93 and the R/P *FLIP* in the San Clemente Ocean Probing Experiment (SCOPE) in September 1993 by the National Oceanic and Atmospheric Administration's Environmental Technology Laboratory (Boulder, Colorado). These data described in Fairall et al. (1997) and Fairall et al. (1996a,b) cover the range of regimes from aerodynamically smooth (at light winds) to aerodynamically rough (at moderate and strong winds).

In TOGA COARE, measurements were carried out from the R/V *Moana Wave* for three cruise legs in the tropical warm pool area, western Pacific Ocean. The ship usually operated in a ''drift'' mode for ocean microstructure measurements. The Scripps Institute *FLIP* was moored about 15 km northwest off the northwestern point of San Clemente Island (off southern California) with good open ocean exposure for northwesterly winds. An identical seagoing flux system was used in these experiments. Detailed description of the measuring system can be found in Fairall et al. (1997). The instruments were deployed at 15 m for TOGA COARE and at 11 m above the sea surface at the end of a 20-m-long boom for SCOPE. The field data were obtained in the wind-speed range from 0.5 to 13 m s^{-1}.

The measurements include about 1000 individual points for TOGA COARE and 300 individual points for SCOPE. Each point represents 50-min averaged covariance and inertial-dissipation estimates of turbulent fluxes of momentum, sensible heat, and latent heat, as well as mean meteorological variables, radiation fluxes, and the boundary layer height. The sea surface temperature was derived from bulk water measurements at the 5-cm depth with a floating thermistor.

Corrections to the measured sea surface temperature for the cool-skin effect were made using the model of Fairall et al. (1996a). This effect was found to be of little importance for SCOPE: the cool-skin temperature increment was ~0.2 K, while the sea–air temperature difference was ~2.5 K. However, the cool-skin effect played an important role for TOGA COARE data where sea–air temperature was about 1 K. A sonic anemometer/thermometer and a high-speed infrared hygrometer were used to measure turbulent fluxes.

Fairall et al. (1996b) and Grachev et al. (1998) have analyzed the TOGA COARE and SCOPE data to examine the sea surface drag coefficient and aerodynamic roughness length, z_{0u}. They have shown that the roughness Reynolds number, $\mathrm{Re}_{0u} = z_{0u}u_*/\nu$, decreased as mean wind velocity decreased down to 4 m s^{-1}. With a further decrease of the wind speeds, Re_{0u} remained constant or slightly increased. The sea surface was definitely rough ($\mathrm{Re}_{0u} > 2$) at wind speeds stronger than 8–9 m s^{-1}.

In this paper, the TOGA COARE and SCOPE data are used to investigate the heat and mass transfer at the sea surface in terms of the scalar increments and roughness lengths.

In Fig. 1, the nondimensional increments in temperature, $\delta\theta/\theta_*$ (Fig. 1a), and humidity, $\delta q/q_*$ (Figs. 1b,c), are presented in a traditional way, namely, versus the mean wind speed u (averaged in wind-speed bins with 1 m s^{-1} width). Here, experimental data show a slight tendency to increase with increasing u. Data from TOGA COARE (Fig. 1c) show more scatter than data from SCOPE (Fig. 1b) due to (i) more variable meteorological conditions and (ii) lower accuracy of ship measurements compared to measurements from the ideal observing platform *FLIP*. Data from TOGA COARE on the temperature increment are not shown. Here, the air–sea temperature differences were so small that the data could not be used.

Figure 2 presents the same increments versus the roughness Reynolds number Re_{0u}. The use of averaged data allows avoiding the so-called artificial correlation in the plot (in both axes u_* is employed to make variables nondimensional). Averaging is performed in the same manner as in Fig. 1.

Figure 2b shows the humidity increment. It provides more convincing evidence of the trend. This is only natural. During SCOPE, the temperature variations were small, which is why the accuracy of measurements was much higher for humidity than for temperature.

Relationships presented by solid curves in Fig. 2 are

$$\frac{1}{k_T}\ln\frac{z_{0u}}{z_{0T}} = \frac{\delta\theta}{\theta_*} = A_\theta \mathrm{Re}_{0u}^{1/2} - B_\theta \quad \text{and} \tag{13}$$

$$\frac{1}{k_q}\ln\frac{z_{0u}}{z_{0q}} = \frac{\delta q}{q_*} = A_q \mathrm{Re}_{0u}^{1/2} - B_q. \tag{14}$$

Reasonably good correspondence with empirical data is achieved taking $A_\theta = A_q = 4.0$, $B_\theta = -3.2$, and $B_q = -4.2$. Other curves in Fig. 2 show some earlier models. The proposed formulation, Eqs. (13) and (14), exhibits the best correspondence to the data. The Liu et al. (1979) formulation is slightly worse but very close to Eqs. (13) and (14). Other formulations presented in the figures essentially underestimate $\delta\theta/\theta_*$ and $\delta q/q_*$ at moderate and strong winds.

Equations (13) and (14) match the smooth regime equations, Eqs. (11) and (12), at $\mathrm{Re}_{0u} = 0.1$. Compared to Eqs. (9) and (10), they include additional terms, B_θ and B_q, respectively. The latter are introduced to describe the transition from the smooth to the rough sea surface regime. Clearly, at $\mathrm{Re}_{0u} \gg 1$, Eqs. (13) and (14) asymptotically approach Eqs. (9) and (10).

4. Conclusions

As follows from the above analysis, the scalar roughness lengths over the sea surface can be calculated (i) at low values of Re_{0u}, through the classical smooth surface regime equations, Eq. (12), and (ii) at moderate and high values of Re_{0u}, through the proposed refined equations, Eqs. (13) and (14). A reasonable interpolation reads

$$\frac{1}{k_T}\ln\frac{z_{0u}}{z_{0T}} = \frac{\delta\theta}{\theta_*} = \begin{cases} -2 & \text{at } \mathrm{Re}_{0u} \le 0.1 \\ 4.0\mathrm{Re}_{0u}^{1/2} - 3.2 & \text{at } \mathrm{Re}_{0u} \ge 0.1 \end{cases} \tag{15}$$

and

$$\frac{1}{k_q}\ln\frac{z_{0u}}{z_{0q}} = \frac{\delta q}{q_*} = \begin{cases} -3 & \text{at } \mathrm{Re}_{0u} \le 0.1 \\ 4.0\mathrm{Re}_{0u}^{1/2} - 4.2 & \text{at } \mathrm{Re}_{0u} \ge 0.1. \end{cases} \tag{16}$$

Here, regimes with swell are not included.

For practical purposes, the aerodynamic roughness length of the sea surface, z_{0u}, can be estimated using the familiar Charnock formula or more advanced techniques. The roughness lengths for scalars, z_{0T} and z_{0q} are immediately calculated using Eqs. (15), (16), and (8). The drag and heat–mass transfer coefficients are calculated using Eq. (5).

Data in Fig. 2 support Eqs. (13) and (14) in a wide range of Re_{0u} including regimes with strong winds and well developed waves. What this means is Eqs. (15) and (16) are applicable even in the presence of foam and spray at the sea surface.

Equations (15) and (16) can be recommended for practical use in climate, weather prediction, and mesoscale air–sea interaction models.

In the interval $\mathrm{Re}_{0u} < 10$, they differ only slightly from the commonly used formulation of Liu et al. (1979). An advantage of the proposed analysis is that it discloses the physical nature of the coefficients A_θ, A_q, B_θ and B_q in Eqs. (13), (14), and by this means offers a physically grounded approach to further improvement of the heat and mass transfer calculation. Thus in future work it is worthwhile to investigate the dependencies of the above coefficients on the wave field parameters and to incorporate these dependencies in a more general formulation based on Eqs. (13) and (14). Here, data related to very strong winds and consequently very high values of Re_{0u} (when the Liu et al. and the proposed formulations diverge) would be especially useful.

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