DANISH METEOROLOGICAL INSTITUTE

——— SCIENTIFIC REPORT ———

03-10

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dmi.dk

COPENHAGEN 2003

ISSN Nr. 0905-3263 (printed)
ISSN Nr. 1399-1949 (online)
ISBN-Nr. 87-7478-486-2

A note on the sea surface momentum roughness length

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1. Introduction

The momentum flux at the air-sea interface depends in a rather complex manner on both the states of the atmosphere and the sea. Similarity theory for the stationary, horizontally homogeneous, neutral surface layer predicts

$$U(z) = \frac{u_*}{k} \ln \frac{z}{z_0}. \tag{1}$$

In (1) u_* is the surface friction velocity, $k = 0.4$ is the Von Karman constant, z is hight above sea level, and z_0 is the momentum roughness length of the sea surface. The complexity in this classical logarithmic wind profile is hidden in z_0. This parameter generally depends on a number of independent parameters, describing the states of the sea surface and the atmospheric surface layer. The surface friction velocity is one of these parameters. Application of (1) and its extensions to the stably and unstably stratified atmospheric surface layer requires a parameterization of z_0. The present note demonstrates how a dimensional analysis can be applied as a guidance for such a parameterization.

2. Dimensional analysis

The momentum flux at the air-sea interface depends on both the state of the atmosphere and the state of the sea. It has been argued that the effect of surface water waves on the momentum flux can be represented by σ, the surface tension of sea water, g , the acceleration of gravity, and c_p, the phase speed at the peak of the sea surface wave spectrum (Clayson et al., 1996). The momentum flux also depends on z_0, the momentum roughness length of the sea surface, ρ_w, the density of sea water and on ν_a, the kinematic viscosity of air. The dependence on ν_w, the kinematic viscosity of sea water, can be dropped from the list, since ν_a/ν_w is approximately constant.

The phase speed of surface waves is approximately

$$c_f = \left(\frac{2\pi}{\lambda} \frac{\sigma}{\rho_w} + \frac{\lambda}{2\pi} g \right)^{1/2}, \tag{2}$$

where λ is the wave length and ρ_w is the density of sea water. Equation (2) has a minimum phase speed $c_{f*}=\sqrt{2}(\sigma g/\rho_w)^{1/4}$ at wave length $\lambda_*=(\sigma g/\rho_w)^{1/2}$. A wind speed larger than c_{f*} is therefore necessary to sustain surface waves, consisting of capillary waves (first term in (2)) and gravity waves (last term in (2)). At the phase speed c_{f*} the capillary and gravity waves have the same wave length. Equation (2) shows that the wave length of the capillary waves decreases with increasing phase/wind speed, while the opposite is the case for the gravity waves.

At wind speeds sustaining surface waves at $c_f \geq c_{f*}$ it is not expected that ν makes any significant contribution to the surface momentum flux. It is, on the other hand, expected that both g, σ, ρ_w and c_p contributes to the surface momentum flux. If no other independent parameters contribute to the surface momentum flux, a dimensional analysis yields

$$z_0 = z_l \cdot F_l \left(\frac{{u_*}^2}{{u_l}^2}, \frac{c_p}{u_l} \right), \tag{3}$$

where the length scale is

$$z_l = \left(\frac{\sigma}{\rho_w \cdot g} \right)^{1/2} = \frac{\lambda_*}{2\pi}, \tag{4}$$

and the velocity scale is

$$u_l = \left(\frac{\sigma g}{\rho_w} \right)^{1/4} = \frac{\sqrt{2}}{2} \cdot c_{f*}. \tag{5}$$

Another choice of scaling parameters gives

$$z_0 = z_m \cdot F_m \left(\frac{1}{z_m} \frac{\sigma}{{u_*}^2 \rho_w}, \frac{c_p}{u_*} \right), \tag{6}$$

where $z_m = {u_*}^2 g^{-1}$ is a length scale replacing z_l. The corresponding velocity scale replacing u_l is $u_m = u_*$. By noting that ${u_l}^2 {u_*}^{-2} = z_l {z_m}^{-1}$ (3) and (6) can be rewritten as

$$z_0 = z_l \cdot F_l \left(\frac{z_m}{z_l}, \left(\frac{z_m}{z_l} \right)^{-1/2} \frac{c_p}{u_*} \right) \tag{7}$$

and

$$z_0 = z_m \cdot F_m \left(\left(\frac{z_m}{z_l} \right)^{-2}, \frac{c_p}{u_*} \right), \tag{8}$$

respectively.

Suppose that F_l can be written as a power series containing terms of the form

$$c(\alpha, \beta) \cdot \left(\frac{z_m}{z_l} \right)^{\alpha} \cdot \left(\left(\frac{z_m}{z_l} \right)^{-1/2} \frac{c_p}{u_*} \right)^{\beta}, \tag{9}$$

where α and β are real numbers and $c(\alpha, \beta)$ is a nondimensional constant. The contribution to z_0 from each of these terms is

$$z_0(\alpha, \beta) = c(\alpha, \beta) \cdot z_l \cdot \left(\frac{z_m}{z_l} \right)^{(\alpha - \frac{1}{2}\beta)} \left(\frac{c_p}{u_*} \right)^{\beta}. \tag{10}$$

The corresponding term in (8) is then

$$z_0(\alpha, \beta) = c(\alpha, \beta) \cdot z_m \cdot \left(\frac{z_m}{z_l} \right)^{(\alpha - \frac{1}{2}\beta - 1)} \left(\frac{c_p}{u_*} \right)^{\beta} \tag{11}$$

Charnock, 1955, suggested

$$z_{0c} = c_c \frac{{u_*}^2}{g}. \tag{12}$$

This result is obtained from (10) (and (11)) for $\alpha = 1$, $\beta = 0$ and $c(1,0) = c_c$ i.e. by assuming that z_0 only depends on the length scale z_m. It is clear from (7) to (11) that the Charnock relation (12) is likely to be an inaccurate approximation to z_0. A generalization of the Charnock relation has been suggested by Maat et al., 1991. They proposed

$$z_{0m} = c_m \frac{{u_*}^2}{g} \left(\frac{c_p}{u_*} \right)^{-1} \tag{13}$$

with $c_m \approx 0.8$. They found support for this relation in the results obtained from the HEXMAS field campaign (Katsaros et al., 1987). The result in (13) is obtained from (10) and (11) for $\alpha = 1/2$, $\beta = -1$ and $c(1/2, -1) = 0.8$. Note that (13) is a special case of the more general result

$$\sum_i z_0(1 + \frac{1}{2}\beta_i, \beta_i) = \sum_i c(1 + \frac{1}{2}\beta_i, \beta_i) \cdot z_m \left(\frac{c_p}{u_*} \right)^{\beta_i} \tag{14}$$

obtained by assuming that z_0 is independent of z_l.

For wind speeds larger than the threshold maintaining capillary waves it is expected that the latter act as roughness elements on the water surface and therefore make a contribution to z_0. Bourassa et al. (Clayson et al., 1996) developed the parameterization

$$z_{0b} = \frac{b\sigma}{{u_*}^2 \rho_w} + 0.48 \frac{{u_*}^2}{g} \left(\frac{c_p}{u_*} \right)^{-1}, \tag{15}$$

valid for $c_p > c_{f*}$. They applied $b = 0.019$. The first term in (15) is obtained from (10) (and (11)) with $\alpha = -1$, $\beta = 0$ and $c(-1,0) = b$. Note that this result is obtained if it is assumed that the contribution from capillary waves to z_0 is independent of the gravity waves (i.e. independent of g and c_p). The second term in (15) is the contribution from gravity waves. It has the same form as in (13), but the constant has been reduced from 0.8 to 0.48.

2.1. The low-wind regime

Below the threshold value for wind speed sustaining capillary waves both molecular friction and (old sea) surface gravity waves are expected to contribute to the surface momentum flux. For these conditions the momentum flux is expected to depend on z_0, ν, g and c_p. A dimensional analysis yields

$$z_0 = z_\nu \cdot F_\nu \left(\frac{{u_*}^2}{(g\nu)^{2/3}}, \frac{c_p}{u_*} \right), \tag{16}$$

where $z_\nu = (\nu^2 \cdot g^{-1})^{1/3}$ is a length scale and $u_\nu = (g \cdot \nu)^{1/3}$ is a velocity scale for the low-wind regime. If it is assumed that the contributions to z_0 from molecular forces and gravity waves are independent of each other and if (16) is written as a power series similar to (10) and (11) it follows that the contribution to z_0 from molecular friction is

$$z_0(-\frac{1}{2}, 0) = c(-\frac{1}{2}, 0)\frac{\nu}{u_*}. \tag{17}$$

Note that $c(-\frac{1}{2}, 0) = 0.11$ gives the formula for the momentum roughness length of an aerodynamically smooth surface.

Finally, with the above assumptions it follows from (16) that the contribution from surface gravity waves is

$$\sum_i z_0(1, \beta_i) = \sum_i c(1, \beta_i)\frac{{u_*}^2}{g} \cdot \left(\frac{c_p}{u_*}\right)^{\beta_i}. \tag{18}$$

Equation (18) must be consistent with (14), i.e. $c(1, \beta_i) = c(1 + \frac{1}{2}\beta_i, \beta_i)$.

2.2. Discussion and conclusion

Based on the analysis presented above it is suggested to parameterize z_0, the momentum roughness length of the sea surface, by the formula

$$z_0 = c_1\frac{\nu}{u_*} \cdot \delta_1 + c_2\frac{{u_*}^2}{g}\left(1 - \exp(-\frac{u_*}{c_p})\right)\delta_2 + c_3\frac{\sigma}{{u_*}^2\rho_w} \cdot \delta_3, \tag{19}$$

where $\delta_1 = 1$, $\delta_2 = 0$ for $c_p = 0$ and $\delta_2 = 1$ for $c_p \geq c_{f*}$ and $\delta_3 = 0$ in the low-wind regime and otherwise $\delta_3 = 1$. Note that the second term in (19) is consistent with (14) and approximately equal to the second term in (15) for wave ages $c_p/u_* > 5$ and $c_2 = 0.48$.

Consider the following hypothetical scenario, consisting of phase 1, 2, 3 and 4. In phase 1 the wind is in the low-wind regime with a calm sea, i.e. with a sea surface without capillary and gravity waves. In this smooth surface regime z_0 is given by the first term in (19). In phase 2 the wind speed has increased to a level, where capillary and gravity waves are sustained at the limiting phase speed c_{f*}. In this phase it is expected that the capillary waves and the gravity waves contribute to z_0 with the same amount, i.e.

$$c_2\frac{{u_*}^2}{g}\left(1 - \exp(-\frac{u_*}{c_{f*}}\right) = c_3\frac{\sigma}{{u_*}^2\rho_w} \tag{20}$$

or

$$u_* \approx \left(\frac{c_3}{4 \cdot c_2}\right)^{1/5} \cdot c_{f*}. \tag{21}$$

With the values $c_2 = 0.48$ and $c_3 = 0.019$ from (15) it follows that $u_* \approx 0.4 \cdot c_{f*}$. By coincidence the constant becomes equal to k, the Von Karman constant. The wind speed at 10 m height above mean sea level in the neutral surface layer is in phase 2 given by

$$U_2(10) \approx c_{f*} \ln(\frac{z}{2c_2k^3} \cdot \frac{g}{{c_{f*}}^2}) \approx 2.4\mathrm{m\,s}^{-1}. \tag{22}$$

The friction velocity in phase 2 is approximately $u_{*2} = 0.09\,\mathrm{m\,s}^{-1}$.

In phase 3 the wind speed increases to large values. Then, according to (19), the contribution to z_0 from the capillary waves decreases proportional to u_*^{-2} and the contribution from the gravity waves of the developing sea becomes proportional to u_*^3/c_p.

Finally, in phase 4 the wind speed decreases to a value below $U(10) = 2.4\,\mathrm{m\,s^{-1}}$, while a surface gravity wave spectrum is still present (old sea). In this phase z_0 is given by

$$z_0 = c_1 \frac{\nu}{u_*} + c_2 \frac{{u_*}^2}{g} \cdot \left(\frac{c_p}{u_*}\right)^{-1}. \tag{23}$$

Note that for

$$u_* < \left(\frac{c_1}{c_2}\right)^{1/3} \cdot u_\nu \cdot \left(\frac{c_p}{u_*}\right)^{1/3} = 0.61 u_\nu \cdot \left(\frac{c_p}{u_*}\right)^{1/3} \tag{24}$$

the contribution to z_0 from molecular forces is larger than the contribution from the waves. The last equality in (24) applies for $c_1 = 0.11$ and $c_2 = 0.48$. It follows from the latter equation that for the weak-wind sea the contribution to z_0 from molecular forces is always larger than the contribution from the waves if the wave age is larger than about 23.

For a growing wind sea Janssen et al., 1994, derived the parameterization

$$z_0 = c_n \frac{\tau}{g} \cdot (1 - \frac{\tau_w}{\tau})^{-1/2}, \tag{25}$$

where τ is the kinematic wind stress, τ_w the corresponding wave stress and $c_n \approx 0.01$. This result is consistent with a dimensional analysis for the situation where the difference between the wind and wave stres only depends on z_0, τ and g, since a dimensional analysis then gives

$$z_0 = \frac{\tau}{g} \cdot F\left(\frac{\tau - \tau_w}{\tau}\right). \tag{26}$$

The result in (25) is obtained for $F = c_n \cdot (\frac{\tau - \tau_w}{\tau})^{-1/2}$. From (19) and (25) follows

$$\frac{\tau_w}{\tau} = 1 - {c_n}^2 \cdot \left(c_2(1 - \exp(-\frac{\tau^{1/2}}{c_p})) + c_3 \frac{g\sigma}{\tau^2 \rho_w}\right)^{-2}. \tag{27}$$

For a well-developed sea (27) can be approximated by $\tau_w/\tau = 1 - (c_n/c_2)^2 \cdot (c_p/u_*)^2$. It follows from this equation that $\tau_w = 0$ for $c_p/u_* = 48$.

In atmospheric models without wave-atmosphere interaction application of relations such as (19) requires a parameterization of c_p. Such a parameterization is non-trivial, since it involves past history of the wind/wave field.

A simple parameterization of c_p is

$$c_p = c_{f*} \left(\frac{V_T}{V_0}\right)^2, \tag{28}$$

where $V_0 = 2.4\,\mathrm{m\,s^{-1}}$ and $V_T = (< u >^2 + < v >^2)^{1/2}$ is a running time mean of the wind at 10 m height. A sudden change in wind direction, typically associated with a surface front, creates a young sea superposed on the old sea and with wave propagation in the new wind direction. This situation is not taken into account in (28) and is clearly a limitation of this simple parameterization of c_p.

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