A NOTE ON WIND SPEED AND SEA STATE DEPENDENCE OF THE HEAT EXCHANGE COEFFICIENT

V.K. MAKIN
Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands

(Received in final form 16 December 1998)

Abstract. Both mean and wave-induced motions generate turbulence in the air flow above sea waves. Assuming a local balance between production of turbulent kinetic energy and its dissipation, an explicit relation for the heat exchange coefficient C_H is obtained. It is shown that C_H follows a square-root dependence on the drag coefficient C_D. However, the proportionality coefficient appears to depend on the sea state, expressed in terms of the coupling parameter. Dependence on the sea state suppresses the $C_D^{1/2}$ wind-speed dependence, and results in a marginal increase of C_H with increase in the wind speed.

Keywords: Heat exchange coefficient, Sea state dependence.

1. Introduction

It is well established by field measurements that the heat (sensible and latent) exchange coefficient over the sea is much less dependent on the wind speed than the drag coefficient (Anderson, 1993; DeCosmo et al., 1996; Friehe and Schmitt, 1976; Geernaert, 1990; Large and Pond, 1982; Smith, 1980, 1988, 1989). However, the actual wind-speed dependence of the heat exchange coefficient is obscured, because difficulties in heat-flux measurements result in a considerable scatter of data. The heat exchange coefficient C_H is usually parameterized as a constant, i.e. wind speed independent C_H = Const. (Anderson, 1993; DeCosmo et al., 1996; Friehe and Schmitt, 1976; Large and Pond, 1982; Smith, 1980, 1988, 1989), with the constant having a value of about 10^{-3}.

However, a dependence on wind speed is not ruled out by field measurements. Large and Pond (1982) argue that for wind speeds above 10 m s^{-1} the parameterization of the heat exchange coefficient in terms of a constant temperature roughness length is more appropriate, though the statistical improvement of such a fit to their data is not significant compared to the constant heat exchange coefficient parameterization. Assuming the logarithmic distribution of temperature above the sea surface, it immediately follows that in this case

$$C_H = c_1 C_D^{1/2} \tag{1}$$

Boundary-Layer Meteorology **91:** 127–134, 1999.

where C_D is the momentum exchange coefficient (the drag coefficient), and c_1 is a constant. For high wind speeds the dependence (1) overestimates the heat exchange coefficient, compared to the constant value of C_H, by more than 50%.

The different wind-speed dependences of the drag coefficient and the heat exchange coefficient can be explained by the difference in exchange mechanisms of momentum and heat close to the sea surface (Makin and Mastenbroek, 1996). Momentum is transported to a large extent by the organised wave-induced motions correlated with the waves (the wave-induced stress). With increase in the wind speed the wave-induced stress increases, which results in the growth of the drag coefficient (Makin et al., 1995). The wave-induced flux of heat plays a negligible role in the heat transport (Makin and Mastenbroek, 1996), so that waves cannot directly influence the exchange of heat over the sea. The heat transport is fully determined by turbulence above waves, and by the molecular processes in the laminar sub-layer next to the surface.

Makin and Mastenbroek (1996) used a differential model of the boundary layer above waves based on the full balance equations of the turbulent kinetic energy (TKE) and its dissipation to show that the heat exchange coefficient does increase with the wind speed, though slower than is described through (1).

Here, assuming a local balance between the TKE production and its dissipation, an explicit relation for the heat exchange coefficient is obtained. The heat exchange coefficient follows $C_D^{1/2}$ dependence; however, the proportionality coefficient is not a constant but depends on the sea state, described in terms of the coupling parameter α (the ratio of the wave-induced stress at the surface to the total stress). This dependence on α suppresses the $C_D^{1/2}$ increase of C_H, which results only in a marginal increase of C_H with increase in the wind speed.

2. Eddy Viscosity Above Waves

Above waves the total stress (u_*^2) is supported by the mean turbulent stress $\tau^t = -\overline{u'w'}$, and the wave-induced stress τ^w due to the organized wave motions in the atmosphere induced by waves (Janssen, 1989; Chalikov and Makin, 1991; Makin et al., 1995), so that

$$\tau^t(z) + \tau^w(z) = u_*^2, \tag{2}$$

and by definition equals the square of the friction velocity u_*.

The local turbulence closure relates the turbulent flux to the gradient of the velocity field u via the eddy viscosity K

$$\tau^t(z) = K\frac{\partial u}{\partial z}. \tag{3}$$

From (2) and (3)

$$K\frac{\partial u}{\partial z} = u_*^2 - \tau^w(z). \tag{4}$$

In terms of the coupling parameter

$$\alpha = \frac{\tau^w(0)}{u_*^2}, \tag{5}$$

and the dimensionless decay function of the wave-induced stress

$$f(z) = \frac{\tau^w(z)}{\tau^w(0)}, \tag{6}$$

Equation (4) is rewritten as

$$K\frac{\partial u}{\partial z} = u_*^2(1 - \alpha f(z)). \tag{7}$$

The decay function $f(z)$ approaches 1 at the surface, and rapidly decays with height above the waves (Makin and Mastenbroek, 1996).

To obtain the eddy viscosity K above waves, a local balance between the TKE production P and its dissipation to heat ε is assumed (Chalikov and Belevich, 1993; Makin and Mastenbroek, 1996),

$$P = \varepsilon. \tag{8}$$

The production of the TKE P above waves results from both the mean and the wave-induced motions (Makin and Mastenbroek, 1996),

$$P = P^t + P^w. \tag{9}$$

The first term on the right-hand side is traditionally written as

$$P^t = \tau^t\frac{\partial u}{\partial z}, \tag{10}$$

and the second term follows from a balance equation of the mean wave-induced energy, where the vertical flux of the wave-induced energy is neglected (Makin and Mastenbroek, 1996), viz.

$$P^w = \tau^w\frac{\partial u}{\partial z}. \tag{11}$$

The TKE production above waves is thus

$$P = (\tau^t + \tau^w)\frac{\partial u}{\partial z} = u_*^2\frac{\partial u}{\partial z}. \tag{12}$$

Using the mixing length theory, and expressing the dissipation in terms of K and the mixing length $l = \kappa z$ (κ is the von Karman constant), $\varepsilon = K^3 l^{-4}$, the equation for the eddy viscosity is found from (7), (8) and (12)

$$K = lu_* (1 - \alpha f(z))^{1/4} . \tag{13}$$

If an erroneous balance between the production due to the mean motion only and the dissipation is assumed (Janssen, 1989; Chalikov and Makin, 1991; Makin et al., 1995), i.e.,

$$P^t = \varepsilon, \tag{14}$$

it follows from (3), (10) and (14) that

$$K = l^2 \frac{\partial u}{\partial z}, \tag{15}$$

and further accounting for (7)

$$K = lu_* (1 - \alpha f(z))^{1/2} . \tag{16}$$

Near the surface as α approaches 1 under strong winds, relation (16) considerably underestimates the eddy viscosity compared to relation (13).

3. The Heat Exchange Coefficient

Above waves the heat flux is supported only by turbulence (Makin and Mastenbroek, 1996), whence

$$-\overline{\theta' w'} = \theta_* u_* = K \frac{\partial \theta}{\partial z}, \tag{17}$$

where θ_* is the temperature scale. This flux is constant with height in the atmospheric surface layer.

From (17) and (13) the heat exchange coefficient is obtained

$$C_H = \frac{\theta_* u_*}{u_{10} \Delta\theta} = \kappa C_D^{1/2} \left(\int_{z_0^\nu}^{10} \left[1 - \alpha f(z)\right]^{-1/4} d(\ln z) \right)^{-1} . \tag{18}$$

In (18) u_{10} is the wind speed at 10-m height, and the drag coefficient is defined as

$$C_D = \frac{u_*^2}{u_{10}^2}. \tag{19}$$

Also $\Delta\theta$ is the temperature difference between 10-m height and the surface, and integration is done from the viscous roughness length z_0^ν to 10-m height. Makin et al. (1995) have shown that the viscous roughness length is related to the surface turbulent stress $\tau^t(0) = u_*^2(1-\alpha)$ through

$$z_0^\nu = 0.1\frac{\nu}{u_*(1-\alpha)^{1/2}} \tag{20}$$

where ν is the kinematic viscosity of the air.

What follows immediately from (18) is that the heat exchange coefficient is proportional to $C_D^{1/2}$, with the proportionality coefficient dependent upon the coupling parameter α. If the sea-state dependence in (18) is ignored, or if it is assumed that the coupling parameter is a slowly varying function of the wind speed, the relation (1) is recovered.

However, the coupling parameter is a strongly varying function of the wind speed. The wind-speed dependence of the coupling parameter is shown in Figure 1. This dependence is obtained by the Makin and Mastenbroek (1996) model. Data of Banner and Peirson (1998), though with only two experimental points available, seem to support the model prediction.

The heat exchange coefficient, calculated according to (18), is shown in Figure 2, together with the open ocean data of Anderson (1993). The dependence of C_H on the coupling parameter suppresses the $C_D^{1/2}$ dependence on the wind speed, which results in a slower increase of the heat exchange coefficient with wind speed compared to the dependence (1). This result was already obtained by Makin and Mastenbroek (1996), although no proper explanation was given by them. For high wind speeds the difference in C_H between (1) and (18) can reach 20% and more.

If an erroneous balance between TKE production and dissipation (14) is used to calculate the eddy viscosity (16), the exponent $-1/4$ in (18) should be replaced by $-1/2$. In this case the suppression is larger, especially for high winds when $(1-\alpha) \to 0$, and the heat exchange coefficient decreases with increase of the wind speed. This erroneous dependence was also shown by Makin and Mastenbroek (1996).

To obtain a simple parameterization for C_H, the integral in (18) is approximated by $13.2(1-0.75\alpha)^{-1/4}$, which gives

$$C_H = 0.031 C_D^{1/2}(1-0.75\alpha)^{1/4}. \tag{21}$$

Relation (21) reasonably approximates (18) (see Figure 2) and can be used in applied studies.

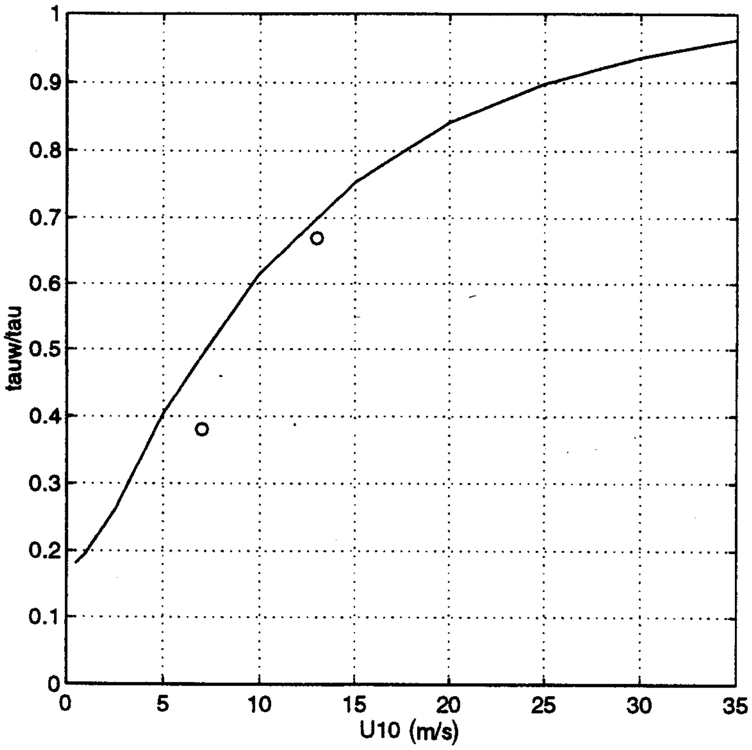

Figure 1. The coupling parameter α versus u_{10}. Circles – experimental data of Banner and Peirson (1998).

4. Discussion

The assumption concerning the local balance between the production of the turbulent kinetic energy due to the mean and the wave-induced motions above sea waves, and its dissipation, allows an explicit relation for the heat exchange coefficient C_H to be developed. It is shown that C_H depends on the square root of the sea drag coefficient C_D. However, the proportionality coefficient appears to depend on the sea state, expressed in terms of the coupling parameter. Dependence on the sea state suppresses the $C_D^{1/2}$ wind-speed dependence, and results in a marginal increase of C_H with increase in the wind speed. This result was already implicitly obtained by Makin and Mastenbroek (1996), using a differential model of the boundary layer above waves based on the full balance equations of the TKE and its dissipation. Here a clearer explanation of this fact is given.

In Makin and Mastenbroek (1996), we also argued that the use of the mixing length theory will result in a decrease of C_H with wind-speed increase. Here, this result is explained as a consequence of an erroneous treatment of the local balance between production of the turbulent kinetic energy above waves due to the mean

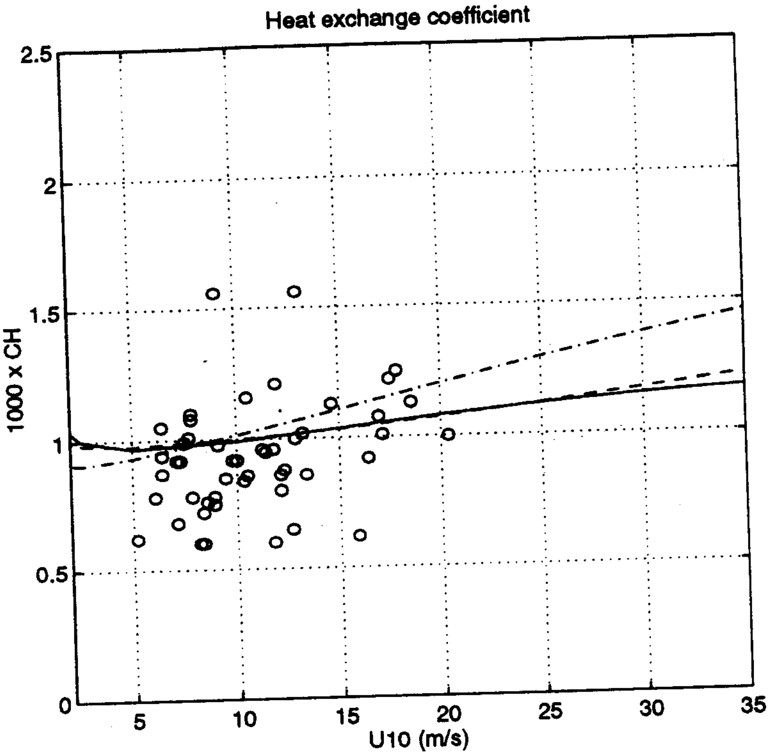

Figure 2. The heat exchange coefficient C_H versus u_{10}. Solid line – relation (18); dashed line – relation (21); dashed-dotted line – dependence (1) with $c_1 = 0.027$. Circles – experimental data of Anderson (1993).

motion only, and its dissipation, which results in an erroneous estimation of the eddy viscosity above waves.

Though experimental data do not distinguish between the wind-speed dependence of the heat exchange coefficient (1), (18), or C_H = Const. because of the large scatter in data, it is thought that the use of the physically based relation (18) is preferable in applied studies. It relates C_H not only to the drag coefficient, but to the sea state too.

It is worthwhile to mention here that sea spray may play a role in heat (sensible and latent) exchanges at the sea surface at wind speeds of about 25 m s^{-1} and above (Makin, 1998). In this case the generalized explicit relations for the sensible heat and humidity exchange coefficients that account for the sea spray effects can be easily obtained by substituting expression (13) for the eddy viscosity coefficient K obtained in the present paper into equations (67)–(72) in Makin (1998).

Acknowledgements

To Vladimir Kudryavtsev for fruitful discussions. This work was supported by EU Environment Programme (Contract ENV4-CT97-0460, ASPEN).

References

Anderson, R. J.: 1993, 'A Study of Wind Stress and Heat Flux Over the Open Ocean by the Inertial-Dissipation Method', *J. Phys. Oceanogr.* **23**, 2153–2161.

Banner, M. L. and Peirson, W. L.: 1998, 'Tangential Stress Beneath Wind-Driven Air-Water Interfaces', *J. Fluid Mech.* **364**, 115–145.

Chalikov, D. V. and Belevich, M. Yu.: 1993, 'One-Dimensional Theory of the Wave Boundary Layer', *Boundary-Layer Meteorol.* **63**, 65–96.

Chalikov, D. V. and Makin, V. K.: 1991, 'Models of the Wave Boundary Layer', *Boundary-Layer Meteorol.* **56**, 83–99.

DeCosmo, J., Katsaros, K. B., Smith, S. D., Anderson, R. J., Oost, W. A., Bumke, K., and Chadwick, H.: 1996, 'Air-Sea Exchange of Water Vapor and Sensible Heat: The Humidity Exchange Over the Sea (HEXOS) Results', *J. Geophys. Res.* **101**, 12,001–12,016.

Friehe, C. A. and Schmitt, K. F.: 1976, 'Parameterizations of Air-Sea Interface Fluxes of Sensible Heat and Moisture by the Bulk Aerodynamic Formulas', *J. Phys. Oceanogr.* **6**, 801–809.

Geernaert, G. L.: 1990, 'Bulk Parameterizations for the Wind Stress and Heat Fluxes', in G. L. Geernaert and W. J. Plant (eds.), *Surface Waves and Fluxes, Vol. 1*, Kluwer Academic Publishers, Dordrecht, 336 pp.

Janssen, P. A. E. M.: 1989, 'Wave-Induced Stress and the Drag of Air Flow over Sea Waves', *J. Phys. Oceanogr.* **19**, 745–754.

Large, W. G. and Pond, S.: 1982, 'Sensible and Latent Heat Flux Measurements Over the Ocean', *J. Phys. Oceanogr.* **12**, 464–482.

Makin, V. K.: 1998, 'Air-Sea Exchange of Heat in the Presence of Wind Waves and Spray', *J. Geophys. Res.* **103**, 1137–1152.

Makin, V. K. and Mastenbroek, C: 1996, 'Impact of Waves on Air-Sea Exchange of Sensible Heat Momentum', *Boundary-Layer Meteorol.* **79**, 279–300.

Makin, V. K., Kudryavtsev, V. N., and Mastenbroek, C.: 1995, 'Drag of the Sea Surface', *Boundary-Layer Meteorol.* **73**, 159–182.

Smith, S. D.: 1980, 'Wind Stress and Heat Flux Over the Ocean in Gale Force Winds', *J. Phys. Oceanogr.* **10**, 709–726.

Smith, S. D.: 1988, 'Coefficients for Sea Surface Wind Stress, Heat Flux and Wind Profiles as a Function of Wind Speed and Temperature', *J. Geophys. Res.* **93**, C12, 15,467–15,472.

Smith, S. D.: 1989, 'Water Vapour Flux at the Sea Surface', *Boundary-Layer Meteorol.* **47**, 277–283.