opdrachtgever:

Rijkswaterstaat, Tidal Waters Division

The dependence of surface drag on waves

A literature survey

October 1991

delft hydraulics

The dependence of surface drag on waves

A literature survey

H.F.P. van den Boogaard, R.E. Uittenbogaard, H. Gerritsen

delft hydraulics

THE DEPENDENCE OF SURFACE DRAG ON WAVES

Contents:

October 1991

ABSTRACT

A literature study has been performed on wave dependent formulations of the winddrag coefficient C_d. This study was inspired by the suggestion that, especially for storm conditions, the CSM-model can be improved by using a wave dependent C_d instead of the 'traditional' form that uses only the wind speed. Therefore, it was aimed at an overview of wave dependent C_d formulas that are feasible for implementation in the CSM-model.

Roughly speaking, the C_d formulas that are proposed in the literature can be divided into two classes. One class consists of formulas that use the complete spectral density of the wave field; the other class is more empirical and uses merely a few wave parameters for the description of the surface drag. The latter approach is most widely used and there is consensus that the so called wave age is the key parameter for the description of the surface roughness.

On the basis of this study it is concluded that inclusion of wave information in C_d, e.g. from results obtained from a numerical wave model, will improve storm surge predictions with CSM.

Although the approaches that use the spectrum tend to have a more sound physical basis, the C_d formulas based on wave age are more promising for implementation in the CSM-model given their computational efficiency.

In the final chapter three promising wave dependent C_d-formulations are proposed.

LIST OF SYMBOLS

α	Charnock's constant
β	Phillips' constant
C_d	windstress coefficient
c_p	phase velocity of frequency component where spectral density is maximal
δ_v	viscous (atmospheric) sublayer at air-water interface
δ_v^+	viscous (atmospheric) sublayer at air-water interface in wall coordinates: $\delta_v^+ = \delta_v \cdot u_* / \nu$
D	depth of sea or lake
E	total power of wave field
f	wave frequency; $f = \omega / 2\pi$
f_p	'peak frequency' (frequency where spectral density $S(\cdot)$ is maximal)
g	acceleration of gravity
h	distance above the water surface
h_s	height of the roughness elements
H_s	characteristic wave height
H_s^*	scaled characteristic wave height; $H_s^* = g \cdot H_s / u_*^2$
H_p	wave height of dominant wave
k	wave number; $k = 2\pi / \lambda$
κ	von Karman's constant; $\kappa \approx 0.4$
λ	wave length
λ_p	wave length of dominant wave
ν_a, ν	kinematic viscosity of air; $\nu_a = 1.8 \cdot 10^{-5}$ m^2/s
ν_T	eddy viscosity
ω	radian wave frequency; $\omega = 2\pi f$
ω_0	lower cut-off frequency; often $\omega_0 = \omega_p$
ω_p	'peak frequency' (radian frequency where spectral density $S(\cdot)$ is maximal)
Re_s	roughness Reynold's number based on roughness length z_0; $Re_s := u_* \cdot z_0 / \nu$
Re_σ	roughness Reynold's number based on root mean square value of geometrical roughness σ; $Re_\sigma := u_* \cdot \sigma / \nu$
R_i	Richardson number
R_s	sea state Reynolds roughness number: $R_s = U_{10} \sigma / \nu$
ρ_a	density of air
$S(\omega)$	spectral density in (radian) frequency domain

$\chi(k)$	spectral density in wave-number domain
σ	root-mean-square wave height (standard deviation of the surface elevation); $\sigma=\frac{1}{4}H_s$
T	period of wave component; $T=f^{-1}$
T_p	period of dominant wave
T_s	significant wave period; $T_s\approx 0.9\cdot T_p$
T_w	time duration of wind field in hours
T^*	scaled wave period; $T^*=g\cdot T_s/u_*$
θ	temperature
θ_s	temperature at the surface
θ_h	temperature at h meters above the air-water surface
τ_s	shear stress at air-water interface
u	horizontal velocity component of wind
U	mean horizontal velocity of wind; $U=\langle u\rangle$
u'	deviation of the horizontal wind velocity from its mean; $u':=u-U$
u_*	friction velocity at air-water interface
U_h	horizontal component of wind velocity at h meter above the air-water surface
U_s	horizontal component of wind velocity at sea surface
U_{10}	horizontal component of wind velocity at 10 meter above the air-water surface
$U(z)$	horizontal component of wind velocity at z meter above the air-water interface
W	vertical velocity component of wind
w	deviation of the vertical wind velocity from its mean; $w:=W-\langle W\rangle$
X	fetch
z	vertical coordinate
z^+	vertical coordinate in wall coordinates: $z^+=z\cdot u_*/\nu$
z_0	roughness length
z_0^*	scaled roughness length; $z_0^*=g\cdot z_0/u_*^2$
$\sim$	proportional to
$\langle\cdot\rangle$	time average of function enclosed by brackets
$\approx$	approximately equal to

1. INTRODUCTION

During the period 1984-1988 the Tidal Waters Division (DGW) of the Dutch Ministry of Transport and Public Works and DELFT HYDRAULICS jointly developed the numerical program CSM (Verboom et al., 1987, Gerritsen and Bijlsma, 1988). CSM predicts the depth averaged tidal flow and water elevation in the North Sea. CSM is an abbreviation for (Dutch) Continental Shelf Model. It is based on a dedicated, spherical coordinate version of the WAQUA system which forms a package for the simulation of water flow and water quality in shallow waters like coastal seas, estuaries and rivers. WAQUA, and therefore CSM, follow a 2Dh approach, i.e. they calculate vertically averaged velocities.

Over the past six years many applications have been performed with this CSM model. These applications showed that the model is able to produce reasonable predictions of water-levels, both at the Dutch coast and at other (British) locations on the Continental Shelf. This holds under mild meteorological conditions. However, under storm conditions, when the wind speed can exceed 15 m/s, significant deviations between predicted and observed water levels have been observed. These discrepancies can be of the order of a half to one meter. In the model it has been assumed that the wind-drag coefficient is a function of windspeed only and it does not explicitly account for the actual sea state. By sea state the small scale shape of the sea surface is meant together with its spatial and temporal variations. This spatial and temporal variation of the sea surface is characterized by a windwave field. In the literature it is commonly accepted, however, that the wind- induced drag is rather sensitive for the state of this air-sea interface.

To improve the model for extreme conditions various research activities were performed in the past. One of these activities concerns the development of a data-assimilation system based on Kalman Filtering (Heemink, 1986). In this approach the model's state variables are calculated in two steps. The first step consists of the prediction of the state variables on the basis of the model. In the second step this prediction is adjusted on

the basis of measurements. In this way much better (short-term) predictions can be generated than in the case that the predictions are not corrected for the observations.
Another activity dealt with the (off-line) further calibration of the wind-stress coefficient C_d for some specific storms that occurred in the past. In this calibration, the wind stress coefficient was still assumed to depend on the wind velocity U_{10} (at 10 meters above the water surface) only: $C_d=C_d(U_{10})$. The dependence of the drag coefficient on the wind velocity was reformulated by a piecewise linear function (two breakpoints). It turned out that the agreement of observed and measured waterlevels could be improved. However, this improvement was not very spectacular with respect to the 'standard' (linear) choice of the drag coefficient. This calibration of $C_d(U_{10})$ and its conclusion form the starting point of the present investigation. As stated earlier, the surface drag is not only a function of the wind speed but also depends on wave parameters. This dependence forms the central topic of this report.

The aim of this report is to summarize a literature survey on wave dependent formulations of the winddrag coefficient and to investigate their feasibility for the improvement of the CSM-model for the prediction of water levels under extreme meteorological conditions.

The report is organized as follows. Chapter 2 gives a more detailed discussion of the relevance of wave dependent drag coefficients. Chapter 3 gives a brief introduction to aspects of waves (terminology, definitions, approaches, wave parameters etc.) that are encountered in wave dependent drag formulations. Chapter 4 presents summaries of a set of relevant papers on wave dependent drag coefficients. On the basis of these summaries the state of the art of C_d modelling is given in Chapter 5. Finally, suggestions for alternative C_d-formulations in the CSM-model will be proposed in Chapter 6.

This study was performed by DELFT HYDRAULICS on commission of the Tidal Waters-Division. The DELFT HYDRAULICS-participants were Dr. H.F.P. van den Boogaard, Ir. R.E. Uittenbogaard and Dr.ir. H. Gerritsen. Prof.dr.ir. A.W. Heemink of DGW represented the contracting party.

2. SURFACE ROUGHNESS AS FUNCTION OF WIND AND WAVE PARAMETERS

In Chapter 1 it was outlined that wind induced surface waves form an important mechanism for wind drag (exchange of momentum) on the waterbody. Nevertheless in numerical models such as the CSM-model the surface drag is usually modelled on the basis of wind speed only. The traditional approach is to take the wind shear stress proportional to the square of (mean) wind speed, the density of air, and a drag coefficient C_d. In its turn this drag coefficient is chosen as a function of the wind speed, i.e. $C_d=C_d(U_h)$. In this equation h is the height above the surface where the wind speed has been measured. This height must be sufficiently greater than the sea surface fluctuations. It is common use to take h=10 m.
Usually the form of $C_d(U_h)$ is determined on the basis of scatter plots of measured (C_d,U_h) values. Such plots suggest a linear, or power law, relation of the drag coefficient and the wind speed:

$$C_d = a + bU_h^p \tag{2.1}$$

Sometimes (as e.g. in the CSM16-model) the prescription of C_d is given by a piecewise linear function instead of a 'single' parameterization.

Well known examples of $C_d(U_h)$ formulations are those by Smith and Banke (1975). Alternative formulations were proposed by Smith (1980), Garratt (1977), Large and Pond (1981) and Wu (1969). See also Table 1, Table 2 and Fig.(2.1) for a more complete overview (from Geernaert, 1990). These tables and the figure illustrate the variability that has been found. This variability suggests a regional dependence of the drag coefficient. It is seen that data collected over lakes, basins and shallow seas tend to correspond to larger C_d values than open ocean data. Moreover, the drag coefficient increases with wind speed.

From Table 1 it is also observed that the scatter in the C_d-U_h plot is significant. This may indicate that the surface drag is not properly described by solely the wind speed. In the literature several authors conclude that for the formulation of the surface drag coefficient it is more realistic to use sea state information rather than solely the (mean) wind speed. The main argument is that surface waves act as roughness elements which influence the momentum flux from the atmosphere to the sea (Kitaigorodskii, 1973; Geernaert et al., 1986).

The most likely reason that in (numerical) hydraulic models usually only the wind speed is taken into account is without doubt the absence of information on the wave field. Therefore, a direct parameterization of the dependence of C_d on its most basal cause, i.e. the wind speed, is the only alternative left.

In recent years progress has been made in the development of numerical wave models. On the basis of meteorological information (atmospheric temperature and wind fields) these models generate ocean/sea surface wave amplitude spectra. These spectra describe the time evolution of the energy distribution of the waves as a function of the spatial coordinates, frequencies and angular direction. See for example the WAM-model (Komen, 1985; The WAMDI Group, 1988).

Noting that the numerical prediction of wave fields (on scales that cover the CSM16 area) become available, the problem is reduced to condensing this (bulk of) information into a possibly improved formulation of the surface drag coefficient. Even if this problem can be solved theoretically (at least in principle) it is not yet evident that such a refined formulation is of practical use. For instance, the drag may depend mostly on short waves which may not be explicitly computed by the wave model. Moreover, it must be verified that the effort that is involved in the **implementation of a wave dependent drag formulation** on one hand, and, the (probably substantially) increased **computational effort** required for the successive **numerical model calculations** on the other hand, relate acceptably to the improvement that is obtained (assuming that an improvement is achieved).

This report aims at the formulation of the shear stress at the sea surface. In the transfer of momentum from the atmosphere to the water body two forms can be discriminated: (i) momentum transfer to the surface waves (to be modelled by a wave model), and, (ii) momentum transfer induced turbulence in the water body leading to changes in the (mean) velocities. With regard to the CSM16-model we are dealing with a vertically averaged model. This discrimination is therefore not relevant as long as the momentum balance is poperly formulated. On the other hand, the results of this report may not be directly suited for 3D hydrodynamic models which, in the context of momentum transfer from the atmosphere to the water body, require the appropriate momentum balance at the surface layer. Neither will the present results be suited for the prediction of turbulent mixing at the water surface.

Summarizing, and putting the preceding considerations in the scope of the CSM-model, the problem thus reads:

"what are feasible wave dependent surface drag formulations for the CSM-model, and will these formulations lead to better water level predictions under storm conditions than the predictions based on the 'traditional' surface drag formulations (i.e. dependent on wind speed only)?"

3. A SURVEY OF IMPORTANT WIND AND WAVE PARAMETERS

In the literature survey on surface drag formulations a variety of formulations were found, each using specific assumptions, wave parameters and notations. The aim of this chapter is to give a brief overview of terminology, important wind/wave parameters as well as their typical values in practice, and the common assumptions used in the derivation of wind drag formulations. In each of the following sections a particular subject will be considered.

3.1 Shear stress, friction velocity and drag coefficient

The aim of the present study is to obtain a surface drag formulation that depends on the actual sea state. The surface drag is given by the shear stress τ_s and it satisfies the following equation:

$$\tau_s = \rho_a u_*^2 \tag{3.1}$$

In this equation u_* is the friction velocity of the water at the surface and ρ_a is the density of air. Typical values for u_* are in the range of 0.01 m/s (for wind speeds of the order of 1 m/s) to 0.8 (for wind speeds of the order of 15 m/s). For the density of air a typical value of 1.225 kg/m^3 holds. For these values of friction velocity and density of air the shear stress varies from 10^{-4} to 0.4 Pa.

Sometimes Eq.(3.1) is written in a form that contains the actual wind speed (at a distance h above the surface) instead of the friction velocity. This form reads:

$$\tau_s = C_d \rho_a U_h^2 \tag{3.2}$$

Here the drag coefficient C_d has implicitly been defined by

$$C_d = u_*^2/U_h^2 \tag{3.3}$$

Values for C_d that are encountered in practice may vary by an order of magnitude from, say, 3.10^{-4} (wind speeds of the order of 1 m/s) to 3.10^{-3} (at wind speeds exceeding 15 m/s).

Given the wind speed U_h it must thus be noted that C_d and u_* are not independent and our task is to find a consistent, sea state dependent description of either C_d or u_*. Given the form of the shear stress τ_s, a functional relationship of u_* on one hand and wind/wave parameters on the other hand is to be preferred to a more indirect approach via a formulation of C_d.

In Section 3.4 a third alternative parameter for the description of the surface roughness will be encountered, namely the roughness length z_0. In literature it is common use to give a formulation for the roughness length z_0 rather than u_* or C_d. The conversion of z_0 into C_d or u_* will be shown in Section 3.4.

3.2 Neutral conditions

Throughout this report it will be assumed that neutral conditions hold at the sea-air interface. This means that temperature gradients, which may significantly affect the velocity profile, are absent. From the literature it is known that the amount of temperature stratification is expressed by the Richardson number R_i. For an ideal gas R_i is defined by

$$R_i = - \frac{g(\partial\rho/\partial z)}{\rho(\partial u/\partial z)^2} = \frac{g(\partial\theta/\partial z)}{\theta(\partial u/\partial z)^2} \qquad (3.4)$$

where θ is the temperature in °K. See e.g. Geernaert (1990). For the calculation of the derivatives Donelan (1990b) uses the temperatures (θ_s) and wind velocities (U_s) at the surface and those at a distance h above the surface (θ_h, U_h). His expression for the Richardson number then reads

$$R_i = \frac{gh(\theta_h - \theta_s)}{\theta_h U_h^2} \qquad (3.5)$$

Donelan (1990b) states that neutral is taken to include cases in which this number is less than 0.01 in magnitude.

To get an idea of the 'critical' temperature gradient that follows from this criterium, the following values are substituted: h=10 m, U_{10}=10 m/s, θ_h=290 °K, g=10 m/s^2. This leads to the condition that the temperature at the surface must not exceed 287 °K, or alternatively, the gradient $\partial\theta/\partial z$ must be less than 0.3 °C/m.

3.3 Roughness of flow, roughness length, and logarithmic velocity profile

Given an unstratified flow and the wind speed at a fixed height above the mean sea surface the transfer of horizontal momentum to the sea is assumed to depend on its surface roughness. This idea is borrowed from extensive research of turbulent flows along rigid "rough" walls; lateron definitions are presented for the roughness length and when a wall is considered to be "rough" or "smooth". The roughness length is related to the spatial amplitude spectrum of the solid-fluid interface provided the amplitude is large enough. The roughness length determines the drag coefficient of the wall (section 3.4). The transferred momentum from air to the sea is spent on i) wave generation, the growth of ii) the mean kinetic or of iii) the turbulent kinetic energy of the water body. At first sight this seems to be of no concern for the prediction of water levels because it is based on a total momentum balance. However, the surface roughness of the movable air-water interface is not likely determined by the mean flow or turbulence in the water body but probably only by the sea state. This point of view is adopted by several researchers like Kitaigorodskii; his model is treated in the next chapters. The sea state partly depends on the local history of wave generation by wind. For some limit conditions such as a long time after wind set up and long distances to the shore(s) a unique limit condition may be anticipated between roughness, sea state and wind speed. Then knowledge of the intermediate processes is not required since a direct, probably empirical, coupling between the drag coefficient and the wind speed is expected.
Either for a reduction of empiricism or for an extension towards more general conditions of relatively small time scales and small distances to shores the temporary and spatial dependence of the roughness on the sea state is needed.

The reasoning given above is the foundation of several models which are treated in chapter 4. This section only introduces briefly the definitions and the terminology used in turbulence research to describe and classify a turbulent flow along rigid walls. The next step is to motivate, supported by experiments, that these findings are applicable to a mobile air-water interface which concludes this section.

Turbulent flow along a rigid wall

Most turbulence theories for boundary layer type flows along walls apply the concept of the eddy-viscosity υ_T to relate the shear stress τ acting on the wall with the only non zero velocity gradient $\partial U/\partial z$ by

$$\tau=\rho_a\cdot(\nu_a+\nu_T)\cdot\frac{\partial U}{\partial z}, \tag{3.6}$$

with ρ_a the density of air.

In (3.6) ν_a is the kinematic viscosity of air and z is the distance to the wall. For a 3D-flow along a wall in (3.6) is τ the magnitude of the shear stress vector and likewise $\partial U/\partial z$ the magnitude of the shear rate. Then the shear stress vector is parallel with the shear rate vector $(\partial U/\partial z, \partial V/\partial z, 0)$ provided z is perpendicular to, and U and V are parallel with the wall. In this section the flow is in x-direction with U the only non-zero mean flow velocity component.
Usually not τ is used but instead the friction velocity u_* defined in

$$\tau = \rho_a\cdot u_*^2. \tag{3.7}$$

The friction velocity u_* has the order of magnitude of the rms-values of the turbulent velocity components and is frequently 3 à 5 % of U. In Maxwell's model for a perfect gas the molecular viscosity is proportional with the product of the free path length of the molecules and the rms-value of their velocity (square root of the gas temperature). Analogous the eddy-viscosity ν_T is the product of the so called "mixing length" L over which turbulent

momentum is transferred and the rms-value of one of the turbulent velocity components.
This is the Kolmogorov-Prandtl mixing length model for the eddy-viscosity. In the boundary layer along a wall the mixing length is proportional with the distance to the wall so that

$$\nu_T = \kappa . u_* z \ , \qquad (3.8)$$

With Von Kármán's constant κ=0.41 , derived from experiments.

From (3.8) follows that the dominance of the turbulent contribution ν_T over the molecular (kinematic) viscosity ν is determined by the ratio

$$\frac{\nu_T}{\nu_a} = \kappa . z^+ \ \ using \ \ z^+ = \frac{u_* z}{\nu_a}. \qquad (3.9)$$

In (3.9) is z scaled to the so-called "wall coordinate" z^+ which is actually one of the many definitions of the Reynolds number. In the boundary layer τ is independent of z and (3.6), (3.8) and (3.9) give the following velocity profiles.

The log-law of the wall for $z^+ \geq \approx 100$: $U = \frac{u_*}{\kappa} \ln(\frac{z}{z_o})$, (3.10a)

or the viscous sublayer for $z^+ \leq \delta_v^+$: $U = u_* . z^+$, (3.10b)

with length scales δ_v and z_0 to be determined.

Between $\delta_v^+ \leq z^+ \leq 100$ there is a transitional or buffer layer where both the turbulent and the molecular effect contribute to the shear stress τ. In the viscous sublayer, where molecular viscosity dominates, the flow is still subjected to the highly temporary and spatial forcing by the turbulent flow.

The semi-empirical log-law (3.10a) is valid if the flow is:
* without large scale recirculation in a plane perpendicular to the wall,
* with negligible pressure gradients in the main flow direction in comparison with the one in the direction perpendicular to the wall,
* with zero or small mean rotation component perpendicular to the wall,
* without density stratification and

* for pipe and duct flows $z^+ < 300$ although it can be extended to 1000 say . with minor deviations.

Whether a wall should be regarded as rough or as (technically) smooth depends on the ratio between the small scale or subgrid modulations of the wall and the thickness δ_v of the so-called viscous sublayer (Schlichting, 1969). First a definition of the thickness of the viscous sublayer is derived. From experiments in **smooth** pipes and smooth ducts $z_o = z_{s_o}$ in (3.10a) and from Nikuradse (1932a) and Laufer (1952) follows:

$$z_{s_o} = \frac{\nu}{E.u_*} \;, \qquad (3.11)$$

with dimensionless constant $E \approx 9.9$.

The definition of the thickness of the viscous sublayer follows from the neglect of the intermediate buffer layer and matching of the velocity profiles given by (3.10a) and (3.10b):

$$\kappa.\delta_v^+ = \ln(E.\delta_v^+) \;\; giving \;\; \delta_v^+ \approx 11.4 \;\; or \;\; \delta_v \approx 11.4\frac{\nu}{u_*}. \qquad (3.12)$$

For **rough** walls in (3.10a) $z_o \triangleq z_{r_o}$ and Nikuradse (1932b) found empirically for the roughness coefficient

$$\frac{z_{r_o}}{\sigma} = \frac{1}{30} \;, \qquad (3.13)$$

with σ the rms-value of the geometrical roughness.

Businger et al. (1971) report for wheat stubble $z_{r_o}/\sigma = 1/7.5$ instead of (3.13) showing the variability depending on the shape (spatial amplitude spectrum) of the roughness forming elements.
With definition (3.13) a wall is defined as fully rough when its roughness length $\sigma >> \delta_v$ i.e. when it largely exceeds the thickness of the viscous sublay-

er. This means that the roughness forming elements directly influence the turbulent flow in the log-layer: this condition is called "form drag" determined by σ which then dominates "viscous drag". Then in (3.10a) for a rough wall $z_o=z_{r_o}$ must be taken instead of $z_o=z_{s_o}$. For a fully rough flow the viscous sublayer is submerged between the roughness elements and the point with $z<z_{r_o}$ is below the peaks of the roughness forming elements; there U=0 should be taken instead of the viscous sublayer formula (3.10b).
There is a transitional regime of roughness where z_0 in (3.10a) depends on the Reynolds number of the flow. The distinction between the different roughness regimes is determined by the "roughness Reynolds number" which Geernaert (1990) defines to be proportional to the ratio between the roughness length of a rough wall z_{r_o} (3.13) and the thickness δ_v of the viscous sublayer (3.12).

$$Re_s = \frac{u_* z_{r_o}}{\nu} = 11.4 \frac{z_{r_o}}{\delta_v}. \tag{3.14}$$

giving the following classes:

smooth : $Re_s<0.13$ then $z_o=z_{s_o}$ of (3.11)

transitional rough: $0.13<Re_s<2.5$ (3.15)

fully rough : $2.5<Re_s$ then $z_o=z_{r_o}$ of (3.13)

Donelan (1990a) uses 0.11 instead of 0.13 in (3.15). Tennekes and Lumley (1982) define a roughness Reynolds number Re_σ based on the rms-value σ of the geometrical roughness rather than Re_s with z_{r_o}. They report $Re_\sigma<5$ as smooth and $Re_\sigma>30$ as fully rough.

Using (3.15) the fully rough regime occurs when $z_{r_o} > \approx 0.2\ \delta_v$ or $\sigma > \approx 75.\nu/u_*$

if $\sigma = 30.z_{r_o}$ is taken. This demonstrates that the criteria for the type of wall roughness is flow dependent. For a mean velocity U decreasing from a large value to zero also u_* and Re_s decreases making an initially rough wall finally a smooth one because of the growing thickness of the viscous sublayer.

An example

Take U=10 m/s then typically u_* =0.5 m/s (5% of U) and the lower limit of a fully rough air flow is $\sigma \geq 2.4$ mm while $\sigma \geq 24$ mm when U=1 m/s is taken. At high air velocities disturbances with only small amplitudes are not fully rough.

Turbulent air flow over an air-water interface

In the preceding part the classification of the turbulent boundary layer along a rigid wall and its velocity profile was presented. The example at the end showed that if the rigid wall has the roughness of the air-water interface in most cases the flow is fully rough except for small amplitudes or at low wind speeds.

To translate the information from a turbulent boundary layer to a mobile air-water interface 4 questions need further consideration.

A. Will the wind profile in the turbulent boundary near a mobile air-water interface also obey the log-law of the (rigid) wall?

B. How important is the stratification of air and will it effect the wind profile ?

C. Are the friction velocity u_* and roughness length z_o measurable ?

D. Is there a procedure to improve the estimate (3.13) given the sea state i.e. making the ratio z_o/σ sea state dependent where σ now means the rms-value deviation of the water surface ?

Question A

In laboratory experiments Hsu et al. (1981) show that the velocity profile of the mean air flow over a mobile air-water interface follows the log-law as if the interface is a very rough and rigid surface.
Because of the large extend of the lower atmosphere the log-layer will easily include the first 10 m above the mean water surface: the upper limit of z^+ of 1000, originating from pipe and duct flows, is too restrictive.
So indeed the information of the preceding part of this section appears to be applicable for mobile air-water interfaces.

Question B

The air flow above water may contain a vertical temperature profile leading to a stable stratification for hot air above a cold sea or vice versa giving an unstable stratification. In general stratification alters the velocity profile, see e.g. Nieuwstadt (1981) for the case of wind over land. Compared with land the greater infrared absorption of water and mixing in the water body reduces the stratification in the turbulent boundary layer of air above sea. Therefore most researchers consider the influence of stratification on the drag of the turbulent air flow on the sea surface as small.

Question C

In practice the parameters z_o and u^* in (3.10a) are relatively easy to determine from measurements of the mean wind profile U(z), Geernaert (1990) calls this the "profile method". However, Geernaert (1990) notes that stratification will deviate the U(z)-profile from the log-law and the U(z)-profile may be modulated by long surface waves. Finally more measuring positions at different locations are needed to determine U(z).
A more accurate method is the direct measurement of the turbulent part of the shear stress τ in the air flow above the sea surface. At 1 m above the sea surface with U=10 m/s the wall-coordinate is already $z^+ \approx 3.10^4$. Then (3.9) shows the insignificance of the molecular viscosity in (3.6) so that τ equals the turbulent shear stress ($-\rho_a \langle u'w' \rangle$) giving

$$\tau = -\rho_a \langle u'w' \rangle + O(\frac{1}{z^+}) \qquad \text{and} \qquad u_*^2 = -\langle u'w' \rangle \ , \qquad (3.16)$$

with u' the streamwise and w' the vertical component of the turbulent velocity and <..> means here time averaging. Available two component velocity meters with small enough measuring volumes and fast time responses can measure both u and w. After subtracting the mean values, u'=u-<u> and w'=w-<w>, the covariance <u'w'> of the fluctuating horizontal and vertical wind velocities can be computed from which follows u_* given in (3.16). Because τ is constant in the first 10 m above the sea level only one measuring position on a rig is required. Geernaert (1990) calls this the 'eddy correlation technique'.

Both methods need measuring times much longer than typical variations in the wind speed (hours). Another difficulty is the position of the instruments on the platform. The rig may influence the measurement because of the formation of a stagnation point and the location of the "ideal" stagnation free instrument position may vary for changing wind directions.

Question D

This question refers to models where the ratio (z_0/σ) depends on the sea state and of course the height σ, the rms-deviation of the water surface, is a sea state parameter. These models attempt to replace the uncertainty in the relation between σ and z_{r_o} and other findings referred below (3.13) for flows along rigid walls.

The modelers of the drag of the sea surface have to enter a domain not yet treated in turbulence models for flows along rigid walls. This important subject is the essence of this report and is treated in Chapter 4.

3.4 The relation of roughness length, drag coefficient and friction velocity

In Section 3.1 it was argued that for the determination of the surface stress the functional dependence of the friction velocity u_* on wind and wave parameters is required. Instead of the friction velocity one may try to find such an expression for the drag coefficient C_d. Due to the definition of this coefficient this does not really change the problem, though.

It turns out that for the description of the surface roughness one may as well express the roughness length z_0 in terms of the wind and wave parameters (instead of C_d or u_*). This is easily seen from the velocity profile:

$$U(z) = \frac{u_*}{\kappa} \cdot \ln(z/z_0) \tag{3.16a}$$

So,

$$u_* = \kappa U_h / \ln(h/z_0) \tag{3.16b}$$

Here U_h is the (average) wind velocity at h meter above the water surface. Usually 10 meters is taken for this height.

It will be seen in Chapter 4 that most expressions for the roughness length contain the friction velocity u_*. So in general the Eq.(3.16b) gives an implicitly defined formula for the shear stress.

Eq.(3.16b) expresses the friction velocity as a function of the roughness length. Alternatively one may express the drag coefficient in terms of the roughness length. Since C_d is defined by u_*^2/U_h^2 it follows that

$$C_d = \kappa^2 \, [\ln(h/z_0)]^{-2} \tag{3.17}$$

In the literature most of the models for the surface stress involve an expression for the roughness length z_0. Since the proposed z_0 formulations will be expressed in u_* (and wave parameters) rather than C_d, Eq.(3.17) includes two dependent variables, namely u_* and C_d. Therefore Eq.(3.16b) has to be preferred.

Only in 'traditional approaches', when C_d is expressed in solely the wind velocity U_h (excluding the friction velocity u_*), a direct parameterization C_d seems to make sense.

3.5 Wave spectrum and wave parameters

In this section a brief outline is given of the representation and 'parameterization' of the (surface) wave fields.

The temporal and spatial evolution of the wind induced wave field is usually described by a directional wave spectrum. This spectrum describes the energy density in terms of the directional wave number and the temporal and spatial coordinates.

In recent years considerable progress has been made in the development of numerical models for the prediction of wave fields. The basis of these models is formed by the energy balance and includes radiative transfer of energy (due to propagation of the waves) together with terms governing the input and dissipation of energy, and terms describing the nonlinear interaction of waves.
For an example of such a wave model we refer to the WAM-model (Komen, 1985; The WAMDI Group, 1988).

In the remainder of this section a brief review is given of the most important aspects/parameters of waves and wave models relevant in the present context. In this review the texts of Geernaert (1990), Donelan (1990a) and Battjes (1982) are followed.

For ocean/sea waves the input is provided by momentum transferred from the atmosphere to the water surface. In the beginning, i.e. for 'young' wave fields, this atmospheric forcing especially affects the higher frequencies. Snyder et al. (1981) have found that this input source term increases linearly with the wave frequency for waves that are actively growing. This growing continues until a level is reached where the energy gain (wind input) and losses (dissipation due to breaking) are in equilibrium. Through nonlinear wave-wave interactions (Phillips 1960; Hasselmann 1962, 1963) the spectrum broadens, and together with dissipation at the short wave length end, the peak of the spectrum shifts to successively longer and faster wave components.

Until recent years the wave frequency spectrum was described by a simple power law:

$$S(\omega) = \beta \cdot g^2 \cdot \omega^{-5} \quad \text{for } \omega \geq \omega_0$$
$$S(\omega) = 0 \quad \text{for } \omega < \omega_0 \qquad (3.18)$$

in which ω_o is a cut-off (radian) frequency at the low-frequency end of the spectrum and the constant β is of the order of 10^{-2}. Note that for this form of the spectrum ω_o coincides with ω_p where ω_p is the radian frequency where this spectral density is maximal (often ω_p is called the peak frequency).
In practice the peak frequency $f_p = \omega_p / 2\pi$ is of the order of 0.1 Hz and the spectrum contains frequencies in the range of 0.05 to 0.5 Hz.
The spectrum of Eq.(3.18) is named after Phillips (1960) and parameter β is usually called the Phillips constant. Phillips derived this form of the spectrum on the basis of the following arguments. Provided that wind duration and/or fetch* are sufficiently large, the energy density in the high frequency part of the spectrum will reach a level where energy input and energy dissipation are in equilibrium. This level will be determined by breaking of the waves and for this breaking only the frequency ω and g (the accelaration of gravity) are relevant. By a dimensional analysis he concluded that at least for the high frequencies the spectral density $S(\omega)$ must be proportional to ω^{-5}.

***NB**. Given a certain position in a wind/wave field, the **fetch** is defined to be the distance to the nearest upwind limitation.

Field measurements confirmed the form of the Phillips spectrum for the high frequency part of the spectrum. However it turned out that β is not a constant in the strict sense but varies over a range of 0.008 to 0.020. The scatter in this constant is probably due to dependence of β on additional wind and wave parameters. As an example, the Phillips constant is larger for conditions of short fetch than for long fetch. For further information on the Phillips constant and spectrum see e.g. Geernaert (1986; parameterisation of β in frequency and wave age, p.7675) and Longuet-Higgins et al. (1963; experimental determination of this constant).

Geernaert (1990) reports that more recently new models for the equilibrium range have been proposed. Phillips (1985) suggests a refinement to his spectral form which in the frequency space is,

$$S(\omega) \approx u_* \cdot g \cdot \omega^{-4} \tag{3.19}$$

This form has also been found by Donelan et al. (1985) for spectra obtained from Lake Ontario.

In contrast to the high frequency part of the spectrum, no (dimensional) argumentation is available for the description of the spectrum at the low frequency part. On the basis of measurements, however, updated formulations of the Phillips spectrum were proposed. Well known is the one by Pierson and Moscowitz (1964). They suggested to maintain the Phillips form for the high frequencies, but introduce a flank at the low frequency part of the spectrum. The position (in the frequency domain) of this flank is determined by the fetch: for increasing fetch the flank shifts towards the lower frequencies. To account for such a flank Pierson and Moscowitz multiplied the Phillips spectrum by the following factor: $\exp[-5/4(\omega/\omega_m)^{-4}]$. In this factor, ω_m is a scale parameter. This modified form of the Phillips spectrum was further modified on the basis of the analysis of the JONSWAP-data (Joint North Sea Wave Project: Hasselmann et al. 1973). The fetch limited wave field was here described by:

$$S(\omega) = 2\pi g^2 \alpha \omega^{-5} \exp[-5/4(\omega_p/\omega)^4 + \ln(\gamma_0) \cdot \exp\{-½(\omega-\omega_p)^2/\sigma^2\omega^2\}] \tag{3.20}$$

where σ is 0.07 for $\omega > \omega_p$ and σ is 0.09 otherwise. The parameter γ_0 was found to be 3.3. The need to modify the Pierson-Moscowitz spectrum originated from the fact that the peaks of the observed spectra were much more pronounced than the ones on the basis of Pierson-Moscowitz spectrum. This led to the inclusion of the following 'peak enhancement factor':

$$\gamma(\omega) = \gamma_0^{\exp[-\frac{1}{2}(\frac{\omega-\omega_p}{\sigma\omega_p})^2]}$$

According to Geernaert (1990), the dominant frequency ω_p may be determined from the observed wind speed U and upwind fetch X according to

$$\omega_p = (7\pi g/U)(gX/U^2)^{-1/3} = 7\pi\{g^2/(X\cdot U)\}^{-1/3} \tag{3.21}$$

The coefficient α may be estimated to be

$$\alpha = 0.76(gX/U^2)^{-1/3} \tag{3.22}$$

Other important relations for wave analysis given by Geernaert (1990) are the phase velocity c_p of the peak wave,

$$c_p = \omega_p/k \tag{3.23}$$

and the dependence of the peak frequency ω_p on the time duration T_w of the wind field is given by:

$$\omega_p = 1.5(T_w u_*^2/g^2)^{-1/3} \tag{3.24}$$

T_w must be expressed in hours. To get an idea of the magnitude of these wave parameters we substitute the following (realistic) values into the preceding equation: U=15 m/s, u_*=0.7 m/s, X=200 km. This leads to: ω_p=0.72 rad/s (f_p=0.11 Hz), c_p=13 m/s k=0.055 m^{-1}, α=0.1 and a wavelength λ_p=118 m.

The preceding expressions for the wave parameters indicate that the several scale and form parameters are not independent. Moreover, measurements of wave spectra for growing seas have shown that the form of the spectrum is relatively independent of the stage of this growth (Hasselmann et al., 1973). In the energy balance this may be explained by a stabilizing influence of the nonlinear wave-wave interaction on the form of the spectrum. This form invariance appears not to be restricted to growing seas in standard wind fields but has also been observed for inhomogeneous and nonstationary windfields (Sanders, 1976). This property is often called the **'self-similar** structure' of the wave field (named after Kitaigorodskii, 1962).

Due to the self-similar property the spectrum can be described by a limited set of scale and form parameters, allowing a **parametric** approach for the description of the evolution of the spectrum.

Often the spectrum is parameterized by one parameter, c_p/u_* (sometimes the alternative parameter c_p/U_{10} is used), i.e. the ratio of the phase velocity of the dominant frequency and the friction velocity u_*. It has a magnitude of the order of 0.1 for young seas to 30 or more for old, fully developed sea's. The parameter c_p/u_* is traditionally known as the **wave age**.

Due to the self-similar structure, the deduced, 'internal' wave parameters (such as total wave energy, significant wave height, wave steepness) are also coupled to the wave age. For an example see Donelan et al. (1985) who fitted a set of spectra obtained from Lake Ontario to ω^{-4} at high frequencies and found that the spectral parameters could be related to the inverse wave age.

Finally we give some definitions associated with the stage of development of the wave field. The wave field is said to be in **equilibrium** if at any time and any spectral component the energy input balances the energy output. The wave field is said to be **saturated** when it has reached the upper limit of its possible growth and increased forcing would lead to breaking of the waves. The condition of **full development** is said to be obtained when the phase velocity of the waves at the spectral peak approach the wind speed, (Donelan, 1990b). Donelan (1990b) defines full development by the condition that the phase velocity of corresponding to the peak frequency exceeds the wind speed by 20% (U_{10}/c_p=0.83).

4. A SURVEY OF LITERATURE ON WIND STRESS FORMULATIONS

A literature scan was carried out for formulations of the surface shear stress, and a set of relevant papers was selected. These papers were studied with respect to drag formulations and will be summarized in this chapter. This inventory forms the basis for suggestions of alternative u_* (or C_d) formulations for the CSM-16 model.

From the consulted literature it became clear that the investigation of a sea state dependent form of surface drag coefficient is all but a recent topic. The interest in this work has its root in the fifties and most likely has the work of Charnock (1955) as its seed. Based on a dimension analysis Charnock proposed a relation between the roughness length (z_0) and the friction velocity over the water surface (u_*). Many approaches that follow are more or less a generalisation of Charnock's formula. Charnock's formula and its generalisations will be encountered in Section (4.2). These formulations have a more or less parametric approach: the roughness length is expressed in (a few) wind and wave parameters.

There are also approaches that express the roughness length in the spectrum $S(\omega)$ without apriori assumptions or parameterization of the spectral density. These formulations will be summarized in Section (4.1).

Roughly stated, existing models of wave dependent drag coefficients fall into two categories: empirical formula's and theoretically derived formulations based on specific assumptions regarding the nature of the roughness length z_0 (Geernaert, 1990).

In the papers that were consulted different notations were used for roughness length, wave parameters, spectra, ... etc... To prevent confusion the notations were standarized conform the list of symbols.

4.1 ROUGHNESS LENGTH AS FUNCTION OF THE COMPLETE WAVE SPECTRUM.

The following two papers propose roughness length formulations that integrate the complete spectrum and do not involve particular assumptions on (or parameterizations of) its form.

4.1.1 Kitaigorodskii (1973)

This book provides one of the earliest formulations of the roughness length that uses the complete form of the spectrum $S(\omega)$. In the derivation of the surface roughness length the wave field is seen as a superposition of many independent surface waves. For every individual wave (of radian frequency ω) a characteristic length of the surface roughness element is calculated. From all these characteristic lengths a mean length is calculated via averaging over a modified spectrum. 'Modified spectrum' refers to a spectrum that is weighed by some function. Here this weight function originates from the calculation of the characteristic wave height in the reference frame of the independent waves. The approach is as follows.

Let 'a' denote the roughness height described by the moving roughness elements (within their frame of reference; 'a' is identified with the amplitude of the wave) and h_s the roughness height in the immobile frame. Given a wave element moving at phase velocity c, Kitaigorodskii derives the following relation:

$$h_s \approx a \cdot \exp(-\kappa c/u_*) \qquad (4.1)$$

In the derivation of this formula, some assumptions were made like (i) the amplitude 'a' can be interpreted as some measure for the height of protuberances of a completely rough immobile wall, (ii) a logarithmic profile holds for the wind speed above the wave, and (iii) the turbulent flow past mobile roughnesses is analogous to flow past an immobile rough wall; this assumption requires that the time scales of turbulence are much smaller than the time scale associated with the evolution of the waves.

In the presence of many waves instead of a single one, the mean amplitude must be taken in Eq.(4.1). This leads to a root mean square average of h_s over the wave spectrum:

$$< h_s^2 > \approx 2 \int S(\omega) \cdot \exp(-2\kappa c/u_*)\, d\omega \tag{4.2}$$

The roughness scale is generally assumed to be proportional to the rough- ness length of the wind profile, z_0, $z_0=C_K h_s$. See also Section (3.3) where it was seen that for an aerodynamically rough surface h_s/z_0 assumes a value of about 30 based on the classical experiments by Nikuradse (1932, 1933). Absorbing this proportionality constant into another one, Kitaigorodskii obtains

$$z_0^2 = C_K \int S(\omega) \cdot \exp(-2\kappa c/u_*)\, d\omega \tag{4.3}$$

The constant C_K must be determined experimentally. The most important comments on this formulation are:

1. Since for deep water the dispersion equation reads $\omega^2 = gk$, and since the phase velocity is $c = \omega/k$, the exponent in the integrand of Kitaigorodskii's formula is of the order ω^{-1}. This means that the roughness length is especially sensitive for the high frequency part of the spectrum.
   Geernaert et al. (1986) states that the maximum contributions to the momentum flux is given by surface waves in the range $2\omega_0$ - $8\omega_0$ when for $S(\cdot)$ a Phillips spectrum is chosen. Thus, still according to Geernaert et al., Kitaigorodskii's model implies a wind stress mechanism that depends on middle and higher frequency wind waves. Geernaert et al. (1986) supported this property by experimental data since they found that the higher frequency waves dominate the magnitude of the wind stress.
   According to Geernaert et al. (1987) Kitaiigorodskii's model can be seen as a friction drag approach.

NB. In Geernaerts terminology (1987, 1990) the stress supported by the long waves (with large directional sensitivity and long adaptation times for changing wind conditions) is called **form drag**, whereas the stress supported by the very short waves (little directional sensitivity and short adaptation times) is called **friction drag**.

---

2. In the derivation of Eq.(4.3) it was argued that in the frame of reference moving with the waves a logarithmic wind profile holds of the form:

$$U(z)-c = u_*/\kappa \ln(z/a) \tag{4.4}$$

Johnson and Vested (1991) argue that Kitaigorodskii's model cannot be used when $U_{10} < \approx c_p$, since the left hand side of Eq.(4.4) will become negative. Therefore they use Kitagorodskii's model for small wave ages and an alternative model of Donelan (1990a) near full development of the waves. Full development of the waves corresponds to wave ages greater than, say, 26. See e.g. Geernaert et al. (1987), and Volkov (1970).

3. As seen in (1) Geernaert et al. (1986) have verified that for the Phillips spectrum the main contribution to momentum surface flux arises from frequency components in the range $2\omega_0$-$8\omega_0$. It is also interesting to note that the frequency where the integrand is maximal is $\omega=0.4\kappa g/u_*$. For $u_*=0.7$ m/s (U=15 m/s) this gives $\omega=2.2$ rad/sec which corresponds to a frequency of 0.36 Hz. This frequency is still in the range of frequencies that is covered by e.g. the WAM model (0.4-0.42 Hz., see e.g. Wamdi, 1988) but approaches the high frequency cut-off. So for the evaluation of Kitaigorodskii's roughness length use will also have to be made of the ω^{-4} tail that WAM prescribes beyond the high frequency cut-off.

4. Sometimes a simplified form of Kitaigorodskii's formula is used,

$$z_0/\sigma = C_k' \cdot \exp(-\kappa \cdot c_p/u_*) \tag{4.5}$$

(Kitaigorodskii, 1973). In the derivation of this formula it has been assumed that the spectrum $S(\omega)$ is concentrated in a narrow band at the peak frequency ω_p. Note that the roughness length is then expressed in the wave age c_p/u_*.

5. Geernaert (1990) and SethuRaman (1979) show that substitution of the Phillips equilibrium spectrum into Kitaigorodskii's formulation leads to an expression of z_0 that is proportional to u_*^2/g, i.e.

$$z_0 = \alpha u_*^2/g \tag{4.6}$$

This corresponds to the 'classical' formulation given by Charnock (1955), see Section 4.2.1.

6. Kitaigorodskii's formula suggests an additive effect of the individual waves on the (squared) roughness length. From a physical viewpoint this is questionable since shear stresses rather than roughness lengths can be superimposed. Given the fact that Kitaigorodskii assumes that the waves are statistically independent his z_0 must be interpreted in a root mean square sense (wave ensemble average).

4.1.2 Byrne (1982)

According to Geernaert et al. (1986, 1990), Byrne (1982) derived a roughness length z_0 expressed in the integrated **slope** spectrum. Byrne assumes the roughness length to be proportional to the sum of the products of the roughness element height and roughness element slope. For the roughness element height the wave height is taken. Thus,

$$z_0 \sim \sum \text{(wave height)(wave slope)} \tag{4.7}$$

Then,

(i) setting the wave height proportional to the amplitude,

(ii) taking the ratio of wave height and wave length as a measure for the slope, i.e. wave slope ~ h/λ,

(iii) using the relation

$$\lambda = 2\pi g/\omega^2 \tag{4.8}$$

(iv) integrating over all contributing waves,

Byrne arrives at:

$$z_0 = C_B \int \omega^2 \cdot S(\omega)\, d\omega \tag{4.9}$$

The coefficient C_B is a parameter to be determined experimentally.

Byrne has shown that by substituting the Phillips spectrum in his roughness length formulation, with the lower frequency limit ω_0 approximated as $g/25u_*$, the model reduces to a form

$$z_0 = C_{B'} u_*^2/g \tag{4.10}$$

which is again consistent with Charnock's formulation (see Eq.4.6).

Geernaert (1990) explains that Byrne's model physically depends on only information in a narrow spectral region around the peak in the equilibrium range. Based on this, Byrne's model may be considered to be a form drag approach, and information on the slope and density of short waves will have insignificant influence on the prediction of the roughness length.

4.2 ROUGHNESS LENGTH EXPRESSED IN WAVE SPECTRUM PARAMETERS

Whereas in Section (4.1) the determination of the roughness length z_0 involved the integration of the complete spectrum $S(\omega)$, in this section alternative formulations will be summarized that use 'simple' shape parameters of the spectrum.

4.2.1 Charnock's formula

Charnock's formula (Charnock, 1955) is one of the earliest formulations of the surface roughness. It reads

$$z_0 = \alpha \, u_*^2/g \tag{4.11}$$

Note that this equation does not contain any wave-dependent parameter. Nevertheless this formulation is mentioned since it forms the basis of many alternative C_d-expressions that do explicitly depend on wave-parameters.

Charnock derived Eq.(4.11) on the basis of a dimension analysis. He assumed the roughness length to be proportional to the shear stress.

It is also possible to derive this equation in a direct way. This is e.g. shown by SethuRaman (1979). He substitutes the equilibrium wave spectrum of Phillips, see Eq.(3.18), into Kitaigorodskii's formula and obtains the 'desired' result. In Section 4.1.2 it was seen that Byrne's model too leads to Charnock's formula when a Phillips spectrum is assumed.

Charnock's formula represents the surface roughness near full development when most of the stress is supported by short gravity waves (Donelan 1990a).

Charnock's equation does not contain any wave parameters and the question may arise how it is related to the pure-wind-speed-drag-formulations. This problem is easily solved since from Eq.(3.17),

$$C_d = U_*^2/U_h^2 = \kappa^2 \, [\ln(z_h/z_0)]^{-2} \tag{4.12}$$

Substitution of the roughness length z_0 according to Eq.(4.11) leads to the following relation between C_d and U_h:

$$C_d = \kappa^2 \, [\ln(gz_h/\alpha C_d U_h^2)]^{-2} \qquad (4.13)$$

For a further discussion see also Geernaert et al. (1987) and Geernaert (1990) who argue that this equation must be solved iteratively (given the wind speed and height h the drag coefficient C_d must be derived). The form of this equation shows an increasing dependence of C_d on wind speed.
So it is seen that Charnock's formula corresponds to a 'classical' C_d-U_h approach in which the C_d-U_h relation is straightforwardly parameterized. For examples see Smith and Banke (1975), Smith (1980), Garratt (1977), Large and Pond (1981) and Wu (1969).

To recognize the connection of Charnock's roughness length formulation with those in the next sections Charnock's formula is written in the following form

$$z_0 = \alpha \, u_*^2/g \, (c_p/u_*)^n \quad , \quad n=0 \qquad (4.14)$$

In the literature many values have been proposed for α. For instance 0.0185 (Wu, 1980), 0.0192 (Geernaert et al., 1986), 0.0144 (Garratt, 1977) and 0.035 (Kitaigorodskii and Volkov, 1965). This variety is believed to be due to different sea states in all these cases and since Charnock's relation does not include the sea state explicitly this 'missing' is 'compensated' by different values of Charnock's 'constant' α.

Only if the sea state is (nearly) in equilibrium with the wind Charnock's equation may be applied. In that case Eq.(4.13) supports the application of a purely wind speed dependent formulation of the drag coefficient. Then, to find C_d either Eq.(4.13) may be used, or $C_d(U_h)$ must be determined by the commonly used regression techniques.

4.2.2 Geernaert et al. (1987)

Geernaert et al. (1987) deals with the wind stress coefficient during storm conditions over the North Sea. This presentation is of special interest since it uses measurements in order to test and evaluate C_d formulations. Summarizing, the most important aspects or remarks that are made in this paper are:

(i) The measurements were obtained during a two week experiment in december 1985 and were conducted on a North Sea platform (FPN-data set) in the German Bight. From these measurements the wind stress could be evaluated over a large range of wind speeds, including severe storm conditions. To calculate the shear stress τ (and hence u_*), the definition of the Reynold's stresses, $\tau = -\rho[\langle u'w'\rangle i + \langle v'w'\rangle j]$ is used (the eddy-correlation technique). The brackets $\langle\cdot\rangle$ stand for temporal averaging. The drag τ is thus found via the covariance of horizontal and vertical wind speeds.

(ii) Geernaert et al. note that many authors argue that the drag coefficient must depend on the stage of wave development and that it is common to introduce the ratio c_p/u_* (= wave age) as a parameter to describe the wave influence on the drag coefficient. Therefore they have plotted the (North Sea) drag coefficient against the wave age. The trend is a rapidly increasing C_d as function of lower wave age values, and a slow, gradual decrease for the higher values of the wave age (i.e. as the wave state approaches equilibrium). The scatter in this diagram is much wider for smaller values of the wave age (less than 25) than for the larger values of c_p/u_* (greater than 30). In C_d terms the scatter is thus larger at its lower values. These results are illustrated by Figures 4.1 and 4.2.

Geernaert et al. remark that for steady state seas the parameter c_p/u_* has a typical magnitude of the order 25-30; this magnitude is exceeded for decaying seas and swell conditions.

(iii) On the basis of a C_d-c_p/u_* scatter plot a best fit relation was formulated according to the following power law:

$$C_d = A\ (c_p/u_*)^B \qquad (4.15)$$

The parameters A and B were found to be 0.0119 and -0.661 respectively. Restriction of this fit to the range of wave conditions where swell is minimized ($c_p/u_* < 40$) leads to A=0.0148 and B=-0.738.

NB. In this approach the **drag coefficient** C_d is made directly dependent on the state of wave development, in contrast to the **parameterizations of the roughness length** z_0 that are more often proposed.

It was verified whether or not the wave-age dependent formulation of C_d (as prescribed by Eq.(4.15)) provides a better description for the surface drag than the 'classical' approach that expresses C_d in (only) the wind speed. Therefore a fit was carried out on a formulation of C_d as a (linear) function of the wind speed. It is seen that the scatter of the data points in the C_d-U_{10} plot is much more pronounced than the scatter in the C_d-c_p/u_* plot. Thus, the drag coefficient correlates better with wave age than with wind speed. This leads to the conclusion that a description of the drag on the basis of wave age is potentially better than a description on the basis of simple wind dependence.

The formula Eq.(4.15) was also validated on a different data set namely the MARSEN (Marine Remote Sensing) set described in Geernaert et al. (1986). It turns out that the power law equation (4.15) again holds, and moreover, the C_d-c_0/u_* data points of the MARSEN set can be represented well by the A=0.012 and B = - 0.66 found for the FPN data set.

Whereas the FPN data were collected in relatively deep water (30 m) the MARSEN data were collected over much more shallow water (15 m).

(iv) On the basis of Eq.(4.15) and the dispersion relation

$$\omega^2 = gk \tanh(kD) \qquad (4.16)$$

the magnitude of C_d as function of the wind speed is predicted for some depths. Although not mentioned by the author we presume that in this calculation the relation

$$C_d = (u_*/U_{10})^2 \tag{4.17}$$

has been used as well: Eq.(4.15) and Eq.(4.17) can be used to eliminate the friction velocity and obtain a C_d formulation expressed in U and c_p.

$$C_d^{1+½B} = A\cdot(c_p/U_{10})^B \tag{4.18}$$

From Eq. (4.16) and the relation $\omega = kc$ it follows that the phase velocity increases with the depth. Since β is negative we have that for given wind speed the drag coefficient is larger for shallow water than for deeper water.

4.2.3 Hsu (1974)

Hsu considers the formulation of a dynamic roughness equation that includes major wind and wave interaction parameters (wind shear, velocity, wave height and phase velocity). He starts with Charnock's hypothesis Eq.(4.11). He argues that for 'the Charnock constant' α a wide range of values have been found by different investigators. The constant α will therefore not be a true constant but will exhibit variations dependent on the characteristics of the wave field. So his purpose is to propose an explicit relationship between the dynamic roughness and wind/wave parameters. His paper then evolves along the following lines:

(i) On the basis of suggestions in the literature the idea is that wave steepness is an important parameter for the roughness length z_0. Manton (1971) theorized that $z_0 \sim H_p/\lambda_p$ where H_p and λ_p are the wave height and wave length of the dominant wave respectively. It is then reasonable to extend Charnock's relation and let it depend on the wave steepness parameter H_p/λ_p. Therefore, it is suggested from dimensional considerations that

$$z_0 \sim \frac{H_p}{\lambda_p} \frac{u_*^2}{g} \tag{4.19}$$

(ii) Because (for **deep water**) the phase velocity c_p is proportional to $(g\lambda_p/2\pi)^{1/2}$ this equation can also be written as

$$z_0 \sim \frac{a^*}{2\pi} \frac{H_p}{(c_p/u_*)^2} \tag{4.20}$$

Here a^* is still an unknown value.

(iii) In order to check this suggested roughness length formulation the values of z_0 and $H_p/(c_p/u_*)^2$ were determined from 19 sets of available field and laboratory data. A scatter-plot of these values showed an excellent linear dependence. From the slope of the fitted line it was concluded that $a^* \approx 1$.

(iv) Hsu emphasizes that his approach is valid only where neutral atmospheric stability conditions exist. In that case a logarithmic wind profile can be assumed for the calculation of z_0 and/or u_*. He is then able to derive a prescription to calculate u_* from wind and wave parameters. The approach is as follows.

Combination of a logaritmic wind profile

$$U(z) = u_*/\kappa \ln(z/z_0)$$

and Hsu's law for the roughness length (Eq.4.20) leads to the following key result of that paper:

$$\frac{2\pi z}{H_p/c^2} = u_*^2 \exp(\kappa U_z/u_*) \tag{4.21}$$

Hsu has constructed a nomogram for solving this equation. Here solving must be understood in the sense that after determination (from field experiments) of wave height H_p, wave period T_p, and wind

speed U_z at height z, the value of u_* must be found.
Note. C_d then follows from $(u_*/U_z)^2$ and is thus a function of wind and wave parameters.

As the sea state evolves the phase velocity c_p develops towards saturation (wind speed independent) and the Charnock form will appear as an asymtotic limit.

4.2.4 Masuda and Kusaba (1987)

Masuda and Kusaba present an extensive discussion on the dependence of the roughness length z_0 on wind and wave parameters. This is done for neutral conditions and local equilibrium between wind and waves. They argue that in this case four physical quantities, which represent wind and wind-waves, are of interest. These four parameters are the friction velocity u_*, acceleration of gravity g, the total power E (also called energy density) of the surface displacement (i.e. the wave field) and the radian frequency ω of the dominant wave. It is supposed that additional material constants (such as e.g. densities of water and air, and molecular quantities such as kinematic viscosities and surface tension) either do not enter in the gross relationship, can be disregarded, or are absorbed into other quantities (as shear stress or power density). Of these four parameters two independent non-dimensional quantities can be composed: $E\omega_p^4/g^2$ and $\omega_p u_*/g$.

The authors argue that the first parameter, $E\omega_p^4/g^2$, is chosen such that it consists of quantities concerning water waves. It represents the wave nonlinearity (slope of the dominant waves) since it is the squared wave steepness. The second parameter, $\omega_p u_*/g$, coincides with the inverse of the wave age. In the authors opinion it measures the **wind effect** relative to **water waves**.

When the roughness length is considered a further simplification is inserted namely that the wave steepness parameter $E\omega_p^4/g^2$ is a function of the wave age. They claim that this is a consequence of the assumption of local equilibrium. Finally, this leads to the following expression for the roughness length z_0:

$$gz_0/u_*^2 = f(\omega_p u_*/g) \tag{4.22}$$

Some more or less special cases are considered for the form of the function $f(\cdot)$. In a brief review of the forms encountered in the literature they mention the following:

(i) Charnock's formula
The function $f(\cdot)$ is a constant. This means that the roughness length z_0 does not depend on (as they call it) the large scales of waves or the dominant frequency ω_p.

(ii) Toba's (1979) formula
Toba (1979) and Toba and Koga (1986) have proposed that $z_0 \sim u_*/\omega_p$. This leads to a function $f(\cdot)$ of the form $f(x)=x^{-1}$.

(iii) If it is supposed that z_0 is completely determined by the wave field only and does not depend on the shear stress velocity u_* we have

$$gz_0/u_*^2 = (\omega_p u_*/g)^{-2} \rightarrow z_0 = g/\omega_p^2 \tag{4.23}$$

This formulation of the roughness length corresponds to a function $f(x)=x^{-2}$. The authors remark that this expression for z_0 corresponds to the wave height of the steep breaking wave at the peak frequency ω_p; observations do however not support this formula.

(iv) On the basis of wave height-frequency relations other forms can be derived for the scaled roughness length gz_0/u_*^2. The idea is to assume z_0 proportional to the wave height $\sqrt{E}$. To find an expression for E two cases are considered: the Phillips spectrum and a form of wave spectrum that has been proposed by Toba (on the basis of "the 3/2-power law"*).

---

*NB. The "3/2 power law" was proposed by Toba (1972) for growing wind waves and was expressed as

$$H^* = BT^{*3/2}, \quad B=0.062 \tag{4.24a}$$

Eq.(4.24a) gives the non-dimensional form of Toba's law. The non-dimensional wave height H^* is defined by $H^*:=gH_s/u_*^2$ and the non-dimensional significant wave period T^* is defined by $T^*:=gT_s/u_*$. In dimensional form the equivalent of Eq.(4.24a) reads:

$$H_s = B(gu_*)^{1/2}T_s^{3/2} \qquad (4.24b)$$

This power law was originally proposed after examination of empirical formulas for the growth of wind waves by Wilson (1965) and experimental data by Toba (1961). For a review see Toba et al. (1990).

Since $T^* = 2\pi c/u_*$, Eq.(4.24a) may alternatively be written as

$$H^* = B'(c_p/u_*)^{3/2} \qquad (4.24c)$$

Using Toba's 3/2 power law it can be seen that the expression $E\omega_p^4/g^2$ (which Masuda and Kusaba define as an index of wave nonlinearity since it is the squared wave steepness) is linearly related to the wave age:

$$E\omega_p^4/g^2 \sim H_s^2\omega_p^4/g^2 = 8\pi^3B^2(u_*\omega_p/g) \rightarrow E\omega_p^4/g^2 = B^\circ(u_*\omega_p/g) = B^\circ(c_p/u_*)^{-1} \qquad (4.24d)$$

For the Phillips spectrum, $S(\omega)\sim g^2\omega^{-5}$, whereas Toba's spectrum is of the form $S(\omega)\sim gu_*\omega^{-4}$. The energy density E follows from integration of these spectra and since z_0 is proposed to be proportional to the square root of E this leads to the following expressions for the dimensionless roughness length:

$$gz_0/u_*^2 = (\omega_p u_*/g)^{-2} \qquad \text{for Phillips' spectrum} \qquad (4.25)$$

and

$$gz_0/u_*^2 = (\omega_p u_*/g)^{-3/2} \qquad \text{for Toba's spectrum} \qquad (4.26)$$

This corresponds to functions $f(\cdot)$ of the form $f(x)=x^{-2}$ and $f(x)=x^{-3/2}$, respectively.

(v) An approach based on Brutstaert and Toba (1986), using a complex formulation for gz_0/u_*^2 that involves the wave steepness as well as a dispersion relation for k and ω, leads for the Phillips spectrum again to a form $f(x) \sim x^{-2}$. For Toba's spectrum a function f(·) of the form $f(x) \sim x^{-0.8}$ is found.

(vi) In Hsu (1974) the wave steepness plays an important role. In this case

$$gz_0/u_*^2 \sim (E\omega_p^4/g^2)^{1/2} \sim (\omega_p u_*/g)^{1/2} \sim (u_*/c_p)^{1/2} \tag{4.27}$$

Summarizing these approaches the authors conclude that all proposed expressions are characterized by an exponent ε that occurs in the relation:

$$gz_0/u_*^2 \sim (\omega_p u_*/g)^{\epsilon} \sim (c_p/u_*)^{-\epsilon} \tag{4.28}$$

So the (dimensionless) roughness length is a power function of the wave age with exponent -ε. For ε the values {-2, -3/2, -1, -0.8, 0, ½} were proposed in the literature, see above.

We note that Geernaert et al. (1987, section 4.2.2) has proposed a very similar formula, though for the **drag coefficient** C_d instead of the **roughness** length as in the present case:

$$C_d = 0.012 \ (c_p/u_*)^{-0.667} \tag{4.29}$$

Despite Geernaert's more direct approach for the parameterization of the drag coefficient, all approaches are unanimous in their use of the wave age as relevant parameter.

Masuda and Kusaba decide to verify the preceding power-relation of roughness length and (inverse) wave age for experimental data that they obtained from flume experiments in what they call 'a preliminary experiment of the Oceanographic Research Project "Measurements and simulations of ocean environment"'.

On the basis of a doubly logarithmic plot of the dimensionless roughness length gz_0/u_*^2 versus the inverse of wave they suggest a 'new' formula

$$gz_0/u_*^2 = 0.0129(\omega_p u_*/g)^{1.10} = 0.0129(c_p/u_*)^{-1.10} \qquad (4.30)$$

So the exponent in the power-law-presciption of the dimensionless roughness length as function of the wave age takes the value $\epsilon = 1.10$. For comparison they have also plotted Charnock's formula and Toba's formula. It is observed that the new formulation provides a better description of the data samples than Charnock's and Toba's formulas.

NB. We feel the need to remark that the range of the data is very limited: only wave ages in the range of 1 to 3 are present. Moreover 4 data samples out of 20 were not recovered by the fit. (The authors comment that these samples 'correspond to the case of the lowest reference wind velocity U=2.5 m/s when wind waves grow rather anomalously with much lower levels of energy and with much higher frequencies. That is, these data do not satisfy the basic condition of local equilibrium.')

The authors observe that their (scaled) roughness length is smaller than the one's of Charnock (see (i) with constant α chosen as 0.0185) and Toba (see (ii)). Moreover, they find an increasing roughness length with decreasing wave age (whereas Toba finds the roughness to increase with wave age). Still, they conclude that the wave age is a key parameter in the formulation of the roughness length z_0. (NB: This is questionable, since the sign of its exponent ϵ varies between $-\frac{1}{2}$ and +2).

A plot (on a doubly logarithmic scale) of the **wave steepness** versus the (inverse) wave age has been composed as well. A very acceptable fit is found and this leads to the folllowing suggestion of their dependence:

$$E\omega_p^4/g^2 = 0.0523(\omega_p u_*/g)^{1.02} \qquad (4.31)$$

This agrees very well with the 3/2 power law of Toba, see Eq.(4.24d).

Finally, Masuda and Kusaba once more emphasize that the present frame work assumes a complete local equilibrium of winds and wind-waves. If the spectrum does not have a single peak the approach will not be usable since in that case other detailed meachanisms must be included.

4.2.5 Maat et al. (1991)

The approach followed by Maat et al. (1991) is very similar to the one followed by Masuda and Kusaba (1987). Again a 'new' roughness equation is proposed and the formulation is calibrated/verified on the basis of field data obtained during HEXMAX/1986. HEXMAX (the HEXos MAin eXperiment where HEXOS stands for Humidity EXchange Over the Sea) was a comprehensive field experiment carried out in the fall of 1986 on and around a platform 9 km off the Dutch coast).

As in Masuda and Kusaba (1987) the dependence of the roughness length on combinations of wave and wind parameters is investigated. It is argued that many of these quantities are interrelated and after eliminating dependent wind/wave parameters only g, z_0, u_*, (wind parameters) and c_p (the phase velocity of the dominant wave) remain. The general hypothesis is then

$$z_{0*} := gz_0/u_*^2 = F(c_p/u_*) \tag{4.32}$$

It is recognized that this formula generalizes the expressions of Charnock (1955), Toba and Koga (1986) and Hsu (1974). In their expressions $F(\cdot)$ is an exponential function of the wave age with exponent 0, 1, and -½ respectively. Therefore the authors want to apply the general formula

$$z_{0*} = \mu(c_p/u_*)^n \tag{4.33}$$

(μ is taken as a constant) to the HEXMAX data. After checking the relationship of some of the wind and wave parameters (e.g. Toba's 3/2-power law, i.e. the wave height is proportional to the 3/2 power of the period of the peak wave, see Eq.(4.24)) they propose the following values for the parameters: μ=0.8 and n=-1.00. This is clearly outside the above range n = -½ to n = 1. It corresponds surprisingly well with the results of Masuda and Kusaba. However, the parameter μ is significantly different in both approaches. It is thought that this is due to the origin of the data. Masuda and Kusaba use data from laboratory experiments and u_* was obtained from wind profile measurements at very low levels above the flume waves leading to an underestimation of u_*.

Whereas for the data of Masuda and Kusaba the range of the wave age varies from 1 to 3 this range is 7 to 45 in the investigation of Maat et al. As in the case of Masuda and Kusaba, the proposed roughness equation performs best for those data samples associated with single-peaked-wave-spectra.

On the basis of Eq.(4.32), a logarithmic wind profile (neutral conditions), and the definition $C_d=u_*^2/U_h^2$ (where h will in general be 10 m) the following implicit expression for C_d can be derived:

$$\frac{U_h^2}{gh} (c_p/U_h)^n = \frac{C_d^{n/2-1}}{\mu} \exp(-\kappa/\sqrt{C_d}) \tag{4.34}$$

In this expression C_d depends on one wind parameter (wind speed U_h) and one wave parameter, namely the phase velocity of the peak wave. The authors argue that this expression reveals an enhanced drag coefficient over younger wind seas only if n is negative. The property of an enhanced wind drag for younger waves is supported elsewhere; the authors refer to Donelan (1982), Geernaert et al. (1987) and Janssen (1989).

Apart from the consistence of n=-1 with the formula of Masuda and Kusaba the consistence with a result by Donelan (1990a) is demonstrated. Donelan (1990a) made a fit between z_0/σ (σ being the RMS wave height) and found that $z_0/\sigma = 1.84(c_p/u_*)^{-2.52}$, see Section (4.2.6). The consistence of this result with the formulation of Maat et al. can be seen as follows.

$$z_0/H_s = z_{0*}u_*^2/gH_s \tag{4.35a}$$

$$= B^{-1}z_{0*}(u_*/gT_s)^{3/2} = B^{-1}(2\pi)^{-3/2}z_{0*}(c_p/u_*)^{-3/2} = \tag{4.35b}$$

$$= \mu B^{-1}(2\pi)^{-3/2}(c_p/u_*)^{n-3/2} \tag{4.35c}$$

Note: In this verification Maat et al. use the significant wave height H_s instead of the RMS wave height σ.

In this formula manipulation Toba's 3/2-power law (Eq.4.24b) was used in the transition from (4.35a) to (4.35b) and the formula of Maat's et al. in the transition of (4.35b) to (4.35c). Since n=-1. the exponent n-3/2 equals -2.5 which compares well with the -2.52 proposed by Donelan (1990a).

4.2.6 Donelan (1990a)

In his paper Donelan gives a broad review of aspects dealing with air-sea interaction. He deals both with the physical mechanisms that play a role in the exchange of momentum between the atmosphere and the water body, and, in a separate paragraph, with the parameterization of the surface roughness. This summary focuses on the last item.

According to Donelan, one of the first formulations for the sea roughness length was offered in Deacon and Webb (1962). These authors suggest that the roughness of the sea surface may be parameterized solely using u_*, υ (the kinematic viscosity of air) and g. Of these parameters only the first will be important; the second varies moderately over typical extremes of atmospheric temperatures, and g is a constant. This leads to

$$z_0 = 0.11\upsilon/u_* \quad \text{for smooth flow} \qquad (4.36)$$
$$z_0 = 0.014u_*^2/g \quad \text{for rough flow}$$

The meaning of 'smooth' and 'rough' has been considered in Section (3.3). Here we recall that smooth flow is associated with flow where the surface roughness elements (i.e. the waves) are within the viscous sublayer whereas for rough flow their size exceeds the thickness of the viscous sublayer. Since the viscous sublayer is of the order of millimeters any flow must in practice be termed rough.

The basic form for the roughness length is Charnock's formula. Donelan notes that other parameters besides u_* and g are important for the formulation of the roughness length.

Apart from (4.36) other roughness length formulations proposed in the literature are considered, e.g. the approach of Kitaigorodskii and Volkov

(1965). They use the complete wave spectrum S(k) in their formulation:

$$z_0^2 = C_K^2 \int S(k)\cdot \exp(-2\kappa c(k)/u_*)\, dk \qquad (4.37)$$

(see Section 4.1.1). Donelan mentions that this approach includes the mobility of the roughness elements (the waves are viewed in a frame of reference moving with the phase speed) but does not account for effects of varying steepness across the spectrum. Moreover **the spectrum must be known to quite high wave numbers k**. Therefore, often a more simple and compact version of this formula is proposed that involves only the peak of the spectrum (Kitaigorodskii, 1973):

$$z_0 = 0.3\cdot \sigma\cdot \exp(-\kappa c_p/u_*) \qquad (4.38)$$

(see Section 4.1.1). Here σ is the standard deviation of the surface elevation. Note that 'once more' a formula is found that expresses roughness length in terms of wave age. In this expression no additional effect of wave steepness on z_0 is included, perhaps, as Donelan notes, because steepness and wave age are quite well correlated.

On the basis of his measurements and data obtained from elsewhere, Donelan has verified a result by Kitaigorodskii that for fully rough flow the **roughness length is proportional to the root mean square wave height**. In this verification several sets of data were used, both for laboratory and for field circumstances. It appeared that the roughness length and wave height are proportional ($z_0 \sim \sigma$) and the constant of proportionality varies over several orders of magnitude depending on wave age. In three logarithmic plots of z_0/σ vs. U_x/c_p [where U_x stands either for (i) the wind velocity at 10 meter above the mean surface, or (ii) the wind velocity at half a wavelength above the mean surface, or (iii) the friction velocity u_*] a linear dependence between these two quantities was shown. It appeared that in the scatter-plots the set of field data on the one hand and the laboratory data on the other were more or less separated into two disjunct clusters. Donelan argues that this is probably due to the use of the wind speed referred to 10 meter which has no relevance for laboratory work.

On the basis of the z_0/σ vs. U_x/c_p plots the following simple regression formula was then proposed to parameterize the sea surface roughness for fully rough flows:

$$\frac{z_0}{\sigma} = A\ (U_x/c_p)^B \tag{4.39}$$

For both the field and laboratory data alternative (iii), i.e. $U_x = u_*$, yields the best fit. So,

$$\frac{z_0}{\sigma} = A\ (u_*/c_p)^B \tag{4.40}$$

The parameters are A=1.84, B=2.53 (field) and A=0.205, B=2.18 (laboratory). In the z_0-u_*/c_p plots also Hsu's formulation (overall steepness σ/λ is the appropriate parameter and is used to modify the constant α in Charnock's relation) and Kitaigorodskii's simplified formula (Eq.(4.38)) were considered. Hsu's formulation agrees well with the data although the slope of its curve is somewhat smaller than suggested by the data. Kitaigorodskii's simplified formula behaves well for wave ages less than, say, 12 but considerably under-estimates the roughness length for the larger wave ages, i.e. near full development. Donelan states that Kitaigorodskii's original formulation will more correctly represent the over the entire spectrum distributed contribution to roughness, but few experiments yield sufficient data to compute the integral across the spectrum.

Finally Donelan formulates some general comments on air/sea interaction. We summarize them pointwise.

1. Donelan mentions that several attempts have been made to integrate laboratory and field data/experiments. Problems that are encountered are the fundamental differences in the flow (e.g. the existence of side walls and return flows in laboratory experiments) and substantial differences in the scaling properties of the field and laboratory data. As an illustration it is remarked that in laboratory circumstances the steepness of the surface elevation frequently approaches the limiting steepness of Stokes' waves. A close packing of these steep waves may reduce their effective height as roughness elements.

Nevertheless laboratory data remain an important means to understand the underlying physics since the range of the governing variables can be extended, controlled, and the sampling variability can be reduced to 'any' desired level.

2. With regard to the part of the wave spectrum that dominates the roughness length it is argued that as the wave field evolves the spectrum will shift towards the longer wave length components. Due to the dispersion relation $c^2=g/k$ these components travel faster and therefore interact less with the wind. So for full development, and c_p of the order of $30u_*$, the burden of the supporting stress is borne by the relatively short waves (short with respect to the energy containing waves).

   Stronger forcing ($U/c_p >> 1$) has the effect that both the short waves and the waves near the peak will contribute to the roughness. This is due to the fact that on the one hand the wave numbers contributing to the roughness approach the peak frequency, and, on the other hand, the steepness of the energy containing waves will steadily grow. For sufficiently strong forcing these contributions overlap and the stress is probably supported largely by the energy containing waves. This idea is supported by laboratory experiments: for very young wind generated waves, the principal cause of changes of z_0/σ arises from changes in the steepness of the energy containing waves. At the other end of the development scale, variations in z_0/σ arise from the changes in the short wave spectrum through which most of the stress is transferred. The young wave fields that are in between include both of these effects.

3. Donelan concludes that in spite of progress in understanding the mechanisms of wind-wave-generation we are yet not able to deduce the surface roughness from the momentum transfer between wind and waves. The principal problem is that the momentum transfer is distributed over the entire spectrum (see Kitaigorodskii's formula) and our knowledge of the wave number spectrum of the short waves is rather rudimentary. He states that for aerodynamically smooth and fully rough conditions the sea roughness may be described by Eq.(4.36) and Eq.(4.40), respectively. The transitional regime between smooth and rough flow must, for the moment, be described by matching the smooth and rough regimes.

NB: Such a hybrid procedure is put into practice by Johnson and Vested (1991), see Section 4.2.9.

4.2.7 Geernaert et al. (1986)

Geernaert et al. (1986) analyzes data obtained in the German Bight during the MARSEN (MAritime REmote SENsing)-experiment. These data were collected during the last quarter of 1979 and are used to identify the relationship between wind stress and surface waves. For this purpose six models proposed in the literature are examined.

First the dependence of C_d on U_h-U_0 (h=10 m.) is examined. A linear least squares analysis was performed yielding the relation $10^3 C_d = 0.1168(U_h - U_0) + 0.1967$. The formula was compared with the results of past investigations (among others Smith and Banke, 1975). It was seen that the results of the various investigators showed little variation at the lower wind speeds. Increasing wind speeds result in diverging magnitudes of C_d. Considering the various C_d values for a given windspeed (at the high end range, say larger than 10 m/s), the authors argue that the lower C_d values appear to be representative for open ocean conditions, while higher C_d magnitudes are associated with closed basins, lakes, shallow seas or estuaries. So, during high wind speeds shallow and fetch limited water bodies are associated with rougher seas and higher drag coefficients than the deep ocean.

In the paper the measured momentum fluxes and sea surface wave spectra were confronted with six models. This was done by comparison of the drag coefficient as predicted by the model and the drag coefficient that was derived from the field data. Two aspects need mentioning:

(1) The results of the models were compared with the model's constants/parameters using the values suggested by the authors.

(2) In order to make an optimal prediction of the wind stress, the adjustable parameters of each model were optimized by minimizing the scatter between measured and modeled drag coefficients (least mean square difference). That way the effectiviness of each model could be examined for the MARSEN-North-Sea-data set.

The six models, together with Geernaert's comments on their 'nature', are:

1. Byrne's model, see Section (4.1.2), Eq.(4.9). In this model the roughness length is expressed in the form of an integrated slope spectrum. The composed integral is governed by a power law -3 (if a Phillips spectrum is used). According to Geernaert et al., this model physically depends only on information in a narrow spectral region around the peak of the equilibrium range; it is unaffected by variations in the higher frequency waves (such as surface tension effects) and can therefore be considered to represent rather the form drag over the long gravity waves than the frictional drag from the short waves.

2. Kitaigorodskii's model, see Section (4.1.1), Eq.(4.3). This approach utilizes an exponentially weighed integral. According to Geernaert et al., the maximum contributions to the momentum flux are supplied by the frequencies around $4\omega_0$ if a Phillips spectrum is used. For wind speeds in the range of 10-15 m/s the model is largely dominated by surface waves within the frequency range $2\omega_0$-$8\omega_0$. Kitaigorodskii's model implies a friction mechanism for momentum transfer rather than a low frequency form drag mechanism.

3. Charnock's model. See Section (4.2.1). This model accounts for a growth of the roughness elements with the wind stress, but no specific information concerning spectral energies is used.

4. Hsu's model. See Section 4.2.3 and Eqs.(4.19-4.21). This model forms an extension of Charnock's since via Charnock's-'constant' α the steepness of the primary local wind wave is included. Hsu proposed:

$$gz_0/u_*^2 = H_p/\lambda_p = a^*/2\pi \; H_p(c_p/u_*)^{-2} \qquad (4.41)$$

See Eq.(4.20).

In Geernaert's approach the height H_p in Hsu's formula is approximated from field data by an alternative height H according to the following formula

$$H = 2 \left(\int_{\omega_p}^{\infty} S(\omega)d\omega \right)^{1/2} \tag{4.42}$$

According to Geernaert Hsu's model is an example of a low-frequency form drag mechanism.

5. The fifth model is an extension of Hsu's model. Hsu (1974) (see Section 4.2.3) modified Charnock's equation by letting Charnock's constant depend on wave parameters.

   Instead of the wave height H_p, Kitaigorodskii's "middle frequency weighted spectral characteristic height" is now employed as the vertical scale. Thus for H_p the following expression is used:

$$H_p = \left[\int_0^{\infty} S(\omega)\exp(-2\kappa c/u_*)d\omega \right]^{1/2} \tag{4.43}$$

   This leads to the following modified Hsu-Kitaigorodskii's formula:

$$z_0 = C_{KH} \, (c_0/u_*)^{-2} \left[\int_0^{\infty} S(\omega)\cdot\exp(-2\kappa c/u_*)d\omega \right]^{1/2} \tag{4.44}$$

   This formula incorporates the effect of the high-frequency frictional drag in Kitaigorodskii's model with a drag modulation due to wave age.

6. The sixth model is the one of Donelan (1982). Donelan proposed that the drag is composed of two additive components, one drag coefficient representing contributions from the lower frequency waves and the other contributing from the higher frequency waves. The lower frequency component involved integration of the wave energy density spectrum between the frequencies 0 and $2\omega_p$ whereas the higher frequency component was calculated by integrating between $2\omega_p$ and ∞. These coefficients were further adjusted by a factor based on the difference between wind speed and phase speed of the wave at the peak in the equilibrium spectrum. For a further discussion of Donelan's model see Section (4.2.8).

   Geernaert et al. use slight modifications of the original formulation by adjusting the low frequency component. This was done to prevent the drag coefficient C_d to become too large due to the presence of large swell exceeding the total local wind wave energy.

Donelan's model considers additive high frequency and low frequency drag coefficients and suggests a wind stress partition between frictional and form drag. Elaborating these expressions Geernaert found that that the higher frequency waves dominated the mean magnitude of the wind stress. The long waves merely gave rise to variations about the mean.

Application of these formulations to the MARSEN-data-set leads to the conclusion that Kitaigorodskii's model performed best as a predictor for the drag coefficient. The mean squared difference of modelled and measured C_d was about 14% better than for Charnock's formula. Taking into account that the data set on which the analysis was performed was statistically small (53 wave records of wave information with in situ wind stress) it is concluded that, although Kitaigorodskii's model performed better than the others, none of the models can be said to have failed.

In his review of 1990 Geernaert recalls that Kitaigorodskii's model seems to be most useful for the prediction of C_d. The author notes however that this model (just as the other models) is not universal since it cannot explain swell-induced variations. It is known that swell can have a significant influence on the wave spectrum. As an example Donelan (1986) is mentioned who found that swell (travelling with the waves) tends to decrease the wind-wave energy and similarly decrease u_* and thus the drag coefficient. When swell travels against the waves the opposite will be true, i.e. the drag coefficient will be increased. When swell propagates at no preferred direction (e.g. open ocean) a natural variability in the C_d may exist.

In an other section Geernaert et al. deal with the dependence of the drag coefficient on the water depth. In their approach the ω-k dispersion relation for (shallow water gravity) waves is used as well as the Phillips spectral distribution of the waves. It is known from the literature that the Phillips constant β shows variability. An analysis of the variability of β on the basis of the present data set led to a parameterization of β in the form of a linear dependence on the radian frequency ω and the wave age

c_p/u_*:

$$\beta(\omega,\ c_p/u_*) = 0.005 + B\omega + 1.5\ (c_p/u_*)^{-2} \tag{4.45}$$

B as a parameter found to be 0.002 s when ω is in units of radians.
The Phillips spectrum with this modified β is then substituted into Kitaigorodskii's formula of the roughness length z_0. Since β depends on the phase velocity, which in its turn depends on the depth, the roughness length z_0 is sensitive for the depth. As a consequence also the drag coefficient is depth dependent. This dependence on depth is absent at lower wind speeds but will noticeably manifest itself at higher wind speeds. This approach explains why drag coefficients over deep water (oceans) may generally be smaller than those observed over shallow lakes and marginal seas.

4.2.8 Donelan (1982)

Donelan (1982) collected measurements in the western part of Lake Ontario. The depth at the measurement site is 12 m and fetches range from 1.1 to 300 km. He uses these measurements to verify a model for the drag coefficient C_d.
The shear stress was calculated on the basis of 20 minute averages of the covariance $\langle u'w' \rangle$. The observed wind speeds U_{10} are in the range 4 to 17 m/s.

The author's viewpoint is that the more likely the roughness elements are to cause flow separation (turbulence), the larger their influence on the roughness length.

Donelan argues that the roughness length at the air-sea interface is complicated by the mobility of the roughness elements, i.e. the waves. The latter forms an important subject in the formulation of his model for the roughness length.

Before actually proposing and verifying his model Donelan examines his data with regard to (i) the roughness Reynolds number (see Section 3.3,Eq.3.14),

(ii) the variation of the roughness length with u_*^2/g and (iii) the dependence of the drag coefficient on wind speed.

With regard to (i) it is seen that the data show a general trend of increasing z_0/H with the roughness Reynold's number (H is the mean height of the waves; for a narrow spectrum it holds that $H=\sqrt{(2\pi)}\sigma$ where σ is the root mean square surface variation). For large values of the roughness Reynolds number the surface approaches the roughness of a solid sand grain surface i.e. z_0/H approaches a value of 1/30.

To examine the dependence of z_0 and u_*^2/g a scatter diagram was composed (with both abscissa and coordinate logarithmically scaled). In this diagram Charnocks formula should be a straight line with slope 1. It turns out that for high values of U_{10}/c_p the data show such a trend, however with a much higher Charnock parameter ($\alpha \sim 0.04$) than the one ($\alpha = 0.0144$) that was found by Garratt (1977). For the lower values of U/c_p the dimensionality arguments that led to Charnock's relation (open ocean measurements) are clearly insufficient to describe the process.

Using a scatter plot and linear regression the dependence of the drag coefficient on wind speed has been examined. While the correlation coefficient of the regression line is respectable (r=0.72) the scatter in the (C_d, U) data samples is considerable and it is clear that a linear dependence does not provide an adequate description of the data. In the C_d-U plot the datapoints were labeled on the basis of their U/c_p value. It turns out that the samples with (approximately) the same U/c_p value are organized along a curve rather than 'randomly' distributed. In this stratification (of the (C_d,U) data points with respect to U/c_p) the high values of U/c_p (4.0-6.0) correspond to higher C_d values.

On the basis of the $\log(z_0)$ vs. $\log(u_*^2/g)$ plot Donelan argues that Charnock's formula is insufficient to describe the surface roughness. A modified form of Charnock's relation could be considered by assessing the dependence of Charnock's 'constant' α on other properties of the interface. However, according to Donelan, little would be gained in our understanding of the drag on the water surface. Therefore use must be made of observable characteristics of the surface to construct a model. This model must satisfy the limits of (a) flow over a comparable rough solid surface for very young waves, and (b) vanishing net form drag for (low frequency) waves as they approach full development.

For his modelling the following relevant phenomena are taken into consideration:

1. The roughness elements cause flow separation and this flow separation influences the roughness length. It is known that flow separation and wave breaking are closely linked and that wave breaking occurs at the crests of the (large) waves near the spectral peak (and although present, less dramatically over the equilibrium range).
2. The roughness length is generally a small fraction of the wave height, but it approaches the value corresponding to certain solid boundaries when the roughness Reynolds parameter is large.
3. In some circumstances the surface seems to be ultra smooth. The condition appears to occur in light winds (≤ 5 m/s). A plausible explanation for this is that some components of the wave field are travelling faster than the wind and transfer momentum to the boundary layer. This momentum transfer results in a wave driven current, i.e. a smoothing effect.

   In Donelans view the effects 2. and 3. are due to the mobility of the roughness elements, i.e. waves.

4. In fetch-limited or nonstationary conditions waves near the spectral peak travel at off-wind angles. On the other hand the shorter waves, in the equilibrium range, are generally closely aligned with the wind.

On this basis the surface is seen as a collection of travelling roughness elements and its spectrum is conveniently separated into two parts:

(1) the peak, characterized by enhancement (peak enhancement at short fetches, Hasselmann, 1973), white caps and off-wind travel
(2) the equilibrium range, characterized by quasi-saturation, micro-breaking* and down-wind travel
    *[is defined by Donelan as follows: "mean breaking which is too gentle

to produce a discernable colour change but in which the fluid just ahead of the crest advances relative to the crest"]

It is admitted that this criterion for separation of the two types of roughness elements is somehow arbitrary. Noting that according to Hasselmann et al. (1973) the spectrum (above the enhanced peak) undershoots the equilibrium range before approaching the equilibrium range level near $\omega=2\omega_p$, this frequency is chosen as the dividing line between the long and short wave regions. The component of the roughness associated with the long waves is then defined by

$$z_{0l} = \beta \left[\int_0^{2\omega_p} S(\omega)\, d\omega \right]^{1/2} \tag{4.46a}$$

$$z_{0h} = \beta \left[\int_{2\omega_p}^{\infty} S(\omega)\, d\omega \right]^{1/2} \tag{4.46b}$$

Donelan thus assumes that the sea surface can be represented by two roughness lengths, one due to the low frequency waves and the second due to the high frequency waves.

Parameter β is a constant of proportionality and is of the order 0.01 to 0.1. One has however, not yet accounted for the mobility of the surface. This is done as follows. For an immobile surface ('the surface frozen at some instant of time'; or in other words a fixed observer) the total surface stress would involve the superposition of $[C_d]_h$ and $[C_d]_l$ where the low and high frequency drag components $[C_d]_.$ are found by substitution of the corresponding roughness lengths $z_{0.}$ into $C_d=(\kappa/\ln(z_h/z_0))^2$.

However, since both components travel at some appreciable fraction of the wind speed an adjustment of the drag coefficients must be carried out:

$$[C_d]_l = [\hat{C}_d]_l \cdot |\cos\theta| \cdot |U_{10}-c_l/\cos\theta| (U_{10}-c_l/\cos\theta)/U_{10}^2 \tag{4.47a}$$

$$[C_d]_h = [\hat{C}_d]_h \cdot (U_{10}-c_h)^2/U_{10}^2 \tag{4.47b}$$

In these expressions,

$\hat{C}_d$ denotes the equivalent immobile surface drag,

θ is the angle between the wind and the waves at the central peak; $\cos\theta$ accounts roughly for the reduction in drag as the waves move away from the wind direction,

c_l, c_h are characteristic speeds of the low and high frequency wave components,

U_{10} is the wind speed at 10 meter

Observational evidence (Bretschneider, 1973) indicates that the spectrum becomes fully developed when U/c_p=0.83. At full development the waves near the peak are less steep and break infrequently. Assuming that under these conditions the long waves do not contribute to the total drag one may choose for c_l: $c_l=0.83c_p=0.83g/\omega_p$. For consistency $c_h=0.83g/2\omega_p$.

The model drag coefficient C_{dM} is defined as the superposition of the contributions $[C_d]_l$ and $[C_d]_h$. It is compared with estimates of the hourly average drag coefficient as derived from the measurements. Parameter β is used as a calibration coefficient; the best agreement was found for β=1/80 and gave a correlation coefficient 0.79.

A slight modification of the formulation of the model drag coefficient was applied by taking the sea-state Reynolds number, here defined as $R_s=U_{10}\sigma/\nu$, into account. The idea is that the degree of whitecap coverage increases with the wind speed and also with the wave height. So, the form drag on the waves is expected to increase with whitecap coverage (in addition to the phenomena already modelled). Regression of the ratio of the measured and modelled dragcoefficient and $\log(R_s)$ leads to the following modification $\check{C}_{dM}$ of the modelled drag coefficient:

$$\check{C}_{dM} = C_{dM}(0.07 + R_s) \tag{4.48}$$

The correlation coefficient of the modelled and measured drag coefficient is then improved to 0.82 (in our view an insignificant improvement compared with the earlier value of 0.79). In the plot of the measured drag coefficient versus the modelled drag coefficient there is still a considerable scatter about the 45° line. Although the model is not a perfect facsimile of the natural process, it is argued that this could be due almost entirely to the observational variability of the measured drag coefficients.

NB. As for practical use, we believe that this article is somewhat dated and less specific, c.q. relevant than the more recent papers on this topic.

4.2.9 Johnson and Vested (1991)

The idea of the paper of Johnson and Vested (1991) is to construct a hybrid roughness-length-model that combines the earlier roughness models by Kitaigorodskii (1973) and Donelan (1990a). The purpose is to obtain a wave dependent C_d formulation whose magnitude is consistent with the one of Smith and Banke.

In their first 'attempt', the simplified version of Kitaigorodskii's formula is used i.e.

$$z_0 = 0.3 \cdot \sigma \cdot \exp(-\kappa c_p/u_*) \tag{4.49}$$

Here, $\sigma = H_s/4$ with H_s the significant wave height. It is noted that the Kitaiigorodskii model is attractive for its inclusion of the mobility of the friction elements, i.e. the waves. Given the assumptions made, the model cannot be used when $U_{10}/c_p < 1$ (i.e. for waves travelling faster than the wind). Furthermore, referring to Donelan (1990a) who confronts models (including the one of Eq.(4.49)) with measurements, it gives small roughness lengths for small u_*/c_p. Therefore Kitaigorodskii's simplified formula, Eq.(4.49), is used for $u_*/c_p > 0.1$ (thus wave ages less than 10). On the other hand, for $u_*/c_p < 0.1$ (wave ages greater than 10) Donelan's formula, Eq.(4.40) is used, i.e.

$$z_0 = 1.84 \cdot \sigma \cdot (u_*/c_p)^{2.52} \tag{4.50}$$

Using this roughness model, drag coefficients were calculated and their realism verified. In this exercise the wave climate (i.e. significant wave heights and peak frequencies) is determined on the basis of the wave prediction equations of the U.S. Army C.E. Shore Protection Manual (1984). The drag coefficients were calculated for several values of water depth and two alternatives for the fetch (an unlimited fetch simulating open ocean conditions, and a fetch of 200 km simulating the measurement site of Smith and Banke). It was found that the C_d values became too large when compared to the C_d according to Smith and Banke. This required an adapted formulation of the hybrid model.

The main considerations leading to the adapted formulation of the model are (i) Following Kitaigorodskii's approach, i.e. moving with the dominant wave speed, one has already accounted for the form drag due to air-flow separation from the wave form, and (ii) the roughness 'a' in Kitaigorodskii's 'preliminary' formula,

$$\frac{U(z)-c}{u_*} = \frac{1}{\kappa}\ln(z/a) \tag{4.51}$$

refers to the high frequency waves. Johnson and Vested call this "skin friction". 'High frequency waves' include all waves with wave number $k>1.5k_p$. On the basis of this definition the earlier hybrid formulation (based on Kitaigorodskii, 1973, and Donelan, 1990a) is rewritten into

$$z_0 = \alpha_k \sigma_{hf} \exp(-\kappa c_p/u_*) \qquad \text{for } u_*/c_p > 0.1 \text{ (smaller wave ages)} \tag{4.52a}$$

and

$$z_0 = \alpha_d \sigma_{hf} \cdot 1.84 \cdot (u_*/c_p)^{2.52} \quad \text{for } u_*/c_p \le 0.1 \text{ (larger wave ages)} \tag{4.52b}$$

Here, α_k and α_d are calibration constants that are determined such that the (magnitude of the) model's predicted C_d values agrees with the one of Smith and Banke for the appropriate site conditions. The wave field parameter $\sigma_{hf}= H_{hf}/4$ where H_{hf} is a "high frequency significant wave height". In terms of the wave number spectrum $\chi(\cdot)$ one finds:

$$\sigma_{hf}^2 = \int_{1.5k_p}^{\infty} \chi(k)dk \tag{4.53}$$

For the evaluation of σ_{hf} the Phillips spectrum is assumed. Moreover the ω-k dispersion relation Eq.(4.16) is used so that σ_{hf} can be derived from the Phillips constant β, peak frequency ω_p, acceleration of gravity g, and the water depth D.

Calibration of the roughness model on the Smith and Banke formula gave α_d=1.12 and α_k=0.31. These values compare well with the original values 1 and 0.3 that are used in the non-adapted formula's for the roughness length (Eqs. 4.50 and 4.49).

So, the adapted model gave a significant improvement of the first hybrid model.

The adapted formulation was also compared with the analysis presented by Donelan (1990a) and Geernaert et al. (1987). It is observed that the model of Johnson and Vested follows the same trend, both quantitatively (same order of magnitudes of z_0 and C_d) and qualitatively (decreasing C_d for increasing wave age, and decreasing C_d for increasing water depth).

The roughness model was also applied to compute drag coefficients in a number of test cases. The test for the North Sea (western wind, 24 m/s) resulted in lower drag coefficients for the northern part than for the southern part. This might be due to differences in water depth and fetch leading to longer waves with smaller form drag contribution in the Northern part than in the Southern part. The average value of C_d is of the same order as the one of Smith and Banke (1975).

5. SUMMARY, CONCLUSIONS AND DISCUSSION

On the basis of the literature survey in Chapter 4 the following main conclusions can be drawn.

1. In the literature, there is consensus that a description of the sea surface roughness in terms of the wind speed alone is inadequate and must include the actual sea state. Therefore wave dependent models for the drag coefficient C_d will be much more realistic than the 'traditional' formulas that use only the wind speed (and thus correspond to the approaches of Smith and Banke, and Charnock).

2. We believe that the preceding conclusion will in particular hold for the North Sea because its limited fetch and depth do not agree with the deep open ocean conditions that allow Charnock's approach. So it is recommended to equip the CSM-model with one or more wave dependent C_d formulas and verify their performance for one or more storm conditions. These wave dependent C_d-formulation will be proposed in Chapter 6.
   In the literature no evidence was found that wave dependent C_d-formulas have been integrated in a $2D_h$ or 3D numerical water flow model, and were verified on the basis of observations (e.g. water levels). So it is not apriori clear to what extent a wave dependent C_d will improve the waterlevels predicted by CSM. We expect however that the RMS difference between predicted and observed water levels can be significantly reduced with regard to the present CSM-model equipped with the $C_d(U_{10})$ formula.

   NB. While finishing this report this expectation has been confirmed by very recent experiments on wave dependent C_d-formulations in the CSM model. These experiments were performed at the KNMI (de Bilt, The Netherlands) by C. Mastenbroek et al. (1991). In this approach a model for the shear stress induced by waves (proposed by Janssen, 1990) has provisionally been coupled to the CSM-model and applied for the conditions of the February 1989 storm. The storm surge predictions (for Dutch and Brittish stations) are significantly improved with regard to the Smith and Banke formula for C_d, see Figure (5.1) (courtesy of C. Mastenbroek). At the moment that the present report was finished these results were not yet reported.

3. The main suggestions for parameterizing the sea roughness involve two, more or less complementary aspects in the roughness of the sea surface. These are form drag arising from the lower frequences, including the peak of the spectrum, and friction roughness arising from the high frequencies. In general (e.g. Donelan 1990a, p.267; Geernaert et al. 1986, p.7678) it appears that the magnitude of the stress is dominated by the higher frequencies. The idea is that the large waves are not (so) steep, and moreover, travel at speeds that approach or exceed the wind speed. So the short waves are the main stress receptors.

4. Usually the drag coefficient is modelled for neutral conditions (in case of stratification appropriate corrections are applied). Most authors model the surface roughness length z_0 rather than the drag coefficient C_d or friction velocity u_*. For neutral conditions the logarithmic wind profile can be used to express one parameter into another.

5. Many formulations for (and discussions on) the dependence of the drag coefficient on wave parameters have been proposed. These formulations vary from relatively simple expressions (based on empirical 'fit' approaches and/or considerations involving dimension analysis) to complicated expressions that involve the complete wave spectrum $S(\omega)$. Inbetween are some 'mixed' or 'hybrid' formulations.

5.1. Of the formulations that use the complete spectral density the expression of Kitaiigorodski seems to be most promising. In verifications of the surface roughness models Geernaert et al. (1986) found that Kitaigorodskii's seems to be most useful in predicting the various observations of C_d. Donelan (1990a, p.263) also expects that Kitaigorodskii's spectral calculation more correctly represents the distributed contribution of the waves to roughness. However, as Geernaert (1990, p.150) points out, this model is by no means universal since it cannot explain swell-induced variations. Both Geernaert (1990) and

Donelan (1990a) note that so far the actual distribution of waves across the spectrum is unknown and so far only the region near the peak has been explored. Yet understanding and predicting of the evolution of wind waves and the rate of kinetic energy input to the oceans/sea is of great importance.

5.2. The 'simple' surface roughness models show a great convergence in their ultimate result: the roughness length is reduced to a function of only one wave parameter: the wave age. The wave age is defined by the ratio of the phase velocity of the dominant wave and the friction velocity. This parameter provides a measure for the stage of development of the wave field. The use of only wave age is justified by the argument that all other possible relevant wave parameters (as wave height, steepness, fetch, etc.) can be expressed in the wave age.

For all expressions of the roughness length z_0 into wave age, Charnock's formula forms the basis. It is remarked that (experimental) estimations of Charnock's constant α show a great variety and it is argued that this is due to the absence of wave parameters in Charnock's formula. Therefore α is made dependent on the wave age. Plots of $\log(z_0)$ versus $\log(c_p/u_*)$ reveal a linear like dependence of these quantities leading to the proposal of a power relation of these quantities:

$$gz_0/u_*^2 = \mu \cdot (c_p/u_*)^n \tag{5.1}$$

See e.g. Maat et al. (1990), Masuda and Kusaba (1987). Donelan (1990a) gives the equivalent form

$$z_0/\sigma = A \cdot (c_p/u_*)^B \tag{5.2}$$

Some of the exponents n (respectively B) can be 'derived' on theoretical considerations. We mention $n=-\frac{1}{2}$ in Hsu's approach that considers steepness of the waves as stress receptors.

In all cases but one negative values are proposed for the exponents n and B. Since the surface roughness is believed to increase with decreasing wave age, positive values for these exponents are highly unlikely.

There seems to be a 'consensus' for n=-1 (corresponding to B=-2½) in Eq.(5.1) and (5.2). See Donelan (1990a), Maat et al. (1991), Masuda and Kusaba (1987). In all these cases this value of the exponent was found experimentally and under conditions with moderate to high wave ages (local equilibrium of winds and wind waves). The estimates of the constant μ were less consistent. Probably this was due to the sites were the data were obtained (laboratory versus field as well as the way and accuracy with which the necessary wind/wave parameters were recorded). Moreover the different wave-age-ranges that were used for the z_0-c_p/u_* fits may be of influence. This may imply that parameter μ can also still be dependent on wave age and other wave parameters.

6. In Chapter 6 wave dependent surface roughness formulas are proposed for implementation and testing in the CSM-model. It must yet be discussed how to obtain the required wave information. Two alternatives seem to be available.
   (i) The wave information is obtained from a wave model, e.g. WAM or NEDWAM.
   (ii) On the basis of waterdepth, fetch and the wind data (U_{10} as function of time and the spatial coordinates) wave prediction equations can be used for the calculation of wave parameters. See e.g. Shore Protection Manual by US Army Corps of Engineers, and Hurdle and Stive (1987).

Alternative (ii) is computationally efficient and is easily coupled to the CSM-model. Note that in this case spectral formulations (e.g. Kitaigorodskii's model) cannot be used since the wave prediction equations give 'condensed' information in the form of significant wave height and period of the dominant wave. Alternative (i) is computational much more expensive and can less simply be coupled to the CSM-model. On the other hand, it has the advantage of producing better estimates of the true wave parameters than method (ii) will presumably do.

On the use of the complete wave spectrum one more comment must be made. One of the C_d formulas that are proposed in Chapter 6 is Kitaigorodskii's formula (4.3). For the evaluation of this formula wave spectra produced by WAM or NEDWAM can be used. These models resolve the spectrum within the frequency band 0.04 to 0.42 Hz. Beyond the high frequency cut-off an f^{-4} tail is added (see Komen, 1985). This analytical continuation may be justified only for (gravity) waves below the capillary region. Donelan (1991) has shown that the capillary part of the spectrum is rather wind sensitive and no appropriate description of the spectrum seems to be available. The capillary region includes waves whose wave number k exceeds 30 m^{-1}. It can be shown that the capillary region can be neglected in the calculation of Kitaigorodskii's roughness length. This is done as follows. According to Geernaert (1986) the waves within the frequency range $2\omega_p$-$8\omega_p$ largely dominate the roughness length in Kitagorodskii's model. According to Geernaert (1990) the peak frequency can be calculated as follows:

$$\omega_p = (7\pi g/U)(gX/U^2)^{-1/4} = 7\pi\{g^2/(X\cdot U)\}^{1/4} \tag{5.3}$$

Given wind velocities U≥3 m/s and fetches X≥32 km (two times the size of a CSM grid cell) we have $\omega_p \le 2.23$ rad/s, or equivalently $f_p \le 0.35$ Hz. In the wave number domain the condition $\omega \le 8\omega_p = 18$ corresponds to $k \le 30\ m^{-1}$ which is the lower bound of the capillary region. So WAM and its analytical continuation beyond 0.42 Hz can be used for Kitaigorodskii's roughness length formula provided the windvelocity exceeds 3 m/s and the fetch is larger than 30 km.

7. The roughness length formulas that are proposed for CSM in Chapter 6 involve one or more **adjustable** parameters. During implementation and testing of the roughness length formulations, the following choices are feasible for these parameters:

7.1 the values proposed in the **literature**

7.2 the values that **optimize** the CSM-mode, i.e. lead to maximum agreement of predicted waterlevels and observed waterlevels (under storm conditions)

Alternative (7.2) involves the calibration of the roughness length formulas. This calibration must take place on the basis of measured water levels in storm conditions. In particular a parameter-setting is desired that improves the performance of the CSM-model for several storms simultaneously. This activity refers to the most important goal of the equipment of the CSM-model with a wave dependent C_d-formulation: the derivation of a 'universal' surface roughness formulation for the North Sea.

6. C_d-FORMULATIONS PROPOSED FOR THE CSM-MODEL

Along the lines of the synthesising conclusions and discussion in Chapter 5 three C_d-formulations are proposed here for implementation in the CSM16-model. We list the formulations, starting with the most promising in view of expected effect and relative ease of implementation:

- Donelan (1990a)
- Johnson and Vested (1991)
- Kitaigorodskii (1973)

6.1 Donelan's formula

Donelan's formula for the roughness length reads:

(i) $z_0 = A \cdot \sigma \cdot (c_p/u_*)^{-2.5}$

In the literature study it turned out that the wave age c_p/u_* is the most important wave parameter for the description of the dependence of C_d on the wave field. Both physical considerations, and field and laboratory experiments, lead to the preceding roughness length description.

6.2 Johnson and Vested's formula

Johnson and Vested propose the following form for the roughness length:

(ii.1) $z_0/\sigma = A \cdot (c_p/u_*)^{-2.5}$, $u_*/c_p < 0.1$

(ii.2) $z_0/\sigma = C_{JV} \cdot \exp(-\kappa c_p/u_*)$, $u_*/c_p > 0.1$

This form of the roughness length is a refinement of the one proposed in (i): Johnson and Vested argue that for small wave ages Kitagorodskii's (simplified) formula (ii.2) is a better description than the one of Donelan (1990).

6.3 Kitaigorodskii's formula

Kitagorodskii's roughness length formulation reads:

(iii) $z_0^2 = C_K \int S(\omega) \cdot \exp(-2\kappa c(\omega)/u_*)\, d\omega$

Several roughness length models proposed in the literature were compared by Geernaert (1986, 1990) who found that Kitaigorodskii's model performed the best as a predictor for the drag coefficient. Therefore Kitaigorodskii's model is recommended for implementation in the CSM-model.

Note 1. Although Charnock's formula does not involve wave parameters it is nevertheless suggested for implementation and testing. Charnock's roughness length formula reads:

(iv) $z_0 = \alpha \cdot u_*^2/g$

Charnock's formula is suggested for the following reasons:

1. The consistency of Charnock's formula with the 'traditional' wind dependent C_d formulation can be verified.
2. The optimal value of Charnock's constant can be determined and compared with it's values reported in the literature.
3. Charnock's formulation is a special case of the roughness length formulation involving the wave age. On the bases of Charnock's z_0 and the one(s) based on wave ages the significance of the dependence of C_d on wave parameters can be verified.

Note 2. For the **testing** of the proposed C_d formulations it is suggested to compare three series of water levels (or surges) at Dutch and British stations:

a. Observed waterlevels.
b. Waterlevels (predicted) according to the CSM-model equipped with the 'traditional' C_d-formulation, i.e. the C_d is a function of solely the

wind speed U_{10}.

c. Waterlevels according to the CSM-model equipped with a wave dependent C_d-formulation.

In the past, the C_d prescribed by (b) has been calibrated for three storm conditions: February 1989, November 1981 and January/February 1983. It is thus obvious to test the wave dependent C_d formulations under these conditions.

7. REFERENCES

Battjes, J.A., Windgolven, Handleiding College b78, University of Delft, Department of Civil Engineering, 1982.

Bretschneider, C.L., Prediction of waves and currents, Look Laboratory, Hawaii, Vol. III(1), pp. 1-17, 1973.

Brutstaert, W. and Y. Toba, A Quasi-Similarity between wind waves and solid surfaces in their roughness characteristics, J. Oceanogr. Soc. Japan, 42, pp. 166-173, 1986.

Businger, J.A., J.C. Wyngard, Y.K. Izumi, and E.F. Bradley, Flux-profile relationships in the atmospheric surface layer, J. Atmos. Sci., 28, pp. 181-189, 1971.

Byrne, H.M., The variation of the drag coefficient in the marine surface layer due to temporal and spatial variations in the wind and sea state, Ph.D. dissertation, Univ. of Washington, 1982.

Charnock, H., Wind stress on a water surface, Quart. J. Royal Met. Soc., 81, pp. 639-640, 1955.

Deacon, E.L. and E.K. Webb, Small-scale interactions, In: The Sea, Vol. 1, ed. by M.H. Hill, Interscience, New York, pp. 43-66, 1962.

Donelan, M.A., The dependence of the aerodynamic drag coefficient on wave parameters. In: First international conference on meteorology and air-sea interaction of the coastal zone, Amer. Met. Soc., Boston, pp. 381-387, 1982.

Donelan, M.A., J. Hamilton, and W.H. Hui, Directional spectra of wind gene rated waves, Philos. Trans. R. Soc. London, Ser. A, 315, pp. 509-562, 1985.

Donelan, M.A., The effect of swell on the growth of wind-waves, In Symposium on Measuring Ocean Waves from Space, ed. by R.C. Beal, The John Hopkins Applied Physics Laboratory, Tech. Digest 8 (1), pp. 18-24, 1986.

Donelan, M.A., Air-Sea Interaction, in: The Sea, Ocean Engineering Science Volume 9, Part A, Wiley Interscience, New York, pp. 239-292, 1990a.

Donelan, M.A. and W.H. Hui, Mechanics of ocean surface waves, in: Surface Waves and Fluxes. Vol I - Current theory, ed. by G.L. Geernaert and W.J. Plant, Kluwer Academic Publishers, Dordrecht, pp. 209-246, 1990b.

Donelan, M.A., The mechanical coupling between air and sea - An evolution of ideas and observations. Preprint, 1991

Garratt, J.R., Review of drag coefficients over oceans and continents, Mon. Wea. Rev., 105, pp. 915-929, 1977.

Geernaert, G.L., K.B. Katsaros, and K. Richter, Variation of the drag coef ficient and its dependence on sea state, J. Geoph. Res., 91, pp. 76-67-7679, 1986.

Geernaert, G.L., S.E. Larsen, and F. Hansen, Measurements of the wind st ress, heat flux, and turbulence intensity during storm conditions over the North Sea, J. Geophys. Res., 92, pp. 13127-13139, 1987.

Geernaert, G.L., Bulk parameterizations for the wind stress and heat flux es, in: Surface Waves and Fluxes. Vol I - Current theory, ed. by G.L. Geernaert and W.J. Plant, Kluwer Academic Publishers, Dordrecht, pp. 91-172, 1990.

Gerritsen, H. and A.C. Bijlsma, Modelling of tidal and winddriven flow: the Dutch Continental Shelf Model. In: Computer Modelling in Ocean Engineering, Schrefler & Zienkiewicz (ed.), A.A. Balkema, Rotterdam, 1988.

Hasselmann, K. On the nonlinear energy transfer in a gravity-wave spectrum, 1. General theory, J. Fluid Mech., 12, pp. 481-500, 1962.

Hasselmann, K. On the nonlinear energy transfer in a gravity-wave spectrum, 2. Conservation theorems, wave-particle correspondence, irreversibility, J. Fluid Mech., 15, pp. 273-281, 1963.

Hasselmann, K. , T.P. Barnett, E. Bouws, H. Carlson, D.E. Cartwright, K. Enke, J.A. Ewing, H. Gienapp, D.E. Hasselmann, P. Kruseman, A. Meerburg, P. Muller, D.J. Olbers, K. Richter, H.W. Sell, and, H. Walden, Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP) (95 pages). Dt. hydrogr. Z., A8 (Suppl.), no. 12, 1973.

Heemink, A.W., Storm surge prediction using Kalman filtering, Ph.D. dissertation, Univ. of Twente, 1986.

Hurdle, D.P. and R.J.H Stive, Review of SPM 1984 wave hindcast model to avoid inconsistencies in engineering applications, Coastal Engineering, 12, pp. 339-351, 1989.

Hsu, S.A., A dynamic roughness equation and its application to wind stress determination at the air-sea interface, J. Phys. Ocean., 4, pp. 116-120, 1974.

Hsu, C.T., E.Y. Hsu and R.L. Street, On the structure of turbulent flow over a progressive water wave: theory and experiment in a transformed, wave-following coordinate system, J. Fluid Mech., 105, pp. 87-117, 1981.

Janssen, P.A.E.M., Wave-induced Stress and the drag of airflow over sea waves, J. Phys. Ocean. 19, pp. 745-754, 1989.

Janssen, P.A.E.M., Quasi-linear theory of wind generating applied to wave forecasting, Personal Memorandum, 00-90-13, KNMI, De Bilt, The Netherlands, 1990

Johnson H. and H.J. Vested, Effects of water waves on wind shear stress, Report Danish Hydraulic Institute, Horsholm, Denmark, 1991.

Kitaigorodskii, S.A., Applications of the theory of similarity to the ana lysis of wind generated wave motion as a stochastic process. Bull. Acad. Sci. USSR Geophys. Ser. 1, pp. 105-117, 1962.

Kitaigorodskii, S.A. and Y. Volkov, On the roughness parameter of the sea surface and the calculation of momentum flux in the near water layer of the atmosphere, Izv. Atmos. Ocean. Phys., 1, pp. 973-988, 1965.

Kitaigorodskii, S.A., The Physics of Air-Sea Interaction (1970), Translated from Russian by A. Baruch, Israel Program for Scientific Translations, Jerusalem, 1973.

Komen G.J., Activities of the WAM (Wave Modelling) group, in: Advances in Underwater Technology. Ocean Science and Offshore Engineering, Vol 6., Oceanology, pp. 121-127, Graham and Trotman, 1985.

Large, W.G., and S. Pond, Open ocean momentum flux measurements in moderate to strong winds, J. Phys. Ocean., 11, pp. 324-336, 1981.

Laufer, J., The structure of turbulence in fully developed pipe flow, Nati onal Advisory Committee for Aeronautics, Report 1174, Washington 25 D.C., 1954.

Longuet-Higgins, M.S., The generation of capillary waves by steep gravity waves, J. Fluid Mech., 16(1), pp. 138-159, 1963.

Maat, N., C. Kraan and W.A. Oost, The roughness of wind waves, Boundary Layer Meteorology, 54, pp. 89-103, 1991.

Mastenbroek, C., G. Burgers and P.A.E.M. Janssen, The dynamic coupling of a wave model and a storm surge model through the atmospheric boundary layer. Personal Memorandum, OO-91-28, KNMI, De Bilt, The Netherlands, Submitted for publication, 1991.

Masuda, A., and T. Kusaba, On the local equilibrium of winds and wind-waves in relation to surface drag, J. of the Ocean. Soc. of Japan, 43, pp. 28-36, 1987.

Nieuwstadt, F.T.M., The noctural boundary layer. Theory and Experiments. Scientific Report W.R. 81-1, KNMI, De Bilt, The Netherlands, 1981.

Nikuradse, J., Gesetzmässigkeiten der turbulenten Strömung in glatten Rohren, VDI-Forschungsheft 356, Berlin, 1932.

Nikuradse, J., Strömungsgesetze in rauhen Rohren, VDI-Forschungsheft 361, Beilage zu "Forschung auf dem Gebiete des Ingenieurwesens", Ausgabe B, Band 4, Berlin, July/August 1933.

Phillips, O.M., On the dynamics of unsteady gravity waves of finite amplitude, Part I, J. Fluid Mech. 9, pp. 193-217, 1960.

Phillips, O.M., The dynamics of the upper ocean, Cambridge Univ. Press, Cam bridge, 1980.

Phillips, O.M., Spectral and statistical properties of the equilibrium range in wind-generated gravity waves, J. Fluid Mech., 156, pp. 505-531, 1985.

Pierson, W.J. and L. Moskowitz, A proposed spectral form for fully develo ped wind seas based on the similarity theory of S.A. Kitaigorodskii, J. Geophys. Res., 69(24), pp. 5181-5190, 1964.

Sanders J.W., A growth-stage scaling model for the wind driven sea, Deutsche Hydrographische Zeitschrift, Band 29, Heft 4, pp. 136-161, 1976.

Schlichting, H., Boundary Layer Theory, translation from German by J. Kest in, McGraw-Hill, New York, 747 pp, 6th edition, 1968.

SethuRaman, S., Momentum Flux and wave spectra measurements from an air-sea interaction buoy, Boundary Layer Meteorology, 16, pp. 279-291, 1979.

Smith, S.D. and E.G. Banke, Variation of the sea surface drag coefficient with windspeed, Quart. J. Royal Met. Soc., 101, pp. 665-673, 1975.

Smith, S.D., Wind stress and heat flux over the ocean in gale force winds, J. Phys. Ocean., 10, pp. 709-726, 1980.

Snyder, R.L., F.W. Dobson, J.A. Elliott, and, R.B. Long, Array measurements of atmospheric pressure fluctuations above surface gravity waves, J. Fluid Mech., 102, pp. 1-59, 1981.

Tennekes, H. and J.L. Lumley, A first course in turbulence, MIT Press, Cambridge, Mass., 330 pp, 1972.

Toba, Y., Drop production by bursting of air bubbles on the sea surface (III). Study by use of wind flume, Mem. Coll. Sci., Univ. of Kyoto, Ser. A, 29, pp. 313-344, 1961.

Toba, Y., Local balance in the air-sea boundary processes, I. On the growth of wind waves, J. Oceanogr. Soc. Japan, 28, pp. 109-121, 1972.

Toba, Y., Study on wind waves as a strongly nonlinear phenomenum. In: Twel fth Symp. on Naval Hydrodynamics, Nat. Acad. Of Sci., Wash. DC, pp. 529-540, 1979.

Toba, Y., and M. Koga, A parameter describing overall conditions of wave breaking, whitecapping, sea-spray production and wind stress, In: Oceanic whitecaps, ed. by E.C. Monahan and G. MacNiocaill, D. Reidel - Publishing Co., Dordrecht, pp. 37-47, 1986.

Toba Y., N. Iida, H. Kawamura, N. Ebuchi, I.S.F. Jones, Wave dependence of sea-surface stress, American Meteorological Society, 20, pp. 705-721, 1990.

U.S. Army Corps of Engineers, Shore Protection Manual, 4th edition, Coastal Engineering Reasearch Centre, Fort Belvoir, Virginia, 1984.

Verboom, G.K., R.P. van Dijk, and J.G. de Ronde, Een model van het Europese Kontinentale Plat voor windopzet en Waterkwaliteitsberekeningen. RWS / DELFT HYDRAULICS, Nota GWAO-87.021/Report Z-96, November 1987.

Volkov, Y.A., Turbulent flux of momentum and heat in the atmospheric surfa ce layer over a disturbed sea-surface, Izv. Atmos. Ocean. Phys., 7, pp. 770-774, 1970.

The WAMDI Group: S. Hasselman, K. Hasselman, E. Bauer, P.A.E.M. Janssen, G.J. Komen, L. Bertotti, P. Lionello, A. Guillaume, V.C. Cardone, J.A. Greenwwod, M. Reistad, L Zambresky and J.A. Ewing, The WAM model - a third generation ocean wave prediction model, J. Phys. Oceanogr., 18, pp. 1775-1810, 1988.

Wilson, B.W., Numerical prediction of ocean waves in the North Atlantic for December, Dtsch. Hydrogr., 18, pp. 114-130.

Wu, J., Wind stress and surface roughness at air-sea interface, J. Geoph. Res., 74, pp. 444-455, 1969.

Wu, J., Wind stress coefficients over sea surface near neutral conditions. A revisit, J. Phys. Ocean., 10, 727-740, 1980.

Table 1 — Surface layer measurements of C_{DN}

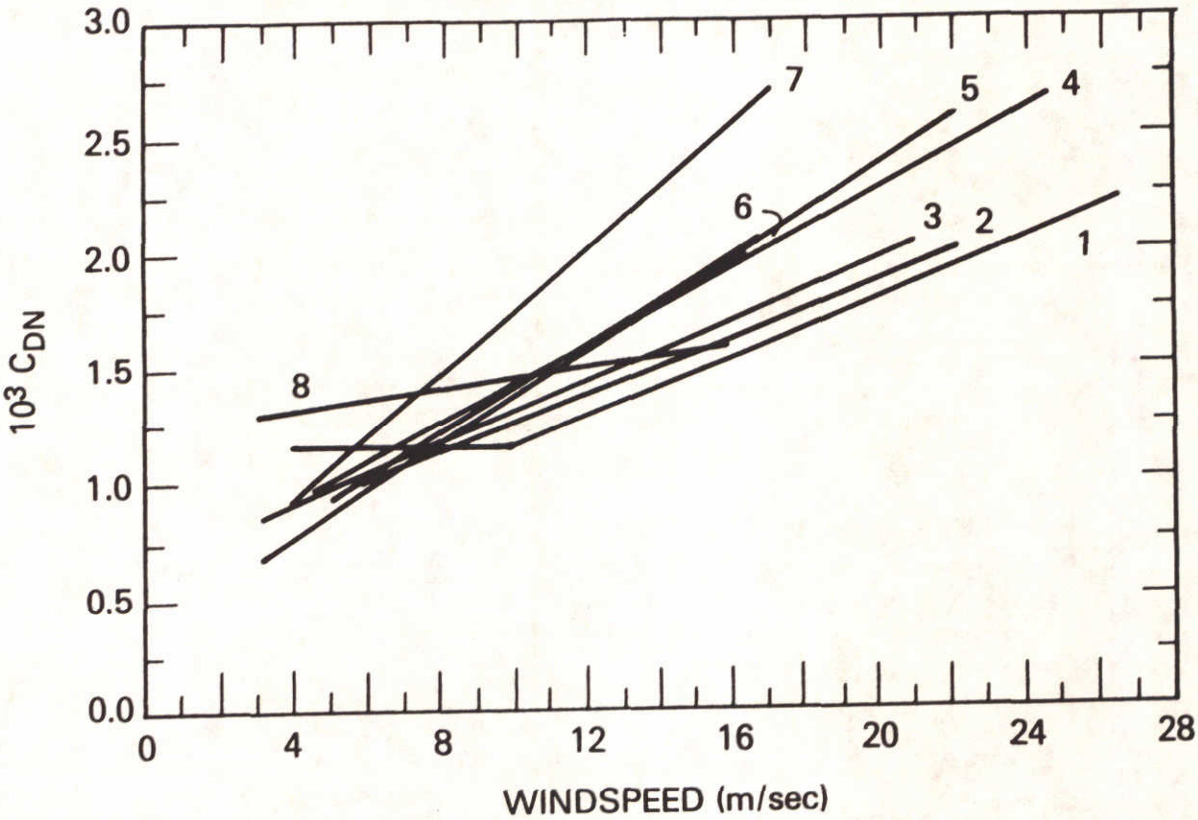
Source	Windspeeds (m/sec)	$10^3 C_{DN}$	Scat (%)	N	[Method]	Platform
Geernaert et al (1987)	5 — 25	.58 + .085 U	20	116	ec	tower North Sea
Geernaert et al (1986)	5 — 21	.43 + .097 U	12	186	ec	mast North Sea
Graf, et al (1984)	7 — 17	1.09 + .094 U	—	145	wp	mast Lake Geneva
Donelan (1982)	4 — 17	.37 + .137 U	28	120	ec	tower Lake Ontario
Large & Pond (1981)	5 — 19	.46 + .069 U	28	120	ec	tower Atlantic
Large & Pond (1981)	4 — 10	1.14	16	590	diss	tower/ship
	10 — 26	.44 + .063 U	16	1001	diss	open ocean
Smith (1980)	6 — 22	.61 + .063 U	25	120	ec	tower Atlantic
Krugermeyer et al. (1978)	3 — 8	1.30	30	394	wp	buoy North Sea
Khalsa & Businger 81977)	3 — 12	1.42	22	12	diss	ship open ocean
Smith & Banke (1975)	2.5 — 21	.63 + .066 U	30	111	ec	mast Atlantic
Hedegaard (1975)	3 — 14	.64 + .14 U	30	80	ec	mast Kategatt
Kondo (1975)	3 — 16	1.2 + .025 U	15	—	waves	tower Pacific coast
Davidson (1974)	6 — 11.5	1.44	?	114	ec	FLIP buoy open ocean
Wieringa (1974)	4.5 — 15	0.6 U	20	126	ec	tower Lake Flevo
		0.86 + .058 U				
Denman & Miyake (1973)	4 — 18	1.29 + .03 U	17	70	diss	ship open ocean
Kitaigorodskii et al (1973)	3 — 11	0.9 to 1.6	>	29	ec	tower Caspian Sea
Hicks (1972)	4 — 10	$0.5\ U^{.5}$	25	75	ec	tower Bass Strait
Paulson, et al. (1972)	2 — 8	1.32	25	19	wp	buoy open ocean
Sheppard, et al. (1972)	2.5 — 16	.36 + .1 U	20	233	wp	tower Lough Neagh
DeLeonibus (1971)	4.5 — 14	1.14	30	78	ec	Bermuda tower Atlantic Ocean
Pond, et al. (1971)	4 — 8	1.52	20	20	ec	FLIP buoy open ocean
Brocks & Krugermeyer (1970)	3 — 13	1.18 + .016 U	15	152	wp	buoy North Sea
Hasse (1970)	3 — 11	1.21	20	18	ec	buoy North Sea
Miyake, et al. (1970)	4 — 9	1.09	20	8	ec	UBC site on
	4 — 9	1.13	20	8	wp	Spanish Bank
Ruggles (1970)	2.5 — 10	1.6	50	276	wp	mast Buzzards Bay
Hoeber (1969)	3.5 — 12	1.23	20	787	wp	buoy open ocean
Weiler & Burling (1967)	2 — 10.5	1.31	30	10	ec	UBC mast on
	2.5 — 4.5	0.90	75	6	wp	Spanish Bank
Zubkovskii & Kravchenko (1967)	3 — 9	0.72 + .12 U	15	43	ec	buoy Black Sea

From Geernaert (1990)

Table 2 — Predicted magnitudes of $10^3\ C_{DN}$ for given windspeeds (m/sec)

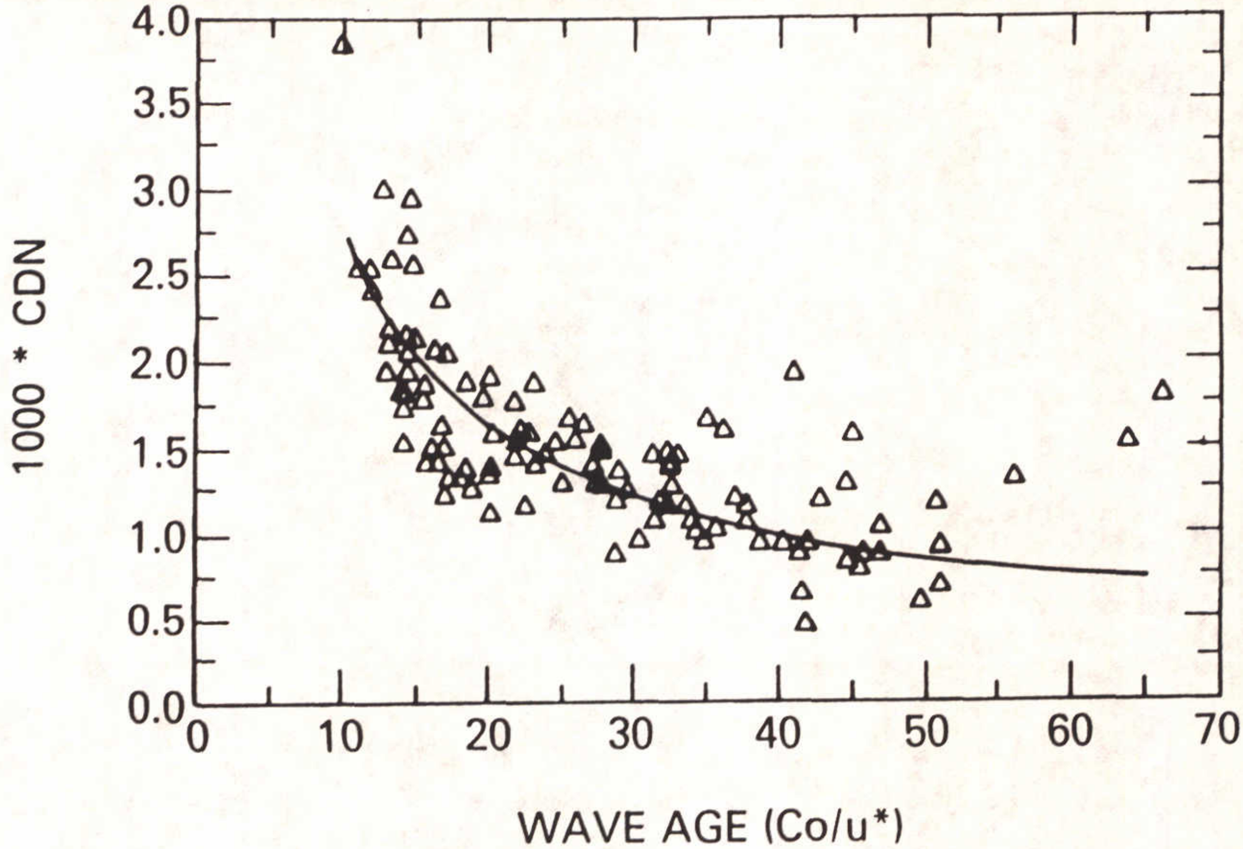
Source (from Table 1)	Windspeed m/sec				
	5	10	15	20	25
Geernaert, et al. (1987)	1.01	1.43	1.86	2.28	2.71
Geernaert, et al. (1986)	0.92	1.40	1.89	2.37	—
Graf, et al. (1984)	—	2.03	2.50	—	—
Donelan (1982)	1.06	1.74	2.43	—	—
Large & Pond (1981) (ec)	0.81	1.15	1.50	—	—
Large & Pond (1981) (diss)	1.14	1.14	1.39	1.70	2.02
Smith (1980)	—	1.29	1.56	1.87	—
Smith & Banke (1975)	0.96	1.29	1.62	1.95	—
Kondo (1975)	1.33	1.45	1.58	1.75	—

From Geernaert (1990)



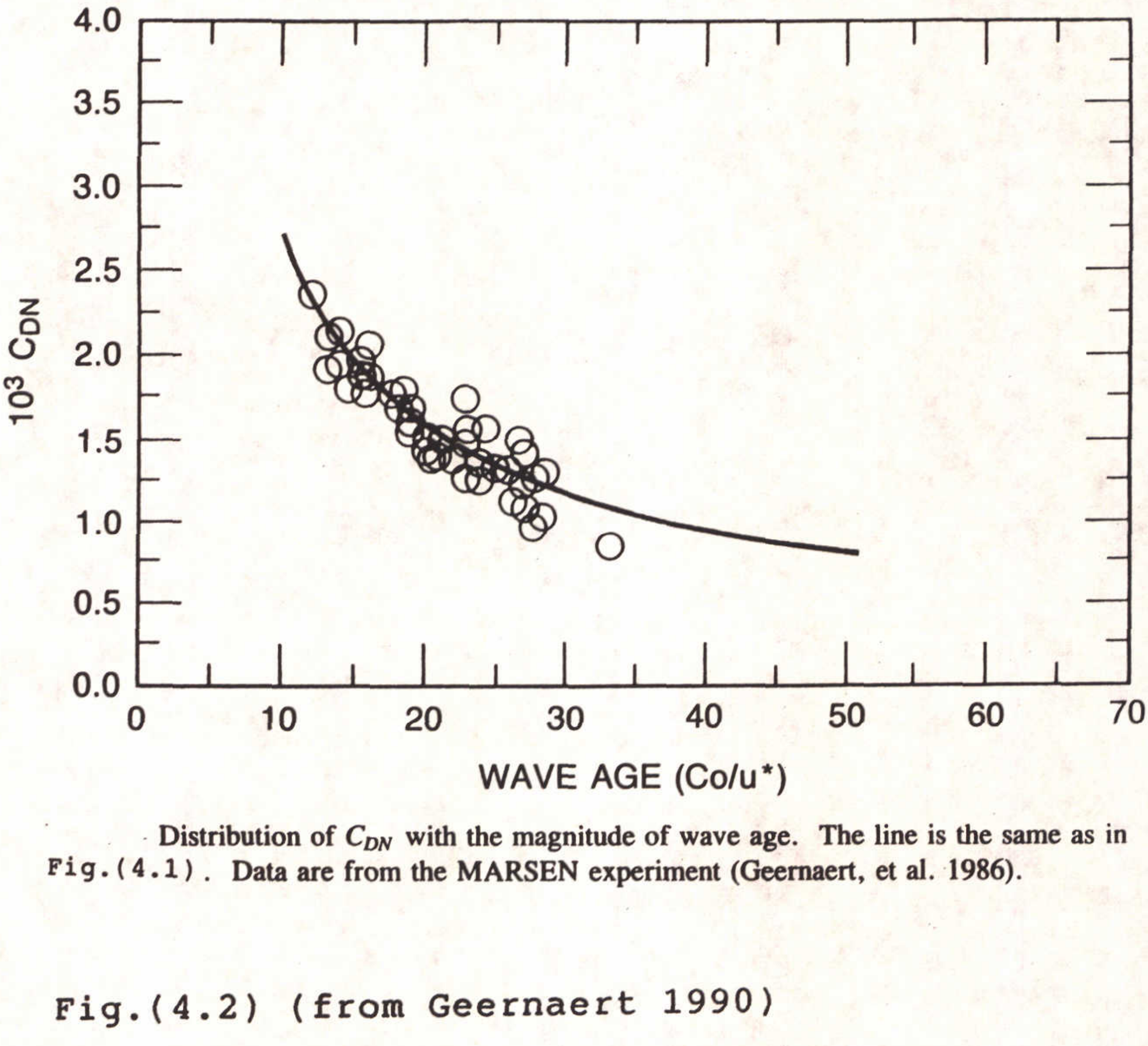
Distribution of C_{DN} with windspeed: 1) Large and Pond (1981), over deep open ocean; 2) Smith (1980) over deep, coastal ocean; 3) Smithe and Banke (1975) overdeep water; 4) Geernaert, et al. (1987) over North Sea depth of 30 m; 5) Geernaert, et al. (1986) over North Sea depth of 16 m; 6) Sheppard, et al. (1972), over Lough Neagh depth of 15 m; 7) Donelan (1982) over Lake Ontario at 10 m depth; 8) Graf et al. (1984) over Lake Geneva at 3 m depth.

Fig.(2.1) (from Geernaert 1990)



Distribution of C_{DN} with the magnitude of the wave age. The best-fit line is $C_{DN} = .012\,(C_0/u_*)^{-2/3}$. Data are from the North Sea (Geernaert, et al. 1987).

Fig.(4.1)



Distribution of C_{DN} with the magnitude of wave age. The line is the same as in Fig.(4.1). Data are from the MARSEN experiment (Geernaert, et al. 1986).

Fig.(4.2) (from Geernaert 1990)

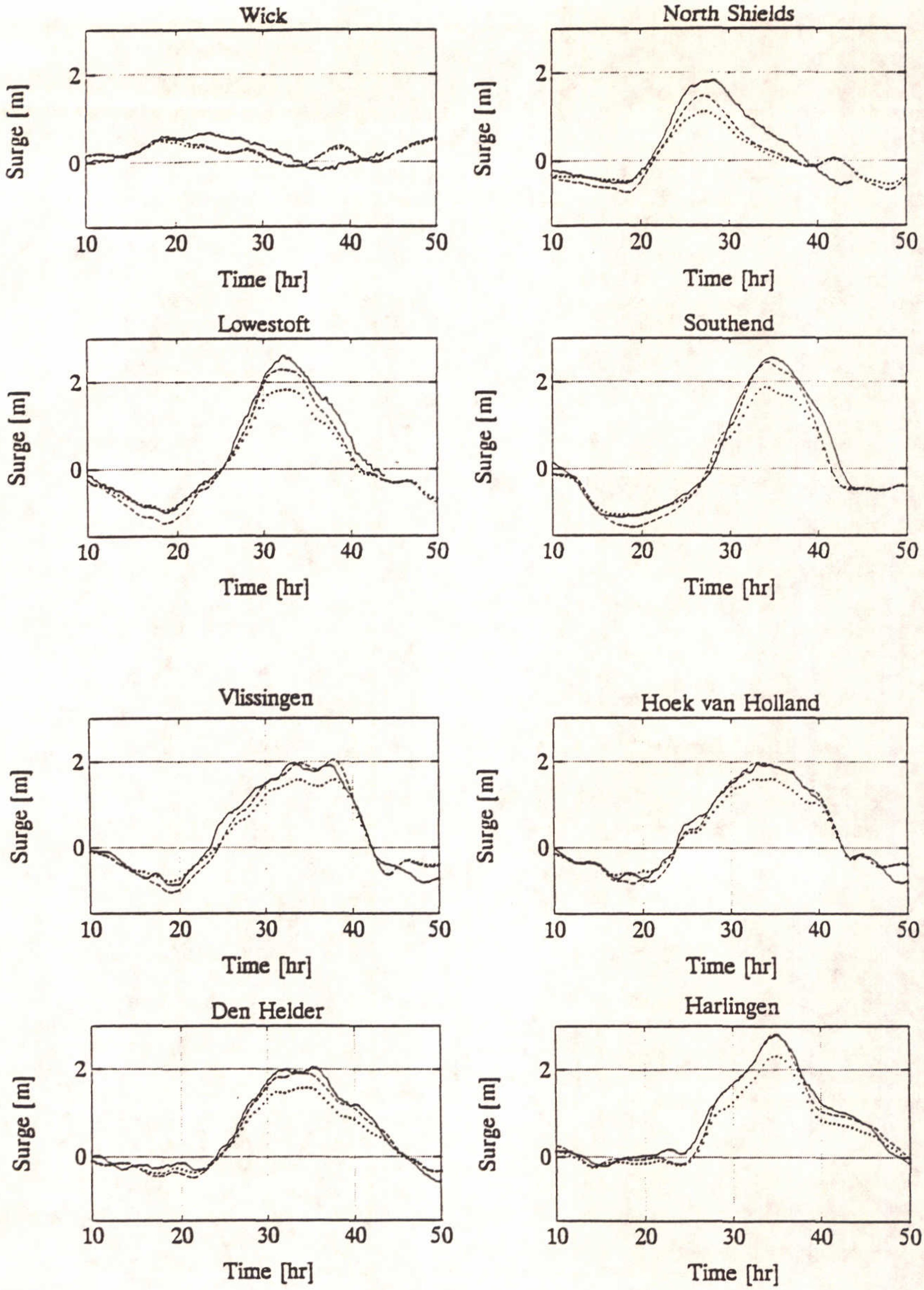


Fig.(5.1) (from Mastenbroek et al., 1991)

main office
Rotterdamseweg 185
p.o. box 177
2600 MH Delft
The Netherlands
telephone (31) 15 - 56 93 53
telefax (31) 15 - 61 96 74
telex 38176 hydel-nl

location ' De Voorst'
Voorsterweg 28, Marknesse
p.o. box 152
8300 AD Emmeloord
The Netherlands
telephone (31) 5274 - 29 22
telefax (31) 5274 - 35 73
telex 42290 hylvo-nl