# Experimental Evidence of the Effect of Surface Waves on the Airflow

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ABSTRACT

Experimental evidence of the effect of surface waves on the airflow is presented. According to the quasi-linear theory of wind-wave generation, the stress of airflow over surface gravity waves depends on both wind speed and the wave-induced stress. Here the wave-induced stress is related to the rate of change of wave momentum due to the wind, and for young wind sea, the wave-induced stress may be a substantial amount of the total stress in the surface layer resulting in a considerable enhancement of the drag of airflow. During HEXMAX, wind speed $U_{10}$, friction velocity $u_* = \tau^{1/2}$, and the one-dimensional frequency spectrum were measured simultaneously. The directional distribution was assumed to be given by the expression proposed by Donelan et al. (1985). Using the measured wind speed and frequency spectrum, it was possible to determine from quasi-linear theory the surface stress and to compare it with the observed stress. Very good agreement between observed and modeled stress is found, much better than when the Wu (1982) formula for the drag coefficient is used.

## 1. Introduction

Because of a growing interest in the problem of the simulation of the earth climate by means of coupled ocean–atmosphere models, much attention has recently been devoted to the physics of the interaction of ocean and atmosphere. In particular, the role of surface gravity waves in the transfer of momentum from air to ocean was studied in some detail (Janssen 1989, 1991; Chalikov and Makin 1991). The principal result of the quasi-linear theory of wind-wave generation (Janssen 1989) was that for young wind waves, having a large steepness, a considerable enhancement of momentum transfer was found, which is reflected by a considerable increase in drag when compared to old wind sea. As it was found that the stress in the surface layer depends sensitively on the sea state, Janssen (1991) studied the interaction of wind and waves by coupling the wave model (WAM) (WAMDI Group 1988) with a simple surface-layer model that has a drag that depends on both wind speed and the rate of change of wave momentum (or the so-called wave-induced stress). Again, a considerable sea-state dependence of the surface stress was found.

A first attempt toward an experimental verification of the quasi-linear theory of wind-wave generation was made by Maat et al. (1991), using experimental data of the HEXMAX [HEXOS (humidity over the sea) Main Experiment] (Katsaros et al. 1987). During HEXMAX, wind speed at 10-m height $U_{10}$, kinematic surface stress $\tau$, and the one-dimensional frequency spectrum $F$ were measured simultaneously. As a measure for the sea state, the wave-age parameter $c_p/u_*$ was taken, where $u_* = \tau^{1/2}$ is the friction velocity and $c_p$ is the phase speed of the peak of the spectrum. Here young wind sea corresponds to $c_p/u_* \approx 5$–$10$, while old wind sea has $c_p/u_* > 25$. By determining the wave age from the measured spectrum $F$ and the measured friction velocity, Maat et al. were able to relate the wave age to the drag coefficient $C_D = \tau/U_{10}^2$. They confirmed that indeed the drag of airflow over sea waves is sea-state dependent, in agreement with results from quasi-linear theory (Janssen 1989).

The theoretical calculations of Janssen (1989) were, however, based on a parameterization of the wave spectrum, with an empirical fit between the Phillips constant and the wave age, which shows considerable scatter. Therefore, a more honest comparison between observations and quasi-linear theory can be obtained by using the observed wave spectrum in the determination of the wave stress. Results of these calculations and the comparison between modeled and observed stress are reported in this paper.

The plan of this paper is as follows. In section 2, the quasi-linear theory of wind-wave generation is briefly introduced, and for practical purposes, an analytical approximation of the effect of sea waves on the wind and the consequences for the drag of airflow over a water surface are discussed. In section 3 the calculation of the surface stress according to quasi-linear theory is presented, and in particular, the sensitivity of the results to the choice of the directional distribution of the waves is studied. In addition, the sensitivity of the stress calculation to errors in the observed wind speed and fre-

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quency spectrum is discussed. Finally, observed and modeled stress are found to be in good agreement, much better than when the Wu (1982) expression for the drag coefficient is used.

## 2. Sea-state dependence of drag of airflow over a water surface

According to the quasi-linear theory of wind-wave generation (Janssen 1989), surface gravity waves may extract a considerable amount of momentum from the airflow, resulting in a sensitive dependence of aerodynamic drag on the sea state.

Parameterizing the effect of waves on the airflow, Janssen (1991) found that the stress $\tau$ of airflow over surface gravity waves is given by

$$\tau = C_D(L)U^2(L), \quad C_D(L) = \left(\frac{\kappa}{\ln L/z_0}\right)^2, \quad (1)$$

where $C_D(L)$ is the drag coefficient at height $L$, $\kappa$ is the von Kármán constant, $U$ is the wind speed, and $z_0$ is a roughness length that depends on the sea state through the wave-induced stress,

$$z_0 = \frac{\alpha\tau}{g}\left(1 - \frac{\tau_w}{\tau}\right)^{-1/2}. \quad (2)$$

Here $g$ is the acceleration of gravity and $\alpha$ is a tuning constant that will be determined later. In the absence of surface gravity waves, Eq. (2) parameterizes the momentum transfer to capillary waves, for example, while in the presence of gravity waves the airflow becomes rougher, because these waves also extract momentum from the airflow. Thus, the wave-induced stress is related to the increase of wave momentum $P$ due to shear-flow instability, or

$$\tau_w = \int df d\theta \frac{\partial}{\partial t}\mathbf{P}|_{\text{wind}}, \quad (3)$$

where the wave momentum depends on the two-dimensional wave-variance spectrum $F(f, \theta)$,

$$\mathbf{P} = \rho_w \omega F(f, \theta)\mathbf{l}, \quad \mathbf{l} = \mathbf{k}/k, \quad (4)$$

and $k$ is the wavenumber. The dispersion relation is $\omega = [gk \tanh(kD)]^{1/2}$, with $D$ the water depth, and the rate of change of the spectrum due to wind was found to depend on the angular frequency $\omega$, the friction velocity $u_*$ and wind direction $\phi$ through the parameter $u_* \cos(\theta - \phi)/c$, and the profile parameter $\Omega = g\kappa z_0/u_*^2$. (Here $c$ is the phase speed of the waves.) Thus,

$$\frac{\partial}{\partial t}F|_{\text{wind}} = \gamma F, \quad (5)$$

with growth rate $\gamma$ given by

$$\gamma = \epsilon\beta\omega\left(\frac{u_* \cos(\theta - \phi)}{c}\right)^2, \quad (6)$$

where $\epsilon$ is the ratio of air to water density,

$$\beta = \frac{1.2}{\kappa^2}\mu \, ln^4\mu, \quad \mu \leq 1, \quad (7)$$

and $\mu$ is the dimensionless critical height,

$$\mu = kz_c = \left(\frac{u_*}{\kappa c}\right)^2 \Omega \exp(\kappa c/u_* \cos(\theta - \phi)). \quad (8)$$

Therefore, for known wave spectrum $F$ the wave stress $\tau_w$ may be determined, and for given wind speed $U(L)$ the stress in the surface layer is obtained solving Eq. (2) iteratively. In this fashion Janssen (1991) coupled the wave dynamics as given by the third-generation WAM model (WAMDI 1988) to the surface layer in air, and it was found that for young wind sea (of which the ratio of wave-induced stress to total stress is considerable because young wind waves are steep) the air flow is much rougher than for old wind sea. Thus, a sensitive dependence of the aerodynamic drag on the stage of development of wind waves was found. Incidentally, the coupled wave model was tuned in such a way that for old wind sea the Charnock relation (with Charnock constant 0.0185) resulted, giving the parameter $\alpha$ in Eq. (3) the value 0.01.

Alternatively, if the observed wind speed and wave spectrum are known, Eq. (2) may be used to determine the stress in the surface layer that may be compared with the observed surface stress. The comparison of the modeled stress with HEXMAX observations will be reported in the next section.

Finally, it should be emphasized that there may be several reasons why the wind waves are steep, hence, why there is an increase in drag coefficient. First of all, for short fetch or duration, or both, it is known that waves are steeper than for infinite fetch and duration. As was pointed out, however, by Geernaert et al. (1986), for example, waves are also steeper in shallow waters, resulting in a depth dependence of the drag coefficient. Therefore, the observations of drag from HEXMAX, which were done in the shallow waters off the Dutch coast, are usually higher than those of typical open-ocean observation (Garrat 1977; Smith 1980; Large and Pond 1981; Wu 1982).

## 3. Comparison of modeled and observed stress

The HEXMAX experiment was a joint effort of 15 groups from 7 countries. The main purpose of the experiment was to measure at Meetpost Noordwijk (North Sea; water depth = 18 m) the dependence of momentum flux and latent and sensible heat flux on environmental parameters, such as wind speed, air–sea temperature difference, and sea state (Smith et al. 1990). Wind speed and friction velocity were measured by sonic anemometers and a pressure anemometer, while the wave spectrum was obtained from a wave rider. In this way a unique database was obtained of simultaneously measured wind speed, friction velocity, and the one-dimensional frequency spectrum. Maat et al. (1991) selected a subset of wind sea cases by considering only wave spectra that have a peak frequency that is larger than the Pierson–Moskovitch frequency, as obtained from the local wind speed. In addition, multipeaked spectra were rejected. They used this subset of cases to study the dependence of the aerodynamic drag on the sea state.

Here, we shall use the same subset of wind-sea cases in order to compare the observed friction velocity with the friction velocity as obtained from the parameterized version of quasi-linear theory. Thus, for given observed wind speed at 10-m height and wave spectrum, the surface stress is obtained by solving Eq. (1) in an iterative fashion. Unfortunately, only the one-dimensional frequency spectrum has been observed; hence, in order to progress, assumptions regarding the directional distribution of the waves have to be made.

Early proposals for the directional distribution of waves made by Mitsuyasu et al. (1975) and Hasselmann et al. (1980) were based on pitch and roll data. The width of the directional distribution was found to depend on the frequency normalized by the peak frequency giving a narrow distribution at the peak of the spectrum, whereas for high frequencies the spectrum broadens considerably. Donelan et al. (1985), on the other hand, found that the broadening of the directional distribution at high frequencies was less considerable. Based on data obtained from an array of wave staffs they found for wind-generated deep-water waves that

$$F(\omega, \theta) = \frac{\beta}{2} E(\omega) \operatorname{sech}^2 \beta(\theta - \bar{\theta}(\omega)), \qquad (9)$$

where $\bar{\theta}(\omega)$ is the mean wave direction and

$$\beta = 2.61(\omega/\omega_p)^{1.3}, \quad 0.56 < \omega/\omega_p < 0.95$$

$$\beta = 2.28(\omega/\omega_p)^{-1.3}, \quad 0.95 < \omega/\omega_p < 1.6$$

$$\beta = 1.24, \quad \text{otherwise.}$$

In this study the spectral presentation (9) was adopted because it is based on the most thorough analysis of directional data and because the distribution (9) resembles at high frequencies the WAM spectra the most. It was assumed that for the HEXMAX data the mean wave direction coincides with the local wind direction.

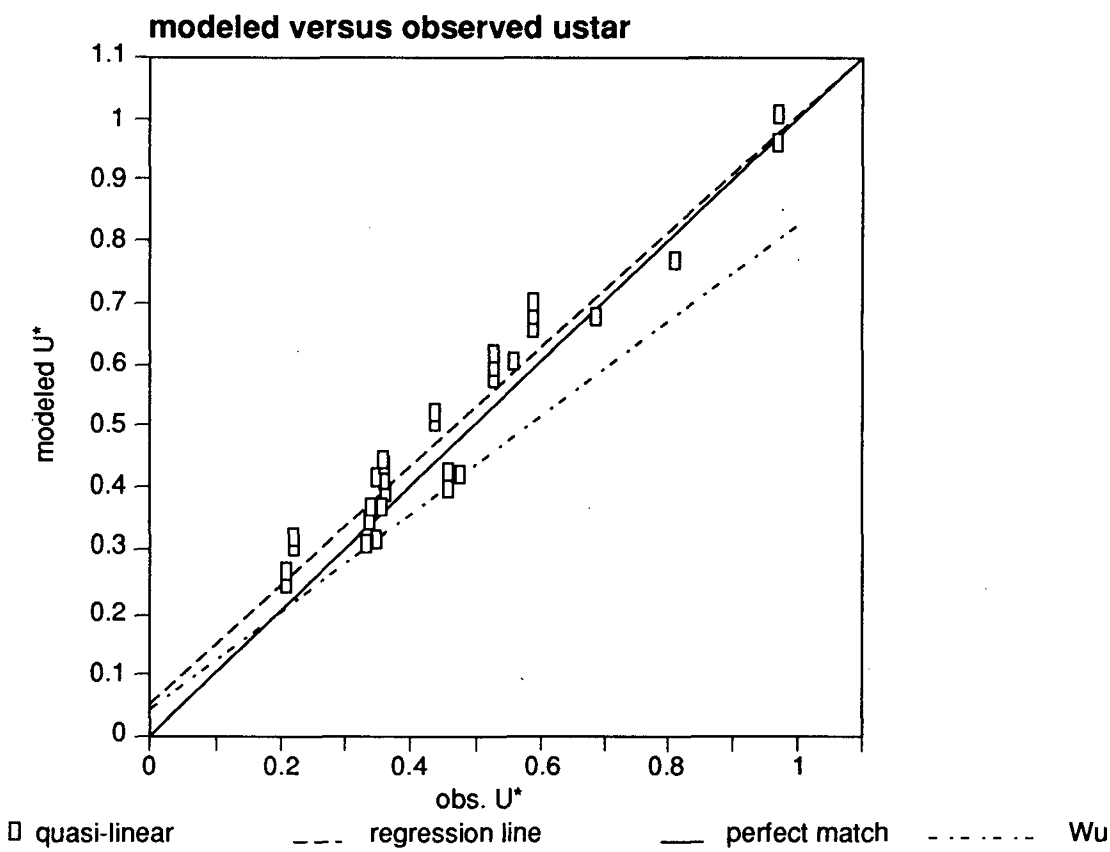


FIG. 1. Comparison of modeled and observed friction velocity. The boxes indicate quasi-linear theory; the dashed line indicates the regression line; the straight line indicates a perfect match; and the dashed–dotted line indicates the Charnock relation.

It is emphasized that the choice of directional distribution is an important one, since, as may be inferred from the definition of the wave-induced stress, a broader directional distribution at high frequencies results in a smaller wave-induced stress.

Therefore, the width of the directional distribution of the high-frequency waves was increased by a factor of 2 using for $\beta$

$$\beta = 2.61(\omega/\omega_p)^{1.3}, \quad 0.56 < \omega/\omega_p < 0.95$$
$$\beta = 2.28(\omega/\omega_p)^{-1.3}, \quad 0.95 < \omega/\omega_p < 2.5$$
$$\beta = 0.69, \quad \text{otherwise}, \tag{10}$$

instead of $\beta$ as given in Eq. (9). Comparing results regarding the friction velocity of the wide and narrow distribution, it was found that the narrow distribution [$\beta$ as in Eq. (9)] gave friction velocities that are 15% larger than for the wide directional distribution. This shows a sensitive dependence on the directional spectrum, although it should be pointed out that a change in width of a factor of 2 is quite large.

Before a comparison of modeled and observed surface stress is made, it should be noted that the wave-induced stress is mainly determined by the medium-to-high frequency range of the wave spectrum. Since a wave rider only produces reliable spectra up to $f = 0.5$ Hz, the spectra were extended beyond 0.5 Hz, with a $f^{-5}$ tail where the Phillips' constant was obtained from the energy densities of the highest three frequency bins.

In Fig. 1 the modeled friction velocity has been plotted against observed friction velocity. Fitting the squares with a linear regression line, a slope of 0.96 and an intercept of 0.05 are obtained, indicating that there is good agreement between observed stress and the stress resulting from quasi-linear theory.

One may wonder, however, how much better a sea state-dependent roughness is doing over the previous sea state-independent roughness, as suggested by Charnock (1955). Therefore, the stress in the surface layer was determined with the roughness length

$$z_1 = \alpha_{CH}\tau/g, \tag{11}$$

where, as suggested by Wu (1981), the value $\alpha_{CH} = 0.0185$ was taken. The resulting regression line is given in Fig. 1 as well: it has a slope of 0.78 and an intercept of 0.06, indicating that a sea state-dependent roughness-length formulation is to be preferred.

Finally, one may wonder to what extent the modeled stress calculation is affected by errors in observed wind speed and wave spectrum. To that end, an allowance was made for a 5% relative error in wind speed and a 10% relative error in the wave spectrum, and the regression analysis was redone. The results are presented in Table 1.

It is concluded from Table 1 that although modeled stresses deviate from the observations, this deviation is within the range of the measurement errors. In addition it is seen that, even taking measurement errors into account, a sea state-independent roughness length formulation gives significantly worse estimates of the surface stress.

TABLE 1. Results of regression analysis.

| | Slope | Intercept | Correlation coef. |
|---|---|---|---|
| Quasi-linear ($QL$) | 0.96 | 0.05 | 0.96 |
| $QL$: $\frac{\Delta U}{U} = -0.05$; $\frac{\Delta E}{E} = 0$ | 0.91 | 0.04 | 0.96 |
| $QL$: $\frac{\Delta U}{U} = +0.05$; $\frac{\Delta E}{E} = 0$ | 1.01 | 0.05 | 0.96 |
| $QL$: $\frac{\Delta U}{U} = 0$; $\frac{\Delta E}{E} = +0.1$ | 1.00 | 0.05 | 0.96 |
| $QL$: $\frac{\Delta U}{U} = 0$; $\frac{\Delta E}{E} = -0.1$ | 0.91 | 0.05 | 0.97 |
| CHARNOCK ($\alpha_{CH} = 0.0185$) | 0.78 | 0.06 | 0.98 |

To summarize the results of this comparison, it is concluded that a sea state-dependent roughness length should be preferred over a sea state-independent formulation.

## 4. Summary of conclusions

In this paper I have presented evidence for the effect of surface gravity waves on the airflow. According to the quasi-linear theory of wind-wave generation, airflow over surface gravity waves depends on the sea state because the wave-induced stress may be a considerable amount of the total stress. This may be seen immediately from Eq. (3), which shows that when $\tau_w \approx \tau$ a considerable enhancement of the roughness length is found, resulting in an increase of the surface stress. Since the wave stress is proportional to the wave-variance spectrum, the increase of the aerodynamic drag is expected for young wind sea because the high-frequency waves then have a large steepness.

The parameterized version of quasi-linear theory, as presented in section 2, was successfully applied to the problem of the coupling of wind and waves by Janssen (1991). The same formulation (with identical coefficients) was used in the comparison between observed and modeled surface stress. The result of this comparison shows that a sea state-dependent roughness length gives a very good agreement with observations, much better than when the Charnock relation for the roughness is used. This provides evidence and support for the claim that knowledge of the sea state will be beneficial for the specification of the weather state in the surface layer over the oceans.

It should be noted that the comparison was confined to wind-sea cases with a single peak in the spectrum. Also, it should be noted that in the theory a number of assumptions regarding the spectral shape for high-frequency waves were made. For example, a change in the width of the directional distribution of a factor of two affects results considerably. Thus, the present theory of the surface stress above ocean waves is promising, although more information on the two-dimensional spectrum of high-frequency waves is needed.

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