DOES WIND STRESS DEPEND ON SEA-STATE OR NOT? – A STATISTICAL ERROR ANALYSIS OF HEXMAX DATA

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Abstract. There have been several claims, either explicit or by implication, either based on experimental evidence or on theoretical reasoning, that the wind stress is modified by the stage of development of the wind sea. However, the overall evidence is weak, because theories are still incomplete and because it is questionable whether the sea-state effect, which is of the order of 10%, can be separated from experimental noise, which is of the order of 20%.

In this paper a rigorous statistical analysis of HEXMAX data is pursued in order to establish the significance of sea-state effects. It appears that the enhanced drag, especially at high winds, which has already been established by previous analyses, cannot be attributed to the effect of young waves. The analysis provides no clues for the actual mechanism, which could be related to breaking or shoaling waves.

As the effect of sea-state on wind stress is much smaller than the experimental noise level, it is hard to detect. Nevertheless, HEXMAX seems to contain a wave effect that is at the edge of statistical significance. It is, however, not the wave age itself that influences the drag, but a parameter involving wave height.

Because the HEXMAX evidence is only indicative, we conclude that the issue set out in this paper cannot be answered on the basis of the HEXMAX data alone. It is recommended that error analyses are also carried out for other relevant observational data sets and that new measurements with suppressed noise will be taken up.

Key words: Sea-state dependent stress, Statistical error analysis, HEXMAX, Charnock parameter, Sea roughness.

1. Motivation

There have been two previous analyses of HEXMAX data (Maat et al., 1991; Smith et al., 1992) that both suggest that the Charnock parameter is inversely proportional to the wave age. A third analysis suggests an even stronger dependence (Monbaliu, 1994).

Although in the HEXOS paper (Smith et al., 1992) strong reservations were made with respect to this wave-age dependence, in the ensuing discussions these were pushed somewhat into the background. As a result this paper has been quoted as pivotal evidence for the wave-age effect, e.g., in Komen et al. (1994), an authoritative guide on ocean waves. In a recent review paper (Komen et al., 1996) a more balanced conclusion was reached: ‘The Hexos-parametrization is a useful fit to the Hexos data. For old waves it gives values that are consistent with open ocean observations. A wave-age independent Charnock parameter does not fit the observations well, and when it reproduces the average value it is not in agreement with the ocean observations’.

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The present paper is intended to revive the discussion on the status of HEXMAX within the context of the parametrization of sea roughness. Do the HEXMAX data really give positive support to the idea of a Charnock parameter inversely proportional to wave age, or do they only hint at it? In order to answer this important question an additional statistical error analysis will be pursued.

On the basis of wind measurements made with a sonic anemometer Maat et al. (1991) found that there is a negative correlation between normalized roughness (i.e., the Charnock parameter) and wave age. They did consider the possibility of spurious correlations due to a common friction velocity (u_*) factor, but disregarded another source of spuriousness, viz. the correlation between wave age and wind speed. The existence of the latter correlation prevents one concluding that the Charnock parameter *depends* on wave age. Though it does not exclude the possibility of a wave-age effect, a dependence on wind speed might however be hypothesized.

Furthermore, neither Maat et al. (1991) nor Smith et al. (1992) provide a full statistical analysis of HEXMAX data. The sheer calculation of a regression line may hint at a plausible relationship, but it doesn't provide grounds for a causal dependency, nor does it ensure the statistical significance of the obtained fit.

In order to establish whether a proposed relationship is statistically significant, it should be subjected to a 'lack-of-fit' test (Draper, 1981; Weisberg, 1985) which, in practice, if error estimates are available, amounts to a chi-squared test. The originally proposed inverse wave-age dependent Charnock parameter (Maat et al., 1991) has not been subjected to such a test; in the present paper we will try to bridge this gap.

It is not the intention of the present study to do more than scrutinize the HEXMAX data. There are, however, other data sets and theories that purport to show that sea drag is wave dependent (Komen et al., 1996). The present paper, but also recent work of Yelland and Taylor (1996) in which wave effects have not been discerned, should, however, offer encouragement to perform additional statistical error analyses on the existing body of evidence for sea-state dependent wind stresses.

2. Theory

The wind stress will be denoted by τ, and for simplicity be defined as $\tau = u_*^2$, where u_* is the friction velocity. Traditionally theories on τ come in two disguises. One group of theories gives the drag coefficient at level z (usually 10 m), C_D, in terms of the wind speed U_z and possibly one or more sea-state parameters (Garratt, 1977; Geernaert et al., 1987; Makin et al., 1995). A popular parameter is the wave age (c_p/u_* or c_p/U_{10}) and a popular hypothesis is that C_D varies inversely with c_p/u_* (Komen et al., 1994).

The alternative group, which may be called the theories on sea-surface roughness, provides formulae for the roughness length z_0 in terms of atmospheric and sea-state parameters (Donelan et al., 1993). Usually self-similar relations are obtained by making regressions between logarithms of nondimensionalized quantities.

This latter procedure has been repeatedly criticized because the two quantities to be correlated often have a common factor that contaminates the result by the introduction of spurious self-correlations (Kenny, 1981; Perrie and Toulany, 1990; Smith et al., 1992).

A second point of criticism against the practice of making unweighted regressions between quantities that are apparently linearly related, is that the result may be severely biased. It is not always justifiable to give every pair an equal weight. Especially if the relation between the derived variables and the original measured quantities is highly nonlinear, the proliferation of errors should be carefully studied and taken into account. If one wants to correlate two variables that depend nonlinearly on measured quantities, one should make a weighted regression. The weights are determined by the errors in the variables, which can be calculated from the errors in the measured quantities. In the following we will develop several regressions, but it will be explicitly shown how the weights have to be defined in order to circumvent the above mentioned pitfalls.

In theories on the roughness length the pivotal quantity is the Charnock parameter α (Charnock, 1955), which can be interpreted as a normalized roughness (often denoted as z_0^*),

$$\alpha = z_0^* = \frac{gz_0}{u_*^2}. \tag{1}$$

The ongoing debate is whether the Charnock parameter is a constant or not (Geernaert et al., 1987; Makin et al., 1995; Nordeng, 1991; Smith et al., 1992; Steward, 1974). As noted by Donelan (1990) the value of α varies from data set to data set; the reported values range from 0.0144 (Garratt, 1977) to 0.035 (Kitaigorodskii and Volkov, 1965). It may well be that the Charnock parameter range is due to geophysical differences between different sites, but it may also reflect discrepancies between different measurement techniques.

A serious challenger of Charnock's hypothesis is the Maat parametrization, which proposes an inverse wave-age proportionality (Maat et al., 1991)

$$z_0^* = \mu(c_p/u_*)^{-1} \tag{2}$$

where μ is a (universal) constant to be determined.

Previous analyses of the HEXMAX data (Maat et al., 1991; Smith et al., 1992) produced evidence that the hypothesis of a constant Charnock parameter should be rejected, whereas the data did not seem to be in conflict with an inverse wave-age dependent z_0^*. HEXMAX data have been used to estimate the free parameter μ in this latter theory; initially it was found that $\mu = 0.8$ (Maat et al., 1991), but later calculations, including corrections due to flow distortion by the platform, produced the lower value $\mu = 0.48$ (Smith et al., 1992).

In a neutrally-stable constant-stress layer, which is a good approximation for the marine boundary layer, theories on the drag coefficient can be transformed into theories on the roughness length and vice versa. The bridging formula that relates drag coefficient and roughness length follows from the logarithmic wind profile, viz.

$$z_0 = z\exp(-\frac{\kappa}{\sqrt{C_D}}) \tag{3}$$

where κ is the Von Kármán constant, the numerical value of which is 0.4.

Any theory on wind stress, be it C_D- or z_0-formulated, may be implicitly reformulated as follows,

$$\tau = \tau(U_{10}, s) \tag{4}$$

where s stands for sea-state parameters such as phase speed c_p and significant wave height H_s. In this form wind stress is directly expressed in terms of the relevant atmospheric and oceanic variables.

Cast in the form (4) the difference between Charnock's hypothesis and Maat's proposal becomes manifest: Charnock has $\tau = \tau(U_{10})$, whereas Maat implies $\tau = \tau(U_{10}, c_p)$. Hence, according to Charnock the ocean acts as a passive element in the dynamically coupled system atmosphere-ocean and the waves are fully 'enslaved' to the wind. The Maat proposal, on the other hand, pictures an ocean that 'slows down' (at fixed wind stress and relative to mature waves) the atmosphere in the early stages of wave development.

There are more theories that endorse the picture of an active ocean via a wave-age effect (Geernaert et al., 1987; Nordeng, 1991; Steward, 1974). However, wave age is not always the exclusive mediating variable. According to a simplified version of Kitaigorodskii's roughness theory (Donelan, 1990; Kitaigorodskii, 1970), wave height as well as wave age determines the roughness length.

There are even roughness theories that take the full wave spectrum into consideration (Kitaigorodskii, 1970; Komen et al., 1994; Makin et al., 1995). From scatterometry we know, however, that short waves respond instantly to a change in the wind (Van Halsema et al., 1989), and are thus enslaved to the wind. Therefore, their effect (if any) is automatically included.

The dominant waves, on the other hand, are not fully enslaved by the local wind, even under steady conditions. Under ideal cases for fetch-limited wave growth, it was found during JONSWAP that pure wind sea states are members of a one-parameter family (Hasselmann et al., 1973). A single parameter describes the stage of development, and it is common practice to adopt a wave-age parameter ξ ($\xi = c_p/u_*$ or $\xi = c_p/U_{10}$) for this task. Hence for the same wind a range of developing sea-states exists, and one might expect that for these pure wind seas $\tau = \tau(U_{10}, c_p)$. Here we have chosen phase speed as the sea-state parameter, but due to self-similarity we might equally well have taken significant wave height, fetch or wave age.

One of the purposes of our statistical analysis is to find out whether the HEXMAX data indeed contain a *significant* dependence of wind stress on the sea-state.

3. HEXMAX

HEXMAX (Humidity Exchange over the Sea Main Experiment) was a field experiment within the context of the HEXOS (Humidity Exchange over the Sea) programme (Katsaros et al., 1987; Smith et al., 1992). It was performed in October-November 1986 at the Dutch research platform *Meetpost Noordwijk* (MPN). Simultaneous measurements of wind and sea-state parameters were made in order to investigate the dependence of the drag coefficient and the roughness length on the sea-state (Smith et al., 1992).

The instantaneous wind speed vector was concurrently measured from a 21m boom, extending upwind from the platform, by a sonic (SON) and a pressure anemometer (PA). The anemometers made recordings at an average level of 6 m above the sea, and were two metres apart.

The collected wind data were corrected for local flow distortion by the platform, for tilting of the instruments and for the presence of tidal currents. Hence the raw data were processed in such a way that the wind relative to the wind-driven water surface was obtained. After elimination of stability effects both the equivalent 10 m neutral wind speed and the wind stress (by the eddy correlation technique) were calculated. For the present study all runs were chopped into 20-minute chunks. As argued by Donelan (Donelan, 1990, p. 251) a period of 20 minutes is suitable for air-sea turbulence studies; it fulfils the requirements of stationarity and sufficient averaging time in an optimal sense. For certain wind directions the flow was too much distorted, and these episodes were discarded from the analyses.

The one-dimensional wave energy spectrum $E(f)$ was determined with a wave rider buoy at a location of about 150 m from the platform. From the spectrum two sea-state parameters were obtained: significant wave height H_s and peak frequency f_p. In order to discriminate between swell and wind sea a criterion based on the Pierson–Moskowitz spectrum (Pierson and Moskowitz, 1964) was used. The sea state is classified as wind sea if for a single-peak spectrum the energy level at f_p is above the Pierson–Moskowitz value, i.e., if the 'peak enhancement factor' (Hasselmann et al., 1973) is greater than 1. For an average Phillips constant of the order of 0.01, the criterion amounts to $f_p^5 E(f_p) > 0.0002$; sea states not satisfying this criterion were discarded.

Another sea-state parameter that is considered to be relevant is the phase speed c_p of the dominant waves. As the water depth d at the measurement site is limited (d = 18 m), c_p has been calculated from the finite-depth dispersion relation ($\omega^2 = gk\,\tanh(kd)$).

After the elimination of swell-contaminated runs, there remain 58 HEXMAX 20-minute runs of concurrent wind measurements by the two anemometers, PA

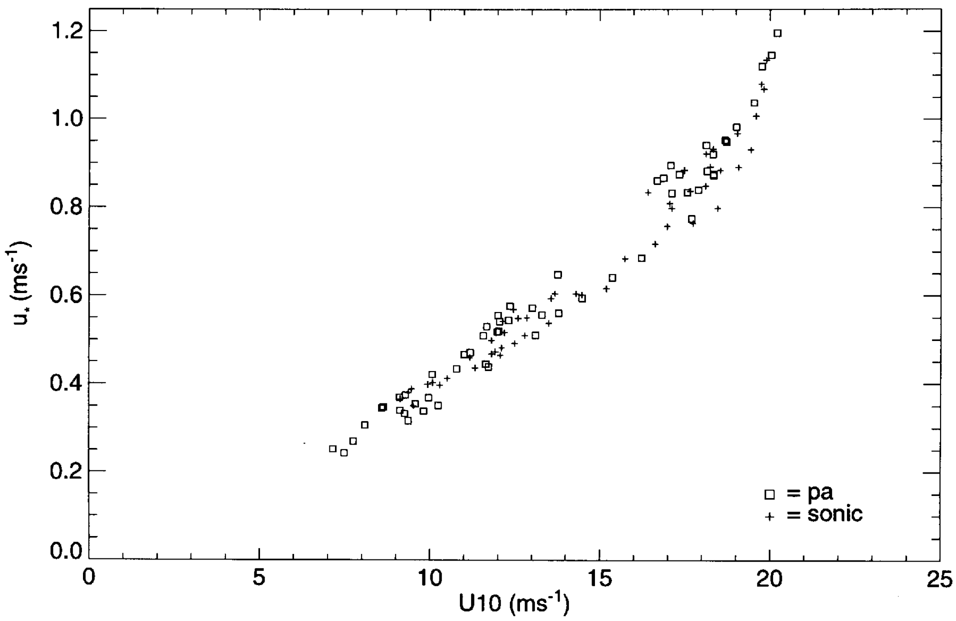

Figure 1. Friction velocity versus wind speed for HEXMAX data.

and SON. During the last 8 runs the PA malfunctioned, therefore these data were discarded. From the raw wind data 10m neutral wind speeds and wind stresses were calculated, both for the PA and SON. Hence there are 58 U_{10} and τ values obtained by the sonic anemometer, and 50 concurrent ones by the pressure anemometer.

The simultaneous measurements of the wave rider yielded 58 values for the wave parameters H_s and c_p, which complete the data set. HEXMAX thus provided a well-documented and carefully processed data set of air-sea interface parameters; the data are presented in the Appendix.

4. Statistical Analysis: Qualitative

The aim of our analysis is to investigate the relation between wind stress on the one hand, and wind speed and wave parameters on the other. If one plots wind stress (or friction velocity) versus wind speed a strong positive correlation is manifest (Figure 1).

Actually wind stress increases faster than quadratic with wind speed. This can be clearly seen if one plots the drag coefficient versus wind speed. The increase of the drag coefficient with wind speed is an established fact, although the precise functional dependence is far from being settled (Blanc, 1985; Garratt, 1977; Geernaert, 1990).

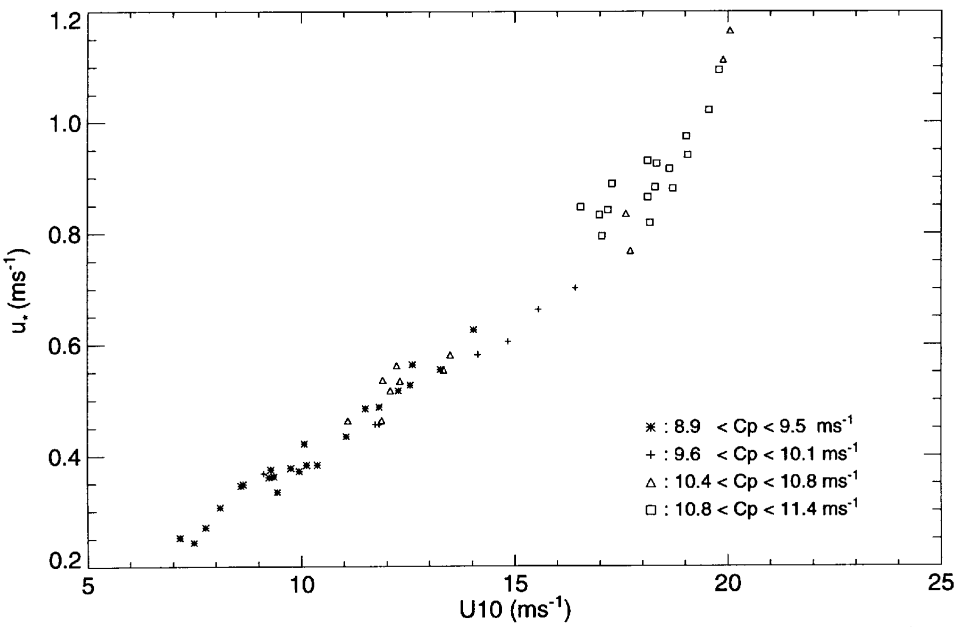

Figure 2a. u_* versus U_{10} plot with distinct classes of c_p.

If the wind stress uniquely depends on wind speed, $\tau = \tau(U_{10})$, and if one could perform perfect measurements (i.e., without errors), then the points in Figure 1 should fall on a single curve.

However, the measurement points in Figure 1 do not line up along a curve, they rather form a band with a certain width. The band width is determined by two factors: random measurement errors and additional stress-determining parameters (i.e., geophysical variability).

Incidentally, it should be noted that *systematic* measurement errors do not contribute to the band width; they may, however, affect the shape of the band and hence introduce a fault in the functional dependence $\tau(U_{10})$.

An often propagated maxim concerning the roughness of the sea reads: young waves are rougher than old waves (Komen et al., 1994). Hence the following rule should hold. In a scatter plot of u_* versus U_{10}, at fixed u_* the measured points sort out such that small phase speeds (young waves) are on the left and high phase speeds (old waves) on the right. In Figure 2a we have plotted the average friction velocity and wind speed of corresponding SON and PA measurements, versus each other. The HEXMAX data divide into four distinct classes of different phase speeds and it appears that the above rule does not apply; if there is a rule at all, the opposite seems to be more likely. Hence, Figure 2a permits the following disenchanting conclusion: there is no such thing as a wave-age effect contained in the HEXMAX data.

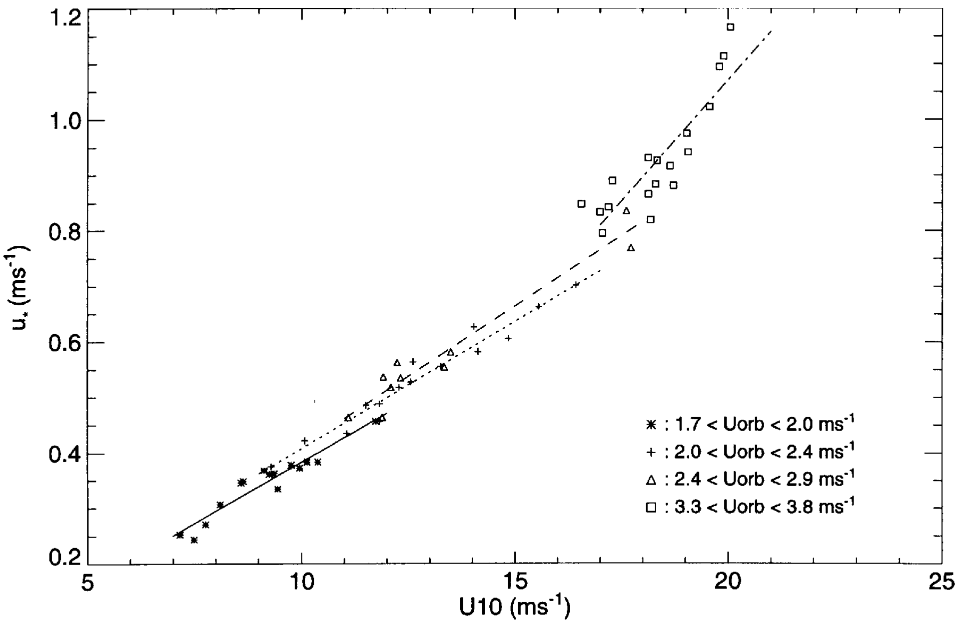

Figure 2b. u_* versus U_{10} plot with distinct classes of U_{orb}.

Does this mean that there is no effect at all of sea waves on wind stress? Not necessarily. In the present analysis we consider two wave parameters: phase speed c_p and wave height H_s. Instead of the latter it is more appropriate to introduce the parameter $U_{\mathrm{orb}} = gH_s/c_p$, which may be interpreted as the orbital velocity of the dominant waves (a correction factor for finite depth will be added later on). According to the well-known JONSWAP picture (Hasselmann, 1973) the whole family of wind sea states is described by a single parameter (wave age), but the similarity of sea states is only approximate. This can be clearly seen in Figure 3; JONSWAP similarity requires that the HEXMAX sea states fall on a curve, but they do not. Therefore it makes sense to investigate the dependence of wind stress on U_{orb}.

In Figure 2b we have regrouped the HEXMAX data, now according to the orbital velocities of the dominant waves. It can be seen that with this sea-state division the data tend to sort out into different roughness classes. Hence, according to the naked eye, there is a (small) sea-state effect on wind stress. One should be careful, however, and check whether this effect is statistically significant or not.

5. Statistical Analysis: Quantitative

In order to pursue a rigorous quantitative error analysis three steps have to be taken. First, one needs to estimate the magnitude of the random errors in the various measured quantities.

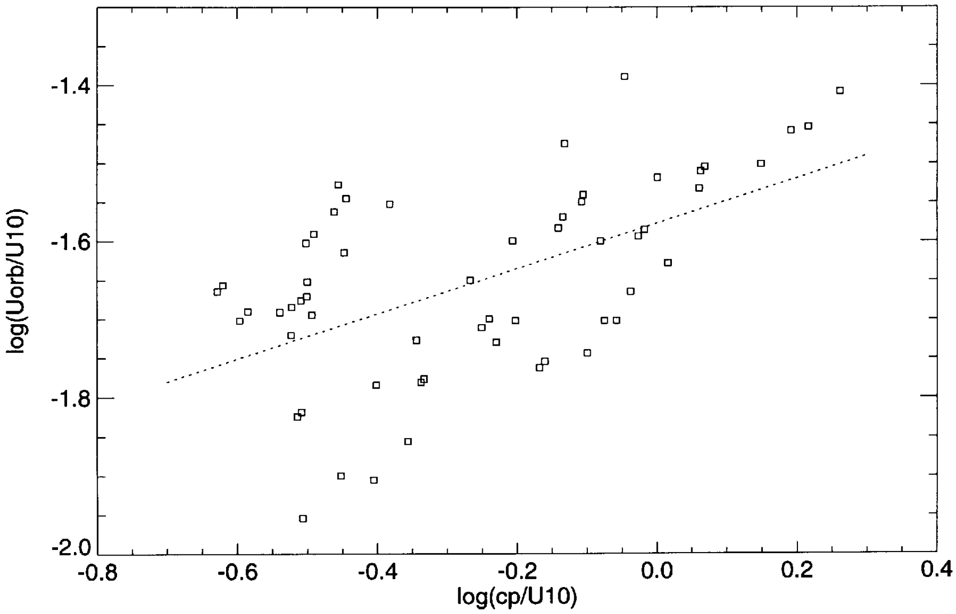

Figure 3. Similarity of air-sea parameters for HEXMAX data.

Secondly, a model is selected that parametrizes the experimentally least accurately known quantity (wind stress) in terms of the other variables (wind speed, phase speed and orbital velocity). Any free model parameter should be optimally estimated from the data.

Thirdly, the capability of the model to fit the data is tested by determining the ratio of the variance between modelled and observed wind stress (= external variance) and the variance in measured wind stress due to random errors (= internal variance).

5.1. Random measurement errors

During HEXMAX 20-minute runs were made in which four basic quantities were measured (see Appendix): wind stress τ, wind speed U_{10}, wave height H_s and phase speed c_p of the dominant waves.

It is assumed that measured values of these quantities equal true values 'in the mean', i.e., systematic errors are absent. In HEXMAX comparatively much effort was invested to accomplish this. Then only random errors remain, which may originate from different sources, the most important being instrumental noise and sampling variability (Donelan, 1990).

It is well-known that wind stress measurements are rather inaccurate, the responsible factor being the high sampling variability (Donelan, 1990). For the quantities wind speed, wave height and phase speed on the other hand, the sampling error is relatively low and measurement accuracy is determined by instrumental noise.

If one compares the wind speed and wind stress measurements of PA and SON (see Appendix A), it appears that the average percentage rms difference error for wind stress is approximately 12%, and for wind speed 2.5%. It is concluded that only the randomness in wind stress needs consideration and that for all practical purposes the errors in the other quantities may be neglected.

The atmospheric quantities τ and U_{10} have been concurrently measured with two anemometers, two metres apart. As long as the ensemble of turbulent structures (eddies) that passes one instrument is distinct from the ensemble passing the other, the error statistics of both anemometers may be considered independent. Especially at higher wind speeds it is to be expected that both ensembles have some overlap and the independence of errors may partially or completely break down. In that case a straightforward statistical analysis is impeded.

However, it is possible to overcome this complication and take error correlations into account (Janssen, 1995). In this way full justice is done to all measured data, but a disadvantage is that the analysis is rather involved and may distract attention from the main point. Therefore in this paper we will not pursue a full analysis of all data, but limit ourselves to the SON data.

As already noted, the magnitude of the random errors in wind stress is mainly determined by sampling variability (Donelan, 1990). The sampling errors for all relevant fluxes in the marine boundary layer have been experimentally determined by Sreenivasan et al. (1978). The relative error in wind stress τ, obtained from a time series of length Ω and at measurement height z, is given by (Donelan, 1990; Sreenivasan et al., 1978)

$$\epsilon_\tau = \frac{\sigma_\tau}{\tau} = \sqrt{30}\left(\frac{z}{U_z\Omega}\right)^{1/2} \tag{5}$$

where U_z is the average wind speed at the measurement level z.

It should be stressed that (5) provides only an estimate for the sampling error, and hence for the total random error in wind stress. The formula was obtained at an open sea site in Bass Strait under stationary geophysical conditions. The validity of the formula in other conditions was checked by Donelan (1990) who found reasonable agreement, even in the laboratory.

HEXMAX has been performed under very non-stationary geophysical conditions that might have caused (5) to underestimate the actual measurement errors. However, this turns out not to be the case, as is shown in Figure 4. Measurement runs of 21 minutes have been broken up into seven sequential three-minute parts to produce groups of seven estimates of 3-minute wind stresses. The average of a group of seven wind stresses yields the best estimate for the wind stress during the corresponding 21-minute run. The standard deviation within such a group of seven provides an estimate for the random measurement error in a 3-minute wind stress. In Figure 4 the HEXMAX estimates have been compared with the estimates

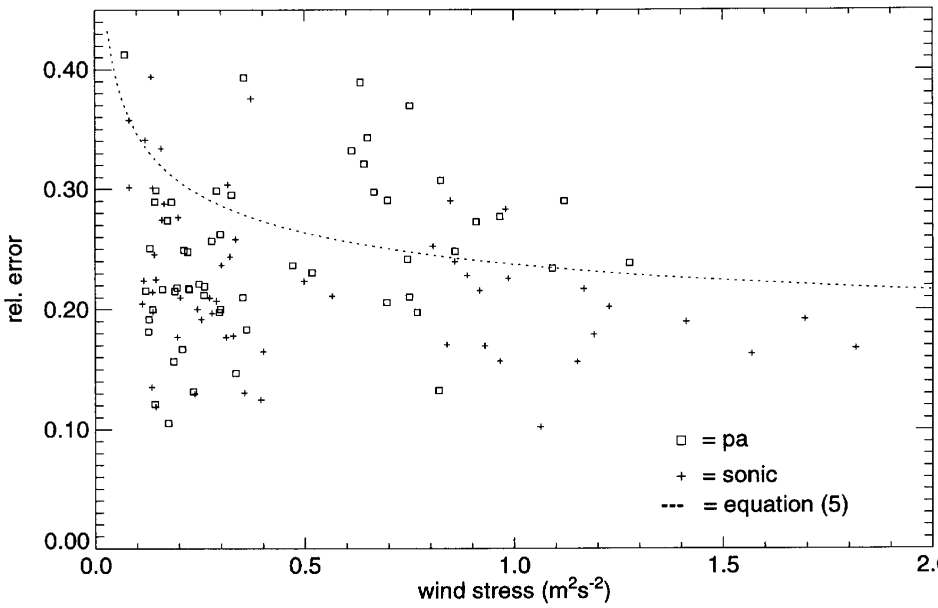

Figure 4. Relative HEXMAX errors in 3-minute wind stress compared with the equation (5) estimate.

according to Equation (5). In the majority of cases the actual error is smaller than the estimate based on (5); hence the latter is a conservative estimate.

The essence of the ensuing statistical analysis is to compare the size of the deviations between modelled and observed wind stress (external error) with the above estimate (internal error).

5.2. Wind stress models and parameter estimation

Consider an unspecified wind-stress model with U_{10} (wind speed at 10 m height) and s (s again stands for the sea-state parameters) as independent variables. In statistical language U_{10} and s are the predictors and τ the response variable,

$$\tau = M(U_{10}, s). \tag{6}$$

The model says that if U_{10} and s are measured, the value for τ to be expected is $M(U_{10}, s)$. In practice the actually occuring value for τ will differ from the expected one due to the random fluctuations previously discussed.

The relative rms error in τ is given by (5) and the usual assumption in measurement theory is that the statistics of τ are Gaussian. In the present case this simplifying assumption is clearly justified, and it is shown in Sreenivasan et al. (1978) that the measured normalized (i.e. with unit variance) probability distribution of τ, although slightly skew, does not deviate very much from the Gaussian bell shape.

Let us subsequently introduce the index i to number different runs (i = 1, . . . , 58) and define random variables X_i that measure wind-stress deviations from model counterparts,

$$X_i = \tau_i - M(U_{10}^i, s^i). \tag{7}$$

The X_i are Gaussian variables, which for an unbiased model have zero average, $\langle X_i \rangle = 0$, and variances $\langle X_i^2 \rangle = \sigma_i^2$ according to

$$\sigma_i^2 = \frac{0.15}{U_6^i} M^2(U_{10}^i, s^i). \tag{8}$$

Equation (8) has been obtained by using (5) and substituting the measurement level (z = 6 m) and measurement time (Ω = 1200 sec) during HEXMAX.

The variables X_i correspond to different runs and may be considered to be statistically independent. Hence they may serve as building blocks for compound statistics that underlie certain tests. An example is the statistic Q that measures the normalized model variance and is used to test a model for lack-of-fit (chi-square test),

$$Q = \sum_{i=1}^{58} \frac{X_i^2}{\sigma_i^2}. \tag{9}$$

If there are no estimated parameters, Q is chi-squared distributed with 58 degrees of freedom. A rule of thumb says that for every estimated parameter the number of degrees of freedom decreases by one (Hogg and Craig, 1978).

Both the Charnock and Maat model contain one undetermined constant; these will now be estimated. Individual measurement points have to be weighted in accordance with the error (8).

The Charnock hypothesis may be formulated as (cf. (1) and (3))

$$\ln(\alpha) = \frac{-\kappa U_{10}}{\tau^{1/2}} + \ln\left(\frac{gz}{\tau}\right) = \text{constant}. \tag{10}$$

Similarly, one has for the Maat proposal (cf. (1), (2) and (3))

$$\ln(\mu) = \frac{-\kappa U_{10}}{\tau^{1/2}} + \ln(\frac{gzc_p}{\tau^{3/2}}) = \text{constant}. \tag{11}$$

Best estimates for α and μ are obtained by making a weighted average over all runs,

$$\widehat{\ln(\alpha)} = \sum_{i=1}^{58} w_\alpha^i \left(\frac{-\kappa U_{10}^i}{\tau_i^{1/2}} + \ln\left(\frac{gz}{\tau_i}\right)\right) \bigg/ \sum_{i=1}^{58} w_\alpha^i \tag{12}$$

$$\widehat{\ln(\mu)} = \sum_{i=1}^{58} w_\mu^i \left(\frac{-\kappa U_{10}^i}{\tau_i^{1/2}} + \ln\left(\frac{gzc_p^i}{\tau_i^{3/2}}\right)\right) \Big/ \sum_{i=1}^{58} w_\mu^i. \tag{13}$$

Note that U_{10}^i and τ_i are the wind speed and stress obtained from the sonic anemometer.

The weights w_α^i and w_μ^i are obtained by looking at the error statistics of ln(α) and ln(μ). These are solely determined by the errors in wind stress. Hence,

$$\delta(\ln(\alpha)) = \left(\frac{\kappa U_{10}}{\tau^{1/2}} - 2\right)\frac{\delta\tau}{2\tau} \tag{14}$$

$$\delta(\ln(\mu)) = \left(\frac{\kappa U_{10}}{\tau^{1/2}} - 3\right)\frac{\delta\tau}{2\tau}. \tag{15}$$

The error variance of wind stress is given by (8). Hence

$$\sigma_{\alpha,i}^2 = \langle(\delta(\ln(\alpha)))^2\rangle = \left(\frac{\kappa U_{10}^i}{\tau_i^{1/2}} - 2\right)^2 \frac{\sigma_i^2}{4\tau_i^2} \tag{16}$$

$$\sigma_{\mu,i}^2 = \langle(\delta(\ln(\mu)))^2\rangle = \left(\frac{\kappa U_{10}^i}{\tau_i^{1/2}} - 3\right)^2 \frac{\sigma_i^2}{4\tau_i^2}. \tag{17}$$

The weights to be substituted in (16) and (17) can now be defined as w_α^i = $1/\sigma_{\alpha,i}^2$ and w_μ^i = $1/\sigma_{\mu,i}^2$. This yields the following parameter estimates,

$$\widehat{\ln(\alpha)} = -3.31 \pm 0.07, \qquad \text{hence} \qquad \alpha = 0.036 \pm 0.003 \tag{18}$$

$$\widehat{\ln(\mu)} = -0.64 \pm 0.05, \qquad \text{hence} \qquad \mu = 0.53 \pm 0.03. \tag{19}$$

The Charnock constant in HEXMAX is in the middle of the range reported in Kitaigorodskii (1970, p. 45) ($0.01 < \alpha < 0.085$), and very close to Kitaigorodskii's ensemble average value of 0.035. The weighted μ estimate is somewhat larger than the previously published unweighted one (Smith et al., 1992). Note that the latter one was based on the average of SON and PA measurements, whereas for the present one only SON data were taken into account.

The performance of both stress models is shown in Figure 5a. Qualitatively, one may infer from this Figure that the Maat model is better at the very high winds, while Charnock has the edge at intermediate winds and that both models perform comparably at low winds. Furthermore the models do not seem to suffer from a severe overall bias. Whether the scatter around the line-of-perfect-fit is in balance with experimental noise will be investigated in the next section.

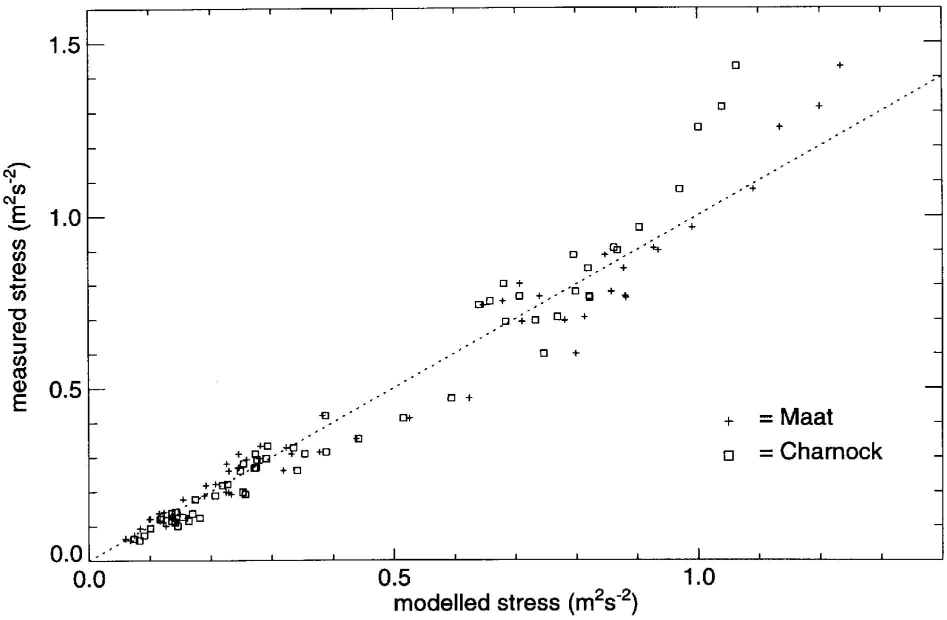

Figure 5a. Measured versus modelled stress for Charnock and Maat model.

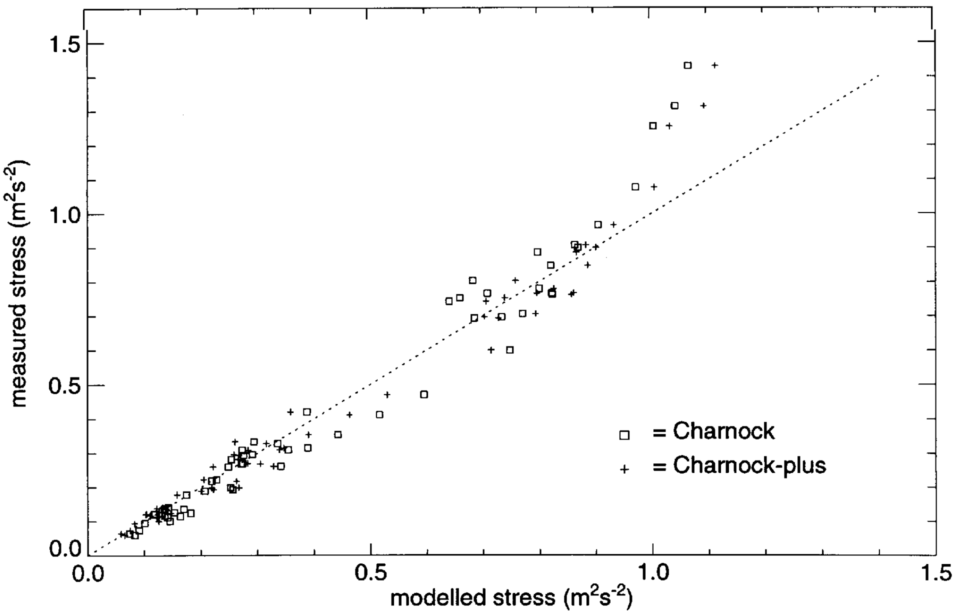

Figure 5b. Measured versus modelled stress for Charnock and Charnock-plus model.

Table I
Analysis of variance for various models

Model	d.o.f.	SNS	MNS	significant?
Maat	57	91.1	1.60	yes, at 0.5% level
Charnock	57	122.4	2.15	yes, at 0.5% level
Charnock plus	54	73.0	1.35	yes, at 5.0% level

Table II
Correlation between stress deviations and wind speed squared

Model	$\rho(U_{10}^2, \delta\tau)$	Significant?
Maat	-0.13	not significant
Charnock	0.24	yes, at 5% level

5.3. Lack-of-fit tests

In order to test for lack-of-fit we perform an analysis of variance based on the Q statistic previously defined in Equation (9). Q is a sum of normalized squares (SNS) and may be interpreted as the normalized model variance. For the case of the Charnock and Maat models Q will be chi-square distributed with 57 degrees of freedom. If Q is divided by the number of degrees of freedom one obtains the mean normalized square (MNS). This latter quantity allows one to compare models that have different degrees of freedom.

In Table I the results of the analysis of variance are presented for the Maat and Charnock model. For both models it appears that there is a very significant (i.e., at the 0.5% level) surplus in model variance. Hence, there is more variance in the data than the models are able to explain.

There might be several causes for the excess of variance. An obvious candidate is insufficient representation of the U_{10}-dependence. As is shown in Table II this possibility can be excluded for the Maat model, whereas there is some significance for Charnock. In this Table we have listed the correlation coefficients (which have been calculated as a weighted average with weighths $\sim 1/\sigma_i^2$) between the stress deviations X_i and U_{10}^{i2}. It thus appears that the shape of the curve $\tau(U_{10})$ may be slightly improved for Charnock.

Omission of additional stress-determining parameters is another cause for excess variance. One may think of the effect of slicks, tide, temperature differences, gustiness, organized boundary-layer structures and non-stationarity. But, in particular, the sea-state is thought to be an important factor. The Maat model does take wave information into account, but Charnock does not. Hence, it may be expected that the deviations of modelled from measured stress do not correlate with wave parameters for the Maat case, and that they might for Charnock.

Table III
Correlation between stress deviations and wave parameters

Model	$\rho(c_p^2, \delta\tau)$	Significant?	$\rho(U_{\text{orb}}^2, \delta\tau)$	Significant?
Maat	0.005	Not significant	0.13	Not significant
Charnock	0.18	Not significant	0.44	Yes, at 0.5% level

From the wave parameters two quantities with the dimension of velocity may be constructed. One is trivial, the phase speed c_p of the dominant waves, whereas the other may be interpreted as the orbital velocity U_{orb} of the dominant waves, and was already previously defined as

$$U_{\text{orb}} = \frac{gH_s}{c_p} \tanh(k_p D) \tag{20}$$

where we have added the factor $\tanh(k_p D)$ to correct for finite water depth D.

On dimensional grounds c_p^{i2} and U_{orb}^{i2} are the appropriate variables to correlate with the stress deviations X_i. It appears that the correlations with the Maat stress deviations are indeed insignificant, whereas in the Charnock case there is significance. The results are summarized in Table III; the correlation coefficients have been calculated with the weights $w_i \sim 1/\sigma_i^2$.

An obvious consequence of the previous correlation exercise is that the Charnock model may be improved by exploiting the wave information. To that end we define a 'Charnock-plus' model as follows

$$\tau_{\text{Char}}^{+} = \tau_{\text{Char}} + a + bU_{10}^2 + cU_{\text{orb}}^2. \tag{21}$$

Note that this model not only incorporates wave information, but also makes use of the U_{10}^2-correlation from Table II, although its value of 0.24 is only marginally significant.

Charnock-plus is a modification of the Charnock model. Therefore we adopt the previously determined value for the Charnock parameter ($\alpha = 0.036$) and do not reestimate it. The additional constants a, b and c still have to be determined from the data.

The appropriate way to do this is by the method of maximum likelihood estimation (Hogg and Craig, 1978). We will not present any calculations, which are quite cumbersome, but only list the result. The maximum likelihood estimators are given by

$$\hat{b} = \frac{\sigma_0}{\sigma_1} \frac{\rho_{01} - \rho_{12}\rho_{02}}{1 - \rho_{12}^2} \tag{22}$$

$$\hat{c} = \frac{\sigma_0}{\sigma_2} \frac{\rho_{02} - \rho_{12}\rho_{01}}{1 - \rho_{12}^2} \tag{23}$$

$$\hat{a} = \overline{\tau - \tau_{\text{Char}}} - \hat{b}\overline{U_{10}^2} - \hat{c}\overline{U_{\text{orb}}^2} \tag{24}$$

where the overbars denote weighted sample means (weights $\sim 1/\sigma_i^2$). The indices 0, 1 and 2 refer to $\tau - \tau_{\text{Char}}$, U_{10}^2 and U_{orb}^2 respectively; σ^2 denotes a weighted sample variance, and ρ is a weighted correlation coefficient. If one evaluates (22), (23) and (24) for the HEXMAX data set it is found that $a = -0.053$, $b = -0.00046$ and $c = 0.020$.

At first sight it may seem a bit strange that the coefficient b appears negative, while Table II would suggest a positive value. There is, however, a positive correlation between U_{10}^2 and U_{orb}^2 and this produces the sign reversal.

The performance of Charnock-plus is depicted in Figure 5b. As a reference the Charnock model points are also plotted to elucidate the improvement by Charnock-plus. Furthermore it is manifest that even Charnock-plus very poorly represents the three highest wind cases.

The quantitative assessment of Charnock-plus is summarized in Table I, which lists the results of the analysis of variance. It appears that the surplus in variance has decreased such that Charnock-plus is an acceptable model at a significance level of 2.5%. However, if one tests the model at the 5% level, it has to be rejected because of the three extreme points. This will be explicitly shown in the next section.

6. Discussion

In this paper three parametrizations of wind stress in terms of wind speed and sea-state have been distilled from, and tested against, the HEXMAX data: Maat, Charnock and Charnock-plus (cf. Table I). In terms of the mean normalized square MNS or ‘the cost per degree of freedom’, and if one takes all sonic data into account, Charnock yields the worst result (2.15), whereas Charnock-plus performs best (1.35); Maat takes the intermediate position (1.60).

It is wide-spread practice to evaluate the goodness-of-fit only in terms of the least sum of square distances between model and measurements. According to this criterion Charnock-plus provides the best fit to the HEXMAX data, whereas Maat is better than Charnock. This latter point provides the rationale for the Maat model (Komen et al., 1996). It should be born in mind, however, that this criterion of ‘minimal cost’ only evaluates models in a relative sense.

There is a second, more refined, criterion to evaluate the goodness-of-fit: the amount of scatter corresponding to the fit. This is an absolute criterion. If there is more scatter in the data than the model is able to explain, the model should be considered to be falsified. It is obvious that the scatter generated by random measurement errors cannot be explained by any model; that is why a perfect model should have an MNS value of approximately 1. Values that substantially deviate from unity hint at defects. If the MNS value is significantly larger than 1 the model is imperfect; if the value is significantly smaller than 1, probably something has gone wrong in the processing procedure.

If we consider the results of the chi-squared test performed on the four models (cf. Table I), it may be concluded that both Maat and Charnock suffer from lack-of-fit at the 0.5% significance level. Hence, neither model acceptably explains (in the statistical sense) the full scatter in the HEXMAX data. To a lesser extent this applies to Charnock-plus; at the 2.5% significance level there is no lack-of-fit and the enhancement of its MNS value above the bottom value 1 might be due to chance. However, at a stricter significance level of 5%, 1.35 is significantly larger than 1, implying that there is some unexplained variance present.

Charnock-plus is a useful model to summarize the HEXMAX data. It has been defined in (21), which shows that the Charnock-plus wind-stress is a sum of a Charnock wind-stress and a correction. In quantitative terms it appears that the correction is of the order of 10% of the wind stress. If we interpret this correction as a sea-state effect, it is immediately clear why it is so difficult to detect – measurement errors in wind stress are usually much larger, of the order of 20%.

The question arises to which physical mechanism the sea-state effect suggested by Charnock-plus refers. However, this question cannot be answered on the basis of the statistical analysis that has been pursued here. It might be hypothesized that bottom effects are responsible for the enhanced wind stresses in HEXMAX. For instance shoaling waves that have higher orbital velocities, and are also steeper than non-shoaling waves at the same wavelength, could contribute to a slight increase of the sea drag by their shape (form drag) or by their dynamical impact. However, to clarify this point additional measurements and theoretical work are surely needed.

In addition it should be stressed that Charnock-plus is an ad hoc model; there are no guarantees that its applicability goes further than HEXMAX. The model is based on a limited range of wind speeds ($7.2 < U_{10} < 20.2$ m s^{-1}) and orbital velocities ($1.8 < U_{\mathrm{orb}} < 3.8$ m s^{-1}). Hence, the model may not claim universal validity and there is also no secure way to generalize the model to encompass a broader range of physical states.

A second reason to be careful with Charnock-plus is that the obtained correlations (cf. Tables II and III), although significant, are rather weak and to a large extent due to the highest wind episodes. This is clearly illustrated in Figure 6, where we have plotted measured minus Charnock stress versus orbital velocity squared.

The excentricity of the three highest wind speed runs is also manifest in Figure 5b; three extreme points are considerably off the trend set by the remaining 55 points. This observation motivates an additional analysis in which the model performance is evaluated in different wind-speed regimes.

Let us return to Figures 5a and 5b. Figure 5a clearly shows that both the Maat and Charnock model perform progressively worse at higher winds. Especially the representation of the three highest wind cases is a nuisance for these models and this also applies to Charnock-plus (cf. Figure 5b). The Maat model has the least awful representation of the three extreme points, and this appears to be the main reason why this model, which originally has been proposed with a number of reservations

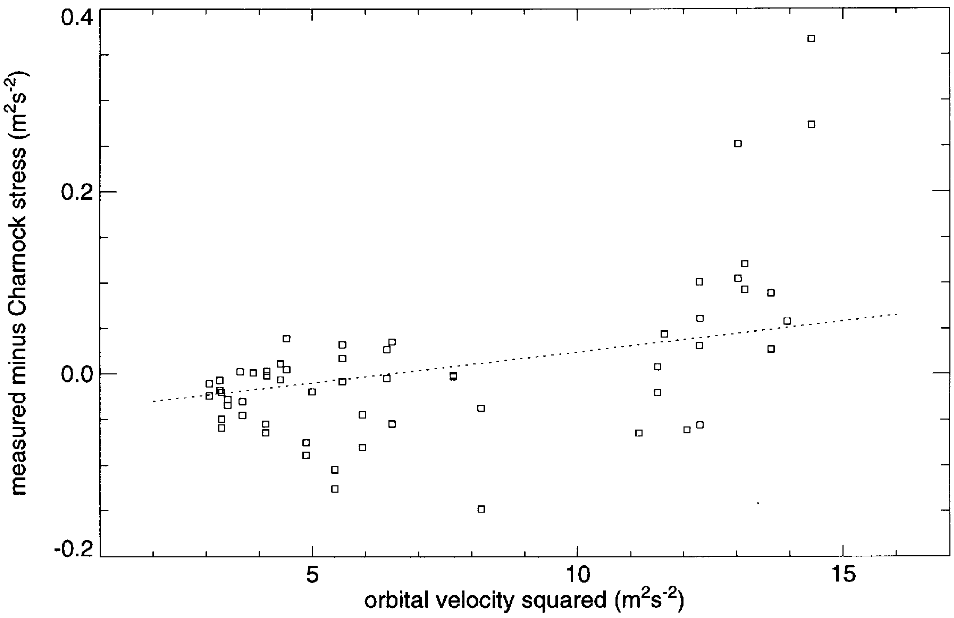

Figure 6. Measured minus Charnock stress versus orbital velocity squared.

(Smith et al., 1992), has been put more and more into the limelight (Komen et al., 1994).

In order to substantiate and quantify the assertions of the previous paragraph we will now reanalyse the HEXMAX data while excluding a number (n_{ex}) of high wind speed runs. We have dropped respectively the highest three, ten and twenty wind speed runs and reestimated the Maat parameter μ, the Charnock parameter α and the parameters a, b and c of Charnock-plus. The results have been listed in Table IV. The accompanying analyses of variance for the Charnock and Maat model have been presented in Table V. It appears that the performance of the Maat model deteriorates (only if more than twenty runs are excluded does improvement occur), whereas the Charnock model is acceptable at the 1% significance level if the twenty highest wind speed runs are excluded.

The values for the Charnock parameter in Table IV are within the range of those previously proposed, whereas the value calculated with the exclusion of 20 high wind speed runs ($\alpha = 0.026 \pm 0.003$) is close to an often cited literature value for coastal sites ($\alpha = 0.0185$, Wu, 1980).

The same exercise carried out with Charnock-plus clearly demonstrates (Table V) the eccentricity of the three extreme HEXMAX runs; if these are excluded Charnock-plus gives a full account of the data. The MNS value of 0.98 indicates a perfect performance.

It may be concluded that the Maat model represents the three extreme data points rather well, but its reproduction of the remaining 55 points is not better

Table IV
Model parameters

n_{ex}	α	μ	a	b	c
0	0.036	0.53	-0.053	-0.00046	0.020
3	0.033	0.51	-0.047	-0.00044	0.019
10	0.031	0.52	-0.047	-0.00042	0.019
20	0.026	0.53	-0.038	-0.00024	0.014

Table V
Analysis of variance for various models

n_{ex}	Model	d.o.f.	SNS	MNS	significant?
0	Maat	57	91.1	1.60	yes, at 0.5% level
	Charnock	57	122.4	2.15	yes, at 0.5% level
	Charnock-plus	54	73.0	1.35	yes, at 5.0% level
3	Maat	54	85.5	1.58	yes, at 0.5% level
	Charnock	54	89.5	1.66	yes, at 0.5% level
	Charnock-plus	51	50.2	0.98	not significant
10	Maat	47	81.0	1.76	yes, at 0.5% level
	Charnock	47	83.6	1.78	yes, at 0.5% level
	Charnock-plus	44	47.2	1.07	not significant
20	Maat	37	63.9	1.73	yes, at 0.5% level
	Charnock	37	56.7	1.53	yes, at 2.5% level
	Charnock-plus	34	43.9	1.29	not significant

than Charnock. This fact by itself provides insufficient reason to prefer Maat to Charnock, but it should motivate us to have a closer look at the extreme wind speed episodes. The validity of this recommendation is supported by the Charnock-plus results previously reported.

Finally, let us discuss the question that we have set out to answer in this paper – does the HEXMAX data set provide any evidence that wind stress depends on sea-state? If one inspects Table III, one is inclined to give a positive answer: there are significant and less significant correlations between the residual stress (i.e., observed stress minus the Charnock, or atmospheric, component) and the wave parameters U_{orb}^2 and c_p^2 respectively. Moreover, the Charnock-plus model has clearly shown that it pays off to include the U_{orb}^2-related stress contribution.

However, two reservations have to be made. The first is that the correlations of Table III, though just significant, are not very impressive and differ considerably. The latter feature is a clear indication that information might be lost if one were to describe the HEXMAX sea states with one parameter instead of two. Indeed, if one adopts the sea-state definition of JONSWAP and imposes a similarity condition, then the remaining wave-development parameter correlates worse with the residual stress than does $U_{\rm orb}^2$.

This is illustrated in Figure 3, where we have plotted the natural logarithms of the normalized quantities $U_{\rm orb}/U_{10}$ and c_p/U_{10} versus each other. It is shown that the HEXMAX sea-states are to a certain extent similar: $U_{\rm orb}/U_{10} \sim (c_p/U_{10})^{0.29\pm0.06}$. Hence, the wave-development parameter $\xi = (c_p/U_{\rm orb})^{1.4}$ should be proportional to the usual wave-age parameter c_p/U_{10}. The correlation coefficient between ξ and the residual Charnock stress appears to be -0.38.

The correlations with wave parameters further deteriorate if one improves the U_{10}-dependence of the Charnock stress model function by exploiting the correlation of Table III. The residual stress then becomes $\delta\tau = \tau - \tau_{\rm Char} - a - bU_{10}^2$, and we find the following correlation coefficients: $\rho(\delta\tau, c_p^2) = 0.002$, $\rho(\delta\tau, U_{\rm orb}^2) = 0.23$ and $\rho(\delta\tau, \xi) = -0.18$. Hence, only the correlation with $U_{\rm orb}^2$ remains marginally significant (i.e. at the 5% level), the others become insignificant. This exercise clearly demonstrates that if one exploits the full predictive power of U_{10}, there is only marginal information on wind stress left in wave parameters. Wind-driven seas appear to be very much enslaved to the wind and the evidence for an oceanic influence on wind stress is very thin indeed.

The second reservation concerns the interpretation of the results of Table III. As we already have speculated it cannot be excluded that the correlation between waves and residual stress is an indirect effect of the shallow-water HEXMAX site. Indeed, the interpretation that the enhanced growth of HEXMAX stresses at high winds is due to shoaling waves is quite plausible, but if it would apply then the HEXMAX sea-state effect would be nothing but a shallow-water effect, and a parametrization in terms of H_s/D, in which D is water depth, would be more appropriate (G. J. Komen, personal communication).

We conclude that the HEXMAX data cannot provide a definitive answer to the question we have set out. The basis is too thin, although there is indeed the beginning of a small wave signal in a noisy background.

Furthermore, our analysis provides no clues to the physical mechanism underlying the enhanced (relative to Charnock) HEXMAX stresses at high winds. It could be the breaking of waves that produces additional stress, but it could also be the bottom that makes the long waves shoal. It cannot even be excluded that the enhancement is spurious, i.e., that the stress measurements at high wind speeds suffered from systematic errors (Oost, 1995).

In fact, as far as the author is concerned, there are no undisputed ‘wave signal claims’ as long as they have not been substantiated by a thorough quantitative statistical analysis. It is recommended that other data sets that purport to show wave effects are subjected to analyses similar to the one that has been pursued in this paper.

The effect of sea-state on wind stress may be estimated to be at most of the order of 10%. Given that conventional measurement errors in wind stress are much higher, it is obvious that detection or rejection of wave signals would be less controversial if experimental noise could be significantly reduced. This is not a new conclusion (Donelan, 1990), but it doesn't harm to repeat it here.

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Appendix A

In the following table the relevant HEXMAX observations have been summarized.

Run number	U_{10} (m s^{-1}) PA	U_{10} (m s^{-1}) SON	τ (m^{2}s^{-2}) PA	τ (m^{2}s^{-2}) SON	c_p (m s^{-1})	H_s (m)
1201	14.48	13.79	0.36	0.31	9.9	2.23
1202	15.20	14.49	0.38	0.35	9.9	2.23
1301	15.75	15.37	0.47	0.41	9.9	2.35
1302	16.63	16.24	0.52	0.47	9.9	2.35
1501	13.57	13.11	0.35	0.26	10.5	2.61
1502	13.69	13.30	0.37	0.31	10.5	2.61
2001	19.82	19.76	1.14	1.25	10.9	4.01
2002	19.59	19.53	1.01	1.08	10.9	4.01
2101	19.89	20.21	1.29	1.43	10.7	4.14
2102	19.75	20.04	1.17	1.31	10.7	4.14
2201	17.05	17.34	0.65	0.76	10.9	4.15
2401	16.42	16.69	0.70	0.74	11.3	4.04
2402	18.55	18.73	0.78	0.90	11.3	4.04
2501	18.13	18.13	0.85	0.88	11.1	4.18
2502	18.34	18.33	0.87	0.85	11.1	4.18
2601	18.25	18.35	0.80	0.77	11.1	3.97
2602	19.04	19.02	0.94	0.96	11.1	3.97
2701	19.44	18.68	0.87	0.91	11.3	3.93
2702	19.08	18.35	0.79	0.76	11.3	3.93
3601	12.86	12.36	0.30	0.33	9.0	1.95
3602	12.80	12.32	0.26	0.30	9.0	1.95
3701	12.50	12.06	0.24	0.29	9.4	2.26
3702	13.50	13.02	0.29	0.33	9.4	2.26
3703	14.31	13.77	0.37	0.42	9.4	2.26
3901	17.74	17.70	0.58	0.60	10.6	3.09
3902	17.66	17.57	0.70	0.70	10.6	3.09

Run number	U_{10} (m s^{-1}) PA	U_{10} (m s^{-1}) SON	τ (m^{2}s^{-2}) PA	τ (m^{2}s^{-2}) SON	c_p (m s^{-1})	H_s (m)
4001	18.11	18.15	0.72	0.78	10.9	3.77
4002	16.98	17.12	0.57	0.69	10.9	3.77
4101	18.46	17.90	0.64	0.71	11.1	3.78
4201	17.49	17.09	0.78	0.80	10.9	4.03
4202	17.12	16.88	0.64	0.75	10.9	4.03
6101	12.20	11.98	0.27	0.27	10.6	2.99
6102	11.18	11.02	0.21	0.22	10.6	2.99
7421	9.14	9.11	0.13	0.14	9.7	1.95
7511	9.94	9.57	0.16	0.13	9.4	1.77
7512	10.30	9.97	0.16	0.14	9.4	1.77
7531	10.52	10.25	0.17	0.12	9.4	1.74
7532	10.09	9.82	0.16	0.11	9.4	1.74
7533	9.38	9.12	0.14	0.12	9.4	1.74
7541	9.46	9.26	0.15	0.11	9.2	1.80
7542	9.52	9.37	0.12	0.10	9.2	1.80
11111	12.60	12.03	0.30	0.27	10.7	2.76
11112	12.15	11.68	0.29	0.28	10.7	2.76
11121	12.12	11.66	0.23	0.20	10.7	2.78
11122	12.46	12.02	0.32	0.31	10.7	2.78
13411	11.82	11.65	0.22	0.20	10.0	2.07
13412	11.93	11.73	0.22	0.19	10.0	2.07
14511	12.08	11.58	0.22	0.26	9.4	2.01
14512	11.82	11.19	0.25	0.22	9.4	2.01
14521	11.33	10.79	0.19	0.19	9.0	2.05
14601		10.08		0.18	9.3	1.93
14602		9.29		0.14	9.3	1.93
14611		8.64		0.12	9.2	1.79
14612		8.59		0.12	9.2	1.79
14621		8.10		0.09	9.4	1.73
14622		7.76		0.07	9.4	1.73
14631		7.49		0.06	9.3	1.66
14632		7.16		0.06	9.3	1.66

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