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SHORE PROTECTION MANUAL'S WAVE PREDICTION REVIEWED

by

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MANAGEMENT PERSPECTIVE

This paper reviews past accepted methods and more recently developed methods which use wind data to predict statistically representative wave heights and periods. In particular, the latest (1984) and earlier methods promulgated by the Shore Protection Manual (SPM) of the U.S. Army Corps of Engineers are examined.

The paper shows that the latest method proposed in the SPM is subject to greater error than earlier methods in the same publication. Apparently, no rigorous verificaiton of the newer method was undertaken prior to publication.

Technical staff should be careful with respect to models adopted for wave prediction.

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PERSPECTIVE DE GESTION

Cet article passe en revue les méthodes reconnues et les méthodes plus récentes qui font appel aux données sur le vent pour prédire les hauteurs et les périodes de vagues statistiquement représentatives. Les méthodes récentes (1984) et anciennes recommandées dans le manuel de protection des rivages du U.S. Army Corps of Engineers font l'objet d'un examen plus serré.

Il ressort que la méthode la plus récente proposée dans le manuel donne lieu à des erreurs plus importantes que les méthodes antérieures recommandées dans la même publication. Apparemment, aucune vérification rigoureuse de la nouvelle méthode n'a été entreprise avant la publication.

Le personnel technique devra faire preuve de plus de prudence en ce qui concerne les modèles adoptés pour la prévision des vagues.

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ABSTRACT

Empirical steady-state wave prediction methods given in the 1984 version of the Shore Protection Manual (SPM) are compared with measured wave data and with three other wave prediction formulas including the one used in 1977 and earlier versions of the SPM. Fetch-limited wave data and overwater wind data from several sources comprise the data set. The other wave prediction formulas are those of Sverdrup-Munk-Bretschneider, JONSWAP and Donelan. Results indicate that the 1984 version of the SPM, which uses an adjusted wind speed factor based on friction velocity, tends to overpredict wave height and period and, statistically, is the poorest predictor of the four methods tested. Use of the adjusted wind speed factor and other wind modifications are discussed.

RÉSUMÉ

Les méthodes empiriques de prévision des vagues en régime permanent données dans la version de 1984 du manuel de protection des rivages sont comparées aux données mesurées sur les vagues ainsi qu'à trois autres formules de prévision des vagues dont celle qui a été utilisée en 1977 et d'autres versions antérieures proposées dans le manuel. Des données de plusieurs sources sur les vagues limitées par le fetch et sur le vent au-dessus des eaux forment l'ensemble de données. Les autres formules de prévision des vagues sont celles de Sverdrup-Munk-Bretschneider, JONSWAP et Donelan. D'après les résultats obtenus, il semble que la version 1984 du manuel, qui fait appel à un facteur de vitesse de vent ajustée basé sur la vitesse de friction, donne en général des prévisions trop élevées de la hauteur et de la période des vagues et est donc, statistiquement, la moins bonne méthode de prévision des quatre méthodes testées. L'utilisation du facteur de vitesse de vent ajustée et d'autres modifications du vent sont analysées.

Shore Protection Manual's Wave Prediction Reviewed

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1.0 INTRODUCTION

Many engineers use empirical formulas with hand-held calculators, nomographs or computer programs to predict wave conditions under an assumed steady-state wind. In North America, the two most commonly used sets of formulas are those of Sverdrup-Munk-Bretschneider (Sverdrup and Munk 1947, Bretschneider 1958, 1970) known as the SMB equations, and those of Hasselmann et al. (1973), known as the JONSWAP equations. A method of applying these formulas is provided in the Shore Protection Manual (SPM) of the U.S. Army Coastal Engineering Research Center. The latest version of the SPM, released in 1984, contains several changes in the choice and use of these empirical wave prediction formulas compared with earlier SPM editions. This paper examines the impact of these changes using wind and wave data from several sources. The formulas of Donelan (1980), which have been favourably compared with JONSWAP and SMB (Bishop 1983), are also used.

2.0 CHANGES TO SPM WAVE PREDICTION

The Shore Protection Manual of the U.S. Army Coastal Engineering Research Center has been and continues to be a widely used guide in coastal engineering. For simplified wave predictions, the first three editions of SPM (1973, 1975, 1977) give nomographs and formulas using the SMB formulation. The wind speed recommended for use in wave predictions was "the mean surface wind speed". There was

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little or no discussion of the wind speed's dependence on elevation, air-sea temperature difference, or land-water locational effects. An effective fetch computation was recommended for restricted fetches, wherein radials were extended in the upwind direction ±45 degrees; this yielded a weighted average fetch with weights based on the cosine of the angle between the radial and the wind direction.

The latest edition of the SPM (1984) replaces the cosine-averaged fetch computation of the SPM (1973, 1975, 1977) with an arithmetically-averaged fetch over the wind direction ±15 degrees. The SPM (1984) gives nomographs and formulas for wave prediction using the JONSWAP results. No justification is given for replacing SMB with JONSWAP formulas. In addition, there is much more information given with respect to wind input. The variation of wind speed with elevation is discussed and an equation is given to adjust wind speed measured at elevation z to a 10 m height appropriate for use in the wave prediction equations. The elevation adjustment equation given in the SPM (1984) is

$$U_{10} = U_z \left(\frac{10}{z}\right)^{1/7} , \quad z < 20 \text{ m} \tag{1}$$

A correction factor, R_L, to compensate for overland (U_L) to overwater (U_W) wind speed differences is given in the SPM (1984) and is shown here as Figure 1, where

$$U_W = R_L \, U_L \tag{2}$$

The correction factor, R_T, for stability effects of air-water temperature differences recommended in the SPM (1984) is given in Figure 2, where

$$U_\beta = R_T \, U_W \tag{3}$$

and U_β is the stability-compensated overwater wind speed.

In an attempt to correct for the observed nonlinear relationship between wind stress (shear velocity) and wind speed, the SPM (1984) introduces the most significant change versus earlier SPM editions via an adjusted wind speed factor, U_A, where

$$U_A = 0.71\ U_\beta^{1.23} \quad , \quad U \text{ in m/s} \tag{4}$$

This parameter is substituted in the place of U_β in the JONSWAP equations. Surprisingly, no comparative justification for doing so using measured wave data is referenced.

Our purpose here is to examine the validity of these various correction factors and to test their effects on wave prediction against an extensive data set drawn from various sources. The idea of using an effective wind speed such as U_A, appears to stem from two assumptions: a) fetch-limited wave development scales with friction velocity u_* rather than wind speed U_β; 2) the relationship between u_* and U_β obtained from open ocean data (e.g., Large and Pond 1981) applies directly to fetch-limited conditions. These assumptions, if correct, provide some justification for incorporating an adjusted wind speed factor into the JONSWAP relations. On the other hand, if they are incorrect, SPM users will suffer substantial overprediction of wave heights (proportional to wind speed in the JONSWAP formulation) and lesser overprediction of peak periods (proportional to the cube root of wind speed in the JONSWAP formulation). The overprediction begins at very low wind speeds at which U_A exceeds U_β; i.e., $U_A = U_\beta = 4.43$ m/s.

3.0 WAVE PREDICTION FORMULAS

The SMB formulas given by Bretschneider (1970) and the Shore Protection Manual (1973-1977 editions) are for the statistically-based

significant wave height, H_s, and period, T_s. More recent wave formulas usually deal with the energy-based wave parameters of characteristic wave height, H_{m_0} and period, T_p, at the peak of the wave energy density spectrum. In deep water it is commonly found that $H_{m_0} = H_s$ (Goda 1974, Longuet-Higgins 1952).

The significant wave period T_s is sometimes multiplied by a constant to estimate T_p. Bretshneider (1970) suggested using a value of 1.06, Goda (1985) suggested 1.05, and in practice, a value of unity is often used. For this study, a value of unity is assumed and tests are run to justify its use.

The formulas from the 1984 Shore Protection Manual, referred to here as the SHORE formulas, are the same as the JONSWAP formulas (Hasselmann et al. 1973) except that U_β is replaced by U_A. Proposed changes to the SHORE formulas by Hurdle and Stive (1989) have virtually no impact on the fetch-limited calculations compared in this paper.

For enclosed water bodies with definable fetch distributions, the formulas developed by Donelan (1980) (see also Bishop 1983) can predict the direction of the dominant wave energy, as well as H_{m_0} and T_p.

4.0 DATA

Data sets from various sources, including the data set that was used by Hasselmann et al. (1973) to determine the original JONSWAP relations, were used to examine the SHORE formulas. The data sets are summarized in Table 1.

Where fetches are not tabulated in the original references, they were calculated as arithmetic averages of radials extended in the wind direction ±15 degrees at 1 degree intervals, and in the wave direction ±15 degrees for the Donelan method. Historically, the SMB formulas have been used with "effective fetches" but this procedure was not endorsed by all users.

Data sets A,K,L,M and O have been selected manually by the authors of the original papers to represent steady-state fetch-limited conditions, whereas data sets T,P and N have been screened by computer programs to select such situations. The methods for screening data sets T,P (Bishop 1983) and data set N (Kahma 1986) are similar except that in data set N there is an additional requirement that the trend of the wind speed must be less than 16 percent per hour. This removes some of the scatter in data set N, but also considerably reduces the number of accepted situations compared with data sets T and P.

5.0 RESULTS

Wave prediction formulas have usually been determined from empirical data using dimensional analysis. The similarity law for the growth of the wave spectrum, also known as the Kitaigorodskii scaling law (Kitaigorodskii 1962), has been found to be valid in a number of individual experiments. It has the advantage of reducing two variables, the fetch X and the wind speed U (or u_* as recommended in Kitaigorodskii's paper), into one variable of dimensionless fetch gX/U^2, so that the dimensionless wave height can be expressed as

$$(gH_{m_0})^2/16U^4 = F_1(gX/U^2) \qquad (5)$$

and the dimensionless frequency can be expressed as

$$2\pi U/gT_p = F_2(gX/U^2) \qquad (6)$$

Figures 3 and 4 are in dimensionless form and show the JONSWAP, SMB and Donelan relations with the composite data of Table 1. For the Donelan formulas, the wind fetch and U, rather than the wave fetch and $U\cos\theta$, where θ is the angle between the wind direciton and the mean wave direction, have been used as a first approximation due to missing data. Even so, all three relations represent the average behaviour of the composite data set fairly well. The following general observations can be made:

- there is considerable scatter in the data;
- for $10^2 < gX/U^2 < 2 \times 10^4$ the Donelan relations predict smaller values of dimensionless wave height and period than do the SMB relations;
- for $10^2 < gX/U^2 < 10^3$ the JONSWAP relations predict smaller values of dimensionless wave height than do the SMB or Donelan relations;
- no one set of predicton relations appears to be consistently superior to the others.

Coverage of the wind-fetch plane by the composite data set is shown in Figure 5. It is typical of average wave conditions, but does not cover extremes.

The four wave prediction formulas were first tested against the composite data set. The stability correction factor R_T was not used at this stage. The results can be seen in Figures 6, 7 and 8. The SHORE formula (Figure 6) clearly overpredicts H_{m_0} relative to measured data; at measured values of H_{m_0} = 3 m, the SHORE predictions range from 3 m to 6 m.

The air-water temperature difference was about 2°C when the highest waves in Figure 6 were measured and therefore the stability correction factor R_T (Figure 2) would reduce the predictions of the SHORE formula by only approximately 20 cm for these highest waves. This is only a small fraction of the actual overprediction.

The predictions of both the JONSWAP and the SMB formulas (Figures 7 and 8) are scattered relative to the measured data, but they are not significantly biased. The Donelan formulas give predictions that are biased low; this is believed to be due to estimating the fetch in the wind direction rather than the wave direction, and to using U rather than $U\cos\theta$.

The composite data set is not useful for the analysis of stability correction factors because there are statistically significant and still unexplained differences between data sets. These differences suggest that there are additional variables controlling the

wave growth. However, as far as we know, no single variable has been convincingly shown to be responsible for these differences. In particular, the stability difference has turned out not to be the main factor. Although large differences between data sets in some cases correlate with stability, equally large differences are not visible within individual data sets having equally large stability differences (Kahma 1986).

Stability correction factors should be tested using homogenous data sets. Data sets T and P were used for this purpose. Air-water temperature differences range from -10.8°C to +3.7°C for data set T, and from -9.5°C to +4.9°C for data set P. Two stability correction methods have been evaluated: one using the Resio and Vincent (1977) results from Figure 2, the other using the procedure given in Large and Pond (1981). The latter method also provides a logarithmic correction for the height of measurement. The Large and Pond method yields a narrower range of values of equivalent R_T than does Figure 2, with values from 0.96 to 1.03. Also, the Donelan formulas were tested using fetches in the wave direction in order to assess the importance of using these rather than wind direction fetches. Since the wave height range in data sets T and P is relatively small, standard error and bias statistics are meaningful. These error statistics are summarized in Table 2.

Use of the Resio and Vincent (1977) stability correction factor leads to generally larger standard error and bias statistics for all the formulas (Table 2). Use of the Large and Pond (1981) stability correction has very little effect on the results. From this analysis of data sets T and P, it can be concluded that under these types of conditions, wave predictions would not suffer by omitting stability corrections. However, unsteadiness in the wind field and the fact that only one wind station was used to represent the wind field and air-water temperature difference for a particular hindcast may contribute significantly to the scatter in the results. Hence, the contribution of the stability effect to the scatter may be masked by the noise in the wind and temperature data.

Typical graphical results for T and P without stability corrections are shown in Figures 9 and 10 respectively. The performance of the Donelan formulas can be seen to be much better than that in Figures 7 and 8 now that wave fetches and $U\cos\theta$ are used. For overall accuracy in wave predictions, averaging results in data sets T (Toronto) and P (Main Duck Island), the Donelan formulas perform best of the four tested, though with a small bias to underpredict both H_{m_0} and T_p. The SMB formulas are the second most accurate in predicting H_{m_0} and the JONSWAP formulas are the third. The SHORE formulas tend to overpredict relative to the other three and the measured data, and are clearly the poorest predictors of H_{m_0} and T_p. For the SMB predictions, the effects of increasing the computed period by 5 or 10 percent as discussed in Section 3.0 are shown in Table 2. The smallest error statistics are achieved by assuming $T_s = T_p$. The range of dimensionless fetch covered by data sets P and T is 0.8×10^3 to 20×10^3.

Comparisons of wave growth curves for wind fetches of 8 and 80 km are shown in Figure 11; again the Donelan formula is used with wind fetches and U rather than $U\cos\theta$.

If the Donelan formulas are used with fetches in the wind rather than the wave direction, performance deteriorates markedly. Clearly this should not be done because the formulas were developed using fetches in the wave direction. If this is done though, the standard error statistics are then comparable to those of the SHORE formulas, while the magnitudes of the negative bias statistics become comparable to the positive bias statistics of the SHORE formulas. Therefore, if one chooses to use the Donelan formulas for hindcasting or forecasting at a specific site it is important that the wind-wave directional relation be determined as described in Donelan (1980) and in Bishop and Donelan (1988). For design wave calculations in which the wind is assumed to blow from the longest fetch, the Donelan formulas can, of course, still be used without further wind-wave directional calculations.

Let us examine the impact of the "adjusted wind speed" U_A of the SHORE formulas on the dimensionless data set. Equation 4 is not dimensionally consistent, so a dimensional constant U_0 is needed to be able to present the SHORE equations in a dimensionless form. The equation for dimensionless energy can be written as

$$(gH_{m_0})^2/16U^4 = F_3(gX/U^2, U/U_0) \tag{7}$$

which means that the SHORE formula will form a set of curves as a function of dimensionless fetch and U/U_0 rather than a single curve. Figure 12 shows how these curves cover the experimental data which, from Figure 5, have wind speeds from about 5 to 15 m/s. Looking at the curve for U = 10 m/s to represent the approximate mean of the data's wind speeds, Figure 12 indicates that the SHORE formulas tend to overpredict dimensionless wave height for values of gX/U^2 greater than about 5×10^3. Similarly, overprediction of dimensionless wave period begins around $gX/U^2 = 2 \times 10^3$. Based on these results, we expect that the SHORE formulas dramatically overpredict the wave height and period at large values of dimensionless fetch.

Figure 13 shows how the dimensionless energy behaves when maximum and minimum wind speed cases are selected from four of the data sets. The SHORE formula predicts that there should be a noticeable difference between data points representing high and low wind speeds. There is no such systematic difference in the data. In some data sets the dimensionless wave energy is higher when the wind is high, in some data sets lower. We have compared the data sets separately to avoid the differences between data sets adding to the scatter. Still, the scatter is the dominating feature and does not seem to be correlated with,or explained by, the additional variable U/U_0.

We have shown that the use of U_A with the JONSWAP relations leads to substantial overprediction of wave parameters. It is of interest to see if any improvement in the correlation between

dimensionless variables is achieved when U_A rather than U_β is used with the composite data set. A marked improvement would argue for the development of new dimensionless relations based on U_A instead of U_β. Figure 14 shows no reduction in scatter over Figures 3 and 4. Therefore, the cause of the scatter remains unknown, but apparently U_A does nothing to relieve it.

It should be emphasized that all empirical wave-prediction formulas are still rather inaccurate, even in well defined situations (at least when fetches in the wind direction are used), and that for example higher than average wave growth has been observed in well documented experiments (Donelan 1978, Kahma 1981). The ad hoc paramaterizations of the "adjusted wind speed", however, only seem to make the predictions worse.

7.0 DISCUSSION

The accuracy of wave estimation clearly depends on the validity of the methods used to arrive at an "adjusted wind speed" and on the empirical formulas used to relate wave parameters to the wind speed. In this section the particular wind speed adjustment procedures of the Shore Protection Manual (outlined in 2.0) are discussed.

The wind velocity profile including stratification is given by:

$$U(z) = \frac{u_*}{\kappa} \left[\ln \frac{z}{z_0} - \psi\left(\frac{z}{L}\right)\right] \tag{8}$$

where $U(z)$ is the mean wind speed at height z

u_* is the friction velocity

κ is von Karman's constant = 0.4 ±0.02

z_0 is the roughness length or virtual origin of the velocity profile

$\psi(z/L)$ is a stability function that has been determined empirically, e.g., Businger et al. (1971), Large and Pond (1981)

z/L is a non-dimensional stability parameter (Monin and Obukhov 1954)

Equation 1 is an approximation, assuming neutral stratification, to Equation 8 for heights between 3 m and 30 m.

The atmosphere over land tends to be neutrally stable except in light winds (Resio and Vincent 1977). In neutral stratification the $\psi(z/L)$ term vanishes and the profile is completely described by the wind at any height in the constant stress layer (of the order of 30m) and the topography-dependent roughness length. This is not an acceptable procedure over water where large stability effects are common.

The SPM adjustment of overland winds to expected overwater winds, given by Equation 2, follows the method of Resio and Vincent (1977). Any such procedure for estimating overwater winds from overland winds is a site specific idealized trend. Whenever possible, such a procedure should be verified by comparing the predicted overwater wind speed (and direction) with any available recorded overwater winds. The correction R_L given by Resio and Vincent is a specific transformation from a level of 6.1 m on land to a level of 19.5 m over water. Using Equation 1 to adjust both levels to 10 m gives the curve shown in Figure 1. The Resio and Vincent curve adjusted to 10 m differs from that given by the SPM (Figure 1) for speeds greater than 10 m/s. In particular, for overland winds above 12.9 m/s the SPM method yields overwater winds that are less than those over land. This implies larger roughness lengths over water than land and, in our opinion, could lead to significant underestimates of the overwater winds.

Hsu (1981) has provided both theoretical and semi-empirical relationships for the U_W/U_L ratio and verified his formulas against an extensive data set employing overwater winds from NOAA data buoys and nearby land stations. In a more recent work (Hsu 1984) he has added data from Hurricane "Frederic" to extend his overland wind speed range to 35 m/s. This extended data set of simultaneous overland and overwater wind speeds is well represented by:

$$U_W = 3.93\ U_L^{1/2} \qquad U_L < 10 \text{ m/s, U in m/s} \tag{9}$$

$$U_W = 1.24\ U_L \qquad U_L > 10 \text{ m/s} \tag{10}$$

Relationships 9 and 10 are also graphed in Figure 1. Both Hsu's theoretical results and compiled data indicate that overwater winds always exceed overland winds. However, it does not appear that elevation corrections such as Equations 1 or 8 were made.

Overwater wind measurements from six meteorological buoys in Lake Erie in 1979 were compared with simultaneous overland wind measurements from six weather stations around Lake Erie by Schwab and Morton (1984). Values of R_L as a function of wind speed and air-water temperature difference are shown in Figure 15. These values have been adjusted using Equation 1 to give ratios appropriate for measurements made at 10 m. Considering only small air-water temperature differences, by averaging curves c and d, the results of Schwab and Morton (1984) indicate good agreement with Hsu's result of $U_W = 1.24\ U_L$ for $U_L > 10$ m/s. However, the results of Schwab and Morton (1984) also indicate the sensitivity of R_L to air-water temperature differences of as little as ± 5°C, which are commonly encountered.

The SPM recommends a stability correction based on air-water temperature difference alone on the grounds that stable boundary layers

are less effective in causing wave growth than unstable boundary layers. A correction of this sort should be made but, although it will have the form of Resio and Vincent's correction, the abscissa cannot be simply the air-water temperature difference but instead must be a stability index with some physical foundation as in Large and Pond (1981) such as: a) the Monin-Obukhov stability index; b) the gradient Richardson number; c) the flux Richardson number or; d) the bulk Richardson number.

Finally, the SPM recommends adjusting the wind speed to account for the nonlinear relationship between friction velocity and wind speed; i.e., the empirical result (Large and Pond 1981, Smith 1980, Garratt 1977) that the drag coefficient increases with wind speed. Battjes et al. (1987) and Janssen et al. (1987) also suggest that there is empirical justification for using u_* rather than U as the wind scaling parameter. However, the JONSWAP measurements are reported in terms of wind speed and, where friction velocity appears, it is merely $u_* = \sqrt{0.001}\, U_{10}$, i.e., derived from an assumed constant drag coefficient. Furthermore, other recent field measurements (Snyder et al. 1981 and Hsiao and Shemdin 1983) and detailed numerical calculations (Al-Zanaidi and Hui 1984) successfully relate wind input to waves with the wind speed rather than the friction velocity.

It might have been more appropriate for the authors of the SPM revision to have reanalyzed the JONSWAP data by calculating values of u_* and then deriving new empirical relations as functions of u_* rather than U_{10}. However, such calculations of u_* should not be based on a drag coefficient that is dependent on wind speed alone. While this might be correct for open ocean waves near full development, in fetch-limited cases, such as JONSWAP, the drag coefficient is also dependent on wave age $(gT_p/2\pi U_{10})$ or, equivalently, on dimensionless fetch (Kitaigorodskii and Volkov 1965).

The SPM's wind stress adjustment procedure was not verified by any referenced comparison with measured data in the 1984 Shore Protection Manual. The present study indicates that the SPM procedure

tends to overpredict wave parameters at wind speeds of engineering significance (greater than 5 m/s).

7.0 CONCLUSIONS

The 1984 version of the Shore Protection Manual recommends using an adjusted wind speed factor based on friction velocity in the JONSWAP formulas for simple steady-state wave predictions. Comparison with measured wave data from various sources reveals that use of the adjusted wind speed factor leads to overpredictions of wave height and period. Comparison with predictions of the Sverdrup-Munk-Bretschneider (used in 1977 and earlier versions of the SPM), JONSWAP and Donelan formulas reveals that use of the adjusted wind speed factor leads to the poorest statistical results of the four methods relative to the measured data. It is suggested that use of the adjusted wind speed factor be discontinued, and, instead return to using the mean wind speed at a 10 m elevation.

The SPM's relationship for adjusting overland winds to give expected overwater winds is compared to other well-documented relationships. There are some differences which could lead to an underprediction of wave parameters. The present study uses overwater winds so this adjustment was not tested.

Two wind speed corrections for stability effects have been evaluated against measured wave data. Results indicate that for steady-state hindcasts on Lake Ontario, the omission of a stability correction is warranted. The SPM's stability correction is unsupported by physical reasoning and should be replaced by accepted methods as discussed.

The Shore Protection Manual has become a standard reference for many practicing coastal engineers. It is hoped that this paper will lead to the revision of methods proposed for steady state wave prediction in the most recent (1984) edition.

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TABLE 1

Summary of the Data

Data Set	Source	Number of Cases	Description
A	Hasselmann et al. (1973)*	121	JONSWAP, North Sea, orthogonal fetch
K	Kahma (1981)	55	Gulf of Bothnia 1976, orthogonal fetch
L	Kahma (1981)	8	Gulf of Bothnia 1979, orthogonal fetch
M	Liu and Ross (1980)	47	Lake Michigan 1977, laser profilometer
N	Kahma (1986)	24	Gulf of Bothnia 1978 and 1980
O	Donelan (1978)	12	Lake Ontario 1976, orthogonal fetch
P	Bishop (1983)**	75	Main Duck Island, Lake Ontario 1972
T	Bishop (1983)**	82	Toronto, Lake Ontario 1972

* Data Set A Extracted from Muller (1976)

** With minor revisions and corrections as part of this study

TABLE 2

Error Statistics for Prediction of H_{m_0} and T_p

Model	Conditions	NPTS	Data Set T: Toronto H_{m_0} Std. Err. (m)	Data Set T: Toronto H_{m_0} Bias (m)	Data Set T: Toronto T_p Std. Err. (s)	Data Set T: Toronto T_p Bias (s)	NPTS	Data Set P: Main Duck Island H_{m_0} Std. Err. (m)	Data Set P: Main Duck Island H_{m_0} Bias (m)	Data Set P: Main Duck Island T_p Std. Err. (s)	Data Set P: Main Duck Island T_p Bias (s)
Donelan	wavef[1],no stabc[2]	82	0.25	-.04	0.66	-.23	75	0.26	-.08	0.53	-.26
	wavef,stabc[3]	95	0.24	0.05	0.60	-.08	92	0.31	0.05	0.64	-.16
	wavef, corstab[4]	78	0.25	-.05	0.67	-.26	76	0.27	-.11	0.55	-.32
	windf[5],no stabc	80	0.39	-.13	1.03	-.49	73	0.39	-.28	1.01	-.76
	windf, stabc	92	0.34	-.06	0.94	-.37	89	0.36	-.18	1.05	-.73
	windf, corstab	77	0.40	-.15	1.04	-.52	74	0.41	-.29	1.03	-.79
JONSWAP	windf, no stabc	82	0.31	0.03	0.92	0.33	75	0.27	-.02	0.82	0.33
	windf, stabc	95	0.34	0.12	0.95	0.43	92	0.34	0.07	0.90	0.31
	windf. corstab	78	0.33	0.03	0.91	0.32	76	0.27	-.04	0.80	0.29
SHORE	windf, no stabc	80	0.38	0.24	1.00	0.58	73	0.34	0.22	0.94	0.61
	windf, stabc	92	0.51	0.34	1.05	0.68	89	0.56	0.35	1.04	0.62
	windf, corstab	77	0.43	0.26	1.02	0.59	74	0.33	0.20	0.91	0.58
SMB	windf, no stabc	82	0.32	0.15	0.77	0.13	75	0.23	0.07	0.55	-.08
	windf, stabc	95	0.39	0.25	0.78	0.29	92	0.38	0.20	0.68	0.01
	windf, corstab	78	0.33	0.15	0.76	0.12	76	0.23	0.05	0.56	-.12
	windf, no stabc, T = 1.10T[6]	80	0.32	0.15	0.93	0.54	73	0.22	0.06	0.65	0.34
	windf, no stabc, T = 1.05T	80	0.32	0.15	0.83	0.34	73	0.22	0.06	0.56	0.13

1 wavef = wave fetch
2 no stabc = no stability correction used
3 stabc = Resio and Vincent (1977) stability correction used
4 corstab = Large and Pond (1980) stability correction used
5 windf = wind fetch
6 T = 1.1T = wave period predicted by SMB increased by 10 percent

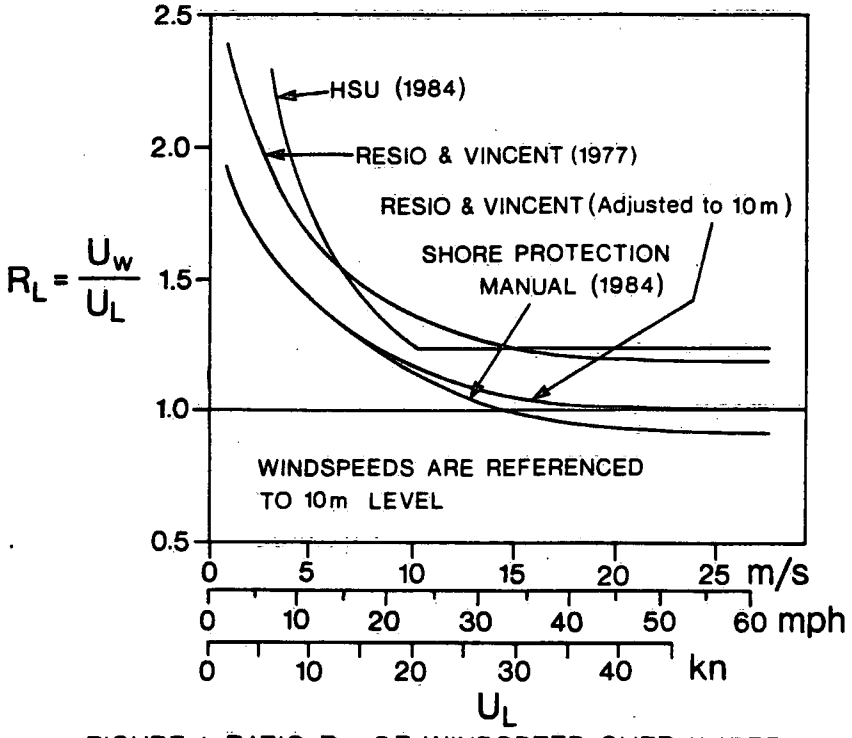


FIGURE 1. RATIO, R_L, OF WINDSPEED OVER WATER, U_w, TO WINDSPEED OVER LAND, U_L, AS A FUNCTION OF WINDSPEED OVER LAND U_L.

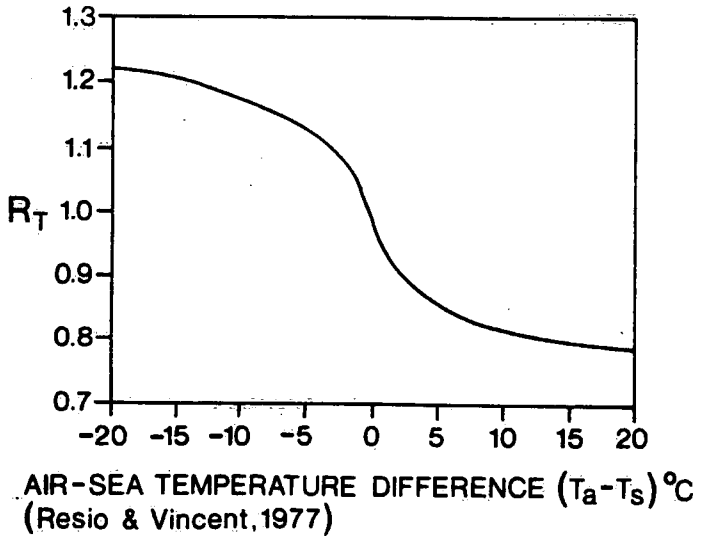


FIGURE 2. AMPLIFICATION RATIO, R_T, ACCOUNTING FOR EFFECTS OF AIR-SEA TEMPERATURE DIFFERENCE.

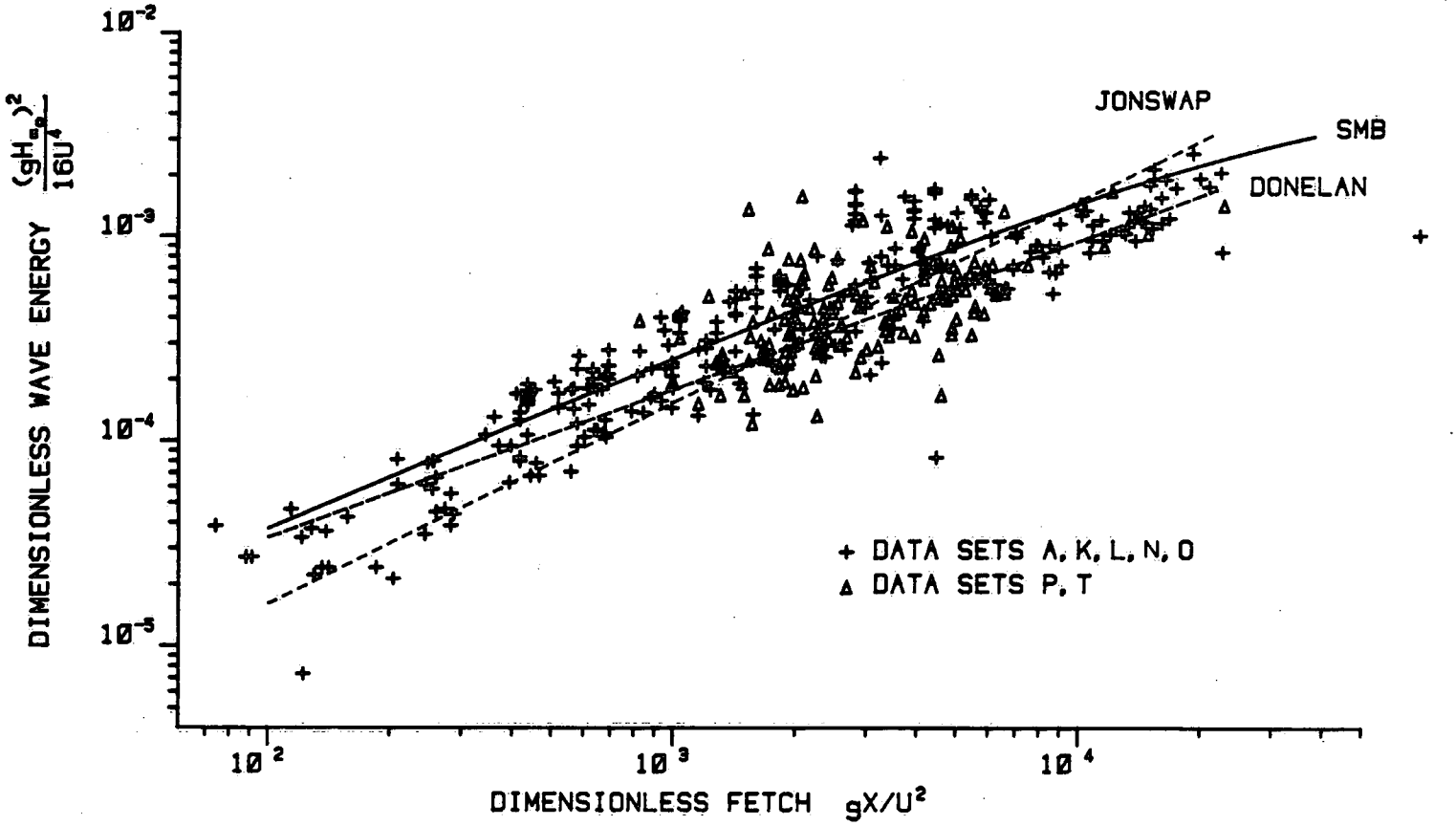


FIGURE 3. DIMENSIONLESS PLOT OF WAVE ENERGY VERSUS FETCH, COMPOSITE DATA SET, AND JONSWAP, SMB AND DONELAN RELATIONS

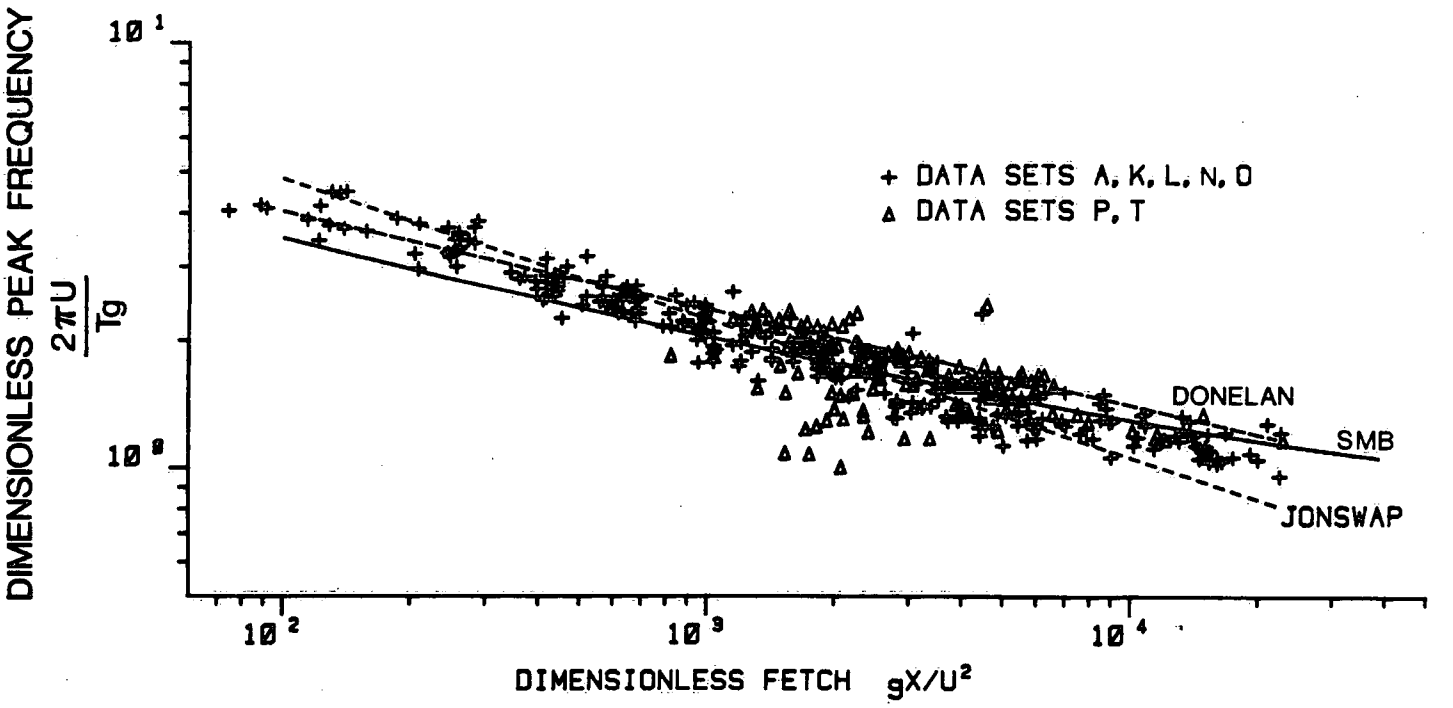


FIGURE 4. DIMENSIONLESS PLOT OF PEAK FREQUENCY VERSUS FETCH, COMPOSITE DATA SET, AND JONSWAP, SMB AND DONELAN RELATIONS

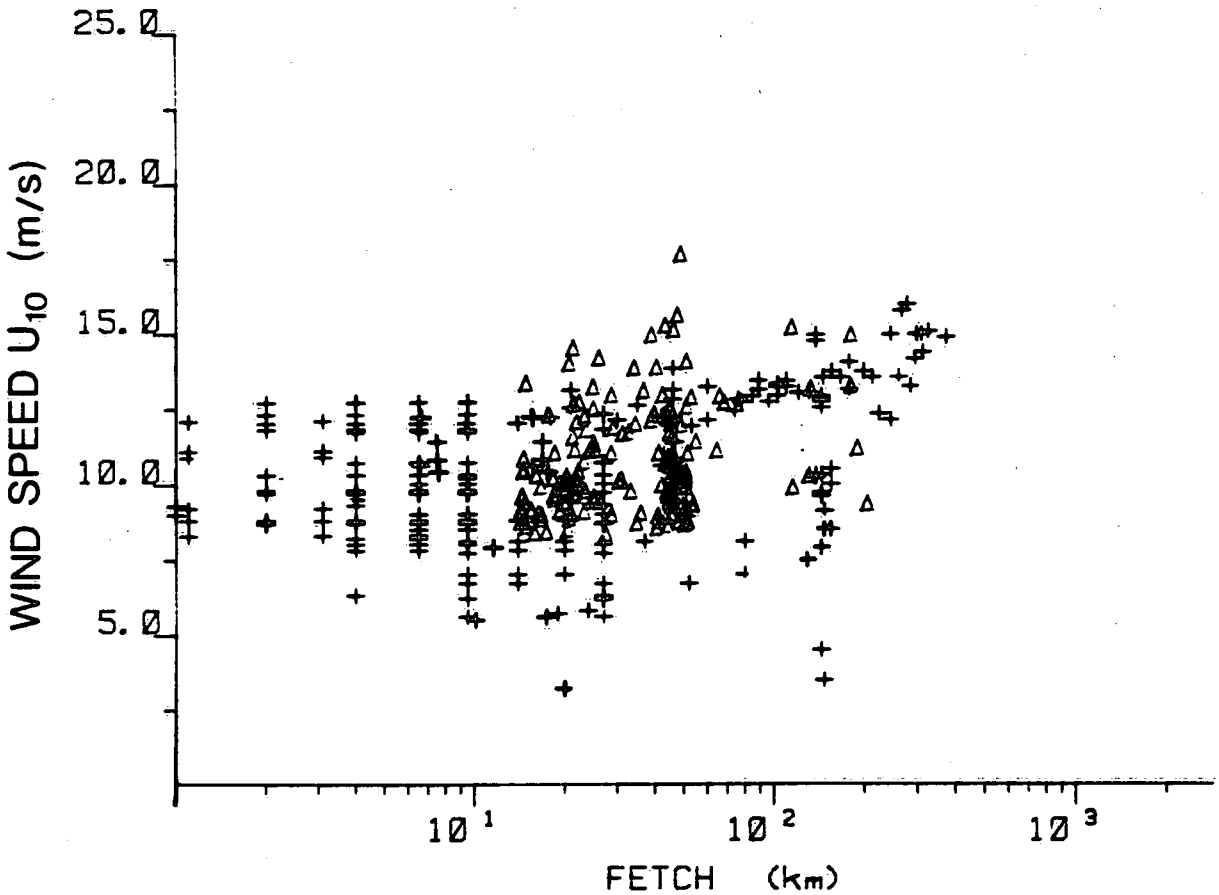


FIGURE 5. THE DISTRIBUTION OF THE DATA IN THE WIND-FETCH PLANE. DATA SETS P, T, Δ; DATA SETS A, K, L, M, N, O, +.

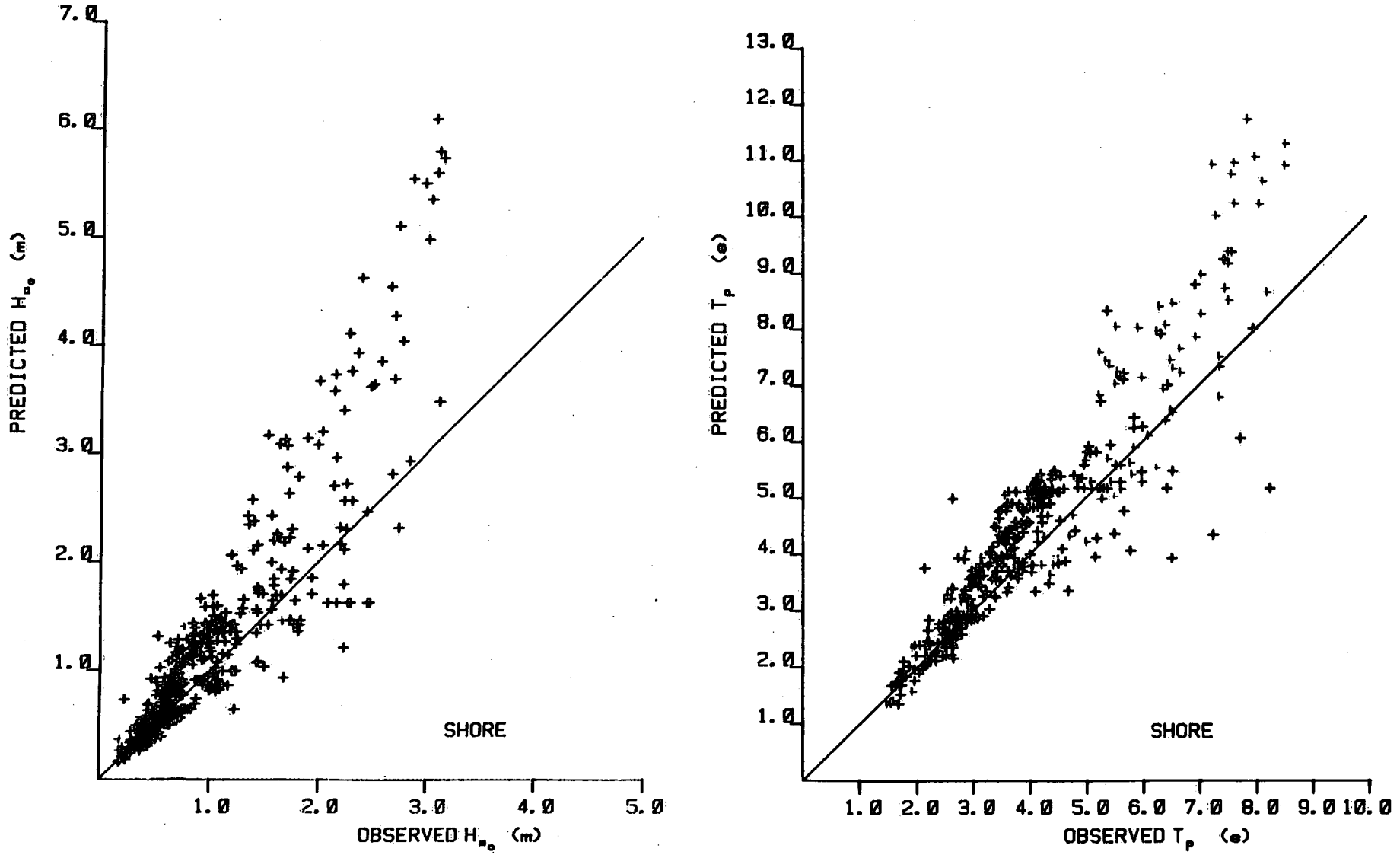


FIGURE 6. COMPARISON OF MEASURED AND PREDICTED PARAMETERS, COMPOSITE DATA SET, SHORE MODEL

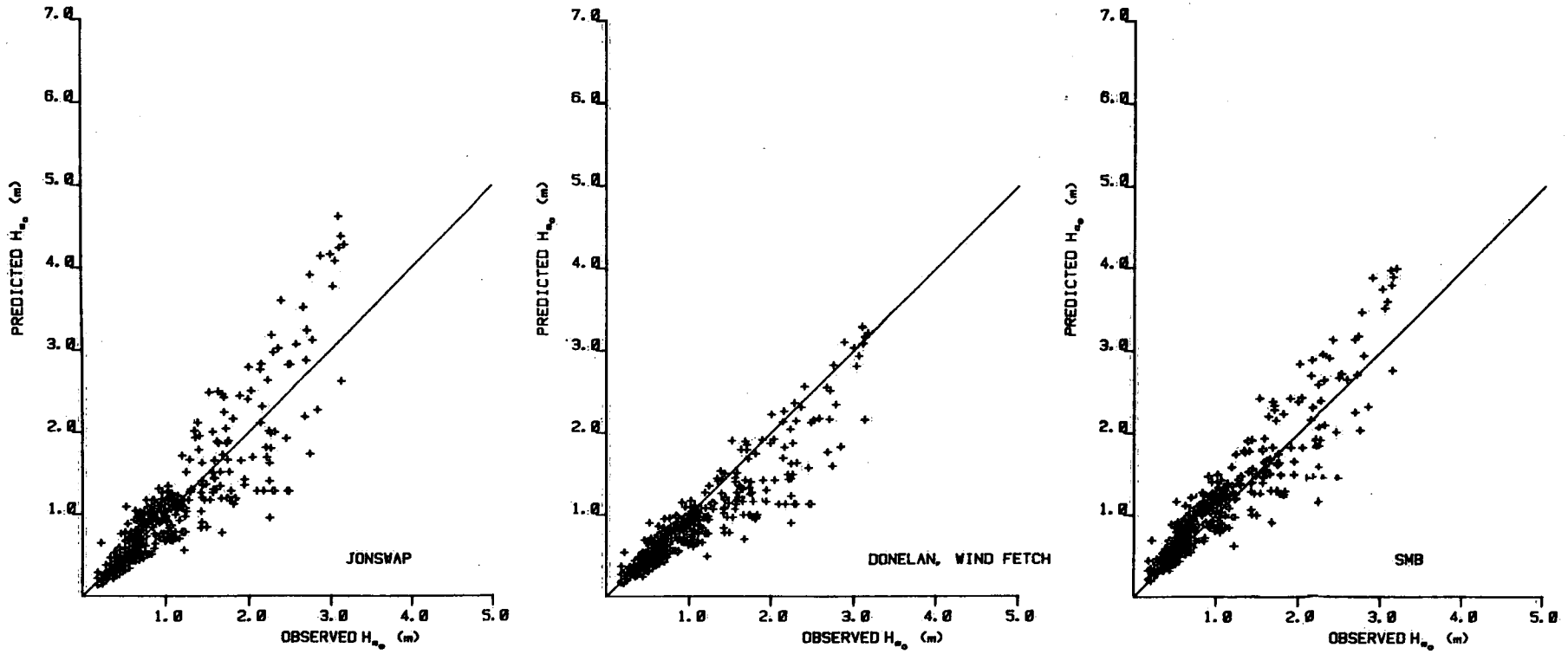


FIGURE 7. COMPARISON OF MEASURED AND PREDICTED H_{m_o}, COMPOSITE DATA SET, JONSWAP, SMB AND DONELAN MODELS

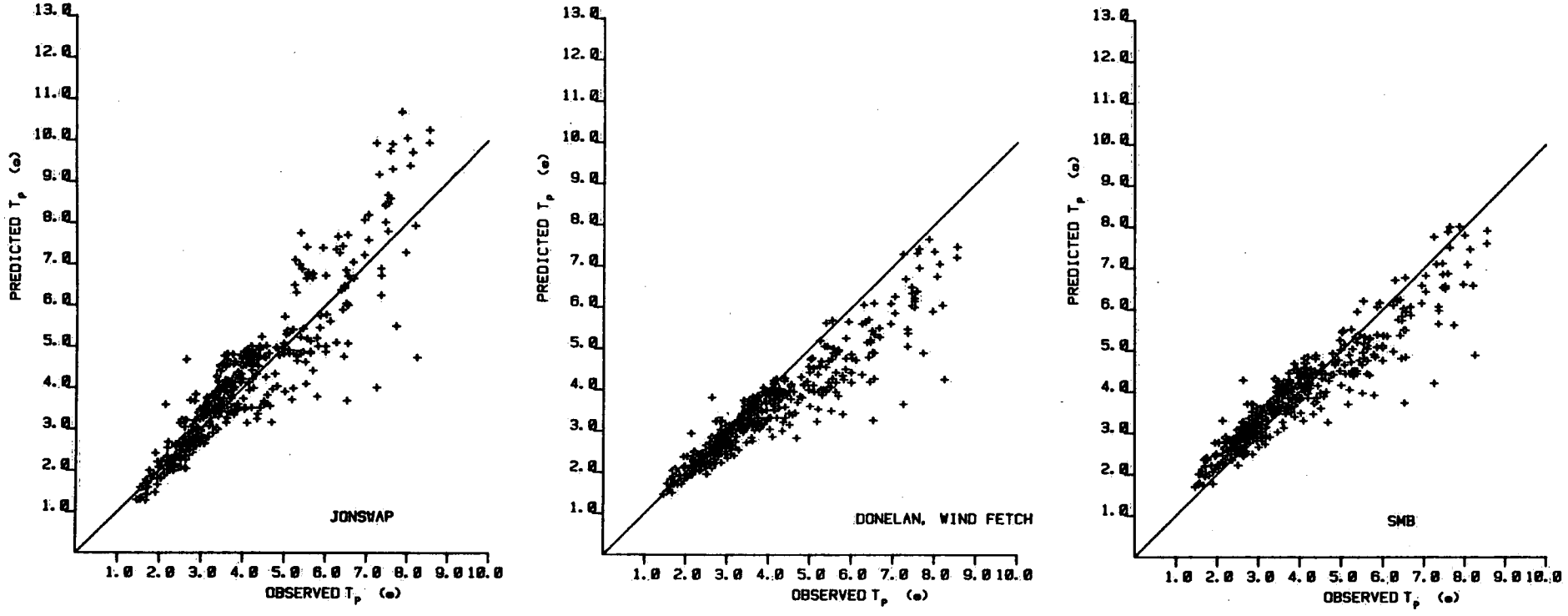


FIGURE 8. COMPARISON OF MEASURED AND PREDICTED T_p, COMPOSITE DATA SET, JONSWAP, SMB AND DONELAN MODELS

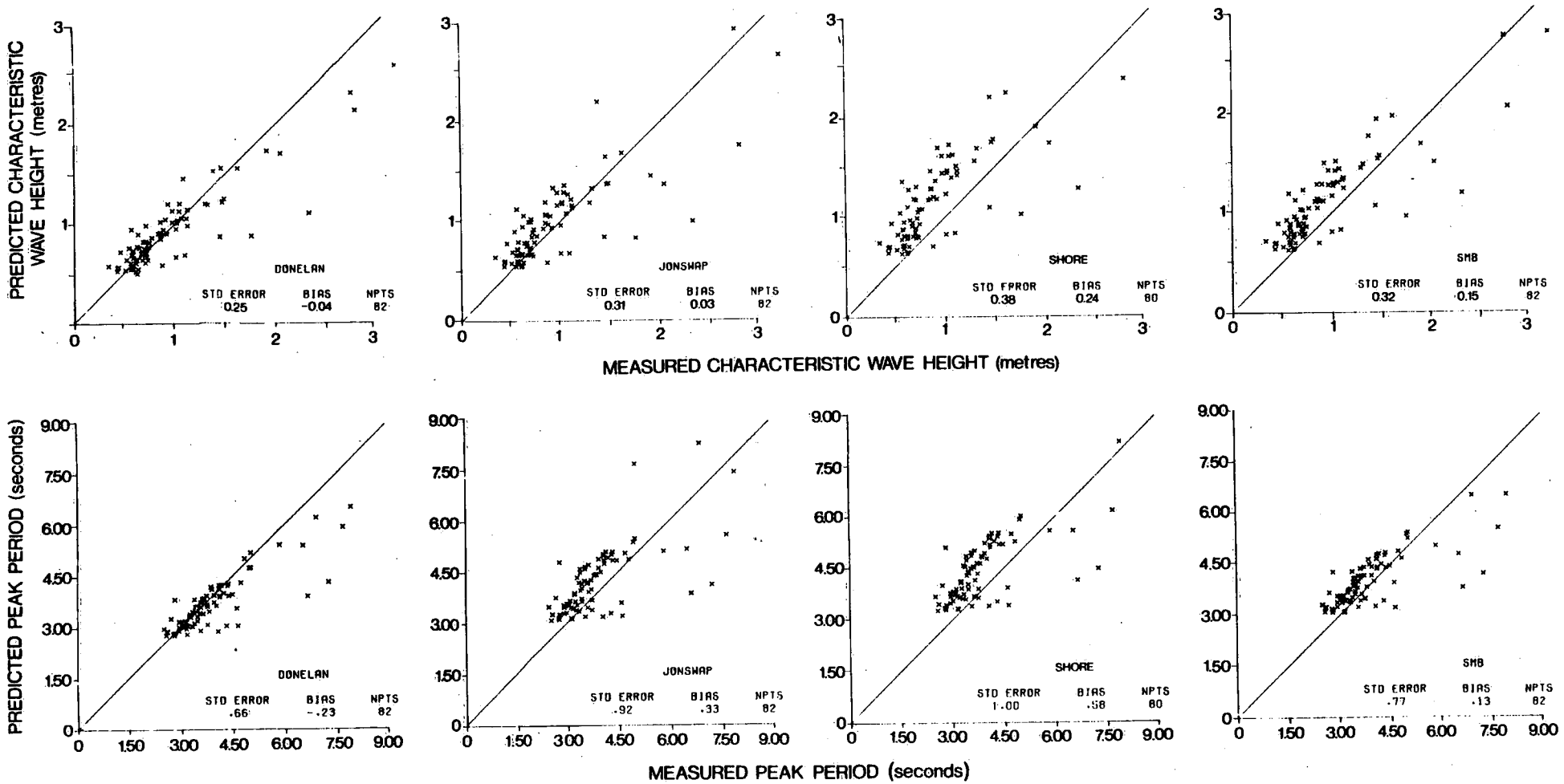


FIGURE 9. COMPARISON OF MEASURED VERSUS PREDICTED WAVE PARAMETERS AT TORONTO

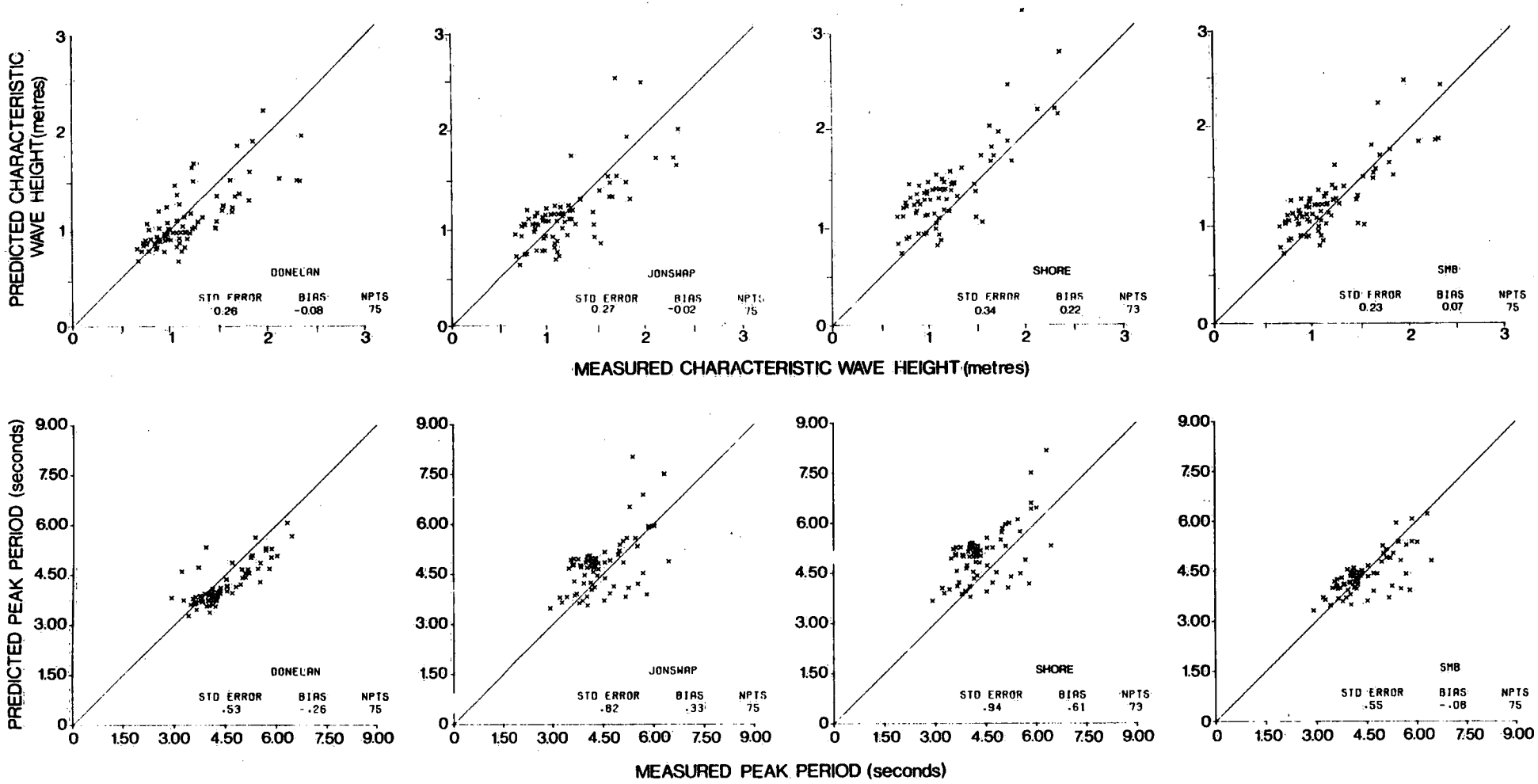
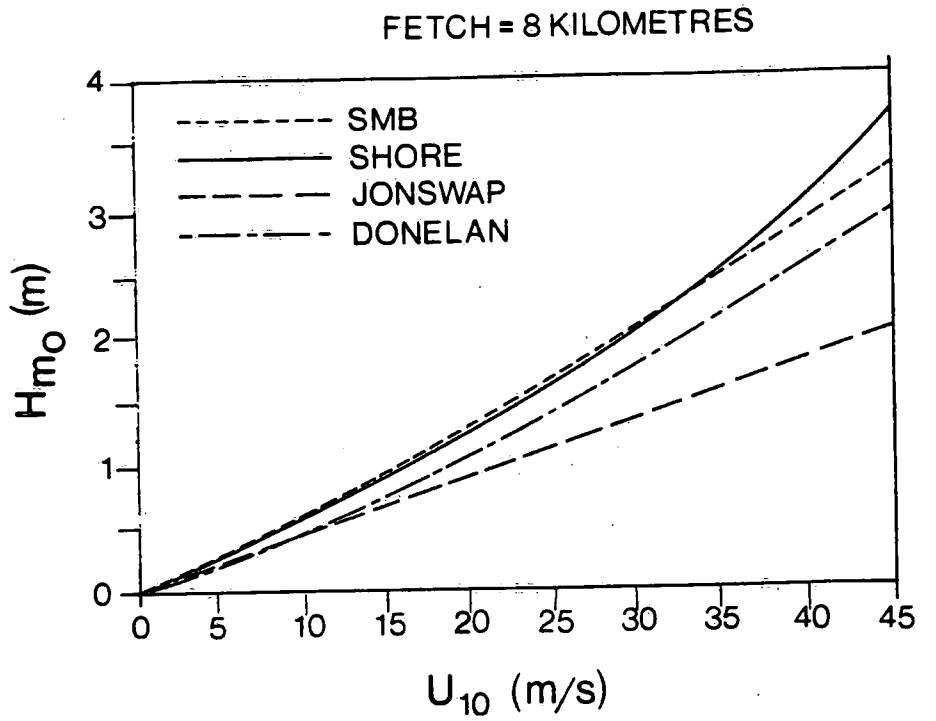


FIGURE 10. COMPARISON OF MEASURED VERSUS PREDICTED WAVE PARAMETERS AT MAIN DUCK ISLAND



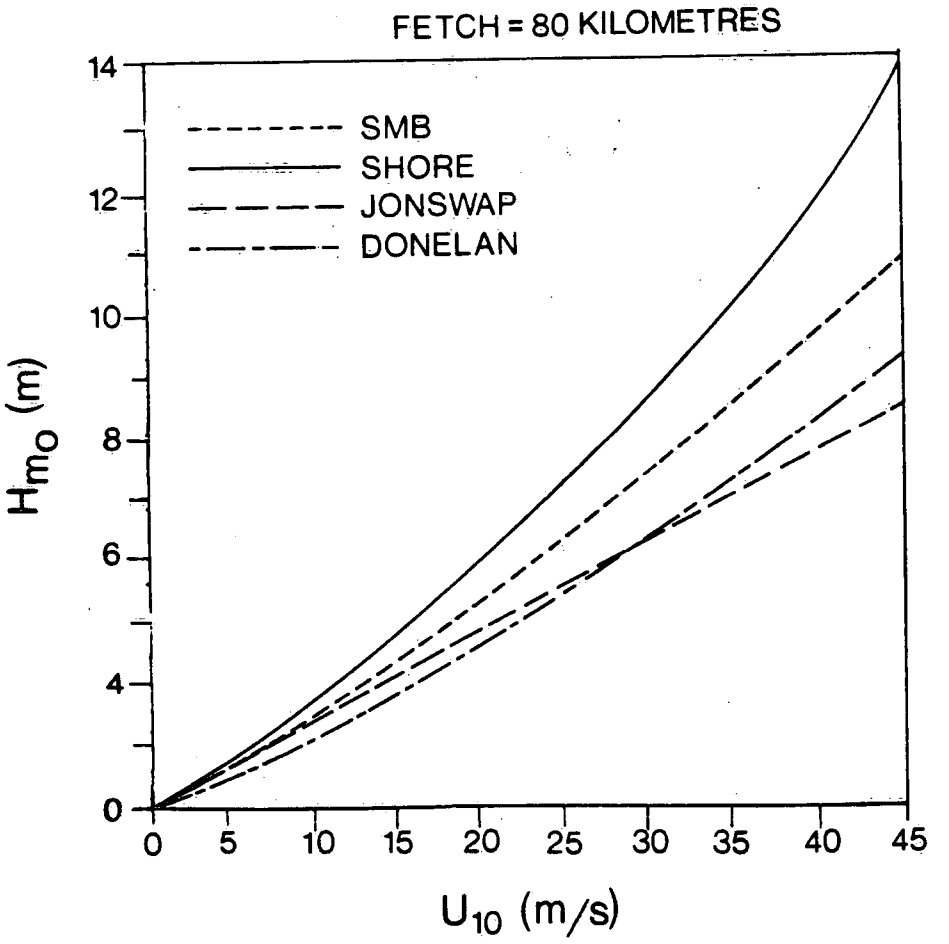


FIGURE 11. COMPARISONS OF WAVE HEIGHT PREDICTIONS FOR WIND FETCHES OF 8 AND 80 KILOMETRES

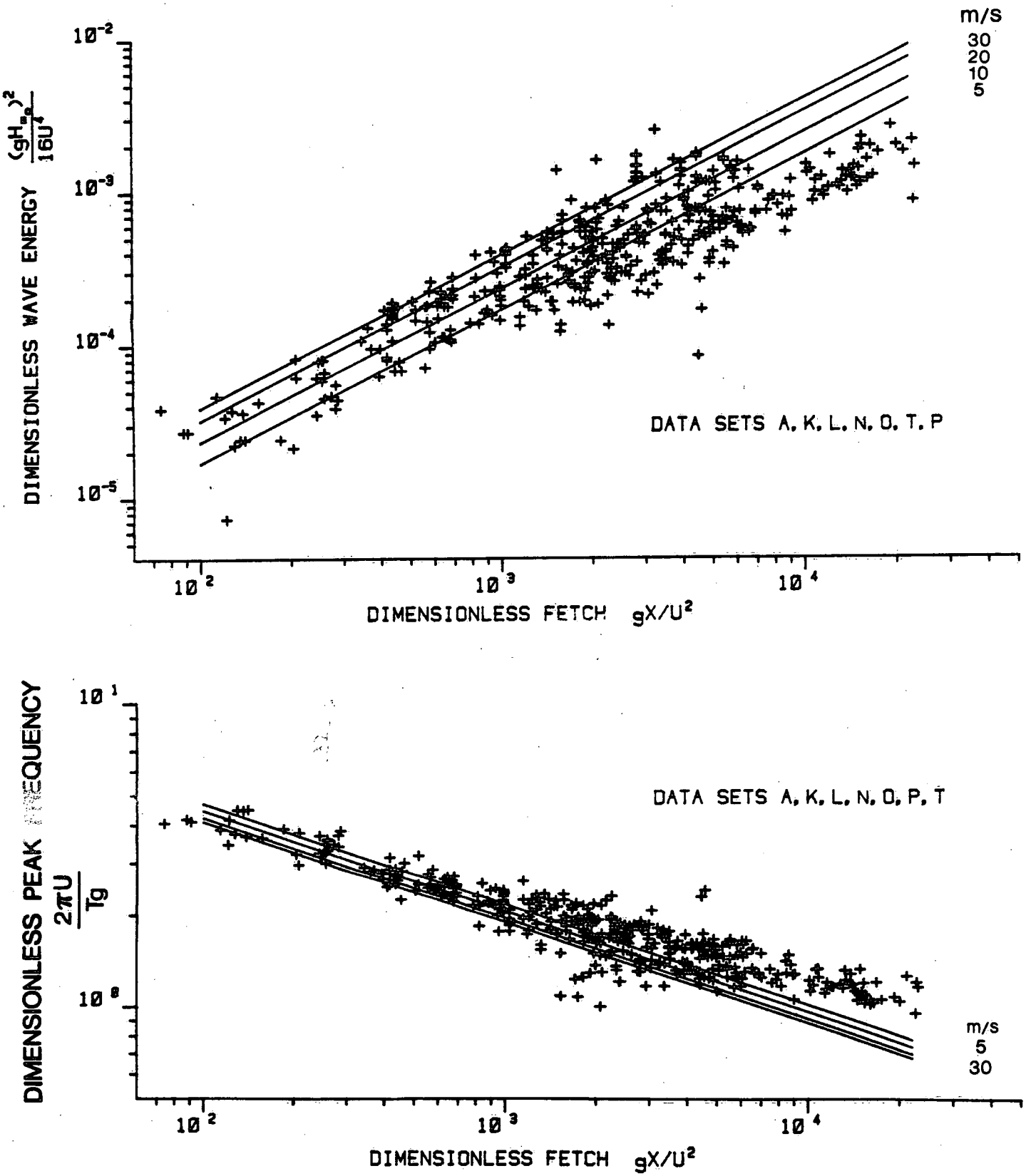


FIGURE 12. THE COMPOSITE DATA SET AND THE SHORE MODEL IN DIMENSIONLESS COORDINATES

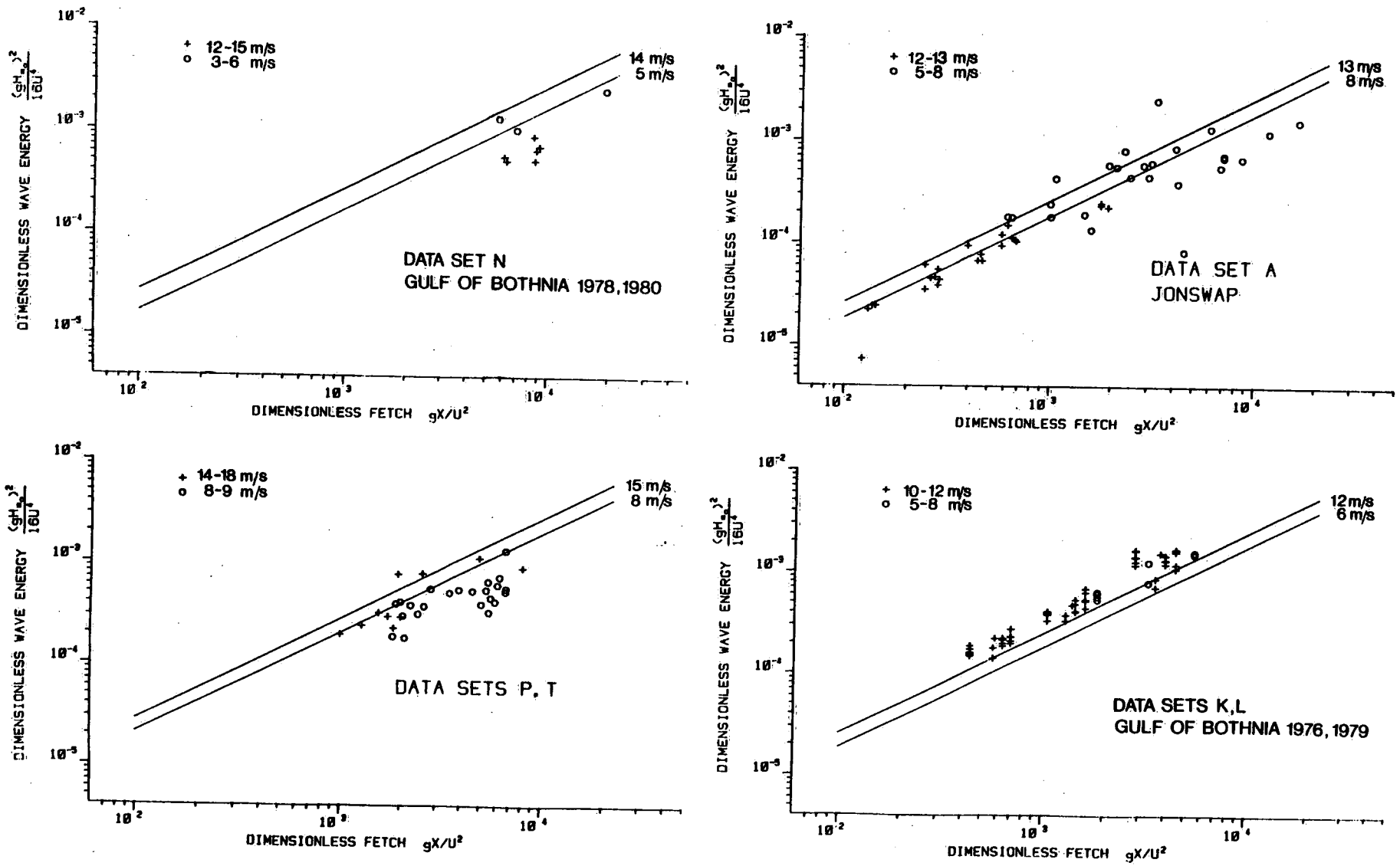


FIGURE 13. MAXIMUM AND MINIMUM WIND CASES SELECTED FROM THE FOUR DATA GROUPINGS. THE LINES DENOTE THE SHORE MODEL

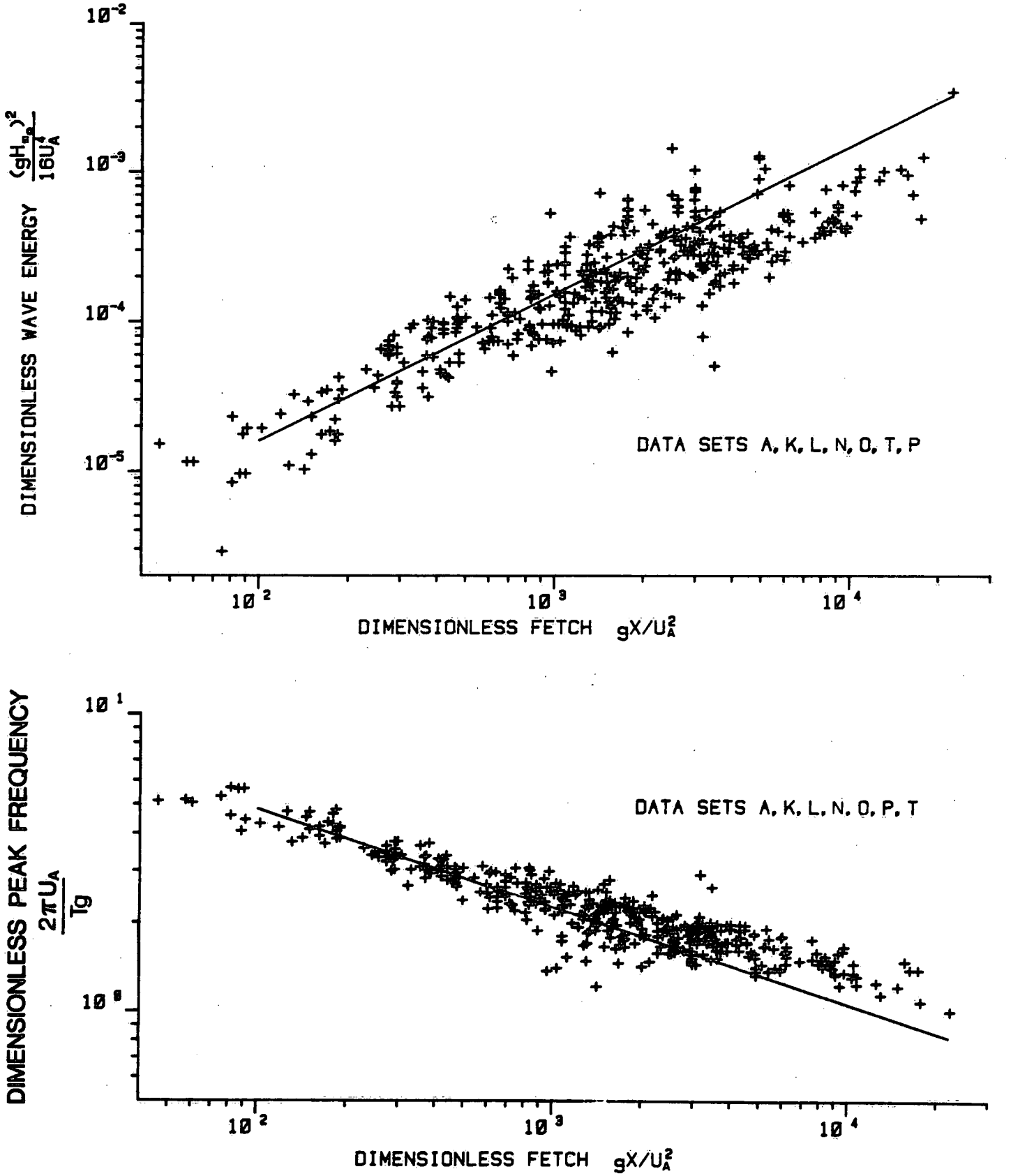


FIGURE 14. THE COMPOSITE DATA SET AND THE SHORE MODEL SCALED BY U_A

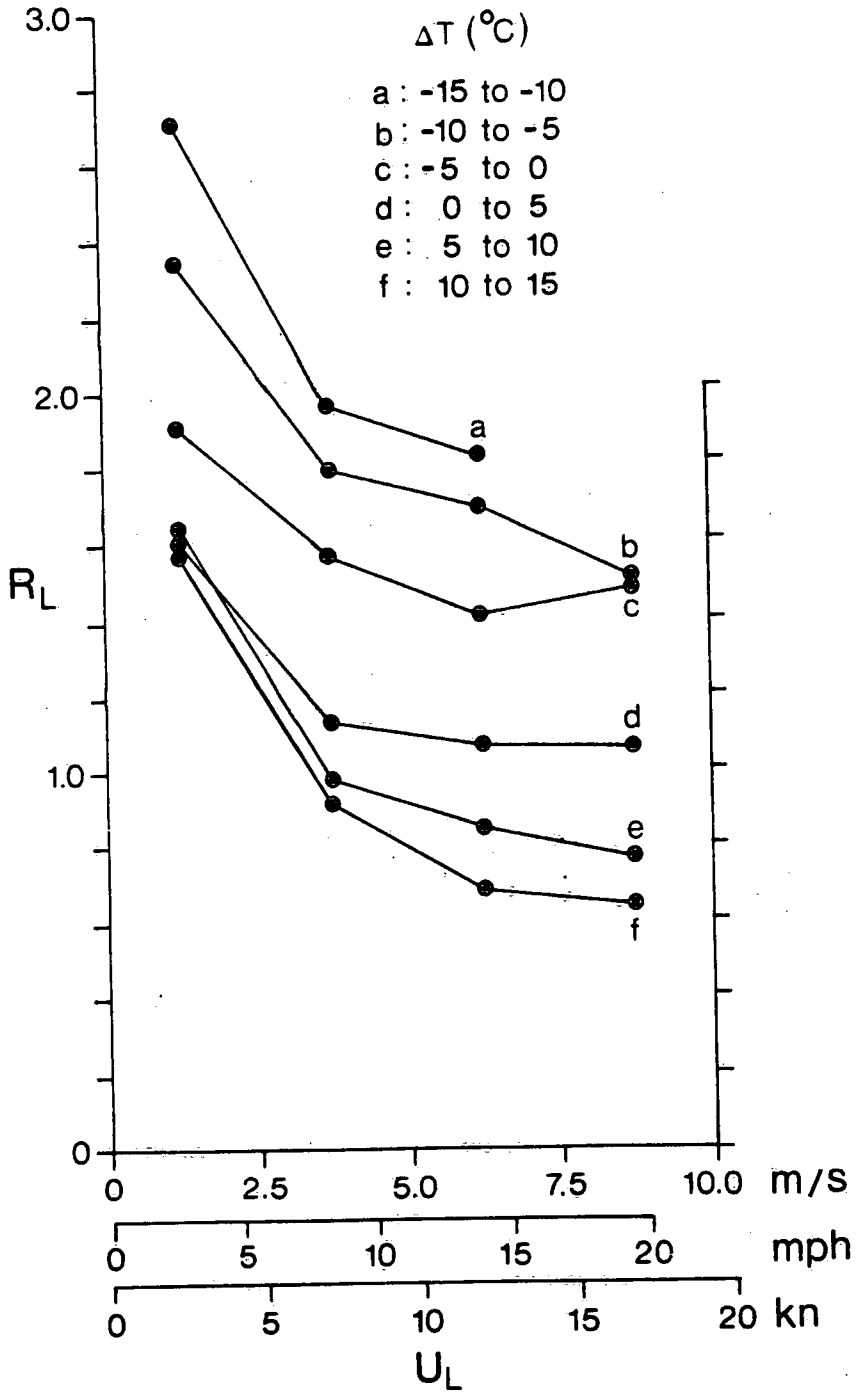


FIGURE 15. RATIO OF OVERWATER WIND SPEED AT 10m TO OVERLAND WIND SPEED AT 10m AS A FUNCTION OF OVERLAND WIND SPEED AND AIR-WATER TEMPERATURE DIFFERENCE (after Schwab and Morton, 1984)