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SHORE PROTECTION MANUAL'S WAVE PREDICTION REVIEWED

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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.

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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. 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 explanation 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 33 ft (10 m) height appropriate for use in the wave prediction equations. The elevation adjustment equation given in the SPM (1984) is

$$U_{33} = U_z \left(\frac{33}{z}\right)^{1/7} , \quad z < 66 \text{ ft} \qquad (1)$$

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

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

$$U_\alpha = R_L U_{33} \qquad (2)$$

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

$$U_\beta = R_T U_\alpha \qquad (3)$$

In an attempt to correct for the observed nonlinear relationship between friction velocity, u_* (= [wind stress/air density]$^{1/2}$) and wind speed, the SPM (1984) introduces an adjusted wind speed factor, U_A, where

$$U_A = 0.589\, U_\beta^{1.23} \quad , \quad U \text{ in mph}$$

or (4)

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

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 neither of which has been proven theoretically or demonstrated adequately experimentally: a) fetch-limited wave development scales with friction velocity u_* rather than wind speed U_{33}; 2) the relationship between u_* and U_{33} 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 taking the JONSWAP relations, which were derived from a relatively narrow range of moderate wind speed conditions ($\bar{U}_{33}$ = 9.4 m/s, range from 5.6 m/s to 12.7 m/s), and extrapolating to higher wind speeds. 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.

In the following we exercise various steady state wave prediction formulas against the data set to explore the effect of SPM correction factors, in particular, U_A. We begin with a brief summary of the wave prediction methods treated, followed by a description of the data sets and their selection criteria. This sets the stage for a comparison of the performance of the formulas in terms of dimensional and non-dimensional variables. We conclude with a discussion of the causes of inaccuracy of various methods and offer arguments for a more physically based procedure for steady state wave forecasting than that given by SPM (1984).

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 equations, are the same as the JONSWAP formulas (Hasselmann et al. 1973) except that U_{33} is replaced by U_A.

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, into one variable of dimensionless fetch gX/U^2, where

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

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 formulas together with the data. The wind fetch and U, rather than $U\cos\theta$, have been used, which are incorrect for the Donelan method. Even so, all three represent fairly well the average behaviour of the composite data set. Coverage of the two-dimensional wind-fetch plane by the composite data set is shown in Figure 5. It is quite typical of average wave conditions encountered in engineering applications, but it does not cover extreme situations.

The four wave prediction formulas were first tested against the composite data of Table 1. 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.

The air-water temperature difference was about 3.6°F (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 0.65 ft (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 clearly too small because the fetch is taken incorrectly in the wind direction rather than the wave direction.

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 -19.4°F to +6.7°F (-10.8°C to +3.7°C) for data set T, and from -17.1°F to + 8.8°F (-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 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. 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 x 10^3 to 20 x 10^3. At shorter dimensionless fetches, typical of some design situations, the JONSWAP formulas predict smaller values of H_{m_0} and T_p, than do the SMB or SHORE formulas. Comparisons of wave height predictions for wind fetches of 5 and 50 miles (8 and 80 km) are shown in Figure 11; again the Donelan formula is used with wind fetches and U rather than $U\cos\theta$. Note that the SHORE values of H_{m_0} are relatively high even though based on the JONSWAP formulas which give relatively low values.

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. As seen in Figures 3 and 4, for these conditions the Donelan formulas predict smaller values of H_{m_0} and T_p than the SMB formulas over a wide range of dimensionless fetch.

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

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

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. It shows that when the wind speed is over 67 mph (30 m/s) the curves for the SHORE formula are above practically all except a few of the most widely scattered data points. Since these highest data points do not represent the highest wind speeds in the data, and the data otherwise do not show the effects Equation 4 predicts, we expect that the SHORE formula dramatically overpredicts the wave height in extreme wind conditions.

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 seems not 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 at high wind speeds. It is of interest to see if any improvement in the correlation between nondimensional variables is achieved when U_A rather than U_{33} is used with the complete data set. A marked improvement would argue for the development of new nondimensional relations based on U_A instead of U_{33}. The use of U_A for prediction with such relations would then be formally correct. 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 paramterizations 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:

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

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_o 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 10 feet (3 m) and 100 feet (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 100 ft (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 20 ft (6.1 m) on land to a level of 19.5 m (64 ft) over water. Using Equation 1 to adjust both levels to 33 ft (10 m) gives the curve shown in Figure 1. The Resio and Vincent curve adjusted to 33 ft differs from that given by the SPM (Figure 1) for speeds greater than 10 m/s. In particular, for overland winds above 25 knots (12.9 m/s) the SPM method yields overwater winds that are less than those over land. This improbable result implies larger roughness lengths over water than land and would 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 extensive data sets employing accurate 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 68 knots (35 m/s). This extended data set of simultaneous overland and overwater wind speeds is well represented by:

$$U_W = 5.48\, U_L^{1/2} \qquad U_L < 19 \text{ knots, } U \text{ in knots}$$

or

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

$$U_W = 1.24\, U_L \qquad U_L > 19 \text{ knots } (10 \text{ m/s}) \qquad (10)$$

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 using 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 33 ft (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 $U_L > 19$ knots (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 ± 9°F (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. However, an appropriate stability correction necessarily balances the mechanical mixing ability of the wind against the ability of density gradients to enhance (unstable) or suppress (stable) vertical mixing. In winds strong enough to produce appreciable wave growth the effects of mechanical mixing usually overwhelm those of density gradients. In fact, the correction for air-water temperature difference given by Resio and Vincent (1977) has nothing to do with the relative wave generating efficiency of unstable and stable boundary layers, but instead arises because of the different wind gradients that occur with different stabilities. Thus a given geostrophic wind will yield larger surface winds when the boundary layer is unstable than when it is stable. 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) that the drag coefficient depends on wind speed. The wind stress (u_*^2 x air density) represents the total transfer of momentum between the air and the water surface. This is partitioned between viscous drag (momentum that acts directly to accelerate the surface current) and momentum input to waves of all sizes. At low wind speeds the first mechanism is dominant and at high wind speeds the second is dominant. Over a substantial range of wind speeds (roughly up to 15 knots or 8 m/s) the viscous term contributes substantially to the total stress and yet has little to do with the amplification of waves large enough to be of engineering significance. It is apparent that, except at relatively high wind speeds when the flow is aerodynamically rough, there is no one-to-one correspondence between total stress and momentum to the wave field. Even when the flow is completely rough a substantial fraction (probably more than 50%) of the momentum transfer is to waves on the quasi-saturated rear face (equilibrium range) of the spectrum. Much of this momentum is immediately lost from the wave field to currents through processes of wave dissipation. Why should we then expect a close connection between the total stress and wave growth with fetch - almost all of which is due to increases of the forward face (low frequency end) of the spectrum?

Apart from these arguments against the use of the friction velocity to parameterize wave growth there remains the practical difficulty of acquiring accurate estimates of the friction velocity in the field. There are substantial difficulties in obtaining good stress measurements from a fixed platform - these are enormously exacerbated on floating platforms - but even after such are acquired the observed variability of the measurements is so large that a particular measurement may be a poor estimate of the mean stress experienced by the waves in travelling over the entire fetch to the point of observation. It is presumably because of this that the JONSWAP measurements are reported in terms of wind speed and, where friction velocity appears, it is merely $u_* = \sqrt{0.001}\, U_{33}$, i.e., derived from an assumed constant drag coefficient.

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. Furthermore, to the best of our knowledge all published fetch-limited field studies, including JONSWAP, have been parameterized in terms of the wind speed and not the friction velocity and, indeed, this is as it should be on physical grounds.

The SPM's wind stress adjustment procedure stands in contrast to the foregoing. In particular, by using the JONSWAP relations, which are based on measured U_{33}, and substituting an artificially adjusted wind speed U_A, the SPM procedure will underpredict at low wind speeds and overpredict at high wind speeds.

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. The physical basis for this procedure is called into question. Comparison with measured wave data from various sources reveals that the 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 the 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 33 ft (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 retraction 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 Müller (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	Data Set T: NPTS	Toronto H_{m_0} Std. Err. (ft)	Toronto H_{m_0} Bias (ft)	Toronto T_p Std. Err. (s)	Toronto T_p Bias (s)	Data Set P: NPTS	Main Duck Island H_{m_0} Std. Err. (ft)	Main Duck Island H_{m_0} Bias (ft)	Main Duck Island T_p Std. Err. (s)	Main Duck Island T_p Bias (s)
Donelan	wavef[1],no stabc[2]	82	0.82	-.13	0.66	-.23	75	0.85	-.26	0.53	-.26
	wavef,stabc[3]	95	0.79	0.16	0.60	-.08	92	1.02	0.16	0.64	-.16
	wavef, corstab[4]	78	0.82	-.16	0.67	-.26	76	0.89	-.36	0.55	-.32
	windf[5],no stabc	80	1.28	-.43	1.03	-.49	73	1.28	-.92	1.01	-.76
	windf, stabc	92	1.12	-.20	0.94	-.37	89	1.18	-.59	1.05	-.73
	windf, corstab	77	1.31	-.49	1.04	-.52	74	1.35	-.95	1.03	-.79
JONSWAP	windf, no stabc	82	1.02	0.10	0.92	0.33	75	0.89	-.07	0.82	0.33
	windf, stabc	95	1.12	0.39	0.95	0.43	92	1.12	0.23	0.90	0.31
	windf. corstab	78	1.08	0.10	0.91	0.32	76	0.89	-.13	0.80	0.29
SHORE	windf, no stabc	80	1.25	0.79	1.00	0.58	73	1.12	0.72	0.94	0.61
	windf, stabc	92	1.67	1.12	1.05	0.68	89	1.84	1.15	1.04	0.62
	windf, corstab	77	1.41	0.85	1.02	0.59	74	1.08	0.66	0.91	0.58
SMB	windf, no stabc	82	1.05	0.49	0.77	0.13	75	0.75	0.23	0.55	-.08
	windf, stabc	95	1.28	0.82	0.78	0.29	92	1.25	0.66	0.68	0.01
	windf, corstab	78	1.08	0.49	0.76	0.12	76	0.75	0.16	0.56	-.12
	windf, no stabc, T = 1.10T[6]	80	1.05	0.49	0.93	0.54	73	0.72	0.20	0.65	0.34
	windf, no stabc, T = 1.05T	80	1.05	0.49	0.83	0.34	73	0.72	0.20	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

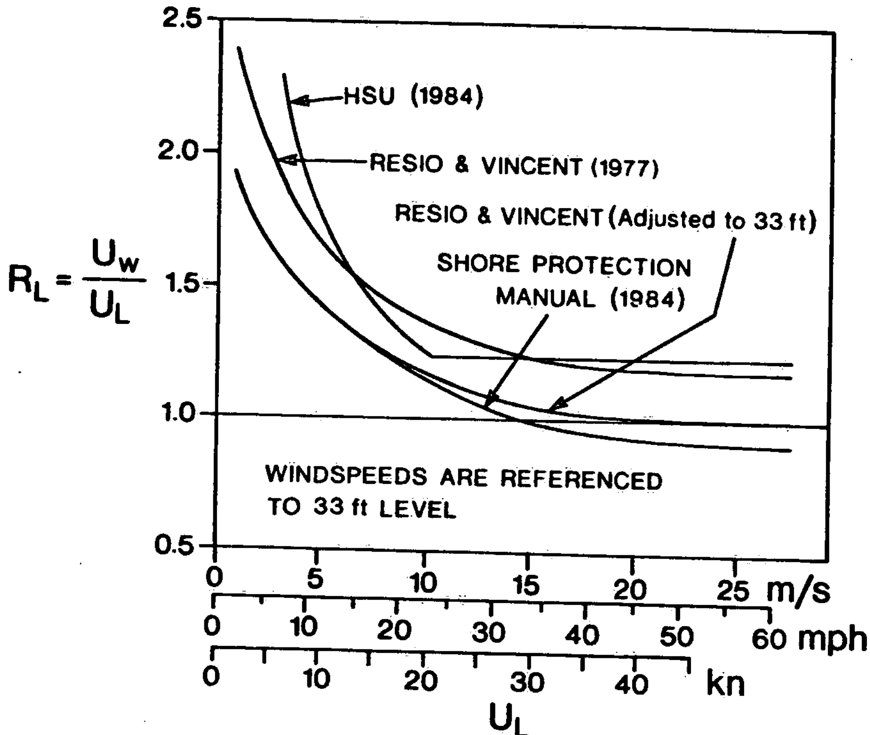


FIGURE 1. RATIO, R_L, OF WINDSPEED OVER WATER, U_w, TO WINDSPEED OVER LAND, U_L, AS A FUNCTION OF WINDSPEED OVER LAND U_L.

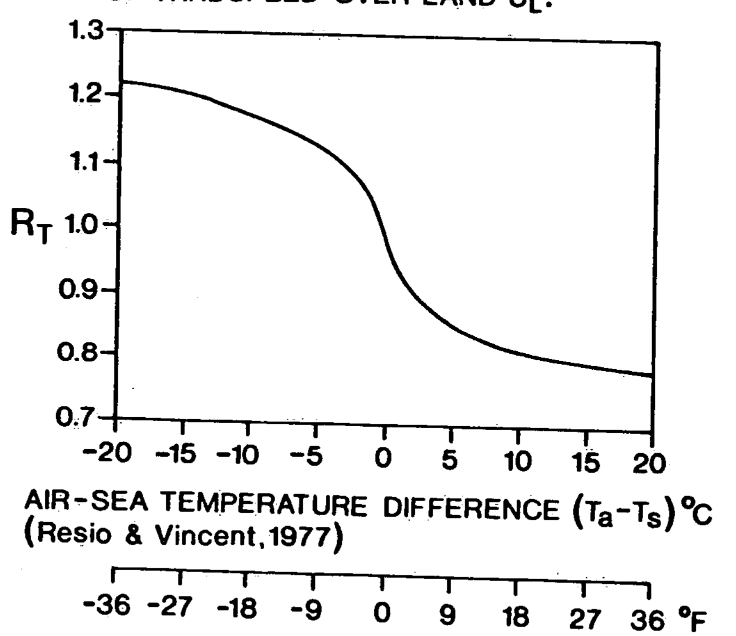


FIGURE 2. AMPLIFICATION RATIO, R_T, ACCOUNTING FOR EFFECTS OF AIR-SEA TEMPERATURE DIFFERENCE.

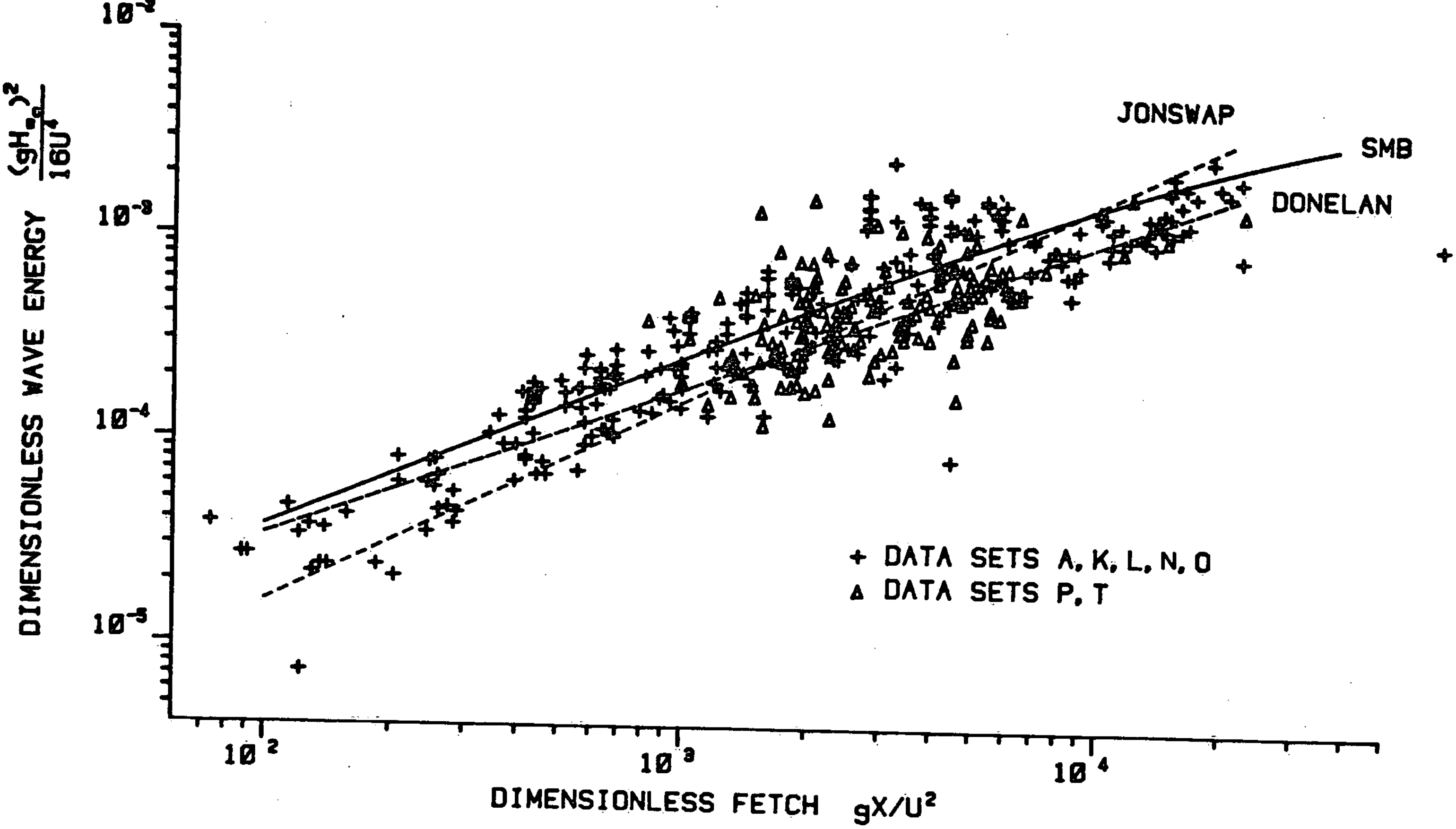


FIGURE 3. DIMENSIONLESS PLOT OF WAVE ENERGY VERSUS FETCH, COMPOSITE DATA SET, AND JONSWAP, SMB AND DONELAN RELATIONS

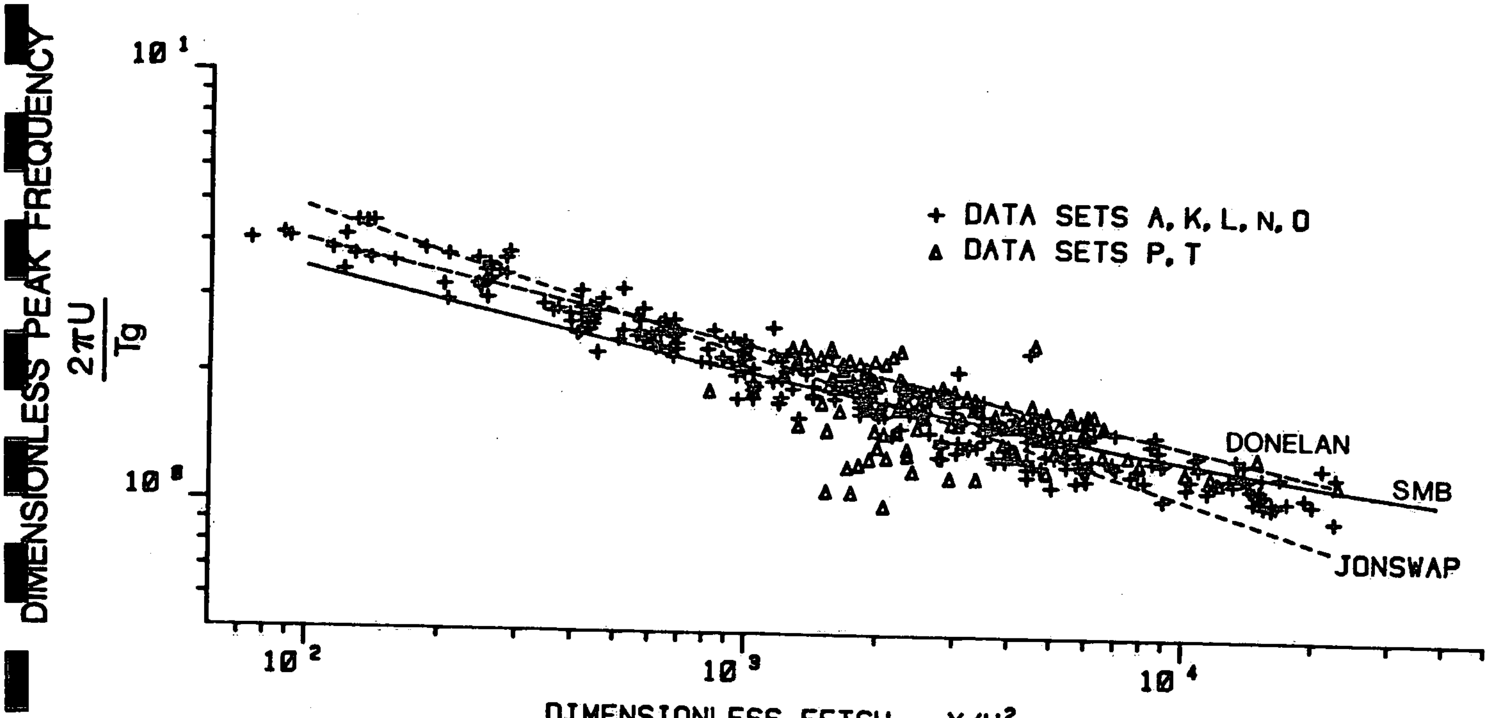


FIGURE 4. DIMENSIONLESS PLOT OF PEAK FREQUENCY VERSUS FETCH, COMPOSITE DATA SET, AND JONSWAP, SMB AND DONELAN RELATIONS

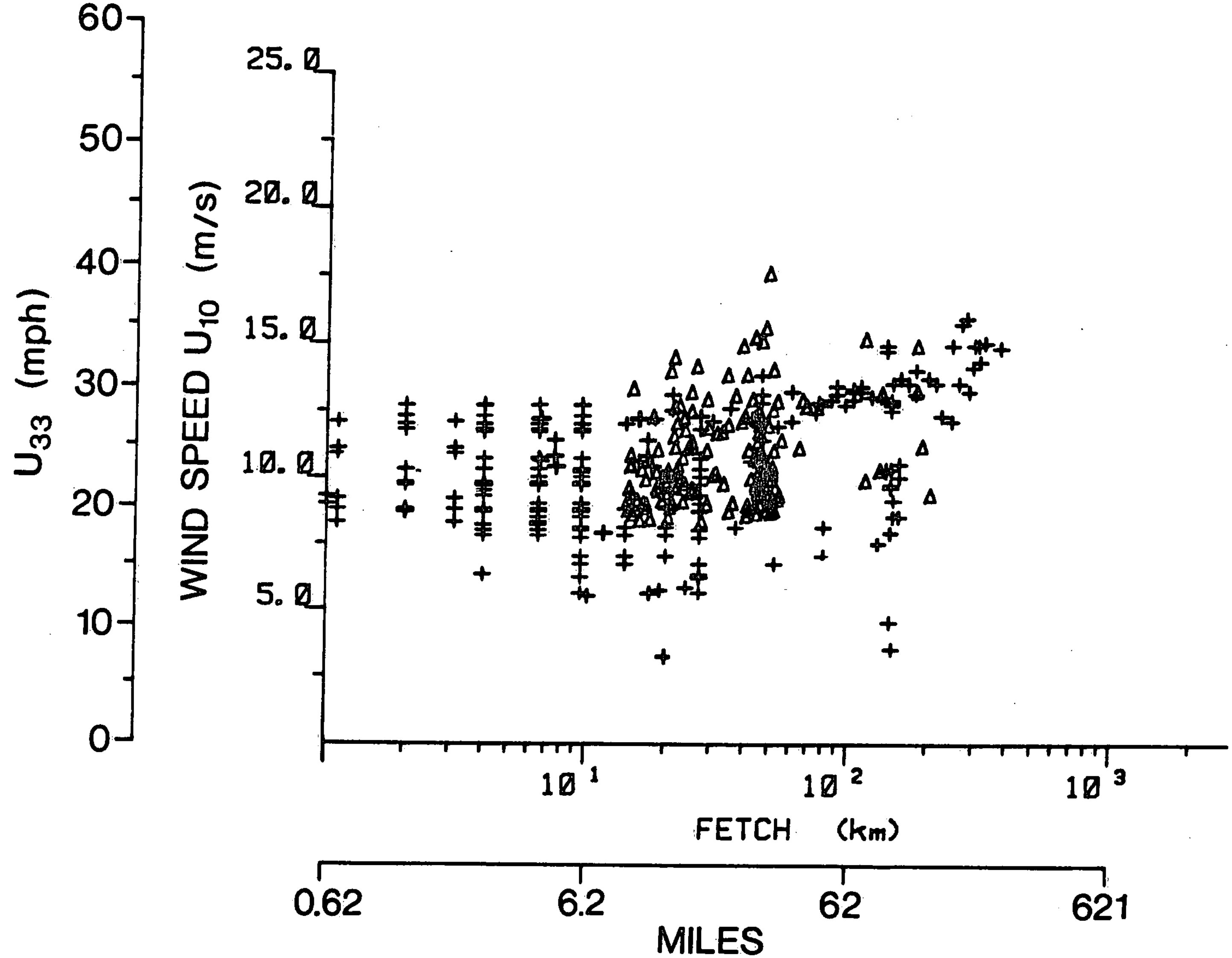


FIGURE 5. THE DISTRIBUTION OF THE DATA IN THE WIND-FETCH PLANE. DATA SETS P, T, Δ; DATA SETS A, K, L, M, N, O, +.

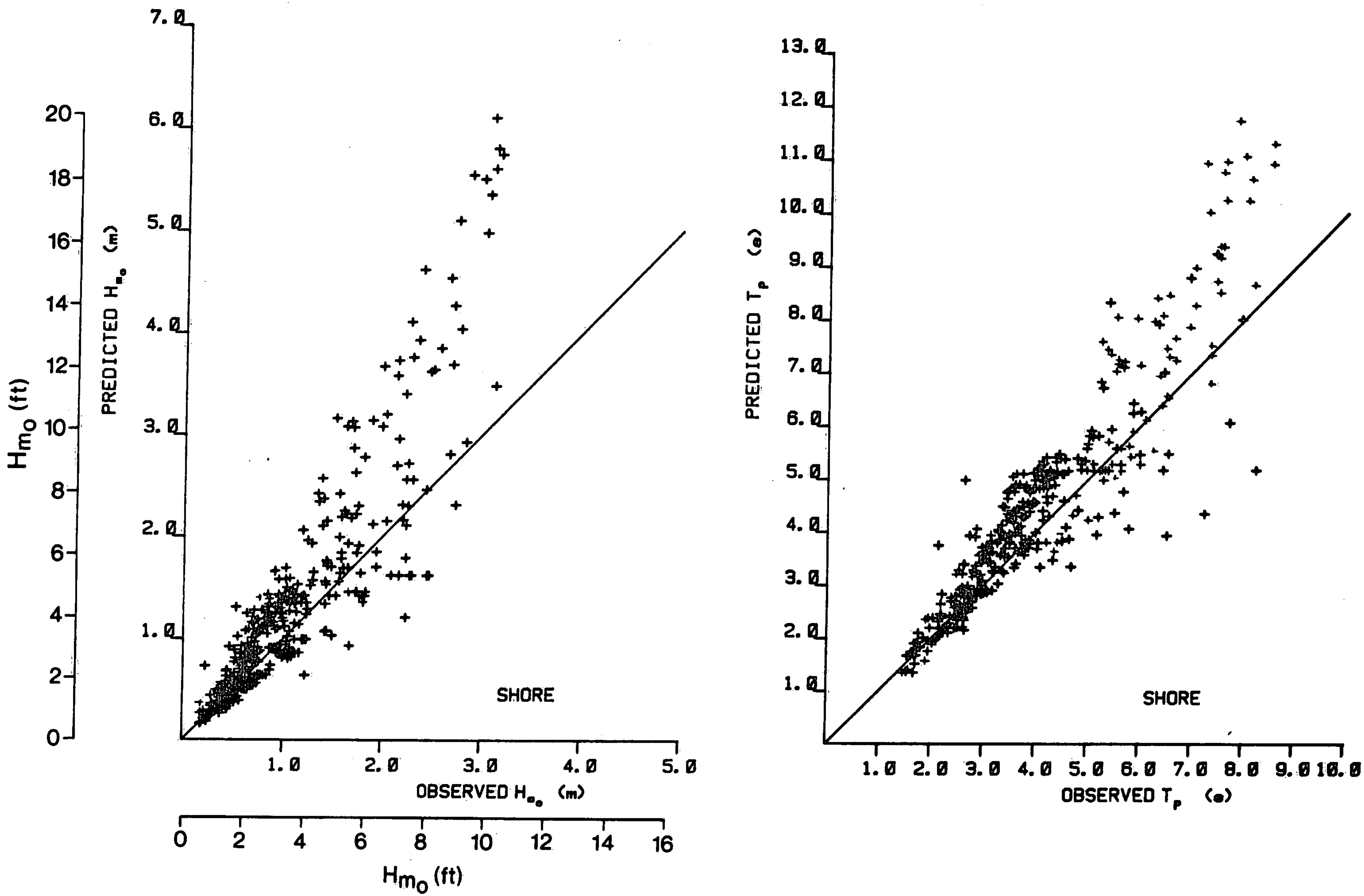


FIGURE 6. COMPARISON OF MEASURED AND PREDICTED PARAMETERS, COMPOSITE DATA SET, SHORE MODEL

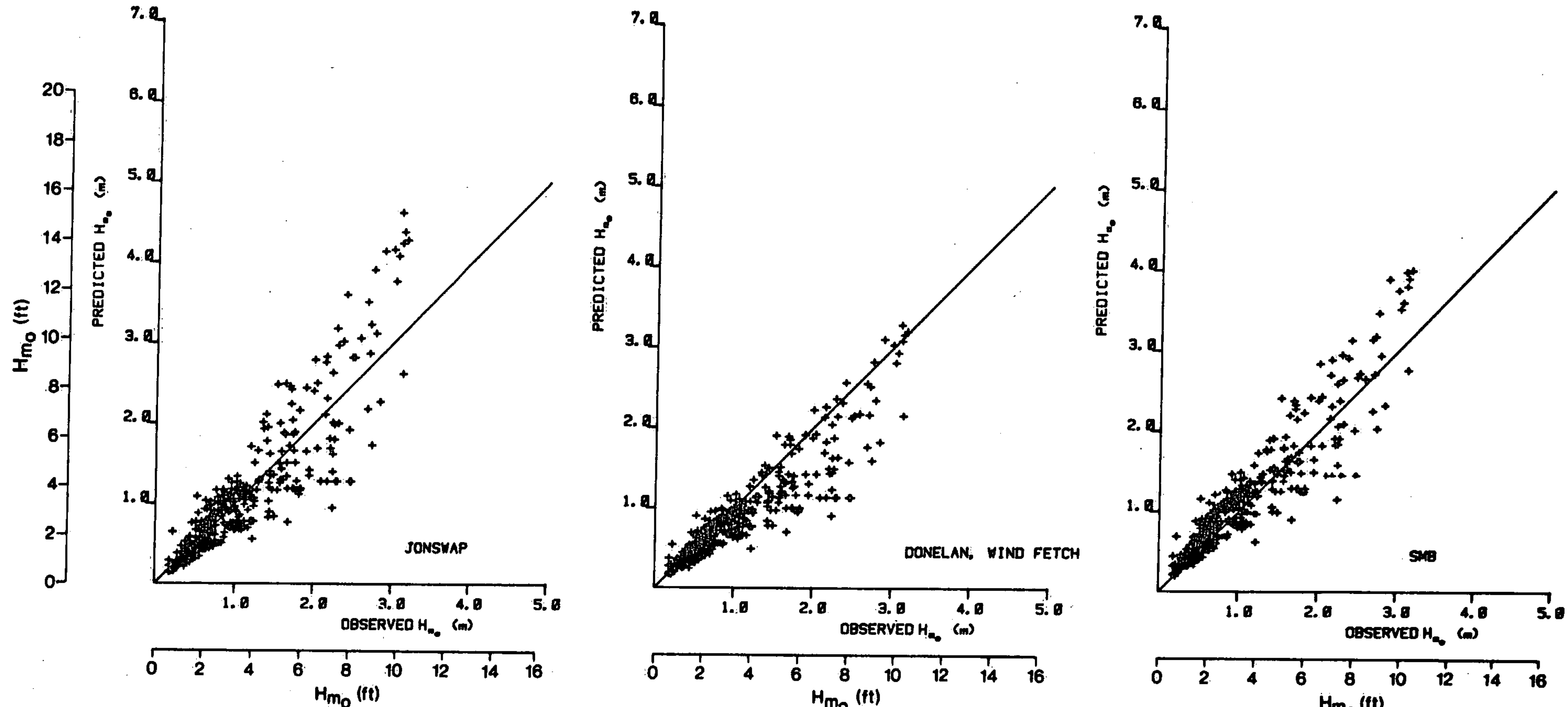


FIGURE 7. COMPARISON OF MEASURED AND PREDICTED H_{m_o}, COMPOSITE DATA SET, JONSWAP, SMB AND DONELAN MODELS

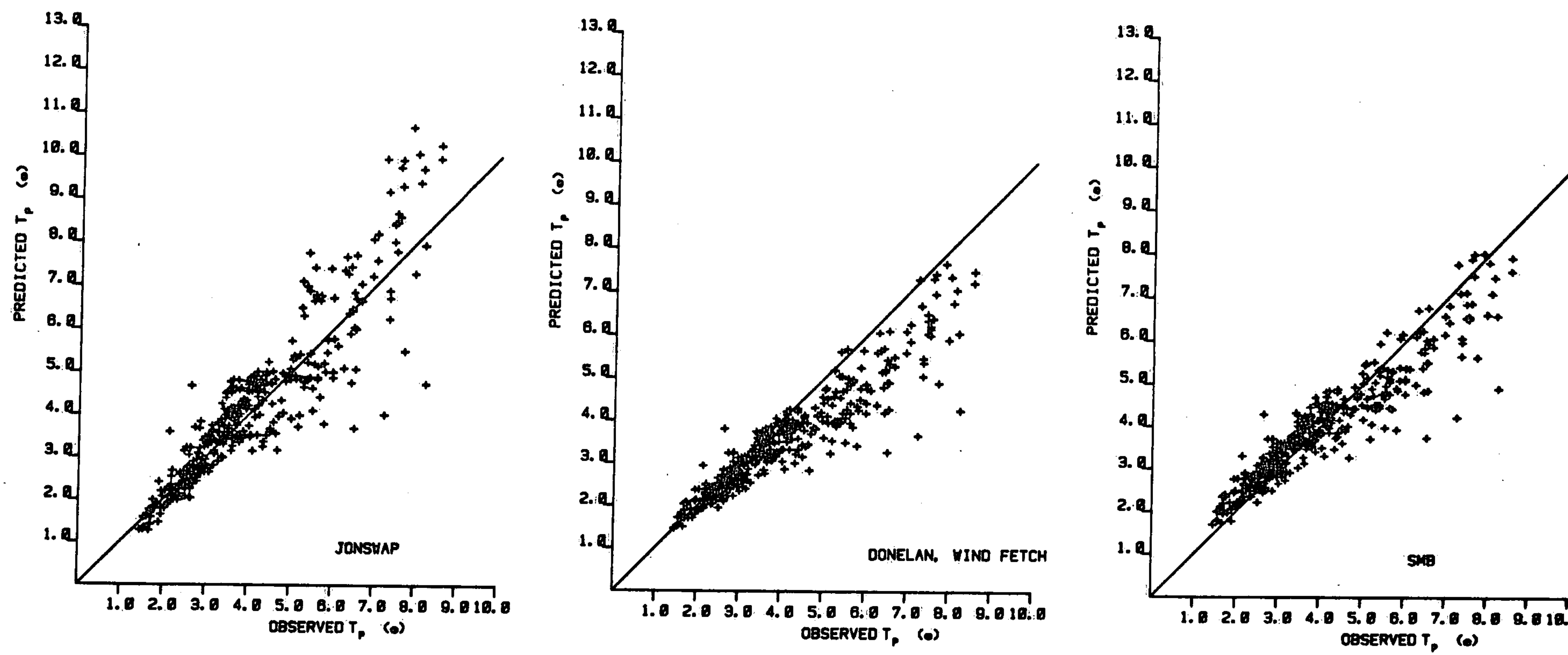


FIGURE 8. COMPARISON OF MEASURED AND PREDICTED T_P, COMPOSITE DATA SET, JONSWAP, SMB AND DONELAN MODELS

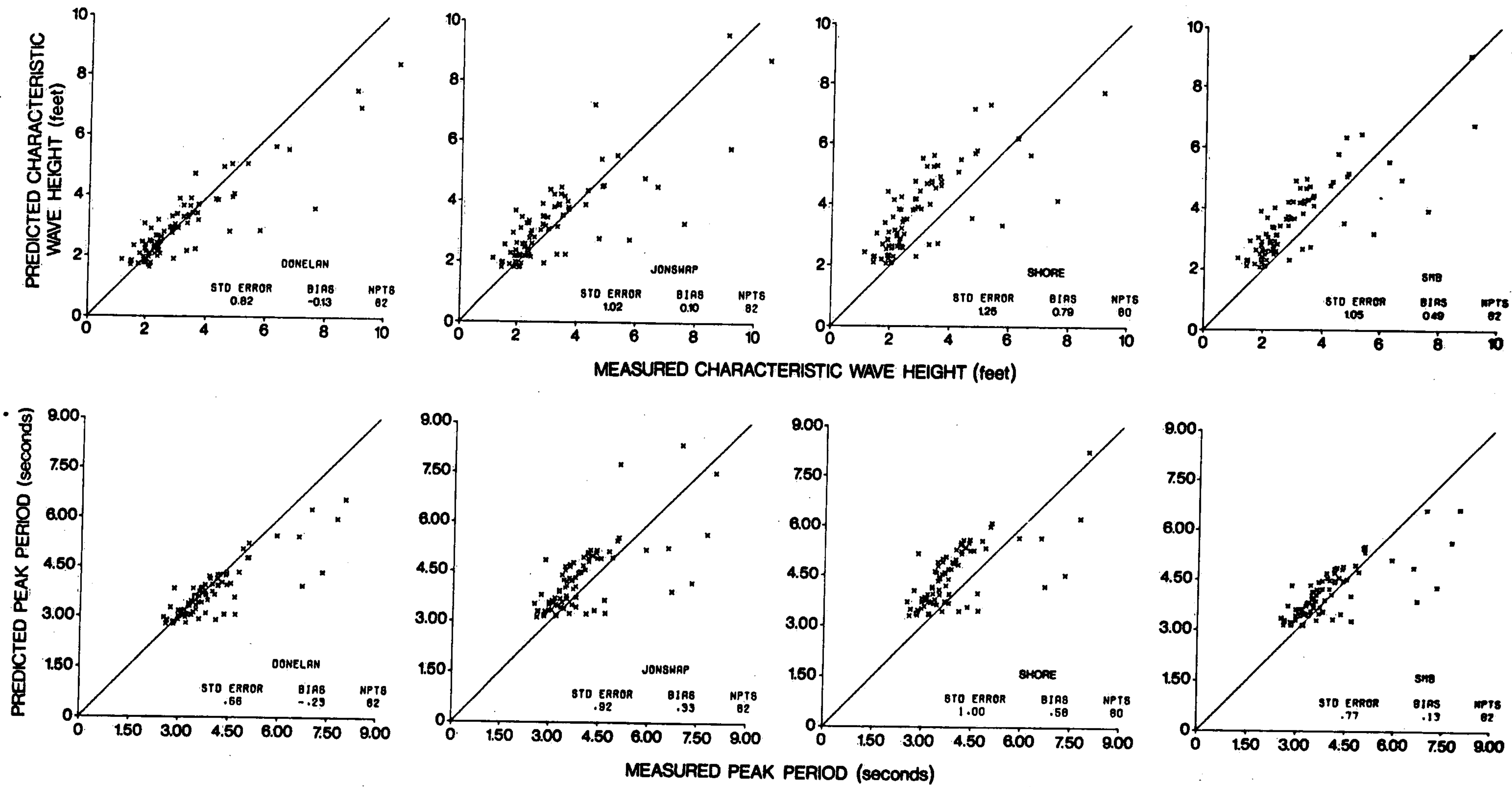


FIGURE 9. COMPARISON OF MEASURED VERSUS PREDICTED WAVE PARAMETERS AT TORONTO

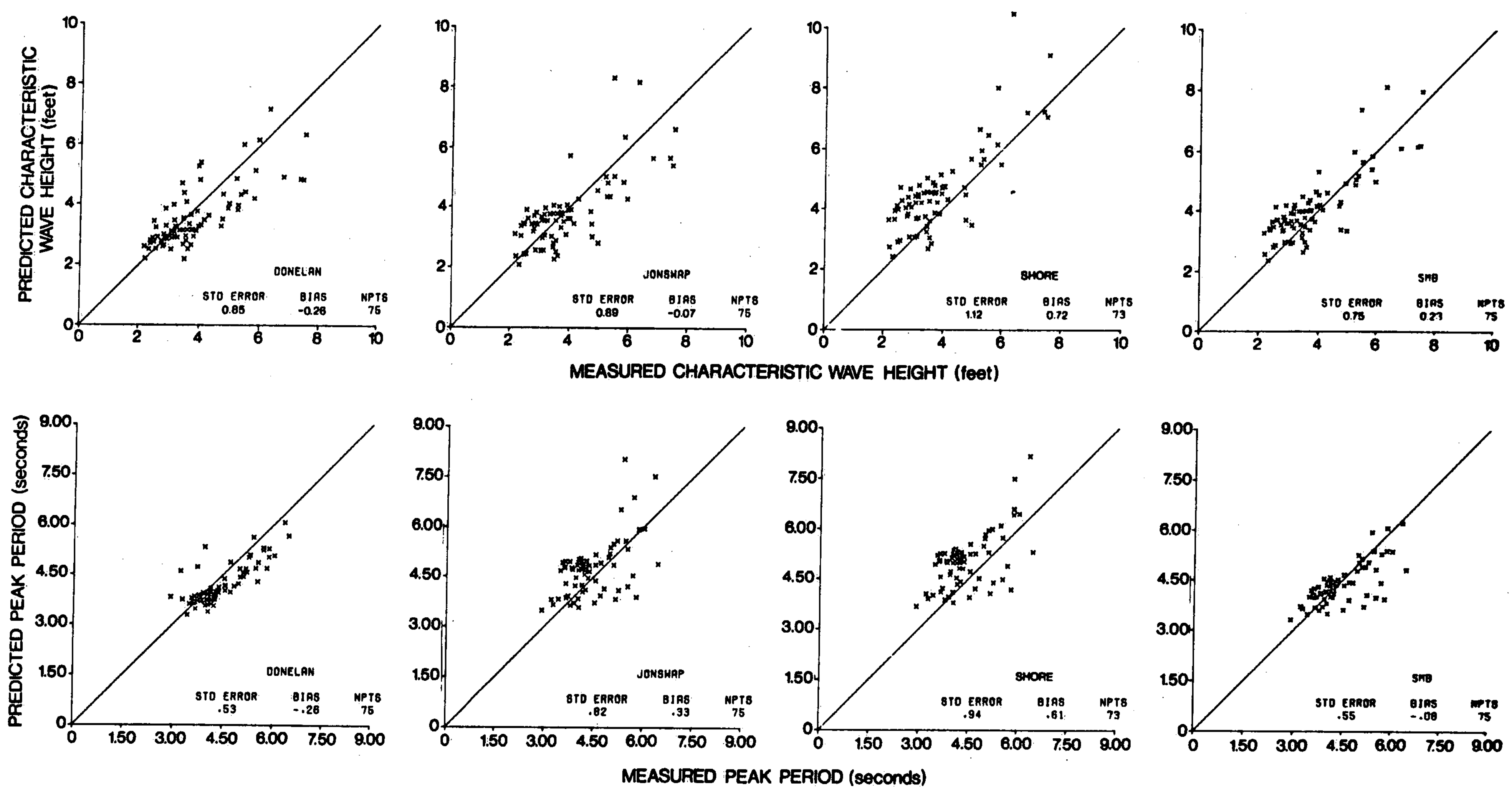


FIGURE 10. COMPARISON OF MEASURED VERSUS PREDICTED WAVE PARAMETERS AT MAIN DUCK ISLAND

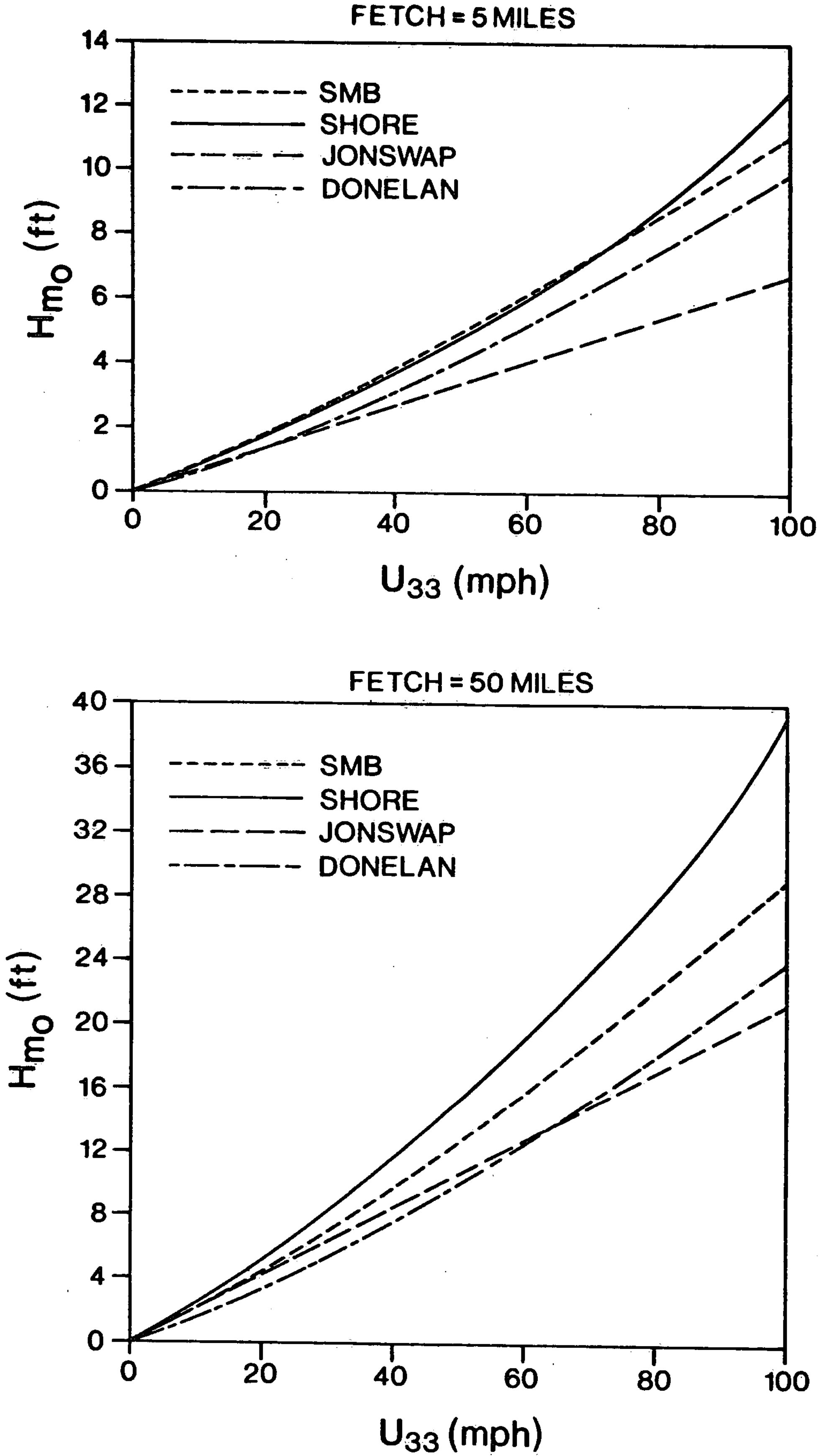
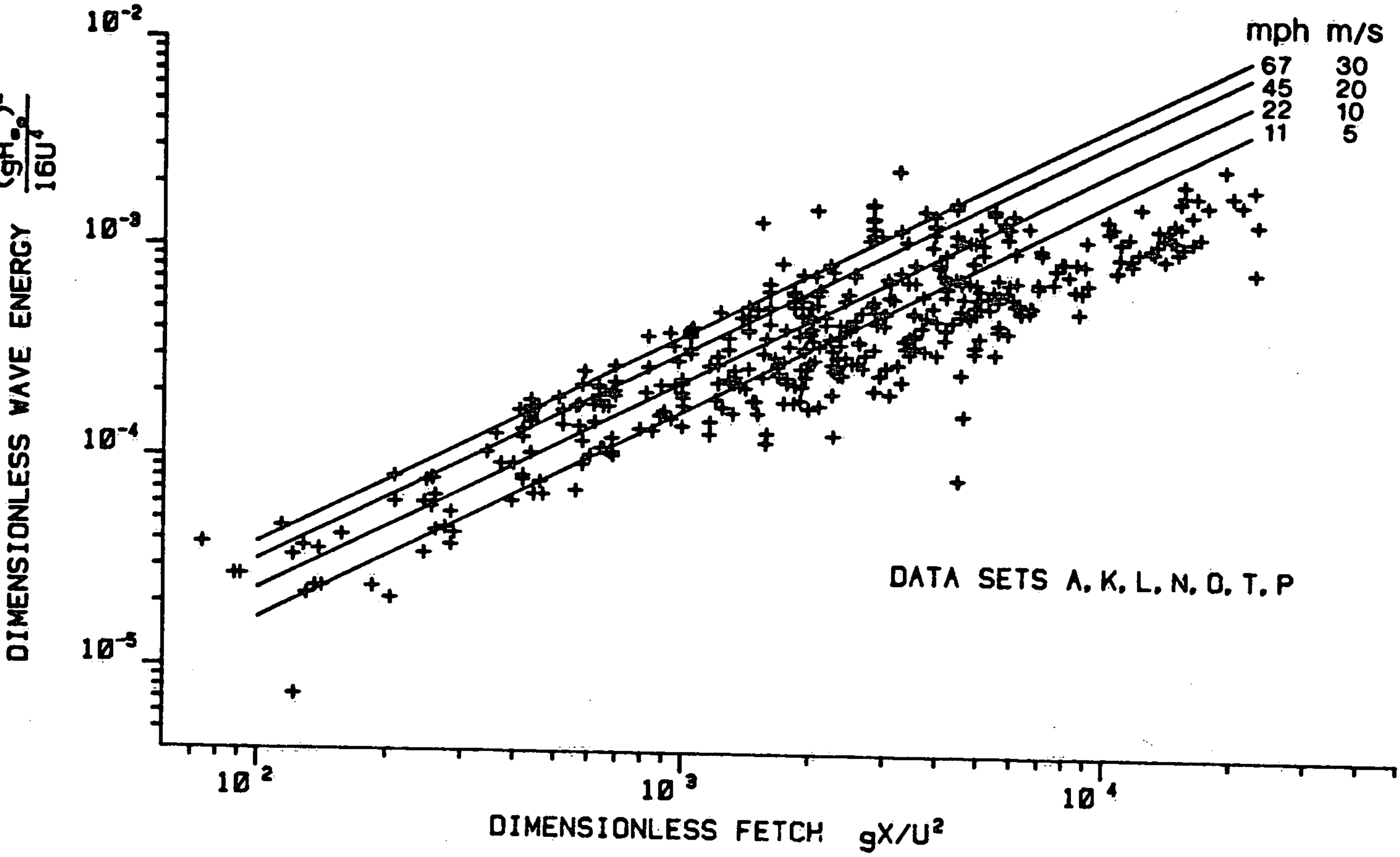


FIGURE 11. COMPARISONS OF WAVE HEIGHT PREDICTIONS FOR WIND FETCHES OF 5 AND 50 MILES



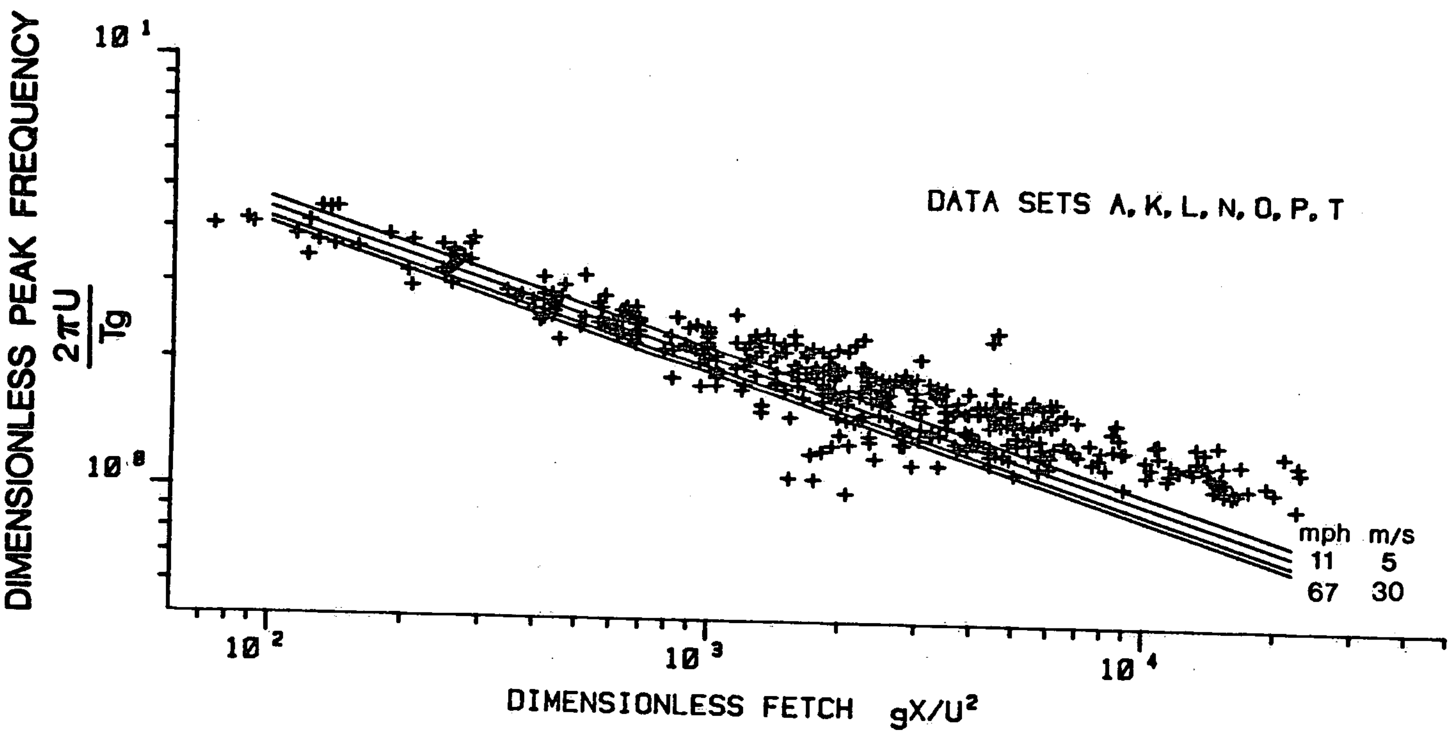


FIGURE 12. THE COMPOSITE DATA SET AND THE SHORE MODEL IN DIMENSIONLESS COORDINATES

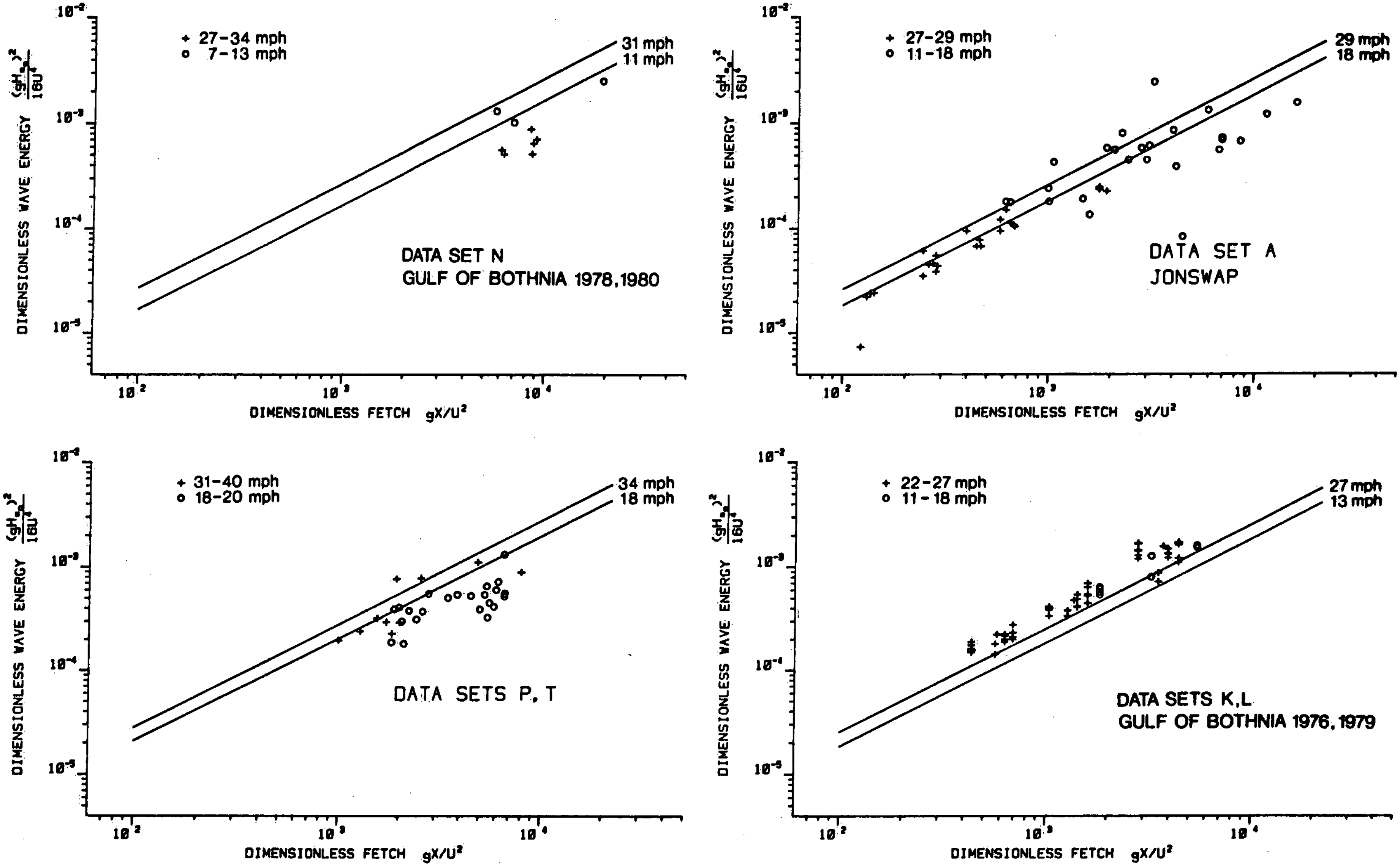
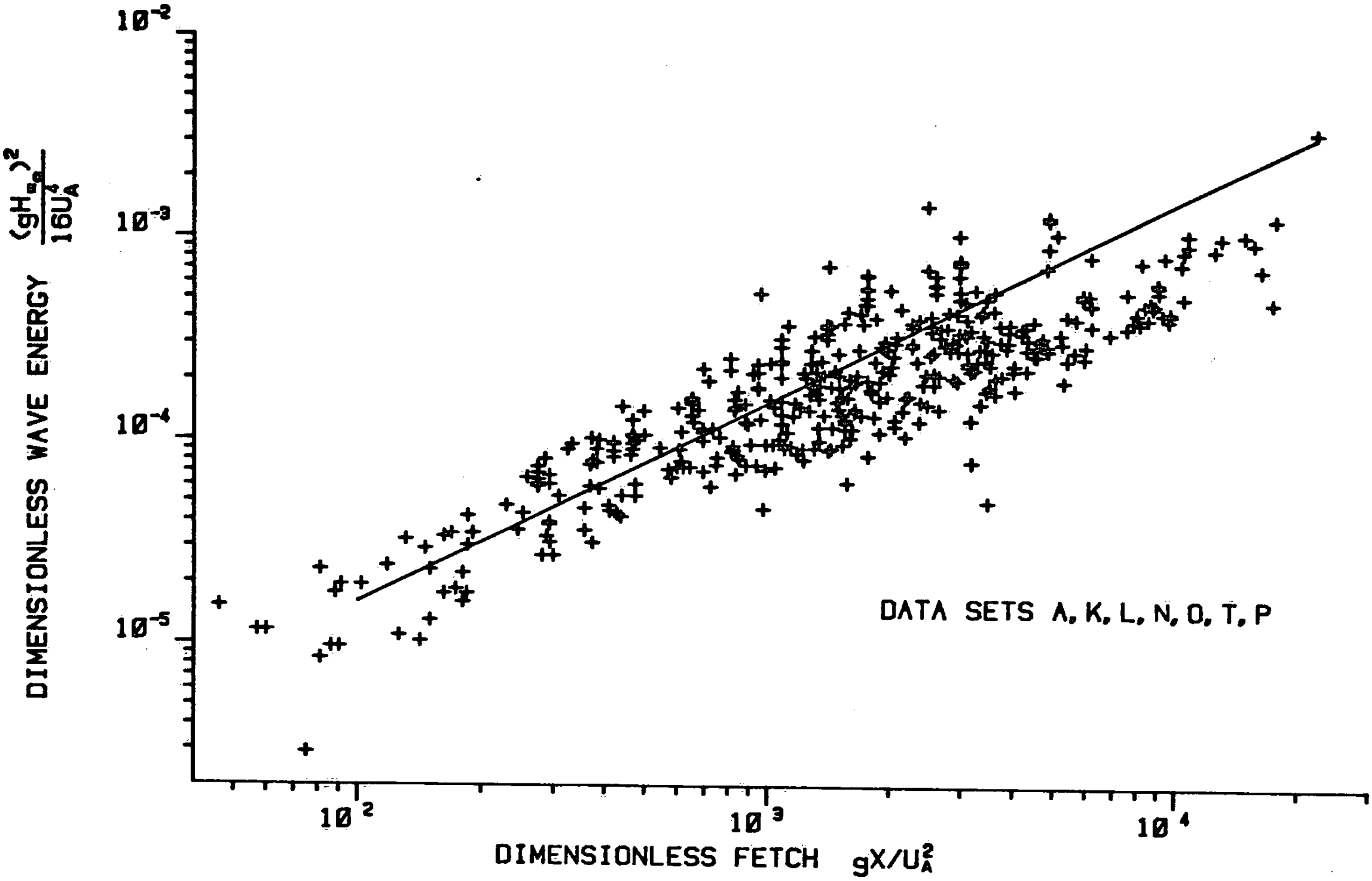


FIGURE 13. MAXIMUM AND MINIMUM WIND CASES SELECTED FROM THE FOUR DATA GROUPINGS. THE LINES DENOTE THE SHORE MODEL



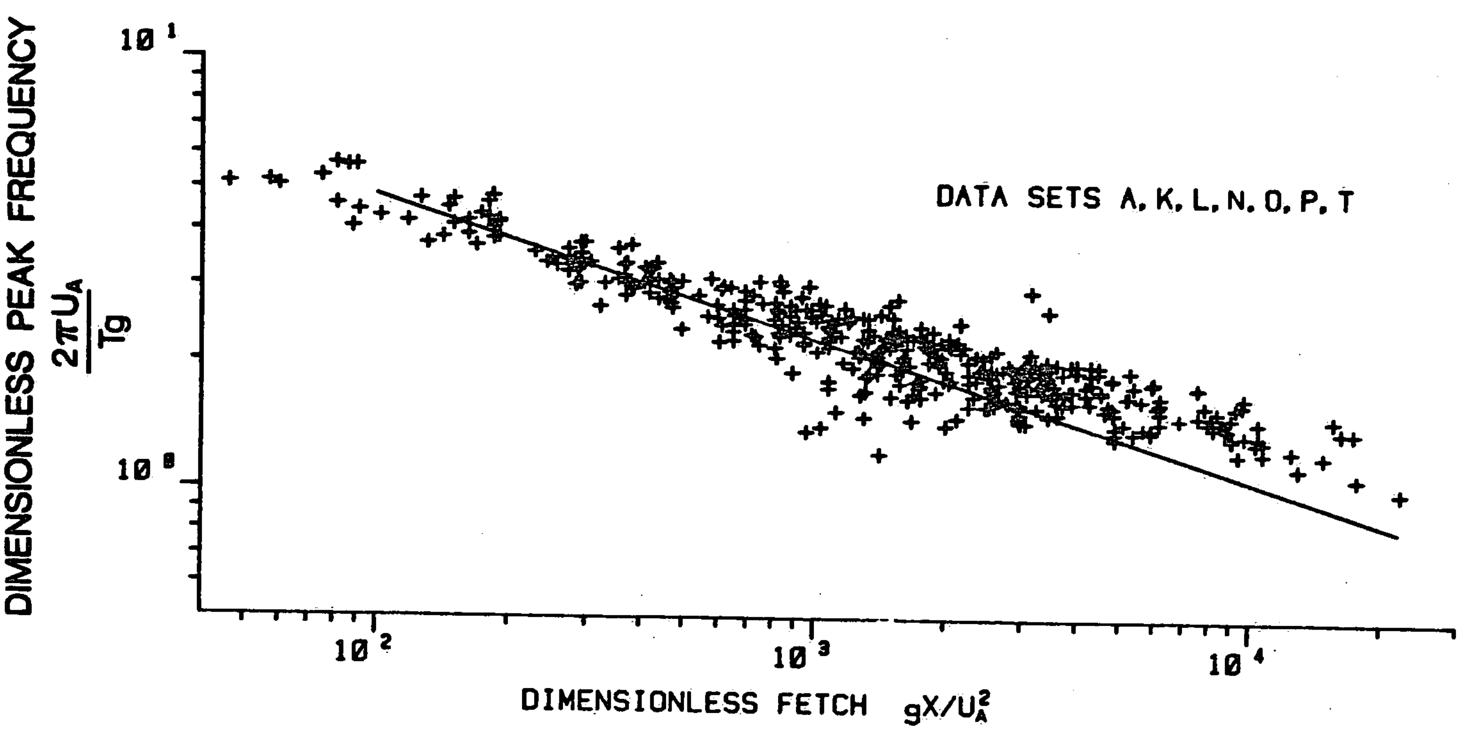


FIGURE 14. THE COMPOSITE DATA SET AND THE SHORE MODEL SCALED BY U_A

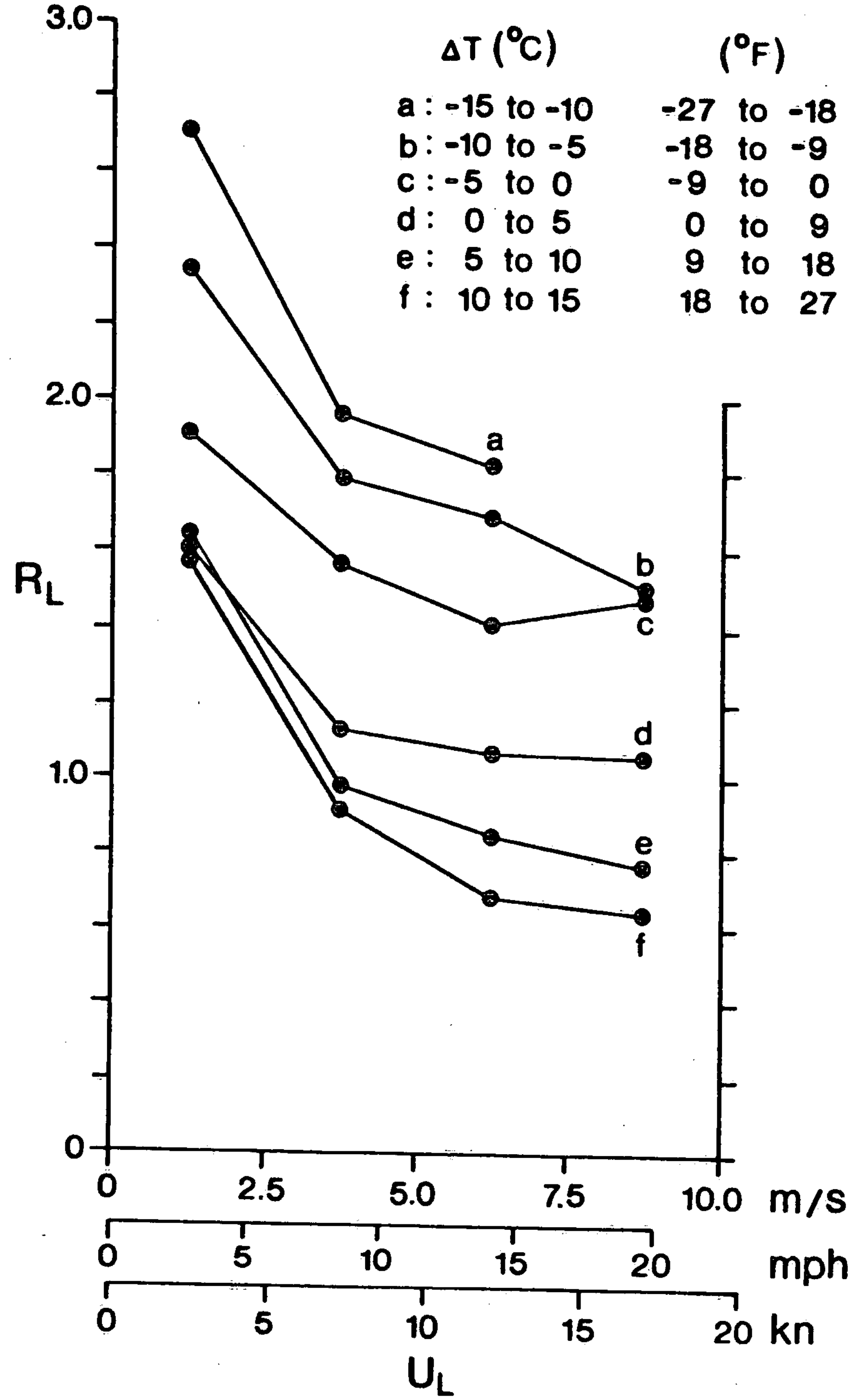


FIGURE 15. RATIO OF OVERWATER WIND SPEED AT 33 FT (10m) TO OVERLAND WIND SPEED AT 33 FT (10m) AS A FUNCTION OF OVERLAND WIND SPEED AND AIR-WATER TEMPERATURE DIFFERENCE (after Schwab and Morton, 1984)