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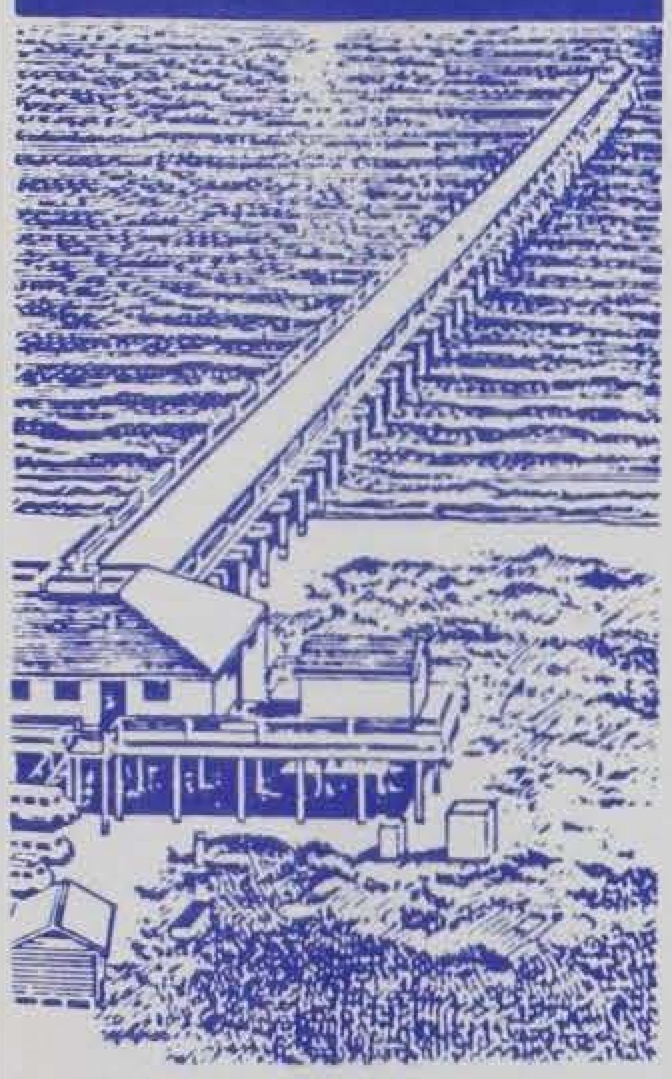

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DEEPWATER WIND WAVE GROWTH WITH FETCH AND DURATION

by

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A simple method for estimating wave height and period for fetch- and duration-limited conditions is developed from the field studies of Mitsuyasu and Hasselmann. The velocity scaling is effectively based on friction velocity which allows incorporation of effects due to temperature stratification in the atmospheric boundary layer and variation in the coefficient of drag with wind speed. The method is the analytical equivalent of the growth relationship used in the US Army Corps of Engineers numerical wave prediction studies. It is intended for use in short fetch (200 km) or less situations.

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PREFACE

The purpose of this report is to outline the development of the deep-water fetch-limited and duration-limited wave estimation method given in the Shore Protection Manual (US Army 1984).

The research summarized in this report was authorized by the Office, Chief of Engineers (OCE), US Army, under Civil Works Research Work Unit Number 31592, "Wave Estimation for Design." Funds were provided through the Coastal Engineering Research Area under the field management of the Coastal Engineering Research Center (CERC) and OCE Technical Monitor, Mr. J. Lockhart.

The study was conducted by the US Army Engineer Waterways Experiment Station (WES) CERC under the direction of Dr. R. W. Whalin, Chief, CERC, Mr. R. P. Savage, former Chief, Research Division, and Dr. J. R. Houston, Chief, Research Division. The report was written by Dr. Charles L. Vincent, former Chief, Coastal Oceanography Branch. Technical editing was done by Dr. S. A. Hughes under the supervision of Dr. E. F. Thompson, Chief, Coastal Oceanography Branch.

Commanders and Directors of WES during the conduct of this study and the preparation of the report were COL Tilford C. Creel, CE, and COL Robert C. Lee, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, US CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

US customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
miles (US statute)	1.609347	kilometres
miles per hour (US statute)	0.44704	metres per second

DEEPWATER WIND WAVE GROWTH WITH FETCH AND DURATION

PART I: INTRODUCTION

1. The growth of waves due to the wind is a complex process that is only partially understood. In recent years, numerical models (Ewing 1971, Cardone et al. 1976, Hasselmann et al. 1976, Resio and Vincent 1976, Resio 1981) have been formulated and proved successful in predicting wave conditions. These models simulate wave growth from spatially and time varying wind fields with complicated fetch geometries. There remains a need for simple wave prediction methods that can be used quickly and inexpensively where project costs or time frames do not allow sophisticated techniques to be applied. These simple methods are limited in their reliability by the degree to which the actual situation must be simplified. Many such wave growth formulae exist, including the widely used Sverdrup-Munk-Bretschneider (SMB) method (Bretschneider 1958, US Army Coastal Engineering Research Center 1977).

2. As part of the Corps of Engineers' efforts to develop a numerical wave prediction model (Resio and Vincent 1976, 1979), extensive reviews of the physics of wave growth and available wave prediction formulae were made to provide a test of the growth characteristics of the wave model. As a result of this review, a wave prediction technology based on use of wind stress and the growth rates determined by Mitsuyasu et al. (1980) and Hasselmann et al. (1973) was determined to represent the current state of the art. Field tests of the model based on these growth rates were satisfactory (Resio and Vincent 1978, Corson and Resio 1981).

3. This report presents a simplified prediction method embodying the same physics as the numerical models. Unification of the numerical and simple analytical methods insures that consistent answers are generated by both. This new method allows the incorporation of effects related to the temperature stratification of the atmospheric boundary layer as well as the variation in the drag coefficient with velocity. Neglect of these factors can substantially bias wave height predictions. The new method appears in the US Army Coastal Engineering Research Center's (CERC) Shore Protection Manual (1984) and is intended for use in simple and short fetch geometries where the wind speed can be presumed constant. No attempt will be made to extend it for

cases of variable wind speed or direction, such as has been developed for the SMB method. In these cases a numerical model may be more appropriate.

4. The report is organized as follows:

   a. The mechanics of the atmospheric boundary layer over sea waves are discussed to provide an understanding of why the stress approach is necessary for predicting waves. The effects of boundary layer stability and drag coefficient variability are shown to be an essential consideration.

   b. Development of the fetch-limited and duration-limited equations for wave growth are presented and prediction nomograms provided.

   c. Procedures for estimation of fetch length and overwater wind speed are discussed.

PART II: ATMOSPHERIC BOUNDARY LAYER

5. Wind waves are one manifestation of the coupling of the atmosphere and water. The growth of waves is directly related to the flux of momentum and energy from the free air through the atmospheric boundary layer and water surface to the water mass. Any method to predict wind wave characteristics must account for this air-sea interaction. Those factors that have been shown to be of practical importance in predicting waves and for which data may be readily available for engineering use are discussed below.

6. A simple model of the atmospheric boundary layer consists of three parts (Cardone 1969, Resio et al. 1981, Resio and Vincent 1976) (Figure 1). At the top of the boundary is a quasi-geostrophic region in which the wind speed and direction are governed by large scale pressure gradients and by the Coriolis force. This region exists approximately 1 km above the water surface. Below this is an Ekman region in which wind speed and direction are

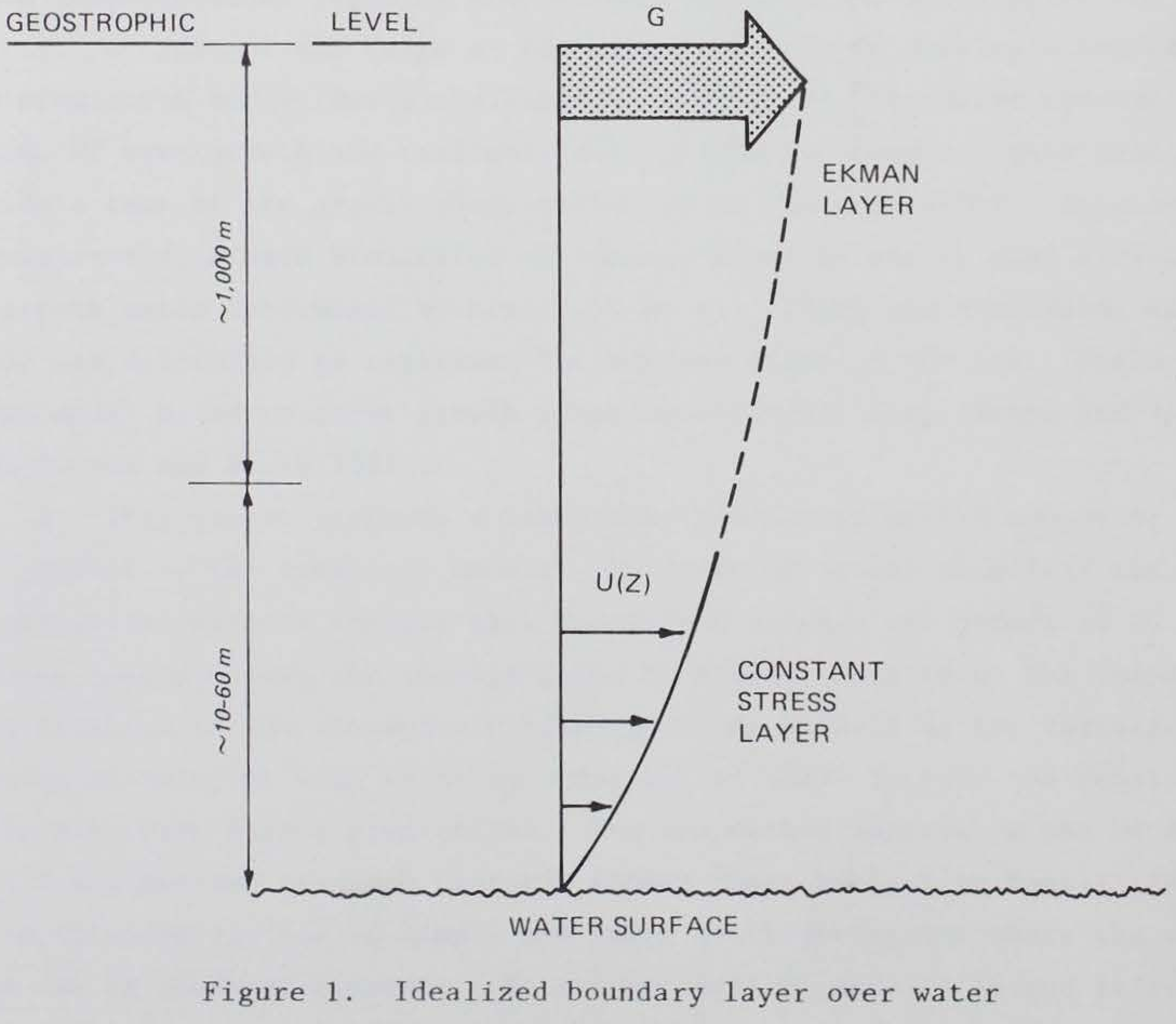

Figure 1. Idealized boundary layer over water

affected by the friction of the water surface and by horizontal and vertical temperature gradients. Just above the water surface is a region in which the shear stress is approximately constant and the vertical profile of wind velocities has a modified logarithmic form. This idealized view of the atmospheric boundary layer can be disturbed by a number of processes. The large scale and local pressure gradients can rapidly change, temperature inversions may occur, or local topography can cause convergence or divergence of the flow. However, this simplified representation of the boundary layer has proven very useful.

7. In practical terms the five variables of interest are (1) the shear stress

$$\tau = \rho U_*^2 \tag{1}$$

where

ρ = air density

U_* = friction velocity

(2) the wind speed $U(Z)$ as a function of elevation Z above the still-water surface; (3) the near surface wind direction; (4) the air and sea temperatures, T_a and T_s ; and (5) the horizontal temperature gradients. Horizontal temperature gradients are important because they can be shown to introduce a vertical variation in wind speed. However, horizontal temperature gradients are not often available for engineering design efforts and are not included here.

8. The constant stress region is of primary interest for wave generation. Without taking into account effects related to horizontal temperature gradients, the marine wind profile can be represented by (Cardone 1969):

$$U(Z) = \frac{U_*}{K}\left[\ln\left(\frac{Z}{Z_o}\right) - \psi\left(\frac{Z}{L'}\right)\right] \tag{2}$$

The parameter Z_o characterizes the roughness of the sea surface and is approximately related to U_* by the Charnock-Ellison relation

$$Z_o = 0.035\,\frac{U_*^2}{g} \tag{3}$$

The parameter L' is the Monin-Obukov length scale. It is related to the effects of temperature fluxes in the atmosphere and can be formulated in terms of the air-sea temperature difference $T_d = T_a - T_s$. The function ψ gives the effect of the vertical temperature gradient on the wind profile (Cardone

1969, Resio et al. 1981). The constant K is normally taken as 0.4.

9. The importance of understanding the mechanics of the atmospheric boundary layer in estimating wave growth is apparent from Equation 2. Wind speed is clearly not a unique indicator of the momentum transferred to the sea surface which is related to U_*. The elevation at which the wind is observed, the air-sea temperature difference, and the actual wind stress (which specifies the local roughness) can all vary, as well as the other factors previously neglected. Variation of these parameters can have significant impact on the relationship between wind speed and momentum transfer to the sea surface. Consider wind speeds measured during conditions when T_d is positive and large and when T_d is negative and large. When the magnitude of the measured speed is the same, the friction velocities could differ by 25 to 50 percent with the wind stresses correspondingly differing by the square of this difference (Figure 2).

10. The parameter Z_o represents the roughness of the water surface. If T_d is zero, substitution of Equation 3 into Equation 2 yields

$$U(Z) = \frac{U_*}{K} \ln \left(\frac{gZ}{0.035\ U_*^2} \right) \tag{4}$$

As the wind stress increases, the roughness length increases nonlinearly compared to the wind stress. Thus, a small increase in observed wind speed may be indicative of a larger increase in wind stress.

11. In most engineering problems it is inconvenient to work in terms of friction velocities because U_* is not a measured quantity. The coefficient of drag $C_{D,Z}$ is used to relate $U(Z)$ to U_*

$$U_*^2 = C_{D,Z} U(Z)^2 \tag{5}$$

For simplicity Z is commonly set to 10 m and the Z subscript is dropped. Garratt (1977) gives an empirical approximation for C_D as

$$C_D \sim U^{0.46} \tag{6}$$

for neutral stability conditions. Thus, from Equations 5 and 6

$$U_* \sim U^{1.23} \tag{7}$$

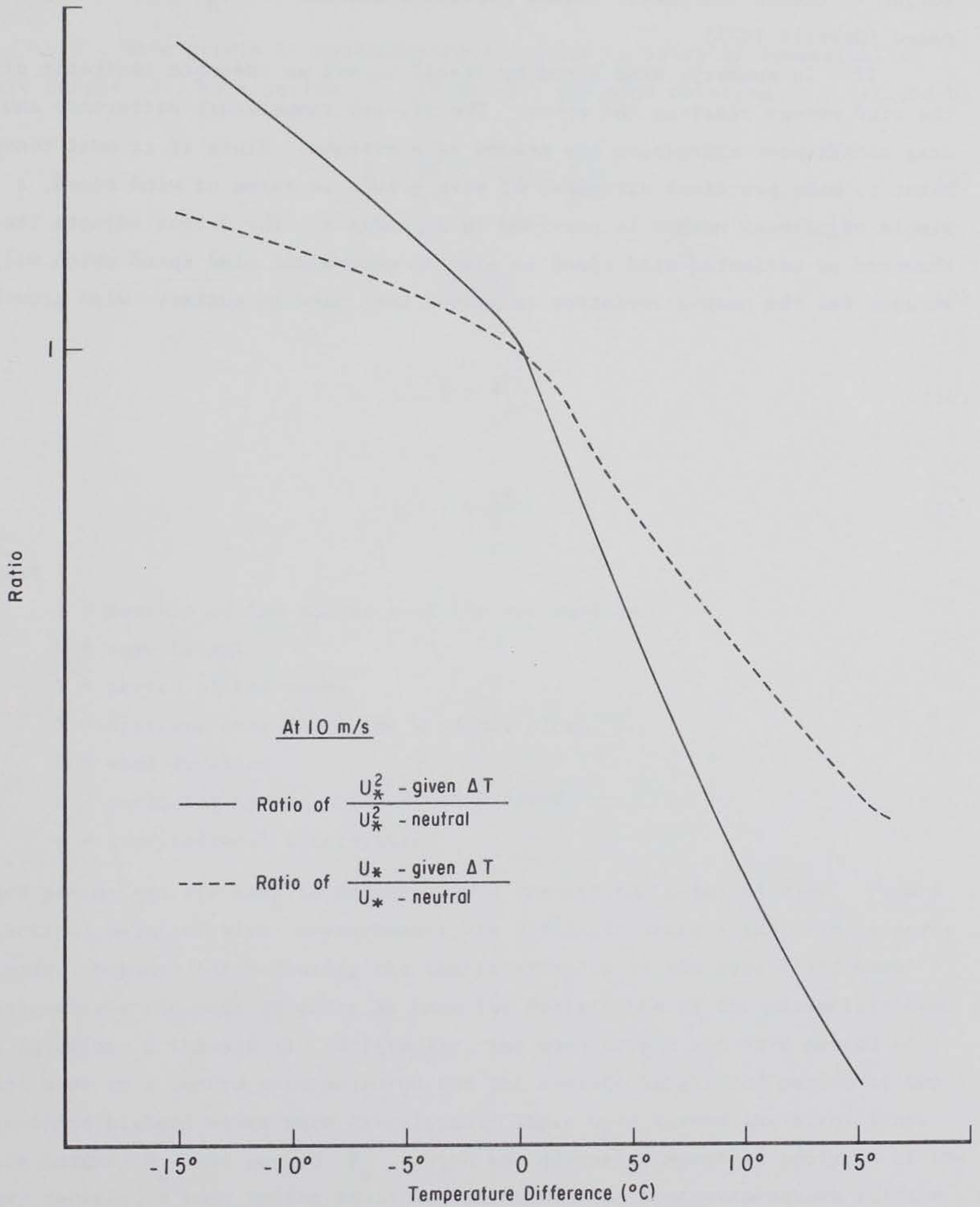

Figure 2. Effect of air-sea temperature difference on friction velocity and wind stress. Friction velocity is U_* and stress is proportional to U_*^2

Equation 7 is a convenient approximation to use for estimating the wind stress acting to create the waves. Other parameterizations of C_D have been proposed (Garratt 1977).

12. In summary, wind speed by itself is not an adequate indicator of the wind stress creating the waves. The air-sea temperature difference and a drag coefficient expression are needed as a minimum. Since it is most convenient to make practical estimates of wave growth in terms of wind speed, a simple adjustment method is provided in Appendix A. The method adjusts the observed or estimated wind speed to give an equivalent wind speed which will account for the proper variation in stress when used to estimate wind growth.

PART III: WAVE GROWTH FORMULAE

13. Wave growth is conveniently discussed in terms of dimensionless wave height $\bar{H}$, wave period $\bar{T}$, fetch $\bar{X}$, and wind duration $\bar{t}$, defined by

$$\bar{H} = \frac{gH}{U^2} \quad \text{or} \quad \bar{E} = \frac{g^2E}{U^4} \tag{8}$$

$$\bar{T} = \frac{gT}{U} \tag{9}$$

$$\bar{X} = \frac{gX}{U^2} \tag{10}$$

$$\bar{t} = \frac{gt}{U} \tag{11}$$

where

E = measure of the variance of the sea surface

H = wave height

T = period of the waves

X = distance over which the wind has blown

t = wind duration

U = parameter having units of wind speed

g = gravitational acceleration

Such parameters are easy to define from a theoretical point of view. From a practical point of view, measurements are difficult because the wind is never steady. Methods for measuring the characteristics of the wave field have changed over the past 30 years as have the definitions of the parameters used in Equations 8 through 11. Originally, the wave height and wave period of each wave in a record were measured and the average height and period of the one-third highest waves were calculated. These were termed the significant wave height H_s and period T_s . With the advent of spectral analysis of the wave records, a wave height equal to four times the root-mean-square surface displacement (which will be termed H_{m_o} here) was calculated and called significant wave height because it is approximately equal to H_s in deep water. The peak frequency of the spectrum, f_m , was recognized as being more fundamentally linked to wave dynamics. Also the dimensionless energy, $\bar{E}$, formulated as $\left(gH_{m_o}/4U^2\right)^2$, has been widely used in wave growth studies. The height and period formulations are close enough that interchanging them does not introduce large errors in deep water.

14. Wave growth has often been studied by determining relationships between dimensionless parameters, such as the following:

$$\bar{H} = F_1(\bar{X},\bar{U}) \tag{12}$$

$$\bar{T} = F_2(\bar{X},\bar{U}) \tag{13}$$

$$\bar{H} = G_1(\bar{t},\bar{U}) \tag{14}$$

$$\bar{T} = G_2(\bar{t},\bar{U}) \tag{15}$$

where relationships F_1 and F_2 represent fetch-limited growth and G_1 and G_2 represent duration-limited growth. Equations 12 through 15 are idealizations of the general problem relating $\bar{H}$, $\bar{T}$ simultaneously to $\bar{X}$, $\bar{U}$, and $\bar{t}$. There is a wide range of equations for estimating wave conditions (Rottier and Vincent 1982). When reduced to an equivalent basis, the formulae are not all in good agreement (Figure 3) so a choice must be made.

15. The reasons for the differences in the wave growth relationships are diverse. There are differences in instrumentation and in parameters measured. Many of the formulae are based on wind speed rather than wind stress. Furthermore, there is always the problem that some cases are not purely fetch-limited or duration-limited but may be a combination of both conditions. The curves are derived empirically so there are statistical uncertainties.

Fetch-Limited Wave Growth

16. The equations developed by Mitsuyasu (1969) and Hasselmann et al. (1973) are very similar and were selected in the Corps' Wave Information Study (Resio 1981) for fetch-limited wave growth because the waves were measured at

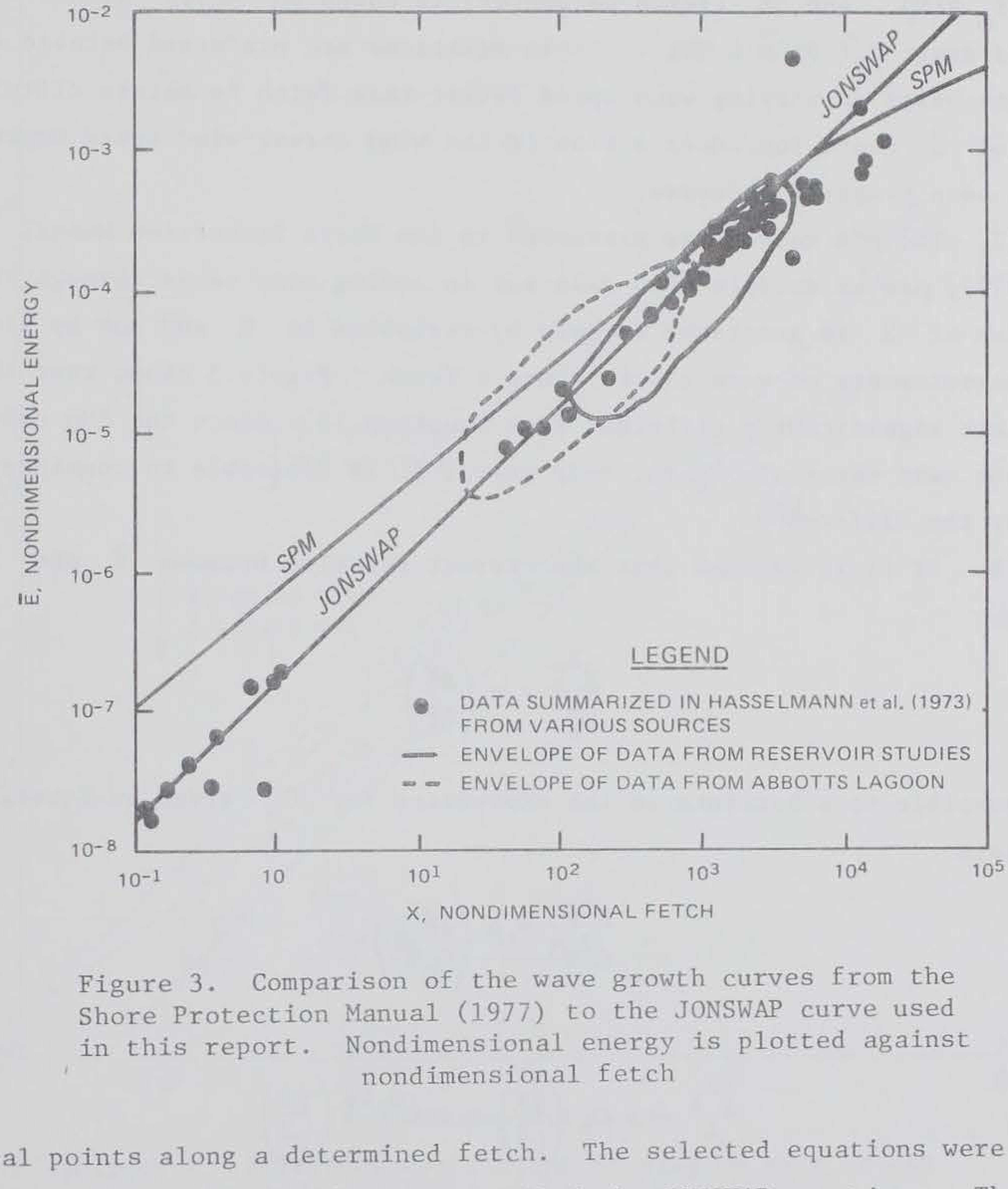

Figure 3. Comparison of the wave growth curves from the Shore Protection Manual (1977) to the JONSWAP curve used in this report. Nondimensional energy is plotted against nondimensional fetch

several points along a determined fetch. The selected equations were given by Hasselmann et al. (1973) and are called the JONSWAP equations. They are the following:

$$\bar{E} = 1.6 \times 10^{-7}\ \bar{X} = \frac{g^2 H_{m_o}^2}{16U^4} \tag{16}$$

$$\bar{f}_m = 3.5 \left(\bar{X}\right)^{-0.33} \tag{17}$$

where $\bar{f}_m = \left(\bar{T}\right)^{-1}$ and $\bar{X}$ (fetch parameter) is based on $U(10)$ with a coefficient of drag $C_D(10) = 0.001$. These equations are preferred because other data sets based on varying wind speed rather than fetch to obtain different values of $\bar{X}$ could introduce a bias if the wind stress-wind speed dependence has not been properly assessed.

17. The SMB curves, as presented in the Shore Protection Manual (US Army 1977), are an example of a data set including many cases through which variation of $\bar{X}$ is generated largely by variation in U and not by simultaneous measurements of wave growth along a fetch. Figure 3 shows that the SMB curves are significantly different from Equation 16. Since the SMB curves have been used successfully for many years, it is desirable to consider reasons for the differences.

18. If it is assumed that the correct relation between $\bar{E}$ and $\bar{X}$ is given by

$$\frac{g^2E}{U_*^4} = a \left(\frac{gX}{U_*^2}\right) \tag{18}$$

it is possible to substitute in the expression for C_D given by Equation 5 and obtain

$$\frac{g^2E}{C_D^2U^4} = a \left(\frac{gX}{C_DU^2}\right) \tag{19}$$

or

$$\frac{g^2E}{U^4} = a\ C_D \left(\frac{gX}{U^2}\right) = a'U^{0.46} \left(\frac{gX}{U^2}\right) \tag{20}$$

The terms a and a' are proportionality constants. If the case of a string of stations along a fetch is considered, the coefficient $a'U^{0.46}$ can be estimated and the basic relationship will appear to have the same exponent as in Equation 18 but with a different coefficient. Curve A in Figure 4 illustrates the variation in $\bar{X}$ obtained by varying X for fixed U . If, instead, $\bar{X}$ is varied by holding X fixed and varying U , a plot of $\bar{E}$ versus $\bar{X}$ (Figure 4) appears to be nonlinear in $\bar{X}$ because of the effect of $U^{0.46}$

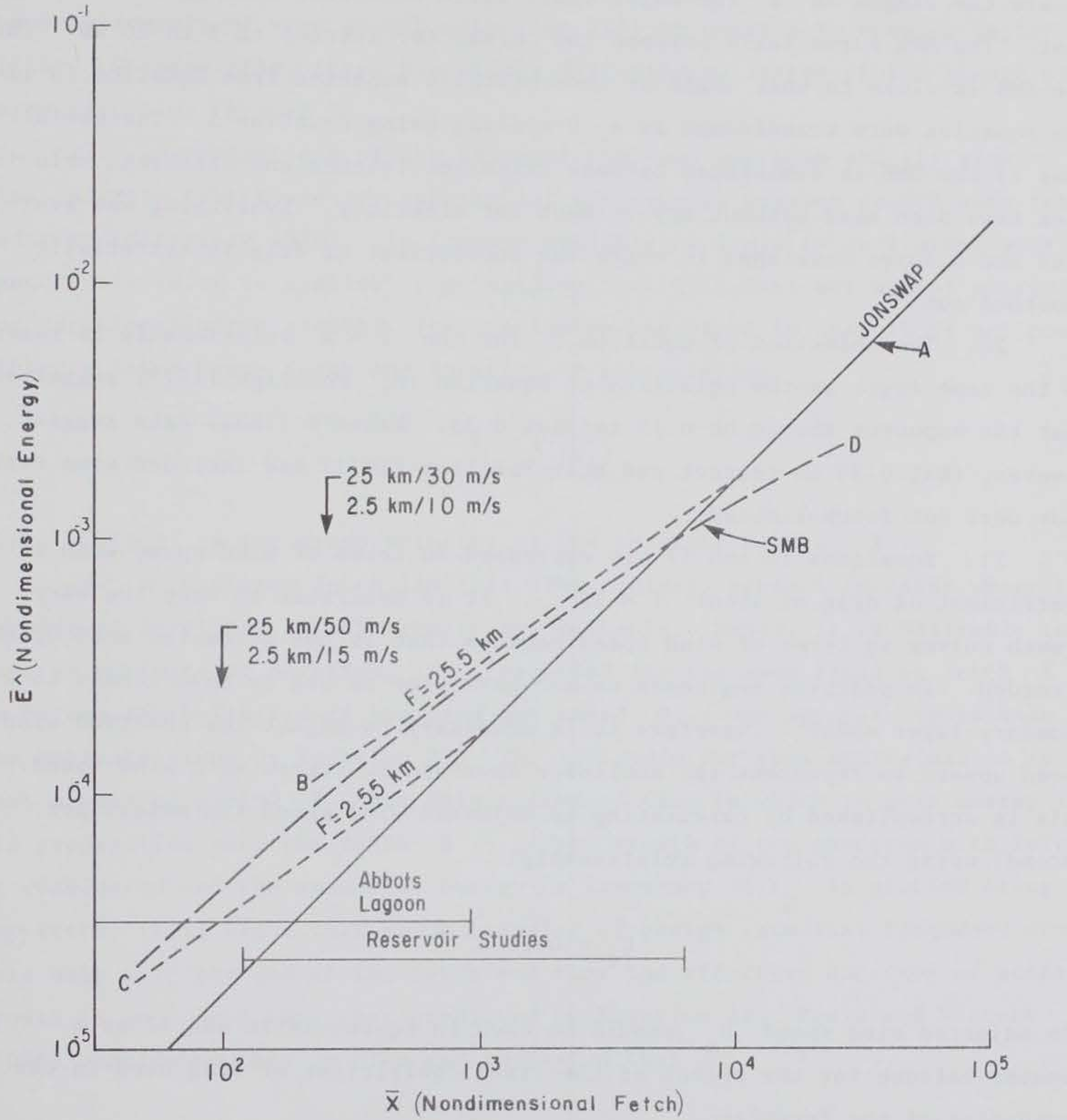

Figure 4. Effect of coefficient of drag on wave growth relations. Curves B and C show how the JONSWAP curve would plot if a nonconstant coefficient of drag were incorporated in terms of wind velocity

(curves B and C). If $U > 1$, then the $\bar{E} - \bar{X}$ relationship will be high with respect to Equation 18.

19. Since the SMB curves are a composite of cases where U is a main variable, the deviation shown in Figure 3 may represent the effect of not scaling on friction velocity which is required by Equation 20 to give the

correct prediction of growth. In Figure 4 the SMB curve is plotted (curve D) as are the ranges in $\bar{X}$ for major short fetch data sets used in its development. The SMB curve falls between the curves for fetches of 3 to 26 km. Thus, the SMB is close to what would be theoretically expected from Equation 16 if the equation were transformed to a U-scaling using Equation 5. The usefulness of the SMB is diminished because different fetches and different velocities have been used without any account for stability. Everything was averaged and a curve developed in which the coefficient of drag is essentially smoothed out.

20. The selection of Equation 17 for the $\bar{T} - \bar{X}$ relationship is based on the same logic as the selection of Equation 16. Phillips (1977) suggested that the exponent should be 0.25 and not 0.33. Kahma's (1981) data suggest, however, that 0.33 is correct and that Phillips (1977) had included some data that were not fetch-limited.

21. Equations 16 and 17 are expressed in terms of wind speed with a coefficient of drag of about 1×10^{-3}. It is desirable to keep the wave growth curves in terms of wind speed because that is the parameter most often recorded. In practice engineers do not have time to use or have access to a boundary layer model. Therefore it is necessary to adjust the observed wind speed upward to represent the nonlinear increase in stress with wind speed. This is accomplished by calculating an adjusted wind speed (in meters per second) using the following relationship:

$$U_a = 0.71\ U^{1.23} \qquad (21)$$

The adjusted wind speed U_a should be used in Equations 16 and 17 as a counter-balance for the effect of the fixed coefficient of drag used in the derivation of the formulae.

Duration-Limited Wave Growth

22. The measurement of fetch-limited wave growth is relatively straightforward. Measurement of growth of waves with time is more difficult. It would appear possible to place a measurement station in the middle of the ocean and obtain the desired data. It is evident, however, that with increasing time, the energy arriving at the station must come from increasingly different distances (varying with wave frequency) from the study point. Unless

the wave field is initially calm everywhere and the wind field is constant, the measurements of wave growth with time will be subject to unknown variability. Consequently, there are widely differing estimates of the growth of waves with time (Figure 5).

23. Investigations of the shape of the wave spectrum and its growth also indicate that there are substantial differences between growth with fetch and time (Mitsuyasu 1980). It appears possible to scale fetch-limited wave spectra according to similarity principles, but this does not appear possible for duration-limited growth. The conclusion therefore is that it is not possible to interchange fetch and duration by the relation

$$t = \frac{X}{C_g(T_p)} \tag{22}$$

where $C_g(T_p)$ is the group velocity of the spectral peak at X.

24. An upstream fetch limit is almost always present in cases where the techniques developed in this report are suitable. Hence, it is desirable to have an estimate of duration, t_F, required for the wave field at fetch X to become fetch-limited if the wind has speed U. One approach is to make the estimate given by Equation 22. The rationale for this approximation is that a wave of period T_p has this period of time in which to gain energy in its propagation over the fetch X. If the growth of the spectrum with fetch is considered and the amount of energy in frequency $1/T_p$ is plotted along the fetch, it is clear that major transfer of energy into that frequency occurs only near the end of the fetch and that the effective duration of actual growth is much less than that predicted by Equation 22. Resio and Vincent (1979) considered this problem and suggested that

$$t_F = \frac{X}{\bar{C}_g} \tag{23}$$

where $\bar{C}_g$ is the group velocity of waves at the spectral peak averaged over the fetch

$$\bar{C}_g = \frac{1}{X} \int_o^X \frac{g}{2\pi} T_p(y)dy \tag{24}$$

obtaining

$$t_F = 68.8 \; X^{2/3} \; U^{-1/3} \; g^{-1/3} \tag{25}$$

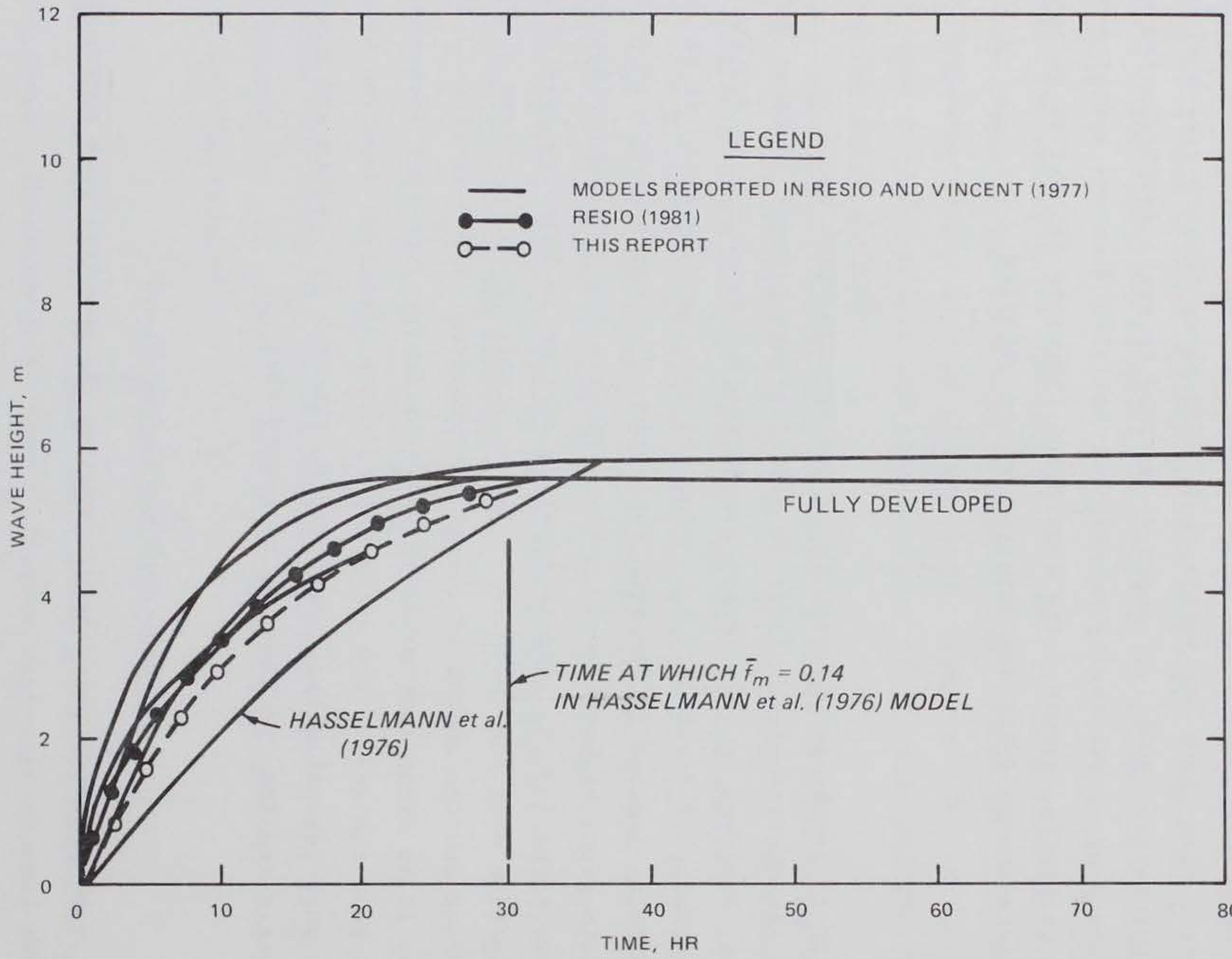

Figure 5. Wave height plotted against duration for different wave growth models (Resio 1981)

25. Equations 16, 17, and 25 provide estimates of wave height and period at the end of the fetch and the time it takes for waves to grow to these values. The next step is to develop an equation for the rate of wave growth.

26. Hasselmann et al. (1976) suggested a simple wave model for spectral evolution based on a parameterized wave spectrum. Two differential equations in their lowest order model can provide estimates of significant wave height and peak period with time. The wind field and wave field are presumed to be uniform in space and the wind is presumed to be constant in space and time for duration-limited growth. Therefore all spectral gradient terms and all time derivatives of the wind speed are zero by definition, and the solutions for duration-limited waves become

$$\frac{gH_{m_o}}{U^2} = 8.293 \times 10^{-5} \left(\frac{gt}{U}\right)^{5/7} \tag{26}$$

$$\frac{gT_p}{U} = 6.76 \times 10^{-2} \left(\frac{gt}{U}\right)^{3/7} \tag{27}$$

27. A comparison of Equation 27 with other growth rates suggests that the rate is low for wave period. As discussed earlier, the rate of growth is not well known. The primary assumption that Hasselmann et al. (1976) used was that the fetch-limited spectral shape also applied for duration-limited growth, but this is inaccurate to some unknown degree.

28. Since the correct rate of growth is uncertain, the objective is to develop a set of growth curves that are not in disagreement with measured data yet yield the correct fetch-limited values of H_{m_o} and T_p given by Equations 16 and 17 (where wind speeds have to be scaled to the correct stress by Equation 21). Calculations of the H_{m_o} and T_p at fetch X for wind speed U were matched with H_{m_o} and T_p calculated for duration t_F. The results for wave height were in close agreement, but those for T_p were not acceptable. The curves from Equations 26 and 27 were adjusted and the following equations were obtained:

$$\frac{gH_{m_o}}{U_A^2} = 8.51 \times 10^{-5} \left(\frac{gt}{U_A}\right)^{5/7} \tag{28}$$

$$\frac{gT_p}{U_A} = 7.02 \times 10^{-2} \left(\frac{gt}{U_A}\right)^{0.411} \tag{29}$$

and give reasonably good agreement (Figure 6) in wave height over all nondimensional fetches. They also agree in period for all but short fetch-low wind speed conditions where the duration-limited value overpredicts the fetch-limited value.

Fully Developed Wave Conditions

29. A wind blowing over the open ocean appears to generate an equilibrium spectrum after some duration. At that time

$$T_p = 8.134 \frac{U}{g} \tag{30}$$

and

$$H_{m_o} = 2.433 \times 10^{-1} \left(\frac{U^2}{g}\right) \tag{31}$$

Equations 16, 17, 28, and 29 therefore should be limited in order not to surpass these values.

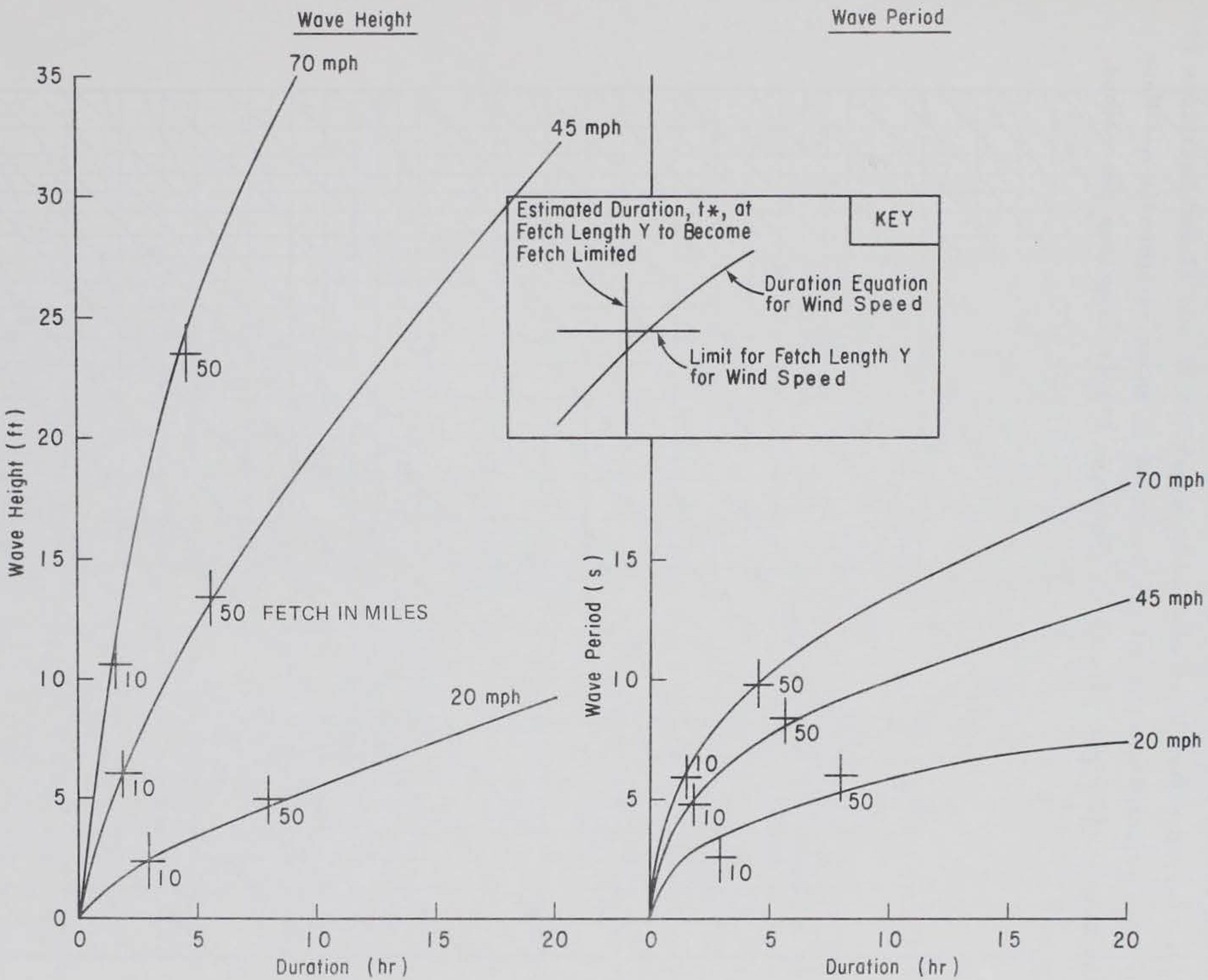

Figure 6. Intercomparison of duration and fetch formulae for wave height and period

PART IV: WAVE GROWTH CURVES

30. Equations 16 and 17 and Equations 28 and 29 are combined into the set of wave growth curves given in Figure 7. The adjusted wind speed is required for use in Figure 7 or when using Equations 16 and 17 and Equations 28 and 29. The adjusted wind speed can be found as shown in Appendix A. Note that the drag coefficient adjustment (Equation 21) is in meters per second.

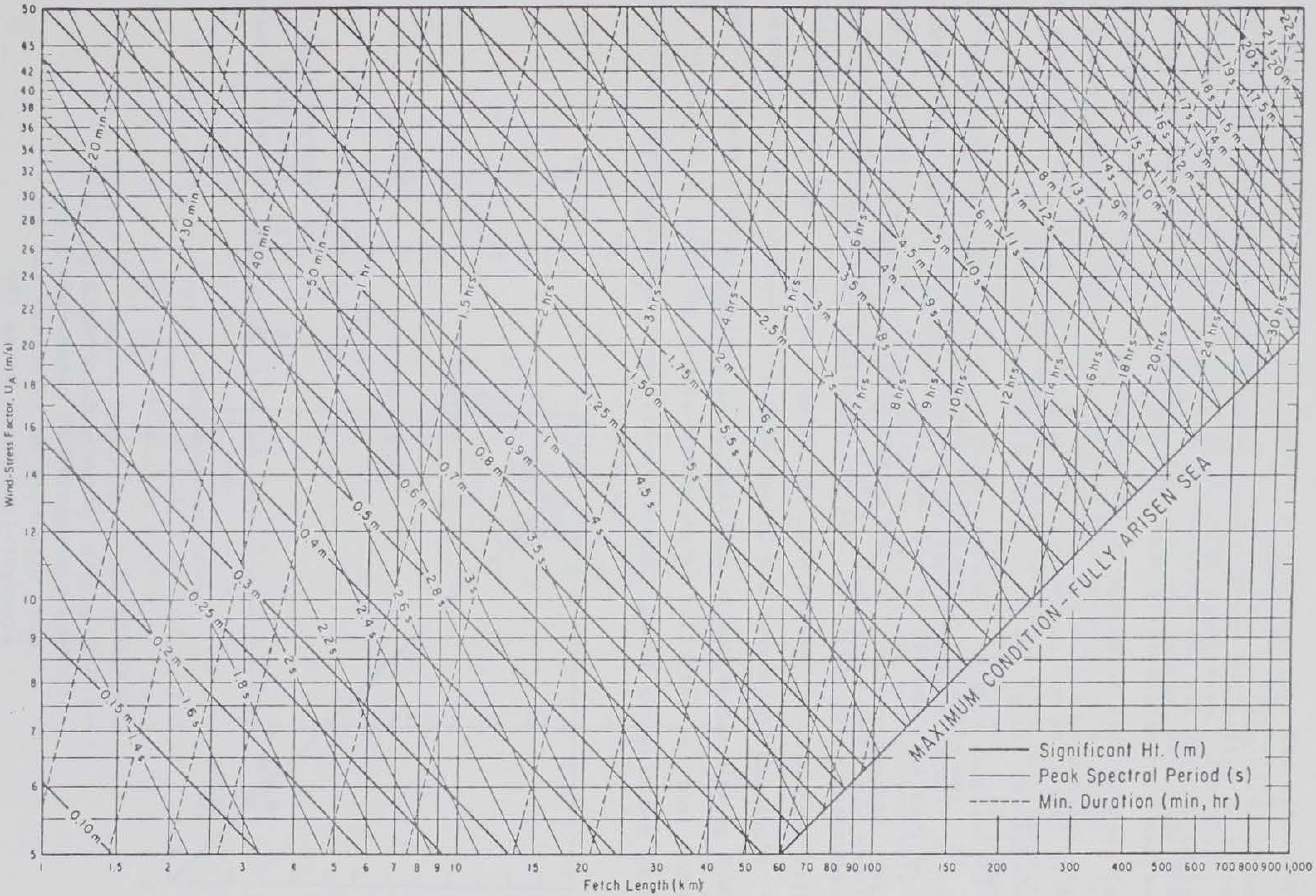

Figure 7. Nomograms of deepwater significant wave prediction curves as functions of wind speed, fetch length, and wind duration

31. Frequently, the geometry of the water body is complex and it is difficult to define the fetch. Saville (1952) developed the effective fetch method to account for the influence of fetch width on wave generation. The method has been successfully used with the SMB curves. When Resio and Vincent (1979) applied this technique to the JONSWAP growth curves contained herein, the predicted wave height was consistently less than that measured (Figure 8). Predictions made with a straight line estimate of fetch were in much closer agreement with the observations.

32. The effective fetch method was developed when the deepwater curves that evolved into the SMB method were first applied to short fetch conditions on lakes and reservoirs. The SMB method provided estimates that were too high in comparison to observations. It was theorized that since the lakes and reservoirs were narrow, the width of the water body restricted wave growth. However, since the SMB curves are biased high with respect to the Mitsuyasu-JONSWAP growth curves due to the effects of scaling on wind speed, it appears possible that the effective fetch method simply attempts to adjust for this bias by reducing the fetch. Since the Mitsuyasu-JONSWAP growth curves are

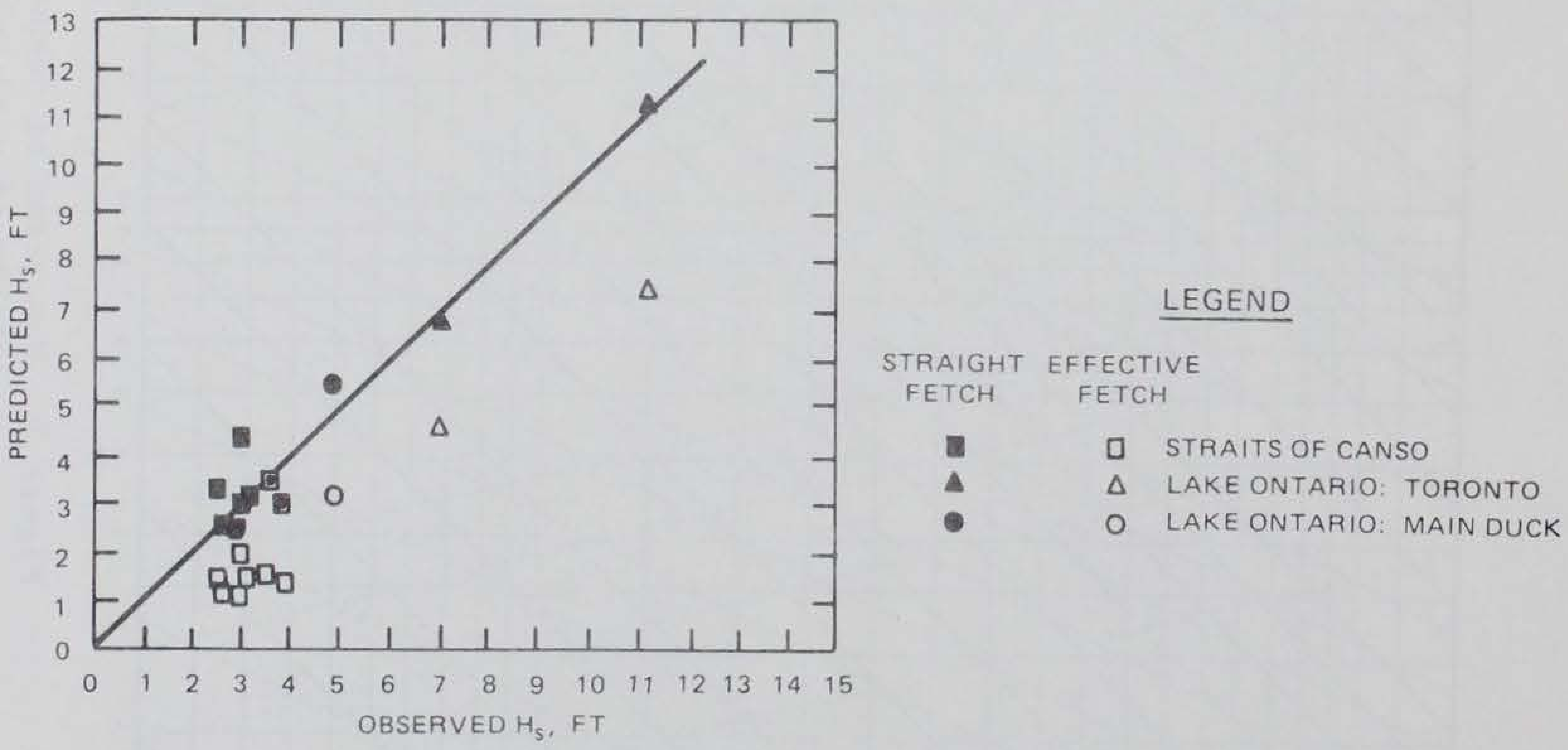

Figure 8. Narrow fetch data (Resio and Vincent 1978). Predictions are made with both an effective and a straight-line fetch using the method of this report

scaled by friction velocity, no such adjustment would be needed. To test this, some of the narrow fetch data used to develop and test the effective fetch method were compared with the method presented here (Figure 9). The observations are in reasonable agreement with the prediction. Therefore, the effective fetch method must not be used with the new curves, while the SMB curves require its use.

33. For Equations 16 and 17, fetch should be either a straight line estimate or an average over an arc of 22-1/2° centered on the principal wind direction. The 22-1/2° arc is suggested because it is the normal resolution for which wind direction is available (16 point compass). Highly complicated fetch-weighting schemes are appealing because they provide a formula to estimate fetch, but they may be inaccurate due to the nature of the available wind data. If the geometry of the fetch is highly irregular, a numerical model may be required.

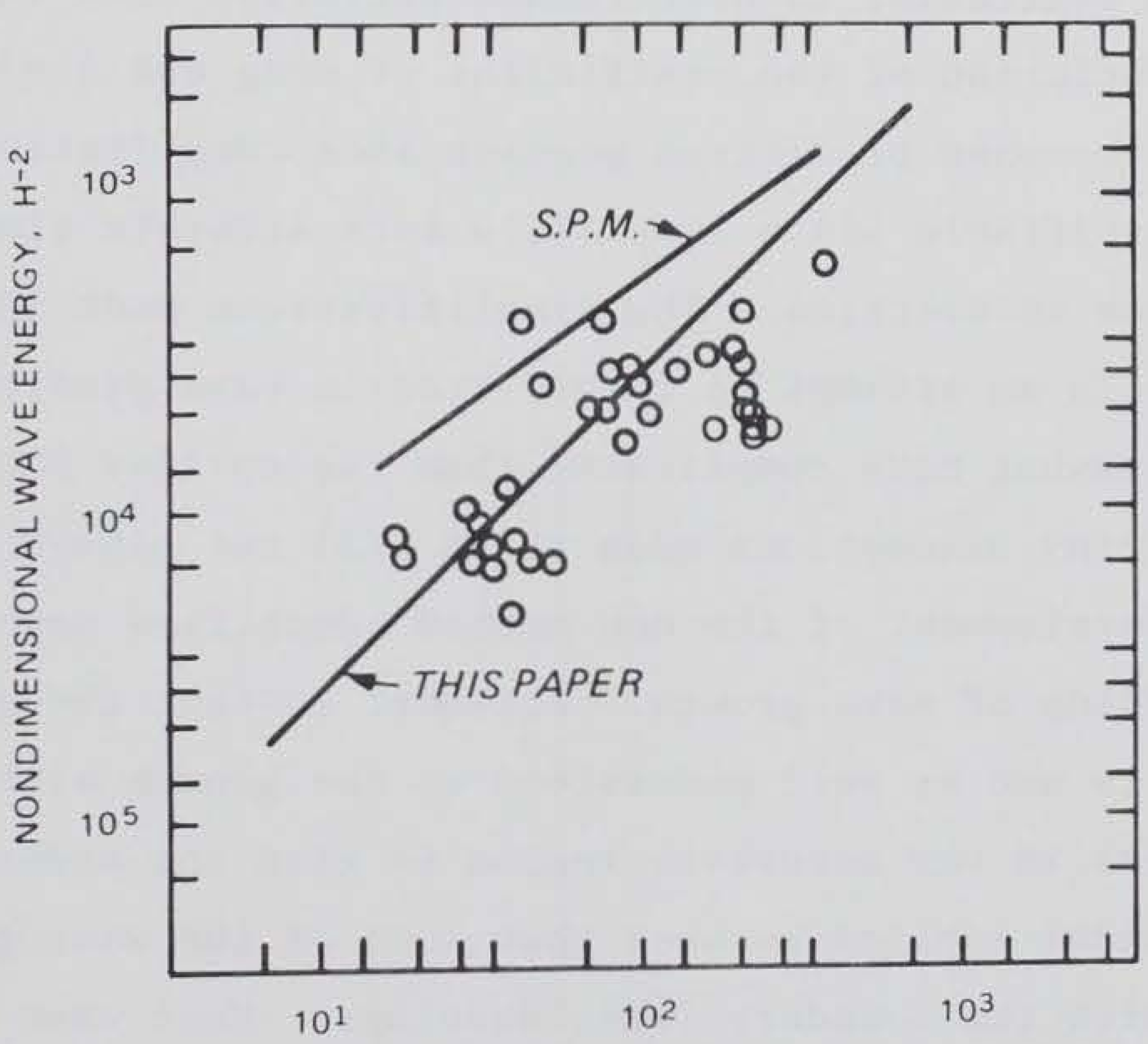

Figure 9. Narrow fetch data from reservoirs (Office, Chief of Engineers, 1962). The fetch data are scaled by straight-line fetch

PART VI: SUMMARY AND CONCLUSIONS

34. This report presents a method for estimating wave height and period for simple fetch- and duration-limited wave growth cases. The method is consistent with the more advanced numerical wave models developed as part of the Corps of Engineers Wave Information Study (Resio et al. 1981). The method differs from the SMB technique presented in the Shore Protection Manual (US Army 1977) in that the wave growth rates are taken from the studies of Mitsuyasu (1980) and JONSWAP (Hasselman et al. 1976) and the velocity scaling relates to friction velocity.

35. The friction velocity scaling allows for perturbations of the observed wind velocity to account for atmospheric stability and the variation of the drag coefficient with wind speed. The adjustments for air-sea temperature difference may not always be possible without measured data. In such cases assuming a temperature difference with a slightly negative value will give a conservative result. Measured data for the air-sea temperature difference should be applied, when available, to help reduce potential bias in wave estimates.

36. The inclusion of the coefficient of drag and air-sea temperature variations into the wave prediction process adds complications. However, the additions are justifiable since they allow more accurate simulation of the physics of air-sea interaction. The simplifications made in developing the new method were made in an attempt to reduce bias in wave prediction. Although the new method is somewhat more complicated than the earlier SMB method, there still have been many assumptions made which will not always hold.

37. The development of the new method identified several deficiencies in the understanding of wave growth. Foremost is that the growth of the wave field with time is not as well understood as the growth with fetch. The development of waves in the nearshore region is also not understood and the boundary layer model applied assumes that much of the wave growth is outside the region in which the boundary layer develops. Most wave growth studies have been at velocities less than 20 meters per second. Data from very high velocity cases would provide a desirable check. These problems are present in all current wave prediction methodologies. There is still debate on the choice of values for the coefficient of drag. The method provided here can easily be updated by modifying Equation 21 if better information on the coefficient of drag becomes available.

38. The new method has been developed with the assumption of a simple fetch and constant wind speed and direction. Use of this technique where such conditions do not exist induces additional error. It is recommended that this method not be used for fetches of 200 km or more. Use of a detailed numerical model is then advised. Problems involving variations in wind speed and direction may also best be solved using a numerical prediction scheme.

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APPENDIX A: WIND ESTIMATION AND WIND SPEED ADJUSTMENT

1. Use of the simple method of wave estimation provided in this report assumes a constant wind speed exists over the fetch of interest for the given duration. Since the wind is actually never constant and observed winds are rarely measured over the water, it is necessary to have some method for estimating winds over the water. The method provided below is based on research conducted in the Great Lakes. It is based on a number of simplifying assumptions that may not apply to sites where topographic convergence or divergence occurs or where there are marked variations in surface roughness. For problems of unusual complexity, meteorological consultations are recommended. It is suggested that wind speed estimates derived from geostrophic analyses of meteorological charts not be used in such circumstances.

2. The wind speed adjustment procedure assumes that wind measurements are available either over the water body or adjacent to it. For measurements not taken directly over the water, it is assumed that the wind field over the water and over the meteorological station are driven by the same pressure gradient. The procedure should not be used if this assumption does not apply. (Thunderstorms or squall lines may represent such a case.)

3. The following equations are given for wind speed adjustments.

I. Height Adjustment. The wind speed U_o (meters per second) must be corrected to a 10-m elevation. If Z_L is the elevation where it was observed, an approximation is

$$U_{10} = \left(\frac{10}{Z_L}\right)^{1/7} U_o \tag{A1}$$

II. Location Correction Adjustment. If the fetch length is less than 16 km,

$$U_W = 1.1\ U_o \tag{A2}$$

If fetch length is greater than 16 km,

$$U_W = R(U_o) \times U_o \tag{A3}$$

where $R(U_o)$ is given in Figure A1.

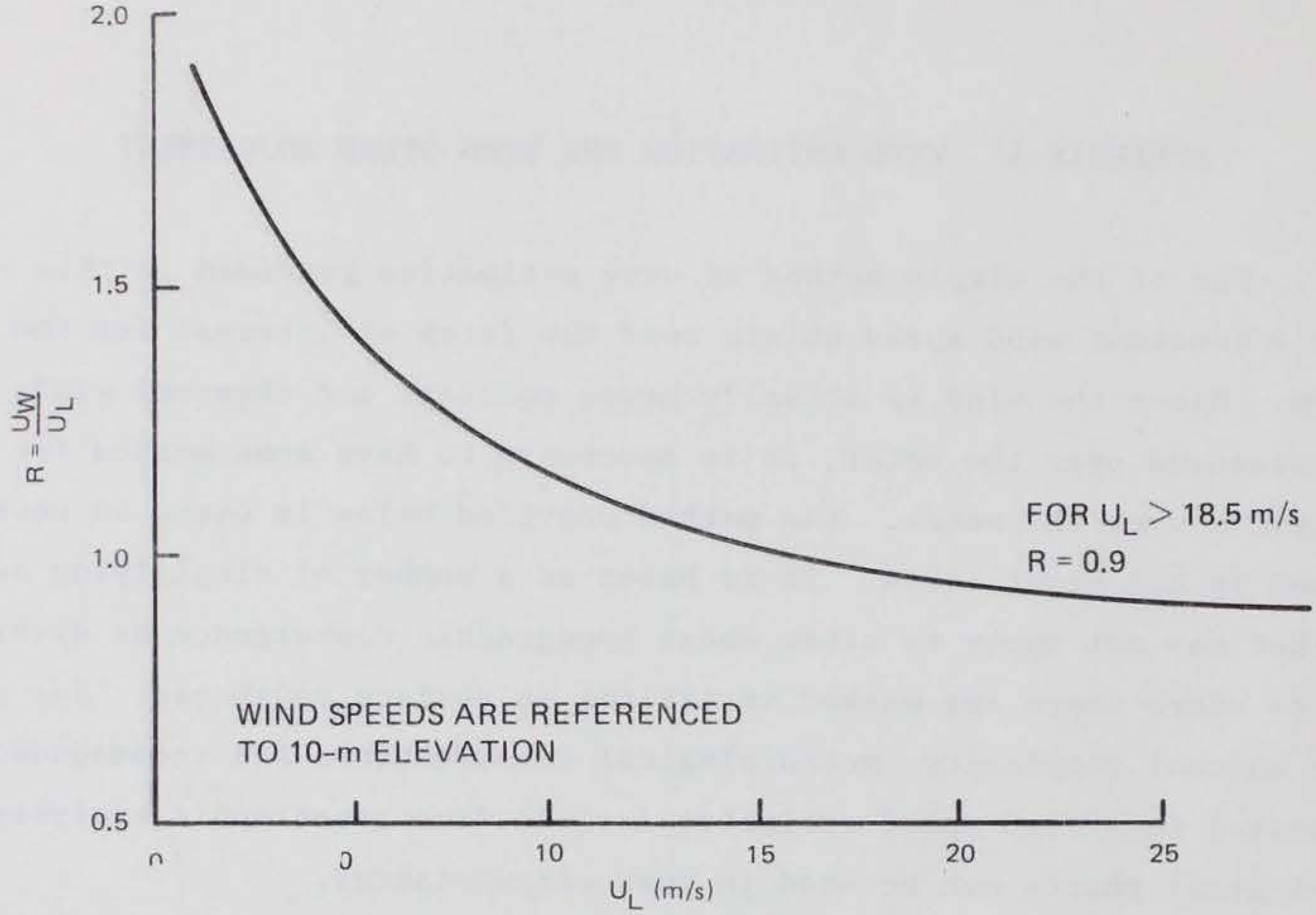

Figure A1. Ratio, R, of wind speed over water, U_W, to wind speed over land, U_L, as a function of wind speed over land, U_L (Resio and Vincent 1976)*

III. Drag Coefficient Adjustment. The over-water wind speed (meters per second) should be corrected for the drag coefficient dependence on velocity by

$$U_C = 0.71\ U_W^{1.23} \tag{A4}$$

In no case should a "corrected" wind speed be assumed.

IV. Stability Adjustment. The wind speed should be corrected according to whether the air is unstable (air-sea temperature difference, $T_d = T_a - T_s < 0$) or stable ($T_d = T_a - T_s > 0$). The correction is given by

$$U_A = R_T U_C \tag{A5}$$

where R_T is taken from Figure A2. If T_d is zero, the boundary layer has neutral stability and $R_T = 1$.

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* References are located at the end of the main text.

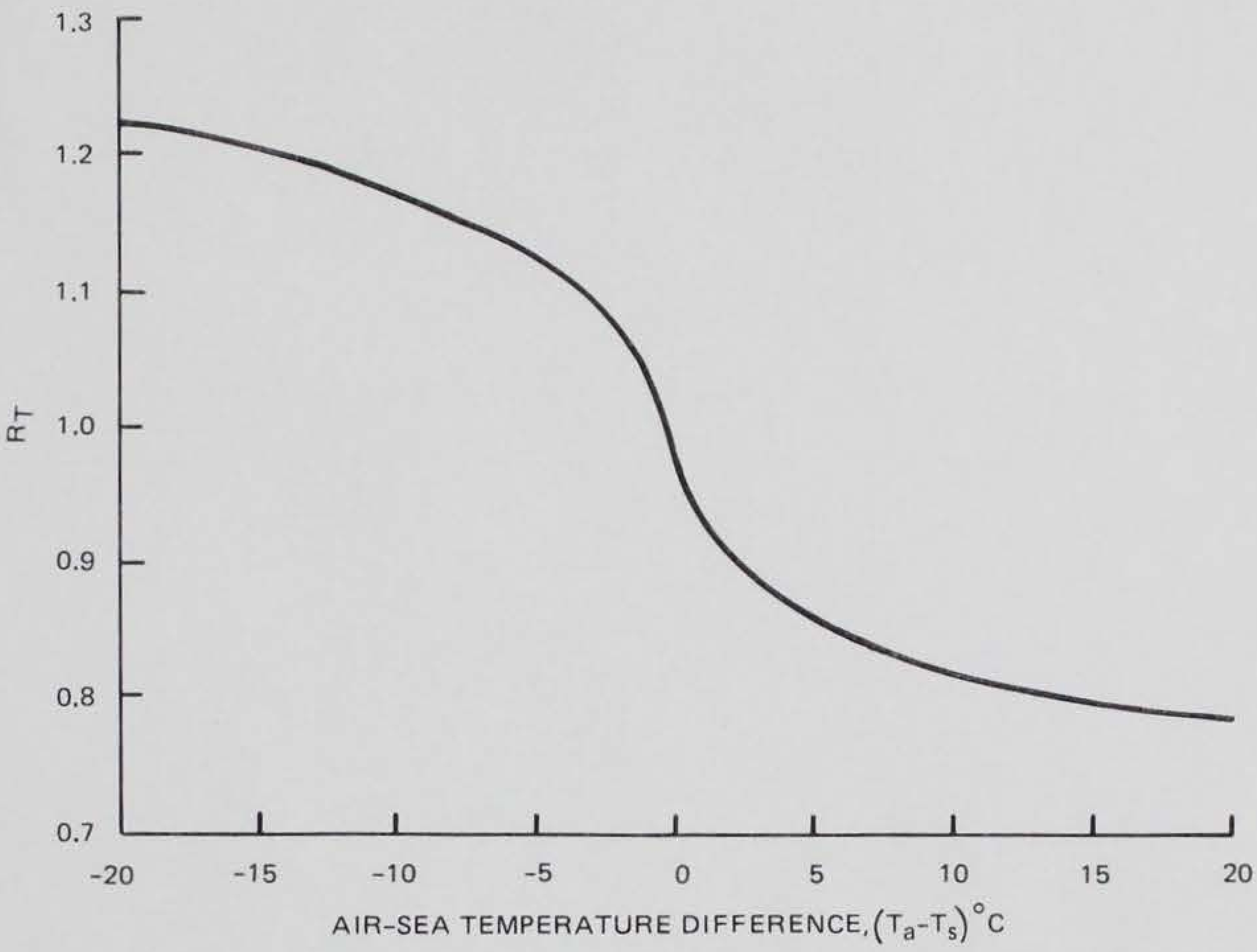

Figure A2. Amplification ratio, R_T , accounting for effects of air-sea temperature difference (Resio and Vincent 1976)

4. The typical meteorological observations and the types of adjustments required are given below. The order of adjustment should be followed:

   a. Winds observed over the water. Adjustments I, III, and IV.

   b. Winds observed over land immediately adjacent to the water (no trees, flat land, less than 0.5 km to water).

      (1) Onshore winds--adjustments I, III, and IV.

      (2) Offshore winds--adjustments I, II, III, and IV.

   c. Winds not observed near the water. Adjustments I, II, III, and IV.

5. Adjustment I is not required if the observation level is 10 m. Adjustments III and IV are always required.

6. If the study requires the use of statistical design winds, then the corrections should be made to the raw data. If air-sea temperature differences are not known, the general trend for a season may be inferred by considering season and likely combinations of wind direction. An automatic assumption of neutral, stable, or unstable air may be unrealistic and introduce unnecessary bias.