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REMARKS

Standard Project Hurricane

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from Tom Richardson

Andy Morang

ENGINEER MANUAL

EM 1110-2-1412
15 APRIL 1986

ENGINEERING AND DESIGN

STORM SURGE ANALYSIS

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College Station, TX

DEPARTMENT OF THE ARMY
CORPS OF ENGINEERS
OFFICE OF THE CHIEF OF ENGINEERS

DEPARTMENT OF THE ARMY
U. S. Army Corps of Engineers
Washington, D. C. 20314-1000

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DAEN-CWH-W

Engineer Manual
No. 1110-2-1412

15 April 1986

Engineering and Design
STORM SURGE ANALYSIS AND DESIGN WATER LEVEL DETERMINATIONS

1. Purpose. This manual provides guidance for storm surge analysis and design and water level determinations in coastal areas.

2. Applicability. This manual applies to all HQUSACE/COE elements and field operating activities (FOA) engaged in civil works functions.

3. Discussion. In coastal regions, storm surge analysis is essential to proper planning and design of engineering works and in assessing the extent and levels of flooding. Surge induced primarily by winds associated with storms when combined with other causes of water level variations, such as astronomical tides, can raise water elevations significantly above normal levels. These abnormal levels accompanied by wind generated surface waves pose a special threat to coastal communities and engineering structures. This manual provides guidance for predicting storm surge and estimating the total rise in water level in coastal areas. All applicable guidance included in this manual must be used to insure proper evaluation of design water levels.

FOR THE COMMANDER:

Arthur E. Williams

ARTHUR E. WILLIAMS
Colonel, Corps of Engineers
Chief of Staff

DEPARTMENT OF THE ARMY EM 1110-2-1412
U. S. Army Corps of Engineers
DAEN-CWH-W Washington, D. C. 20314-1000

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Table of Contents

APPENDIX C

CRITERIA FOR DETERMINING SPH AND PMH WIND FIELDS

C-1. General. This appendix summarizes the necessary meteorological criteria presented in Technical Report NWS 23 (item 57 in Appendix A) for developing wind fields in connection with a Standard Project Hurricane (SPH) and the Probable Maximum Hurricane (PMH). Details and justification for adopting the various criterions as presented herein are omitted; however, such information can be found in the original report.

C-2. Meteorological Parameters.

a. The various meteorological parameters used for describing hurricane wind fields are identified as:

peripheral pressure (p_n)
central pressure (p_o)
radius of maximum winds (R)
forward speed (V_f)
track direction (θ)
inflow angle (α)

which were presented in Chapter 1. In defining wind fields it is also necessary to consider wind speed distribution and the limits of rotation of the wind.

b. All of the parameters, with the exception of the peripheral pressure p_n and the inflow angle α, generally vary along the Gulf and East Coasts of the United States. As a consequence the National Weather Service developed a standard chart with distances along the abscissa with mileposts beginning (mile 0) at the United States-Mexico border and ending at United States-Canada border. These mileposts are adopted for all storm surge studies conducted by the Corps of Engineers.

c. The meteorological parameters are to be determined as follows:

(1) Peripheral Pressure. For the SPH and PMH the peripheral pressure p_n or the sea-level pressure at the outskirts of the hurricane is to be taken as 29.77 in. (100.8 kPa) and 30.12 in. (102.0 kPa), respectively. (It is noted that atmospheric pressure given herein in units of inches (in.) implies inches of mercury.)

(2) Central Pressure. The lowest sea-level pressure p_o at the hurricane center is determined from Figures C-1 and C-2 for the SPH and PMH for a given coastal location.

(3) Radius of Maximum Winds. Figures C-3 and C-4, respectively, show the radial distances from the hurricane center to the regions of maximum winds R for SPH and PMH. It is to be noted that R can vary in a range between the upper and lower limits specified.

(4) Forward Speed. The range of translation speed V_f of the hurricane center for the SPH and PMH is shown in Figures C-5 and C-6.

(5) Track Direction. The permissible range of track direction θ for the SPH and PMH is shown in Figures C-7 and C-8, respectively. Categories A, B, and C indicated in these figures refer to forward speed V_f of the hurricanes. These speed categories are defined in Table C-1.

C-3. Pressure Distribution. The mathematical expression for defining the pressure distribution (item 45 of Appendix A) within a SPH and a PMH is:

$$\frac{p - p_o}{p_n - p_o} = e^{R/r} \qquad [C-1]$$

in which p is the sea-level pressure at the radial distance r from the hurricane center. This expression is used to develop the maxi-

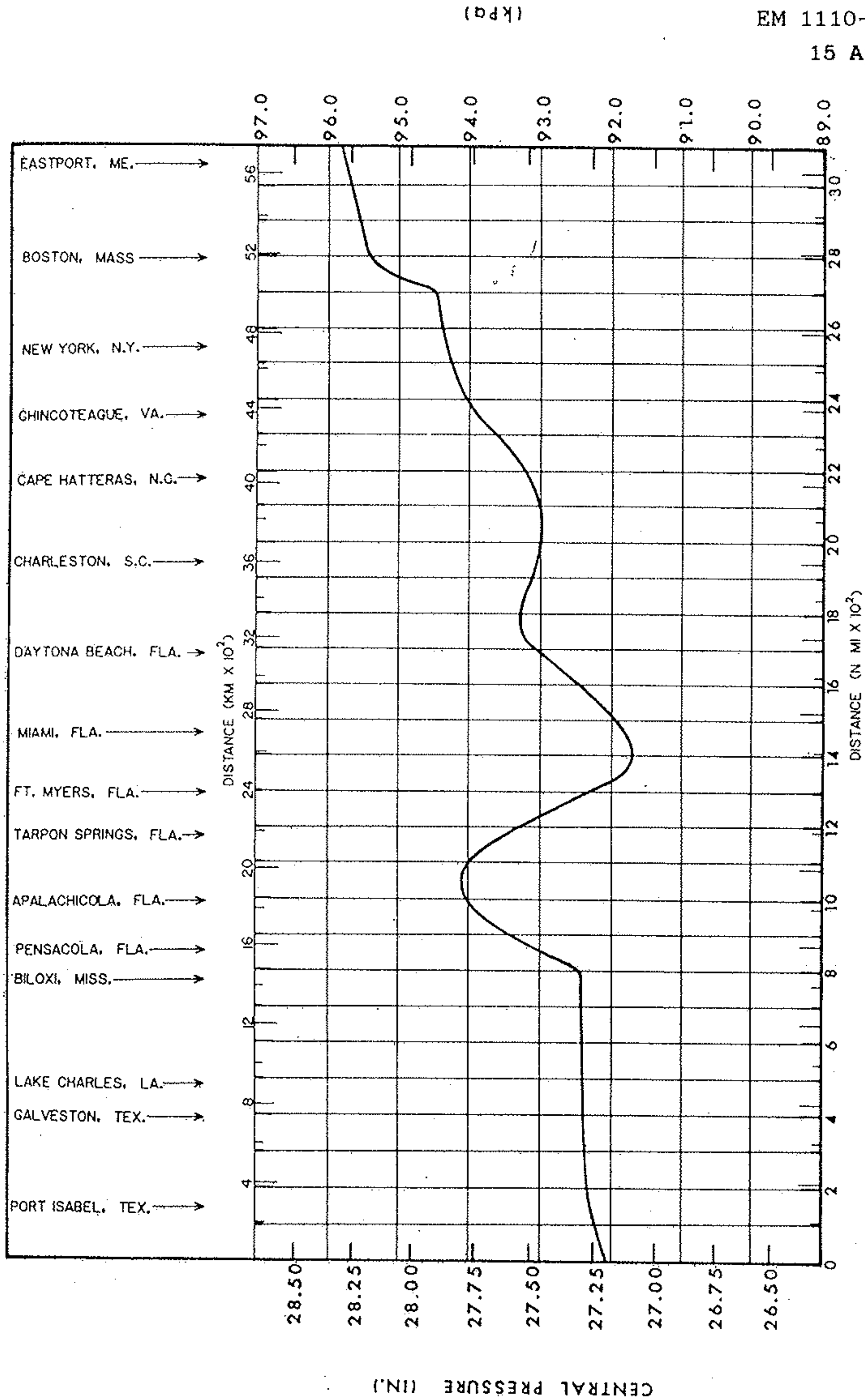

Figure C-1. Plot showing the SPH p_o. (item 57 of Appendix A)

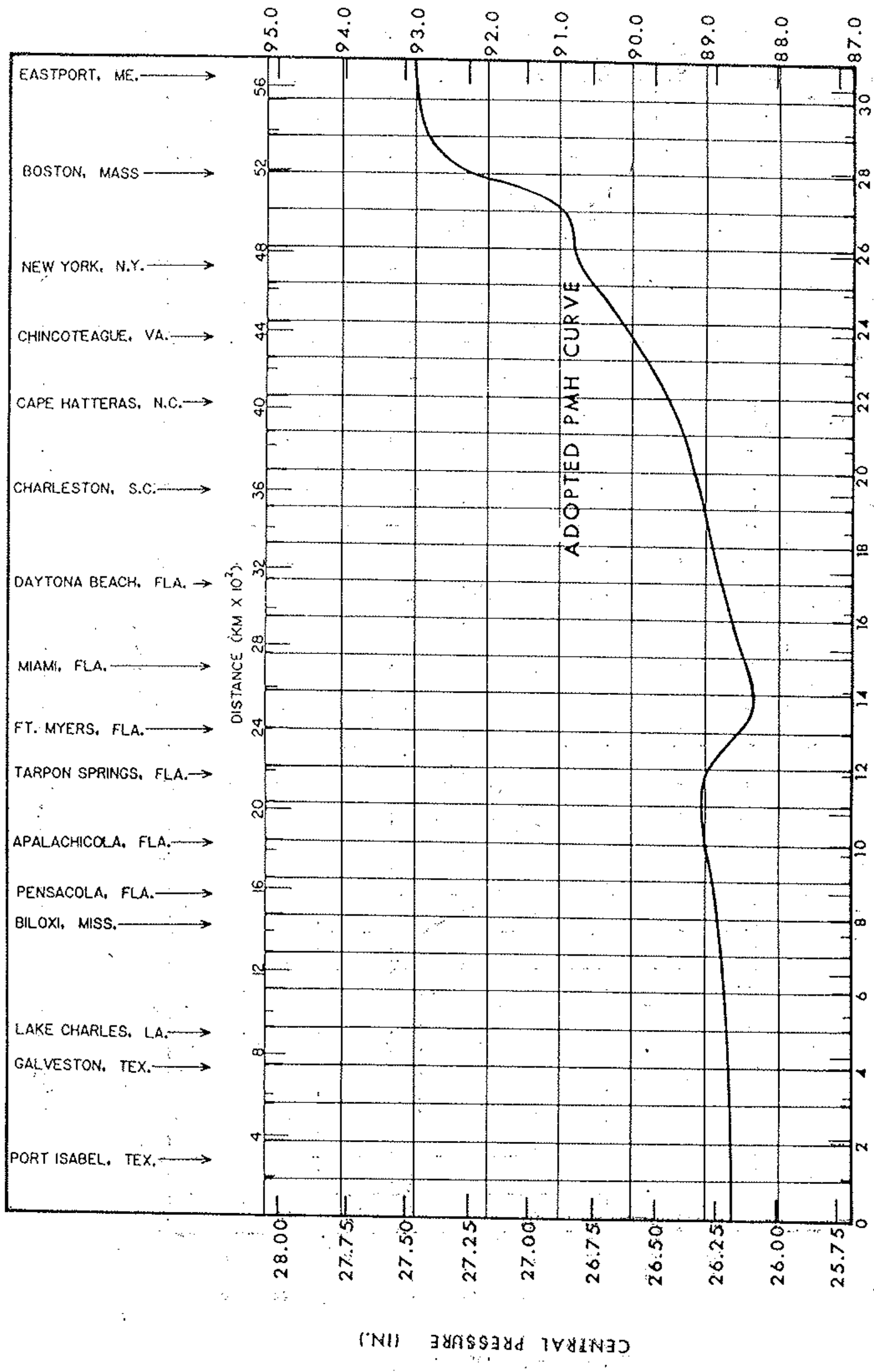

Figure C-2. Plot showing the PMP P_o. (item 57 of Appendix A)

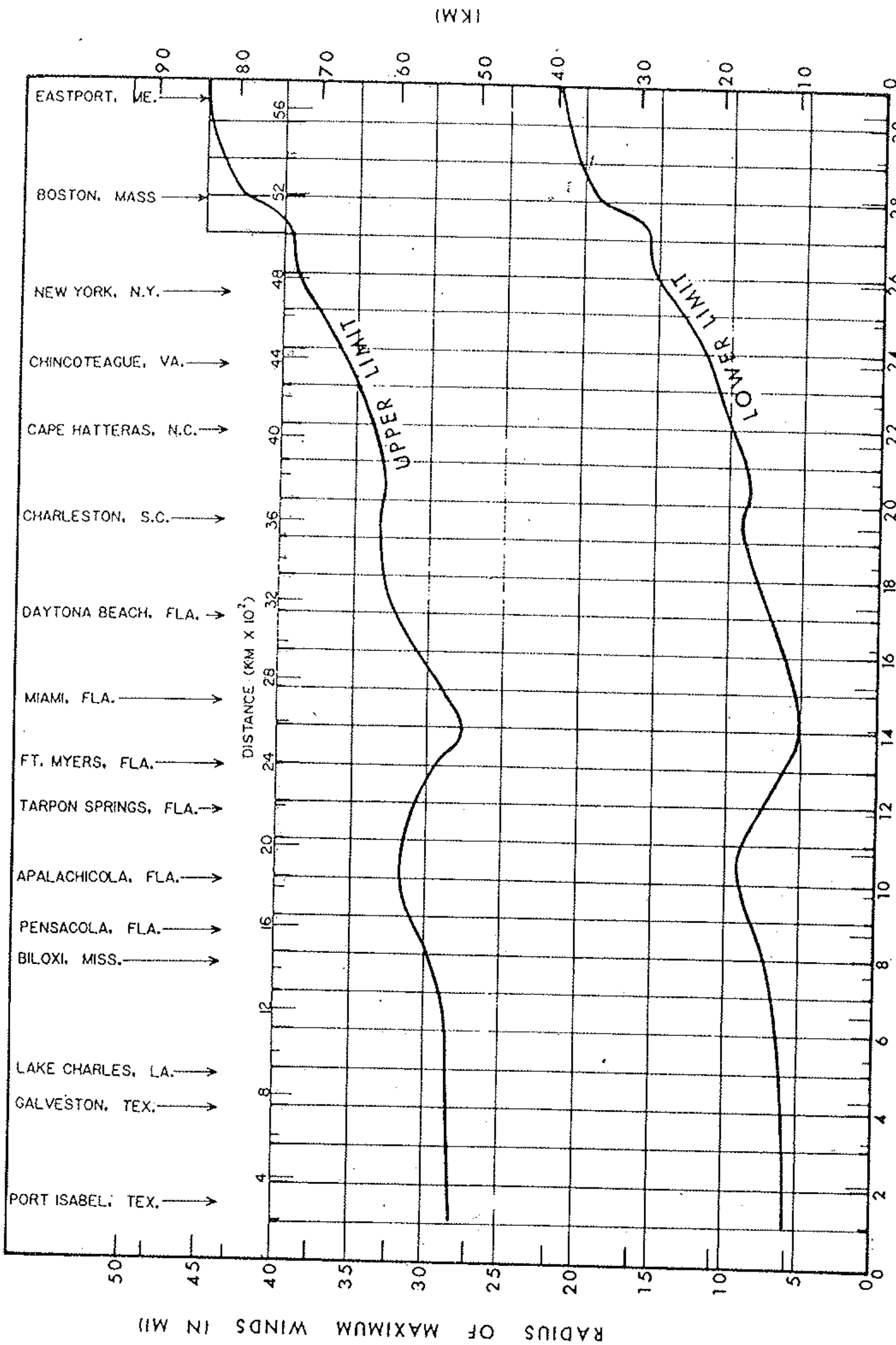

Figure C-3. Upper and lower limits of radius to maximum winds for the SPH. (item 57 of Appendix A)

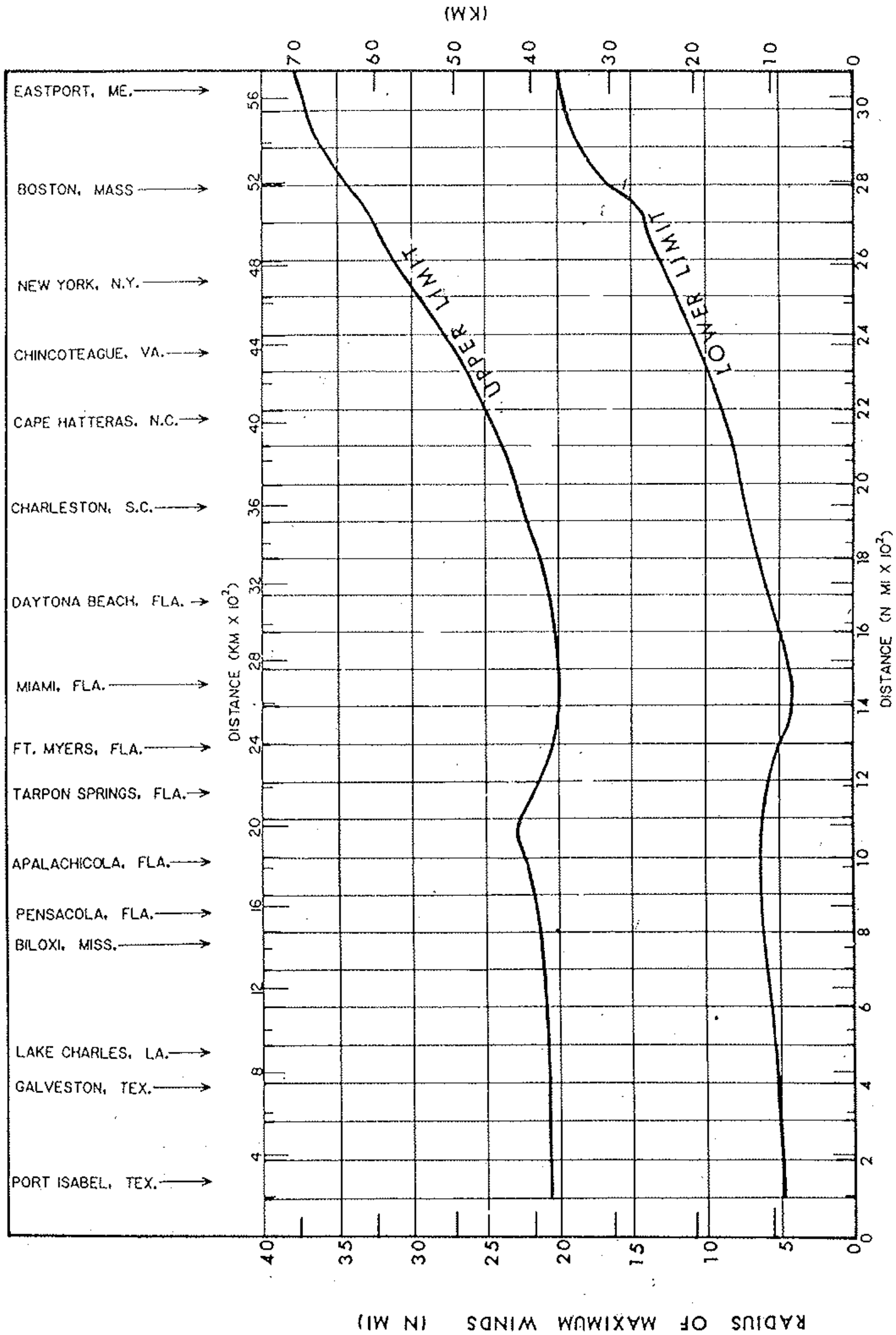

Figure C-4. Upper and lower limits of radius to maximum winds for the PMH. (item 57 of Appendix A)

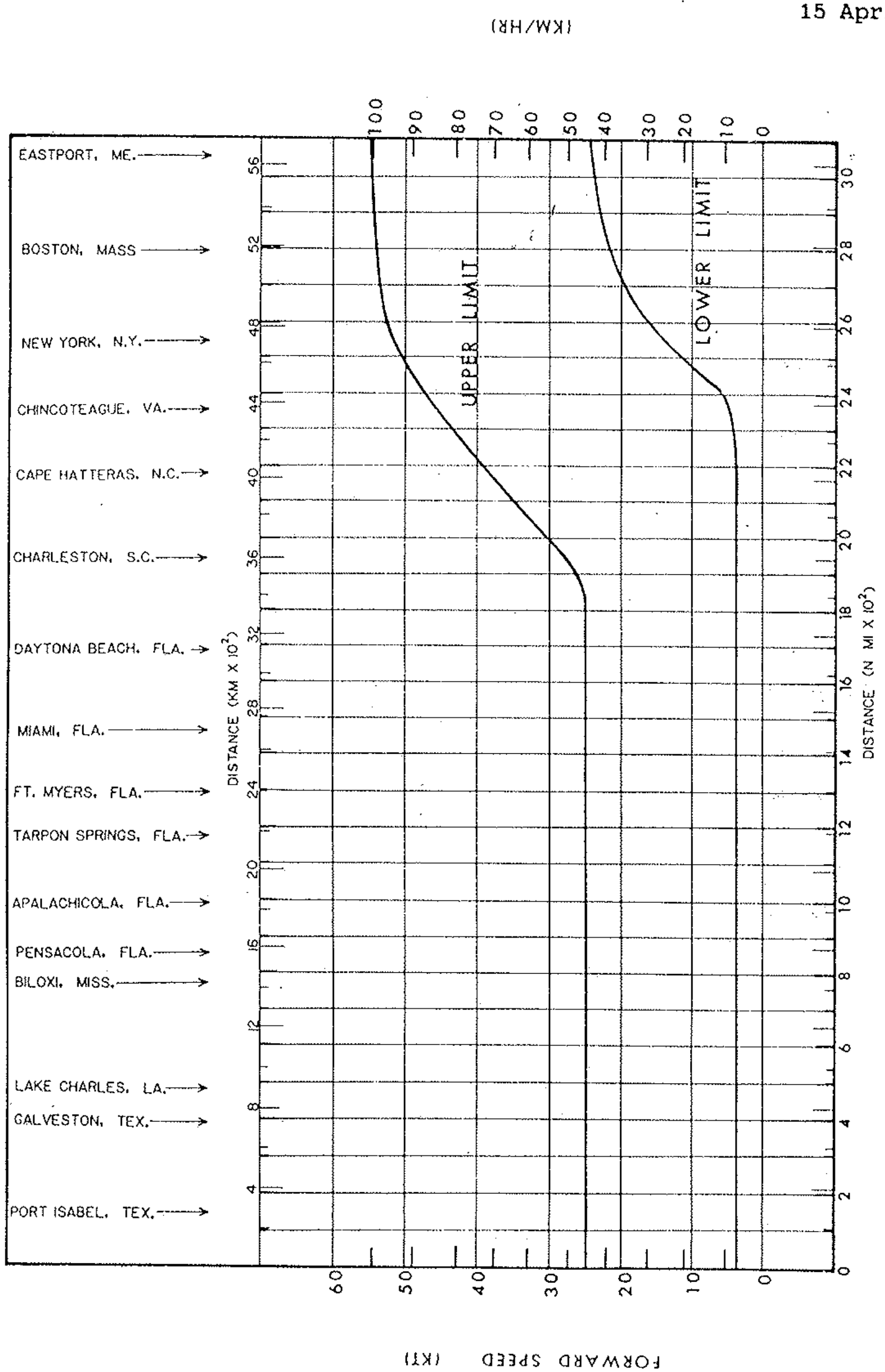

Figure C-5. SPH upper and lower limits of V_f. (item 57 of Appendix A)

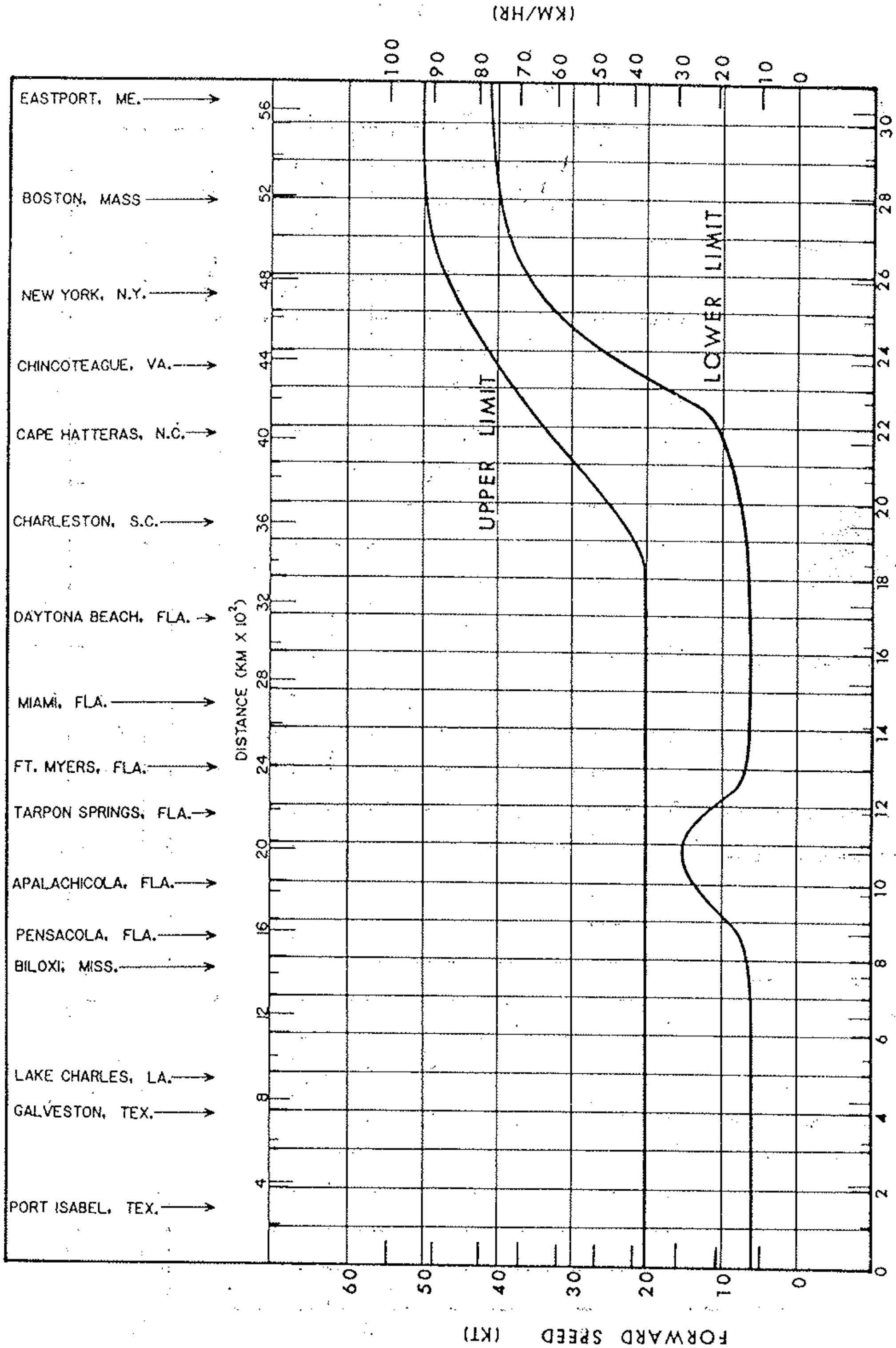

Figure C-6. PMH upper and lower limits of V_f. (item 57 of Appendix A)

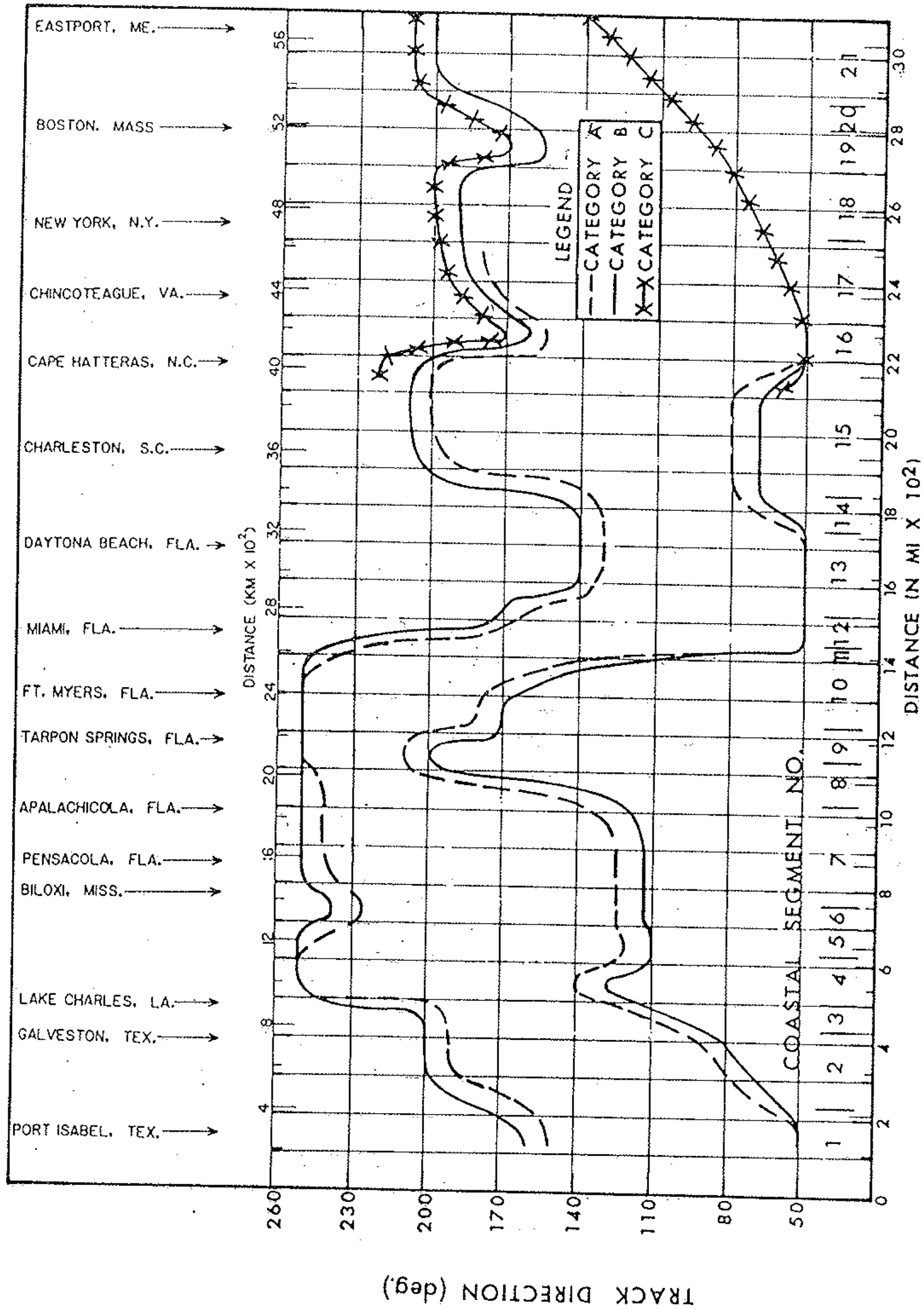

Figure C-7. Maximum allowable range of SPH θ. (item 57 of Appendix A)

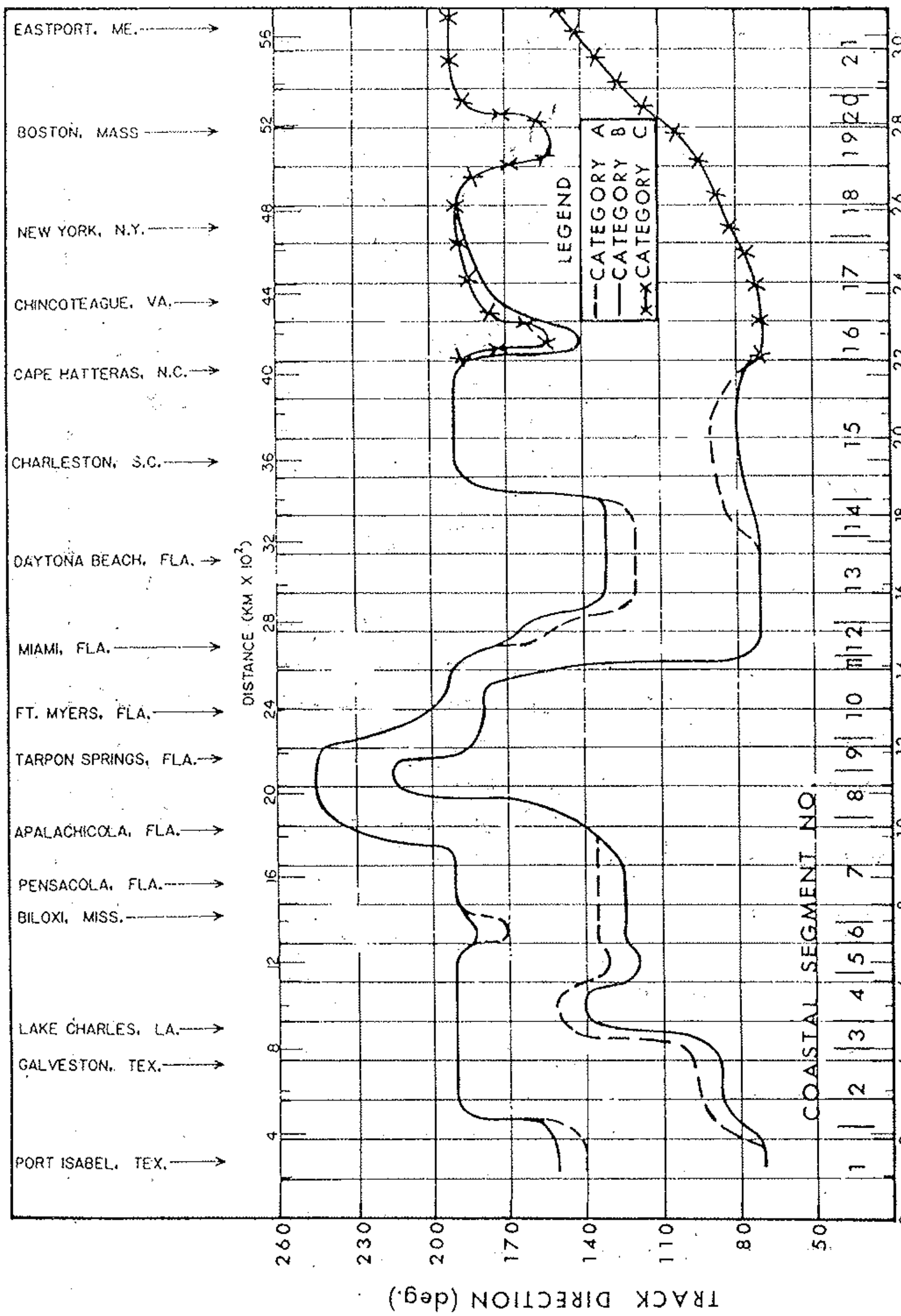

Figure C-8. Maximum allowable range of PMH θ. (item 57 of Appendix A)

Table C-1

Speed Categories Used in Determining
the Relation Between V_f and θ.

Speed Category		Forward Speed
SPH	A	$6kt \leq V_f \leq 10$ kt
	B	10 kt $\leq V_f \leq 36$ kt
	C	$V_f \leq 36$ kt
PMH	A	4 kt $\leq V_f \leq 10$ kt
	B	10 kt F $V_f \leq 36$ kt
	C	$V_f > 36$ kt

mum gradient wind speed as given in the subsequent section. In addition, this expression is used to develop a relation for evaluating the pressure setup which is covered in Appendix D.

C-4. Wind Field Specification. This section is concerned with estimating the winds 10m (32.8 ft.) above the water surface and the modification of wind when the rotating wind crosses overland areas.

a. Overwater Maximum Gradient Winds. The maximum gradient winds (V_{gx}) are the peak hurricane winds blowing parallel to the isobars under conditions of circular motion. An expression for this wind (see Chapter 12, NWS 23 (item 57 of Appendix A) for derivation) is

$$V_{gx} = K (p_n - p_o)^{1/2} - \frac{Rf}{2} \qquad [C-2]$$

in which f is the Coriolis parameter and K is a coefficient that is inversely proportional to the square root of the air density just above the water surface. Because air density is influenced by sea-surface temperatures K is dependent on the earth's latitude. Figures C-9 and C-10 show the relation between the coefficient K and latitude for three units of measurement for the SPH and PMH, respectively.

b. Overwater Maximum Winds in a Stationary Hurricane. The maximum 10-m, 10-minute averaged winds for a hurricane at rest (V_{xs}) have been found from observations to be a fixed fraction of the maximum gradient winds V_{gx}. The adopted empirical relations for defining the maximum wind is

$$V_{xs} = 0.9 \ V_{gx} \text{ , for SPH} \qquad [C-3]$$

and

$$V_{xs} = 0.95 \ V_{gx} \text{ , for PMH} \ . \qquad [C-4]$$

c. Overwater Maximum Winds in a Moving Hurricane.

(1) An asymmetry factor must be added to the maximum winds in a stationary hurricane to account for a moving hurricane For a moving hurricane, the maximum wind V_x, for the SPH is:

$$V_{xm} = 0.9 \ V_{gx} + 1.5 \ (V_f^{0.63}) \ (V_{fo}^{0.37}) \cos \beta \qquad [C-5]$$

and for the PMH

$$V_{xm} = 0.95 \ V_{gx} + 1.5 \ (V_f^{0.63}) \ (V_{fo}^{0.37}) \cos \beta \qquad [C-6]$$

in which V_{fo} = 1 when units are in knots, 0.514791 when units are meters per second, 1.853248 when units in kilometers per hour, and 1.51556 when units are in miles per hour. The angle β is the angle between the hurricane track and the maximum surface wind vector. At a particular position in the right rear quadrant of a hurricane the maximum wind can blow in a direction parallel to the track direction, and in this case β =0 and cos β =1. However, the region of maximum winds are allowed to occur at any position between 0 degrees and 180 degrees clockwise from the track direction. The latter limits of rotation of the wind fields were adopted based on observations from past hurricanes.

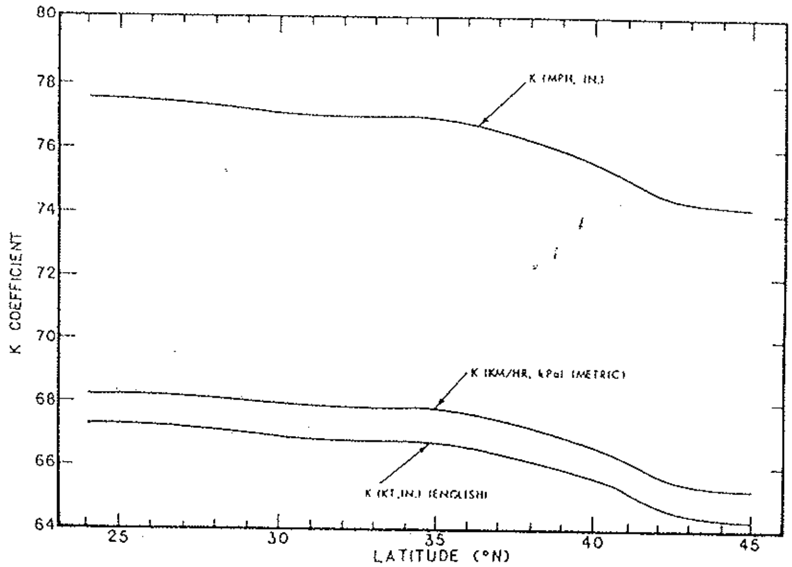

Figure C-9. Values of the latitude - dependent K coefficient for three units of measurement for the SPH. (item 57 of Appendix A)

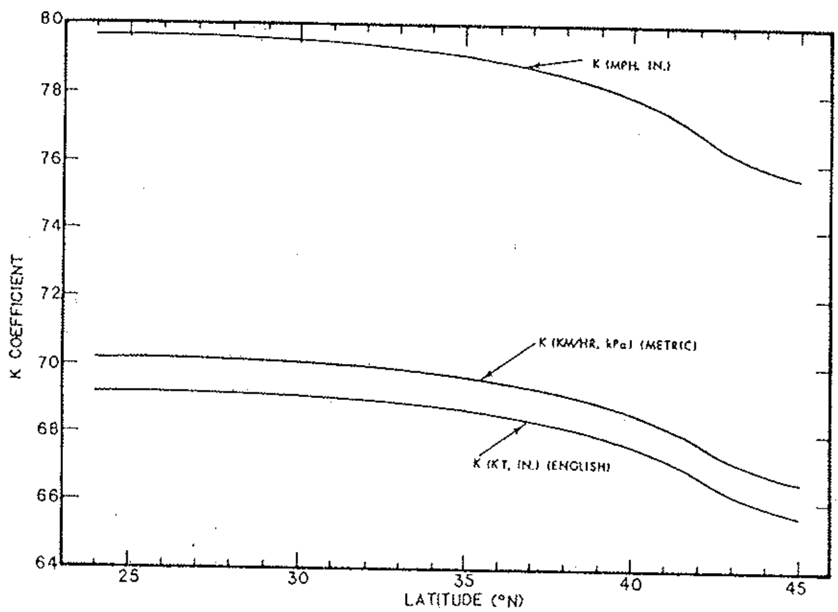

Figure C-10. Values of the latitude - dependent K coefficient for three units of measurement for the PMH. (item 57 of Appendix A)

(2) In previous discussions, the wind relations given provide estimates of the maximum winds. A general expression for estimating the wind speed V_r at any radial distance r from the hurricane center is:

$$V_r = V_s + 1.5\ (V_f^{0.63})\ (V_{fo}^{0.37}) \cos \beta \qquad [C-7]$$

in which V_s is the wind speed in stationary hurricane at radius r. Figure C-11 shows the relative wind speed ratio V_s/V_{xs} versus the distance r outward from R for various radii R. Figure C-12, on the other hand shows the speed within the radius of maximum winds.

d. Wind Inflow Angle. As indicated in Chapter 1, winds blow spirally inward toward the hurricane center. The angle between a tangent line on an isovel circle and the associated wind vector is defined as the wind inflow angle α. The inflow angle in degrees versus the distance from the hurricane center is shown in Figures [C-13] and [C-14] for the SPH and PMH, respectively, for various radii R.

e. Wind Modification Due to Frictional Effects. When revolving hurricane winds begin to sweep over inundated coastal terrain the winds lose speed due to increased surface friction. At the coast there is an abrupt decrease in wind speed and as the wind continues to blow overland the wind speed is further reduced until finally an approximate state of equilibrium is reached where no further reduction occurs. After the wind circles back over the ocean, or encounters a water body such as an embayment, the wind speed begins to increase and if the wind travels over the water surface for a sufficient distance it is essentially restored to its full strength. In general, the reduction of wind speed in inundated low-lying land areas due to frictional effects can be determined from

$$V_k = k\ V_r \qquad [C-8]$$

where V_k is the wind speed adjusted for frictional resistance and k is the surface friction coefficient. Figure C-15 shows the variation of k with distance along the wind path for four different

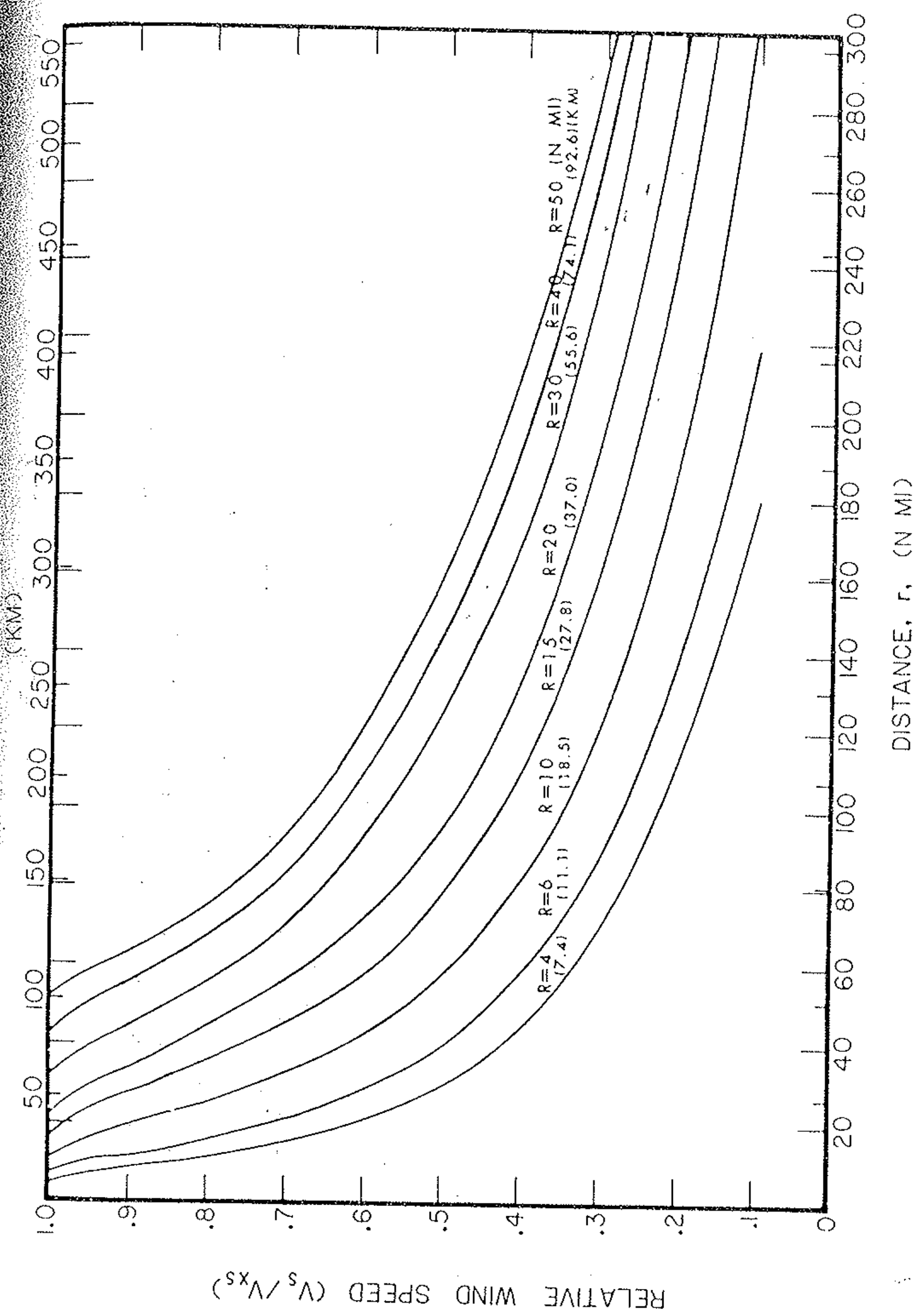

Figure C-11. Standardized wind profiles outward from R for the stationary SPH and PMH. (item 57 of Appendix A)

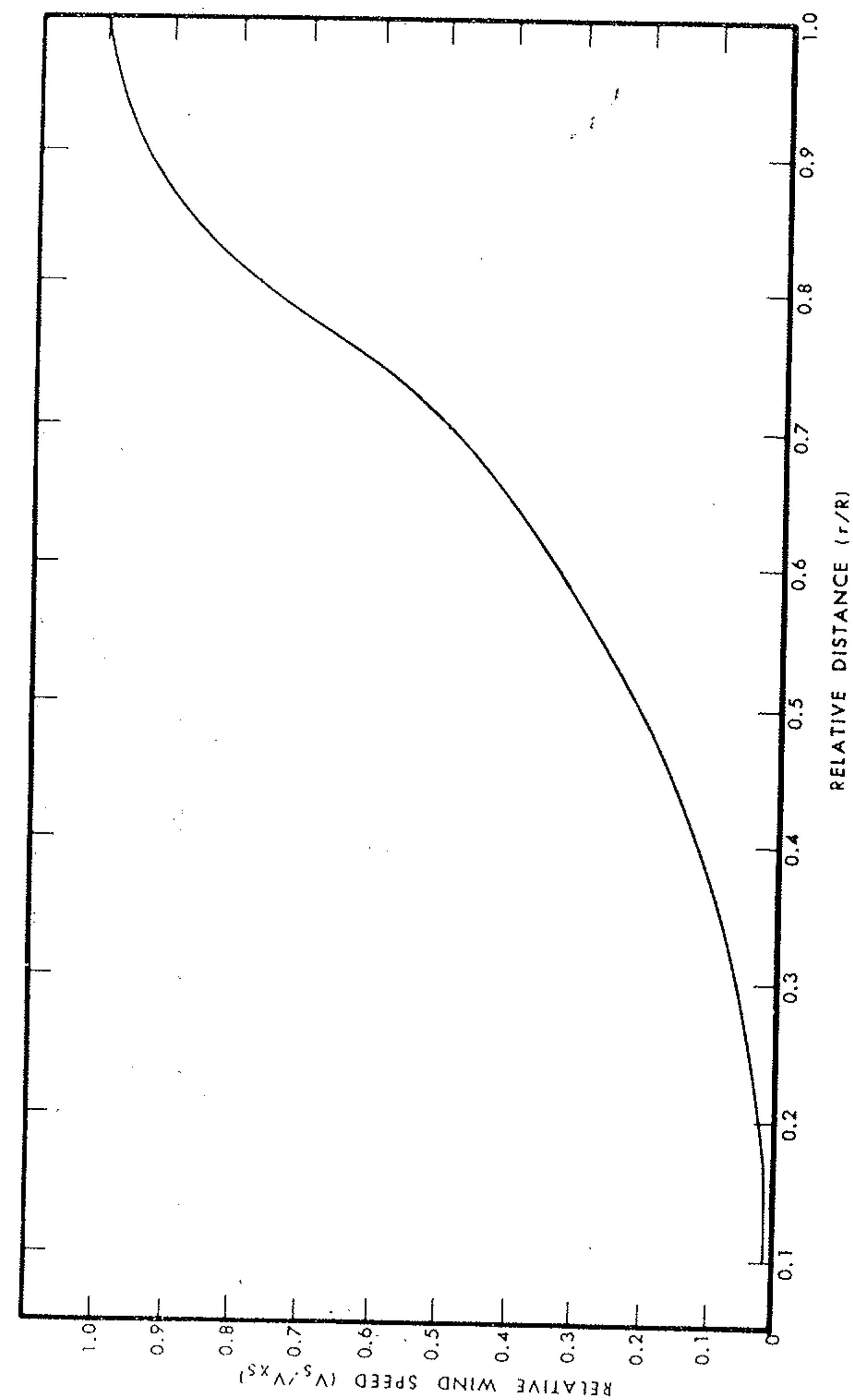

Figure C-12. Variation of relative wind speed with relative distance within the radius of maximum winds for the stationary SPH and PMH. (item 57 of Appendix A)

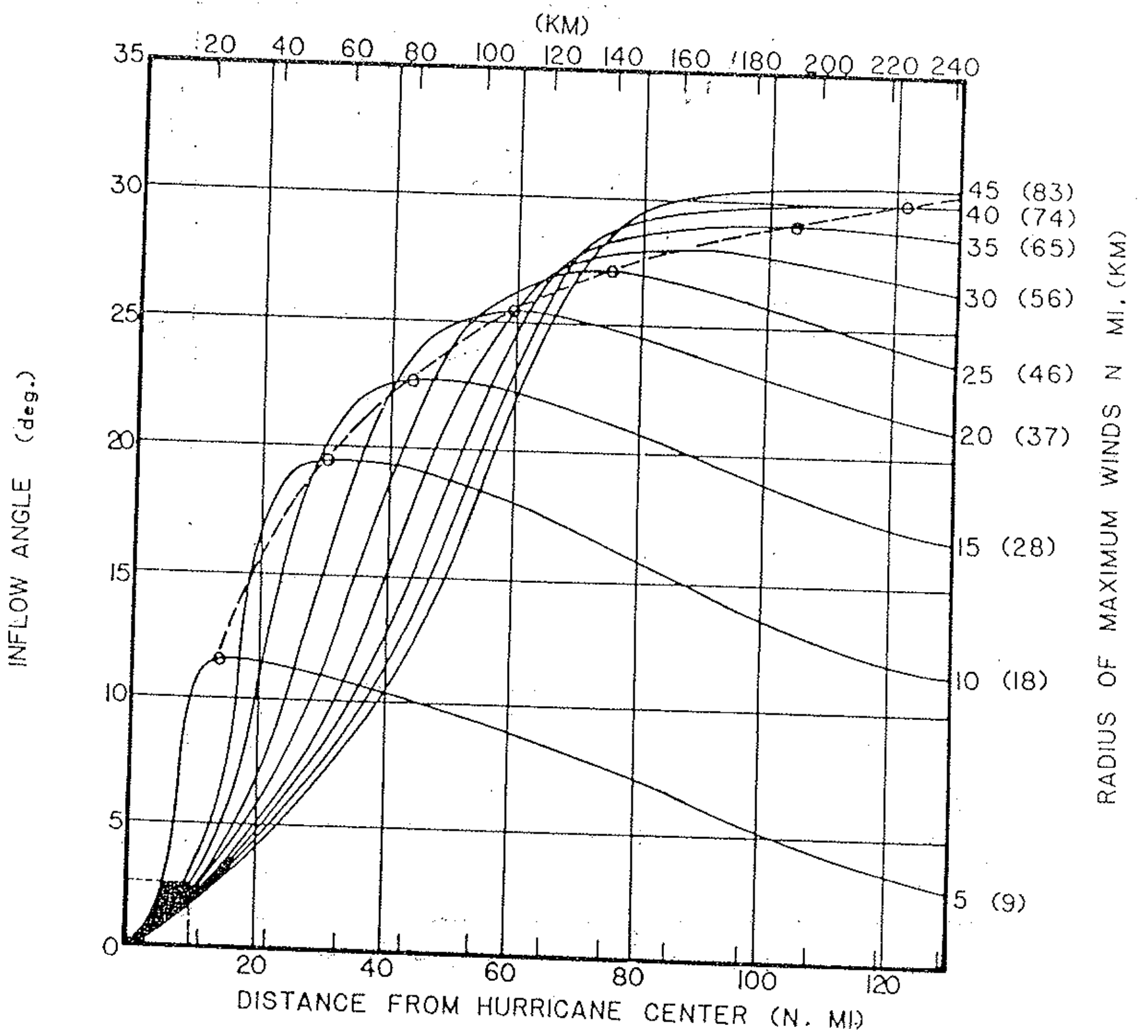

Figure C-13. Adopted SPH inflow angles versus distance from the hurricane center at selected R values. Open circles denote maximum inflow angle at each R. (item 57 of Appendix A)

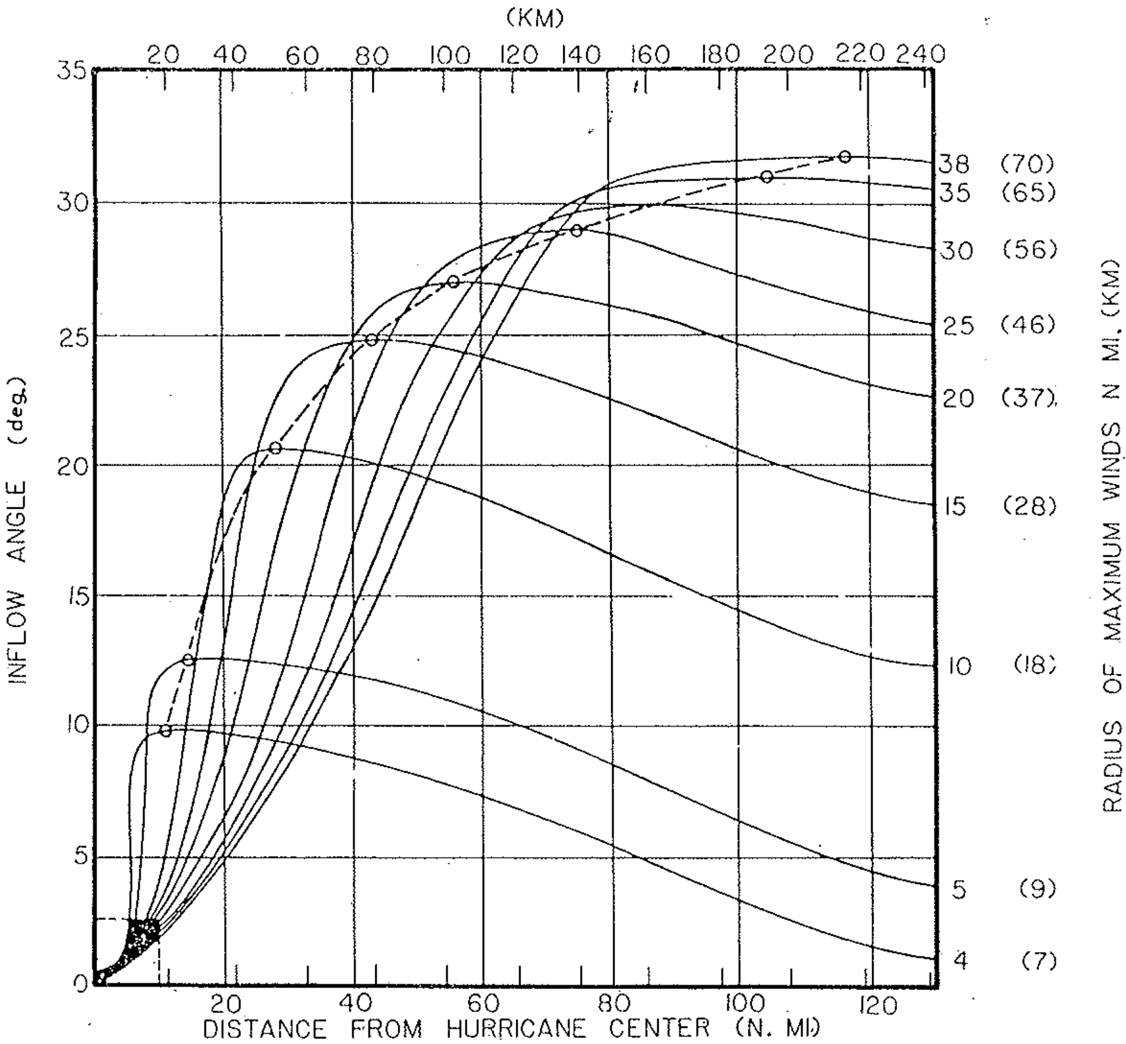

Figure C-14. Same as Figure C-13 except for the PMH. (item 57 of Appendix A)

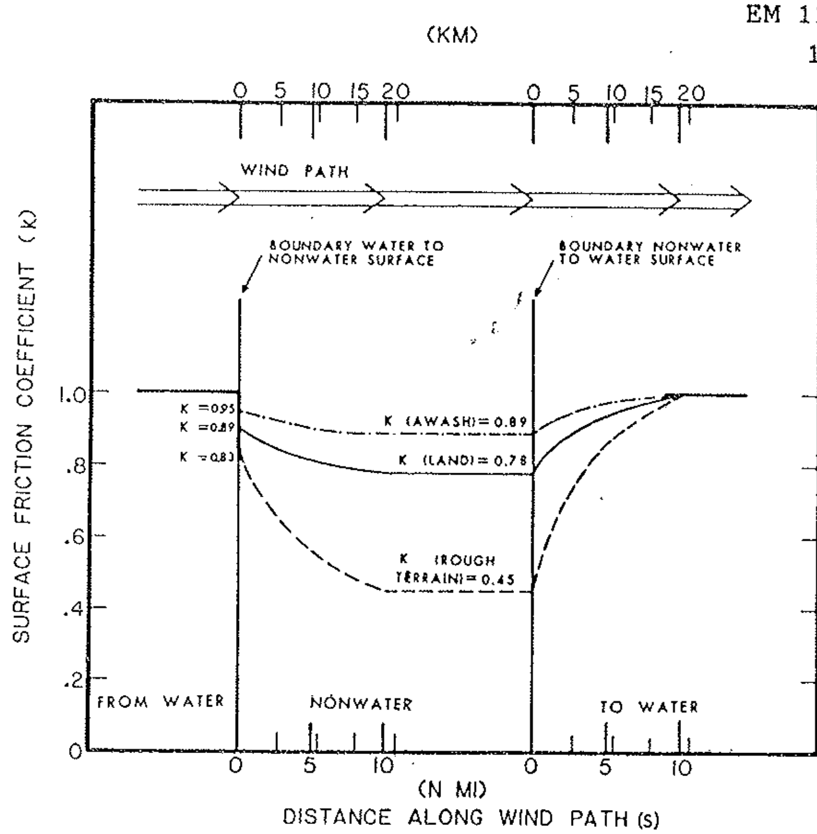

Figure C-15. Schematic of near shore frictional adjustments. (item 57 of Appendix A)

roughness categories which are designated as over water, awash, and rough terrain. According to technical Report NWS 23, awash is defined as normally dry ground with tree or shrub growth, hill dunes, which are noninundated; land--relatively flat noninundated terrain or buildings; rough terrain--major urban areas, dense forest, and mountains with abrupt changes in elevation over short distance. It is to be noted from Figure C-15 that the surface friction coefficient k varies only over a distance of 10 nautical miles when wind blows from water to nonwater areas or from nonwater areas to water areas.

g. Adjustment of Wind Speed for Filling Overland. When the hurricane center or eye crosses the coast and moves into inundated land areas the winds speed decrease due to filling. This weakening of the hurricane may be approximated by reducing the overwater SPH and PMH wind speed values by an adjustment factor. This factor has been derived for three separate geographic regions A, B, and C. The adjustment factor for these regions are shown in Figure C-16 and the geographic regions are shown in Figure C-17.

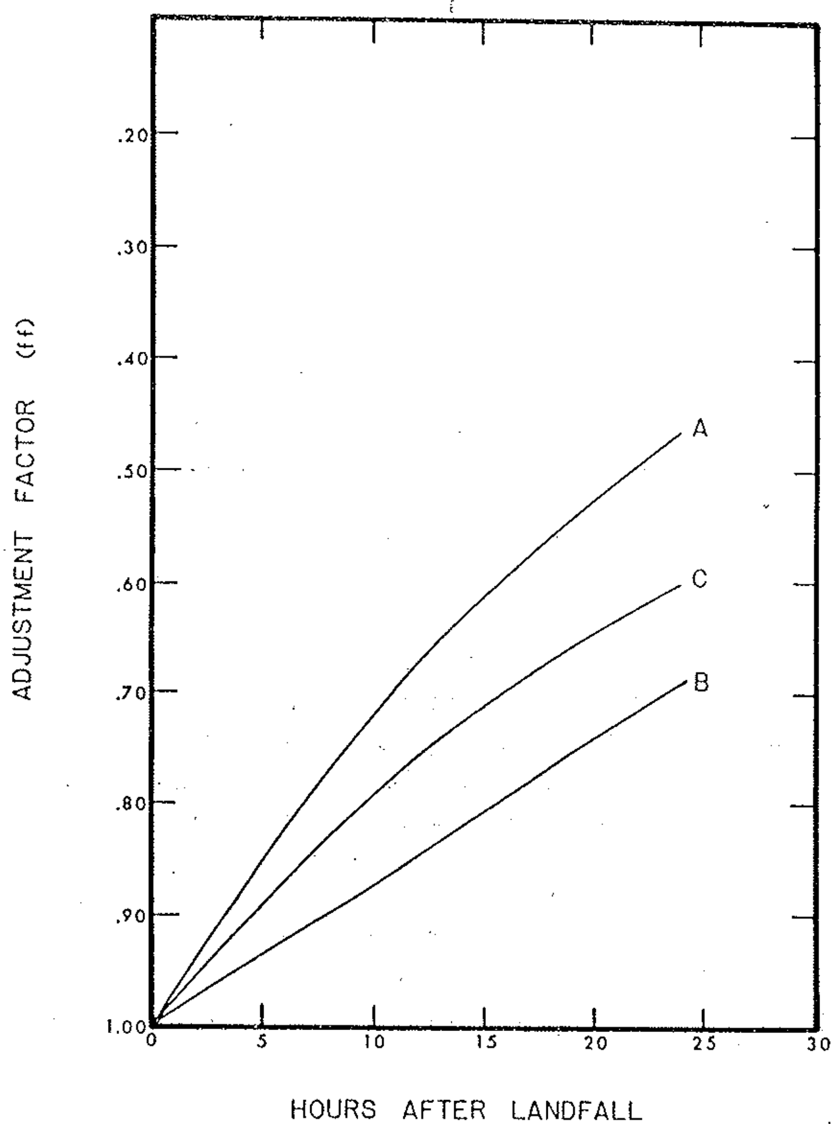

Figure C-16. Smoothed adjustment factor curves for reducing hurricane wind speeds when center is overland for three geographic regions defined in Figure C-17. (item 57 of Appendix A)

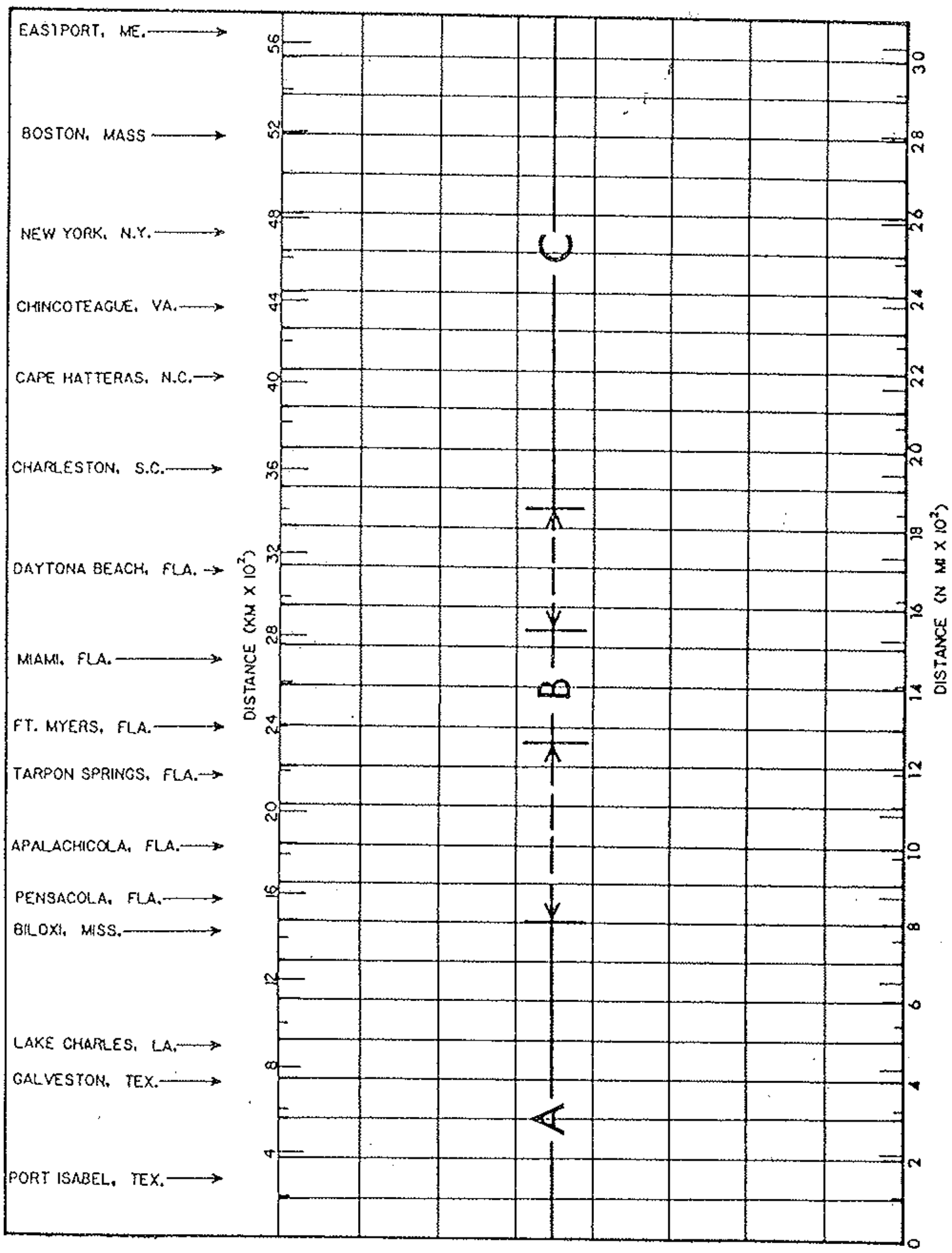

Figure C-17. Limits of three geographic regions (A, B, and C). Dashed lines delineate where linear interpolation should be used to develop intermediate curves in Figure C-16. (item 57 of Appendix A)

f. The Stalled PMH. A slow moving PMH is defined as being stalled when the forward speed V_f < 5 knots (9km/hr). Wind speeds decrease with time after stall provided that the forward speed is maintained in the stalled range. The percentage decrease in the winds for a PMH with time after stall is shown in Figure C-18. The curve provided in this figure is applicable along the gulf and east coasts south of Virginia-North Carolina border (milepost 2260).

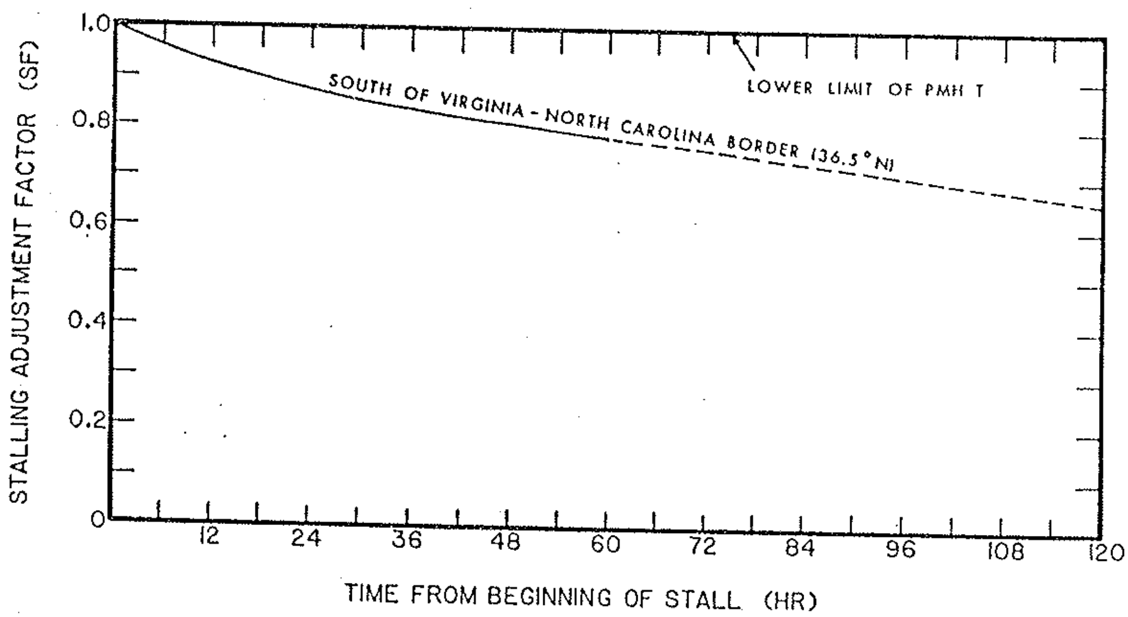

Figure C-18. Stalling adjustment factor curve for the PMH to be used south of the Virginia - North Carolina border (36.5° N). (item 57 of Appendix A)

APPENDIX D

ATMOSPHERIC PRESSURE SETUP

In Chapter 1, it was noted that atmospheric pressure variations over the sea cause the water level to rise in areas of low pressure and fall in areas of high pressure. This appendix is concerned with estimating the amount of rise attributed to the decrease in atmospheric pressure associated with hurricanes. A rise in water due to the pressure effect is commonly referred to as "pressure setup". The response of the water to pressure is like that of an inverted barometer and thus also frequently is referred to as the "inverted barometer effect". An expression for the atmospheric pressure in a hurricane was given in Appendix C (see Equation [C-1]) as

$$p = p_o + (p_n - p_o)\, e^{-R/r} \qquad [D-1]$$

in which p is the pressure at a radial distance r from the hurricane center; p_o is the central pressure; p_n is the peripheral pressure; and R is the radius of maximum winds. Equation [D-1] may be readily written in terms of the rise in water level at any distance r from the hurricane center, or specifically

$$\xi = 1.14\,(p_n - p_o)\,(1 - e^{-R/r}) \qquad [D-2]$$

in which ξ is, as before (Chapter 1), an equivalent head of water in feet when the pressures p_n and p_o have units of inches of mercury. A certain lapse of time is required for the water to respond to a change in sea-level pressure, thus pressure setup is a time dependent process which requires that water in higher pressure areas be transported to the lower pressure area. As a consequence, Equation [D-2] is considered more valid for slow moving hurricanes and in regions where the water depth is relatively deep. In shallow coastal areas the equilibrium pressure setup, as predicted by the expression given, would be seldom reached due to the effects of bottom friction. Generally, the pressure setup effect can be neglected in shallow bays and estuaries. The gradient pressure setup which appears in the equations of motion as given in Chapter 1 can be expressed from Equation [C-2] as:

$$\frac{\partial \xi}{\partial x} = 1.14 \, (p_n - p_o) \, \frac{R}{r^2} \, e^{-R/r} \cos \beta \qquad [D-3]$$

$$\frac{\partial \xi}{\partial y} = 1.14 \, (p_n - p_o) \, \frac{R}{r^2} \, e^{-R/r} \sin \beta \qquad [D-4]$$

in which β is the angle between the x-axis and the radial line from the storm center to the point in which the pressure setup is to be evaluated.

APPENDIX E

HURRICANE GENERATED SURFACE WAVES

E-1. General. In the prediction of short period surface waves generated by hurricane winds, the determination of the wave fetch and duration from a wind field is more difficult than for more normal weather conditions. Difficulties arise because hurricane winds blow spirally inward toward the center as the storm system moves over the ocean. Fetch areas in which the wind speed and direction remain approximately constant are always small and a fully arisen sea would seldom be realized. A mathematical model developed for estimating wave characteristics in a hurricane is described in the Shore Protection Manual (1977). This model provides a reasonable approach for predicting hurricane waves provided that the model is modified to account for the more recent SPH wind field criteria that were presented in Appendix C. The original model together with the necessary modifications are described herein and an example problem is given to illustrate the computational procedures for predicting hurricane waves.

E-2. Prediction Method. For a moving hurricane, the following expressions can be used to obtain an estimate of the deep water significant wave height and period at the point of maximum wind:

$$H_o = 16.5 \exp\left(\frac{R\ \Delta p}{100}\right)\left(1 + \frac{0.208\ \kappa\ V_f}{V_{xm}{}^{1/2}}\right) \qquad [E-1]$$

$$T_o = 8.6 \exp\left(\frac{T\ \Delta p}{200}\right)\left(1 + \frac{0.104\ \kappa\ V_f}{V_{xm}{}^{1/2}}\right) \qquad [E-2]$$

where

$\exp(x)$ = e^x, in which e = 2.71828. . . . . .

H_o = deep water significant wave height in feet

T_o = the corresponding significant wave period in seconds

R = radius of maximum winds in nautical miles

Δp = $p_n - p_o$ in inches of mercury in which p_n is the peripheral pressure and p_o is the central pressure

V_f = forward speed of hurricane in knots

V_{xm} = maximum sustained wind speed in knots at radius R.

$$V_{xm} = 0.9 \ V_{gx} + 1.5 \ V_f^{0.63} \cos \beta \qquad [E-3]$$

and for the PMH

$$V_{xm} = 0.95 \ V_{gx} + 1.5 \ V_f^{0.63} \cos \beta \qquad [E-4]$$

β = angle between the hurricane track direction and the maximum surface wind direction

V_{gx} = maximum gradient wind speed, see Equation [C-2]

$$V_{gx} = K \ (\Delta p)^{1/2} - \frac{Rf}{2} \qquad [E-5]$$

K = a coefficient that depends on the air density just above the sea surface and can be obtained from either Figure C-9 or C-10 for the SPH and PMH, respectively

f = Coriolis parameter = $2 \omega \sin \phi$ in which ϕ is the geographical latitude of the hurricane eye

ω = $2\pi/24$ radians per hour

κ = a coefficient depending on the forward speed of the hurricane and the increase in effective fetch due to the hurricane translation. For a slow moving hurricane it is suggested that $\kappa = 1.0$.

a. After determination of H_o for the point of maximum wind it is possible to obtain the approximate deepwater wave height H_o for other points within the hurricane by use of Figure E-1. A sufficient approximation of the deepwater significant wave period can be obtained from

$$T_o = 2.13\ H_o^{1/2} \qquad [E-6]$$

in which H_o is in feet. The latter expression is derived from empirical data which show that the wave steepness H/T^2 will be about 0.22.

*********************** EXAMPLE PROBLEM ***********************

Given: Consider a SPH at latitude 37 degrees N situated over the ocean (mile post about 2300 n mi.) with R = 34 nautical miles and V_f = 26 knots.

Find: The deepwater significant wave height and period.

Solution: The Coriolis parameter is given by

$$f = 2\ \omega \sin \phi = 2\left(\frac{2\pi}{24}\right) \sin 37 = 0.315\ .$$

For a SPH, P_n = 29.77 inches.

At the mile post given the central pressure p_o, according to Figure C-1, is approximately 27.65 inches. Therefore,

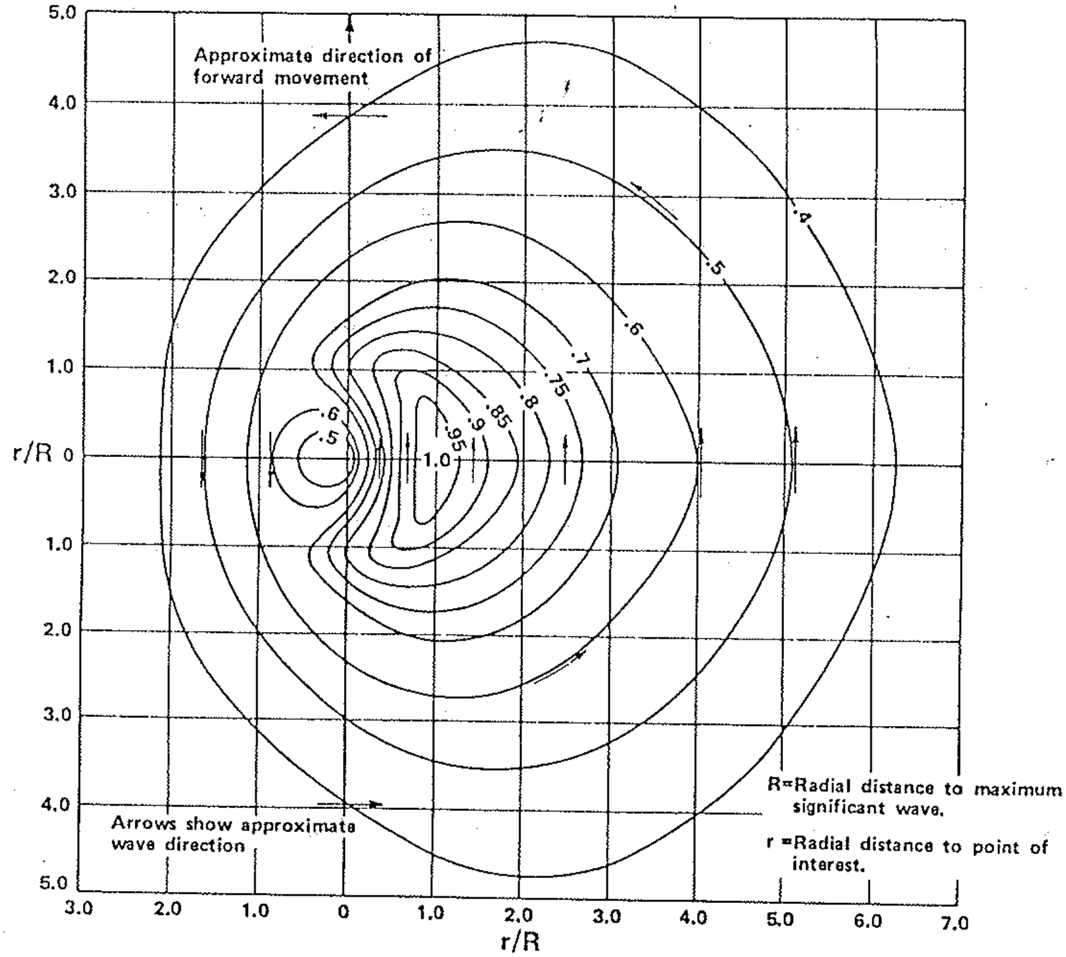

Figure E-1. Isolines of relative significant wave height for slow-moving hurricane.

$$\Delta p = 29.77 - 27.65 = 2.12 \text{ inches.}$$

The coefficient K found from Figure C-9 is about 66.6 knots-inches. Using Equation E-5

$$V_{gx} = K\,\Delta p^{1/2} - \frac{rf}{2} = 66.5\ (2.12)^{1/2} - \frac{35(0.315)}{2} = 91.3 \text{ knots.}$$

Using Equation [E-3] and assuming that the maximum wind is blowing in a direction parallel to the hurricane path ($\beta = 0$), then

$$V_{xm} = 0.9\ (91.3) + 1.5\ (26)^{0.63}\ (1) = 93.9 \text{ knots.}$$

Assume for simplicity that $\kappa = 1$. Using Equation [E-1]

$$H_o = 16.5 \exp\left(\frac{R\,\Delta p}{100}\right)\left(1 + \frac{0.208\ \kappa\ V_f}{V_{xm}^{1/2}}\right)$$

$$H_o = 16.5 \exp\left[\frac{35(2.12)}{100}\right]\left[1 + \frac{0.208\ (1)\ (26)}{(93.9)^{1/2}}\right] \approx 54.0 \text{ feet.}$$

Using Equation [E-2]

$$T_o = 8.6 \exp\left(\frac{R\,\Delta p}{200}\right)\left(1 + \frac{0.104\ \kappa\ V_f}{V_{xm}^{1/2}}\right)$$

$$T_o = 8.6 \exp\left[\frac{(35)\ (2.12)}{200}\right]\left[1 + \frac{0.104\ (1)\ (26)}{(93.9)^{1/2}}\right] = 15.9 \text{ sec .}$$

Using Equation [E-6]

$$T_o = 2.13\ (H_o)^{1/2} = 2.13\ (54)^{1/2} = 15.7 \text{ sec}$$

which shows that the latter simple relation is of sufficient accuracy and will be used in subsequent calculations. With a knowledge of the deepwater significant wave height and period it is possible to determine the changes in these wave characteristics as the hurricane moves over the continental shelf. In order to make this determination it is necessary to account for the combined effects of bottom friction, refraction, the continued action of the wind and the forward speed of the hurricane. It is necessary to use relatively short wind fetch length due to the revolving winds and thus a numerical integration procedure must be utilized. When waves refract over the bottom contours, it will be also necessary to use appropriate refraction diagrams as presented in the Shore Protection Manual (1984). In the use of the numerical procedure, an effective fetch length F_e is required which is given by

$$F_e = \left(\frac{H_o}{0.0555\ V_{xm}}\right)^2 . \qquad [E-7]$$

For the preceding example problem

$$F_e = \left[\frac{54.0}{(0.555)(93.9)}\right]^2 = 107.4 \text{ n mi.}$$

The deepwater significant wave height H_o can be evaluated by using a modified version of Equation [E-7] as given by

$$H_o = 0.0555\ V_{xm}\ (F'_e + \Delta F)^{1/2} \qquad [E-8]$$

in which F'_e is defined in the procedures outlined below and ΔF is a specified fetch length interval used in the numerical integration technique. The procedure for calculating the surface waves over the continental shelf is illustrated by using a bottom profile seaward of the Chesapeake Bay entrance (profile taken from the 1977 Shore Protection Manual) and the hurricane taken from the previous example. The water depths used are assumed to include the storm surge and astronomical tide over the shelf area. Refraction is neglected in this example. The result of the computations are shown in Table E-1. Explanation of the computations are as follows:

Column 1 of Table E-1 is the distance in nautical miles measured seaward from the entrance to Chesapeake Bay, using increments of 5 n mi. for each section.

TABLE E-1. Computation Of Wind Waves Over Continental Shelf

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
X	d_1	d_2	$\bar{d}_t$	F_e	H_o	T_o	$\frac{\bar{d}_t}{L_o}$	$\frac{f_f H_o \Delta X}{(d_t)^2}$	K_f	H_o'	F_e'	T_o'	$\frac{d_2}{L_o'}$	K_s	H
65	1004	504	754	107.4	54.0	15.7	0.597	0.029	1.000	54.0	107.4	15.7	0.399	0.9758	52.7
60	504	194	349	107.4	54.0	15.7	0.277	0.135	0.985	53.2	104.2	15.5	0.158	0.9130	48.6
55	194	158	176	107.4	54.0	15.7	0.139	0.530	0.930	50.2	92.9	15.1	0.135	0.9156	46.0
50	158	122	140	97.9	51.6	15.3	0.117	0.800	0.900	46.4	79.2	14.5	0.113	0.9239	42.9
45	122	116	119	84.2	47.8	14.7	0.108	1.026	0.850	40.6	60.8	13.6	0.123	0.9192	37.3
40	116	116	116	65.8	42.3	13.9	0.118	0.956	0.890	37.6	52.1	13.1	0.133	0.9161	34.4
35	116	110	113	57.1	39.4	13.4	0.123	0.938	0.880	34.7	44.3	12.5	0.136	0.9154	31.8
30	110	88	99	49.3	36.6	12.9	0.116	1.135	0.870	31.8	37.3	12.0	0.119	0.9209	29.3
25	88	78	83	42.3	33.9	12.4	0.105	1.496	0.830	28.1	29.1	11.3	0.119	0.9209	25.9
20	78	68	73	34.0	30.4	11.7	0.103	1.734	0.810	24.6	22.3	10.6	0.120	0.9204	22.6
15	68	62	65	27.3	27.2	11.0	0.106	1.957	0.790	21.5	17.0	9.9	0.124	0.9189	19.8
10	62	52	57	22.0	24.4	10.5	0.101	2.283	0.750	18.3	12.3	9.1	0.123	0.9192	16.8
5	52	44	48	17.3	21.7	9.9	0.095	2.863	0.720	15.6	9.0	8.4	0.121	0.9200	14.4
0	44	36	40	14.0	19.4	9.4	0.088	3.686	0.650	12.6	5.9	7.6	0.122	0.9196	11.6

Column 2 is the depth d_1 at the beginning of each section.

Column 3 is the depth d_2 at the shoreward end of each section.

Column 4 is $\bar{d}_t$ the average of Columns 2 and 3 to the nearest foot.

Column 5 is the effective fetch F_e in nautical miles, and is determined for the first step directly from Equation [E-7]. For successive steps, $F_e = F'_e + \Delta F \leq 54.9$ n mi. where F'_e is given in Column 12 one line above in each case, and $\Delta F = 5$ n mi.

Column 6 is the deepwater significant wave height H_o and is obtained from Equation [E-1] on the first step and Equation [E-8] for the succeeding steps.

Column 7 is the deepwater significant wave period and is obtained by Equation [E-6].

Column 8 is the average water depth $\bar{d}_t$ divided by the deepwater wave length L_o where

$$\frac{\bar{d}_t}{L_o} = \frac{2\pi \bar{d}_t}{g T_o^2}$$

Column 9 is the parameter in Figure E-2

$$\frac{f_f H_i \Delta X}{d^2} = \frac{f_f H_o \Delta X}{(\bar{d}_t)^2}$$

in which friction factor f_f is assumed to be 0.01 $\Delta X = 5$ (6080) = 30,400 feet.

Column 10 is the friction factor K_f which is obtained from Figure E-2 using column 8 and column 9.

Column 11 is the equivalent deepwater wave height H'_o and is obtained from $H'_o = K_f H_o$ (the products of column 6 and 10).

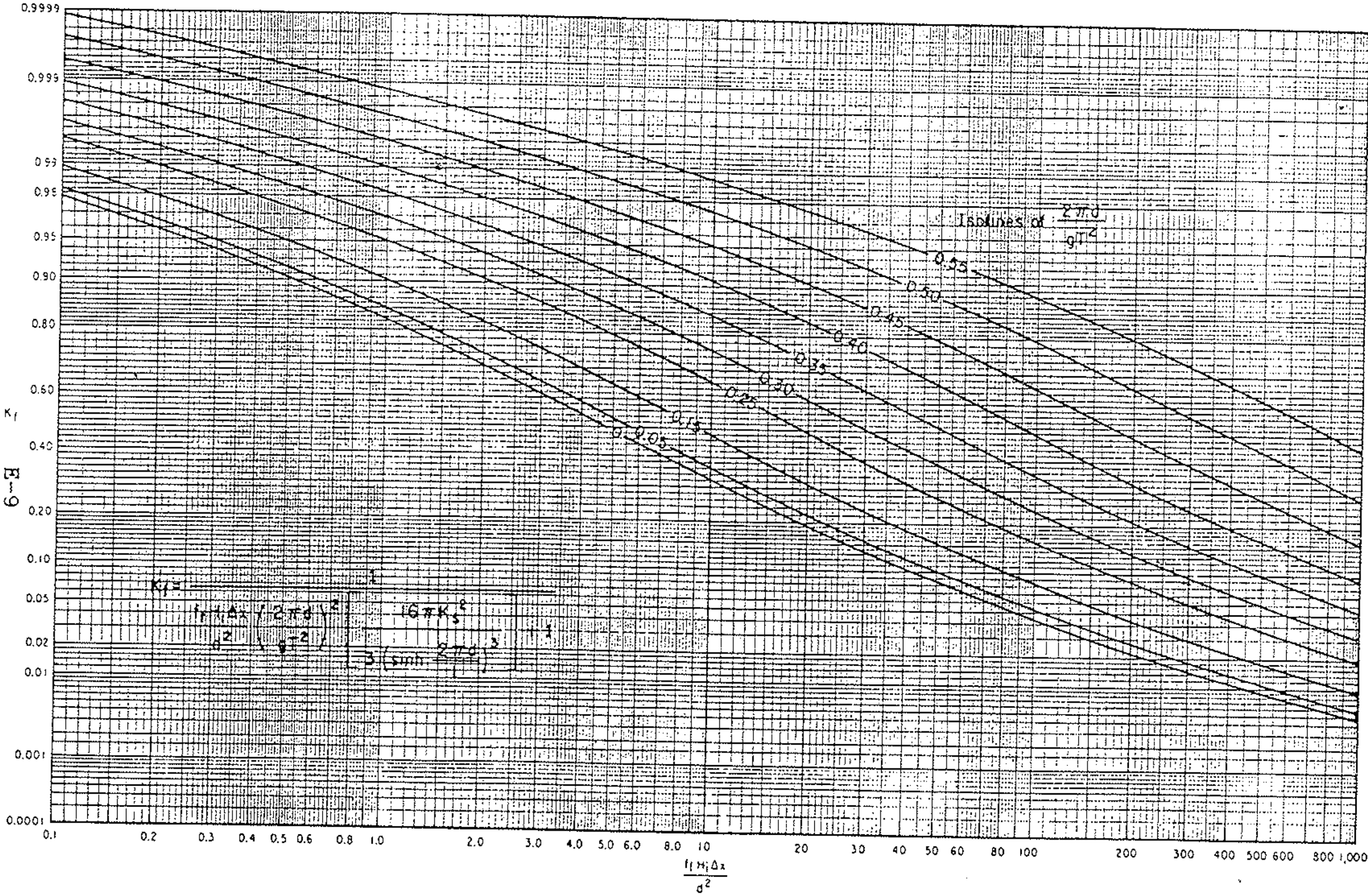

Figure E-2. Relationship for friction loss over a bottom of constant depth. (item 5 of Appendix A)

Column 12 is the equivalent effective lenght F_e and is obtained from Equation [E-7] by replacing H_o by H'_o or

$$F'_e = \left(\frac{H'_o}{0.0555 \; V_{xm}}\right)^2 \quad .$$

Column 13 is the equivalent deepwater wave period T_o in seconds and computed by

$$T'_o = 2.13 \; (H'_o)^{1/2} \quad .$$

Column 14 is the depth d_2 divided by the equivalent deep water wave length

$$L_o = 5.12 \; (T'_o)^2 \quad .$$

Column 15 is the shoaling coefficient K_s which can be obtained from Table C-1, Appendix C of the Shore Protection Manual in which $H/H'_o = K_s$ as a function of d_2/L_o (column 14).

Column 16 is the significant wave height H in which

$$H = K_s \; H'_o$$

or the products of Columns 11 and 15.

After completing the computations for the first row, the computations are commenced on the second row etc., until the table is completed.

APPENDIX F

APPLICATION OF HISTORICAL FREQUENCY METHOD

The following problem illustrates the computational procedures involved in calculating the magnitude and frequency of occurrence of water levels at the State Pier, Providence, Rhode Island based on the formula and procedures discussed in Chapter 3. The basic and ordered annual peak water level data are given in Table F-1. The last two rows in the basic data, columns 3 and 4, shows historic water elevations of 18 feet for years 1635 and 1638. Historic data for these years are not considered a part of the more recent systematic record. By ignoring the historic record for the present, it is found by summing columns 4, 5, and 6 that:

$$\Sigma x = 269.1; \qquad \Sigma x^2 = 1908.95$$

and

$$\Sigma x^3 = 16{,}352.259 \quad .$$

For the systematic record (N = 43) the mean, standard deviation, and skew coefficient according to Equations [3-6], [3-7b], and [3-8b] are:

$$\mu = \frac{\Sigma x}{N} = \frac{269.1}{43} = 6.2581$$

$$\sigma = \left[\frac{(\Sigma x^2) - \frac{(\Sigma x)^2}{N}}{N - 1}\right]^{1/2} = \left[\frac{1908.95 - \frac{(269.1)^2}{43}}{43 - 1}\right]^{1/2} = 2.3143$$

$$G = \frac{N^2 (\Sigma x^3) - 3N (\Sigma x) (\Sigma x^2) + 2 (\Sigma x)^3}{N (N - 1) (N - 2) \sigma^3}$$

$$= \frac{(43)^2 (16352.259) - 3(43)(269.1)(1908.95) + 2(269.1)^3}{43 (43 - 1) (43 - 2) (2.3143)^3} = 3.2053 \quad .$$

Use Equation [3-13] to test for high outlier.

$$\eta_H = \mu + K_N \sigma$$

TABLE F-1. ANNUAL PEAK WATER LEVELS, STATE PIER PROVIDENCE, R. I.

BASIC DATA						ORDERED DATA					HISTORICAL DATA INFORMATION	
1	2	3	4	5	6	7	8	9	10	11	12	13
MO	DAY	YEAR	x ELEV (FT)	x^2	x^3	RANK	YEAR	x ELEV (FT)	PLOTTING POSITION	$x - \bar{\mu}$	COLUMN 11 SQUARED	COLUMN 11 CUBED
10	11	1931	4.2	17.64	74.088	1	1635	18.0	.0029	11.874	140.992	1555.251
11	30	1932	5.3	28.09	148.877	2	1638	18.0	.0058	11.874	140.992	1555.251
1	27	1933	6.0	36.00	216.000	3	1938	16.0	.0058	9.874	97.496	957.419
1	16	1934	4.5	20.25	91.125	4	1954	14.9	.0220	8.774	76.983	
9	15	1935	4.3	18.49	79.507	5	1944	10.1	.0455	3.974	15.793	
10	1	1936	5.6	31.36	175.616	6	1960	8.0	.0691	1.874	3.512	
10	23	1937	5.0	25.00	125.000	7	1963	7.9	.0926	1.774	3.147	
9	21	1938	16.0	256.00	4096.000	8	1974	7.0	.1161	0.874	0.764	
4	2	1939	5.5	30.25	166.375	9	1950	7.0	.1397	0.874	0.764	
11	27	1940	5.2	27.04	140.608	10	1953	6.7	.1632	0.574	0.329	
5	11	1941	4.9	24.01	117.649	11	1942	6.6	.1867	0.474	0.225	
3	3	1942	6.6	43.56	287.496	12	1970	6.4	.2102	0.274	0.075	
3	6	1943	5.7	32.49	185.193	13	1972	6.3	.2338	0.174	0.030	
9	14	1944	10.1	102.01	1030.301	14	1966	6.3	.2573	0.174	0.030	
11	22	1945	6.3	39.69	250.047	15	1945	6.3	.2808	0.174	0.030	

TABLE F-1. ANNUAL PEAK WATER LEVELS, STATE PIER PROVIDENCE, R. I. (Con't)

BASIC DATA						ORDERED DATA				HISTORICAL DATA INFORMATION		
1	2	3	4	5	6	7	8	9	10	11	12	13
MO	DAY	YEAR	x ELEV (FT)	x^2	x^3	RANK	YEAR	x ELEV (FT)	PLOTTING POSITION	$x - \bar{\mu}$	COLUMN 11 SQUARED	COLUMN 11 CUBED
11	10	1946	5.0	25.00	125.000	16	1951	6.1	.3044	-0.026	0.001	
3	3	1947	5.9	34.81	205.379	17	1933	6.0	.3279	-0.126	0.016	
12	20	1948	5.1	26.01	132.651	18	1973	5.9	.3514	-0.226	0.021	
10	22	1949	5.6	31.36	175.616	19	1947	5.9	.3750	-0.226	0.021	
11	25	1950	7.0	49.00	343.000	20	1962	5.9	.3985	-0.226	0.021	
2	7	1951	6.1	37.21	226.981	21	1943	5.7	.4220	-0.426	0.181	
10	0	1952	4.8	23.04	110.592	22	1958	5.7	.4456	-0.426	0.181	
11	7	1953	6.7	44.89	300.763	23	1971	5.7	.4691	-0.426	0.181	
8	31	1954	14.9	222.01	3307.949	24	1968	5.6	.4926	-0.526	0.277	
10	16	1955	5.6	31.36	175.616	25	1936	5.6	.5162	-0.526	0.277	
3	16	1956	5.0	25.00	125.000	26	1955	5.6	.5397	-0.526	0.277	
2	15	1957	4.8	23.04	110.592	27	1949	5.6	.5632	-0.526	0.277	
4	3	1958	5.7	32.49	185.193	28	1964	5.5	.5867	-0.626	0.392	
12	29	1959	5.2	27.04	140.608	29	1939	5.5	.6103	-0.626	0.392	
9	12	1960	8.0	64.00	512.000	30	1975	5.4	.6338	-0.726	0.527	

TABLE F-1. ANNUAL PEAK WATER LEVELS, STATE PIER PROVIDENCE, R. I. (Con't)

BASIC DATA						ORDERED DATA				HISTORICAL DATA INFORMATION		
1	2	3	4	5	6	7	8	9	10	11	12	13
MO	DAY	YEAR	x ELEV (FT)	x^2	x^3	RANK	YEAR	x ELEV (FT)	PLOTTING POSITION	$x - \bar{\mu}$	COLUMN 11 SQUARED	COLUMN 11 CUBED
1	16	1961	5.3	31.36	148.877	31	1969	5.3	.6573	-0.826	0.682	
12	6	1962	5.9	34.81	205.379	32	1932	5.3	.6809	-0.826	0.682	
11	30	1963	7.9	62.41	493.039	33	1961	5.3	.7044	-0.826	0.682	
11	20	1964	5.5	30.25	166.375	34	1959	5.2	.7279	-0.926	0.857	
12	29	1966	6.3	39.69	250.047	35	1940	5.2	.7515	-0.926	0.857	
11	12	1968	5.6	31.36	175.616	36	1948	5.1	.7750	-1.026	1.053	
12	11	1969	5.3	28.09	148.877	37	1937	5.0	.7985	-1.126	1.268	
3	3	1970	6.4	40.96	262.144	38	1956	5.0	.8221	-1.126	1.268	
3	1	1971	5.7	32.49	185.193	39	1946	5.0	.8456	-1.126	1.268	
11	26	1972	6.3	39.69	250.047	40	1941	4.9	.8691	-1.226	1.503	
4	4	1973	5.9	34.81	205.379	41	1957	4.8	.8926	-1.326	1.758	
12	2	1974	7.0	49.00	343.000	42	1952	4.8	.9162	-1.326	1.758	
4	3	1975	5.4	29.16	157.464	43	1934	4.5	.9397	-1.626	2.643	
8	15	1635	18.0			44	1935	4.3	.9632	-1.826	3.334	
8	3	1638	18.0			45	1931	4.2	.9868	-1.926	3.709	

From Table 3-1, $K_N = 2.71$ for N = 43, thus

$$\eta_H = 6.2581 + (2.71)(2.3143) = 12.5 \text{ feet} \quad .$$

A review of the systematic record reveals that the peak elevation of 16.0 feet in 1938 and the peak elevation of 14.9 feet in 1954 exceed the threshold value of 12.5 feet. Due to the fact that the systematic record is extended considerably as a result of the historic events, only the 1938 event will be used as a high outlier and the 1954 event will be considered as part of the systematic record. Because of the high outlier the statistics of the systematic record are re-evaluated as follows:

$$\Sigma x = 269.1 - 16 = 253.1$$

$$\Sigma x^2 = 1908.95 - 256 = 1652.95$$

$$\Sigma x^3 = 16{,}352.259 - 4096 = 12256.259 \quad .$$

Thus for N = 42

$$\mu = \frac{\Sigma x}{N} = \frac{253.1}{42} = 6.0262$$

$$\sigma = \left[\frac{(\Sigma x^2) - \frac{(\Sigma x)^2}{N}}{N - 1}\right]^{1/2} = \left[\frac{1652.95 - \frac{(253.1)^2}{42}}{42 - 1}\right]^{1/2} = 1.7650$$

$$G = \frac{N^2 (\Sigma x^3) - 3N (\Sigma x) (\Sigma x^2) + 2(\Sigma x)^3}{N (N-1) (N-2) \sigma^3}$$

$$= \frac{(42)^2 (12256.259) - 3(42)(253.1)(1652.95) + 2(253.1)^3}{(42) (42 - 1) (42 - 2) (1.765)^3} = 3.5209 \quad .$$

Adjustment of the statistics is required to account for the historic data including the high outlier. The weight factor W according to Equation [3-14] with a historic period from 1635 through 1975 or 341 years is:

$$W = \frac{H - Z}{N} = \frac{341 - 3}{42} = 8.0476 \quad .$$

The sum of the historic water levels is:

$$\Sigma x' = 18 + 18 + 16 = 52 \quad .$$

By Equation [3-15]

$$\bar{\mu} = \frac{W\ (\Sigma x) + \Sigma x'}{H} = \frac{(8.0476)(253.1) + 52}{341} = 6.126 \quad .$$

Based on the adjusted mean, $x - \bar{\mu}$ is computed as shown in column 11, $(x - \bar{\mu})^2$ in column 12 and $(x' - \bar{\mu})^3$ in column 13.
The sums are:

$$\Sigma\ (x\ - \bar{\mu})^2 = 128.03$$

$$\Sigma\ (x' - \bar{\mu})^2 = 379\ 48$$

$$\Sigma\ (x' - \bar{\mu})^3 = 4310.949 \quad .$$

By use of Equation [3-16] it is found that

$$\bar{\sigma} = \left[\frac{W\Sigma(x - \bar{\mu})^2 + \Sigma(x' - \bar{\mu})^2}{H - 1}\right]^{1/2} = \left[\frac{(8.0476)(128.03) + 379.48}{341 - 1}\right]^{1/2}$$

$$= 2.0363 \quad .$$

From Equation [3-17]

$$\bar{G} = \frac{H}{(H - 1)(H - 2)\ \sigma^3}\left[\frac{W(N - 1)(N - 2)\ \sigma^3 G}{N} + 3W\ (N - 1)\ (\mu - \bar{\mu})\ \sigma^2 + WN\ (\mu - \bar{\mu})^3 + \Sigma(x' - \bar{\mu})^3\right]$$

$$\bar{G} = \frac{341}{(340)(339)(2.0363)^3}\ \left[\frac{(8.0476)(41)(40)(1.765)^3\ (3.5209)}{42}\right.$$

$$+ 3(8.0476)(41)(6.0262 - 6.126)(1.765)^2$$

$$\left. + (8.0476)(42)(6.0262 - 6.126)^3 + 4310.949 \right] .$$

$$\bar{G} = 3.5341, \text{ say } 3.5 \quad .$$

Table F-2 shows summaries of the exceedence frequency curve. The first column is a tabulation of the prescribed exceedence probabilities and column 2 shows the corresponding frequency factors for $\bar{G} = 3.5$. (The K values can be found in Bulletin No. 17b.) Column 3 shows the frequency factor times the standard deviation and column 4 is the solution of Equation [3-18], or

$$\eta = \bar{\mu} + \bar{\sigma}K \quad .$$

The upper and lower confidence limits for levels of significance of .05 and .95 are computed as follows:

The standard normal deviate t at confidence level 0.05 is 1.64485 as found in Bulletin No. 17b for zero skew. From Equations [3-26] and [3-27] it is found that

$$a = 1 - \frac{t^2}{2(N - 1)} = 1 - \frac{(1.64485)^2}{2\ (42 - 1)} = 0.967$$

$$b = K^2 - \frac{t^2}{N} = K^2 - \frac{(1.64485)^2}{42} = K^2 - .0644174172 \quad .$$

The values of K^2 are shown in column 5 in Table F-2 and the values of b are shown in column 6. The solutions of Equation [3-24] and [3-25] are shown in columns 9 and 10. The upper and lower confidence limits for the water levels according to Equations [3-22] and [3-23] are shown in columns 11 and 12, respectively. The water level elevations corresponding to the expected probabilities are shown in column 13. These are determined by using Equation

TABLE F-2. FREQUENCY CURVE AND CONFIDENCE LIMITS

EXCEEDENCE FREQUENCY CURVE				CONFIDENCE LIMITS								
1	2	3	4	5	6	7	8	9	10	11	12	13
P	K	$K\bar{\sigma}$	η(FT)	K^2	b	ab	$(K^2 - ab)$	K_u $\frac{K+Col.8}{a}$	K_L $\frac{K+Col.8}{a}$	η(FT) .05 LIMIT	η(FT) .96 LIMIT	η(FT) EXPECTED PROBABILITY
.002	6.64627	13.5337	19.5	44.1729	44.1085	42.6529	1.2329	8.1481	5.5981	22.6	17.5	21.7
.005	5.25291	10.6965	16.8	27.5930	27.5286	26.6202	0.9863	6.4521	4.4122	19.2	15.1	18.2
.010	4.22473	8.6028	14.7	17.8483	17.7839	17.1970	0.8071	5.2035	3.5343	16.7	13.3	15.7
.020	3.22641	6.5699	12.7	10.4097	10.3433	10.0020	0.6385	3.9968	2.6762	14.2	11.6	13.3
.040	2.26862	4.6120	10.7	5.1466	5.0822	4.9145	0.4818	2.8443	1.8480	11.9	9.9	11.1
.100	1.09552	2.2308	8.4	1.2002	1.1358	1.0983	0.3192	1.4630	0.8028	9.6	7.8	8.5
.200	0.32171	0.6551	6.8	0.1035	0.0391	0.0378	0.2563	0.5977	0.0676	7.4	6.3	6.8
.500	-0.41253	-0.8400	5.3	0.1702	0.1058	0.1023	0.2606	-0.1571	-0.6961	5.8	4.7	5.3
.800	-0.56242	-1.1453	5.0	0.3163	0.2519	0.2436	0.2696	-0.3028	-0.8604	5.5	4.4	5.0
.900	-0.57035	-1.1614	5.0	0.3253	0.2620	0.2534	0.2681	-0.3126	-0.8671	5.5	4.4	5.0
.950	-0.57130	-1.1633	5.0	0.3264	0.2620	0.2534	0.2702	-0.3114	-0.8702	5.5	4.4	5.0
.990	-0.57143	-1.1636	5.0	0.3265	0.2621	0.2535	0.2702	-0.3115	-0.8704	5.5	4.4	5.0

NOTE: $\bar{G} = 3.5$

$\bar{\sigma} = 2.0363$

$\bar{\mu} = 6.126$

[3-28a] through [3-28f], interpolation of the intermediate expected probabilities and plotting the resulting frequency curve. Figure F-1 shows the expected probability curve derived together with the observed peak water levels.

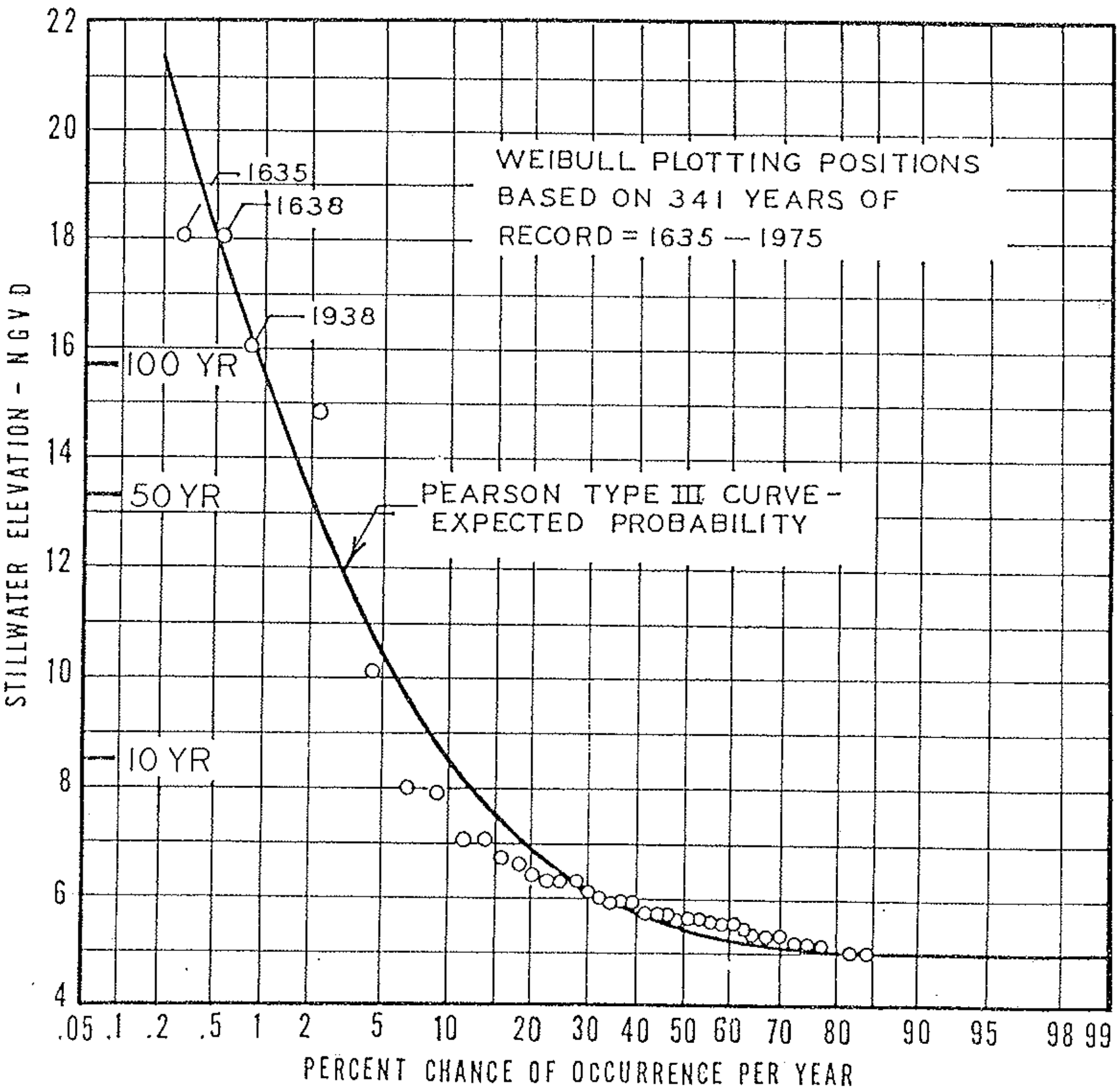

Figure F-1. Frequency of water levels at the State Pier, Providence, R. I.

Hurricane Surge Hydrograph
A continuous graph representing the difference between the hurricane stage hydrograph and the water stage hydrograph that would have prevailed at the same point and time if the hurricane had not occurred.

Hurricane Wind Pattern or Isovel Patterns
An actual or graphical representation of near-surface wind velocities covering the entire area of a hurricane at a particular instant. Isovels are lines connecting points of simultaneous equal wind velocities, usually referenced to a level 10 meters or about 33 feet above the surface, in knots or mph; wind directions at various points are indicated by arrows or deflection angles on the isovel charts. Isovel charts are usually prepared at each hour during a hurricane, but for each half-hour during critical periods.

Hydrography
(1) A configuration of an underwater surface including its relief, bottom materials, coastal structures, etc. (2) The description and study of seas, lakes, rivers, and other waters.

Hypothetical Hurricane ("Hypo-Hurricane")
A representation of a hurricane, with specified characteristics, that is assumed to occur in a particular study area, following a specified path and timing sequence.

a. Transposed. A hypo-hurricane based on the storm transposition principle is assumed to have wind patterns and other characteristics basically comparable to a specified hurricane of record, but is transposed to follow a new path to serve as a basis for computing a hurricane surge hydrograph that would be expected at a selected point. Moderate adjustments in timing or rate of forward movement may be made also, if these are compatible with meteorological considerations and study objectives.

b. Hypo-Hurricane Based on Generalized Parameters. Hypo-hurricane estimates based on various logical combinations of hurricane characteristics used in estimating hurricane surge magnitudes corresponding to a range of probabilities and potentialities. The Standard Project Hurricane (SPH) is most commonly used for this purpose, but estimates corresponding to more severe or less severe assumptions are important in some project investigations.

c. Standard Project Hurricane (SPH). A hypothetical hurricane intended to represent the most severe combination of hurricane parameters that is reasonable characteristic of a specified region, excluding extremely rare combinations. It is further assumed that the SPH would approach a given project site from such direction, and at such rate of movement as to produce the highest hurricane surge hydrograph, considering pertinent hydraulic characteristics of the area. Based on this concept, and extensive meteorological studies and probability analyses, a tabulation of "Standard Project Hurricane Index Characteristics" mutually agreed upon by representatives of the U. S. Weather Bureau and the Corps of Engineers, is available.

d. Probable Maximum Hurricane (PMH). A hypo-hurricane that might result from the most severe combination of hurricane parameters that is considered reasonably possible in the region involved, if the hurricane should approach the point under study along a critical path and at optimum rate of movement. This estimate is substantially more severe than the SPH criteria.

e. Design Hurricane. A representation of a hurricane with specified characteristics that would produce hurricane surge hydrographs and coincident wave effects at various key locations along a proposed project alignment. It governs the project design after economics and other factors have been duly considered. The design hurricane may be more or less severe than the SPH, depending on economics, risk, and local considerations.

Hydraulic Model
A physical or numerical replica of a real system that is constructed or developed for the purpose of simulating water motions.