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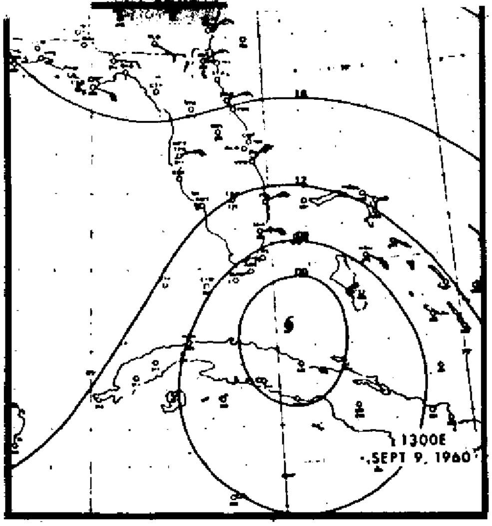
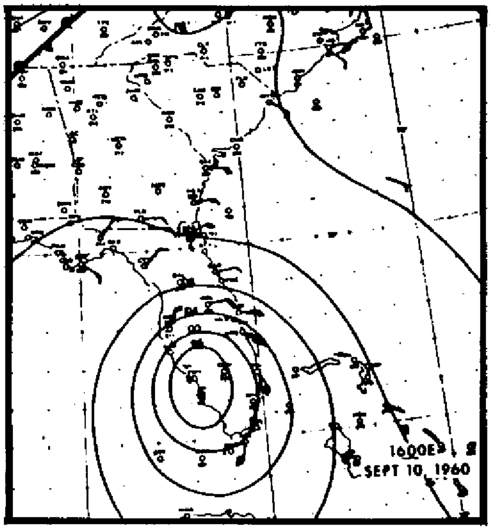
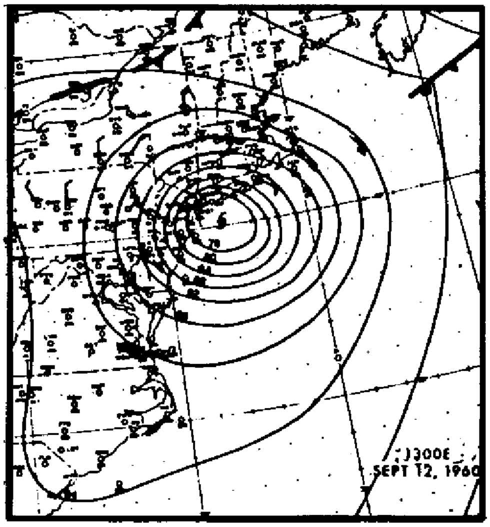
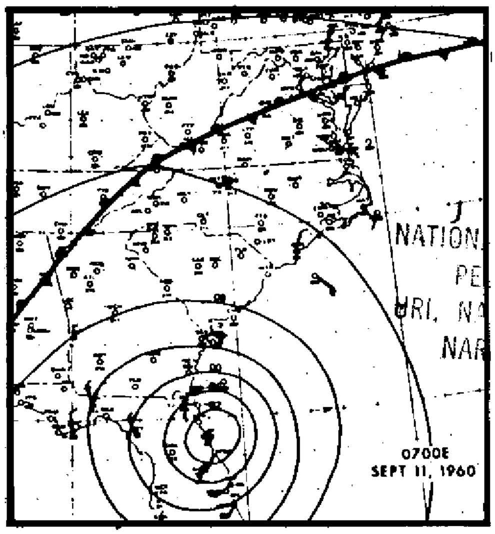


D. Lee Harris





THE PREDICTION OF HURRICANE STORM SURGES



A state-of-the-art survey

THE PREDICTION OF HURRICANE STORM SURGES

A State-of-the-Art Survey

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PREFACE

This publication has been prepared to give the non-specialist an understanding of the problems involved in the prediction of coastal floods, the available technology for solving those problems, and, in some cases, of ongoing efforts to improve the technology. Its primary purpose is to encourage and assist non-meteorologists in making the maximum use of the available technology. It may also be helpful in pointing out areas in which additional research efforts are most likely to be fruitful.

References to the sources of data presented in figures and references to additional information on the topics discussed are presented at the end of the report.

ACKNOWLEDGEMENTS

The author would like to express his appreciation to the National Hurricane Center for providing a copy of the synoptic chart for Hurricane David, to the National Ocean Survey for providing the data displayed in Figures 7 and 8, to Lillean Pieter for the original drawings which first appear in this publication and to Cynthia Vey for typing the manuscript.

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1. INTRODUCTION

What should you do when a hurricane warning is received for your section of the coast? Should you evacuate? Should you batten down the hatches and wait out the storm? Or should you continue business as usual? After all the warnings always cover a large area which does not experience the extreme storm conditions.

The decision is much like a game of chance with high stakes, such as Russian roulette. All hurricanes have tremendous potential for death and destruction. Precise predictions of hurricane motion, hurricane intensity and hurricane effects are not yet possible.

Drownings due to coastal floods are a major cause of hurricanes deaths in the United States and elsewhere. Drownings have been less frequent in U. S. hurricanes since 1960, partly because of improved warning and evacuation systems and partly because of remarkably good luck. The potential for a disaster is growing as a consequence of the growing population density in coastal communities, as shown in Figure 1.

Table I provides a summary of the loss of life and damages due to past hurricanes in Florida.

The element of chance in the decision of how to respond to a hurricane warning is demonstrated by the record of accuracy in past predictions of hurricane motion. The overall average error in predicting the position of a hurricane center 24 hours in advance is about 109 nautical miles. It has been reduced only about 10% in the last 25 years. The distribution of errors in the official forecasts of the hurricane position for 12 and 24 hours in the future are shown in Figure 2. Prospects for substantial improvement within the next decade are not bright. Since the average length of the coastline which suffers serious damage is only about 50 miles, it can be seen that an adequate warning may have to cover more than five times the area which actually suffers serious damage.

Imperfect predictions of storm motion are not the only factor contributing to uncertainty in the storm surge forecast. Storms may change in their intensity as they move. A storm which comes inland on a high tide has a greater potential for damage than the same storm when its greatest flooding coincides with a low tide. Tornadoes develop in many but not all hurricanes.

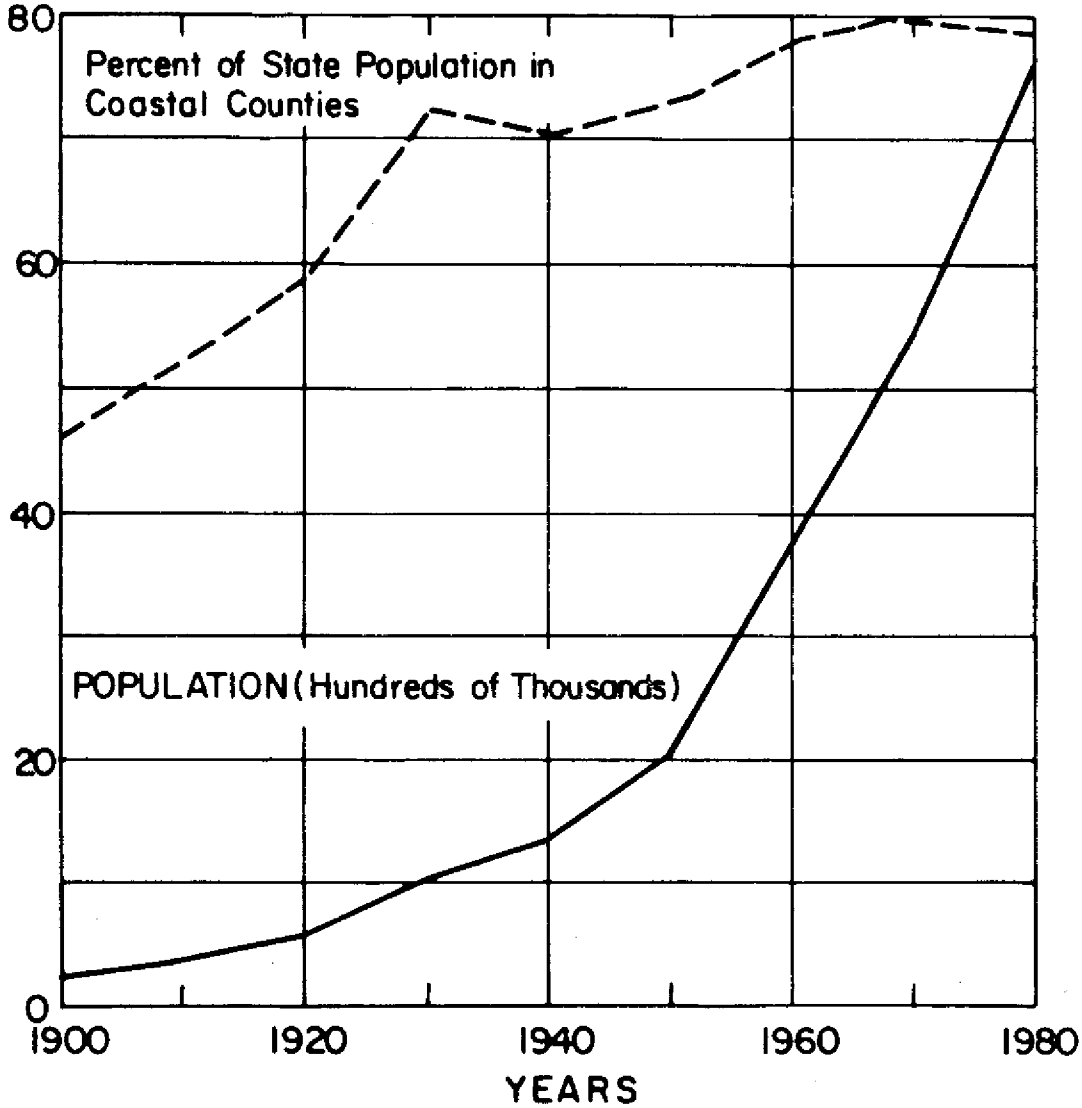


Figure 1. Population growth in Florida.

Table I

Damage and Fatalities in

Florida from Hurricanes,

1926-1975

Year		Fatalities	Damage
1926		243	$115,495,000
1928		1,838	26,235,000
1929		3	821,000
1930		0	75,000
1932		1	150,000
1933		2	4,120,000
1935	(2 storms)	405	11,500,000
1936		7	200,000
1937		15	5,000
1939		1	52,000
1941		6	690,000
1944		18	60,000,000
1945		4	54,130,000
1946		0	7,200,000
1947	(2 storms)	17	51,900,000
1948	(2 storms)	3	17,500,000
1949		2	45,000,000
1950		6	31,600,000
1951		0	2,000,000
1953		0	4,952,000
1956		7	7,299,605
1957		5	75,000
1958		0	(Minor)
1959		0	1,656,000
1960		13	305,050,000
1963		1	50,000
1964	(3 storms)	11	362,000,000
1965		13	139,300,000
1966		9	15,000,000
1968		9	6,650,000
1972		9	41,000,000
1975		2	100,000,000
1979		0	195,000,000

Data for 1926-1975 compiled by the Florida Division of Disaster Preparedness, based on data obtained from U.S. Department of Commerce, Hurricanes, Florida and You, NOAA, National Weather Service, 1976, and Published in "Florida Hazard Analysis." Data for 1979 taken from the NOAA Storm Report for September, 1979.

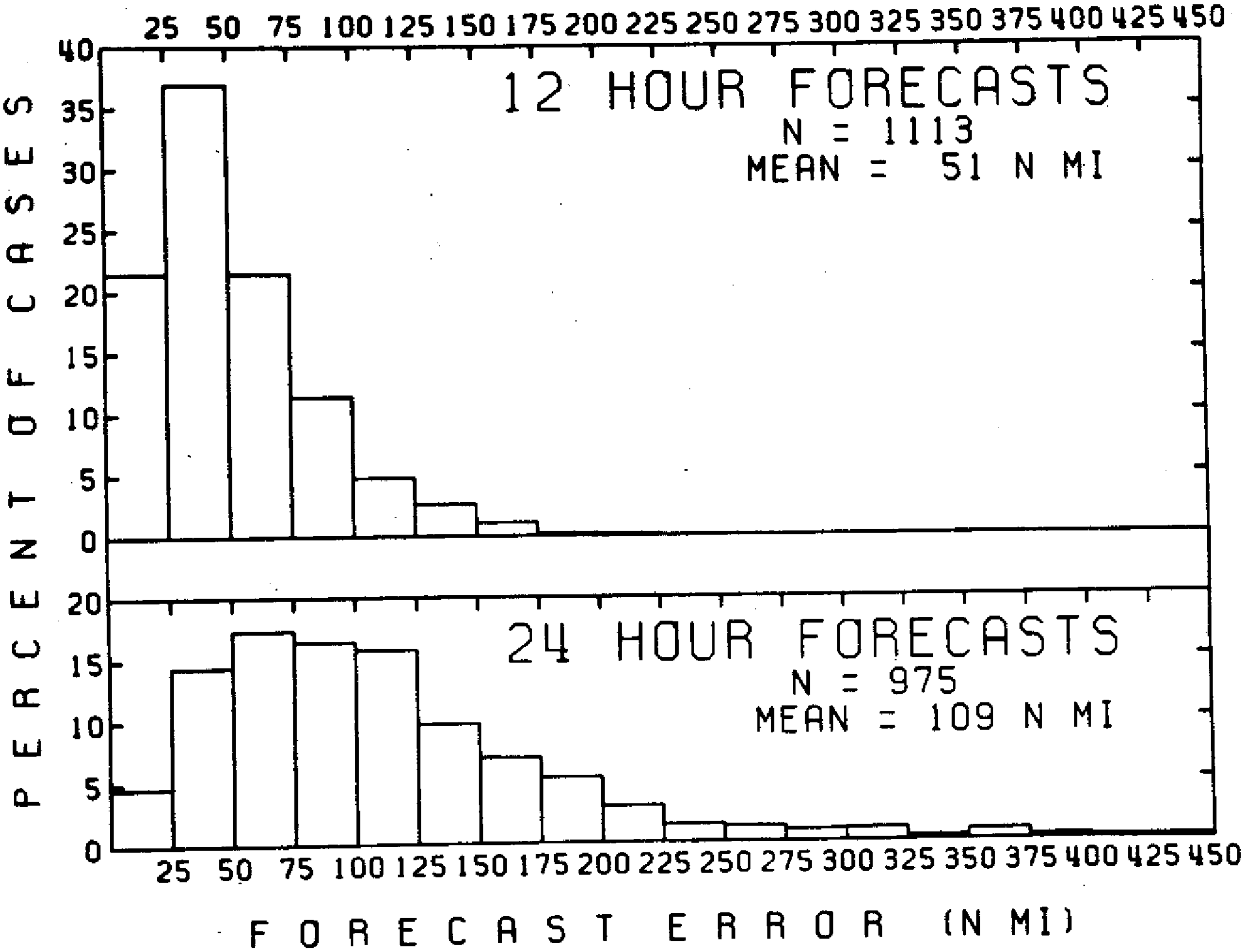


Figure 2. Distribution of the magnitude of errors in predicting future hurricane positions.

The importance of many factors which affect the uncertainty in the forecast can be identified a short time before storm landfall. Thus the forecaster can be more confident in some predictions than in others. A part of the uncertainty results from a lack of scientific understanding and may not be eliminated in the near future.

Storms contribute to coastal flooding by three nearly distinct processes:

(1). A drop of atmospheric pressure at sea level is accompanied by a rise in water level, so that the combined pressure of air and water tends toward a constant value at some level beneath the water surface.

(2). The winds in the atmosphere generate currents in the sea. When the motion of these currents is impeded by land, the water level rises.

(3) The winds also generate waves, and when the motion of the waves is impeded by land, part of the energy lost by the waves appears as an increase in the mean water level on the beach.

Within estuaries, bays, and some low-lying but normally dry areas storm rainfall may make a significant contribution to the flooding produced by the storm.

The most persistent variation of water level along the open coast and in many bays and estuaries is produced by the astronomical tides. A few other processes such as long period variations in sea level make minor contributions.

Severe coastal flooding results from an unfavorable combination of all the phenomena listed above. Each of these phenomena is discussed separately in the following sections. The combined effect is given approximately by the sum of the separate contributions. The possibility that one phenomenon may be modified by another is identified in several cases.

The astronomical tides are discussed first in Section 2 as these are best understood and most independent. An understanding of the contribution by tides will be useful in evaluating the uncertainty associated with storms.

Problems associated with storm description and prediction are discussed in Section 3. Specification of the pressure gradients and wind fields responsible for storm surge generation is essential for the prediction of the storm effects on the sea. Uncertainties about the storm description affect the strategy for dealing with storm surge predictions.

A description of storm surge generation and the technology available for prediction is presented in Section 4.

The status of hurricane prediction skills and protection plans is reviewed in Section 5. It is shown that nowhere in Florida does the frequency of hurricane conditions exceed one day in a thousand. But that hurricane conditions are experienced between one and three times for each ten days for which hurricane warnings have been issued.

A summary is presented in Section 6.

2. NORMAL WATER LEVEL VARIABILITY IN THE SEA

Both the sun and the moon exert gravitational pulls on each particle of the earth. This force is proportional to the mass of the sun or moon and inversely proportional to the square of the distance between the particle of the earth and the center of the sun or moon. Although the distance from the earth to the sun is much greater than the distance to the moon, the mass of the sun is so much greater than the mass of the moon, that the sun dominates this gravitational force.

In general the distance between any two particles of the earth and the centers of the sun or moon is slightly different. Thus the pull of each heavenly body is slightly different at the two locations. It is the difference in the pull by the moon or sun at two locations which produces the astronomical tide. This difference is nearly proportional to the mass of the heavenly body divided by the cube of the distance between that body and the earth. Because of this extra factor involving the distance, the moon has a greater tide generating force than the sun. Water particles on the side of the earth facing the sun or moon are caused to accelerate toward the subsolar point or the sublunar point. On the opposite side of the earth the gravitational pull on the water particles is less than that on the solid earth. Thus water particles are caused to accelerate toward the point on the earth's surface which is most distant from the sun or moon as illustrated in Figure 3.

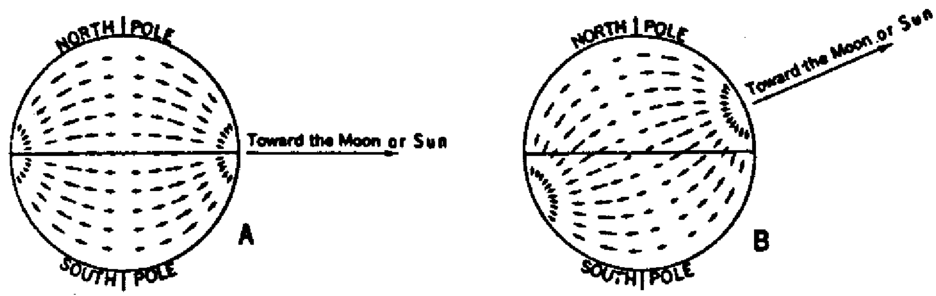


Figure 3. Tide-producing forces. The arrows represent the magnitude and direction of the horizontal component of the tide-producing force on the Earth's surface: A-when the Moon is in the plane of the Equator, the forces are equal in magnitude at the two points on the same parallel of latitude and 180° apart in longitude; B-when the Moon is at north (or south) declination, the forces are unequal at such points and tend to cause an inequality in the two high waters and the two low waters of a day.

The tide generating forces of the sun and moon are additive when the centers of sun, earth and moon form an approximately straight line as indicated in Figure 4a. The tides are generally highest at these times, and are called "spring tides." Spring tide occurs at intervals of about two weeks. The word "spring" as used in this connection refers to the increased speed of tide flow in rivers. It has nothing to do with the season of "spring." The tide generating forces of sun and moon are opposed when the lines joining the sun and moon to the earth form a right angle as illustrated in Figure 4b. The tides are lowest at these times and are called neap tides.

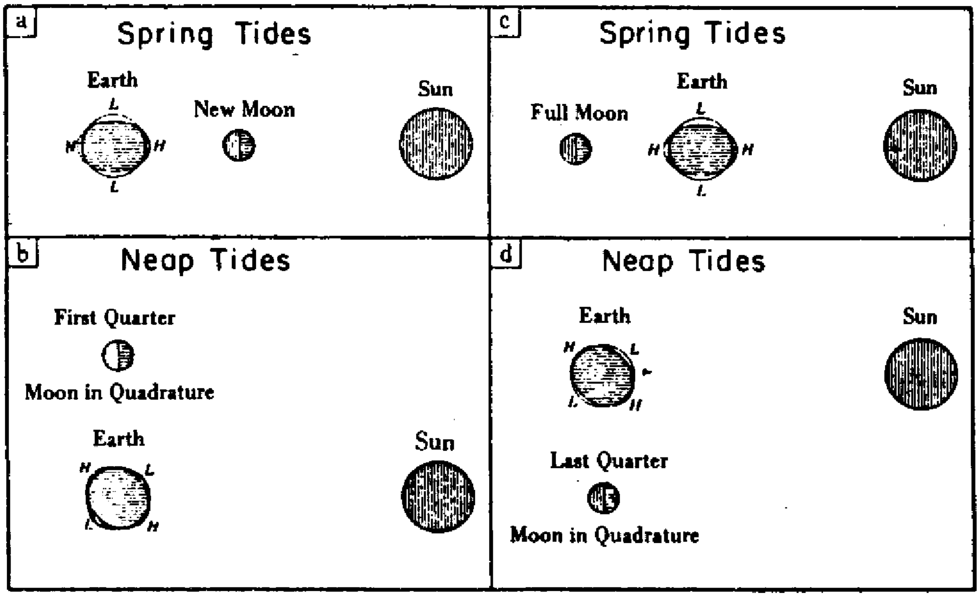


Figure 4. Spring and neap tides during a lunar month.

The distance between each point of the earth's surface and the sun or moon varies continually with many periods from one day to approximately 19 years. This leads to a continuous but predictable variation in the tide generation force. Tide predictions at specific locations may be made by comparing recorded tides at those location to the tide generating force for a period of approximately one year, and assuming that the relations established in this manner will hold in the future. Tide predictions for locations without extensive tide records are made by extrapolation or interpolation between the predictions for "reference" stations for which detailed predictions are made.

Florida experiences a greater variety of astronomical tides than any other state, besides Alaska. Predicted tides for a one month period for seven locations in Florida are shown in Figure 5. Note that the dominant period is "diurnal" (about 24 hours) at Pensacola but "semidiurnal" (12.4 hours) along the Altantic coast. Both diurnal and semidiurnal cycles are prominent at some locations.

An amplitude variation with a period of about two weeks is prominent at all locations. Amplitude variations with periods of one year and of about 19 years are also prominent. This variation in amplitude at all seven stations is summarized in Figure 6. The upper figure on the left on each plot gives the minimum water level change within one tidal day for the 19 year period 1963-1981. The lower figure on the right gives the maximum one day range. The upper figure on the right gives the average diurnal range, and the lower figure on the right gives the maximum range of the astronomical tide for the entire 19 year period. Storm effects and long term trends have been eliminated from these figures. It can be seen that on many days the astronomical tide can be neglected in coastal flooding predictions for the Pensacola area, but that it should be considered on other days. At Mayport a coastal flood which may be only a minor inconvenience if it coincides with the lowest of normal tides, could be a disaster if it coincides with the highest of normal tides. Most of this difference in normal tide levels can take place within a time period of about six hours.

LONG TERM TRENDS IN SEA LEVEL. Figure 7 shows a plot of recorded annual mean sea levels in Florida relative to the land, for the period of record. The year to year variability is large, but the long term trend is clearly upward. This is consistent with the record from other areas at similar latitudes, and with the geological record for the last few thousand years. This long term trend is too small to justify consideration for real time predictions. A plot of the monthly mean water levels for several Florida tide records is shown in Figure 8. It may be seen that the sea level is generally lowest in winter and highest in the fall, but that the pattern varies considerably from year to year. A plot of daily mean water levels, with tide effects removed, would show many small anomolies with periods varying from a few days to a few weeks. The Weather Services in Apalachicola, Key West, Pensacola, Tampa and Miami are equipped with real time tide recorders. Thus any short term anomaly in local sea level is readily identified, and is unlikely to produce a major problem.

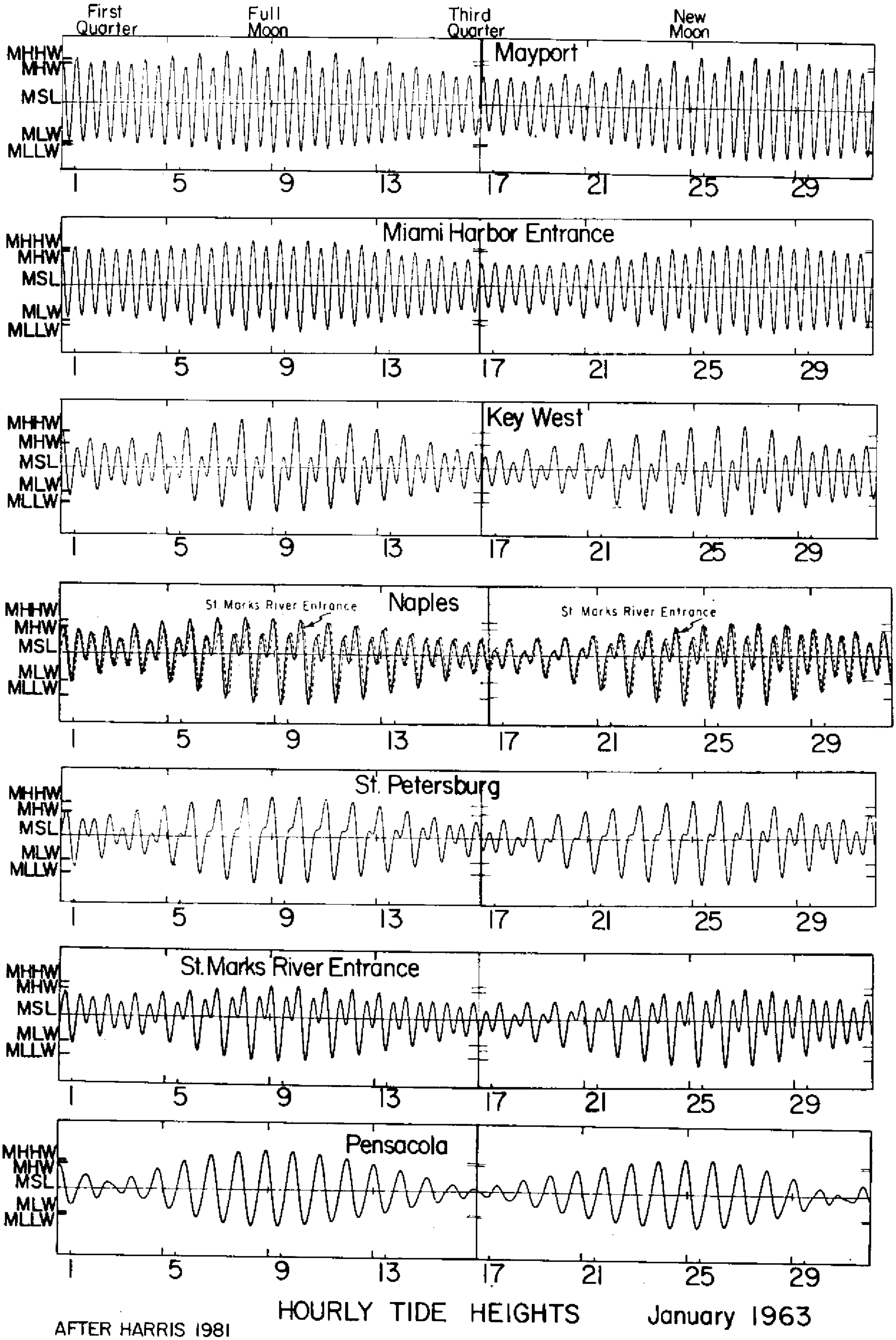


Figure 5. Predicted astronomical tides for Florida ports, January 1963.

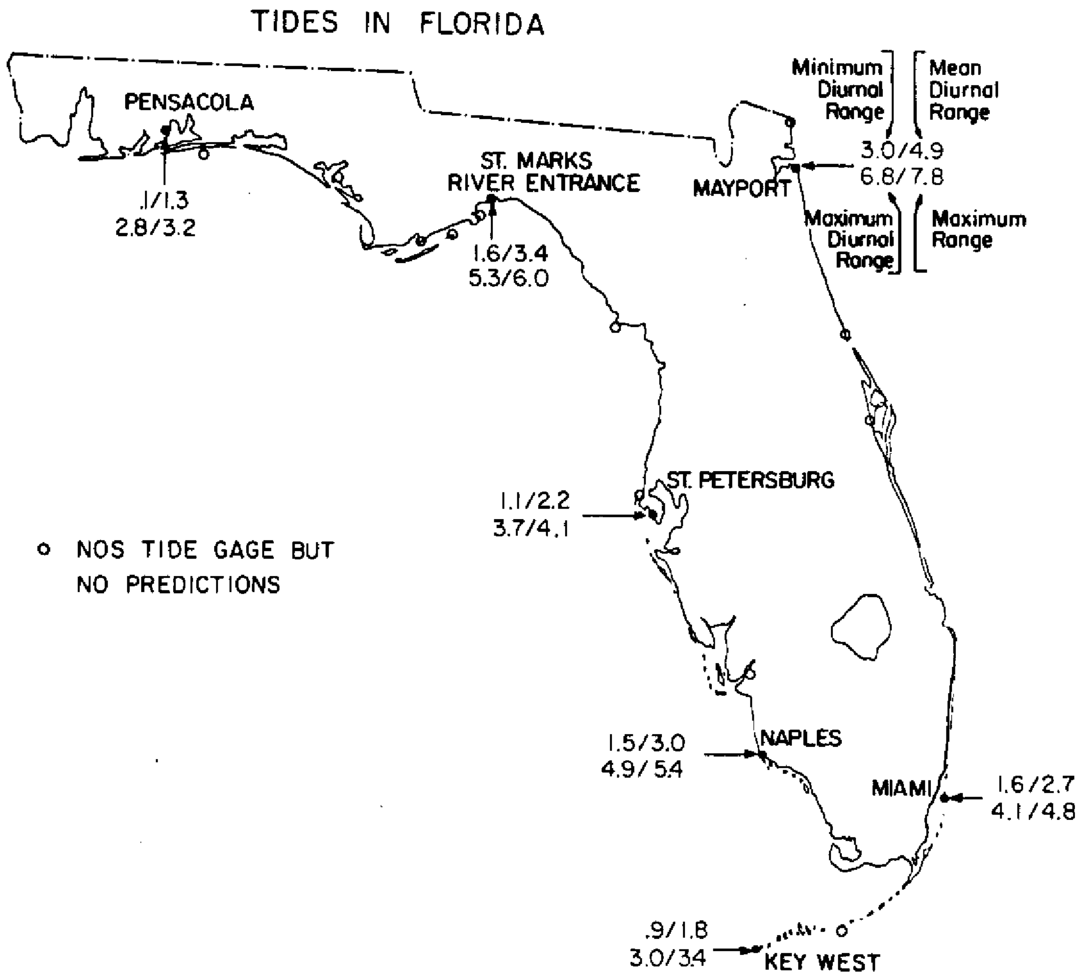


Figure 6. Chart showing the location in Florida for which tide prediction constants are available. The minimum, mean, and maximum tide diurnal ranges, in feet, and the extreme range of the predicted tides for the epoch 1963-1981 are also shown.

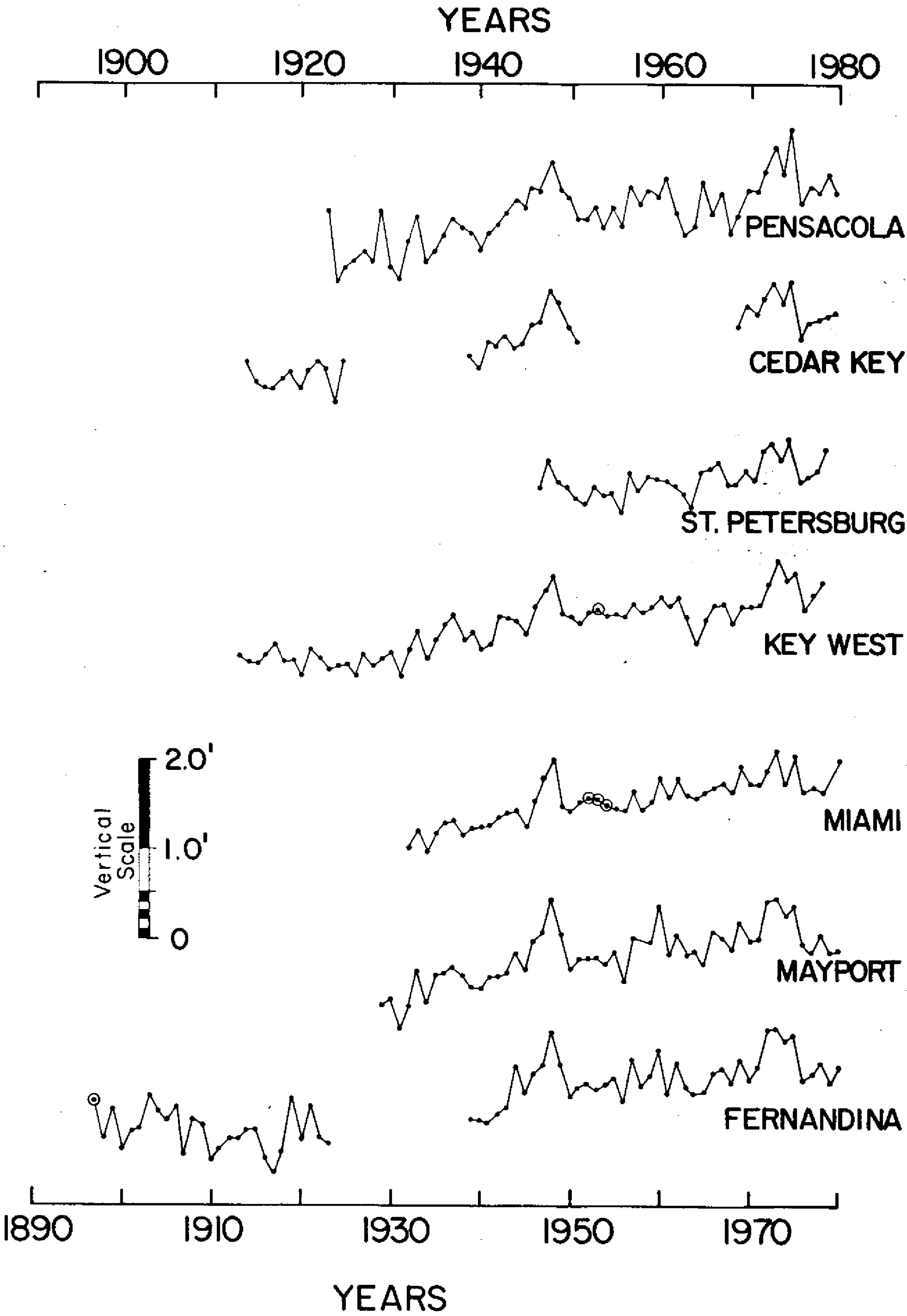


Figure 7. Annual mean sea level at Florida ports. Circled points indicates the use of interpolated data.

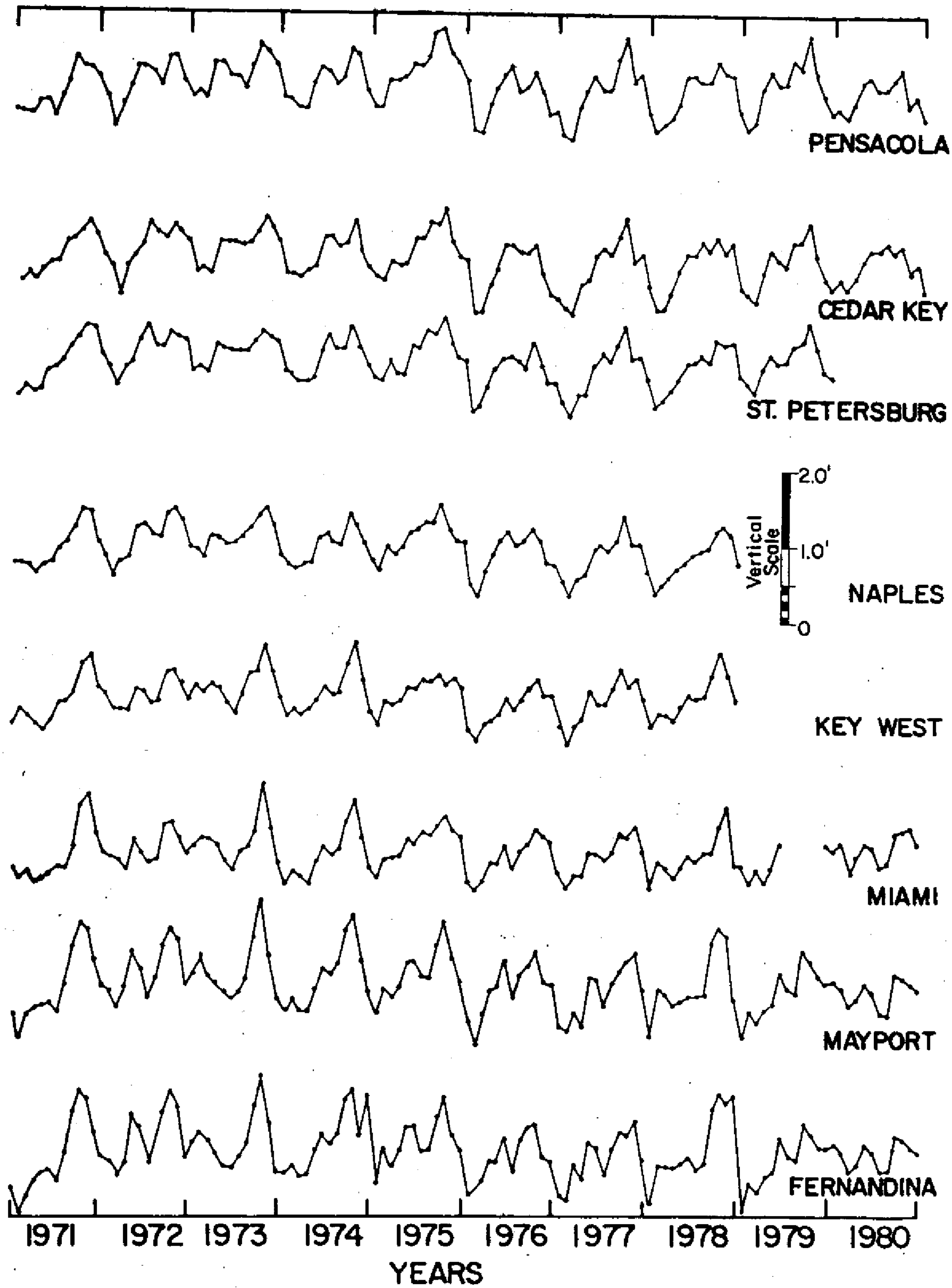


Figure 8. Monthly mean sea level at Florida ports, 1971-1980.

3. STORMS

Storm surges are generated by friction between wind and water and by the reduction of atmospheric pressure near a storm center. The first step in the prediction of storm surges must be a prediction of the winds and atmospheric pressure near the water surface. Two distinct storm types and an intermediate type must be recognized. The most common storm type is called an "extratropical cyclone." Storms of this type form along the boundary between cold and warm air masses. The boundary between air masses is called a warm front, if the warm air is advancing in the lower layers of the atmosphere, and a cold front when the cold air is advancing. This type of storm obtains its energy from the thermal contrast between the warm and cold air masses. The high wind speeds are generally concentrated in the cold air near the fronts. Storms of this type vary from about 500 to more than 1,500 miles across. Most areas of the United States come under the influence of an extratropical cyclone about once every five days on the average. Extratropical cyclones do not produce severe storm surges in the southeastern states, but north of Cape Hatteras, North Carolina, they may produce storm surges about as severe as those produced by hurricanes. Extratropical cyclones are not discussed in detail in this publication.

Hurricanes have been responsible for all severe storm surges recorded in Florida. Hurricanes are the most severe stage of a storm type called "tropical cyclones." Tropical cyclones form over warm tropical seas. They differ from extratropical cyclones in having a nearly uniform temperature at the surface. The storm derives its energy from the latent heat of condensation, released by the copious rainfall produced by tropical cyclones. Tropical cyclones lose intensity rapidly after moving over cold water or land. Tropical cyclones are called "tropical storms" and, according to present practice, are assigned names if the surface wind speed exceeds 39 miles per hour.

Tropical storms are called "hurricanes" if the wind speed exceeds 74 miles per hour. The highest winds in a tropical storm generally occur at a distance between 10 and 50 miles from the center and on the righthand side of the storm track. On the average, 8.4 tropical storms, of which 4.9 qualify as hurricanes at some time during their life span, occur in the North Atlantic Ocean each year. On the average only 3.3

tropical storms, of which 1.8 are hurricanes, affect the United States each year. Hurricanes also occur in the Pacific and Indian Oceans.

Since 1968 an intermediate type of storm, called a "subtropical storm," which has some tropical and some extratropical characteristics has been recognized. Storms of this type are generally combined with the tropical storms in statistical summaries. Six subtropical storms have been identified in or near Florida.

Tornadoes are small, very intense storms of short duration. They may occur within hurricanes or extratropical storms. Nationally the tornadoes associated with hurricanes tend to be smaller than those associated with extratropical storms. There are not enough records from Florida to justify a local comparison. The average path width of tornadoes associated with hurricanes is 97 yards compared with 250 yards for all tornadoes. The average reported path length of tornadoes associated with hurricanes is 7.6 miles compared with 16 miles for all tornadoes. No measurements of the wind speed in tornadoes associated with hurricanes are known. Wind speeds in excess of 200 miles per hour have been reported for extratropical tornadoes. Because of the small size and short life times it is not possible to predict specific places and times for tornado occurrence. Conditions favorable for tornado development can often be recognized a short time before the tornado actually occurs and tornado warnings may be issued. Because of the small size and short durations tornadoes are not believed to be significant factors in the development of storm surges.

<u>HURRICANE CHARACTERISTICS OF IMPORTANCE FOR STORM SURGE PREDICTION</u>. Figure 9 shows the surface pressure analysis and reported surface wind vectors for six synoptic weather charts near the time of landfall for Hurricane Donna, 1960. The point of a wind arrow over the water indicates the location of a ship at reporting time. The arrow points in the direction toward which the wind is blowing. The number of barbs on the arrow indicates the wind speed. Each complete report also includes the surface atmospheric pressure and temperature, information about clouds, weather and visibility and possibly the water temperature and ocean waves. This chart indicates the amount of information generally available about weather conditions in a hurricane while it is still at sea when a storm surge forecast is needed.

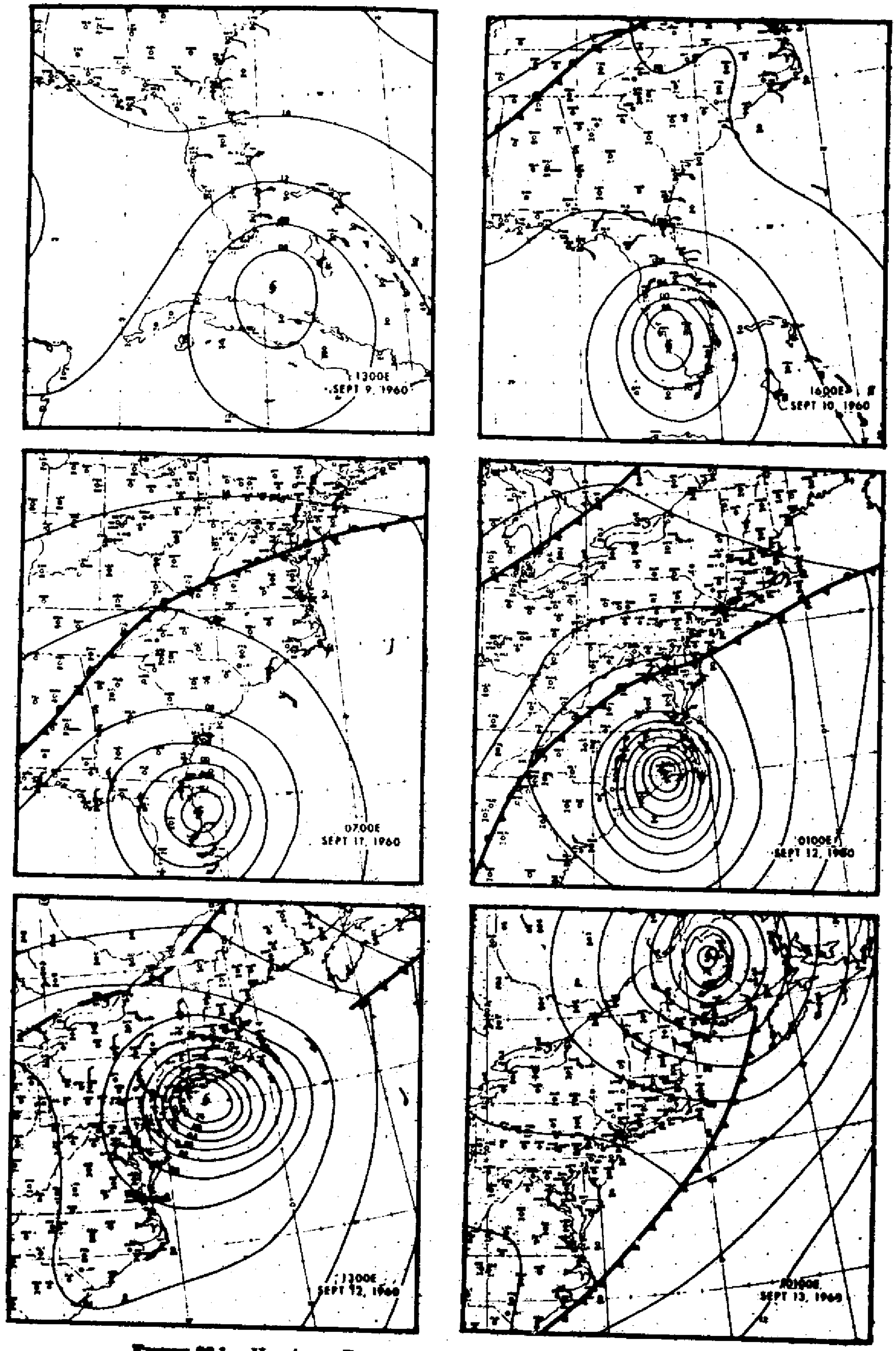


FIGURE 26.1.—Hurricane Donna, 1960, September 9–13. Synoptic charts.

Figure 9. Surface synoptic weather charts for Hurricane Donna 1960, near the time of landfall. Locations of available weather reports are indicated by arrows, feathered on only one side. Head of the arrow indicates location of the report. The number of feathers on the arrow increases with wind speed.

Figure 10, copied from the National Hurricane Center operational forecast chart shows the locations of all surface weather reports available for Hurricane Frederic at 1:00 AM, September 12, 1979. Few if any weather charts show a greater density of weather reports over the sea in a hurricane. The lowest pressure reported from a ship was 997 millibars. The three concentric circular isobars are symbolic to indicate an intense pressure gradient that cannot be fully analyzed. The central pressure for this chart was obtained by dropping a barometer into the eye of the storm. Pressure measurements were transmitted to the aircraft by radio until the instrument reached the sea.

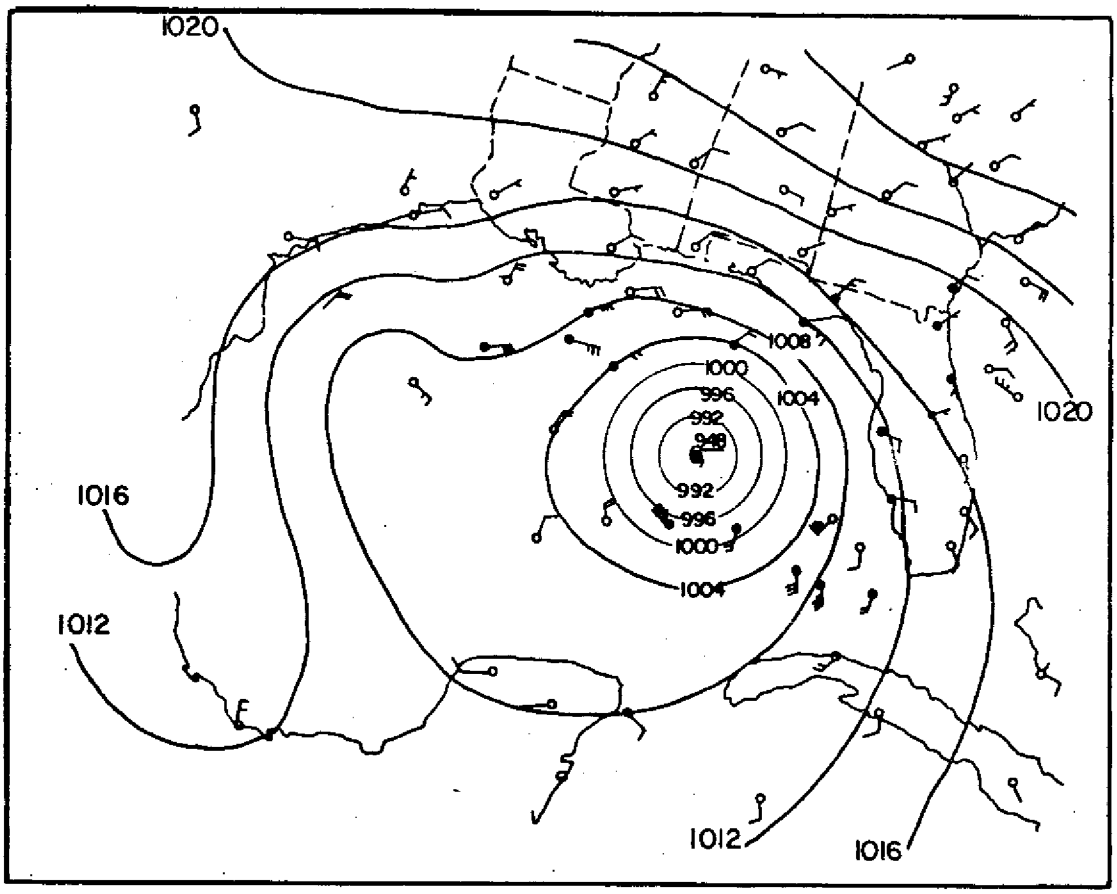


Figure 10. Synoptic chart for Hurricane Frederic, 1:00 EST, 12 September, 1979. Same notation as Figure 9.

When so little information is available at one time, a better understanding of the complete field of wind velocity and pressure can be obtained by combining all data collected from a single storm over a period of several hours. Combining data from several storms may be useful if the data can be properly adjusted for storm intensity and size. This can be accomplished on a research basis after the storm is over by first locating the "best storm track," that is the smooth storm track that provides the best fit to all data obtained for a single storm once the track has been defined. In the second step, each available weather report is located as x miles east or west and y miles north or south of the storm center. In the third step each weather report is plotted at the appropriate x, y position as illustrated in Figure 11. In this manner it is possible to use data collected over a period of several hours to provide a more complete two-dimensional picture of the storm. One of the best examples developed for the period before aircraft reports from hurricanes became available is shown in Figure 12.

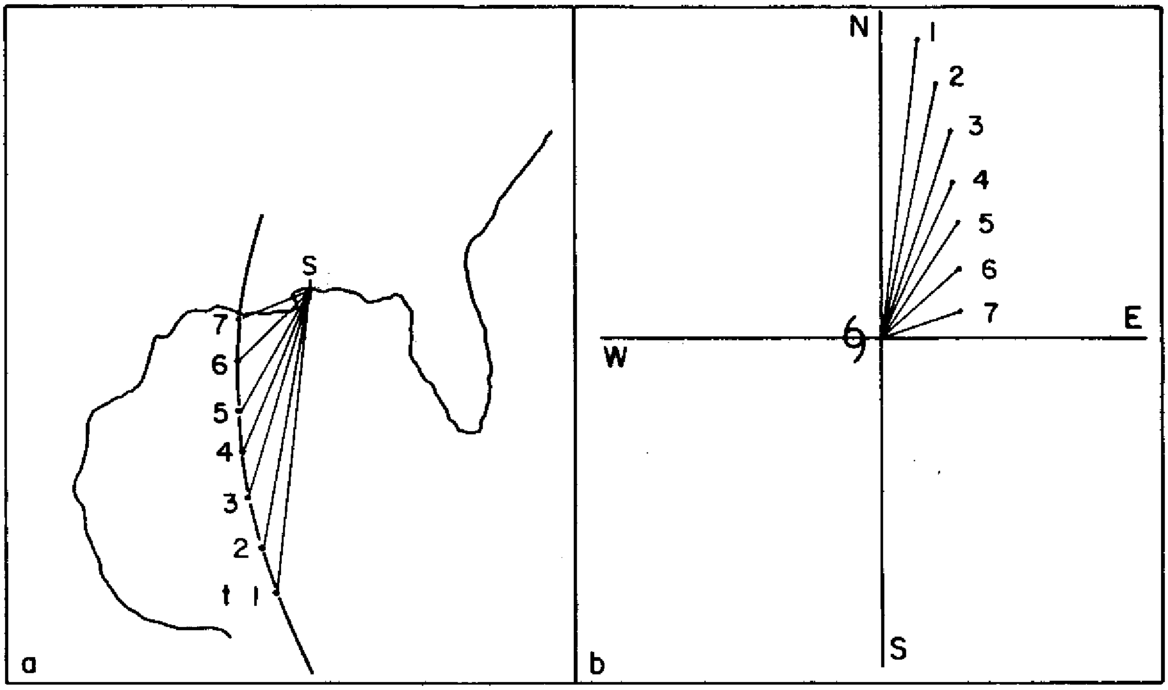


Figure 11. Definition sketch used to illustrate the technique for combining observations at one site over a period of time to obtain data from several locations relative to the hurricane center.

Aerial reconnisance of hurricanes became common in the 1950's and the compositing technique described above has been extended to the analysis of data obtained on board the hurricane hunter aircraft. Wind velocities at cloud level may be obtained by following the motion of cloud images on a radar scope. Figure 13 shows a sample of wind data obtained by these techniques. The data are averages in time and space as preferred for storm surge calculations. The compilation, however could not be achieved until long after the storm moved inland. The latest development along this line is shown in Figure 14. These flight level winds were transmitted to the National Hurricane Center in real time where they were available for use in forecasting storm motion. The amount of data collected within a given time span can be greatly increased, and the quality of the data made more uniform by collecting the data on board aircraft. Data obtained in this manner are clearly useful in understanding the structure of the storm. The wind speed and direction, however, change with elevation, and the problem of converting wind measurements made on board aircraft into precise estimates of the surface wind has not yet been fully solved. Therefore they do not yield precise estimates of the wind field near the water.

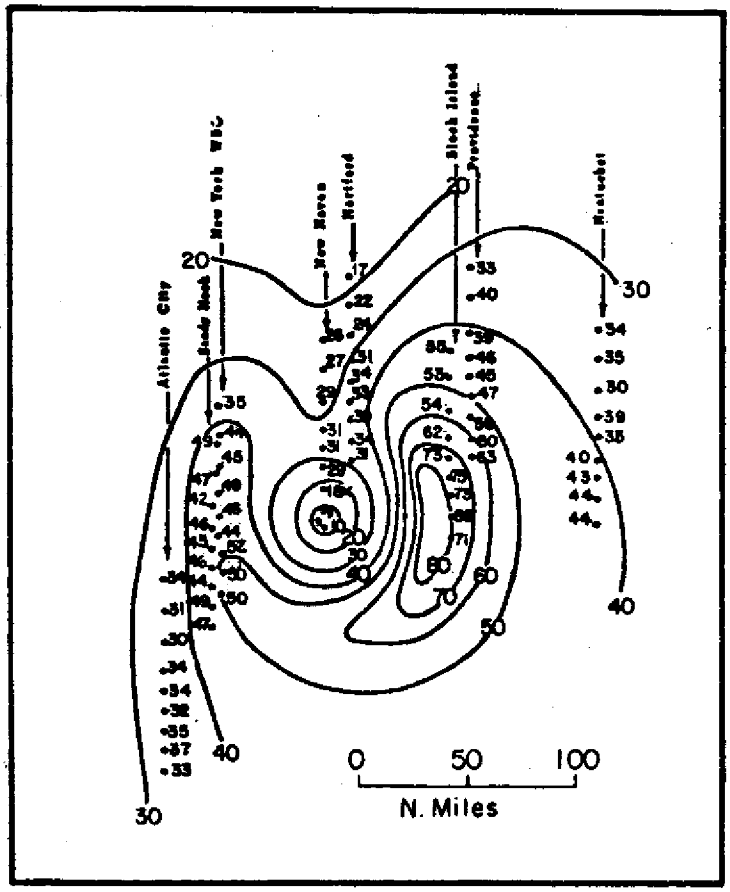


Figure 12. Sample time composite of hurricane data. Surface wind speeds (adjusted to 30 ft. off-water and 1500 EST intensity of storm) plotted relative to pressure center "X", 1400-1600 EST, September 21, 1938. Speeds are in miles per hour.

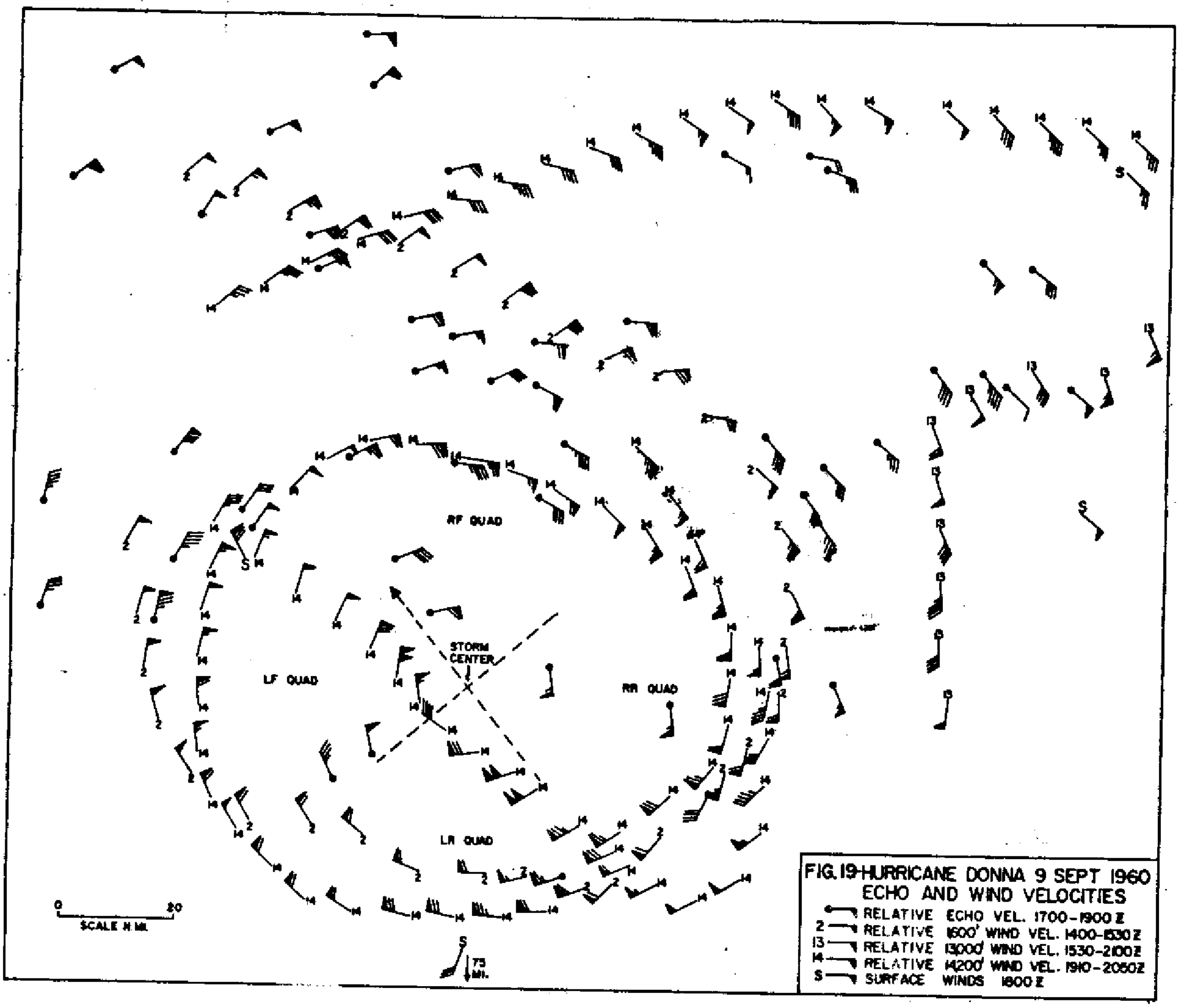


Figure 13. Composite wind chart based on surface winds and winds derived from aircraft observations and cloud echo movement as observed by radar. Wind arrow shafts point in the direction toward which the wind is blowing. Each solid triangle indicates a wind speed of 50 knots. Each full length barb indicates 10 knots and each half barb 5 knots.

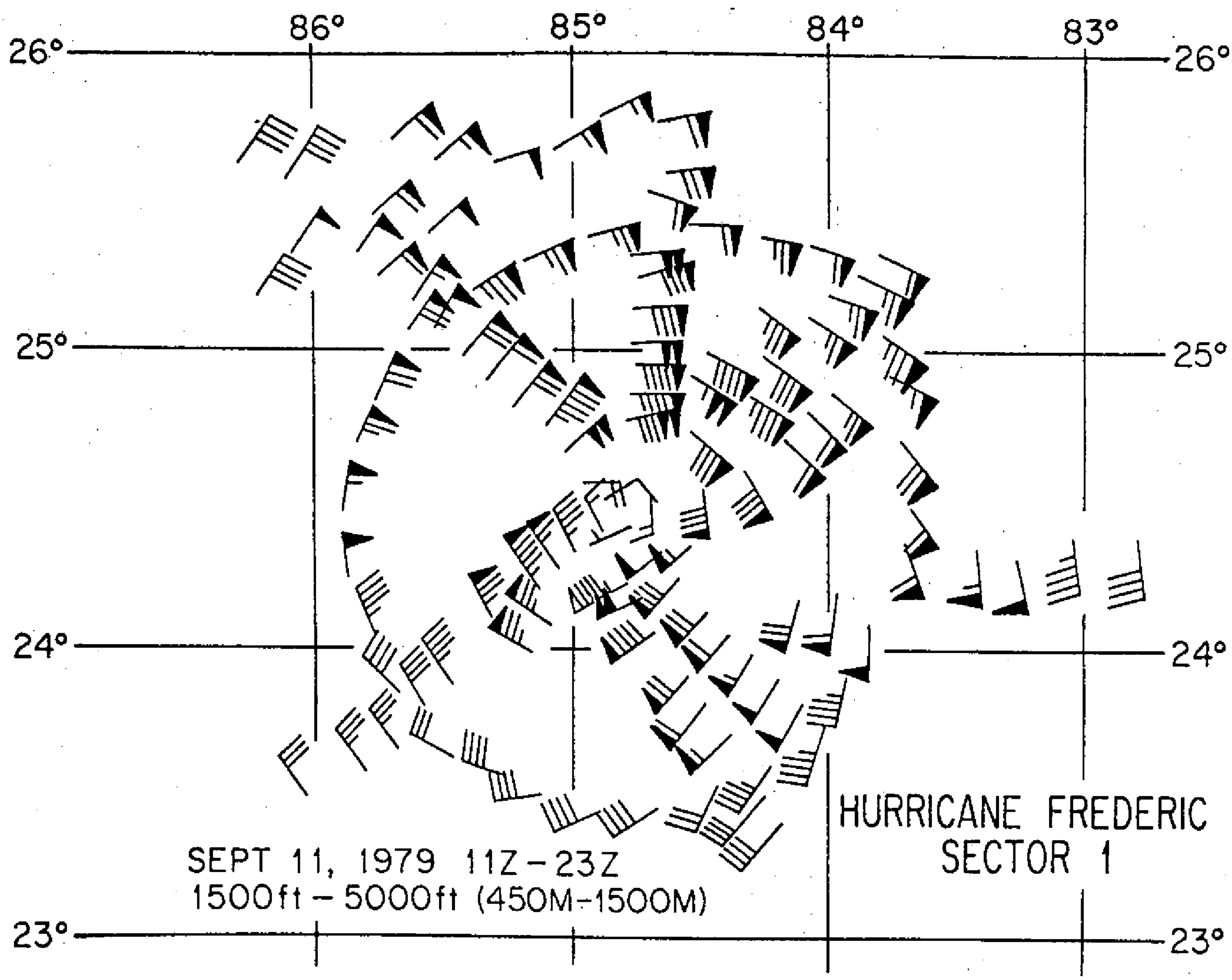


Figure 14. Winds observed, recorded and transmitted by satellite from a NOAA research aircraft to NHC from Hurricane Frederick at 1500 and 5000 ft. levels for 6:00 AM to 11:00 PM, 11 September, 1979.

MODELS OF THE HURRICANE PRESSURE AND WIND FIELDS. A complete specification of the pressure and wind fields within the storm is essential to the numerical prediction of storm surges. The obervations available at forecast time never provide enough measurements to satisfy this requirement directly. It is necessary to rely on idealized "model storms" which permit specification of the complete wind and pressure field on the basis of a few parameters which can be estimated from the available data. These models are not unique. Several models may be specificed by the same parameters but yield significantly different wind or pressure fields. These, however, should provide useful but not entirely accurate approximations to the true wind and pressure fields.

The specification of a hurricane wind model generally begins with a specification of the surface pressure field within the storm. There are two fundamental reasons for this procedure.

First and most important, the actual wind field is highly variable, the wind speed frequently varies by a factor of 50% and the direction frequently varies by sixty degrees or more, several times within a ten minute interval. Since the density of the water is about 800 times as great as that of the air, the water cannot respond to these rapid changes in air motion. A smoothed value of the wind velocity, averaged over several square miles and a time interval of several minutes such as those shown in Figures 13 and 14 is more useful for storm surge predictions than point values. Averaged values of the wind field can be inferred from a specification of the pressure field.

The second reason for preferring to work with the pressure field is that the pressure field near the center of the storm can be approximated by circular isobars with a high degree of accuracy even when the storm is moving. The wind field can retain this simplicity only approximately, only in the free air and only when the storm as a whole is not moving.

THE PRESSURE MODEL. The most widely used model for the pressure field in a hurricane was first published about 1954 in the form

$$(p-p_0) = (p_1-p_0)\, e^{-R/r} \qquad (1)$$

where the symbols were defined as

p is the pressure at a radius r

p_0 is the pressure at the center of the storm

p_1 is the pressure at a great distance from the center

R is the radius of the maximum wind speed

r is the radius to an arbitrary point.

The parameters p_0, p_1, and R as needed for equation (1) have been evaluated for most hurricanes which have entered or come close to the United States coast since 1900. These data have been further analyzed to provide reasonable estimates of the future probability of hurricanes with given parameter values which will occur at any location along the Atlantic or Gulf coasts of the United States.

THE WIND MODEL. Although it has never been possible to obtain enough wind measurements near the water surface for a complete description of the hurricane wind field, useful estimates may be obtained by combining the available observations with theoretical considerations.

In the free air, if the storm is not moving, the winds are parallel to the isobars and blow around the storm center in a counterclockwise direction (in the Northern hemisphere) at a speed which is determined by the rate of atmospheric pressure increase with distance from the storm center. The heavy rainfall in the high wind speed zone demonstrates that humid air from the surface layers is rising in this zone. Hence the surface air in this zone must be spiraling inward, crossing the isobars toward low pressure. The clear or nearly clear sky near the center of the storm demonstrates that the air in the eye of the storm is sinking. The high temperatures observed from aircraft in the eye of the storm also demonstrate a downward vertical velocity in this region. Hence in the eye of the storm, the wind must cross the isobars toward higher pressure. Some early wind models used a constant inflow angle throughout a stationary storm. It is now known by hurricane specialists that this is unrealistic. Nevertheless this assumption continues to be used in the wind model combined with some storm surge models.

At high elevations, the air spirals outward from the storm center in a clockwise direction thus maintaining mass continuity. This can be readily observed in some of the satellite photography.

The horizontal wind flow is generated by the pressure gradient throughout the air column and dissipated by friction with the land or water surface. Thus the wind speed near the surface must increase with elevation. The energy and momentum lost by the low level winds to the water is replaced by the frictional drag of the wind at higher elevations on the surface wind. Thus a truly satisfactory model of the surface wind field would have to consider some three dimensional aspects of the storm. None of the wind models widely used for storm surge calculations in 1982 deal with the three dimensional aspects of the storm.

The most widely used hurricane wind field models are developed by first estimating the maximum wind speed for a nonmoving storm from the pressure equation. The second step is to estimate the wind at any location as a fraction of the maximum wind. The fraction to be employed depends on the distance from the center of the storm and the storm size. The storm size is usually expressed in terms of the distance from the storm center to the maximum wind speed zone. This result is then corrected for the assumed inflow angle and the velocity of the storm center.

Several wind models have been developed to provide estimates of the wind speed and direction throughout a hurricane. Most, perhaps all of these models are based on specified values of $(p_1 - p_0)$, R, the velocity of motion of the storm center and a law which expresses the angle at which the wind crosses the isobars toward lower pressure. All of these models specify a wind speed that increases rapidly with distance from the storm center to a maximum value between about 10 and 50 miles from the center and decreases slowly with increasing distance. The detailed pattern varies from storm to storm and with time in a single storm. A few hurricanes show two zones of maximum wind speeds. The fine structure cannot be defined without a detailed analysis of all observational data obtained from the storm. This cannot be accomplished until long after the storm is over. Several idealized models of the storm wind field which can be specified in terms of measurements made before landfall, or treated in terms of climatic parameters have been developed. All models used for storm surge prediction prescribe the ratio of the wind speed at a given distance from the storm center, to the maximum wind speed, V_{max}, as a function of the radius of maximum wind speed, R, and the radius to the point of interest, r. Only the ratio r/R appears in the model used by the National Hurricane Center for storm surge warnings. Some other models require both this ratio and the actual value of R.

The wind field used by NHC and two other widely used wind field models are plotted in Figure 15, to show both the similarity and divergence in views about this aspect of the prediction program. The J wind model, used by the NHC yield higher maximum wind speeds for a given value of $(p_1 - p_0)$ than the other two models. The wind speed model must be combined with a wind stress law to obtain the friction between the wind and the water. This is generally expressed in the form

$$\text{stress} = kV^2 \qquad (2)$$

where V is the wind speed and k is a constant in the J model but increases with speed in the other two models. The inflow angle is assumed to be constant in the T model, but varies in a more realistic manner in the other two models.

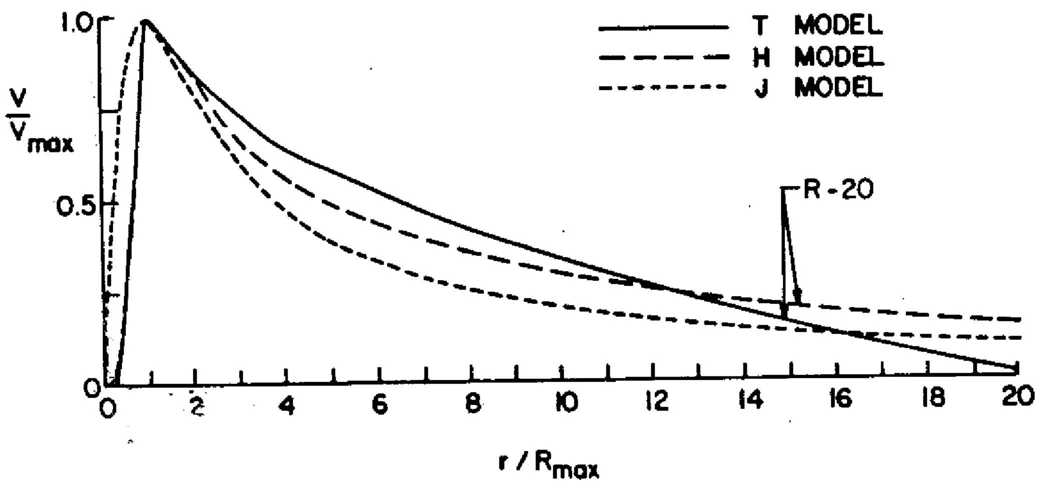


Figure 15. Hurricane wind speed models, the ratio of the wind speed at any radius, r, to the maximum wind speed is given as a function of the ratio of the variable radius, r, to the radius of maximum wind speed, R. Ratios for T and H models are shown only for R = 20 nautical miles. Ratios will be slightly larger for smaller values of R and slightly lower for larger values of R.

Although several comparisons of one wind field model to another have been carried out, few if any data have been published to demonstrate the agreement between any of these models and measured winds. Meaningful comparisons will be difficult to make because the models have been designed to approximate the time and space averaged wind vectors needed for storm surge calculations. The observations, on the other hand, are point measurements which display the gusty nature of the true wind.

LOCATION OF THE STORM. The above discussion has been concerned with a specification of the pressure and wind field relative to the storm center. The problem of locating the storm center must also be considered. This is really composed of two problems, locating the storm center at the beginning of the forecast period and predicting the storm displacement during the forecast interval.

Figures 9 and 10 indicate that the data required for an unambiguous location of the storm center before landfall are rarely available. Operational predictions must be based on a relatively quick analysis of the data available at forecast time. Much additional data and time for a more thorough analyses becomes available after the storm. These additional data and analyses are used in the construction of a "best track" chart, which is used as the standard for post storm studies. A comparison of the initial positions used for operational forecasting with the "best track positions" determined after the storms shows that the average position error for the period 1970-79 was about 20 nautical miles. In many cases the initial and final positions are identical, but several positioning errors exceeding one degree of latitude (60 nautical miles) are reported.

A distribution of forecast errors has been shown in Figure 2. The average error in the 24-hour displacement forecast is about 109 nautical miles. The difficulty of the forecast varies with the amount of data in the storm area at forecast time and the complexity of the weather pattern. A plot of the annual average forecast error as adjusted for forecast difficulty for the period 1954-1980 is shown in Figure 16. The figure displays a slight improvement with time. The rate of improvement was greater in the early part of the period than in the later years. It appears that substantial additional improvement is not to be expected in the near future.

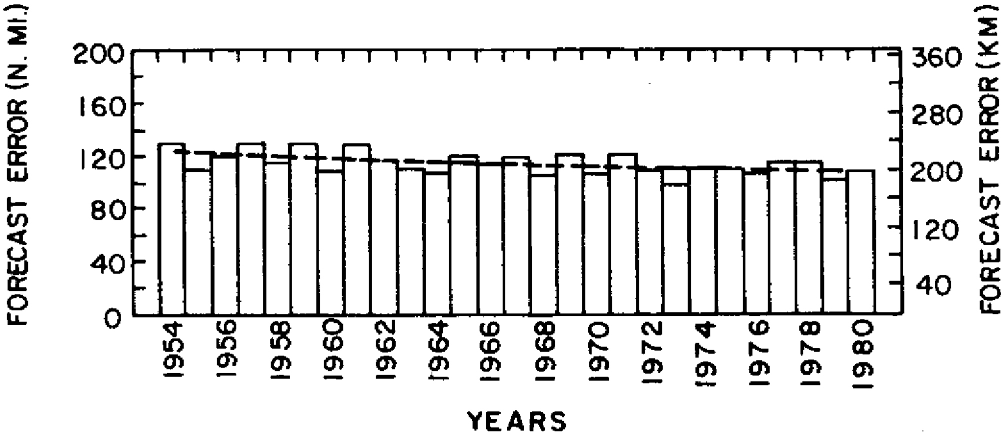


Figure 16. Official forecast errors, 1954-80, after having been adjusted for forecast difficulty (FDL) and analysis disparities (as reflected by storm longitude). Secular trend is given by dashed line.

Until the 1950's, estimates of central pressure for an incoming hurricane had to be obtained by extrapolation toward the center from standard weather reports. Rather large errors were to be expected. For the last several years, central pressure estimates when the storm is approaching shore have been obtained by dropping a radio equipped barograph into the center of the storm from an airplane. This measurement is now believed to be reliable. The radius of maximum winds is not subject to precise and rigorous measurement before the storm moves inland. Estimates may be obtained from the storm image on radar. In a few cases, information has come to light, years after a storm occurred which led to changing the estimated value of R by as much as 30 per cent. Although no exact method for measuring R has been determined it is believed that the average uncertainty in the estimate is of the order of 10-20 per cent of the stated value.

<u>SUMMARY OF THE DISCUSSION OF HURRICANES:</u> Hurricanes are rare, severe, tropical storms generated over the open sea. Identification of the storms with useful estimates of intensity, size and location at least a day or two before landfall is nearly always possible. Forecasts based on the limited information available before the storm crosses the coast show an average error of 109 nautical miles in a 24 hour prediction of

the future location of the storm center. Consequently, if all communities which will be subjected to the most intense part of the storm are to be warned, the section of the coast included in the warning message must be significantly larger than that which actually experiences the most severe conditions.

4. THE STORM SURGE

<u>EVIDENCE FROM THE RECORD</u>: Figure 17 shows the observed tide record, the calculated astronomical tide and the difference between them at the Pleasure Pier, Galveston, Texas during Hurricane Carla, September, 1961. The observed and predicted tides were adjusted to provide the same mean water level for the month. Thus the difference represents the effect of Hurricane Carla, free of any long term change in mean sea level.

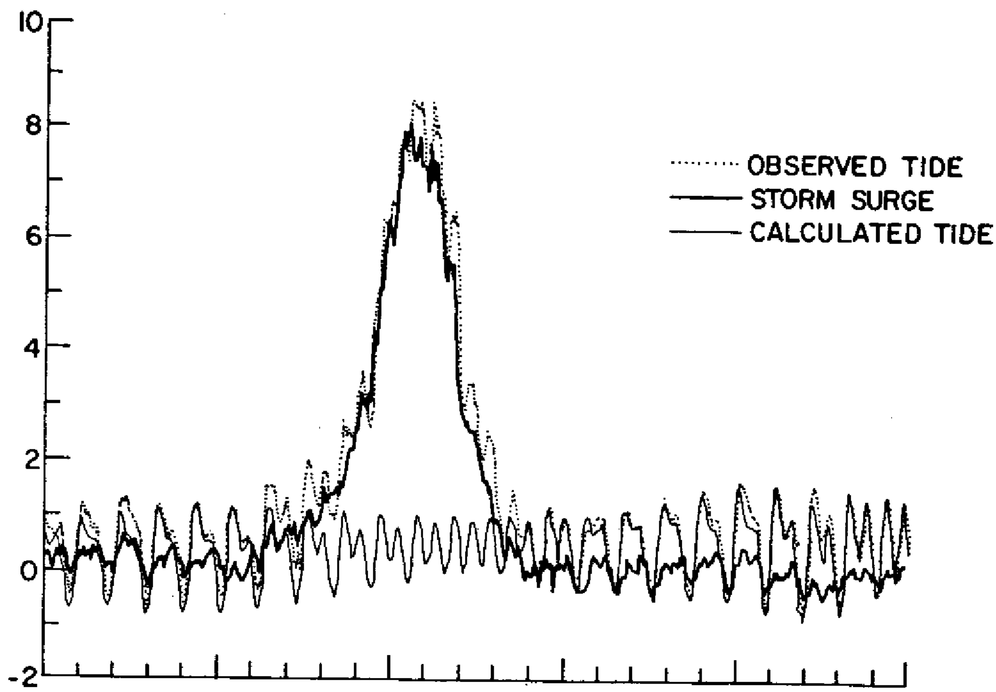


Figure 17. The observed tide, the calculated astronomical tide and the storm surge, defined as the difference between the observed and predicted tide for the NOAA tide gage at Pleasure Pier, Galveston, Texas for Hurricane Carla, September 1961.

The Pleasure Pier extends into the Gulf of Mexico, normal to the shore and provides one of the most ideal tide gage locations in the United States. It is equipped with a standard National Ocean Survey tide gage which provides good time resolution of the water level. Data from this gage in storm free periods have been analyzed to permit primary tide calculations for this location. This is essential for a clear determination of storm effects on the water level. The storm surge rose slowly for a day or two as the storm approached from the open sea, then more rapidly as the high wind speed zone crossed the coast. Hurricane Carla moved more slowly than most hurricanes, and the storm surge remained near its peak value for more than a day. A drop in water level associated with the diurnal low water is clearly apparent. The water dropped below the prestorm level after the storm. This reduced water level following a hurricane is frequently observed. The difference curve shows an oscillation of tidal period, but much reduced amplitude. The reduced amplitude of this oscillation demonstrates that substraction of the predicted tide from the observed tide does give a clearer indication of the storm effects than that provided by the original record. The fact that the tide period appears in the difference curve shows that the tide and the storm surge are not entirely independent.

Tide gage records provide the only quantative evidence of the growth and decay of the storm surge during the approach and passage of the hurricane. Tide gages, however are too widely separated to provide an adequate record of the horizontal extent of coastal flooding. High water marks, based on streaks left by the water inside buildings or in other locations protected from direct wave attack must be used for this purpose. Figure 18 shows an unusually dense collection of high water marks identified shortly after Hurricane Donna, 1960. Wherever a similar dense collection of high water marks is located, a variation on the order of three feet between the highest and lowest high water marks is common. Several variations of this magnitude are displayed in Figure 18.

It appears from Figure 18 and many similar figures that storm surges involve water level disturbances of several different horizontal scales. The major disturbance has about the same horizontal extent as

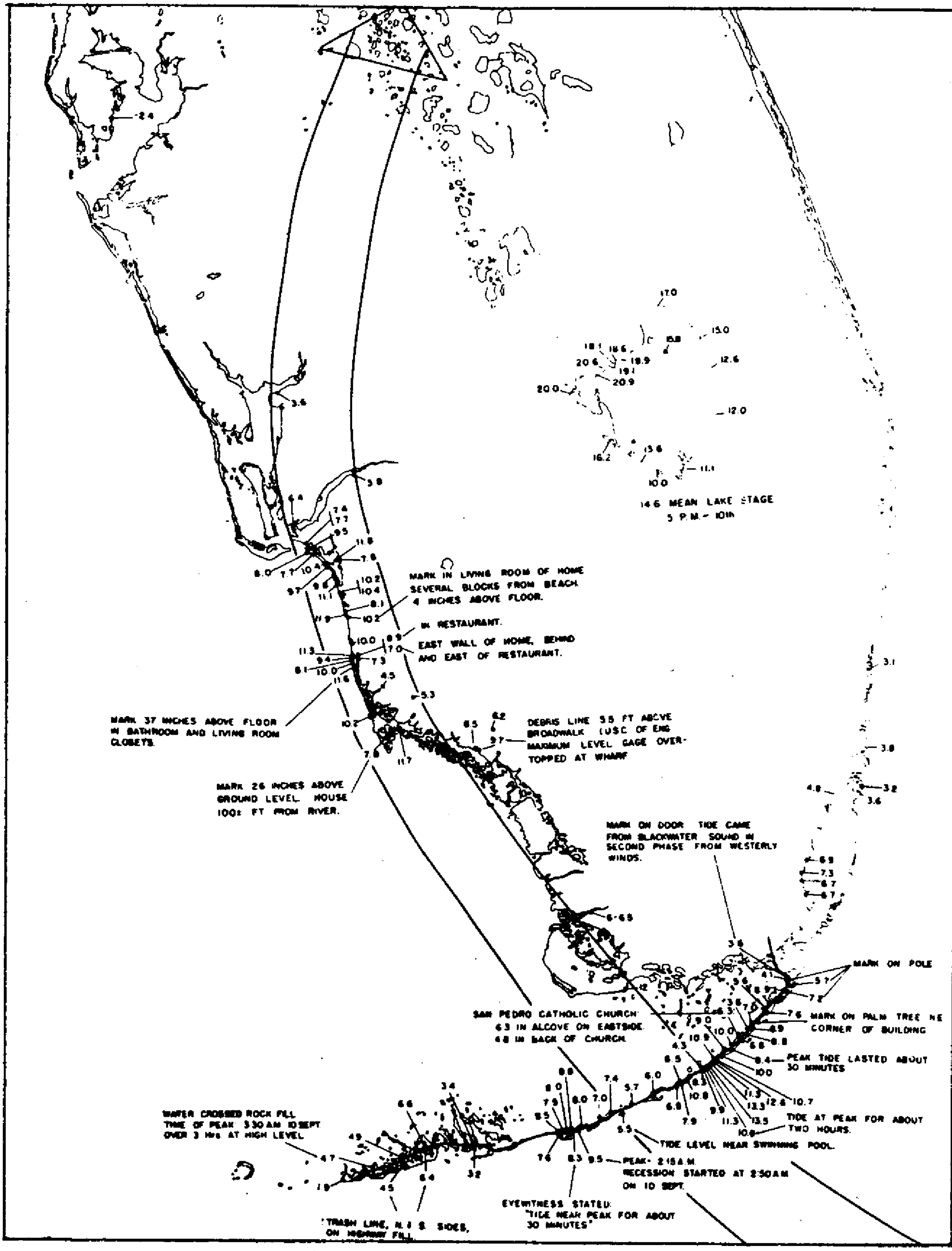


FIGURE 26.6—Hurricane Donna 1960, September 9–13. High water mark chart for Florida. (Based on data obtained from the Jacksonville District of the U.S. Army Corps of Engineers.)

Figure 18. High water marks produced by Hurricane Donna, September 9–13, 1960. (Based on data obtained from the Jacksonville District of the U.S. Army Corps of Engineers.)

the storm. Several somewhat smaller but still significant disturbances of much smaller horizontal extent are superimposed on the major disturbance.

It is not clear that the small scale disturbances can ever be predicted in detail. At present, the best that the forecaster can hope to do, is to predict the expected behavior of the large scale disturbance and to allow for superimposed small scale disturbances by quoting a range of values.

PROCESSES OF STORM SURGE GENERATION: Four distinct processes by which hurricanes produce abnormal water levels are described below.

The Inverted Barometer Effect: The low atmospheric pressure near the center of a hurricane exerts a suction effect on the water. In deep open water a quasi-equilibrium between the low atmospheric pressure and the elevated sea surface gives a rise in sea level of about one foot for each drop of one inch in the height of the mercury column in a barometer. In shallow water this may be amplified or decreased by dynamic effects which depend on water depth and the speed of translation of the storm center. The inverted barometer effect is sometimes called the "pressure set-up."

The Wind Set-up: Friction between air and water tends to generate a surface current which moves in the same direction as the wind but with only about three per cent of the wind speed. The depth of penetration of this current into the water increases with the duration of the wind and with increasing turbulence in either air or water. With the passage of time, dynamic effects resulting from the rotation of the earth cause the surface current to rotate to the right of the wind direction. Further rotation toward the right takes place with increasing depth into the water.

If the current penetrates to the bottom, a frictional boundary layer develops at the bottom. Within this bottom friction layer, the current speed is reduced and the current rotates toward the left as the bottom is approached. The thickness of the layer required for these rotations increases with the turbulence of the flow. Thus for strong winds and shallow water the top and bottom boundary layers may overlap so that very little rotation of the current direction is experienced.

The stress of the wind on the water is approximately proportional to the square of the wind speed. The effects of this stress on the slope of the water surface is approximately proportional to one divided by the water depth.

If the free flow of the water is impeded by the coastline, the water level must rise in the direction of the current, or the direction of the current must change to parallel the coast. Both effects may occur. The rise in water level where the flow of the wind generated current is impeded by the coastline is called "the wind set-up." It is the major component of the storm surge near coasts.

The large scale disturbance in water level due to the storm results from a combination of pressure set-up and wind set-up.

Wave Set-up: The storm winds also generate waves with periods in the range of one to twenty seconds. The water particles move in elongated oval orbits in response to the wave motion. Thus the waves are accompanied by a current, proportional to the square of the wave height and traveling in the same direction as the waves. The waves propagate through the water at a much greater speed than the wind generated current. They are affected in a somewhat different way by variations in water depth and friction. Thus they should be treated separately. When the waves move into shallow water, their heights increase to the breaking point, and the magnitude of their associated current increases. When the waves break near the shore, the associated current is converted into a water level rise known as the wave set-up and a component of the current parallel to the beach. The direction of wave travel can be changed by variations in water depth. The wave current and the wave set-up tends to be focused in relatively shallow areas. When the overall water level has been increased by the large scale storm surge, the wave set-up may be focused by features of the land that are normally dry. The focal points for wave set-up are determined by bottom topography and the direction of wave approach shortly before breaking.

It is believed that the variability in wave set-up is responsible for much of the small scale variability in the storm surge high water marks displayed in Figure 18. Small scale variability in the wind and channeling of the flow by surface irregularities may also play a role in determining the small scale variability in storm surge heights.

Rainfall Runoff: Hurricanes generate copious rainfall. The accumulated rainfall within small landlocked bayous with moderately large drainage areas can contribute a foot or more to the storm surge in these areas. Rainwater may also collect in low spots on normally dry land.

STORM SURGE MODELS: Coastal flooding results from the coincidence of several nearly independent processes. Each process depends on the water depth and the distance to the nearest coast. The water depth increases and the effective coast moves inland as flooding develops. The processes are too complex for a simple mathematical solution.

A solution can be obtained by means of a numerical model. A numerical model is constructed by establishing an array of grid points which cover the region of interest as shown in Figure 19, and a set of equations which describe the rate at which the water level and velocity at each grid point is changing in response to conditions at the same and nearby grid points. The accuracy of the predictions obtained in this manner is improved by decreasing the distance between grid points. The number of calculations required for a prediction is approximately proportional to the cube of the number of grid points involved. Thus, decreasing the distance between points in a two dimensional array by one half, leads to an increase in the number of calculations by a factor of eight.

The storm surge predictions for a real storm cannot be started until the storm motion forecast has been completed. They must be completed in time to be included in the hurricane warning if they are to be useful. Thus there is a limit to the number of calculations which can be made in an operational forecast. An improvement in the use of available facilities has been obtained in some recent storm surge models by employing variable spacing to provide the most accuracy where accuracy is most useful, and less accuracy on the open sea as shown in Figure 20.

Predictions for hypothetical hurricanes are useful for the development of evacuation plans, for establishing setback lines and insurance rates, and for other procedures designed to reduce the loss of life and property due to hurricanes. It is necessary to consider a large number of possible storm scenarios when storm surge models are

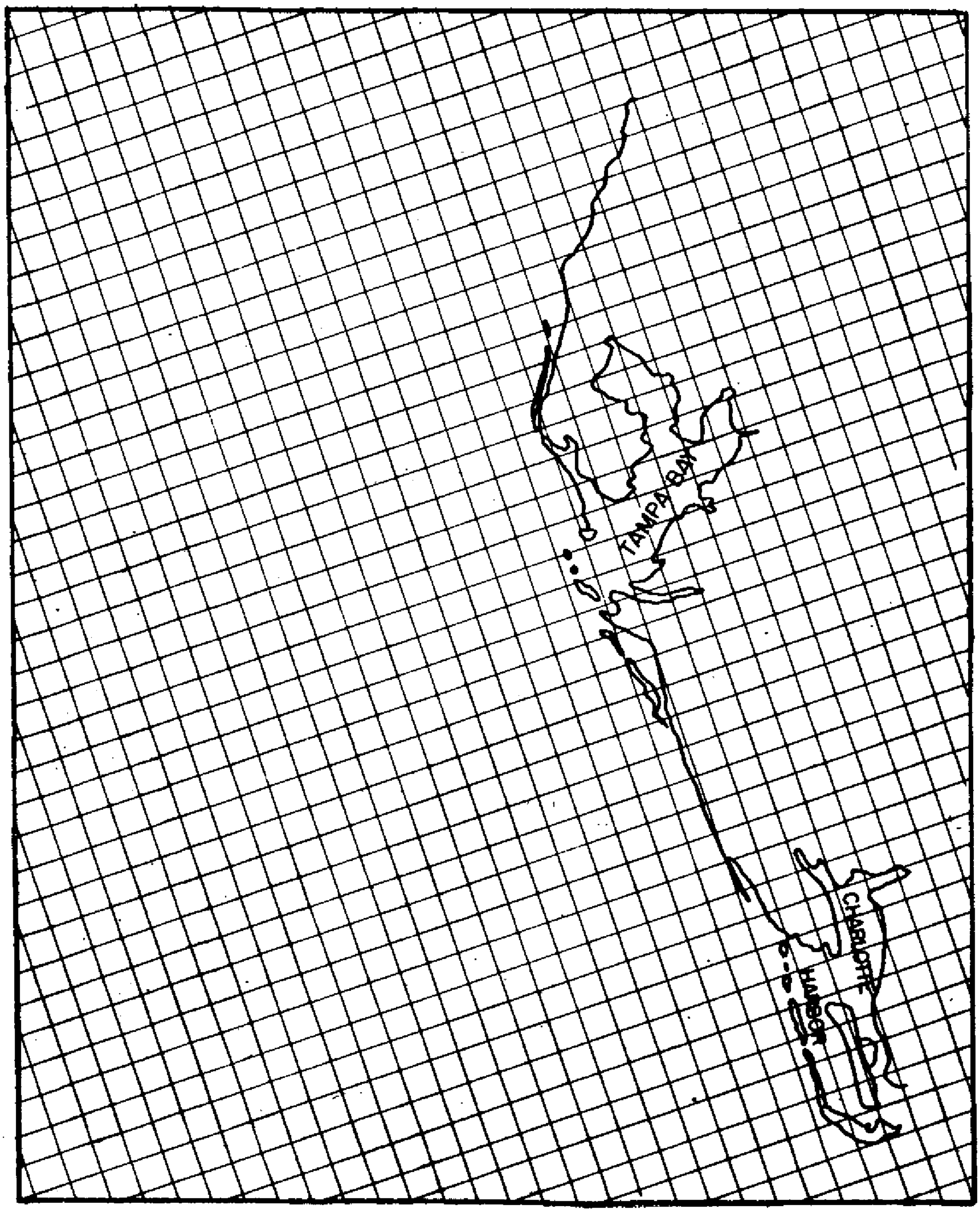


Figure 19. Computational chart for the computation of storm surges in Tampa Bay as used in early numerical models. The grid is rectangular in shape, all elementary computation areas (squares), are the same size. In order to avoid clutter, only each third line in the actual computational grid is shown.

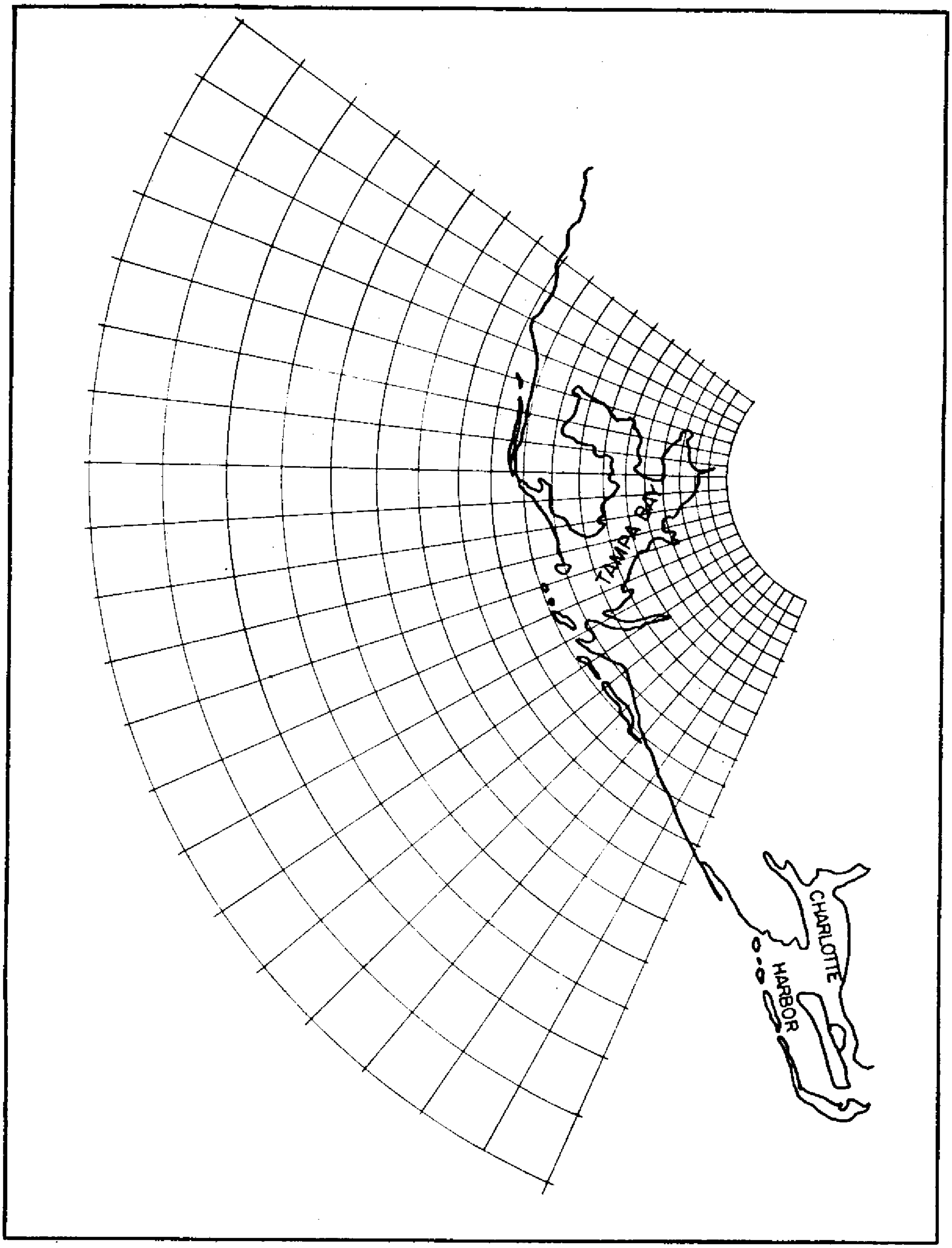


Figure 20. A modern computational grid for the problem shown in Figure 19. The grid is composed of concentric circles and radial lines to obtain a systematic variation in the computational grid size with most detail near shore, where most detail is needed. As in Figure 19, only one grid line in three is actually used as shown.

used in this way. Although the operational limit on computer time is less rigid than when the goal of calculations is a real time hazard forecast, the limit on funds available for any specific investigation continues to limit the available computer time.

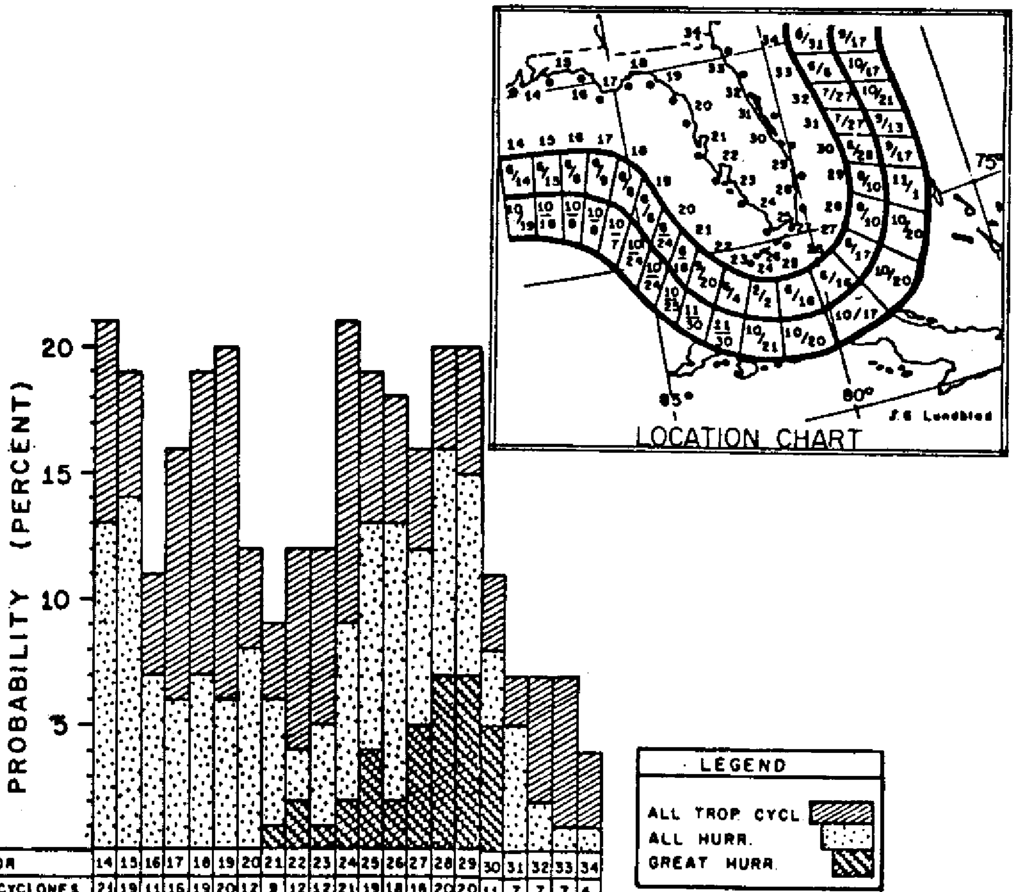
Several storm surge computer models which produce reasonable predictions have been developed. All are similar but they differ in detail. Thus for any specific location and storm, one model can be expected to produce more accurate predictions than the others, but as yet there is no assurance that any one model will always be more satisfactory than the others.

5. WHERE DO WE STAND

Figure 21 shows the probability that a tropical storm, hurricane or great hurricane will affect a 50 mile segment of the Florida coast. A hurricane is defined as a tropical storm in which the maximum wind speed exceeds 74 miles per hour (mph). A Great Hurricane is one in which the maximum wind velocity is 125 mph or greater.

It can be seen from Figure 21 that every portion of the Florida coast can expect to experience hurricane activity at least once per century. The probability of experiencing a hurricane in a particular year nowhere exceeds 0.16 per year. Thus, even if the possibility of experiencing each hurricane on two successive days is considered, the probability of experiencing a hurricane on any arbitrary day is everywhere less than one in a thousand. In some sections of the coast it is less than one in ten thousand.

When typical forecast errors and the resulting need to warn a larger section of the coast than is actually affected by the storm is considered it appears that the probability of experiencing the severity of weather covered by the warning message is about one in three or four. The uncertainty in predicting the time of the maximum storm surge can exceed six hours. Thus, in order to insure adequate warning, it is often assumed that the maximum surge will coincide with the maximum tide level for the day. The maximum surge could coincide with low tide, thus significantly reducing the maximum flooding in many locations.



COASTAL SECTOR	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
ALL TROPICAL CYCLONES	21	19	11	16	19	20	12	9	12	12	21	19	18	18	20	20	11	7	7	7	4
ALL HURRICANES	13	14	7	6	7	6	8	6	4	5	9	13	13	12	16	15	8	5	2	1	1
GREAT HURRICANES	-	-	-	-	-	-	-	1	2	1	2	4	2	5	7	7	8	-	-	-	-

Figure 21. Probability of occurrence of tropical storms in any one year period. It is assumed that each storm will affect the 50 mile sector of the coast which it crosses and the sector to the right. Tropical cyclones are tropical storms with wind speeds exceeding 40 mph. Hurricanes are tropical storms with winds greater than 74 mph. Great hurricanes with wind speeds greater than 124 mph.

When the weaknesses of the existing warning system are considered, it appears that sections of the coast cited in a hurricane warning have about one chance in three of experiencing the very severe weather of the storm, and about one chance in ten of experiencing the extreme flooding cited in the warning.

The odds are about four out of five that the most severe part of the storm will miss any particular location within the area covered by the warning, and about even or slightly less than even that the peak surge will occur on the low water side of the tide cycles. This should be interpreted as meaning that the most severe flooding will be significantly less than predicted in one third to one half of the storms, and that it will occur in the location of greatest interest to an individual in about one fifth of the storms. From this point of view, neglecting the warning to evacuate is much like playing Russian roulette. One has an excellent chance of winning when he bets that conditions will not be as bad as predicted, but the prize for winning is small and the penalty for losing may be one's life.

Several communities in Florida have developed detailed plans for evacuation of lowlying areas when hurricane landfall is imminent (7). Storm surge models have been used with a number of hypothetical storms to delineate trouble spots, where highway flooding would impede evacuation, and to determine the areas which should be evacuated for storms with specific characteristics. These studies include estimates of the time required for evacuation.

These studies have shown that some communities require more warning time than the present forecasting skill can provide unless one is willing to accept an overwarning factor much larger than three. A larger overwarning factor, however, is highly undesirable.

<u>WHAT CAN BE DONE?</u> The flattening out of the curve which describes forecasting skill suggests that substantial improvement in predicting storm movement in the near future is not to be expected. Some improvement could be achieved by installing more reliable observations at sea, or instituting more data gathering flights over the ocean. Either procedure would be expensive. Neither would solve the entire problem for more basic understanding of the storms is needed. Research now underway should lead to improved understanding of the surface wind field and better measurements of actual storm surges.

Improved post-storm observations, designed to provide the information needed to determine which of the available storm surge models, or which features of each model are most satisfactory will reduce the confusion caused now by the use of a variety of models by the different federal and state agencies. This determination would improve the accuracy of predictions for hypothetical models used for planning, but it cannot greatly reduce the uncertainty associated with real time warnings until improved storm motion forecasts are possible.

The time required for evacuation could be reduced by providing safe havens in coastal communities. When Hurricane Audrey came inland near Cameron, Louisiana in 1957, a large fraction of the local population found a safe haven in a stone courthouse.

Stone buildings which can resist the forces of the flood, or structures built on stilts which will permit free passage of the storm waters at ground level can provide safety with less warning time than is required for evacuation to high ground. The ground floors of such structures could be used during normal weather conditions, if they are designed with breakaway walls, and if they are maintained as open spaces, or spaces which can be cleared quickly when potential flood conditions are predicted.

The designation of certain buildings as places of refuge from the storm may require more thorough inspection during building to make certain that the construction is sound. If extra strength is required, public subsidy for the construction of a suitable number of safe buildings may be a more certain and less expensive means of providing safety from natural disasters than the construction of more highways and bridges to facilitate rapid evacuation.

SUMMARY

Severe hurricanes and related storm surges occur somewhere in Florida two or three times per decade on the average. Each occurrence produces extensive property damage. Only extensive evacuation of the regions subjected to flooding prevents extensive loss of life. Although southeast Florida is affected most frequently, no part of the State is completely immune to the devastation of hurricanes.

Hurricane conditions are not experienced more frequently than one day in a thousand anywhere in the State and less frequently than one day in ten thousand in some areas. The existence of a tropical storm which might give hurricane conditions to specific communities can generally be detected a day or more in advance. Detailed observations of the surface wind patterns within the storm as it approaches land are not possible now and may never be possible. Predictions of storm motion and future intensity always involves some uncertainty. Flooding or high winds may prevent evacuation from some localities before it is clear that evacuation is essential. Consequently, evacuation must be recommended or required for some regions which do not experience hazardous conditions.

There is little reason to expect an early improvement in the quality of the meteorological forecasts. The extent of the evacuation required could be reduced by providing safe shelters near the places where people live, thus reducing the travel time required for evacuations.

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