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OPERATIONAL MARINE ENVIRONMENTAL PREDICTION PROGRAMS OF THE TECHNIQUES DEVELOPMENT LABORATORY

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Operational Marine Environmental Prediction Programs of the Techniques Development Laboratory

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ABSTRACT

The Techniques Development Laboratory of the National Weather Service began developing automated marine environmental prediction programs in 1965. These programs are organized into three tasks--oceanic forecasting, coastal forecasting, and Great Lakes forecasting. The seven programs which are used for operational forecasting are briefly described. They are programs for forecasting ocean waves, extratropical storm surges, hurricane storm surges, coastal winds, Great Lakes winds, Great Lakes waves, and Lake Erie storm surges.

INTRODUCTION

The Techniques Development Laboratory of the National Weather Service became involved in developmental work in marine environmental prediction in 1965. It started with the hiring of one person who was scheduled to work only part time on marine environmental problems. The increased requirements for operational forecast techniques in the marine area have led to increased effort. We now have eight professional persons and usually one or two part time student trainees in our Marine Techniques Branch.

The work of the Branch is organized into three tasks--oceanic forecasting, coastal forecasting, and Great Lakes forecasting. The three tasks are subdivided as shown below:

1. Oceanic Forecasting
   a. Ocean Waves*
   b. Oil Spill Trajectories

2. Coastal Forecasting
   a. Hurricane Storm Surge*
   b. Extratropical Storm Surge*
   c. Coastal Wind*
   d. Beach Erosion
   e. Coastal Waves

3. Great Lakes Forecasting
   a. Wind*
   b. Waves*
   c. Storm Surge*
   d. Fog

In the above list, the seven sub tasks marked by asterisks are those in which automated operational forecast techniques have been derived. This does not mean that the ultimate forecast method has been developed, but rather that a forecast technique has been automated for operational use. These techniques will be improved with future research and development work. Development work is going on in the other areas indicated above, but this work will not be described in this paper.

The purpose of this paper is to give a very brief description of these seven automated forecast methods. Additional detail on the methods can be obtained from the Techniques Development Laboratory.

The seven programs to be described are those for ocean waves, extratropical storm surge, hurricane storm surge, coastal wind, Great Lakes wind, Great Lakes waves, and Lake Erie storm surge.

OCEAN WAVE FORECAST PROGRAM

The Weather Service wave forecast technique is patterned after the 1966 version of the Navy's Fleet Numerical Weather Facility (FNWF) method, which is an adaptation of the Sverdrup-Munk-Bretschneider system. The forecast program consists of two main parts--one for the forecasting of wind-waves and the other for forecasting swell conditions. Wind-waves are waves which are being formed and built up by the wind. They are under the influence of the generating wind. Swell are waves which have traveled out of their generating area and may propagate through areas of calm or opposing wind.

The wave forecast program is run twice daily at the National Meteorological Center (NMC) and uses the wind forecasts of the Primitive Equation (PE) model as input. The 1000-mb PE wind forecasts are the basis of the wind-wave forecasts. Comparison of these wind calculations with observed winds at the Ocean Station Vessels for a one-year period showed that the PE wind forecasts can be adjusted to agree closely with OSV winds in both speed and direction as a function of wind direction. These adjustments are made to the winds before they are used in the wave forecast procedure and are considered to be adjustments for low level atmospheric stability.

The wind-wave program is used for calculating the significant wave height and significant wave period. Significant wave height is defined as the average height of the one-third highest waves. Significant wave period is the average period of the one-third highest waves.

Calculations are made for ocean points of the NMC octagonal grid as shown in figure 1. The program is given information which specifies which of the grid points are land or polar ice, so that wave forecasts will be made only for ocean areas. The distribution of land and ice is also considered in determining fetch length restrictions.

The winds for the 18-hour period prior to the time of the wave forecast are considered. To make a wind-wave forecast for time T, the winds at times T, T-6, T-12 and T-18 hours are used.

For any particular forecast time wind data are obtained from:

1. The current PE forecast, and
2. A wind and wave history file updated by the previous program run made 12 hours earlier.

The duration of the wind is determined by comparing the wind direction at time T with that at time T-6, etc., until a wind shift of more than 45° is found. The duration is therefore determined to be 0, 6, 12, or 18 hours.

Once the duration at a grid point is determined, an effective wind speed is calculated for that duration time. The effective wind speed is a weighted mean such that the more recent winds are given heavier weight. Each wind contributes as much as all of the earlier winds in the calculation.

The expressions for wave height and period are:

$$H_w = K_1 V^2 D + K_2$$

$$T_w = V (K_3 + K_4 D) + K_5$$

where H_w is significant wave height,
T_w is significant wave period,
V is effective wind speed,
D is duration of wind, and
K's are constants.

At computation points near land or ice, consideration is given to the possibility of fetch limitations. A determination is made in the upstream direction from each computation point for the existence of land or ice within approximately 1 or 2 grid lengths. If land or ice is found within 1 grid length, the wave height is reduced to 70 percent of its value. Land or ice between 1 and 2 grid lengths causes the wave height to be reduced to 90 percent of the computed value.

Wind-wave calculations are made for +00, +12, +24, +36, and +48 hours from the time of the latest PE output. Variables which can be printed out include effective wind speed, significant wave height, period, and direction.

Calculations of swell are made for ocean points of the NMC octagonal grid. The program is given a map factor at each grid point. These map factors are used to determine the map projection distance the swell travels, since this distance is a function of latitude.

The swell forecasts are based upon the +00, +12, and +24 hour forecasts of the wind-waves. A minimum travel time of 15 hours is required before a wind-wave is considered to have moved from its generation area to become a swell. Therefore, to make a swell forecast for time T, wind-waves at times T-24, T-36, T-48, T-60, and T-72 hours are used.

For any particular forecast time, wind-wave data and swell data are obtained from a wind and wave history file updated by the previous program run made 12 hours earlier.

Starting from the oldest field on the wave history tape (T-72 hours), each wind-wave having a height greater than 5 feet is considered as a potential swell. A preliminary swell travel distance is computed. Travel distance (d) of waves depends on group velocity of the waves (C_g) and the travel time (t) in the following form:

$$d = C_g \times t$$

The group velocity (C_g) depends upon the period of waves as shown here:

$$C_g = A \times T$$

where T is the period of the waves,

and A is a constant.

As swell propagate from the area of generation, the longer period components (with the larger group velocities) outrun the shorter period components. This results in increasing periods of significant swell with increasing distance from the generation area.

The expression for approximate swell travel distance therefore is:

$$d = C_1 \bar{T} t m$$

where d is distance traveled,

$\bar{T}$ is the mean of the period of waves when they leave the generation area (T_w) and their period when they arrive as swell at the forecast point (T_s),

t is travel time,
m is the map factor at point of generation,
and C_1 is a constant.

Once the preliminary travel distance has been computed, a search is made along the entire path of the wave. If land or ice has been specified within 0.72 grid lengths of the path of the wave, the wind-wave is discarded.

Each wave train is allowed to spread 75 degrees either side of the center line of travel. A more accurate travel distance is computed for each grid point over water (affected point) within a 150 degree spread about the center line of swell propagation. The expression for computing this distance is the same as the expression for approximate swell travel distance, except m is replaced by $\bar{m}$, which is an average map factor over the area traveled. The affected point is then tested against a distance requirement. This requirement is that the affected point lies within the range of travel distance of the swell for the particular forecast period. If this requirement is satisfield, swell period and height are computed for the affected point by the following expressions:

$$T_s = (T_w^2 + C_2 t)^{1/2}$$

$$H_s = H_w (T_s/T_w)^{C_3} \cos \alpha$$

where T_s is the period of the swell,
T_w is the period of the wind-wave leaving the generation area,
t is travel time from generating point to affected point,
H_s is the swell height,
H_w is the initial wind-wave height,
α is the angle between direction of center line of swell propagation and direction to affected grid point,
and C_2 and C_3 are constants.

Since any grid point can be hit by many swells, only the greatest swell height is retained at the affected point.

Swell calculations are made for +24, +36, and +48 hours. Variables which can be printed out include swell height, period, and direction.

An overall wave condition, a combined-height field, is constructed as the square root of the sum of the squares of the wind-wave and swell heights.

Northern Hemisphere charts of wind-wave height, swell height, and combined-wave height are prepared. Sections of these hemispheric charts are extracted for facsimile transmission. Figure 2 is a sample Pacific area chart for the west coast FOFAX circuit. Wave heights are depicted by contours drawn at 3-foot intervals with maximum values printed at the centers.

This wave and swell forecasting system is for deep-water wave conditions on the high seas. At this point we feel that the wave conditions in offshore waters of moderate depth may be adequately forecast. Certainly, breaker and surf forecasts are not to be implied from these high seas forecasts.

Although the significant wave height (defined as the average height of the one-third highest waves) is the variable which is forecast, other properties of wave height distribution are of value. Statistical analyses and theoretical investigations (U.S. Army Coastal Engineering Research Center, 1966) show the following relationships:

a. Mean wave height = 0.6 x significant wave height.
b. Mean height of highest 10% of waves = 1.3 x significant wave height.
c. Maximum wave height = 1.9 x significant wave height.

These relationships indicate possible wave heights, for any given forecast, to be almost double the significant wave height.

Little confidence can be placed in the wave forecasts in the vicinity of tropical storms. The spacing of NMC grid points precludes adequate depiction of wave conditions in these areas unless the storm is large enough to affect values of parameters at grid points at initial and forecast times.

COASTAL WIND FORECAST PROGRAM

A method for forecasting winds for light station locations off the east and west coasts of the United States has been developed. The program for the east coast became operational in January 1975 and the west coast program was implemented in May 1976. Locations of the forecast points are shown in figure 3.

The forecast.method is of a statistical form and consists of single station regression equations. There is a separate set of forecast equations for each location. Predictand data consisted of surface wind observations at the light stations. The period of record used for the forecast locations varied from 3 to 5 years. The data were divided into two 6-month periods of April through September (summer) and October through March (winter).

The Model Output Statistics (MOS) approach was used in the development of forecast equations. Multiple screening regression was used to relate the surface wind observations (predictands) to PE model forecasts of meteorological variables. Separate equations were derived for the U-component, the V-component, and for the wind speed. Also, a separate set of equations was derived for each PE model origin time (0000 GMT and 1200 GMT). Each equation set is for forecast times to 42 hours in advance at 6-hour intervals.

The 24-hour wind speed forecast equation for the Columbia River light station based on 1200 GMT winter PE model output is shown below as an example:

$$SPD = 340.4 - .390P_1 - .074P_2 + .700P_3 - .353P_4 + .071P_5 + .175P_6 - .276P_7 + .439P_8$$

SPD = SFC windspeed (kts)
P_1 = 24-hour boundary layer U (m/sec)
P_2 = 24-hour boundary layer V (m/sec)
P_3 = 24-hour 850 mb geostrophic speed (m/sec)
P_4 = 24-hour surface pressure (mb)
P_5 = COS (Day of Year)
P_6 = 18-hour 850 mb geostrophic U (m/sec)
P_7 = 24-hour 850 mb V (m/sec)
P_8 = 18-hour 850 mb geostrophic V (m/sec)
Total reduction in variance by 8 predictors = .39
Standard Error of Estimate =8 knots

This equation is typical of equations developed at other forecast locations and at other projection times in that the first three predictors tend to be directly wind related.

Figure 4 shows a sample teletype message for wind forecasts along the east coast. This message is for 1200 GMT on the 6th of the month (061200). The third line shows the valid times of the forecasts from 6 hours to 42 hours in advance. The body of the message contains the wind forecasts in the form ddff--dd in tens of degrees and ff in knots.

HURRICANE STORM SURGE FORECAST PROGRAM

Whenever a hurricane approaches or crosses the coastline the sea level increases from a few feet to more than 20 feet above the normal tide level. Much of the loss of life associated with these storms is caused by the storm-induced rises of sea level. Examples of storms costly in terms of lives are the hurricane of September 1900, in which over 6000 were lost in the Galveston area, hurricane Audrey of June 1957 which claimed several hundred lives in Louisiana, and most recently hurricane Camille of 1969 which was responsible for many lost lives in Mississippi and Louisiana. Tremendous property damage is also caused by the storm surges in harbors and along the open coast.

The storm surge is defined as the rise or fall of the sea level caused by a meteorological disturbance and is closely approximated by the algebraic difference between the observed tide and the normal astronomical tide as shown in figure 5.

Storm surge forecasts are valuable and essential to plan for protection of life and property in areas subject to storm surges. The Weather Service's National Hurricane Center is responsible for predicting storm surges associated with hurricanes and tropical storms for the Gulf of Mexico and Atlantic areas. Successful forecasting of hurricane storm surges depends, of course, upon accurate forecasts of the intensity, size, and movement of the hurricanes themselves. Actual storm surge forecasts are made with the SPLASH (Special Program to List Amplitudes of Surges from Hurricanes) computerized numerical model for the east and Gulf coasts from Long Island to Texas (Jelesnianski 1972, 1974). This model consists of a storm traveling across a rectangular basin of variable depth. The storm surge driving forces from pressure and wind are determined from a tropical storm model. The driving forces are applied to a version of the storm surge equations. Numerical calculations are generally made for a grid distance of 4 mi (6 km) with a 2.5 min time interval between computations. The SPLASH model can be used for two types of storms: those that cross the coast and those that travel along the coast but do not actually landfall. For storms expected to cross the coast, the following information is given to the model: the landfall position of the storm; pressure drop in the storm while it traverses the continental shelf; the mean compass direction in which the storm will traverse the continental shelf just prior to landfall; the average storm speed just prior to landfall; and the radius of maximum wind, which is a measure of storm size.

For storms that do not landfall, five storm positions at 6-hr intervals are supplied to the model. Pressure drop and radius of maximum wind can also be varied in this version of SPLASH.

The results of the model computation--the expected storm surge--are displayed by programmed computer output. This includes a resume of storm variables given to the model, a list of correction factors to update the surge forecast for a variation of storm pressure drops, a plotted graph of the envelope of the highest storm surges along the coast, and a listing of the astronomic tide levels for selected locations for several hours before and after the predicted time of maximum surge.

The first versions of SPLASH treated the coastline as straight. The latest improvement in the model is a modification in which the storm surge equations of motion and the driving forces of the storms are transformed to correspond approximately to a curvilinear coordinate system. This allows the model to consider coasts with moderate curvature and will extend the model's usefulness to areas such as New England. Figure 6 shows storm surge calculations made by SPLASH, with the curvilinear coordinate system, for several locations during hurricane Donna in 1960.

EXTRATROPICAL STORM SURGE FORECAST PROGRAM

The National Weather Service has developed and put into routine operation a technique for forecasting storm surges caused by extratropical storms along the northeast coast of the United States. Storm surge is defined as the difference between the observed sea level and the sea level that would have occurred in the absence of the storm. This type of storm surge is caused by the strong winds associated with extratropical storms over nearshore areas.

The Atlantic coastal storm of March 5-8, 1962, affected the entire Atlantic coast of the United States and produced record breaking high tides at locations between Long Island and Cape Hatteras. This storm was the most devastating extratropical storm on record affecting the U. S. Atlantic coast, as it caused damage estimated to be over $200 million. Even though storms approaching this magnitude are rare, important storms of less damage potential occur several times each winter. Accurate and timely forecasts of flooding and beach erosion caused by these storms are important. It is desirable to have an objective technique for forecasting extratropical storm surges and to have this technique automated and used with meteorological data from an atmospheric prediction model.

Empirical forecast equations have been derived for the 11 locations from Portland, Maine, to Charleston, South Carolina, shown in figure 7. The forecast equations are based on data mainly from 68 storms that occurred from 1956 through 1969. A statistical approach was used in the development because of the large number of cases for which there are available storm surge and meteorological data. Meteorological data used in the development consisted of sea-level atmospheric pressure at a network of grid points near the east coast. Forecast equations for the 11 locations were determined by the statistical screening-regression technique. A sample forecast equation, that for New York City, is shown in figure 8.

Calculations of storm surge, made from sea-level pressure analyses for the March 1962 storm agree quite well with observed storm surges (figure 9). Input data to the method, when used operationally, are values of sea-level pressure as forecast by the Primitive Equation numerical weather prediction model of the National Meteorological Center. The first severe coastal storm to which the method was applied was that of February 18-20, 1972. The storm surge calculations, based on pressure analyses, agreed reasonably well with the observations of storm surge. This comparison is shown in figure 10.

The forecasts are transmitted via teletype circuit (figure 11) to National Weather Service offices. The storm surge forecasts are combined with calculations of the astronomical tide and the resulting forecasts of storm tide are helpful to the marine forecasters of the Weather Service in preparing actual forecasts.

Our experience with the method has shown the great importance of accurate sea-level pressure forecasts when used as input data to the storm surge forecast method. Indications are that the method is useful and will be expanded to include other locations.

GREAT LAKES WIND FORECAST PROGRAM

An automated method of forecasting winds over the Great Lakes has been developed and put into operational use (Feit and Barrientos, 1974). The method was implemented in March 1973. The forecast technique is statistical in nature and is based on the Model Output Statistics (MOS) technique, which matches the output from a numerical model with observations and computes prediction equations.

The predictand data were marine observations taken by anemometer equipped ships participating in the National Weather Service's Great Lakes Marine Observations Program. The anemometers on these ships are checked for accuracy by the National Weather Service. These marine observations, unlike land based observations, have the problem of not being made at fixed locations. Therefore the observations were grouped according to the section of the Great Lakes in which they were made. These sectors were arbitrarily defined by dividing each lake into two or three relatively homogeneous parts. The 12 lake sectors are shown in figure 12.

There is generally more than one vessel taking wind observations in a given lake sector at any observation time. The problem of determining a representative wind observation was approached by selecting the maximum wind from all simultaneous observations and assuming that this wind occurs at the center of the lake sector. The marine observations are taken no closer than 5 miles to shore. Therefore, the land effects are considerably reduced and the observations are assumed to be representative of the over-water wind conditions.

The multiple regression-screening procedure was used to derive forecast equations. The data from all 12 lake sectors were pooled because of scarce data amounts in some lake sectors. This generalized approach results in some loss of accuracy in individual sectors but this loss is expected to be small. Predictors included PE model forecasts such as wind components, temperatures, and heights at various levels. These predictors were interpolated to the forecast points at the center of the 12 lake sectors as shown in figure 12.

Forecast equations were derived for forecast times of +00, +06, +12, +18, +24, +30, and +36 hours, for each PE model origin time (0000 GMT and 1200 GMT) and for two seasons, April through September and October through March. Equations were derived for the north-south and east-west components and for the wind speed. The following is a +12 hour wind speed forecast equation for the winter season for 0000 GMT PE model runs:

$$S = 11.693 + .730(X_1) + .001(X_2) + .453(X_3) - 7.290(X_4) - .004(X_5) - .334(X_6) - .001(X_7)$$

where S = Wind Speed (knots)
X_1 = 12-hr projection, boundary layer wind speed (m/sec),
X_2 = 12-hr projection, 850-mb height (cm departure from 145700 cm),
X_3 = 18-hr projection, boundary layer wind speed (m/sec),
X_4 = 12-36 hr surface pressure change (mb/10 departure from 90 cb),
X_5 = 36-hr projection, 850-mb height (cm departure from 145700 cm),
X_6 = 12-hr projection, 850-mb temperature (deg C)
X_7 = 36-hr projection 1000-mb height (cm departure from 11300 cm).

Figure 13 shows a sample teletype message for wind over the 12 sectors of the Great Lakes. The first line indicates this forecast is for the 12th of the month at 1200 GMT (121200). The third line shows the valid times of the forecasts from 6 hours to 36 hours in advance. The body of the message contains the wind forecast message in the form ddff--dd in tens of degrees and ff in knots.

GREAT LAKES WAVE FORECAST PROGRAM

The National Weather Service began making automated wave forecasts for 64 points in the Great Lakes in January 1975. The wave forecasts are based upon the automated wind forecasts for the Great Lakes. These wind forecasts extend to 36 hours at 6-hour intervals for 12 areas of the lakes. Lakes Erie, Ontario, and Huron are divided into two sections and Lakes Michigan and Superior into three. Locations of the 64 wave forecast points are shown in figure 14.

Wave forecasts at the points within any lake section are based on the wind forecasts for that section of the lake. Wave height calculations are based upon the method of Bretschneider (1970). The basic method relates the wave heights to the wind speed, fetch length, and duration time. The usual application of the method calls for the subjective estimation of such variables as fetch length and wind duration time. Many alterations to the standard method were made so that it could be completely automated.

A brief description of the method follows:

a. For each forecast point, fetch lengths for directions at 15° intervals are tabulated. Some of these are corrected for fetch width restrictions. Fetch length is then chosen for the wind direction at forecast time. No consideration is given to the effect of ice on the reduction of fetch length. This means that during late winter the actual fetch lengths will be less than those used in the calculations. Perhaps at a later time ice conditions can be considered in determining fetch lengths.

b. The effect of duration time of the wind--the length of time the wind has been from the same general direction--is important in wave generation. The duration time is determined objectively for each forecast time by examining the wind directions during the previous 30 hours at 6-hour intervals. The time that the wind is within 45° of the wind at forecast time is used. In this manner the duration time is estimated to be 3, 9, 15, 21, 27, or 33 hours.

c. An effective wind speed is determined by weighting the winds over the duration time such that the winds closest to forecast time are weighted the heaviest. A future improvement in the method may be more direct consideration of atmospheric stability by applying the air-lake temperature difference as an adjustment to the wind speed.

d. Effective fetch is calculated as a function of the duration time and the effective wind speed. The effective fetch is compared to the real fetch and the smaller of the two is used in the wave height calculation.

e. Significant wave height and wave period are then calculated by the Bretschneider method.

The Great Lakes wave forecast program is run twice daily after the 0000 GMT and 1200 GMT numerical weather model runs and the subsequent Great Lakes wind forecast runs. The wave forecasts are transmitted via teletype circuits as soon as practical after they are generated.

Figure 15 shows a sample teletype message for wave forecasts at the 64 forecast locations. The first line indicates this forecast is for the 6th of the month at 1200 GMT (061200). The forecasts are for +00, +12, +24, and +36 hours and are expressed in feet.

LAKE ERIE STORM SURGE FORECAST PROGRAM

The effects of several types of water level fluctuations on Lake Erie combine to produce the observed lake level. These fluctuations can be classed as long range, seasonal, and meteorologically-generated fluctuations.

Long range fluctuations in the level of Lake Erie are caused mainly by variations in the amount of precipitation in the Great Lakes Basin. Periods of higher than normal precipitation are followed by periods of higher lake level.

Another type of water level fluctuation is the seasonal variation that occurs regularly, with high levels during summer and low levels in winter. They are caused by seasonal differences of weather conditions over and near the lake.

The third type of variation consists of the water level changes caused by storms crossing the Great Lakes area. The most significant are the winter storms which approach the Great Lakes from the central part of the country and cause strong southwest winds over Lake Erie. This results in a storm surge, which is essentially the pile-up of water by the wind. The result of southwest winds is a tilted lake surface--the eastern end of the lake is raised and the western end is lowered.

Occasionally a storm system will pass south of Lake Erie, bringing northeast winds over the lake. When this happens, the reverse water level situation occurs, with the pile-up of water occurring in the western portion of the lake.

The National Weather Service began making automated forecasts of storm surges on Lake Erie in October 1969 (Richardson and Pore, 1969). Forecasts are made for two locations--Buffalo, New York and Toledo, Ohio. Storm surge values were determined as the difference in actual lake level and the monthly mean lake level. The lake level data were recorded by water level gages of the Lake Survey Center.

The forecast method is statistical and was derived by the perfect prog method. In this method, observations of the predictand are related to observed or analyzed values of predictors. Specifically, storm surge at Buffalo and Toledo were related to analyzed values of sea level pressure at the six grid points shown in figure 16. The pressures at these grid points pretty well define the wind flow over Lake Erie, which causes the storm surge. The multiple correlation screening procedure was used to derive forecast equations. Sea level pressure with various time lags were screened as possible predictors. A sample forecast equation for storm surge at Toledo is shown in figure 16.

On November 14, 1972 an intense low pressure system passed to the south of Lake Erie and caused strong northeast winds over the lake. The resulting storm surge of over 4 feet added to the existing level of more than 2 feet in excess of the long term mean caused extensive flooding and damage. Over a thousand homes were severely damaged. Figure 17 shows the observed storm surge curves for Toledo and Buffalo and the calculated storm surge curves based on sea-level pressure analyses.

A sample teletype forecast message for storm surge at Buffalo and Toledo is shown in figure 18. This message is for 0000 GMT on the 28th of the month (280000). The third line shows the highest and lowest values forecast at

Buffalo and Toledo during the 48-hour forecast period. The body of the message contains the storm surge forecasts, expressed in feet, for Buffalo and Toledo. Forecast values are given for each hour at Buffalo and for every second hour at Toledo.

The method is presently being expanded to include three additional forecast locations--Essexville, Michigan (Saginaw Bay), Lakeport, Michigan (Southern Lake Huron), and Green Bay, Wisconsin.

SUMMARY

The Techniques Development Laboratory has implemented several marine environmental prediction programs in recent years. These programs are for forecasting ocean and Great Lakes waves, hurricane storm surges, extratropical storm surges along the Atlantic coast and on Lake Erie, coastal wind conditions along the U. S. Atlantic and Pacific coasts, and winds over the Great Lakes.

These automated forecasts are used primarily as guidance at Forecast Offices of the National Weather Service in the preparation of the official forecasts. These marine environmental forecasts are nearly all based on input from numerical atmospheric models. Whenever a forecaster recognizes a deficiency in the forecasts of the numerical atmospheric model for a particular time, he can generally improve upon the automated marine environmental forecasts.

The automated marine environmental forecasts described in this paper are generally considered to be useful. The Techniques Development Laboratory will attempt to improve the existing marine forecast programs, expand them to include additional geographic areas, and will develop new programs for additonal variables such as beach erosion and visibility.

ACKNOWLEDGMENTS

Appreciation is expressed to the members of the Marine Techniques Branch of the Techniques Development Laboratory who have developed the forecast methods described in this report. Appreciation is also expressed to Herman Perrotti who prepared many of the figures and to Mary-Blue Battle for typing the manuscript.

REFERENCES

Bretschneider, C. L., "Forecasting Relations for Wave Generation," Look Lab Hawaii, Vol. 1, No. 3, July 1970, pp. 31-34.

Feit, D. M. and C. S. Barrientos, "Great Lakes Wind Forecasts Based on Model Output Statistics," Proceedings of 17th Conference on Great Lakes Research, 1974, pp. 725-732.

Jelesnianski, C. P., "SPLASH (Special Program to List Amplitudes of Surges form Hurricanes) I. Landfall Storms," NOAA Technical Memorandum NWS TDL-46, April 1972, 52 pp.

Jelesnianski, C. P., "SPLASH (Special Program to List Amplitudes of Surges from Hurricanes) Part Two. General Track and Variant Storm Conditions," _NOAA Technical Memorandum_ NWS TDL-52, March 1974, 55 pp.

Richardson, W. S. and N. A. Pore, "A Lake Erie Storm Surge Forecasting Technique," _ESSA Technical Memorandum_ WBTM TDL 24, August 1969, 23 pp.

U. S. Army Coastal Engineering Research Center, "_Shore Protection Planning and Design_," Technical Report No. 4, Third Edition, 1966, 580 pp.

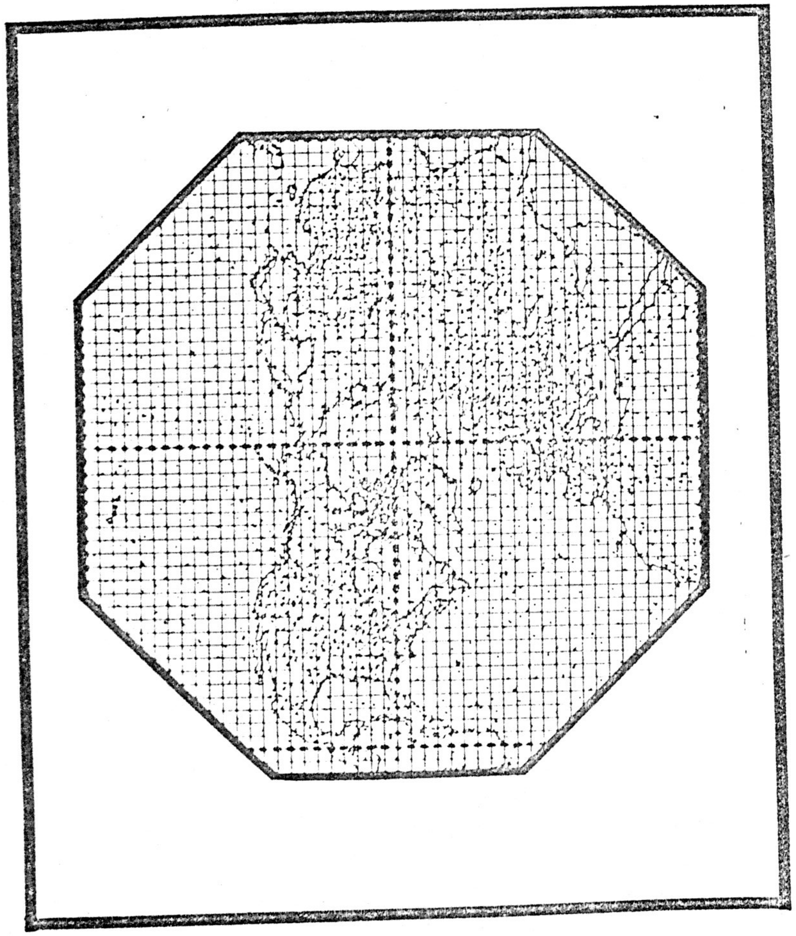


Figure 1. National Meteorological Center 1977 point grid used for computation.

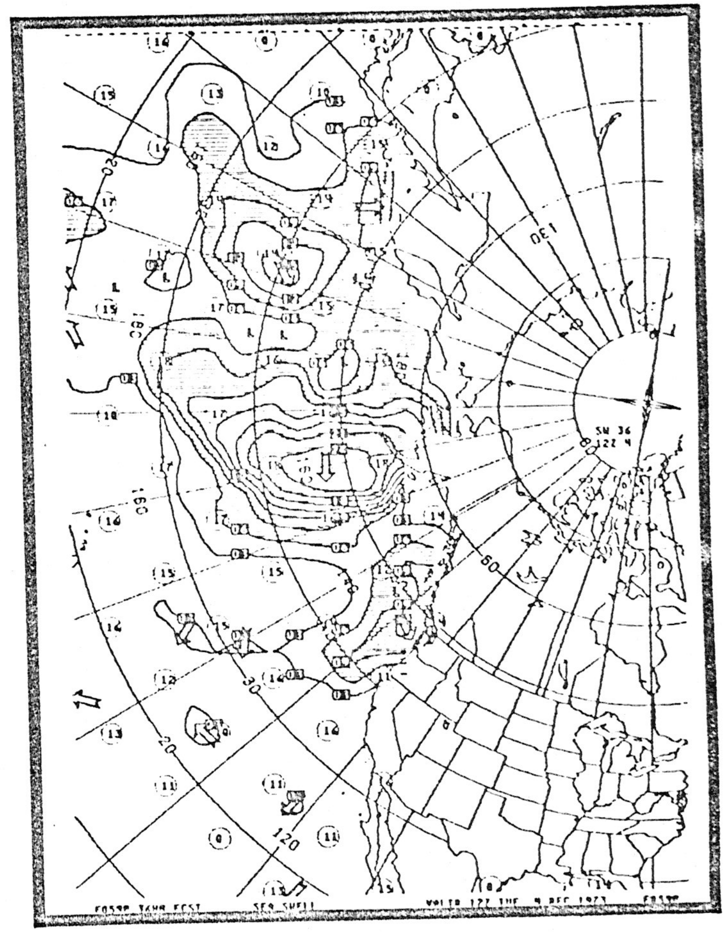


Figure 2. Sample 36-hour swell forecast chart for the Pacific. Height contours are drawn at intervals of 3 feet.

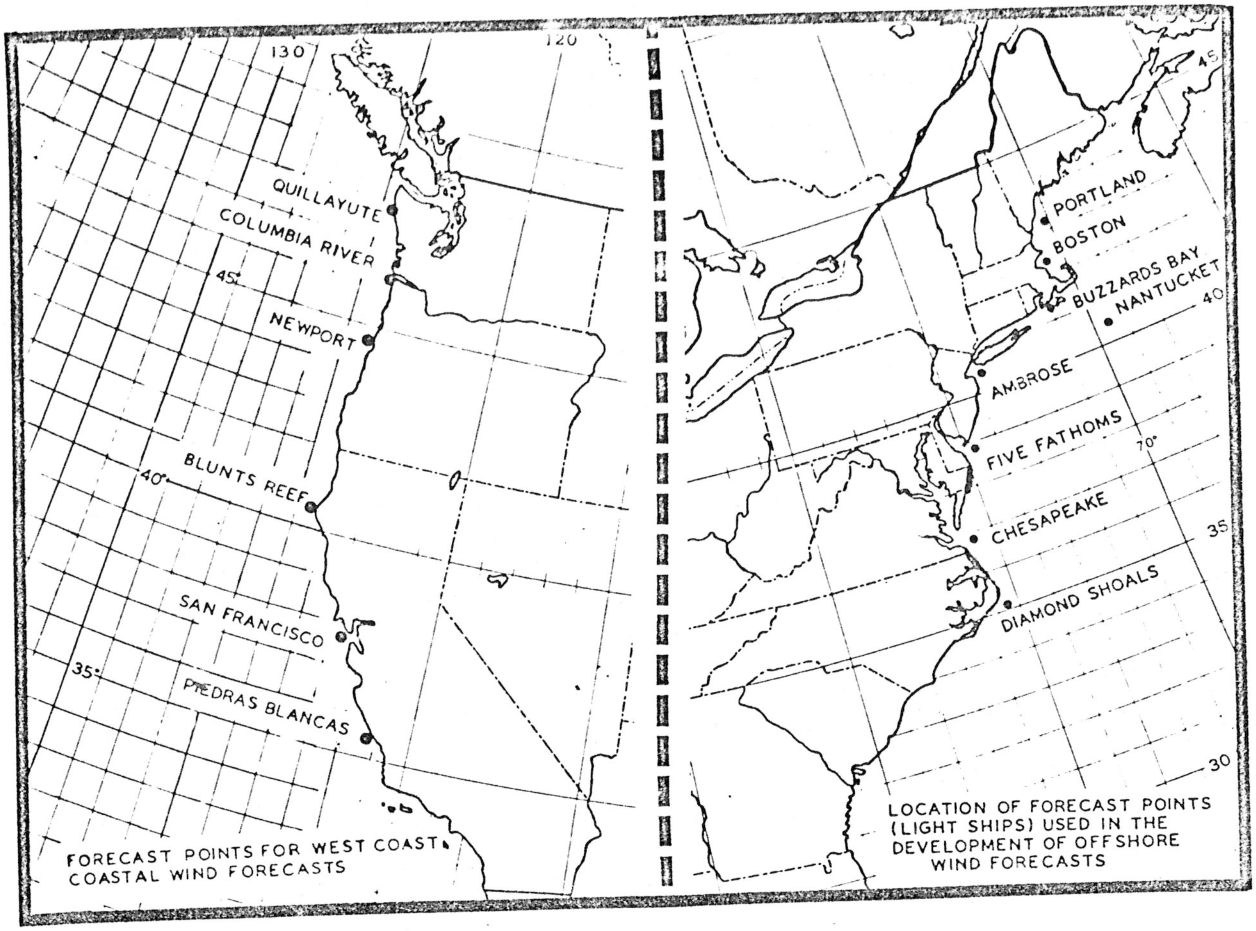


Figure 3. The forecast locations for which wind forecast equations were derived.

FZUS5 KWBC 061200
WIND FORECAST FOR EAST COAST OFSHORE LOCATIONS

LOCATION	18Z	00Z	06Z	12Z	18Z	00Z	06Z
PORTLAND LS	1415	1617	2412	2612	2410	2615	1320
BOSTON LS	2017	1813	2814	2710	2419	1918	1620
BUZZARDS BAY LS	2221	2017	2615	2517	2024	1518	2019
NANTUCKET LS	2208	2415	2609	2521	2117	1712	1927
AMBROSE LS	2317	2419	2509	1910	1723	3024	2626
FIVE FATHOMS LS	2421	2723	2108	2022	2234	2834	3036
CHESAPEAKE LS	1513	2012	1908	1613	1307	2024	2327
DIAMOND SHL LS	2521	2515	2814	3013	2412	2418	2722

Figure 4. Wind forecast teletype message for East coast locations. Format of forecasts in body of report is ddff, where dd is direction in tens of degrees and ff is wind speed in knots.

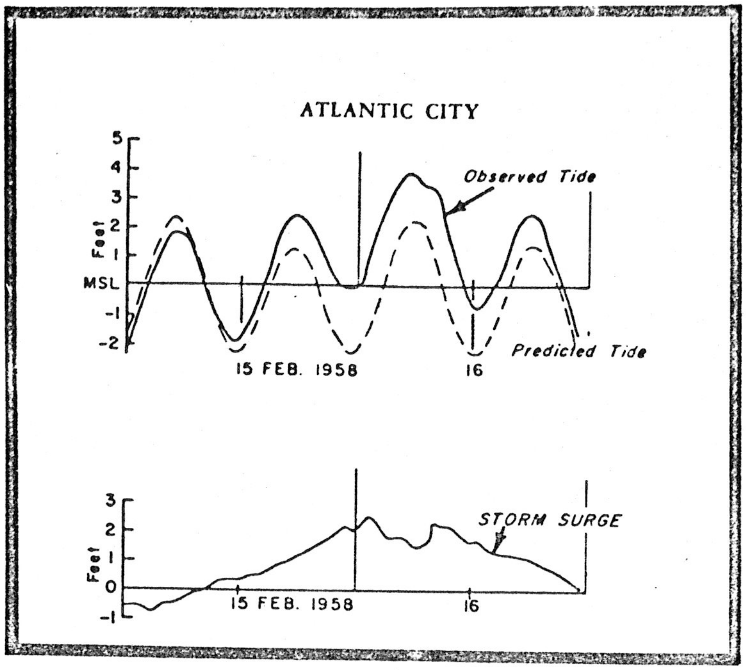


Figure 5. Example of Atlantic City tide data showing the observed tide, the predicted tide and the storm surge.

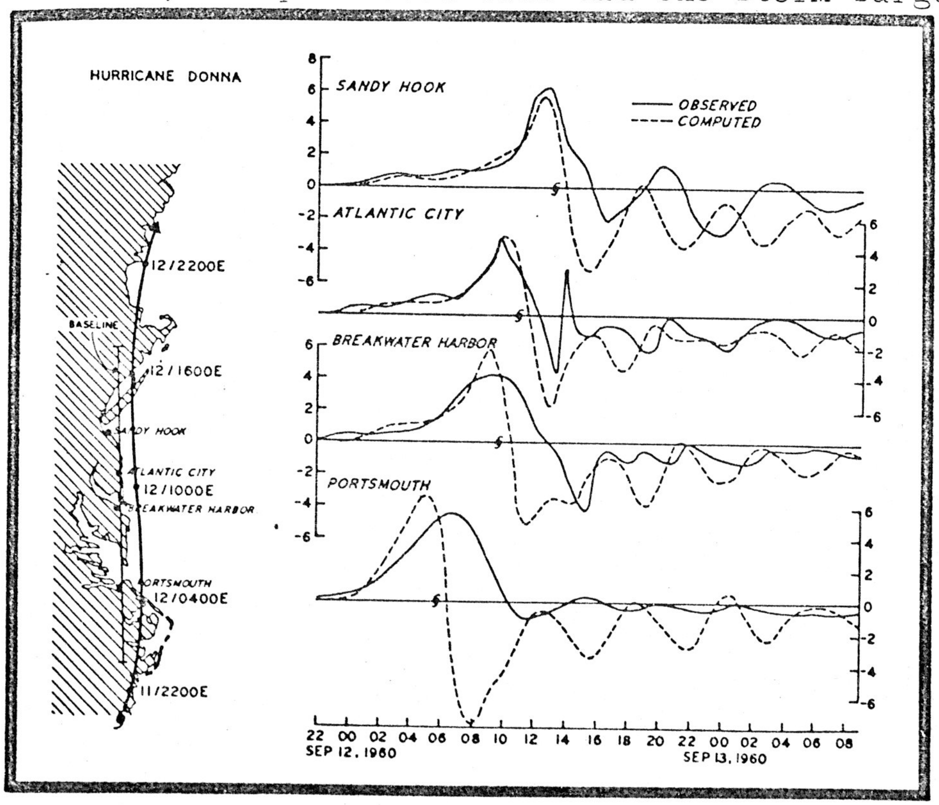


Figure 6. Observed storm surges and surges calculated by the SPLASH model for Hurricane Donna of 1960.

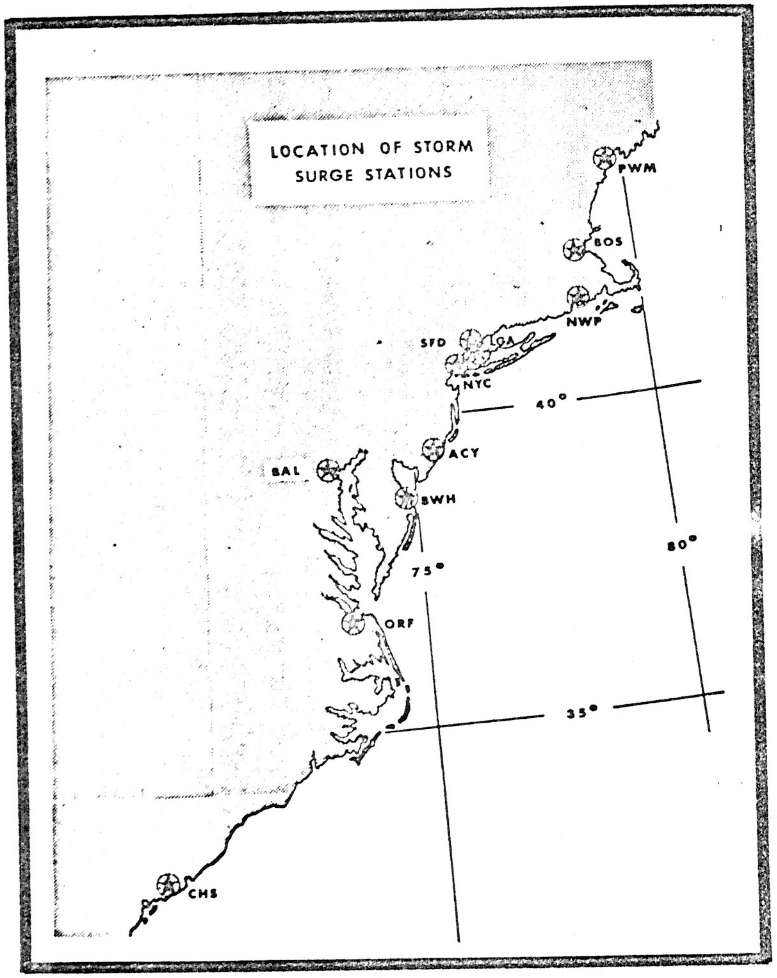
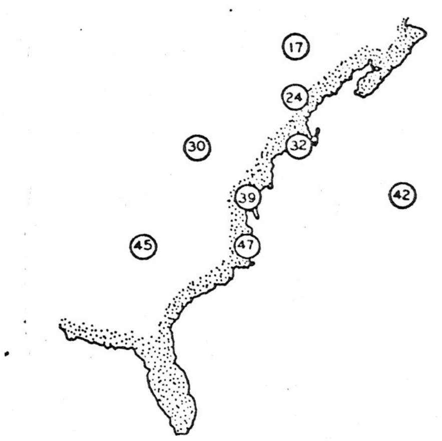


Figure 7. The 11 forecast locations for which extratropical storm surge forecast equations were derived.



$$SS(NYC)_t = A - B(47)_{t-6} + C(17)_{t-6} - D(42)_{t-6} - E(30)_{t-6} + F(24)_{t-6} - G(39)_{t-6} + H(32)_{t-6} + I(45)_t$$

Figure 8. An extratropical storm surge forecast equation for New York. SS is storm surge. The number in parentheses of each term is the grid point for which sea-level pressure is used as a predictor. The subscript on each term is the lag of the predictor in hours.

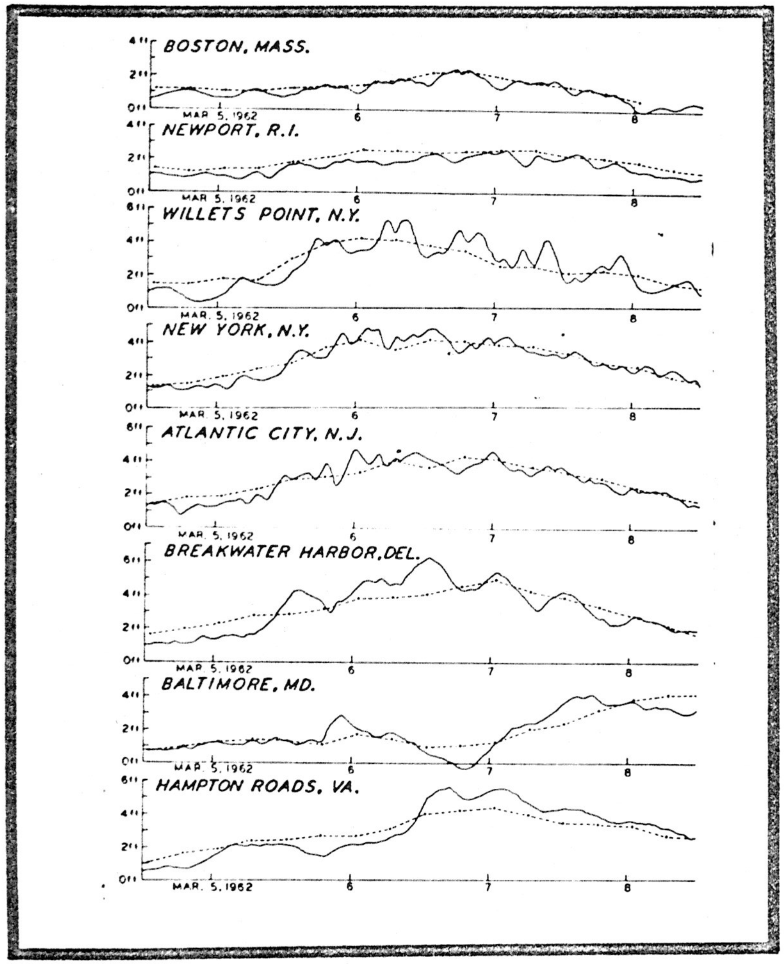


Figure 9. Observed storm surge and calculated storm surge for eight locations during the March 1962 storm. Solid curves are observed storm surge. The dashed lines connect storm surge calculated at 6-hourly intervals, based upon analyses of sea-level pressure.

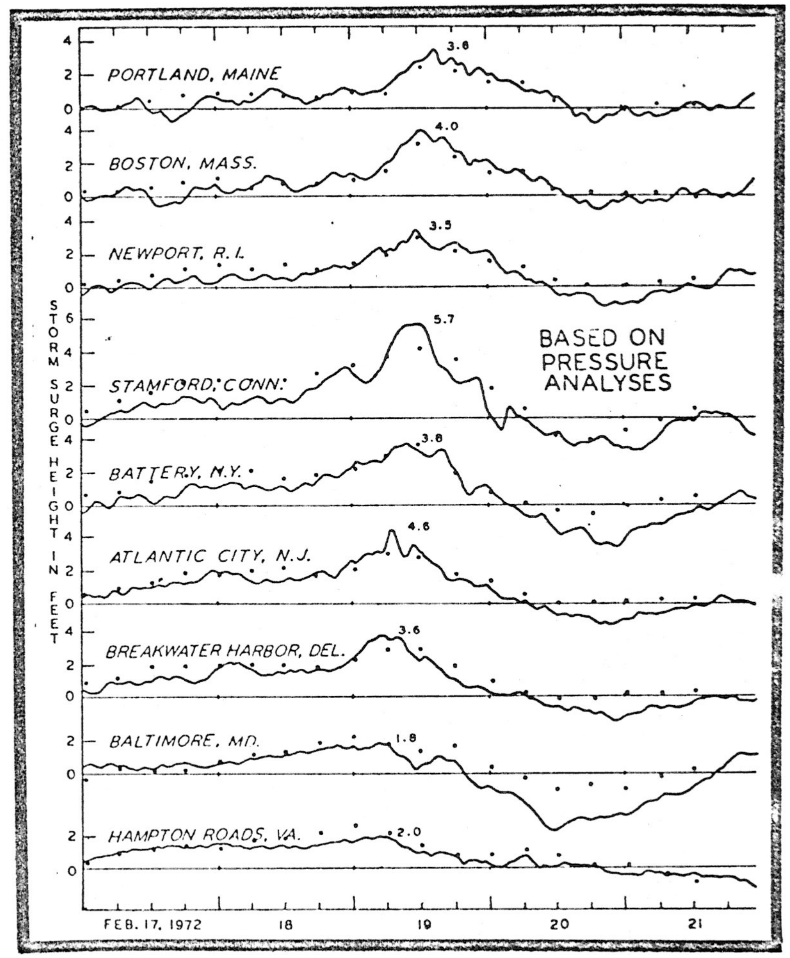


Figure 10. Storm surge calculations for Feb. 17-21, 1972, based on sea-level pressure analyses, are shown by dots. Solid curves indicate observed storm surges. The date for each day is placed at the 1200 EST position. Maximum value of observed surge is placed near peak of each curve.

FZUS3 KWBC 021200
EAST COAST STORM SURGE FORECAST IN FEET

	12Z	18Z	00Z	06Z	12Z	18Z	00Z	06Z	12Z
PWM	0.1	0.4	0.5	0.7	0.7	0.9	0.8	0.9	0.7
BOS	0.1	0.2	0.3	0.4	0.4	0.5	0.4	0.6	0.3
NWP	0.8	1.0	1.1	1.2	1.2	1.3	1.1	1.1	0.9
SFD	1.0	1.1	1.2	1.2	0.9	0.7	0.6	0.1	0.0
LGA	1.0	1.0	1.0	1.3	1.2	1.0	1.0	0.8	0.7
NYC	1.2	1.3	1.4	1.4	1.3	1.2	1.0	0.9	0.7
ACY	0.8	0.9	1.0	0.9	0.9	0.9	0.8	0.8	0.7
BWH	1.1	1.1	1.2	1.0	0.9	0.9	0.7	0.7	0.6
BAL	2.4	2.5	2.6	2.8	2.8	2.6	2.4	2.0	1.9
ORF	0.9	0.8	0.9	0.8	0.8	0.8	0.7	0.6	0.9

PWM Portland, Maine
BOS Boston, Massachusetts
NWP Newport, Rhode Island
SFD Stamford, Connecticut
LGA Willets Point, New York
NYC Battery, New York
ACY Atlantic City, New Jersey
BWH Breakwater Harbor, Delaware
BAL Baltimore, Maryland
ORF Hampton Roads, Virginia

Figure 11. Extratropical storm surge forecast message. Forecast heights are in feet. Valid times are indicated above each column. Station call signs are identified below message.

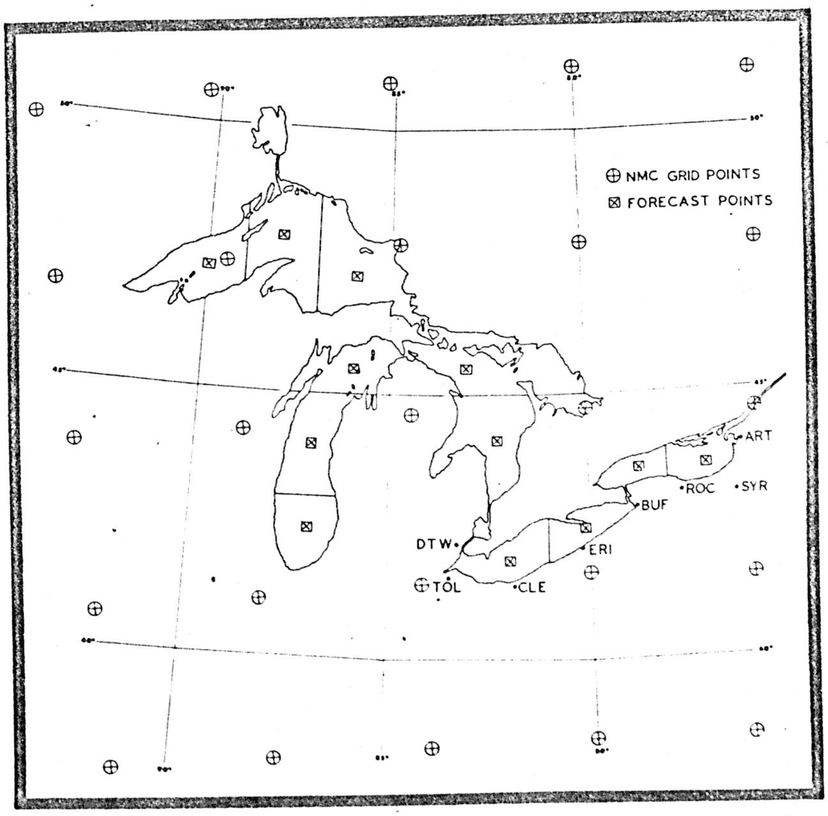


Figure 12. The 12 areas of the Great Lakes for which wind forecasts are made.

```
FZUS4 KWBC 121200
WIND FORECASTS FOR THE GREAT LAKES
 LOCATION            18Z  00Z  06Z  12Z  18Z  00Z
 EAST ONTARIO       1529 2028 2631 2930 3130 3026
 WEST ONTARIO       1629 2328 2728 2927 3125 3225
 EAST ERIE          1830 2427 2824 3226 3322 0623
 WEST ERIE          2132 2725 3023 3527 3425 0323
 SOUTH HURON        2231 2730 2926 3024 2818 3023
 NORTH HURON        2429 2730 2927 2924 2718 2922
 SOUTH MICHIGAN     2830 3028 3324 3323 3223 3319
 CENTRAL MICHIGAN   2932 3031 3226 3223 3020 3219
 NORTH MICHIGAN     2830 2932 3026 3023 2820 3120
 EAST SUPERIOR      2926 2931 3026 3023 2821 3020
 CENTRAL SUPERIOR   3127 3031 3026 3022 2822 3019
 WEST SUPERIOR      3130 3030 3025 3022 2722 3018
```

Figure 13. Wind forecast teletype message for the Great Lakes. Format of forecasts is ddff where dd is direction in tens of degrees and ff is speed in knots.

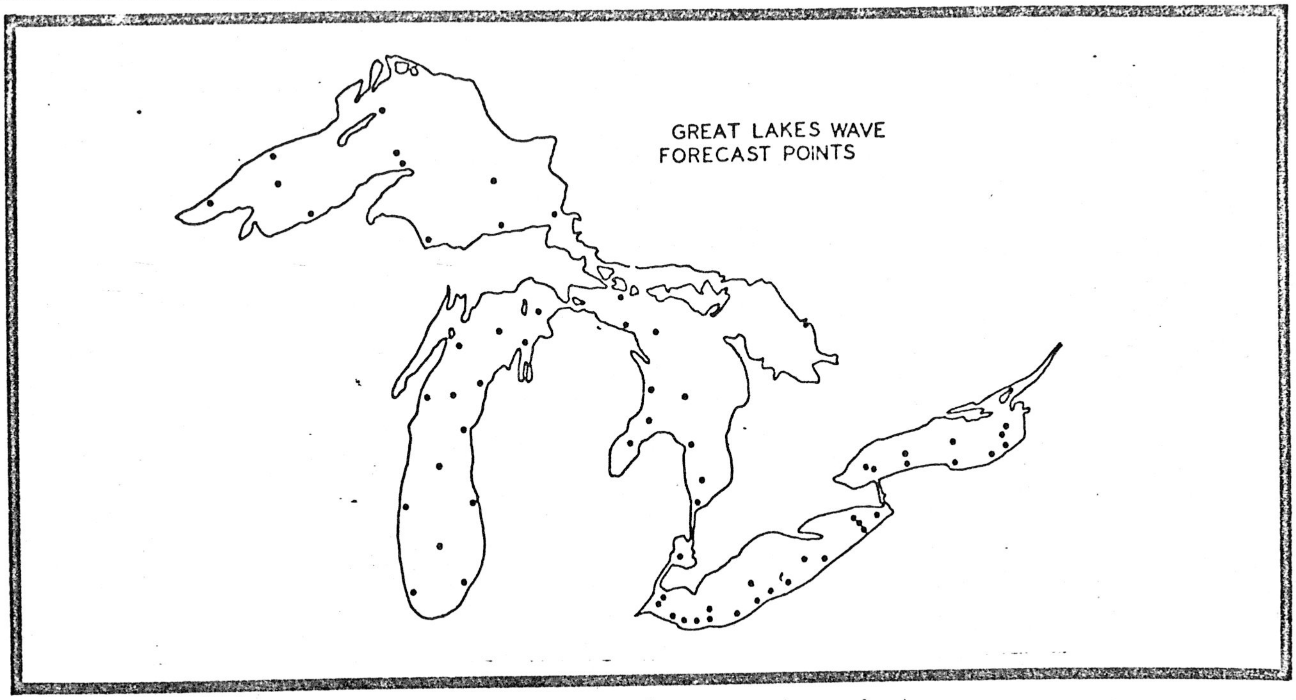
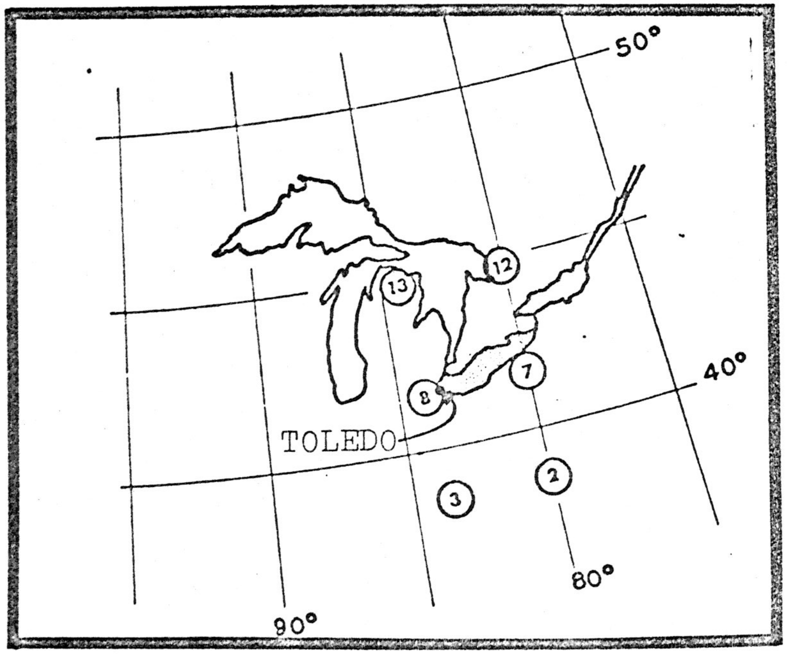


Figure 14. Great Lakes wave forecast points.

```
FZUS2 KWBC 061200
GREAT LAKES WAVE FORECAST HEIGHT IN FEET
   00 HR
POINT NO.   1  2  3  4  5  6  7  8  9. 10 11 12 13 14 15 16 17 18 19
SUPERIOR   01 02 03 03 02 02 02 02 02 02 02
MICHIGAN   04 05 04 02 05 04 02 05 05 02 06 06 03 07
HURON      03 02 03 02 05 03 03 02 03 02
ERIE       03 04 04 03 03 03 04 05 03 06 05 06 03 05 04 04 06 06 05
ONTARIO    04 03 04 03 04 03 03 03 04 04
   12 HR
POINT NO.   1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19
SUPERIOR   01 02 03 03 02 03 04 01 04 04 04
MICHIGAN   02 03 03 02 02 02 02 02 02 02 01 02 02 01
HURON      02 03 04 02 04 03 03 03 03 03
ERIE       02 02 03 03 03 03 04 05 05 05 05 05 06 05 06 05 04 04 04
ONTARIO    04 05 05 05 07 04 06 07 07 07
   24 HR
POINT NO.   1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19
SUPERIOR   02 02 03 04 02 02 02 02 02 02 02
MICHIGAN   03 03 03 03 03 03 03 03 03 03 02 03 03 03
HURON      02 02 02 02 02 02 02 02 02 02
ERIE       02 03 02 02 02 02 02 02 02 03 02 02 02 02 02 02 02 02 02
ONTARIO    03 03 04 04 05 02 04 05 05 05
   36 HR
POINT NO.   1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19
SUPERIOR   02 02 04 06 03 05 05 05 07 07 06
MICHIGAN   05 06 05 03 06 05 03 06 06 03 07 06 04 07
HURON      02 05 05 03 04 04 04 02 04 02
ERIE       02 04 03 02 02.03 03 04 03 05 04 03 02 04 03 02 04 04 03
ONTARIO    03 02 03 02 04 02 02 03 04 05
```

Figure 15. Great Lakes wave forecast teletype message. The body of the message consists of wave height forecasts in feet.



$$\text{TOL SS}(4) = -34.7 + 0.0639\ P(13)_{-6} - 0.1735\ P(3)_0 + 0.0865\ P(8)_{-6} + 0.0573\ P(13)_0$$

Figure 16. A sample forecast equation for storm surge at Toledo, Ohio. Predictors are sea-level pressure at the grid points indicated. Subscripts indicate time lags in hours.

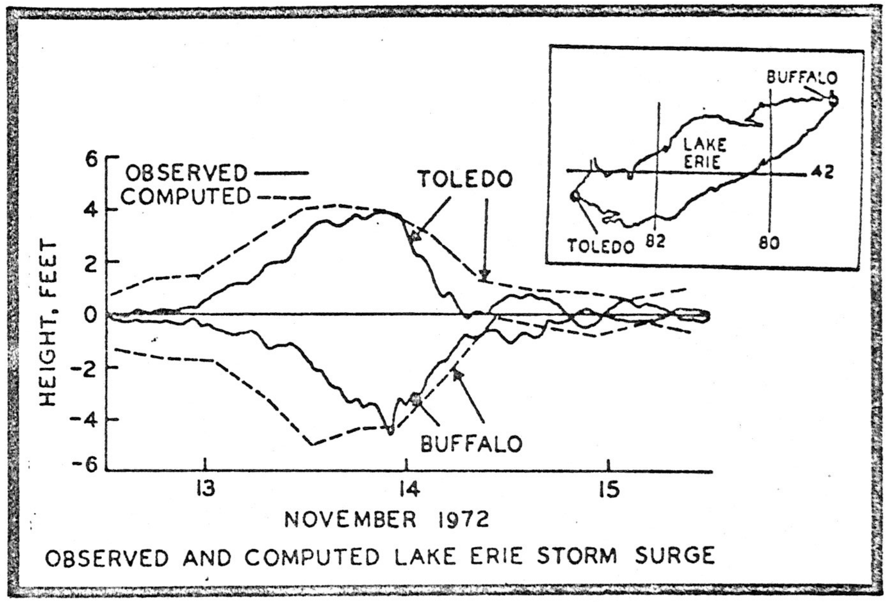


Figure 17. Observed and computed storm surge at Toledo and Buffalo during the storm of November 14, 1972.

FZUS1 KWBC 280000
LAKE ERIE STORM SURGE FORECAST
BUFFALO MAX 2.1 MIN -1.1 TOLEDO MAX 0.3 MIN -2.1

TIME GMT	BUFFALO SURGE	TOLEDO SURGE	TIME GMT	BUFFALO SURGE	TOLEDO SURGE	TIME GMT	BUFFALO SURGE	TOLEDO SURGE
01	0.0		17	-0.8		09	1.2	
02	-0.0	-0.2	18	-1.0	-1.0	10	1.5	-1.4
03	-0.0		19	-1.1		11	1.7	
04	-0.1	0.2	20	-1.0	-0.6	12	1.9	-1.4
05	-0.1		21	-0.8		13	2.1	
06	-0.1	-0.0	22	-0.7	-0.1	14	2.0	-1.6
07	-0.2		23	-0.6		15	2.0	
08	-0.2	-0.1	00	-0.4	0.3	16	1.9	-1.9
09	-0.2		01	-0.3		17	1.8	
10	-0.2	-0.2	02	-0.1	-0.2	18	1.7	-2.1
11	-0.2		03	0.1		19	1.6	
12	-0.2	-0.3	04	0.2	-0.7	20	1.6	-1.8
13	-0.2		05	0.4		21	1.7	
14	-0.3	-0.5	06	0.6	-1.2	22	1.7	-1.5
15	-0.5		07	0.8		23	1.8	
16	-0.6	-0.7	08	1.0	-1.3	00	1.9	-1.2

Figure 18. Teletype message for storm surge at Buffalo and Toledo. Body of message consists of storm surge height forecasts in feet.