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OBSERVED VERSUS SLOSH MODEL STORM SURGE FOR CONNECTICUT, NEW YORK AND UPPER NEW JERSEY IN HURRICANE GLORIA, SEPTEMBER 1985

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UNITED STATES DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration Anthony J. Calio, Administrator / National Weather Service Richard E. Hallgren Assistant Administrator

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ABSTRACT

The peak storm surge generated by the SLOSH model is within ± 2 ft of the observed surge at all locations. Also, the occurrence of the peak surge generated by SLOSH is within ± 1 h of the observed surge at all locations.

1. INTRODUCTION

The Army Corps of Engineers, Federal Emergency Management Agency and the National Weather Service are extensively involved in determining the areas that are prone to flooding by hurricane storm surge along the U.S. Atlantic and Gulf of Mexico coastlines. Determination of flood prone areas is an essential prerequisite to evacuation planning.

Flood potential could be specified through a study of past events if, for the region of interest, a horizontal network of meteorological (pressure and wind) and hydrographic (tide gage) sensors had continuously recorded data during hundreds of historic hurricanes of varying intensity, direction, and forward speed. In reality, hurricanes are very rare events for any region along the Atlantic and Gulf coastlines. Also, in the historical cases that do exist, many of the meteorological and hydrographic sensors failed during passage of the hurricane. Thus, for most of the U.S. coastline, the climatology of hurricane storm surge flooding is very limited.

To compensate for this lack of historical data, the National Weather Service developed a numerical model termed SLOSH (Sea, Lake, and Overland Surges from Hurricanes). The SLOSH model, given hurricane input parameters, computes storm surge heights over a geographic area that is covered by a network of grid points. This network, or model domain, is called a basin. At present, 27 basins cover approximately 90% of the U.S. Atlantic and Gulf of Mexico flood plains. The basin that covers the flood plains of Connecticut, New York and upper New Jersey has been designated the "Long Island Sound basin."

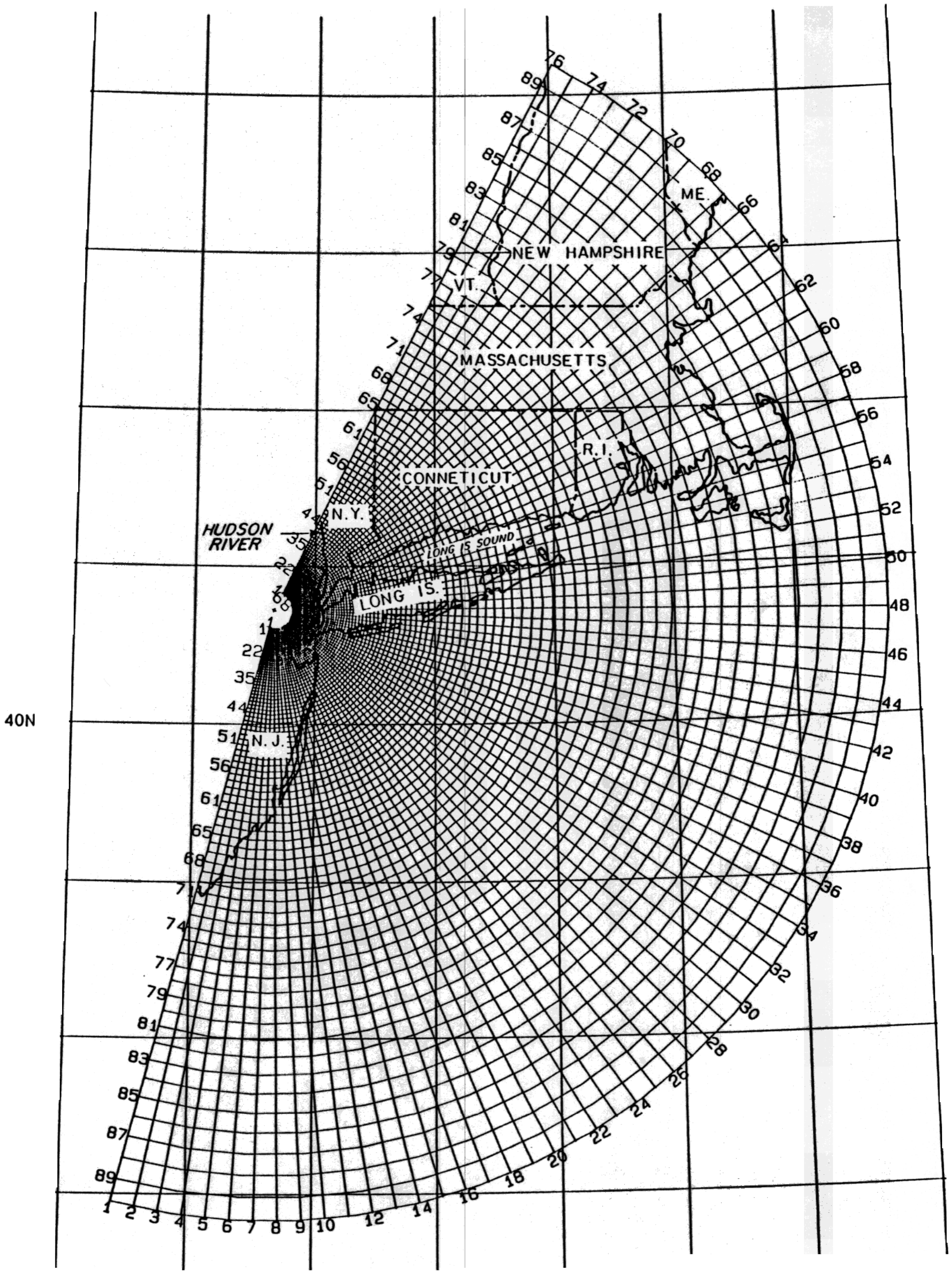
A hurricane evacuation study is under way for Connecticut, New York and upper New Jersey. A series of hypothetical hurricanes of varying intensity, direction, and forward speed has been simulated using the SLOSH model in the Long Island Sound basin. The storm surge data generated by the SLOSH model simulations determines the flood-prone regions. With this knowledge, evacuation plans are being formulated for future use. During an evacuation study, historical hurricanes are also simulated with the SLOSH model. The comparison of the SLOSH model storm surge values and the observed storm surge values determine the confidence in the model (Jarvinen and Lawrence, 1985). Unfortunately, in the Long Island Sound region, simultaneous observations of the storm surge and hurricane meteorological parameters for historical hurricanes have been almost nonexistent. However, during the 1985 hurricane season, Gloria presented an opportunity for a comparison in the Long Island Sound basin. The purpose of this paper is a comparison of observed versus SLOSH computed hydrographs in the Long Island Sound basin for Hurricane Gloria.

2. LONG ISLAND SOUND BASIN

The Long Island Sound basin grid is shown in Figure 1. The grid is a telescoping polar coordinate system with 90 arcs and 76 radials. Unlike a true polar coordinate grid, which would have a radial increment that was invariant with radius, this grid uses a radial increment that increases with increasing distance from the grid's pole. The result is that, in each grid of the mesh, the radial increment of the square is approximately equal to its arc length.

The telescoping grid is a compromise. It is desired that a large geographical area with small detailed topography be modeled. In the Cartesian coordinate system, this combination of large area and spatially small grid increments requires a computational mesh with many grid squares. A large grid requires a computer with a large central processing unit as well as time to perform calculations in the numerous grid squares. The telescoping grid, by comparison, resolves these conflicting needs: it has an acceptably small spatial resolution of 1 to 10 mi^2 per grid square over land which is the area of the greatest interest. Thus, topographic details, such as highway and railroad embankments and dikes in harbors of cities, are included in the model. However, the range increment contained in each grid square becomes progressively larger with increasing distance from the pole. As a result, a large geographic area is included in the model, and the effects of the model's boundaries on the dynamics of the storm surge are diminished.

The grid is tangent to the earth at Coney Island, New York, at 40°36'13"N and 74°03'15"W. There, the grid increment is 0.675 statute miles. The pole (or origin) of the grid is located at 40°43'20"N and 74°20'30"W.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3. SLOSH MODEL AND HURRICANE INPUT PARAMETERS

The SLOSH model's governing equations are those given by Jelesnianski (1967), plus a finite amplitude effect. Coefficients for surface drag, eddy viscosity and bottom slip are given by Jelesnianski (1972). There is no calibration or tuning to force agreement between observed and computed surges; coefficients are fixed and do not vary from one geographical region to another.

Special techniques are incorporated to model two-dimensional inland inundation, routing of surges inland when barriers are overtopped, the effect of trees, the movement of surge up rivers, and flow through channels and cuts and over submerged sills.

The SLOSH model requires hurricane input parameters at specified time intervals. These parameters include the latitude and longitude of the eye, the atmospheric sea-level pressure in the eye, and the radius of the maximum surface wind speed (RMW).

4. METEOROLOGY:

4.1 Track

Gloria represents a classical recurving Cape Verde hurricane. Figure 2 shows Gloria's track with positions marked every 24 h at 0000 UTC[1]. After forming in the Cape Verde region on September 17, Gloria moved generally westward for 5 days before beginning a gradual recurvature to the west-northwest as the center approached the Lesser Antilles. A more northwesterly direction in movement began as the center approached the eastern Bahamas on the 24th. In the next two days, Gloria began to increase its forward motion and gradually turned toward the north. Gloria made its first landfall near Cape Hatteras, NC, on September 27, between 0500 and 0600 UTC. The forward motion at landfall at Cape Hatteras was approximately 30 mph. Influenced by a strong southerly deep-layer tropospheric steering, Gloria continued to accelerate toward the north-northeast. Gloria raced by Delaware and New Jersey on the 27th and made landfall on Long Island moving about 40 mph at approximately 1600 UTC on the same day. The hurricane continued across Long Island into Connecticut and affected several other New England states and Canadian maritime provinces before reemerging in the Atlantic Ocean, where it dissipated on October 2.

Figure 3 shows hourly eye locations of Gloria during its passage by Delaware and New Jersey and into New England. The hourly locations are labeled by three values separated by slashes. The first value is Eastern Standard Time (EST). The second value is the central sea-level pressure in millibars. The final value is the RMW in statute miles. For example, 1000/958/24 means 1000 EST, 958 mb central sea-level pressure, and a radius of maximum wind of 24 statute miles.

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[1] UTC is Universal Time Coordinated. Subtract 5 hours to convert to Eastern Standard Time.

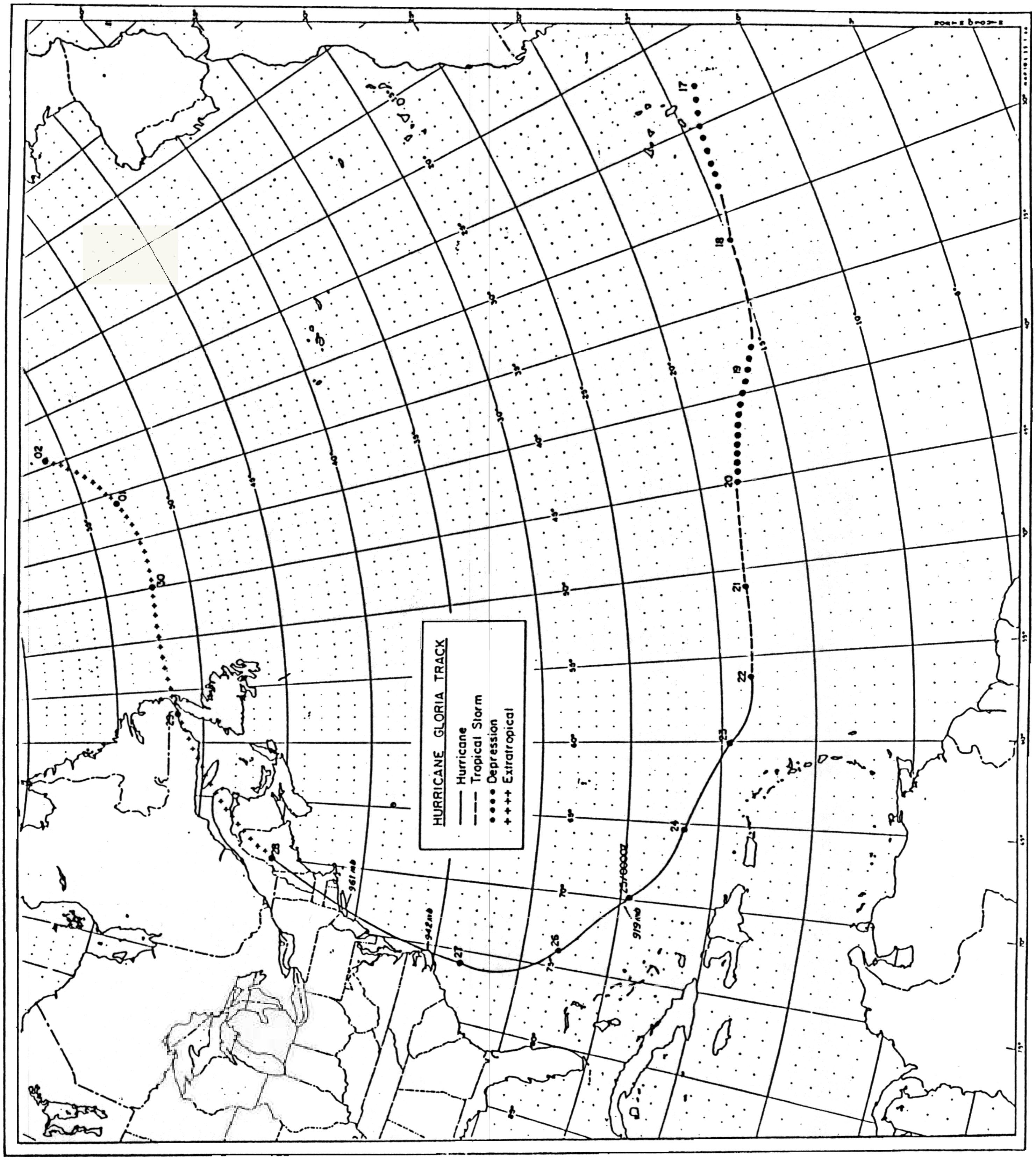


Figure 2. Track of Hurricane Gloria, 17 September to 2 October 1985.
Positions are given every 24 h at 0000 UTC.

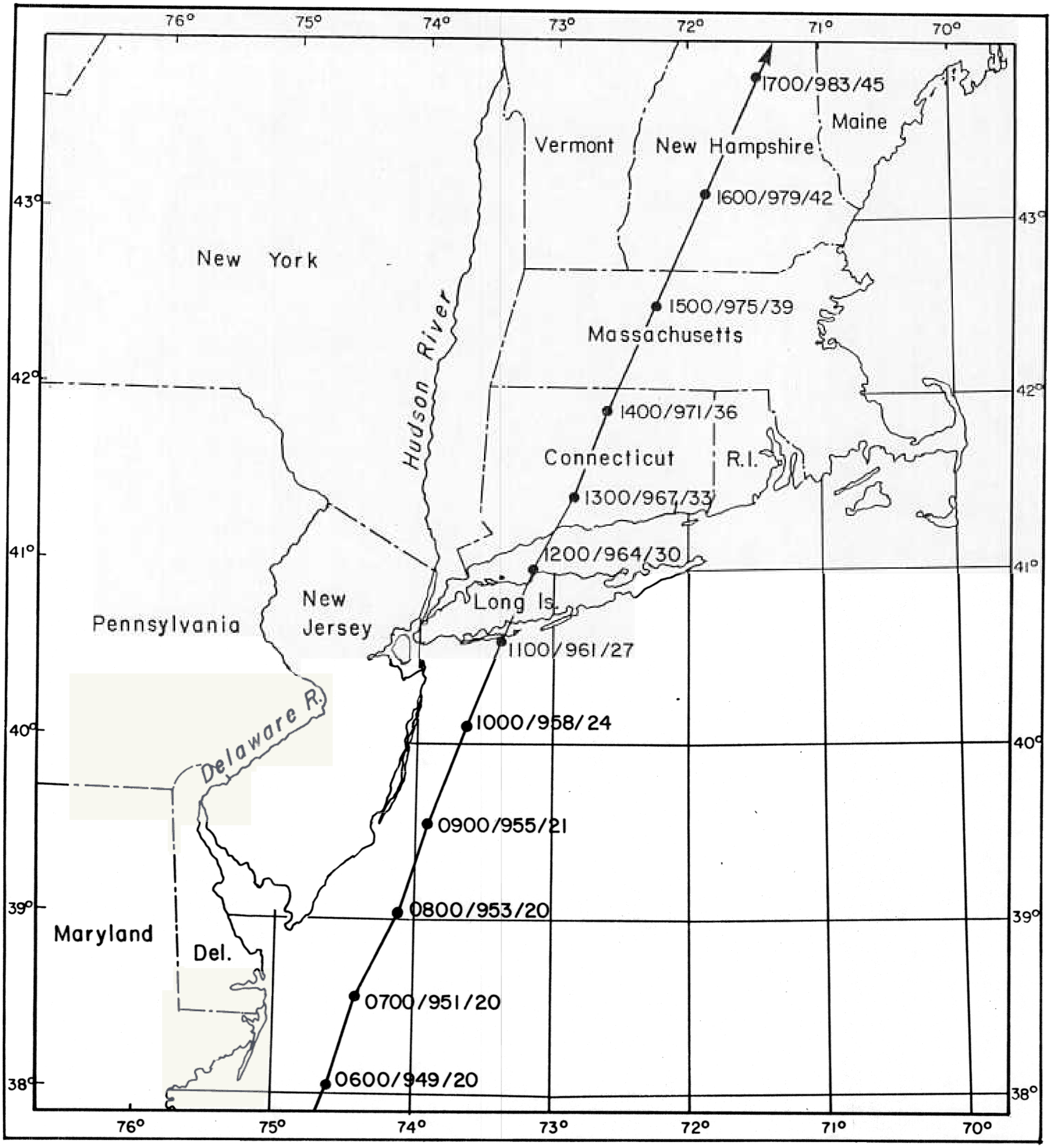


Figure 3. Track of Hurricane Gloria abeam of Delaware and New Jersey into New Hampshire. Hourly locations are indicated with a dot. Legend example: 0700/960/25--0700 EST/960 mb central sea-level pressure/25 statute miles radius of maximum winds.

The hourly positions over the Atlantic Ocean were obtained by reanalyzing all land-based radar center fixes and locations of minimum central sea-level pressure as observed by reconnaissance aircraft. In determination of the hourly positions, heavy weight was given to the surface pressure locations. For the portion of the track over or near land, a two-dimensional isobaric analysis was made using all available surface pressure observations (i.e., land stations and ships of opportunity) to obtain the center position. An example, without the observations is shown in Figure 4.

4.2 Intensity and Radius of Maximum Wind (RMW)

The lowest central sea-level pressure values in Hurricane Gloria are shown for selected times in Figure 2. Gloria's lowest pressure of 919 mb occurred on 25 September at 0100 UTC. As Gloria recurved up the east coast, the central pressure rose, reaching 942 mb near Cape Hatteras, NC, and 961 mb at Long Island, NY. Hourly central sea-level pressure values and RMW are shown in Figure 3. Over the Atlantic Ocean, the determination of the minimum surface pressure in the eye and the RMW were determined primarily from aircraft measurements. Over land, the determinations were made from analyses of pressure and wind measurements at surface observing stations. Figure 3 shows that Gloria's central sea-level pressure was increasing, or the hurricane was "filling," as it moved into New England. The filling rates were: from 0600 to 0900 EST, 2 mb h^{-1}; from 0900 to 1300 EST, 3 mb h^{-1}; from 1300 to 1700 EST, 4mb h^{-1}. The RMW remained almost constant from 0600 to 0900 EST and then began a steady increase until 1700 EST, where it was more than double its value at 0600 EST.

5. HYDROLOGY

Hydrographic records from eight tide gages along the Connecticut, New York and upper New Jersey shorelines were obtained during Gloria's passage. Figure 5 shows the locations and names of the gages. Hydrographs recorded at The Battery and New London are shown in Figure 6. The period is from 0400 EST 26 September to 0400 EST 28 September. The dominant regular feature is the semi-diurnal tide oscillation. Superimposed on this tide oscillation on 27 September is the storm surge caused by Hurricane Gloria. Storm surge is defined as the observed tide minus the predicted astronomical tide. Thus, to determine the hydrograph of the storm surge, it is necessary to subtract the astronomical tide. This was done by using predicted hourly and maximum and minimum National Ocean Survey (NOS) tide values and subtracting them from the actual hydrograph. Figure 7 shows the same hydrographs as Figure 6, with the NOS-predicted tide curves and the storm surge hydrographs. It is useful to note that the peak storm surge occurred near low astronomical tide at both The Battery, New York, and New London, Connecticut. Also, at both locations negative storm surges occurred because of offshore winds after the center of Gloria had passed.

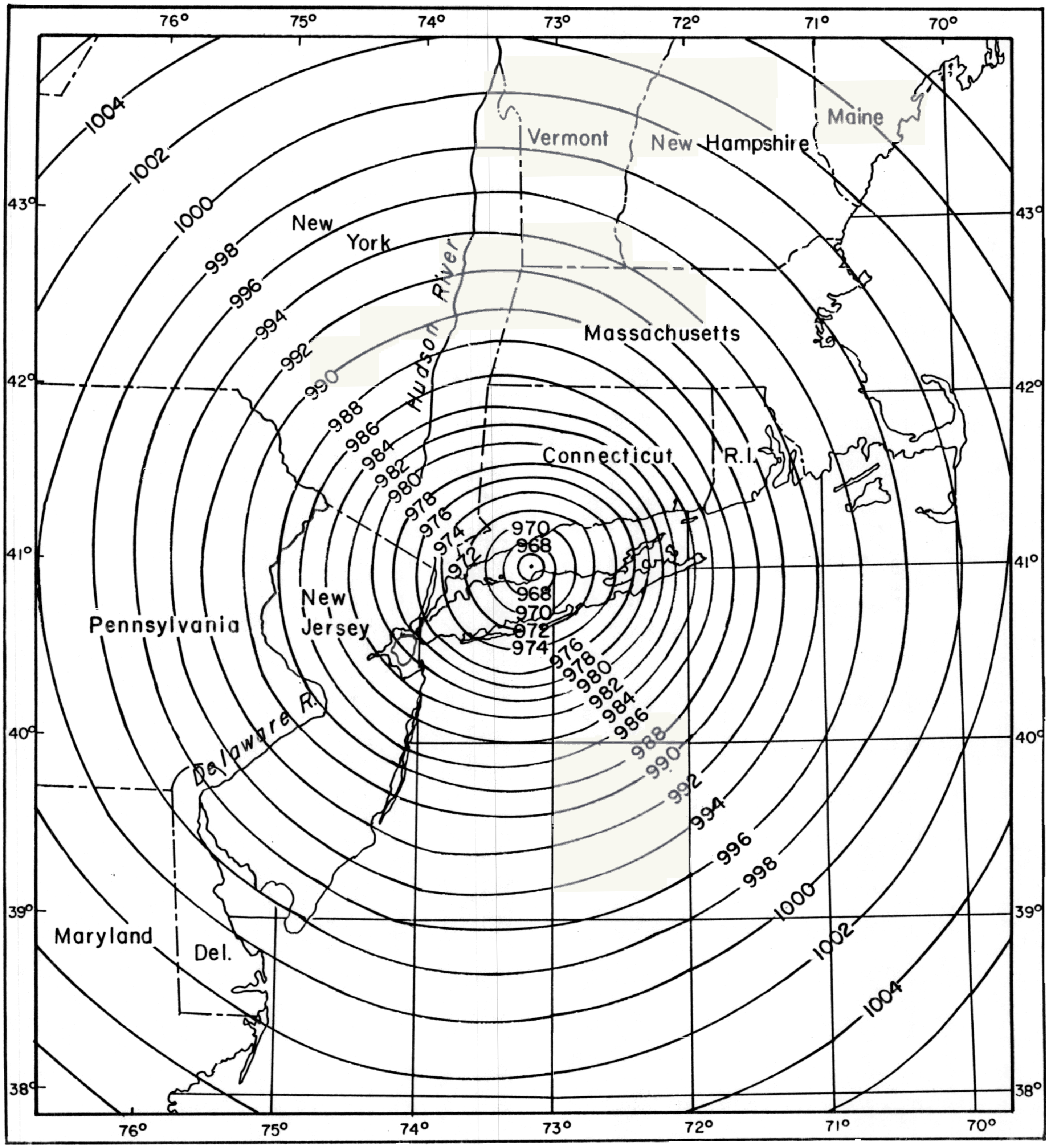


Figure 4. Surface isobaric analysis at 1200 EST 27 September
Contour interval is 2 mb.

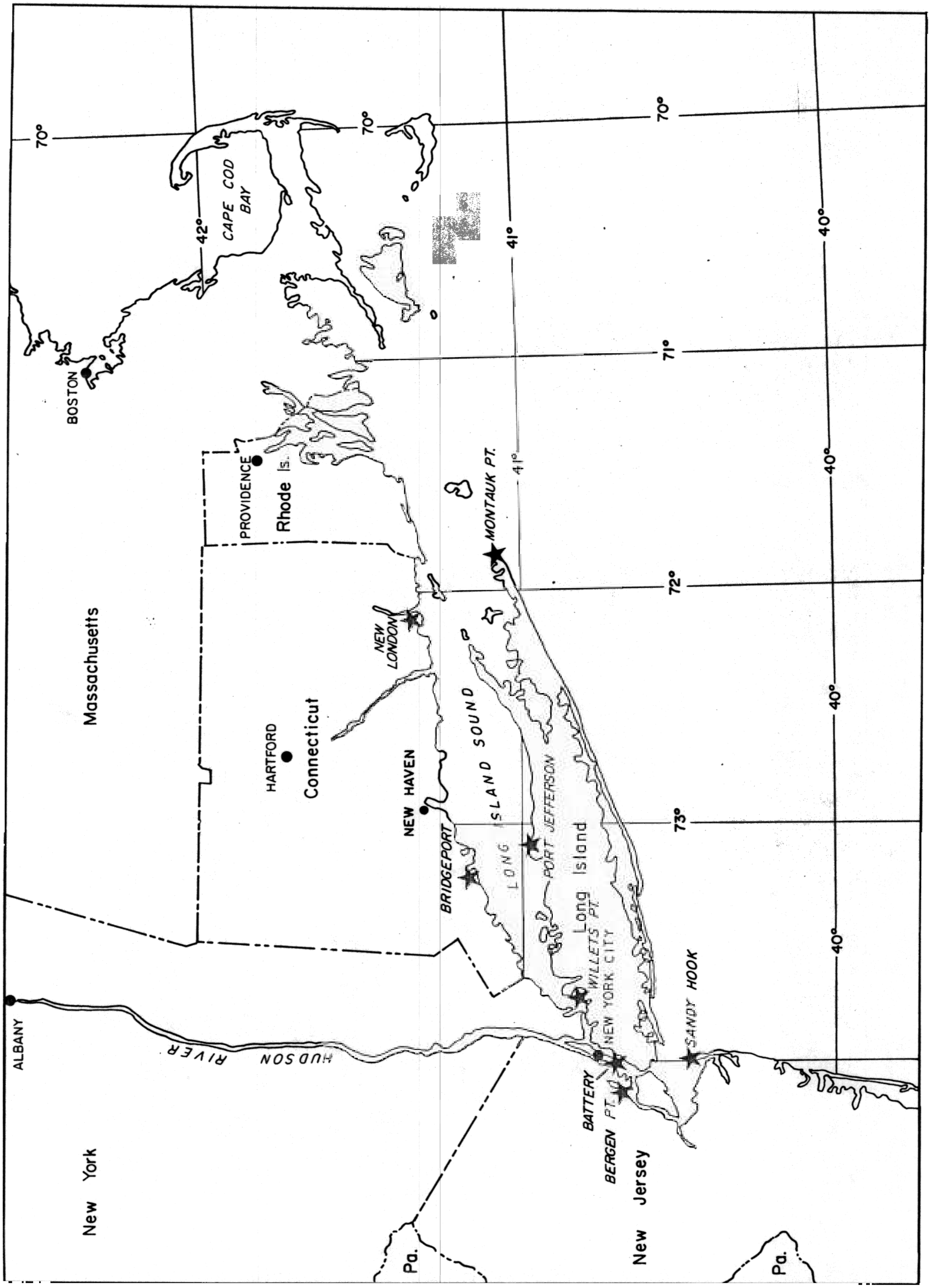
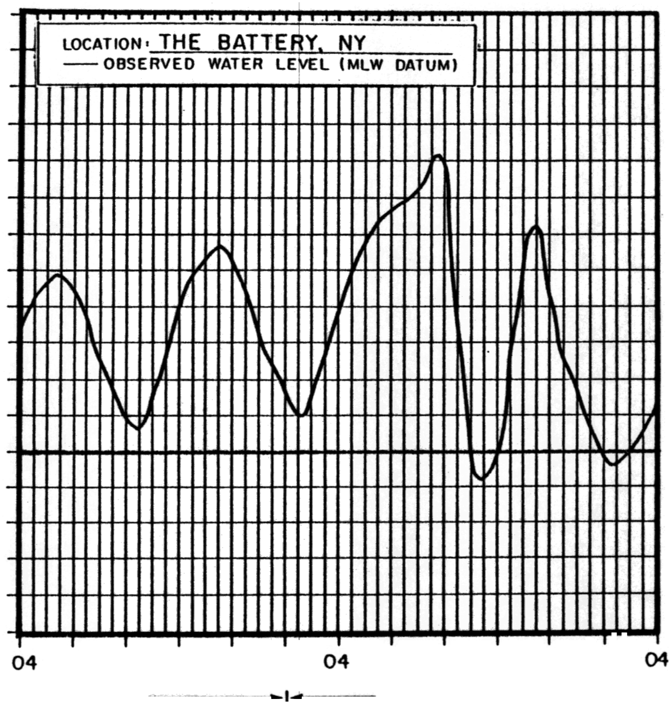
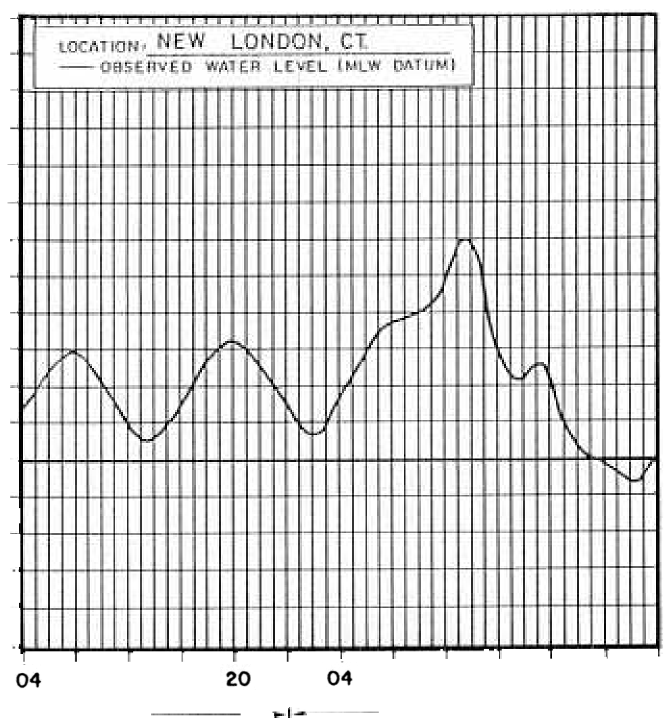


Figure 5. Stars indicate location of tide gages in Connecticut, New York and upper New Jersey.





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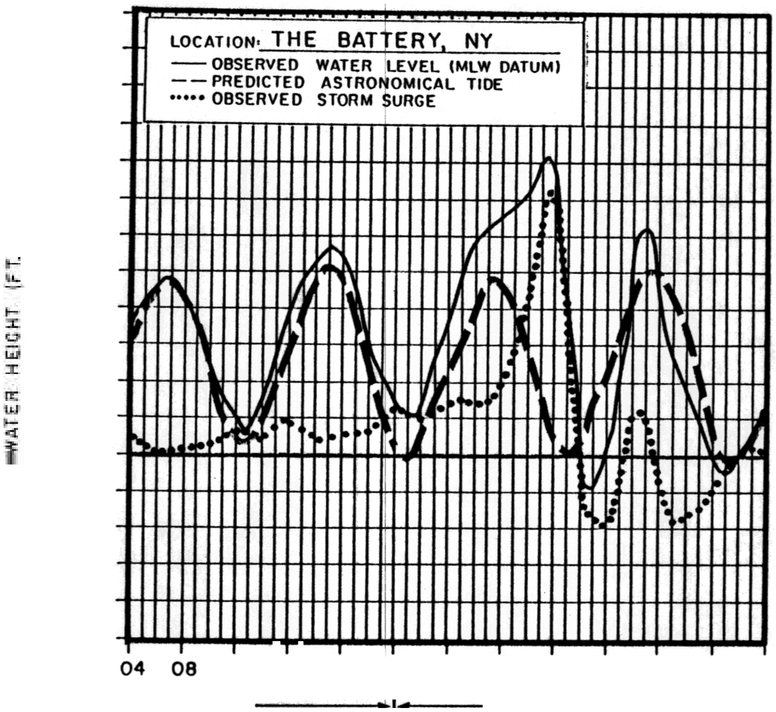

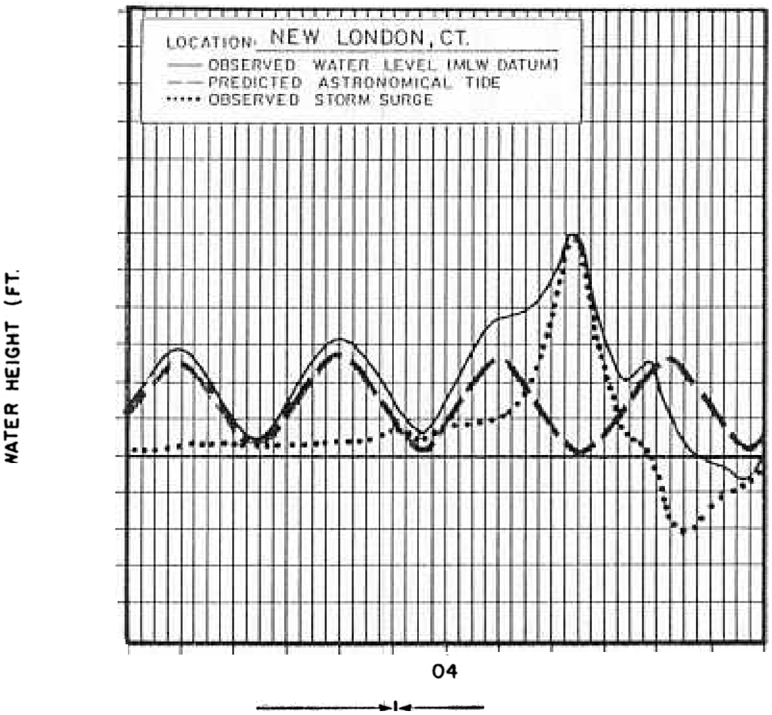

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Using this technique to remove the astronomical tide, we determined the storm surge hydrographs for the remaining six stations. The eight measured storm surge hydrographs are shown in Figures 8a and 8b. Also plotted on Figures 8a and 8b are the SLOSH model-generated storm surge hydrographs for the same location based upon Hurricane Gloria input parameters as shown in Figure 3.

Comparison of results shows that:

1. The peak storm surge value generated by SLOSH is within ± 2 ft of the observed storm surge at all locations.

2. The time of peak surge generated by SLOSH is within ± 1 h of the observed surge at all locations.

3. The SLOSH model reproduces the double peak surge at Willets Point. The SLOSH model shows that the first peak is caused by water being driven from the Atlantic into Lower New York Bay, into Upper New York Bay, into the East River and Willets Point. The second peak is caused by water being driven west in Long Island Sound. Inspection of the time of occurrence of these two peaks will show a surprising result when compared to the hourly track in Figure 3. The first peak occurs near 1300 EST when the center of Gloria is in Connecticut. The second and highest peak occurs approximately four hours later, near 1700 EST, when Gloria's center is located in New Hampshire! Observed surface winds at 1700 EST at stations near Willets Point show values ranging from 15 to 25 mph, blowing from the west. It seems paradoxical that the surge at the west end of Long Island Sound continues to rise as the wind is decreasing intensity and blowing from west to east. The SLOSH model explains this paradox by showing that as Gloria approached Long Island tremendous wind energy was converted into water momentum in front of Gloria's eye in Long Island Sound. This momentum continued toward the west, converged and rose even as the hurricane passed over and moved to the northeast.

4. The model tends to overestimate the negative surges occurring after eye passage at The Battery, Sandy Hook and Bergen Point.

A useful product of the SLOSH model is a two-dimensional envelope of high water (EOHW). The EOHW represents the peak value of storm surge that was computed for each SLOSH grid square. Note that the EOHW is independent of time. Figure 9 shows the analyzed EOHW for Hurricane Gloria in the Long Island Sound basin. Each labeled contour represents storm surge height. Spot values near shorelines and up rivers are also indicated. Storm surge values of less than or equal to 2 ft were not analyzed for the Atlantic Ocean. The track of Gloria is indicated by a dashed line. Features of note are:

1. The storm surge heights along most of the outer coast of Western Long Island were 7-8 ft.

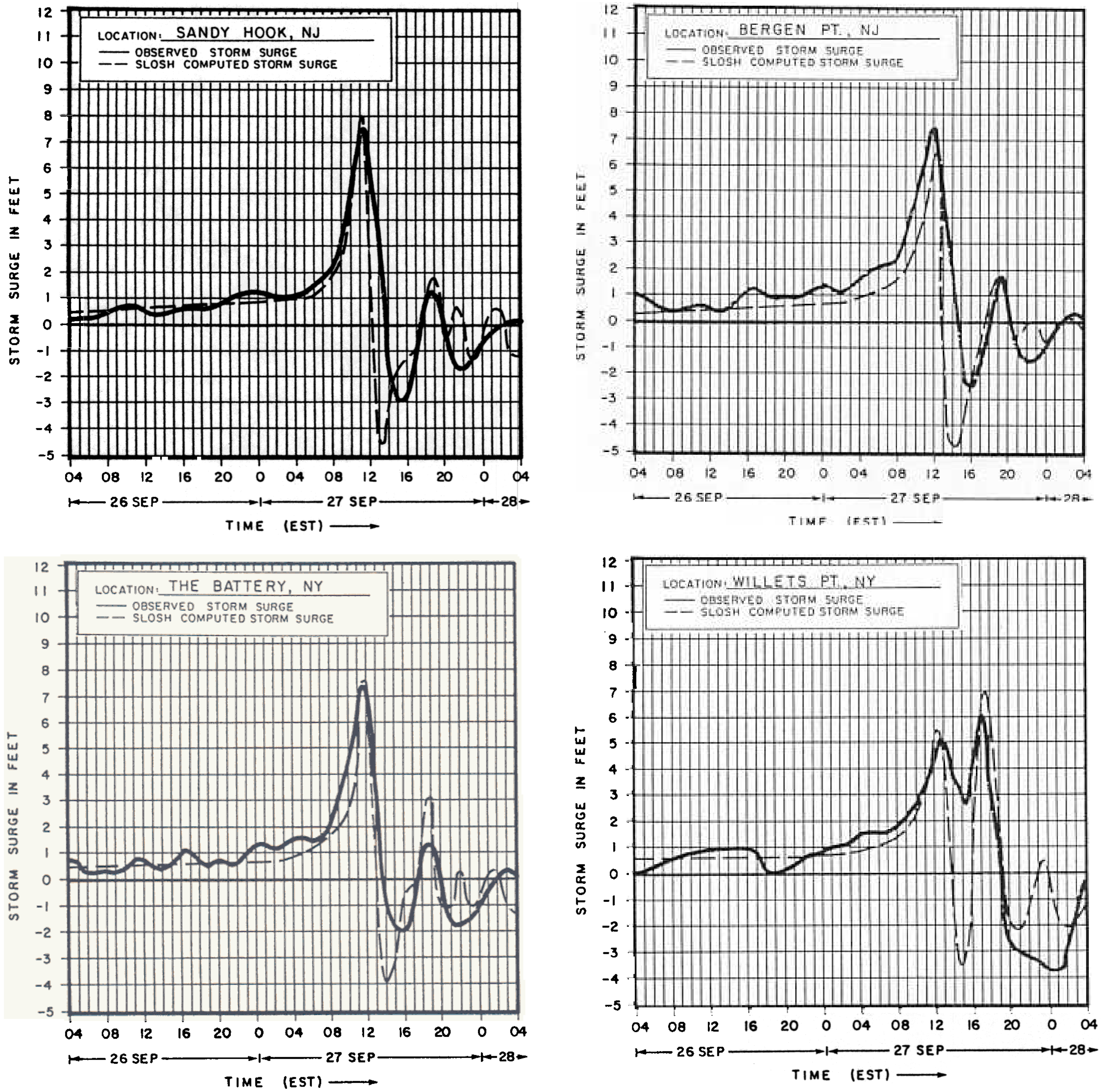
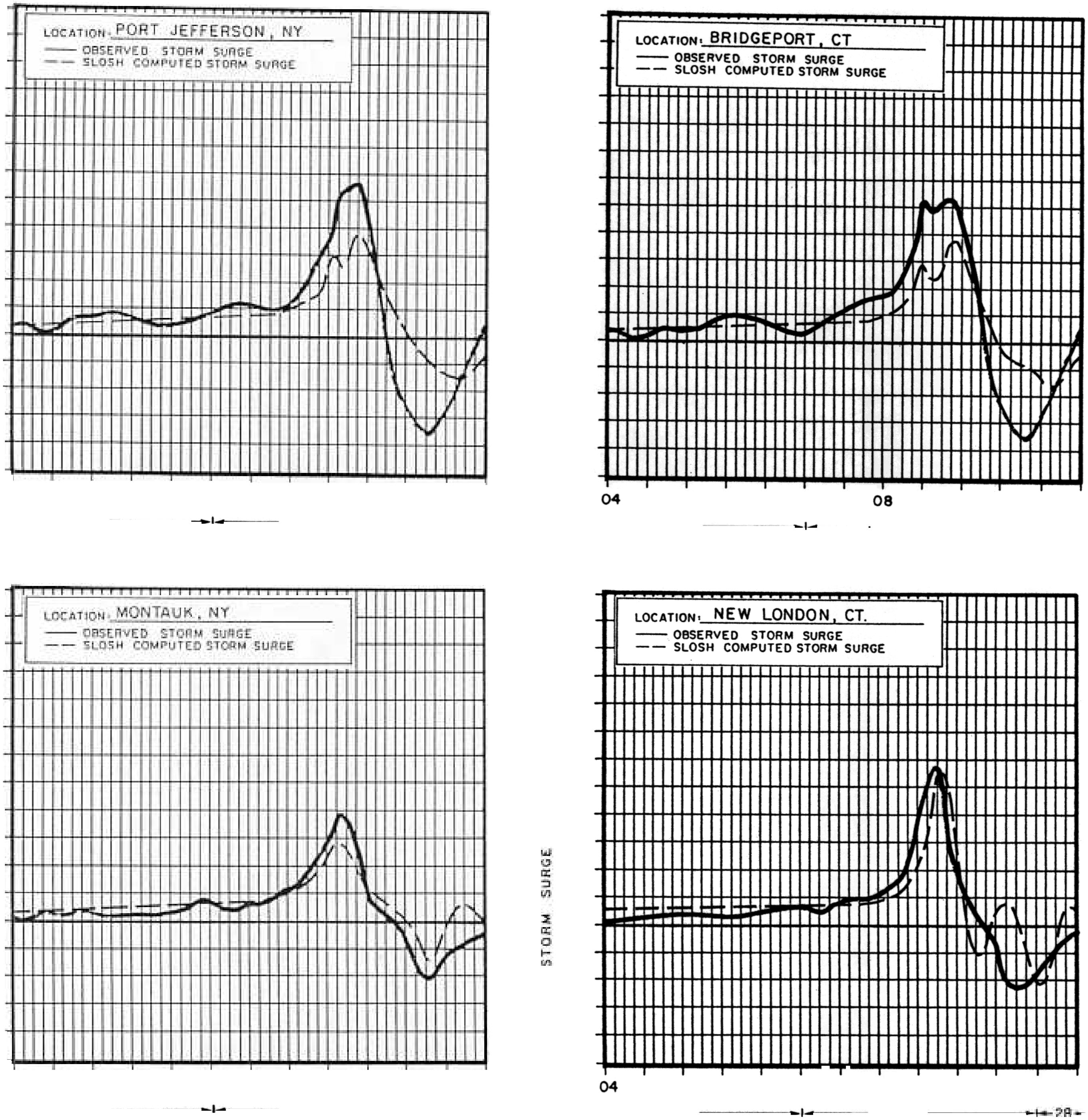


Figure 8a. Comparison of observed versus SLOSH model computed storm surge hydrographs for four locations in Figure 5.


LOCATION: PORT JEFFERSON, NY
OBSERVED STORM SURGE
SLOSH COMPUTED STORM SURGE
LOCATION: BRIDGEPORT, CT
OBSERVED STORM SURGE
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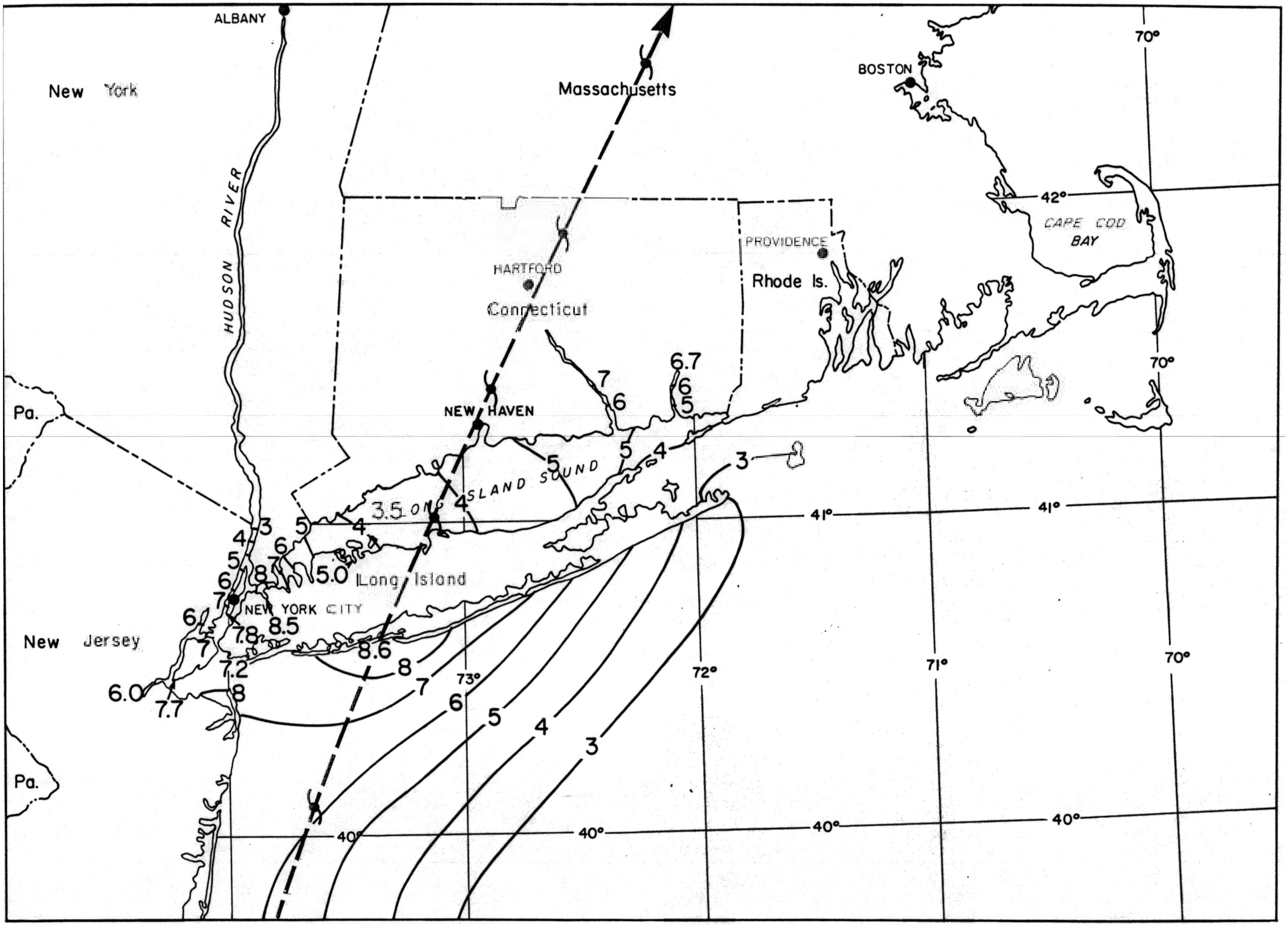
ALBANY
New York
Massachusetts
BOSTON
HUDSON RIVER
CAPE COD BAY
PROVIDENCE
Rhode Is.
HARTFORD
Connecticut
NEW HAVEN
Pa.
LONG ISLAND SOUND
Long Island
NEW YORK CITY
New Jersey
Pa.
42°
41°
40°
73°
72°
71°
70°

2. The maximum surge of approximately 8.6 ft occurred on Long Island near the point of eye landfall.

3. Moving from east to west in Long Island Sound the storm surge heights first increased from about 3 to 5.5 ft, then decreased 5.5 to 3.5 ft, then increased again to 8 ft near Willets Point.

4. The storm surge was not localized at the coastline, but extended well out on the continental shelf. For example, Figure 9 indicates a 8.6 ft storm surge near the western end of Fire Island, New York, but, 15 miles off shore, the storm surge was still 6 ft.

6. CONCLUSIONS

The Long Island Sound SLOSH model, using Hurricane Gloria input data, produced acceptable peak storm surge results when compared with the observed data. Analysis of the observed Gloria hydrographic data also shows the importance of phasing of the peak storm surge and the astronomical tide. During this event, many locations in the basin fortunately experienced peak storm surge at the time of low astronomical tide. In contrast, a peak storm surge arriving at high astronomical tide represents the "worst case" scenario.

Acknowledgments

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