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COMPARISON OF OBSERVED VERSUS SLOSH MODEL COMPUTED STORM SURGE HYDROGRAPHS ALONG THE DELAWARE AND NEW JERSEY SHORELINES FOR HURRICANE GLORIA, SEPTEMBER 1985

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ABSTRACT

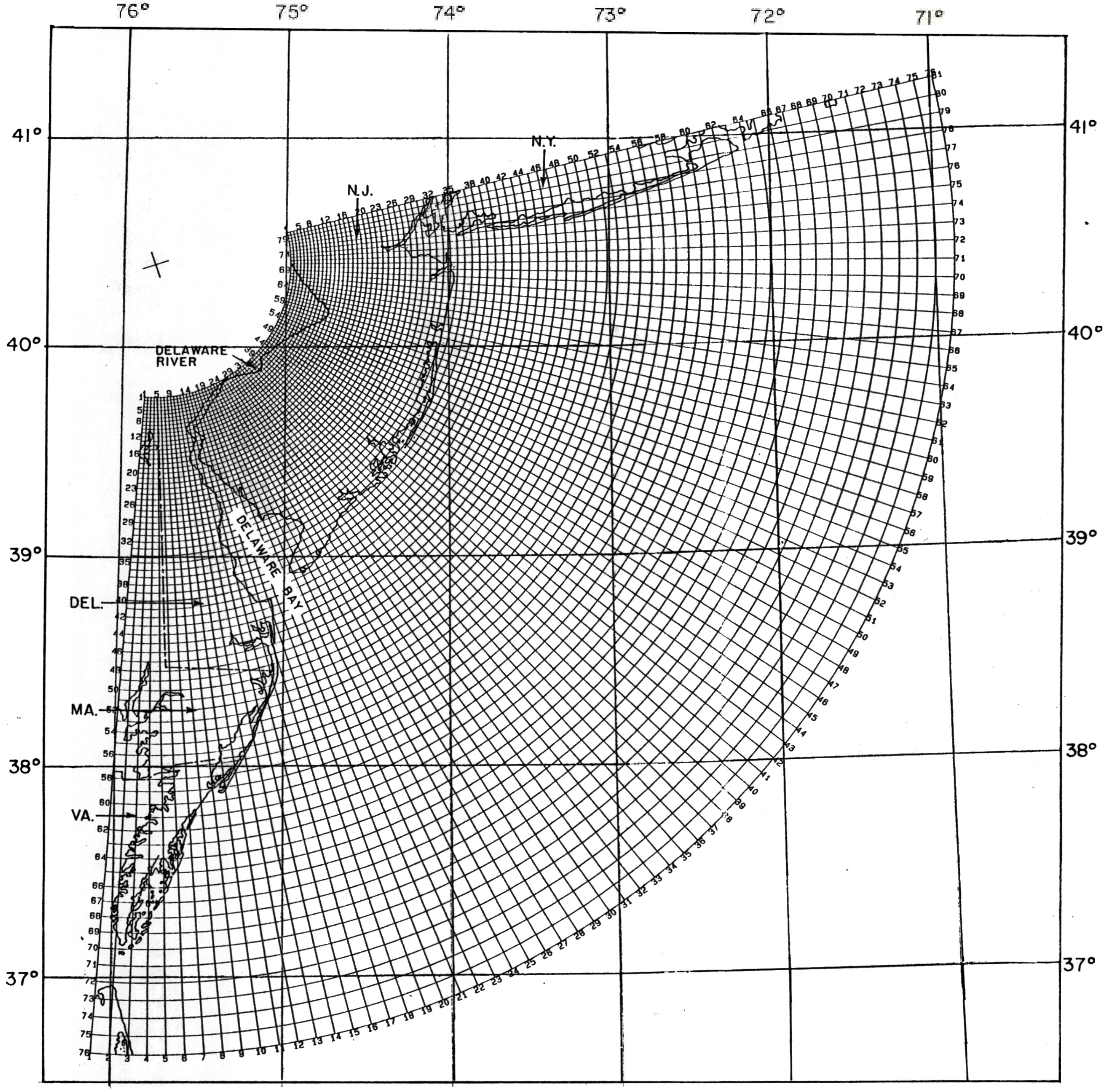
The comparison showed that the peak storm surge generated by SLOSH is ± 1 ft of the observed surge at all locations. Also, the occurence of the peak surge generated by SLOSH is within ± 1 h of the observed at all but two locations. The importance of the phasing of the storm surge and astronomical tide is addressed.

1. INTRODUCTION

The Army Corps of Engineers, Federal Emergency Management Agency (FEMA), and the National Weather Service (NWS) 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, of the historical cases that do exist many of the meteorologic and hydrographic sensors failed during passage of the hurricane. Thus, for most of the U.S. coastline, the climatology of the 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 ≈ 90% of the U.S. Atlantic and Gulf of Mexico flood plains. The basin that covers the flood plains of Delaware and New Jersey has been designated the "Delaware Bay basin."



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A hurricane evacuation study is under way for Delaware and New Jersey. A series of hypothetical hurricanes of varying intensity, direction, and forward speed has been simulated using the SLOSH model in the Delaware Bay 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 Delaware Bay 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 Delaware Bay basin. Thus, the purpose of this paper is a comparison of observed versus SLOSH computed hydrographs in the Delaware Bay basin for Hurricane Gloria.

2. DELAWARE BAY SLOSH BASIN

The Delaware Bay basin grid is shown in Figure 1. The grid is a telescoping polar coordinate system with 76 arcs and 81 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 increment of arc length of the side of a grid "square" is approximately equal to the radial increment of the square.

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 (CPU), 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, so that the effects of the model's boundaries on the dynamics of the storm are diminished and the storm's physics are better emulated.

The grid is tangent to the earth at the basin center, Cape Henlopen, Delaware, at 38°48'14"N and 75°05'50"W. There, the grid increment is 2.8 statute miles. The pole (or origin) of the grid is located at 40°23'40"N and 75°48'20"W.

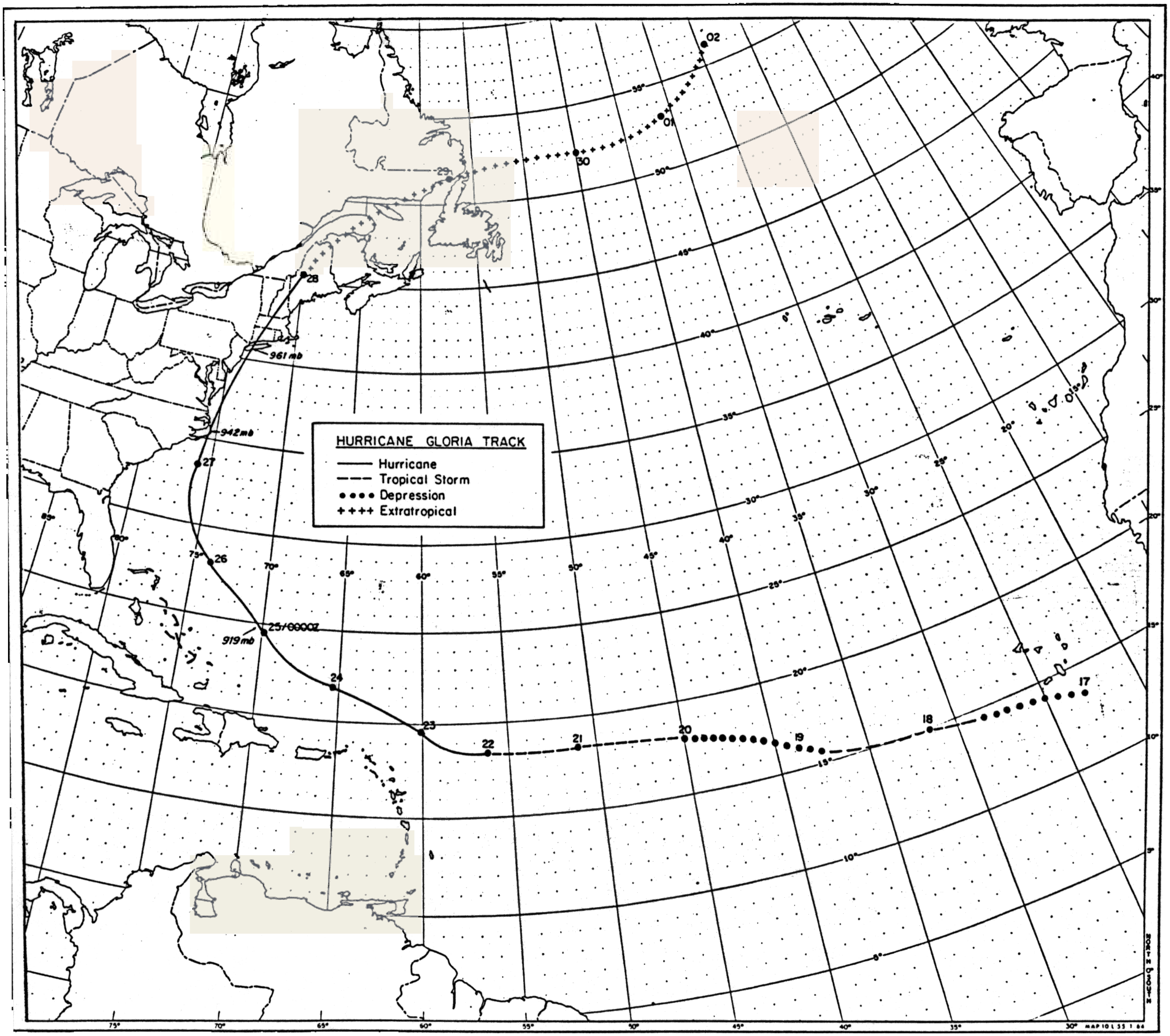

Figure 2. The time period is 17 September to 2 October 1985
Positions are given every 24 h at 0000 GMT.

3. SLOSH MODEL AND HURRICANE INPUT PARAMETERS

The SLOSH model's governing equations are those given by Jelesnianski (1967), except now they include the finite amplitude effect. Coefficients for surface drag, eddy viscosity and bottom slip are the same as those used in the earlier model (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 winds. It is interesting to note that the intensity of a hurricane is generally measured by the speed of the maximum surface winds and the lowest sea-level pressure in the eye. A moderate negative correlation exists between sea-level pressure in the eye and the maximum surface wind speed. The maximum surface winds occur some radial distance out from the center of the eye. This distance is termed the radius of maximum winds (RMW). The SLOSH model requires input of the sea-level pressure in the eye and RMW. With this information, it computes a radial surface wind profile. Thus, directly measured radial surface wind profiles are not needed.

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 GMT[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 GMT. 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 GMT on the same day. The hurricane continued across Long Island into Connecticut and affected several other

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[1] GMT is Greenwich Mean Time. Subtract 5 hours to convert to eastern standard time.

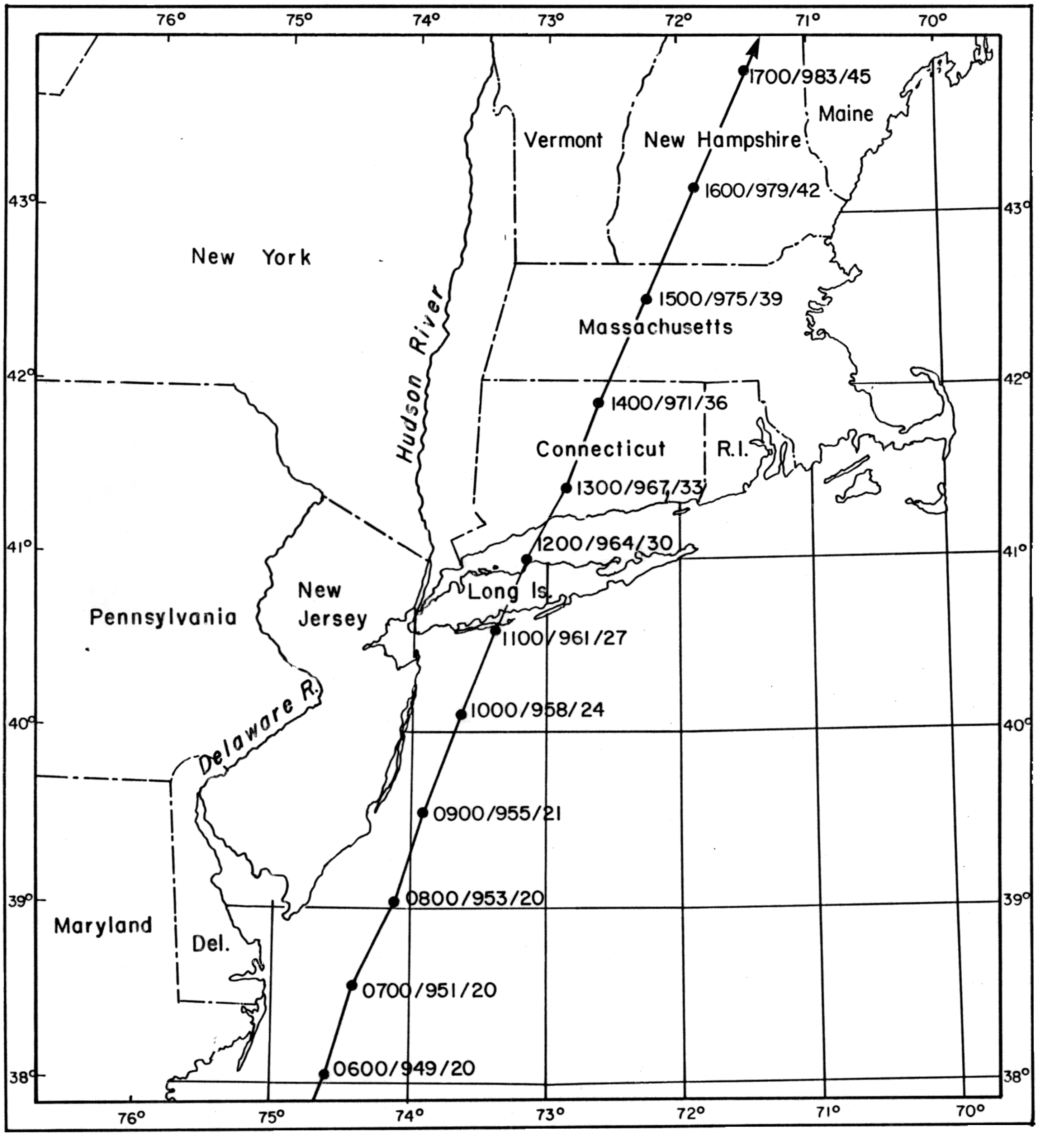


Figure 3. Track of Hurricane Gloria abeam of Delaware and New Jersey. Hourly locations are indicated with a dot. Legend example: 0700/960/25--0700 EST/960 mb central sea-level pressure/25 statute miles radius of maximum winds.

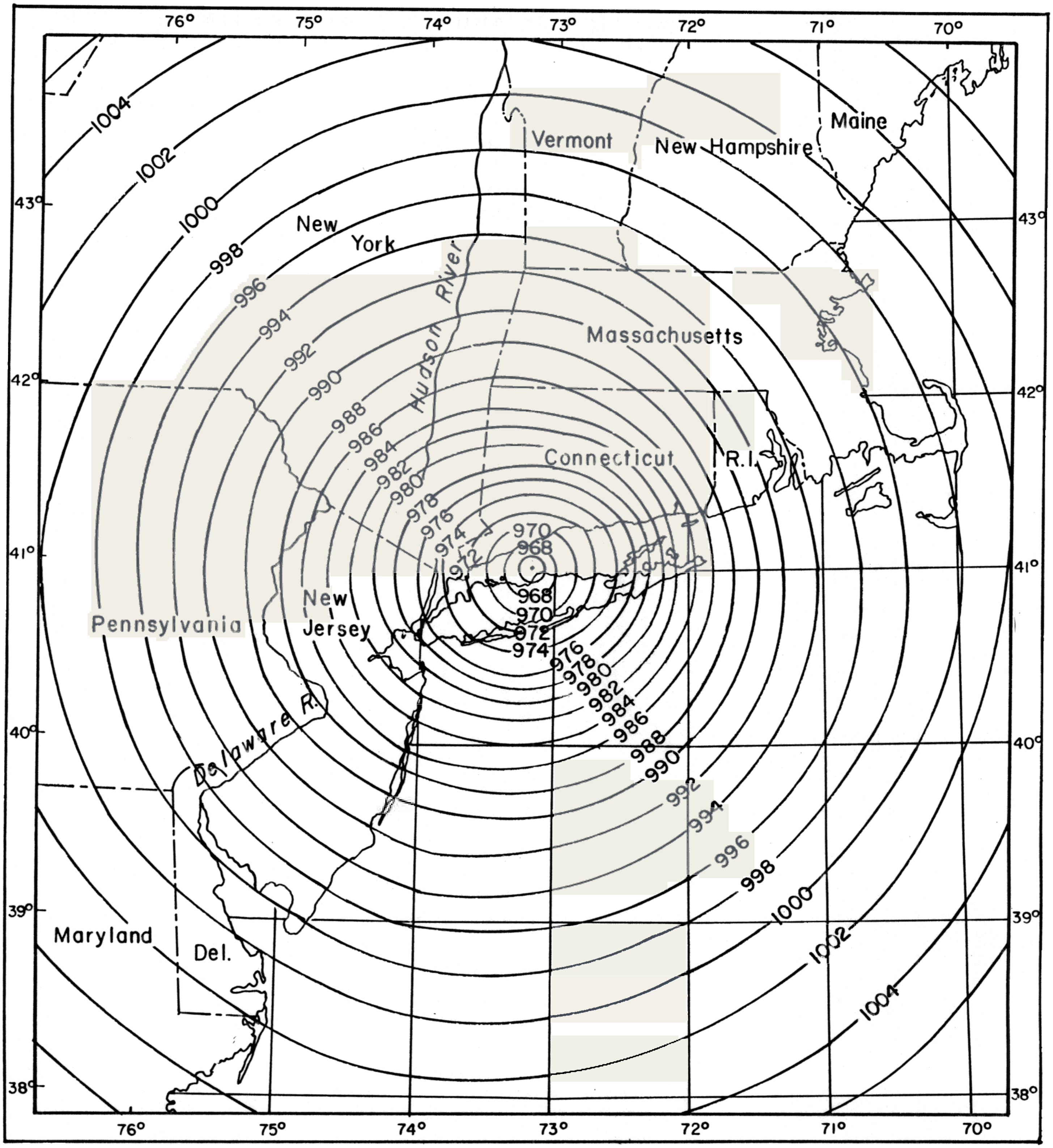


Figure 4. Surface isobaric analysis at 1200 EST 27 September.
Contour interval is 2 mb.

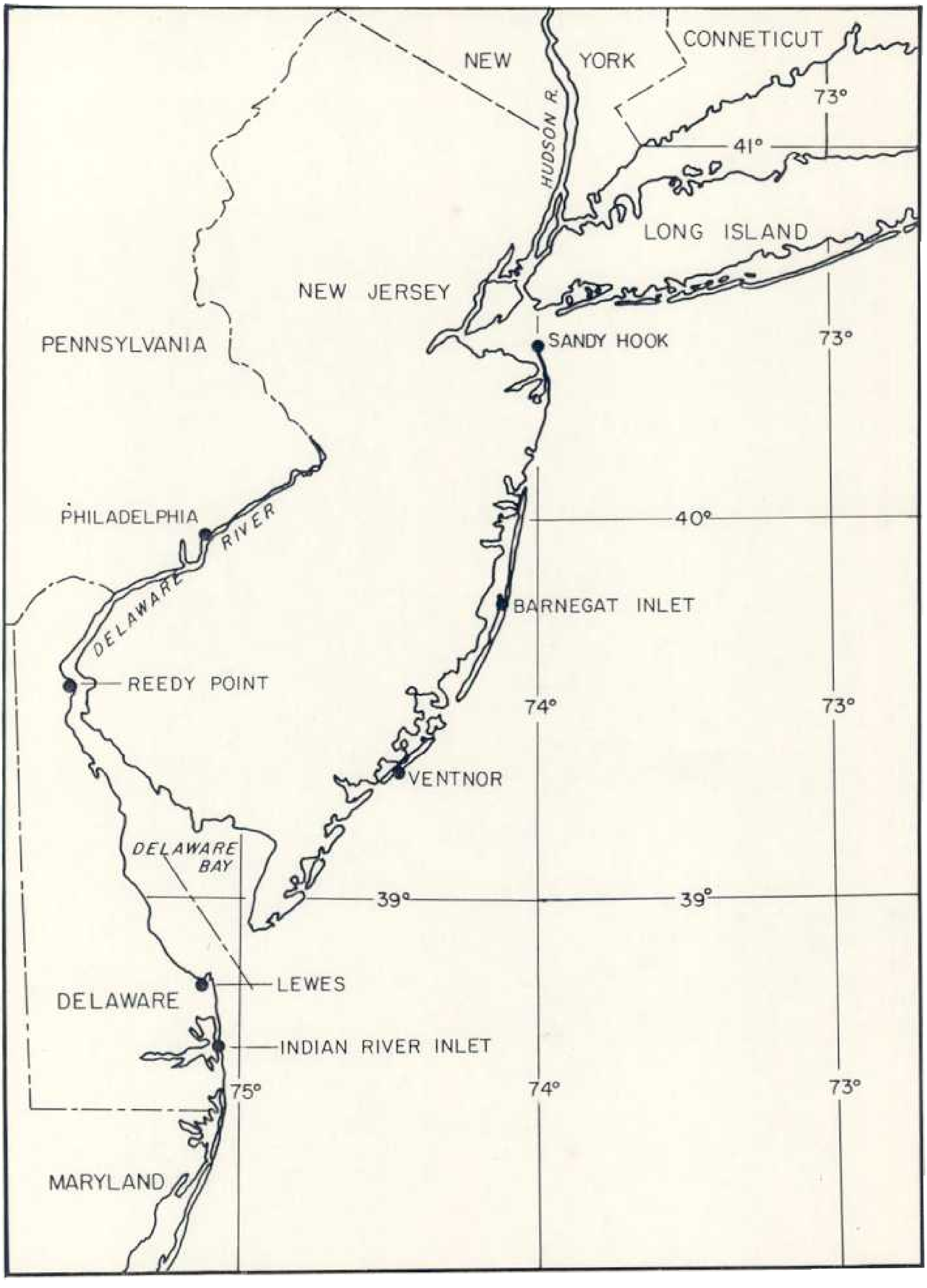


Figure 5. Location of tide gages in Delaware and New Jersey.

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 have an attendant label specifying three values separated by slashes. The first value is eastern standard time (EST). The second value is the sea-level pressure in millibars in the eye. The final value is the radius of maximum winds in statute miles. For example, 1000/958/24 means 1000 EST/958 mb sea-level pressure in the eye/24 statute miles radius of maximum wind.

The hourly positions over the Atlantic Ocean were arrived at by reanalyzing all land-based radar center fixes and locations of minimum sea-level pressure in the eye as observed by reconnaissance aircraft. In determination of the hourly position's, 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 is shown in Figure 4.

4.2 Intensity and Radius of Maximum Wind (RMW)

The lowest sea-level pressure values in the eye of Hurricane Gloria are shown for selected times in Figure 2. Gloria's lowest pressure of 919 mb occurred on 25 September at 0100 GMT. As Gloria recurved up the east coast, the central pressure continued to rise reaching 942 mb near Cape Hatteras, NC, and 961 mb near Long Island, NY. Hourly surface pressure values and the 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 sea-level pressure was constantly 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 seven tide gages along the Delaware and New Jersey shorelines were obtained during Gloria's passage. Figure 5 shows the locations and names of the gages. Two hydrographs recorded at two of the gages are shown in Figure 6. The period is from 0800 EST 26 September to 2400 EST 27 September. The dominant regular feature is the semi-diurnal tide oscillation. Superimposed on this

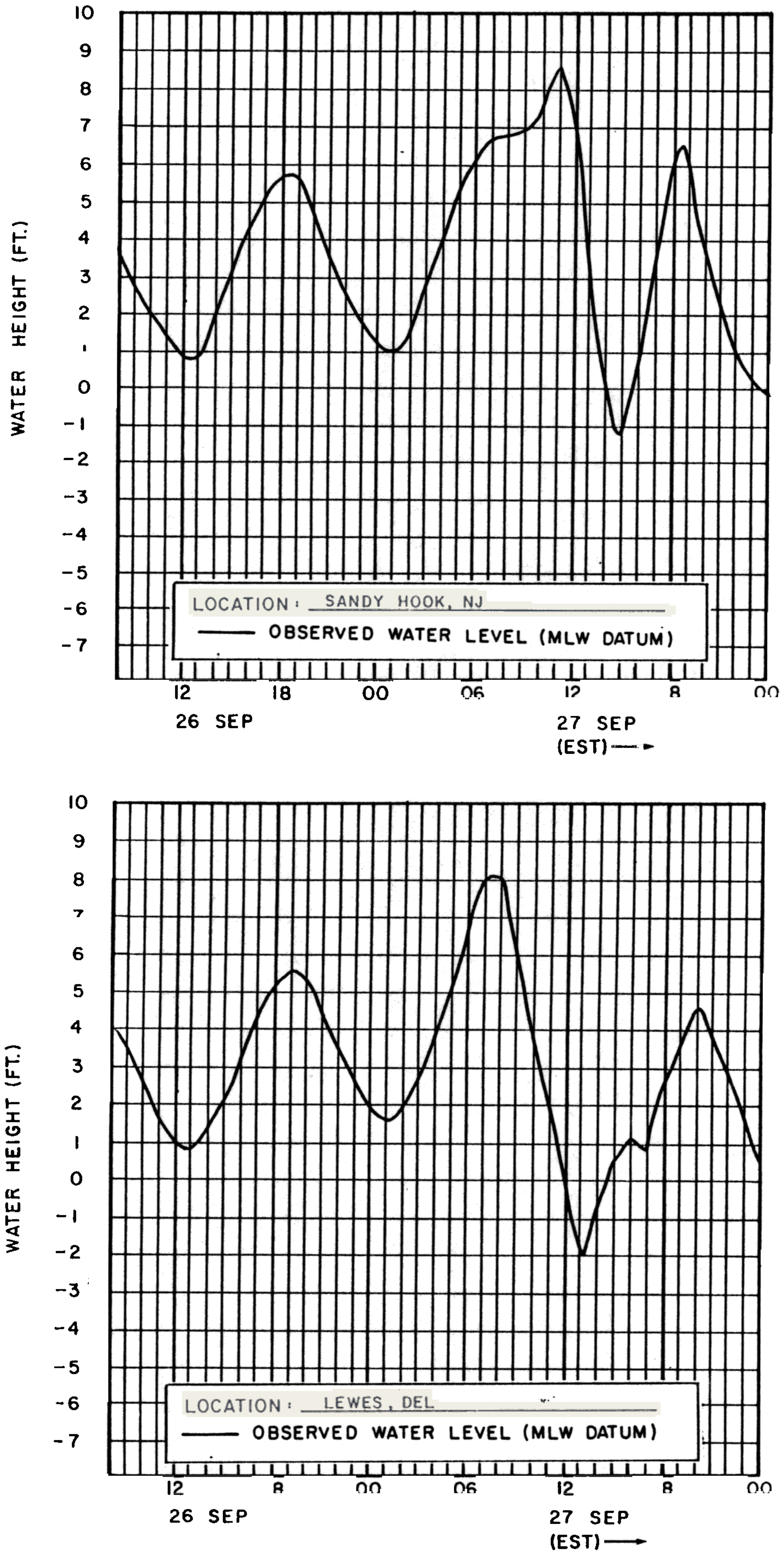
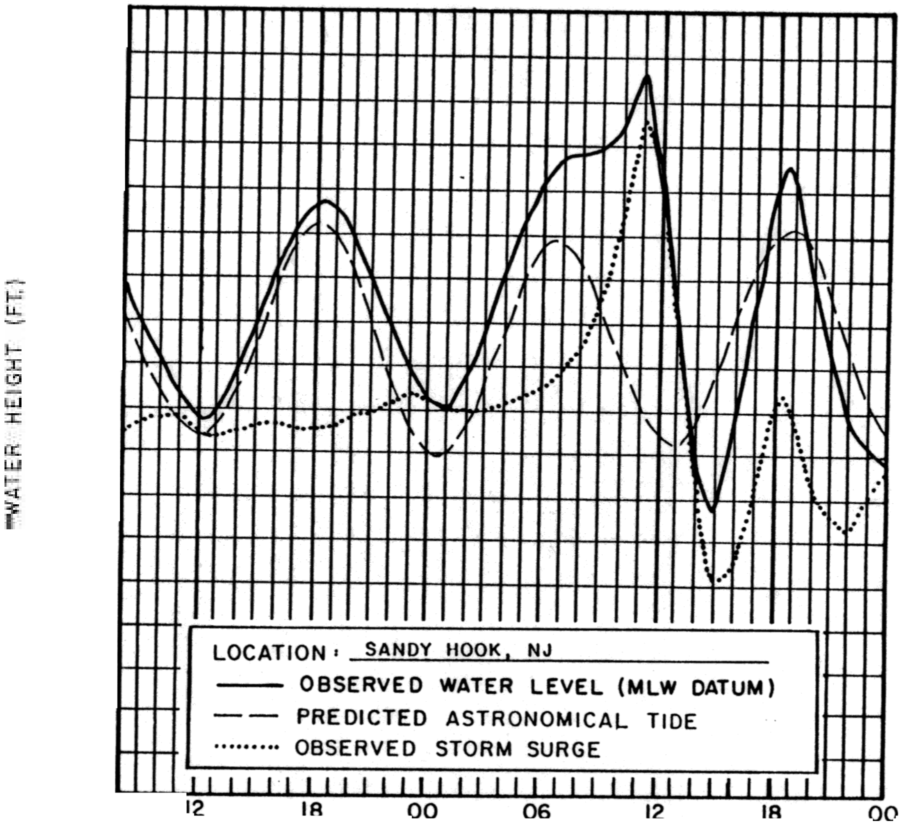


Figure 6. Hydrographs from the Sandy Hook, New Jersey, and Lewes, Delaware, tide gages covering the period before, during, and after Hurricane Gloria's passage.


WATER HEIGHT (FT.)
LOCATION: SANDY HOOK, NJ
OBSERVED WATER LEVEL (MLW DATUM)
PREDICTED ASTRONOMICAL TIDE
OBSERVED STORM SURGE
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12
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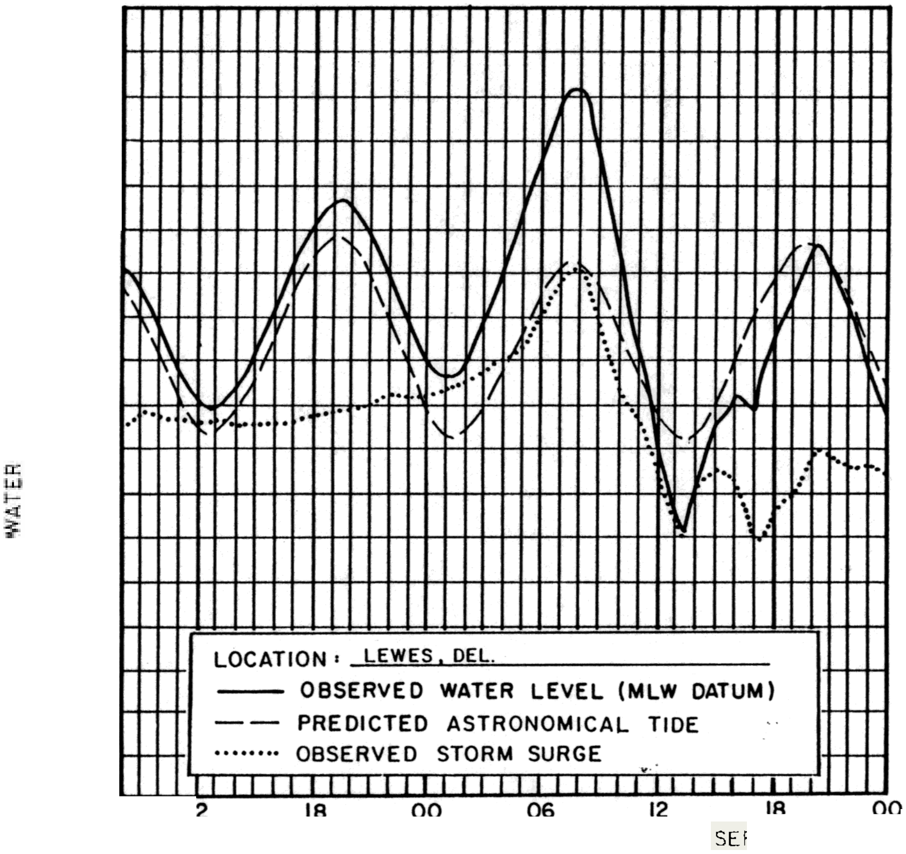
WATER
LOCATION: LEWES, DEL.
OBSERVED WATER LEVEL (MLW DATUM)
PREDICTED ASTRONOMICAL TIDE
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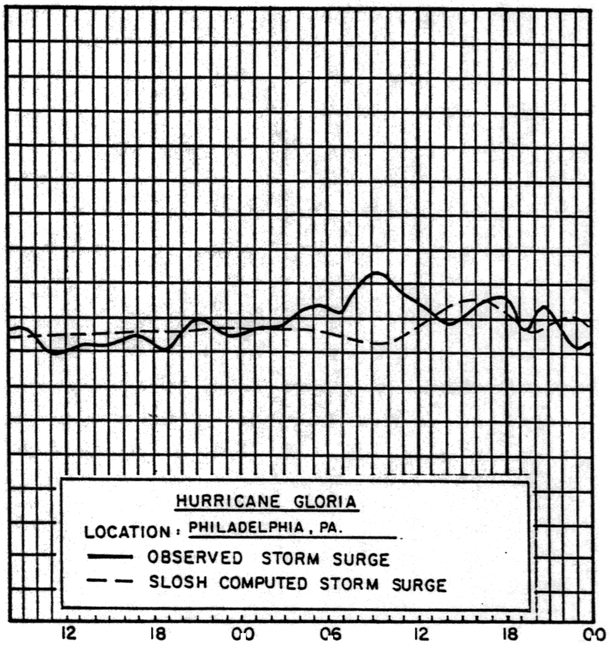

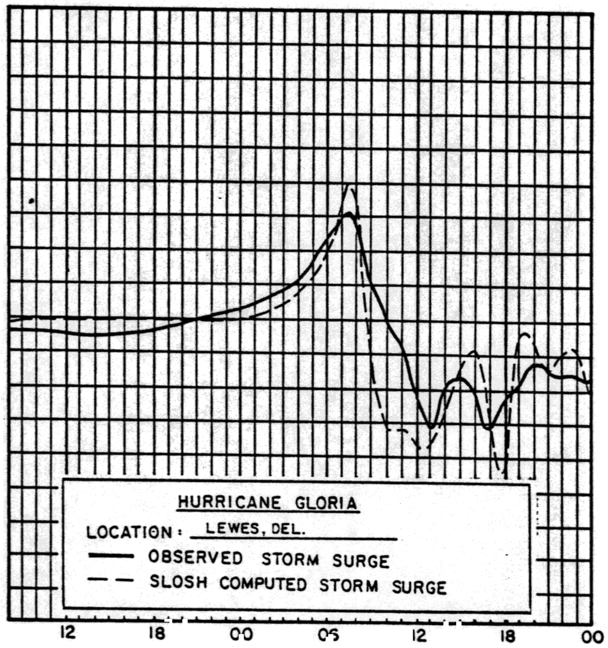

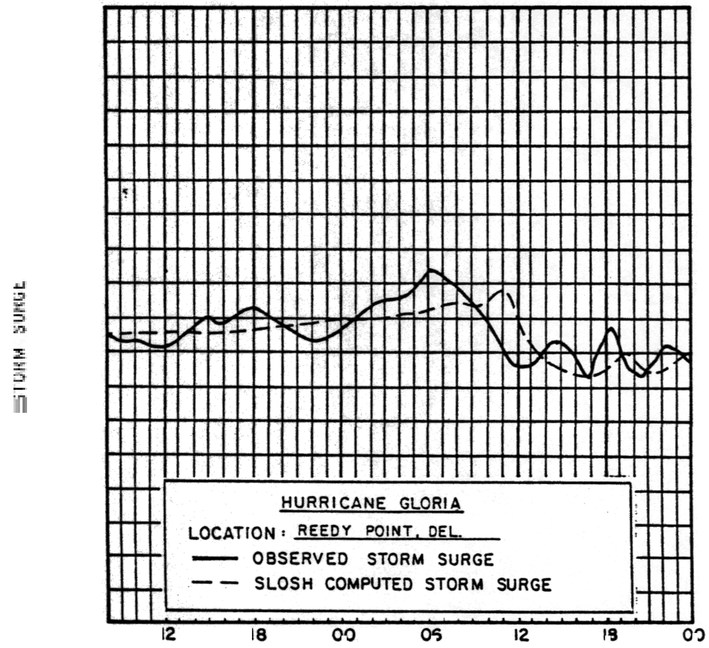

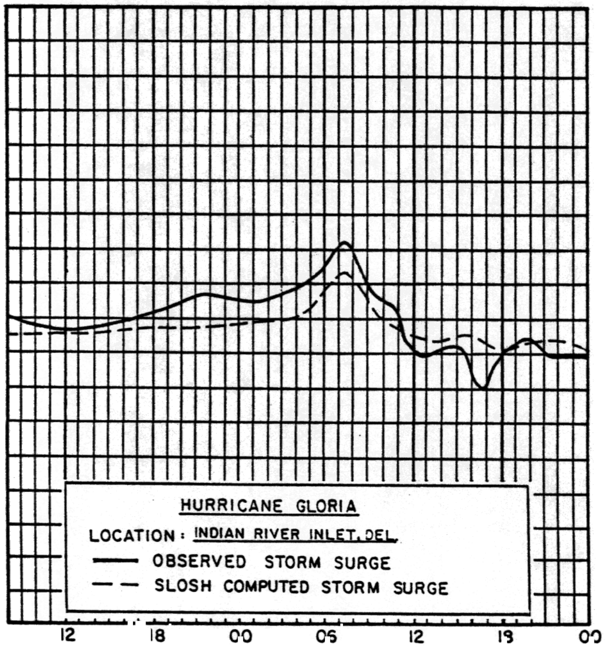

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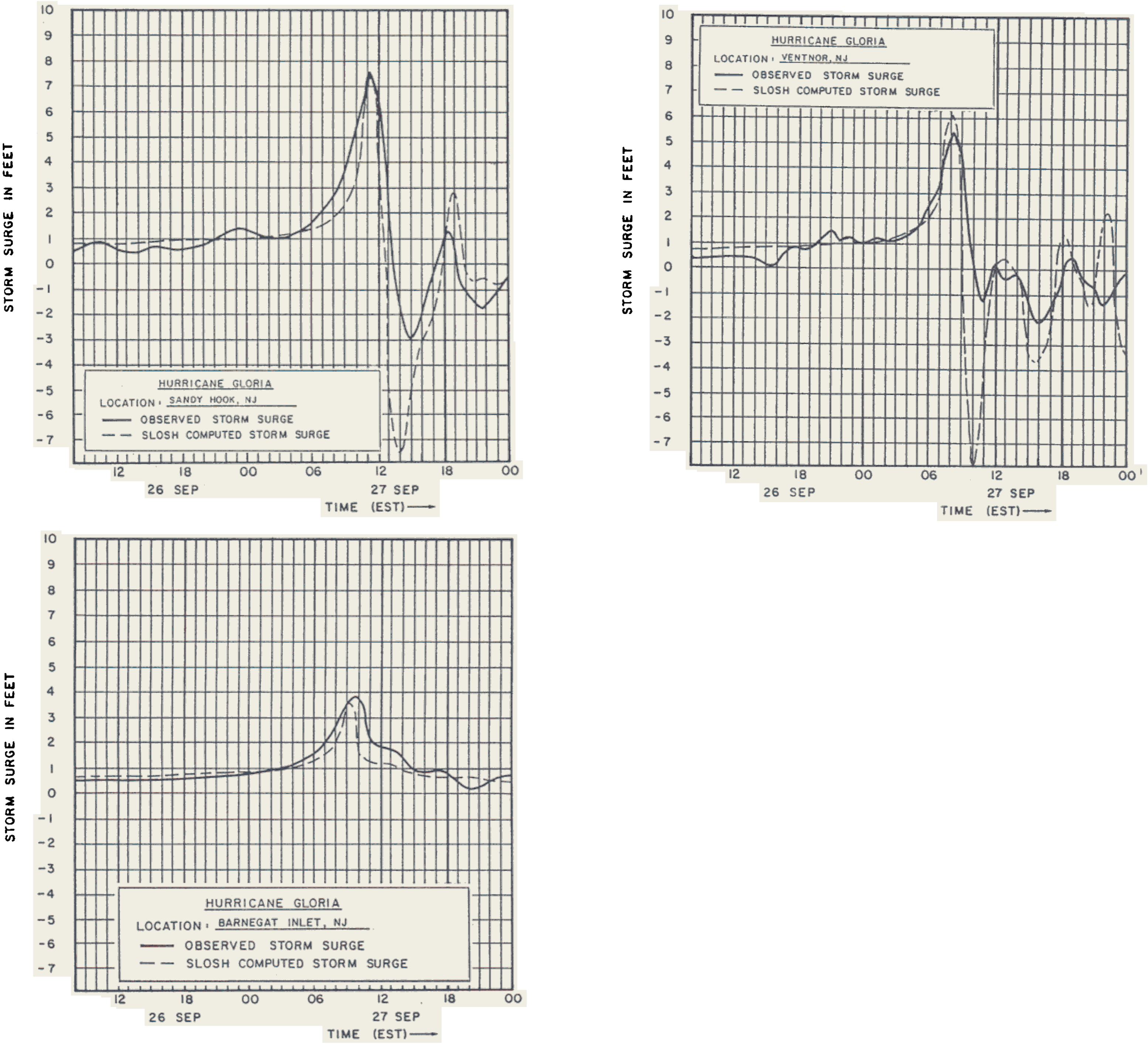

Figure 8b. Comparison of observed versus SLOSH model computed storm surge hydrographs for three locations in Figure 5.

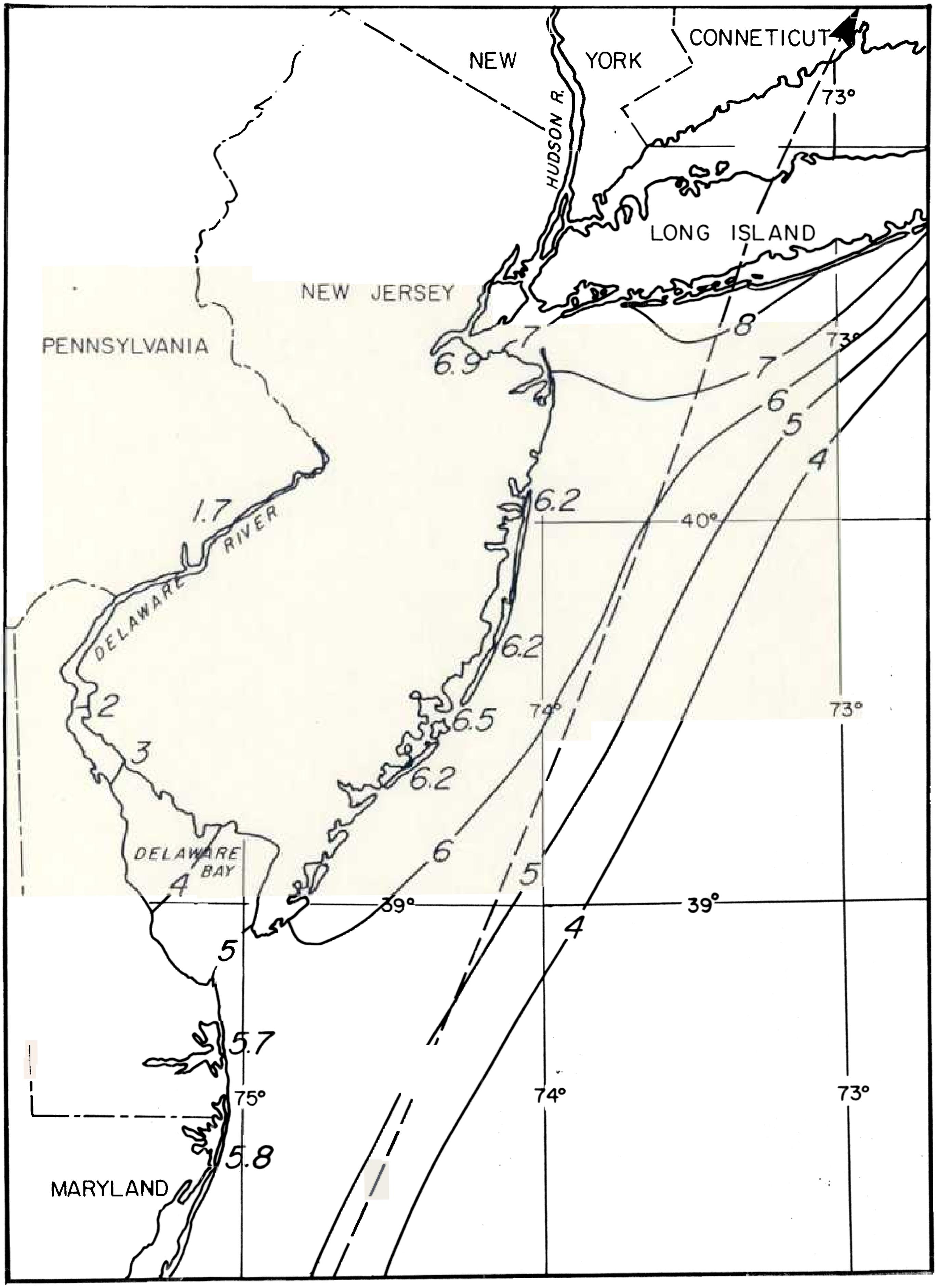

Figure 9. SLOSH model two-dimensional envelope of high water for Hurricane Gloria. Values represent magnitude of storm surge. Contour interval is 1 ft.

tide oscillation on 27 September is the storm surge caused by Hurricane Gloria. 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 Sandy Hook, New Jersey, but occurred almost precisely at high tide at Lewes, Delaware. Also, at both locations negative storm surges occurred because of offshore winds after the center of Gloria had passed.

Using this technique to remove the tide, we determined the storm surge hydrographs for the remaining five stations. The seven 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 ± 1 ft of the observed storm surge at all locations.

2. Except for the tide gages at Reedy Point and Philadelphia, the time of the peak surge generated by SLOSH is within ± 1 h of the observed.

3. At both Reedy Point and Philadelphia, the SLOSH model peak storm surge occurs later than the observed by ≈5 to 6 h, although the amplitude of the surge is < 2.5 ft. Comparison of the observed wind speed and direction from land stations near these sights and the SLOSH model wind speed and direction with time showed good agreement. Thus, the wind stress generating forces for storm surge in the model and those observed are in good agreement. This result suggests that some other hydraulic process may occur in the river system in addition to the astronomical tide and storm surge.

4. The model tends to overestimate the negative surges and resurgences occurring after the eye passage at Sandy Hook, Ventor, and Lewes.

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 occurred in the hydrograph for each SLOSH grid square. Note that the EOHW is independent of time. Figure 9 shows the analyzed EOHW for Hurricane Gloria in the Delaware Bay basin. Each labeled contour represents storm surge height. Spot values near shorelines and up rivers are also indicated. Storm surge values of ≤ 3 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 New Jersey were 6-7 ft.

2. The maximum surge of $\approx$ 8.5 ft occurred on Long Island near the point of eye landfall.

3. The storm surge heights decreased from about 5 ft at the entrance to Delaware Bay to about 2 ft at the Delaware River.

4. The storm surge was not localized at the coastline, but extended well out on the continental shelf. For example, Figure 9 indicates a 6.2 ft storm surge at Atlantic City, New Jersey, but, 12 miles off shore, the storm surge was still 6 ft.

6. CONCLUSIONS

The Delaware Bay 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 experienced peak storm surge at the time of high astronomical tide, while other locations in the same basin experienced peak storm surge near the time of low astronomical tide. For planning, a peak storm surge arriving at high astronomical tide represents the "worst case" scenario.

Acknowledgments

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