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A STORM SURGE ATLAS FOR THE SABINE LAKE AREA*

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*Encompasses the area from south of Galveston Bay, TX to Atchafalaya Bay, LA.

UNITED STATES
DEPARTMENT OF COMMERCE
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Atmospheric Administration
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National Weather
Service
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NOTICE TO USERS

This atlas was prepared utilizing "SLOSH", the National Weather Service storm-surge model. The SLOSH model, like any other operational model, is subject to prediction errors. Some of these are inherent in the model itself; others are related to initial data uncertainities; still others are tied to our incomplete understanding of air-sea interaction. The model was specifically developed for use in preparing community hurricane evacuation plans and as guidance in operational forecasting. Accordingly, the National Weather Service assumes no responsibility for further uses or interpretations of SLOSH model output without its specific written concurrence. NOTE: These values may differ significantly from those developed by the Federal Emergency Management Agency to delineate flood hazard zones and to assign actuarial rates under the National Flood Insurance Program (NFIP). NFIP values should not be used for hurricane evacuation planning. Storm evacuation values developed from the SLOSH model should not be used for setting insurance rates.

ACRONYMS AND DEFINITIONS

CAT	Category - used to indicate the intensities of hurricanes on the Saffir/Simpson scale. Ranges from 1 to 5 with 1 being a minimal hurricane and 5 being a maximum hurricane.
CPA	Closest Point of Approach of the center or eye of a hurricane to a particular geographical location.
Delta-p or Δp	The difference between ambient and central sea-level pressure in a hurricane.
EOWH	Envelope Of High Water - the SLOSH model-generated grid of highest water for an individual hurricane.
GMT	Greenwich Mean Time - also called Z or Zulu.
LST	Local Standard Time - ranges from 0000 to 2400 hours. The Sabine Lake basin is on 90th meridian time, which is GMT - 6 hours.
Marigram	A continuous plot of water height versus time.
mb	Millibar - a measure of pressure that can be converted directly to inches of mercury.
MEOW	Maximum Envelope Of Water - (1) the SLOSH model-computed highest water that occurs over a region generated by a series of hurricanes of given intensity and direction, or (2) a composite of the highest water over a region for a series of hurricanes of given intensity and direction.
Miles	All references are to statute miles unless so stated.
MSL	Mean Sea Level - the mean location of sea level relative to some datum obtained by averaging the hourly tide values over a period of time.
NGVD	National Geodetic Vertical Datum of 1929. In 1929 the land and sea, in the United States, were "tied" together and mean sea level (MSL) was established. Thus, in 1929 NGVD and MSL were the same. However, mean sea level changes in time. This difference is incorporated in initial datums that are supplied before a SLOSH model run is made.
RMW	Radius of Maximum Wind - the radial distance from the center or eye of a hurricane to the strongest winds.
SLOSH	Sea, Lake, Overland Surges from Hurricanes - a numerical storm-surge model with inland inundation.
SPLASH	Special Program to List Amplitudes of Surges from Hurricanes - a numerical storm-surge model without inland inundation. Computed high-water values apply at the shoreline only.
Z	Zulu time. Same as GMT.

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INTRODUCTION

Storm surge is the abnormal rise of the sea surface caused by wind pressure forces of a hurricane. Storm surge produces the great bulk damage and most of the deaths from drowning associated with tropical rms that make landfall or that closely approach a coastline (Anthes, 2).

A numerical storm surge model developed by Jelesnianski (1967, 1972) Jelesnianski and Taylor (1973) has been applied to the northwestern st of the Gulf of Mexico. The model, which calculates sea, lake and rland surges from hurricanes, and has the acronym "SLOSH," is a ring of a model of a hurricane coupled to a model for storm surge. wford (1979) discussed some preliminary results using this model in southeast Louisiana region.

The purpose of this atlas is to provide maps of modeled heights of rm surge and extent of flood inundation. The maps summarize surge culations that were made using the SLOSH model, after it was tialized with observed values (depths of water and heights of terrain barriers) in the region centered on Sabine Lake, Texas/Louisiana. model was supplied data describing hurricanes possessing various binations of strength, forward speed and direction of storm motion. ength was modeled by use of the central pressure and storm eye size, five categories of storm intensity, as categorized by Saffir and pson (Simpson and Riehl, 1981). Three speeds and four storm headings e selected as being representative of storm behavior in this region, ed on observations by forecasters at NOAA's National Hurricane ter.

GEOGRAPHY

A. The Grid for the SLOSH Model of Sabine Lake

Figure 1 illustrates the area covered by the grid for the Sabine e SLOSH model. The gridded area is called a "basin"--the "Sabine e Basin." The grid is a telescoping polar coordinate system with arc lengths ($1 \leq I \leq 64$) and 70 radials ($1 \leq J \leq 70$). Unlike a true ar coordinate grid, which would have radial increment (ΔR) that was ariant with radius, this grid uses a ΔR that increases with reasing distance from the grid's pole, so that in each grid of the h the increment of arc length (ΔS) of the side of a grid "square" is roximately equal to the radial increment of the "square," or $\Delta S \approx \Delta R$.

The telescoping grid is a compromise between conflicting needs. What is desired is that a large geographical area, but with small, detailed topography be modeled. In a Cartesian coordinate system, this combination of big area, but spatially-small grid increment, requires that a computational mesh with many grid squares be used. A large mesh requires a computer with a large central processing unit (CPU) as well as more time to perform calculations in the more numerous grid squares. The telescoping grid, by comparison, permits a resolution of these conflicting needs: it has an acceptably small spatial resolution, less than 1 square mile per grid square over land, which is the area of greatest interest. Thus, topographic details, such as dikes and levees 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, Sabine Point, at 29°40'57"N and 93°50'18"W. There, the grid increment is 1.6 statute miles. The pole (or origin) of the grid is located at 30°22'N and 93°40'W.

The telescoping grid has some disadvantages. Primarily, these stem from the distortion that occurs when the basin is remapped (Figure 2) onto a display that has constant-sized increments in the vertical and horizontal, as happens when the basin is printed out by a conventional (computer) line printer. This distortion from remapping produces some difficulties in "reading" the results by the uninitiated. For example, neither latitude nor longitude lines remain uncurved, and "parallels" become non-parallel. However, the projection is conformal. The projection scheme results in each grid square at I = 1, closest to the pole, representing an area of about 0.3 square miles, while at I = 64, at maximum distance from the pole, each grid square contains about 18.5 square miles. The distortions require that aids be provided to "read" and interpret the results. These aids include Figure 3, which displays a map of the basin, with numbers of major highways circled, and Figure 4, which depicts the basin's topography, with contours in feet above mean sea level, and also the intracoastal waterway, which is shown by the dotted line. (Transparent overlays of Figures 3 and 4, for use with the maps in this atlas, are included in the pocket attached to the inside rear cover.)

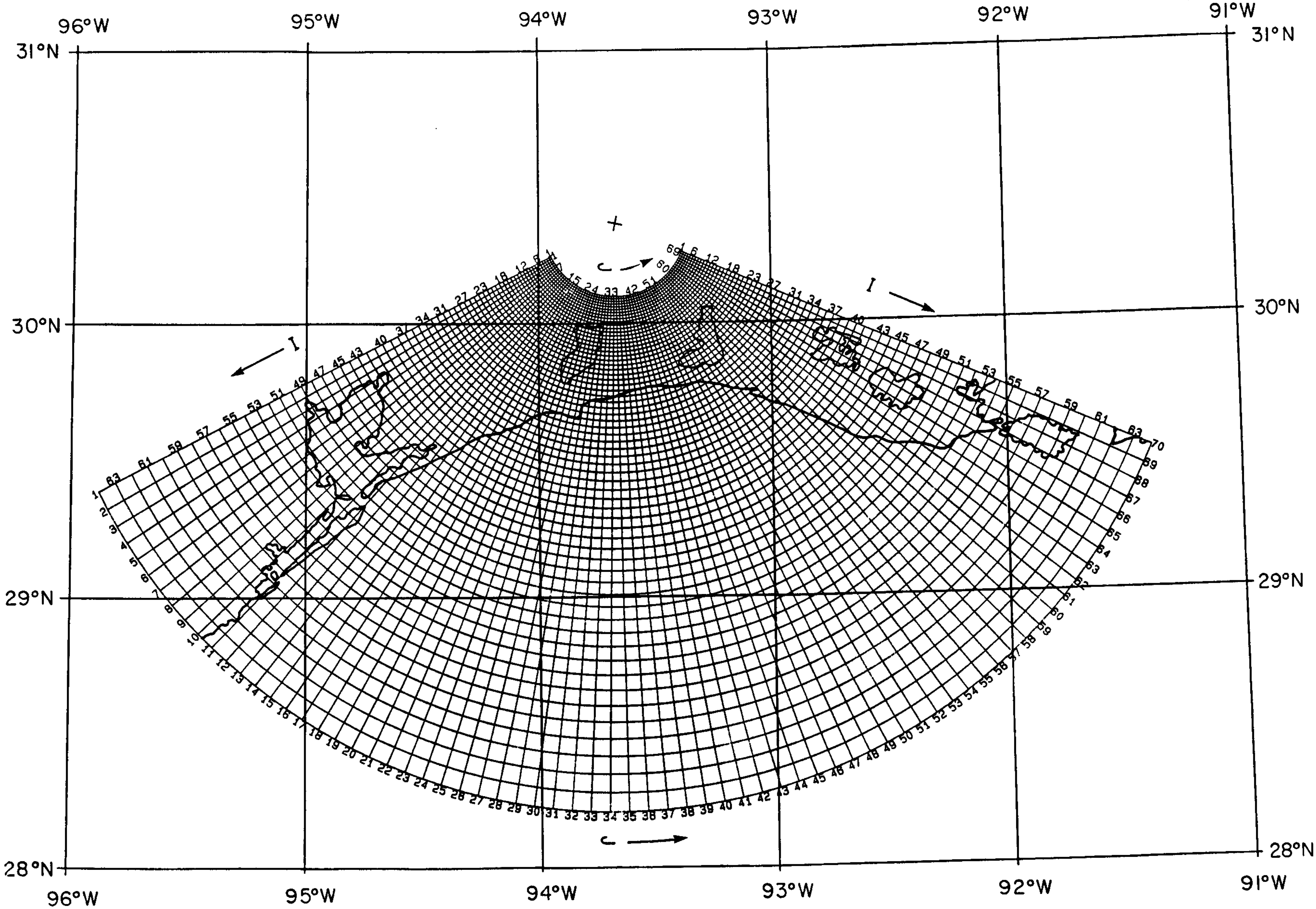


Figure 1. Grid mesh for SLOSH model for Sabine Lake, Texas/Louisiana basin.

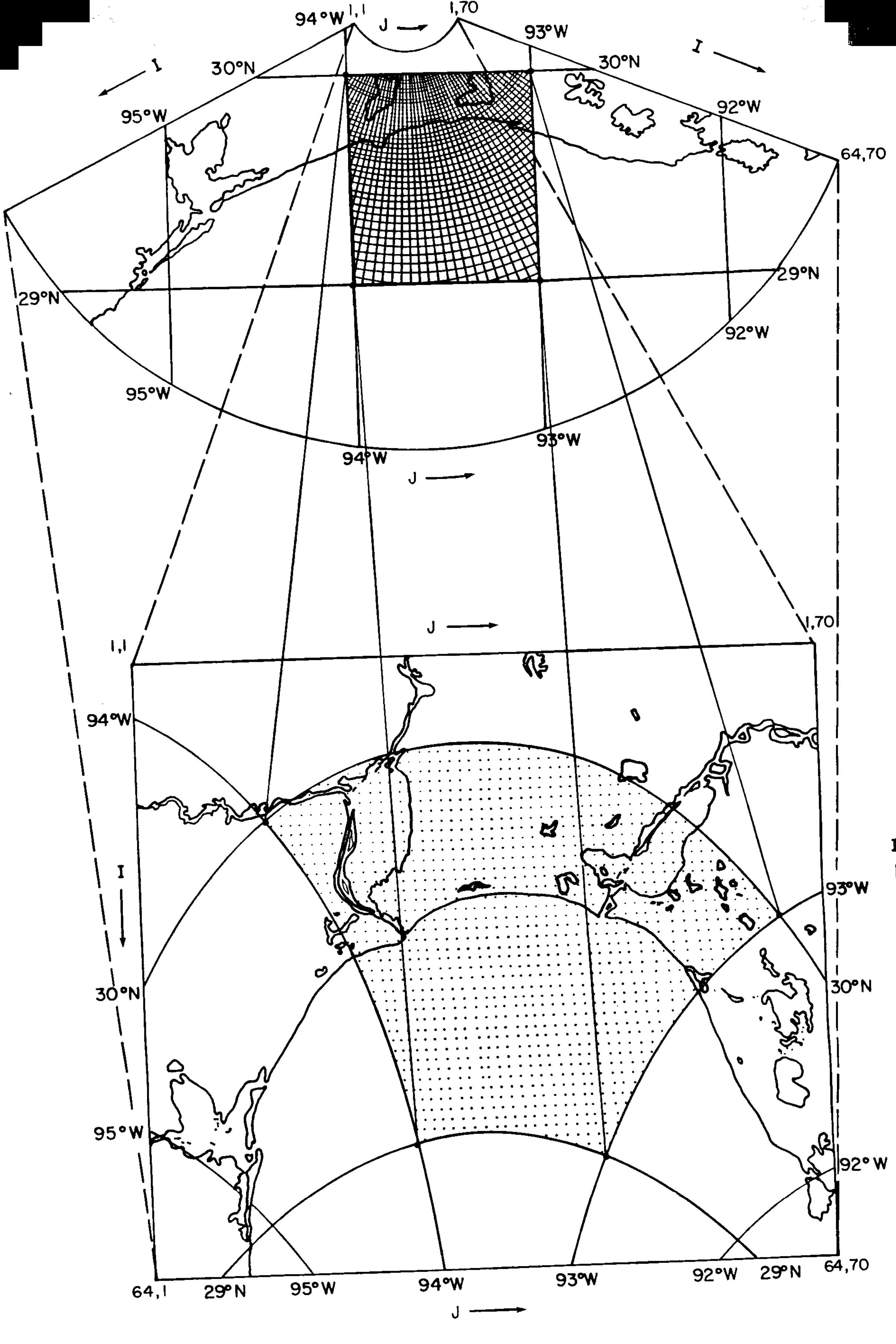


Figure 2. Projection of polar grid (Figure 1) onto an equally-spaced printout grid.

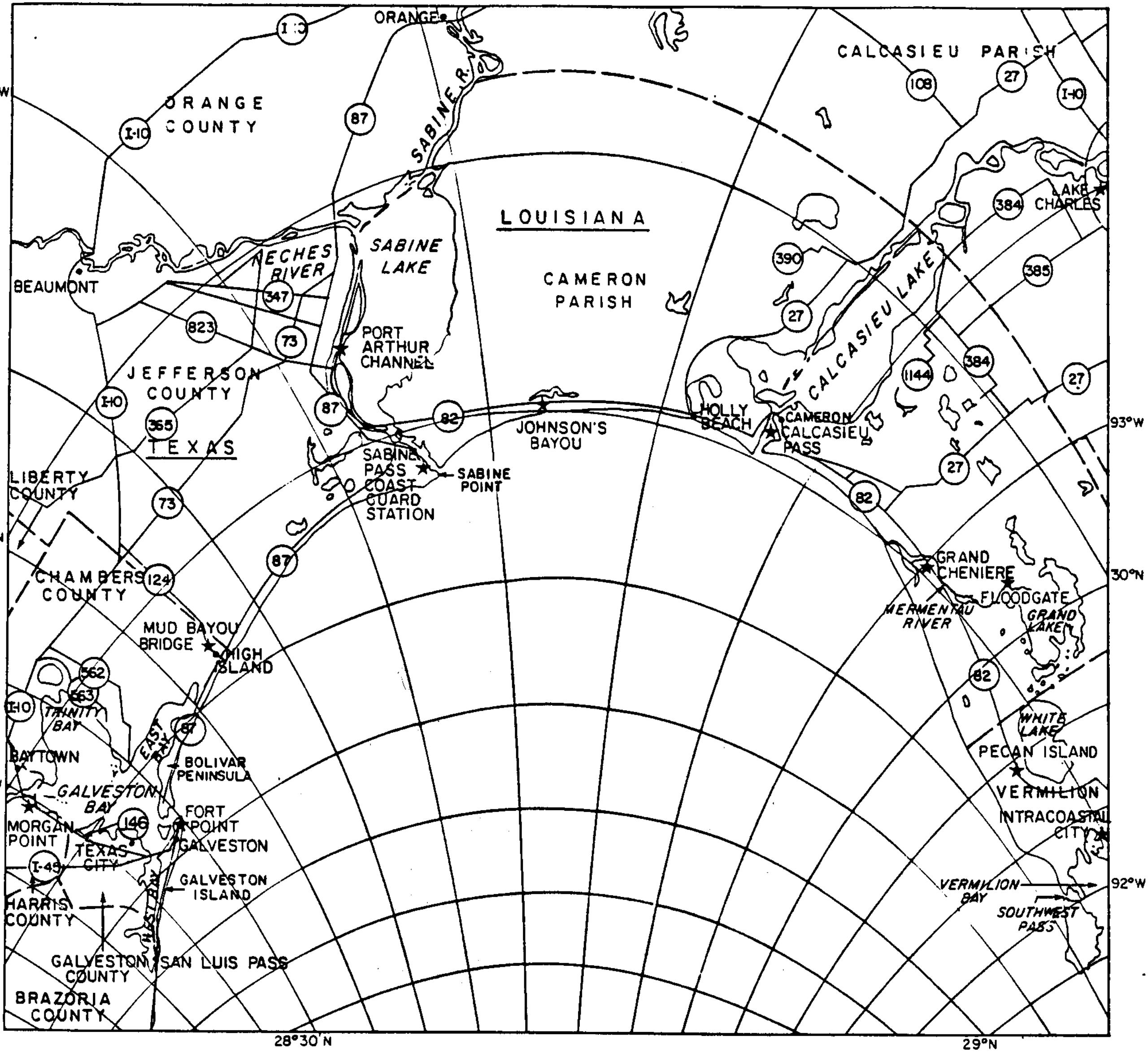


Figure 3. Location of counties/parishes, cities, major highways, lakes, passes and bays in the Sabine Lake Basin.

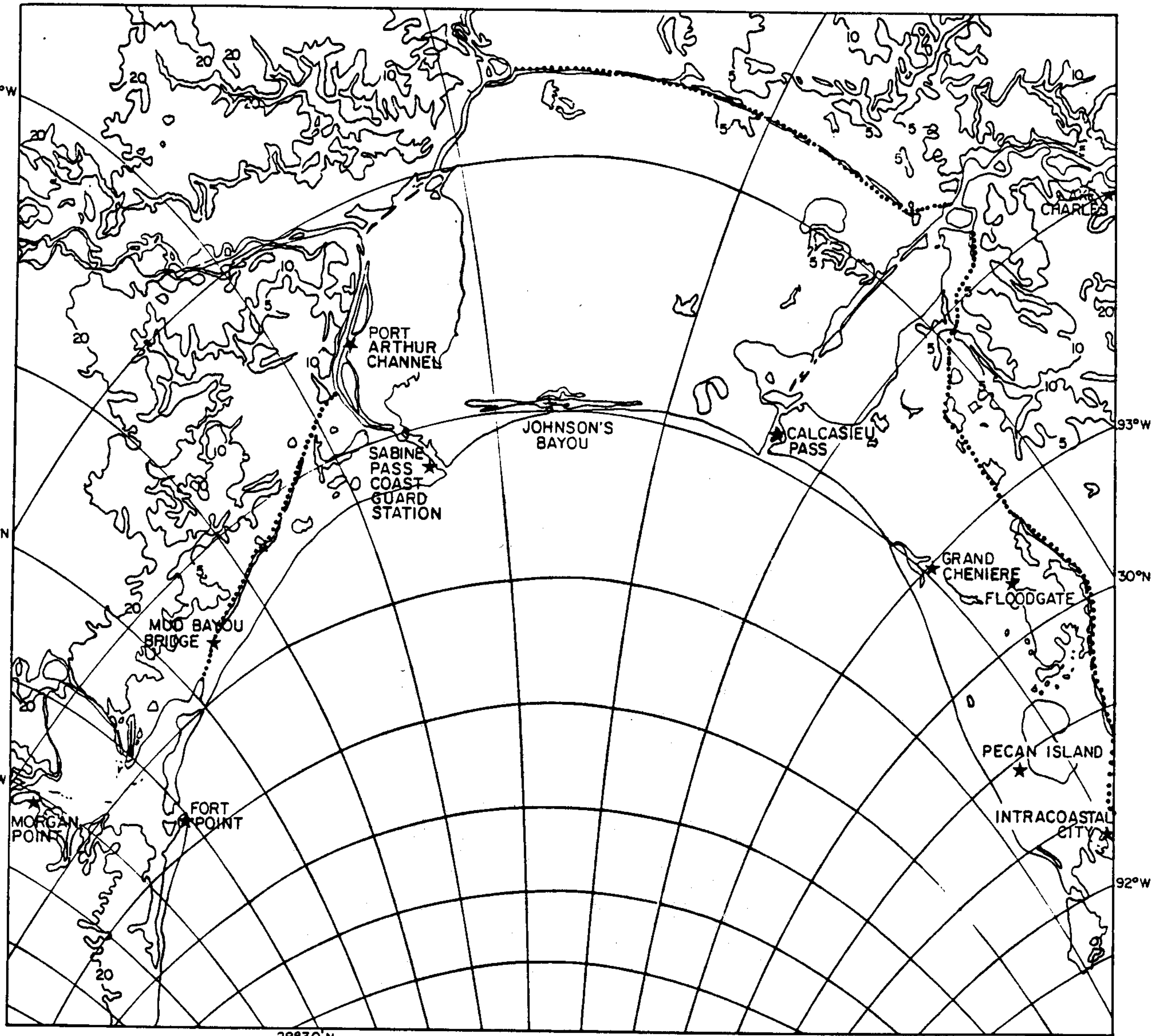


Figure 4. Topography of Sabine Lake Basin. Contours at 10-ft intervals. The dotted line represents the Intracoastal Waterway. Starred locations indicate sites where histories of storm surge, wind speed and wind direction were computed.

B. Topography and Bathymetry in the Sabine Lake Basin

The coastline of the Gulf of Mexico contained in the Sabine Lake sin (Figure 1) extends westward from Atchafalaya Bay, Louisiana, to a int about 40 miles southwest of Galveston, Texas. The Basin's geo-aphy (Fisher et al., 1972, 1973) is characterized by shallow slopes of e Gulf floor and inland terrain, and by many lakes and extensive rshes. There are four lakes that each have surface areas exceeding 50 uare miles: White Lake; Grand Lake; Calcasieu Lake; and Sabine Lake. ne of these lakes exceeds 10 ft in depth, although Sabine and lcasieu have ship channels that are dredged about 1000 ft wide and ft deep and connect each lake to the Gulf. Galveston Bay (including inity, East and West Bays), covers more than 550 square miles in the sin's southwest corner. The bay complex is everywhere less than feet deep, although it is traversed by a dredged channel that is miles long, about 400 feet wide and 40 feet deep.

Most of the river systems which feed the bay/lakes in this basin ander within broad marshy regions. Marshes cover most of the Trinity ver Delta and the lower Trinity Valley. The lower 15 miles of the ches Valley and a similar distance in the Sabine Valley are marshy. also are all portions, lying within this basin, of the Calcasieu ver, the Mermenteau River and the Lacassine River. The widespread rshland and wooded swamps often are 5 or fewer feet above mean sea vel (MSL) and have slopes of 3 ft or less per mile. Few natural rriers exceed 6 ft MSL, and often are in the form of discontinuous dges ("chenieres") paralleling the coast. Extensive areas with titudes exceeding 15 ft MSL are not found until about 15 to 20 miles land. Terrain higher than 20 ft MSL is confined to the part of this sin that overlays Texas, except for only a small region in Louisiana ar Lake Charles. The 20 ft contour is roughly parallel to, and 10-15 les coastward of, the Basin's northwestern boundary--a region bounded ughly by $J < 15$ and the north end of Trinity Bay ($I < 42$). Terrain ceeding 20 ft MSL also is found southwest of Galveston Bay, in the rt of the basin grid with $J < 8$ and $I > 51$.

There are many man-made barriers, and some exceed 6 ft MSL. Among ese are spoil banks (8-18 ft MSL) adjacent to and resulting from edging the Intracoastal Waterway (ICW) that traverses the entire eadth of this Basin. Other barriers include roads and railroads on bankments, and dikes or levees surrounding rice fields, pasture, tificial surface reservoirs, gas and oil well fields and wildlife fuges. Barriers near cities include one (15-18 ft MSL) which was ilt on the Gulf front of Galveston Island, to prevent recurrence of saster caused by surge like that from the 1900 storm; and the spoil bank dike (17-21 ft MSL) on the lakefront of Port Arthur.

The multitude of barriers serves to make the Sabine Lake Basin among the most complex of all SLOSH basins.

Land heights and the depths of the Gulf waters are both measured from a fixed "zero" level. This zero is based on the geodetic mean sea level of 1929, which defines "0 altitude" in the "National Geodetic Vertical Datum" (NGVD). Sea level along the Atlantic and Gulf coasts is slowly rising, as Harris (1958) and others have noted. Also, in the Galveston Bay region, land has been sinking. Within this century, an area about 80 miles in diameter, centered about 10 miles west-northwest of Baytown, Texas, has sunk at least 2 ft, and maximum subsidence there exceeds 8 ft.

The slope of the ocean's bottom affects the height of storm surge. Shallower slope--a wider continental shelf--will force higher surges than would a steeper slope with a narrower shelf, for the same storm conditions. In the northwest quarter of the Gulf of Mexico, the bottom has a very gentle slope. For example, the edge of the continental shelf is more than double the distance offshore than is typically found elsewhere along the Atlantic seaboard. The 100 ft depth contour is 40 to 70 miles offshore. Even the 10 fathom (-60 ft MSL) contour is 24 to 40 miles offshore; by comparison, 10 fathoms lies about 6 miles offshore Brownsville, Texas, and less than 3 miles offshore Miami, Florida.

Thus, the northwestern Gulf of Mexico has the gentle bottom slope that aids formation of large storm surges. In addition, the low, relatively featureless terrain offers only little hinderance to any incoming storm surge. The combination has been and will be deadly.

3. SLOSH MODEL

A. Hurricane Model and Input

As noted earlier, the SLOSH model consists of a hurricane model which drives a storm surge model. The hurricane model was developed by Jelesnianski and Taylor (1973). It is a trajectory model of a stationary vortex, and balances the forces from pressure gradient, centrifugal, Coriolis and surface frictional effects. Adjustments are made to the computed vector wind to incorporate the hurricane's forward motion. The model's input includes the radius of maximum wind (RMW) and the difference (ΔP) in sea-level pressure between the ambient value and the minimum value in the storm center. Directly measured wind vectors are ot used. The model also requires input of the coordinates of the torm's center. Thus, input data include thirteen sets of latitude, ongitude, ΔP and RMW, at six hour increments, beginning 48 hours before torm landfall and ending 24 hours after landfall. The model then inearly interpolates this set into values/positions at hourly (or maller) time increments. (The model will accept a limited amount of forced in" data at hourly increments, in place of the interpolated ourly values.)

Figure 5 shows the streamline field (heavy lines) of a hypothetical urricane with a ΔP = 60 mb (central pressure ≈ 950 mb), RMW = 25 miles, oving northward at 10 miles per hour, at the time it moved ashore 20 iles west of Sabine Point, Texas. Storm positions are labelled with he hurricane symbol at hourly intervals. For the same storm, the sotach field is depicted by dashed lines, which represent 1-minute verage winds, with speeds in miles per hour. Attention is called to he following:

) Asymmetry of the wind speed on the hurricane's right side (over land) versus on the left side (over water).

) Angle made between the streamlines and isotachs, which is an approximate measure of the inflow angle. (Inflow angle is the angle between a streamline and an isobar.)

) Decrease of the wind speed near the shoreline, which results in larger inflow angles at, and inland from, the shoreline. Any changes in storm-surge height caused by decreases in wind speed are offset by increases in convergence by the greater inflow angle.

This model generates the meteorological forces which drive the ıderlying ocean, by way of surface stress and the gradient of atmo- ›heric pressure.

B. Storm Surge Model

Storm surge is the response by the ocean to meteorological forces. ıe model's governing equations are those given by Jelesnianski (1967), cept now for the inclusion of the finite amplitude effect. Coeffi- ents for surface drag, eddy viscosity and bottom slip are the same as ose used in an earlier model (Jelesnianski, 1972). There is no libration or tuning to force agreement between observed and computed rges; coefficients are fixed, and do not vary from one geographical gion to another.

Computational overrides are incorporated to model two-dimension inland inundation, routing of surges inland when barriers are ove topped, the effect of trees, the movement of the surge up rivers, a flow through channels and cuts and over submerged sills. Besides surg other processes affect water height (section 4B), but are not inco porated in the model.

Nor surprisingly, the accuracy of modeled surge values increases the accuracy of the input (storm data) improves.

4. OUTPUT AND INTERPRETATION OF THE MODEL RESULTS

A. Output from the SLOSH Model

The output for the Sabine Lake SLOSH model consists of a map water heights and also an array of 12 time history plots. At each gr point, the water height is the maximum value that was computed at th point during the 72 (maximum) hours of model time. Thus, the m displays the highest water levels and does not display events at a particular instant in time. The analyzed envelopes of high water sh the track of the hurricane (with hourly positions of the eye), shad areas that represent dry land which has been inundated, and contours high water relative to mean sea level (MSL). Height of water abo terrain was not calculated because terrain height varies within a gr square. For example, the altitude of a grid square may be assigned value of 6-ft MSL, but that may represent an average of land heigh ranging from 3 ft to 9 ft MSL. Thus, a surge value of 8 ft in th square, implying 2 ft average depth of water over the grid's terrai would cover some terrain with as much as 5 ft of water, with other are remaining high and dry. Therefore, the depth of surge flooding abo terrain at a specific site in the grid square is deduced by subtracti the actual terrain height from the model-generated storm surge height that square.

B. Interpretation of Results

Even if the model is supplied accurate data on storm position intensities and sizes, the computed surges may contain errors of ± 2 of observed water levels. These primarily stem from:

1) Maps that are outdated. The maps which supplied heights of terra and depths of water sometimes did not include changes, often ma made, that had been made to the heights and positions of barrie

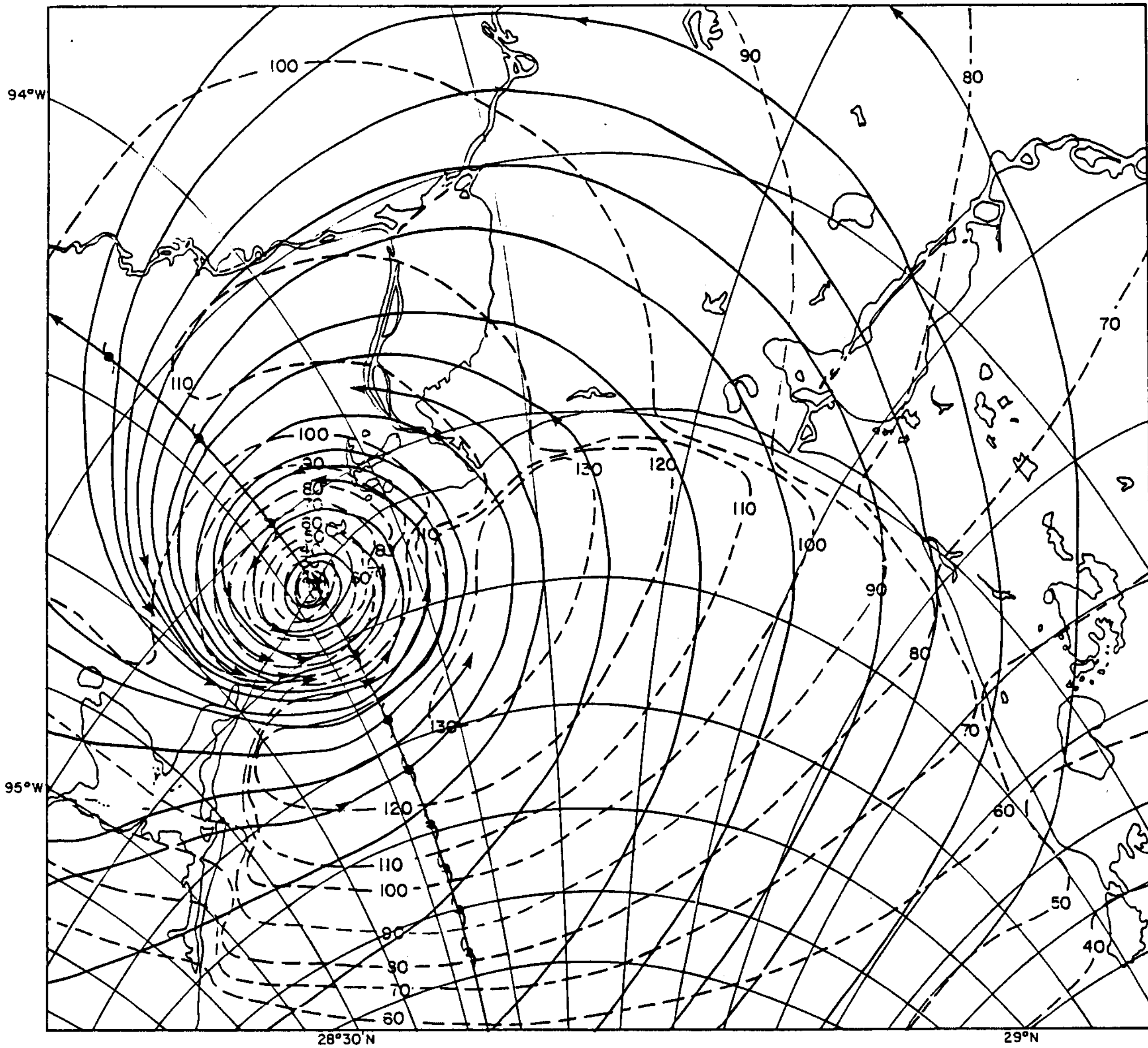


Figure 5. A hypothetical hurricane at the time its center made landfall in the Sabine Lake Basin, 20 miles west of Sabine Pass. The storm was heading northward at 10 mph, had a radius of maximum winds of 25 statute miles and was a category 3 storm (with a minimum sea level pressure of about 950 mb). Streamlines are dark lines, isotachs (mph) are light lines and eye center positions are indicated each hour by the hurricane symbols.

highway and railway embankments) and depths and locations of ·ls. At the time that the Sabine Lake Basin data set underwent ›pment, an inspection was made of the terrain. Map values of ·r locations and heights were checked and corrections made to ata before inclusion in the model. However, any changes in ·aphy that have been made since then (June 1982) are not incor- ·d. Inaccuracies of topography or bathymetry will contribute :ly to errors in the modeling of all storm surges.

lous water heights. Sea level can be at an altitude different 'mean sea level," days or even weeks before a storm is actually :ing a basin. The value of the actual, local sea level--the datums" for pre-storm anomaly in the Gulf of Mexico and l lakes--must be supplied to the model before calculations are ıted.

processes, such as waves, astronomical tides, rainfall and ing from overflowing rivers. These processes are usually led in "observations" of storm surge height but are not surge ıre not calculated by the SLOSH model. Often, the maximum t of water is measured by debris lines, drift lines or water lines. But these watermarks frequently include the effects of and swells riding on top of the surge, with the entire ›le superimposed upon astronomically-induced tides. To measure the surge (which has a period of a few hours), the effect of and swells (with periods of seconds and combined amplitudes ps as large as 10 ft) must be removed, as well as the effects e astronomical tides (which usually have regular, predictable ds of hours and diurnal ranges of 1-3 ft in this basin; see s, 1981). (Water height measurements from tide gages usually evoid of the effects of shorter-period waves.)

ıomical tide is predictable at any site where tides have been sly recorded for at least 13 months. Predictions were gene- three sites with tide gages on the Gulf coast: at the mouth ton Bay, of Sabine Pass and of Calcasieu Pass. At these sites, ved storm surge was calculated by subtracting the astronomical the observed storm tide. But elsewhere--inside the lakes or gage observed storm tide was assumed to be the "observed storm The effects of astronomical tides have been included in only he time histories in section 6; unless otherwise stated, tidal e excluded. If the peak of the storm surge were to occur at /low tide, then at most +1.5/0/-1.5 ft of water would have to to the storm surge values on the Gulf coast in this basin.

The foregoing indicates some of the factors that must be considered when comparisons are made between modeled and observed values of storm surge.

5. HURRICANE CLIMATOLOGY

A. Tracks

Between 1886 and 1985 23 tropical cyclones of hurricane intensity passed within 100 miles of Sabine Point, Texas (Neumann et al., 1981), for an average of one hurricane within 100 miles every 4.3 years. As seen in Table 1, eleven of these hurricanes have passed within 50 miles, for an average of one hurricane every nine years within 50 statute miles of Sabine Point.

Figures 6-11 show hurricane tracks in this basin. Figure 6 shows the tracks of all 23 hurricanes and the 100 mile circle. The tracks represent "best estimates" and are based on a variety of data sources. Historically, storm strength, location and motion were only inferred from analyses of wind, pressure and cloud observations made at ships and land stations being influenced by the storm. In 1943, aircraft reconnaissance of hurricanes began. Not until 1959 were there land-based weather radars, as now at Brownsville, Galveston, Lake Charles and New Orleans, to observe and record structure, development and motion of precipitation fields, and to infer center location and radius of maximum winds. The 1960's saw the advent of photography from weather satellites of tropical storms. Observations by aircraft, radar and satellite have shown that the tracks of centers of hurricanes contain wobbles, gyrations and cycloidal motions (Lawrence and Mayfield, 1977), and that there often are rapid developments in size and intensity of rain bands, contractions of eyewall diameters and formation of concentric ("double") eyewalls. Every one of these factors indicates asymmetries in the storm's dynamical structure; every one of these dynamical asymmetries affects the storm's surge. But these factors were not documented in the earlier storms and remain beyond the reach of present-day forecasting skill.

The tracks in Figures 6-10 are labelled at 6-hour intervals with month/ day/hour (GMT). Most storms headed towards the northwest, but with no simple pattern. A few actually were heading northeastward at landfall. None of the storms exited the continent and headed offshore, but most other directions were to be found. More than two-thirds of the storms made landfall within 20 miles of Galveston, Texas. There is no readily apparent "scenario" of storm track direction, either as a

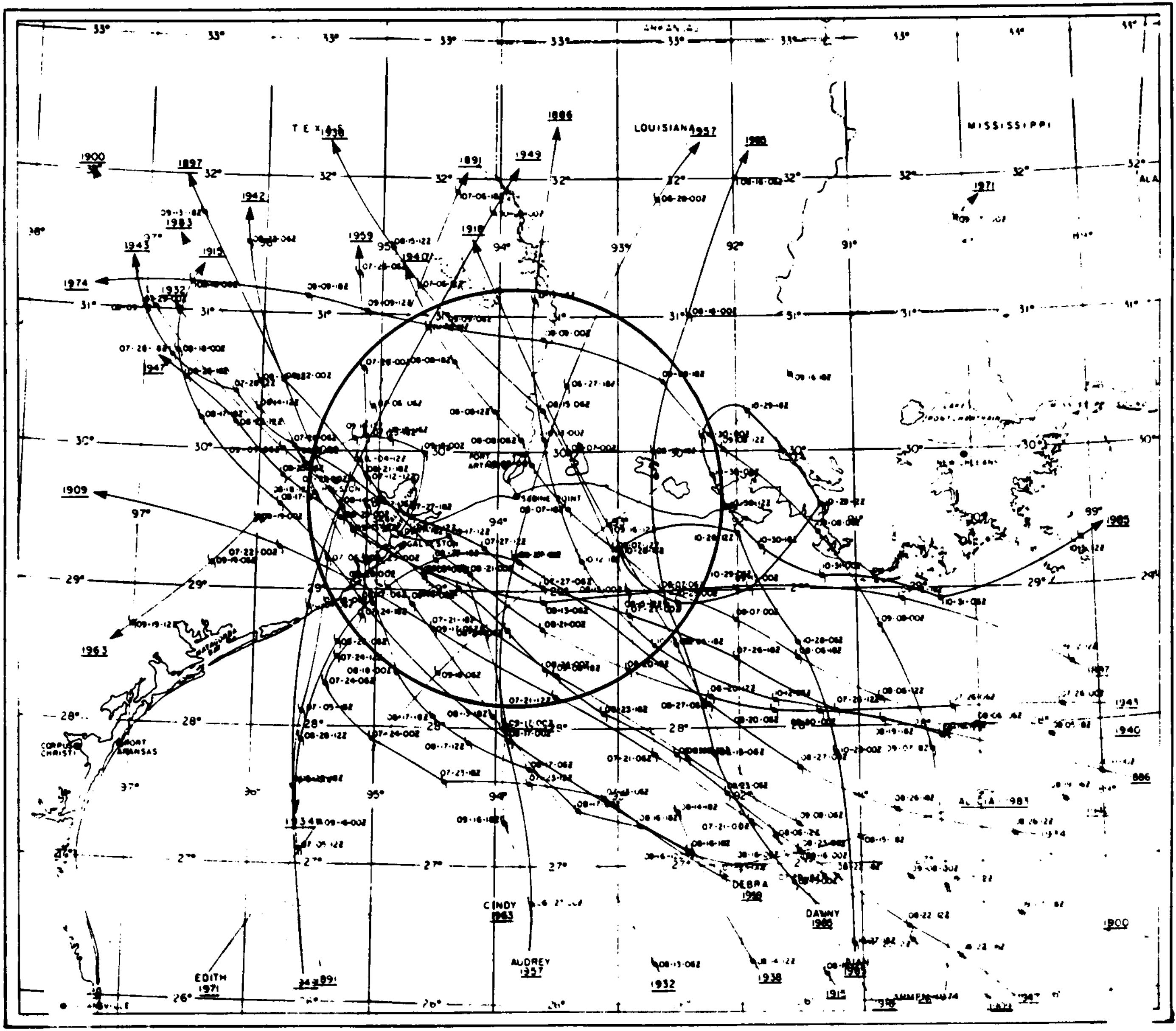


Figure 6. Tracks of hurricanes passing within 100 miles of Sabine Point, Texas, since 1900.

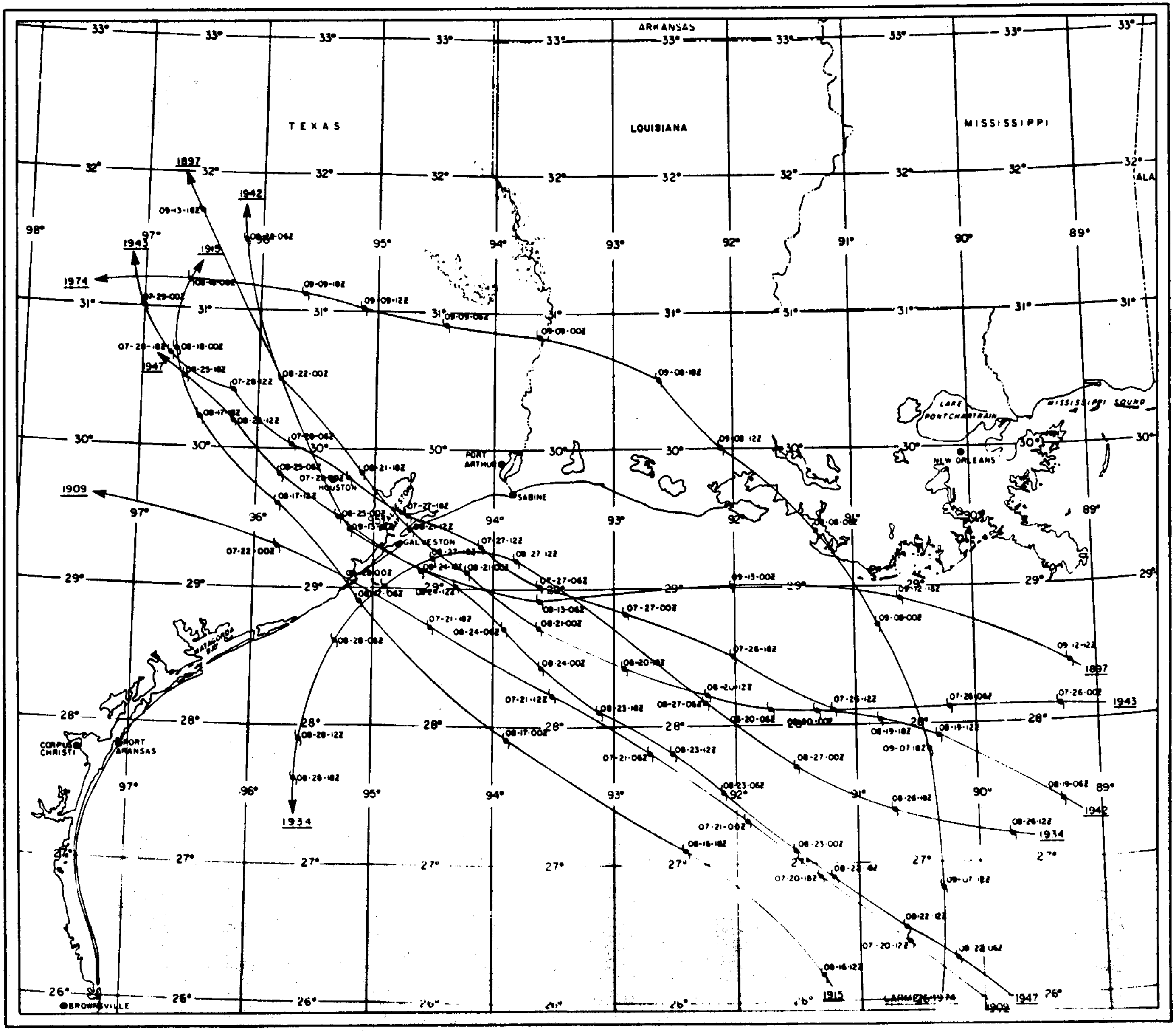


Figure 7. Same as Figure 6, except for west-northwestbound storms only.

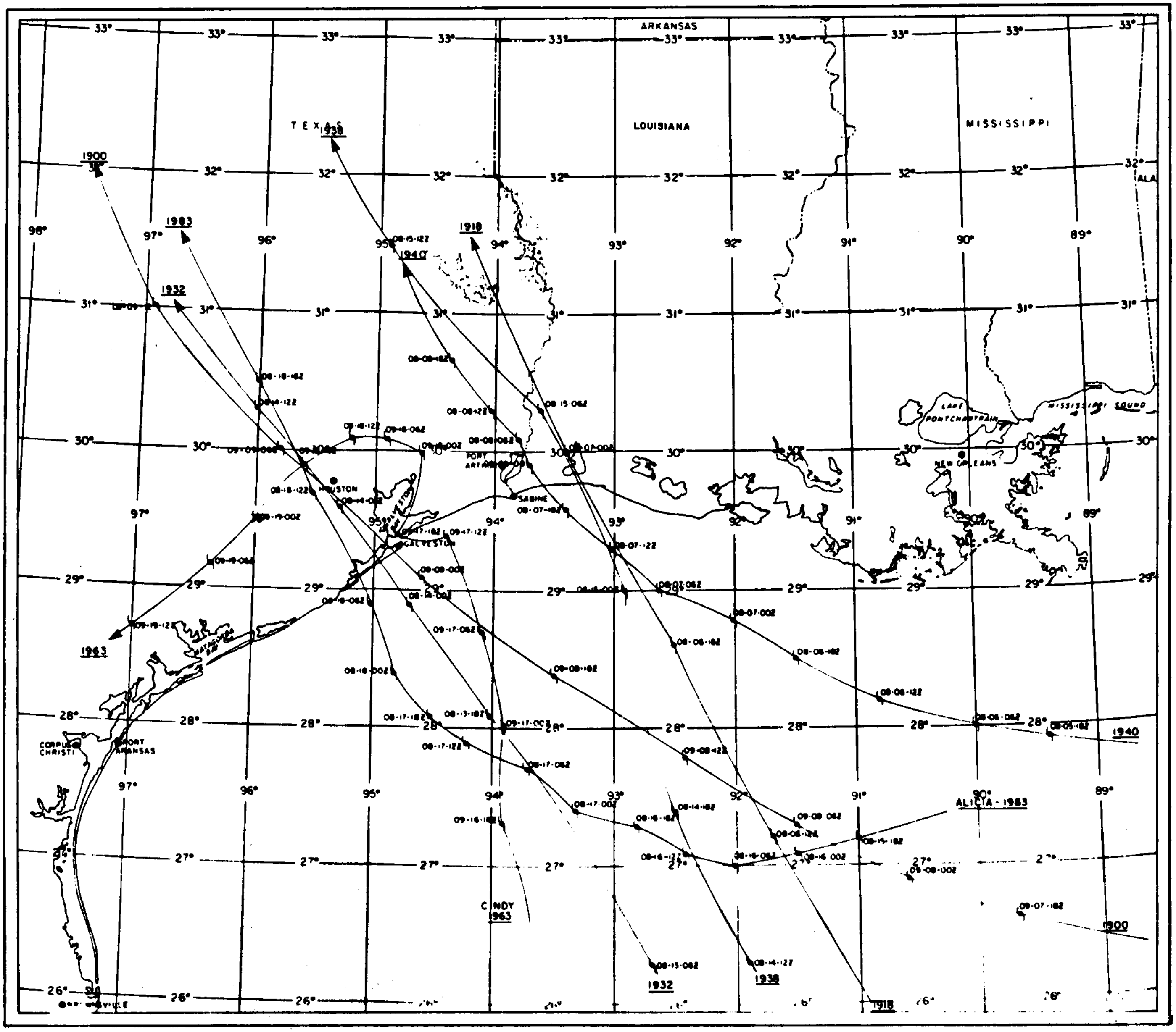


Figure 8. Same as Figure 6, except for north-northwestbound storms only.

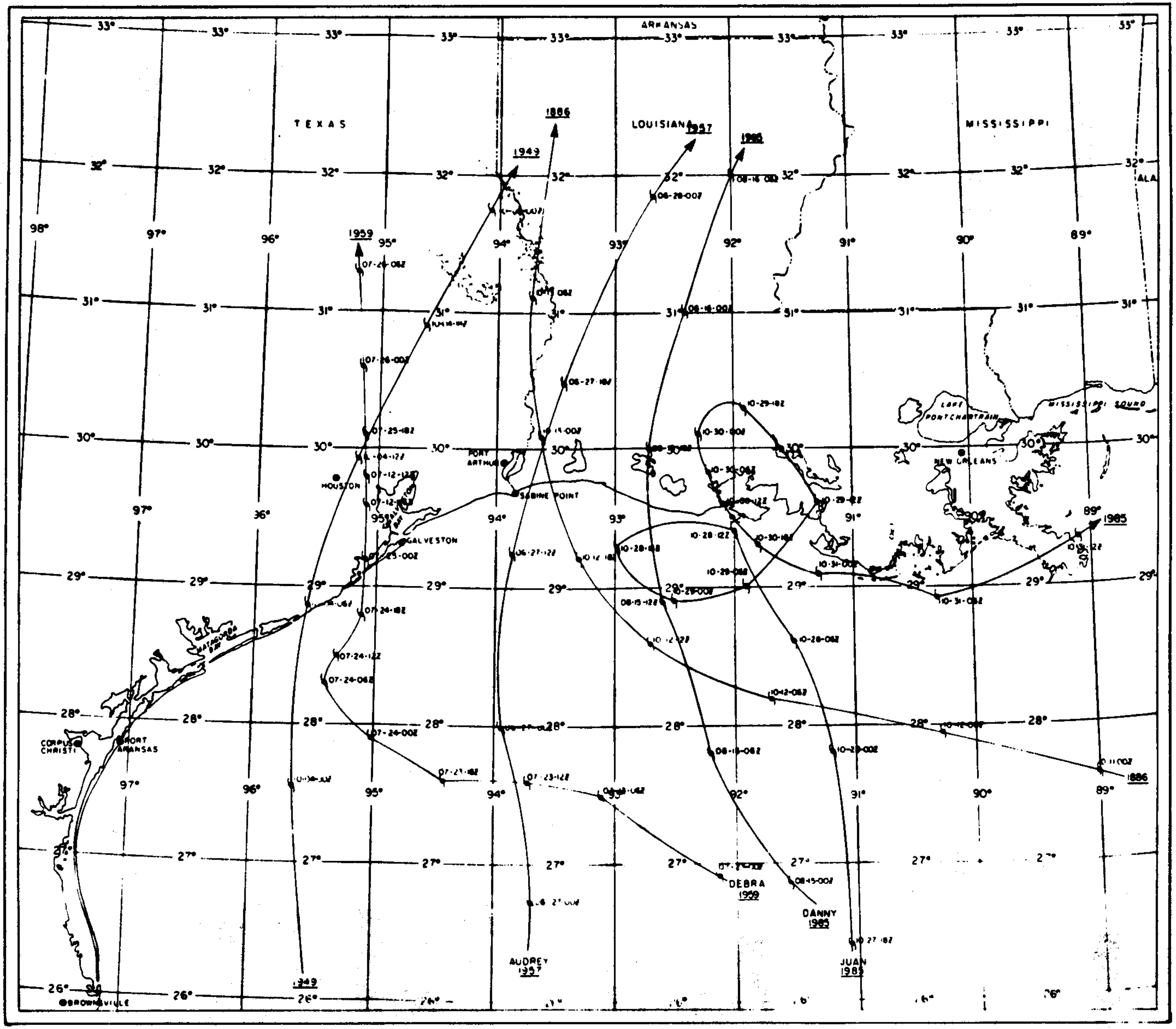


Figure 9. Same as Figure 6, except for northbound storms only.

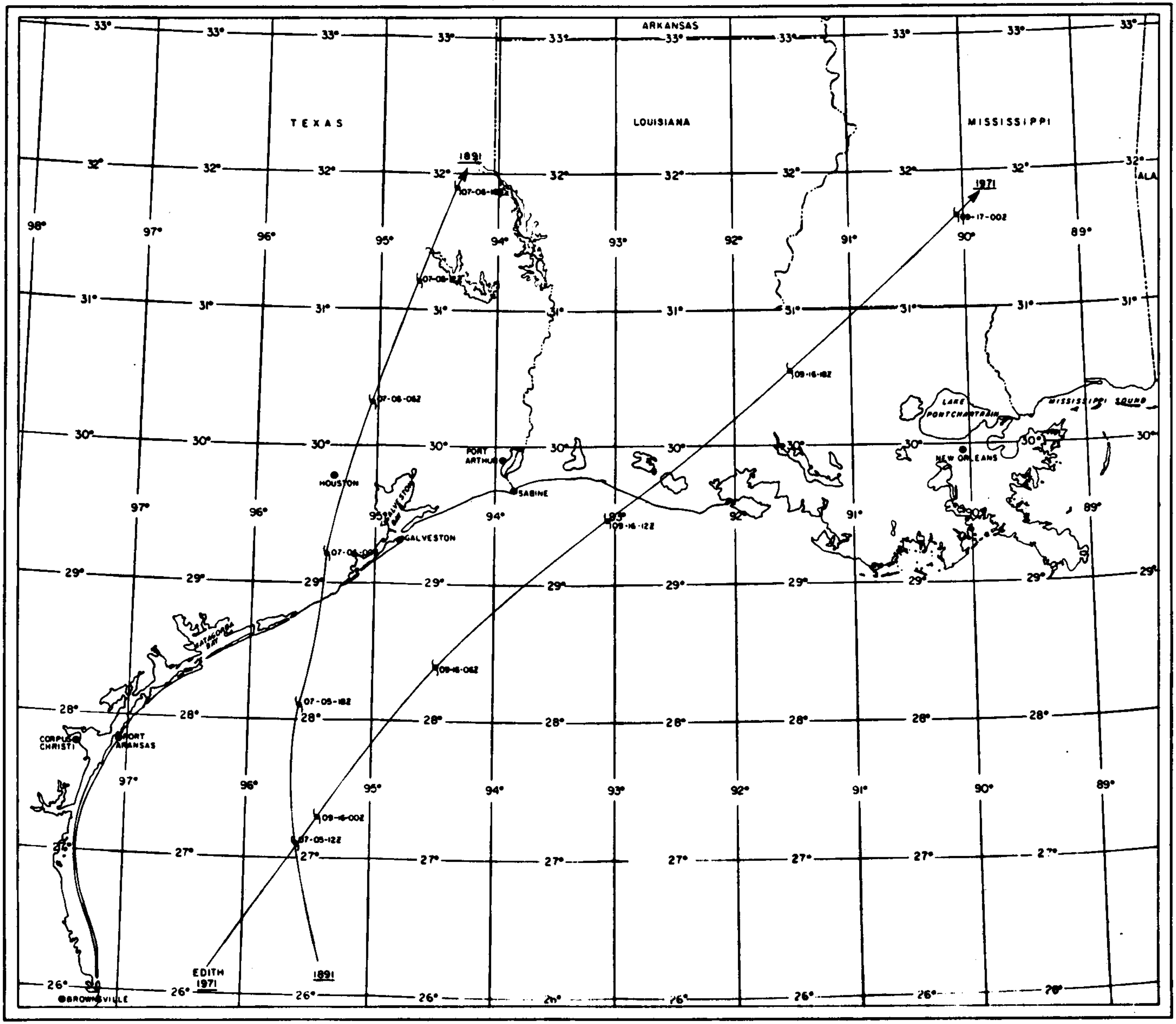


Figure 10. Same as Figure 6, except for northeastbound storms only.

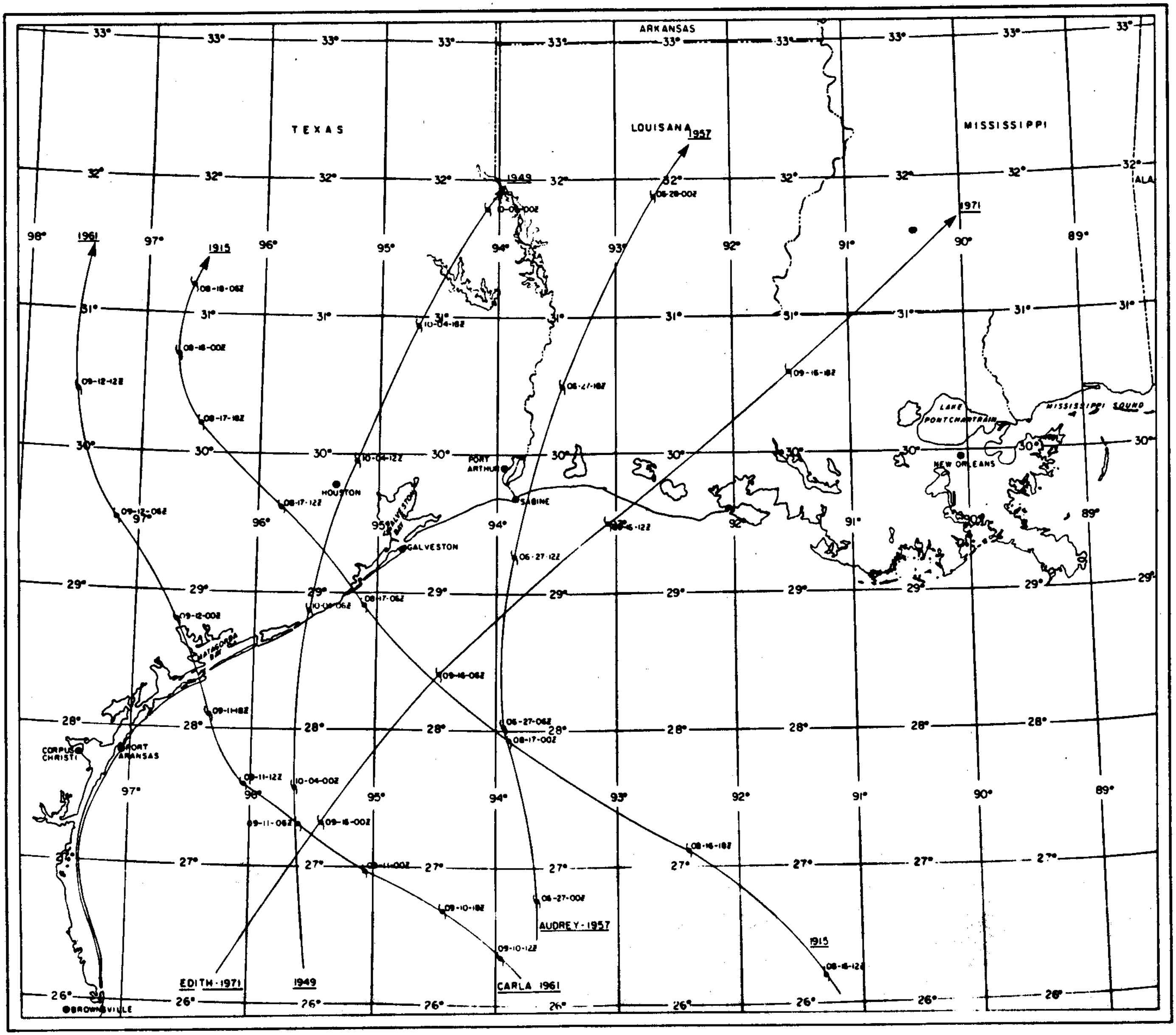


Figure 11. Tracks of the five hurricanes discussed in section 6.

function of month of the year, or of storm strength. Typically, storms forming in June are weak; but in this basin, the only June hurricane was Audrey--and it was one of the deadliest in history. Carla (1961) had a profound influence on people and property in this basin. Although her center before landfall was always beyond 170 miles from Sabine Point, was outside the 100 mile circle, and so was not listed in Table 1, Carla will be included among the historical storms to be discussed in this atlas in section 6.

Figure 7 is the same as Figure 6, except it depicts only the tracks of west-northwestbound storms. Figure 8 displays tracks for only the north-northwestbound storms, while Figure 9 shows tracks for northbound storms plus Juan, which was northbound before making two loops. Tracks for northeastbound storms are in Figure 10. In Figure 11 are tracks of the five historical storms discussed in section 6.

B. Intensities

Hurricane intensity is usually defined by measurements at sea level of the maximum sustained wind speed and/or by minimum barometric pressure. Neither of these is easily obtained. Accurate estimates of these parameters at sea level were acquired only when a ship or land station was traversed by the storm's "eye". Minimum central pressure was gotten only when a barometer was in the precise path of the storm's center. Because the area covered by the strongest winds is much larger than that covered by the pressure minimum, strength of many older storms was deduced from measurements of wind speed. However, with the advent of aircraft reconnaissance, measurements made at flight level of meteorological parameters allow the calculation of barometric pressure at sea level. By comparison, winds at sea level are not so readily deduced from flight level data. For all the storm tracks in Figure 6, an estimate was made of the maximum wind speed at intervals of 6 hours. For some storms, there exists only very indirect evidence of actual speeds. From the hourly values of the maximum wind speed inside the 100 mile circle, the largest value was selected. This maximum sustained wind speed for the hurricane is listed in Table 1 under the heading of "wind (in circle)." Storm heading and forward speed at the hour of closest point of approach are listed in the last two columns.

The values listed in column 6 sometimes are poor estimates of the maximum wind speed; the following must be considered:

1) Actual wind speeds and directions exhibit gustiness;

Table 1. Hurricanes passing within 100 statute mile circle
Point (29.7°N, 93.8°W), during 1886-1985.

			>>>At Closest Point of Approach: (@CPA) <<<		
Index (1)	Date (@CPA) (2)	Storm Name (3)	Range/Bearing (miles/degrees) (to CPA) (4) / (5)		Wind (in circle) (mph) (6)
1	1886 Oct 12	Unnamed	21	068	98
2	1891 Jul 6	Unnamed	84	283	92
3	1897 Sep 13	Unnamed	21	355	79
4	1900 Sep 8	Unnamed	60	216	132
5	1909 Jul 21	Unnamed	78	211	121
6	1915 Aug 17	Unnamed	75	224	132
7	1918 Aug 7	Unnamed	35	050	90
8	1932 Aug 14	Unnamed	74	232	109
9	1934 Aug 27	Unnamed	30	188	81
10	1938 Aug 15	Unnamed	35	064	77
11	1940 Aug 7	Unnamed	16	061	81
12	1942 Aug 21	Unnamed	45	216	81
13	1943 Jul 27	Unnamed	31	211	86
14	1947 Aug 24	Unnamed	54	211	81
15	1949 Oct 4	Unnamed	81	292	132
16	1957 Jun 27	Audrey	8	038	143
17	1959 Jul 25	Debra	76	271	86
18	1963 Sep 17	Cindy	32	269	78
19	1971 Sep 16	Edith	37	161	98
20	1974 Sep 9	Carmen	78	010	81
21	1983 Aug 18	Alicia	88	239	115
22	1985 Aug 15	Danny	67	092	92
23	1985 Oct 28	Juan	54	108	86

Notes:

(1) Storm number for this list.
(2) Year, month and date that storm was closest to Sabine
(3) Storms were not formally named before 1950.
(4)-(5) Distance (statute miles) and direction (degrees) to S when storm passed abeam.
(6) Maximum sustained wind speed near storm center while within 100 statute miles of Sabine Point. This is no the wind recorded at a given site.
(7)-(8) Storm heading and forward speed (mph) at hour of CPA.

2) The "average wind speed" has been calculated with a variety of time intervals over the years; thus, one can find historical wind records that have used time periods such as 1 hour, or 10 or 5 minutes or 1 minute as the "standard" period of measurement. Given the same record from a recording anemometer, the use of each of these measurement periods would likely yield a different average wind speed, with shorter periods probably giving higher average speeds.

3) The platforms for measuring maximum surface wind speed have changed over the years; data from ship and land stations now are supplemented by remotely-sensed data from aircraft, satellites and radar. However, the remote platforms, especially the last two, observe the motions of clouds or precipitation echoes, and these motions are not wind speed, nor are they at sea level.

Because of these limitations in determination of maximum wind speed, the SLOSH model uses storm-center sea-level pressure as a measure of storm intensity.

6. CASE STUDIES OF HISTORICAL HURRICANES

A. The Storms That Were Chosen and Why

Five historical hurricanes have been selected to demonstrate the Sabine Lake SLOSH model and each will be discussed separately in the remainder of this section. The hurricanes occurred in 1915, 1949, 1957 (Audrey), 1961 (Carla), and 1971 (Edith). Tracks for these storms are plotted in Figure 11. The 6-hourly positions used in the model calculations are labelled with month, day, hour (LST) and, on a second line, pressure (mb), delta-P (mb) and RMW (statute miles). Envelopes of high water for each of the storms are displayed in Figures 12, 15, 22, 29 and 38, respectively. At each of the 12 sites in Figure 4 having a star symbol next to its name, time histories of the storm surge, wind speed and wind direction were calculated for each storm. These histories are presented in Figures 13, 20, 28, 37 and 40, respectively. In these, the hurricane identification number is listed in the upper left-hand corner. The name and location of each point in the (I,J) grid is given. The predicted storm surge, given by the heavy line, is in feet relative to mean sea level with its reference scale given by the left ordinate. The average depth or height of the grid square is indicated by the top-most line of the hatched area. Any location with a depth below -10 ft MSL is shown as -10 ft. Some locations may be above MSL and storm-surge history in these will show only after the water rises high enough to inundate the grid square.

The horizontal axis represents time, using a 24-hour clock. Thus 6 a.m. is "6" but 6 p.m. is "18," etc. Wind speeds (right-hand scale are in miles per hour, and represent a 1-min sustained wind predicted b the model. The wind speed may be plotted into the hatched area. Direc tions are meteorological, with north wind blowing from the top of th page. A hurricane symbol is plotted on the time axis at the approximat hour of landfall.

The 1915 storm flooded Port Arthur, as indicated by contemporar comments and photos, with at least 3 ft of water on terrain at 5 f MSL. The 1949 and 1957 storms had the headings (northbound at landfall and the winds (exceeding 100 mph) to cause widespread flooding in thi basin. Also, during both storms, numerous recording tide gages gathere data that have been used in comparisons with modeled surge heights. Th 1961 storm (Carla) tested the model's skill at handling a slow wandering, large storm whose center stayed south of the southernmos boundary of the basin by at least 50 miles at all times. Edith (1971 had an unusual direction and the model had to be tested for its modelin skill in this situation.

B. 1915 Hurricane (Not Named)

About 5 August 1915, a tropical disturbance apparently formed in th vicinity of the Cape Verde Islands. It moved westward, became a hurri cane on the 8th and passed between Barbados and Dominica in the Windwar Islands on the 10th. Its center passed north of Jamaica, with gale force winds over the island on the night of the 12th. It then heade northwestward, traversed the western tip of Cuba on the 14th and crosse the Texas coast between Galveston and Freeport on 17 August 1915 between midnight and 1 a.m. After landfall, the lowest baromete reading was 952.9 mb at Velasco, with 955 mb reported at Housto (Frankenfield, 1915).

Maximum 5-minute wind speed at Galveston was 71 mph and a 1-minut wind was estimated at 120 mph. The city was generally protected fro wave action by the seawall (which was built after the disasterous 190 storm which caused approximately 6000 deaths.) As evidence of the powe of the storm, each of three 20-ton granite blocks that were part of th seawall's ballustrade were ripped loose, lifted upward and moved westward 50-150 feet, onto the seawall's roadway. The greatest damage wa done outside of the seawall area, with the greatest single loss bein the substantial destruction of the causeway connecting Galveston Islan to the mainland. On Galveston Island, 53 lives were lost, 42 from th area outside the protection of the seawall. Overall, 275 died, with 6

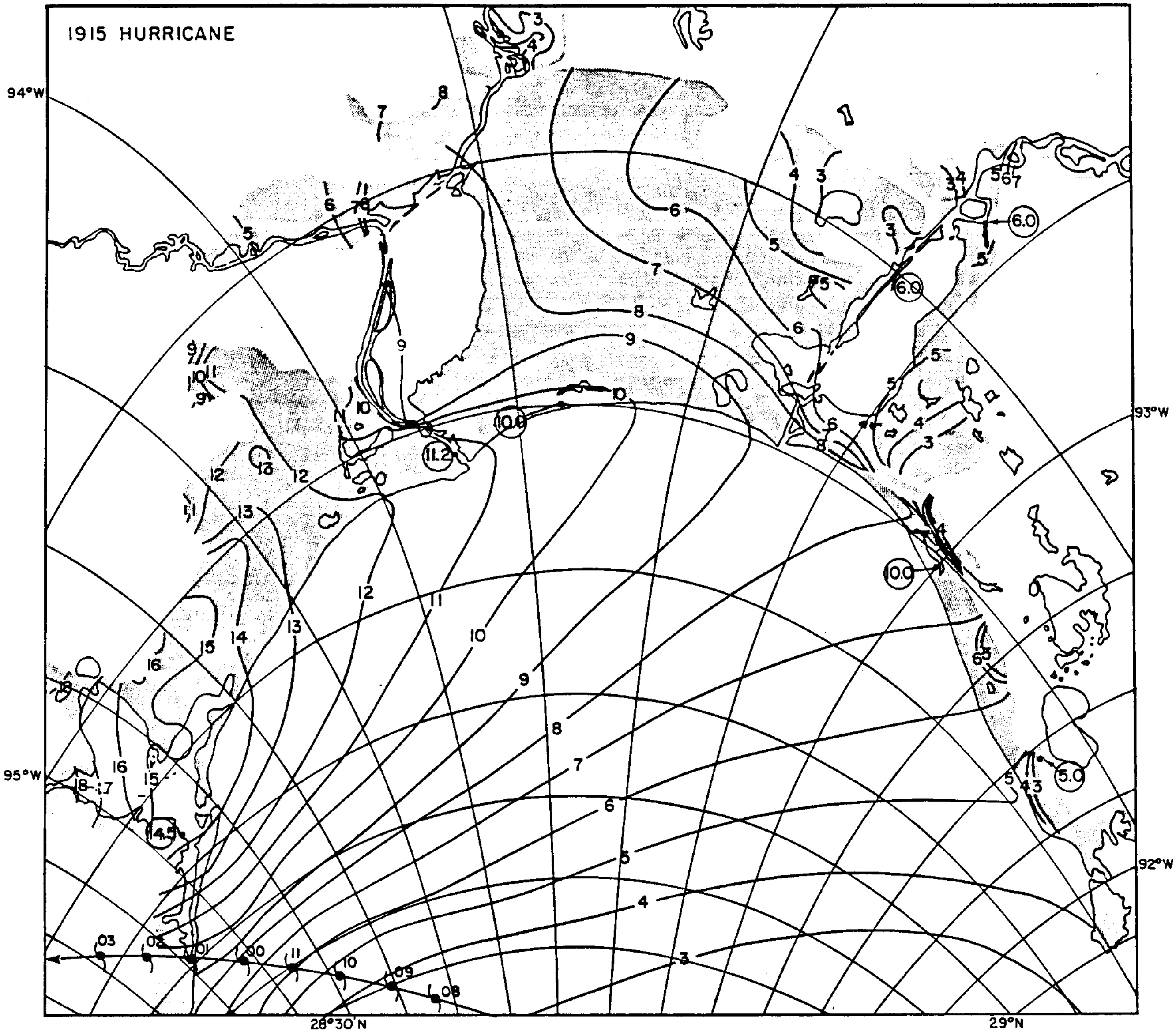


Figure 12. Modeled envelope of high water for hurricane of 17 August 1915; circled numbers represent observed (MSL) heights.

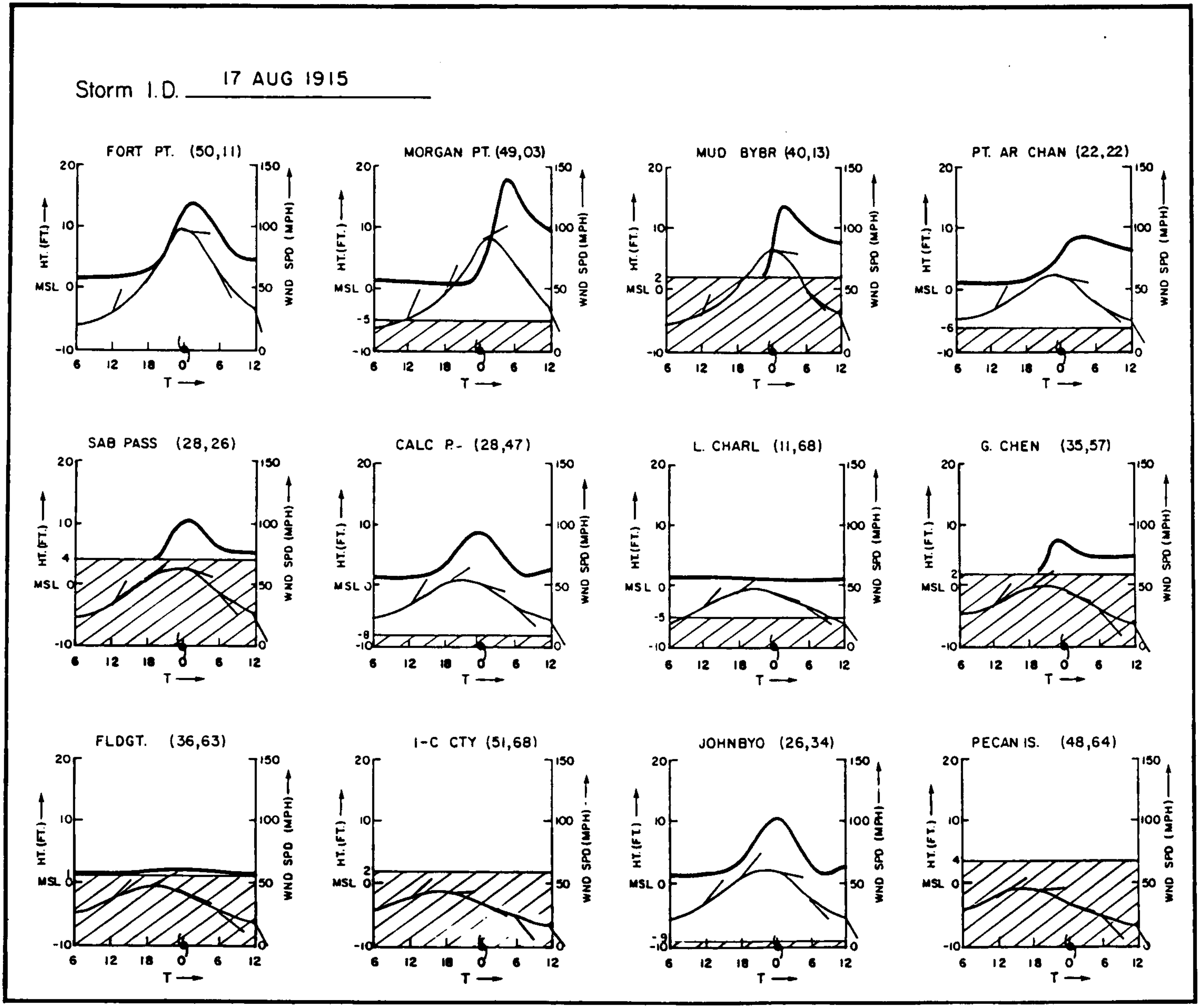


Figure 13. Time histories of storm surge, wind speed and wind direction at 12 selected points (see Figure 4) for 1915 hurricane.

lost in wrecking or sinking of ships. Damage was estimated at over $56M, with crop destruction in the Texas interior accounting for most of the loss. Nearly all open cotton, corn and early rice were destroyed by the high winds and torrential rains. Heavy, damaging rains that caused floods and beat down crops in the nation's midsection continued as the storm headed northeastward from Texas to Lake Erie and down the valley of the St. Lawrence River.

During the hurricane's traverse of the Gulf of Mexico, high storm tides were observed along the coast from Matagorda Bay to the mouth of the Mississippi River, even though the storm center was always more than 100 miles from the Louisiana coast. The highest tide reported was 15.3 ft mean low Gulf (14.5 ft MSL) near Galveston at Virginia Point (Graham and Hudson, 1960). Galveston Island was overflowed by storm surge of over 12 feet, which, with superimposed waves, resulted in crest altitudes of 18-20 ft MSL. There were no official storm tide records at Galveston because tide gages and records were carried away by the storm. The duration of inundation from the surge was about 40 hours at Galveston--much longer than that from the 1900 storm. Farther east, storm tides of 11.2 ft at Sabine Pass and 7.3 ft at Port Arthur were reported. Practically all of Port Arthur was inundated, with water standing several feet deep in houses and buildings. In Louisiana, storm tides were reported to have been 10 feet at Grand Cheniere, 10.3 ft at Cameron, 5 ft at Pecan Island, 6 ft at Hackberry and 11 ft at Calcasieu near Carmeron (U.S. Army, 1972). Flooding extended for 10-20 miles inland from the coast.

For input to the SLOSH model, the storm's size, strength (ΔP) and coordinates of eye center were chosen to be within the range of those cited in earlier reports (Kutschenreuter et al., 1975; Harris, 1959; Graham and Hudson, 1960). Thus, ΔP was set at 45 mb, grew to 55 mb at landfall and weakened to 15 mb 24 hours after landfall. RMW was a constant 35 statute miles, but after landfall increased linearly to 45 statute miles. Initial datums were set at +1.5 ft MSL. Landfall of the eye center was about 8 miles southwest of San Luis Pass before 1 a.m. on August 17th.

The envelope of high water modeled for this hurricane is depicted in Figure 12. The numbers that are inscribed in circles are some of the observed surge heights. These values may include the effects of rain flooding, especially in the area east of Calcasieu Pass and inland from the coastline. Also, the circled values may include astronomical tide--and the tide was high or rising at the hour of storm landfall. Modeled values may include effects from present-day barriers which did not exist in 1915. Note that Port Arthur was modeled to remain unflooded, although this is contrary to what was observed (U.S. Army, However, surge heights were modeled to be about 9 ft MSL in Sab in front of Port Arthur. In this region, the model conta present-day 15+ ft barrier, absent in 1915. Without that barr ft surge atop Port Arthur's terrain (4-6 ft MSL) would result depths of 3-5 ft on Port Arthur--which approximate depths that were measured at the time. Water heights depicted for this st for others, below) demonstrate that surge maxima lie to the righ track of the storm and are in the region of the maximum winds. surge at the coastline is high enough to overtop a barrier islan 14 feet in front of Bolivar Peninsula) then surge can "run up" inland--as seen by the 18+ feet MSL modeled in the northwest Galveston Bay.

Displayed in Figure 13 are 12 time histories generated by th At two of the sites--Intracoastal City at (15, 68) and Pecan I (48, 64)--no surge is plotted because water was not modeled risen high enough to have wet the grid square.

C. 1949 Hurricane (Not Named)

On 27 September 1949, a weak low pressure area began to dev the Pacific coast of El Salvador. The area moved northward Guatemala and into the Gulf of Mexico. By October 1, the lo sified into a tropical storm just off the Yucatan Peninsula, and the next day was classified a hurricane. It headed northward landfall between Matagorda and Freeport, Texas, about 11:30 October 3rd. Lowest reported pressure was 978 mb at Freepor also had maximum sustained winds of 100 mph and peak wind gus mated at 135 mph. The storm's center passed between the airport city offices of the Weather Bureau at Houston. Storm rainfal large area exceeded 10 inches, with over 14.5 inches at Good miles north of Houston (Zoch, 1949).

Total storm damage was estimated at about $8M. Of this, mated $1M was property damage, including about $800,000 damag rigs off the Texas coast. Crop damage was about $6.7M. Two l lost as a result of the storm's passage.

As with the 1915 storm, the values for storm size and stre were input to the SLOSH model were within the range of values earlier by others (Kutchenreuter et al., 1957; Harris, 1959; G Hudson, 1960). RMW and ΔP are displayed in Figure 14. Initi were set at +2.0 ft MSL.

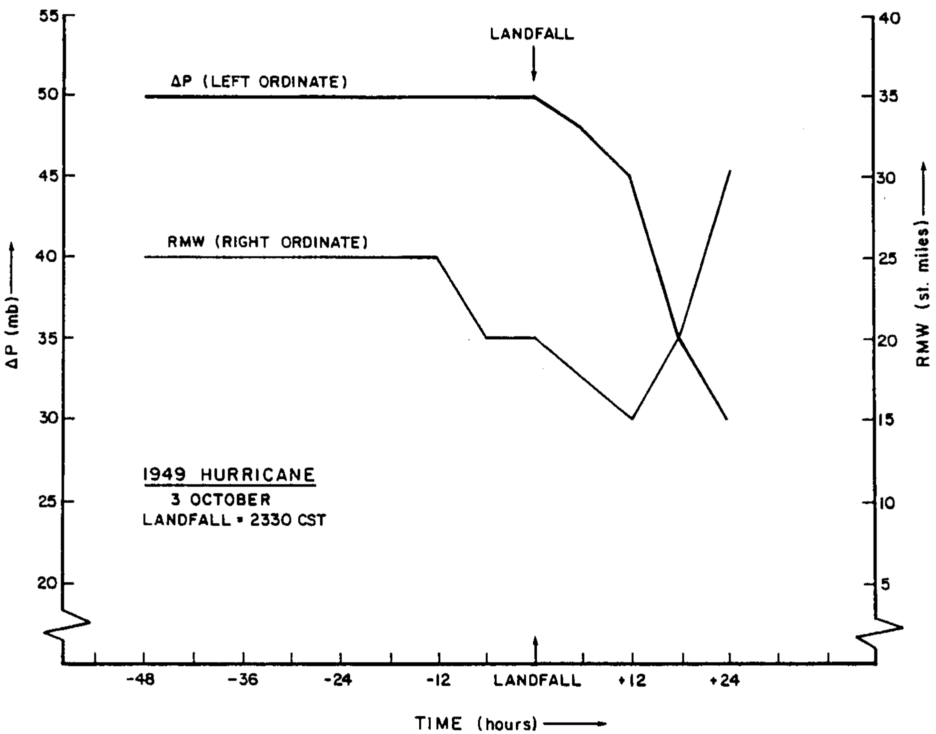


Figure 14. Data for 1949 hurricane: Delta-P (left axis) and radius of maximum wind (right axis).

For this storm, the envelope of high water calculated by the S model is shown in Figure 15, which also depicts some observed max values, inscribed in circles. Surge heights exceeding 5 ft MSL only found in Texas.

Gage observations of this hurricane's storm tide at four sites tabulated and time histories were plotted. In Figures 16-19, obse surge is the dashed line, observed storm tide is the heavy solid l astronomical tide (the steady, small amplitude oscillation) is the solid line, and SLOSH model results are plotted with the dotted line

Figure 16 is the time history at Fort Point, Texas, on the north end of Galveston Island. The maximum observed storm tide was 5.4 ft (Harris, 1963), while 5.94 ft MSL was modeled by SLOSH. The obse surge has some large amplitude variations, which were not enti eliminated by removing the astronomical tide. The hour when max water height was calculated to occur agrees with that which observed, but there is only moderate agreement between the shapes of observed and the SLOSH-calculated curves.

When the astronomical tide is removed from the observed storm at Sabine Pass (Figure 17), the observed surge is seen to have rea able agreement with that modeled by SLOSH; but the modeled maximu about three hours later than was observed.

The gage at the Mud Bayou Bridge, on the ICW north of High Isl recorded a storm surge with a maximum of 3.7 ft MSL (Figure 18). was a site not modeled to have been flooded, although the SLOSH pro modeled surges nearby of 3 ft MSL at the east end of East Bay. Th however, a 4-5 ft barrier prevented any modeled flow further northw up the ICW, to the grid square containing the gage.

At the Port Arthur field office of the Corps of Engineers, the record (Figure 19) had a maximum water height at about 5 a.m., with minor maxima before the major one. The oscillation could not explained using astronomical tide data from the nearest site, which in the Gulf (Sabine Point) and not in the lake. By comparison, modeled curve had a monotonic ascent to the maximum value, followed decrease. Observed storm tide was always larger than that calculate SLOSH.

In Figure 20 are displayed 12 time histories generated by the S model.

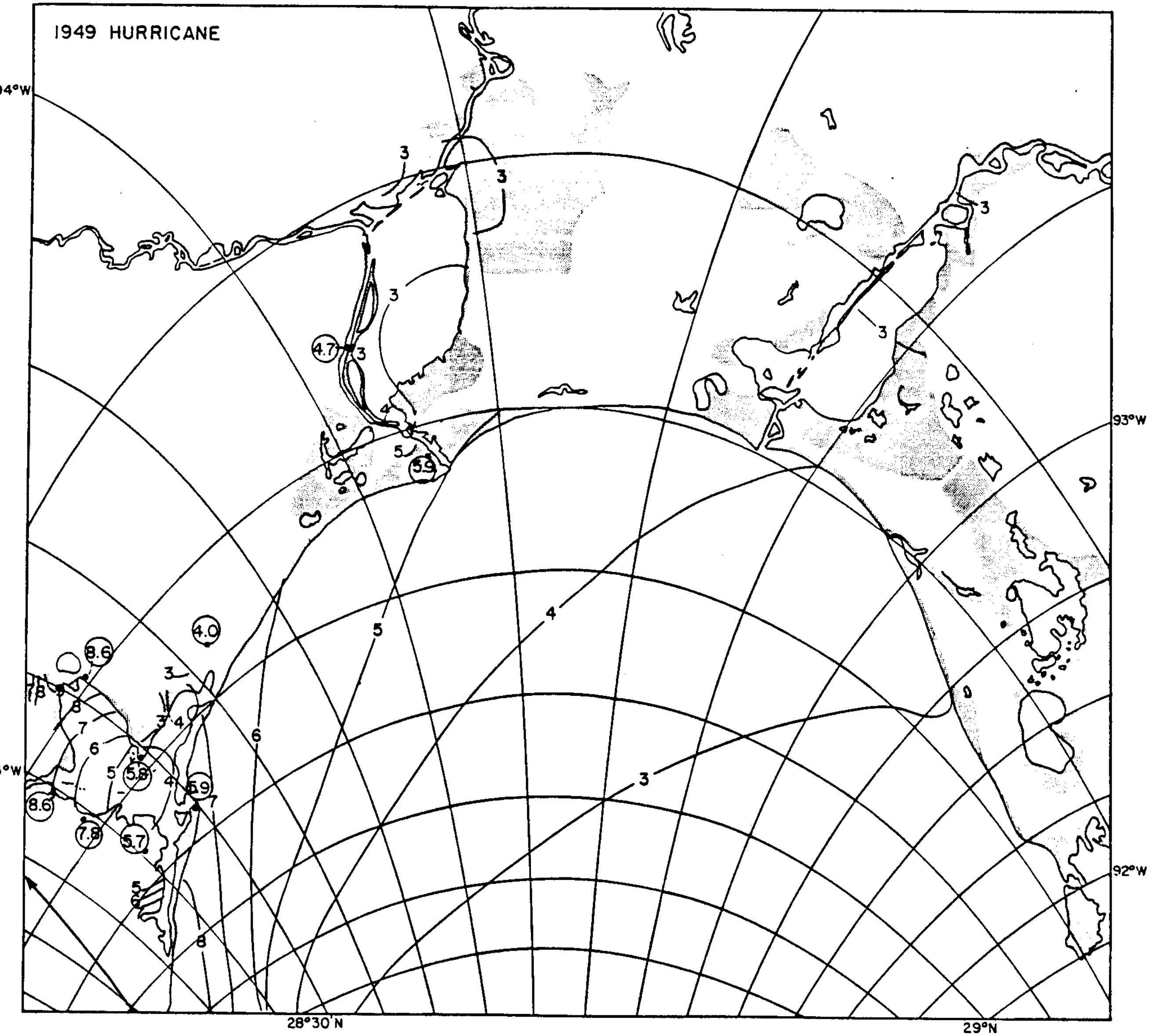


Figure 15. Modeled envelope of high water for hurricane of 3-4 October 1949.

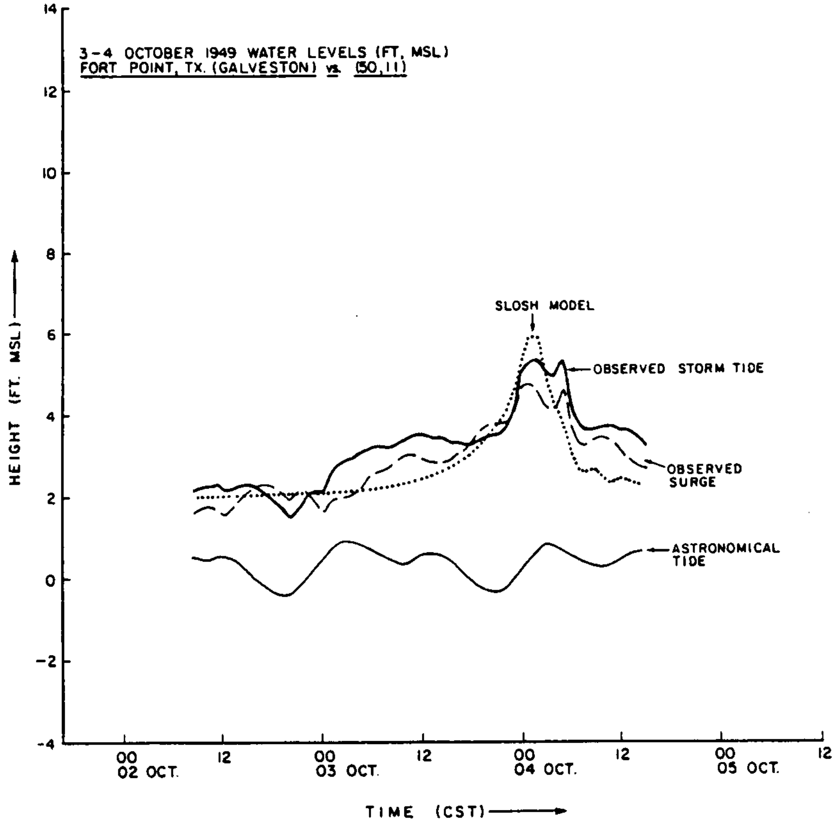


Figure 16. Marigrams at Fort Point, Texas.

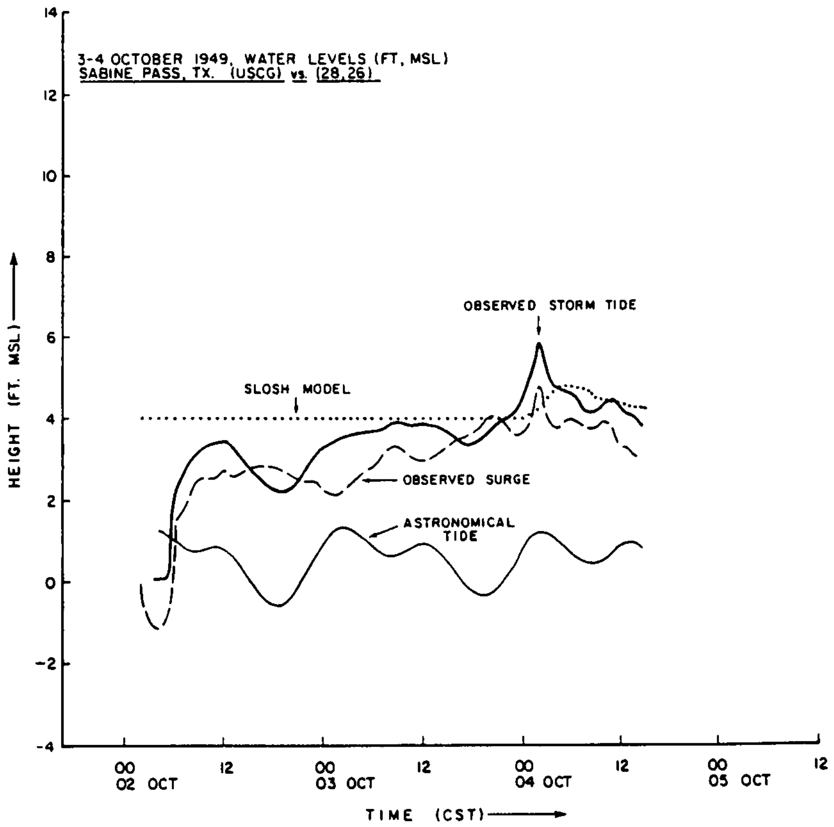


Figure 17. Marigrams at Sabine Pass, Texas.

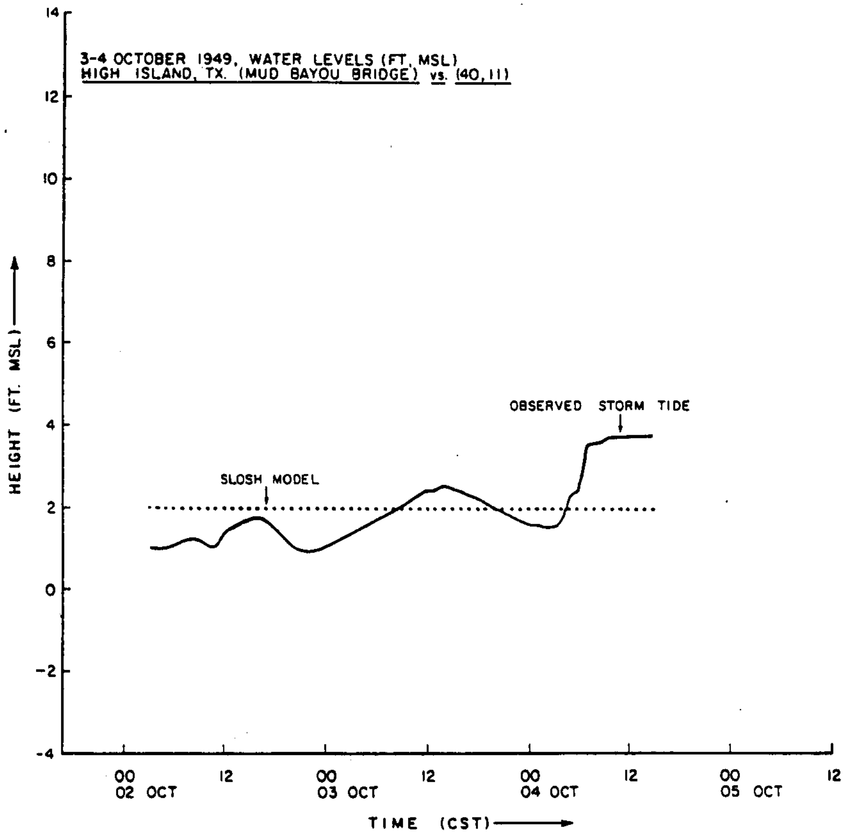


Figure 18. Marigrams at Mud Bayou Bridge, near High Island, Texas.

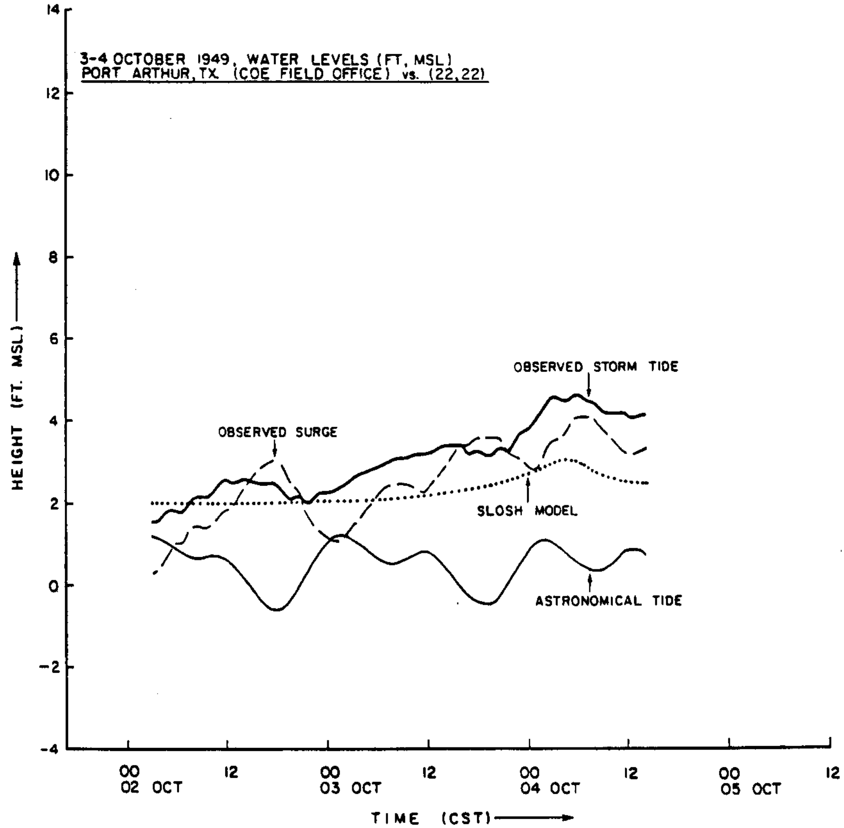


Figure 19. Marigrams at Port Arthur, Texas.

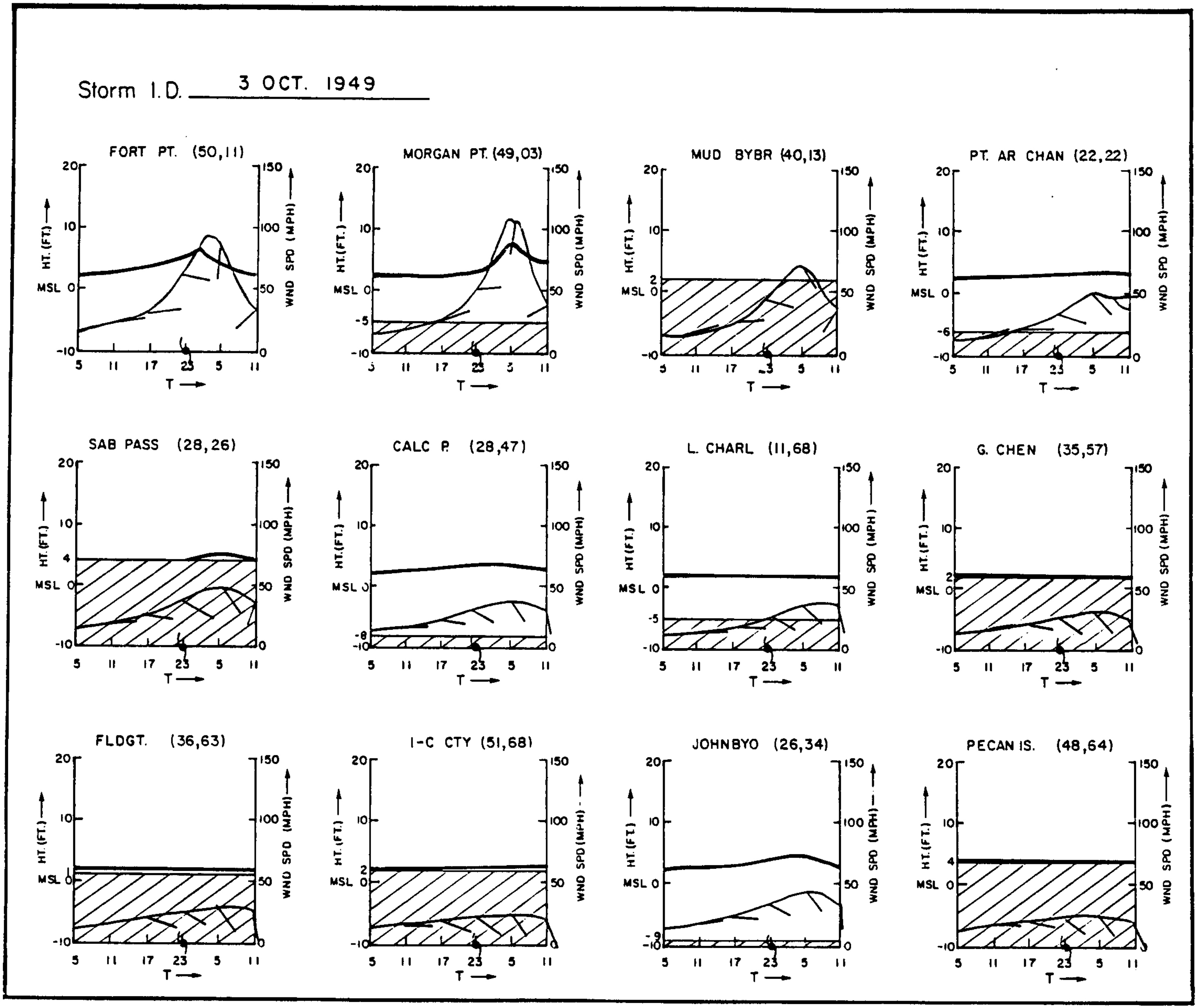


Figure 20. Same as Figure 13, but for 1949 hurricane.

D. 1957 Hurricane (Audrey)

The disasterous effects of Hurricane Audrey included more than 500 deaths, over $200M (equivalent, in 1985, to over one billion dollars) in property and crop damage, and at least 40,000 head of cattle drowned. Over 95% of the houses in Cameron and lower Vermilion parishes (counties) were destroyed or severely damaged.

Audrey dumped 6-9 inches of rain in this basin. But most of the loss in this low, flat, easily flooded terrain was from Audrey's storm surge. It exceeded 12 ft depth at the coast and it extended 20 to 30 miles inland from the Louisiana shoreline west of the Mississippi River.

Audrey was first reported as a nearly stationary tropical depression in the Bay of Campeche (Ross and Blum, 1957) on 24 June. Aircraft reconnaissance on the 25th found minimum surface pressure of 989 mb in the morning and 979 mb in the late afternoon. Air reconnaissance on the 26th found a central pressure--the last one acquired before landfall--of 973 mb (Moore and Staff, 1957). Although there was a radar tracking flight during the night of the 26th which reported that "the precipitation field was considerably more intense than observed 24 hours previously" (Moore and Staff, 1957), the probable changes in size and structure of Audrey's eyewall and rain areas during the last 6 hours or so before landfall went undocumented.

After Audrey accelerated northward, her eye crossed the Louisiana coast some 15 miles east-northeast of Sabine Point between 8 and 9 a.m. on the 27th, and her maximum surge topped 12 ft MSL. She had traversed several oil rigs and oil barge tenders and they had recorded winds exceeding 100 mph, with some gusts registering over 140 mph. It is probable that when Audrey's eye made landfall, her central pressure had fallen more than 30 mb lower than at the last aircraft report, one day earlier. But, "there was no observation of the minimum pressure in (Audrey) at the time the center moved inland" (Graham and Hudson, 1960). The lowest observed pressure (28.30"; 958.3 mb) was at Hackberry, Louisiana, about 15 miles inland. However, based on empirical formulae using winds, a much lower central pressure-about 945 mb--was probable at landfall.

For the SLOSH model, ΔP and RMW were derived from ship, reconnaissance aircraft and land station observations and are plotted in Figure 21. Initial datums were +0.7 ft in the Gulf of Mexico and +1.7 ft elsewhere. Figure 22 illustrates the envelope of high water modeled for Audrey as well as some observed maxima (U.S. Army, 1957). It is a portrait of an unresolved dilemma. The largest observed surges were

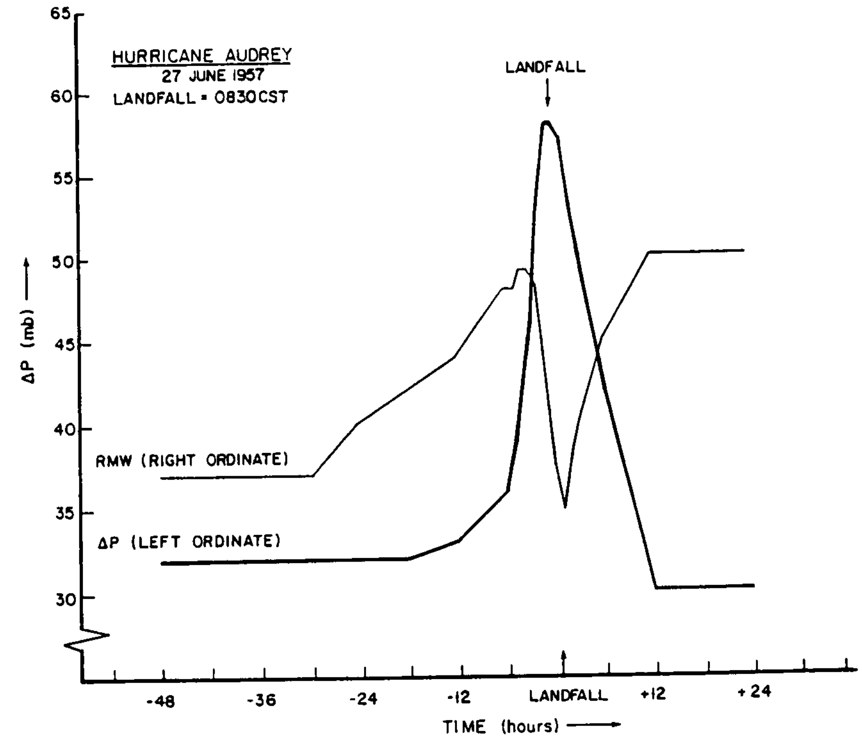


Figure 21. Data for Hurricane Audrey: Delta-P (left axis) a[nd radius] of maximum wind (right axis).

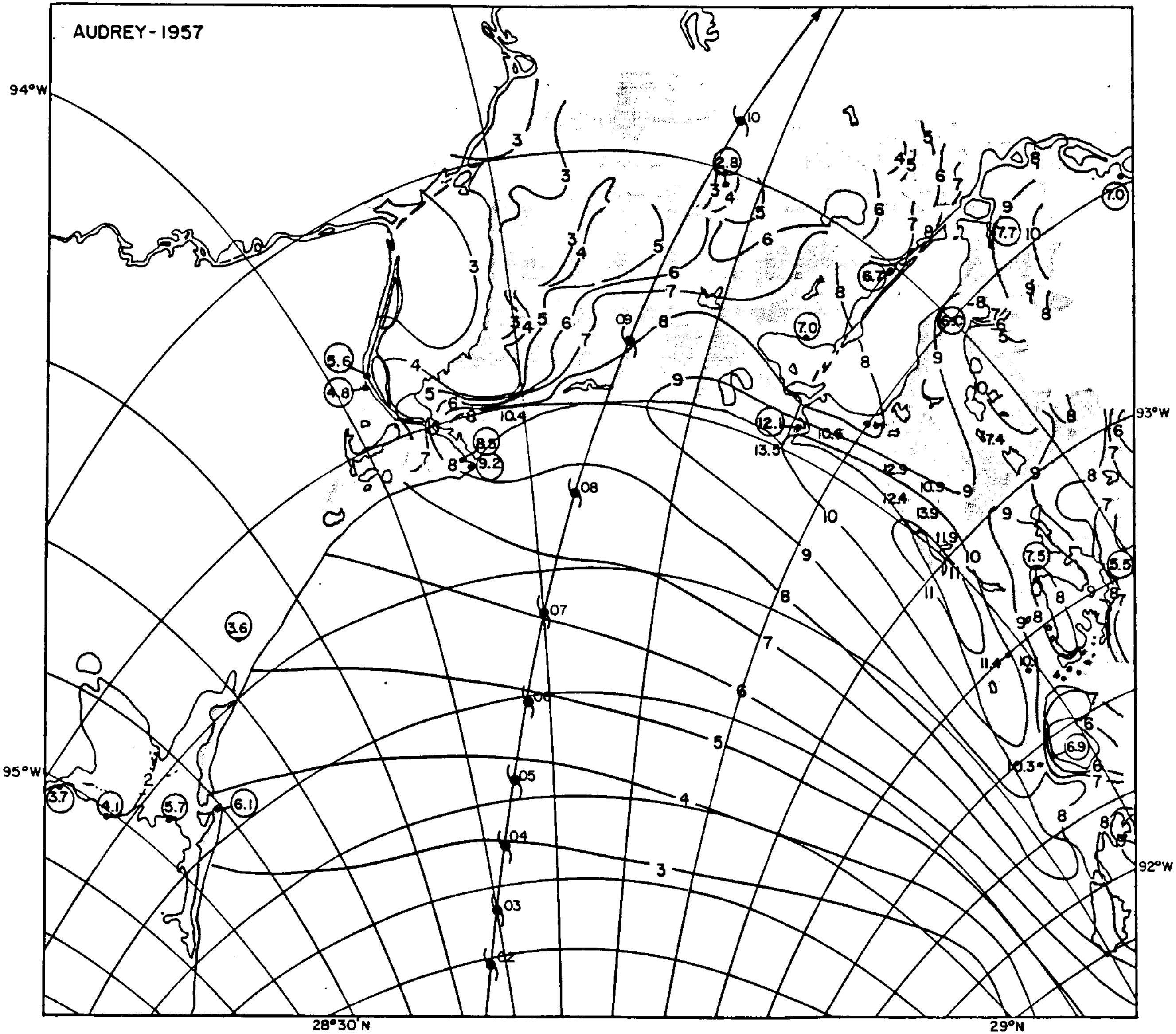


Figure 22. Modeled envelope of high water for Hurricane Audrey, 27 June 1957.

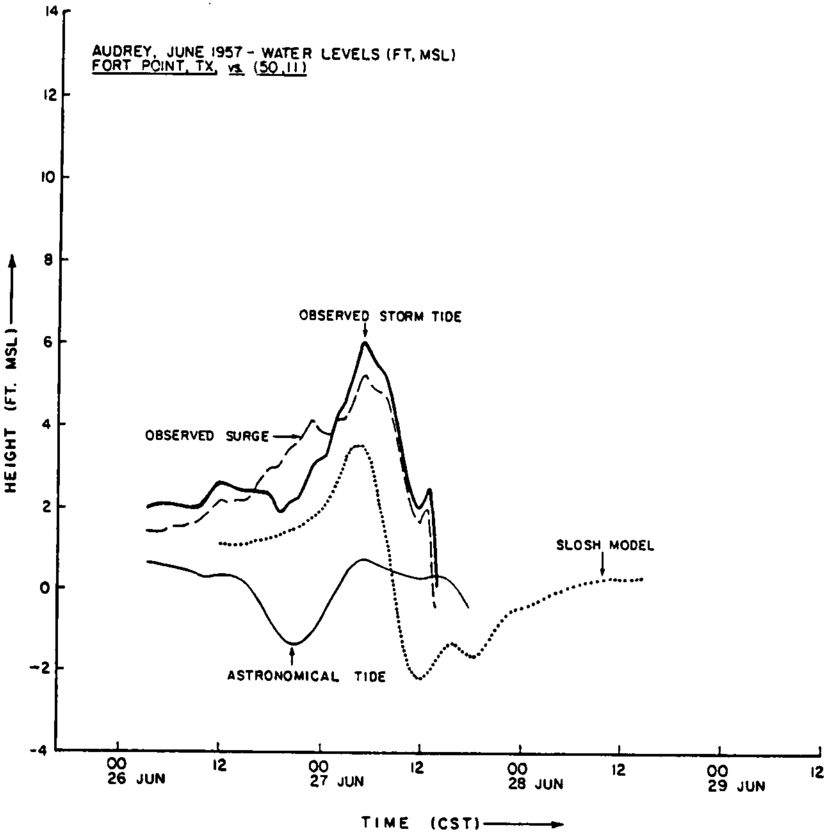


Figure 23. Marigrams at Fort Point, Texas.

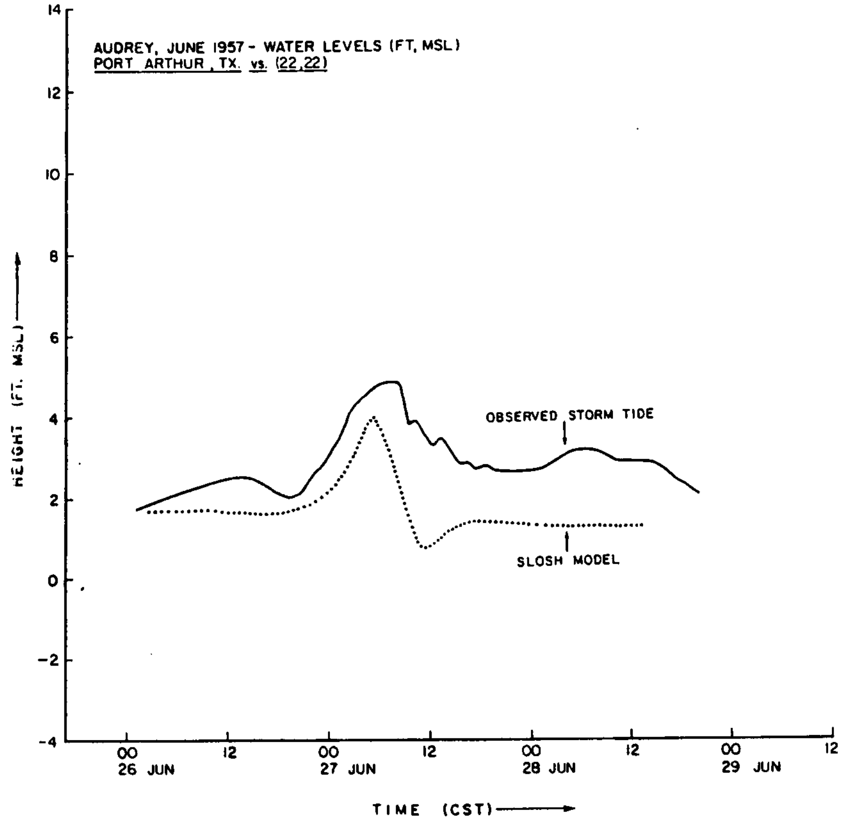


Figure 24. Marigrams at Port Arthur, Texas.

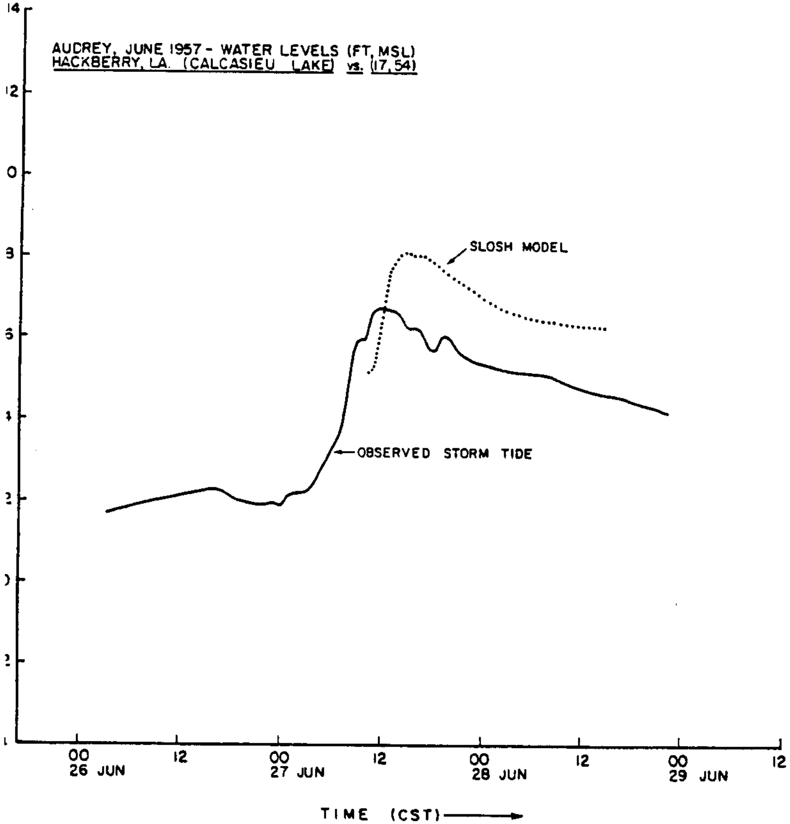


Figure 25. Marigrams at Hackberry, Louisiana.

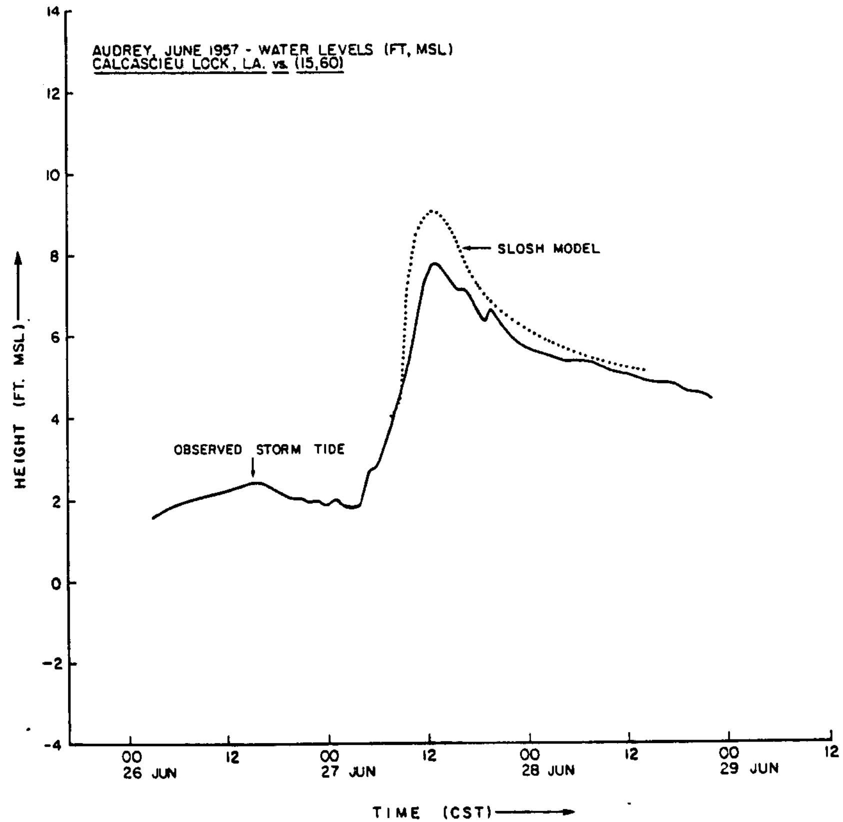


Figure 26. Marigrams at ICW lock on east side of Calcasieu Lake.

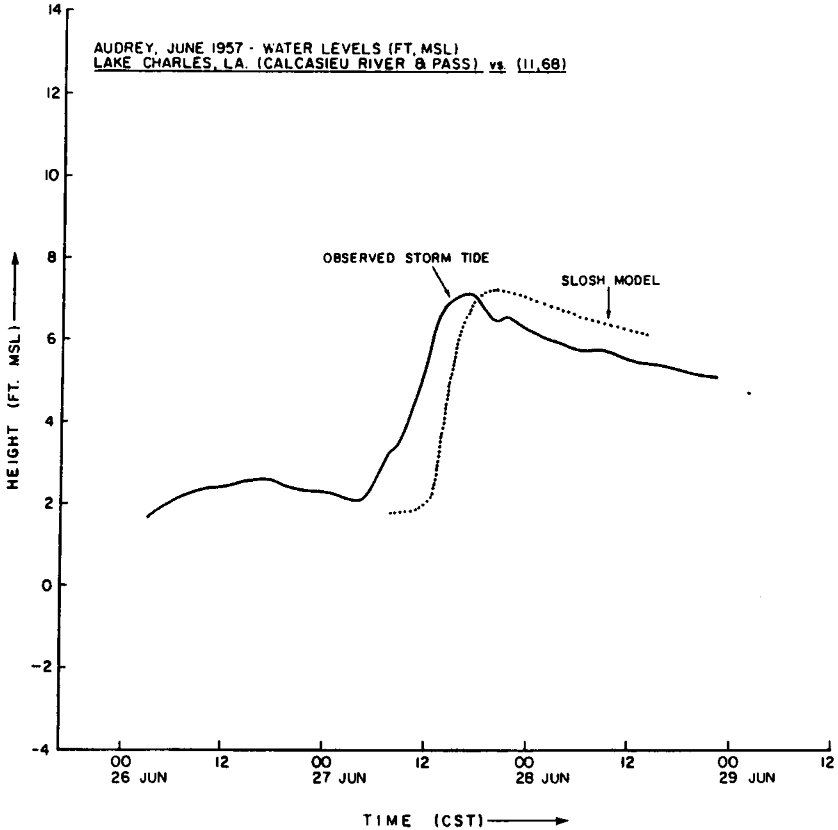


Figure 27. Marigrams at Lake Charles, Louisiana.

south of Lake Calcasieu, flanking longitude 93°15' west; they w
feet larger than modeled by SLOSH. By contrast, observed valu
less than modeled ones at sites further inland, north and east
Calcasieu. Thus, the area that includes Lake Charles Airport, wh
not flooded by Audrey, was modeled to have been covered by 10 f
surge, which would have produced an average water depth there
3 ft. To the left of Audrey's track, many modeled values wer
than those observed.

Audrey's storm tide was measured at dozens of locations
1958; 1963). For some of these gages, comparisons were made
gaged and SLOSH time histories. Figures 23-27 present comparis
sites: Fort Point and Port Arthur, Texas; and in Louisiana,
Charles, at the Calcasieu Lock of the Intracoastal Waterway,
Hackberry.

Figure 23 shows that at Fort Point, maximum observed surge
MSL) occurred at high tide (0500 local time). The model calcul
ft MSL, at 0400 to 0500 local time. Thus, the model's timing w
but the magnitude was too small.

No astronomical tide was incorporated into Port Arthur's st
values (Figure 24). The modeled maximum (3.88 ft MSL) occurred
this was two hours before the observed maximum, 4.8 ft MSL, but
foot of its height.

In Figure 25, the storm surge at Hackberry, on the west
Calcasieu Lake, had a modeled maximum of 8.05 ft MSL at 1500 lo
compared to the observed maximum of 6.7 ft MSL at 1100 LT. Ast
tide was unknown at this site but would probably not have acco
the disparities between these graphs.

On the east shore of Lake Calcasieu, the gage at the lock o
recorded a maximum of 7.7 ft MSL at 1300 LT (Figure 26). SLOS
a larger value (9.03 ft MSL), but at the same hour.

The maxima at Lake Charles (Figure 27) were similar (6.9
observed, vs. 7.09 ft modeled) but the times of occurrence di
four hours.

Figure 28 displays an array of 12 time history plots gen
the SLOSH model.

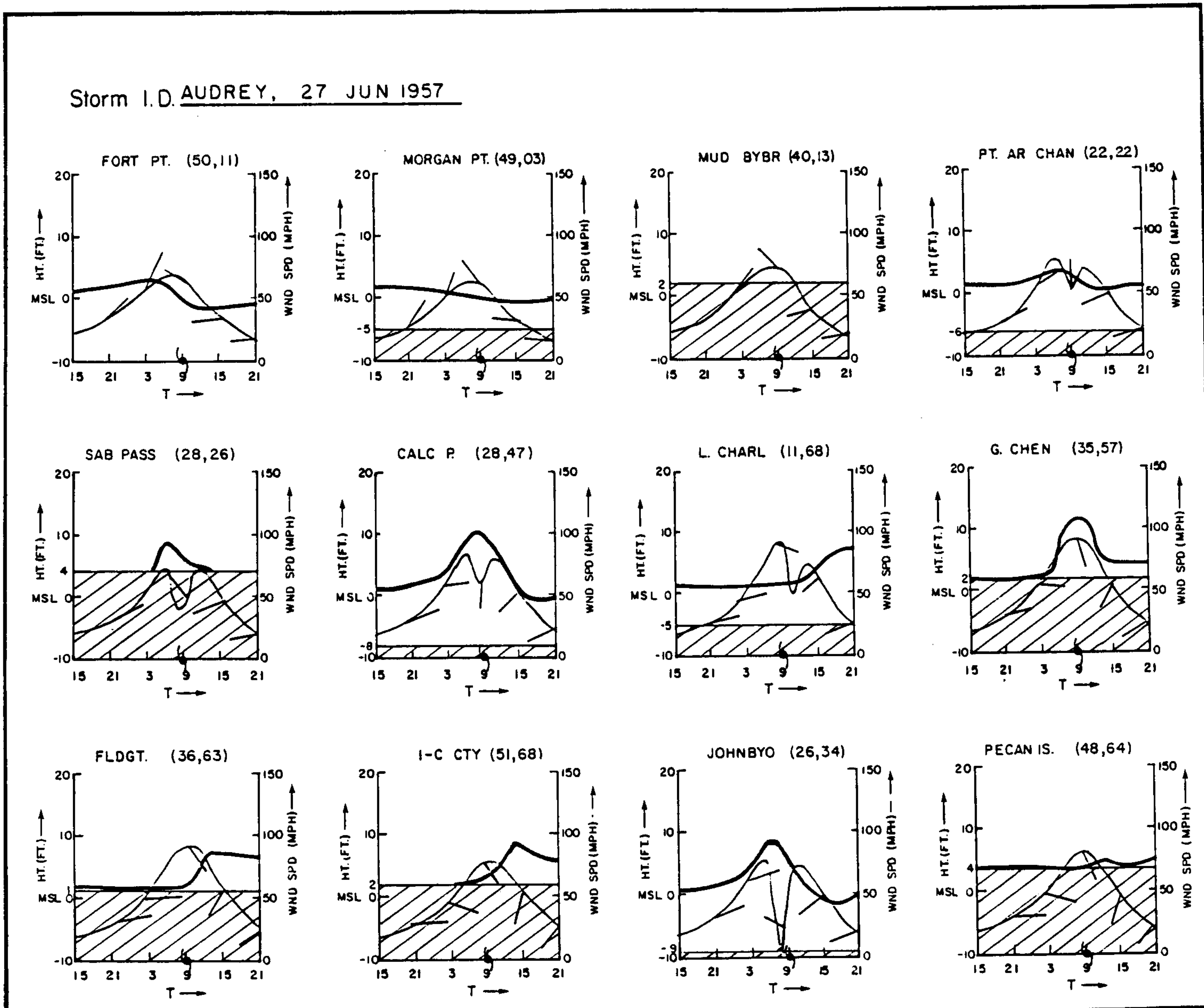


Figure 28. Same as Figure 13, but for Hurricane Audrey.

E. 1961 Hurricane (Carla)

Carla (1961) set new records for depth, duration and areal extent of ding from hurricane storm surge. Because of Carla's large size and ', erratic approach to the Texas coast, "...water levels remained in a foot or so of their peak values for nearly 24 hours" (Harris,). However, the slow advance of the storm gave residents of coastal low-lying parts of Texas and Louisiana time to move to higher ain; an estimated 350,000 did so, in the largest evacuation in the up to that time. Property damage exceeded $300M (over one billion ars in 1985 money) and was largely due to surge-induced flooding. e were over 40 deaths, caused mostly by the 20 or so tornadoes that a spawned.

Two to four days before landfall, while Gulf waters steadily rose g the Texas coast, Carla moved at only 5 to 10 mph. The track of eye, as seen by weather radars at Brownsville, Galveston and Lake les, was complicated by erratic, cycloidal motions. Sustained winds eding 75 mph were reported from Corpus Christi to Galveston for many s before landfall, and hurricane-force gusts were felt along almost entire length of the Texas coast. For at least two days before lfall, Carla's central pressure was below 950 mb. It was 931 mb at lfall, which was near Port O'Conner, Texas, about 3 p.m., on 11 ember 1961 (Dunn and Staff, 1962). Until landfall, Carla's center never less than 170 miles from Sabine Point, and therefore was irely south of the Sabine Lake SLOSH basin. The highest surges rred south of this basin's southern limit, on the coast near Port ca, where surges exceeded 12 ft MSL, and a high water line luding wave action) inside Lavaca Bay measured over 22 ft MSL. rding to Harris (1963), surge values on the Texas coast reached ir peak at a time when winds were parallel to the coast or even had a ht offshore component.

For input to the SLOSH model, Carla's eye center positions were se listed by Ho and Miller (1982). Radius of maximum wind 48 hours re landfall (LF) was initialized as 50 miles; was successively eased to 36 miles at LF; and was set to a constant 35 miles for the aining 24 hours. Delta-P varied from 70 mb, at LF-48 hours, to mb, at LF, and then decreased to 37 mb at and after LF+18 hours. er heights in the Gulf and inland lakes were initialized at +3 ft .

The envelope of high water computed for Carla as well as some gage sured surge heights (U.S. Army, 1962) are displayed in Figure 29. le 2 shows that maximum surge heights modeled by SLOSH generally were less than the gaged values, although, along the coastline, the discrepancy usually was less than a foot. At the last three sites, located inside Galveston Bay, the magnitudes of the gaged values are not readily explained (Harris, 1963), but may be the result of water oscillations within the bay being superimposed on Carla's surge. In any case, SLOSH-modeled values there are 2-4 ft too low.

Observed hourly values of surge height (U.S. Army, 1962) for Carla were compared with modeled values and are seen in Figures 30-36. Two of the gage sites were on Galveston Island--Pleasure Pier, facing the Gulf (Figure 30); and Pier 21, in Bolivar Roads (Figure 31). At both sites, there was good agreement between the observed and the modeled time histories of surges during the three days.

The gage site at Sabine Pass (U.S. Coast Guard station) is about 2 miles inland from the coastline. There is moderately good agreement between observed and modeled time histories (Figure 32), if one ignores short duration, small amplitude oscillations.

In Sabine Lake, no attempt was made to calculate the astronomical tide. At the Port Arthur gage (Figure 33), the modeled surge values were smaller and peaked sooner than was actually observed. At the gage at Orange (Figure 34), the observed surge began a prolonged rise on September 10 with decreasing water heights 2+ days later. The modeled surge started too late, model calculations ceased too soon (before the modeled values stopped increasing), the maximum value was much too small and the curves are in poor agreement.

At Baytown, Texas, the gage record (Figure 35) began late, after noon on September 11, and with a high value. The modeled surge decreased slightly the first day and then began a steady increase to a maximum (10.3 ft MSL) about 8 p.m. on the 11th, with a decrease thereafter, until calculations stopped. Although the observed surge was more than 3 ft higher than modeled, the timing of the two maxima agrees fairly well.

Figure 36 displays the surge time histories at the Mud Bayou Bridge over the ICW, northwest of High Island, Texas. The modeled values of storm surge were too low and the maximum was modeled to occur at a time later than that observed.

In Figure 37 are displayed 12 time histories generated by the SLOSH model.

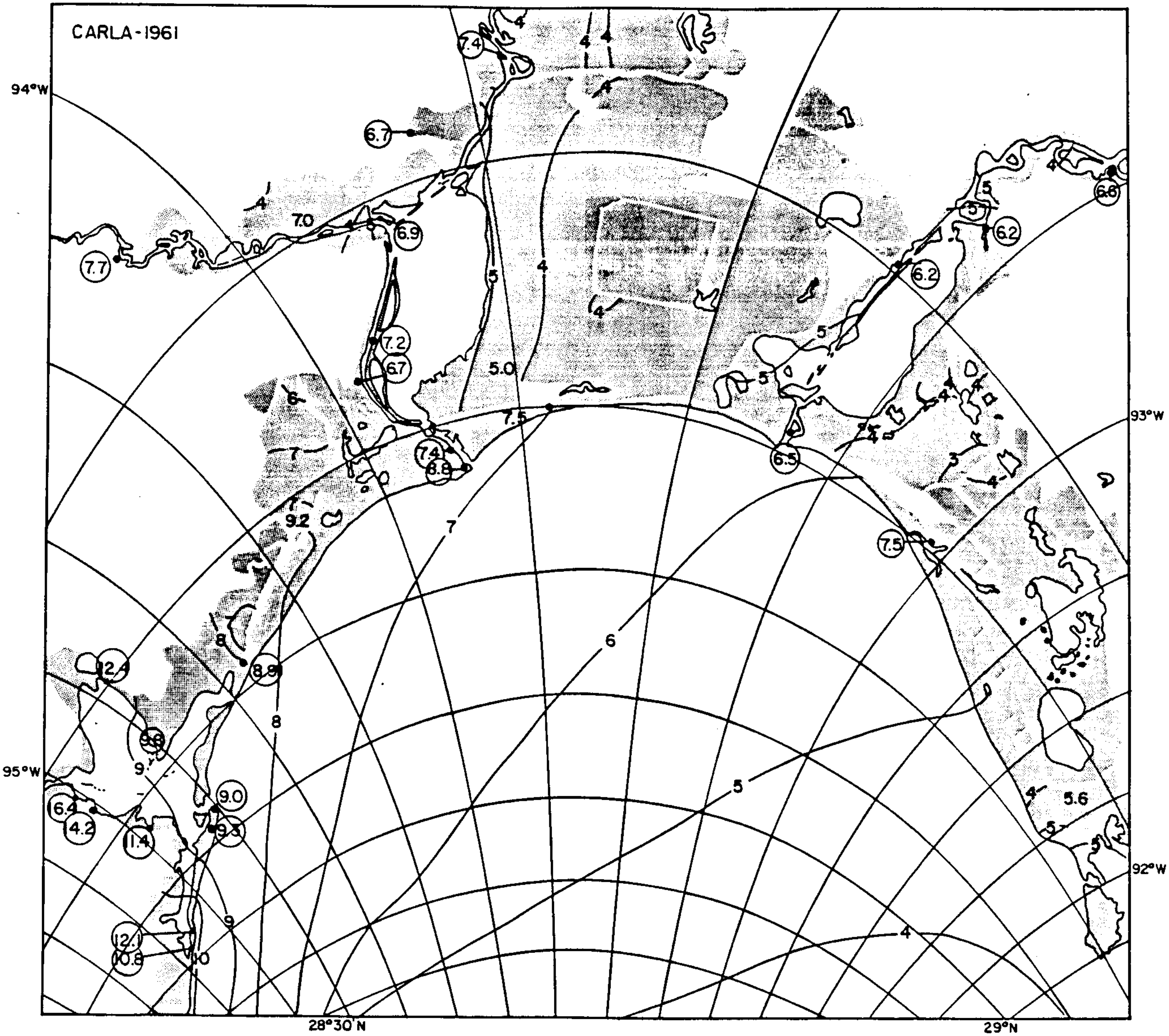


Figure 29. Modeled envelope of high water for Hurricane Carla, 11 September 1961.

Table 2. Surge heights at selected sites.

	Maximum Surge (feet, MSL) Observed	Modeled
A. Gulf Coast Sites:		
Calcasieu Pass, Louisiana	6.6'	6.2'
Sabine Pass, Texas (U.S. Coast Guard)	7.4'	7.2'
Sabine Pass, Texas (jetties)	8.8'	7.0'
Galveston, Texas (Pleasure Pier)	9.3'	8.8'
B. Other Sites:		
Grand Cheniere, Louisiana	7.5'	5.6'
ICW locks on Calcasieu Lake, Louisiana	6.1'	4+'
Port Arthur, Texas	7.1'	5.7'
Orange, Texas	7.4'	3.8'
Beaumont, Texas	7.7'	3+'
Anahuac, Texas	12+'	9.5'
Baytown, Texas	13.7'	10.3'
Kemah, Texas	14.2'	10.0'

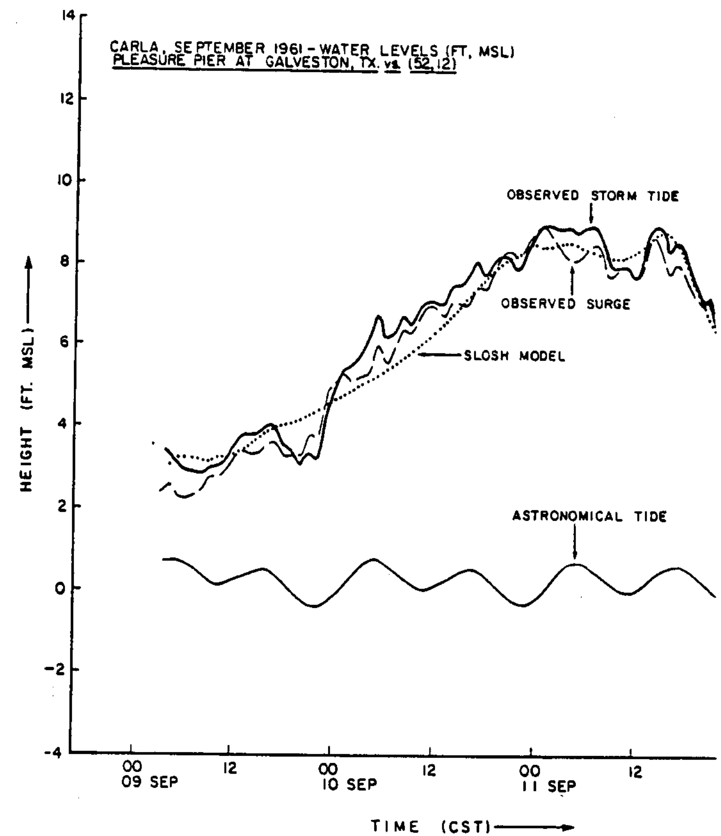


Figure 30. Marigrams at Pleasure Pier, Galves

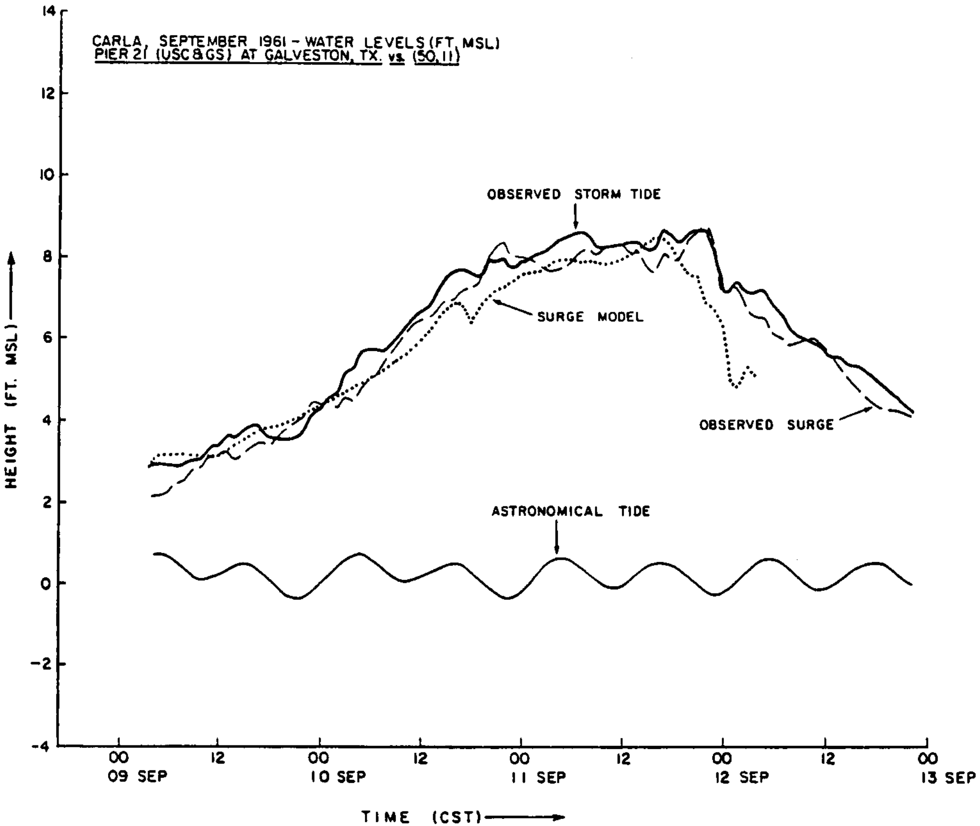


Figure 31. Marigrams at Pier 21, Fort Point, Texas.

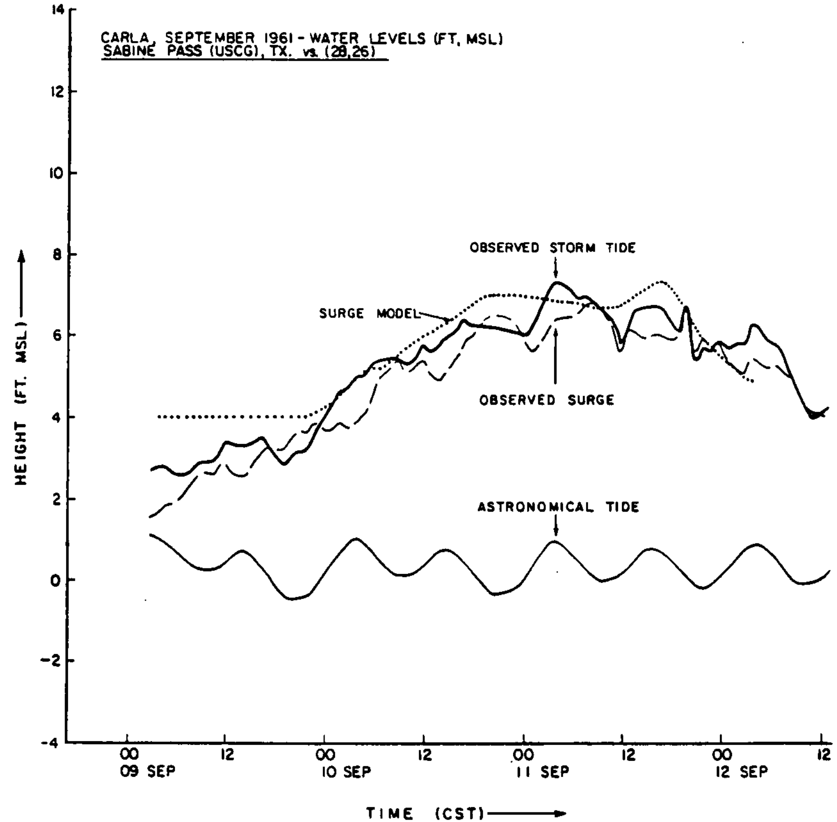


Figure 32. Marigrams at Sabine Pass, Texas.

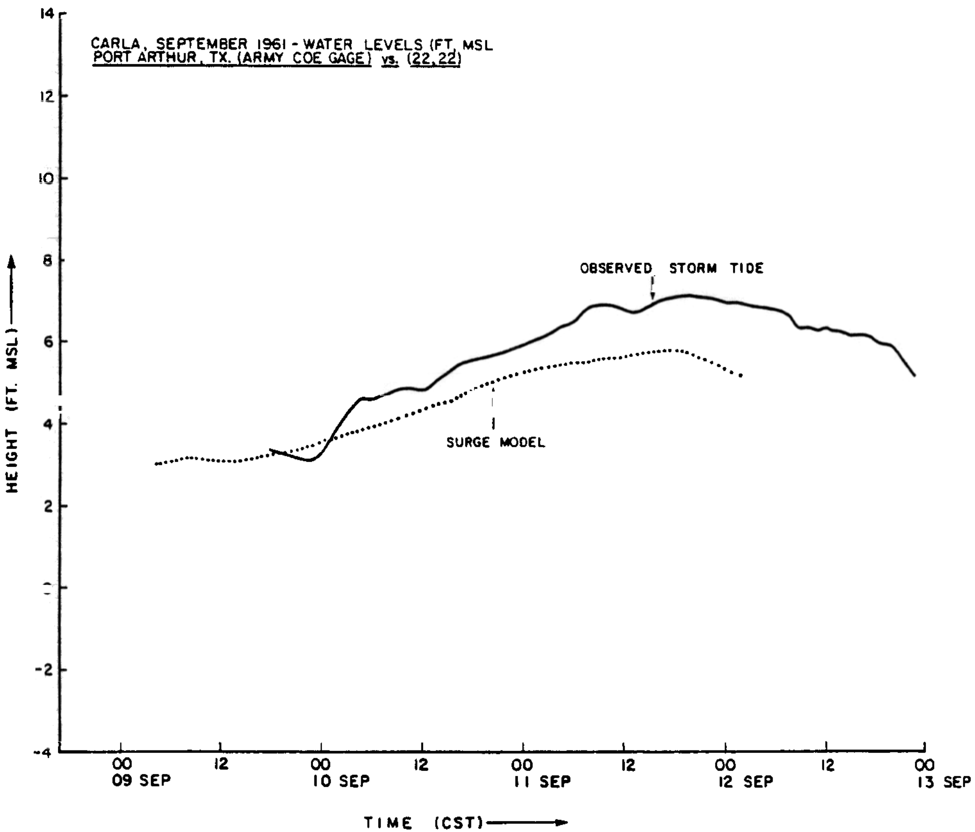


Figure 33. Marigrams at Port Arthur, Texas.

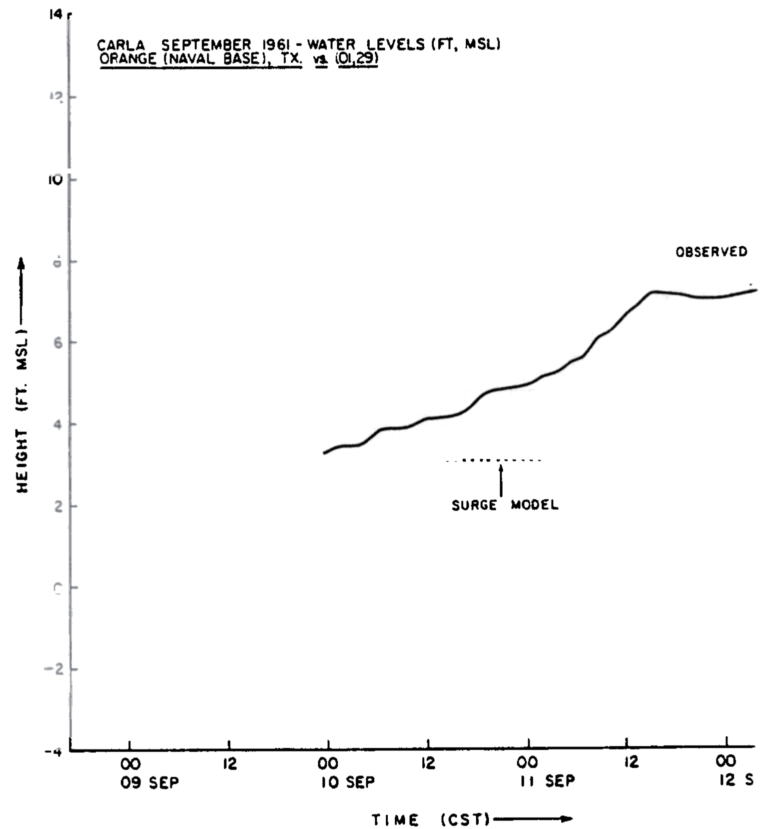


Figure 34. Marigrams at Orange Texas.

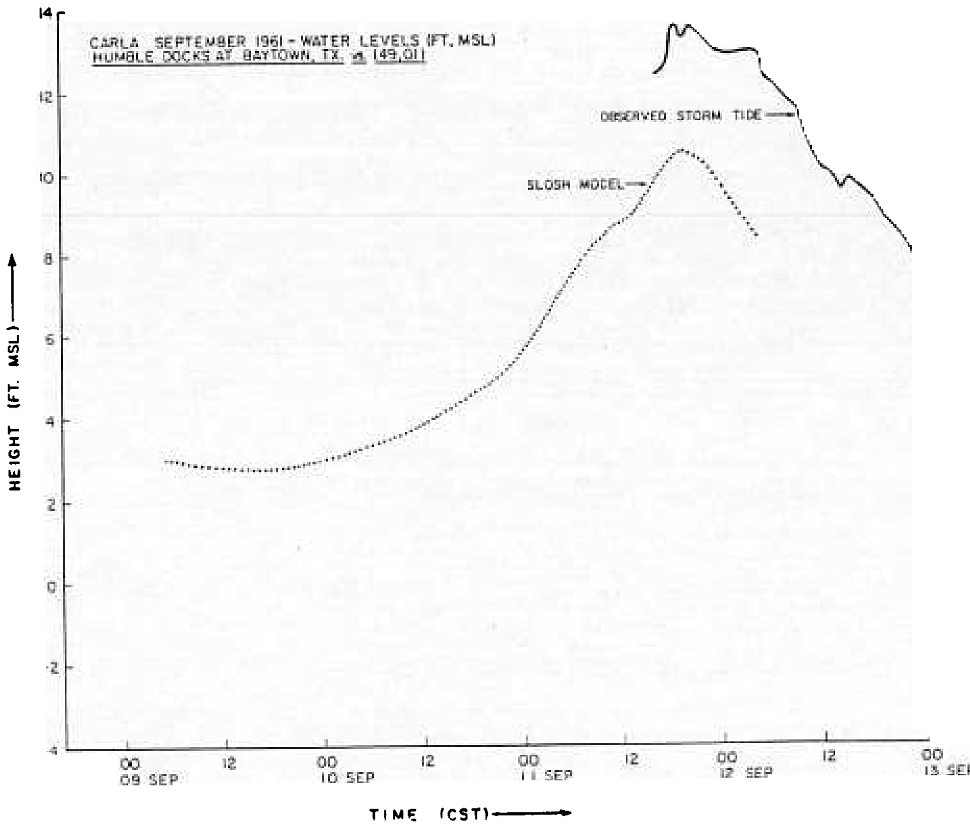


Figure 35 Marigrams at Baytown Texas

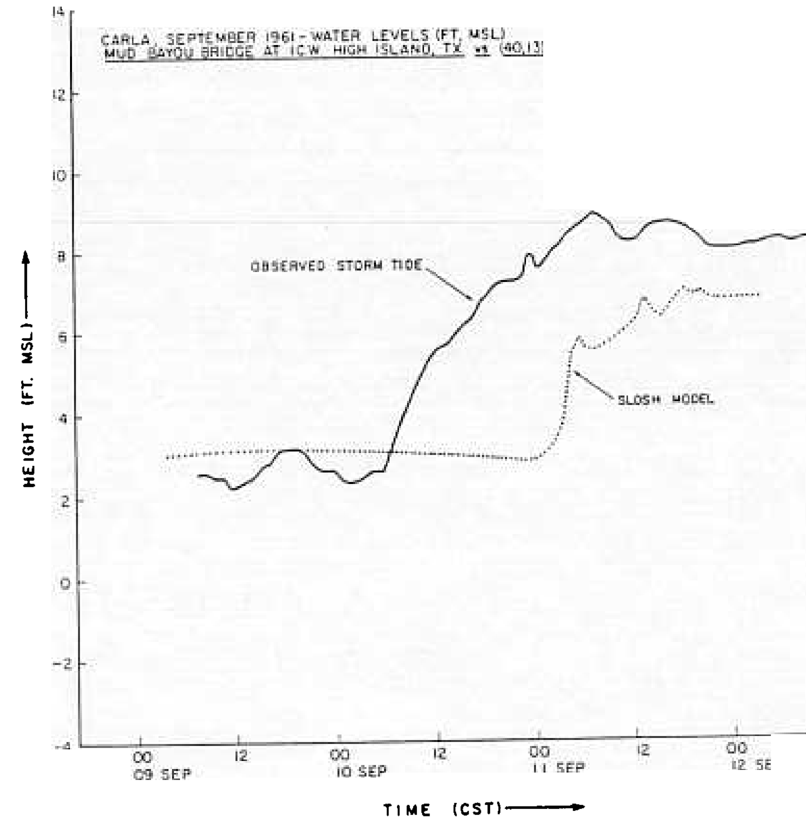


Figure 36. Marigrams at Mud Bayou Bridge, near High Isl

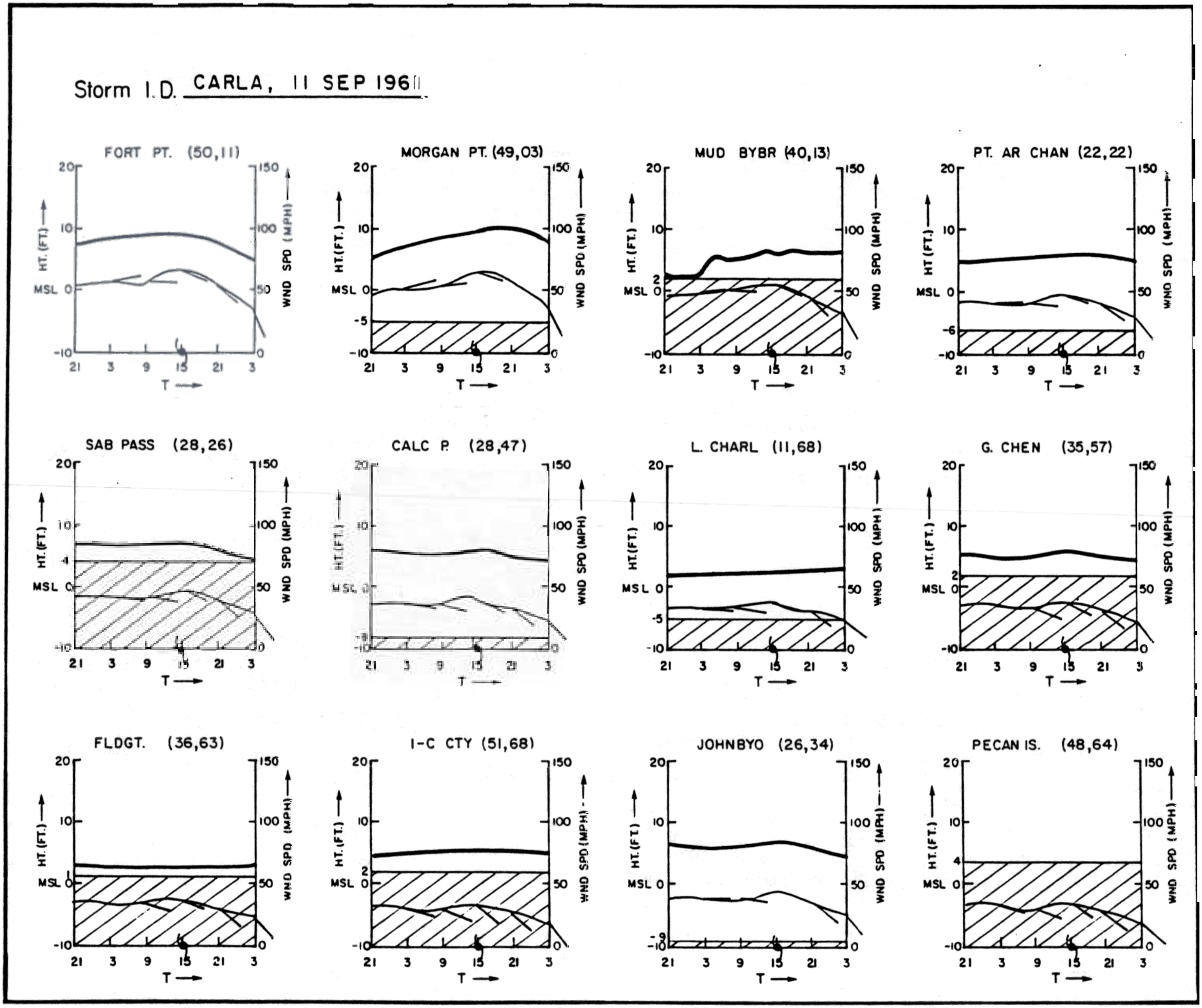


Figure 37. Same as Figure 13, but for Hurricane Carla.

71 Hurricane (Edith)

time Edith (1971) crossed the Louisiana coast, during her final landfall, she was once again intensifying. Two weeks a disturbance in the Intertropical Convergence Zone on 2, became a closed low (depression) on the 5th, deepened to pical Storm Edith on the 7th and a hurricane less than 24 . According to Simpson and Hope (1972):

luring the next 6-hour period as the center approached Gracias (Nicaragua) on September 9, the pressure fell lly to 943 mb. A reconnaissance plan at 5000-ft eleva- measured sustained winds of 140 knots (160 mph) just e the center reached the coast at midday. The recon- ance crew reported extreme turbulence, jeopardizing the rity of the aircraft and safety of the crew. Edith's ctly formed eye shrank at times to 5 miles in ter."

lost strength while crossing Honduras. She moved over the nduras, made a second landfall on the British Honduras (now ast and was poorly organized while crossing the Yucatan On September 13, Edith moved offshore, over the Bay of intensified little, moved slowly west-northwestward, stalled evening and then drifted slowly northward. During the the 15th, Tropical Storm Edith began accelerating northeast- ntensifying. By noon, she again was a hurricane, with a essure of 982 mb. Her center's last landfall was at an area between Grand Cheniere, Louisiana, and the Rockefeller fuge, about 8 a.m. on the 16th. After this, she weakened and as her circulation center continued northeastward.

and, highest winds were 69 mph, with gusts to 96 mph at uisiana. In the United States, no fatalities were attributed even though she spawned several tornadoes. Rain depths of ches were reported. Crop losses in Louisiana accounted for ith's $25M in damages. Storm tides ranged up to about 8 feet n Bay and Cote Blanche Bay, Louisiana.

issance aircraft in Edith found that the eye was about 20 iameter shortly after midnight on 16 September, with no size d during a flight five hours later. Therefore, for input to ' model, the RMW was set at (a constant) 20 miles for all 72 odel time. Minimum sea level pressure at the last report) from the aircraft was 977 mb; using this, ΔP at landfall (LF) was set to 32 mb. At LF-48 hours, ΔP was assumed to be 10 mb, to grow linearly to 32 mb at LF, to decrease linearly to 10 mb at LF+18 hours and to be 10 mb for the last six hours. Datums were +1.6 ft.

The envelope of high water for Edith, as well as five (circled) gage-measured maxima are displayed in Figure 38. The observed 9.7 ft MSL high water mark at Cypremort Point (in Vermilion Bay; lower right corner of Figure 38) is not well modeled.

Records of gage traces of Edith's storm tides were not available. However, there were occasional reports of water heights from Calcasieu Pass (near Edith's point of landfall) that were included in statements from the Weather Bureau Office at Lake Charles, Louisiana (U.S. Dept. of Commerce, 1971). They were used to fabricate a time history at Calcasieu Pass, and are shown in Figure 39. The modeled values are seen to be too low by as much as two feet during the period of record. Also, the record gives no indication of the maximum value or decrease of the observed surge.

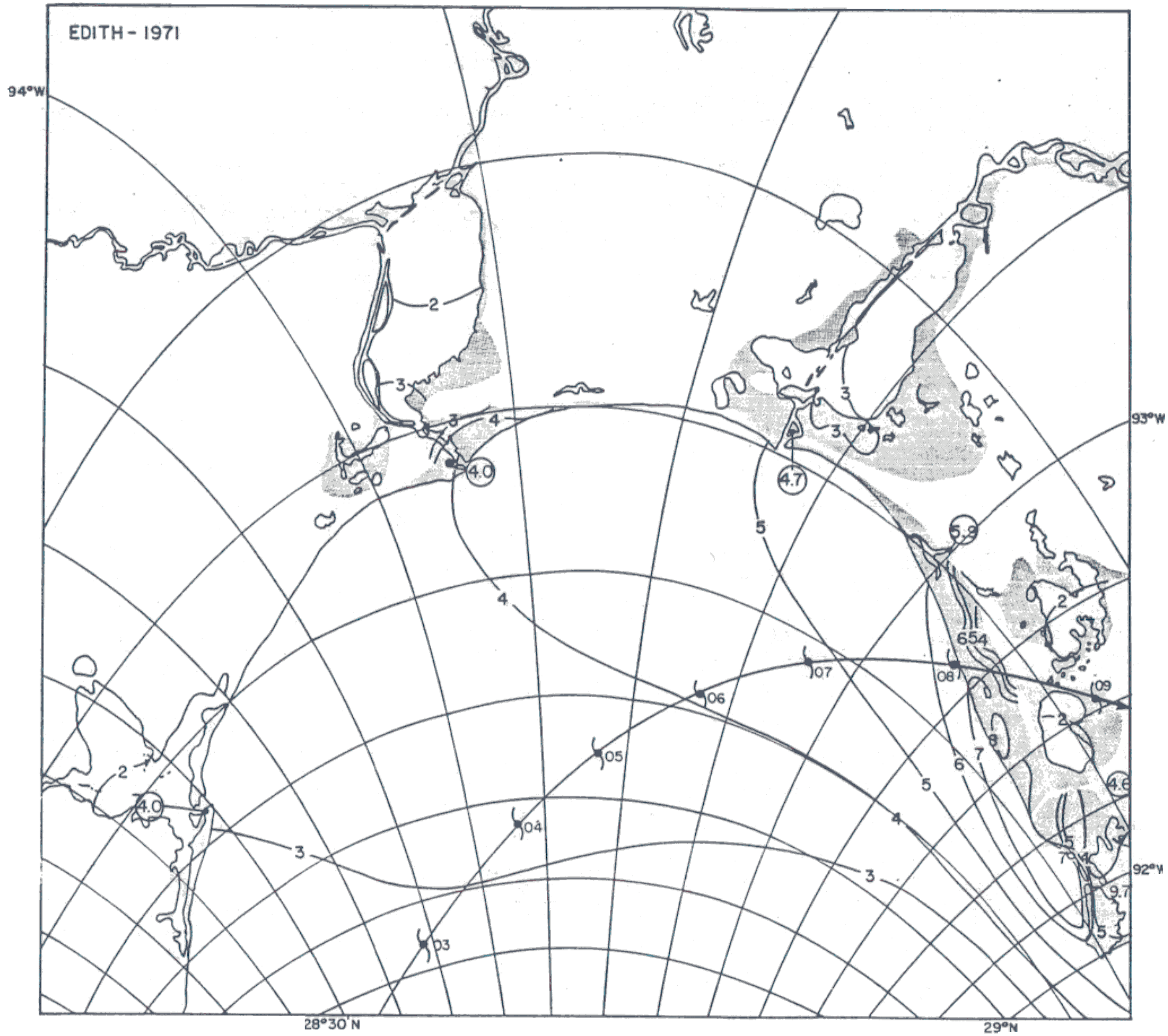
In Figure 40 are displayed 12 time histories generated by the SLOSH model.

7. MAPS OF MAXIMUM ENVELOPE OF WATER ("MEOW") FROM SLOSH RUNS USING DATA FOR HYPOTHETICAL HURRICANES

A. Hypothetical Storm Tracks and Populations

Comparisons between observed and modeled surge values in five historical hurricanes (section 6) indicated that SLOSH possesses some modeling skill. Furthermore, a study by Jarvinen and Lawrence (1985) indicated that the mean absolute error in surge height calculated by SLOSH was about 1.4 ft, based on a comparison between modeled and observed surges at 523 sites, during 10 hurricanes. Although the error range was from -7.1 ft to +8.8 ft, the standard deviation was only 2.0 ft and 79% of the errors lay within one standard deviation of the mean error, -0.3 ft. (On the average, the model slightly underpredicted surge values.)

SLOSH-modeled storm surge calculations were used to create maps of surge flooding in the Sabine Lake Basin for use in evacuation planning. The model was supplied with data from hypothetical storms and the resulting surge calculations were composited to produce maps of the maximum envelope of water. This section details why these calculations were made and how the compositing was done.


EDITH - 1971
94°W
93°W
92°W
28°30'N
29°N
4.0
4.7
5.9
4.0
9.7
03
04
05
06
07
08
09

ed ope Ed
ept

Storm surge height, at any particular location, partly depends on distance between that site and the storm's center. For a single storm, the model would produce a map of surge height for the modeled period of time (usually 72 hours), with values valid for only that particular storm track. If there were two storms, identical in every respect, except that one followed a track that was parallel to but separated from the other by 50 miles,† and if the model was run with first one and then the other storm, and a comparison made of surge values, then very likely there would be geographic sites with surge values from one storm that differed markedly from those modeled for the other storm. When preparing plans for emergency evacuation, this dependency of surge height on storm track can be troublesome. What is needed is surge flooding potential for the entire basin--a map of surge heights that depends only on intensity (using the categories defined by Saffir and Simpson), storm speed and direction. To do this, a procedure was adopted that involved making surge calculations for each of an ensemble of six to eight storms, all having the same intensity and speed, and on parallel headings, separated (usually) by 20 miles. Then at each grid square, the maximum surge value that was calculated from any storm in the ensemble was extracted and saved. After this procedure was performed for all grid squares, the result was a basin map depicting the "maximum envelope of water," or MEOW, for the specified storm category, direction and speed. For this basin, the hypothetical storms were specified to move in one of four straight line directions, and at one of three constant speeds, as summarized in Table 3. There were seven tracks for the west-northwestward moving storms (Figure 41), eight tracks for the north-northwestward (Figure 42) and also for the northward (Figure 43) moving storms and six storm tracks comprised the ensemble for the storms heading northeastward (Figure 44). Altogether, 356 sets of data for hypothetical storms were run, using the SLOSH model, to create the results to be presented below. The selection of directions and speeds was based on advice of hurricane specialists at the NOAA's National Hurricane Center.

†A difference ("error") of 50 miles in storm track is not very large when compared to the vagaries of tracks of real hurricanes. The average error of 12-hour forecast position, for U.S. Atlantic coast tropical cyclones, during 1970-1979, was about 59 statute miles, while for 24-hour forecasts, position error was about 125 statute miles (Neumann and Pelissier, 1981). Thus, if a storm eye were forecast to make landfall 20 miles east of Sabine Point in 24 hours, and if, in fact, it made landfall anywhere along the coast in this basin, the error in forecast position would be no worse than average.

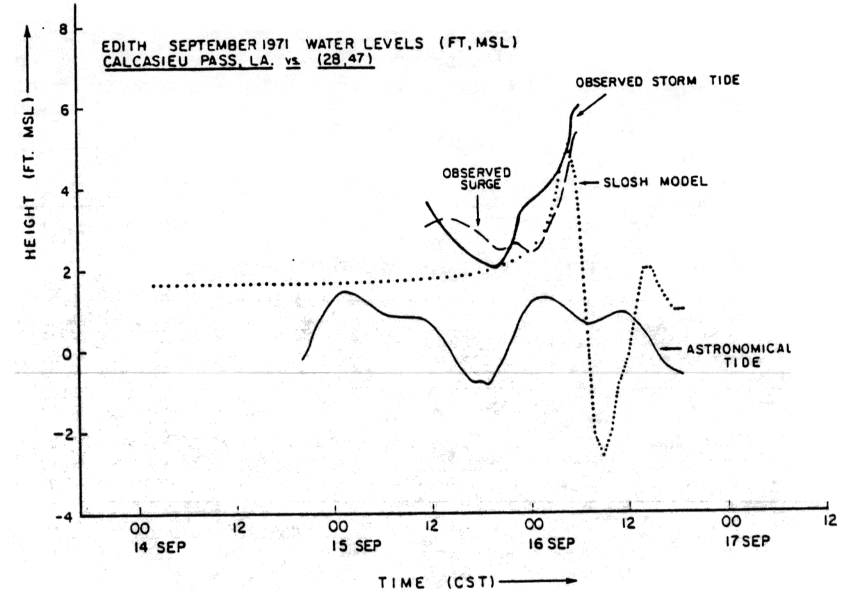


Figure 39. Marigrams at Calcasieu Pass, Louisiana.

Table 3. Sabine Lake Basin's hypothetical storms: Directions, speeds, (Saffir/Simpson) intensities, number of parallel tracks and the (resulting product) number of runs.

Direction	Speeds (mph)	Intensities	Tracks	Runs
WNW	5, 10, 20	1, 2 and 3		63
WNW†	5, 10, 20	4 and 5	5, 4	27†
NNW	5, 10, 20	1 through 5	8	120
N	5, 10, 20	1 through 5	8	120
NE†	10, 20	, 2 and 3	6, 4, 3	26†

†Several NE and WNW moving hurricanes near or over land cannot maintain all intensity levels.

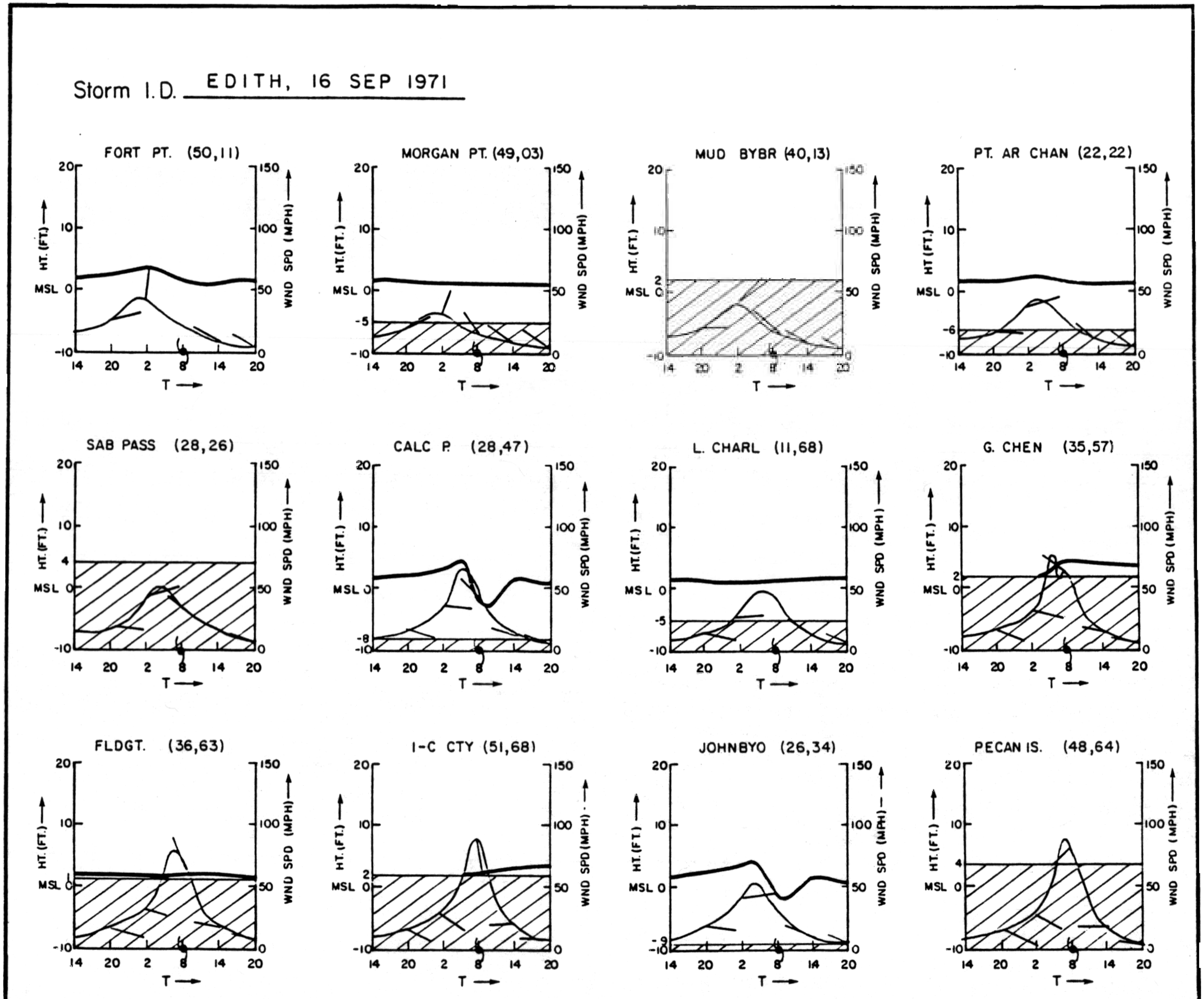


Figure 40. Same as Figure 13, but for Hurricane Edith.

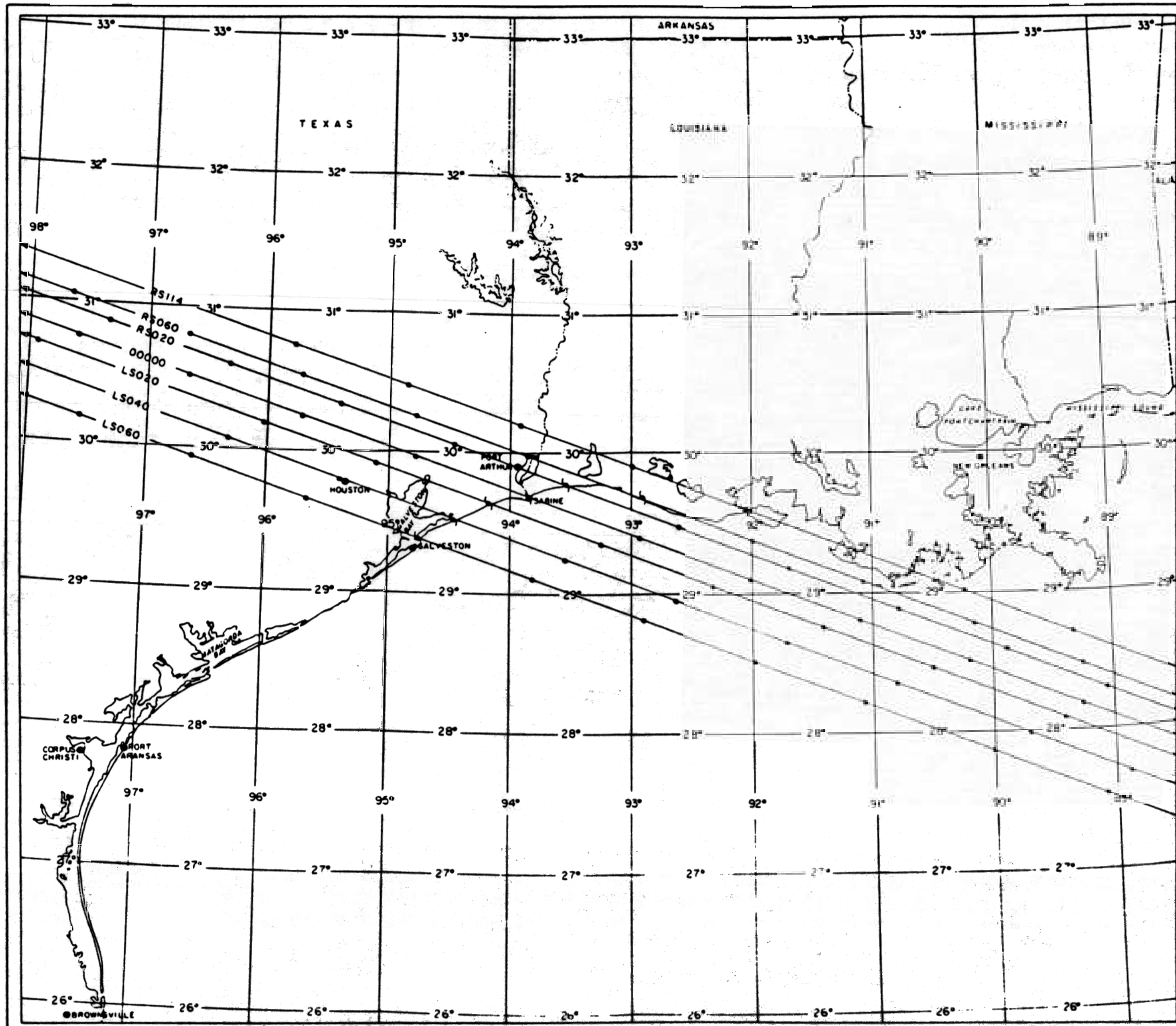
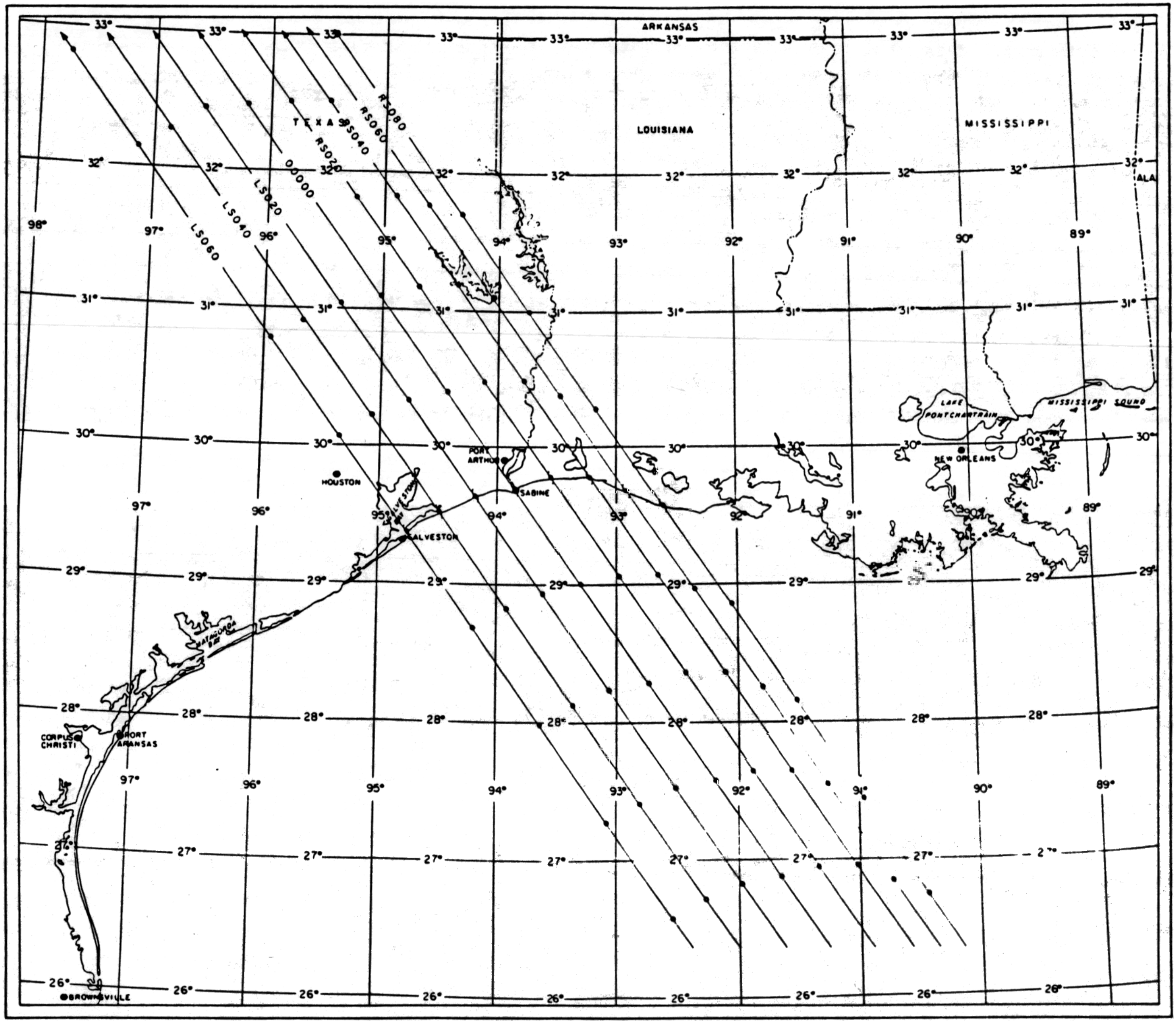


Figure 41. Tracks of the hypothetical hurricanes that were used for calculating the maximum envelope of water (MEOW). Hurricane symbol is at point of landfall of eye of storm, and dots are eye positions at 6 hour increments (10 mph). Tracks are identified by the distance (in miles) of their landfall point to the left side (LS) or



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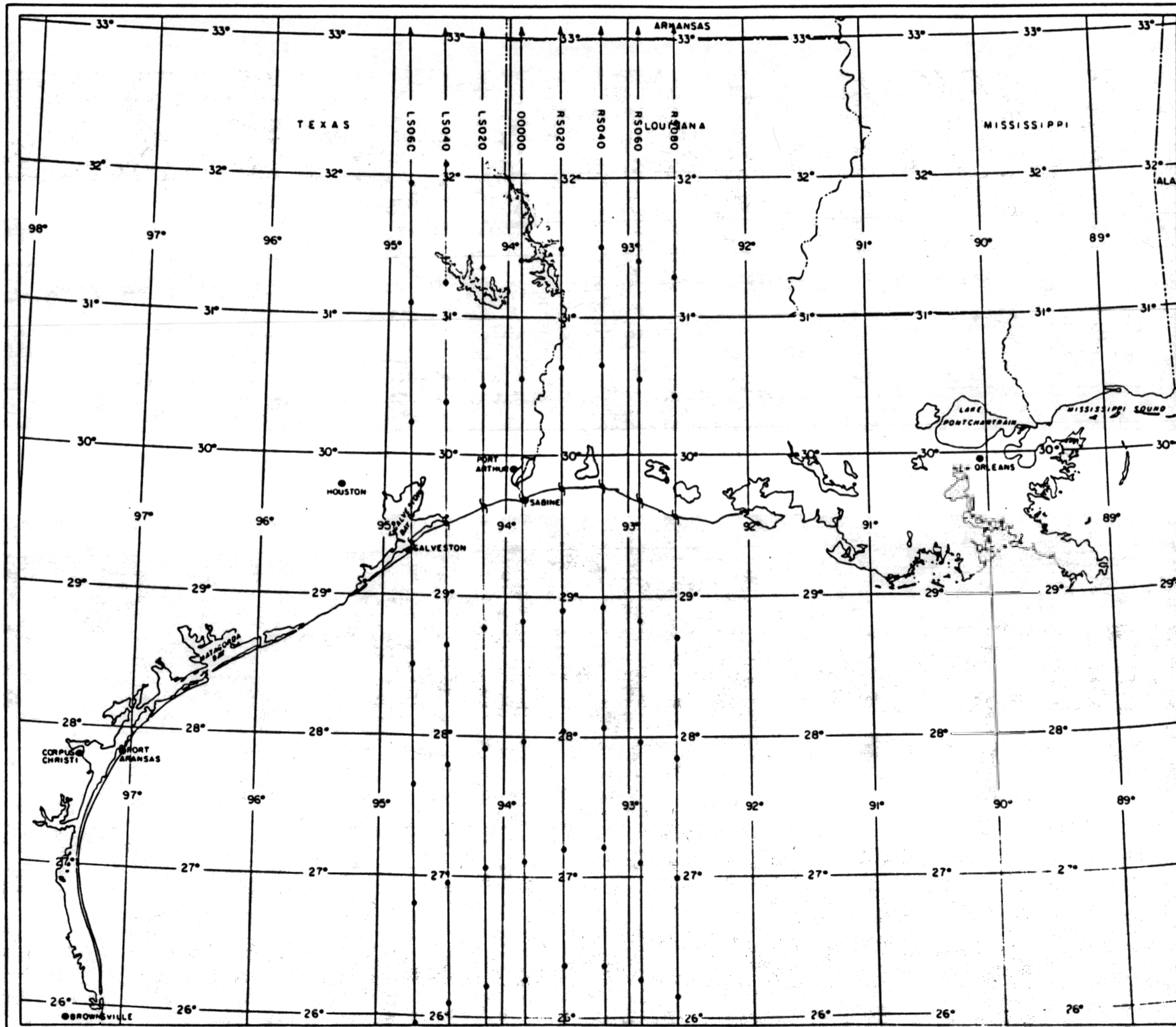

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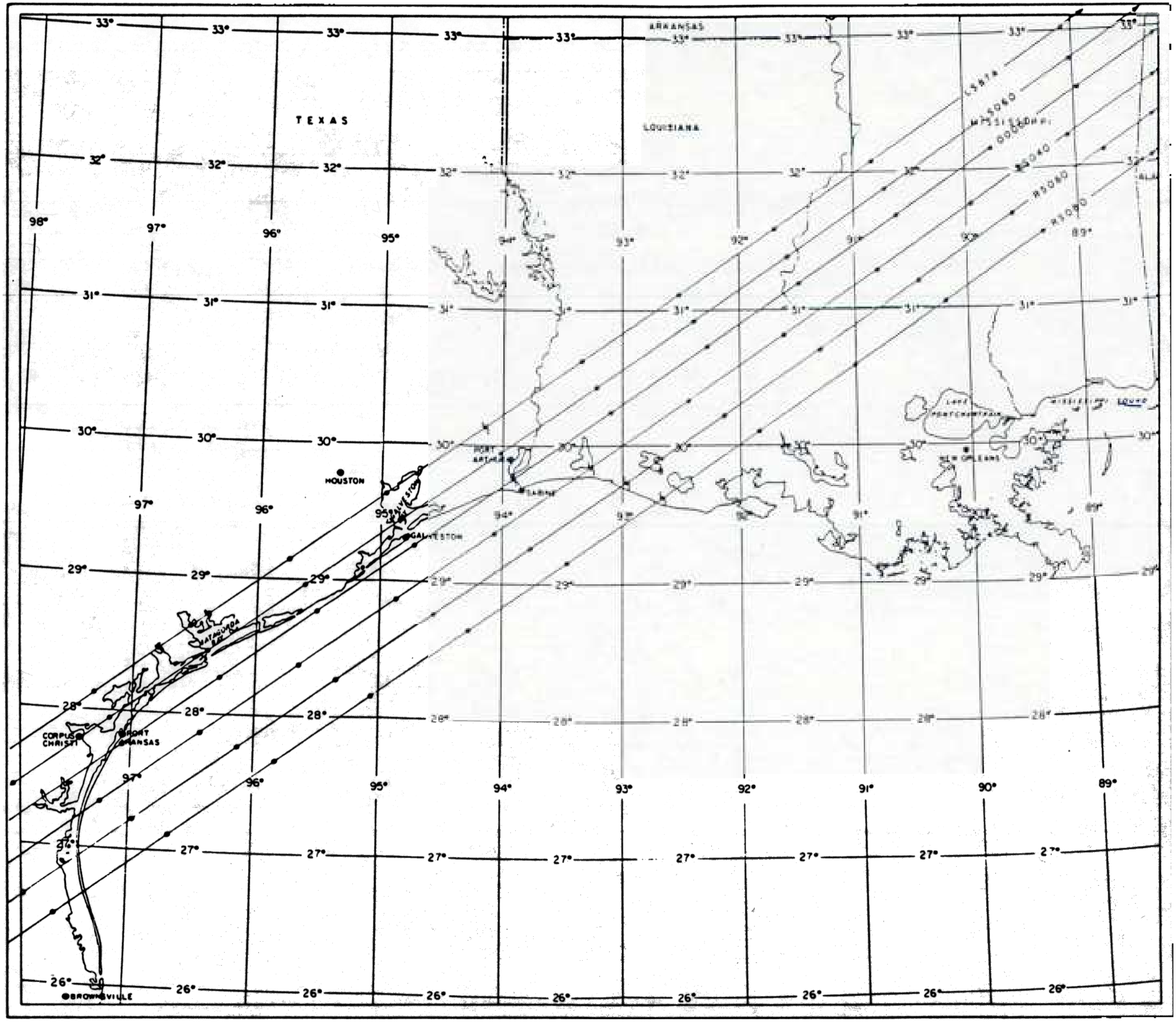


Figure 44 Same as Figure 4 but only northeastbound storms

B. Intensities and Radii of Maximum Winds of Hypothetical Storms

Most hurricanes weaken after making landfall because the central pressure increases (the storm "fills") and the RMW tends to increase. Table 4 summarizes the rates of pressure filling and RMW increases that were used in the calculations for the hypothetical storm runs. The rates were based partly on the work of Schwerdt et al. (1979).

C. Initial Water Height

Based on observations from tide gages in the area of this basin, tidal anomalies of about +2 ft MSL before arrival of a hurricane are not uncommon. Thus, all SLOSH runs of hypothetical hurricanes were supplied with initial datums of +2 ft MSL. In an actual hurricane, if tide gage data in this basin indicate that there is no tide anomaly, then subtract 2 ft from the modeled values found in the maps (below).

D. The "MEOW" Figures

There are 51 MEOWS: six for northeastward moving storms and 15 for each of the three other directions. They are presented in the Appendix in Figures A1 through A51. As in the case of the historical storms, the contours represent the height of water above mean sea level, in 1-ft increments. The shaded areas indicate land areas that were modeled to have been inundated.

8. MAXIMUM ENVELOPES OF WATER ("MEOW") SERIES "A"

In all of the MEOW figures, we have omitted analyses of surge heights in the lower left portion of the figures bounded by the curved, heavy line. This was done because this region had no onshore winds from any hypothetical storm, even those furthest west from Sabine Point. (Surge height calculations in the blank region can be obtained from the atlas of surges modeled with the Galveston Bay basin.)

The MEOW figures are grouped principally by track direction, then by (increasing) speed and then by (increasing) intensity category. Thus, storms heading west-northwestward (WNW) are in Figures A1-A5 (storm speed of 5 mph), Figures A6-A10 (10 mph) and Figures (A11-A15) (20 mph). Storms heading north-northwestward (NNW) are in Figures A16-A20 (5 mph), Figures A21-A25 (10 mph) and Figures A26-A30 (20 mph). Northbound (N) storm MEOWS are depicted in Figures A31-A35 (5 mph), Figures A36-A40

Table 4. Time change of pressure difference and radius of maximum wind for hypothetical hurricanes in the Lake Sabine/Lake Calcasieu region.

(A) Values of pressure difference (ΔP, millibars) and radius of maximum wind (RMW, statute miles), beginning at time of landfall (LF) of center of storm and every six hours after LF.

	[illegible]		LF + 6		[illegible]		LF + 18		LF + 2[illegible]	
Category	ΔP	RMW	ΔP	RMW	ΔP	RMW	ΔP	RMW	ΔP	RMW
1	20	25	15	30	11	35	10	40	10	45
2	40	25	22	30	14	35	11	40	10	45
3	60	25	35	25	22	30	16	35	12	40
4	80	25	38	25	24	30	17	35	13	40
5	100	15	40	20	25	25	17	30	13	40

(B) Values of pressure difference (ΔP, millibars) at landfall (LF) and at each of the first six hours after LF.

Category	Landfall ΔP	LF+1 ΔP	LF+2 ΔP	LF+3 ΔP	LF+4 ΔP	LF+5 ΔP	LF+ ΔP
1	20	19	18	17	16	15	15
2	40	37	34	31	28	25	22
3	60	54	50	45	41	38	35
4	80	63	56	51	47	43	38
5	100	67	58	53	48	44	40

(10 mph) and Figures A41-A45 (20 mph). MEOWS for storms heading northeastward (NE) are displayed in Figures A46-A48 (10 mph) and Figures A49-A51 (20 mph). Within each direction/ speed set, MEOWS for the weakest (category 1) are followed by MEOWS for storms of successively stronger categories.

In general, bigger surge heights at the coastline were calculated to result from faster-moving and/or stronger storms; inundation would extend further inland from slower-moving and/or stronger storms; and the coastal region with the highest surges would be further eastward (near Vermilion Bay) from northeast-moving storms than from storms with any other heading.

Category 1 storms (Figures A1, A6, A11, A16, A21, A26, A31, A36, A41, A46 and A49) would flood land areas at 2-3 ft MSL, lying north and east of Sabine Lake and also the region adjacent to or east of Calcasieu Lake. There would be sharp gradients ("waterfalls") in surge height at Sabine Pass and Calcasieu Pass. The northern limit of much of the modeled category 1 flooding would be the spoil bank on the south flank of the Intracoastal Waterway (ICW). Flooding inland from the coast between the passes would usually be constrained by the embankment carrying Louisiana Highway 82, and flooding of shore areas east and west of Calcasieu Lake would be impounded by Highway 27. However, both these highways would be overtopped, in places, by surges from NNW/20 (Figure A26) and N/20 (Figure A41) storms. Maximum surge heights in the lakes would be about 4 ft MSL for northbound storms, and less from storms with other headings.

On the coast, category one storms would produce their maximum surge values in the region near Sabine Point. Values exceeding 8 ft MSL were calculated for NNW/20 mph storms (Figure A26) and N/20 storms (Figures A41). Surges exceeding 7 ft were calculated for WNW/20 (Figure A11), NE/20 (Figure A49), NNW/10 (Figure A21) and N/10 (Figure A36) storms, while surge heights exceeded 6 ft MSL for WNW/10 (Figure A6), NNW/5 (Figure A16), N/5 (Figure A31) and NE/10 (Figure A46) storms. Maximum surge along the coast would be only about 5 ft MSL for storms moving WNW at 5 mph (Figure A1).

Category 2 storms' MEOWS are displayed in Figures A2, A7, A12, A17, A22, A27, A32, A37, A42, A47 and A50. Surge maxima along the coast would exceed 12 ft MSL for WNW/20 (Figure A12), NNW/20 (Figure A27) or N/20 (Figure A42) storms. Lowest surge maxima (about 9 ft MSL) were modeled for some 5 mph storms, as seen in Figures A2, A17 and A32. Louisiana Highways 27 and 82 would be substantially or completely overtopped. Flooding would occur along the Sabine River, northward towards Orange, Texas, and along the Neches River, which feed: northwest part of Sabine Lake. Storms heading north or north- (Figures A17, A22, A27, A32, A37 and A42) would produce sur that would exceed 9 ft MSL along the Sabine and also the Nech and that would exceed 7 ft MSL on the Calcasieu River u Charles. East of Calcasieu Lake, the complex of chenieres would restrict surge flow, so that many regions would h gradients in surge height. The spoil banks of the ICW woul flanked and isolated by surges from storms heading north-no north. Surge heights in the north part of Vermilion Bay wo 12 ft MSL, but would be less from the 20 mph storms.

Category 3 storms' MEOWS are illustrated in Figures A3, A18, A23, A28, A33, A38, A43, A48, and A51. Large portion of would be flooded. Surges at the coast would be not less than for NE/10 mph storms, Figure A48. On the coast, surges from storms (Figures A3, A18 and A33) would be over 10 ft MSL; 10 mph storms (Figures A8, A23, and A38) they would exceed and from the 20 mph storms (Figures A13, A28 and A43) they wo 17 ft MSL. Port Arthur, Texas, was modeled to avoid surge flo storms heading west-northwest (Figures A3, A8 and A13) and (Figures A48 and A51). But the city would be flooded by storms heading north-northwest (Figures A18, A23 and A28) (Figures A33, A38 and A43). Surge "run-up" between Sabin Galveston Bay would exceed 15 ft MSL for west-northwest storms be over 20 ft MSL for north-northwest or northbound storms. of the Neches River and the Sabine River would undergo flooding from storms from any direction except northeast.

In Louisiana, the ICW would act as a barrier to surges fr 3 storms heading northeastward, but storms with other direct produce flooding around the spoil banks flanking the ICW; a storms (Figure A43) would overtop the banks. Category 3 sto north or north-northwest would flood the Lake Charles Airport. East of Calcasieu Lake, surge run-up would exceed for 5 mph storms from west-northwest (Figure A3) and f northwest (Figure A18).

Category 4 storms were modeled to flood essentially Louisiana portion of this basin, as seen in Figures A4, A9, A24, A29, A34, A39 and A44. Over land, water heights were ca exceed 11 ft MSL everywhere. The area around Lake Charles would retain some unflooded land only when storms headed wes (Figures A4, A9 and A14) or when they moved at 5 mph (Figu and A34). Port Arthur, Texas was modeled to be flooded, spoil bank between it and Sabine Lake, and especially by storms heading north-northwest (Figures A19, A23 and A29) or north (Figures A34, A39 and A44). Surge run-up south of Beaumont would be at least 18 ft MSL (west-northwest/20; Figure A14) and as much as 27 ft MSL (N/20; Figure A34).

As seen in Figures A5, A10, A15, A20, A25, A30, A35, A40 and A45, storm surges from the hypothetical category 5 storms in this study were somewhat smaller than their category 4 counterparts. This circumstance results from the RMW for category 5 storms (15 statute miles) being less than that of the other categories, as noted in Table 4. If the RMW of the category 5 storms had been the same as those used to simulate the category 4 storms, the surges from the 5's would have been even larger than that modeled for the 4's.

9. ACKNOWLEDGMENTS

We appreciate the instruction and guidance we received from Drs. Chester Jelesnianski, Jye Chen and Albion Taylor, of NOAA's Techniques Development Laboratory; without them, this basin's data set and modeling abilities would not have been developed. We thank Joan David for her painstaking and meticulous illustrations, and Tom Tatnall for his photographic skills. Editing by Constance Arnhols of AOML and typing by Gail Derr are very much appreciated.

10. REFERENCES

Anthes, R. A. (1982): Tropical cyclones--their evolution, structure and effects. Amer. Meteor. Soc. Meteor. Monogr. 19, 208 pp.

Crawford, K. C. (1979): Hurricane surge potentials over southeast Louisiana as revealed by a storm-surge forecast model: A preliminary study. Bull. Amer. Meteor. Soc., 60, 422-429.

Dunn, G. E. et al. (1962): The hurricane season of 1961. Mon. Wea. Rev., 90, 107-113.

Fisher, W. L., L. F. Brown, Jr., J. H. McGowen and C. G. Groat (1972) Environmental geologic atlas of the Texas coastal zone--Beaumont-Port Arthur area. Univ. Texas, Austin, Bureau of Economic Geology 91 pp., 9 maps.

Fisher, W. L., J. H. McGowen, L. F. Brown, Jr. and C. G. Groat (19 Environmental geologic atlas of the Texas coastal zone--Galves Houston area. Univ. Texas, Austin, Bureau of Economic Geology pp., 9 maps.

Frankenfield, H. C. (1915): The tropical storm of August 10, 1 Mon. Wea. Rev., 43, 405-412.

Graham, H. E. and G. N. Hudson (1960): Surface winds near the cente hurricanes (and other cyclones). U.S. Dept. of Commerce, Nati Hurricane Research Project, Report #39, 200 pp.

Harris, D. L. (1958): Hurricane Audrey storm tide. U.S. Dept. Commerce, National Hurricane Research Project, Report #23, 19 pp

______ (1959): An interim hurricane storm surge forecasting gu U.S. Dept. of Commerce, National Hurricane Research Project, Re #32, 24 pp.

______ (1963): Characteristics of the hurricane storm surge. Dept. of Commerce, Weather Bureau Tech. Paper #48, 139 pp.

______ (1981): Tides and tidal datums in the United States. Spe Report #7, U.S. Army Corps of Engineers, Coastal Enginee Research Center, Fort Belvoir, VA, 22060.

Ho, F. P. and J. F. Miller (1982): Pertinent meteorological hurricane tide data for Hurricane Carla. U.S. Dept. of Comme National Oceanic and Atmospheric Administration, Tech. Report 32, 111 pp.

Jarvinen, B. R. and M. B. Lawrence (1985): An evaluation of the S storm-surge model. Bull. Amer. Meteor. Soc., 66, 1408-1411.

Jelesnianski, C. P. (1967): Numerical computations of storm surges bottom stress. Mon. Wea. Rev., 95, 740-756.

______ (1972): "SPLASH" (Special Program to List Amplitudes of Su from Hurricanes): I. Landfall storms. U.S. Dept. of Comme National Oceanic and Atmospheric Administration, Tech. Memo. TDL-46, Washington, D.C., 52 pp.

__ and A. D. Taylor (1973): A preliminary view of storm surges efore and after storm modifications. U.S. Dept. of Commerce, ational Oceanic and Atmospheric Administration, Tech. Memo. ERL MPO-3, Washington, D.C., 33 pp.

henreuter, P. H. et al. (1957): Survey of meteorological factors ertinent to reduction of loss of life and property in hurricane ituations. U.S. Dept. of Commerce, National Hurricane Research 'roject, Report #5, 87 pp.

'nce, M. B. and B. M. Mayfield (1977): Satellite observations of rochoidal motion during Hurricane Belle, 1976. Mon. Wea. Rev., 05, 1458-1461.

:, P. L. et al. (1957): The hurricane season of 1957. Mon. Wea. ?ev., 85, 401-408.

ınn, C. J. and J. M. Pelissier (1981): An analysis of Atlantic :ropical cyclone forecast errors, 1970-1979. Mon. Wea. Rev., 109, 248-1256.

__, G. W. Cry, E. D. Caso and B. R. Jarvinen (1981): Tropical :yclones of the North Atlantic Ocean, 1871-1980. U.S. Dept. of :ommerce, National Oceanic and Atmospheric Administration, National :limatic Center, Asheville, NC, 174 pp.

, R. B. and M. D. Blum (1957): Hurricane Audrey, 1957. Mon. Wea. Rev., 85, 221-227.

:rdt, R. W., F. P. Ho and R. R. Watkins (1979): Meteorological :riteria for standard project hurricane and probable maximum hurri- :ane wind fields, Gulf and east coasts of the United States. NOAA 'ech. Report NWS 23, U.S. Dept. of Commerce, National Oceanic and \tmospheric Administration, National Weather Service, Washington,).C., 317 pp.

;on, R. H. and J. R. Hope (1972): Atlantic hurricane season of .971. Mon. Wea. Rev., 100, 256-267.

__ and H. Riehl (1981): The Hurricane and Its Impact. Louisiana ;tate University Press, Baton Rouge, LA, 398 pp.

Army (1957): Memorandum Report, Hurricane Audrey, 27 June 1957, outhern Louisiana. U.S. Army, Corps of Engineers, New Orleans, LA, 0 pp., 20 plates.

U.S. Army (1962): Report on Hurricane Carla 9-12 September 1961. U.S. Army, Corps of Engineers, Galveston, TX, 77 pp., 30 plates.

U.S. Army (1972): History of hurricane occurrences along coastal Louisiana. U.S. Army, Corps of Engineers, New Orleans, LA, 43 pp., 20 plates.

U.S. Army (1979): Texas coast hurricane study, feasibility report. U.S. Army, Corps of Engineers, Galveston, TX, 76 pp., 5 plates.

U.S. Department of Commerce (1971): Hurricane Edith, 5-17 September 1971, preliminary report. National Oceanic and Atmospheric Administration, National Weather Service, Off. Met. Oper., 72 pp.

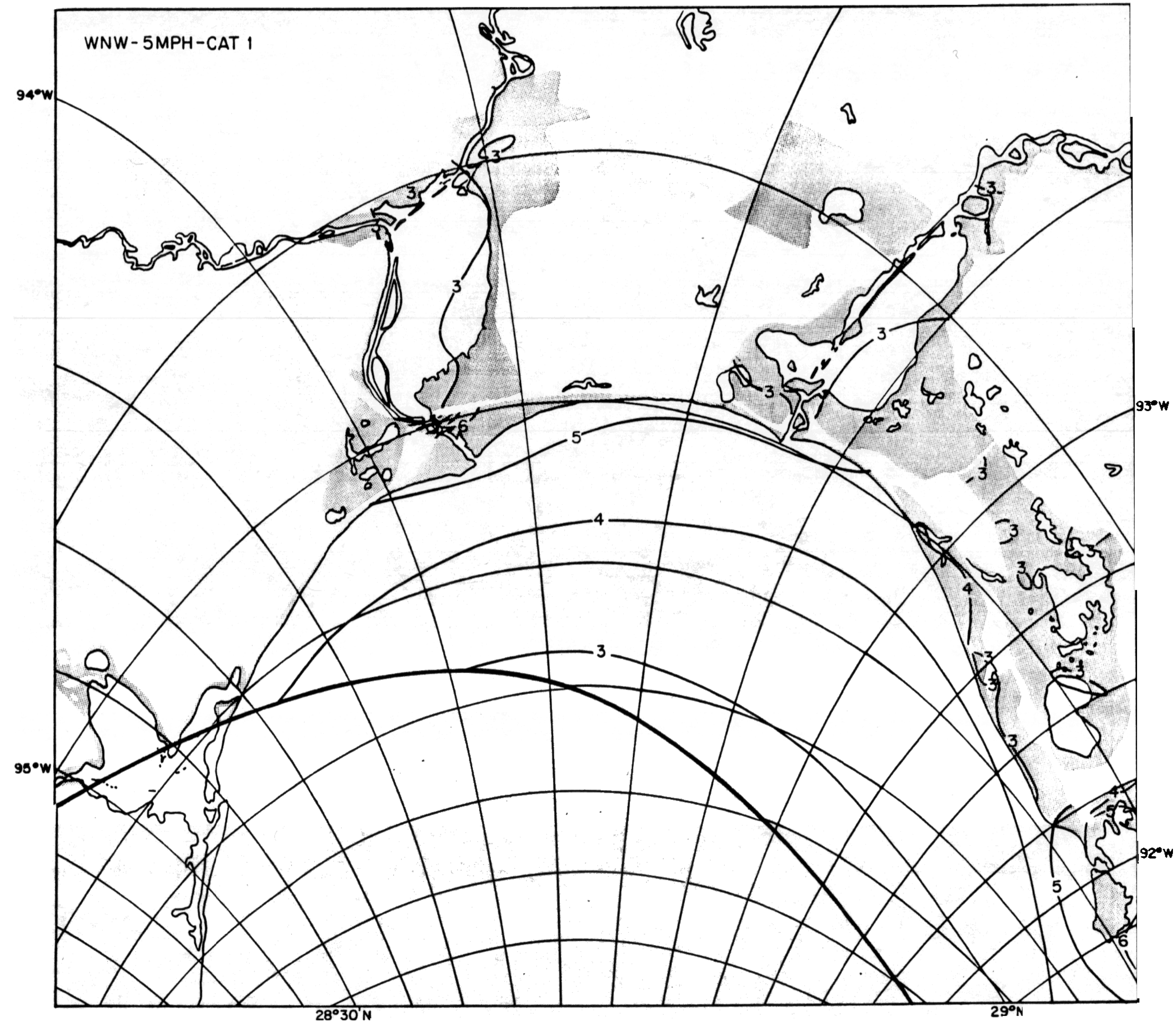
Zoch, R. T. (1949): North Atlantic hurricanes and tropical disturbances of 1949. Mon. Wea. Rev., 62, 339-341.

APPENDIX: Maximum Envelopes of Water ("MEOW")

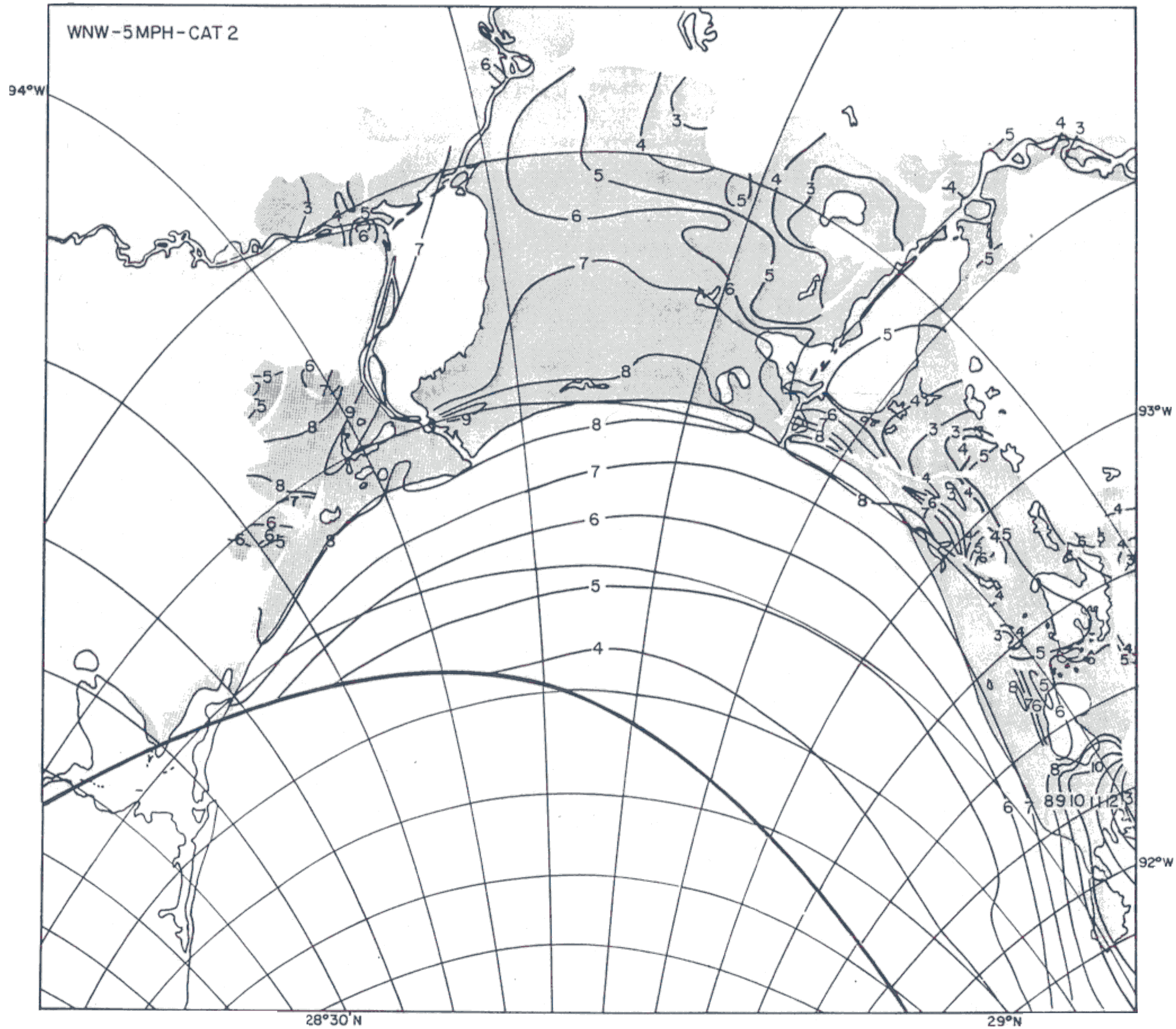
Page		Title
A-1	MEOW	West-northwestbound, 5 mph, category 1 hurricane.
A-2	MEOW	West-northwestbound, 5 mph, category 2 hurricane.
A-3	MEOW	West-northwestbound, 5 mph, category 3 hurricane.
A-4	MEOW	West-northwestbound, 5 mph, category 4 hurricane.
A-5	MEOW	West-northwestbound, 5 mph, category 5 hurricane.
A-6	MEOW	West-northwestbound, 10 mph, category 1 hurricane.
A-7	MEOW	West-northwestbound, 10 mph, category 2 hurricane.
A-8	MEOW	West-northwestbound, 10 mph, category 3 hurricane.
A-9	MEOW	West-northwestbound, 10 mph, category 4 hurricane.
A-10	MEOW	West-northwestbound, 10 mph, category 5 hurricane.
A-11	MEOW	West-northwestbound, 20 mph, category 1 hurricane.
A-12	MEOW	West-northwestbound, 20 mph, category 2 hurricane.
A-13	MEOW	West-northwestbound, 20 mph, category 3 hurricane.
A-14	MEOW	West-northwestbound, 20 mph, category 4 hurricane.
A-15	MEOW	West-northwestbound, 20 mph, category 5 hurricane.
A-16	MEOW	North-northwestbound, 5 mph, category 1 hurricane.
A-17	MEOW	North-northwestbound, 5 mph, category 2 hurricane.
A-18	MEOW	North-northwestbound, 5 mph, category 3 hurricane.
A-19	MEOW	North-northwestbound, 5 mph, category 4 hurricane.
A-20	MEOW	North-northwestbound, 5 mph, category 5 hurricane.
A-21	MEOW	North-northwestbound, 10 mph, category 1 hurricane.
A-22	MEOW	North-northwestbound, 10 mph, category 2 hurricane.
A-23	MEOW	North-northwestbound, 10 mph, category 3 hurricane.
A-24	MEOW	North-northwestbound, 10 mph, category 4 hurricane.
A-25	MEOW	North-northwestbound, 10 mph, category 5 hurricane.
A-26	MEOW	North-northwestbound, 20 mph, category 1 hurricane.
A-27	MEOW	North-northwestbound, 20 mph, category 2 hurricane.
A-28	MEOW	North-northwestbound, 20 mph, category 3 hurricane.
A-29	MEOW	North-northwestbound, 20 mph, category 4 hurricane.
A-30	MEOW	North-northwestbound, 20 mph, category 5 hurricane.
A-31	MEOW	Northbound, 5 mph, category 1 hurricane.
A-32	MEOW	Northbound, 5 mph, category 2 hurricane.
A-33	MEOW	Northbound, 5 mph, category 3 hurricane.
A-34	MEOW	Northbound, 5 mph, category 4 hurricane.
A-35	MEOW	Northbound, 5 mph, category 5 hurricane.
A-36	MEOW	Northbound, 10 mph, category 1 hurricane.
A-37	MEOW	Northbound, 10 mph, category 2 hurricane.
A-38	MEOW	Northbound, 10 mph, category 3 hurricane.
A-39	MEOW	Northbound, 10 mph, category 4 hurricane.
A-40	MEOW	Northbound, 10 mph, category 5 hurricane.
A-41	MEOW	Northbound, 20 mph, category 1 hurricane.
A-42	MEOW	Northbound, 20 mph, category 2 hurricane.
A-43	MEOW	Northbound, 20 mph, category 3 hurricane.
A-44	MEOW	Northbound, 20 mph, category 4 hurricane.
A-45	MEOW	Northbound, 20 mph, category 5 hurricane.
A-46	MEOW	Northeastbound, 10 mph, category 1 hurricane.
A-47	MEOW	Northeastbound, 10 mph, category 2 hurricane.
A-48	MEOW	Northeastbound, 10 mph, category 3 hurricane.
A-49	MEOW	Northeastbound, 20 mph, category 1 hurricane.
A-50	MEOW	Northeastbound, 20 mph, category 2 hurricane.
A-51	MEOW	Northeastbound, 20 mph, category 3 hurricane.

The MEOW represents the maximum high water that can occur i Sabine Lake Basin for a particular hurricane direction, speed intensity category. For the west-northwestbound (WNW) storms, were seven runs for each of categories 1, 2 and 3; five runs category 4 and four runs for category 5. For the north-northwest (NNW) and northbound (N) storms there were eight runs used for category. For the northeastbound (NE) storms, there were six run category 1 storms, four runs for category 2 and three runs for cat 3 storms.

The MEOWS are analyzed at 1-ft contour intervals. The value relative to mean sea level. The dark-shaded areas represent dry that has been inundated. Each MEOW is identified with a label i upper left corner.



WNW-5MPH-CAT 1
94°W
95°W
93°W
92°W
28°30'N
29°N
3
4
5
6



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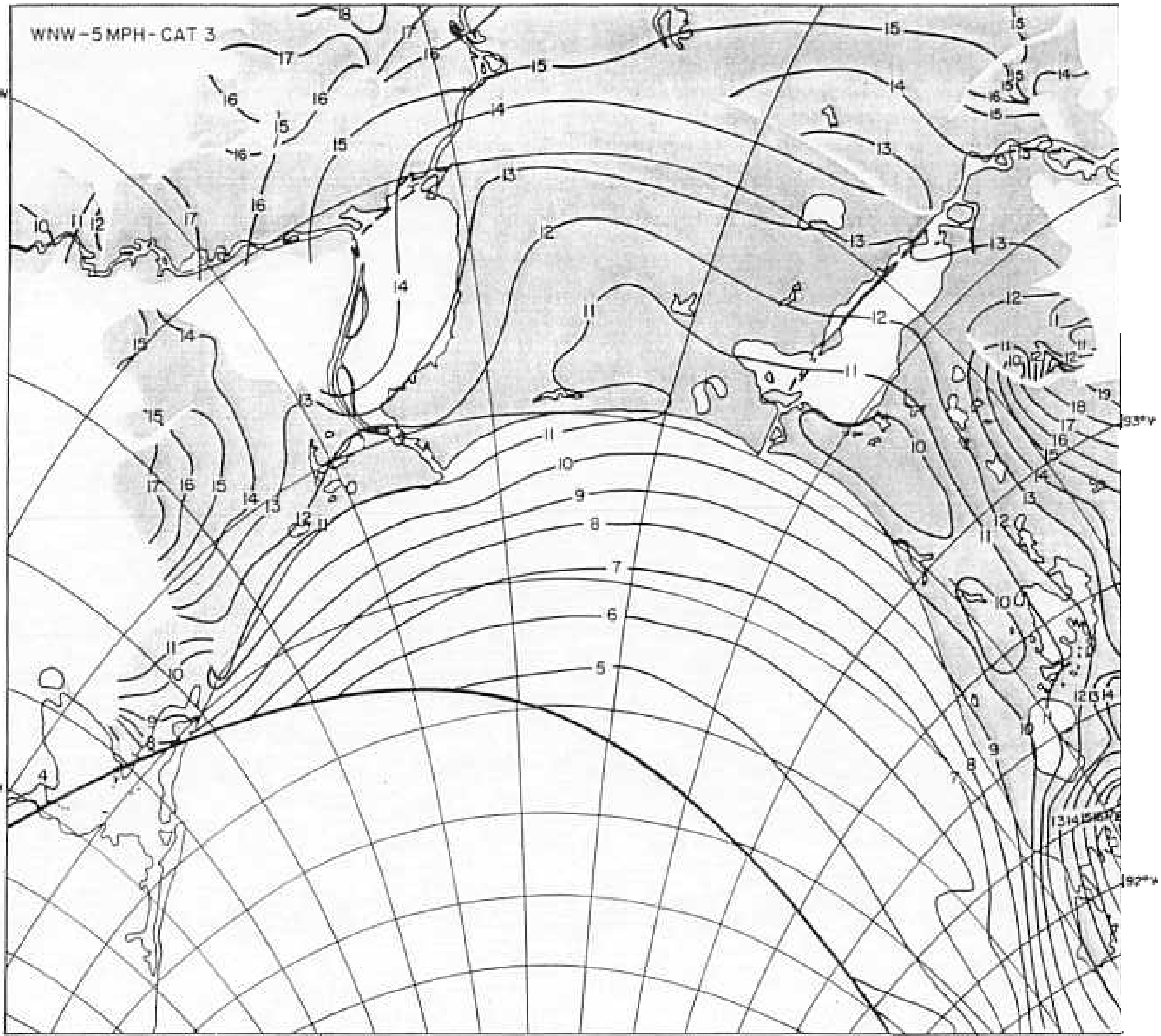
93°W
92°W
28°30'N
29°N


WNW-5MPH-CAT 3
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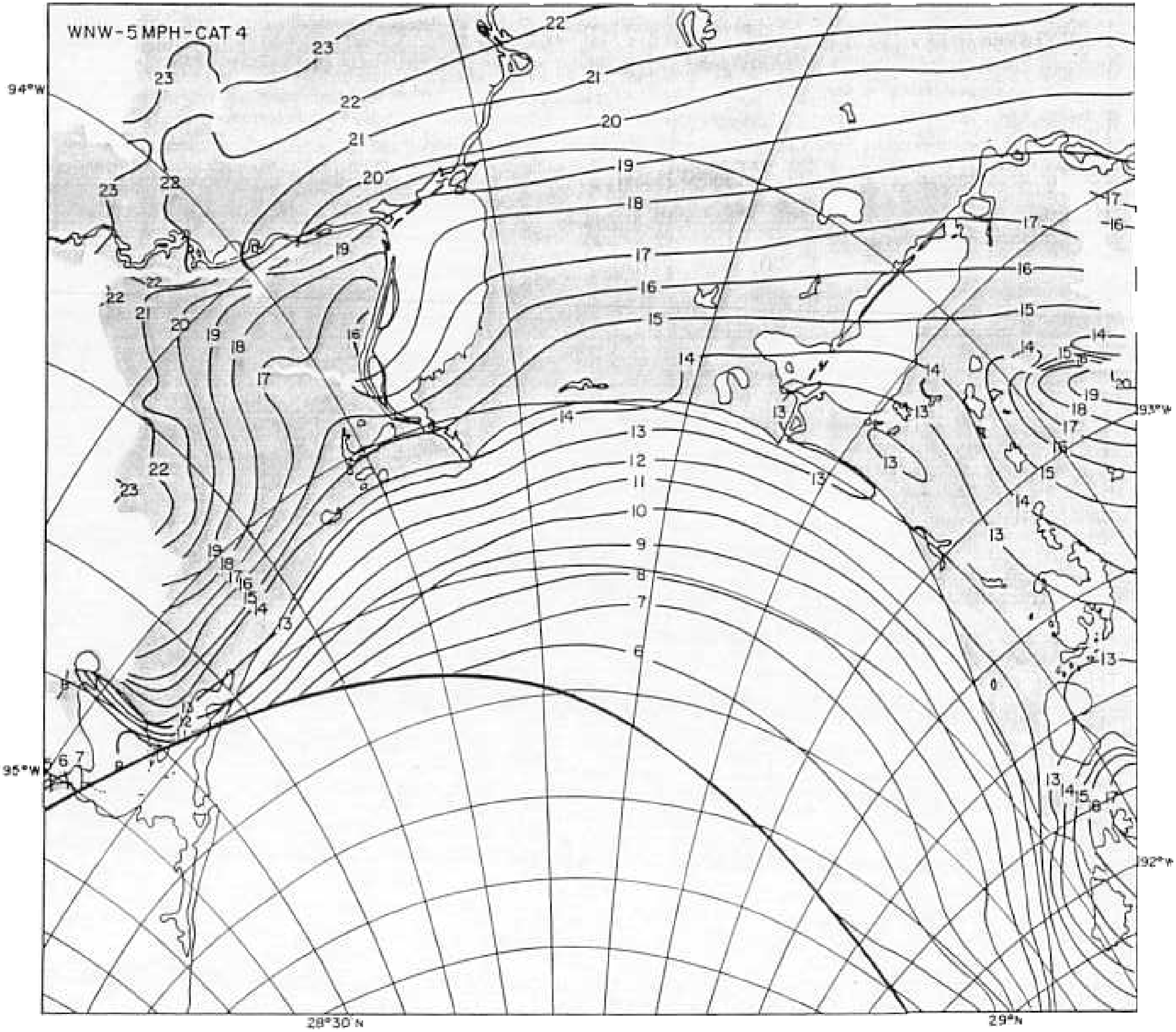
93°W
92°W
29°30'N
29°N


WNW-5 MPH-CAT 4
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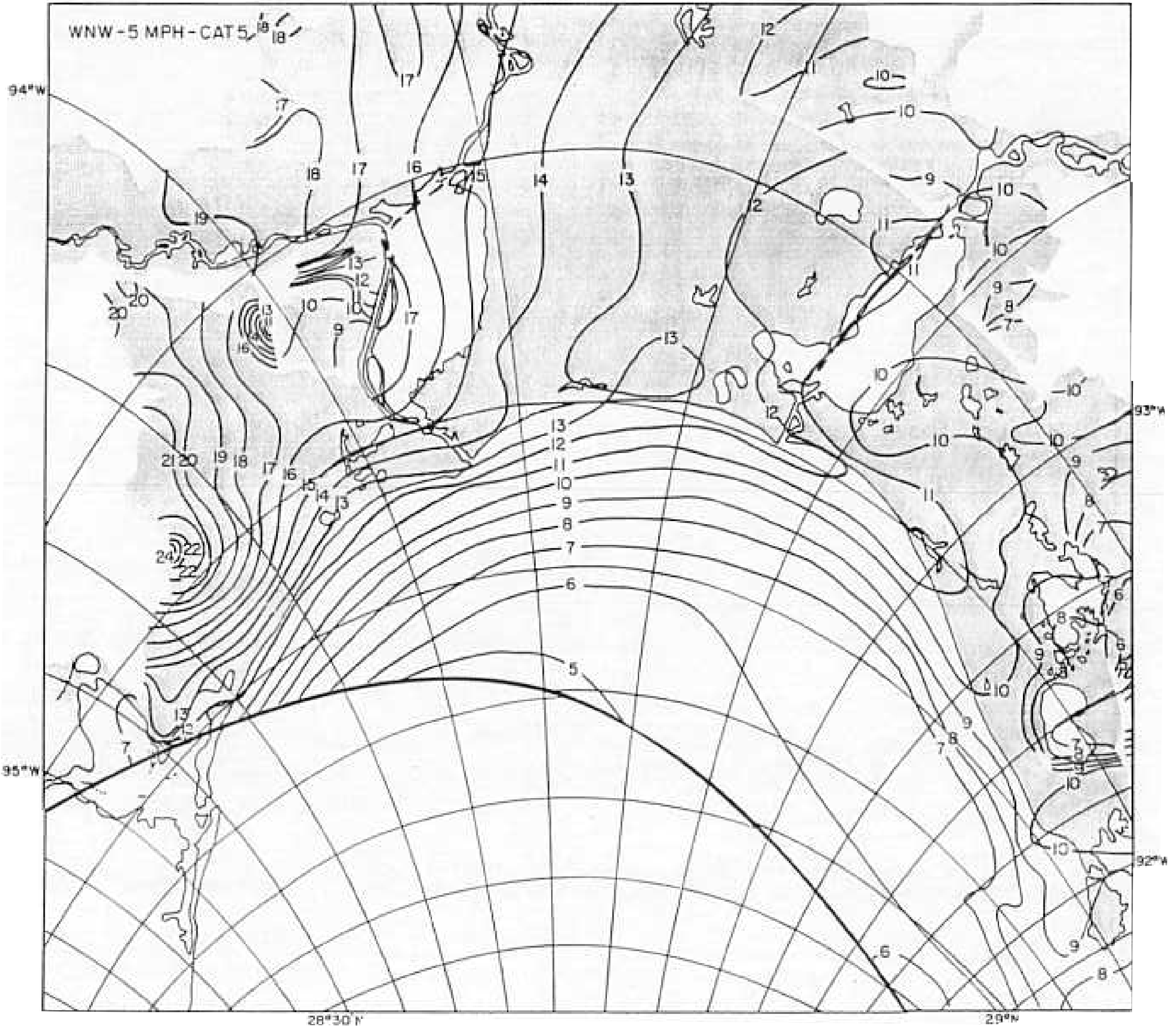
93°W
92°W
28°30'N
29°N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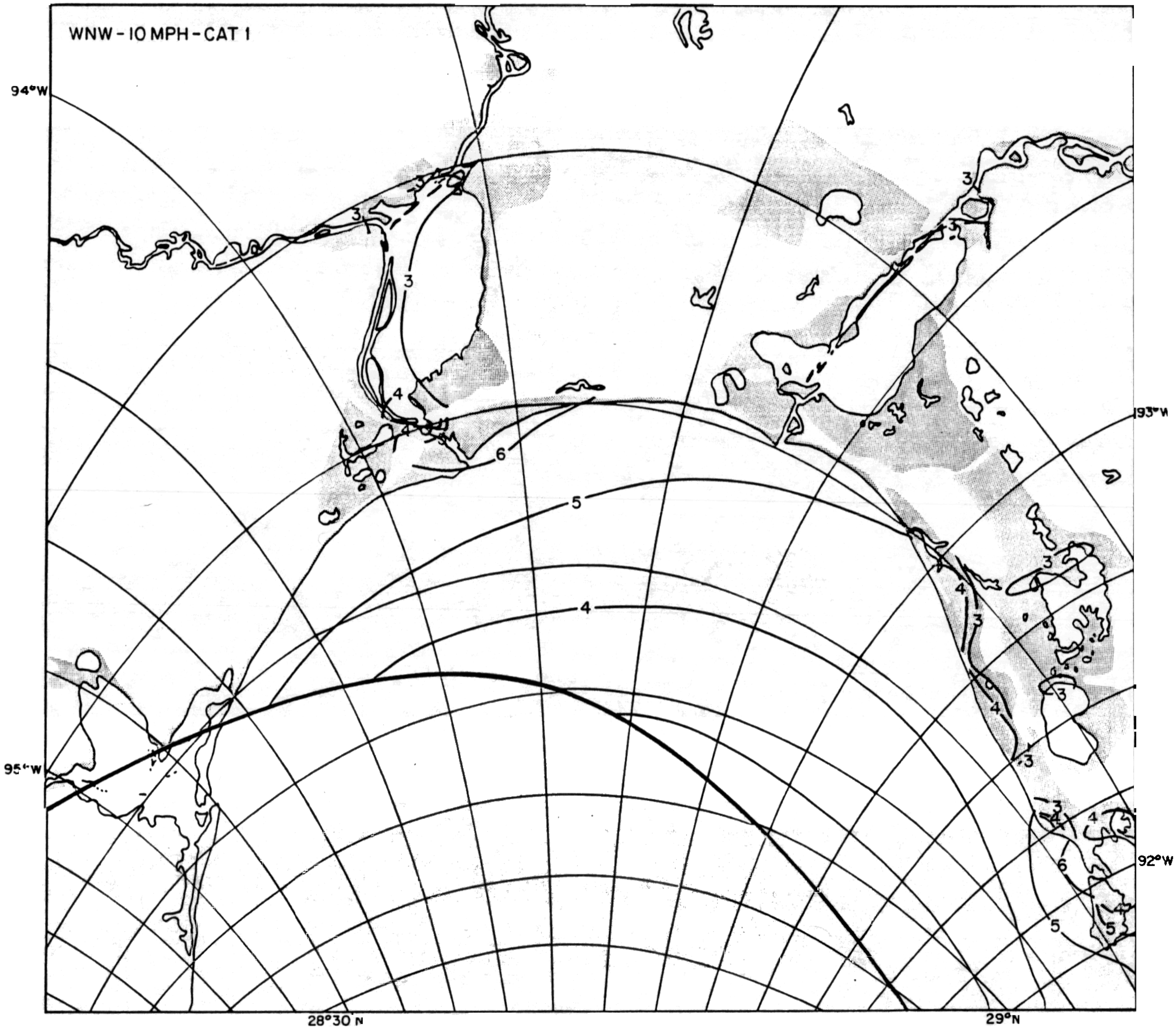
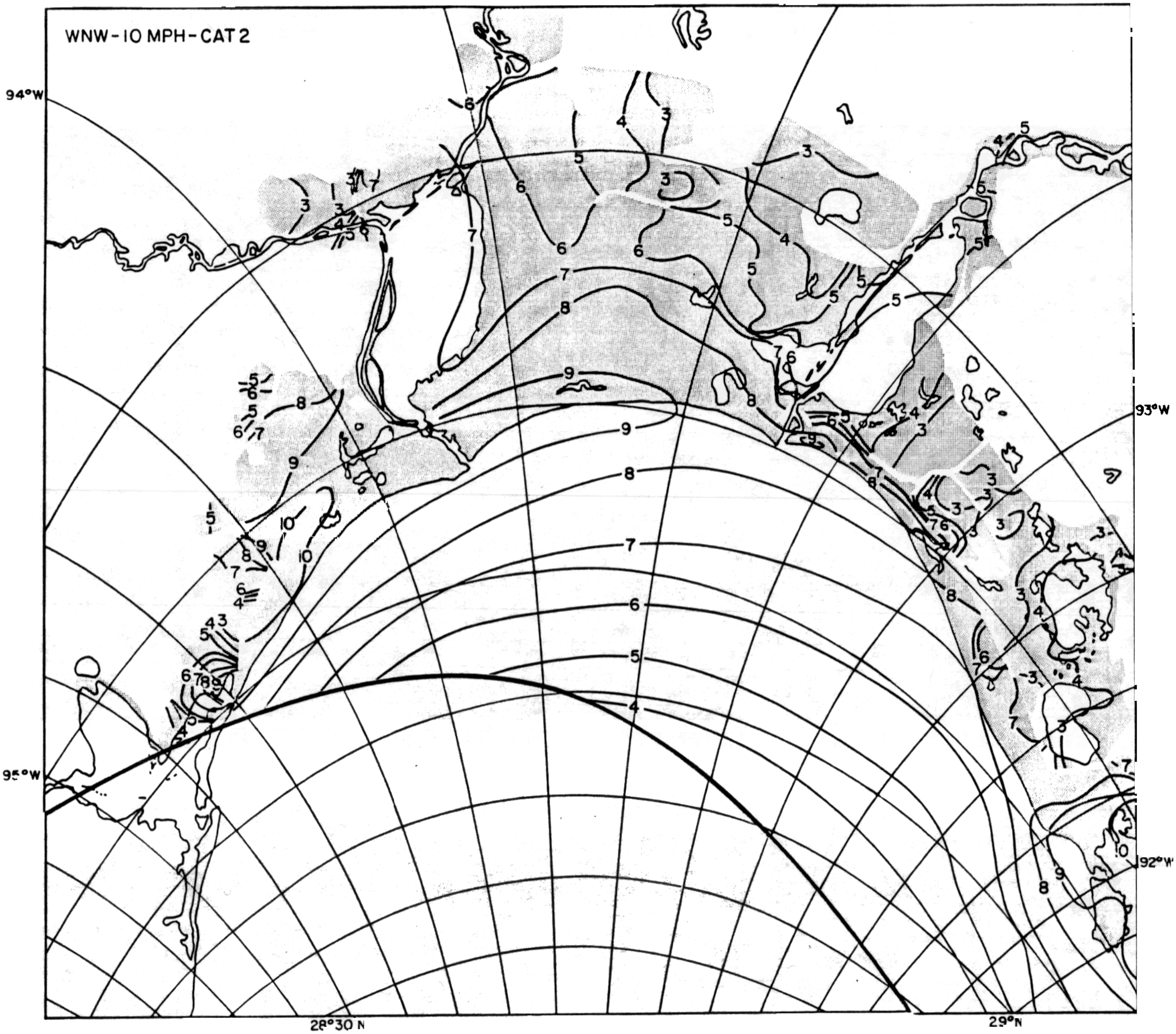
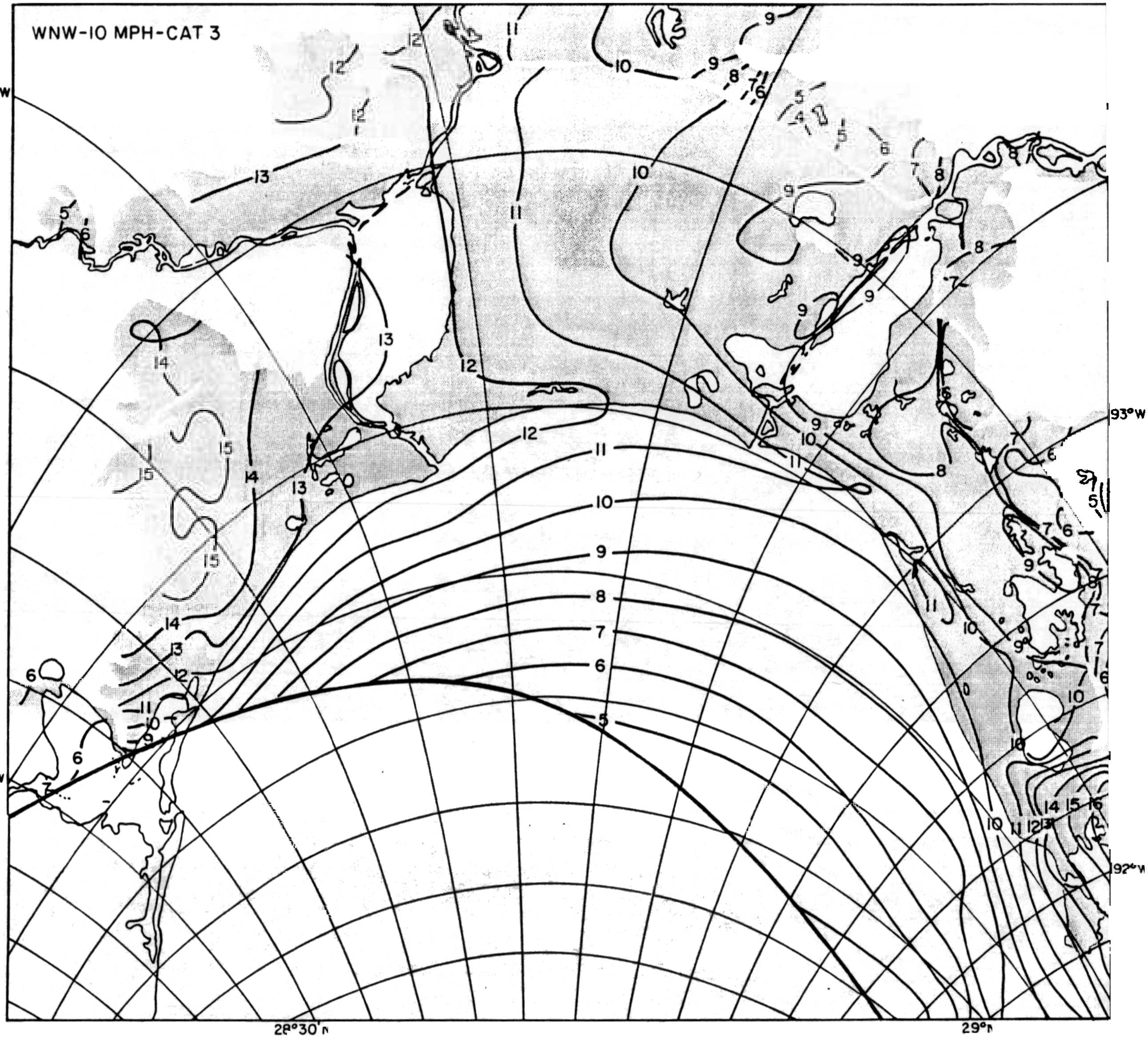
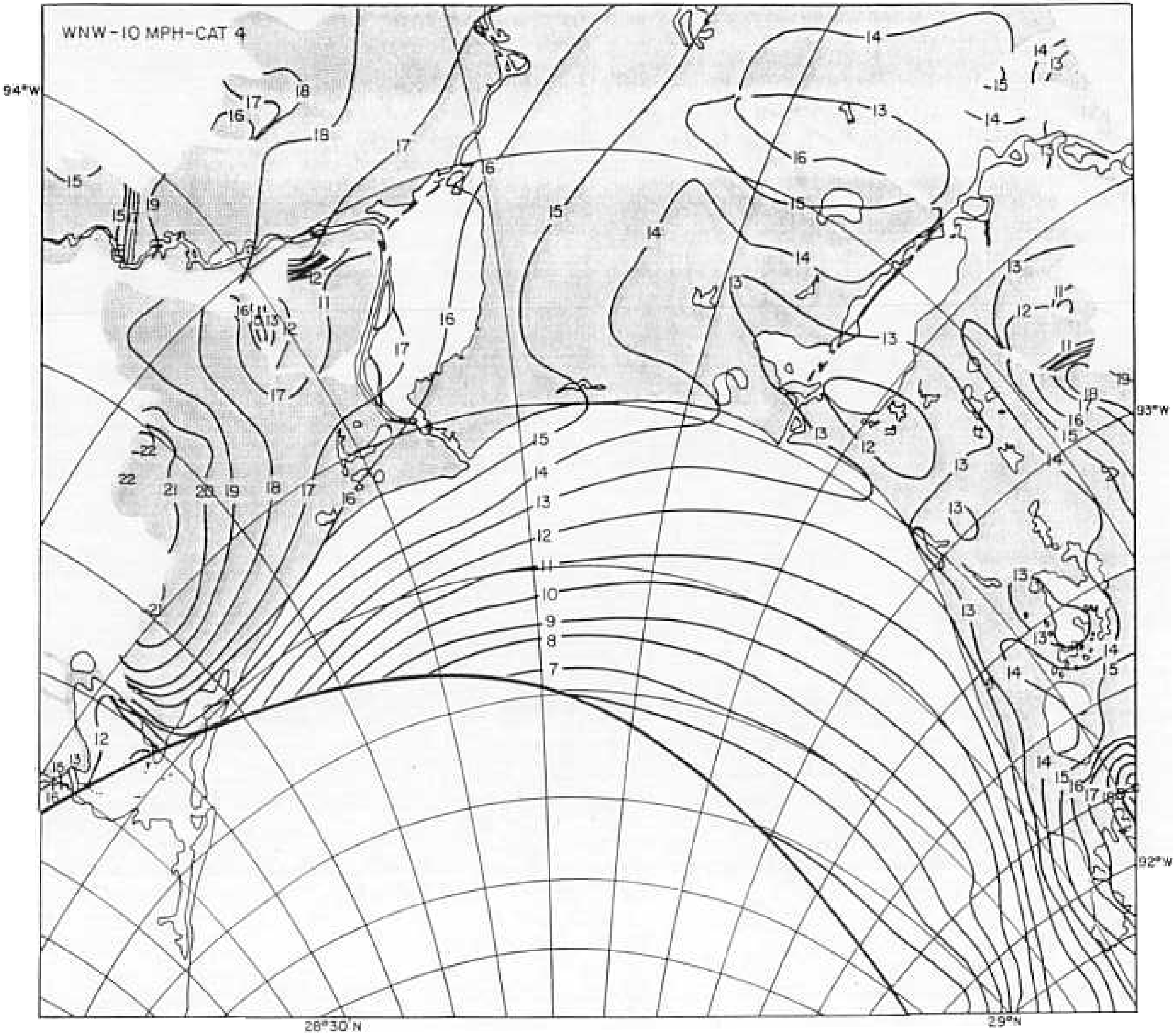
92°W
28°30'N
29°N



WNW - 10 MPH - CAT 1
94°W
93°W
95°W
92°W
28°30'N
29°N
3
4
5
6


WNW-10 MPH-CAT 2
94°W
93°W
95°W
92°W
28°30 N
29°N


WNW-10 MPH-CAT 3
94°W
93°W
92°W
95°W
28°30'N
29°N


WNW-10 MPH-CAT 4
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92°W
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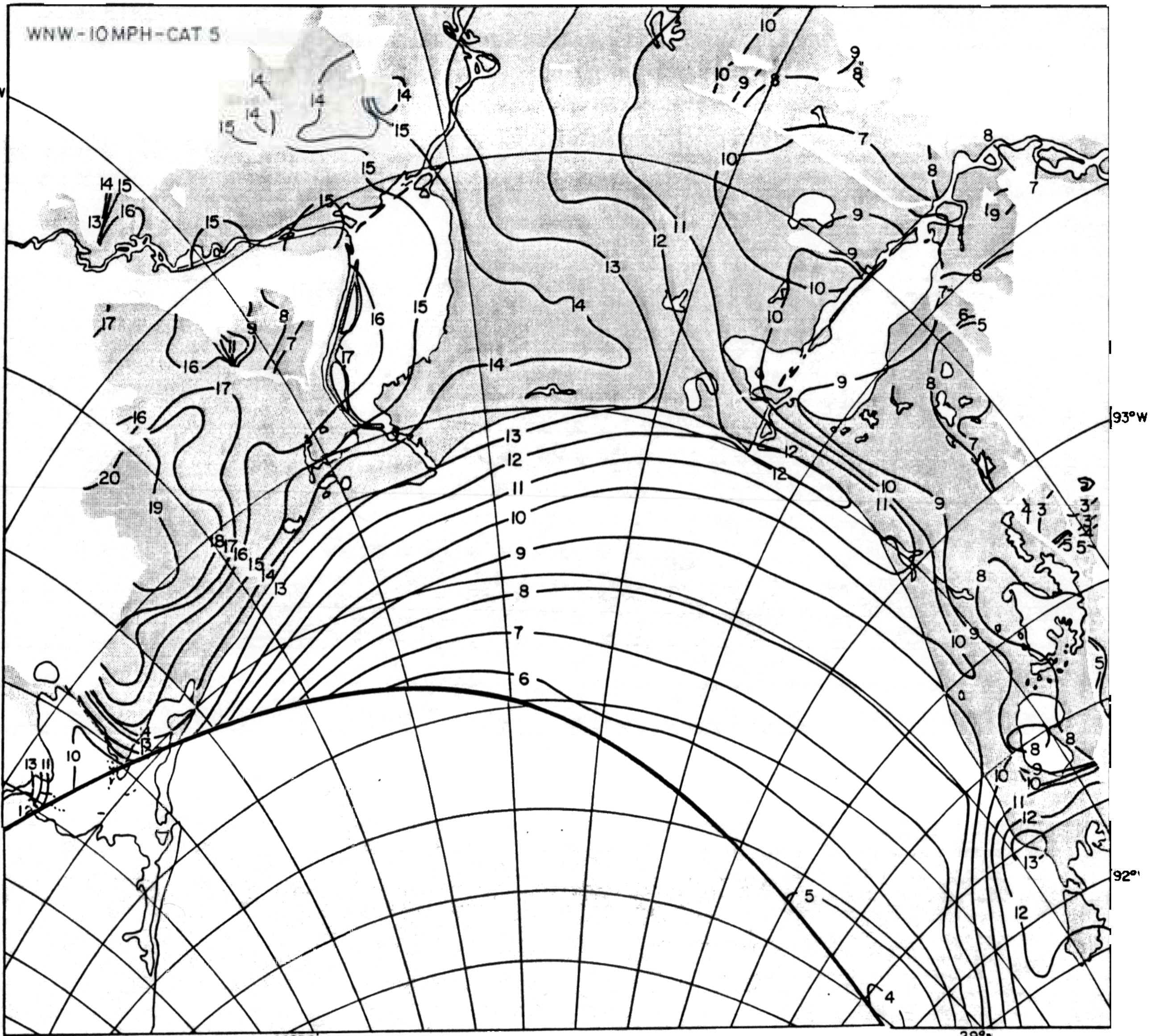
29°N


WNW-10MPH-CAT 5
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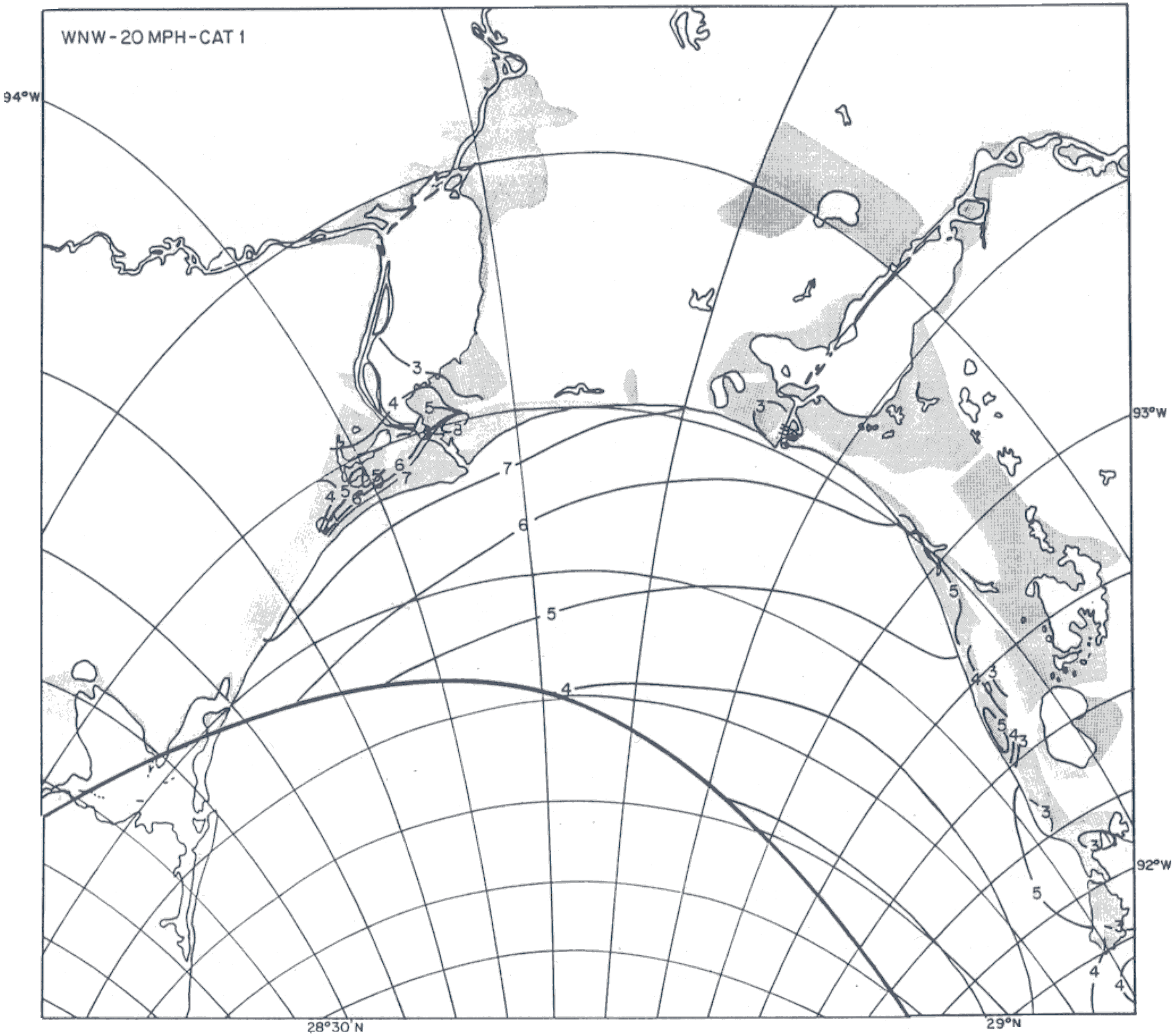
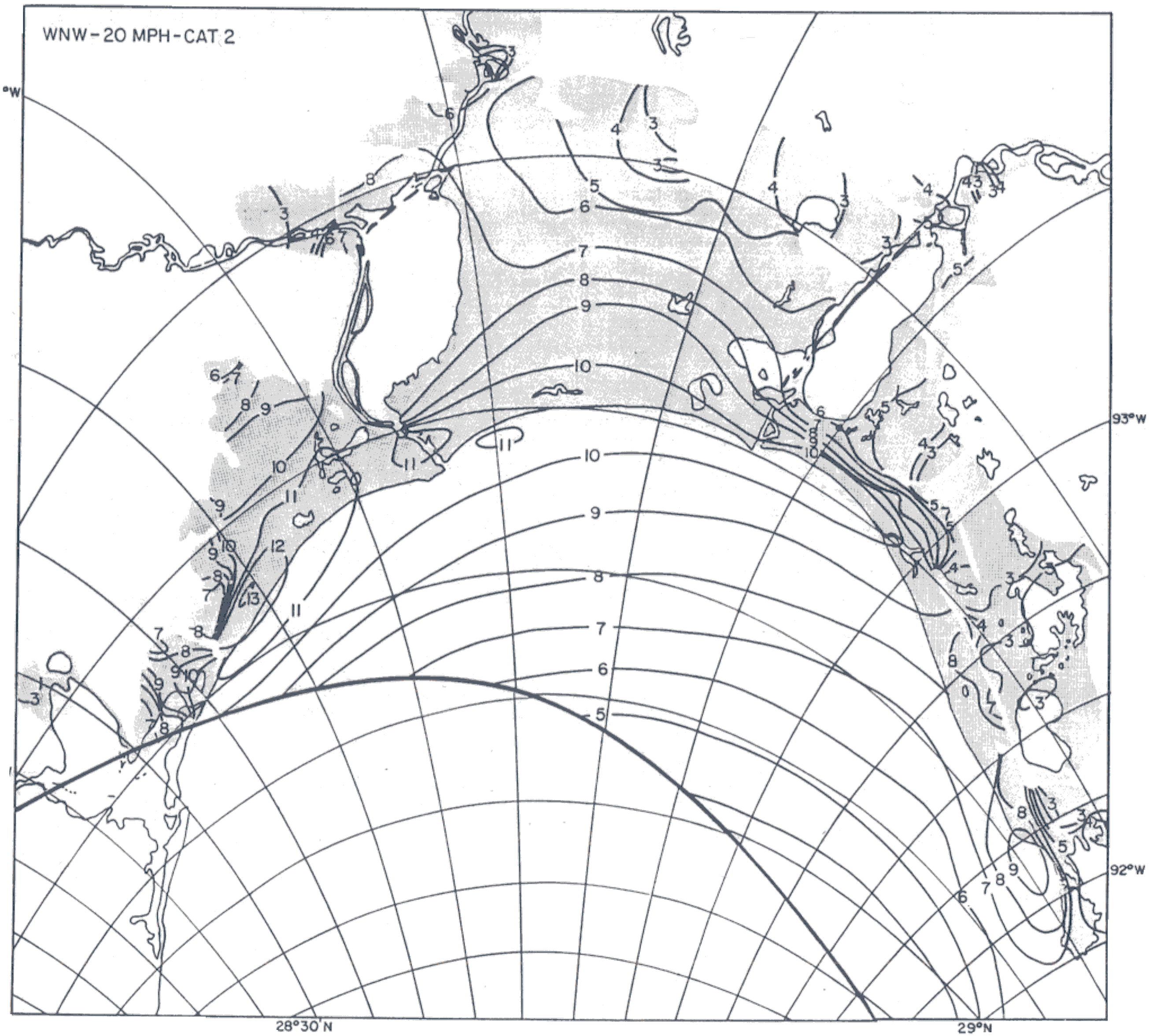
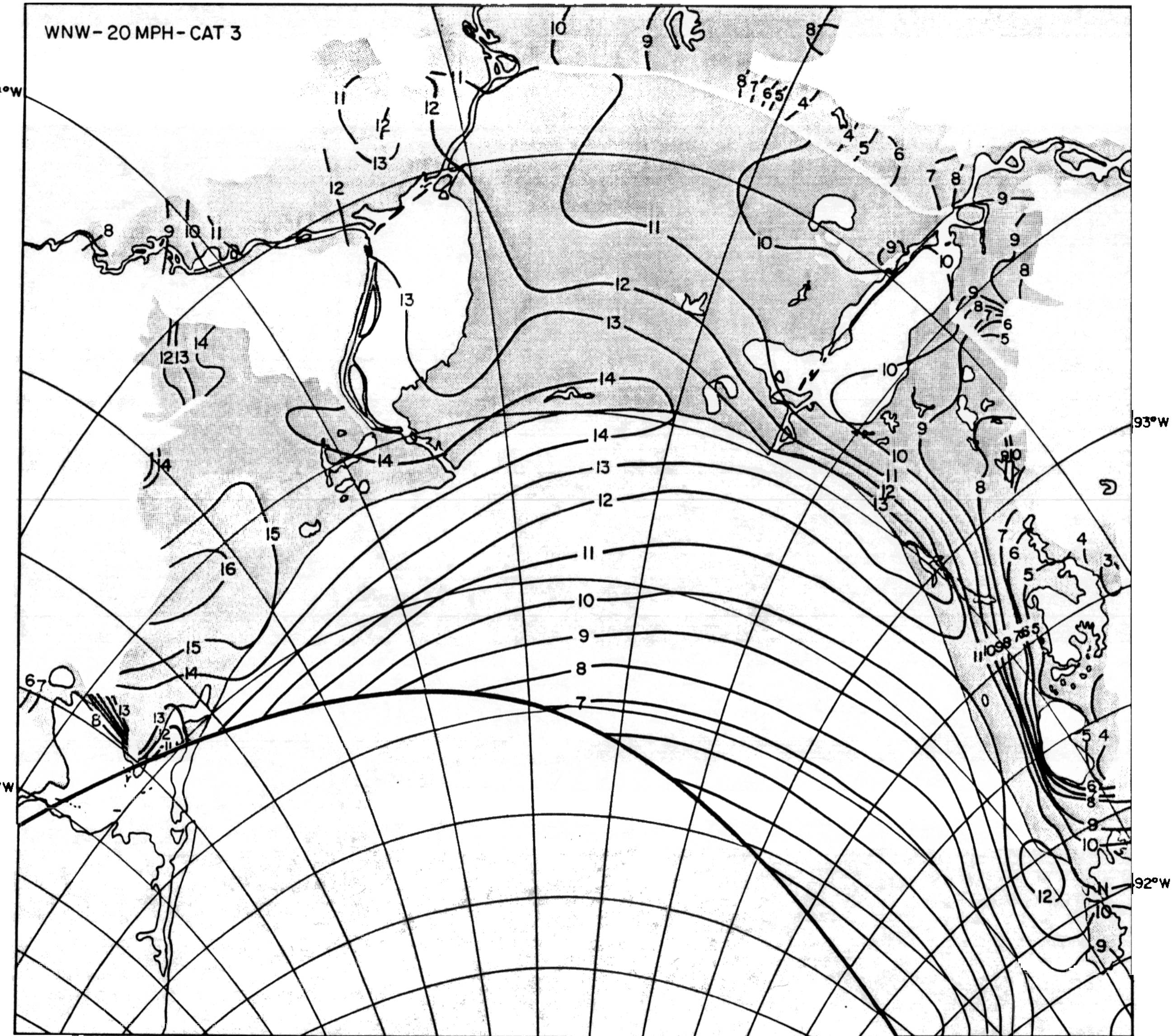
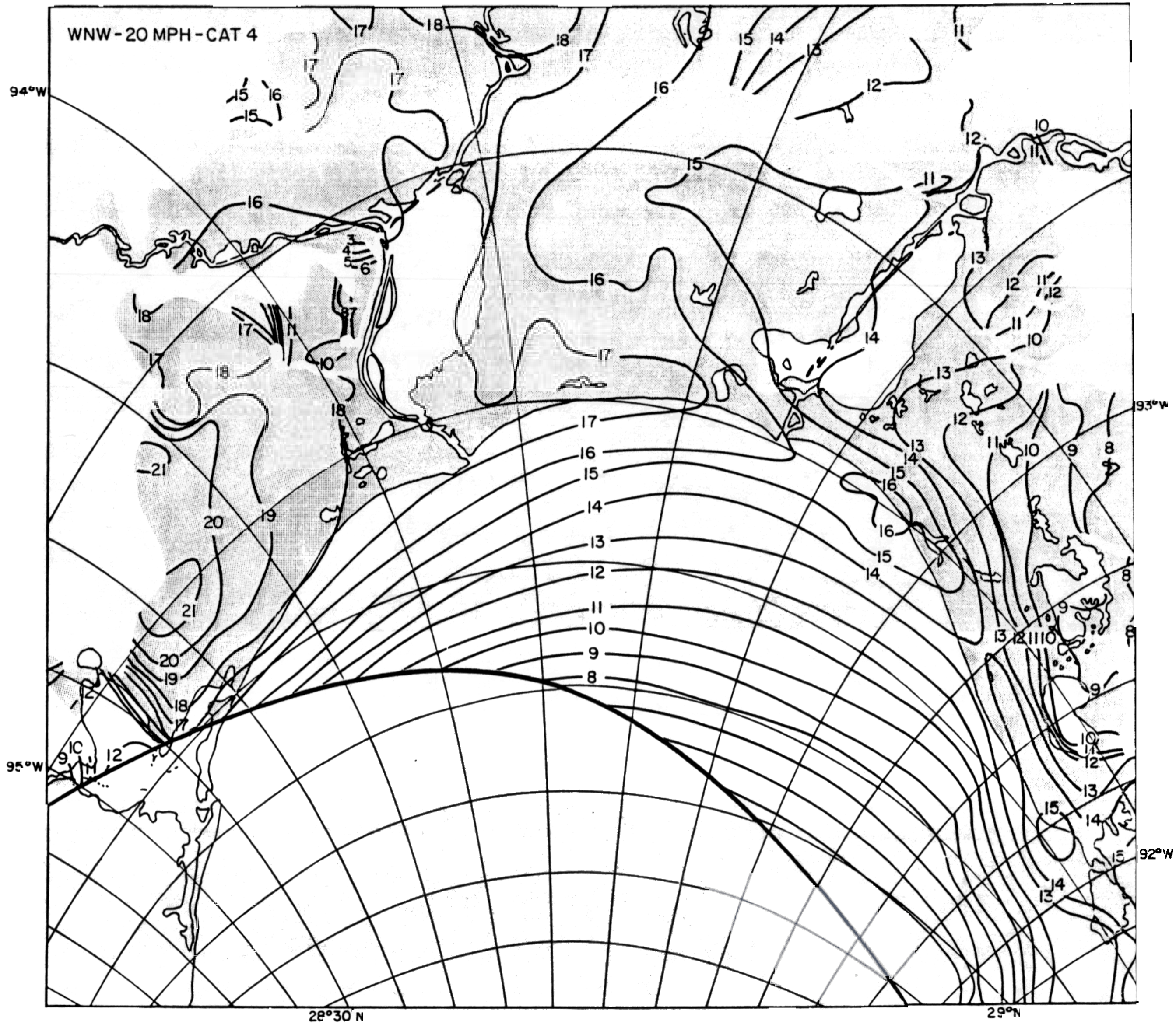
93°W
92°W
95°W
28°30'N
29°N

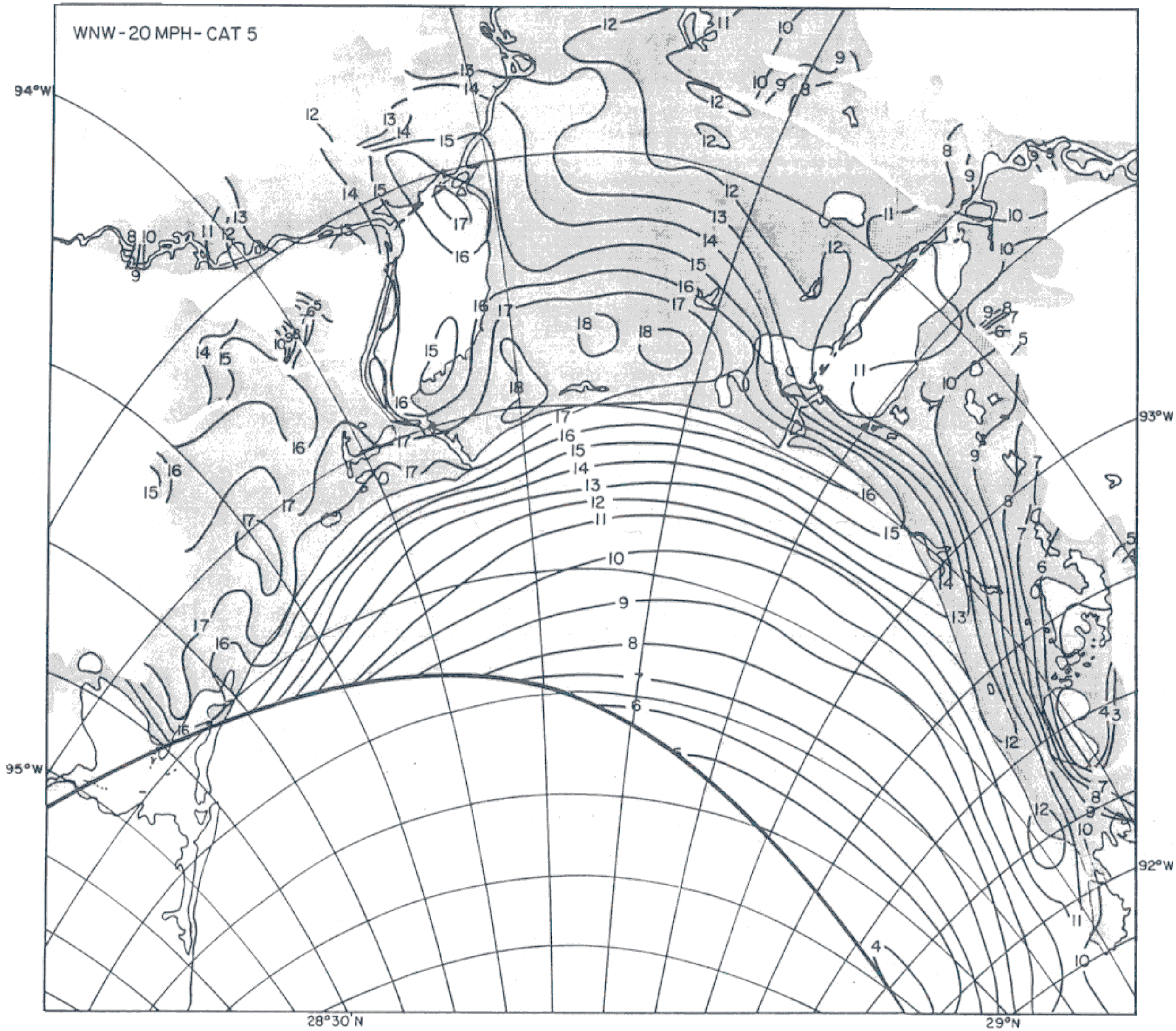

WNW-20 MPH-CAT 1
94°W
93°W
92°W
28°30'N
29°N

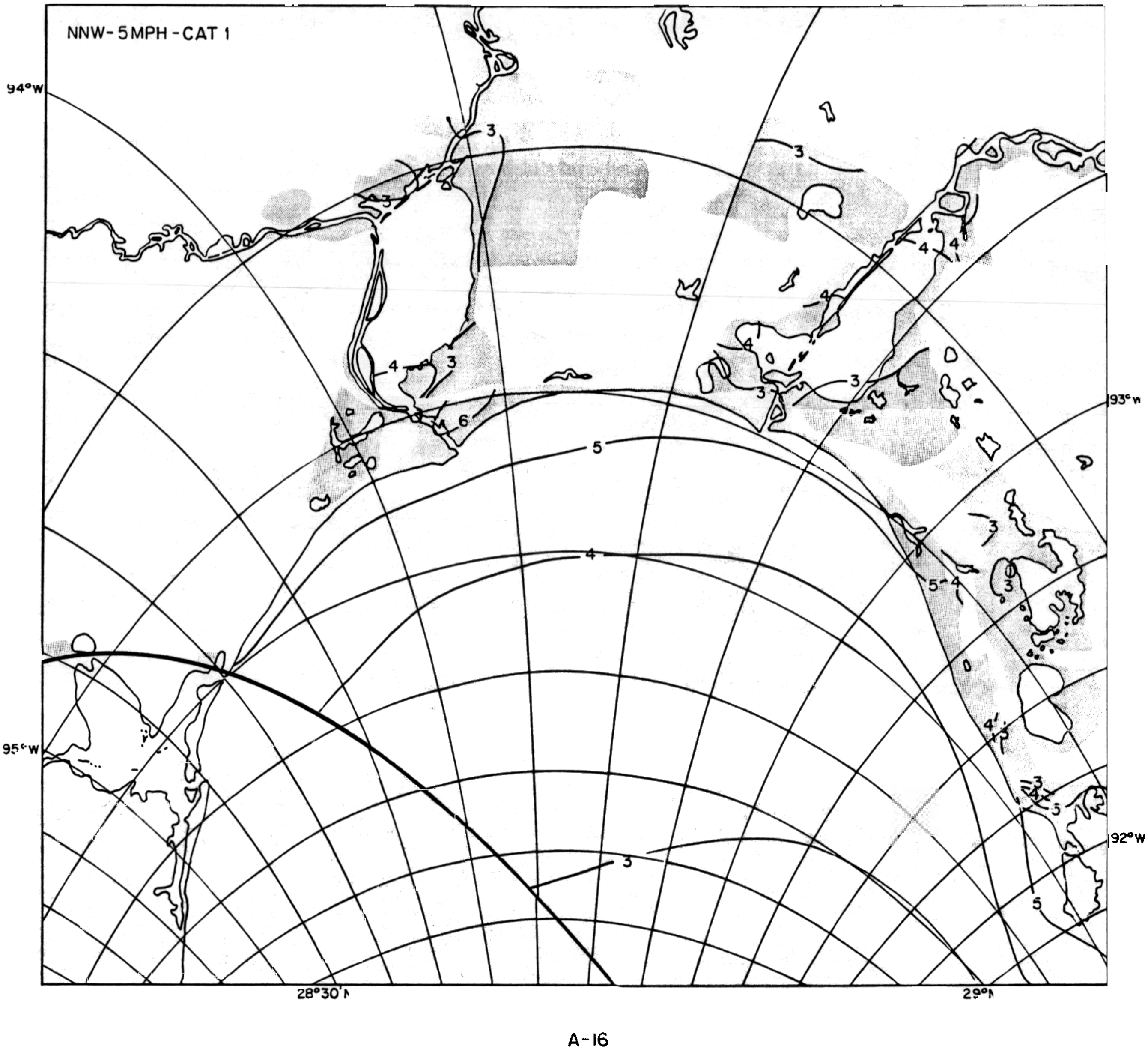


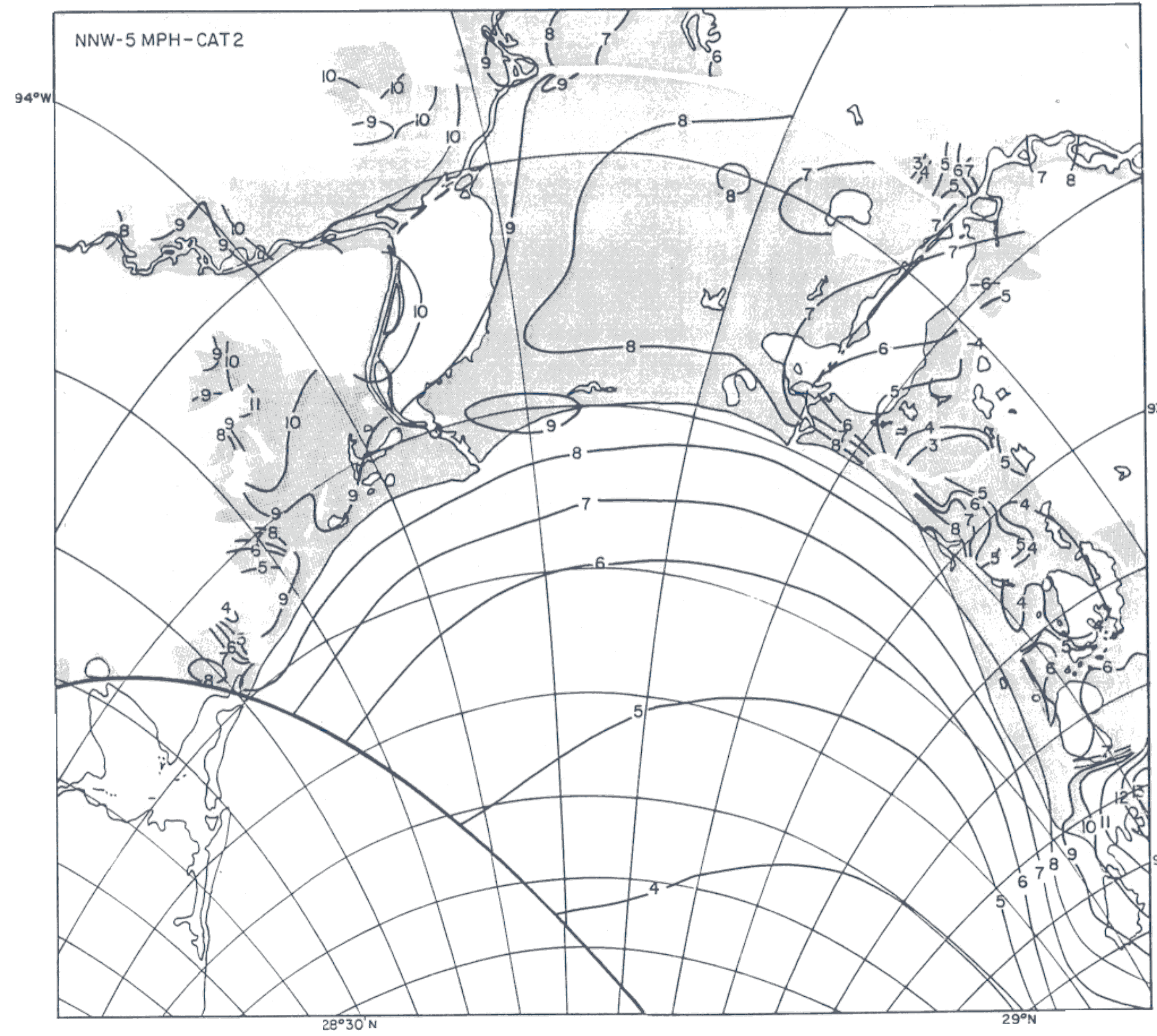
WNW-20 MPH-CAT 2
°W
93°W
92°W
28°30'N
29°N

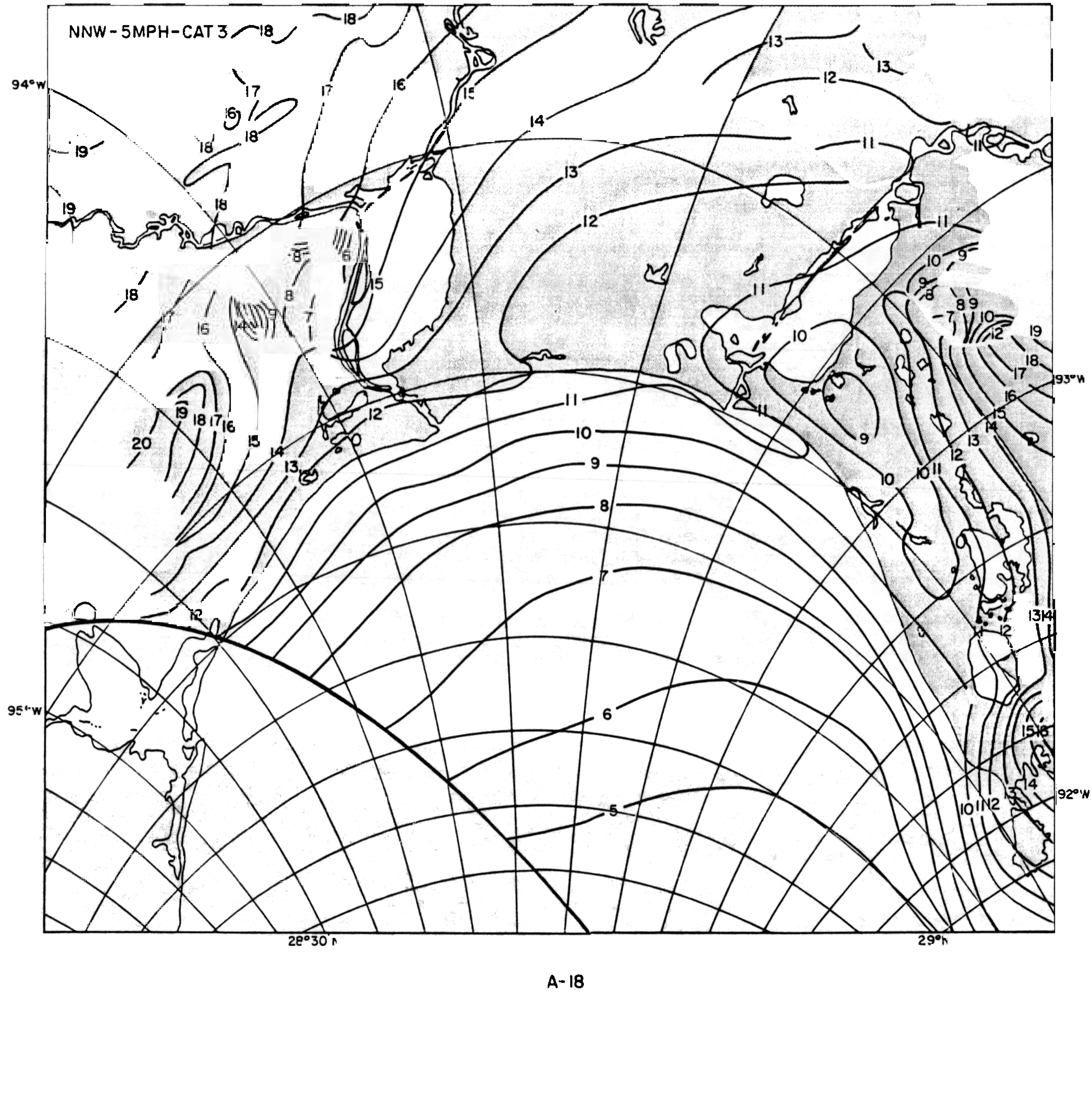

WNW-20 MPH-CAT 3
94°W
95°W
93°W
92°W
28°30'N
29°N
N

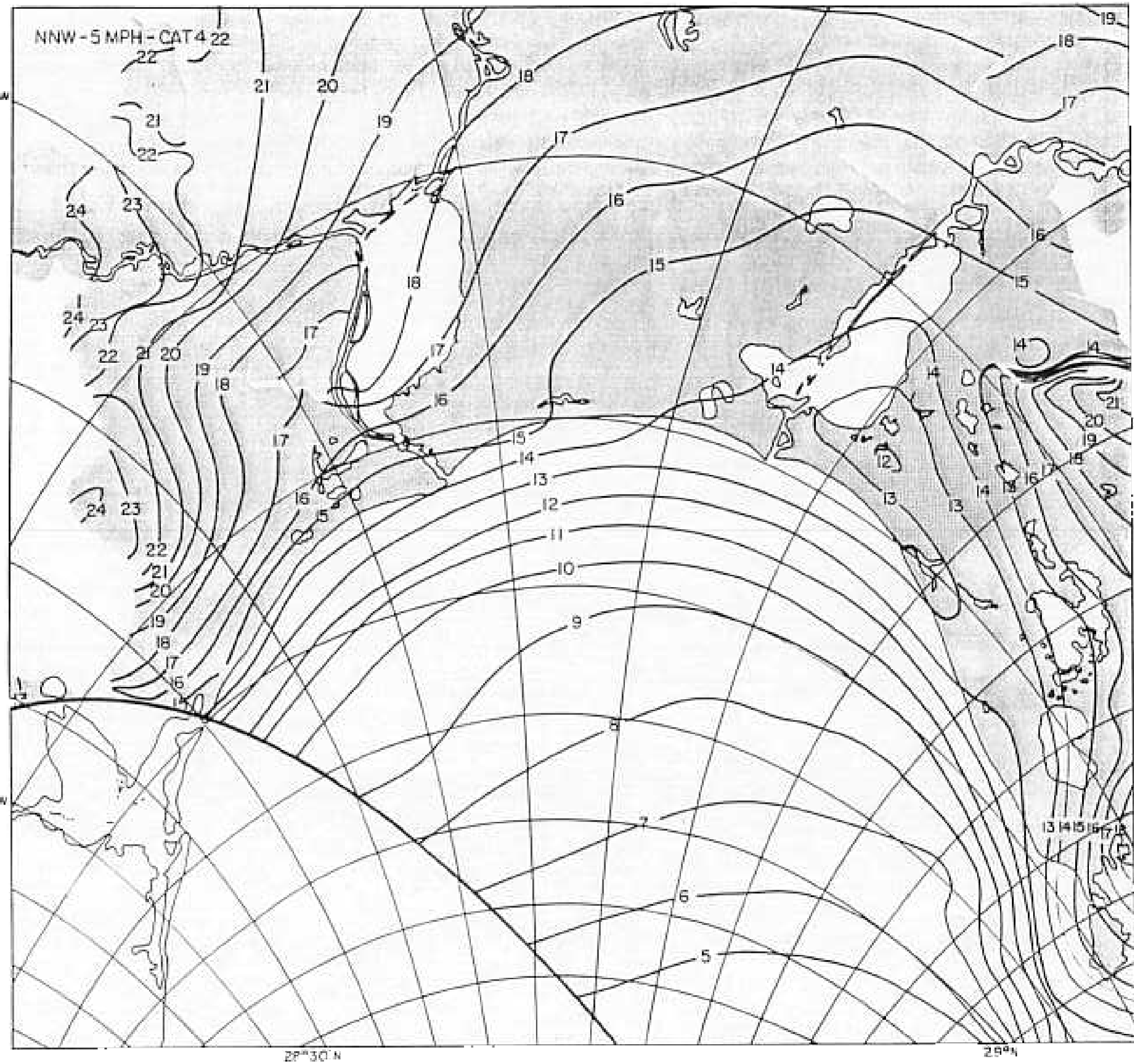

WNW-20 MPH-CAT 4
94°W
95°W
93°W
92°W
28°30'N
29°N

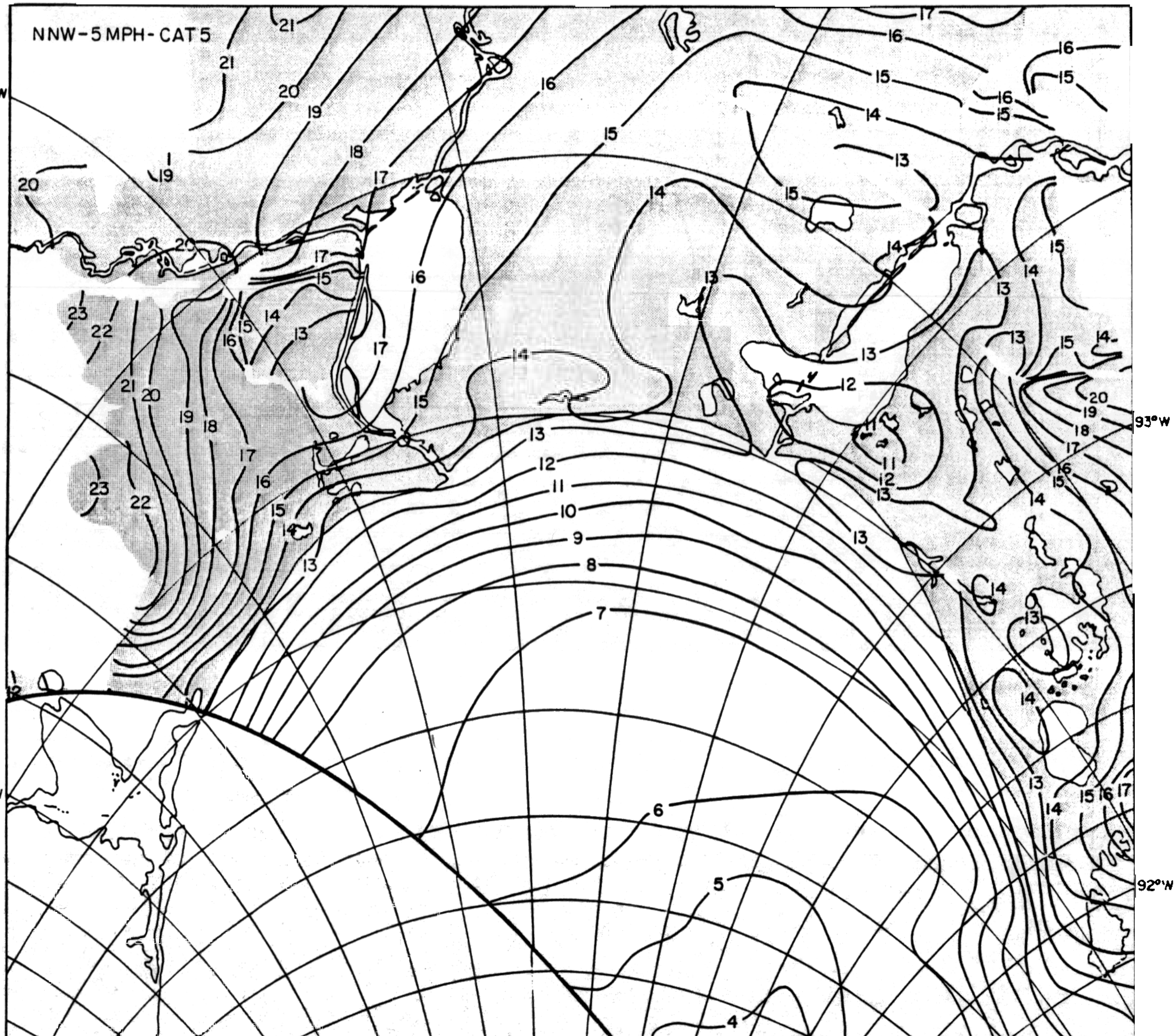

WNW-20 MPH-CAT 5
94°W
95°W
93°W
92°W
28°30'N
29°N

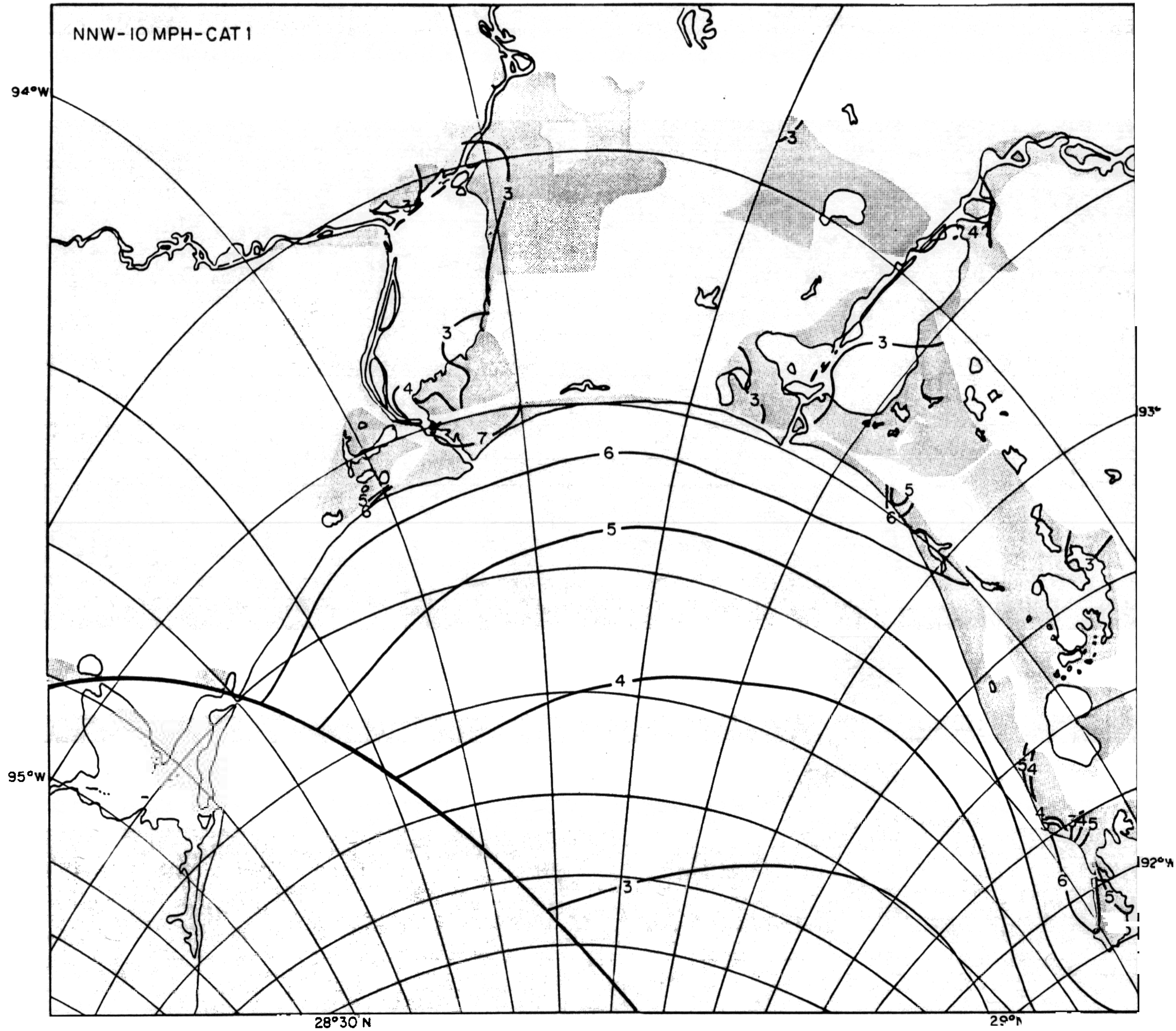

NNW-5MPH-CAT 1
94°W
95°W
93°W
92°W
28°30'N
29°N
3
4
5
6
3
4
5
3

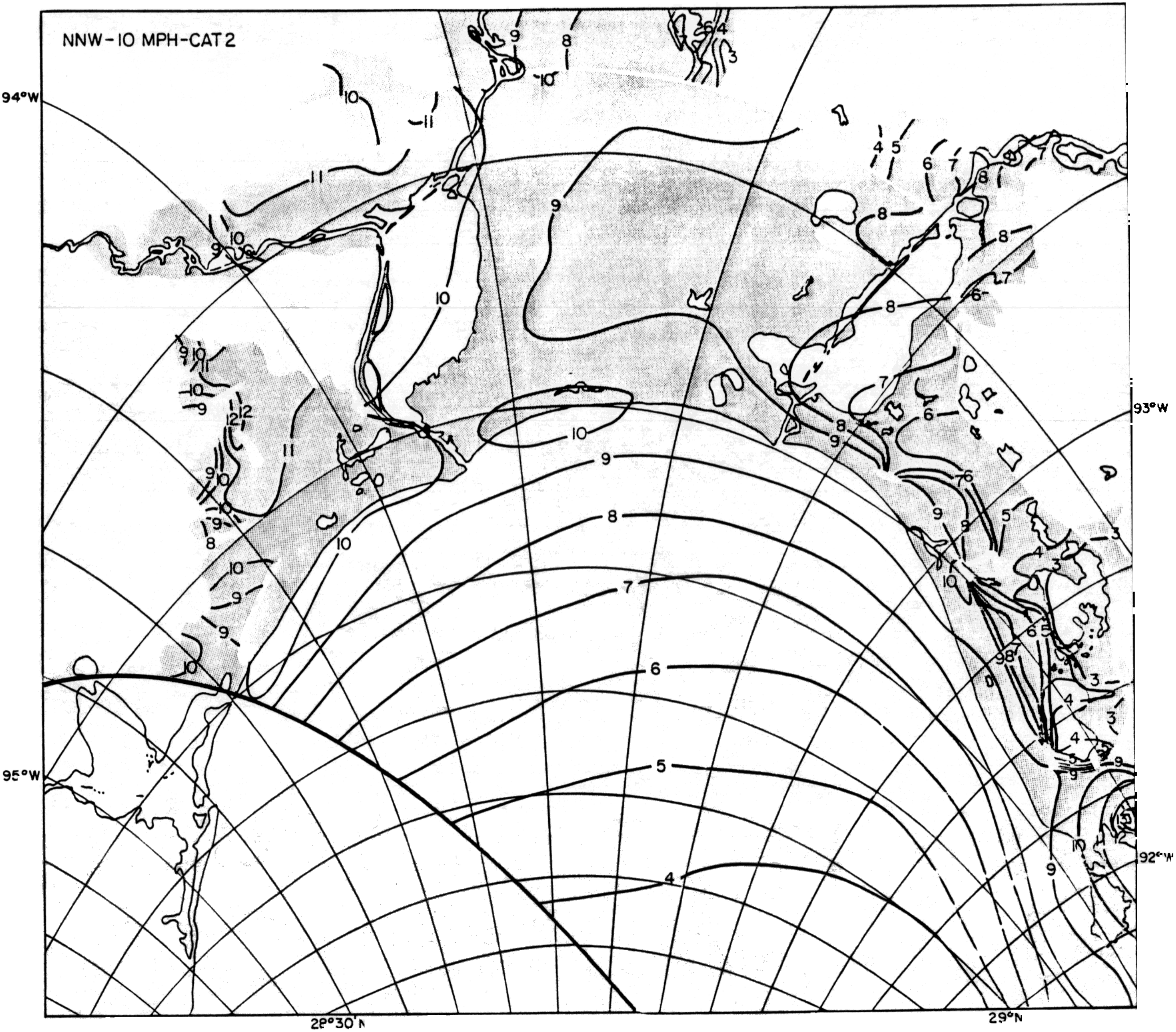

NNW-5 MPH-CAT 2
94°W
93°W
92°W
28°30'N
29°N

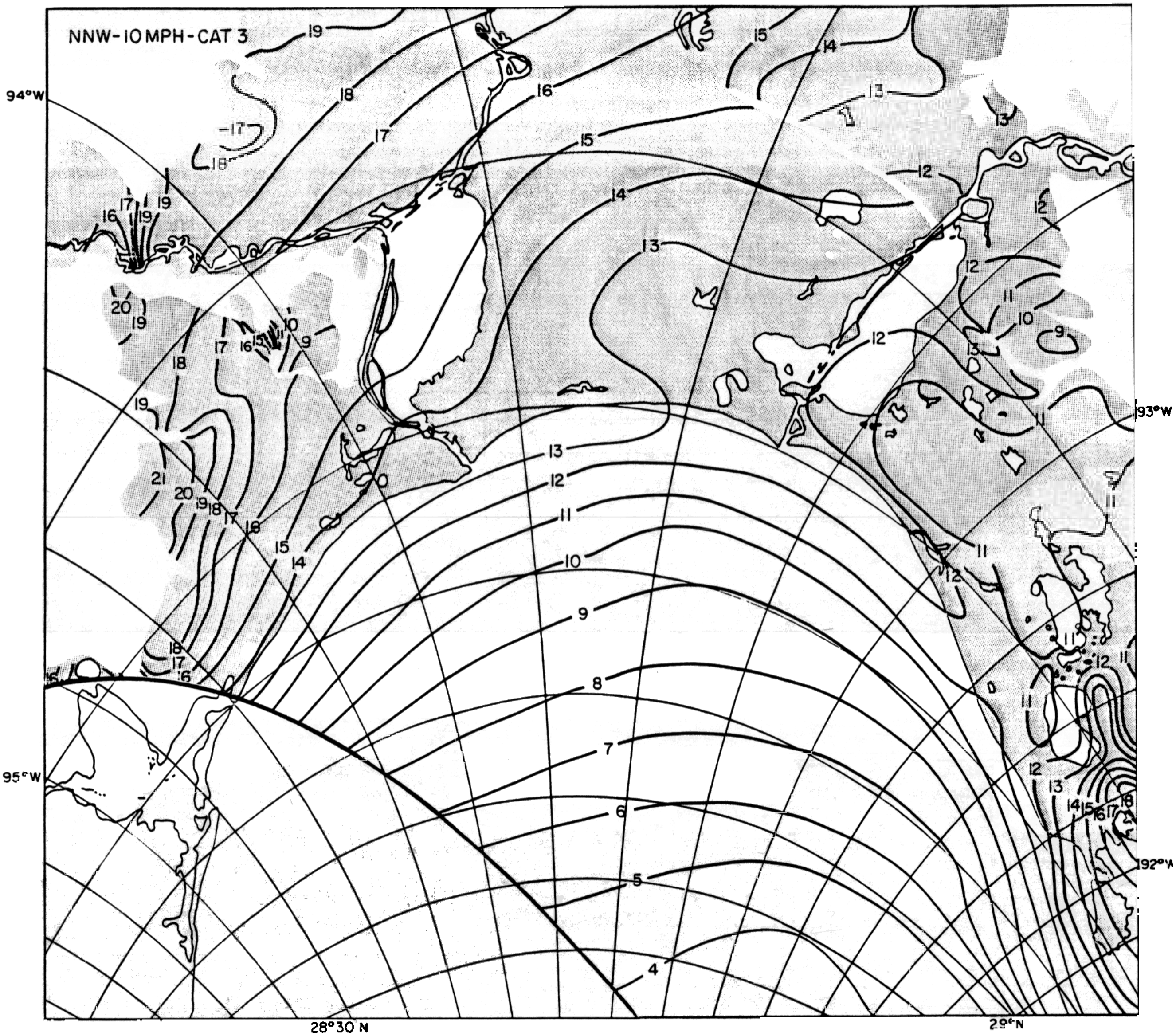

NNW-5MPH-CAT 3
94°W
95°W
93°W
92°W
28°30'N
29°N

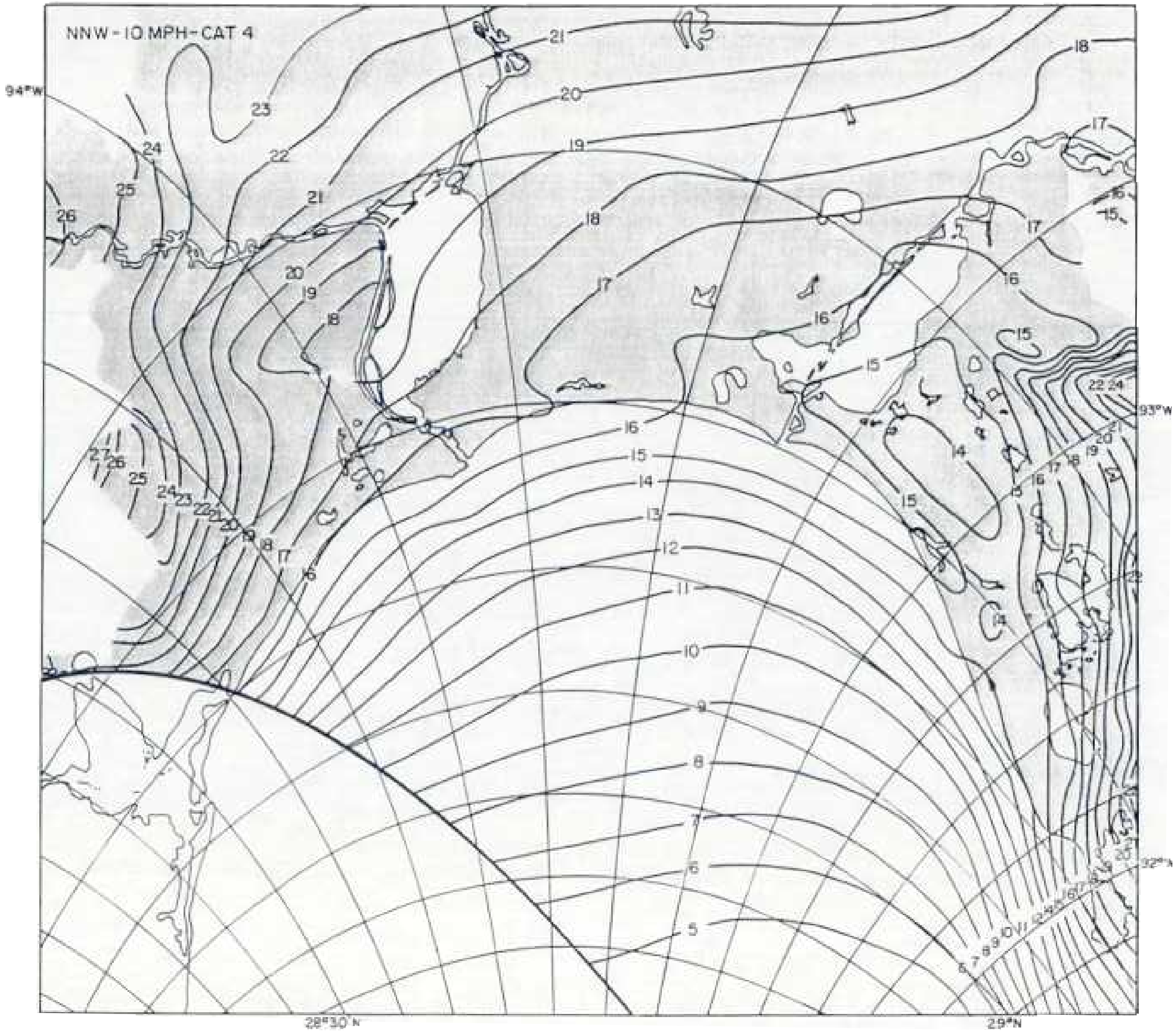

NNW - 5 MPH - CAT 4
94°W
95°W
93°W
92°W
28°30'N
29°N

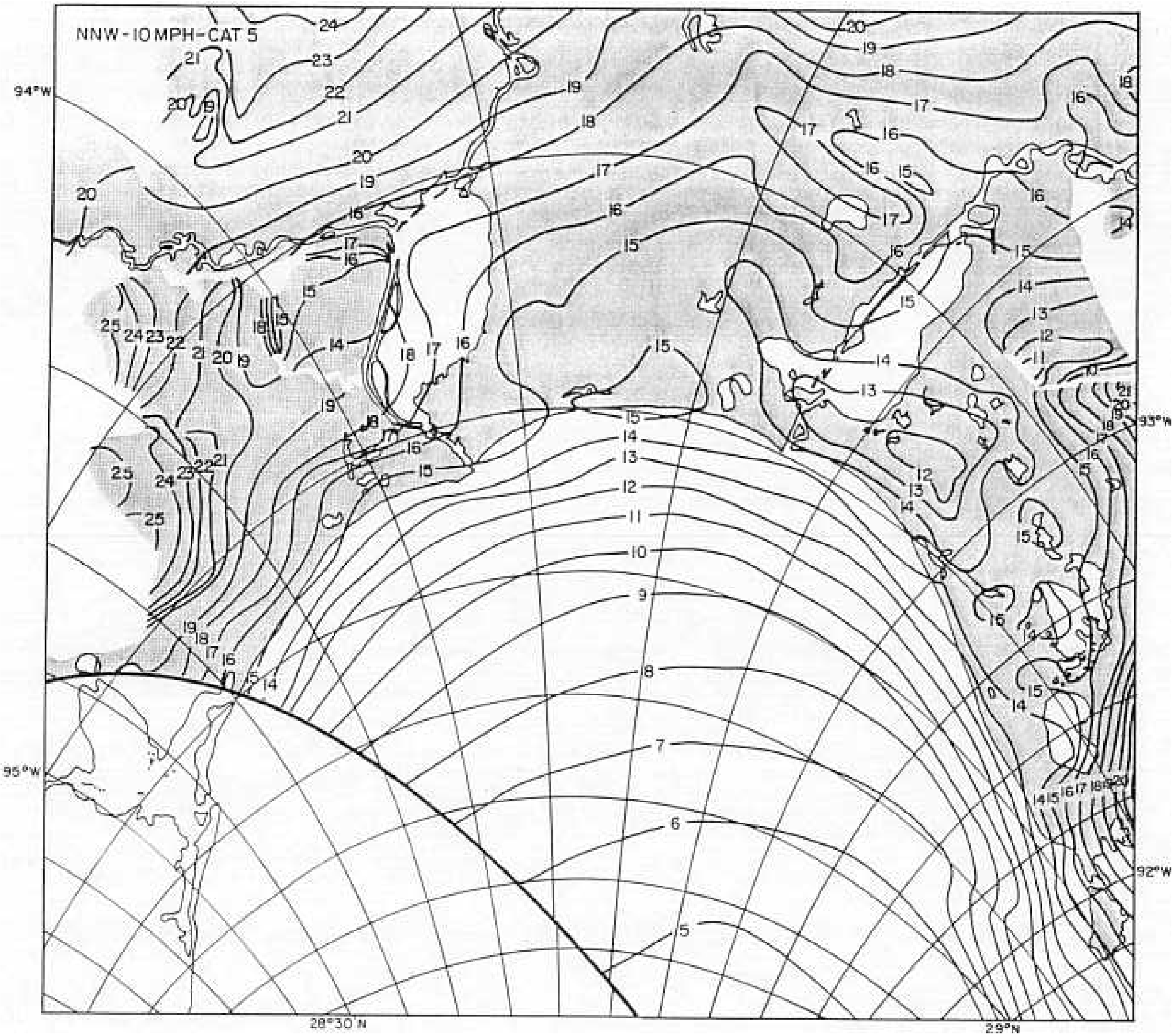

NNW-5 MPH-CAT 5
94°W
93°W
95°W
92°W
28°30'N
29°N

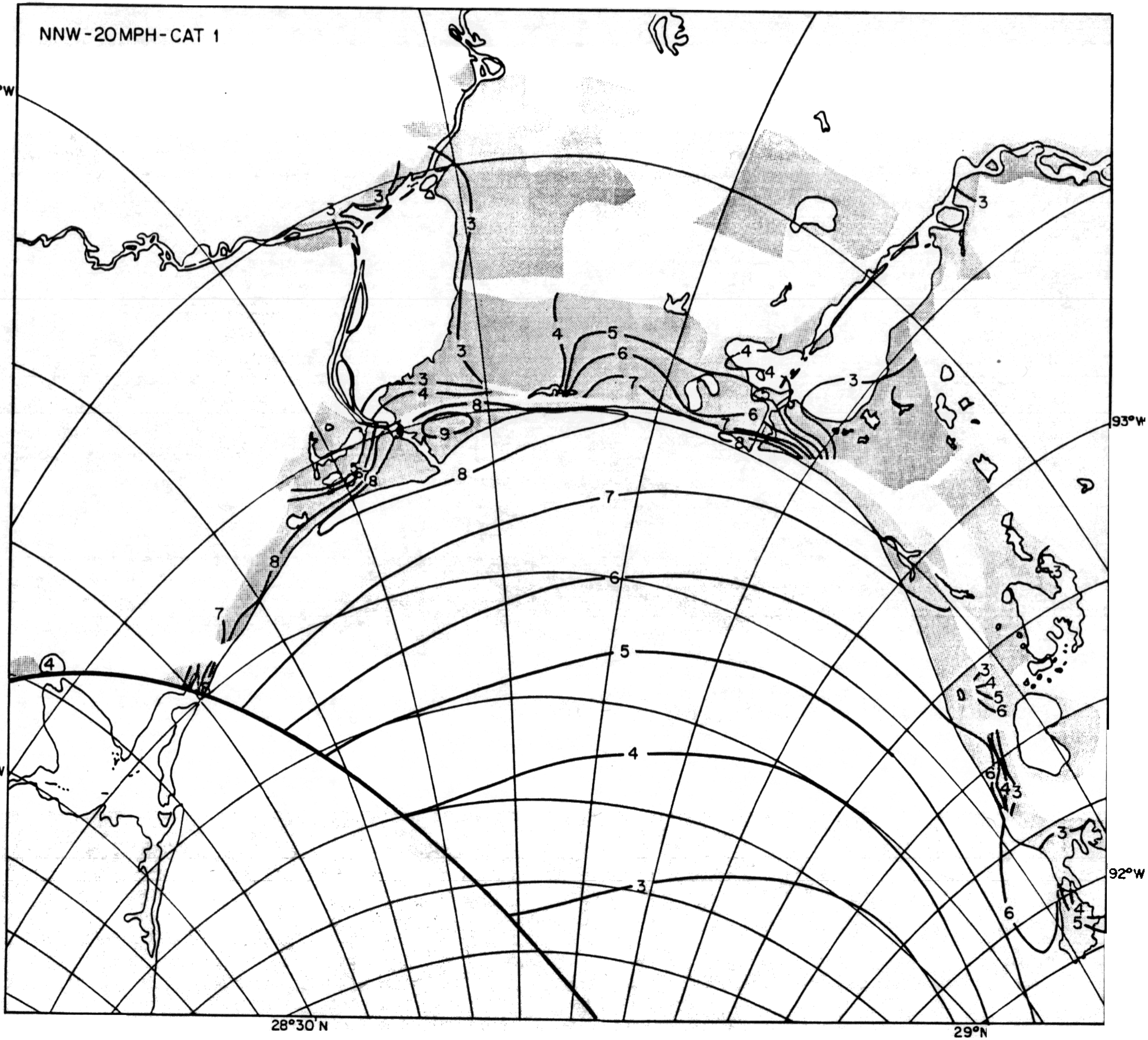

NNW-10 MPH-CAT 1
94°W
95°W
93°
92°W
28°30'N
29°N
3
4
5
6
7


NNW-10 MPH-CAT 2
94°W
93°W
95°W
92°W
28°30'N
29°N


NNW-10 MPH-CAT 3
94°W
95°W
93°W
92°W
28°30'N
29°N


NNW-10 MPH-CAT 4
94°W
93°W
92°W
28°30'N
29°N


NNW-10 MPH-CAT 5
94°W
95°W
93°W
92°W
28°30'N
29°N


NNW-20MPH-CAT 1
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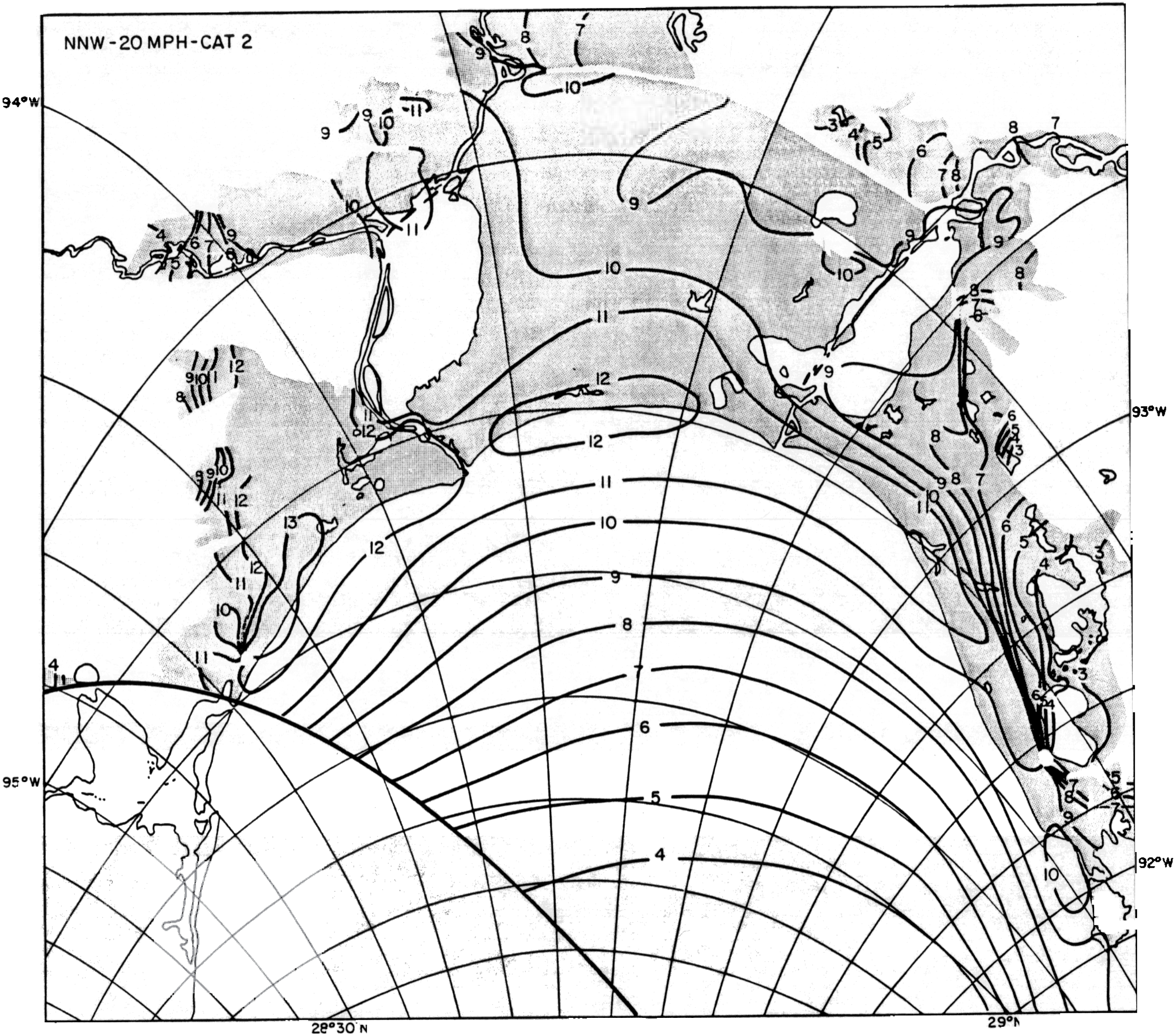
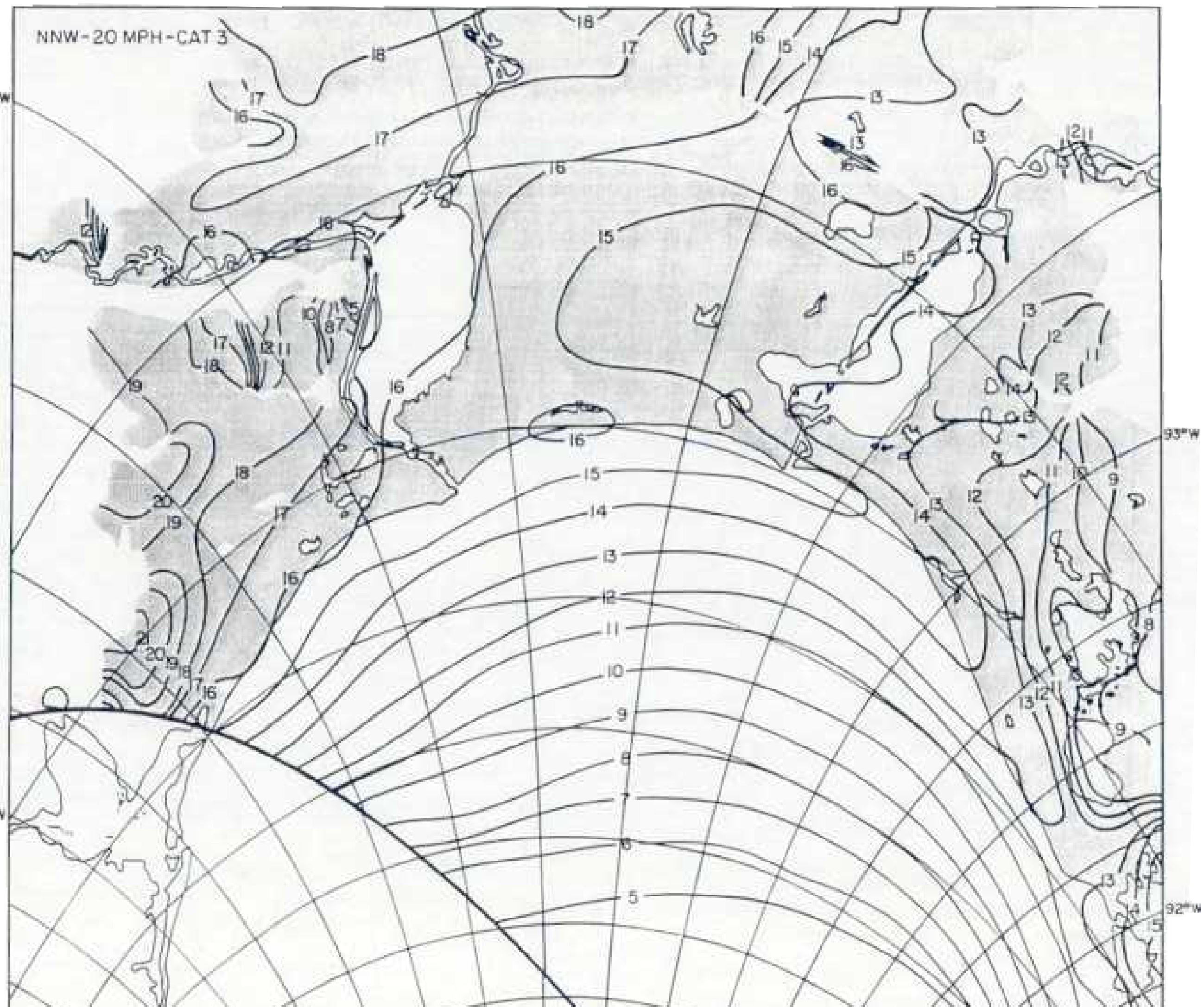
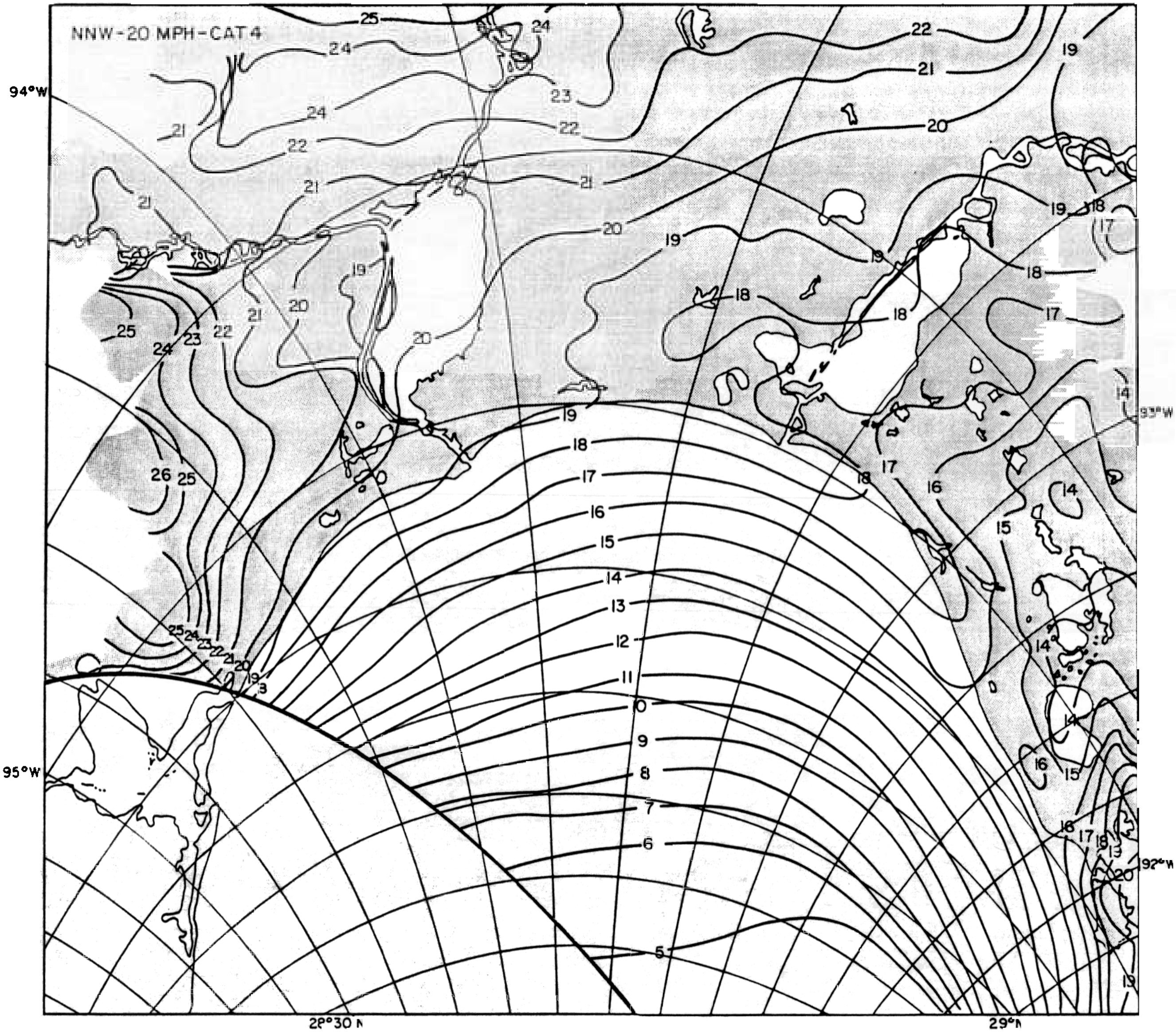
95°W
93°W
92°W
28°30'N
29°N


NNW-20 MPH-CAT 2
94°W
95°W
93°W
92°W
28°30'N
29°N



NNW-20 MPH-CAT 3
94°W
93°W
92°W
28°30'N
29°N



NNW-20 MPH-CAT 4
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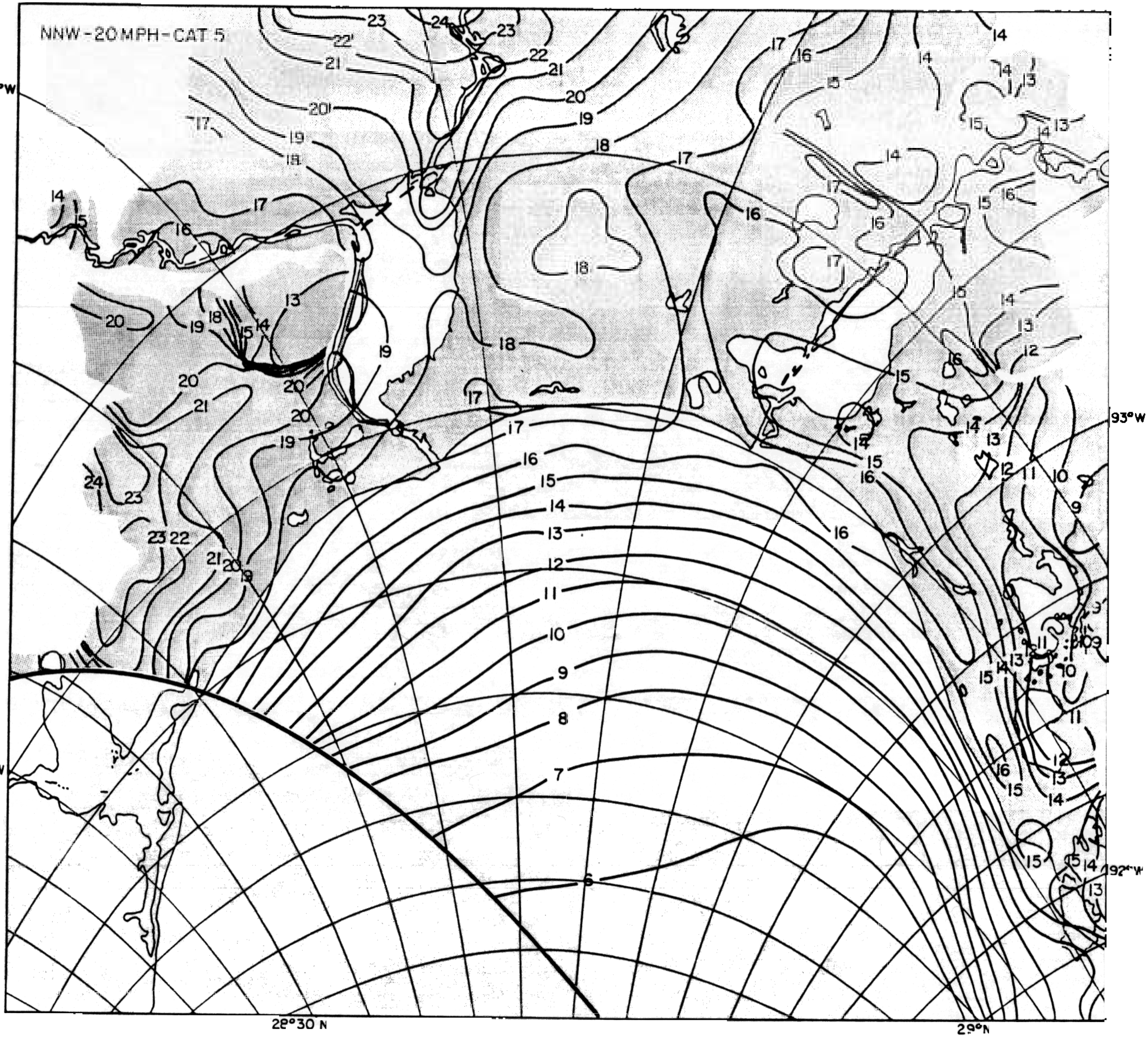
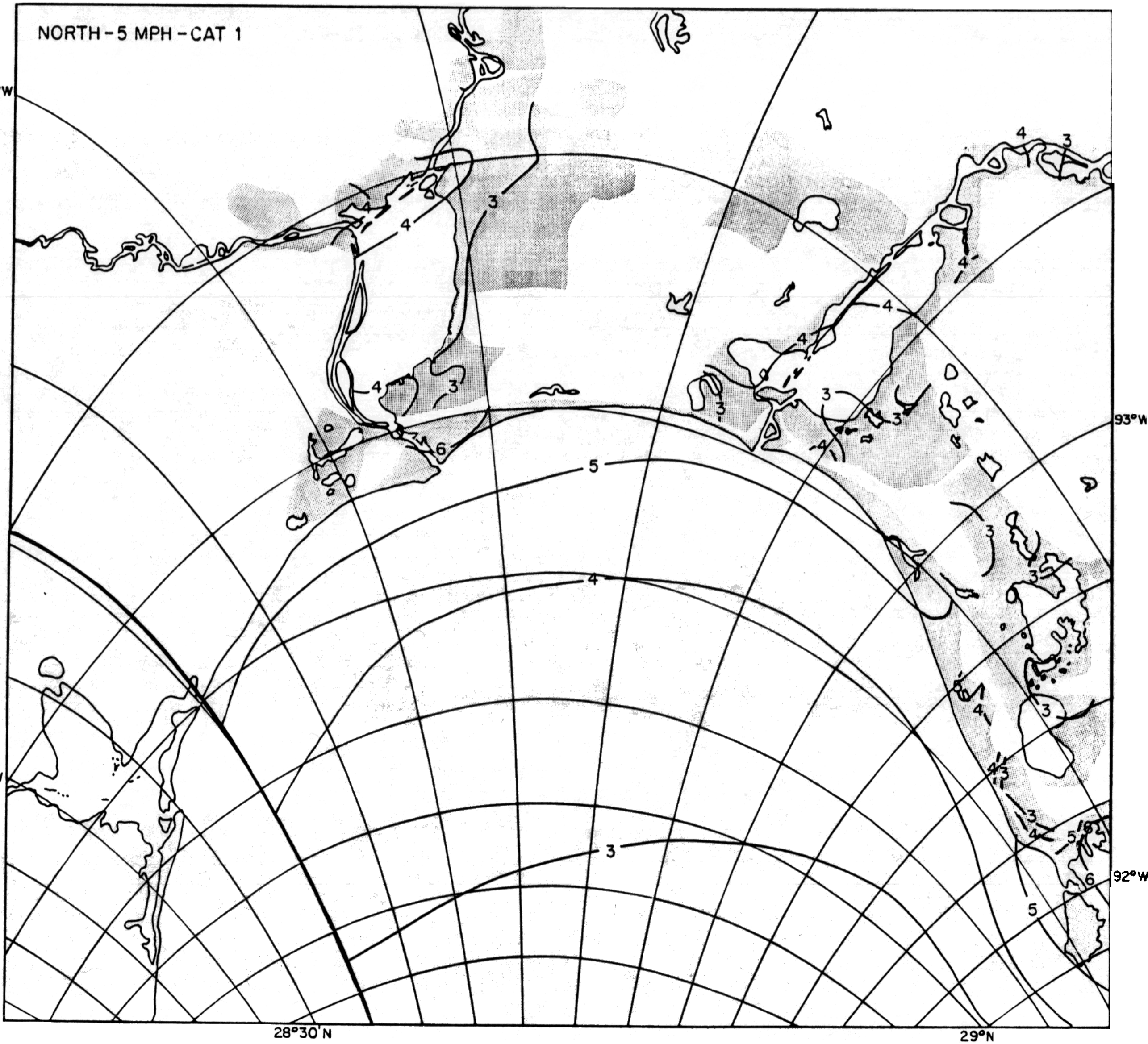
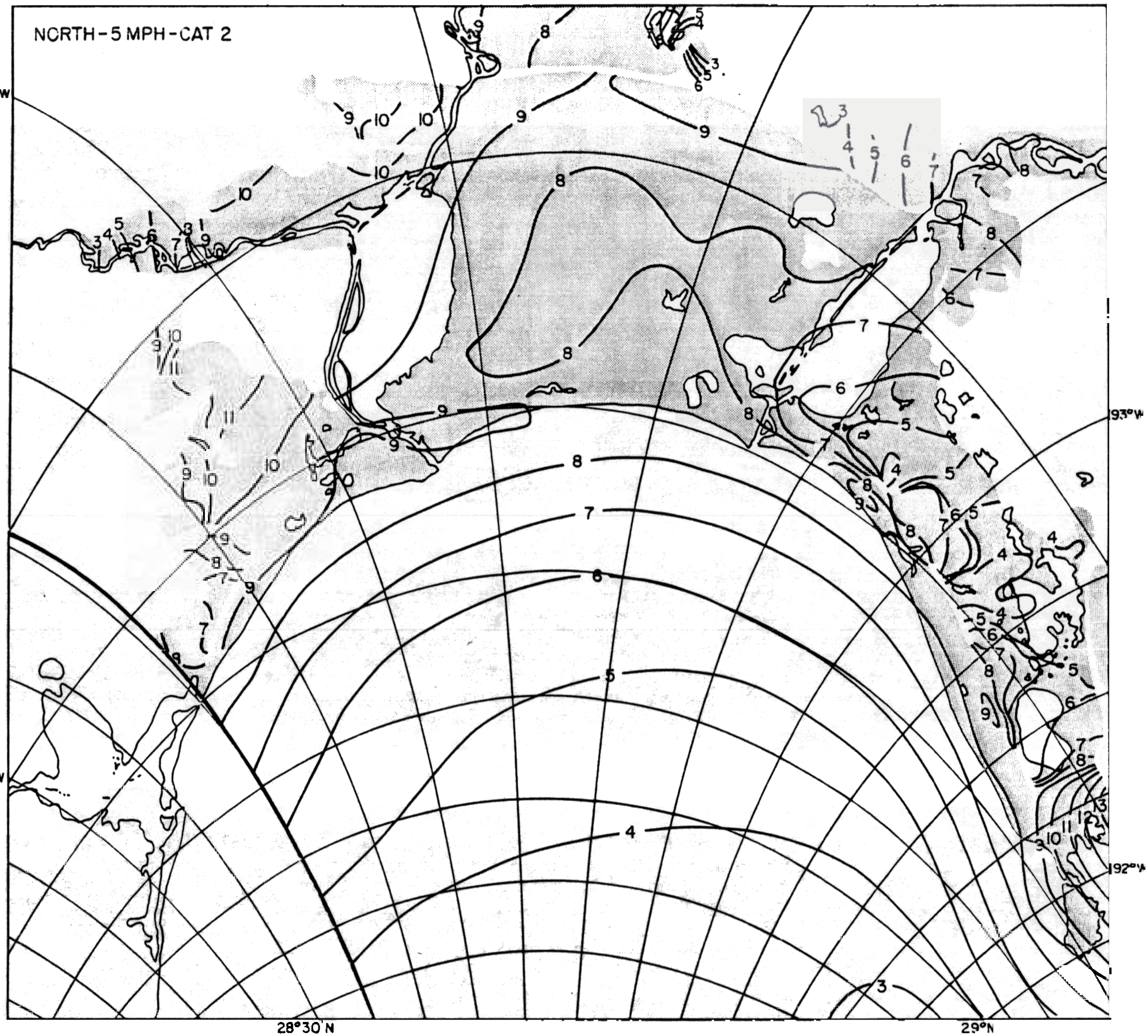
95°W
93°W
92°W
28°30'N
29°N


NNW-20 MPH-CAT 5
94°W
95°W
93°W
92°W
28°30 N
29°N


NORTH - 5 MPH - CAT 1
94°W
95°W
93°W
92°W
28°30'N
29°N
3
4
5
6


NORTH-5 MPH-CAT 2
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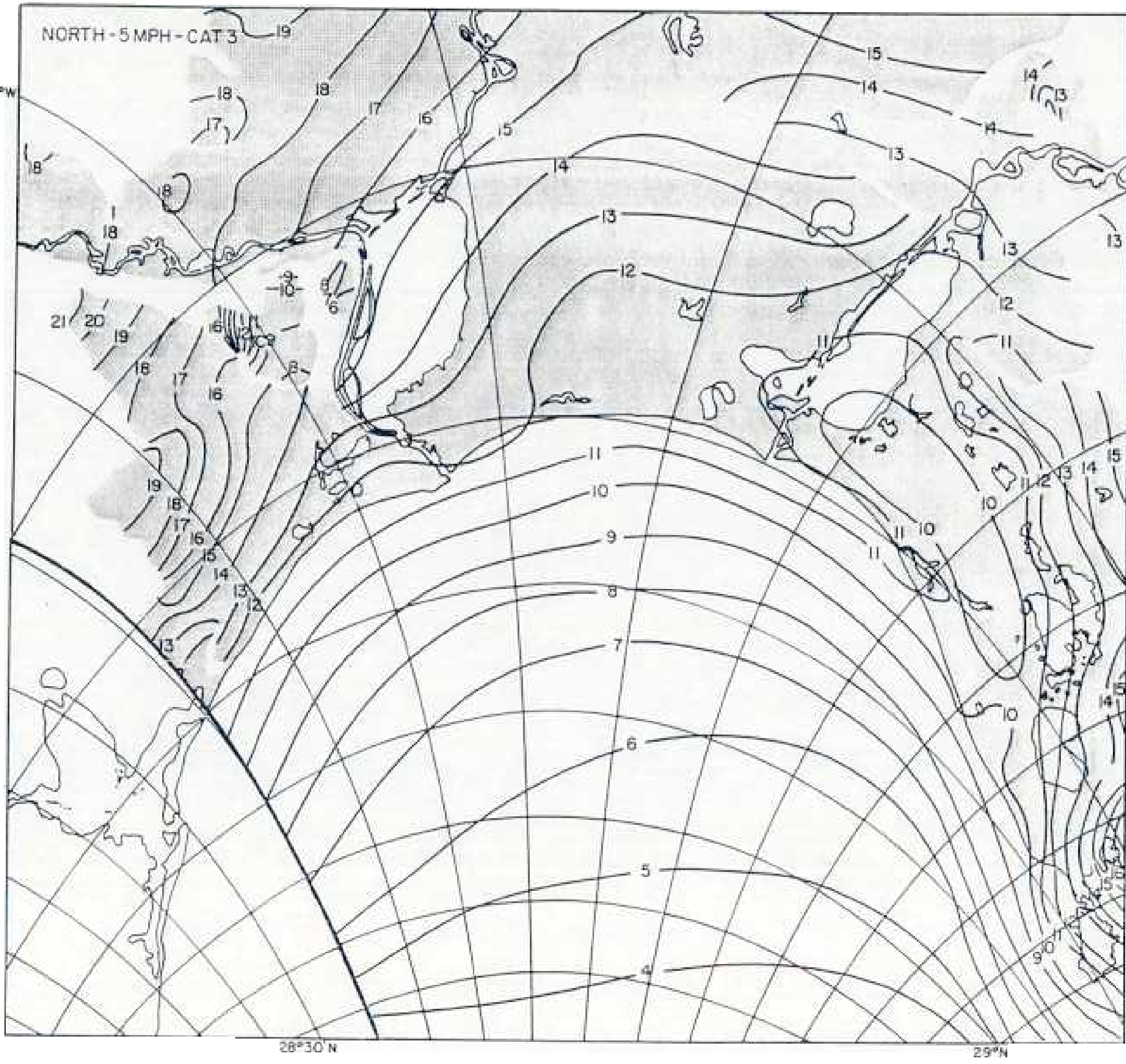
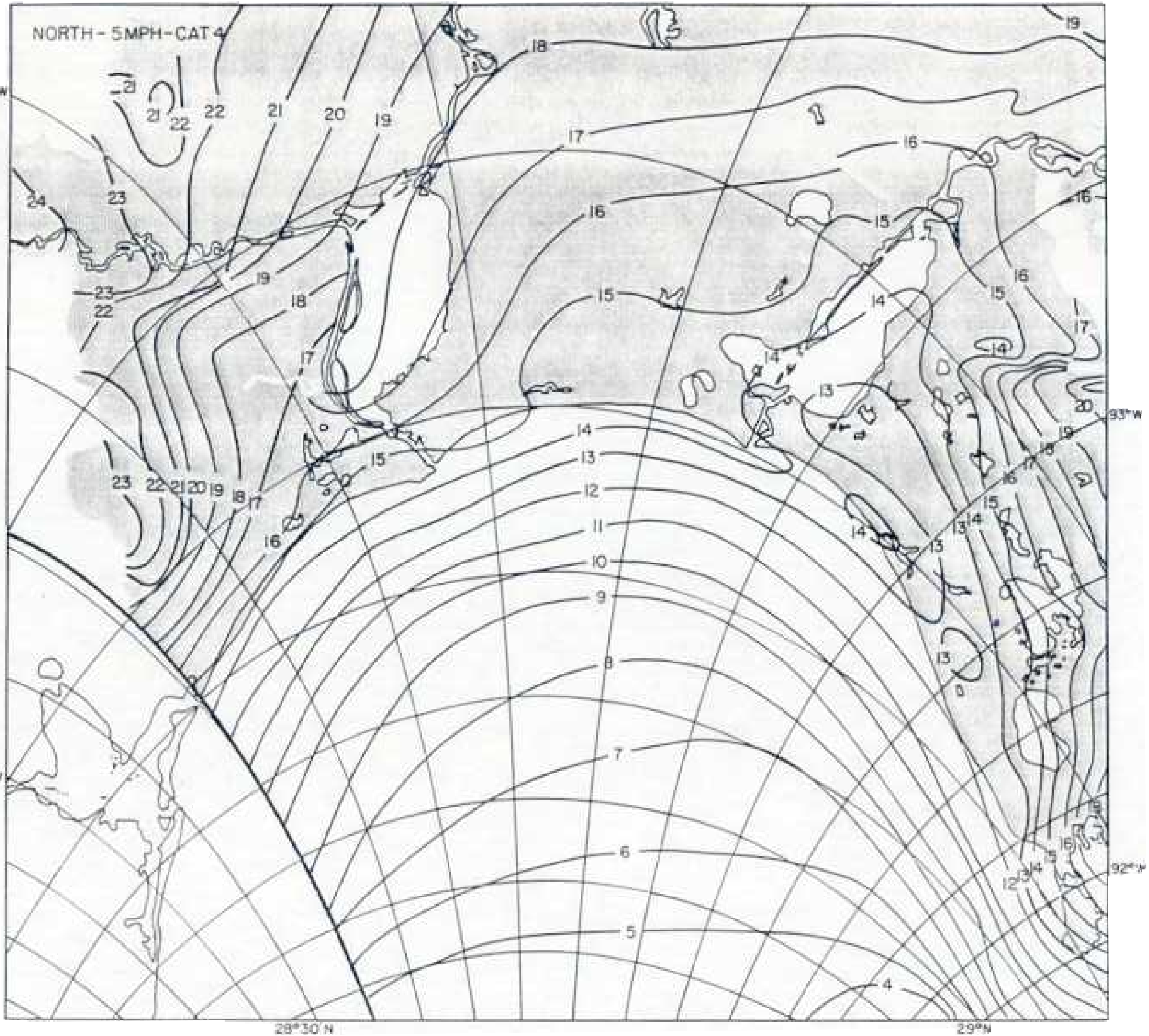
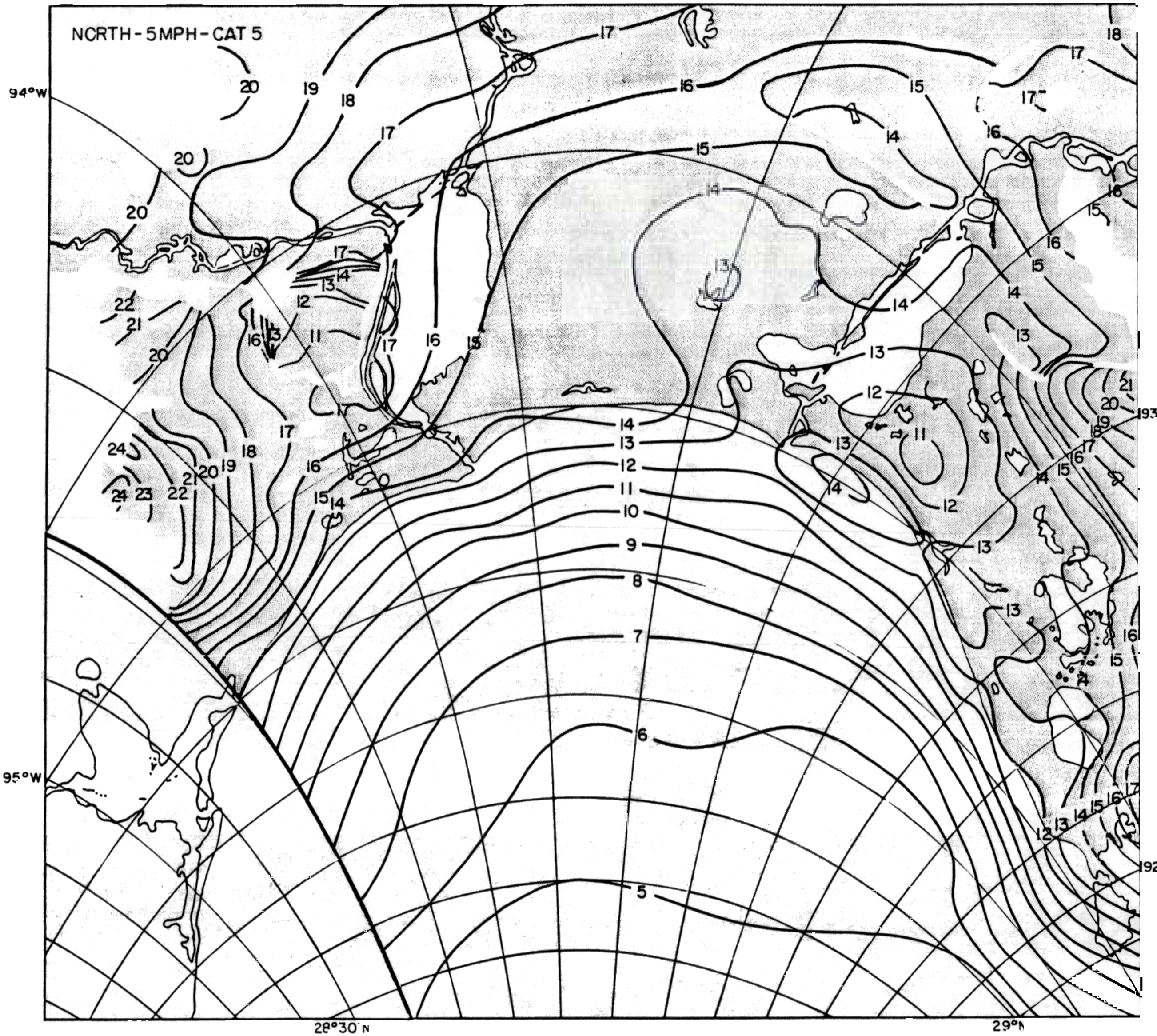
95°W
93°W
92°W
28°30'N
29°N


NORTH - 5 MPH - CAT 3
94°W
93°W
92°
28°30'N
29°N



NORTH - 5MPH - CAT 4
94°W
95°W
93°W
92°W
28°30'N
29°N


NORTH-5MPH-CAT 5
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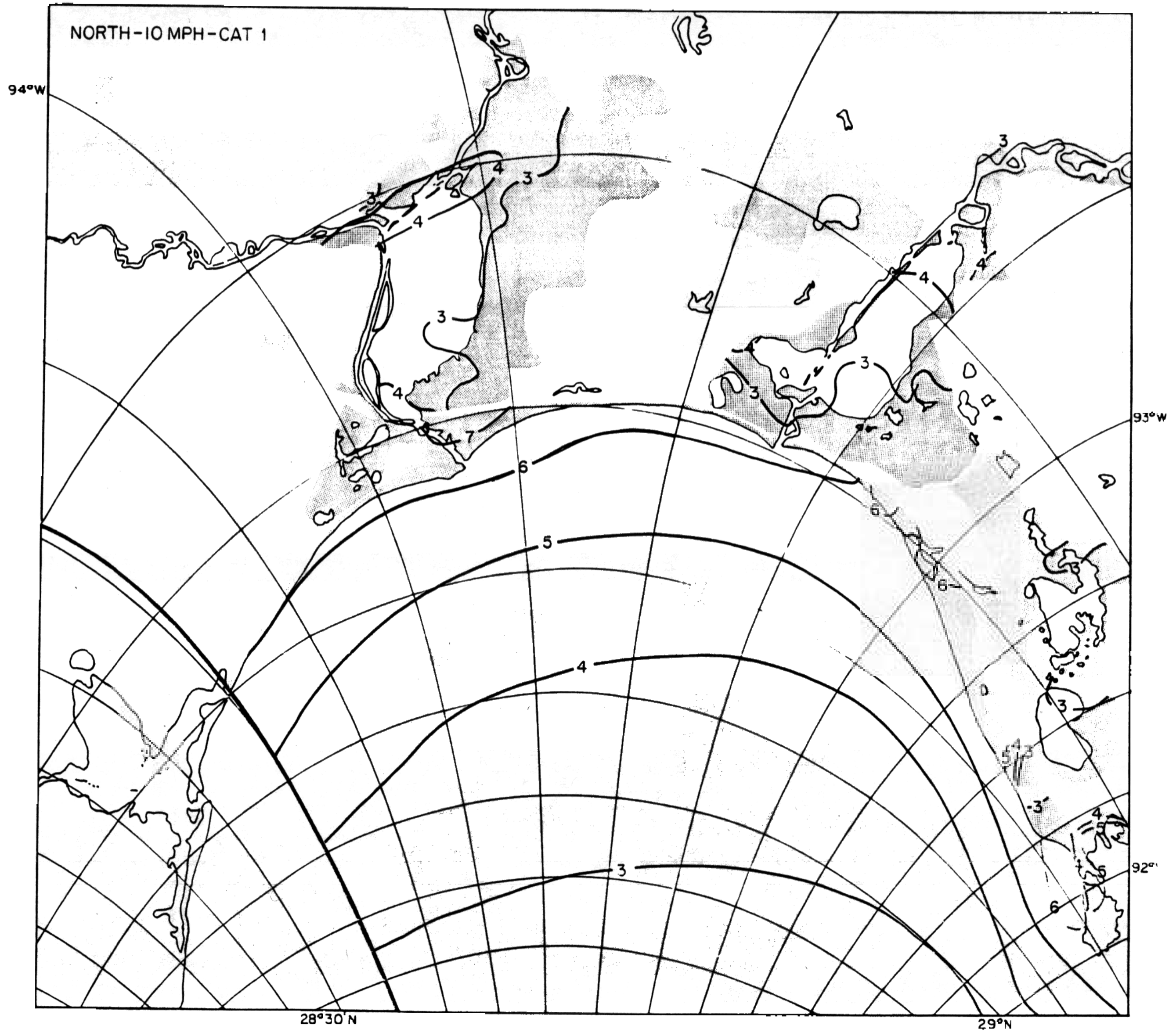
93°W
92°W
28°30'N
29°N



NORTH-10 MPH-CAT 1
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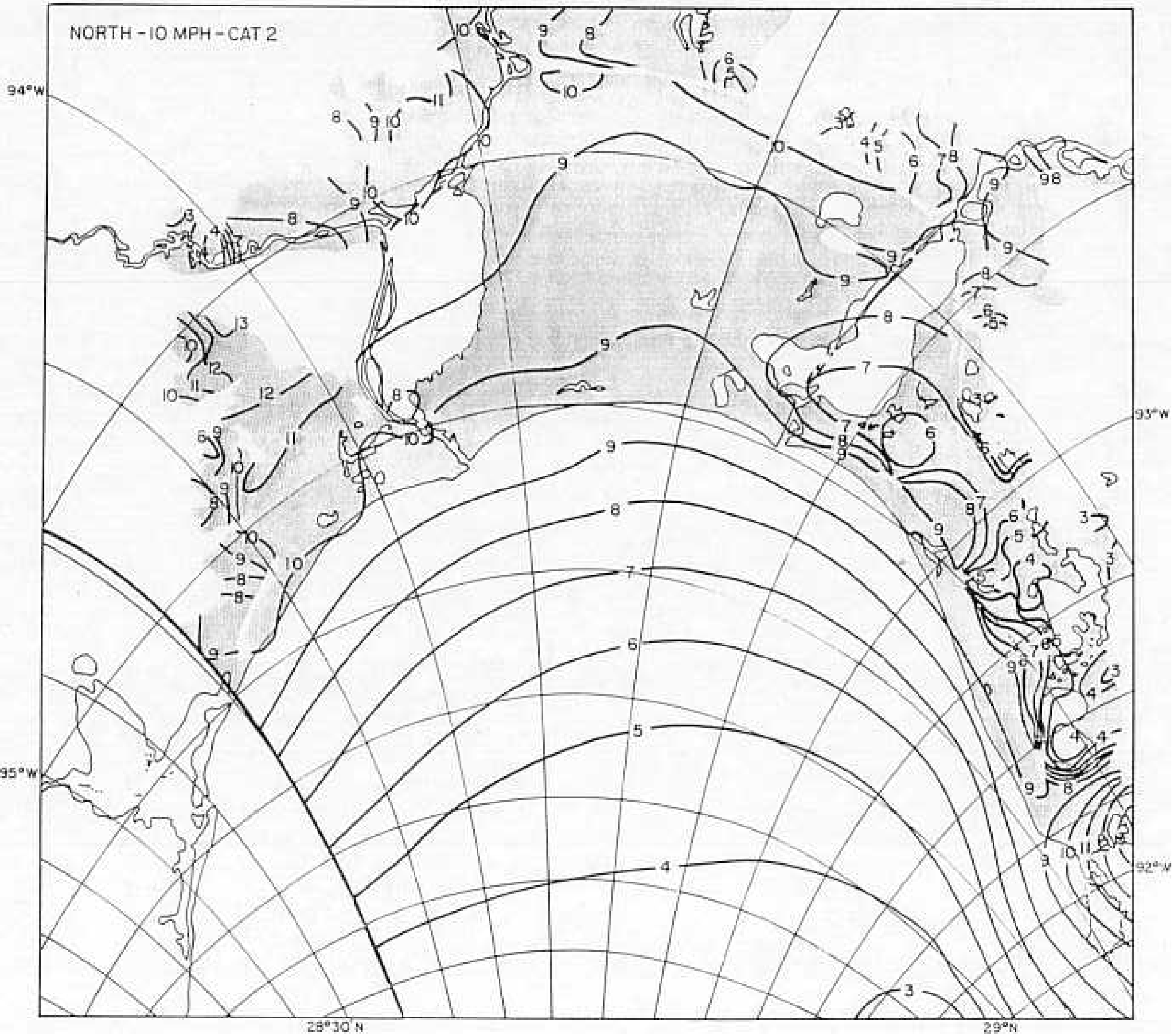
93°W
92°
28°30'N
29°N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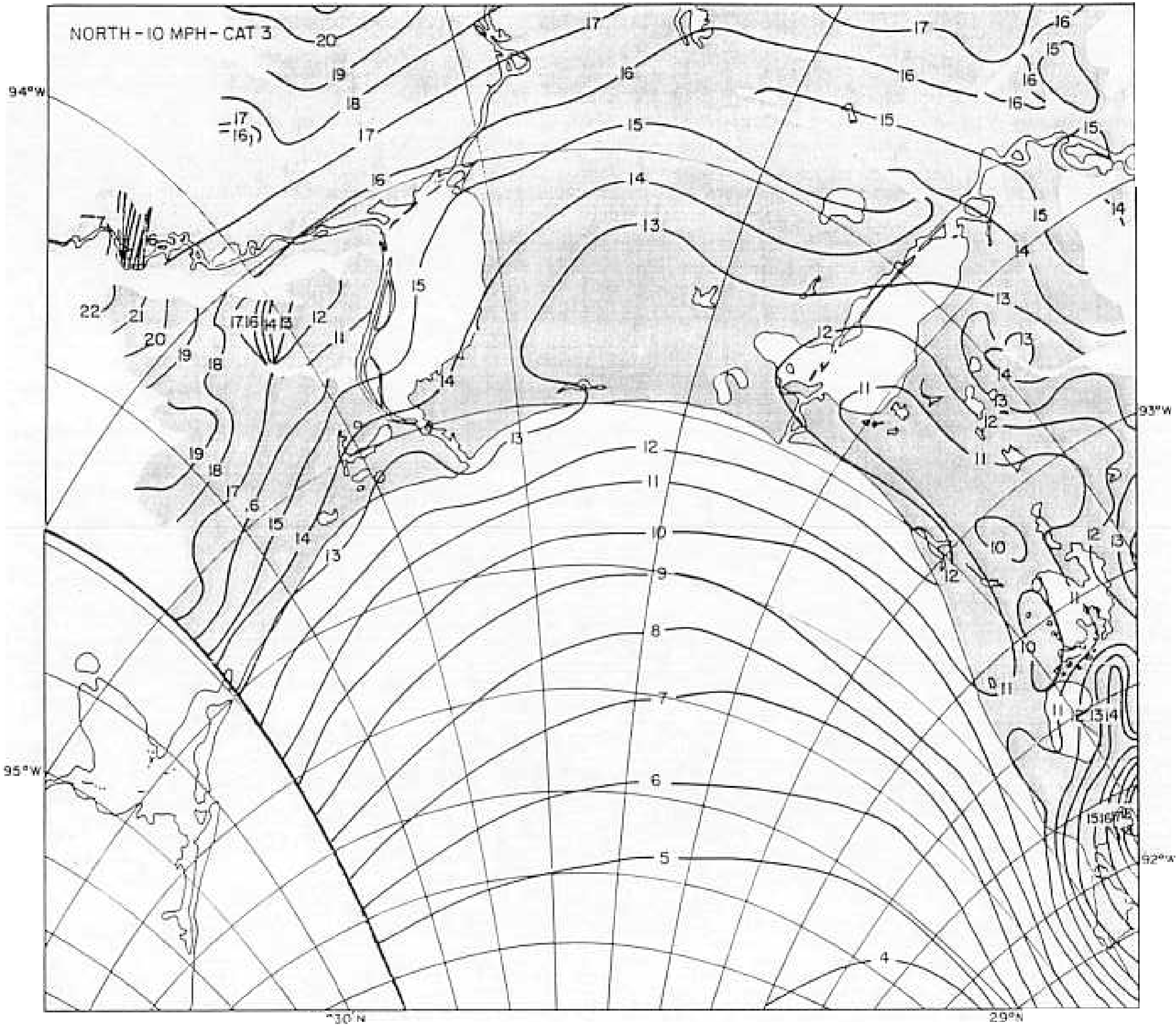
95°W
93°W
92°W
28°30'N
29°N


NORTH - 10 MPH - CAT 3
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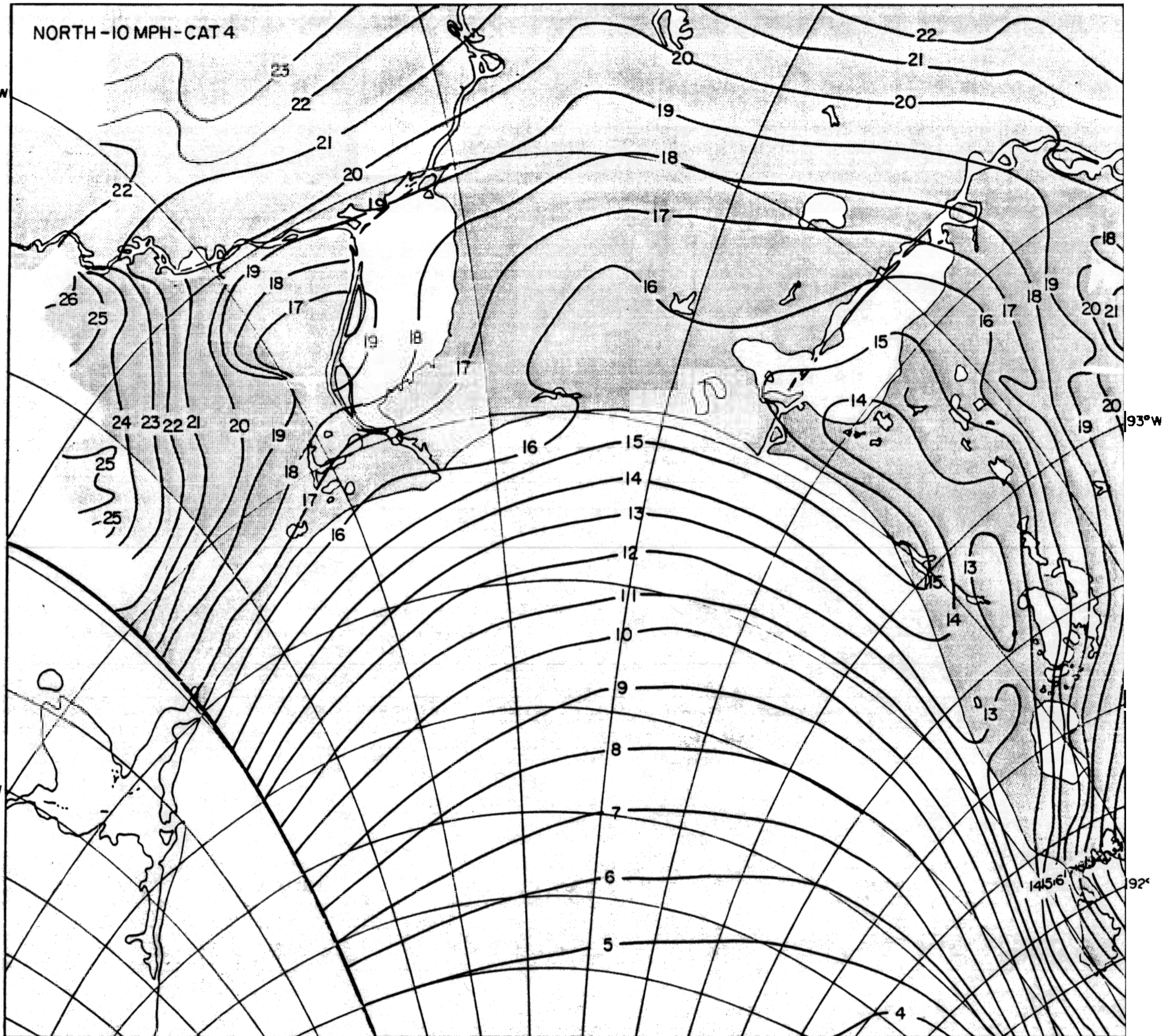
95°W
93°W
92°W
30°N
29°N


NORTH-10 MPH-CAT 4
94°W
95°W
93°W
92°
28°30'N
29°N
26
25
24
23
22
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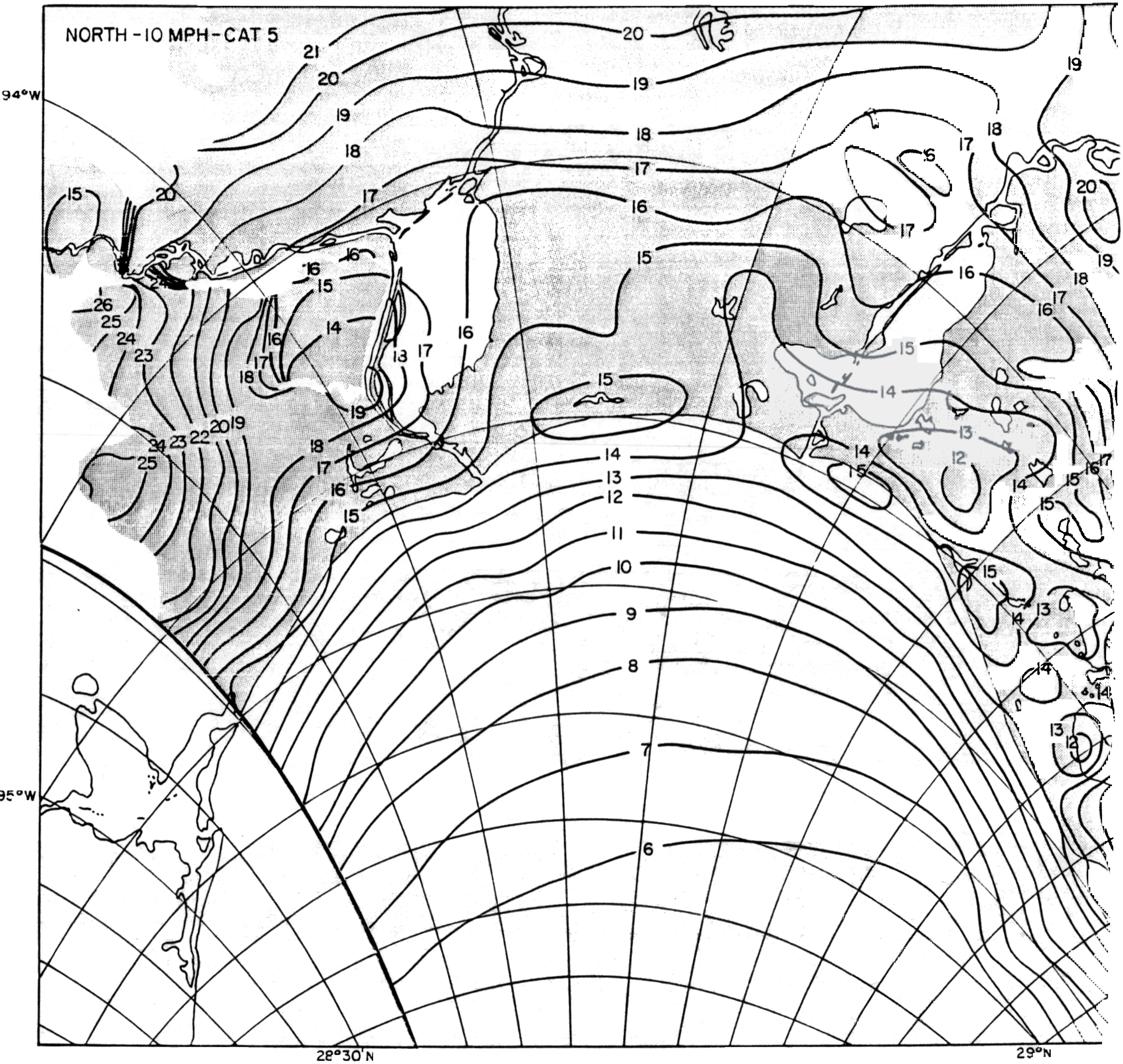
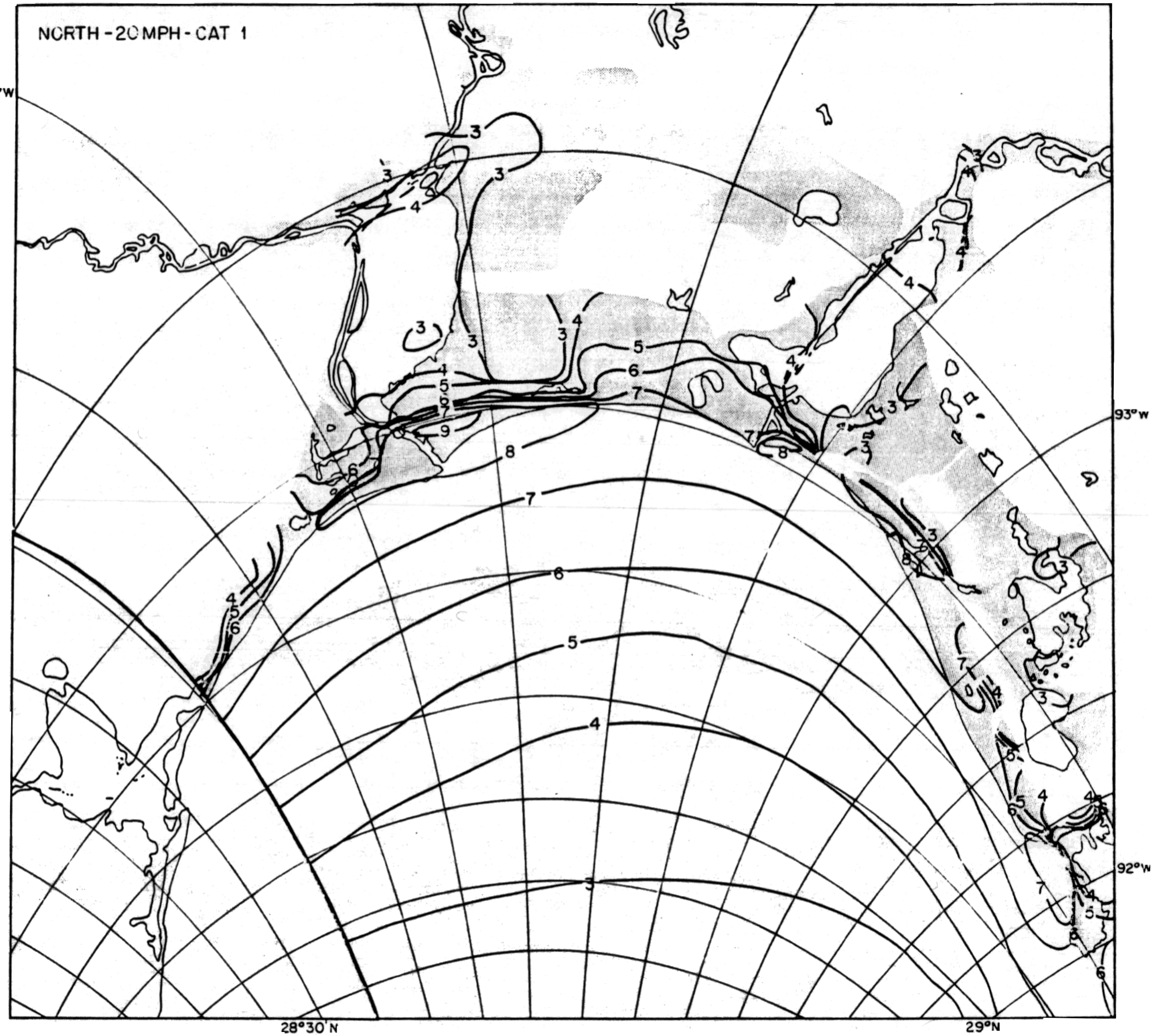

NORTH - 10 MPH - CAT 5
94°W
95°W
28°30'N
29°N


NORTH - 20 MPH - CAT 1
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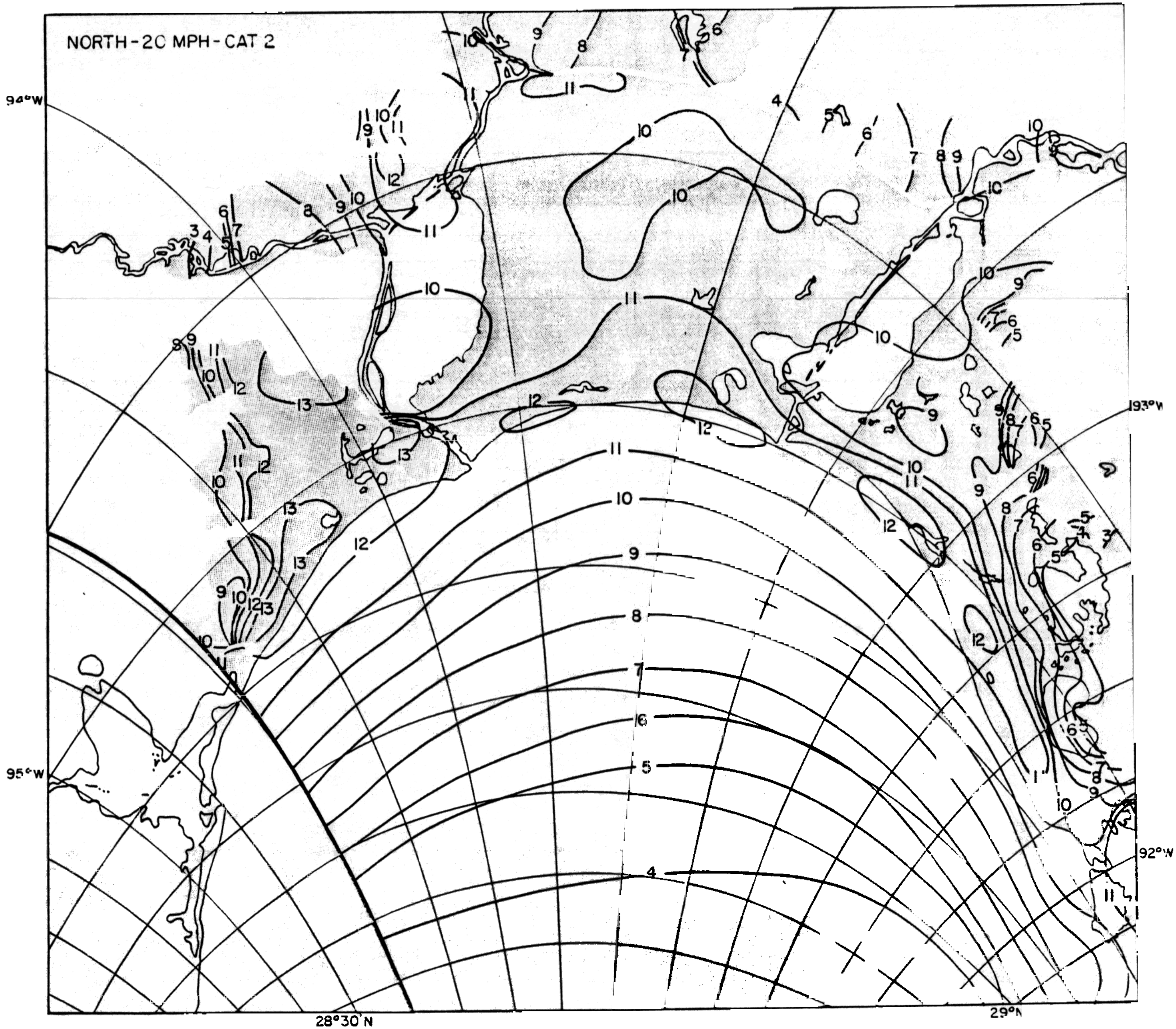
92°W
28°30'N
29°N



NORTH-20 MPH-CAT 2
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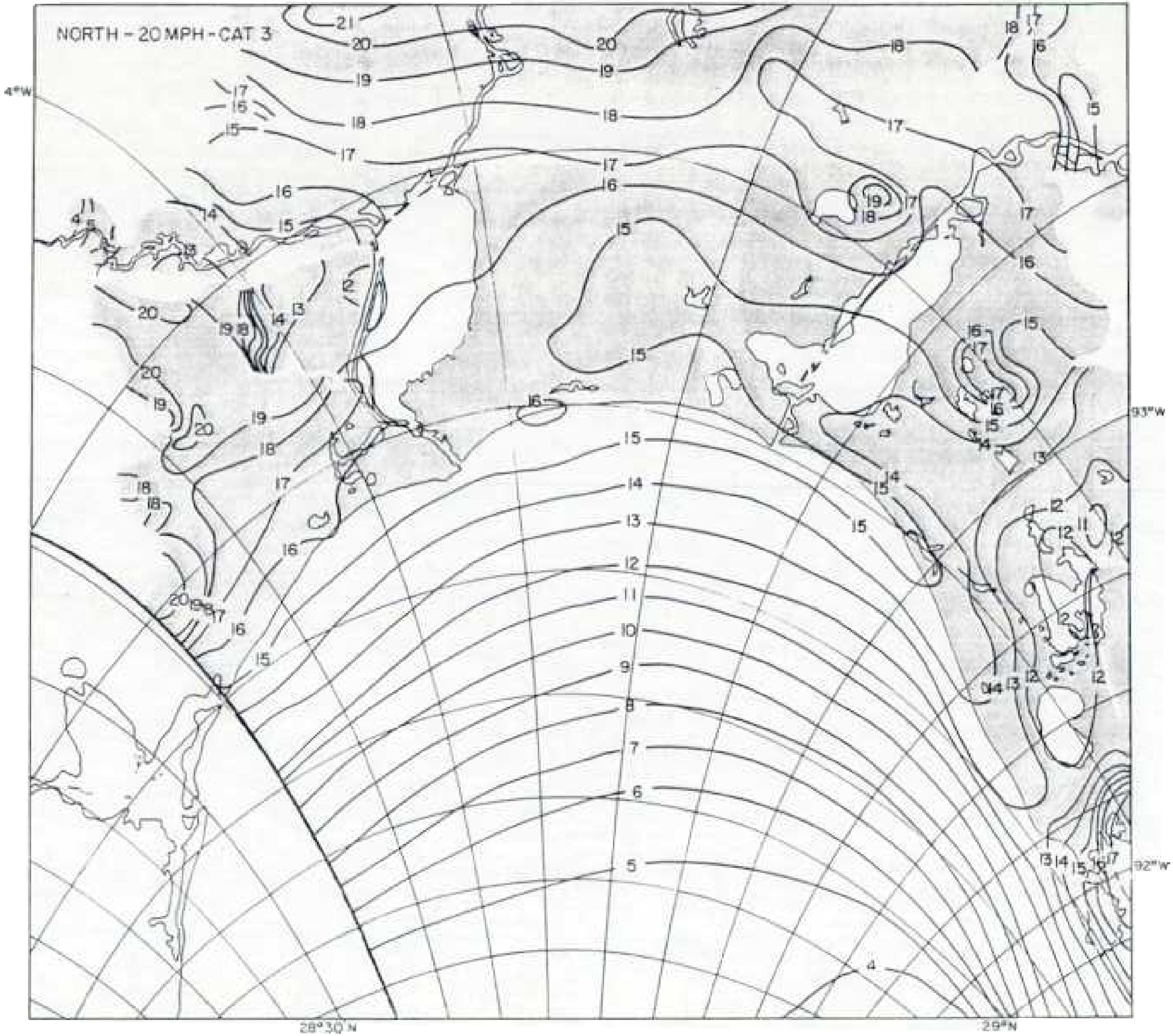
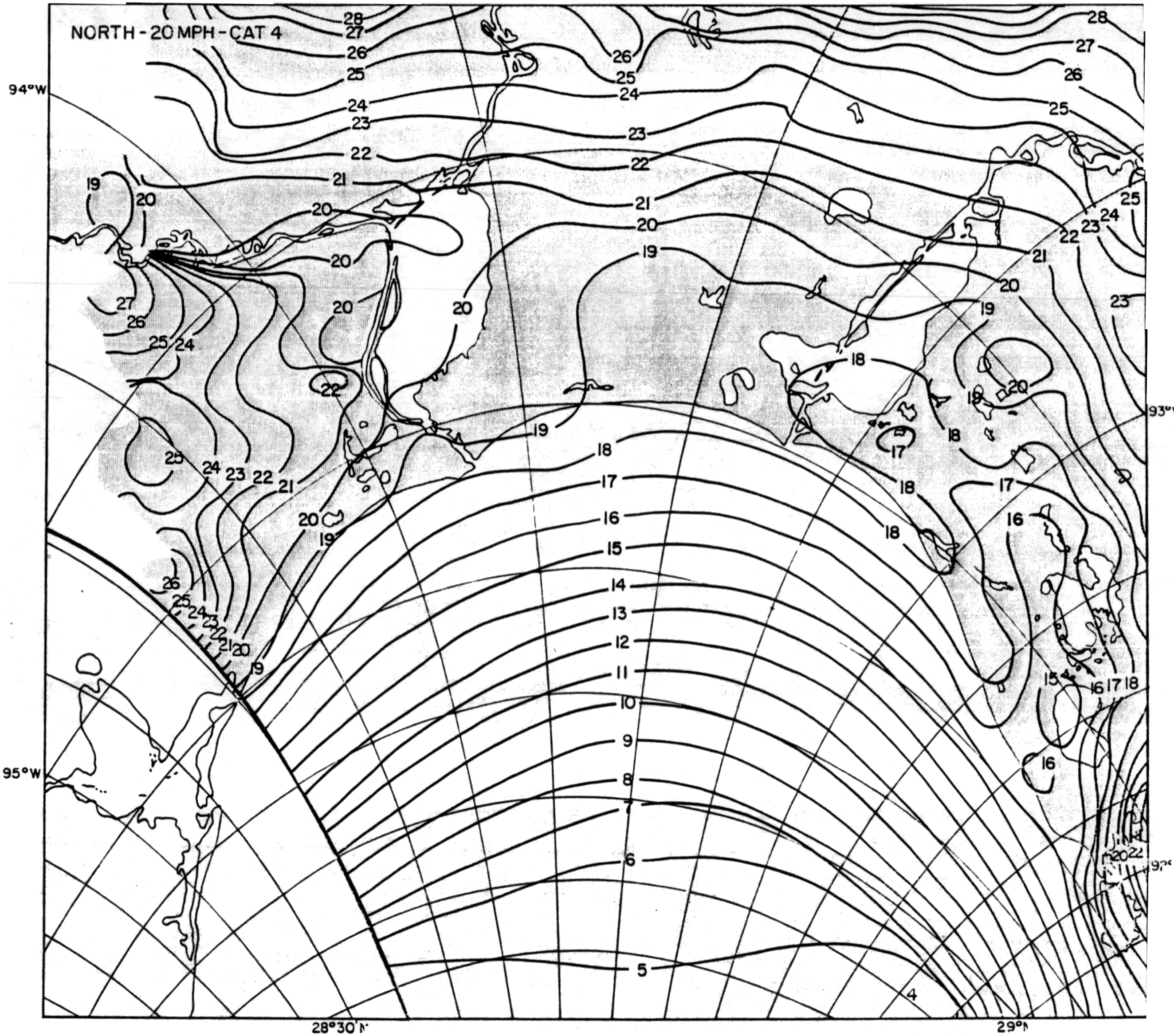
93°W
92°W
28°30'N
29°N


NORTH - 20 MPH - CAT 3
4°W
93°W
92°W
28°30'N
29°N


NORTH - 20 MPH - CAT 4
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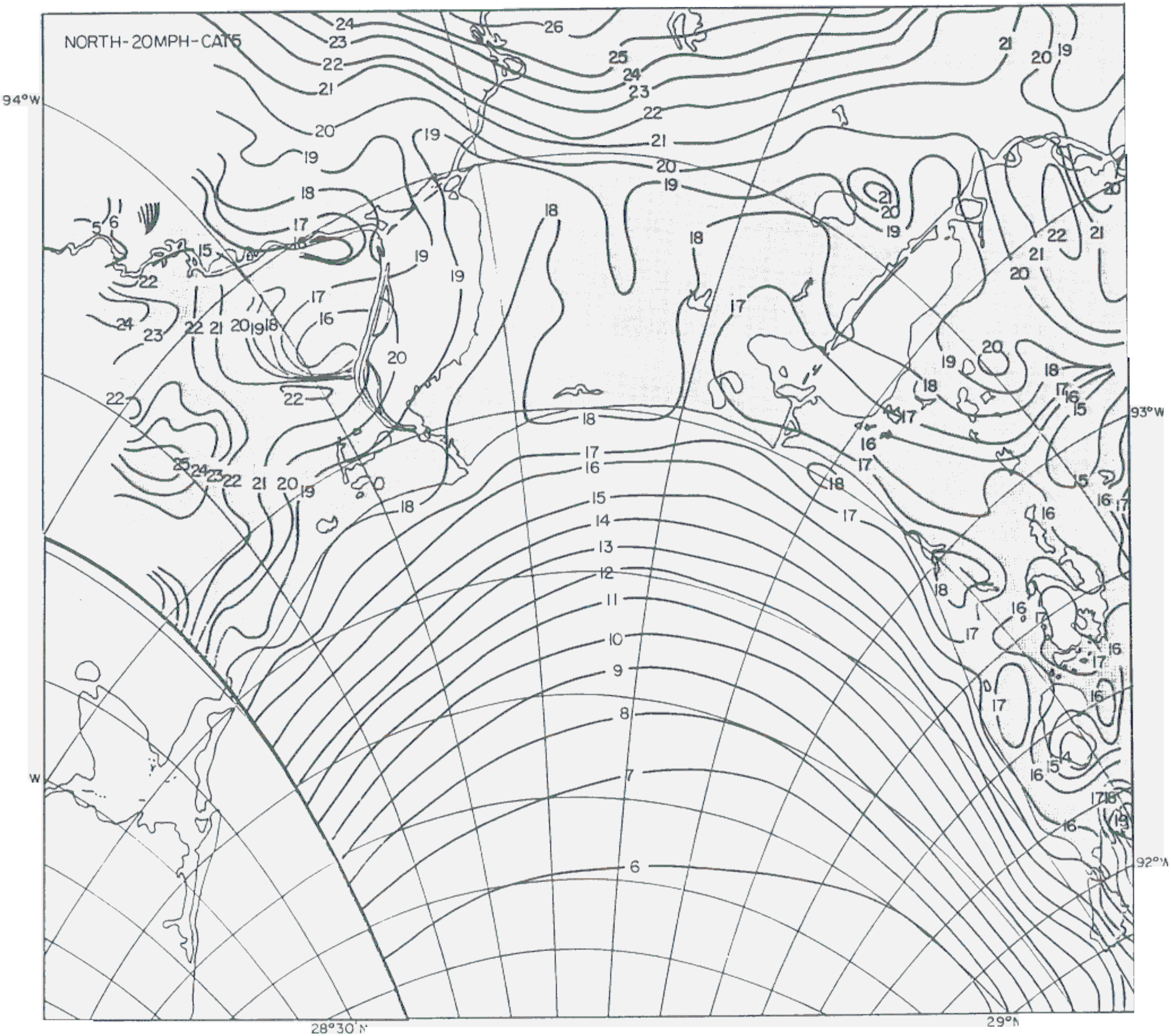
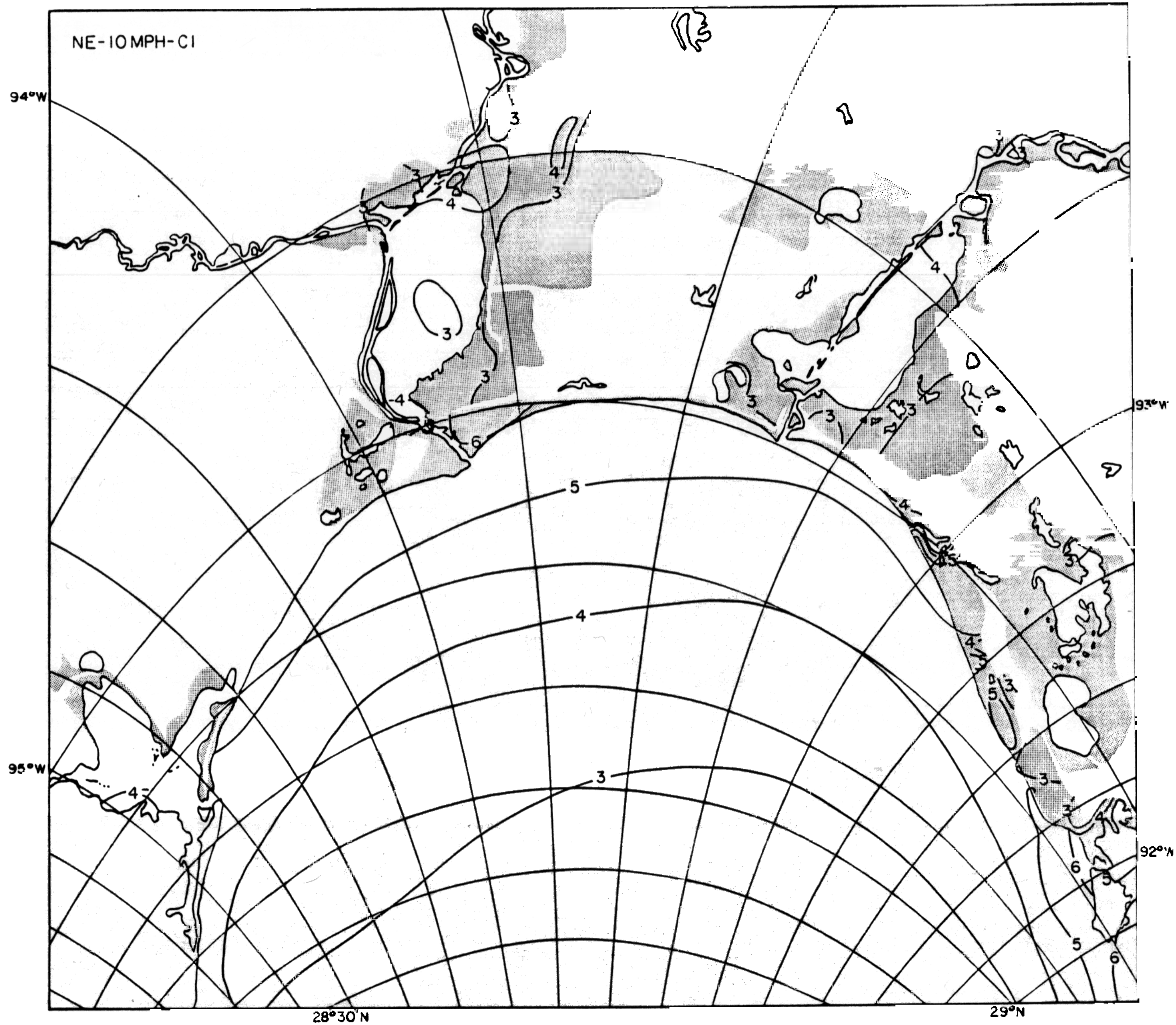
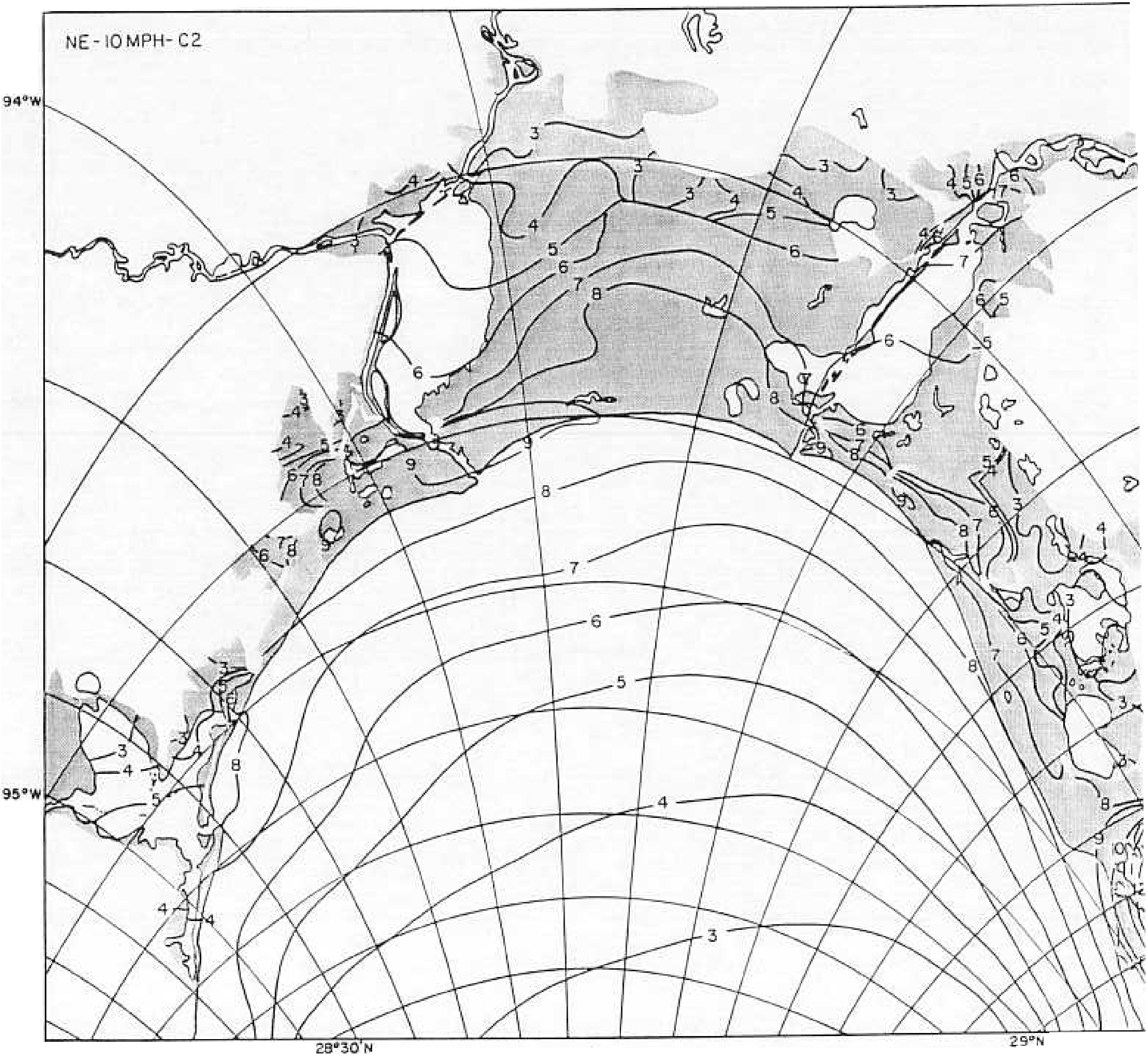
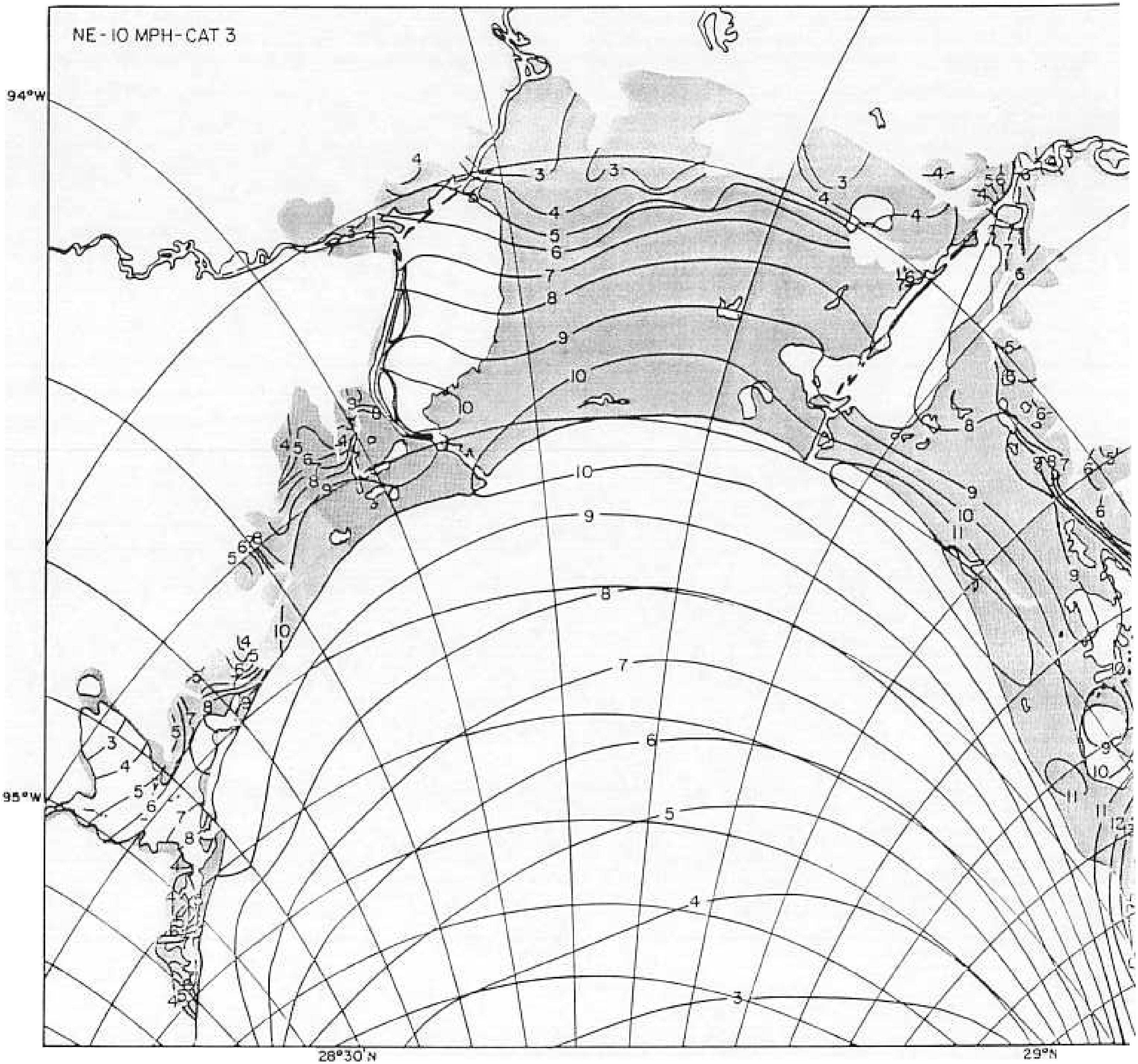
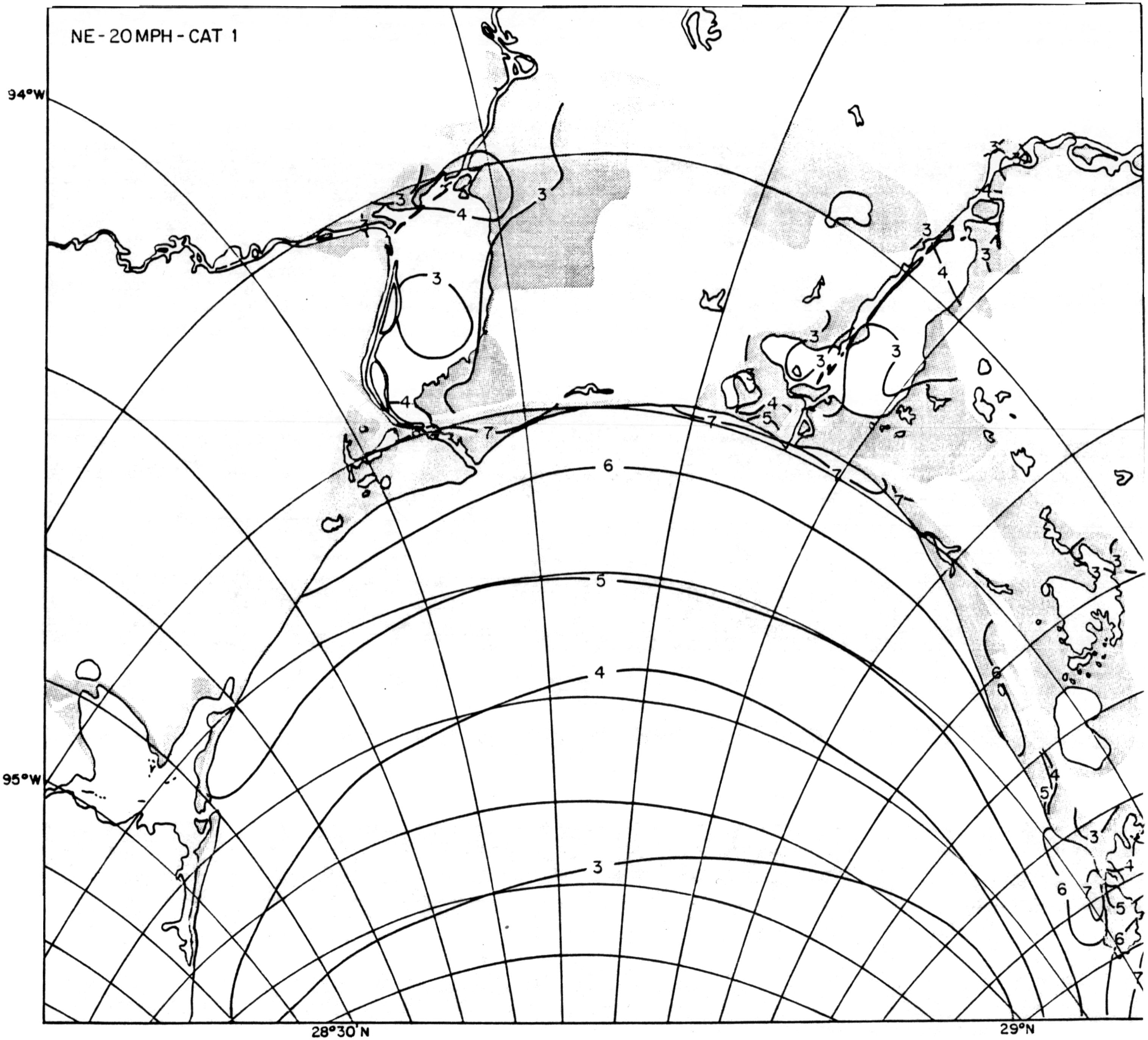
95°W
93°W
28°30'N
29°N

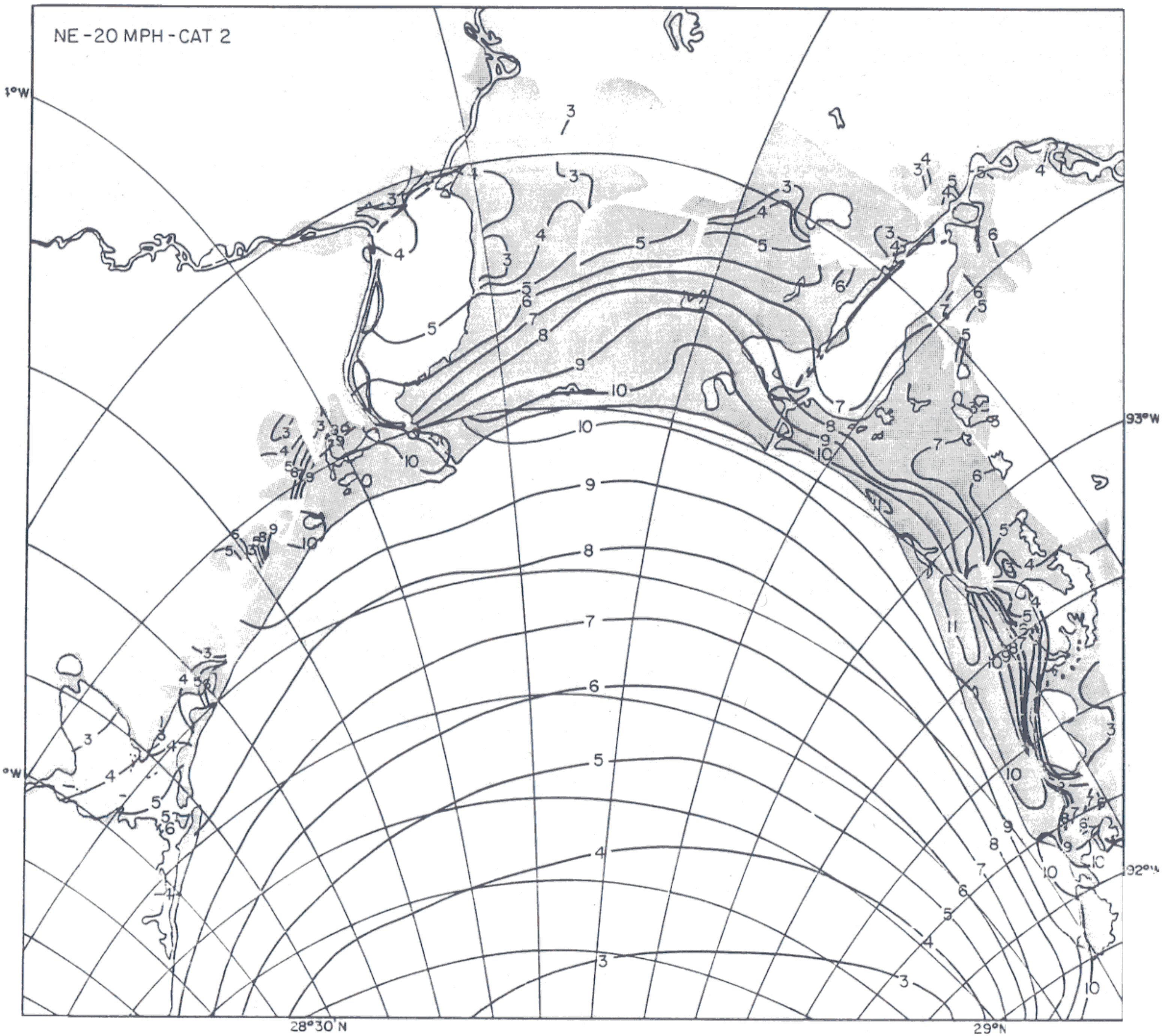

NORTH-20MPH-CAT5
94°W
93°W
92°W
28°30'N
29°N

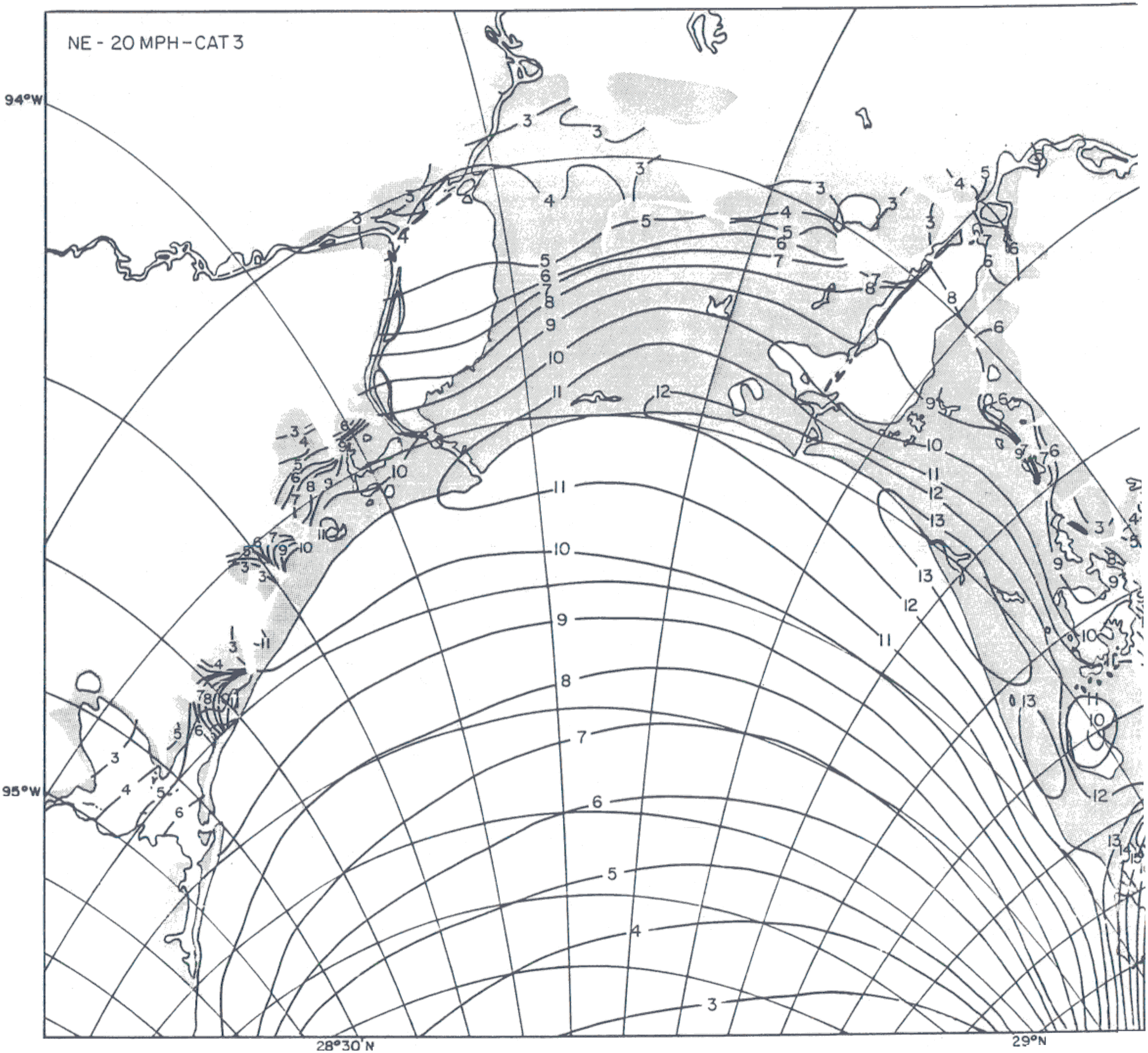

NE-10MPH-C1
94°W
95°W
93°W
92°W
28°30'N
29°N
3
4
5
6


NE-10MPH-C2
94°W
95°W
28°30'N
29°N


NE-10 MPH-CAT 3
94°W
95°W
28°30'N
29°N


NE-20MPH-CAT 1
94°W
95°W
28°30'N
29°N
3
4
5
6
7


NE-20 MPH-CAT 2
93°W
92°W
28°30'N
29°N



NE - 20 MPH - CAT 3
94°W
95°W
28°30'N
29°N