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Reports of the Department of Geodetic Science and Surveying
Report No. 333

A GLOBAL ATLAS OF SEA SURFACE HEIGHTS BASED ON THE ADJUSTED SEASAT ALTIMETER DATA

by

Richard H. Rapp

Prepared for

National Oceanic and Atmospheric Administration
Rockville, Maryland 20852
Contract No. 78-4326

OSU

The Ohio State University
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1958 Neil Avenue
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Abstract

This report consists of 53 maps of all the oceans covered by Seasat altimeter data. These maps have been constructed from the adjusted altimeter data. The maps have a two meter contour interval based on predictions on a $1° \times 1°$ grid. The available subsatellite tracks area also plotted on these maps.

Foreword

This report was prepared by Richard H. Rapp, Professor, Department of Geodetic Science and Surveying, The Ohio State University. This work was supported, in part, by NOAA Contract No. 78-4326, The Ohio State University Research Foundation Project 711581.

Most of the computer funds needed for the generation of these maps was provided by the Instruction and Research Computer Center through the Department of Geodetic Science and Surveying.

Introduction

The use of altimeter information has provided an excellent tool for studying the shape of the sea surface. The most global coverage of the oceans has been obtained through Seasat although there are areas where the Geos-3 data is more dense.

The altimeter data in its generally distributed form is not suitable for the direct surface mapping as the data contains significant orbit error. Such error can be significantly reduced through crossover analysis techniques. Such procedures were used with Geos-3 data (Rapp, 1977, 1978) to obtain adjusted observations. The information described by Rapp (1978) was used by Kearsley (1977) to produce a series of 26 maps in areas of Geos-3 coverage. A large scale global map using Geos-3 data was prepared by Rapp (1979).

The Seasat altimeter data provides a similar opportunity. A global map of the initial Seasat altimeter data has been described by Marsh and Martin (1982). The disadvantage of such a map is the scale where the size of the map is too small to adequately portray the information in the altimeter data. Consequently we felt that it was appropriate to take our adjusted Seasat altimeter data and produce a set of regional maps at the same scale as the Geos-3 data.

The Adjusted Seasat Altimeter Data Base

The basic discussion of the Seasat altimeter data processing is found in Rowlands (1981). In his study Rowlands carried out a primary adjustment of 549 arcs with a resulting root mean crossover discrepancy after the adjustment of ±28 cm. These arcs were then held fixed in four regional adjustments: North Atlantic, South Atlantic, Pacific Ocean, Indian Ocean. The details of these adjustments can be found in Rowlands (ibid). The location of the originally edited data and the four regional adjustment areas are shown in Figure 1. (In the original adjustments the Pacific area was a single region.)

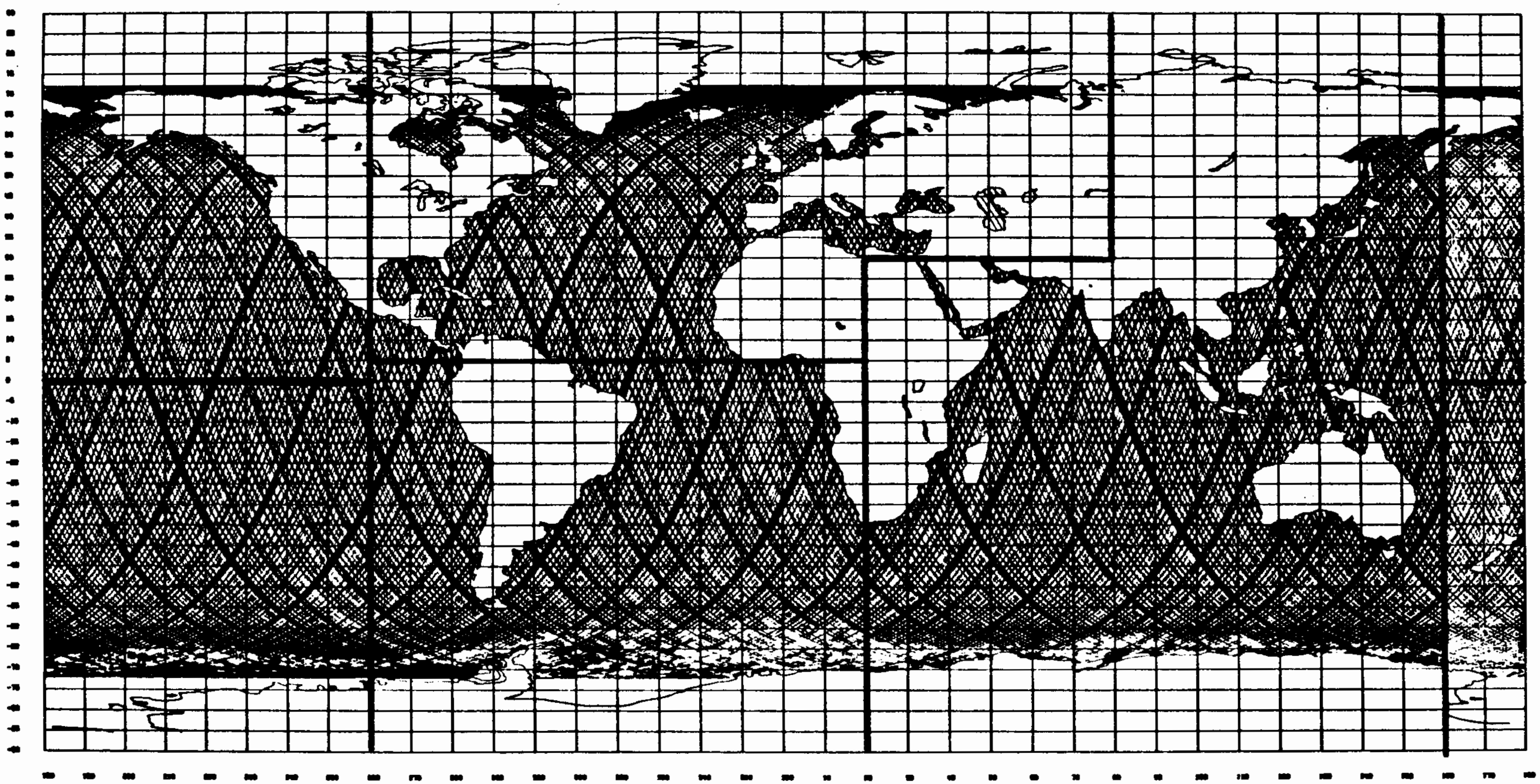


Figure 1: Edited Seasat Altimeter Data Base Showing Location of Five Regions in which Data was Adjusted

After Rowlands had completed his works tests showed that in certain limited areas the adjustment was weak due to the neglect of certain crossover information. This weakness primarily occured in the northeast Pacific. In addition it had been realized that certain invalid tides were used in the original adjustment. With these considerations a decision was made to re-adjust our previously edited data. In doing this we kept the original 549 arc primary adjustment and the adjustment of the South Atlantic as neither area was affected by the crossover problem.

We also had some indications that a better adjustment in the Pacific region could be obtained if the region were split approximately in half. This led to two additional regional adjustments.

The four areas specifically adjusted in this new solution were in the North Atlantic, the North Pacific Ocean, the South Pacific Ocean and the Indian Ocea. All tides were set to zero in the North Atlantic and Indian Ocean areas where the Schwiderski tide models were not valid. In addition the North Atlantic was adjusted first including data in the Hudson Bay and then excluding such data. This second adjustment was carried out due to the separation of the bay from the North Atlantic and because of concern about unmodeled tide effects. A separate adjustment was also carried out with data in the Mediterranean Sea area holding fixed three arcs. This adjustment was carried out because of indications of slope problems of the adjusted data in the large North Atlantic adjustment. Statistical information on these new adjustments is given in Table 1 that is comparable to Table 8 of Rowlands (ibid). The new adjustments were carried out by Mr. Jaime Cruz. The adjusted data will not include all the data shown in Figure 1 as a few arcs are edited out in the adjustment process.

The final adjusted data forms a data base for the construction of the sea surface height maps. In generating the maps we use the adjusted data for each region. When constructing the maps for the North Atlantic the regional adjustment that excludes the Hudson Bay data will be used. For the map of the Hudson Bay, the North Atlantic adjustment that includes this data will be used. For the construction of the Mediterranean Sea and Black Sea maps the data from the Mediterranean Sea adjustment will be used.

Table 1

Local Adjustment Statistics

	North Atlantic with Hudson	North Atlantic w/o Hudson	North Pacific	South Pacific	Indian	Med. Sea
No. of Arcs	867	812	664	480	746	230
No. of Parameters	1461	1371	1146	893	1371	230
No. of Crossovers						
Local & Primary	14256	13834	8946	12814	18072	60
Local & Local	28179	27086	16588	16861	17784	1180
Total	42435	40920	25534	29575	35856	1240
RMS Crossover Discrep. Before Adj (m)						
Local & Primary	±1.02 m	±0.99 m	±1.59 m	±1.41 m	±1.58 m	±2.60 m
Local & Local	1.28	1.17	1.92	1.92	1.64	2.59
Total	1.19	1.18	1.81	1.72	1.61	2.59
RMS Crossover After Adj (m)						
Local & Primary	±0.33 m	±0.25 m	±0.34 m	±0.32 m	±0.25 m	±0.41 m
Local & Local	0.31	0.26	0.32	0.23	0.24	0.12
Total	0.32	0.26	0.33	0.27	0.25	0.15
No. of Observations	394365	386089	384549	468219	690100	22509

The Generation of the Sea Surface Height Grid

The maps to be developed are to be based on the contouring of data estimated on a uniform 1°x 1° grid. Such a grid was selected as a compromise between estimation accuracy, desired contour interval (±2 m), and computer support. A denser grid would allow for a more accurate contour generation but it might only be needed in areas of steep sea surface height gradients.

Given the adjusted data it is thus necessary to generate the predicted sea surface height (and prediction accuracy). Various methods for doing this are discussed by Katsambalos (1980). We elected to continue to use the least squares collocation procedure as also used by Kearsley (1977).

The basic prediction equations are (Katsambalos, 1980, p. 2):

$$\hat{N} = \underline{C}_{Nh} (\bar{C}_{hh} + \bar{D})^{-1} (\underline{h} - \underline{h}_{mean}) + h_{mean} \quad (1)$$

$$\sigma_N^2 = C_{NN} - \underline{C}_{Nh} (\bar{C}_{hh} + \bar{D})^{-1} \underline{C}_{hN} \quad (2)$$

where:

- $\hat{N}$ is the predicted sea surface height:
- C_{NN} is the mean square value, in a global sense, of the sea surface height being estimated;
- σ_N^2 is the predicted accuracy of $\hat{N}$;
- $\underline{C}_{Nh}$ are the covariances between the sea surface height being predicted and each of the given (adjusted) sea surface heights;
- $\underline{C}_{hh}$ are the covariances between the given sea surface heights;
- $\bar{D}$ is taken as a diagonal matrix whose elements are the variances of the altimeter measurement noise;
- $\underline{h}$ is the vector of the given sea surface heights;
- h_{mean} is the mean sea surface height in the area. Using h_{mean} "centers" the observations.

The number of data points selected for use in the prediction is a variable that needs to be selected. We choose to select the five closest points to the grid point for use in the estimation.

The covariances needed in evaluating (1) and (2) were taken to be covariances related to geoid undulations which are well approximated by sea surface heights. The covariances were specifically generated in tabular form based on the covariances, with respect to an ellipsoidal reference field, described in Tscherning and Rapp (1974).

The maps were to be generated in approximately a 30°x 30° area. The computer program used for the computations was called F425 which has evolved over the years. For economy in the grid point predictions not all the data could be used in the estimations. To limit the data for all regions, except the Mediterranean Sea and the Hudson Bay, every 10th data point would be selected along a given track. Because of the number of tracks available we would have approximately 10 known points in each 1°x 1° block. In the two other regions every 3rd point was selected.

The predictions were carried out at the 1°x 1° intersections within the general map area. The average accuracy of the prediction at a grid point is ±30 cm. But this is sensitive to the data density. Although accuracy maps were produced they have not been included because the sub-satellite tracks have been included on the sea surface height maps.

The contouring of the data was carried out using the Geodetic Science Plotting Package (GSPP) described by Sünkel (1980).

The Maps of Sea Surface Topography

Using the data and procedures described in the previous sections 51 maps were prepared. The map projection used for data point definition and map generation is basically the Plate Carree projection (Pearson, 1977). This is a simple cylindrical projection implemented with the following coordinate equations:

$$\begin{aligned} x &= c(\phi - \phi_0) \\ y &= c(\lambda - \lambda_0) \end{aligned} \qquad (3)$$

where c is a scale factor, ϕ , λ are the coordinates of a point, and ϕ_0 , λ_0 are the coordinates of an origin point. Since we are computing data at equal $1^\circ \times 1^\circ$ grid intervals, the use of (3) will yield points on the plane grid at an equal distance interval. In addition all the maps are on the same projection so that they can be brought together to form a larger map of the world or a specific area.

The scale factor c was chosen to be 0.2056 inches per degree which was used earlier in Geos-3 work. Such a value allows the plots to fit, without reduction, on a report page. Although the scale is formally defined, the effective scale depends on the mechanical operation of the plotter and it can be slightly inconsistent from one plot of the next.

The location of the 53 maps is shown in Figure 2. The individual maps at a contour interval of 2 meters follow in the sequence identified in Figure 2.

The heights refer to the ellipsoid of the Geodetic Reference System 1980: $a = 6378137$ meters, $f = 1/298.257222$. Because of the manner in which the constant tide due to the sun and moon were handled in the original Seasat data reduction, the sea surface heights portrayed here refer to the permanently deformed ocean surface.

In order to portray the sea surface heights in the south polar region a slightly different procedure was used. First the sea surface heights were predicted selecting every data point for possible use in the predictions. This data was then used for predictions on a $1^\circ \times 1^\circ$ grid from - -65° to -72° in latitude using the data from the various regional adjustments. This data was then used to prepare maps on the Azimuthal Equal Area Polar projection. The resulting maps, prepared by C. Wichiencharoen, are given in Figures 52 and 53.

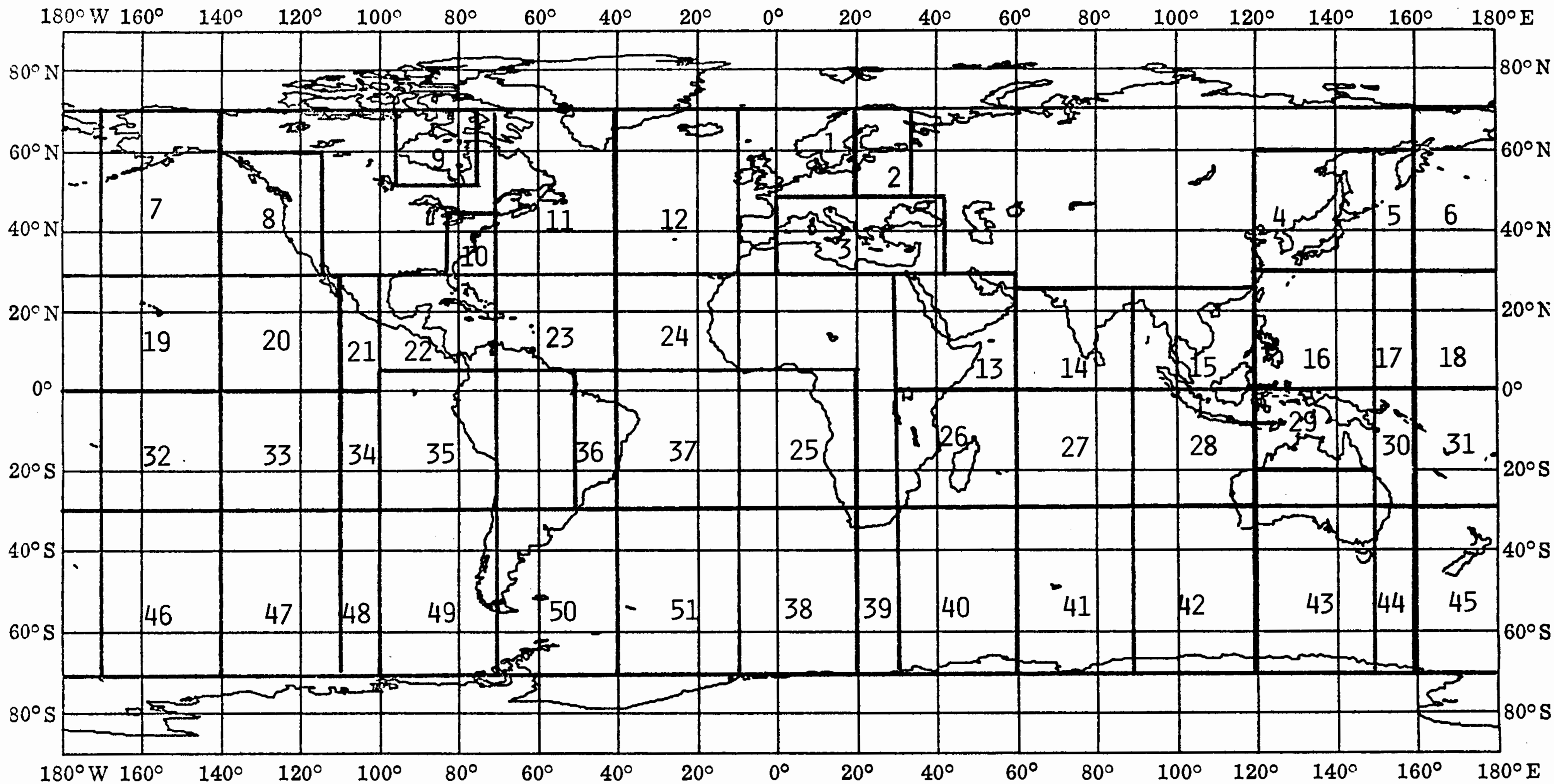
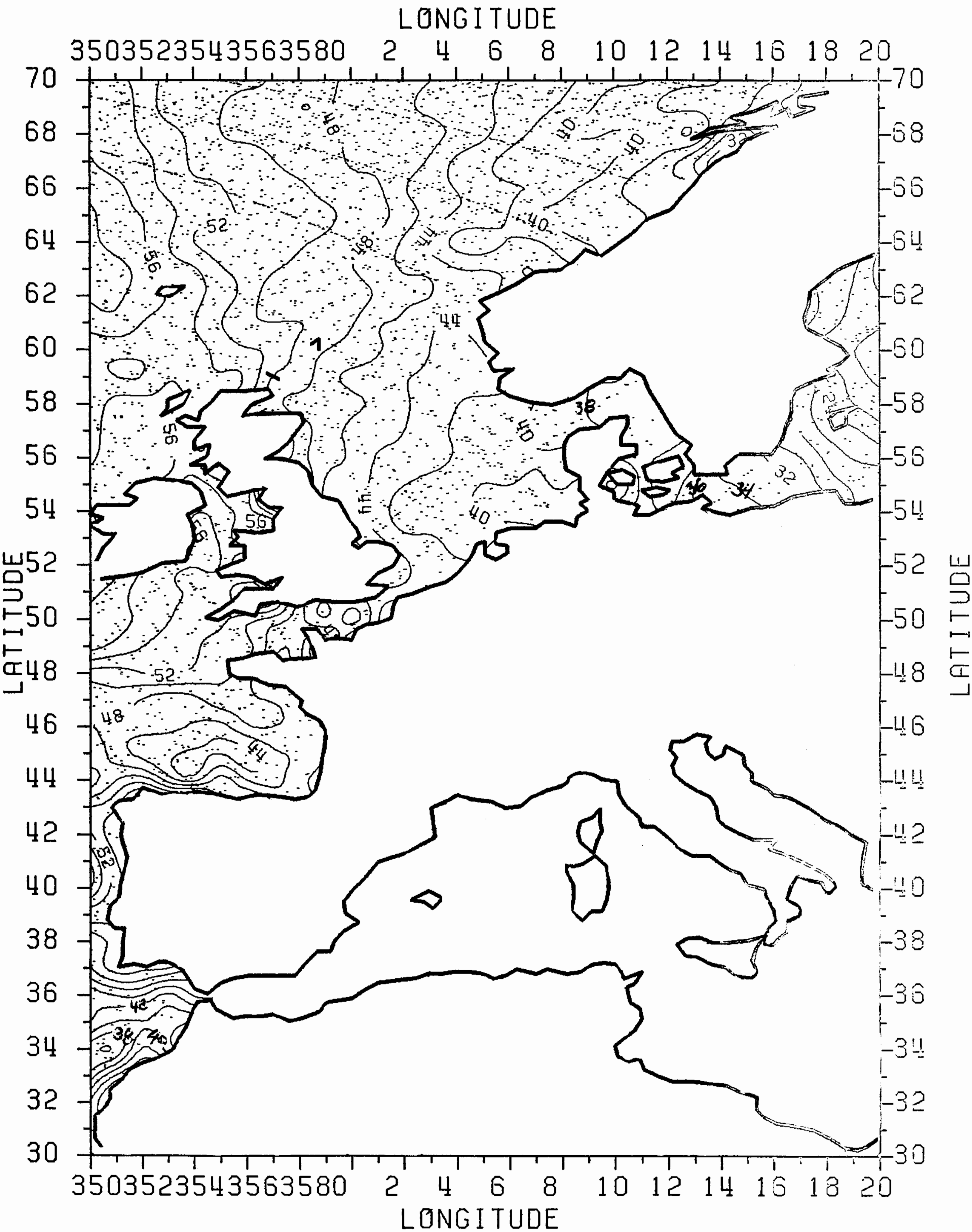
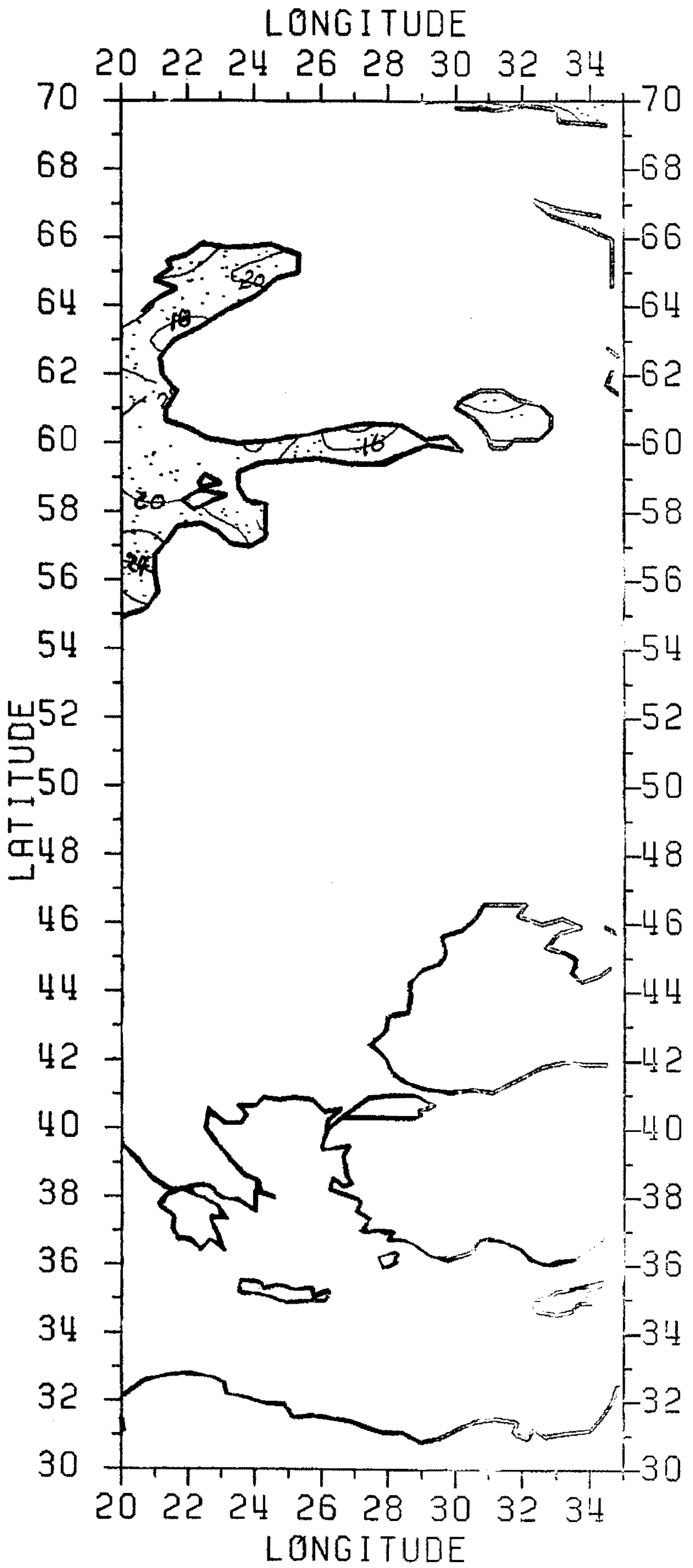


Figure 2: Sea Surface Height Map Locator

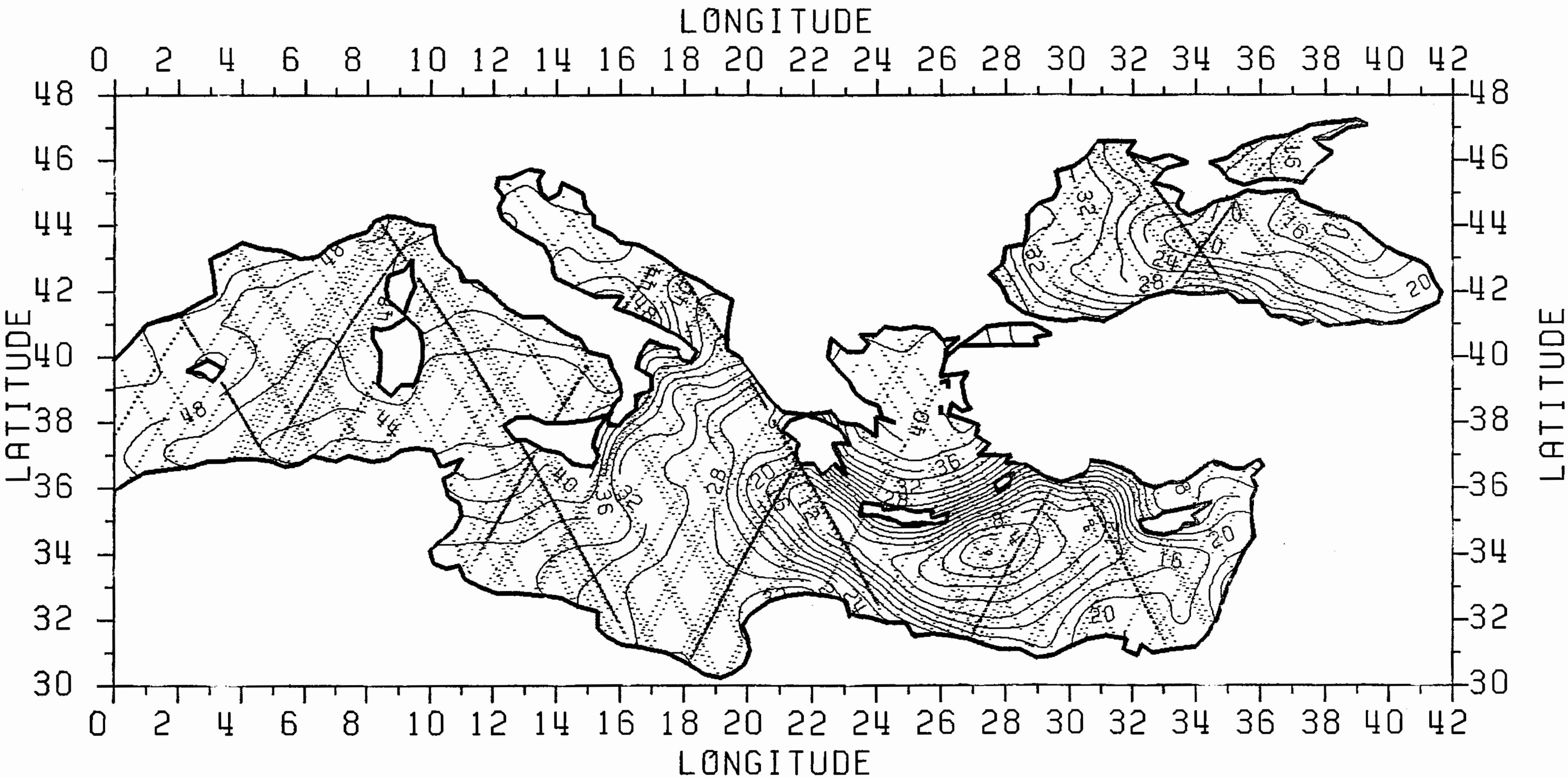
South Polar Region: Map 52 and 53



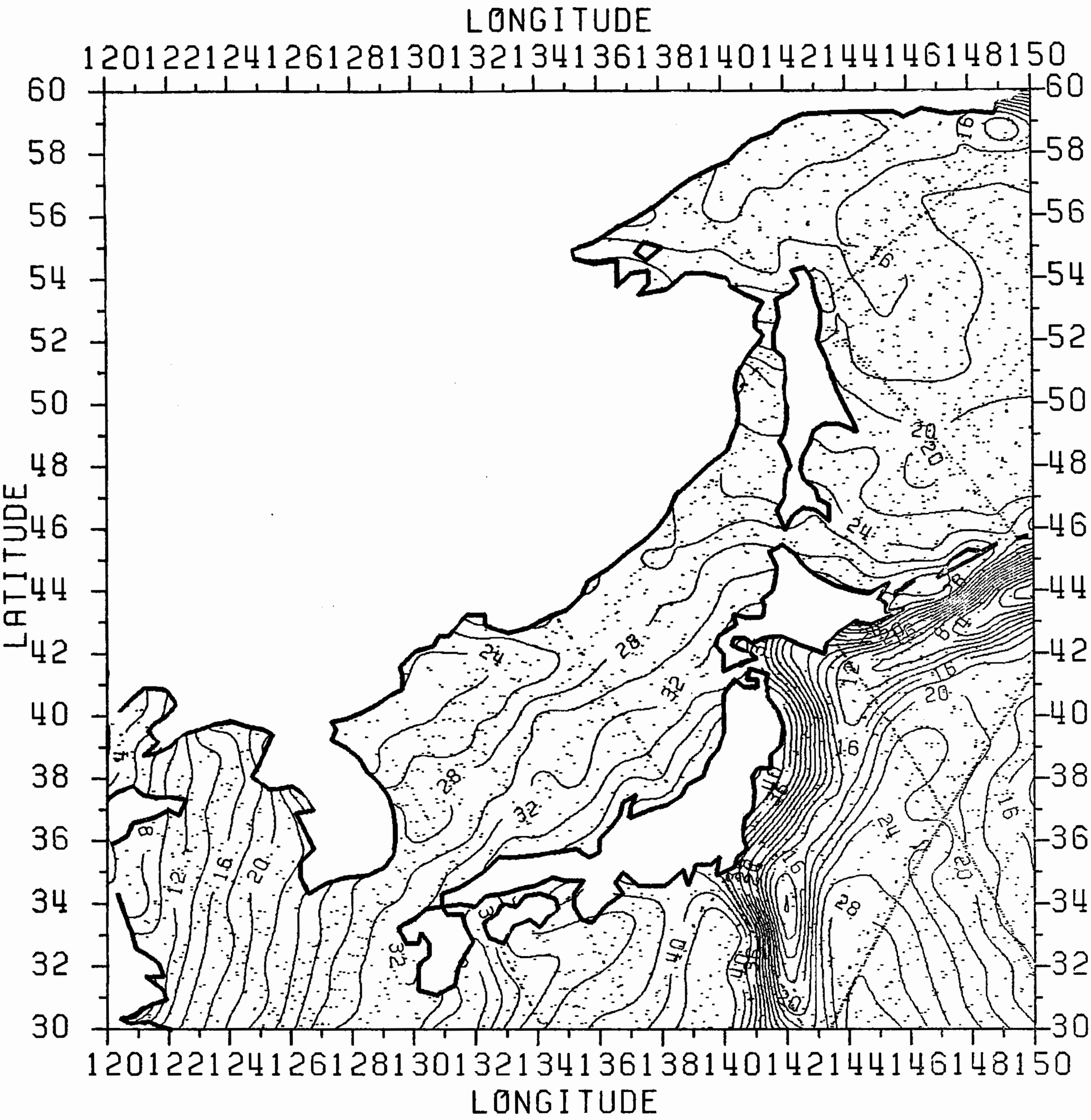
Sea Surface Height Map 1



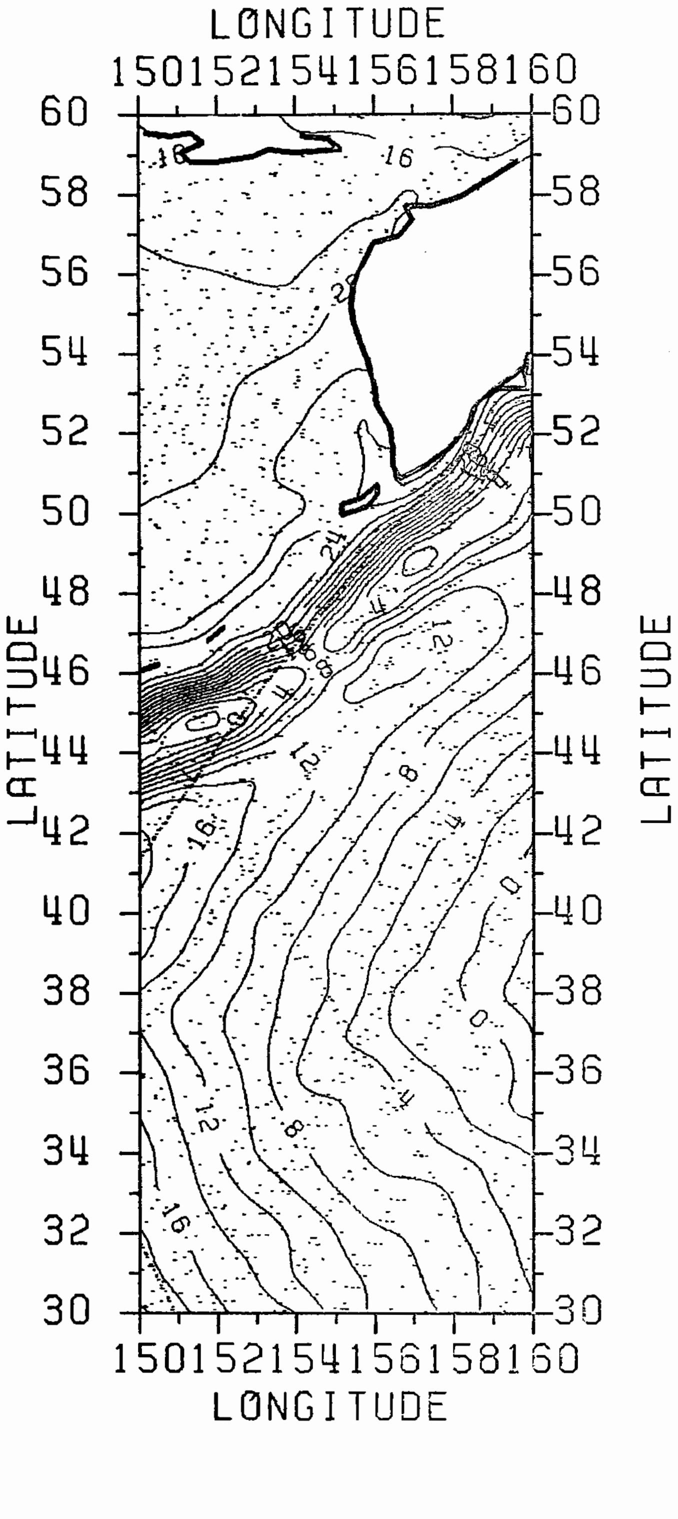
Sea Surface Height Map 2



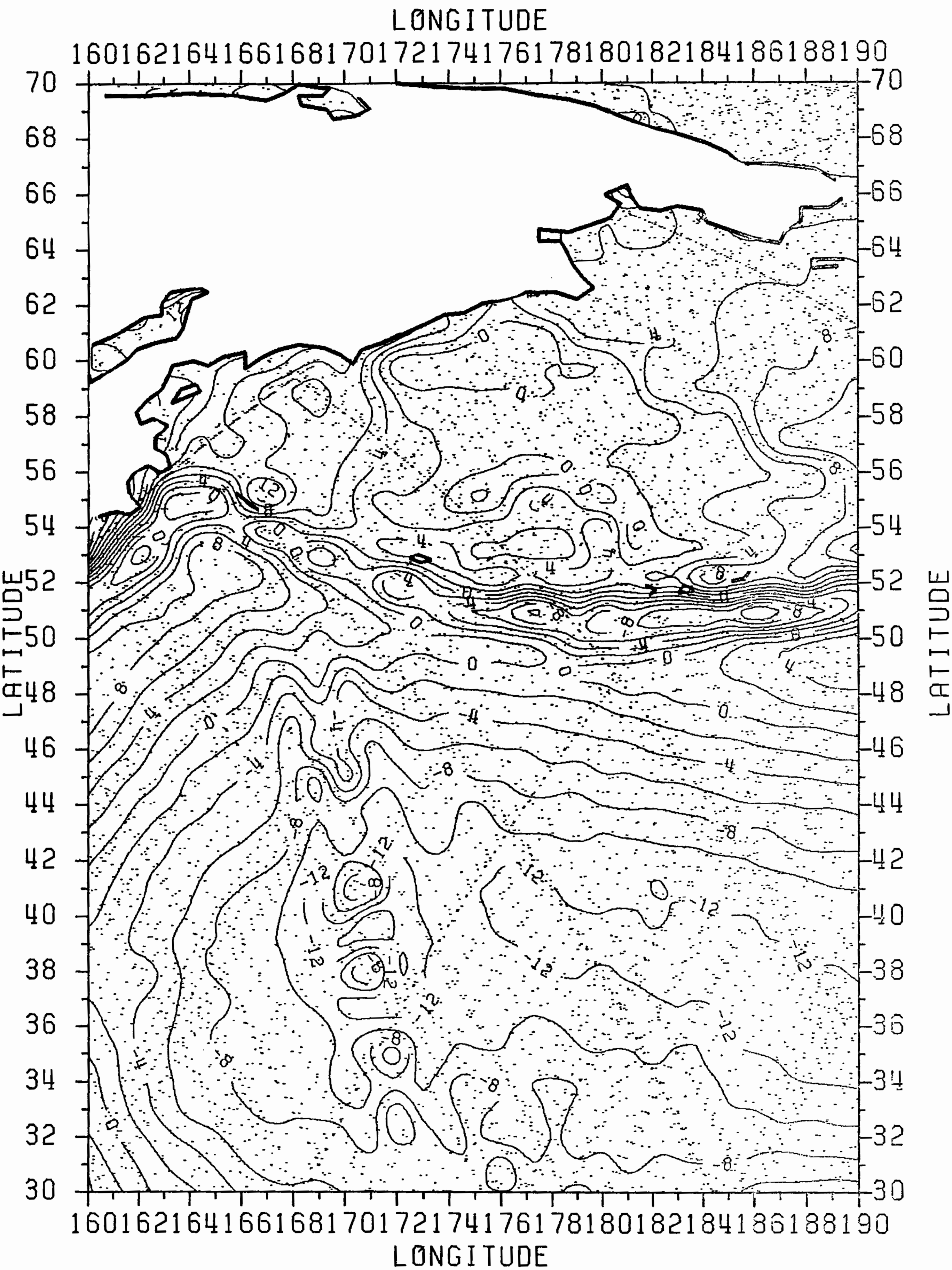
Sea Surface Height Map 3



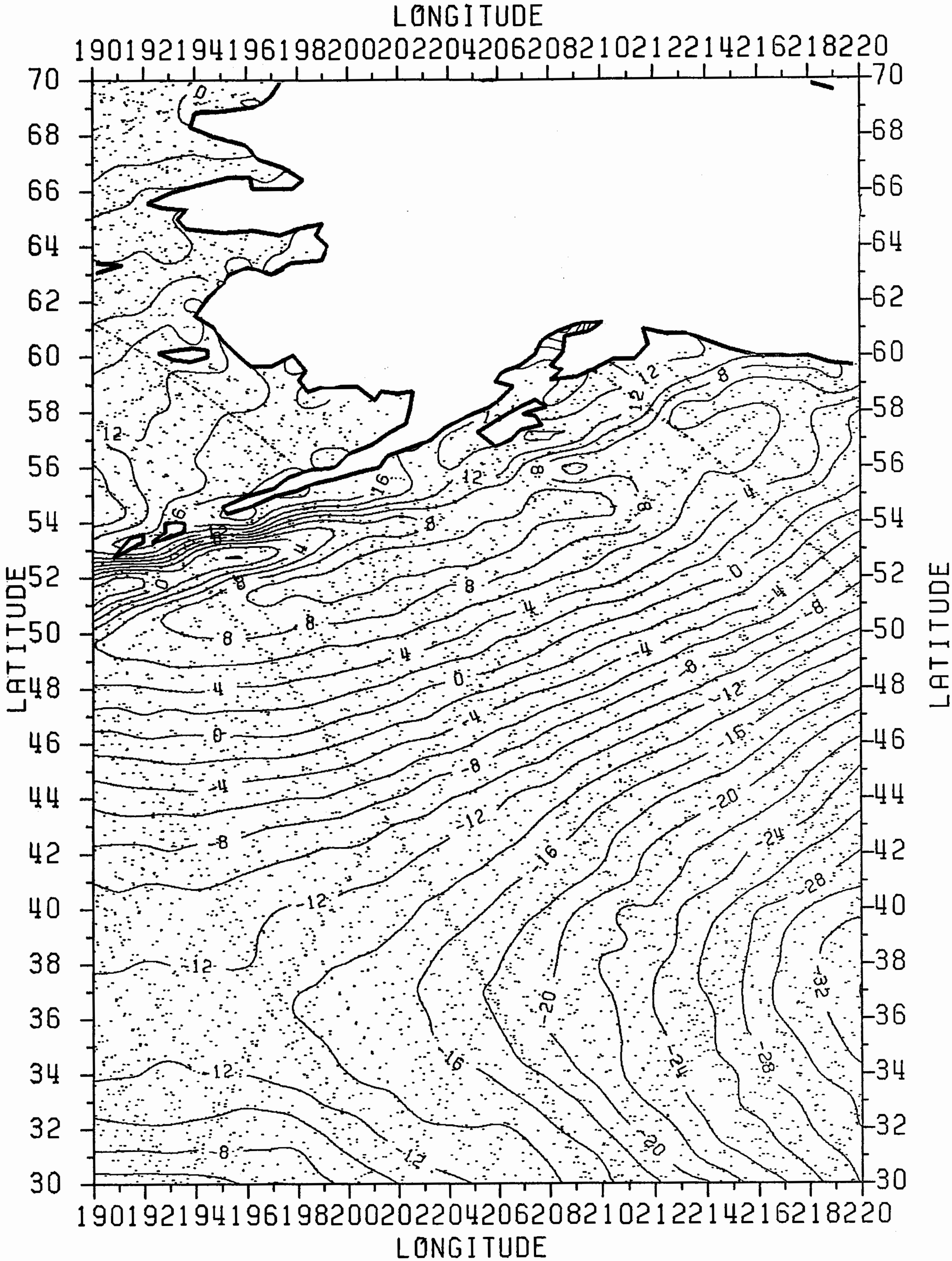
Sea Surface Height Map 4



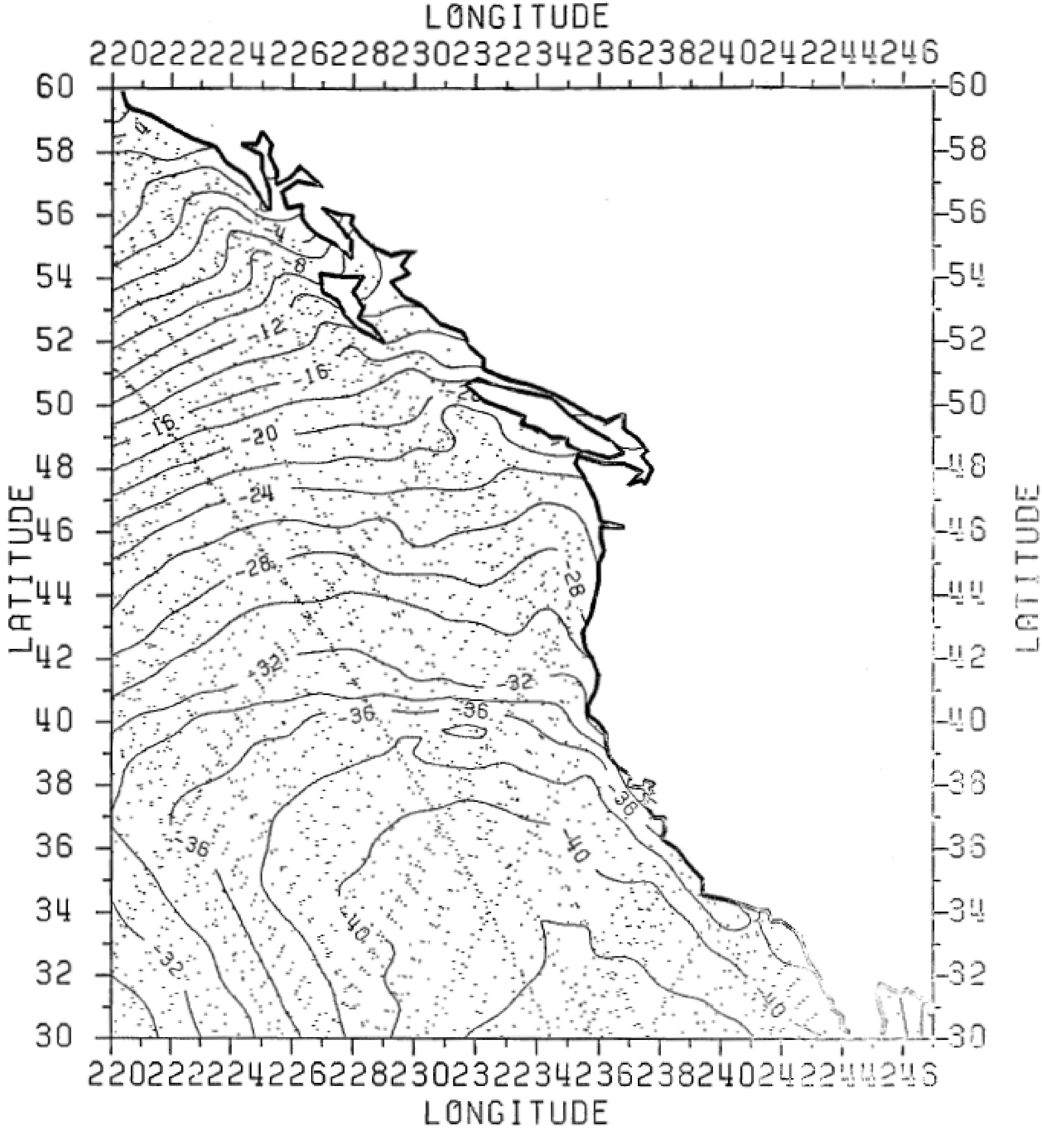
Sea Surface Height Map 5



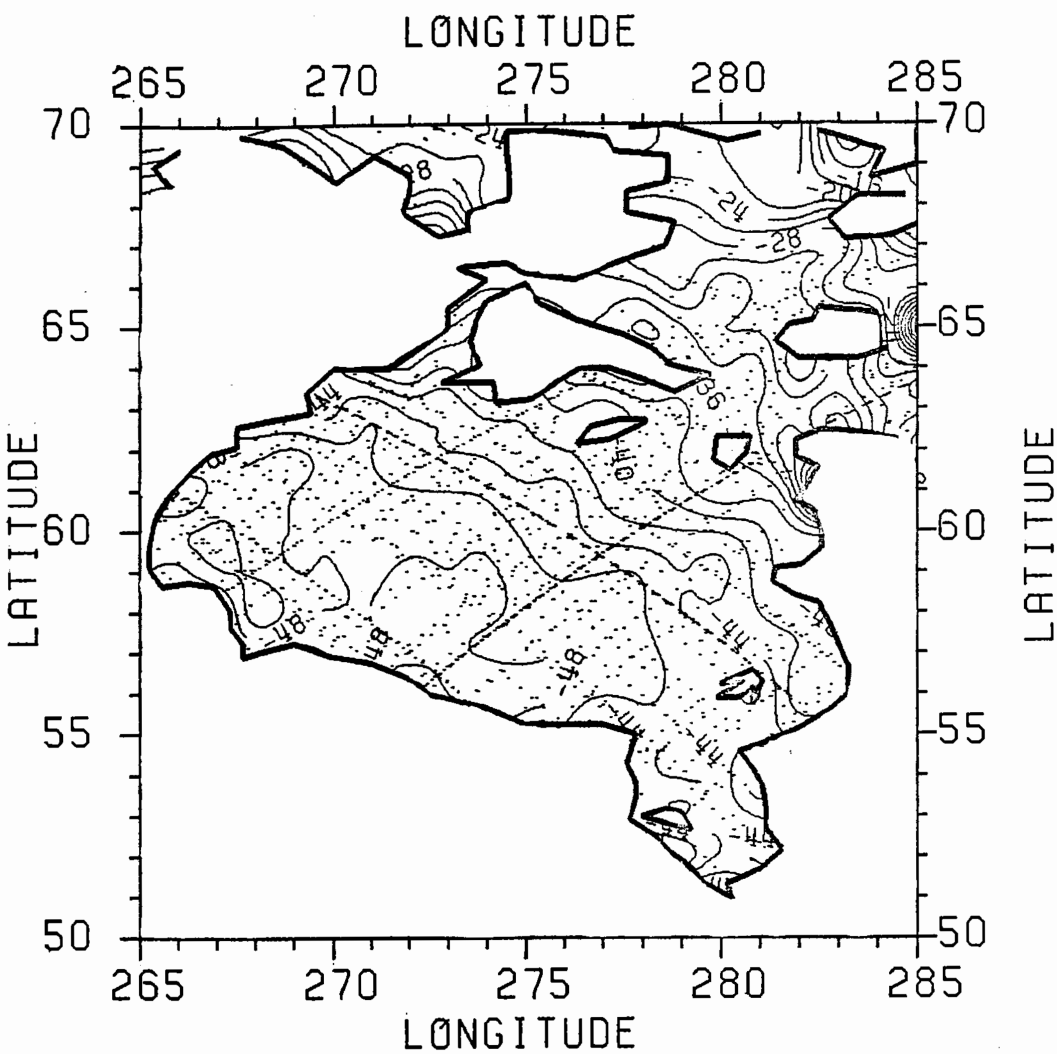
Sea Surface Height Map 6



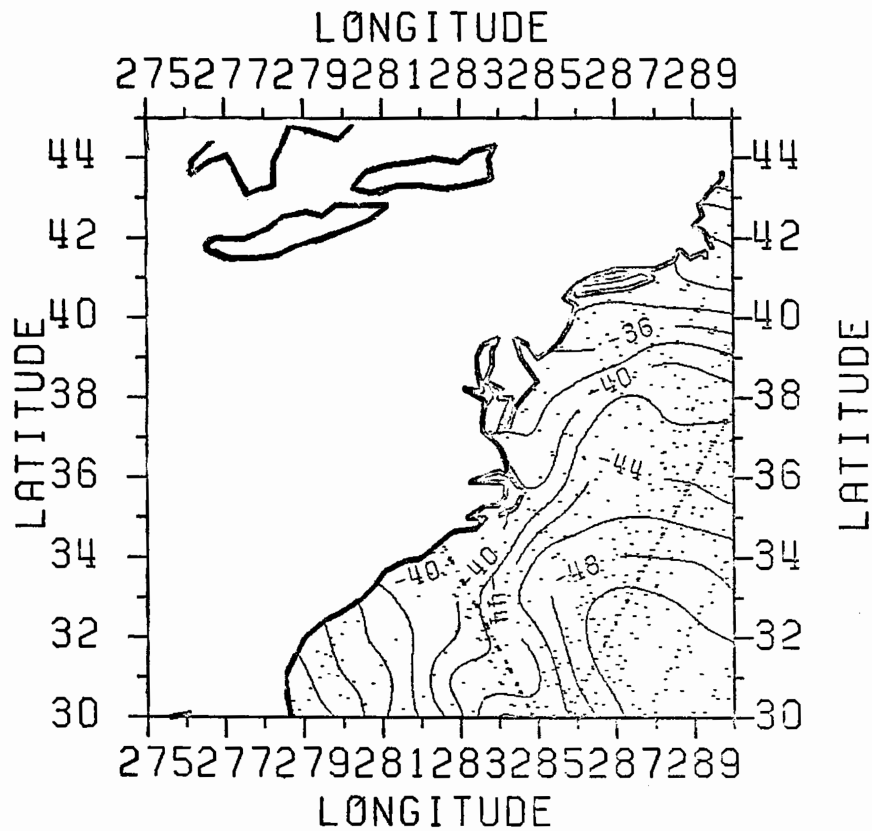
Sea Surface Height Map 7



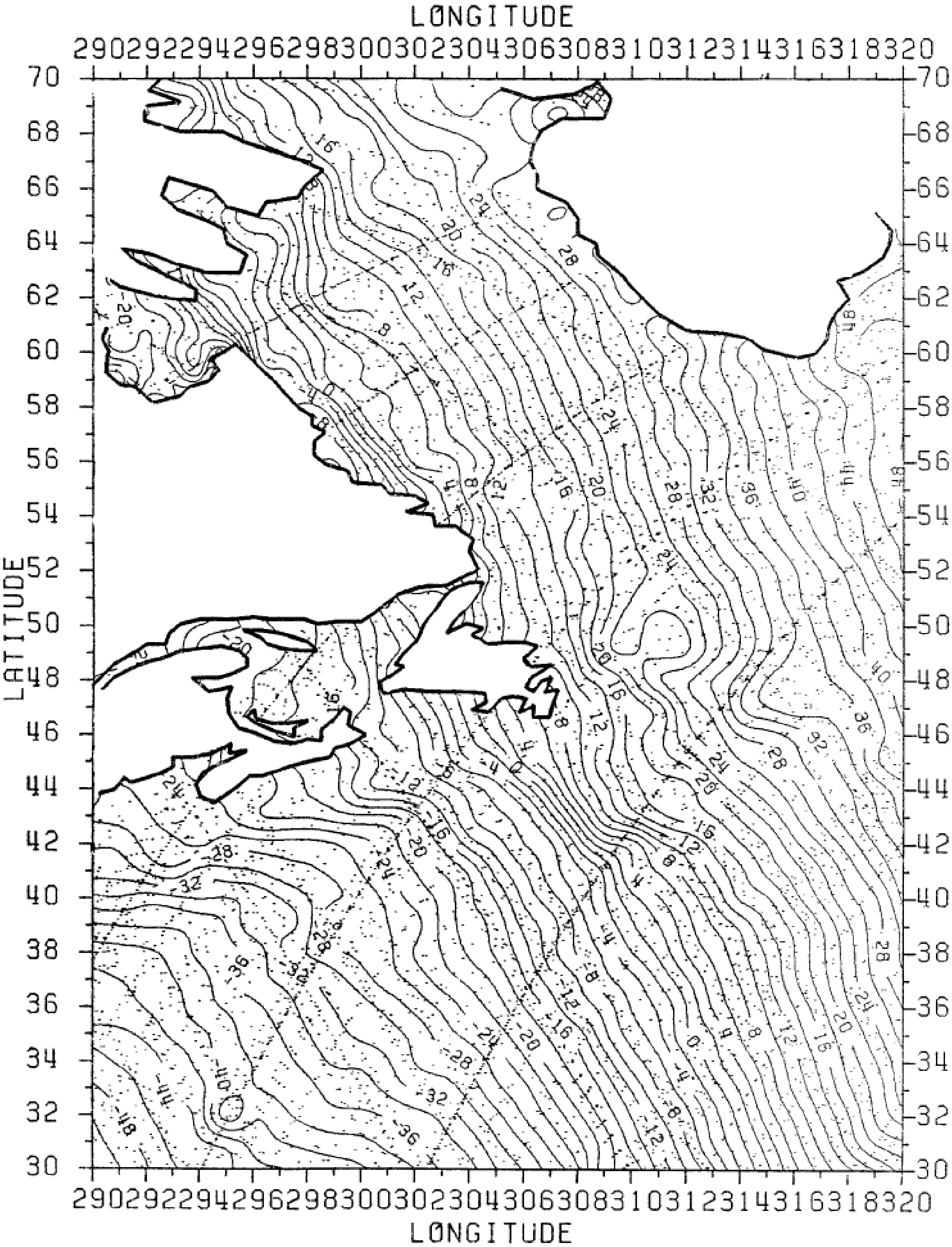
Sea Surface Height Map 8



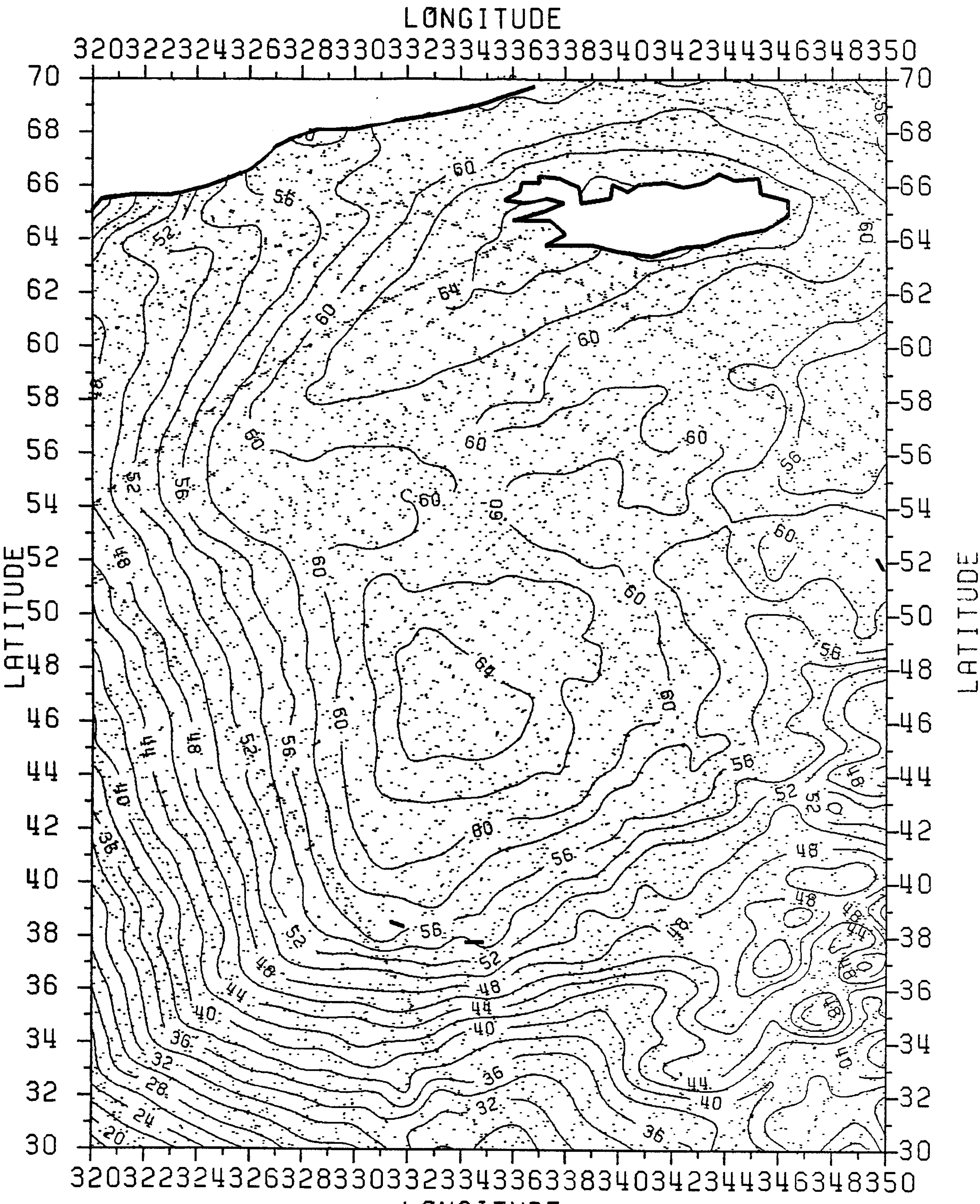
Sea Surface Height Map 9



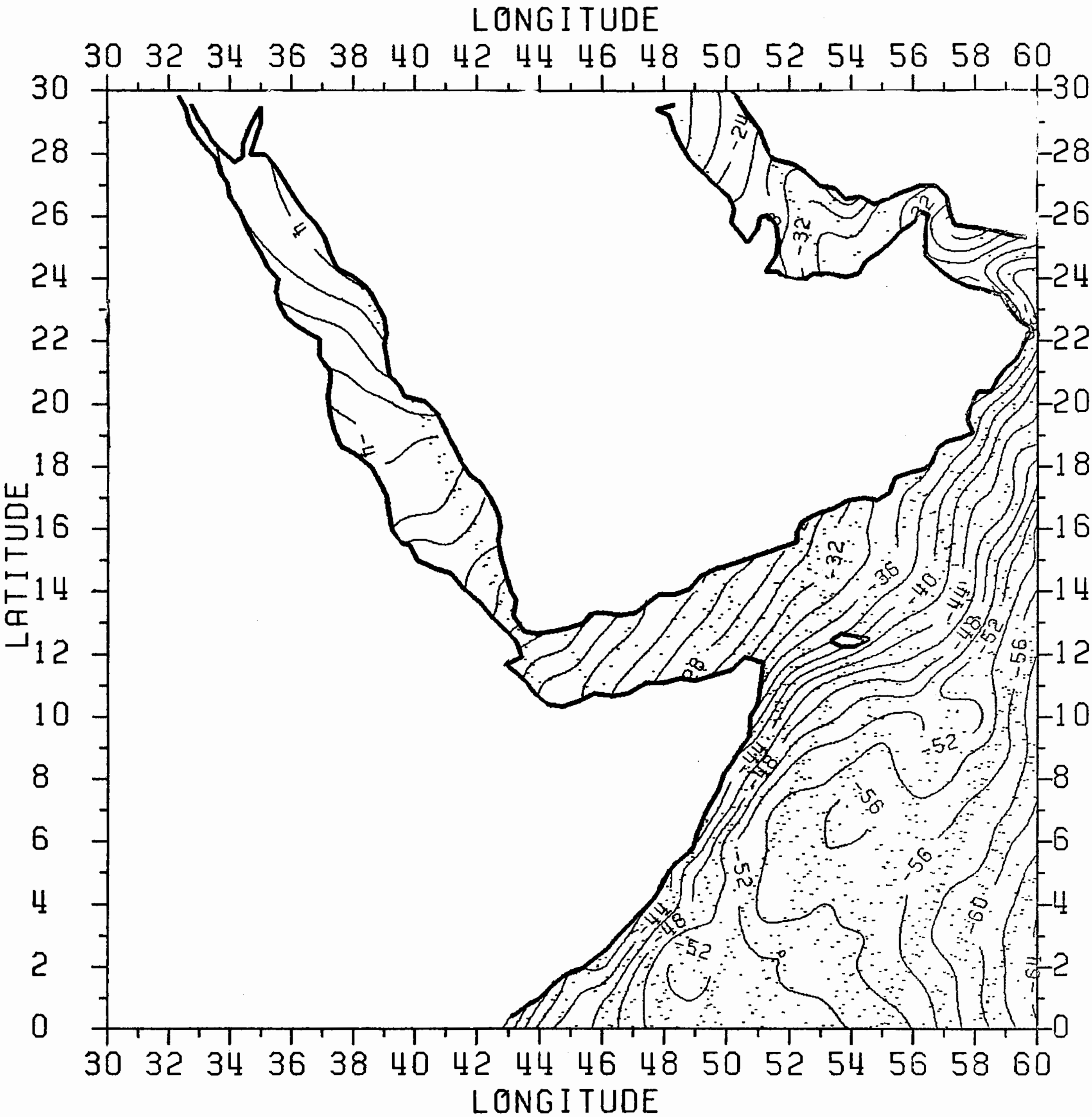
Sea Surface Height Map 10



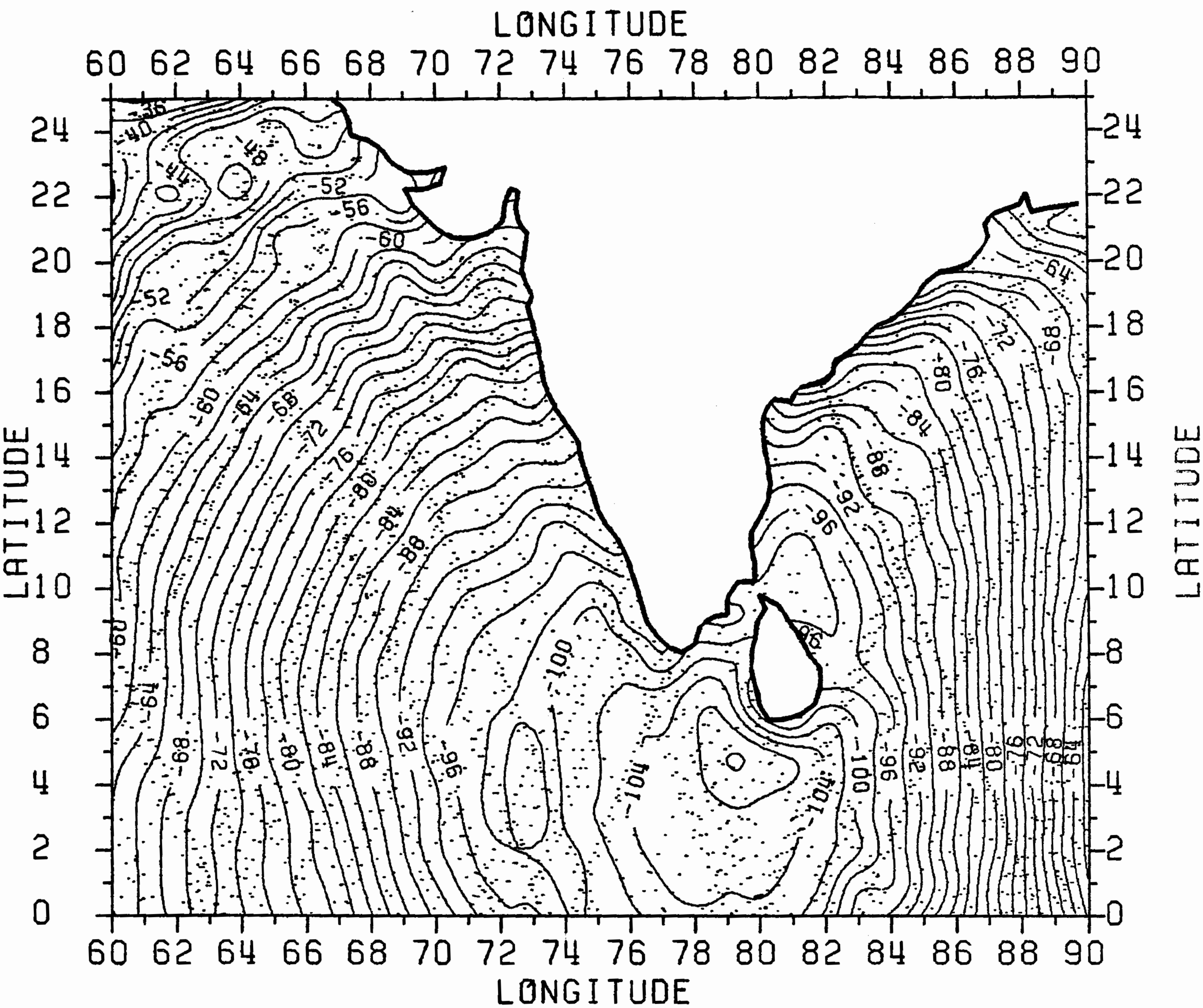
Sea Surface Height Map 11



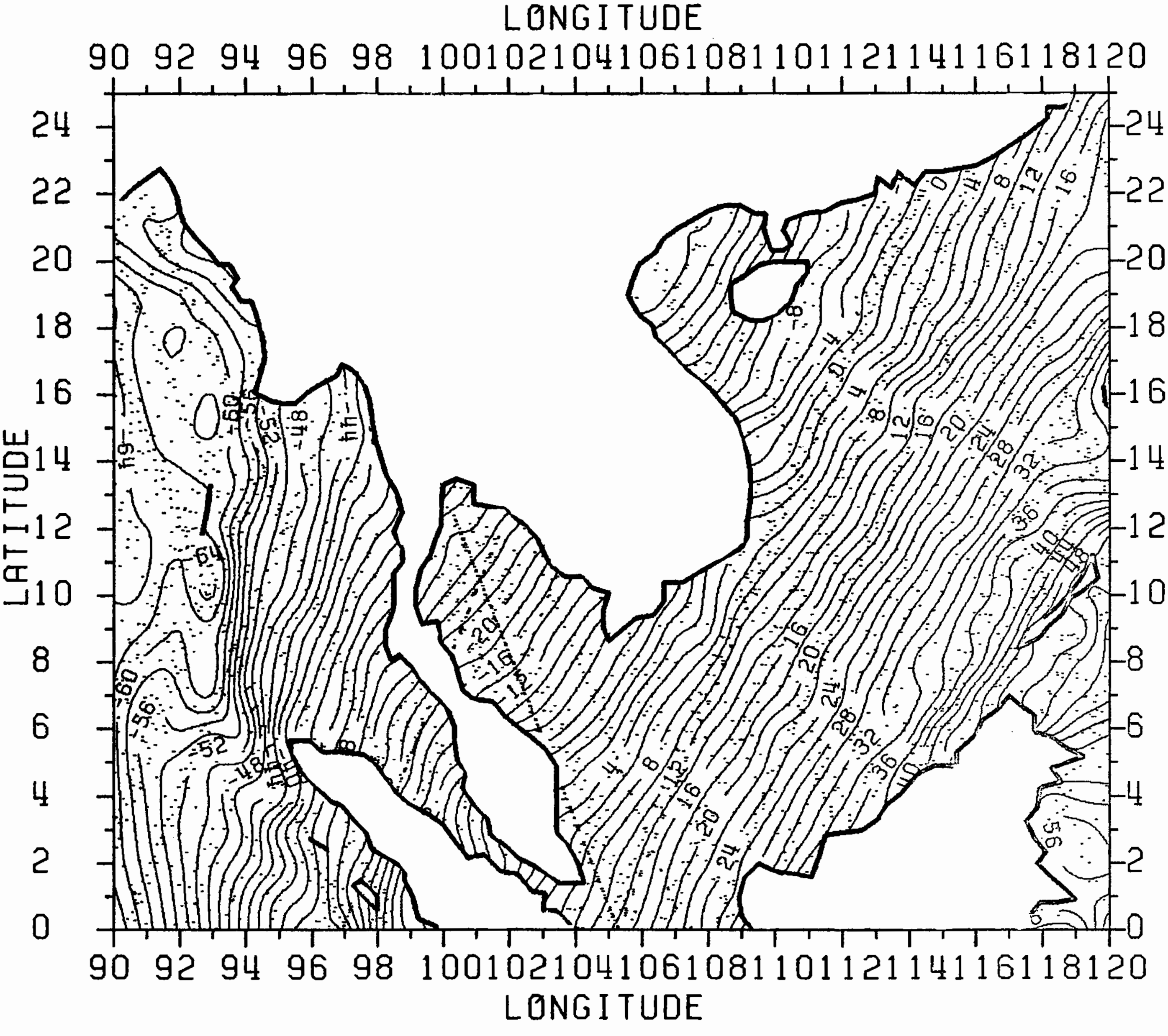
Sea Surface Height Map 12



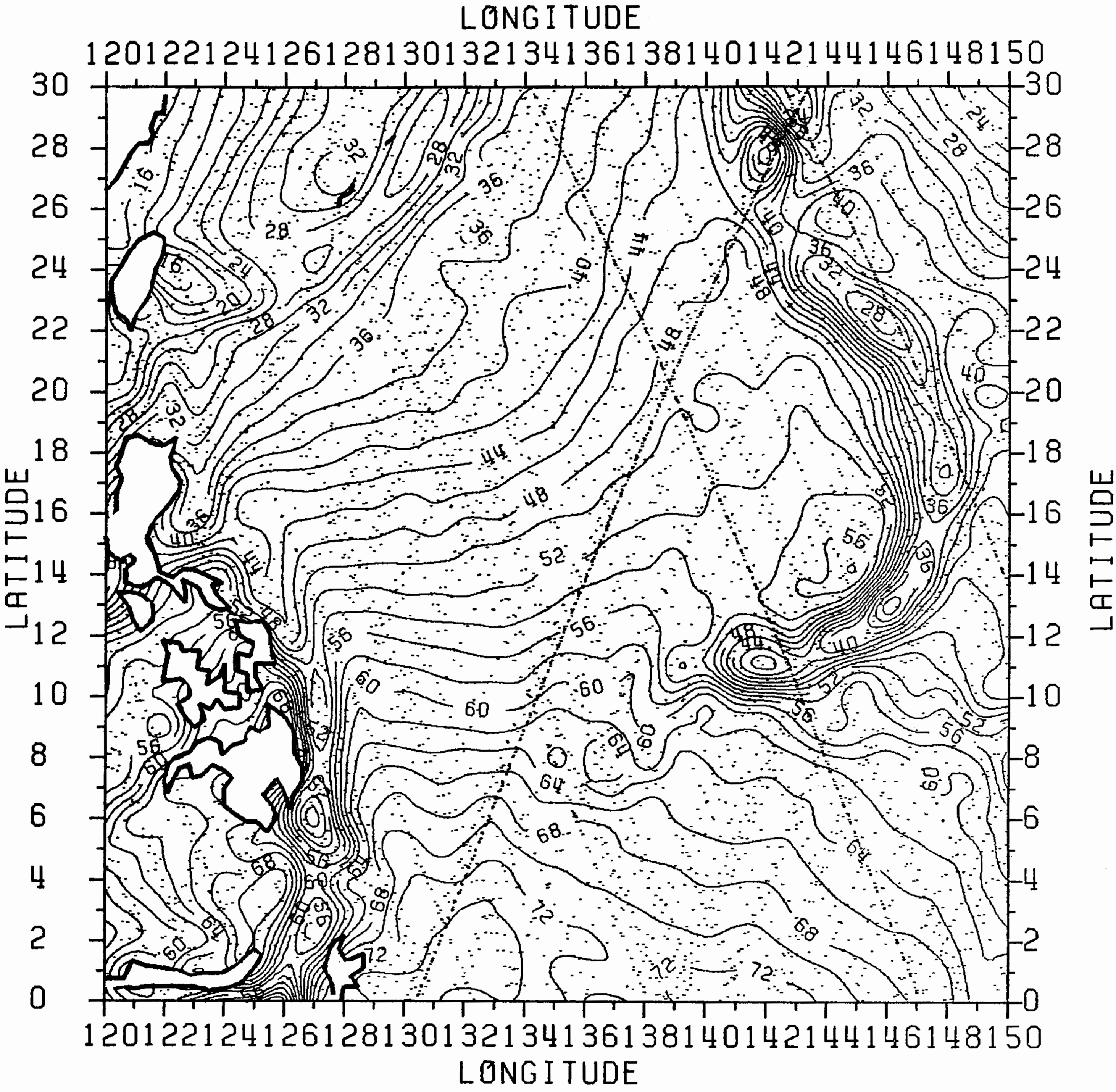
Sea Surface Height Map 13



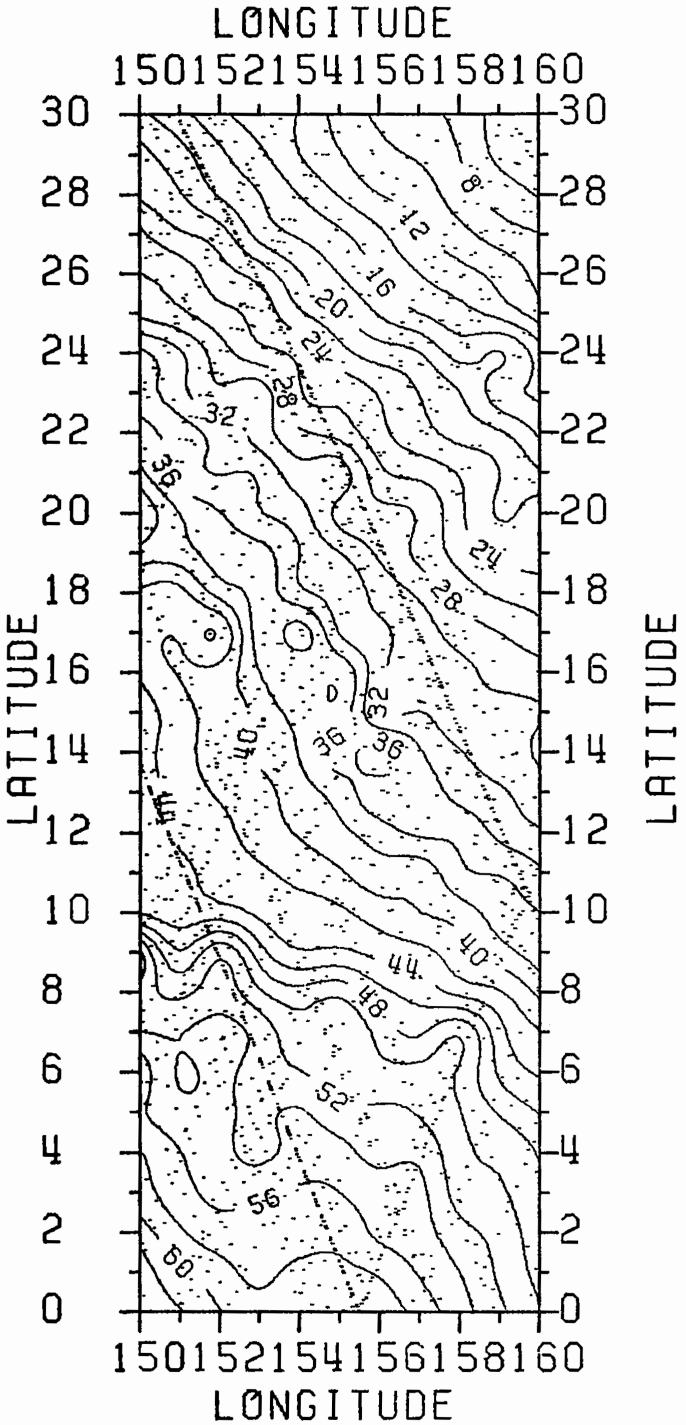
Sea Surface Height Map 14



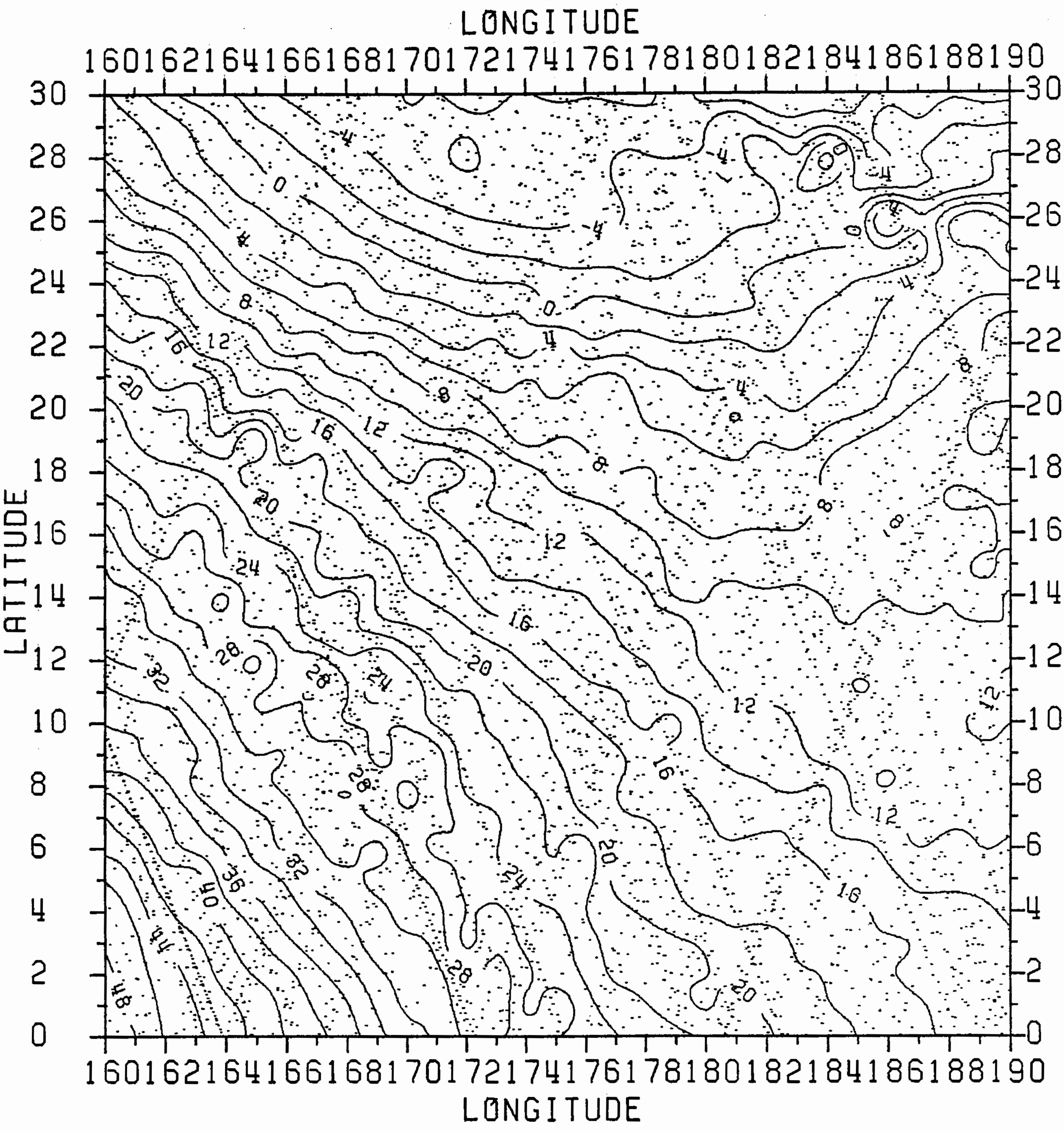
Sea Surface Height Map 15



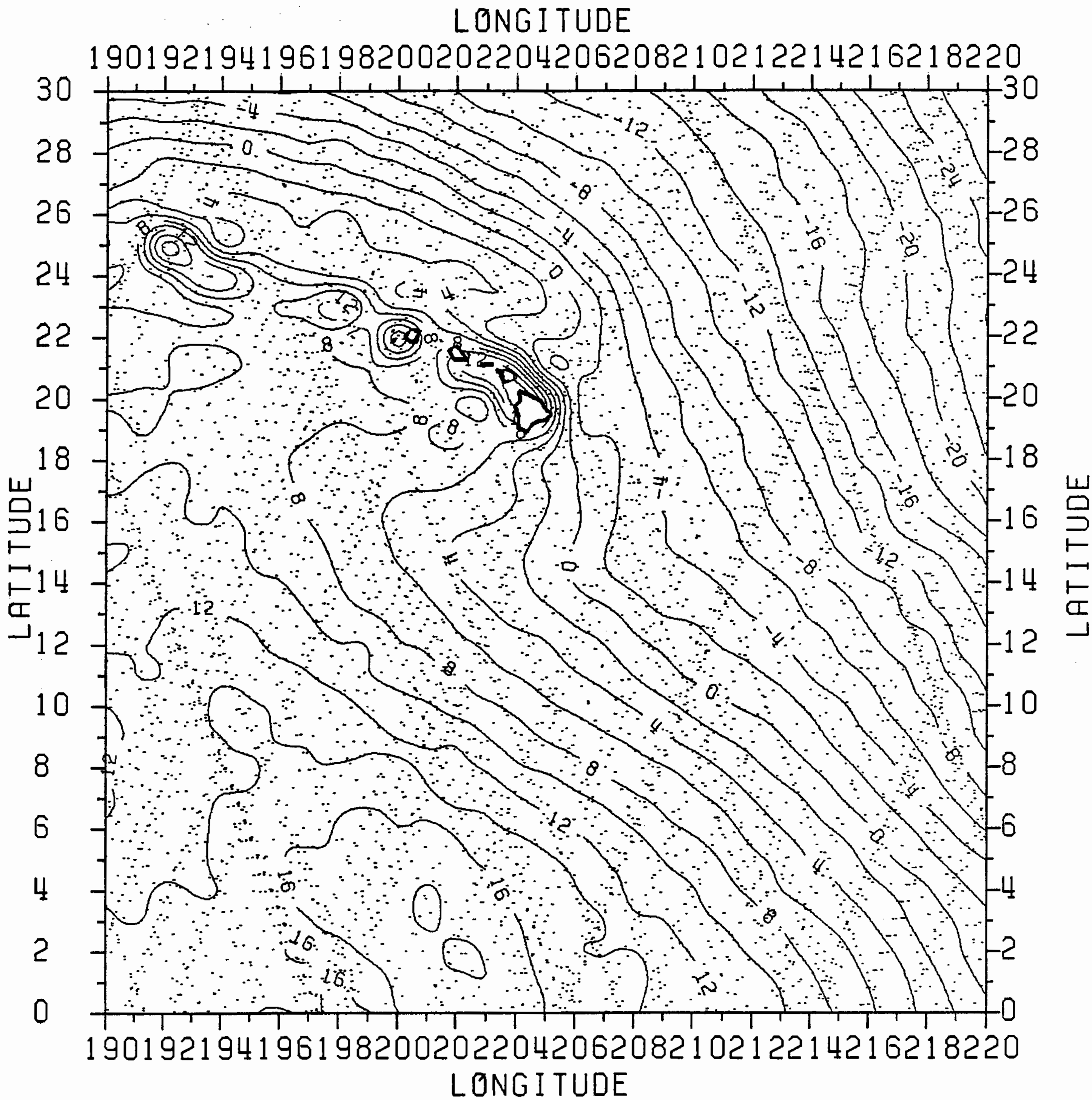
Sea Surface Height Map 16



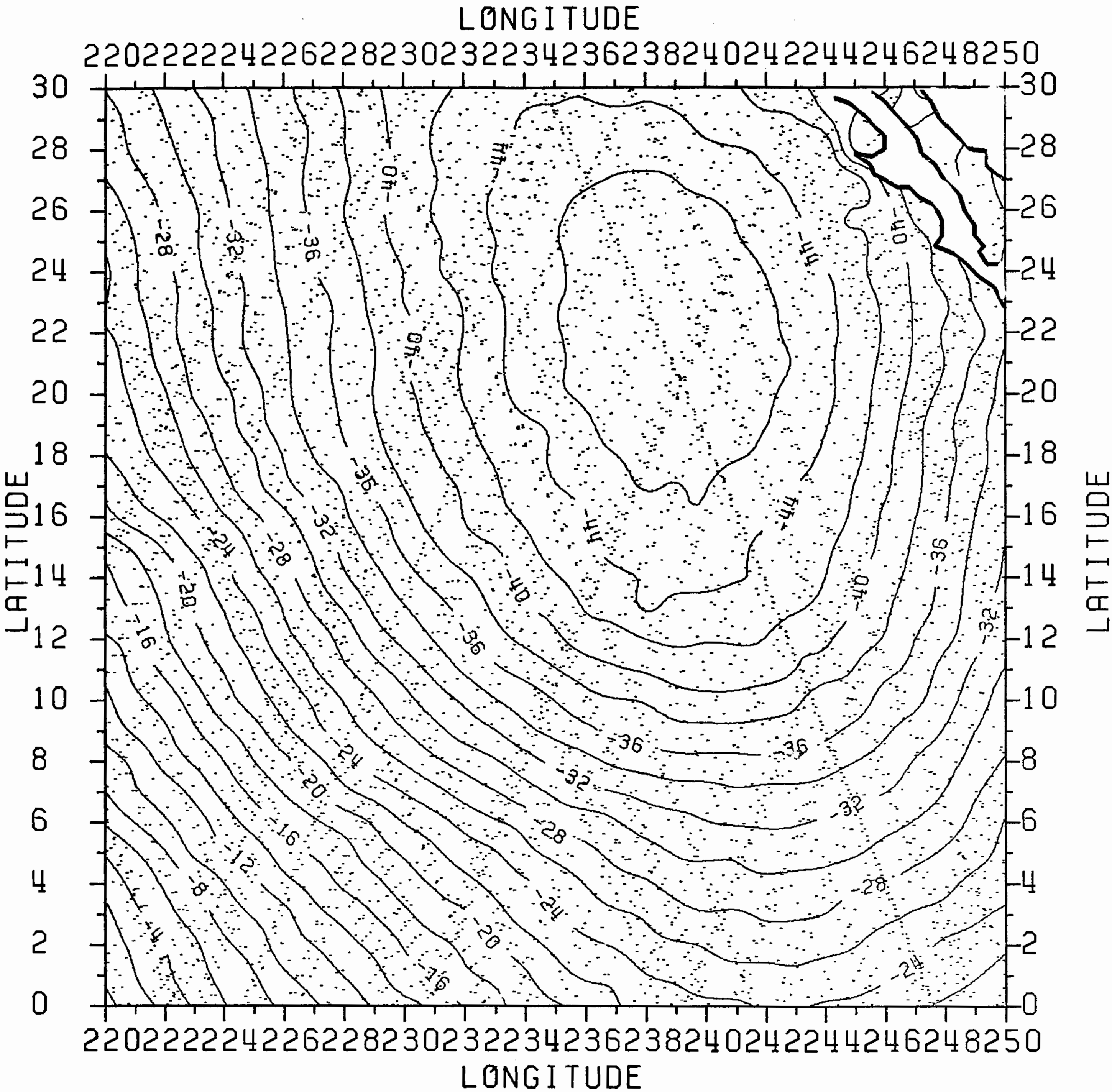
Sea Surface Height Map 17



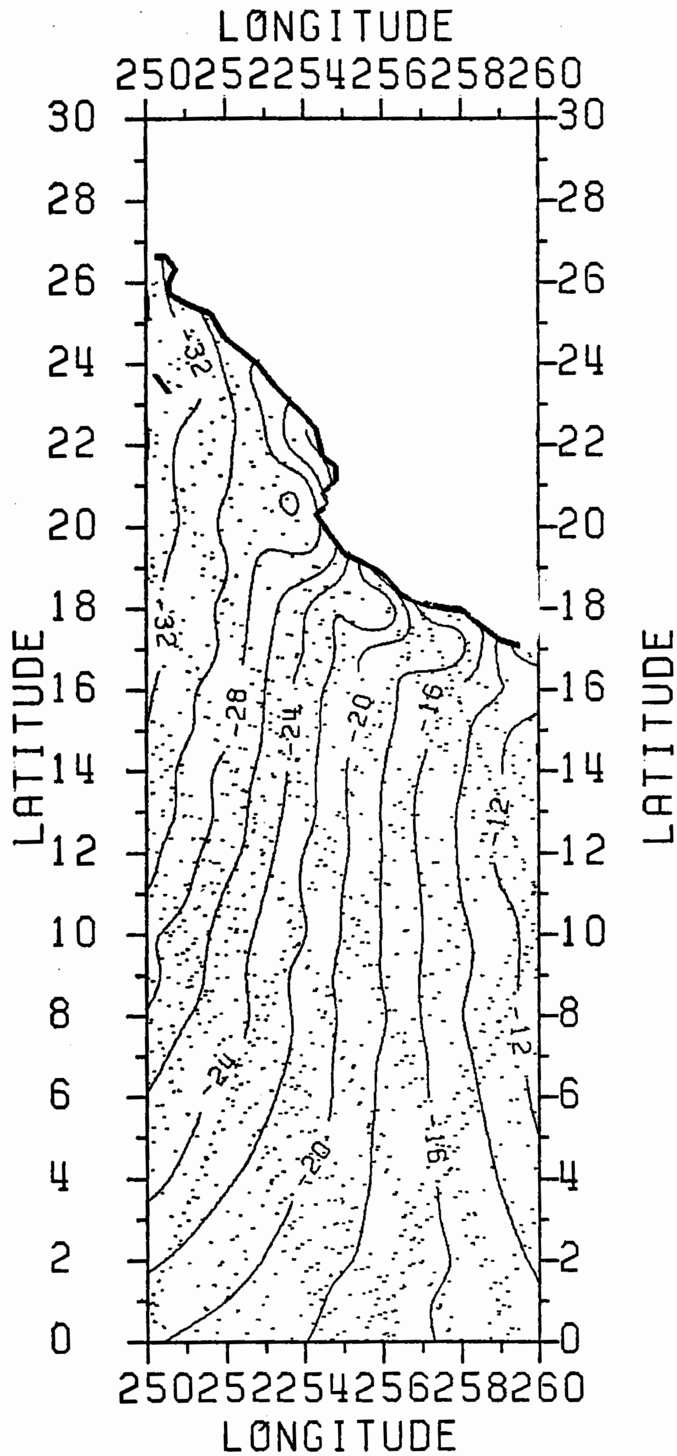
Sea Surface Height Map 18



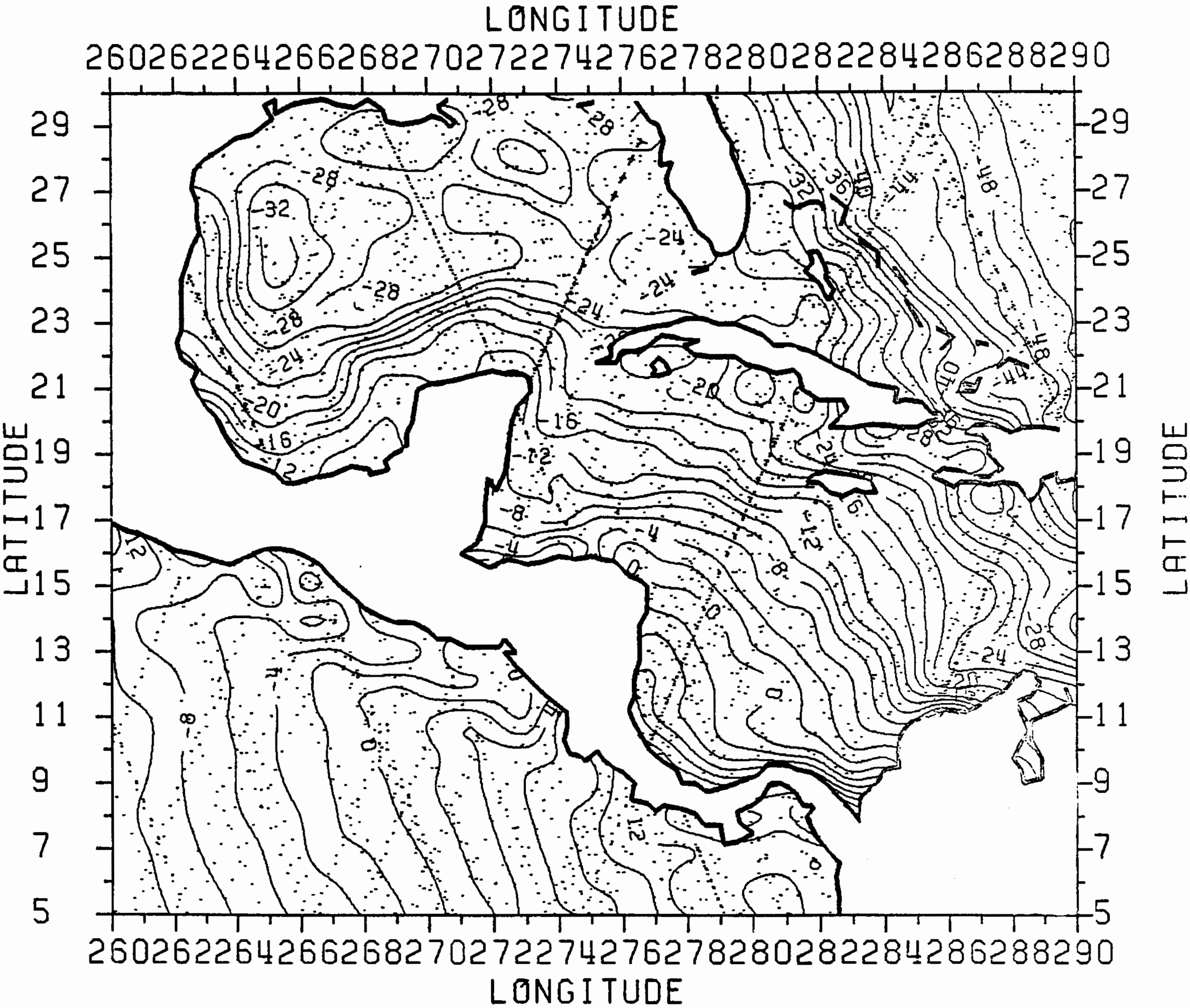
Sea Surface Height Map 19



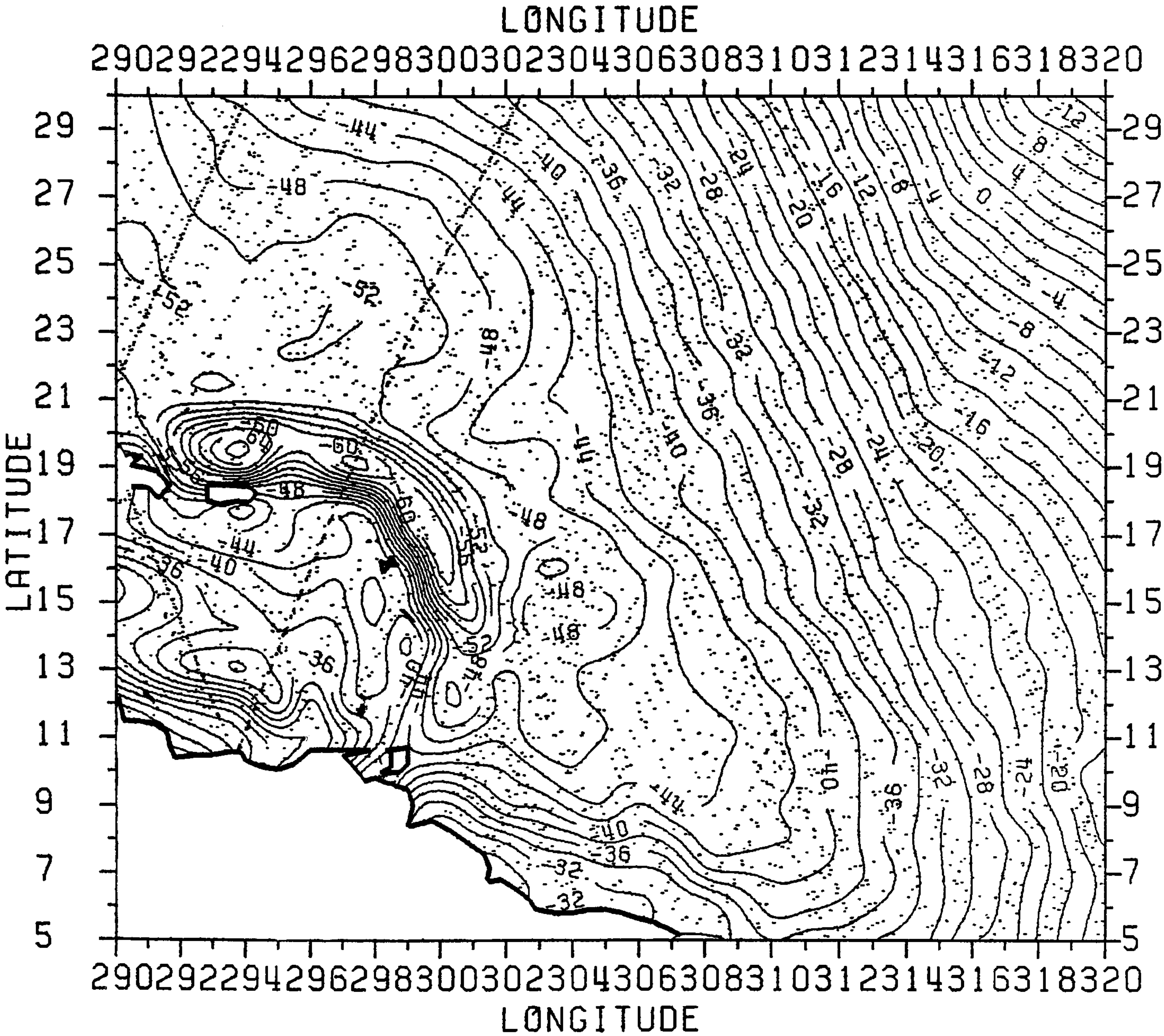
Sea Surface Height Map 20



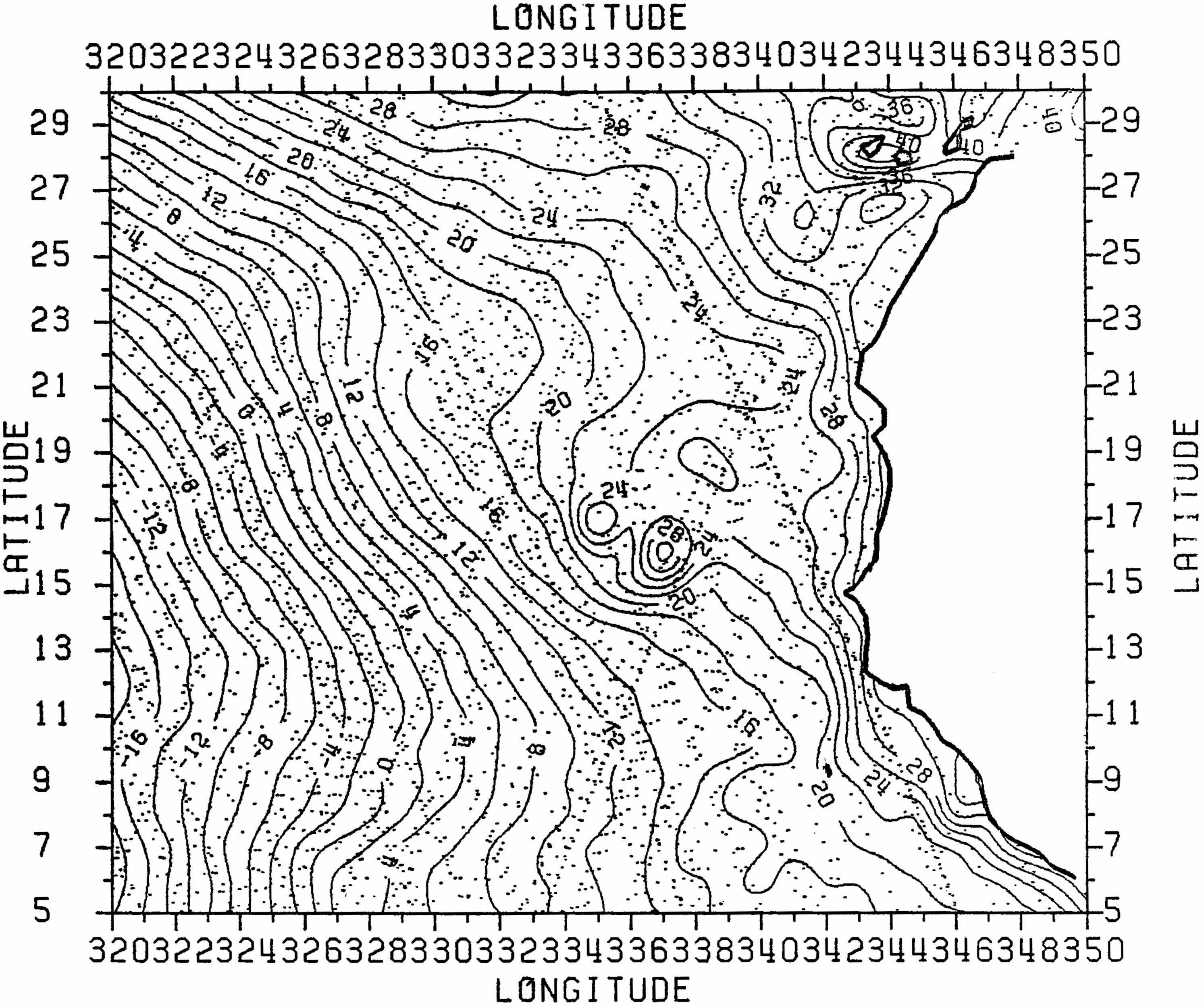
Sea Surface Height Map 21



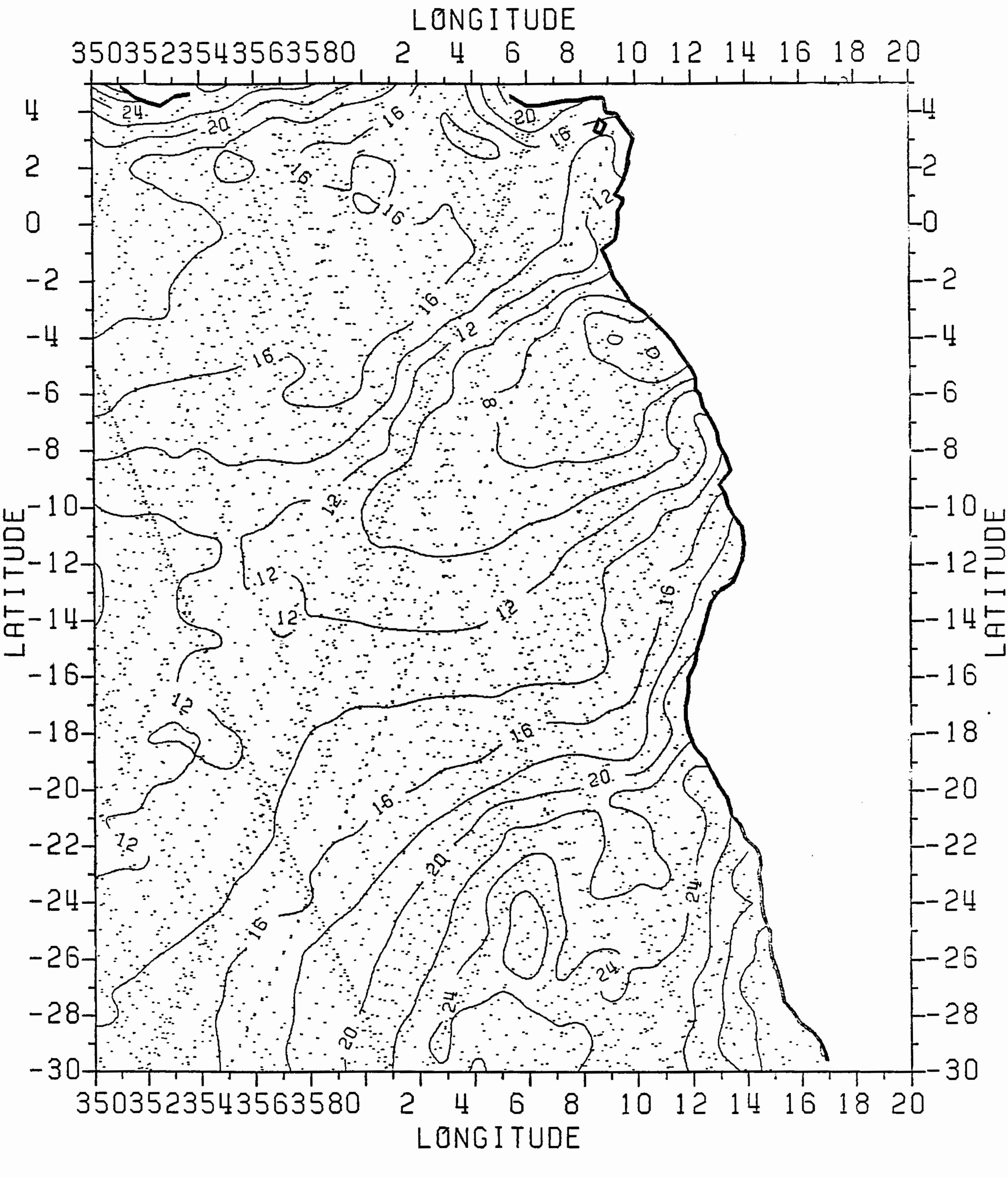
Sea Surface Height Map 22



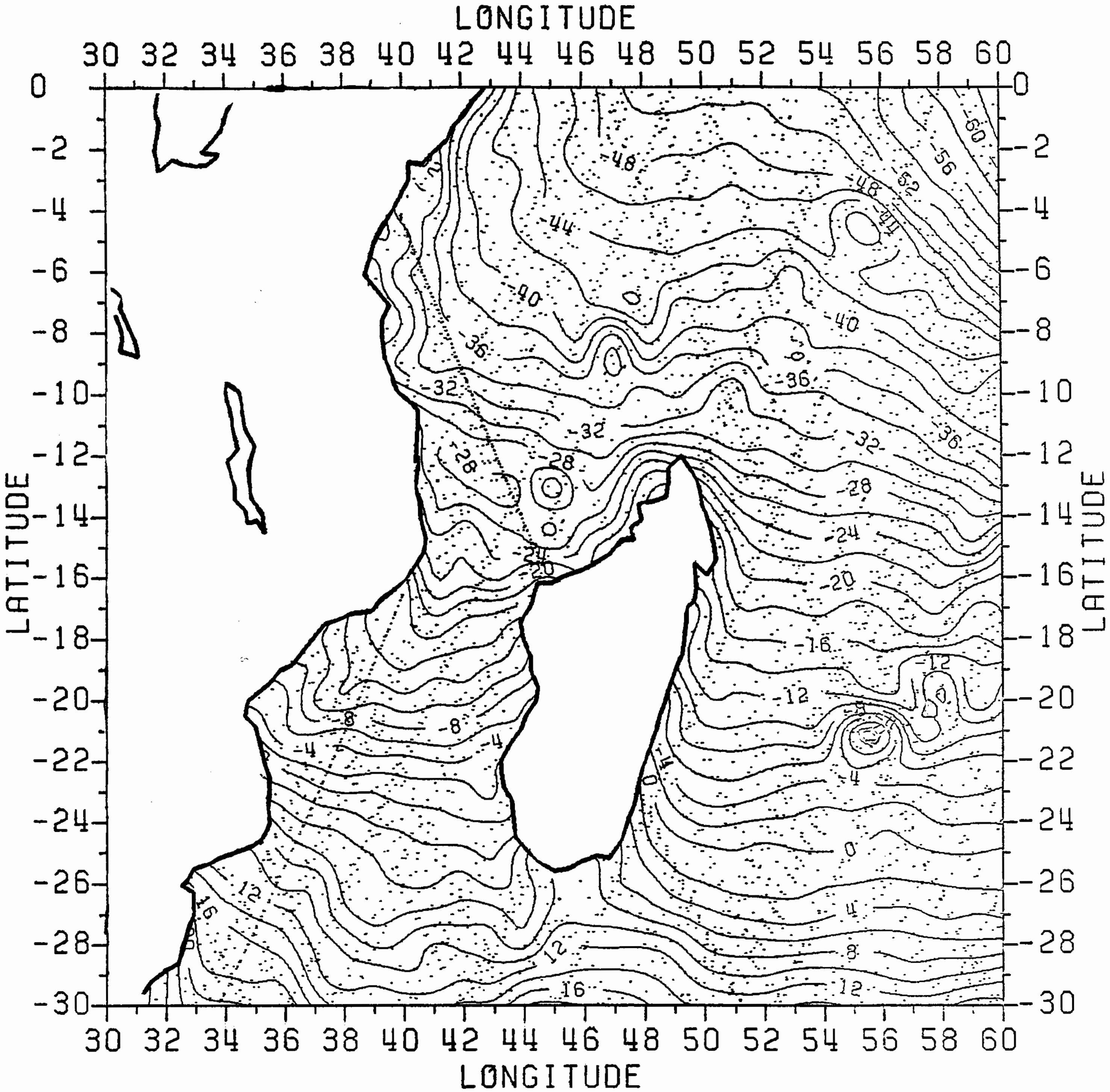
Sea Surface Height Map 23



Sea Surface Height Map 24



Sea Surface Height Map 25



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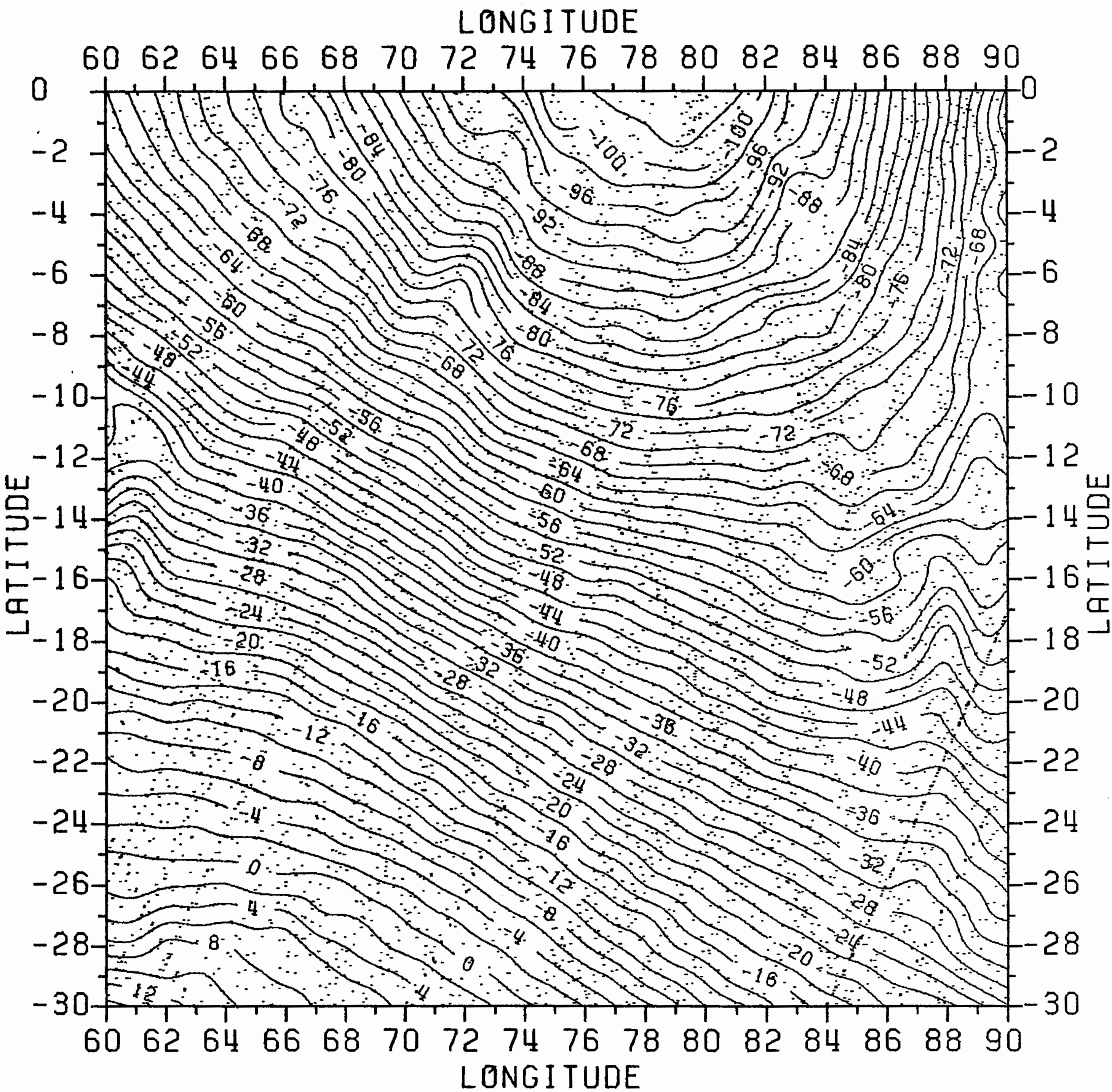
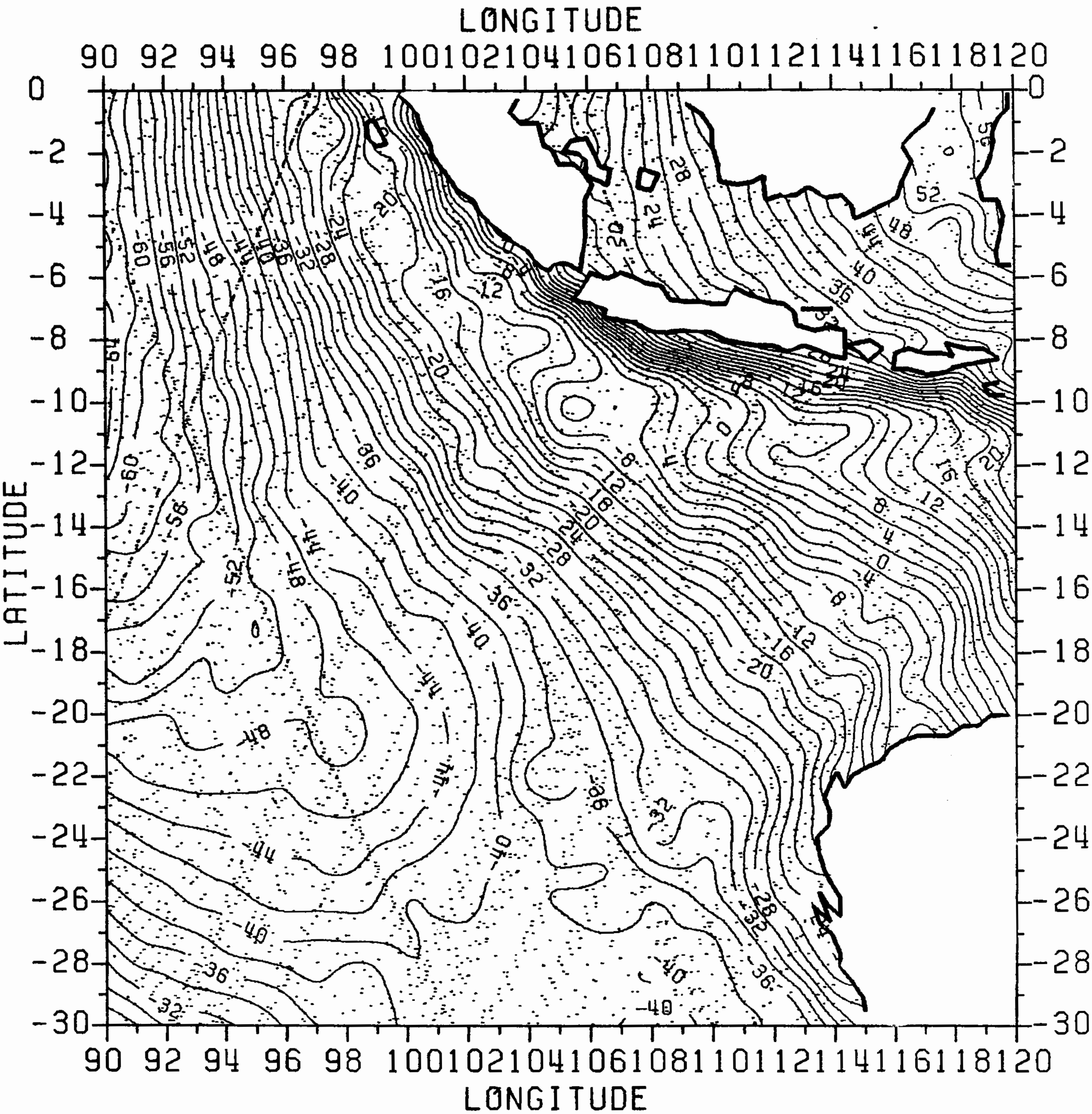
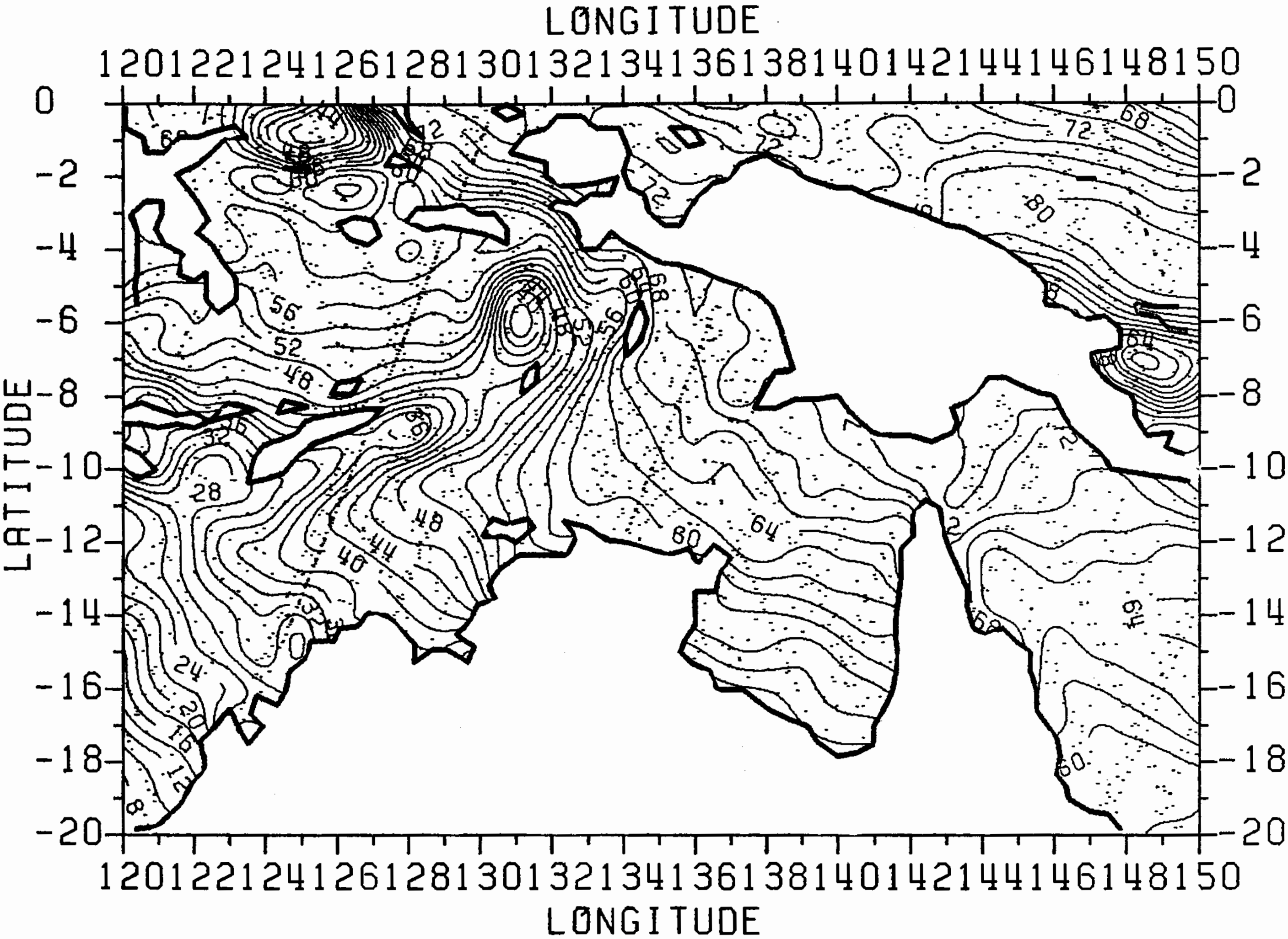


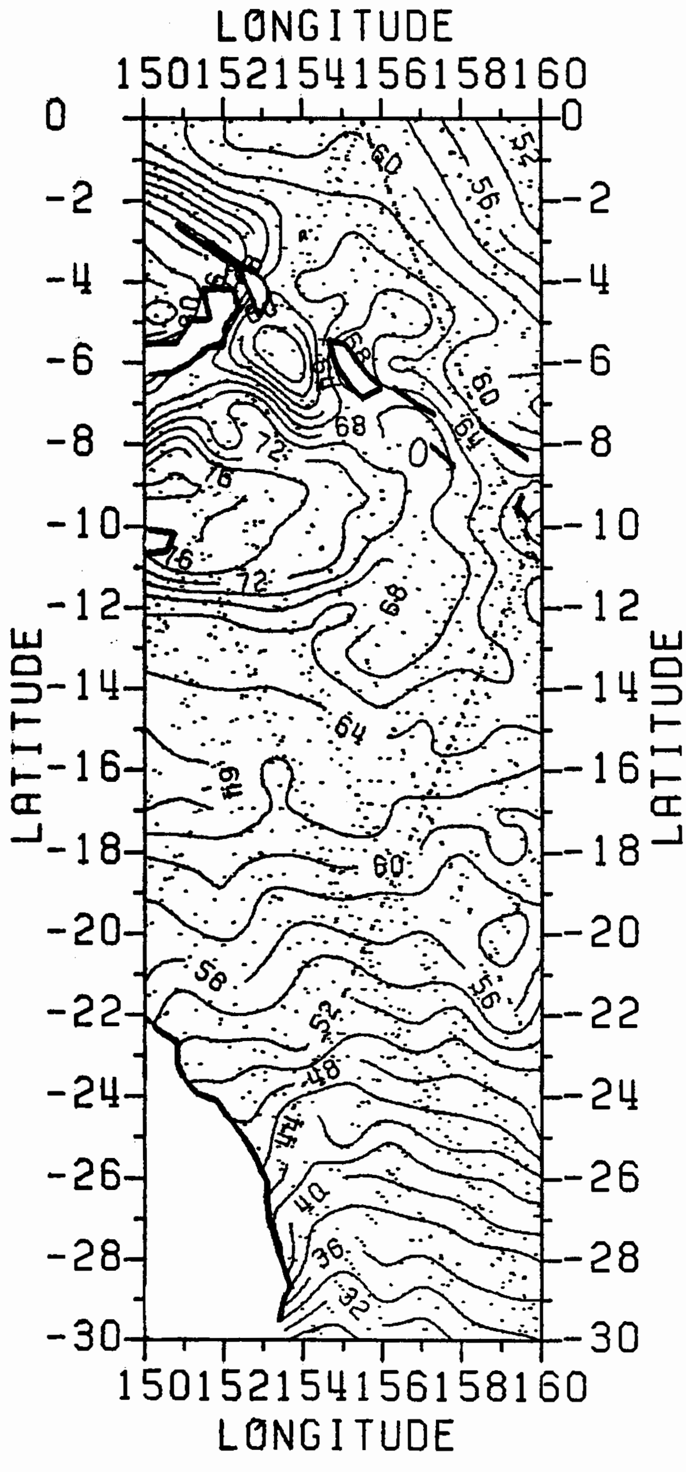
Sea Surface Height Map 27



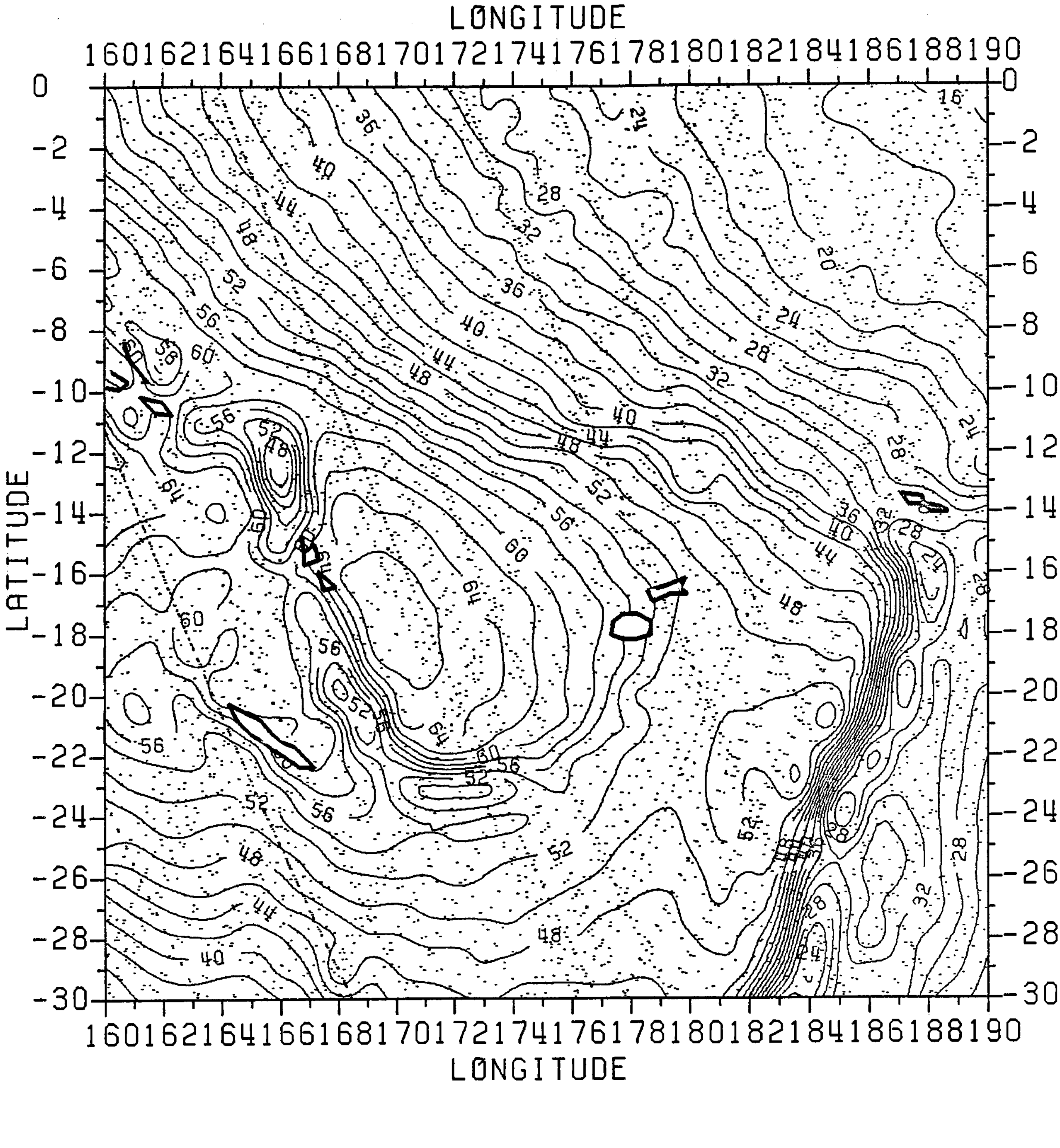
Sea Surface Height Map 28



Sea Surface Height Map 29



Sea Surface Height Map 30



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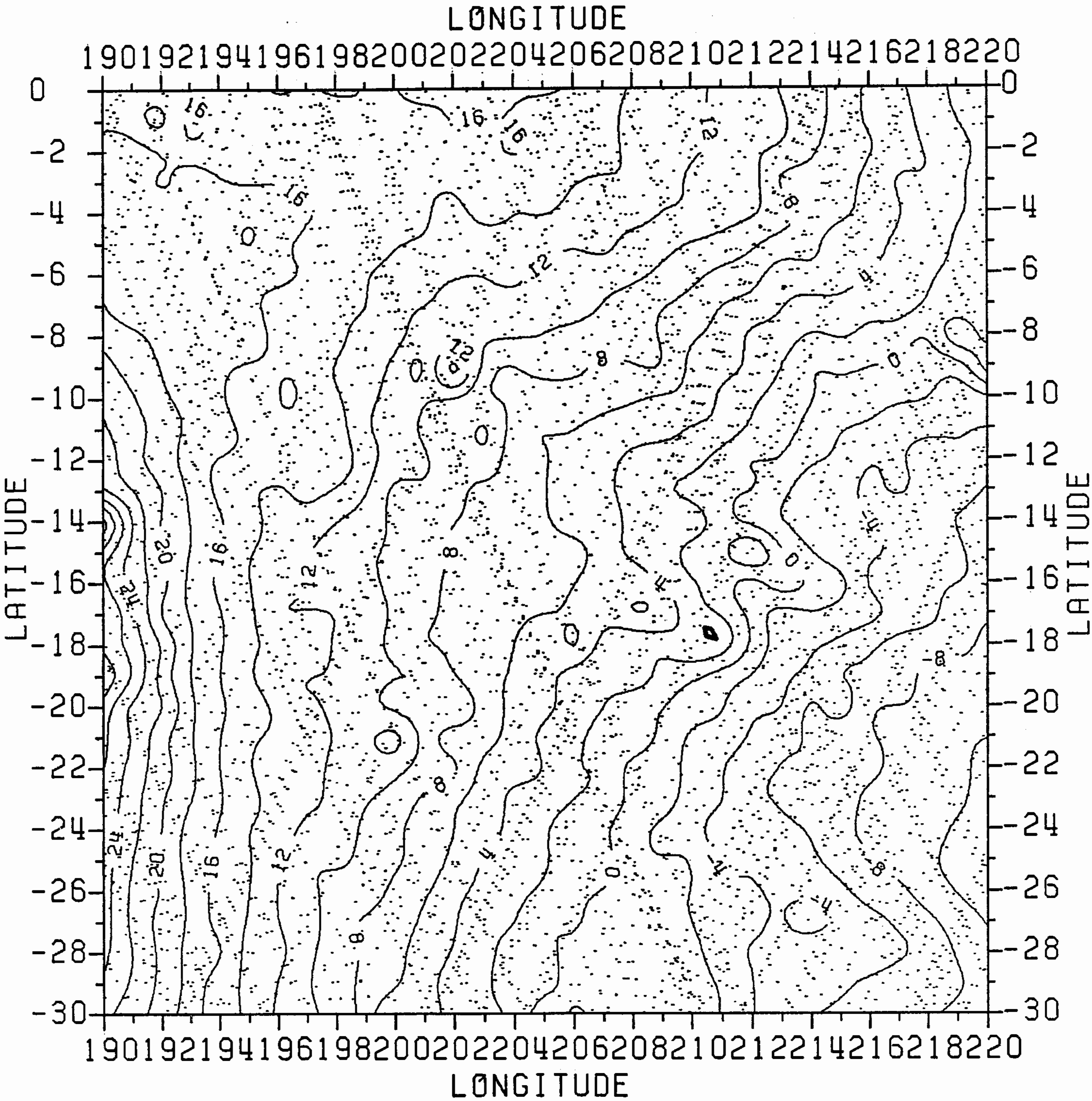
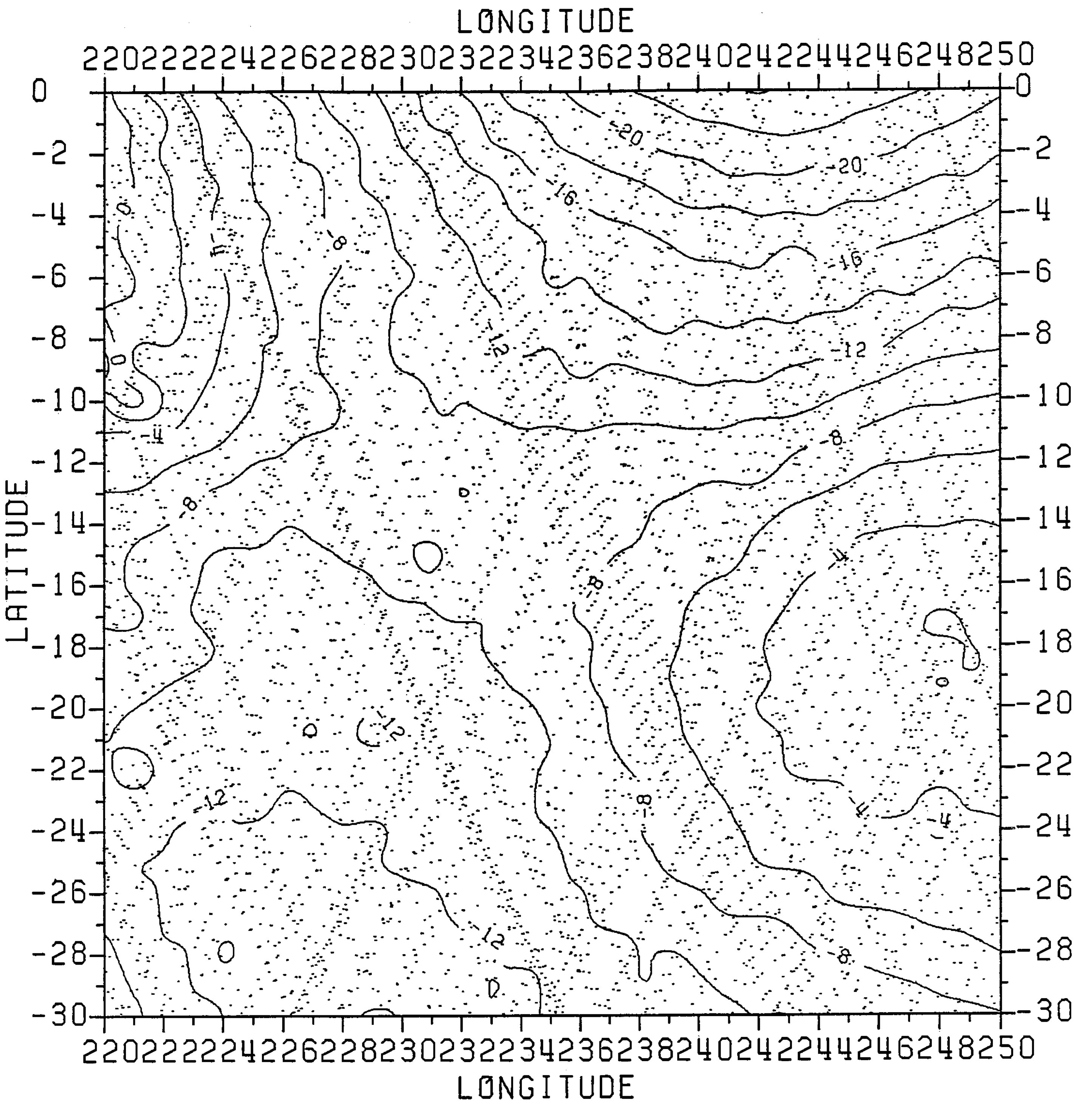
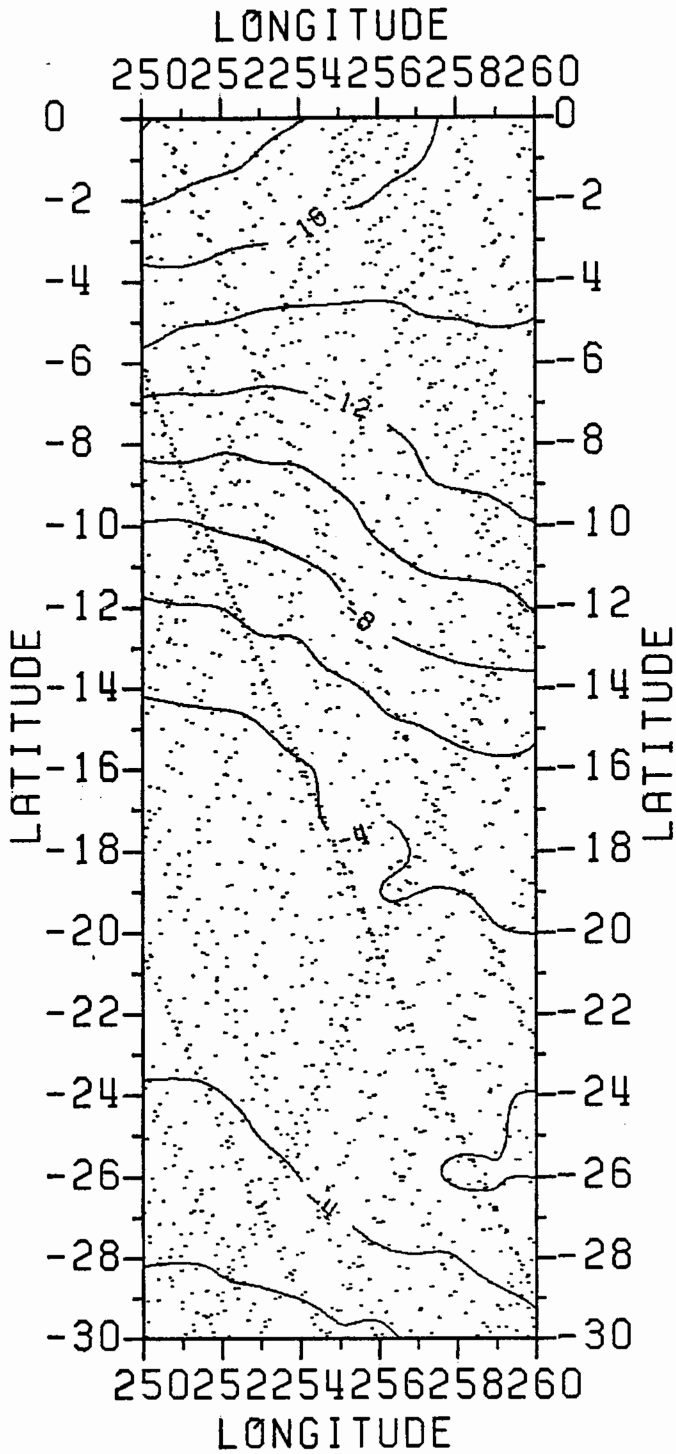


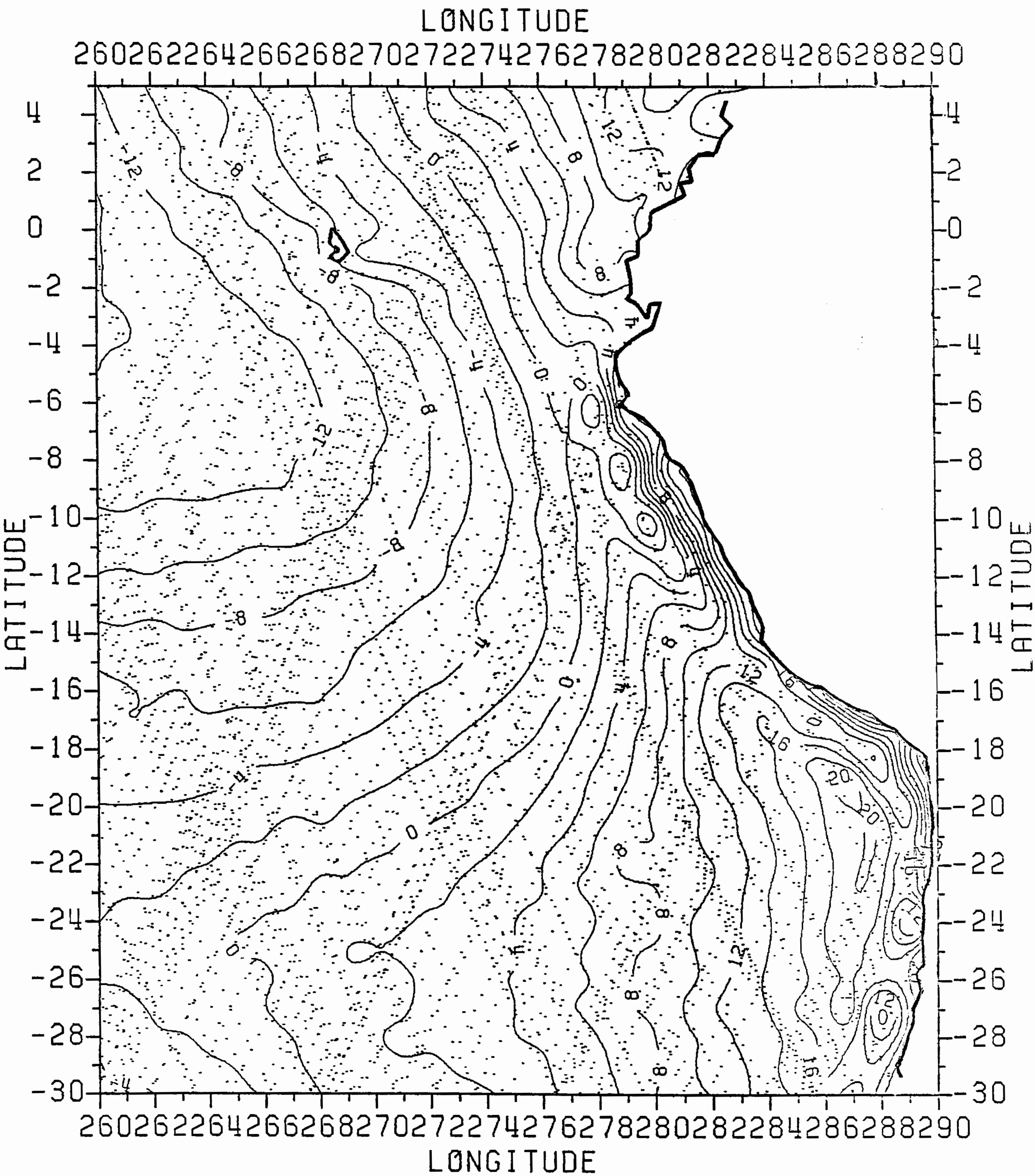
Sea Surface Height Map 32



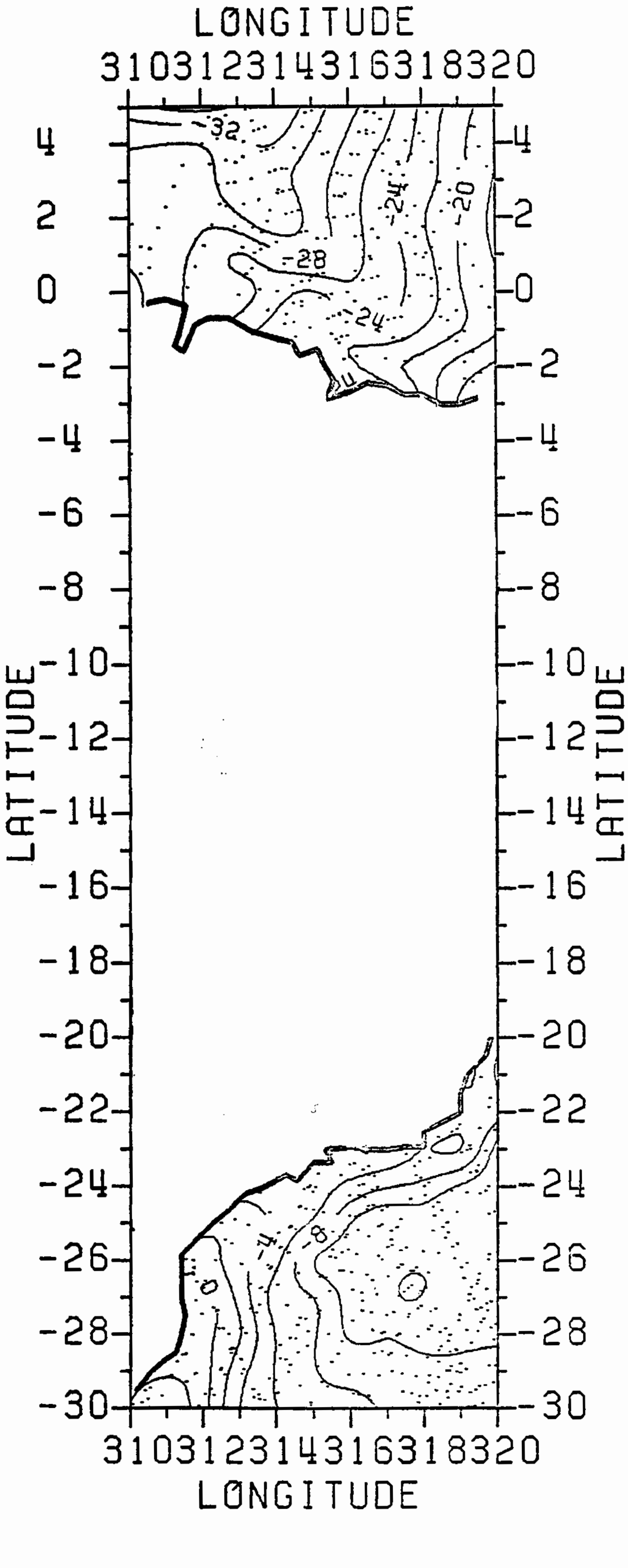
Sea Surface Height Map 33



Sea Surface Height Map 34



Sea Surface Height Map 35



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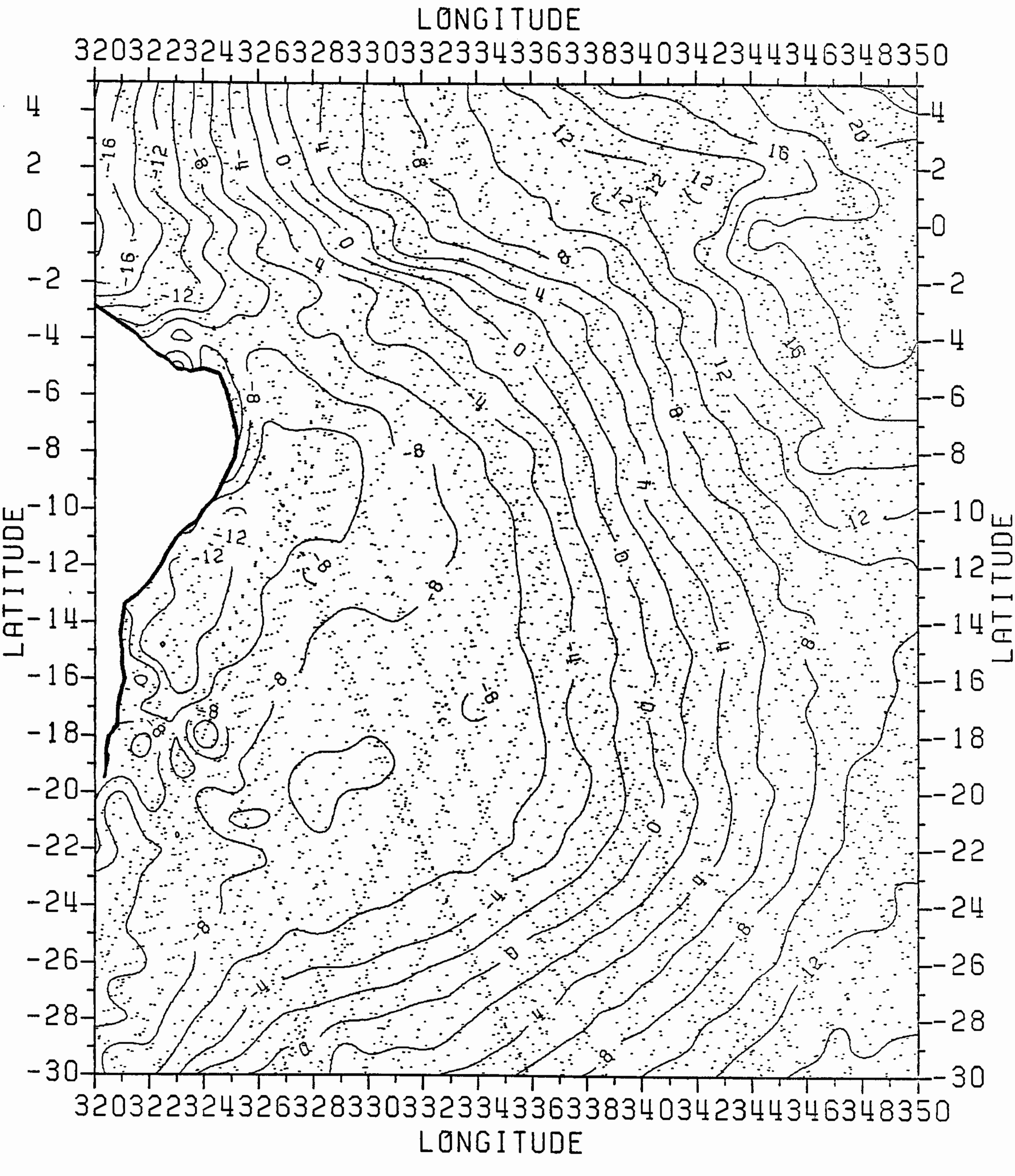

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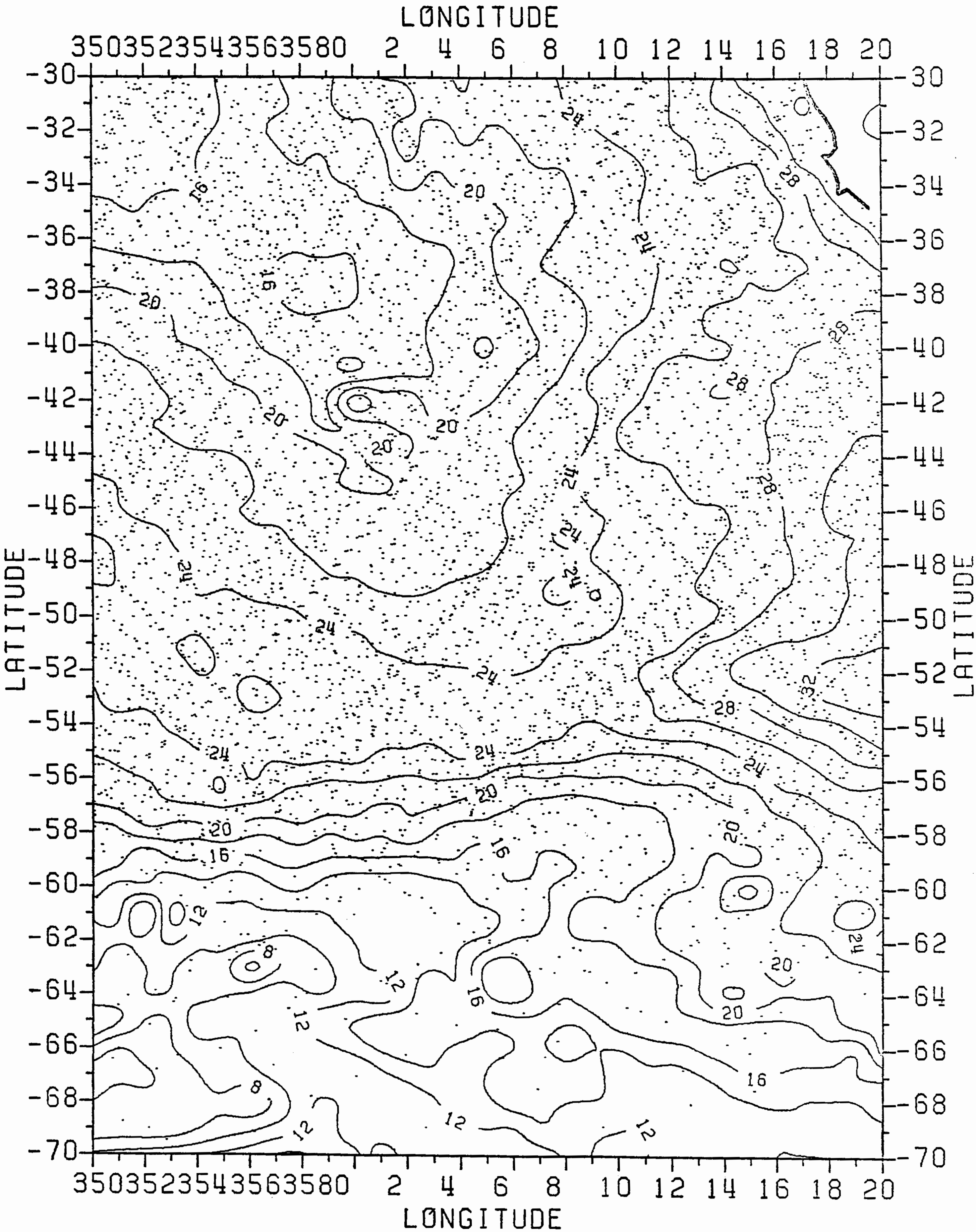
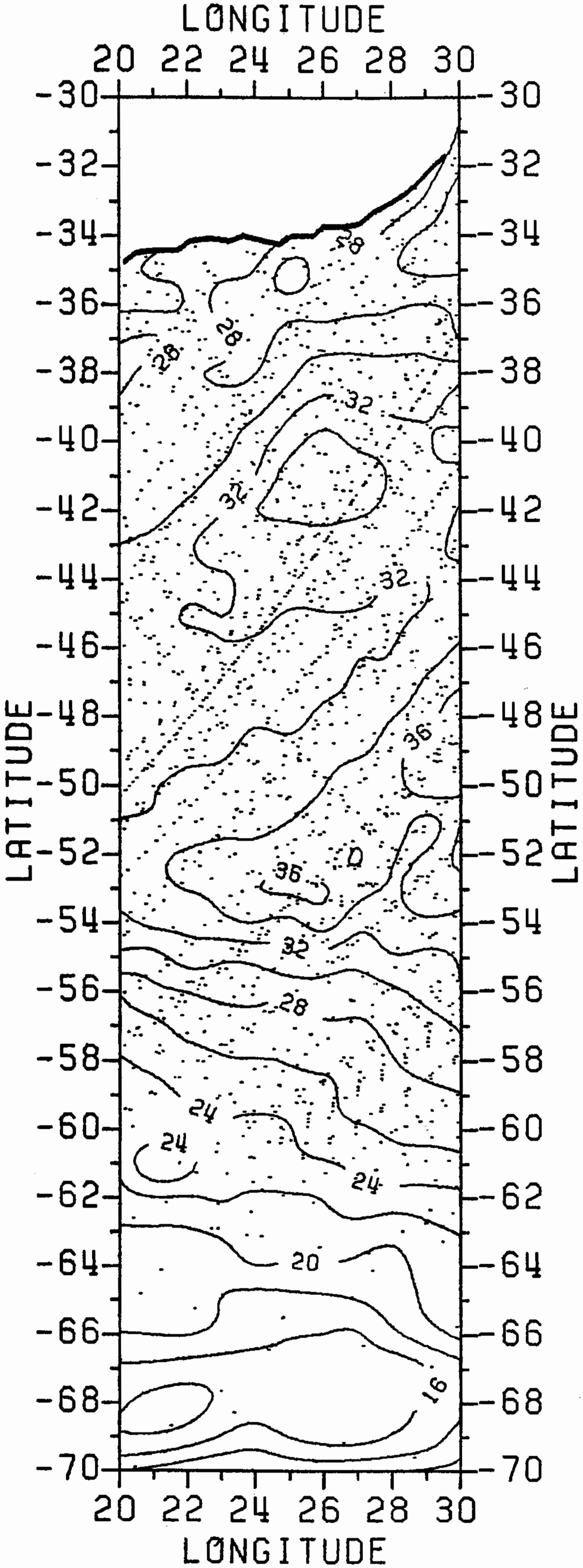
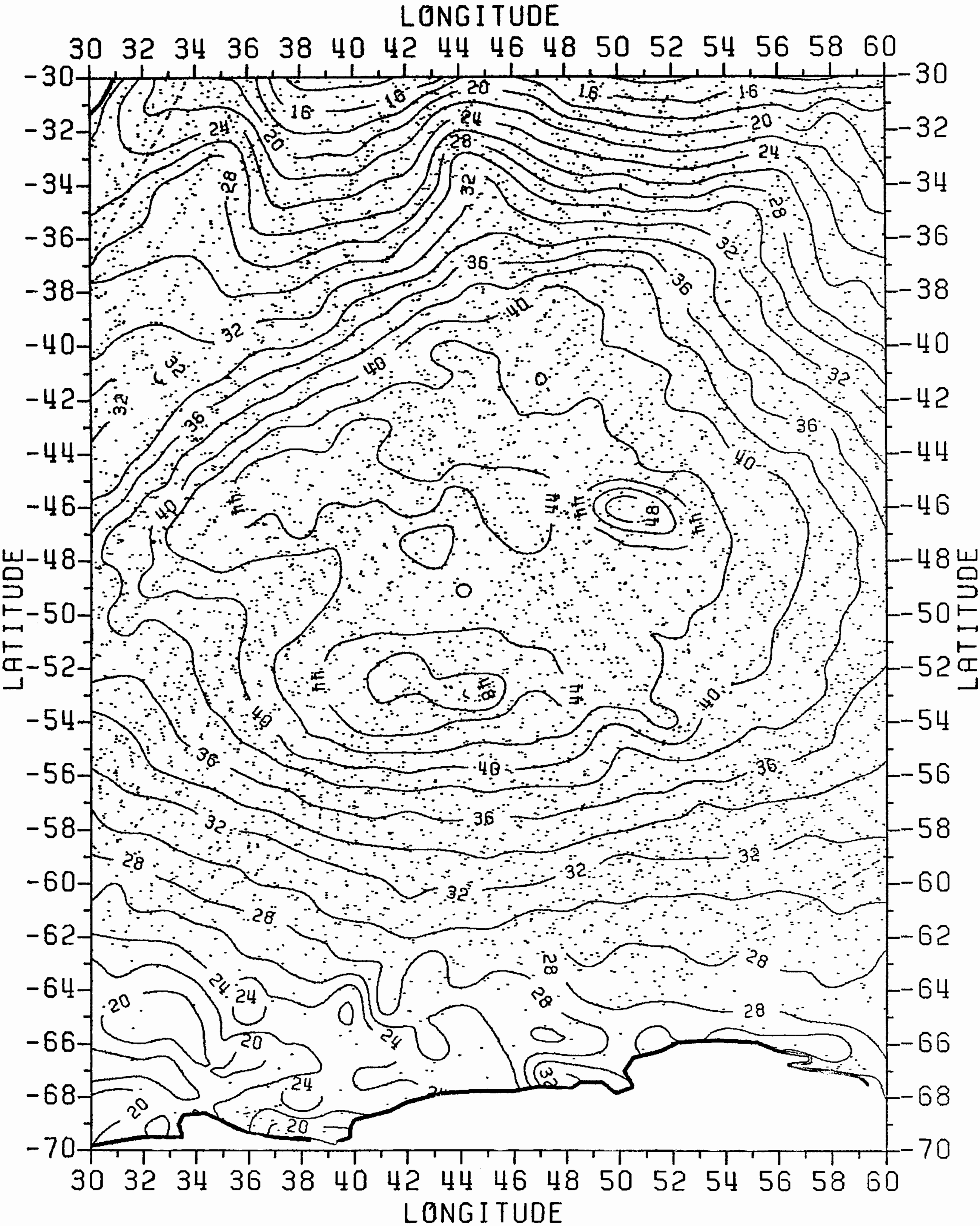


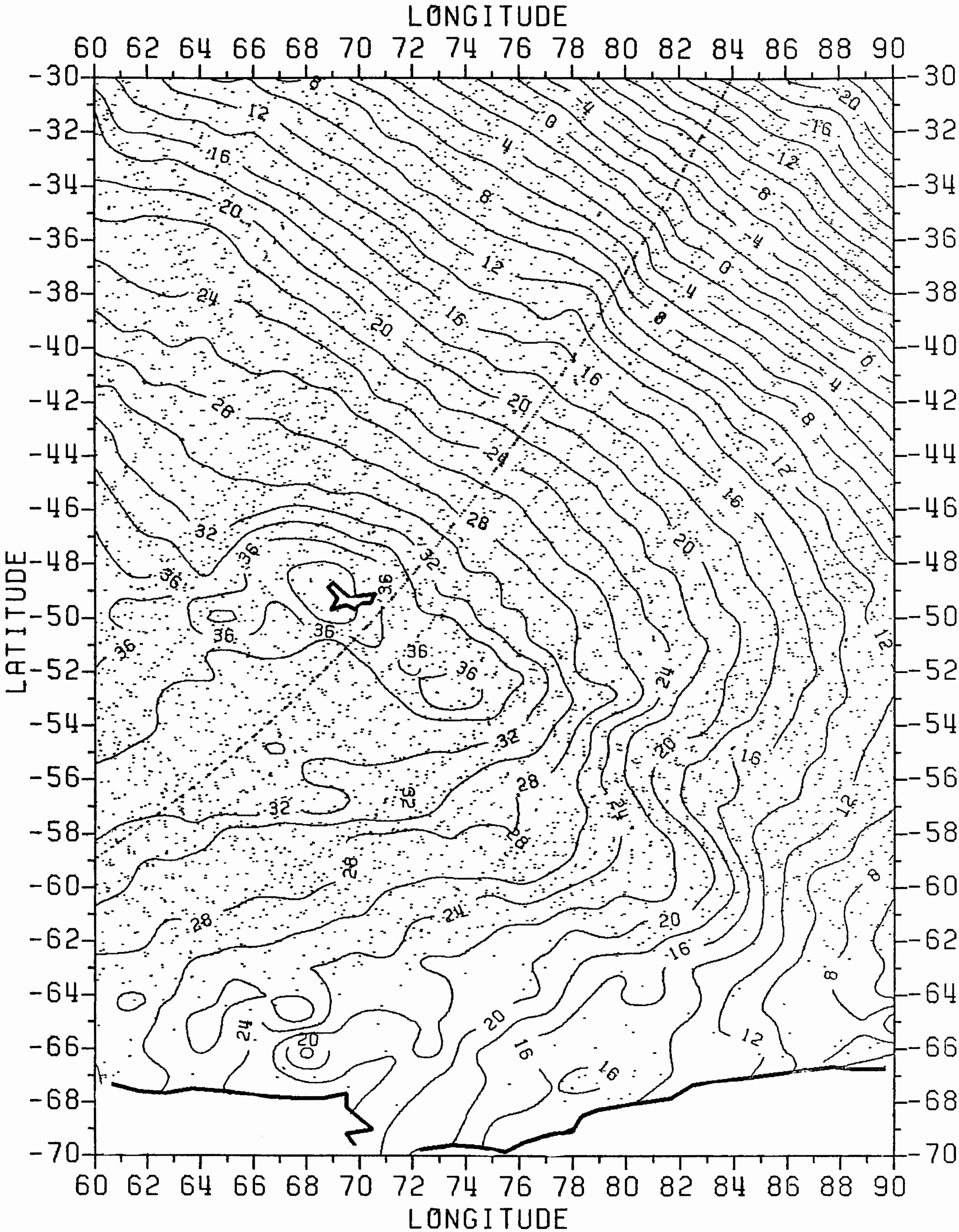
Sea Surface Height Map 38



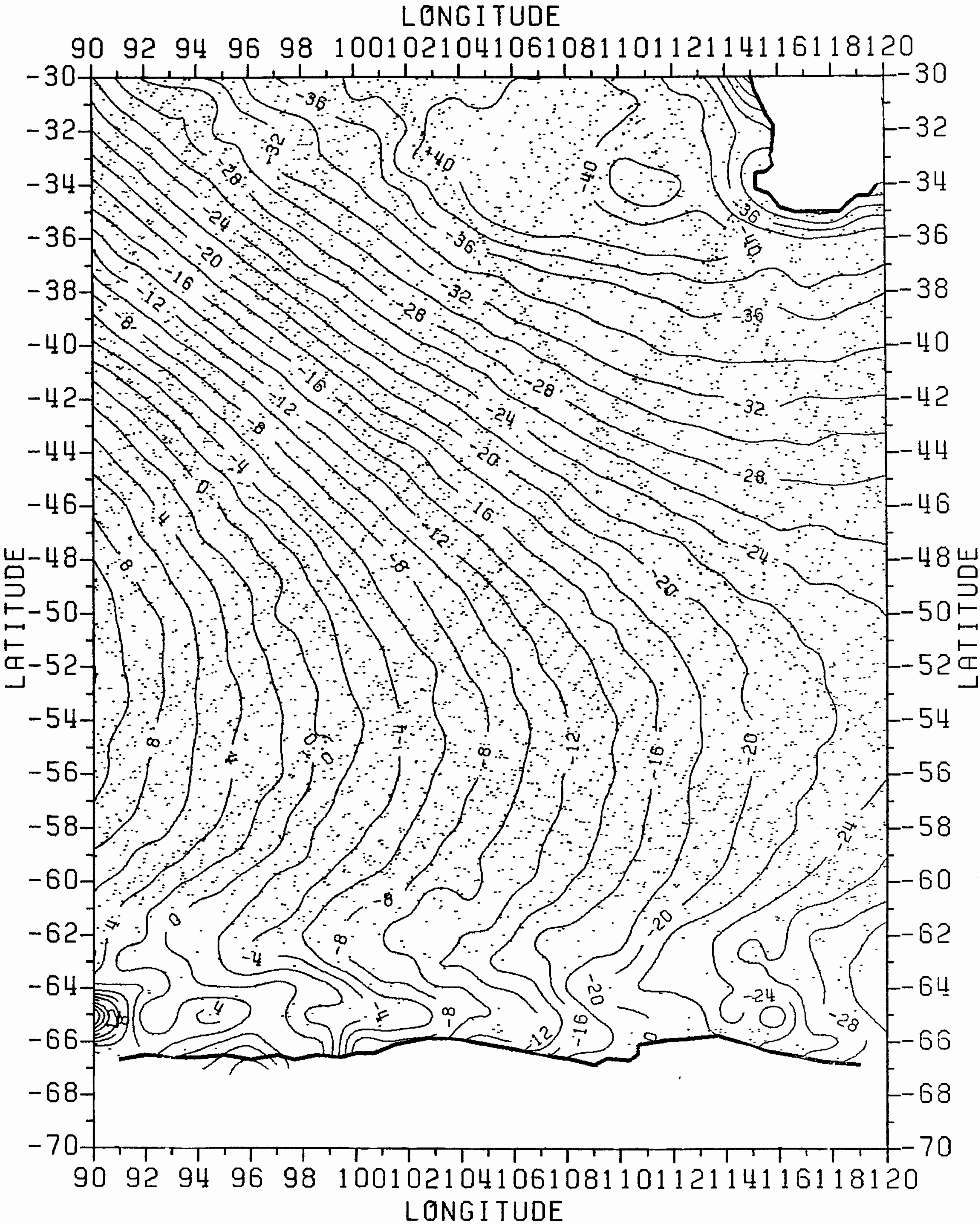
Sea Surface Height Map 39



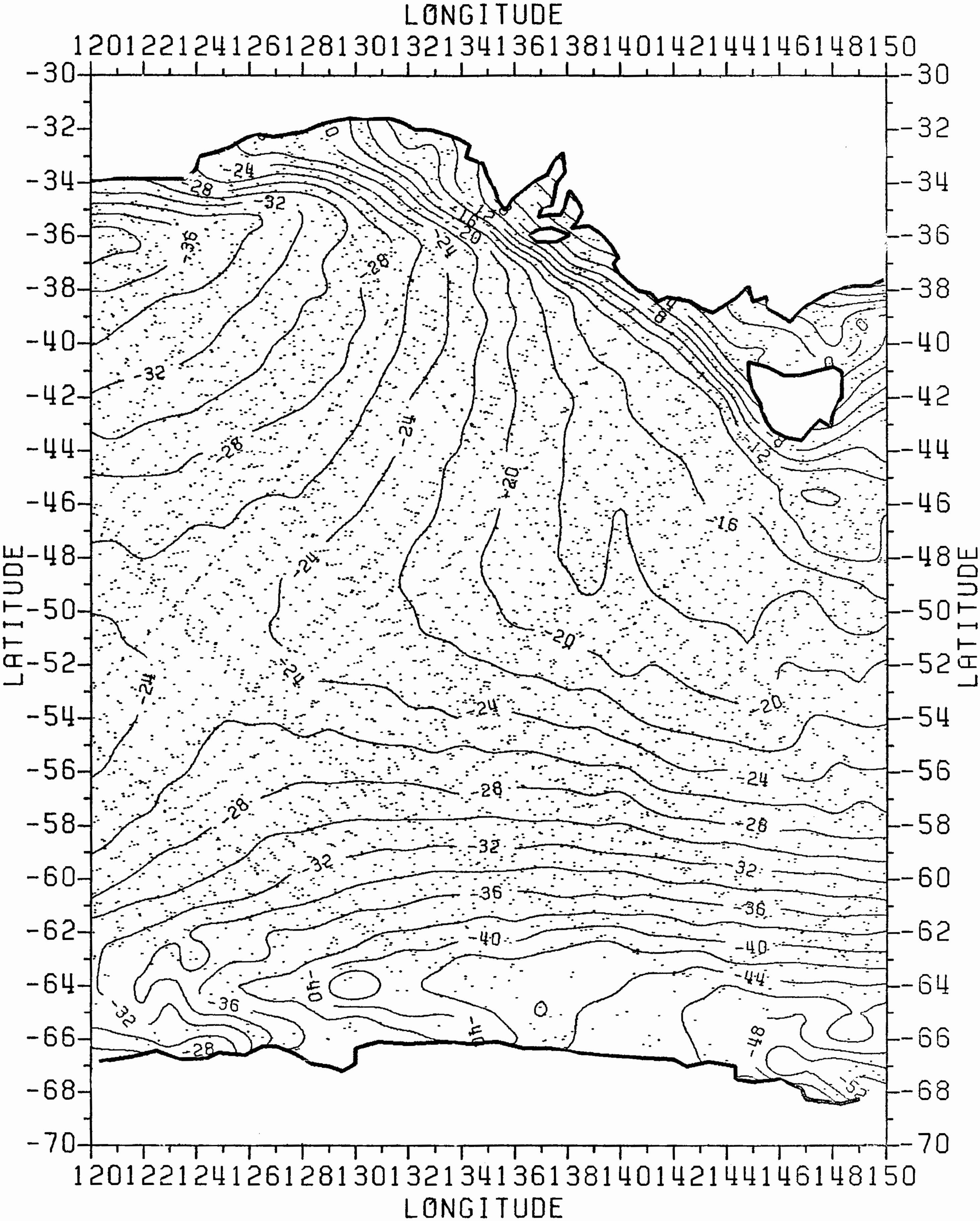
Sea Surface Height Map 40



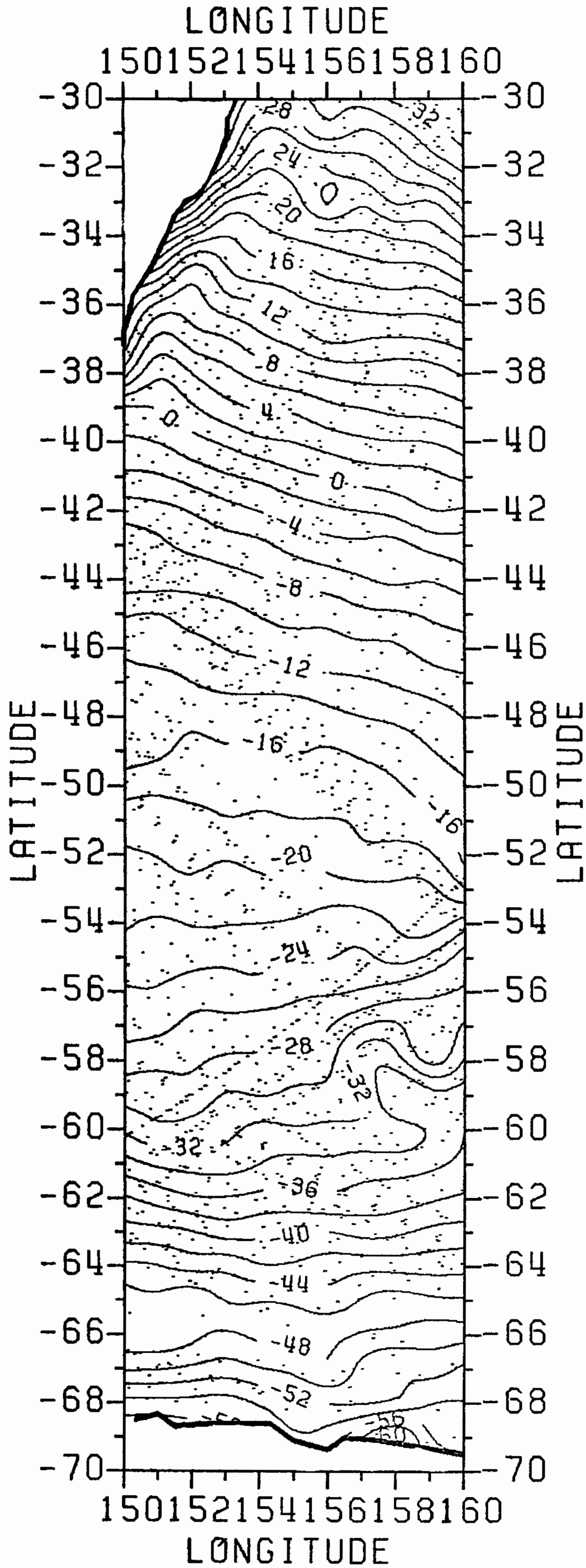
Sea Surface Height Map 41



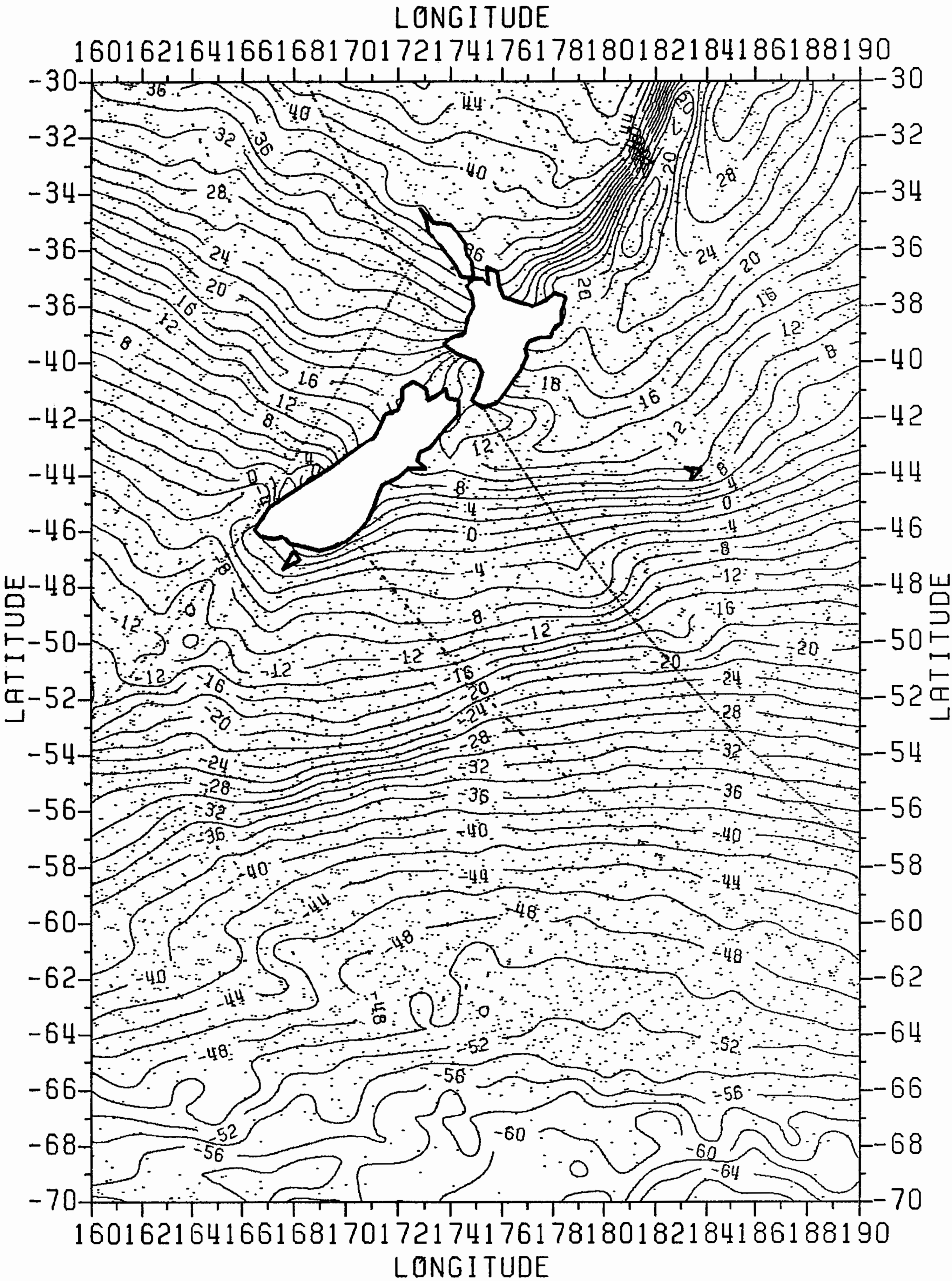
Sea Surface Height Map 42



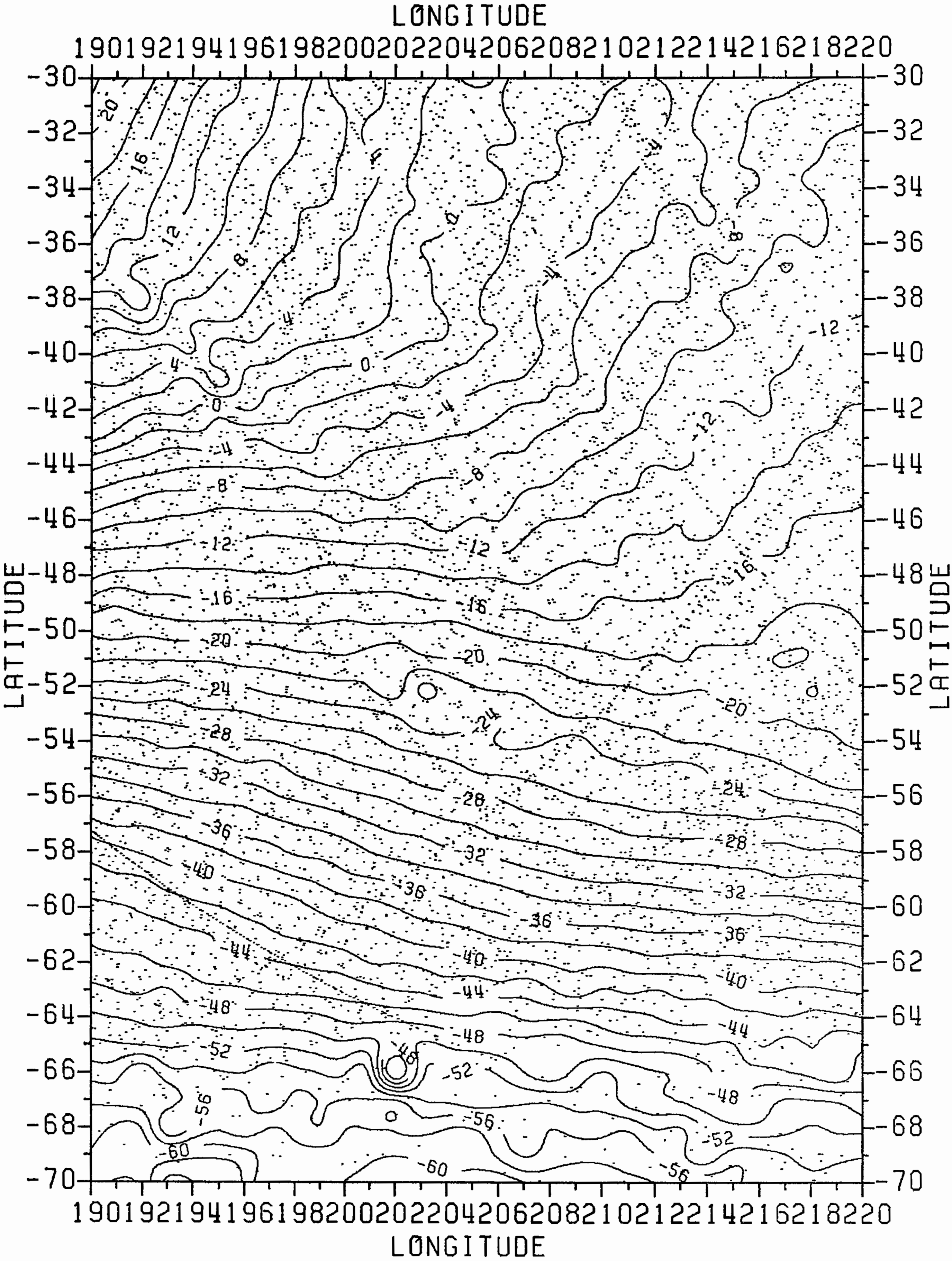
Sea Surface Height Map 43



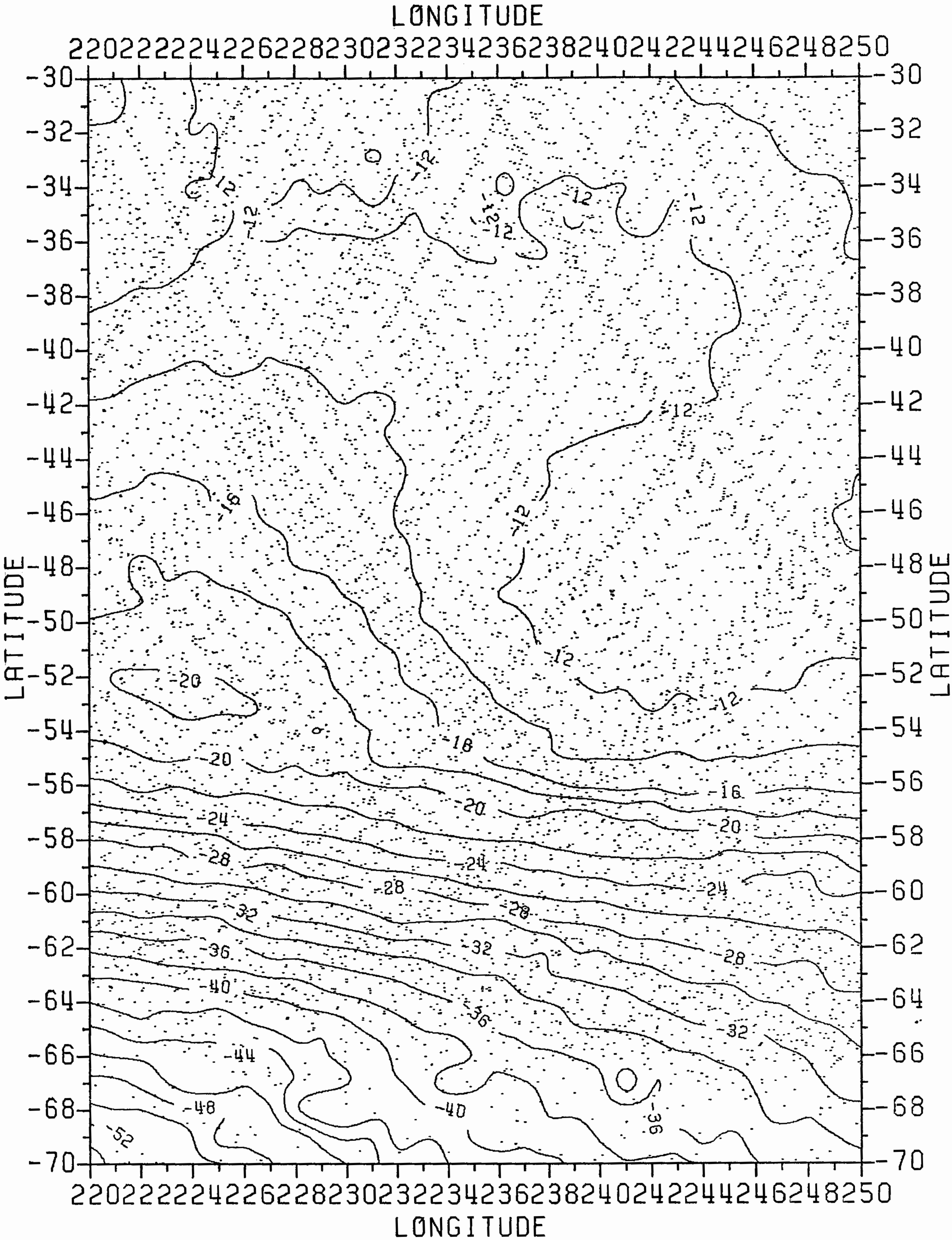
Sea Surface Height Map 44



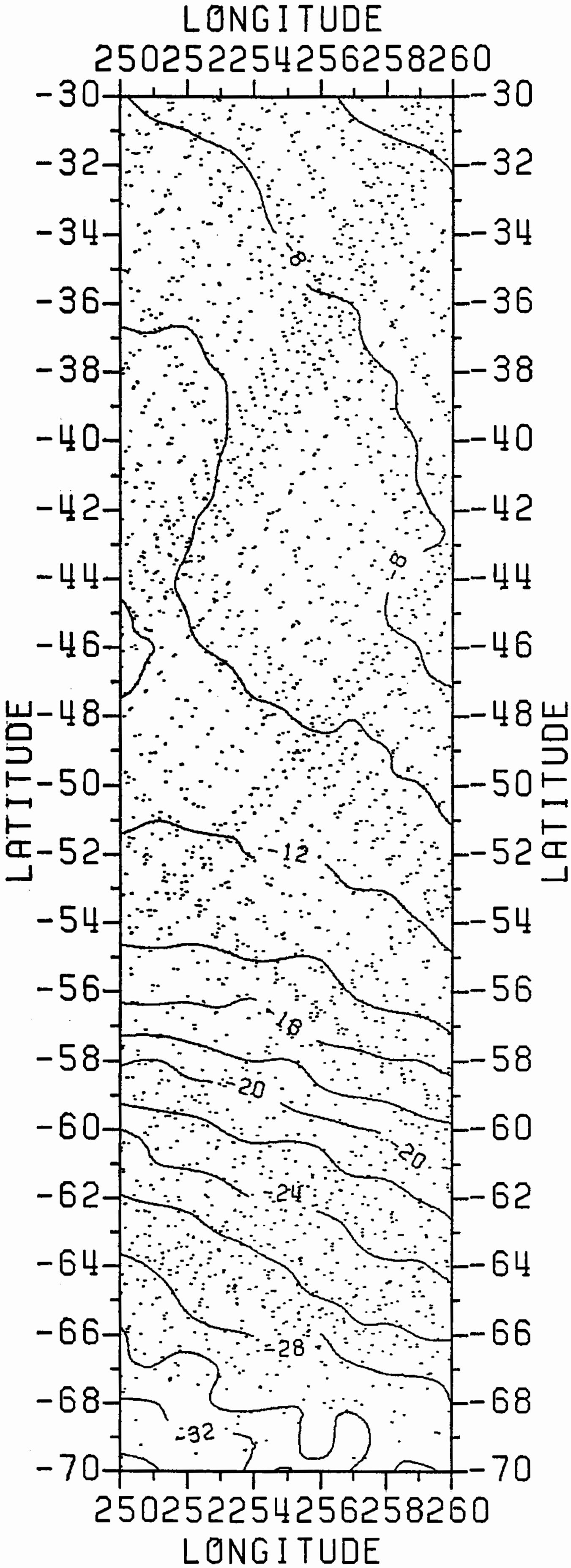
Sea Surface Height Map 45



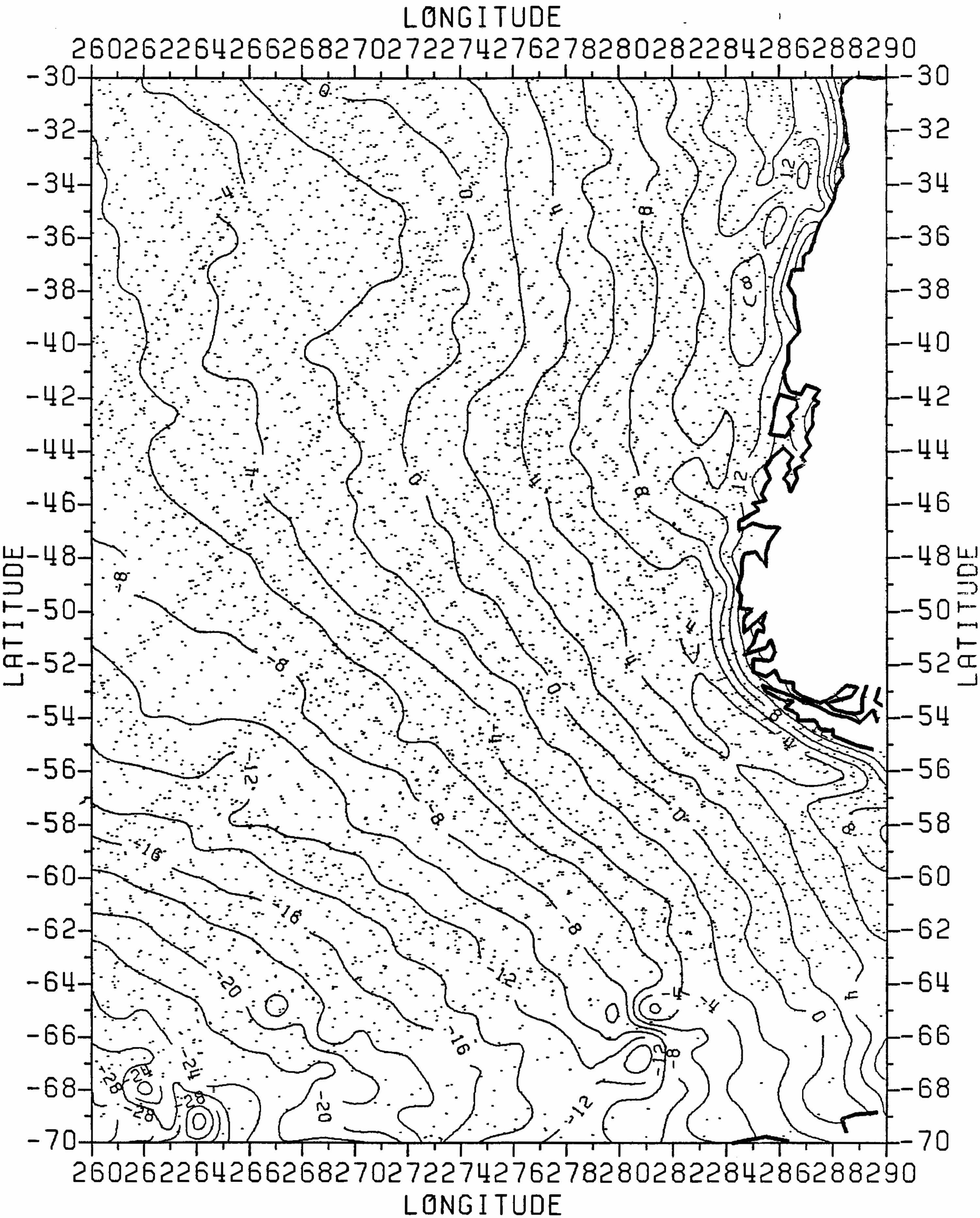
Sea Surface Height Map 46



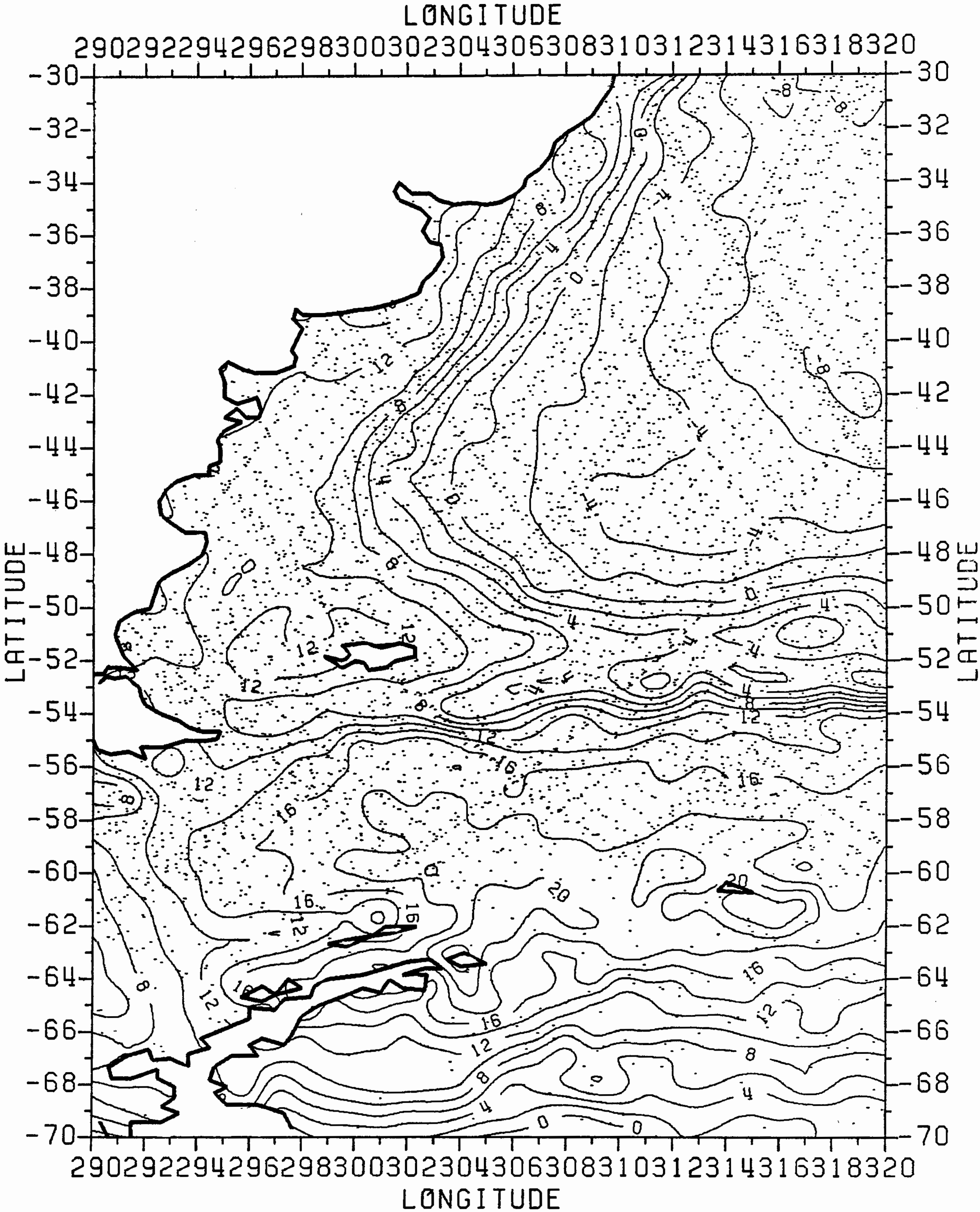
Sea Surface Height Map 47



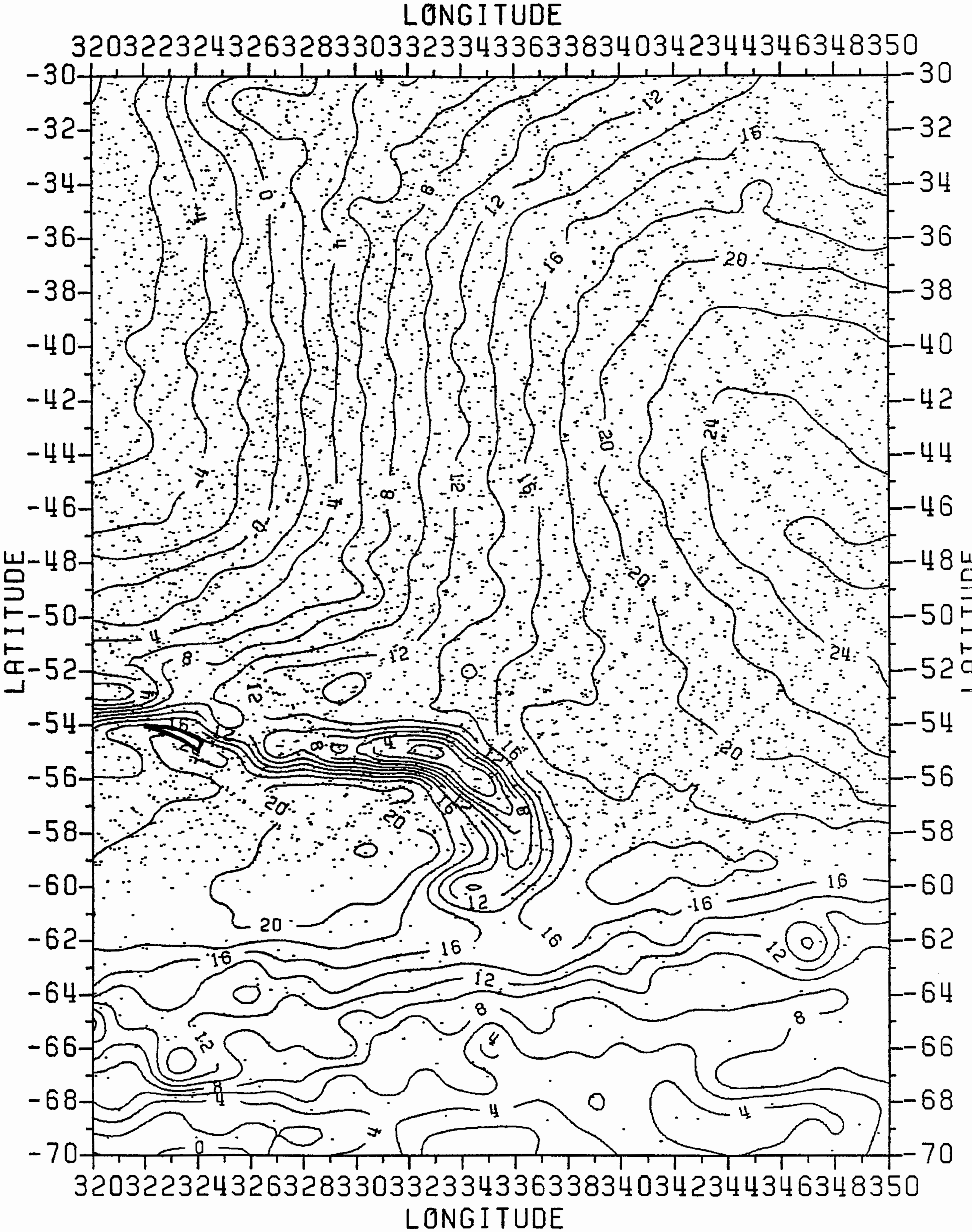
Sea Surface Height Map 48



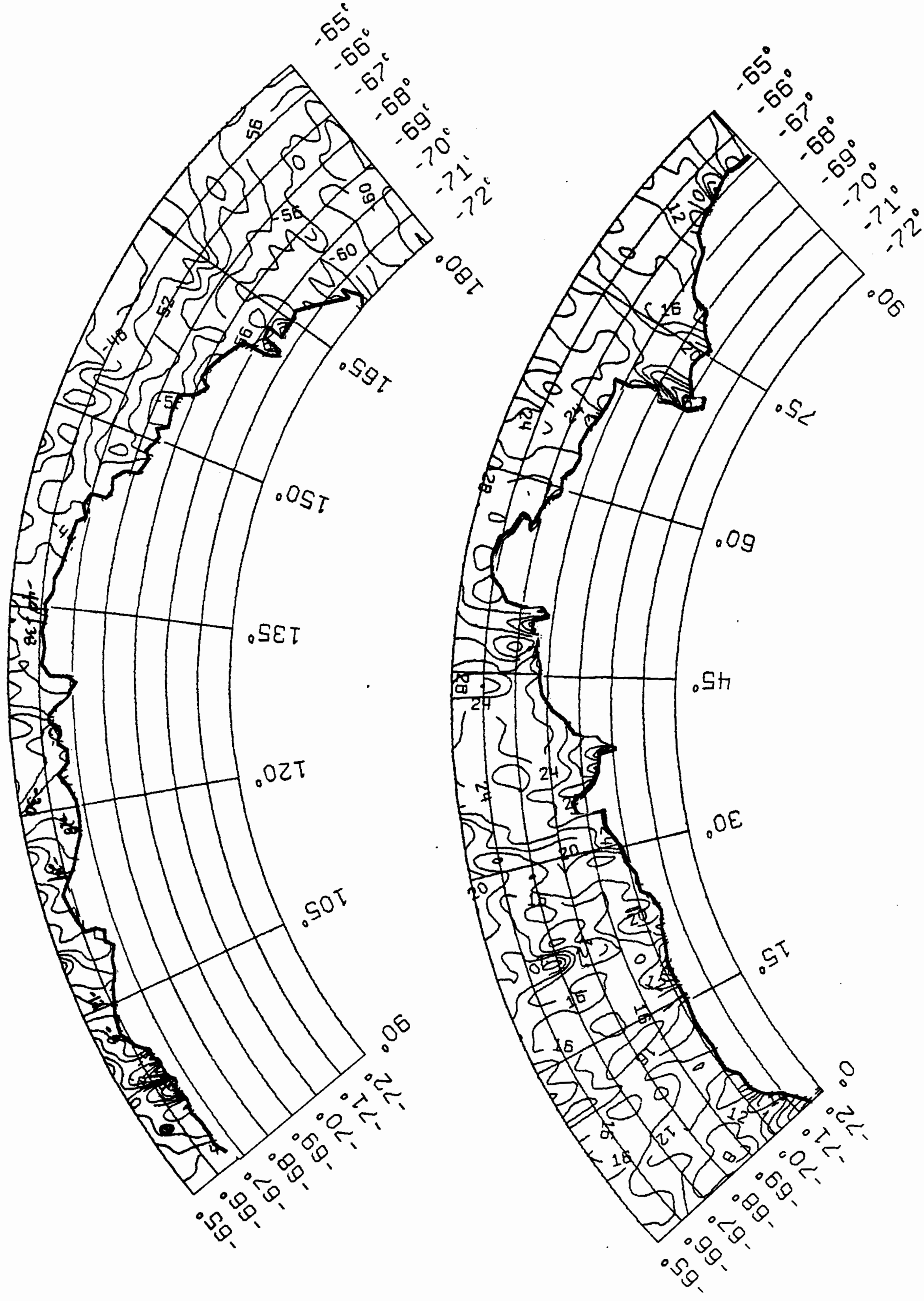
Sea Surface Height Map 49



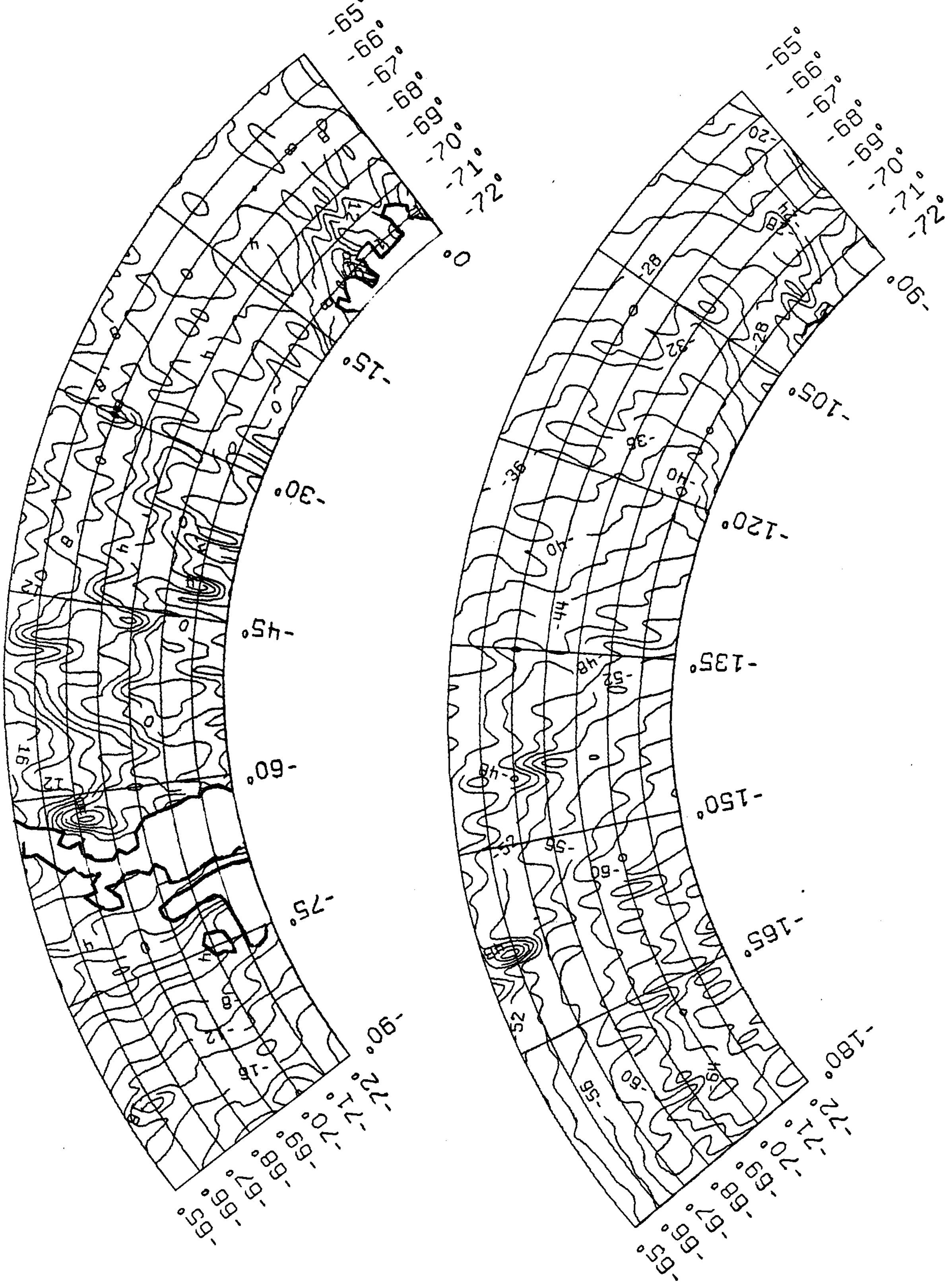
Sea Surface Height Map 50



Sea Surface Height Map 51



Sea Surface Height Map 52



Sea Surface Height Map 53

Summary

This report describes the generation of sea surface heights for the oceans based on adjusted Seasat altimeter data. The contour maps were developed using point data predicted on a uniform $1° \times 1°$ grid on the basis of the 5 closest altimeter measurements using least squares collocation. Due to the coarseness of the grid (chosen to make the computer requirements reasonable) and the selection of every 10th data point, some high frequency signal can be missing from the maps.

The complete set of predicted sea surface heights on the $1° \times 1°$ grid is available on tape.

More detailed maps using a denser grid interval, more complete data selection, and a smaller contour interval can easily be generated in areas of specific interest.

References

Katsambalos, K., Comparison of Some Undulation Prediction Techniques from Altimeter Data, Report No. 303, Dept. of Geodetic Science The Ohio State University, Columbus, 30pp, July 1980.

Kearsley, W., The Prediction and Mapping of Geodal Undulations From Geos-3 Altimetry, Report No. 267, Dept. of Geodetic Science, The Ohio State University, Columbus, 72pp, December 1977.

Marsh, J., and T. Martin, The SEASAT Altimeter Mean Sea Surface Model, J. Geophys. Res., 87, 3269-3280, 1982.

Pearson II, Frederich, Map Projection Equations, Report NSWC 101 TR-3624, Naval Surface Weapons Center, Dahlgren, VA, March 1977.

Rapp, R.H., Mean Gravity Anomalies and Sea Surface Heights Derived from Geos-3 Altimeter Data, Report No. 268, Dept. of Geodetic Science, The Ohio State University, Columbus, 1977.

Rapp, R.H., Global Anomaly and Undulation Recovery Using Geos-3 Altimeter Data, Report No. 285, Dept. of Geodetic Science, The Ohio State University, Columbus, 1979.

Rowlands, D., The Adjustment of Seasat Altimeter Data and a Global Basis For Geoid and Sea Surface Height Determination, Report No. 325, Dept. of Geodetic Science and Surveying, The Ohio State University, Columbus, 1981.

Sünkel, Hans, A General Surface Representation Module Designed for Geodesy, Report No. 292, Dept. of Geodetic Science, The Ohio State University, Columbus, 1980.

Tscherning C., and R. Rapp, Closed Covariance Expressions for Gravity Anomalies, Geoid Undulations, and Deflections of the Vertical Implied by Anomaly Degree Variance Models, Report No. 208, Dept. of Geodetic Science, The Ohio State University, Columbus, May 1974.