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Synoptic Analyses and Prediction of Conditions and Processes in the Surface Layers of the Sea

(A summary review of methods, their accuracy and future prospects)

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Note: A limited number of copies of this paper is on hand for reference in the Secretariat

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Abstract

This paper reviews the present status of numerical synoptic analysis and forecasting of sea surface temperature, waves, surface currents, mixed layer depth, subsurface thermal structure and other semi-dependent parameters. The methods of analysis and forecasting are briefly outlined and examples of numerical computerized analyses and forecasts are given. Future prospects for improving observations and forecasting models are discussed.

The opinions expressed in this paper are those of the authors and do not necessarily reflect the opinions of the Navy Department at large.

1. Introduction

The atmosphere and the ocean are a coupled energy system, with each providing some of the driving force for the other. The properties and state of the interface between these two fluids, which is the sea's surface, determine to a large extent the exchange of mass and energy between these two media. Most of man's activities at sea are concerned with surface layers. There is a multitude of reasons for the synoptic analysis of the physical and dynamical properties of the sea surface. Additionally, the properties of the sea surface and their changes are indicative of many processes below the surface. This review concerns itself with modern methods of synoptic numerical analysis and forecasting of some of the important properties of the sea surface and subsurface layers to 1200 feet.

2. Synoptic analyses of the ocean

A prediction of the change of a given property in nature requires, besides a knowledge of the forces and processes, an accurate assessment of the initial state -- i.e. an analysis. Due to relative sparsity of oceanographic data, a variety of methods is necessary for the analysis of oceanographic parameters, and the initial state must often be derived from the driving forces, which are primarily atmospheric. Thus there is a great similarity between the methods applied to analysis and those used in forecasting. The equation of motion in its primitive forms finds little application in oceanographic forecasting for a number of reasons, most of which were pointed out by the pioneers in oceanography over half a century ago. One of the main reasons, often overlooked, is the relative slowness of motion which would require a grid size of a few miles, and a time step of less than an hour for the reproduction of synoptic changes. Besides the obvious limitation of computer size in carrying out such computations, it is at present impossible to determine the initial state and boundary conditions with sufficient accuracy for forecasting with so-called "primitive equations."

It should be pointed out that synoptic changes in the surface layers, due to internal processes as well as exchange processes, are approximately in the same space and time scale as the atmospheric processes on the surface, and that there are interdiurnal changes of properties in surface layers which can exceed the magnitude of annual range of monthly mean values of the same property (see Hubert and Laevastu, 1966).

2.1 Sea surface temperature (SST)

The main source of synoptic SST data is the marine weather reports from voluntarily observing and reporting vessels. About 1200 such reports are available every 12 hours from the N. Hemisphere. This density is too low for effective synoptic analysis using only 12 hours of observations. As sea surface temperature changes are not exceptionally abrupt in most locations, it is feasible to keep three and a half days of data in the analyses, provided the analysis scheme allows some indirect weighing by the age of the data. Figure 1 shows the SST data density during a given three and a half day period in March 1967. This figure indicates that the data density is reasonable between about 25°N and 60°N. It should be noted here that in some areas the density is also affected by communication difficulties. The input of other SST data, such as from BT observations or from ART, are very minor, but are also used at Fleet Numerical Weather Facility.

The quality (accuracy) of SST observations is relatively poor. First, different methods are used, such as bucket thermometers are not checked by port meteorological officers. Notoriously poor are the intake temperatures. Furthermore, the coding practice allows a ±0.75°C rounding off error. It has been estimated that the average deviation of SST is about ±1.6°F (Carstensen and Wolff, 1966). Besides the error in observation, the sea surface temperature has a certain amount of "ambient noise," the level of which varies with locations and seasons. The average amplitude of this ambient noise has been estimated to be ±0.5°F (Wolff and Stevenson, 1966). Obviously, there are areas and seasons when this amplitude can be either ±0.2°F or ±1.0°F.

The optimum numerical analysis of SST must take into consideration the data density, the speed and magnitude of variation of SST in the oceans, and the data accuracy, in determining the optimum grid size, analysis period and the length of data collection. The analysis period at Fleet Numerical Weather Facility is 12 hours, corresponding to the analysis period of the meteorological driving forces. The grid size varies from ca. 100 n. miles in hemispheric analyses to about 20 n. miles in some zoom (small-scale) analyses. A detailed description of the SST analysis method is given by Carstensen and Wolff (1966).

The data are subject to a gross error check before being entered into the analysis. A median seeking voting technique (Carstensen's method) is used in the analysis to reduce the influence of erroneous reports. All observations are placed in their proper geographic locations and their difference from the first guess field (previous analysis) is interpolated to the nearest grid point. If the interpolated value is greater or smaller, a predetermined value, or vote, is added to or subtracted from the gridpoint value. Several passes are made through the data, the predetermined increment being decreased during each pass. Slight relaxation and smoothing are applied between each pass. The oldest data are loaded first, followed by the more recent data in proper time sequence.

In dense data areas the value at the gridpoints is determined by the latest reports; in areas of no data it is only very slightly modified by relaxation and smoothing.

An example of a hemispheric analysis is given in Figure 2, which also indicates the limitations imposed by data density and other considerations. An example of a small-scale zoom analysis is given in Figure 3. Table 1 gives an example of verification of a hemispheric analysis. As seen from this table, the probable error of the analysis is only slightly higher than the probable error of observations.

Sea surface temperature analyses can be used for computation of the anomalies from long term mean (Figure 4) as well as for other methods of anomaly computations by pattern separation (Figures 5 and 6). These pattern separations serve several purposes in oceanographic analysis/forecasting and in medium range weather forecasting over the oceans.

By computing the second derivative of SST in the direction of maximum first derivative, the positions of the current and water type boundaries can be determined. (Figure 7) (Clarke and Laevastu, 1966.) These boundaries can also be deduced in some areas from SST SD pattern separation (Figure 6).

2.2 Sea and swell analyses

The numerical sea (wind waves) and swell analysis and forecasting methods have been developed by Hubert (1964). The analysis and forecast program for wind waves uses a "singular" technique to obtain significant wave height and period. Surface geostrophic winds at three-hourly intervals and wave observations are the basic inputs. Duration is determined to the nearest three hours and fetch corrections are made in regions of offshore flow. The formulae for wave height and period as functions of duration D_f and geostrophic wind speed U_g used at Fleet Numerical Weather Facility are

$$H_{1/3} = a\,(U_g)^2\,D_f + bU_g$$

$$T_{1/3} = (c + dD_f)\,U_g + e$$

A sample wave analysis is shown in Figure 8.

Swell is defined as waves which have traveled more than 24 hours from a generating area. Based on a history tape of wave heights, periods and directions at 12-hourly intervals, travel distance, swell height and swell period are computed from the following equations:

$$D = a_1 T_f \bar{m} t$$

$$T_D = \left(T_F^2 + \frac{b_1 D}{\bar{m}}\right)^{\frac{1}{2}}$$

$$H_D = H_f \left(\frac{T_D}{T_f}\right)^{-2.65}$$

where D is travel distance, T_f is the period at the end of fetch, $\bar{m}$ is the mean map factor, t is decay time, T_D is the swell period, H_D the swell height, H_f the height at end of fetch, and a_1 and b_1 are constants. Swell analyses and forecasts are plotted in the same manner as the wind waves. Sea and swell height are added to form combined sea height (Figure 9) using the following relation:

$$H_C = \sqrt{H_{1/3}^2 + H_D^2}$$

Forecasts of the sea and swell are computed utilizing the same method as the analyses; the difference being in selection of the surface wind fields. However the analyses are also influenced by the wave observations in the following manner: after computation of the analysis field, the synoptic wave observations are considered by forming a smoothed difference field between the analyzed and observed values and adding this difference field to the analysis. The same procedure is followed in swell analyses.

The accuracy of sea and swell observations is notoriously poor (see Table 2). Therefore, verification with single observations must be done with considerable care. The most reliable single observations usually originate from weather ships. An example of wave height verification on a hemispheric scale is shown in Table 3. In general, verification errors are of the same order of magnitude as that of the observations, indicating that further improvement of models requires either a drastic improvement of the accuracy of wave observations, or an improvement of the computation and forecasting of surface wind over the sea, or both.

2.3 Mixed layer depth (MLD)

The analysis and forecasting of mixed layer depth is one of the several steps in Fleet Numerical Weather Facility's subsurface thermal structure analysis. An oversimplified scheme of this analysis is shown on Figure 10. The basic computations in this analysis are as follows:

1) The monthly mean climatology of MLD is interpolated daily. The previous analysis field is compared with this interpolated climatology field and moved 1/8 of the difference towards climatology. The resulting field is the "first guess field."

2) The mixed layer depth which would be caused by wave mixing along is computed from the previous and actual wave height analysis and thermocline stability:

$$D = 10H_c - k_2\ 0.1H_c^2$$

$$k_2 = \frac{SST}{T_{s_{12}} - T_{600}}$$

where D is mixed layer depth due to wave mixing, 10 and 0.1 are tuning constants, H_c is the combined wave height (the highest value in either recent or previous analysis), k_2 is the stability factor, SST is the sea surface temperature, $T_{s_{12}}$ is the SST 12 hours ago, and T_{600} is 600 foot temperature.

3) The depth to which convective stirring caused by cooling at the surface would be effective is computed utilizing the following formula:

$$\Delta D = \frac{100\Delta T_s}{T_{s_{12}} - T_{600}}$$

where ΔD is the change of MLD due to convective mixing, ΔT_s is the change of surface temperature during the last 12 hours, $T_{s_{12}}$ is SST 12 hours ago and T_{600} is 600 foot temperature.

4) The fields of 1, 2 and 3 are compared and the deepest value selected at each gridpoint. The MLD of this field is moved up or down with convergence/divergence as computed from surface current field

$$\Delta D = (u_1 + u_3 - u_4 - u_2 + v_1 + v_2 - v_3 - v_4) \frac{MLD}{4L}$$

where L is the grid size.

5) Finally, the MLD is determined from a 60 hour collection of synoptic BT reports. The BT is placed in its proper geographic location, the difference between the observed and computed MLD field (4 above) is computed and this difference field is smoothed and added to 4 above. An example of a hemispheric MLD analysis is shown on Figure 11. Zoomed analyses of MLD are also prepared.

There are at present only about 150 to 200 synoptic BT reports per day available from the N. Hemisphere, most of them originating from naval and fisheries vessels. The quality of the data also leaves much to be desired. For example, there are over ten different codes in use for reporting BT temperatures. Furthermore, the mechanical BT often goes out of calibration.

There is a new era coming in synoptic observations of subsurface thermal structure with the introduction of the XBT. This instrument allows continuous observation of temperature down to 1500 feet while underway at any speed and in any sea state.

The accuracy of hemispheric MLD analysis varies with season, being about ±25 feet in summer and about ±40 feet in winter. The accuracy of zoom analysis is somewhat better

It should be noted that the thermocline can fluctuate up and down considerably during 24 hours. This fluctuation is at present predicted partly on physical and partly on statistical-empirical basis. It should also be noted that a single BT cast is not an absolute measure of MLD and subsurface thermal structure as there is no means at present to determine at which stage of the thermocline fluctuation the BT cast was taken.

Besides the seasonal or permanent MLD prediction, the magnitude and depth of the transient thermoclines are computed from heat exchange and wave-mixing considerations. These are decayed with wave mixing, currents and cooling (see Figure 12B).

2.4 Subsurface thermal structure analyses

The subsurface thermal structure is analyzed twice daily down to 1200 feet. This analysis is done by 100 foot fields (below 400 feet the interval is 200 feet). The interpolated climatology, SST and MLD analyses are the basic ingredients of this analysis. The resulting profile below the MLD is moved up and down with convergence with a resulting change in temperature. Finally, the BT temperatures are used to modify the thermal structure provided they pass a test of "tolerance" limits. General schemes of subsurface thermal structure analyses are given on Figures 12A and B. Further details and review of various methods of MLD and thermal structure analyses are given by Laevastu and Hubert (1965). Automatic BT data processing (BT-ADP) has been described by Samples (1966). An example of computer plotted thermal structure profiles, which are extracted from these fields, is shown on Figure 13.

The approach of ocean thermal structure analysis used by the Fleet Numerical Weather Facility has sometimes been referred to as the heat budget method. The origin of this designation is somewhat uncertain, but is caused most probably from the fact that in describing the early approach of ocean thermal structure forecasting, the description of the heat budget occupied most of the publication (Laevastu 1960). It should, however, be pointed out that heat budget is one of several inputs and its effects on short time scale are relatively minor.

2.5 Surface currents

The details of the surface current analysis and forecasting programs have been described earlier by Hubert (1964). Essentially, the computational procedure accounts for two principal current components -- (1) the 'characteristic' or thermohaline flow, and (2) the mass transport due to wind and waves.

Assuming a level of zero current velocity at some depth (ΔZ), the geostrophic thermal current at the surface is computed from the mean temperature, $\overline{T}$, in the layer

$$\mathbb{V}_c = - \frac{g \, \Delta Z}{f \, \overline{T}} \nabla \overline{T} \; | K$$

In practice, the mean temperature is obtained from a weighted combination of a climatological temperature field at 200 meters and the synoptic SST analysis described earlier.

The wind-driven current as determined by Witting (1909) is obtained from

$$W_w = k_3 W_g^{\frac{1}{2}}$$

where W_g is the mean geostrophic wind speed for a 36 hour period.

Figure 14 is an example of a current transport chart (in nautical miles per day) obtained at Fleet Numerical Weather Facility on a synoptic basis. As can be seen from this figure, well-known features such as the Gulf Stream, Kuroshio, Equatorial Counter Current, etc., are quite well defined by this procedure. Since the computations are carried out in component (u,v) form, directional fields are also available.

In order to obtain a single continuous field displaying both direction and speed of the computed currents, a stream function (ψ) analysis is made using methods similar to those employed by Bedient and Vederman (1964) to represent atmospheric flow in the tropics. The vorticity of the current flow is determined from the (u,v) component fields and the Poisson equation

$$\nabla^2\psi = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

is solved for ψ using relaxation techniques.

The stream function field which corresponds to the current transport chart in Figure 14 is shown in Figure 15. The derived stream function is nondivergent while there is divergence in the initial velocity field. In general, however, this appears to be small in most places, and the stream field provides a good representation of the current pattern.

It is interesting to note that the stream function analysis shows close correlation to the large-scale SST analysis shown in Figure 2. As one should expect, thermohaline considerations (as influenced by the semipermanent circulation of the atmosphere) determine the large-scale current pattern while mass transport by wind and waves contributes toward smaller scale details.

Zoomed current analyses are made for a few areas in the NW Atlantic in cooperation with the U. S. Coast Guard. These programs contain additional components, such as the mean hydro-clime of dynamic topography and the influence of the continental slope.

From the computed currents one can determine the change in SST which would be due to advection alone. Since the 'permanent' or thermohaline component would be nearly along the sea surface isotherms, the advective patterns should result primarily from atmospheric driving forces of synoptic scale. This approach is also used for verification and tuning of surface current analysis/forecasting programs, whereby analyzed SST changes, heat exchange, and mixing effects are compared to advectional effect quantitatively.

2.6 Other ocean analyses

It is difficult to separate functionally some of the meteorological analyses from oceanographic ones, such as energy (heat) exchange analyses and forecasts (Figure 16), fog analyses (Figure 17), and others.

Of greater oceanographic interest is the analysis of water type boundaries (Clarke and Laevastu, 1966). The subjective delineation of water type boundaries can be made by observing water color, surface temperature, salinity or current changes. However, sea surface temperature provides the best mean at present for synoptic numerical analysis of water type boundaries as described briefly at the end of chapter 2.1 (see Figure 7). Verifications of this product have given good results indeed.

The analysis of ice distribution and properties is nearly as old as the analysis/prediction of tides in the ocean. Ice observations are obtained from ships, aircraft and satellites. Due to limited areas and small amounts of data, the re-analysis can best be made manually. However, for ice forecasts, a multitude of auxiliary information, such as heat exchange, currents, etc., is required, which can only be handled satisfactorily on computers.

3. Forecasting of the ocean conditions

Forecasting of the conditions in the sea is based on the known behavior of these parameters in relation to the driving and modifying forces. Thus, the forecasts are primarily based on the forecasts of meteorological elements which change the distribution of properties in the surface layers of the sea and set it in motion, and on the analysis of the initial conditions.

The forecasting of Sea Surface Temperature (SST) is made by computing the heating or cooling from heat exchange. The heat exchange forecasts are based on meteorological forecasts. The additional heat or cooling is distributed throughout the turbulent, thoroughly mixed layer, the thickness of which is computed from wave forecasts and from convective stirring. This thickness does not necessarily coincide everywhere with Potential Mixed Layer Depth (MLD). In addition to above, the surface temperature is advected with the forecast surface currents. If the mixing of deeper water from below the MLD would affect the SST, this contribution is evaluated and added.

The Potential Mixed Layer Depth (MLD) is forecast with the same model as it is analyzed. The difference is that in the forecast the forward interpolation of climatology and the use of forecast sea surface temperature and forecast wave heights are used, and no BT's modify the forecast.

The verification of forecasts is done by comparison with subsequent analyses and observations. The accuracy in forecasts is obviously greatly dependent on the accuracy of the input meteorological forecasts. Sincle standard deviation values for overall accuracy are meaningless as the accuracy varies considerably in space and time, as well as with the scale of the analyses. As general limits of the accuracy, the following numbers could be presented:

Sea surface temperature	0.3 to 1.8°C
Temperature below thermocline	0.3 to 1.3°C
Mixed layer depth	20 to 50 feet
Wave height	1.5 to 4 feet
Current speed	0.1 to 0.4 knots
Current direction	10 to 50°

4. Future prospects

The future prospects fall into three different categories: (a) improvement of the network, codes and accuracy of maritime meteorological and oceanographic observations; (b) improvement of analysis and forecasting models, and (c) further application of the oceanographic forecasts to fisheries, navigation and long-term weather forecasts.

The last aspect is probably the most important. Besides the present naval applications, further demands for oceanographic analyses must be created by the economical application to fisheries problems. Fortunately, this application is making rapid progress in the United States and also in Europe. The use of oceanographic and heat exchange analyses in long-term weather forecasts is still only a subject of general talk. As is apparent from the brief descriptions given earlier, the further development and improvement of oceanographic analyses are dependent on the improvement and in-time extension of meteorological forecasts, which will largely be based on energy exchange considerations. Investigations in progress on these subjects at Fleet Numerical Weather Facility have yielded promising results indeed and it is anticipated that a numerical model for medium range forecasting will be operational in the near future.

Synoptic oceanographic observations are scarce indeed at present. However, the XBT, as a synoptic tool, is just making its entry. The available XBT data already demonstrate relatively large changes of temperature over short time intervals below 1000 feet in some areas, where such changes were not expected on the basis of earlier available data. Some additional information on the synoptic behavior of deeper thermocline and subthermocline layers has also been obtained with the XBT recently.

Futther development in maritime meteorological observations will come from automatic weather stations on shipboard. Considering the accuracy and instrumental reliability, the extensive use of buoys and satellites is still many years away, although experimental work on these means must be carried out now.

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Table 1

Difference between reported and analyzed sea surface temperature 12Z 21 March 1967

Temperature interval of	Number of reports
* > 10.5	151
+9.5+10.4	17
+8.5+9.4	27
+7.5+8.4	35
+6.5+7.4	21
+5.5+6.4	55
+4.5+5.4	86
+3.5+4.4	199
+2.5+3.4	345
+1.5+2.4	591
+0.5+1.4	1084
-0.4+0.4	2437
-1.4-0.5	870
-2.4-1.5	439
-3.4-2.5	232
-4.4-3.5	137
-5.4-4.5	88
-6.4-5.5	66
-7.4-6.5	39
-8.4-7.5	34
-9.4-8.5	20
-10.4-9.5	26
* >-10.5	155

Standard deviation	2.47°F
Probable error	1.66°F

*Remarks: The majority of these reports have errors in ship position and/or transmission and other gross errors. They have been excluded in computation of standard deviation.

Table 2

Standard errors in sea (wind wave) observations (after Verploegh 1961)

Wave height meters	Standard error meters
1.5	0.3
3.0	0.6
4.5	0.8
6.0	1.0
Standard error in wave direction	10° to 13°
Standard error in wave period	1.8 seconds

Table 3

Verification scores of sea height analyses and forecasts on 12Z 13 March 1967

WH VERIFICATION SCORES (SCORES IN FEET)

ANAL0 = ANALYSIS WH 12Z 13 MAR 67
ANAL12 = ANALYSIS WH 00Z 13 MAR 67
FCST12 = 12-HOUR FCST WH 00Z 13 MAR 67
ANAL24 = ANALYSIS WH 12Z 12 MAR 67
FCST24 = 24-HOUR FCST WH 12Z 12 MAR 67

	ANAL12 - ANAL0		FCST12 - ANAL0		ANAL24 - ANAL0		FCST24 - ANAL0	
	PILLOW	RMSE	PILLOW	RMSE	PILLOW	RMSE	PILLOW	RMSE
ENTIRE NORTHERN HEMISPHERE								
F1 SEA POINTS ONLY	+.2	+2.1	-.0	+2.0	+.1	+2.2	-.1	+2.3
DIVISION BY LATITUDE BANDS								
65N OR ABOVE	+.1	+.4	+.0	+.4	+.1	+.6	+.0	+.4
35N OR ABOVE, SO. OF 65N	+.1	+2.5	+.1	+2.4	+.0	+2.6	+.1	+3.0
20N OR ABOVE, SO. OF 35N	+.2	+1.7	+.0	+1.6	+.3	+2.1	+.1	+1.5
0 N OR ABOVE, SO. OF 20N	+.1	+1.1	-.1	+1.0	-.0	+1.1	-.2	+1.1
DIVISION BY SEA AREAS								
ATLANTIC, GULF OF MEXICO	+.2	+2.2	-.1	+2.0	-.2	+2.1	-.3	+2.3
PACIFIC	+.3	+2.1	+.0	+2.1	+.3	+2.4	+.0	+2.4
INDIAN OCEAN	-.1	+.4	-.1	+.4	-.1	+.6	+.0	+.6
MEDITERRANEAN	-.7	+1.8	-.4	+1.7	-.1	+2.4	-.4	+2.4

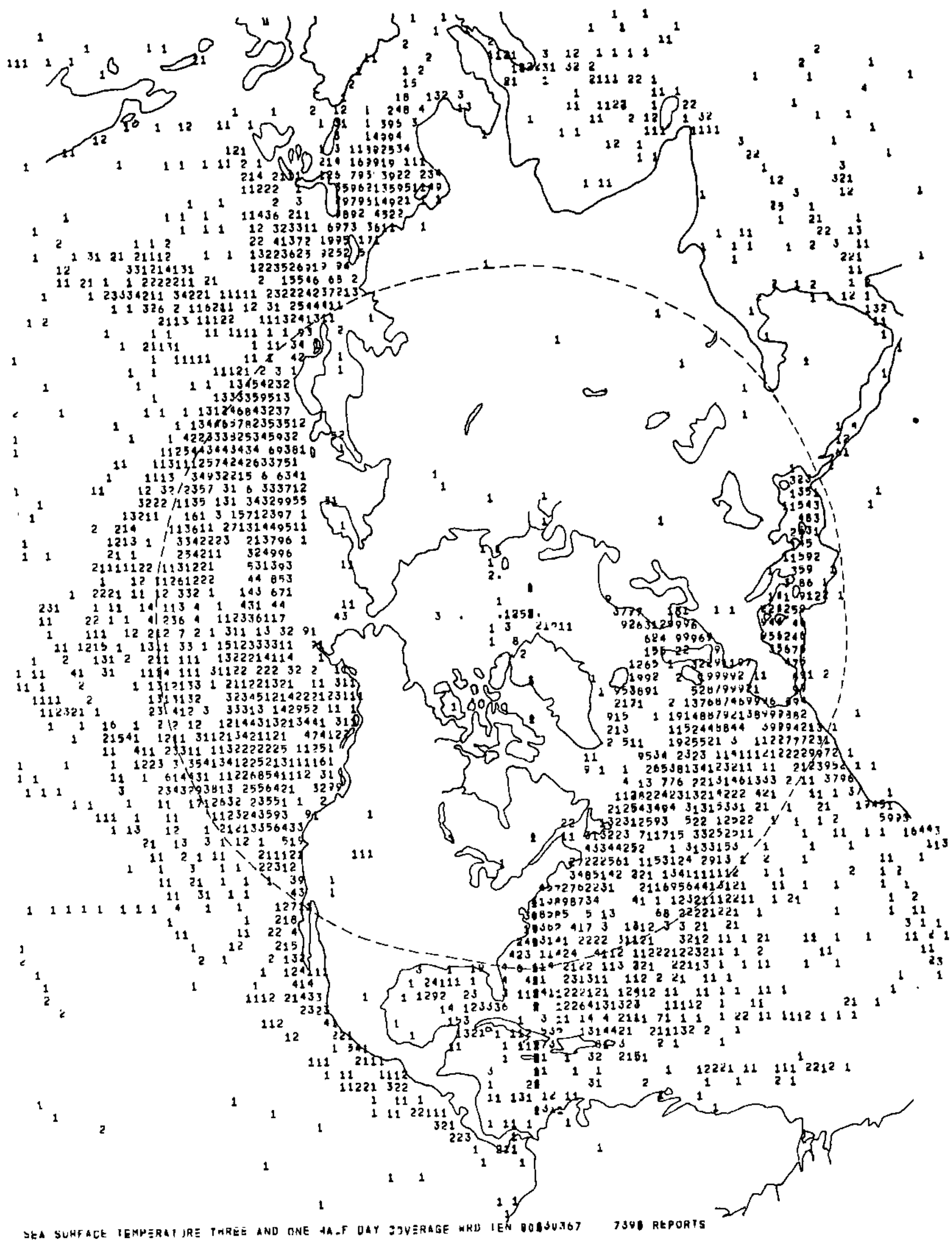

FIGURE 1 DENSITY OF SYNOPTIC SEA SURFACE TEMPERATURE REPORTS DURING THREE AND A HALF DAYS, PERIOD ENDING ON 00Z 13 MARCH 1967. THE NUMBERS ON THE CHART INDICATE THE NUMBER OF REPORTS UNDER THE AREA OF THE FIGURE. 9 MEANS 9 OR MORE REPORTS.

F 2

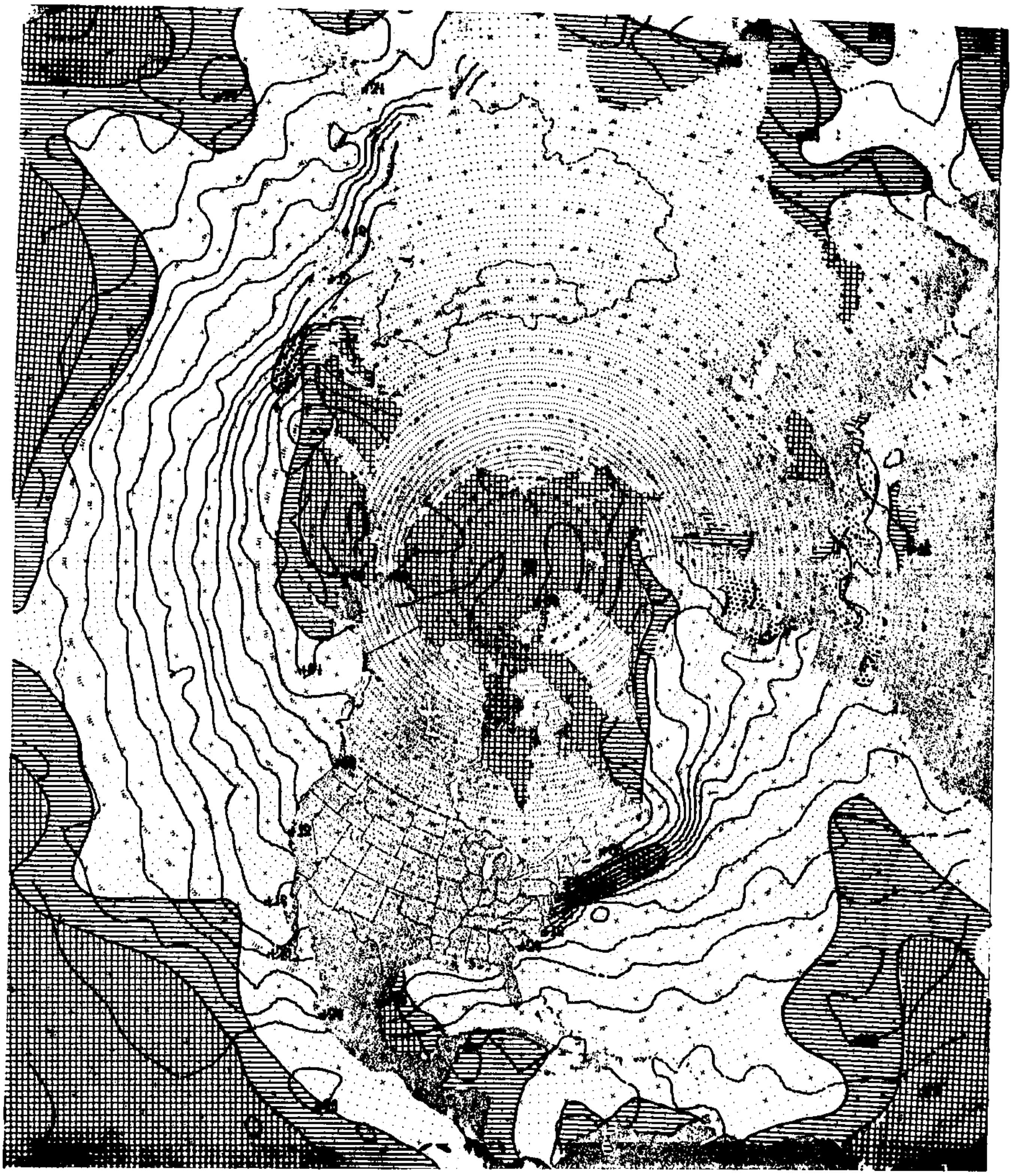

FIGURE 2 HEMISPHERIC SST ANALYSIS ON 00Z 13 MARCH 1967.

The areas where grid size is limiting the accuracy are dotted; areas where the accuracy is decreased by low data density are hatched and in cross-hatched areas the analysis is unreliable due to lack of synoptic data.

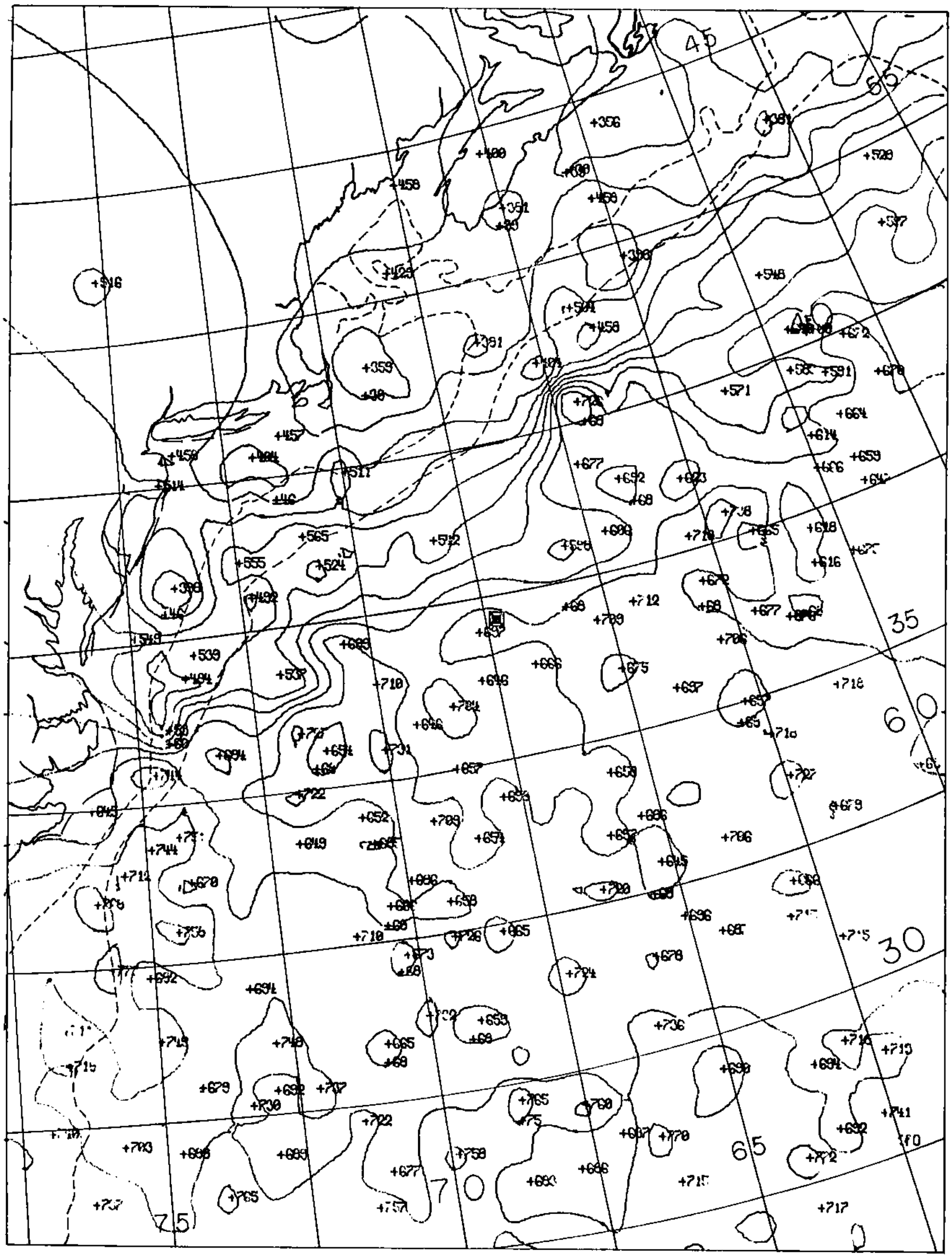

FIGURE 3 ZOOM ANALYSIS OF SST OFF EAST COAST OF UNITED STATES (NFK ZOOM) ON 00Z 21 JAN 1967.

F 4

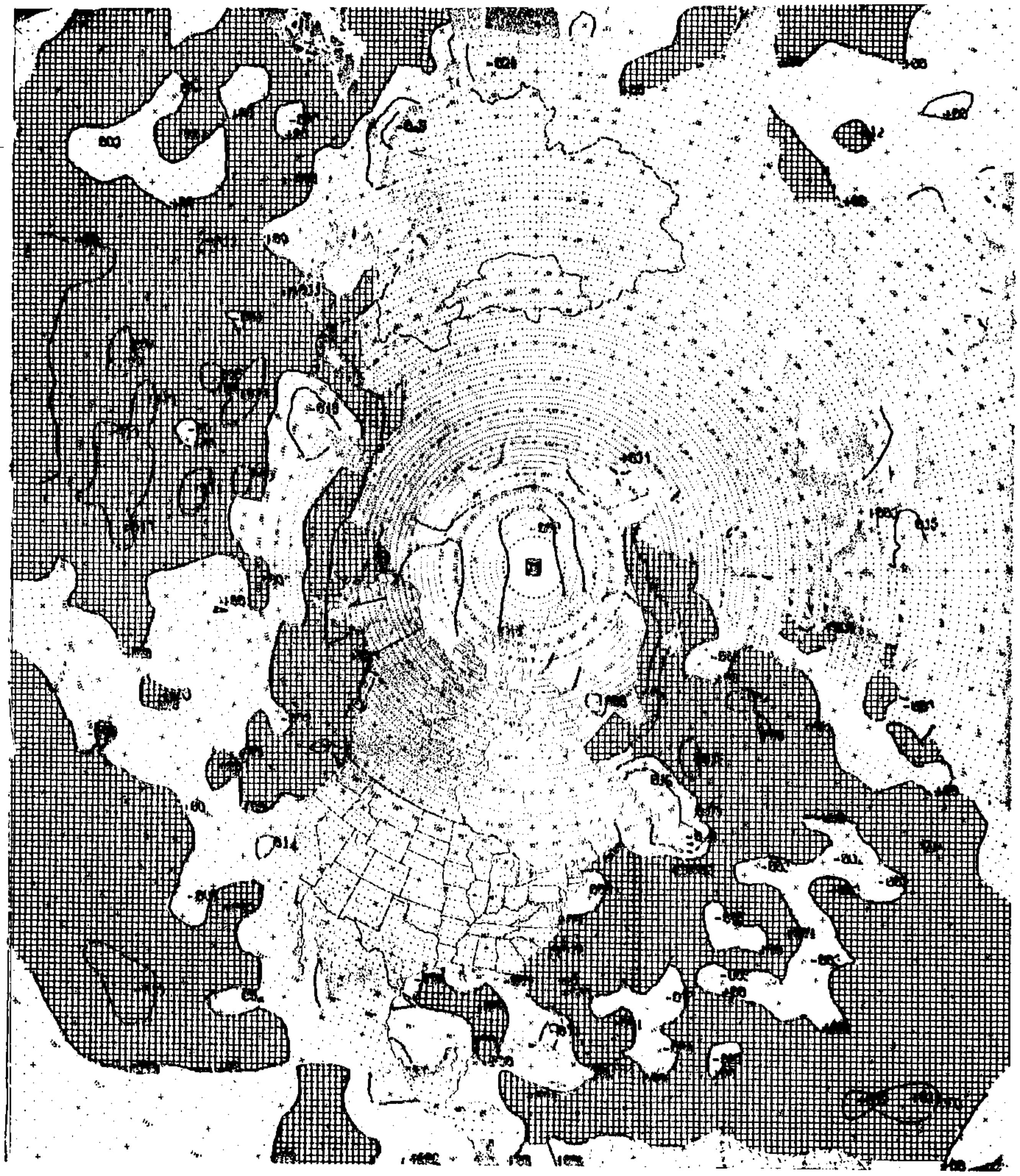

FIGURE 4 MONTHLY MEAN ANOMALY OF SST FROM LONG TERM MEAN, 1 TO 30 JAN 1967.

F 5

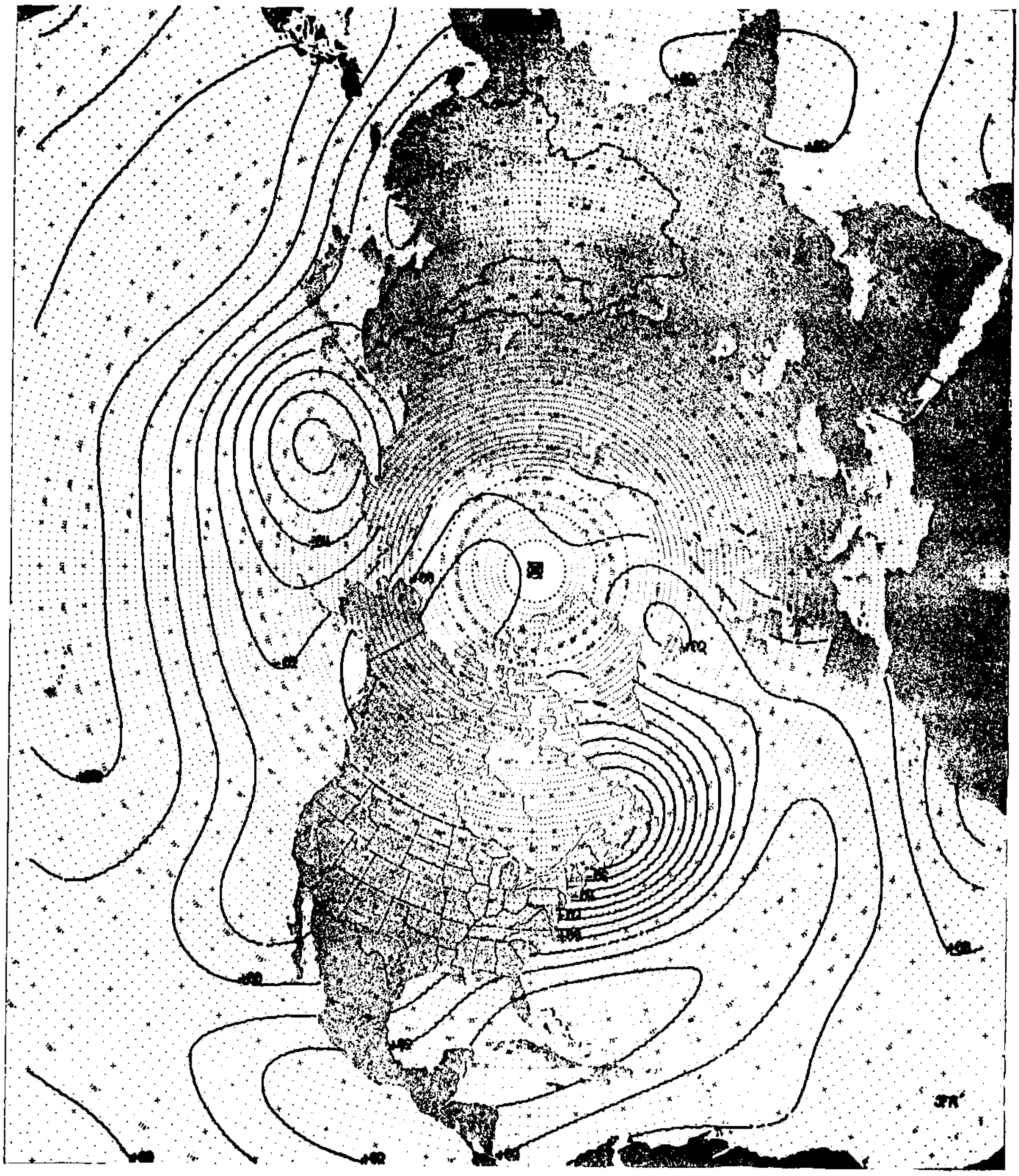

FIGURE 5 LARGE SCALE (9L) SST PATTERN SEPARATION (LATITUDINAL ANOMALIES) ON 00Z 13 MARCH 1967.

F 6

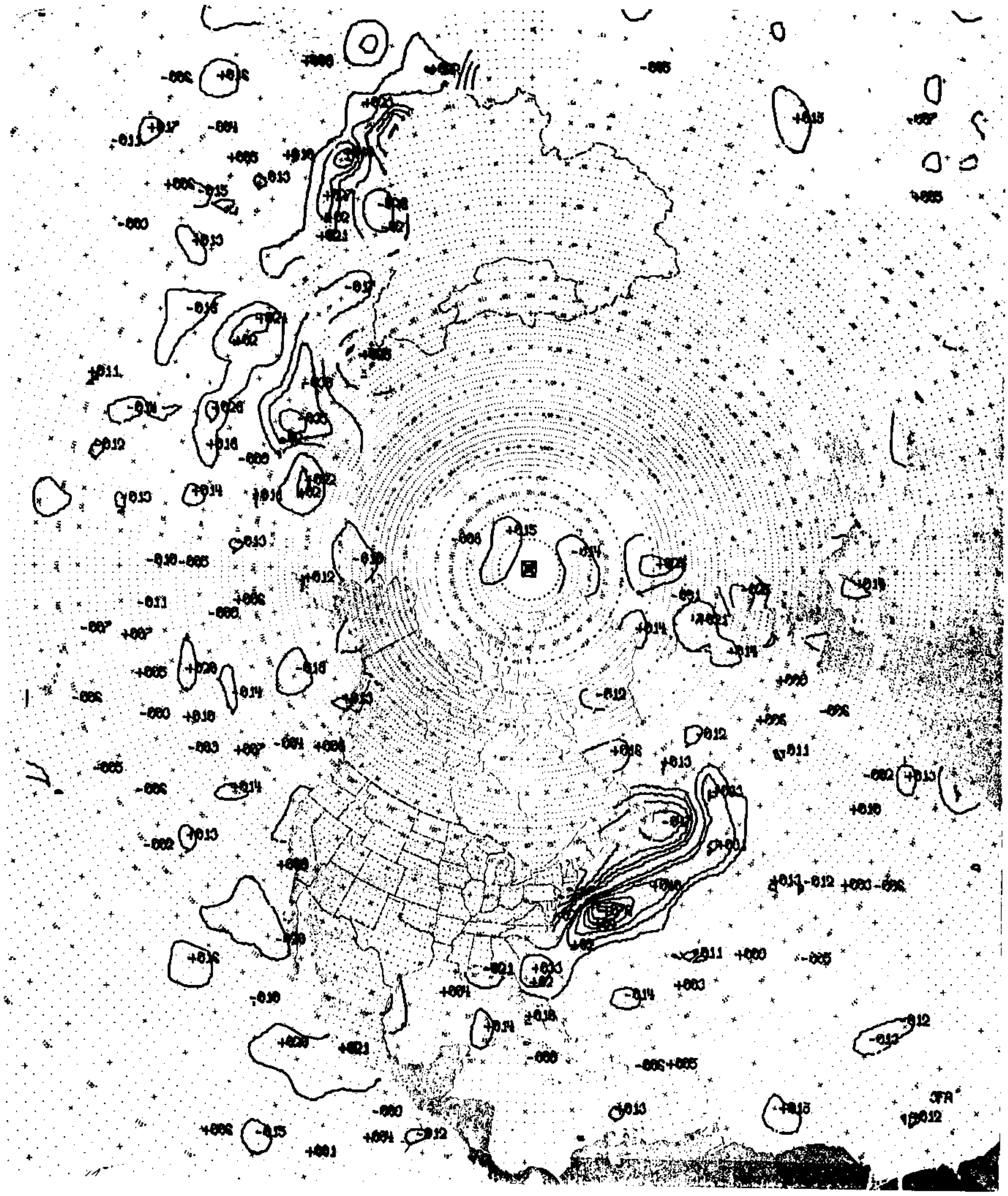

FIGURE 6 SMALL SCALE (SD) PATTERN SEPARATION (LATITUDINAL ANOMALIES) ON 00Z 13 MARCH 1967.

F 7

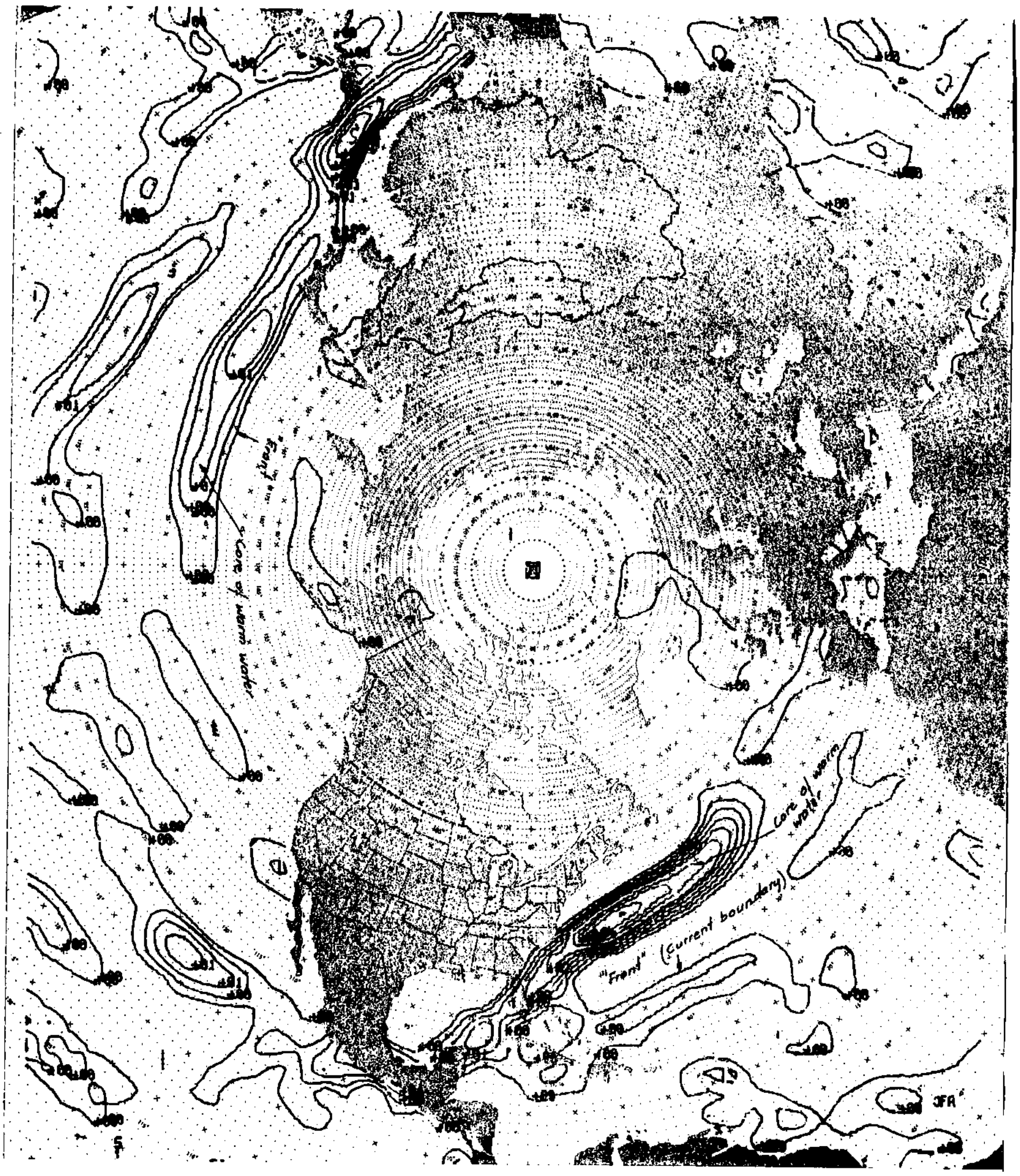

FIGURE 7 GG THETA (INDICATING CURRENT BOUNDARIES) ON 00Z 12 MARCH 1967. (DERIVED FROM SST ANALYSES.)

F8

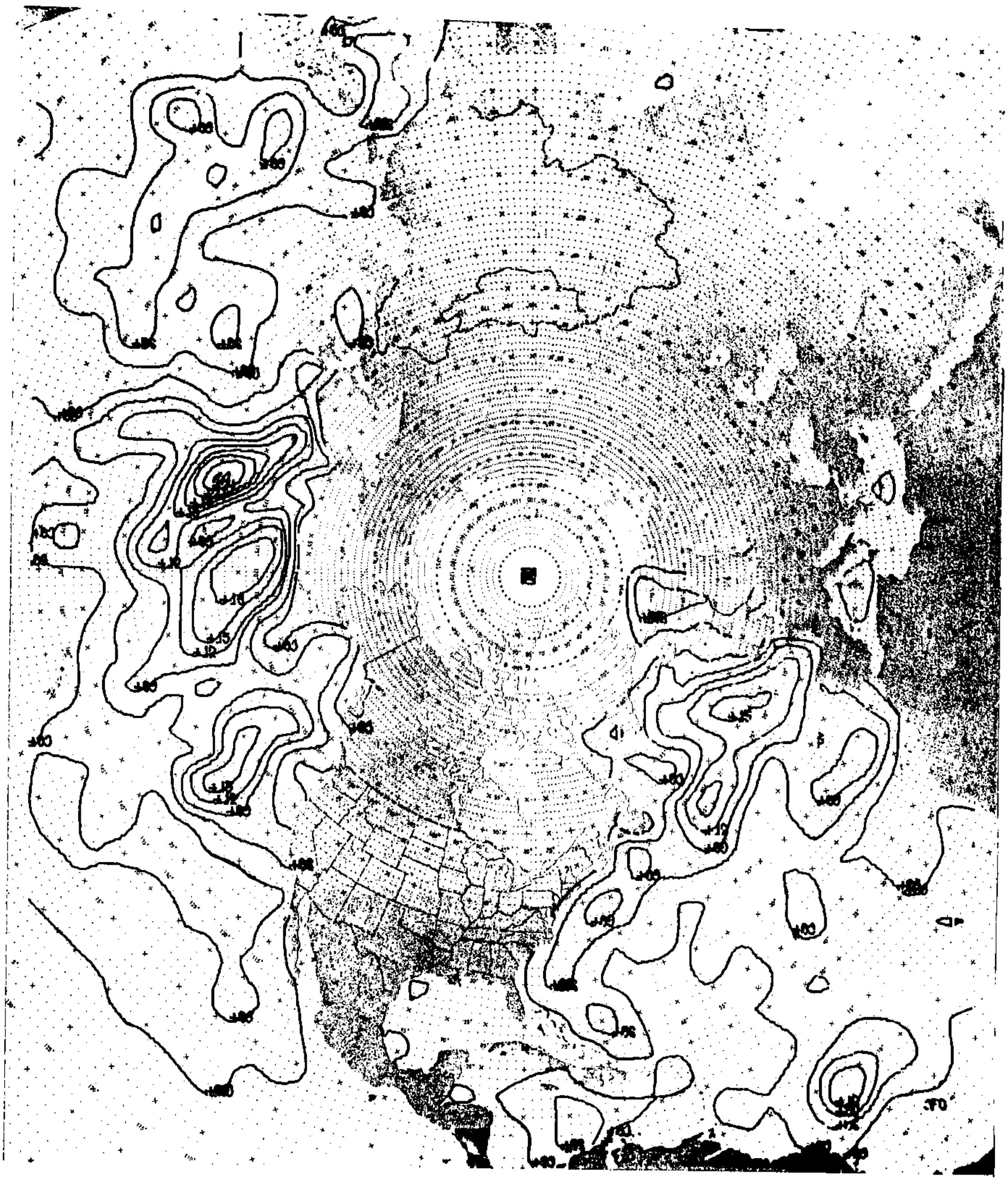

FIGURE 8 WIND WAVE HEIGHT ANALYSIS ON 00Z 13 MARCH 1967.

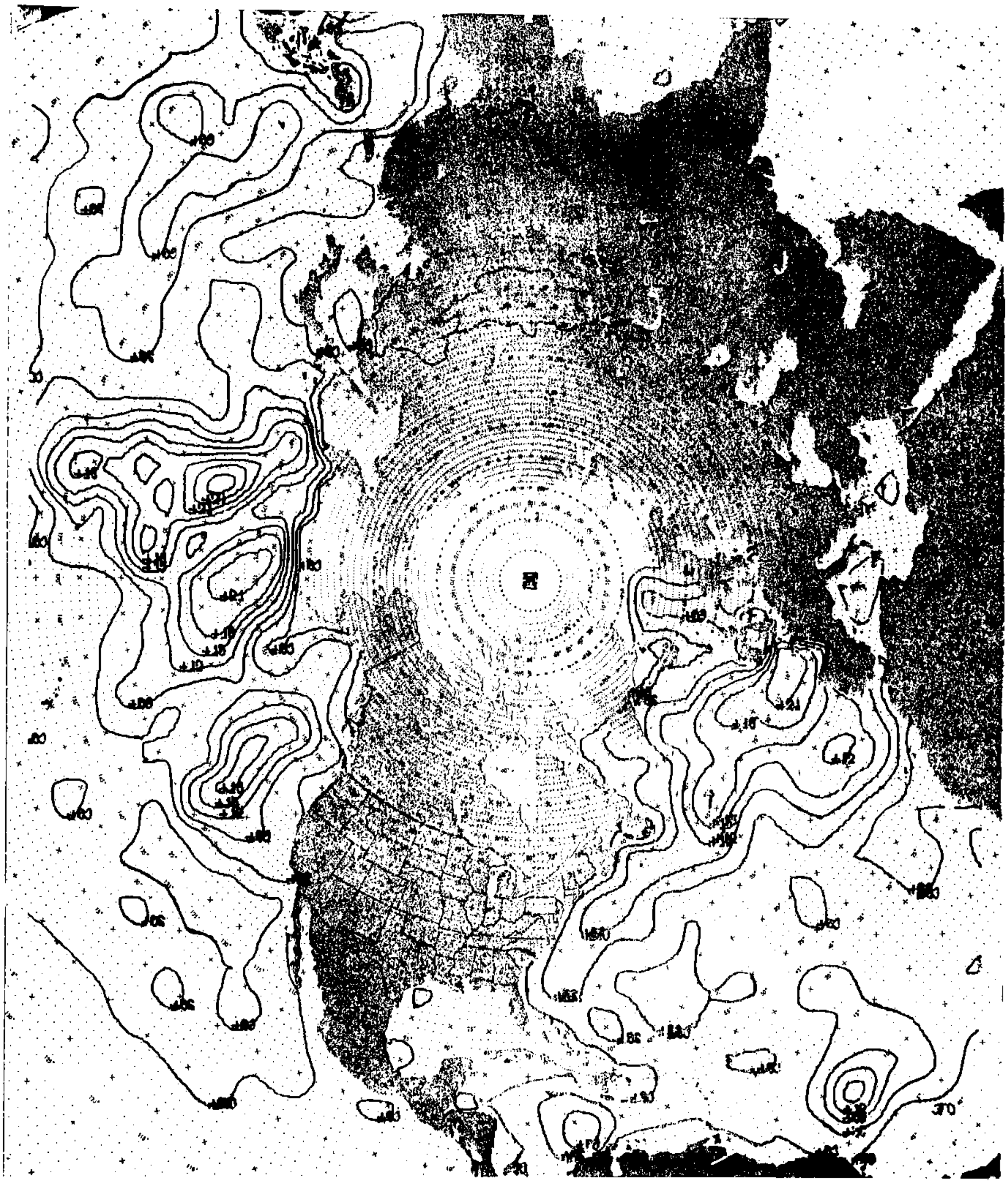

FIGURE 9 COMBINED SEA HEIGHT ANALYSIS ON 00Z 13 MARCH 1967.

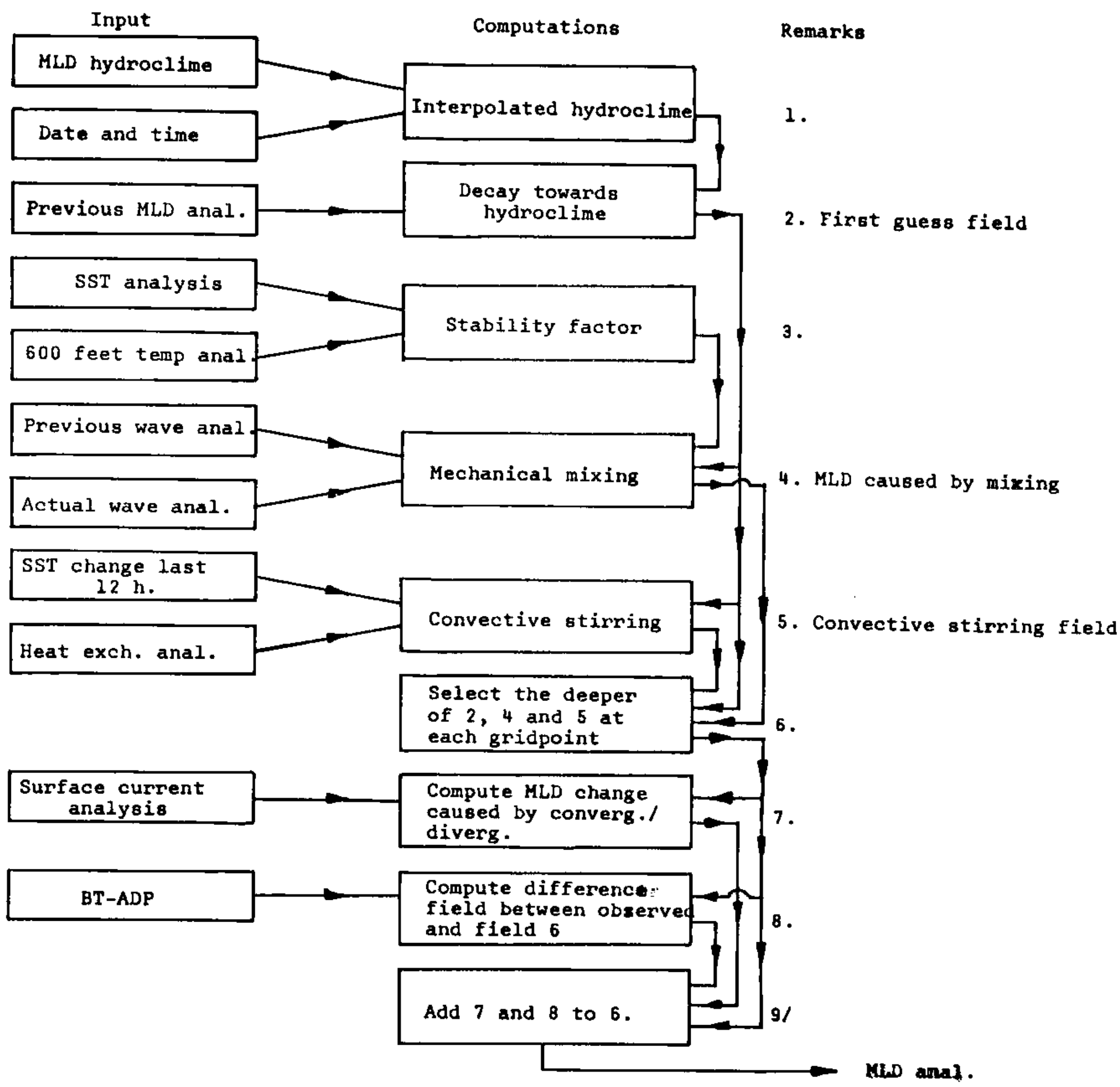

FIGURE 10 SIMPLIFIED FLOW DIAGRAM FOR NUMERICAL ANALYSIS OF MIXED LAYER DEPTH.

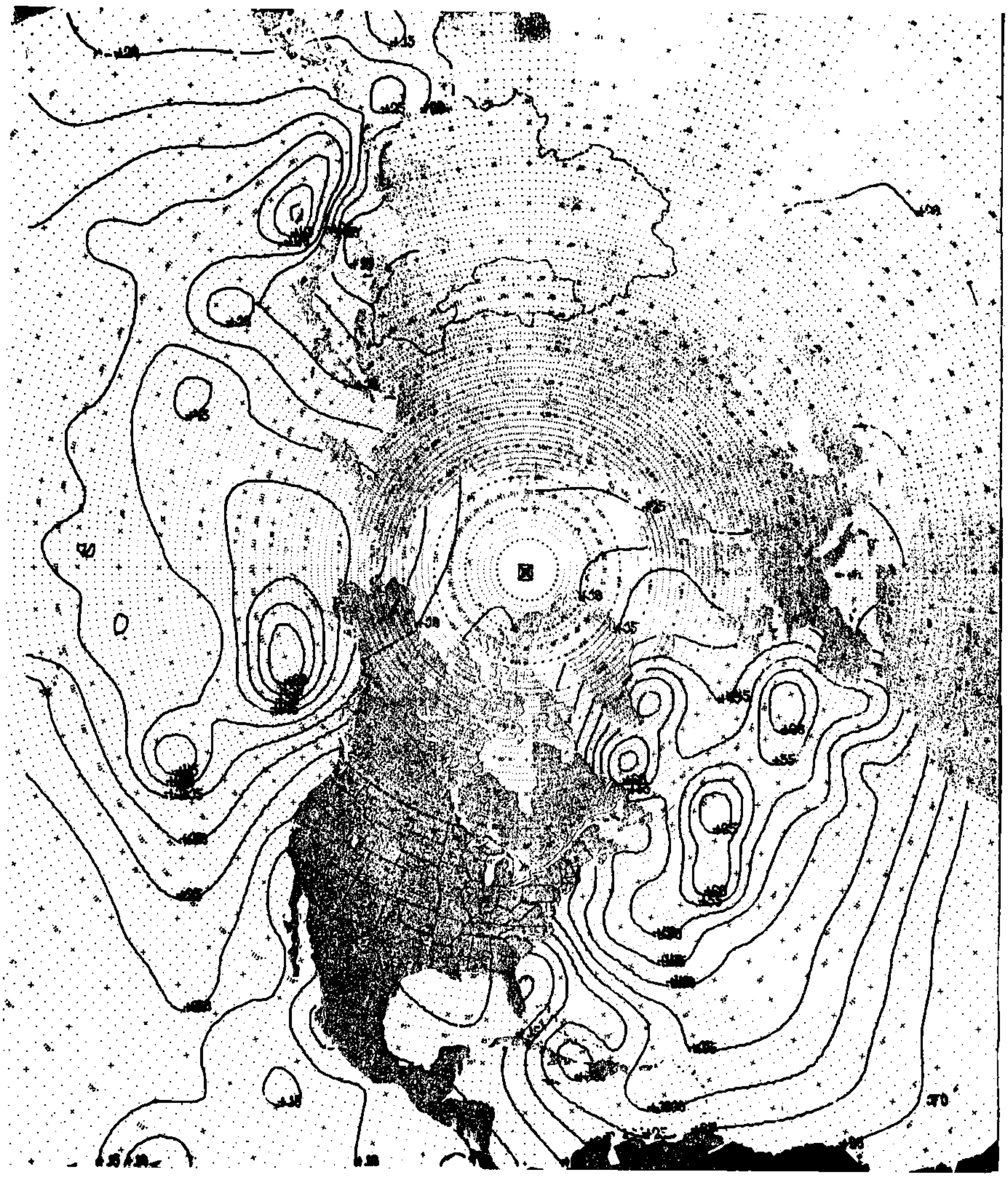

FIGURE 11 MIXED LAYER DEPTH ANALYSIS ON 00Z 16 MARCH 1967.

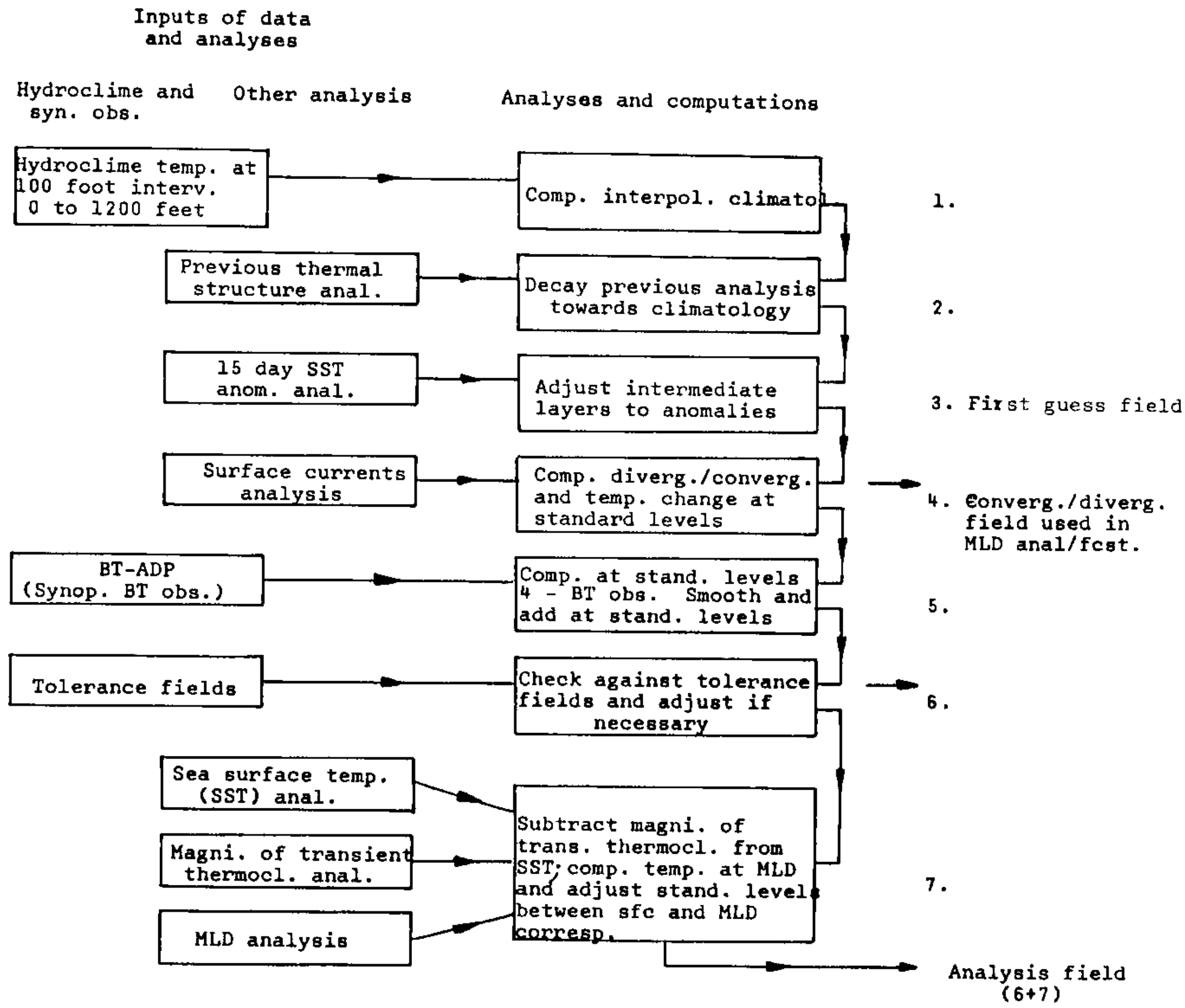

FIGURE 12A BASIC THERMAL STRUCTURE ANALYSIS SCHEME 0 TO 1200 FEET.

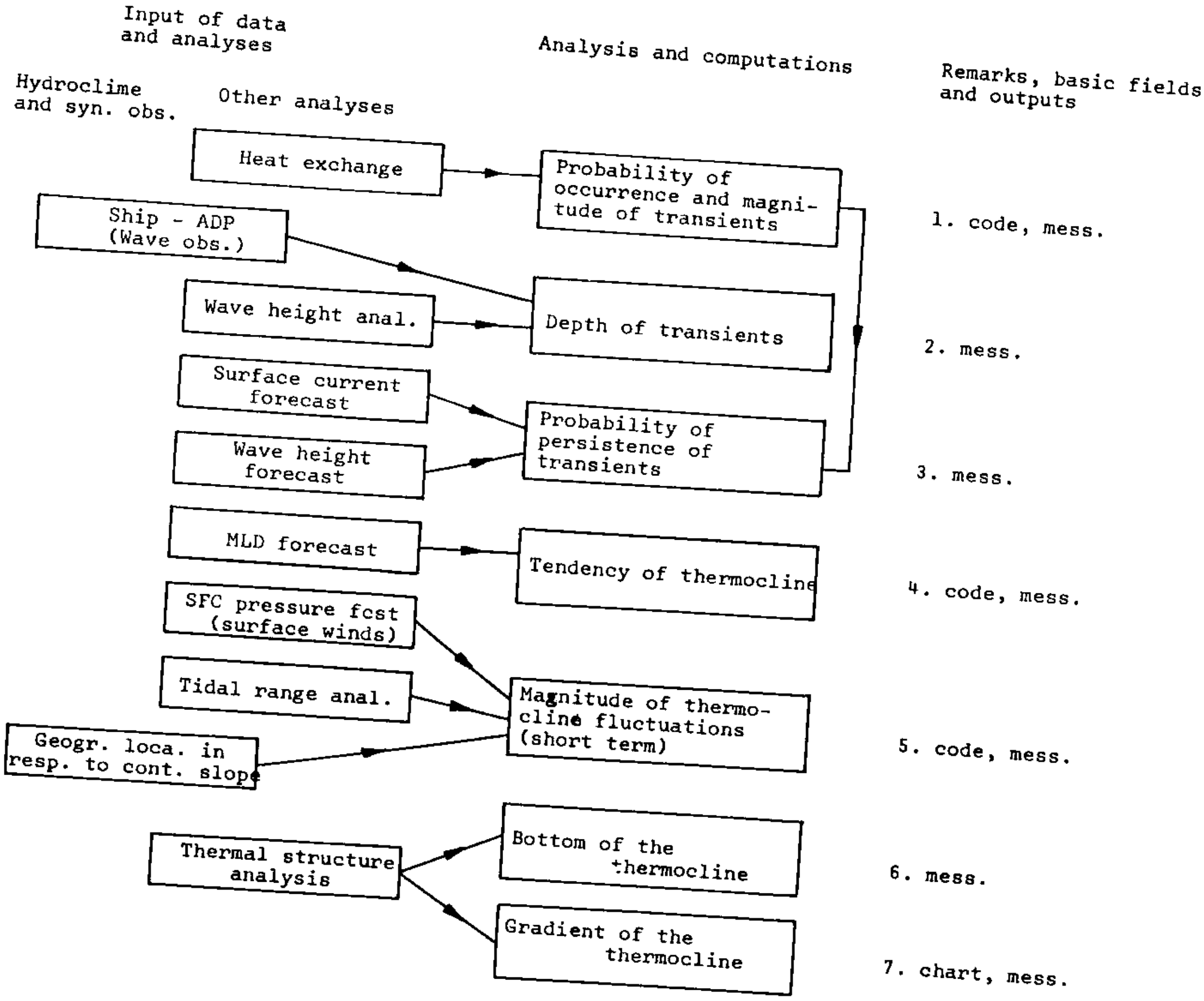

FIGURE 12B SCHEME FOR COMPUTATION OF ADDITIONAL PARAMETERS IN THERMAL STRUCTURE ANALYSIS.

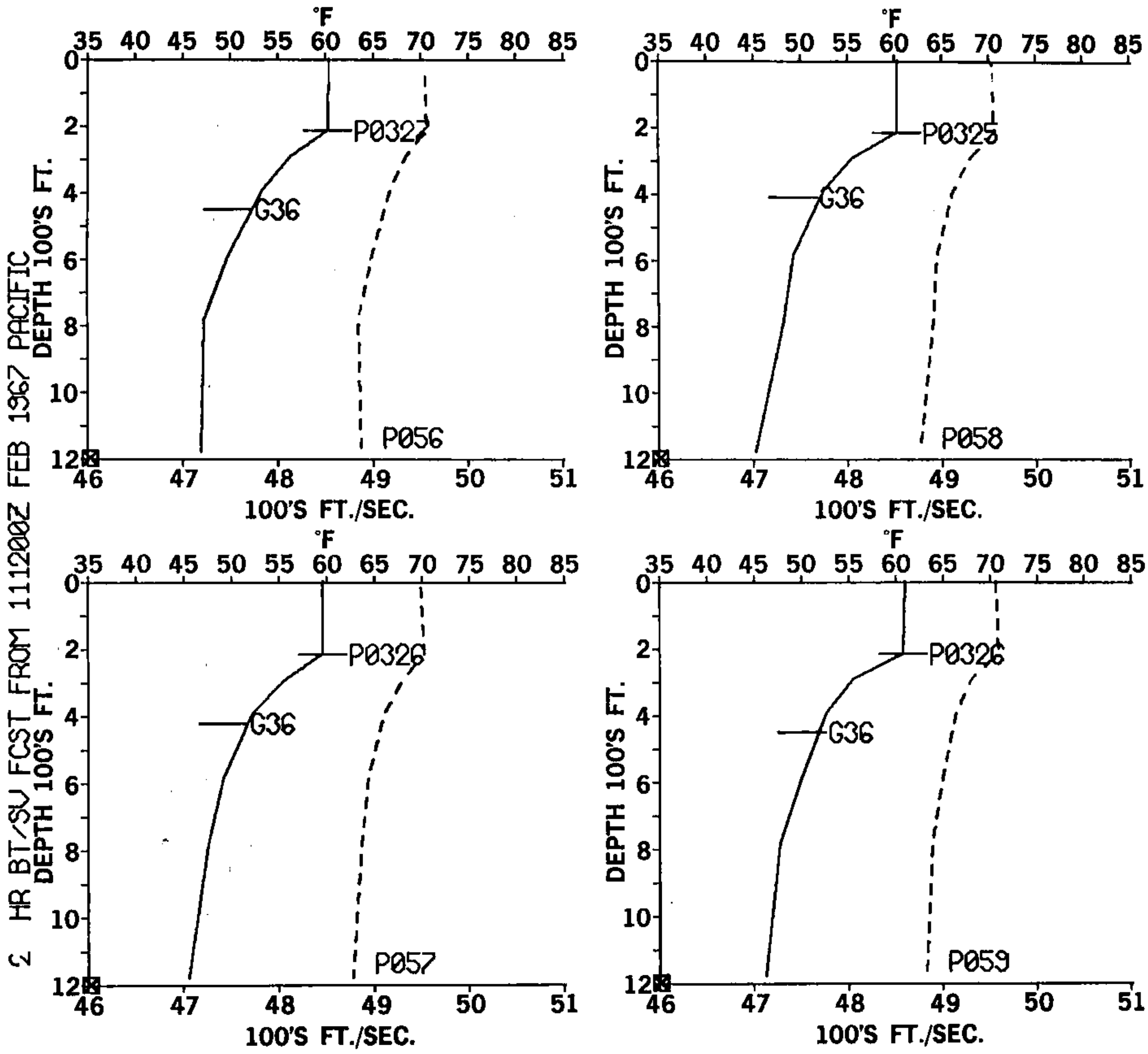

FIGURE 13 EXAMPLE OF SUBSURFACE THERMAL STRUCTURE FORECAST AT SOME CLOSELY SPACED LOCATIONS IN N. PACIFIC.

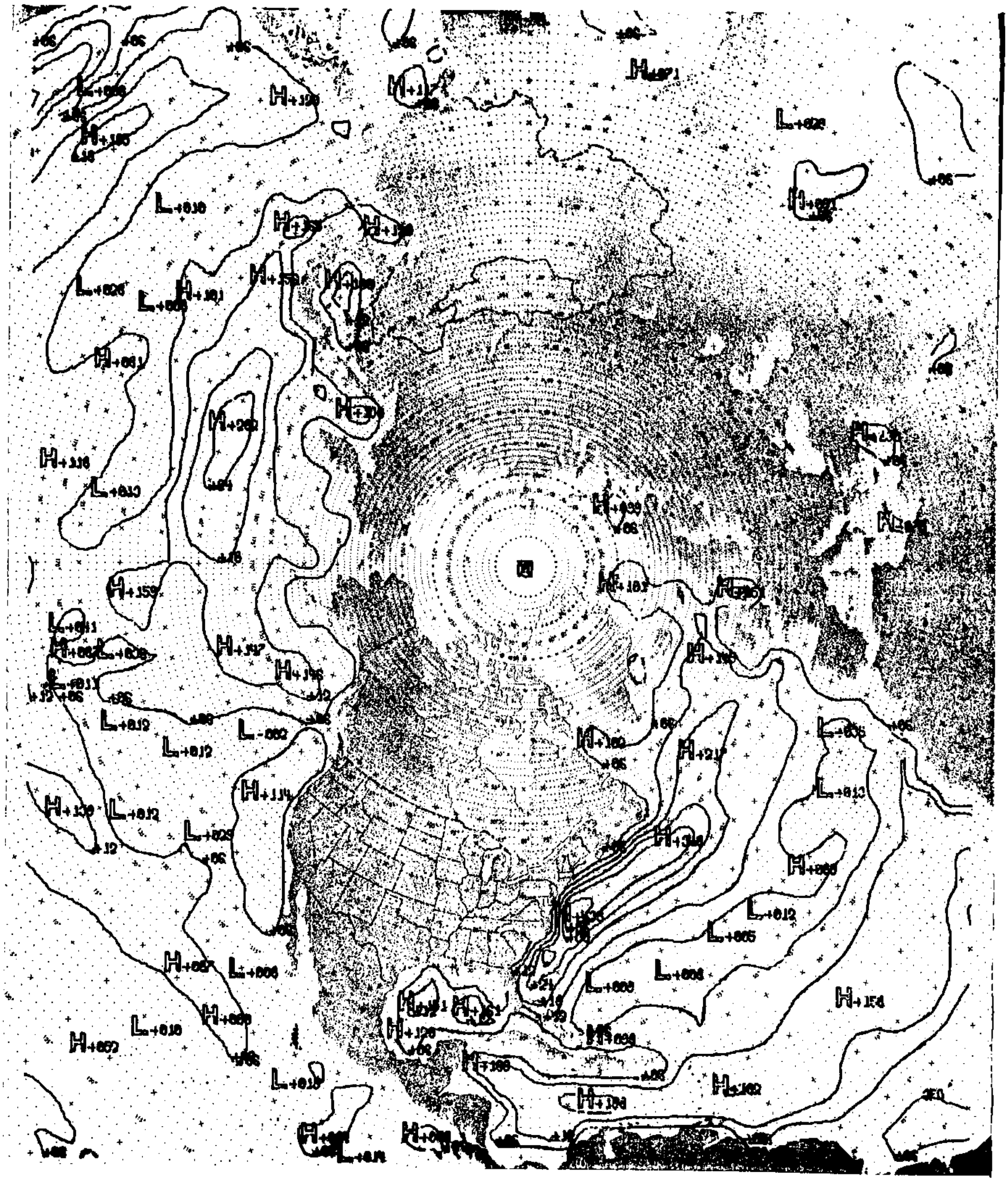

FIGURE 14 SURFACE CURRENT TRANSPORT (IN NAUTICAL MILES PER DAY) ON 12Z 6 MARCH 1967.

G 2

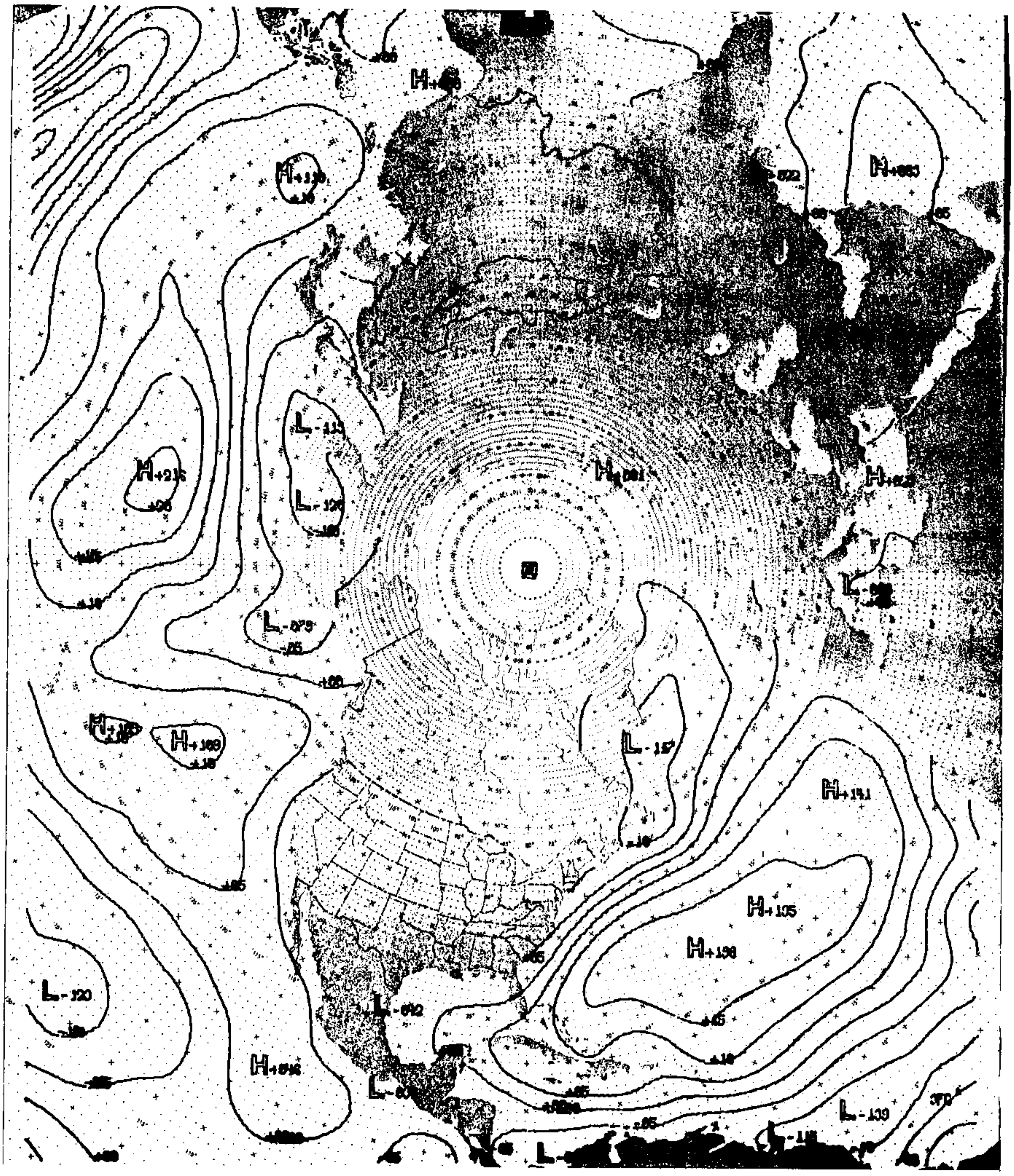

FIGURE 15 SURFACE CURRENT STREAM FUNCTION ON 12Z 6 MARCH 1967.

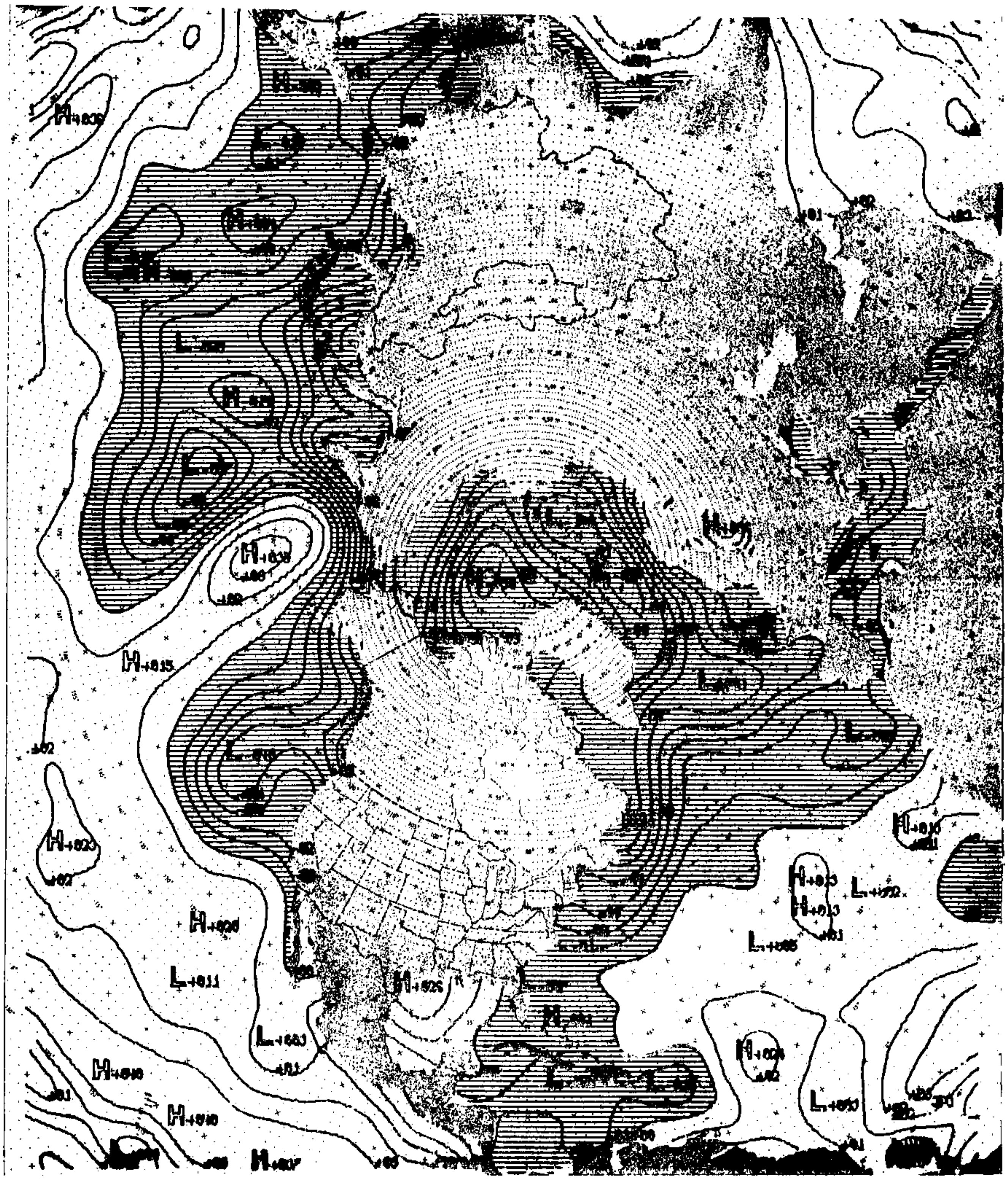

FIGURE 16 TOTAL HEAT EXCHANGE ON 00Z 13 MARCH 1967. (AREAS OF HEAT LOSS FROM THE OCEAN ARE HATCHED.)

FIGURE 17 36H FORECAST OF LOW VISIBILITY AND FOG PROBABILITY FROM 00Z 12 MARCH 1967.