DENDROCLIMATIC VARIABILITY IN THE AMERICAN SOUTHWEST

A.D. 680 to 1970

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INTRODUCTION

The variability of ring widths in tree-ring series from drought sensitive conifers in the semi-arid Southwest has long been known to contain a significant amount of information on climatic conditions that prevailed during the years in which the trees were growing (Schulman 1956). Long ring chronologies, constructed of ring series from many individual trees, provide data on annual variability in rainfall and temperature during the time spans encompassed by the chronologies. Recent research in the subdiscipline of dendroclimatology has produced a number of analytical techniques for extracting some of this climatic information from such tree-ring sequences (Fritts and others 1971; Fritts 1965, 1974). The many long ring chronologies derived from archaeological materials from various areas within the American Southwest provide a vast reservoir of information on past fluctuations in climate throughout most of the region. This resource of data on areal and temporal variability in climate over the past 1200 years remained largely untapped until the National Park Service sponsored the Southwest Paleoclimate Project from 1967 through 1971 and from 1975 through 1976.

The Southwest Paleoclimate Project enabled the Laboratory of Tree-Ring Research to construct a network of dendroclimatic tree-ring chronologies based on archaeological materials from several areas within the Southwest. A different research project, funded by a grant from the Advanced Research Projects Agency, permitted the collection of samples from living trees growing in all but one of the archaeological network station areas. Combining the archaeological chronologies with their modern counterparts produces a network with a time depth ranging from prehistoric times up to the present.

This specially-constructed network of dendroclimatic tree-ring chronologies provides a basis for reconstructing relative areal and temporal

variability in general climatic conditions during the last 1200 years. Such reconstructions are vital to an adequate understanding of the adaptations of prehistoric and historic plant, animal, and human populations to changing environmental conditions during the time period involved. The reconstructed variations in past precipitation and temperature can be compared with known events in the prehistory of the Southwest - migrations, abandonments, subsistence shifts, population changes, etc. - to estimate the possible effects of environmental changes on past human behavior.

The Southwest Paleoclimate Project undertook a reconstruction of relative climatic variability in the Southwest for the period A.D. 680 to 1969. This work involved several operations. First, paleoclimatic tree-ring chronologies were constructed from data already in hand and several additional chronologies were evaluated for dendroclimatic potential. Second, archaeological and modern ring series for each station were tested for compatibility and then combined into a single station chronology. Third, computer programming and debugging work necessary for the analysis of the chronologies was done. Finally, a series of maps that illustrate spatial and temporal variability in tree-growth, and therefore relative variability in rainfall and temperature, throughout the northern Southwest from A.D. 680 to 1969 was produced.

The analysis is based on a 25-station network of archaeological and modern tree-ring chronologies (Table 1) assembled by the Southwest Paleoclimate Project (Robinson and Dean 1969). The network represents the maximum achievable coverage of the region and ranges from the Natural Bridges area on the north to the Salt River on the south and from the Coconino Plateau on the west to east of the Rio Grande. Each station chronology has been constructed so as to contain a maximum of dendroclimatic information and to represent the tree growth of a fairly restricted, environmentally homogeneous area.

The development of climatic chronologies such as these differs in many respects from the construction of dating chronologies. Individual specimen components are carefully screened to ensure that only those with a high probability of containing a large proportion of climate-related variance are included. Statistical parameters that characterize the ring series of living climate-sensitive trees in the Southwest provide the criteria for specimen selection. The parameters considered include the nature of the growth trend and the mean, standard deviation, mean sensitivity, and autocorrelation of the ring-width indices. This screening process eliminates specimens that, though they date, owe much of their variance to factors other than climate. Insofar as possible, only specimens with more than 100 measured rings are used in these chronologies in order to minimize potential growth trend and long-term variation problems that often accompany the use of short ring series.

Each chronology in the network is developed for the maximum possible number of years, depending on the availability of suitable specimens from the area involved. Nearly half of the chronologies have been augmented by samples from living trees and span from around 1500 to nearly 2000 years

Table 1. List of Stations.

Station	Coordinates		Interval (Yrs.A.D.)
1. Natural Bridges	37-37	110-00	0094-1971
2. Navajo Mountain	37-05	110-45	0340-1271, 1469-1971
3. Tsegi Canyon	36-45	110-30	0381-1970
4. Coconino Plateau	35-25	112-15	0610-1124, 1448-1975
5. Flagstaff	35-15	111-30	0570-1972
6. Central Mtns., North	34-15	110-10	0965-1381, 1596-1972
7. Central Mtns., South	33-50	110-40	1096-1385, 1642-1971
8. Hopi Mesas	35-50	110-25	0500-1971
9. Puerco River, West	35-25	109-25	0426-1283, 1512-1972
10. Canyon de Chelly	36-10	109-25	0001-1316, 1376-1971
11. Mesa Verde	37-10	108-30	0480-1971
12. Chuska Valley	36-20	108-45	0532-1262
13. Cibola	35-20	108-30	0435-1972
14. Quemado	34-25	108-30	0441-1282, 1490-1972
15. Cebolleta Mesa	34-50	107-45	0680-1972
16. Chaco Canyon	36-05	107-55	0660-1127, 1381-1972
17. Gobernador	36-45	107-30	0623-1971
18. Jemez Mountains	35-40	106-30	0598-1972
19. Chama Valley	36-17	106-32	0759-1972
20. Rio Grande, North	36-15	105-40	1104-1972
21. Santa Fe	35-42	105-50	0878-1972
22. Chupadero Mesa	34-25	106-10	1294-1648, 1656-1972
23. Durango	37-14	107-35	0034-1089, 1330-1971
24. Reserve	33-45	108-45	0578-1286, 1520-1967
25. Little Colorado	34-22	109-27	0916-1345, 1687-1973

continuously back from the present. Others cover only a part of this time range, and some have gaps in periods not represented by either modern or archaeological tree-ring material.

In building each of these chronologies every effort was made to use specimens from sites distributed over a limited, environmentally uniform area, under the assumption that the builders of the sites did not venture any farther afield than necessary for constructional wood. Naturally, the geographic area represented by each chronology varies in response to the differential spatial and temporal distributions of sites from area to area and to the availability of tree-ring samples from the sites.

Ideally, all 25 chronologies in the network should be constructed from the same species of tree. This, of course, is impossible given the geographic distributions of the various species throughout the Southwest, the selective use of species by the prehistoric peoples involved, and the vagaries of archaeological excavation and preservation. In a few cases it was possible to build an entire station sequence from a single species, but the species involved differ from station to station. Other chronologies are comprised of ring widths from two or more different species. This limits our network analyses to statements about those aspects of climate that affect the growth of all species and prohibits consideration of more specific information that can be derived from the analysis of a single species or of paired species.

Quantitative data accumulated during the Laboratory's comprehensive review of all Southwestern archaeological tree-ring samples in its possession (Robinson, Harrill, and Warren 1975:1-2) were used in the construction of the climatic network chronologies. As a routine part of the review project, the ring widths of representative samples from nearly every site were

measured to the nearest 0.01 mm. These data were analyzed by a computer program (Fritts, Mosimann, and Bottorff 1969) that transforms them to standardized growth indices and calculates the statistical parameters of each ring series.

Standardized indices are produced by fitting a negative exponential curve to the sequentially arrayed ring-width values for each specimen and then calculating the percentage departure of each ring-width value from the value of the trend line at that point. This produces a set of indices with a mean of 1.00 and a standard deviation unique to each individual series. Standardization enhances the amount of climate-related variance in each ring series by removing several variables, notably the growth trend and mean ring width, that are related to factors peculiar to the growth of individual trees rather than to external climatic conditions. The statistical parameters of the standardized data are used in the manner previously described to select specimens for inclusion in the climatic chronologies. The indices of the individual specimens chosen to represent a station are averaged to produce each of the 25 climatic sequences that comprise the network. Although each index chronology has a mean of 1.00, the standard deviations of the indices differ from station to station.

The network of tree-ring chronologies provides a basis for reconstructing past climatic fluctuations in the northern Southwest for any time interval represented by an array of stations that encompasses the entire region. These reconstructions are accomplished by computer programs that calculate standard normal deviations from mean growth at each station, plot the values on a map of the region, and contour the array with isopleths representing equal positive and negative departures from the station means.

The standard normal deviation of one increment within a tree-ring chronology is calculated by subtracting the chronology mean from the growth index involved and dividing the result by the standard deviation of the chronology. Carried out for the entire length of the chronology, this operation produces a sequence with a mean of zero and a standard deviation of one. This procedure reduces the variability of each chronology to an identical scale so that they can be legitimately compared to one another. In order to achieve an average departure from the mean for a decade, the ten standard normal deviation values for the decade are each multiplied by a constant ($10\sqrt{n}$, where n=10), and the results are summed algebraically and divided by 10n. This process produces a decade departure value expressed in terms of standard deviation units. For example, a value of +2 indicates that the departure average for the decade involved is two standard deviations above the mean for that particular chronology. The ten-year departures are plotted on a map of the Southwest and contoured in standard deviation unit intervals by CONTOUR, a program developed by this project (Appendix 1). The maps produced by this program (Appendix 2) give a graphic display of the spatial and temporal distributions of deviations from average growth throughout the Southwest. Variation that exceeds two standard deviation units in either direction is considered to be significant in the sense that such departures are sufficiently rare to have had potential adaptive consequences for plant, animal, and human populations. Thus, we are interested in those values that lie outside the range of 95% of the variability about the mean. It is important at this point to make explicit exactly what these contour maps are intended to show and what their limitations are. Each local tree-ring chronology in the data network represents the variation of annual tree growth around the mean growth for that station. Statistical and physiological studies show

that tree growth is highly correlated with certain climatic variables, primarily precipitation and temperature. Therefore, we can consider each local chronology to be a good estimate of past fluctuations in rainfall and temperatures at that locality. The inclusion of several different species in the network chronologies limits us to statements about those climatic variables that effect the growth of all the species involved. In practice, this means that we are dealing with the combined effects of annual precipitation and temperatures at each station. The maps, then, represent changing spatial patterns of variations in tree growth, and therefore yearly rainfall, throughout the Southwest during the period of analysis. Positive departures indicate greater than normal rainfall and lower than normal temperatures; negative departures reflect lower than normal precipitation and above normal temperatures.

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Appendix 1

Program CONTOUR

I. DESCRIPTION

CONTOUR is a computer program designed to produce a two-dimensional contour map of any set of spatial data given in Cartesian Coordinates. It is written in FORTRAN for use on the CDC 6400 in conjunction with the 665 Calcomp digital-pen plotter.

The CONTOUR program was constructed to allow for an economical means of generating a number of digital-pen plotter maps in a format suitable for publication. To this end, CONTOUR has been broken down into the following discrete divisions: data and parameter input, map generation, grid generation, statistics output, and, finally, contour generation.

A. DATA AND PARAMETER INPUT

This routine, through card input, reads all mapping directives and parameters for program control, map labeling grid and contouring, and data entry. All CONTOUR control cards are described in the General Instructions section.

In the event of illegal control cards or erroneous parameter entries, the program is aborted. Otherwise control is transferred to the next routine.

B. MAP GENERATION

In this routine all labels of the contour map not directly related to the contour lines themselves are generated and plotted as specified by the previous parameter routine. Among the available options are: a map outline, tic marks on the outline, boundary labels at the corners of the outline, a map title, and plotting of individual data points. If the combined size of the map and these options remain within the physical limits of the plotter (eleven inches in the y-direction) control is transferred to the next routine.

C. GRID GENERATION

Here the processing of the original data matrix begins. The original raw data are mathematically weighted and transformed into a grid matrix which is compatible with the contour generating routine. The size of the grid is decided at parameter input time. As the number of grid points increases, so does processor time, cost, and quality and refinement of the map.

D. STATISTICS OUTPUT

At the option of the user, all program information may be printed. This information will include all parameters, data, and data matrices generated by the program. This option is decided upon at user input time.

E. CONTOUR GENERATION

The final routine takes the data matrix generated by the gridding routine and creates a series of line segments between the grid points for all specified contour intervals. These represent the actual contour lines. Contour labels are also generated at this time. Upon termination of the plot, control returns to the parameter and data input routine for the next logical record of input if further plotting is desired. If no additional input is encountered the program terminates normally.

II. GENERAL INSTRUCTIONS

All parameters are passed to CONTOUR through card input. Unless otherwise stated, parameter cards may assume an arbitrary order. Data may be input on cards or via an external (disk or magnetic tape) file with the explicit local file name "DATA."

All information is passed to CONTOUR through use of keywords.

Information is passed in single card sets. Keywords may use not more than one field (alpha, decimal, or integer) for passing information.

NOTE: ALPHA FIELDS MAY CONTAIN ANY COMBINATION OF CHARACTERS.

DECIMAL FIELDS MAY CONTAIN ONLY NUMBERS WITH A DECIMAL POINT AND OPTIONAL MINUS SIGN.

INTEGER FIELDS MAY CONTAIN ONLY NUMBERS, RIGHT ADJUSTED, WITH AN OPTIONAL MINUS SIGN.

FIELDS NOT USED SHOULD BE LEFT BLANK.

Most input parameters have default values. Currently these values are set for compatibility with Tree-Ring Lab research. All parameters, however, may be changed at run time. Parameter default values are explicitly stated in the following pages.

III. CONTOUR CONTROL CARDS

All input may be classified into one of four categories: program control, map labeling, grid and contouring, and data entry.

A. PROGRAM CONTROL

Currently there are three Program Control cards. Two control printer output of parameters and data for documentation of individual plots. The third, SAVE LAST RUN, allows the user flexibility to retain all parameter information from the run directly proceeding this run. If this is the first run the card is ignored. If this card is not entered, all parameters return to their default values.

NOTE: This card must be the first in the set of control cards for this plot. If the card occurs elsewhere in the input stream, CONTOUR will fail to recognize it and abort the job.

After this card has been specified, any legal control cards may follow. This allows the user to decide which parameters he wishes to save and which he wishes to override.

KEYWORD	FIELD	DEFAULT
PRINT PARAMETERS	none	selected
SUPPRESS PRINTING	none	not selected
SAVE LAST RUN	none	not selected

B. MAP LABELING

1. Size of plotting surface

The first order of business is to describe the dimensions of the plotting area. Length is specified with the X AXIS LENGTH control card; height with the Y AXIS LENGTH control card.

2. Map boundaries

The following options are available:

a) Outlining of the plotting surface is controlled with either of the following control cards: OUTLINE; NO OUTLINE. Deselecting this option automatically deselects the tic mark and corner boundary options. This cannot be overriden.

b) The user may specify that tic marks be placed along either or both axes of the map outline at various intervals. The following options are available: TIC MARKS; NO TIC MARKS; TICS ON X AXIS; TICS ON Y AXIS.
The first of these directs CONTOUR to use the default values. The latter two allow the user to select his own intervals. Count only those tics which actually appear on the line. Tics are never made at corners. Example: For a tic to be plotted every two inches on a ten inch axis, specify four tics.

c) Corner boundaries optionally allow the user to have the maximum and minimum X and Y values displayed at the outside corners of the outline. A special option exists to suppress negative symbols of these labels (useful when using latitude and longitude in the western hemisphere). The minimum and maximum values are taken from the MAXIMUM X VALUE, MINIMUM Y VALUE, etc., cards as described in the data entry section which follows. BOUNDARIES; NO BOUNDARIES; SUPPRESS NEGATIVE BOUNDS; HEIGHT OF BOUNDARIES.

d) A title up to twenty characters in length may be plotted below the map. Centering of the title is automatic. TITLE; CHARACTERS IN TITLE; TITLE HEIGHT.

e) Data points may be indicated on the plot by either an optional symbol or individual magnitues (Z values). In choosing a symbol, any as described in the University of Arizona Computer Center Plotter Manual under subroutine SYMBOL defined as special characters, are available. Only one symbol may be used to define all points. DATA PTS LABELED; NO DATA POINTS; DATA PT. CHARACTER.

3. Intra-plot labeling

The magnitude of contour lines may be labeled. This is similar to labeling of elevation as seen on a standard USGS topographical map. The frequency of this labeling may also be changed. A USGS map labels every fourth contour line. This would be done in CONTOUR by using the keyword LABEL 1 CONTOUR OF with a parameter value of four. The square of the distance between any two labels on a given single contour line is set with the DISTANCE BETWEEN LABELS card. LABEL EVERY CONTOUR; LABEL 1 CONTOUR OF; DIGITS IN CONTOUR LABEL; DISTANCE BETWEEN LABELS; LABELS HEIGHT.

C. GRID AND CONTOURING

This section is by far the most important step in producing the plotted output. It is here that the user has the flexibility to create a map which represents a true illustration of his data or merely an image distorted in various ways due to inequities in the gridding technique. Recall that a grid matrix was to be generated from the original data. First, the size of the grid matrix must be chosen. This is done by specifying the GRID DISTANCE, the distance between any two given consecutive grid points. For example, if the plotting surface were 12 inches by 10 inches, one might choose a grid matrix of 25 X 21. This would give a grid point every one half inch and thus 0.5 would be specified as the grid distance. Another parameter which should be considered at the same time is LIMIT OF RADIUS SEARCH. In creating the grid matrix, each grid point is designed to indicate the magnitude at this new location. This can only be done by mathematically weighting the raw data nearest the new point. A point farther from the new grid point means less in determination of the new value than one that is nearer. The limit is set by giving the number of nearest points to be searched for and used. Care must be taken to avoid obvious inequities: too large a search limit with a minimal raw data sampling; natural clustering of data in too large of a plotting surface (redefine the boundaries of the plot); too few grid points with an abundance of raw data; etc.

Once an acceptable grid can be assumed, the user makes the final decisions as to what the map will look like. Density of the contour lines is crucial. A map should have neither too dense nor too sparse of any area with lines. This is done by controlling the CONTOUR INTERVAL. For example, if data ranged between values of 800 and 900 it would be erroneous to choose an interval of 50.0 or 0.25. A reasonable entry might be 10.0 or 20.0. Further, the user has available the options of CENTER POINT WEIGHT and SMOOTHING OF CONTOURS.

KEYWORD	FIELD	DEFAULT
GRID DISTANCE	decimal	0.5 inches
LIMIT OF RADIUS SEARCH	integer	3
CONTOUR INTERVAL	decimal	0.25
CENTER POINT WEIGHT	decimal	1.0
SMOOTHING OF CONTOURS	integer	1 (on)

D. DATA ENTRY

The data entry section was designed to allow the user maximum flexibility in the input process. Data input is possible from cards, tape, or both. It is conceivable that after his first plot, the user may wish to save his XY coordinates for several additional plots. On subsequent runs he need only indicate to save all information from the prior plot and then enter a new sample for the magnitude values. Further, all data may be retained and only labeling or gridding information changed.

The following options are available if data is not saved from the previous run:

1) XYZ VALUES	(card input)
2) XYZ ON TAPE	(magnetic tape or disk input)
3) Z VALUES ON TAPE followed by XY VALUES	(magnetic tape or disk input followed by card input)

The following options are available if data is saved from the previous run:

1-3)	any of the above	
4)	Z VALUES ON TAPE	(magnetic tape or disk input)
5)	Z VALUES	(card input)
6)	XY VALUES	(card input)
7)	none	(no input)

NOTES: When splitting Z and XY values, ordinal integrity of the data must be maintained!!
All above mentioned cards must include a format statement in the alpha field. Enclosing parentheses are required.
All Z values left blank will be considered missing data and, hence, will be ignored during grid generation.
If data is to be read from tape or disk the local file name must be "DATA."
When values are to be read from tape the control card may be placed anywhere in the input stream.

When values are read from cards the control card must be the last parameter card in this logical record. The card may be followed only by the data from cards until input of the current logical record is exhausted. The task of generating the map then begins.

The remaining control cards set limits on the ranges of XYZ data values. X and Y limits are used in determination of the boundaries of the area plotted. Z limits are used for the pruning of extreme or erroneous data and exist merely for the convenience of the user.

KEYWORD	FIELD	DEFAULT
XYZ VALUES	alpha	none
XYZ ON TAPE	alpha	none
XY VALUES	alpha	none
Z VALUES	alpha	none
Z VALUES ON TAPE	alpha	none
MAXIMUM X VALUE	decimal	none
MAXIMUM Y VALUE	decimal	none
MINIMUM X VALUE	decimal	none
MINIMUM Y VALUE	decimal	none
LOWER DATA BOUND	decimal	-10.0
UPPER DATA BOUND	decimal	10.0

IV. PROGRAM RESTRICTIONS AND ERRORS

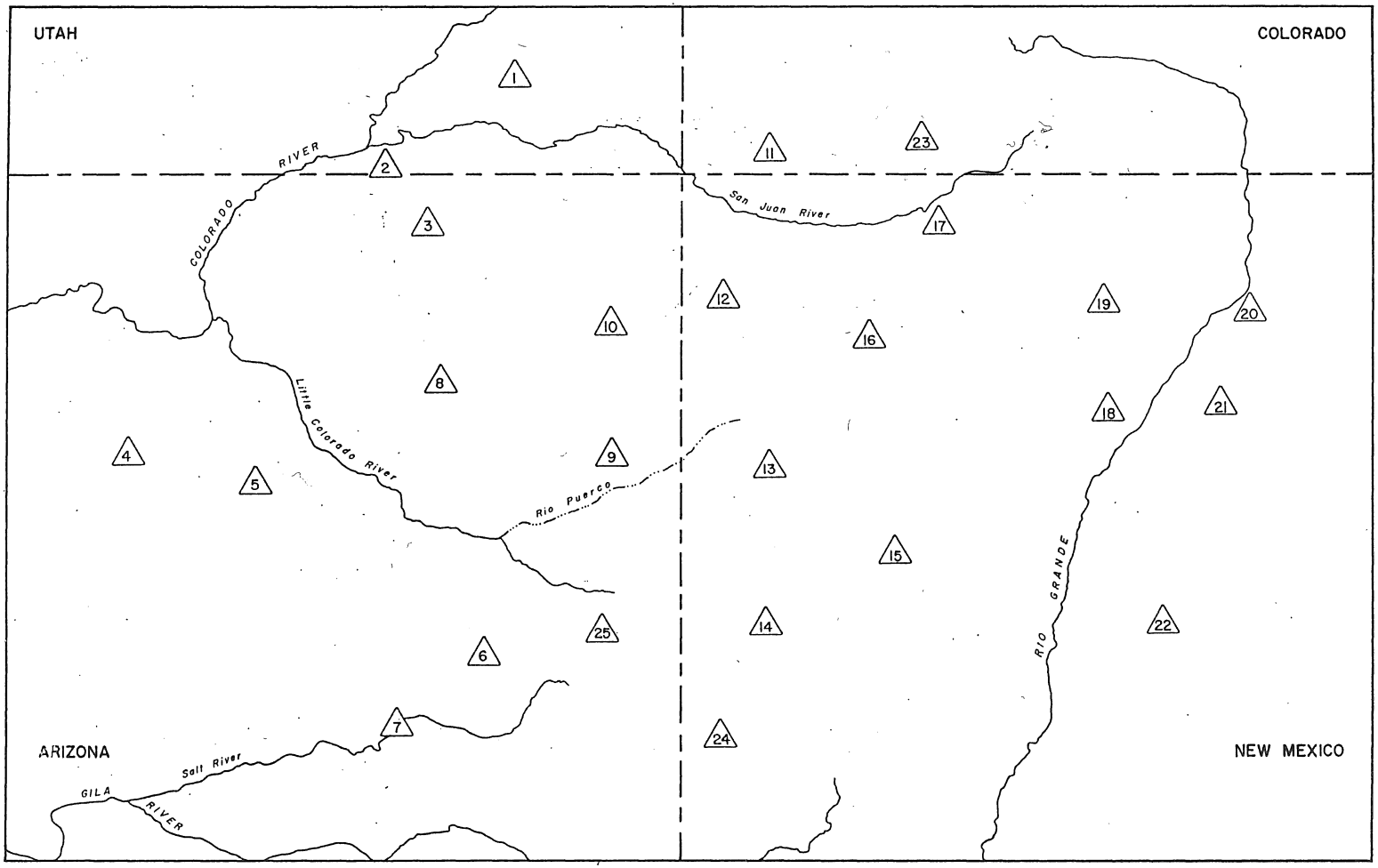
The current version of CONTOUR is limited to a raw data matrix of 50 points and a maximum grid matrix of 700 points. This may easily be increased by modification of the source code. These limits are set low to minimize core requirements and hence facilitate speedy job turn-around time.

This program is also restricted to use of a plotter with an eleven inch plotting bed. Use the following equation to determine whether y-direction requirements are within this limit:

unused space=11.0- Y AXIS LENGTH-TITLE HEIGHT-4 * HEIGHT OF BOUNDARIES.

This document assumes the user is sufficiently familiar with CDC Fortran to debug errors in coded input (i.e. reading a character in integer mode).

All error messages are self explanatory with, perhaps, the following exception: AMBIQUITY IN INPUT OF DATA MATRIX. This indicates improper use of data entry cards. For example, if XYZ ON TAPE were followed by Z VALUES ON TAPE, the job would abort since only one set of Z values is allowed.


UTAH
COLORADO
ARIZONA
NEW MEXICO
COLORADO RIVER
San Juan River
Little Colorado River
Rio Puerco
RIO GRANDE
Salt River
GILA RIVER
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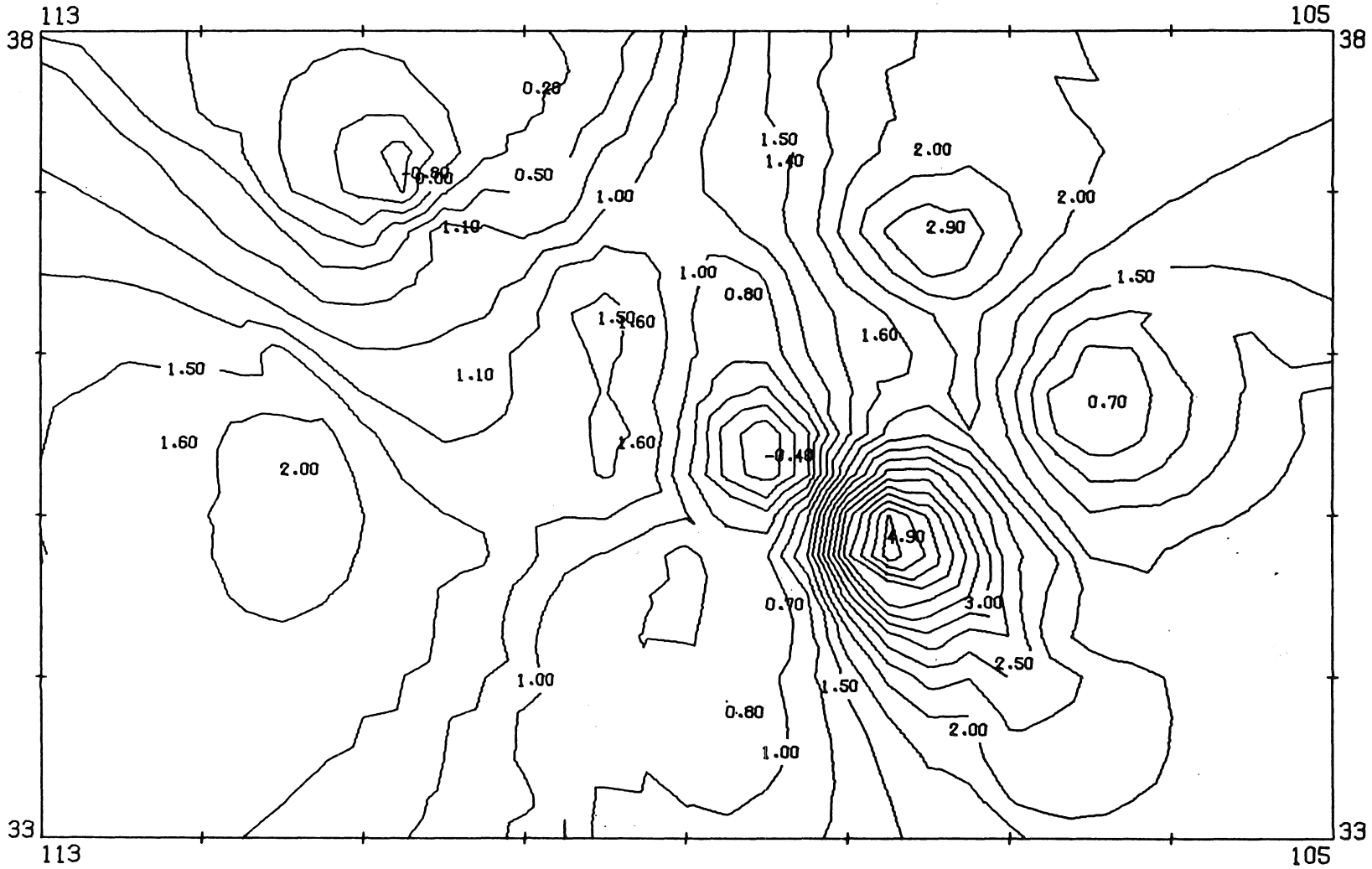
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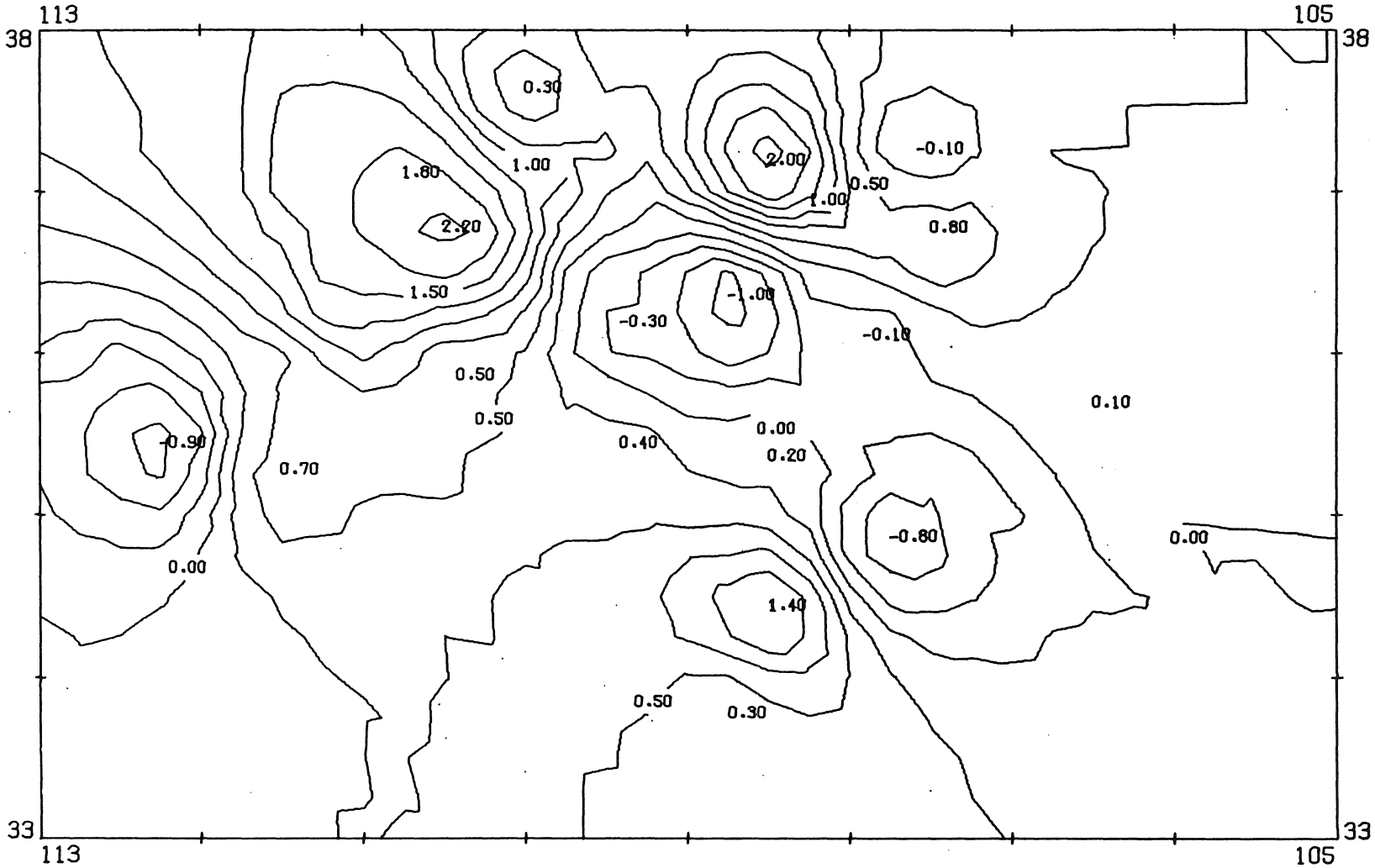
0.80
0.70
-0.40
4.90
3.00
2.50

0680-0689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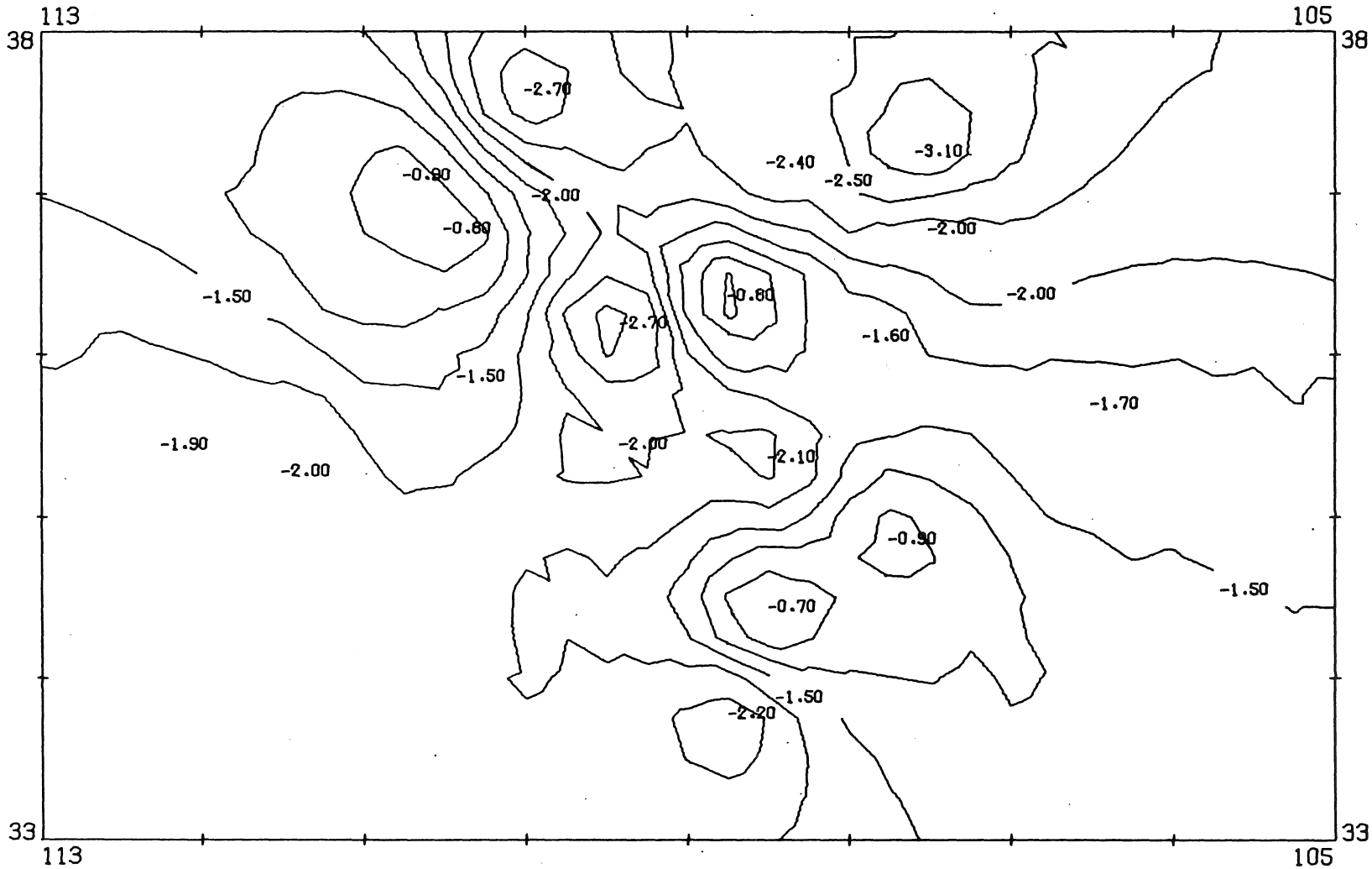
0690-0699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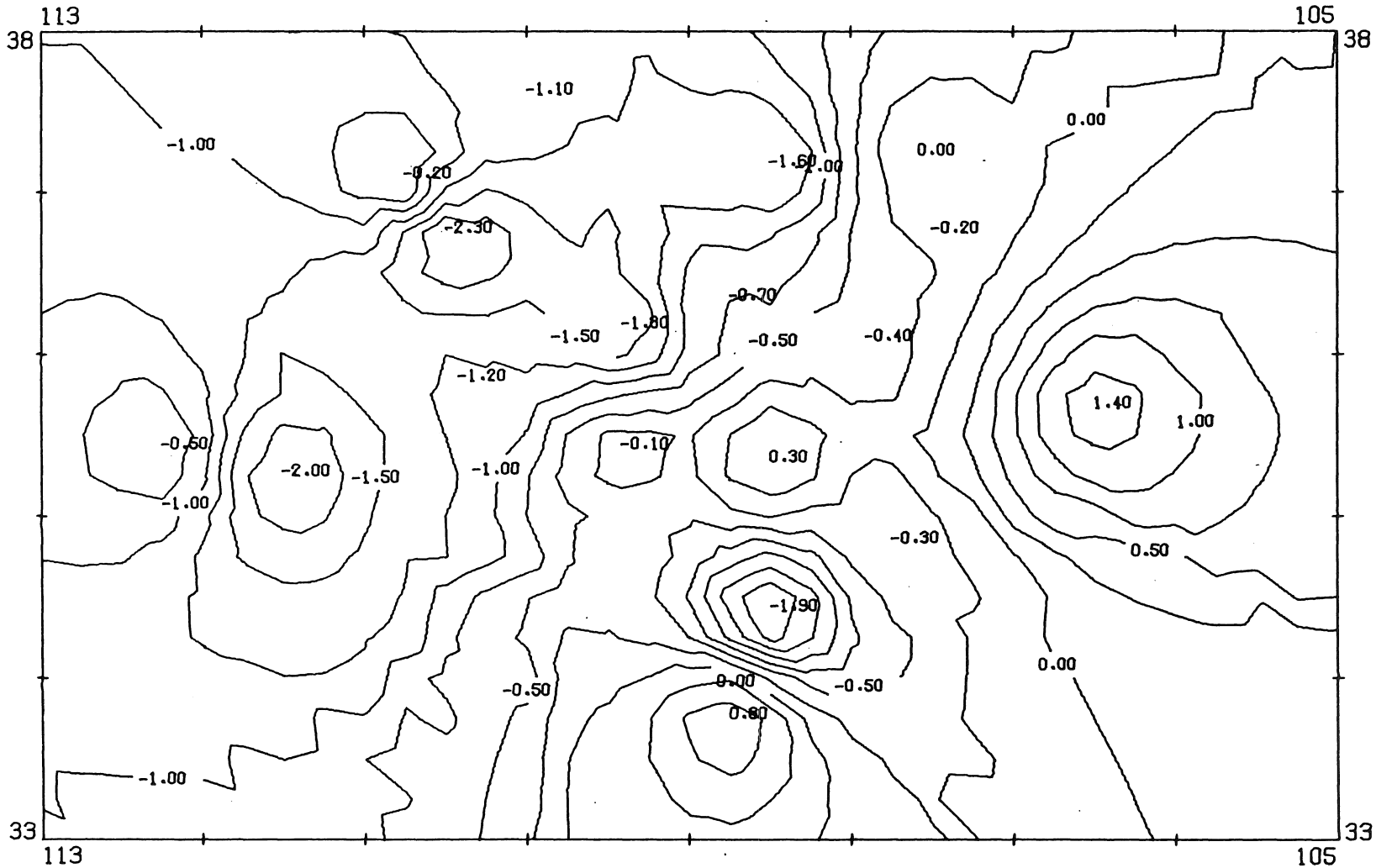
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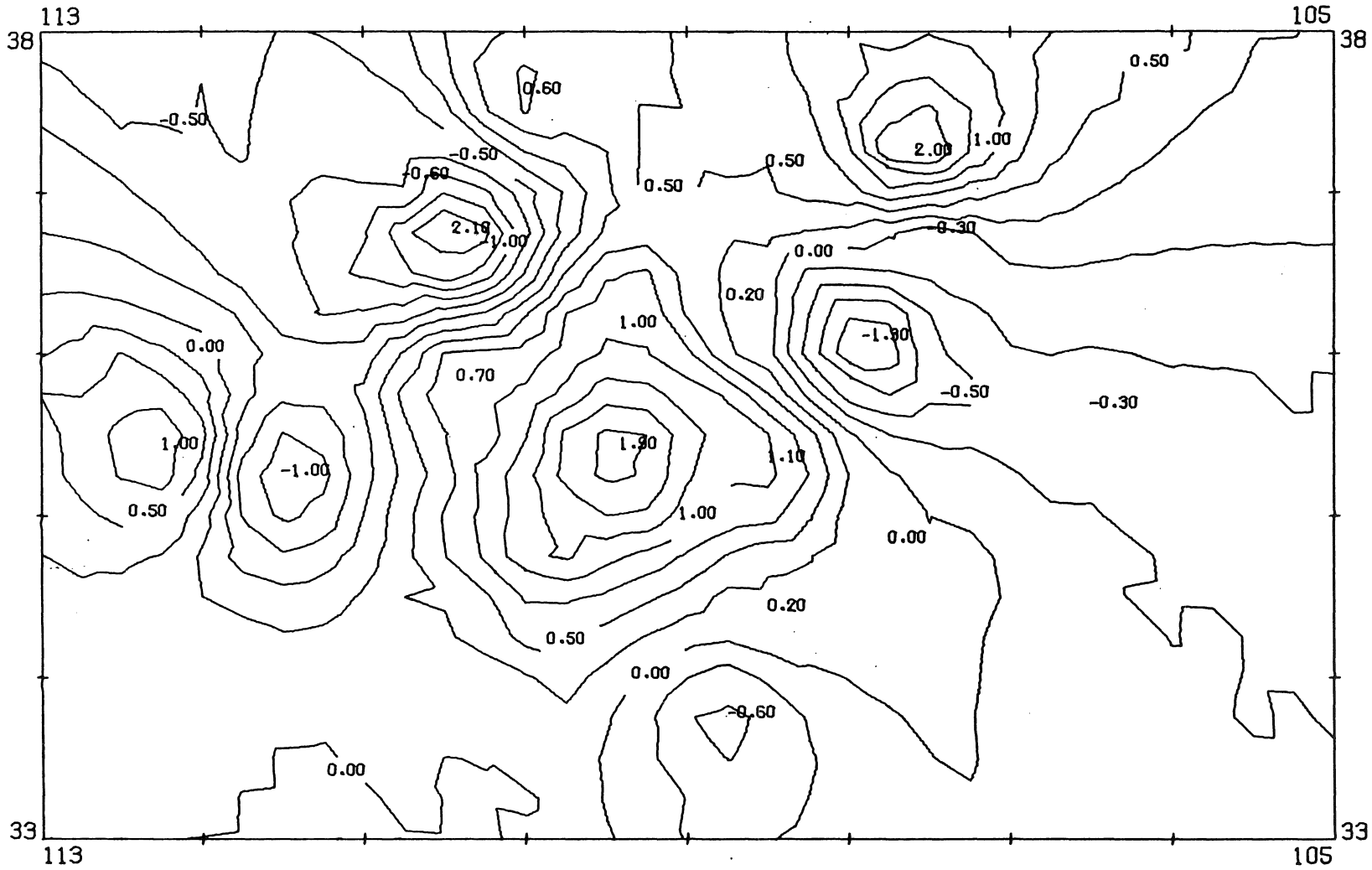
0710-0719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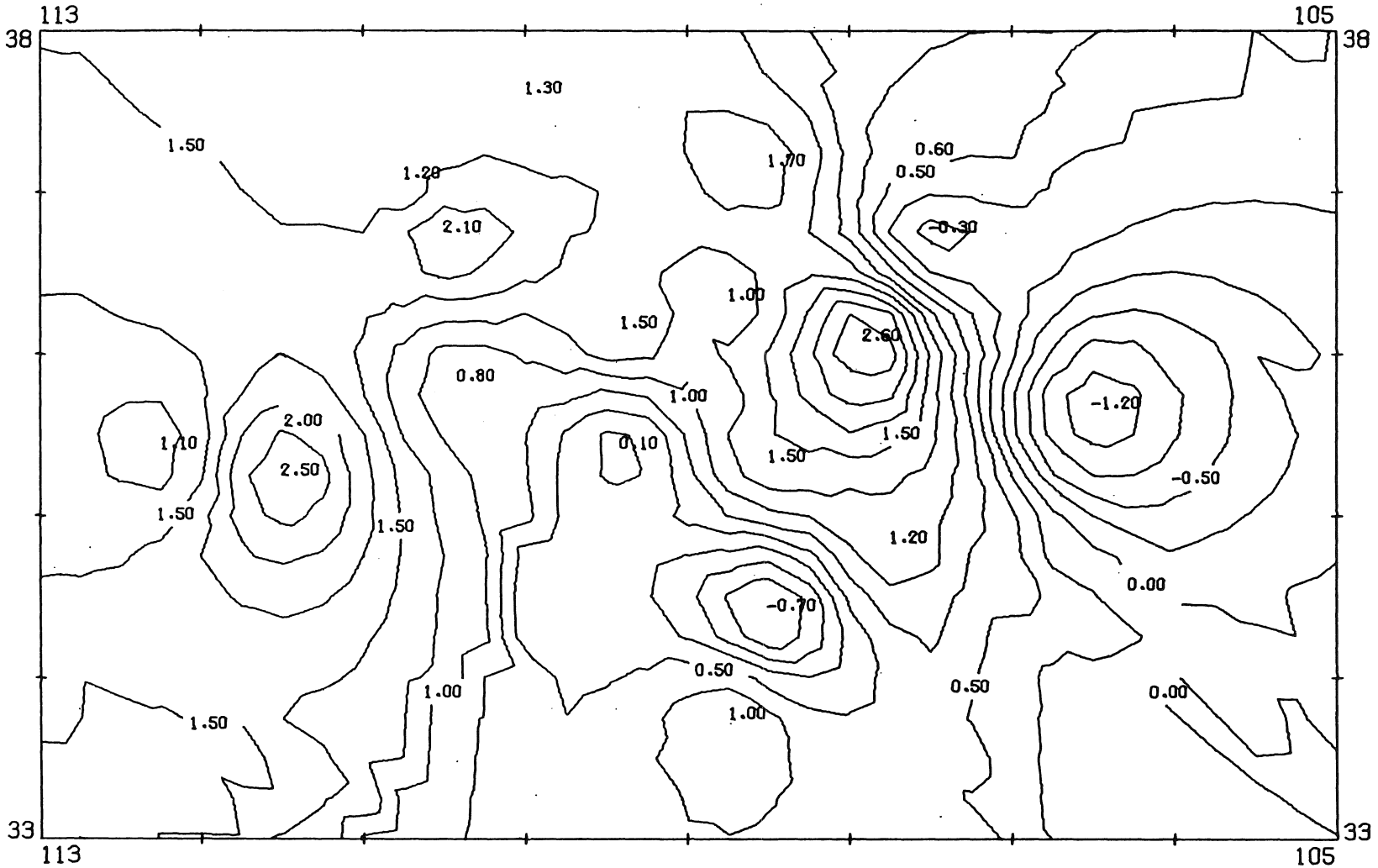
0720-0729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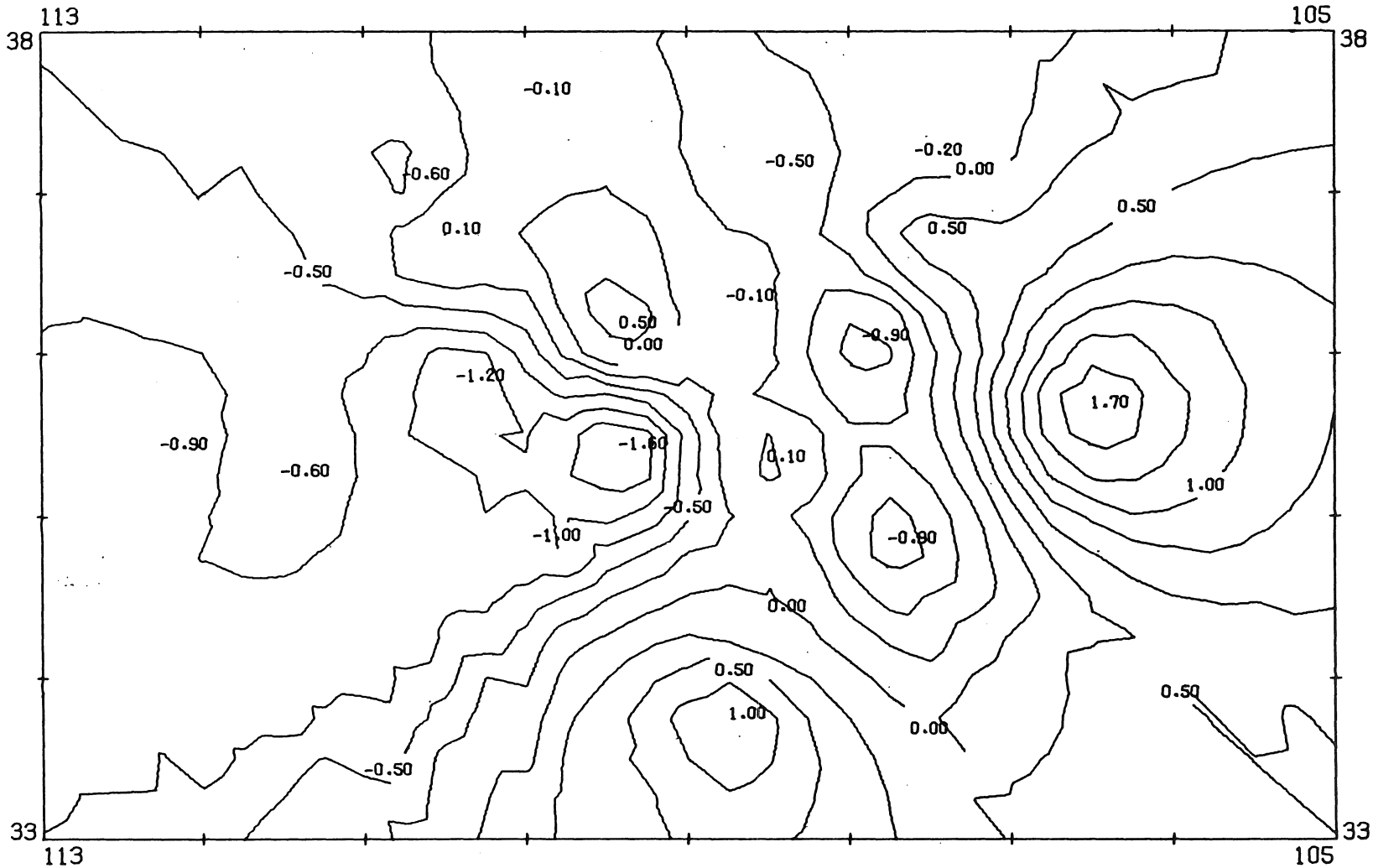
0730-0739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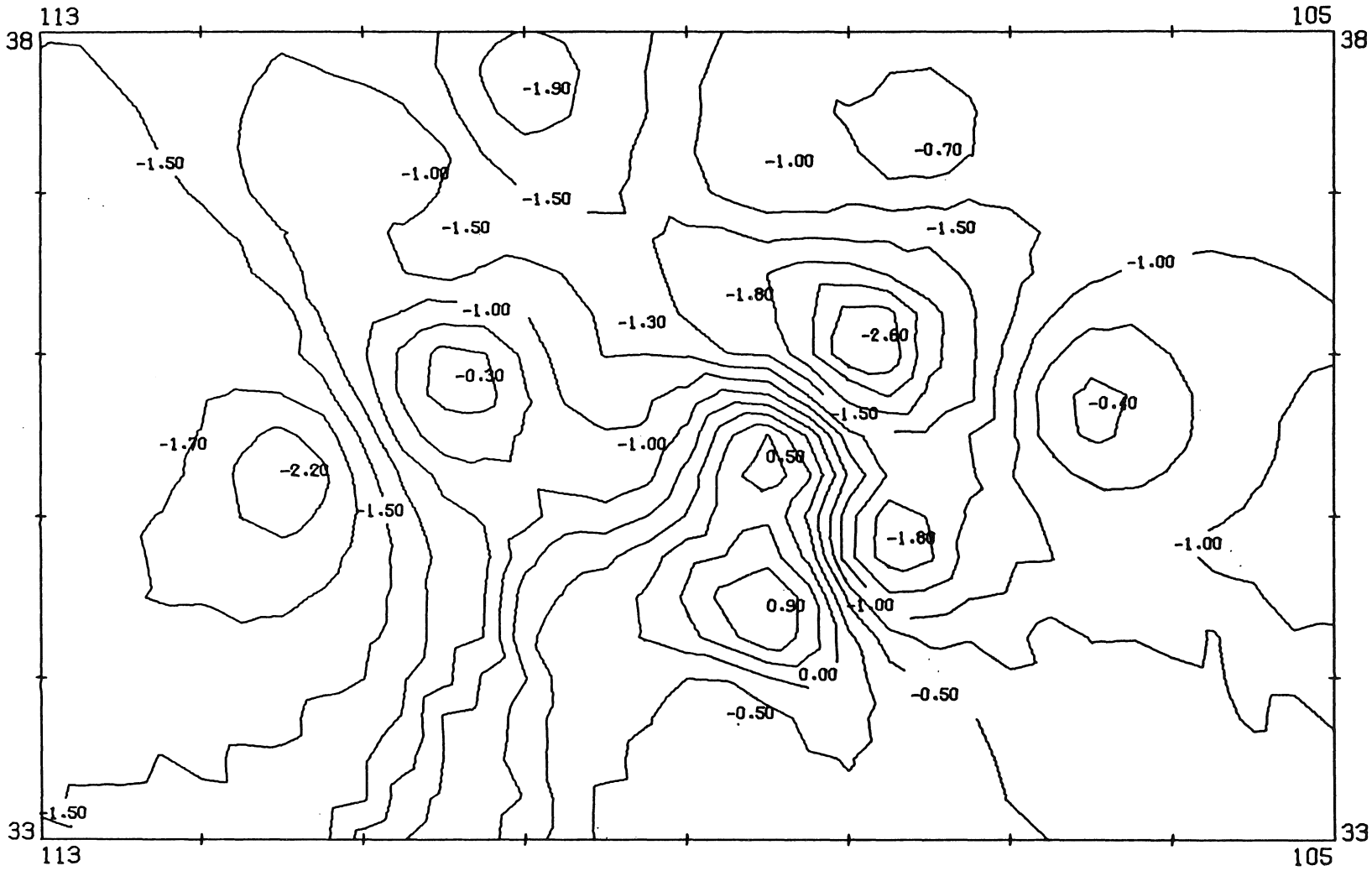
0740-0749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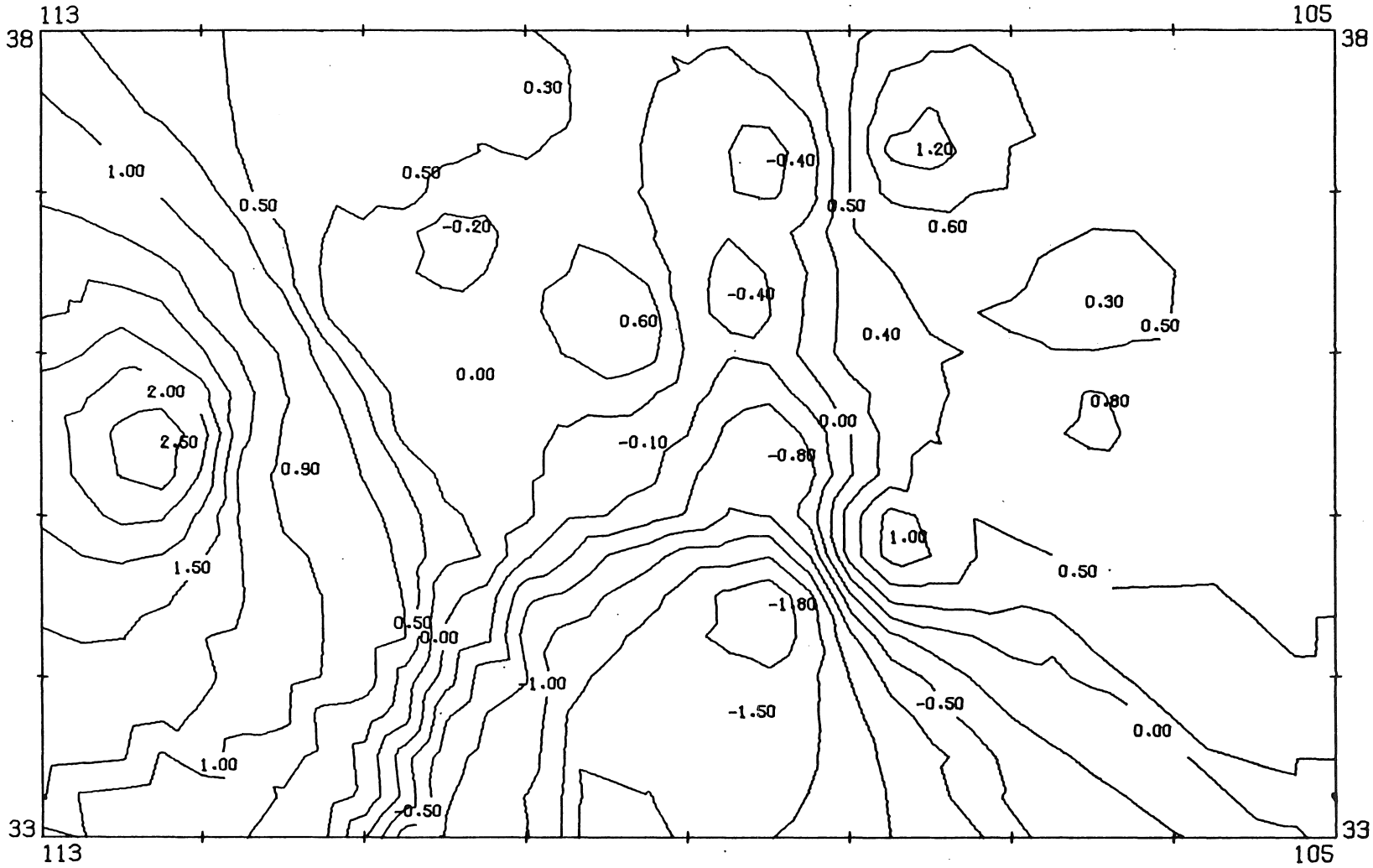
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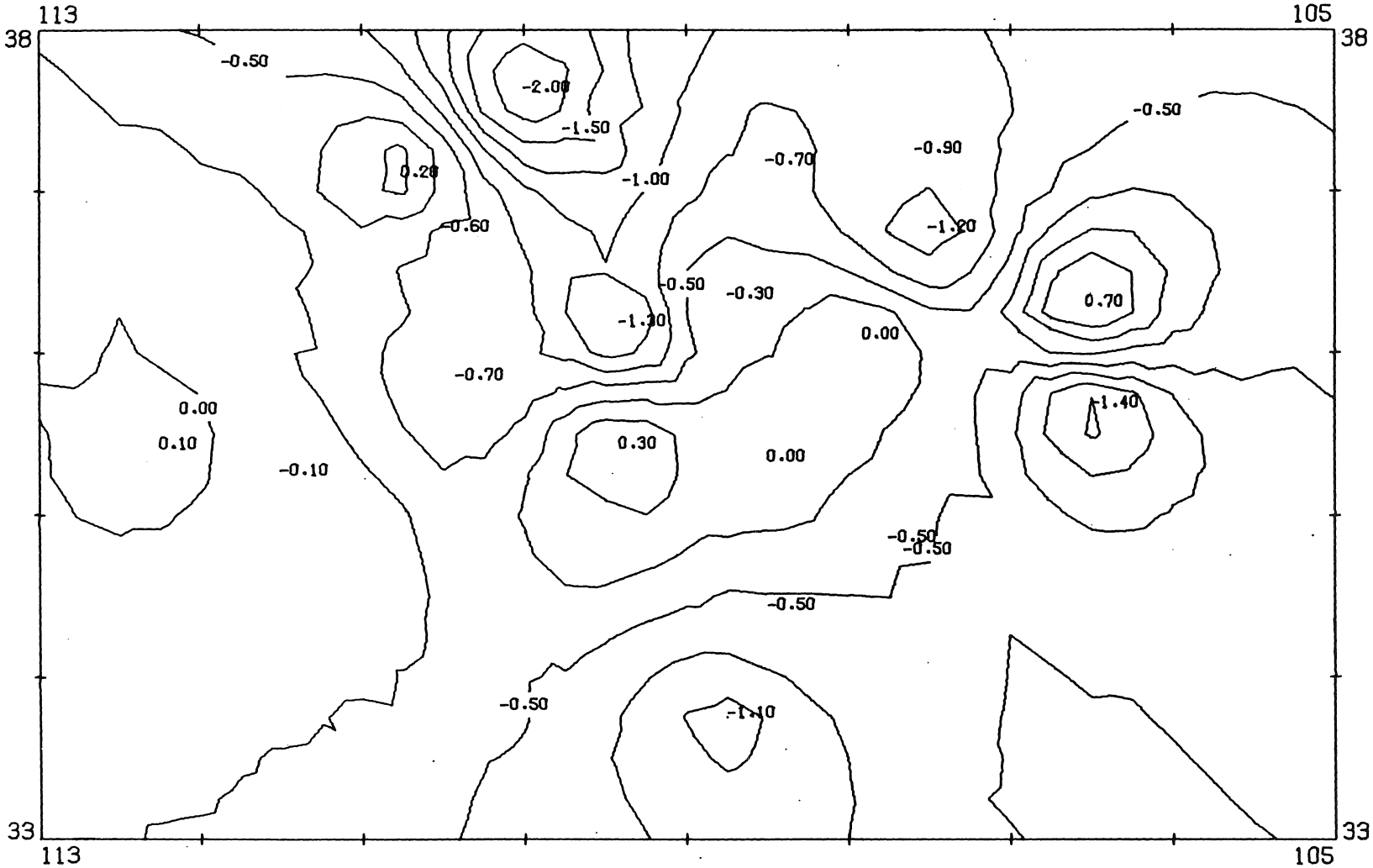
0760-0769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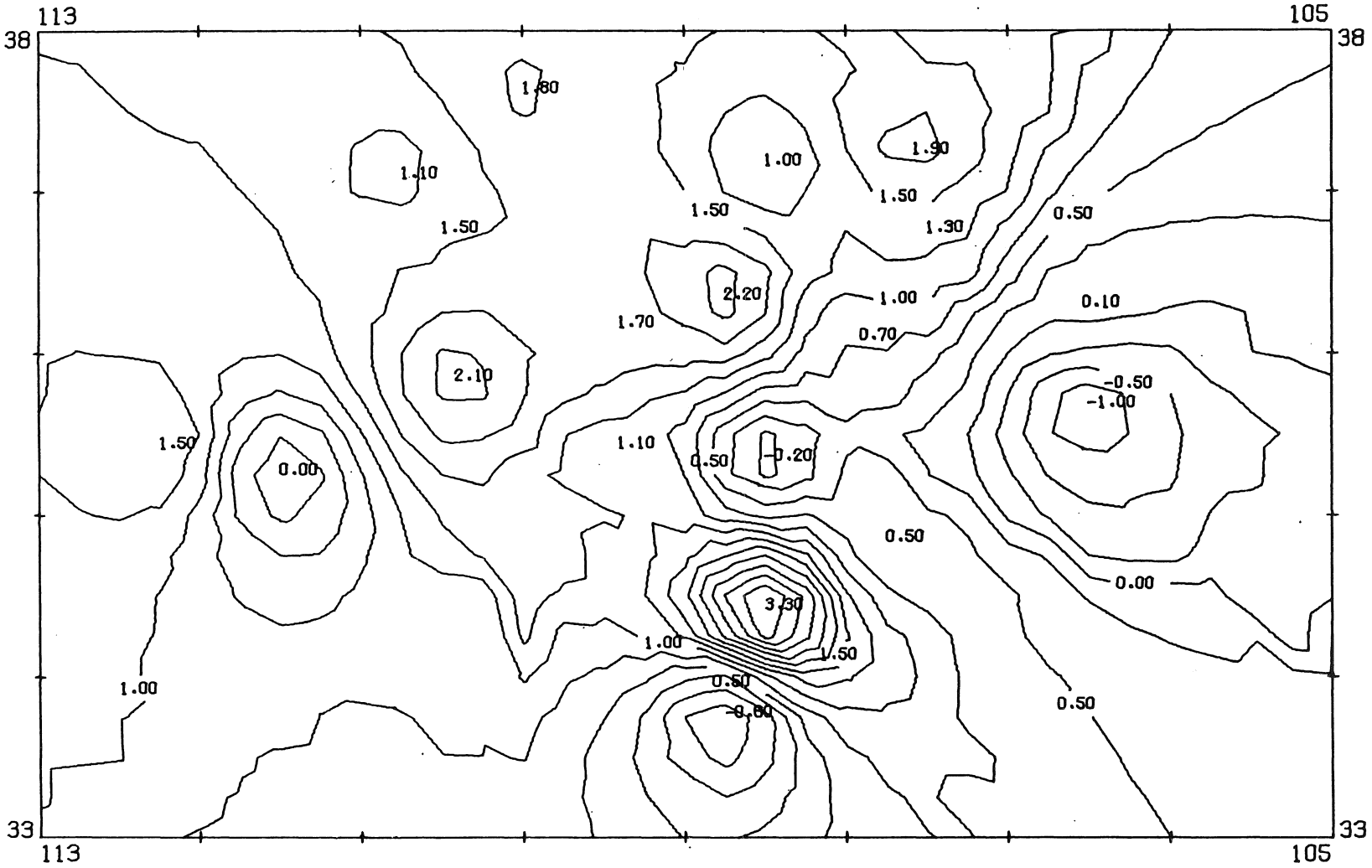
0770-0779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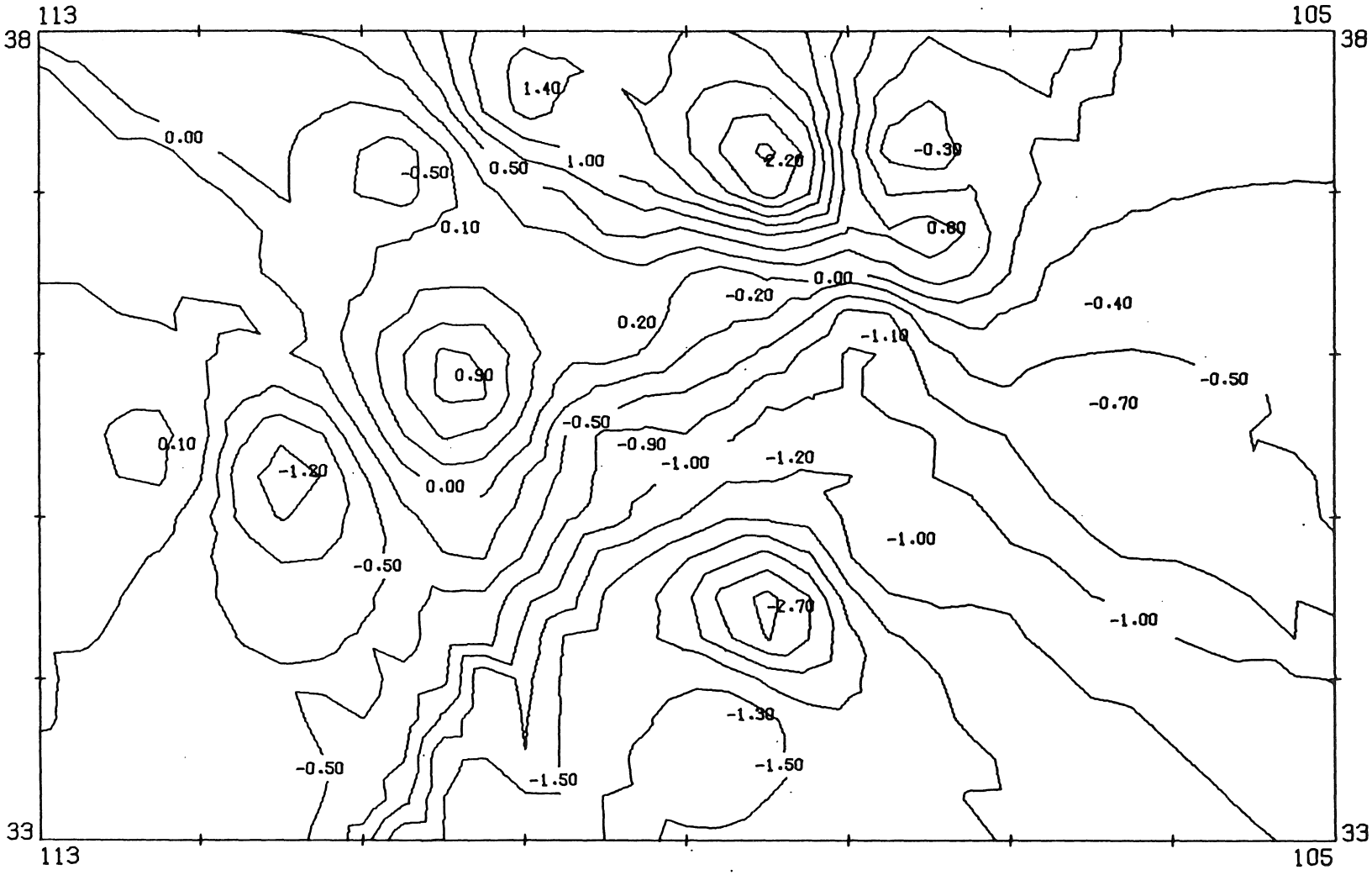
0780-0789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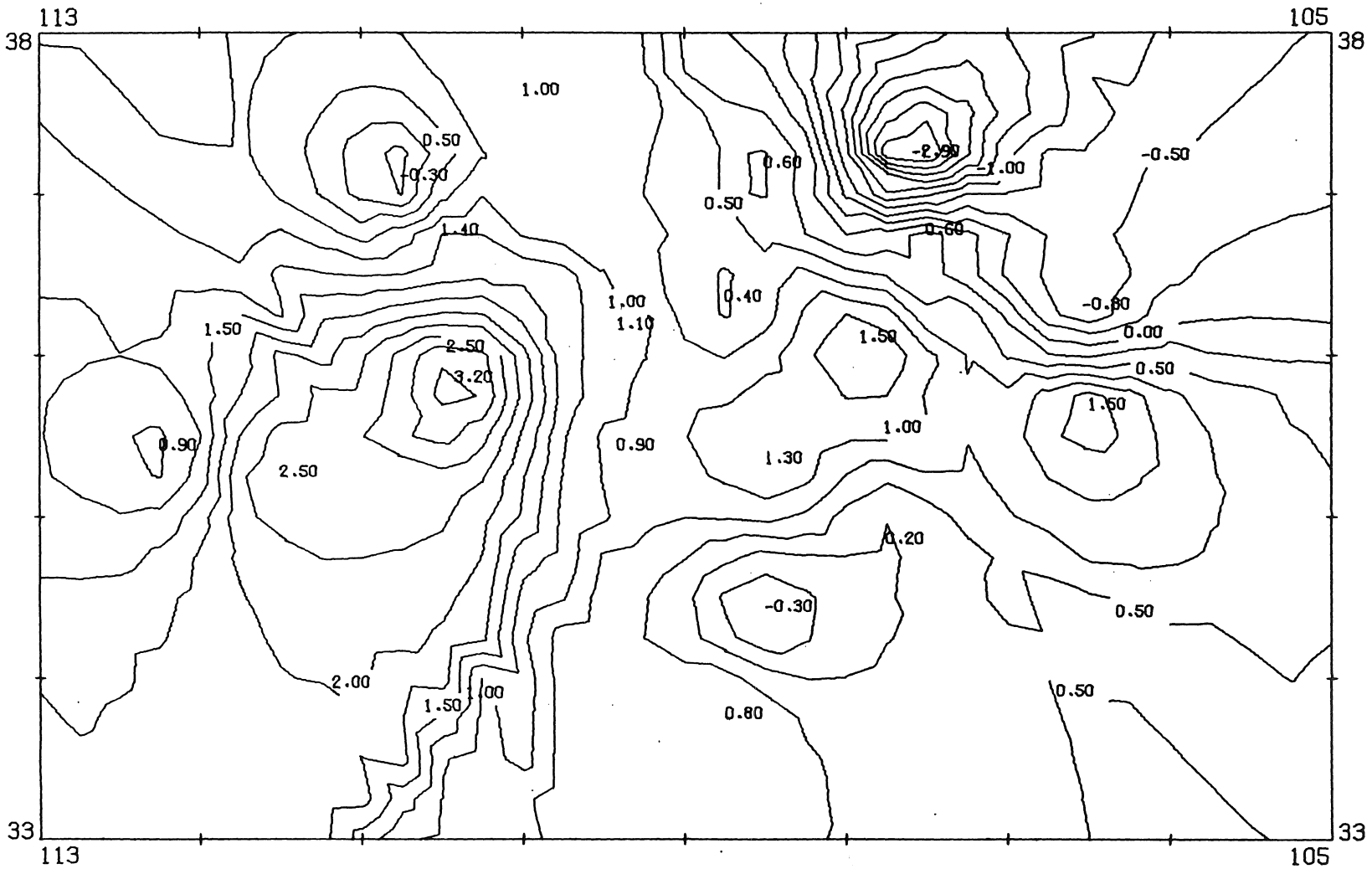
0790-0799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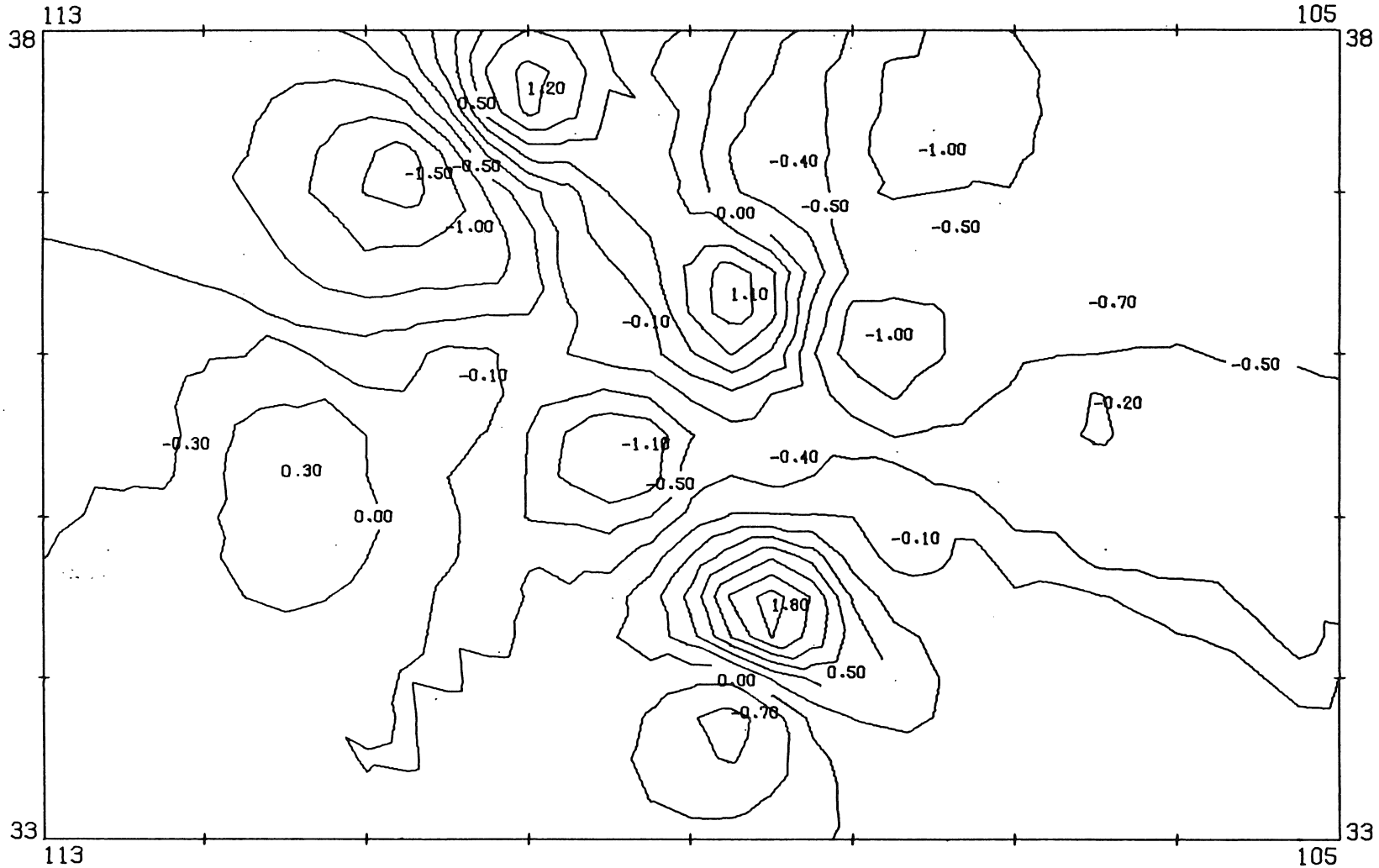
0800-0809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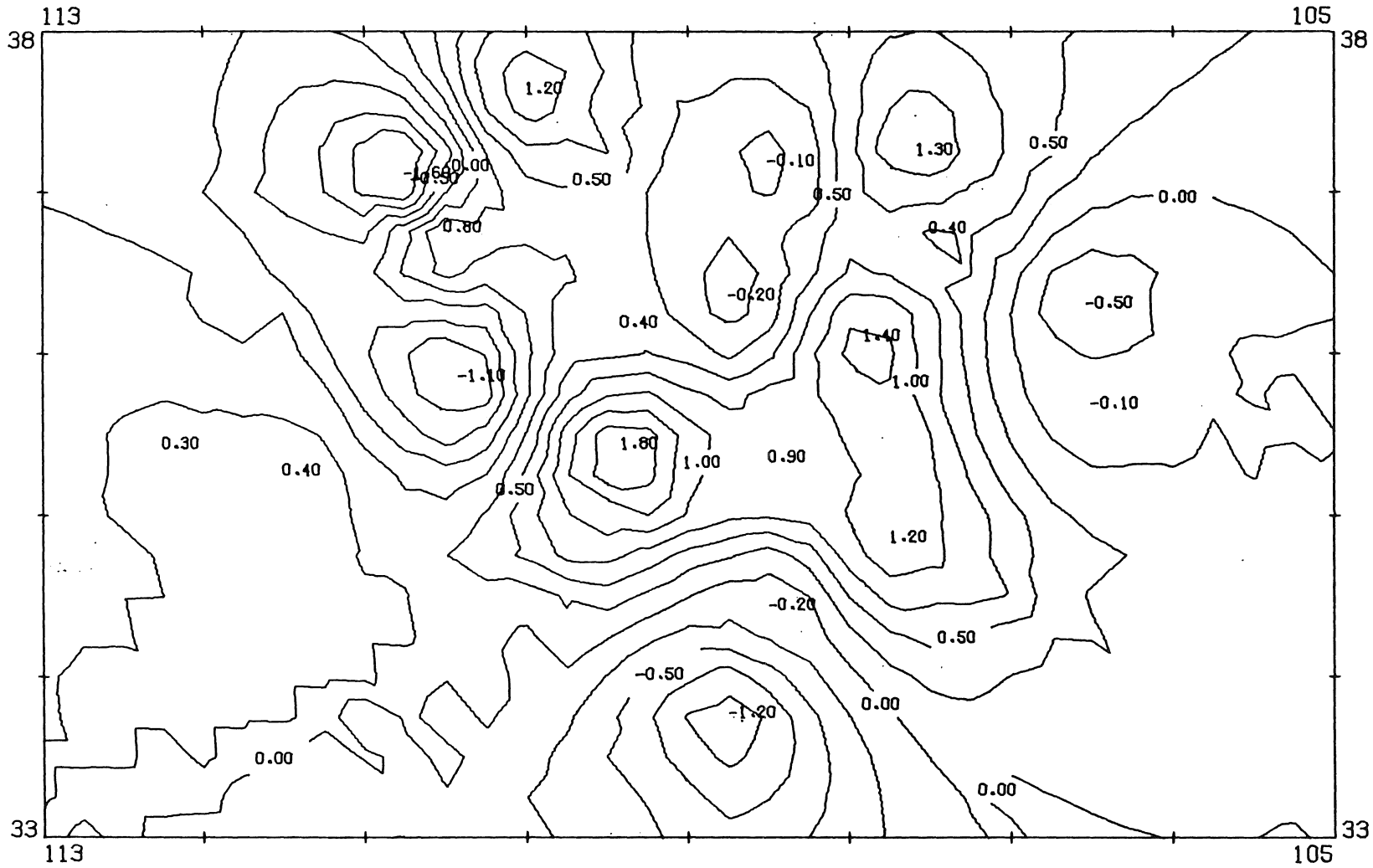
0810-0819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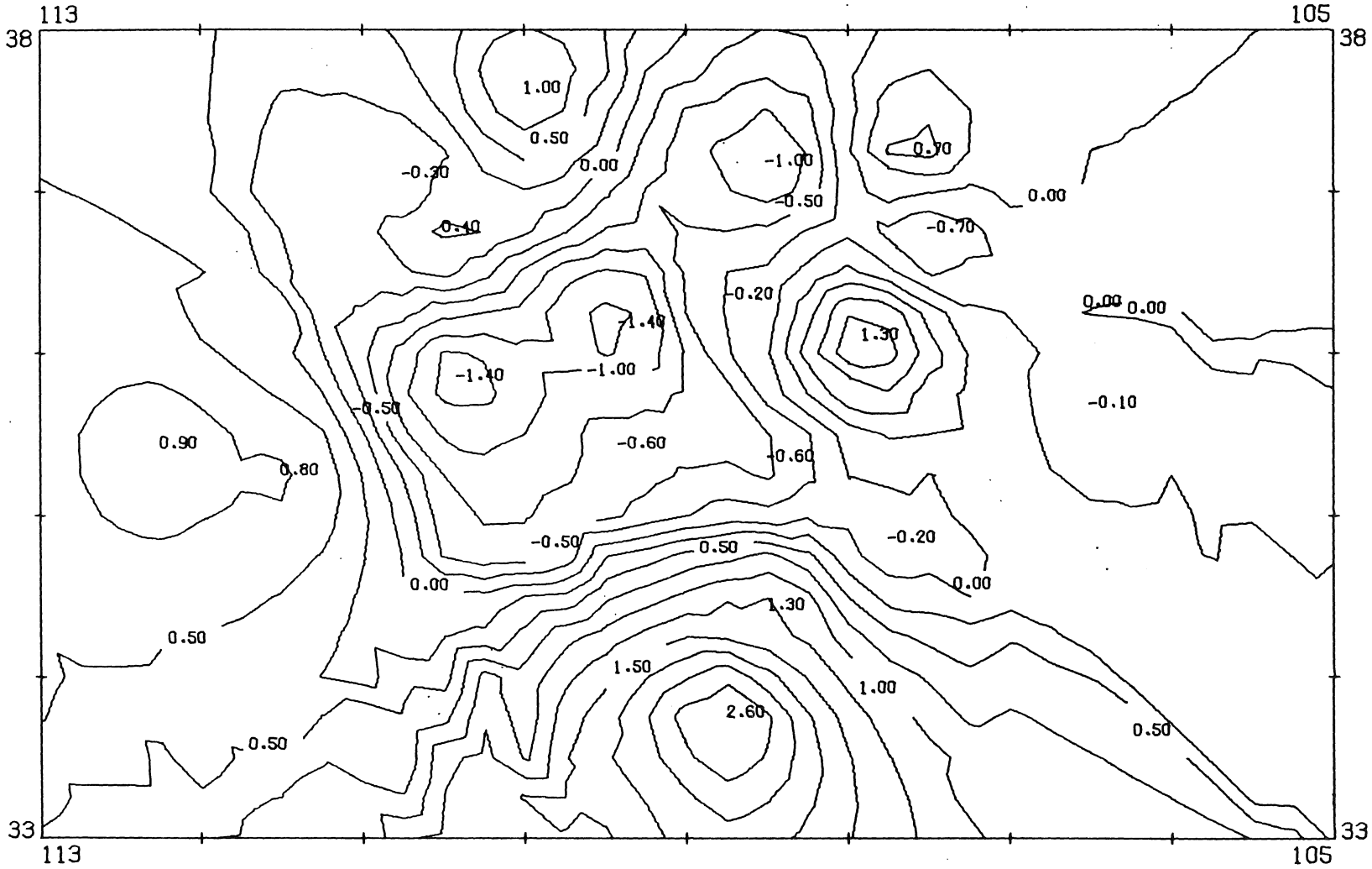
0820-0829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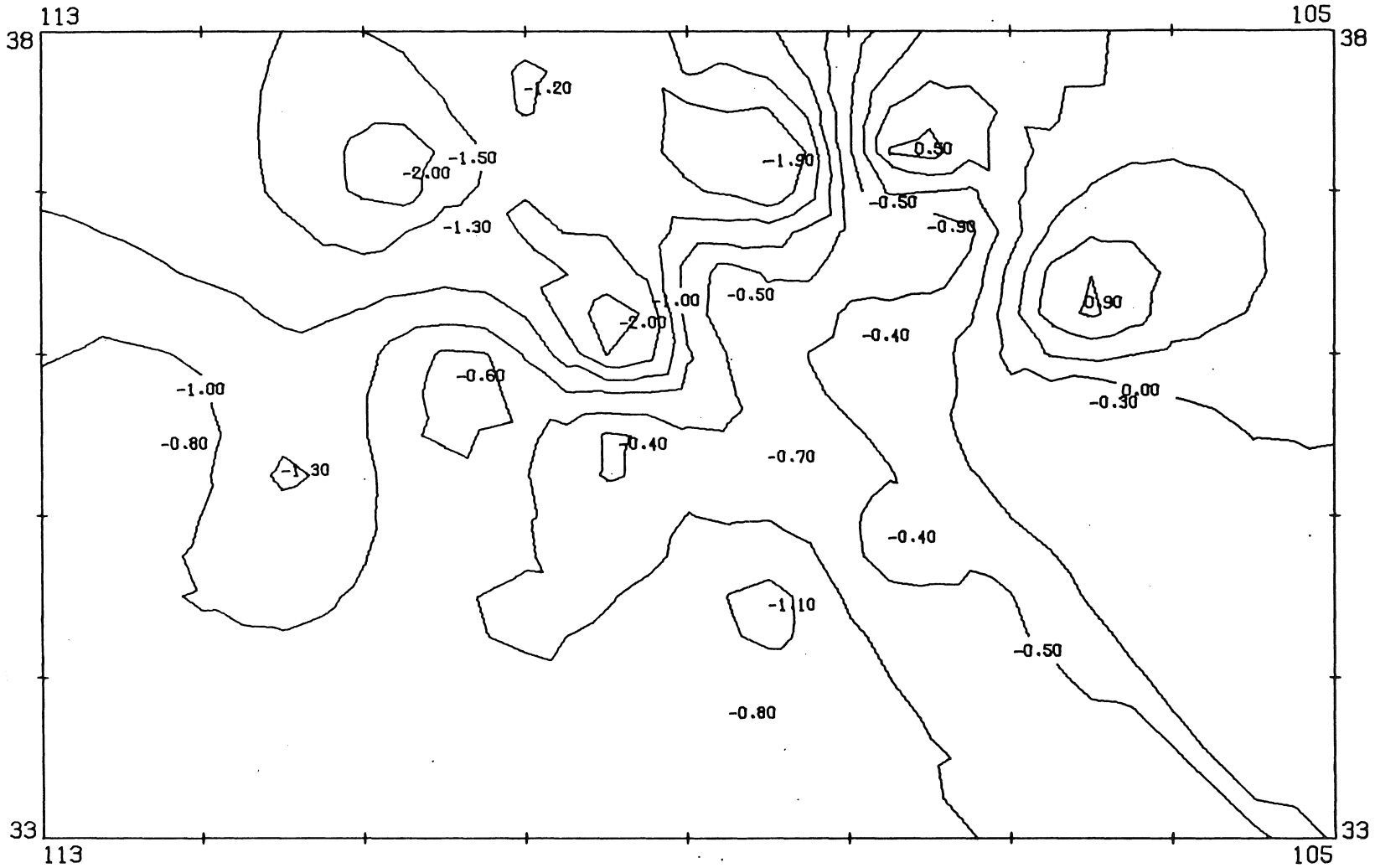
0830-0839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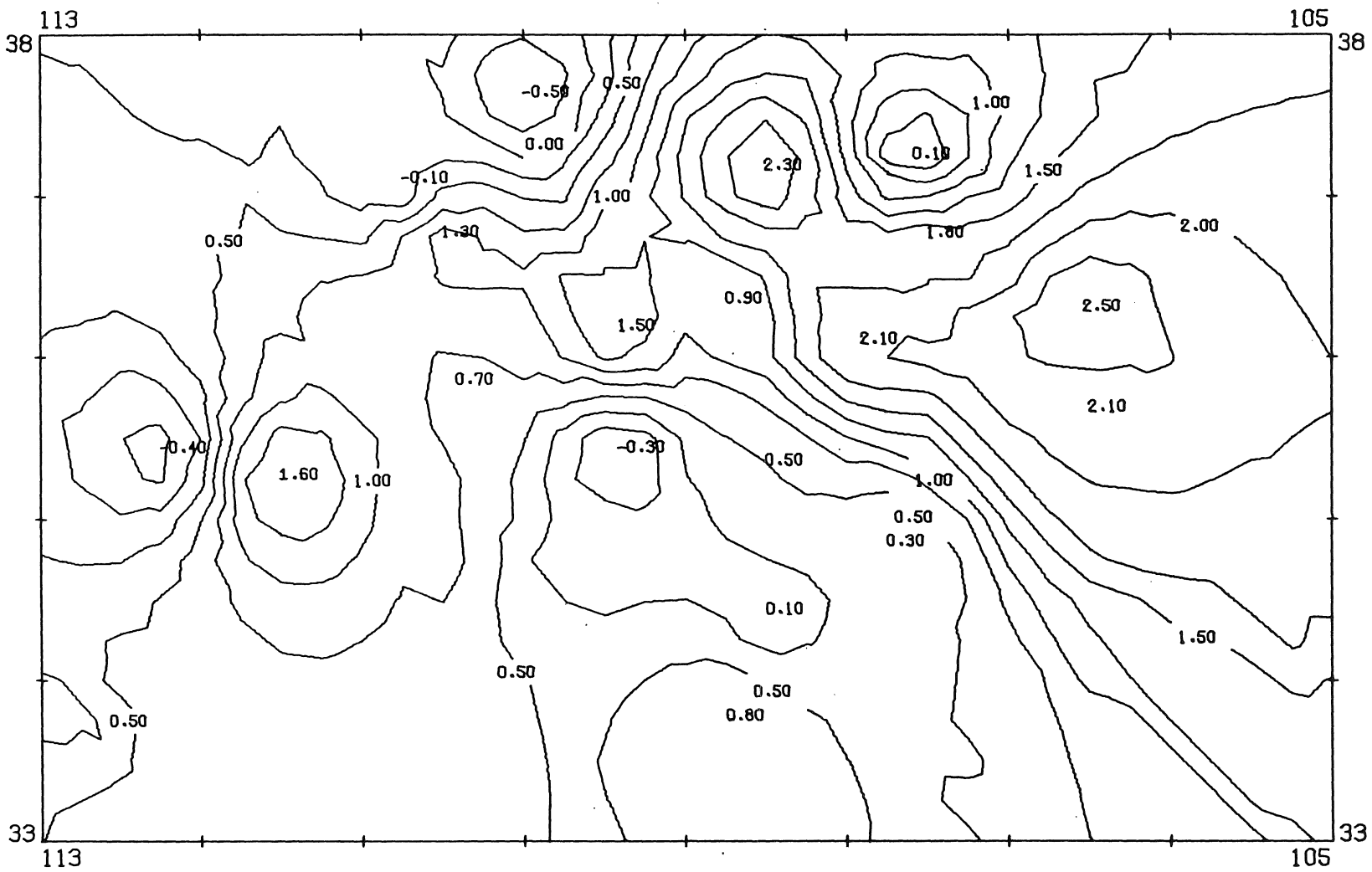
0840-0849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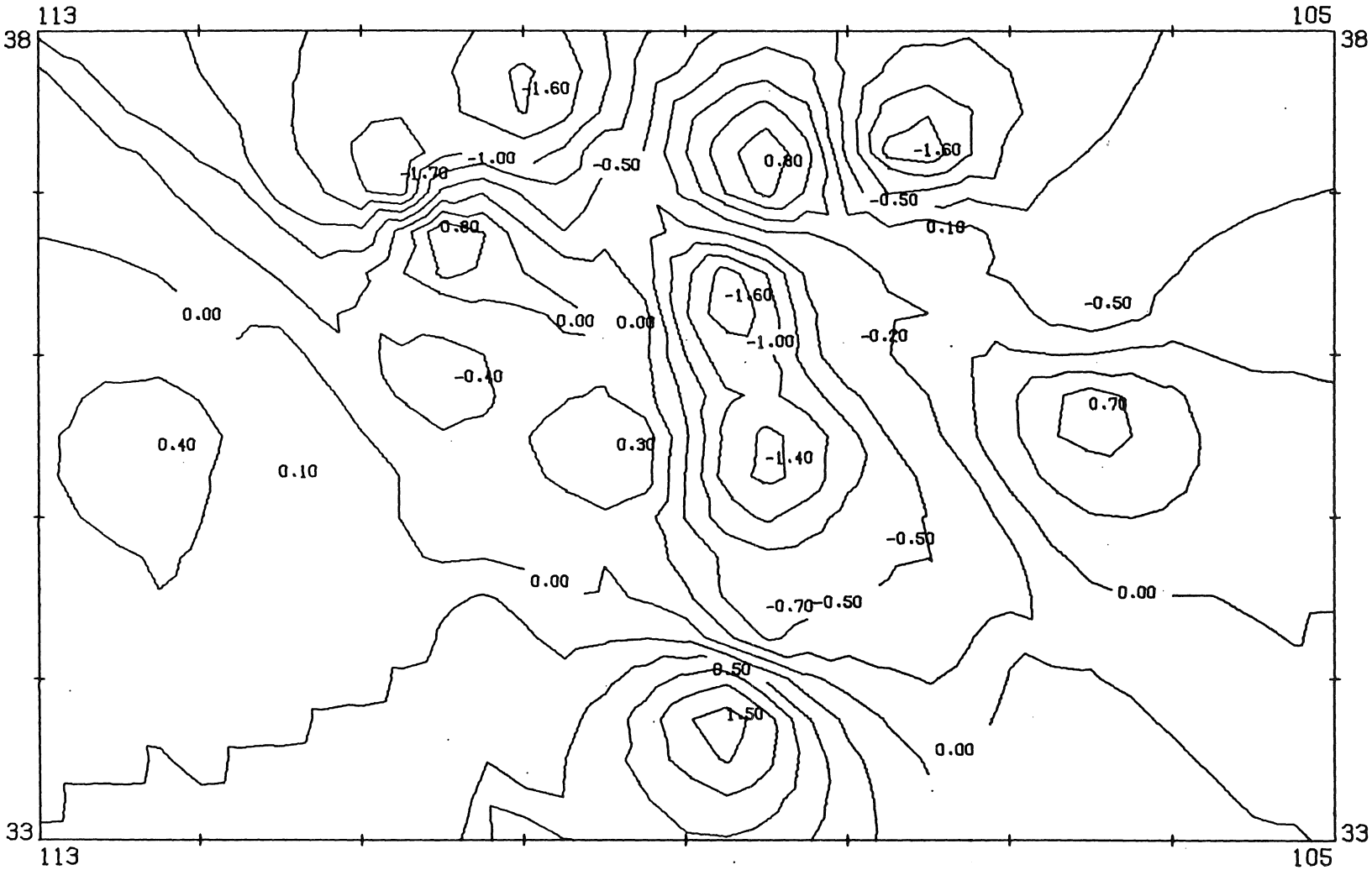
0850-0859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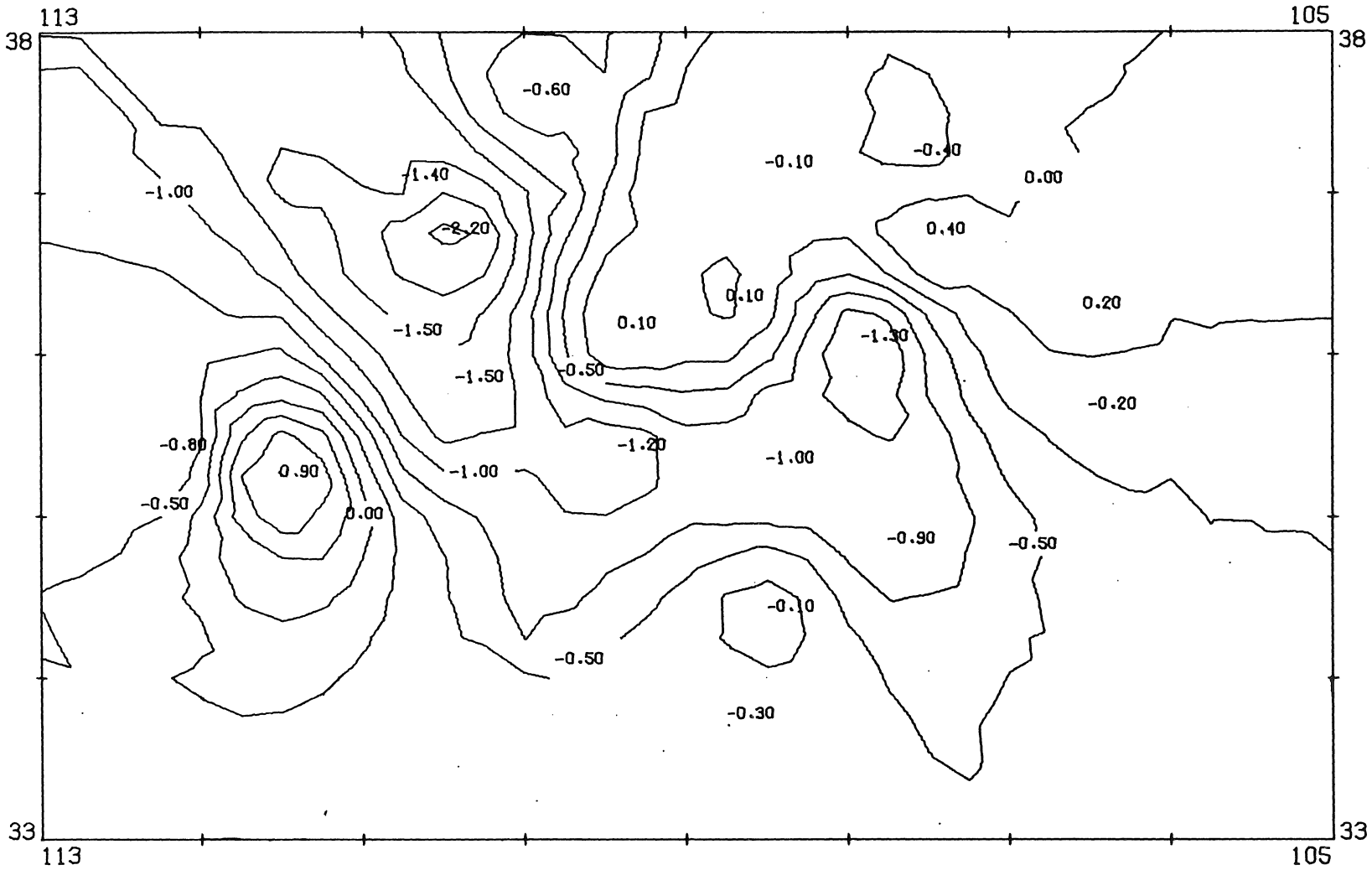
0860-0869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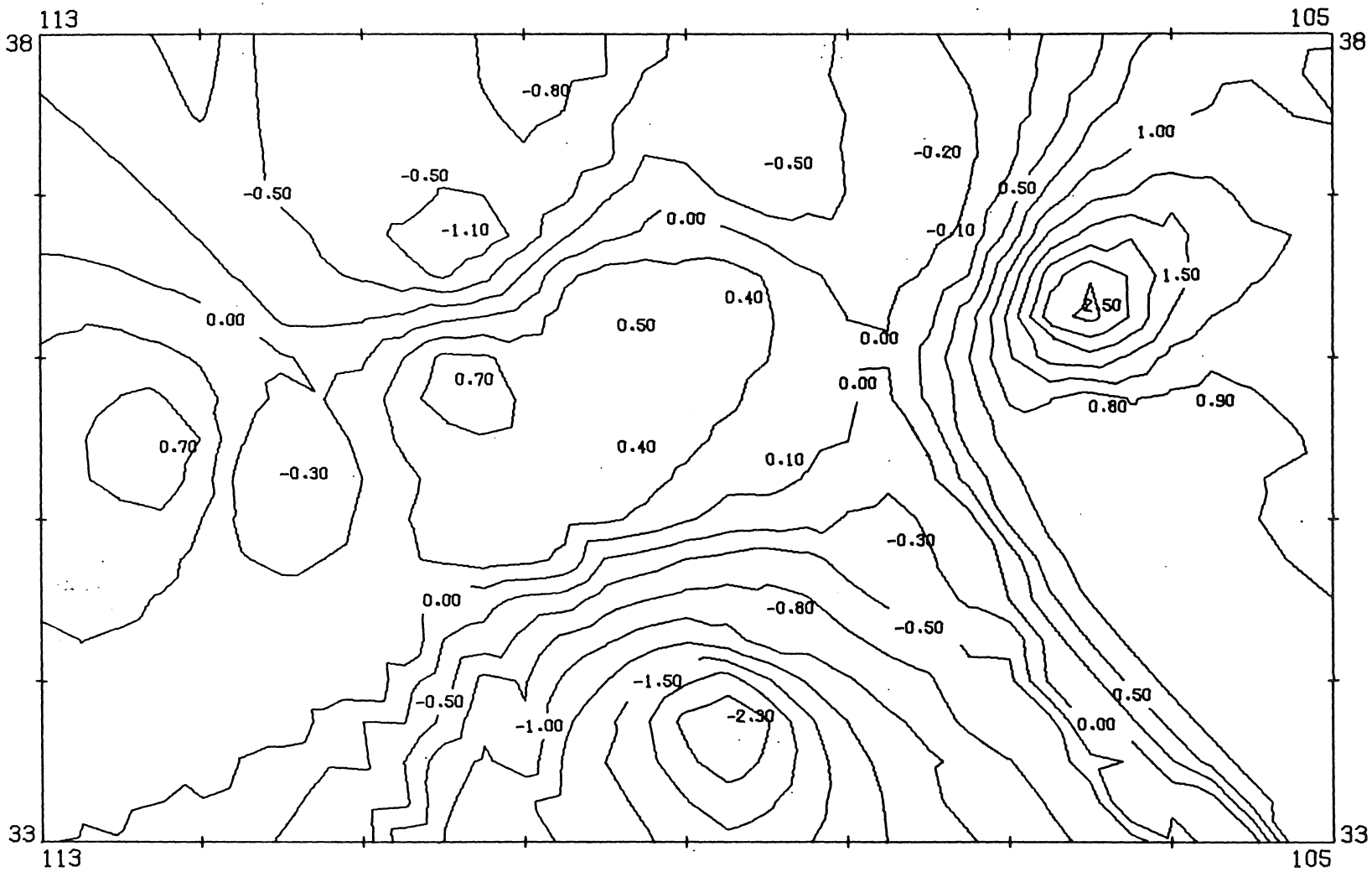
0870-0879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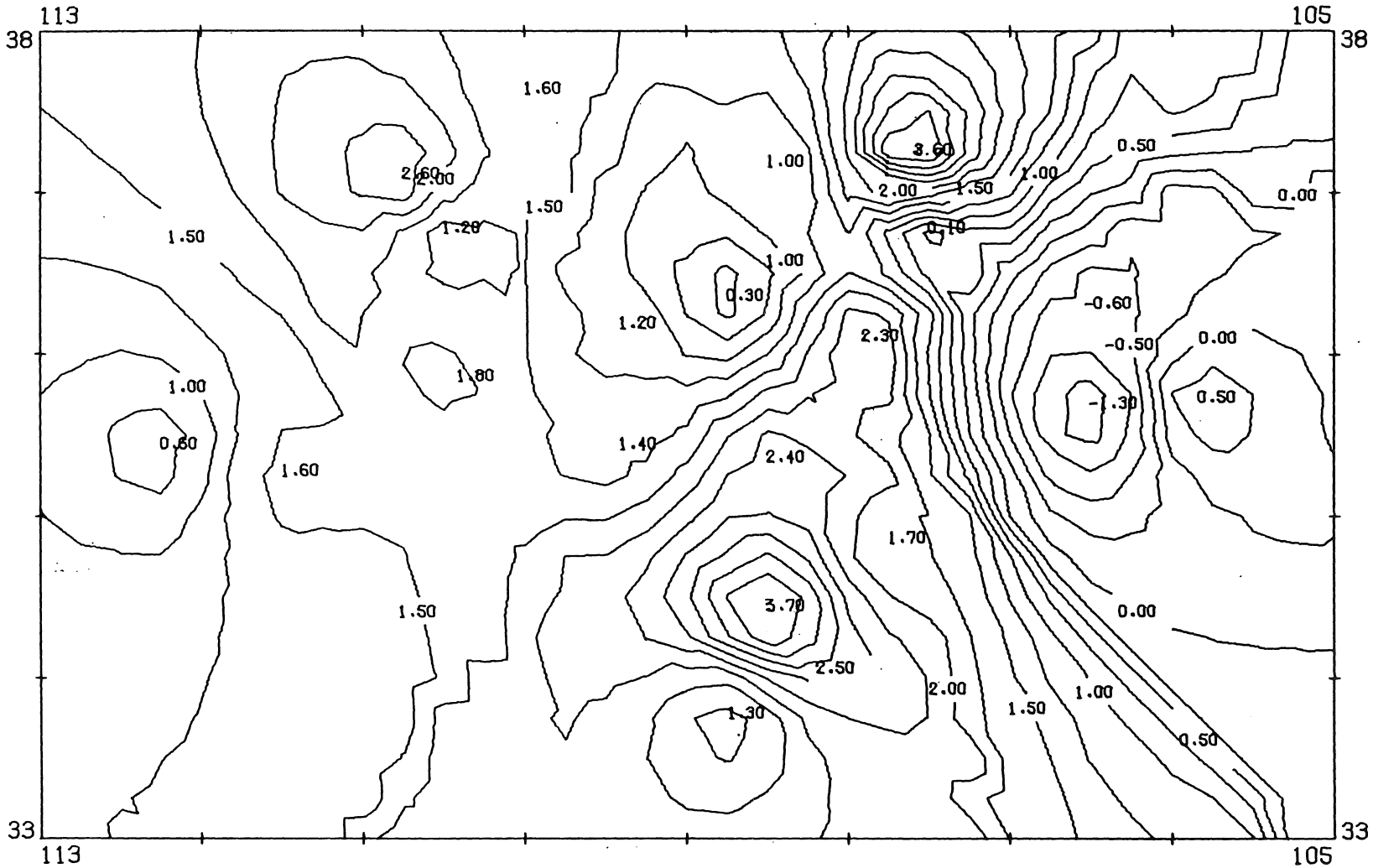
0880-0889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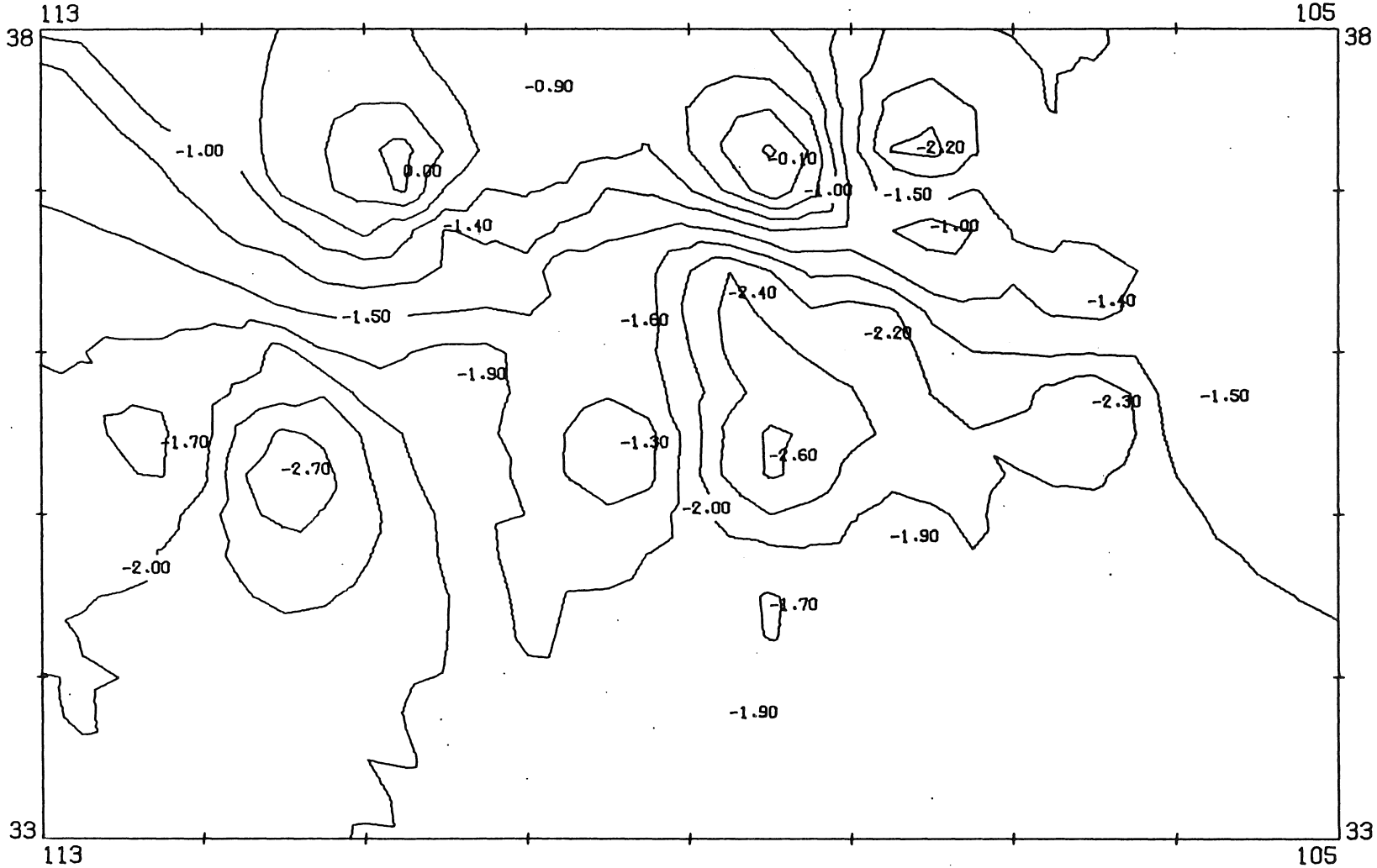
0890-0899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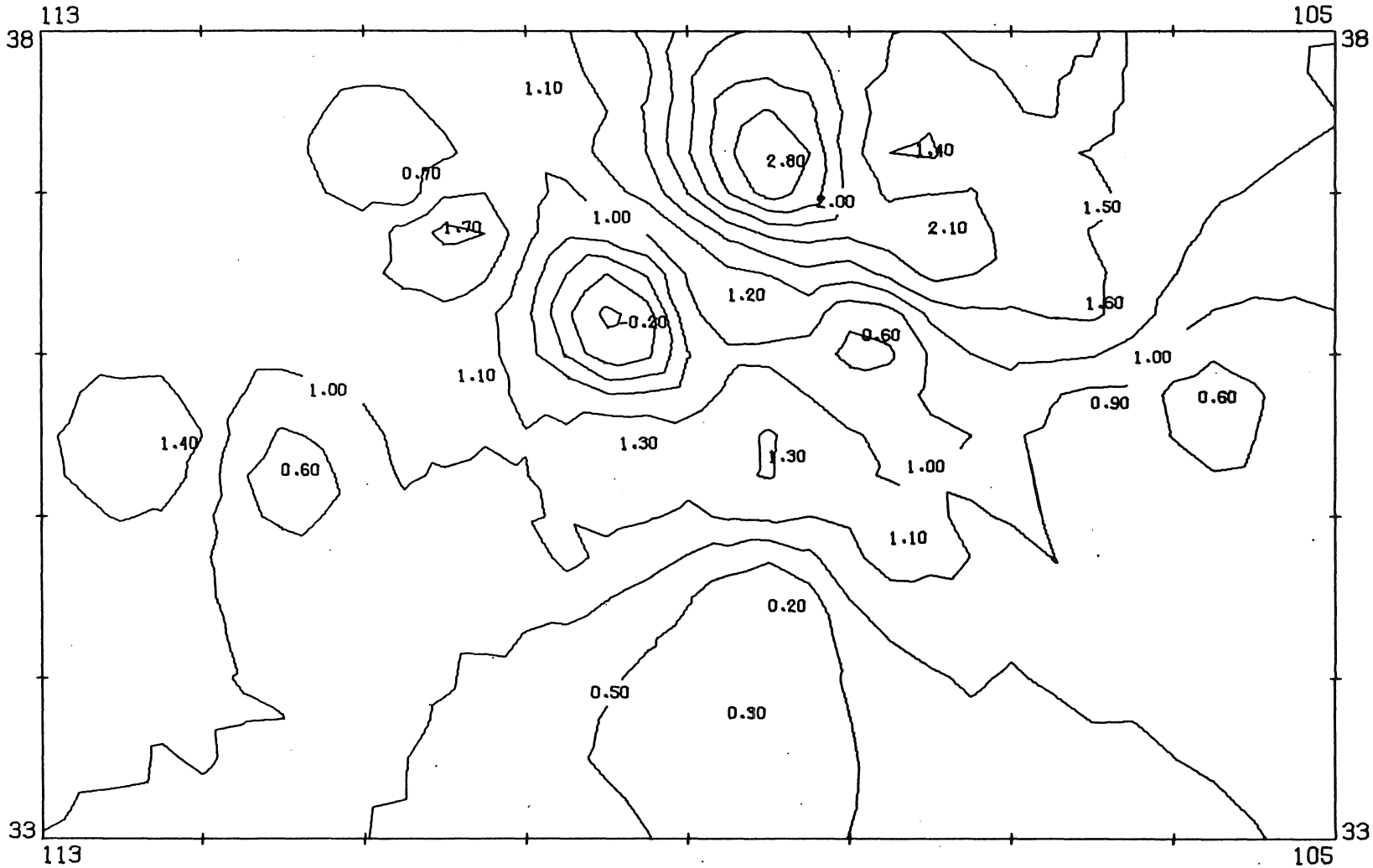
0900-0909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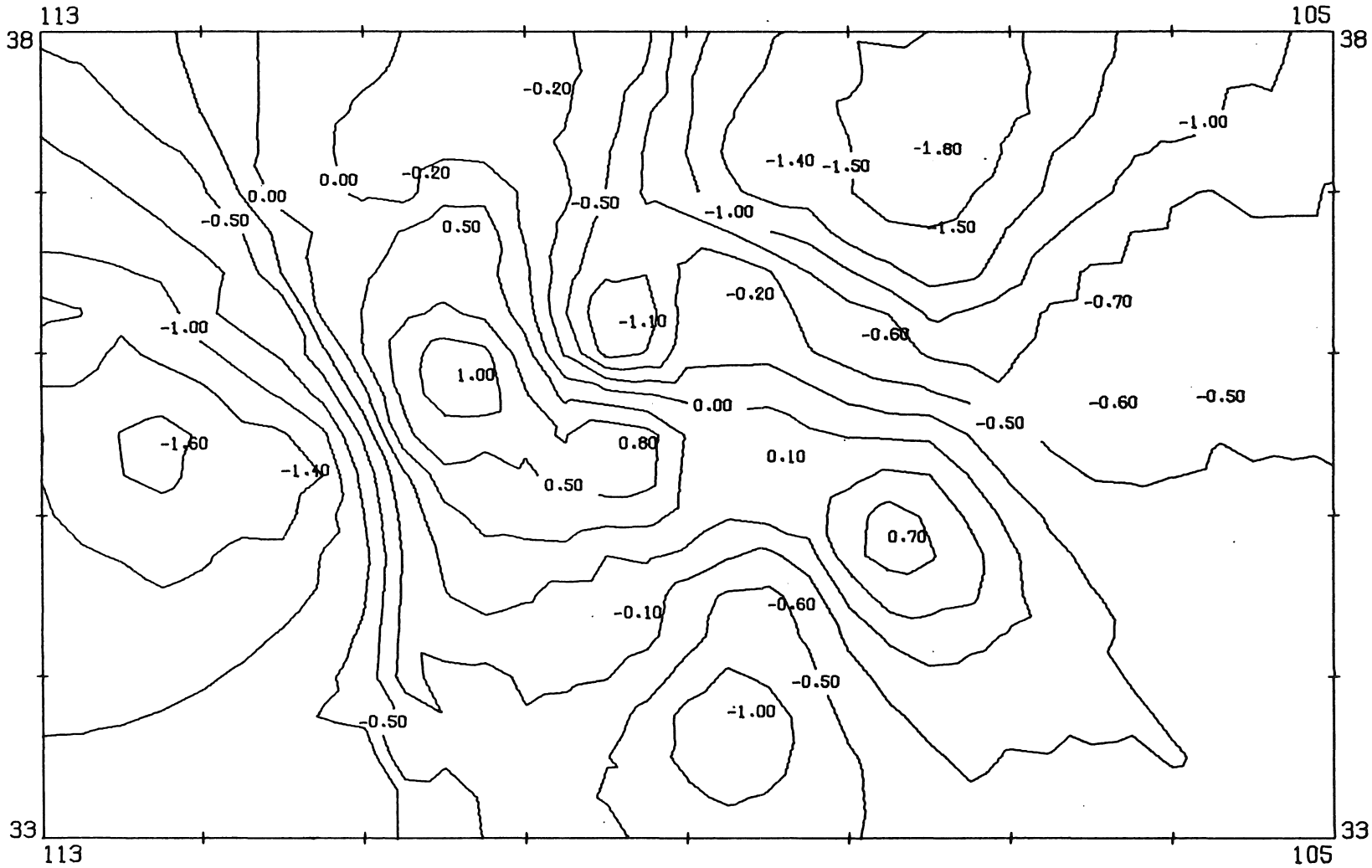
0910-0919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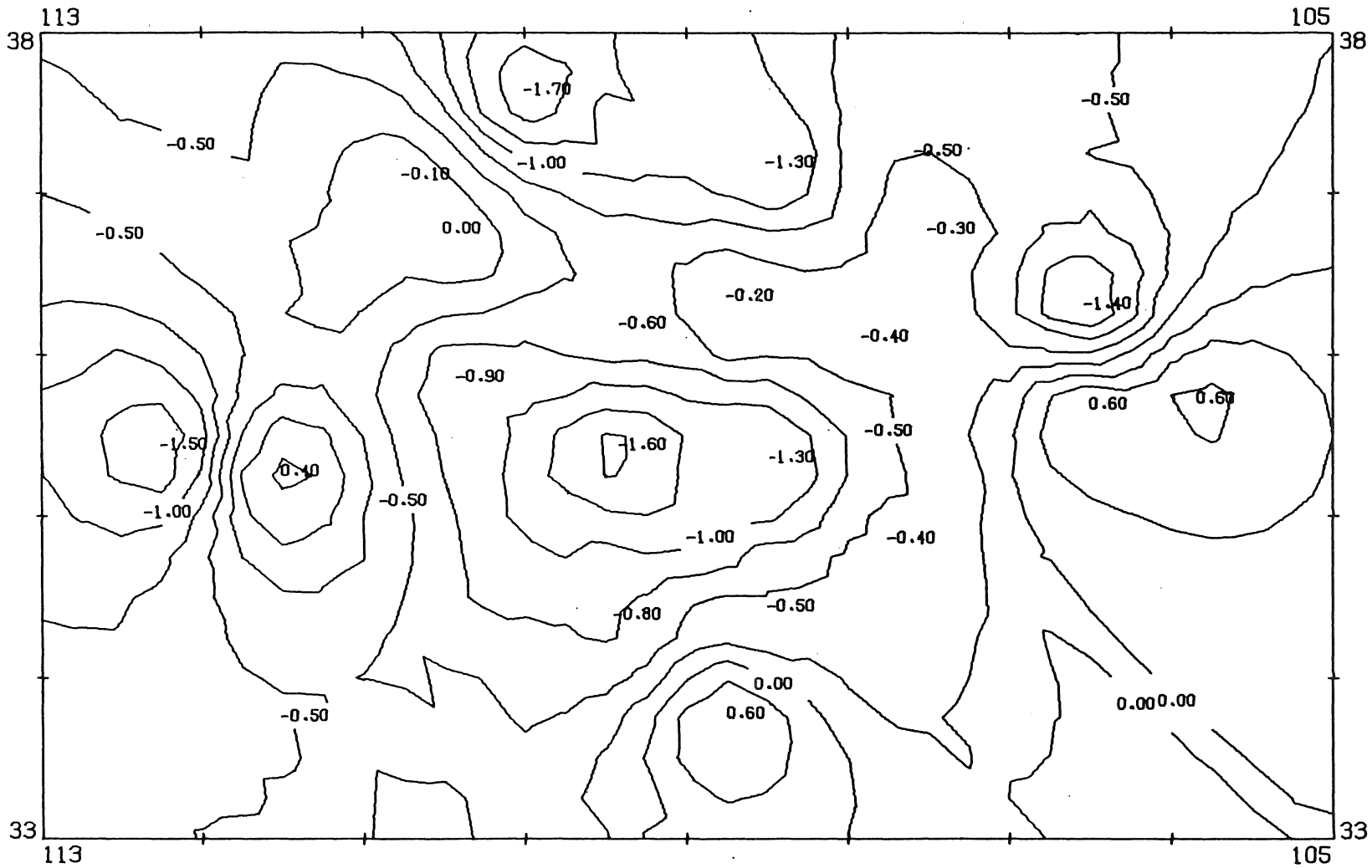
0920-0929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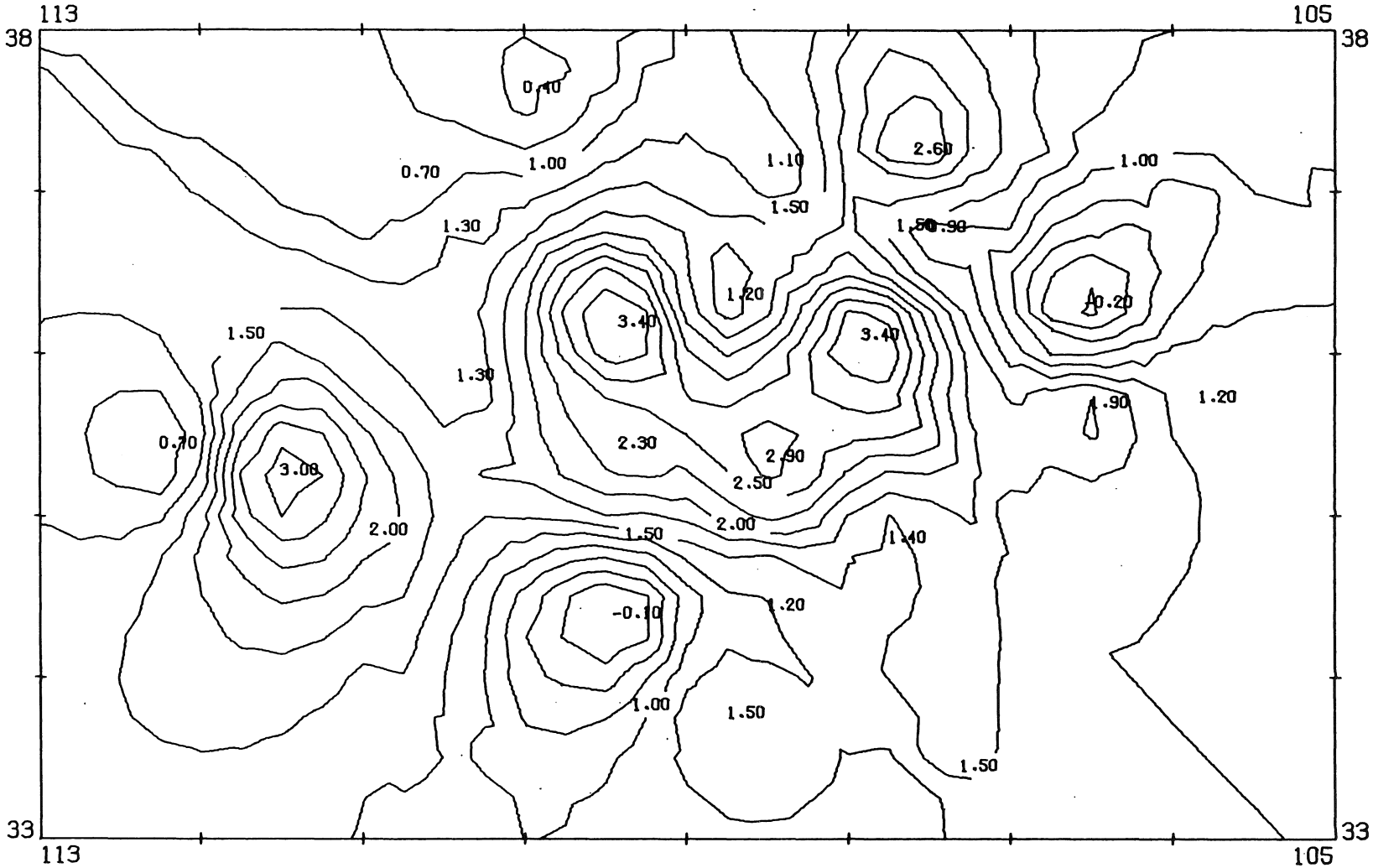
0930-0939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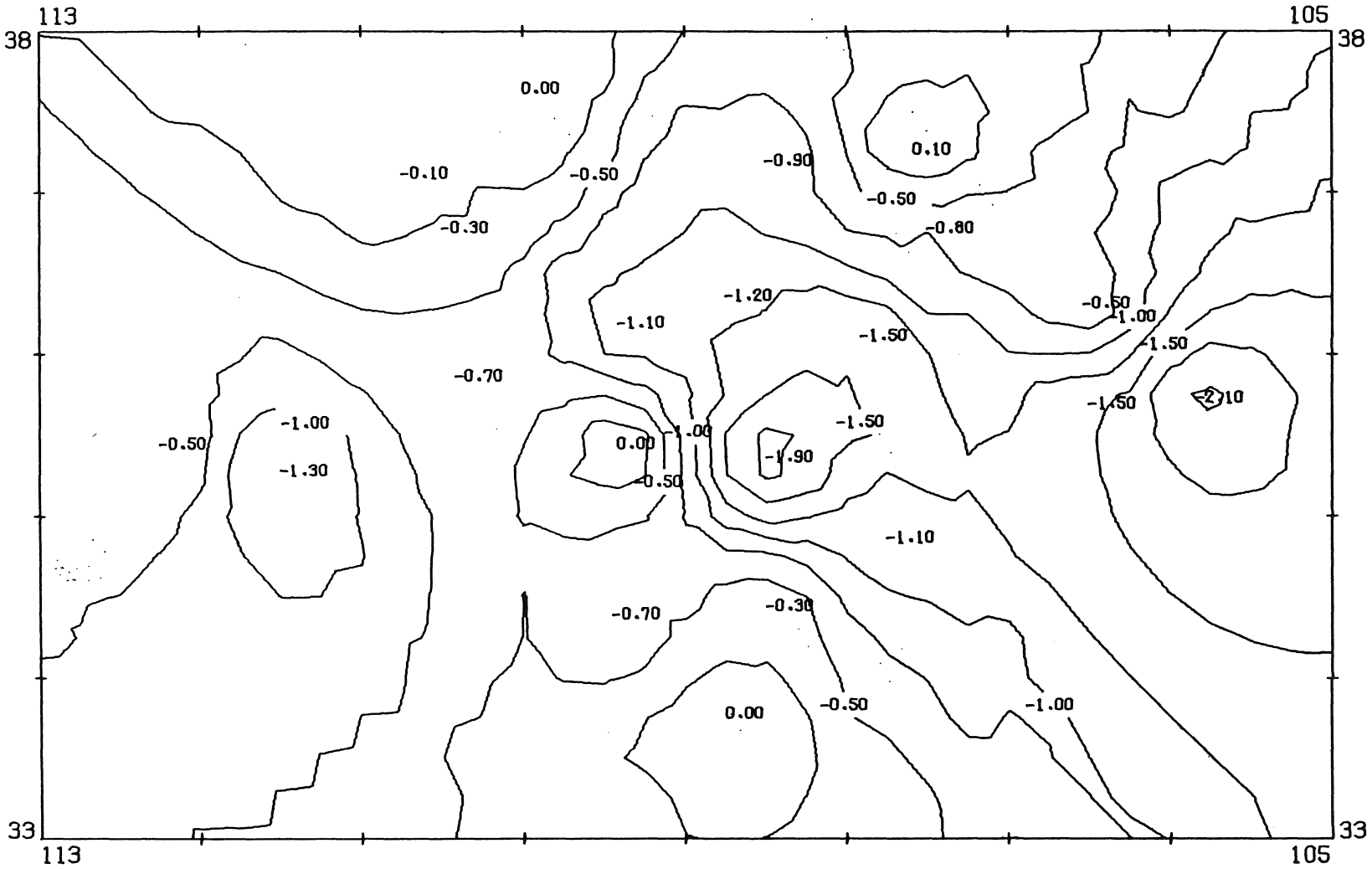
0940-0949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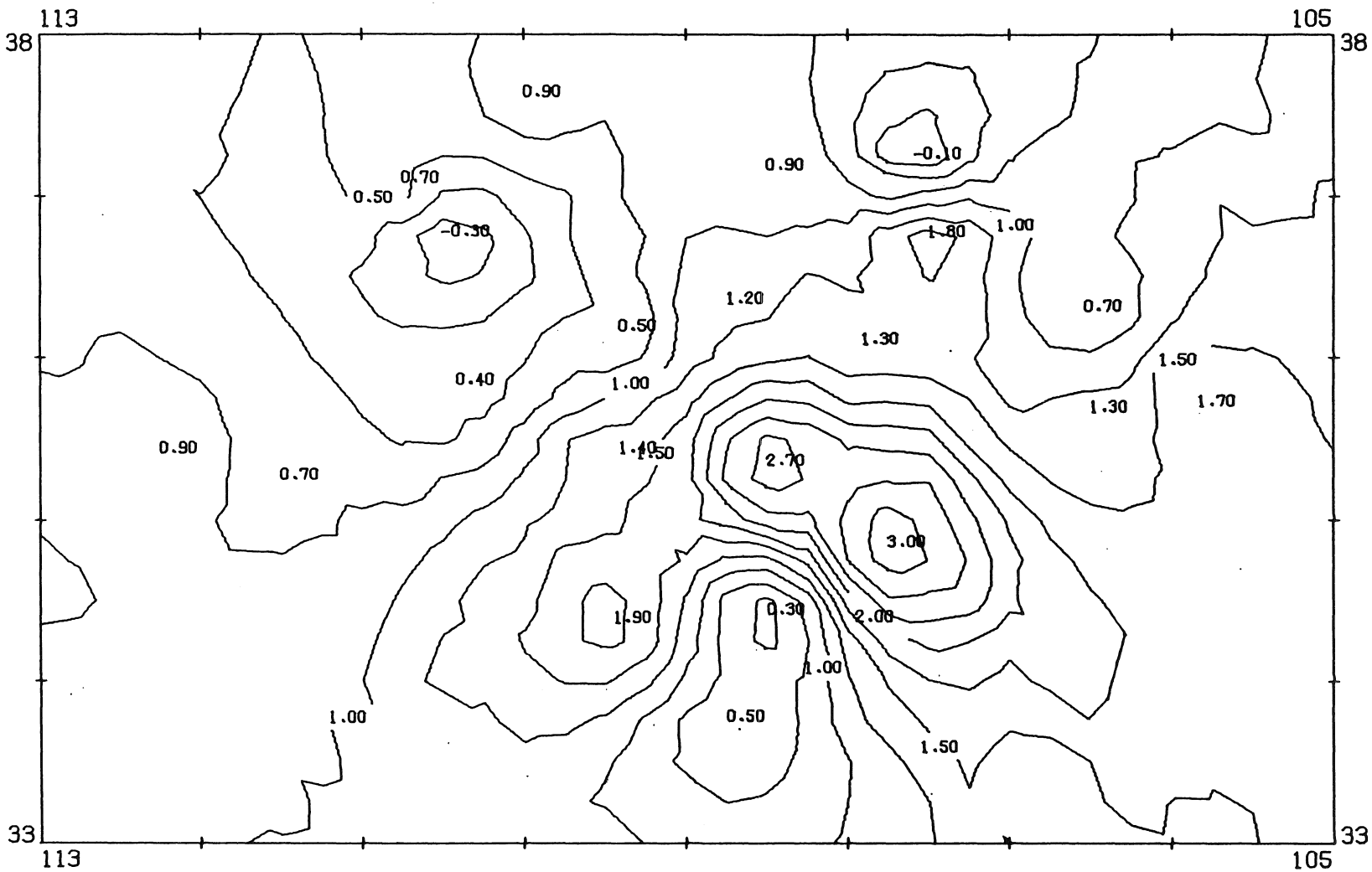
0950-0959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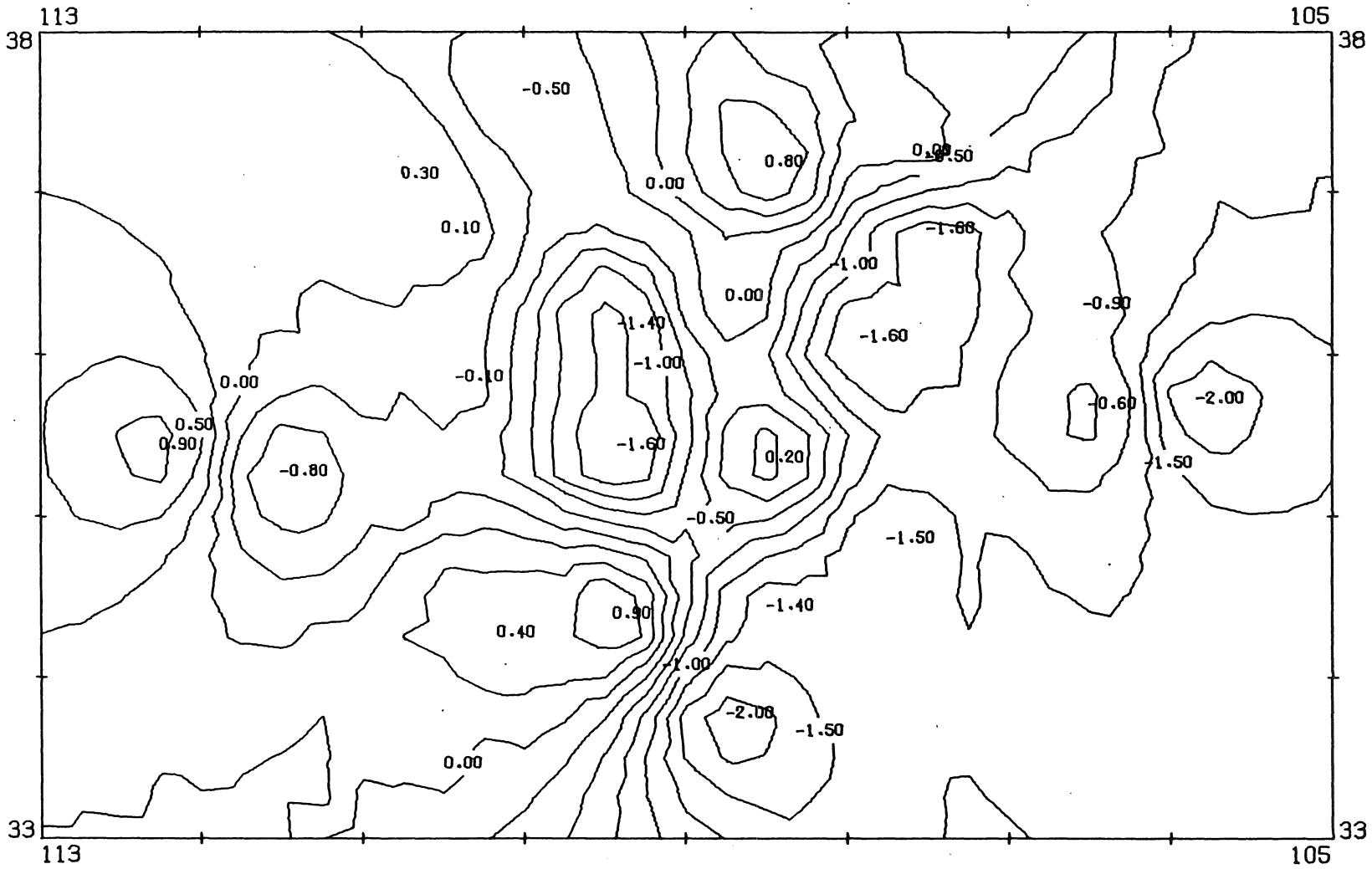
0960-0969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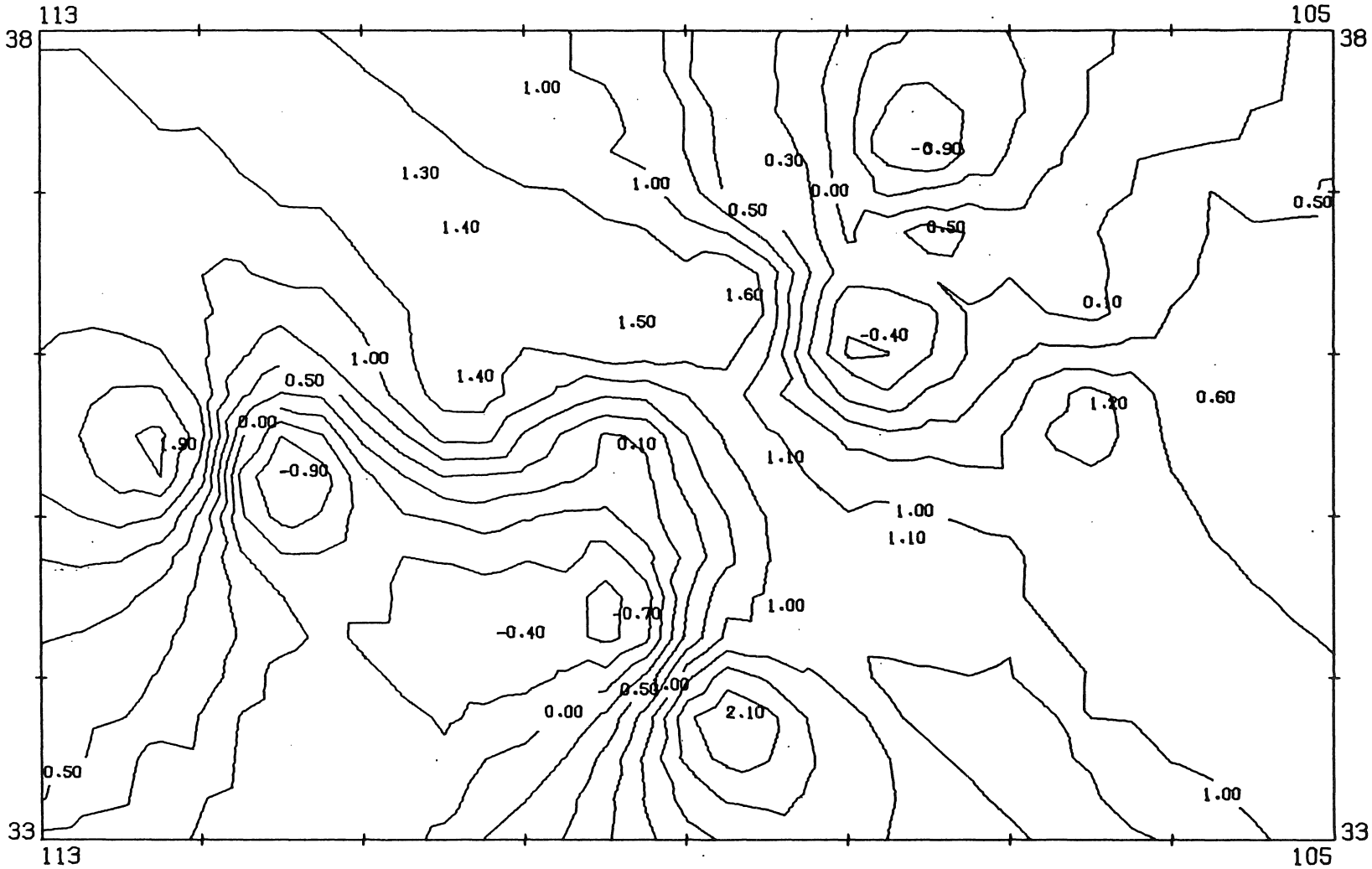
0970-0979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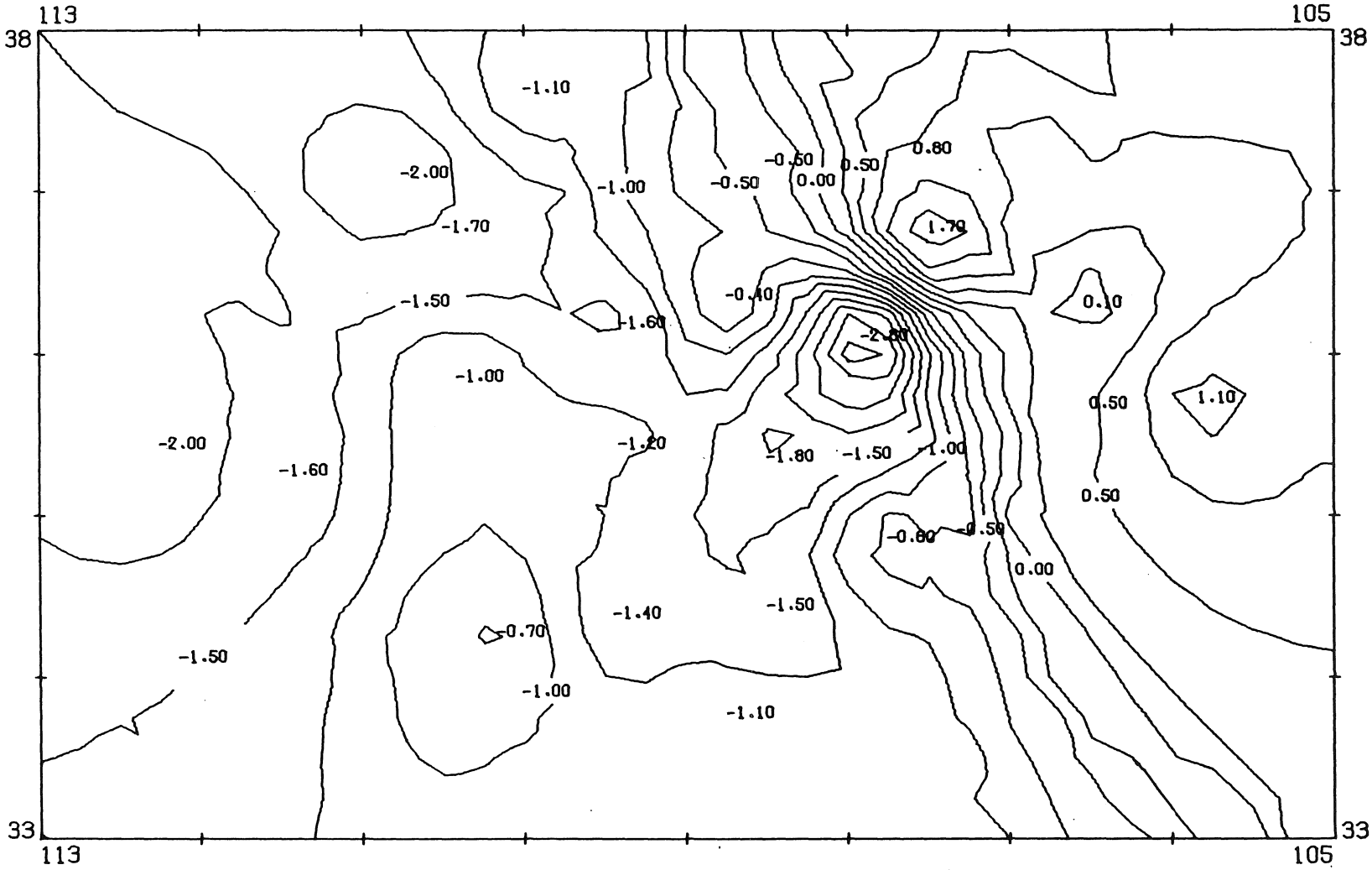
0980-0989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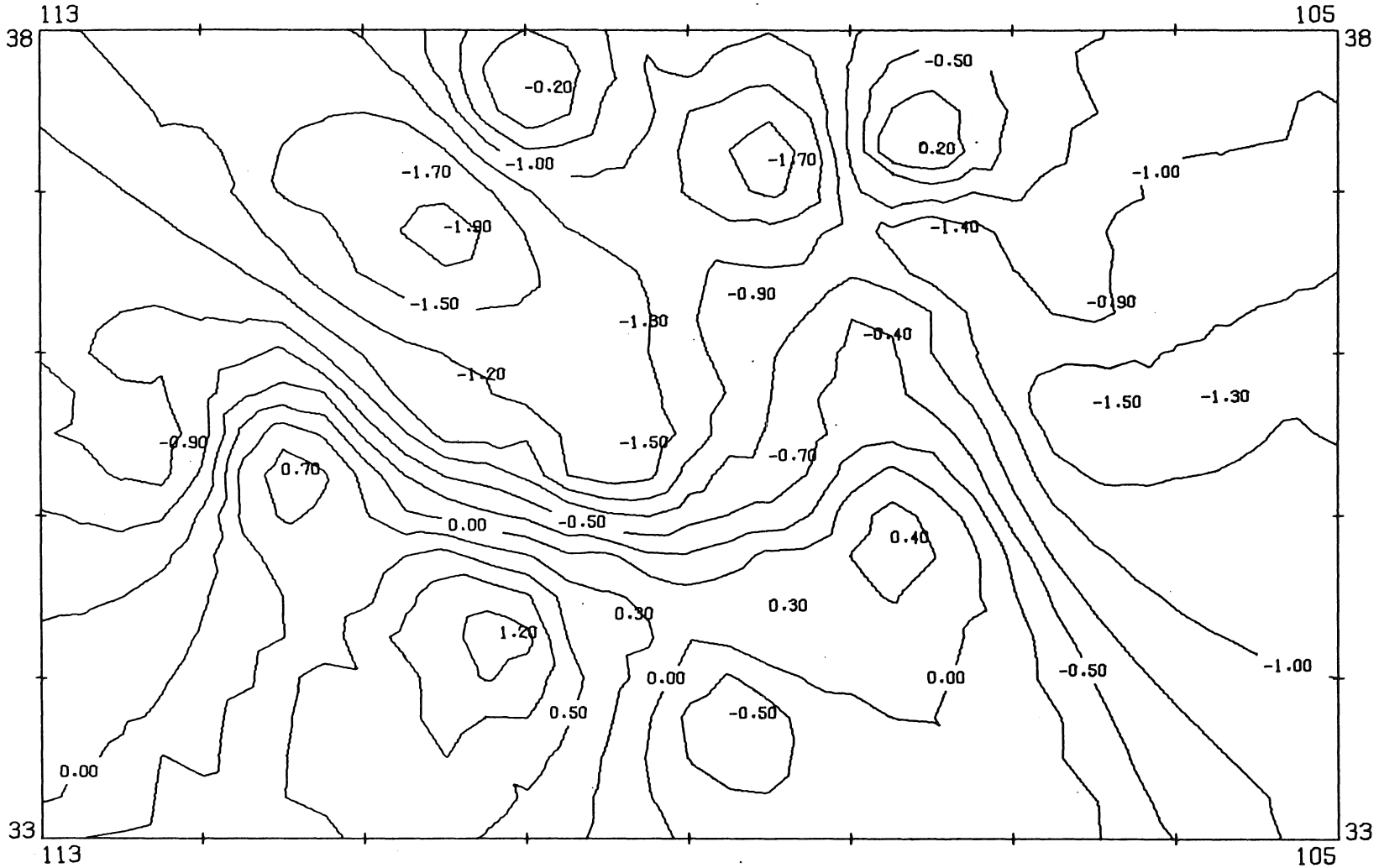
0990-0999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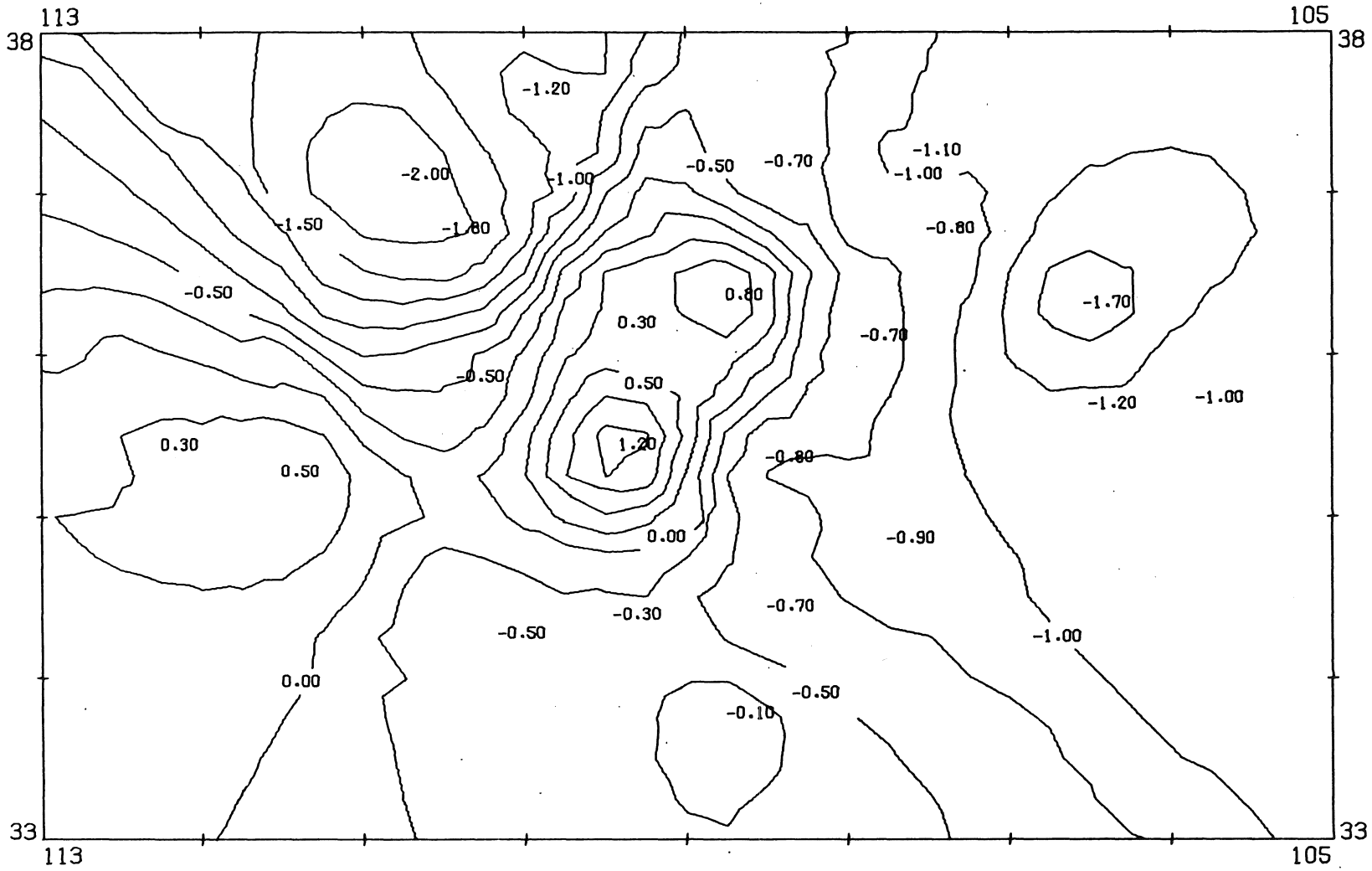
113
105

1000-1009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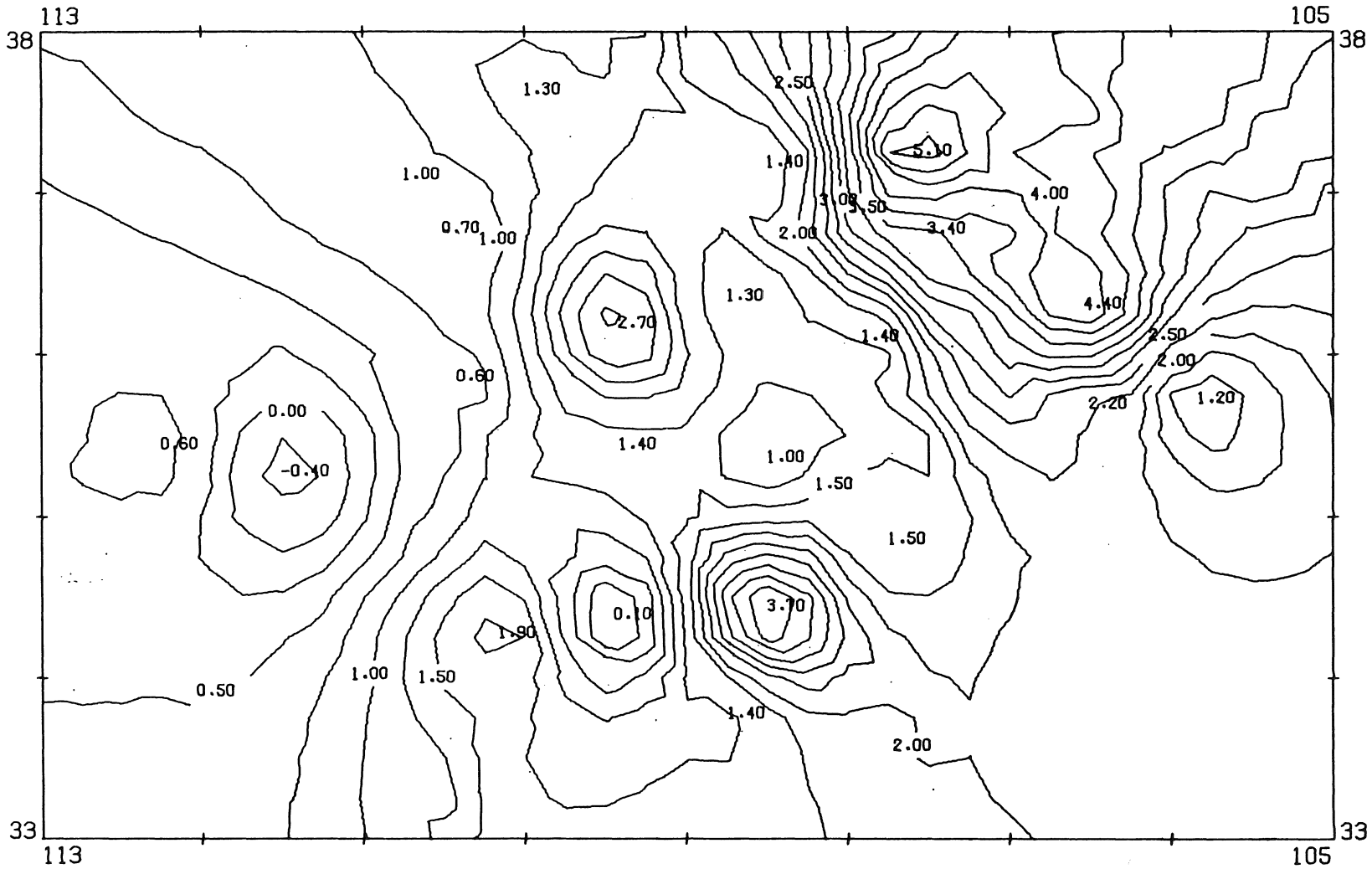
1010-1019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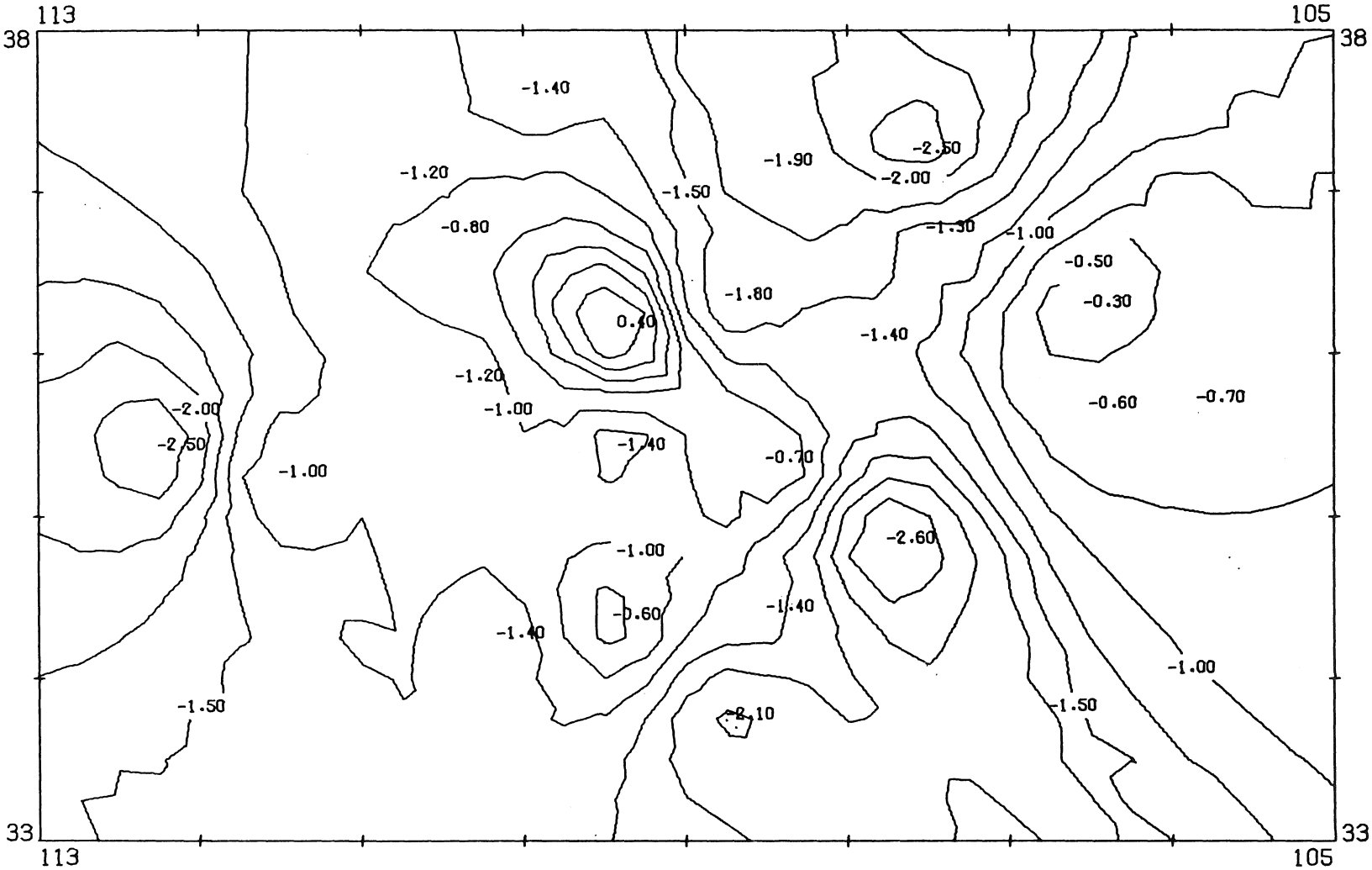
2.00

1020-1029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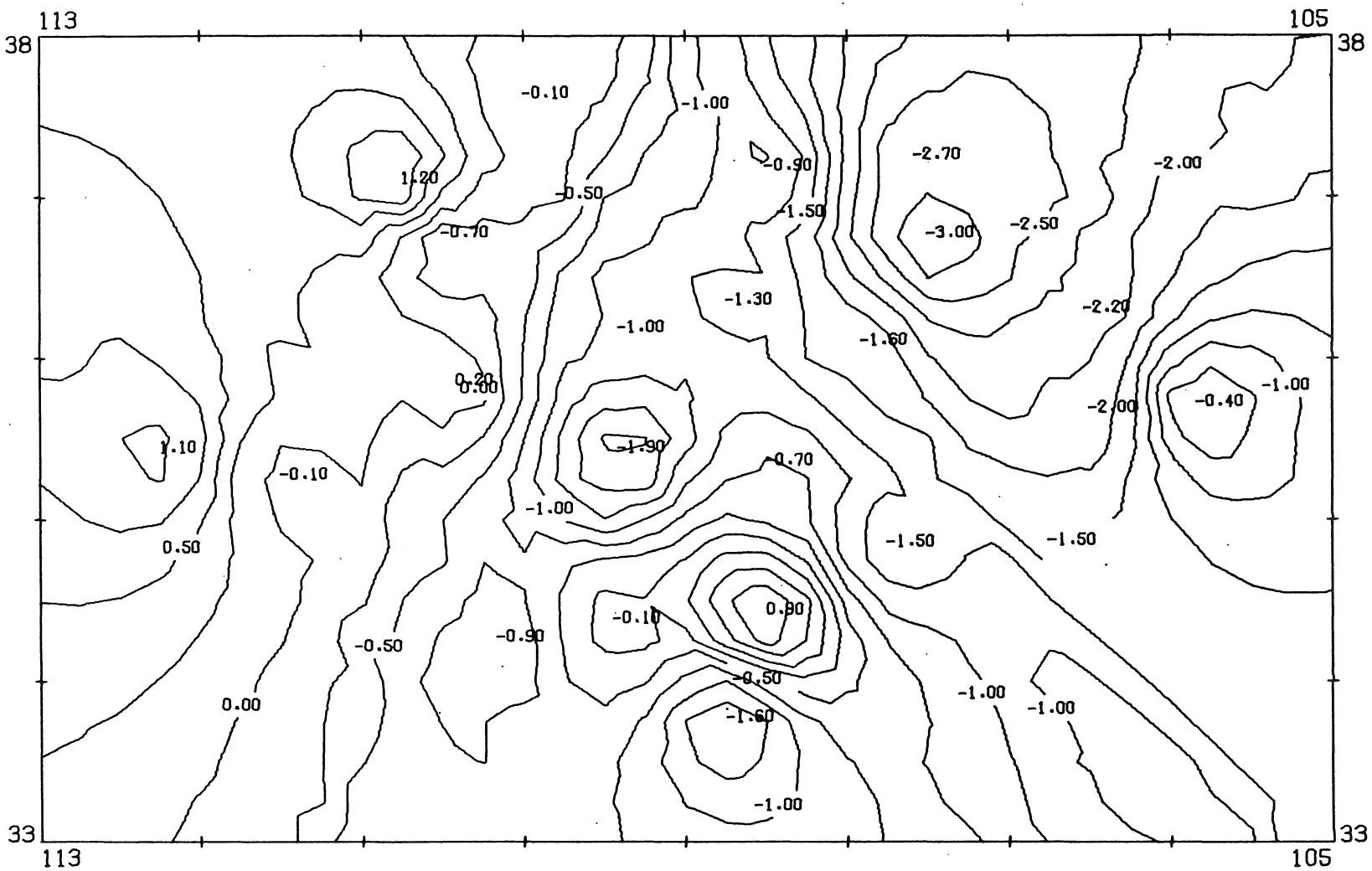
1030-1039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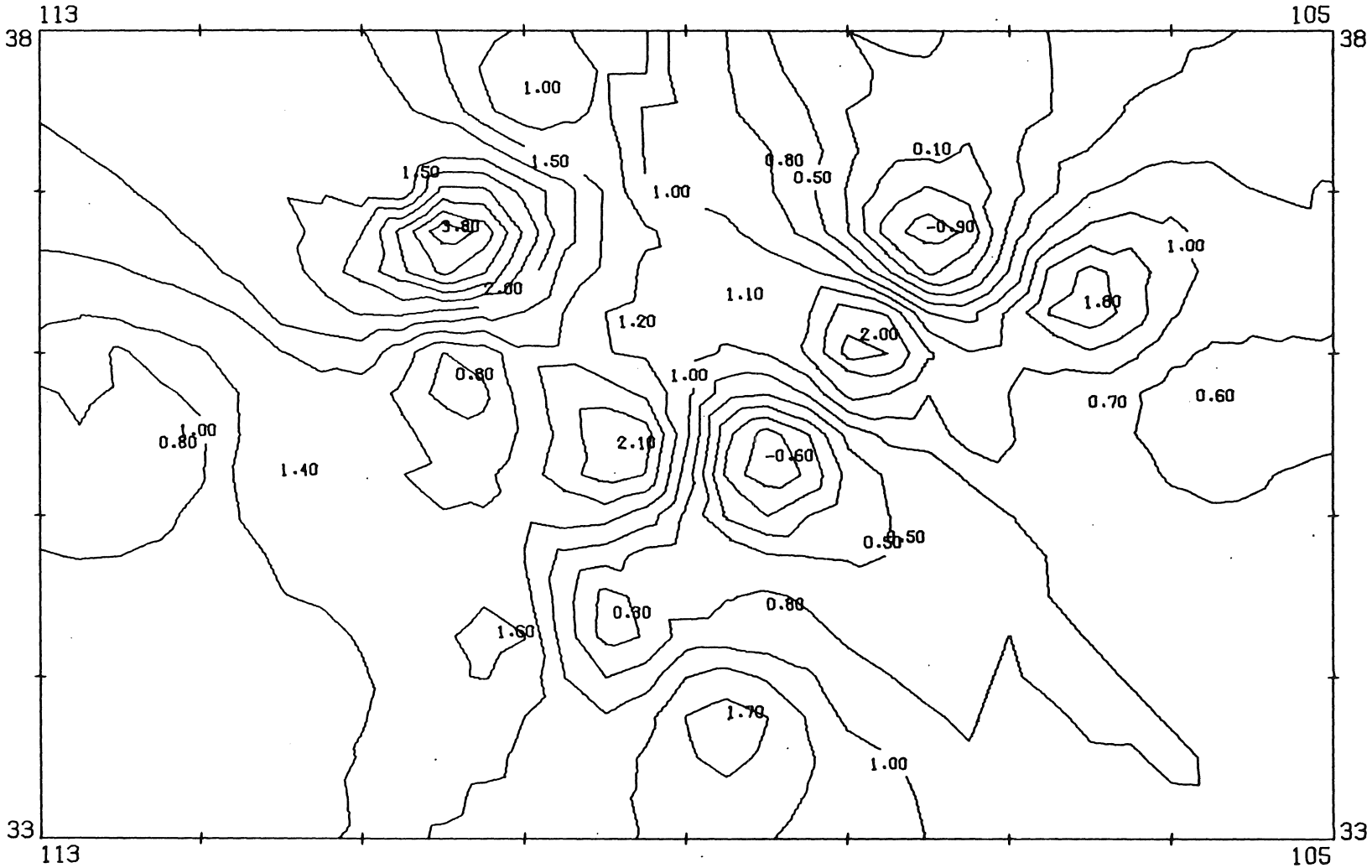
1040-1049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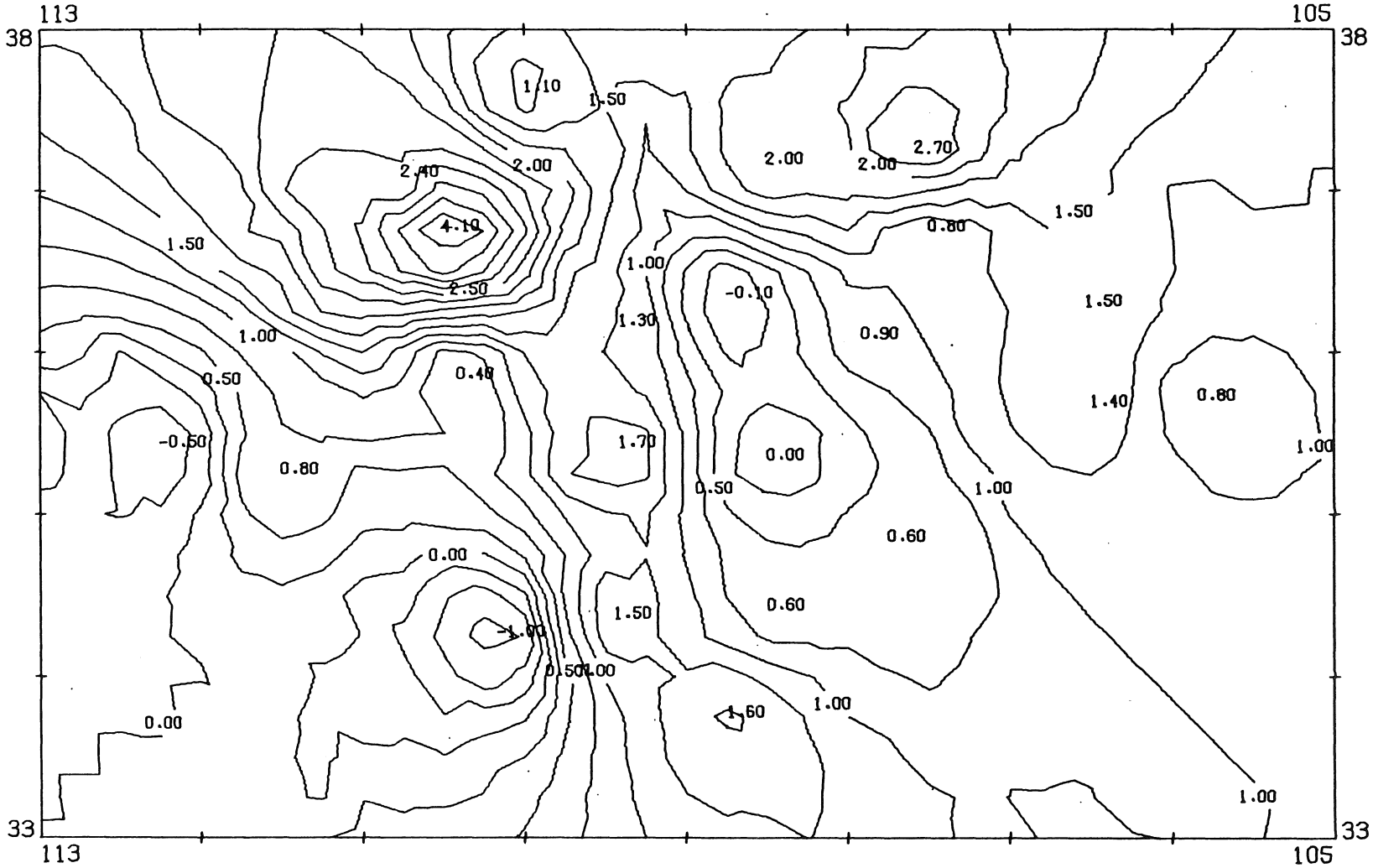
1050-1059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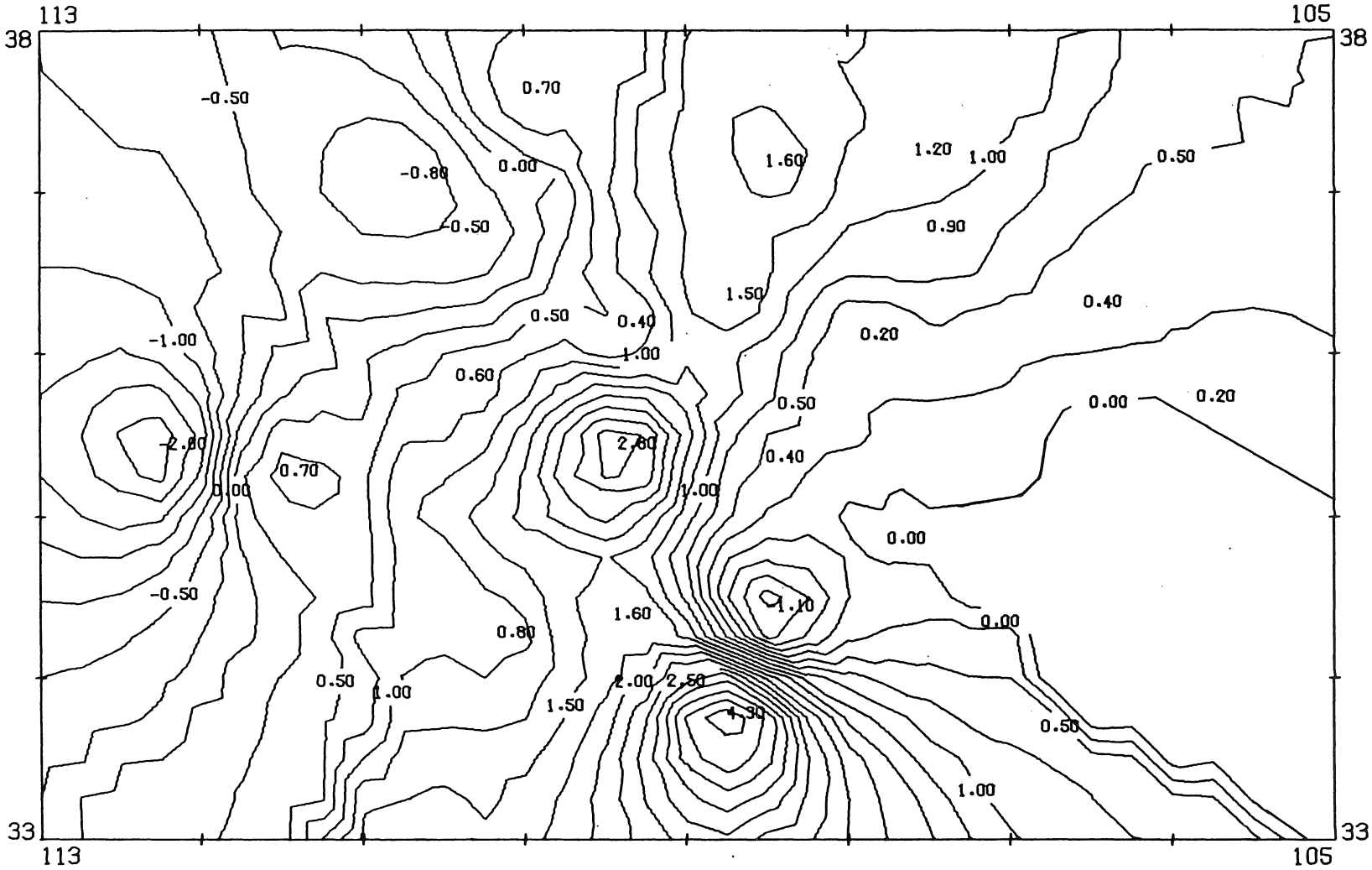
1060-1069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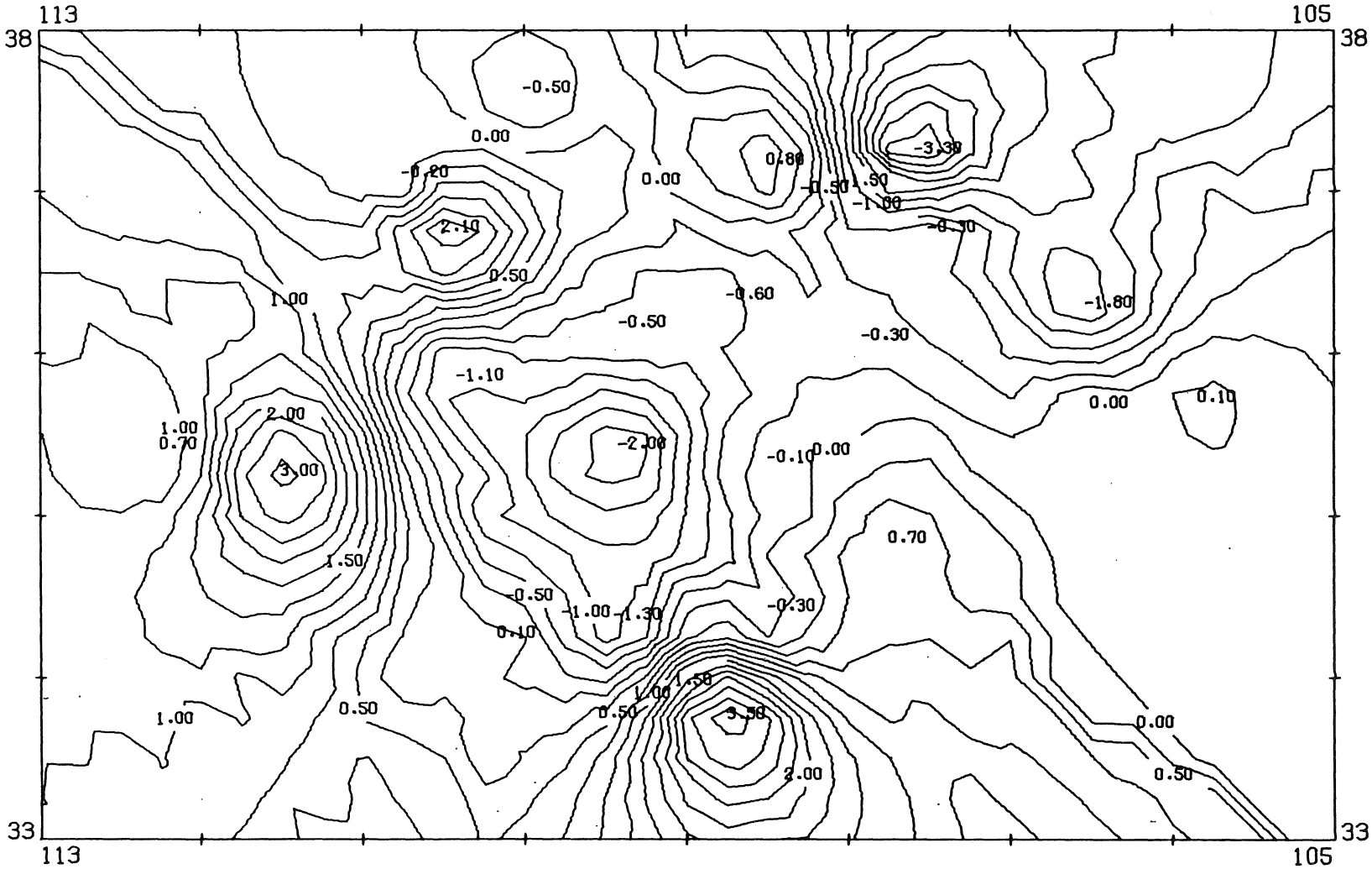
1070-1079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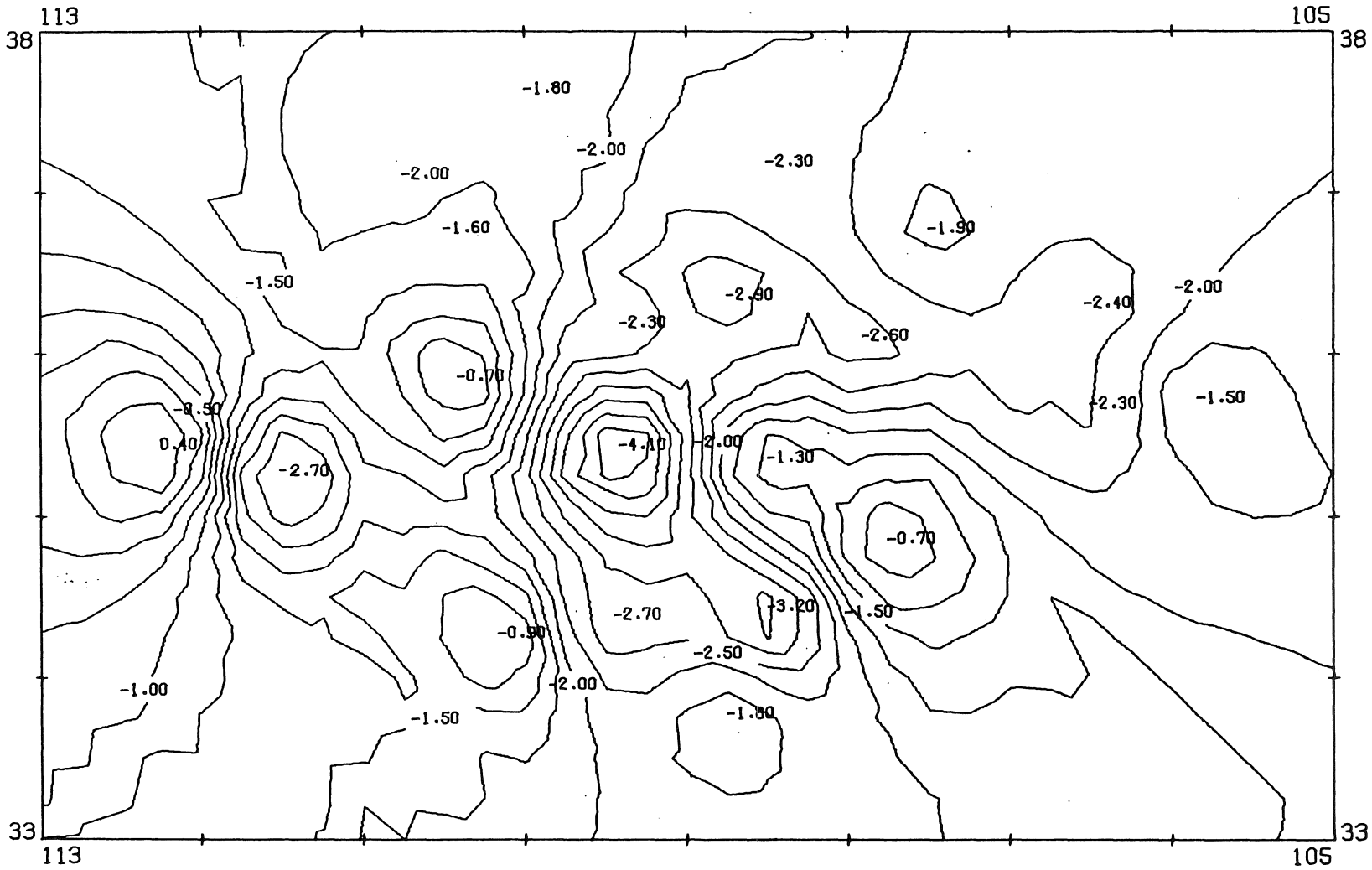
1080-1089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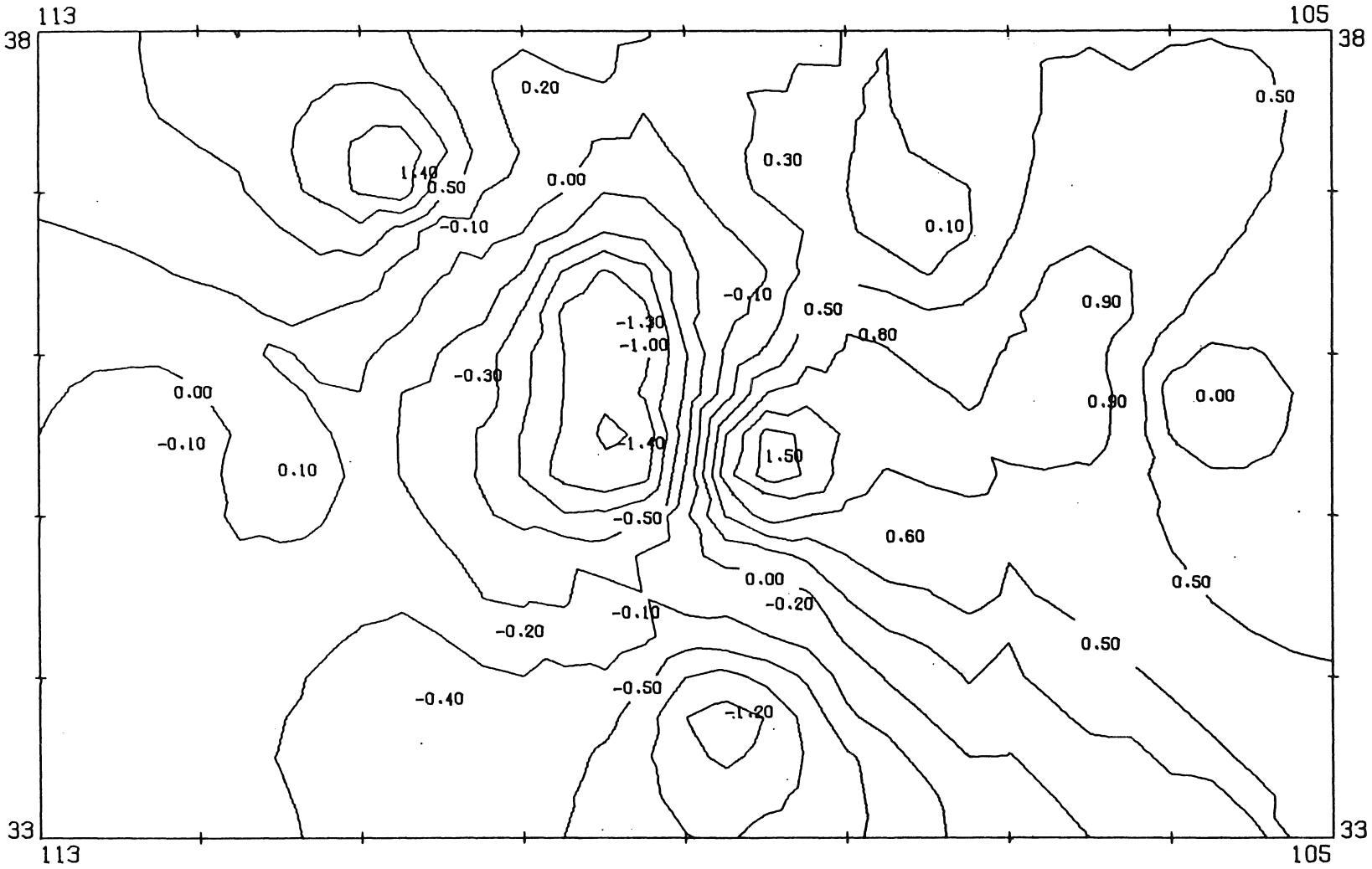
1090-1099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-0.10
0.50
0.90
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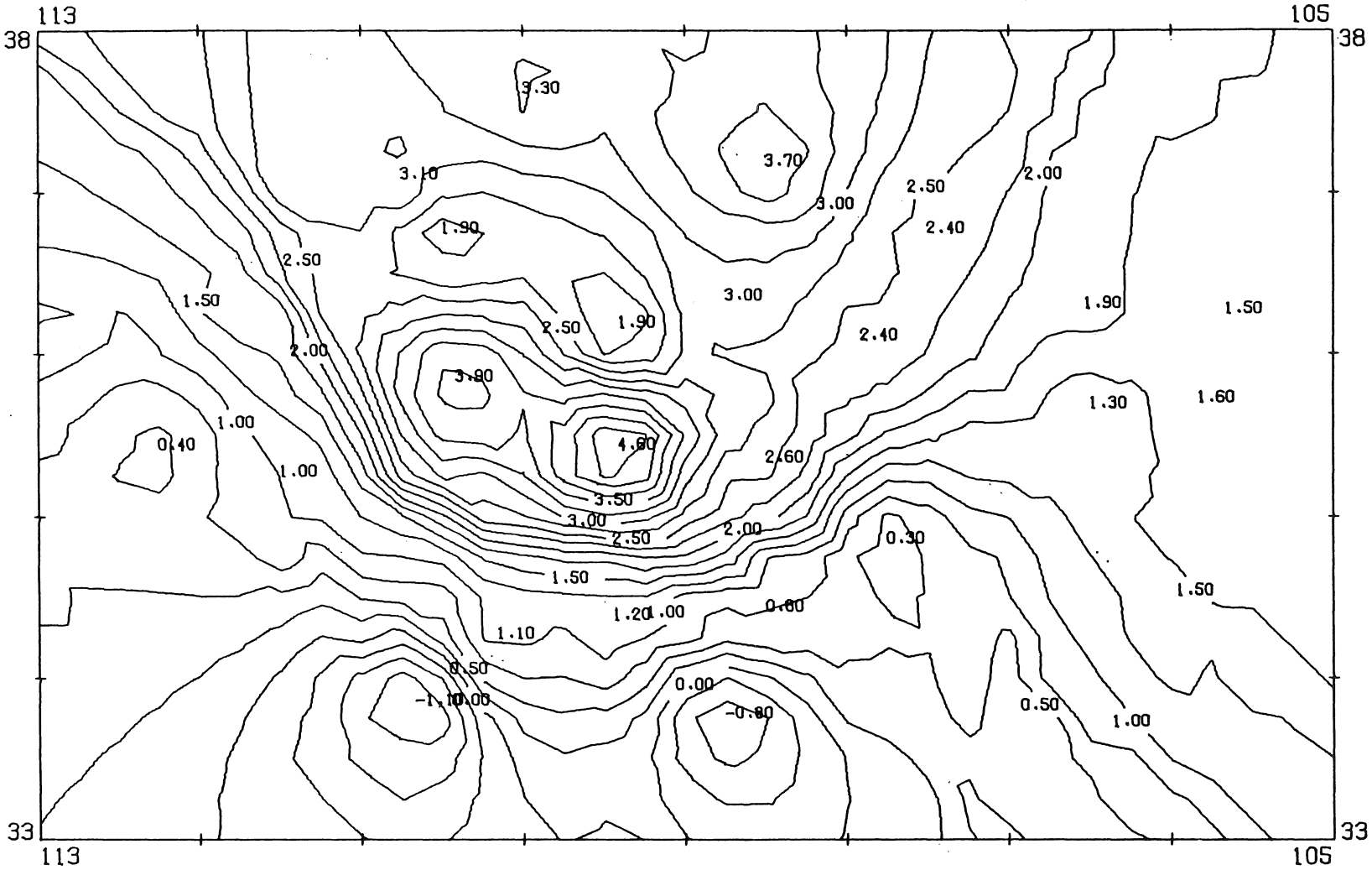
1100-1109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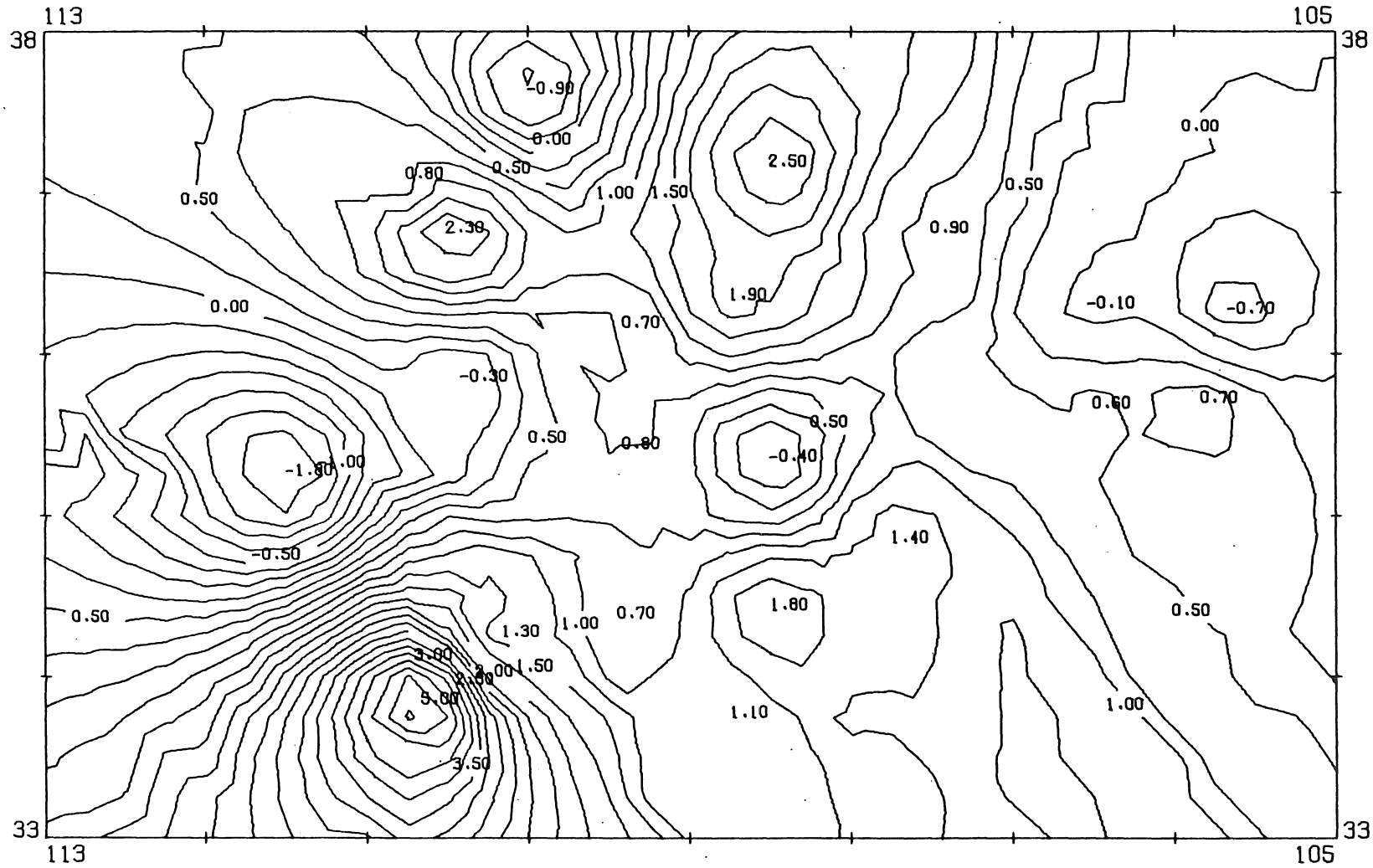
1110-1119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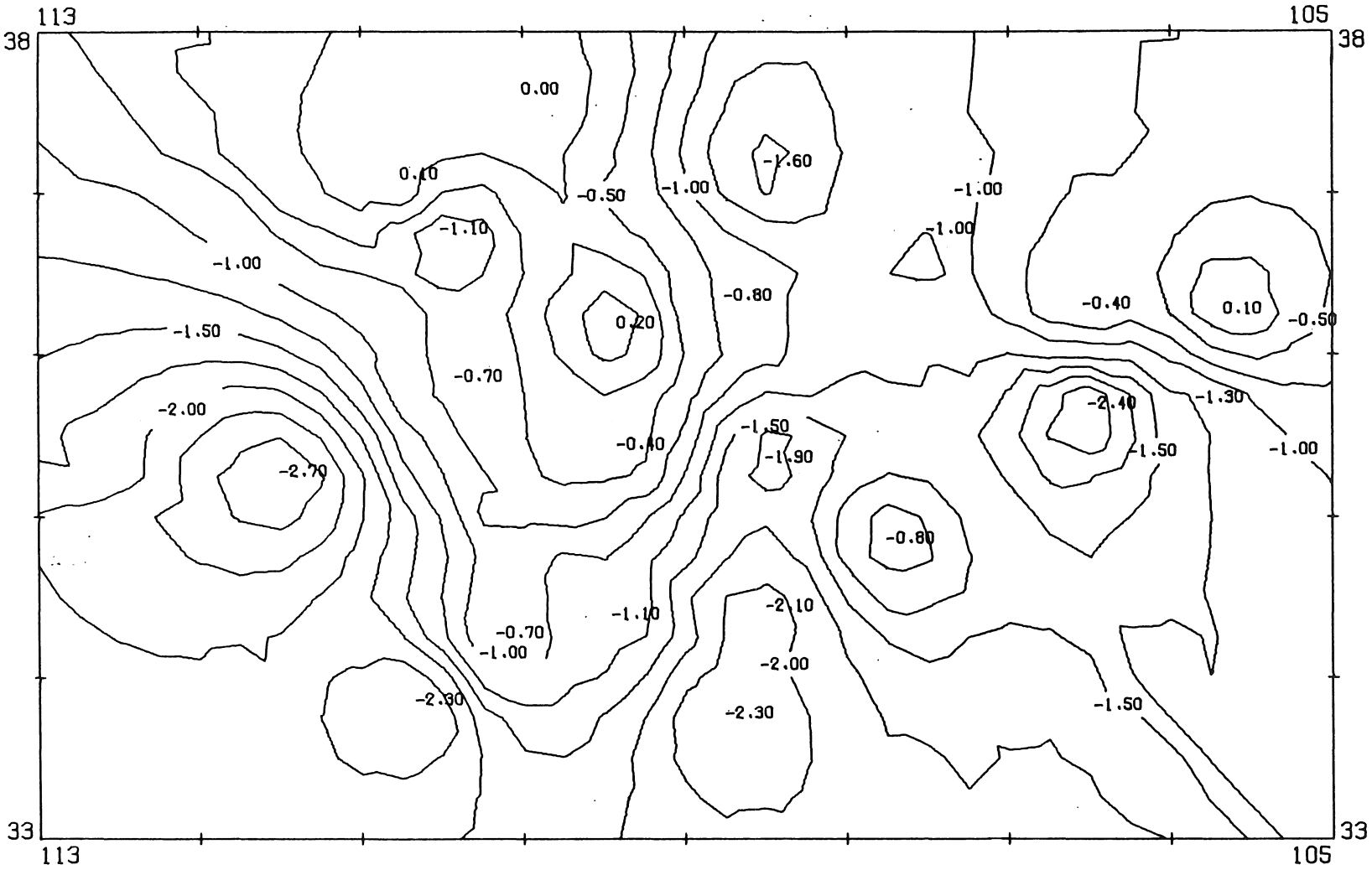
3.50

1120-1129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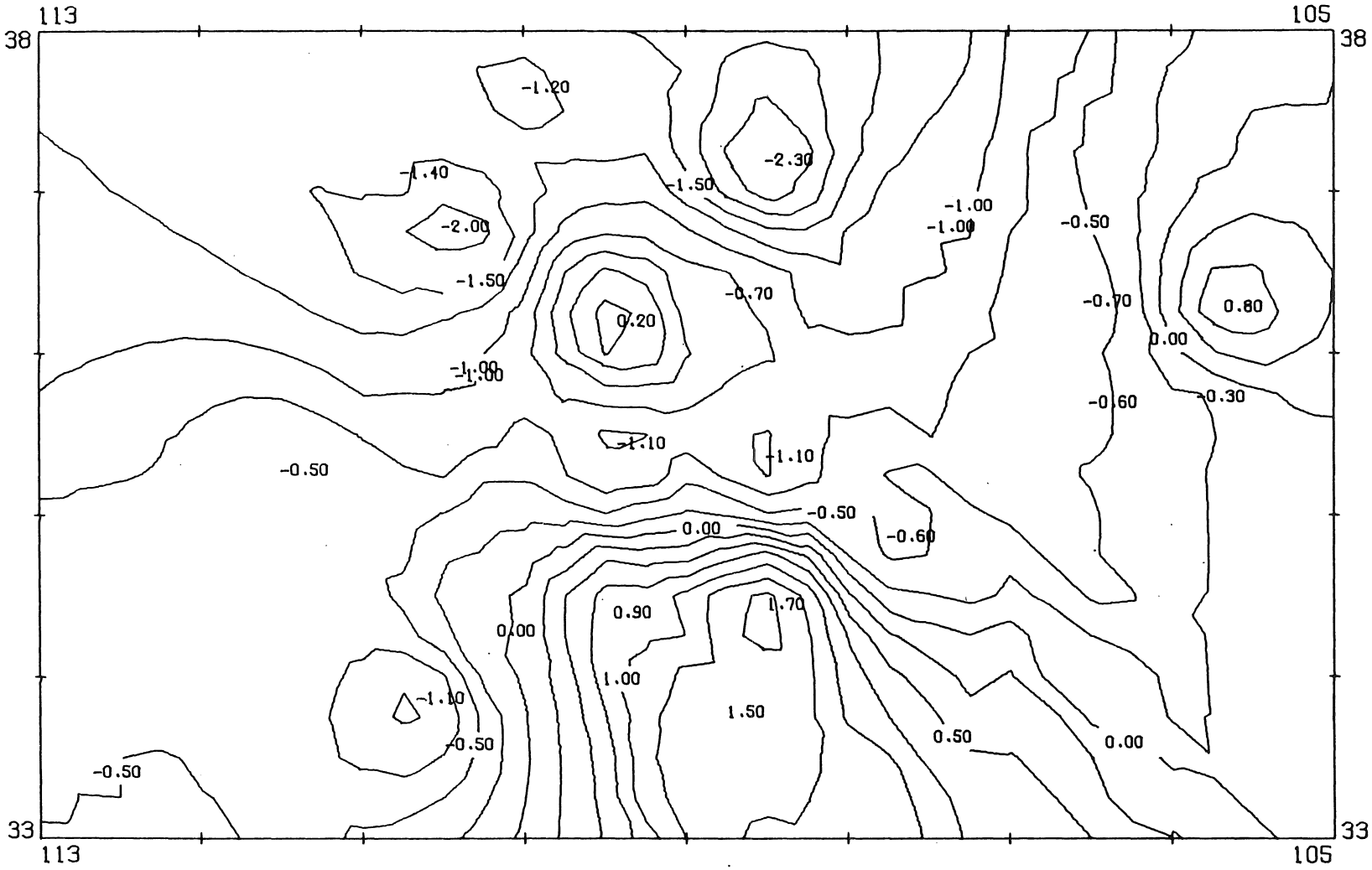
1130-1139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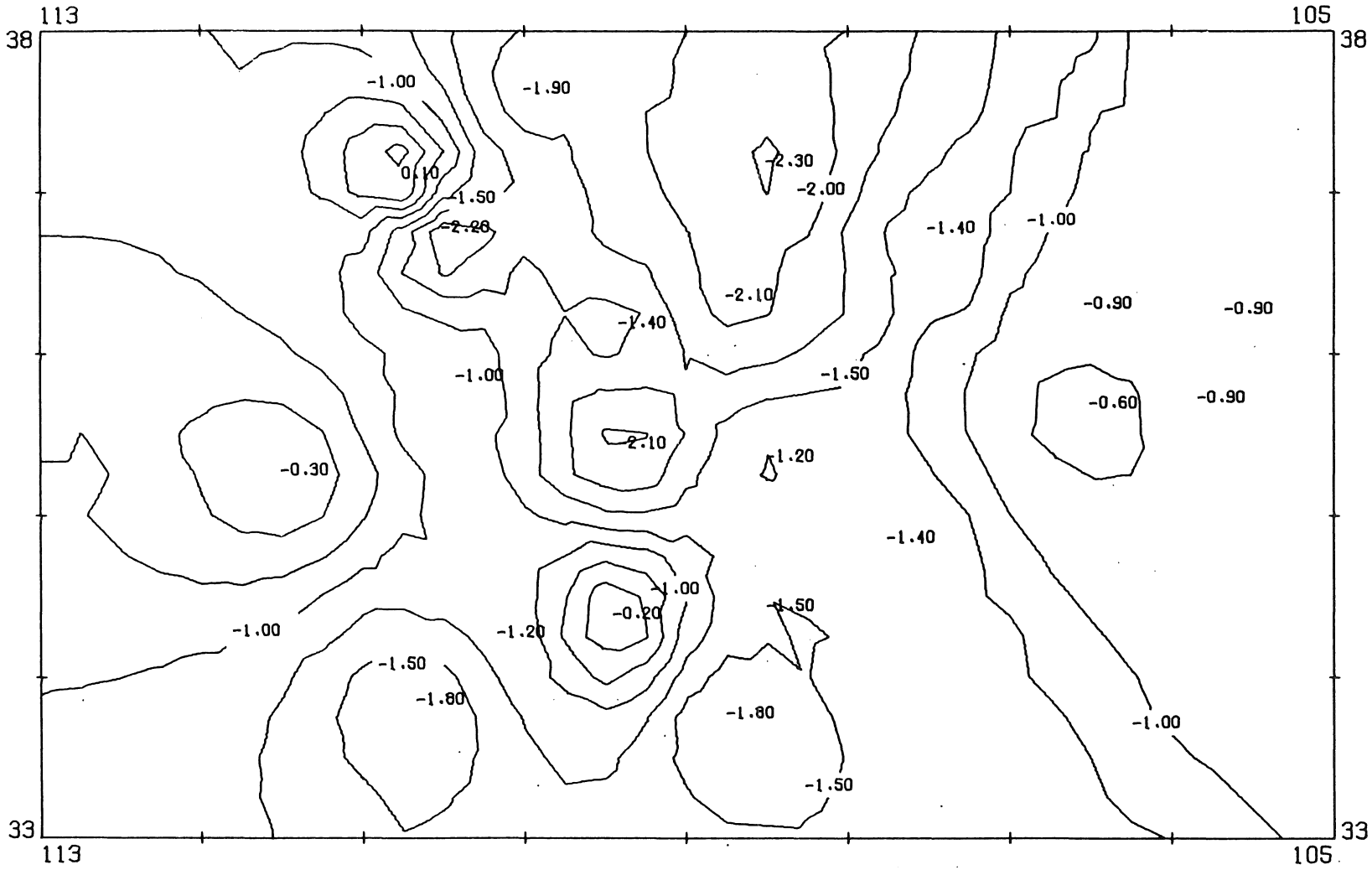
1140-1149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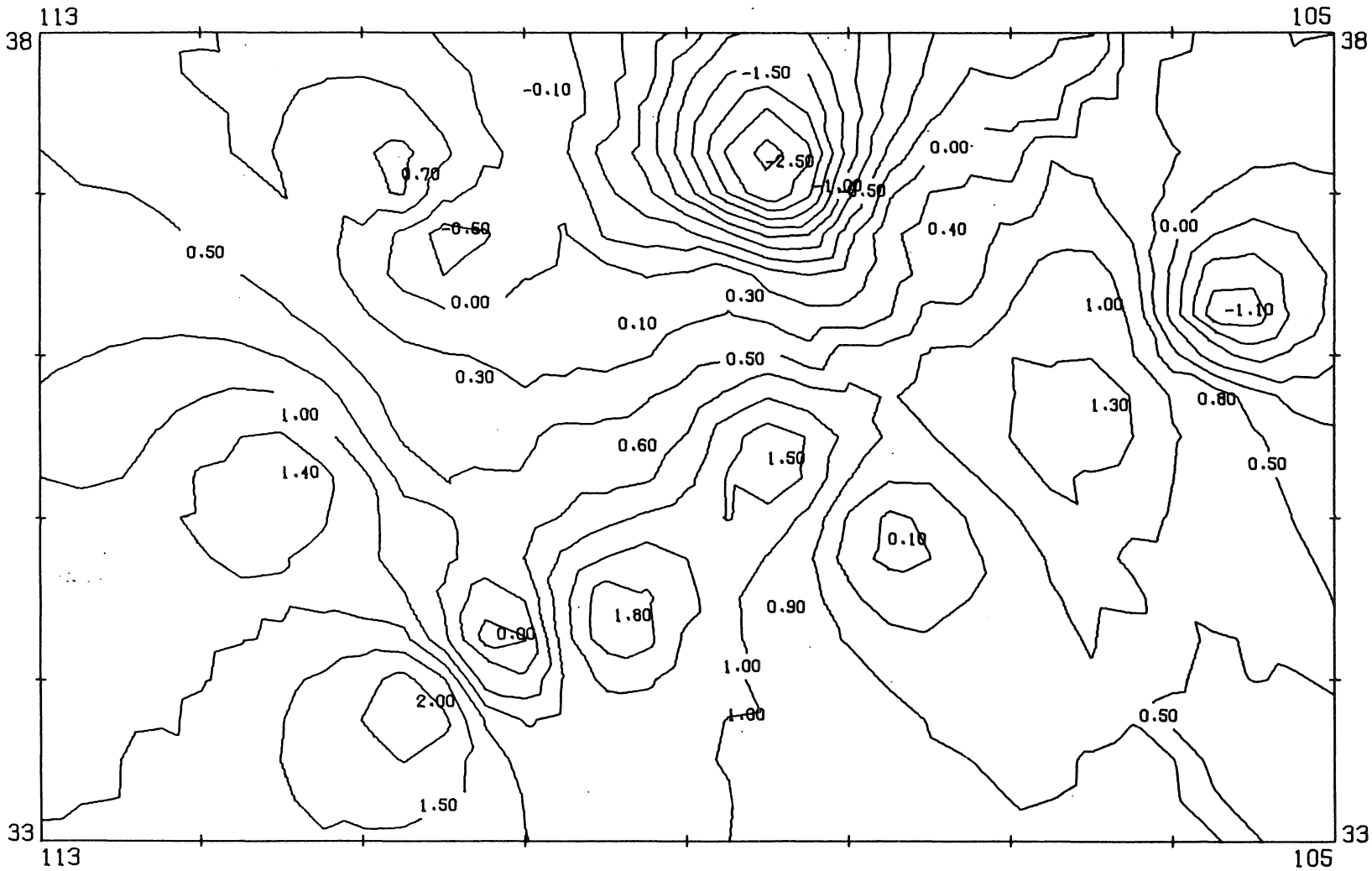
1150-1159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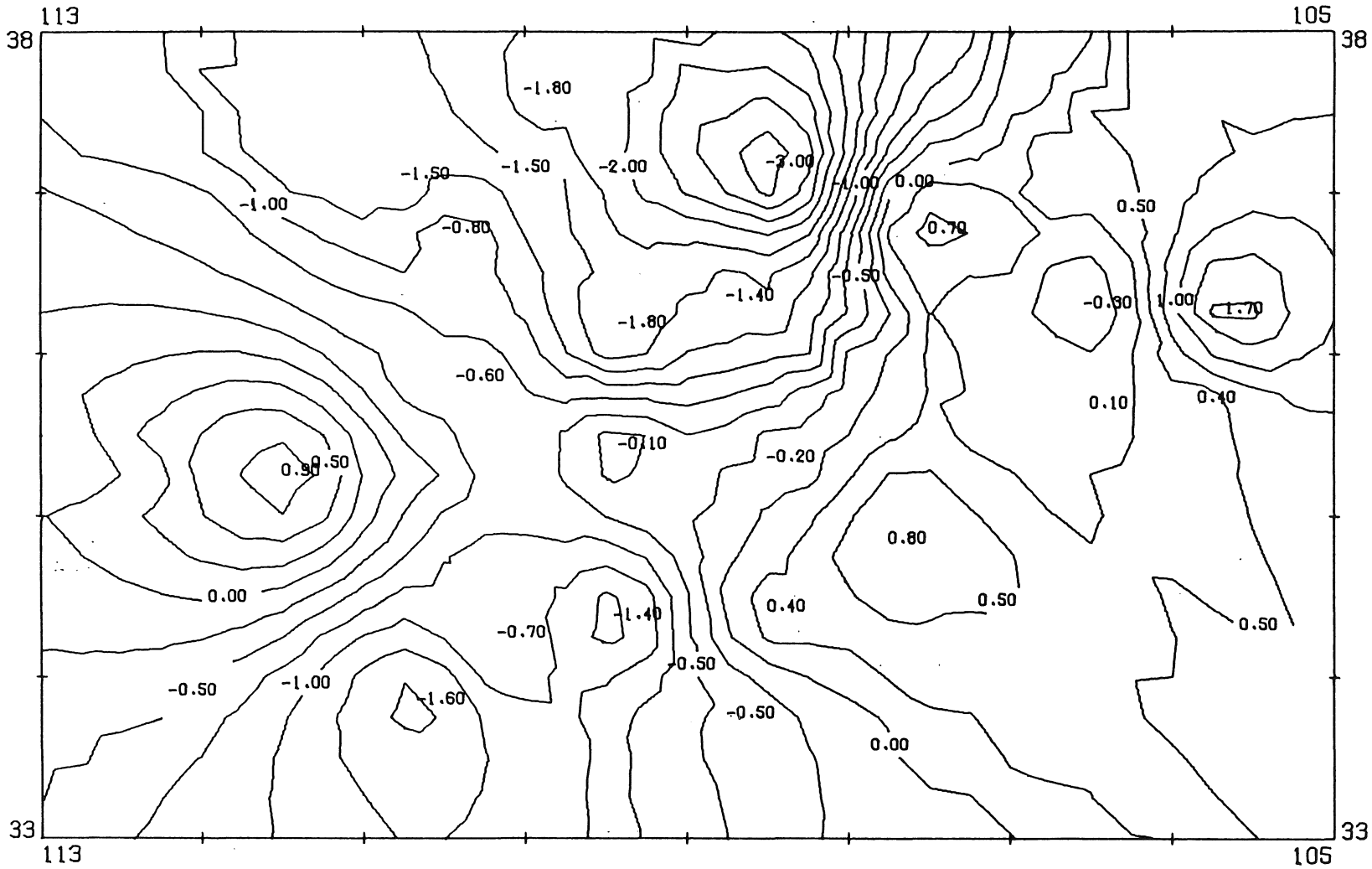
1160-1169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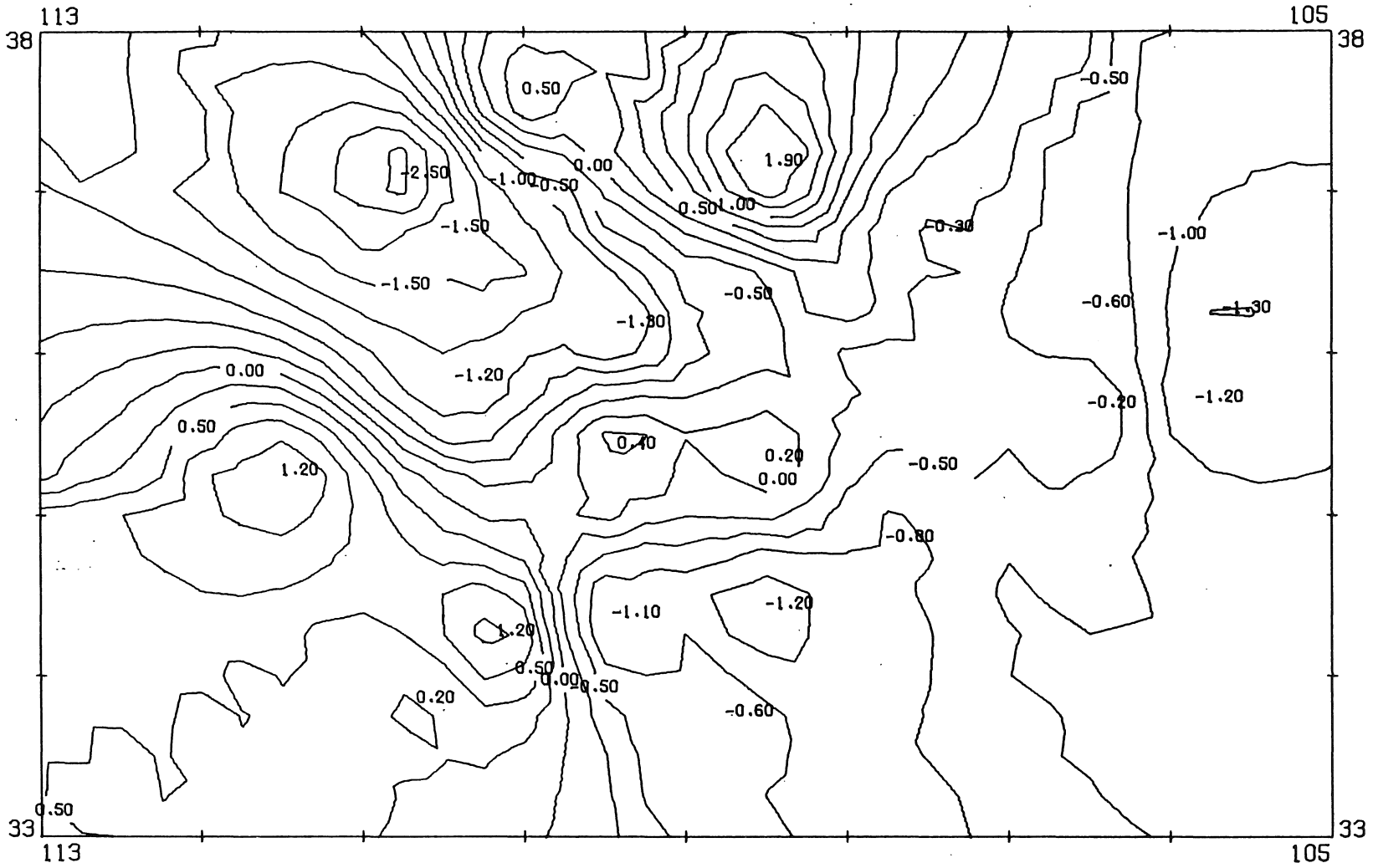
1170-1179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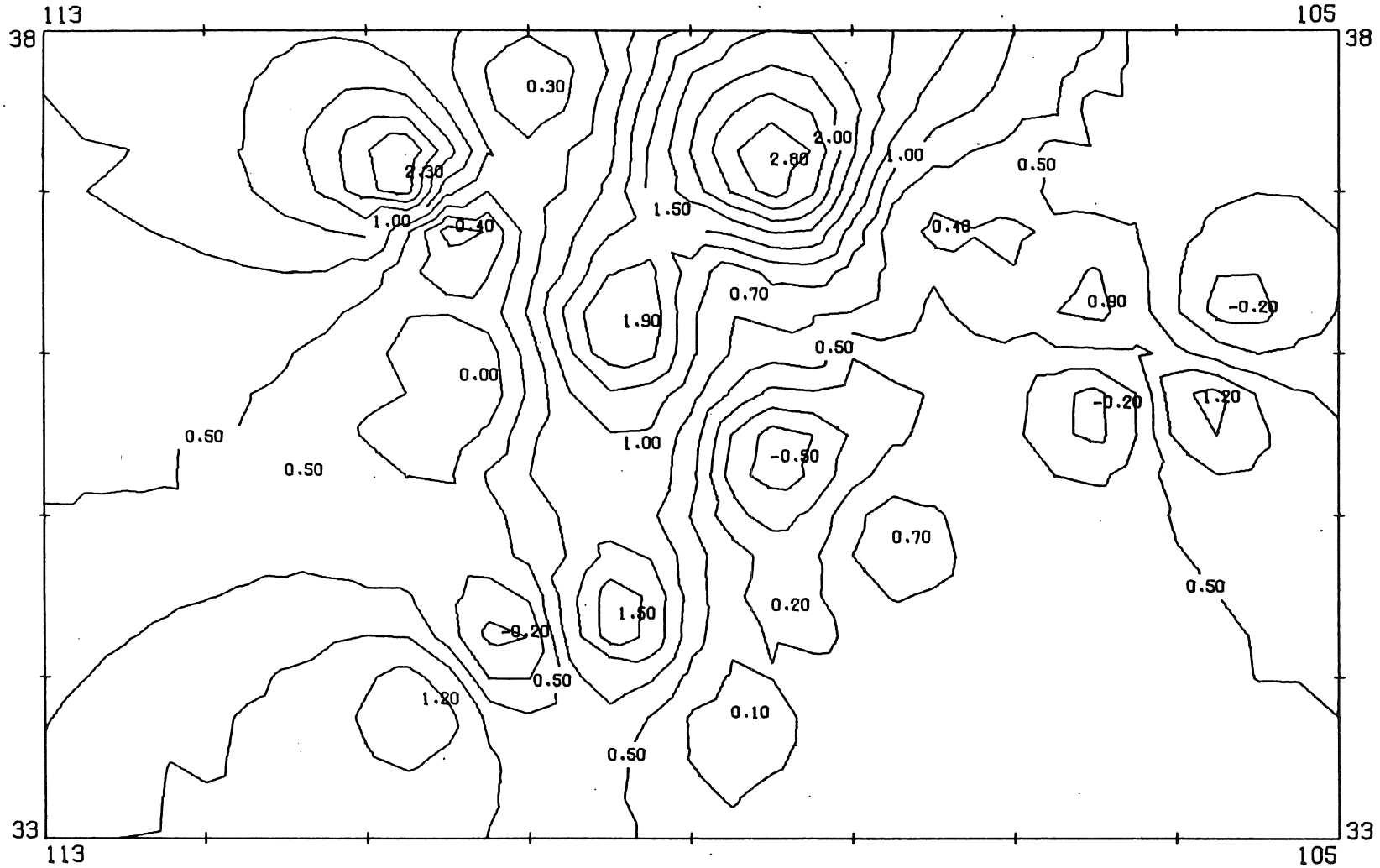
1180-1189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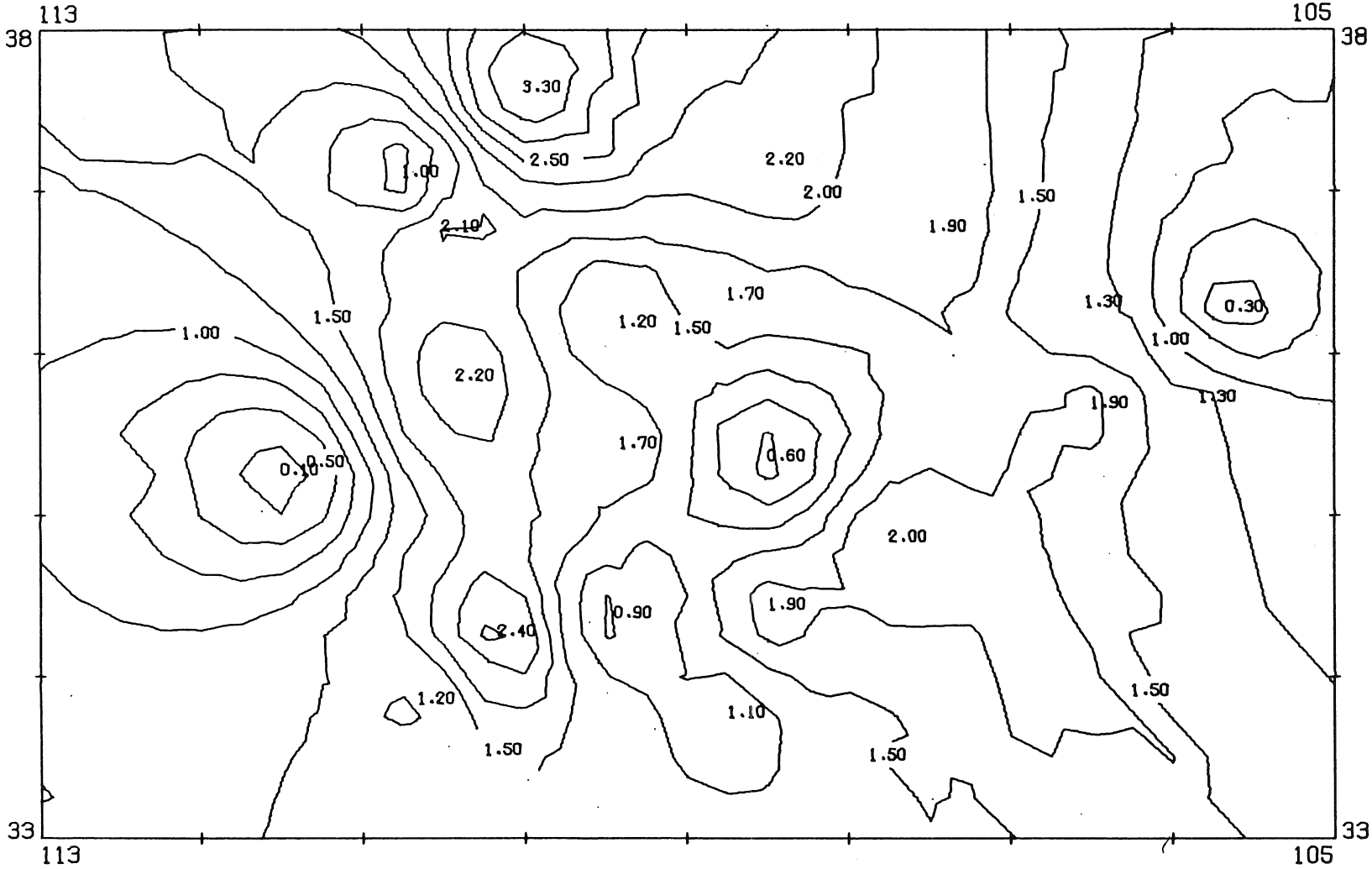
1190-1199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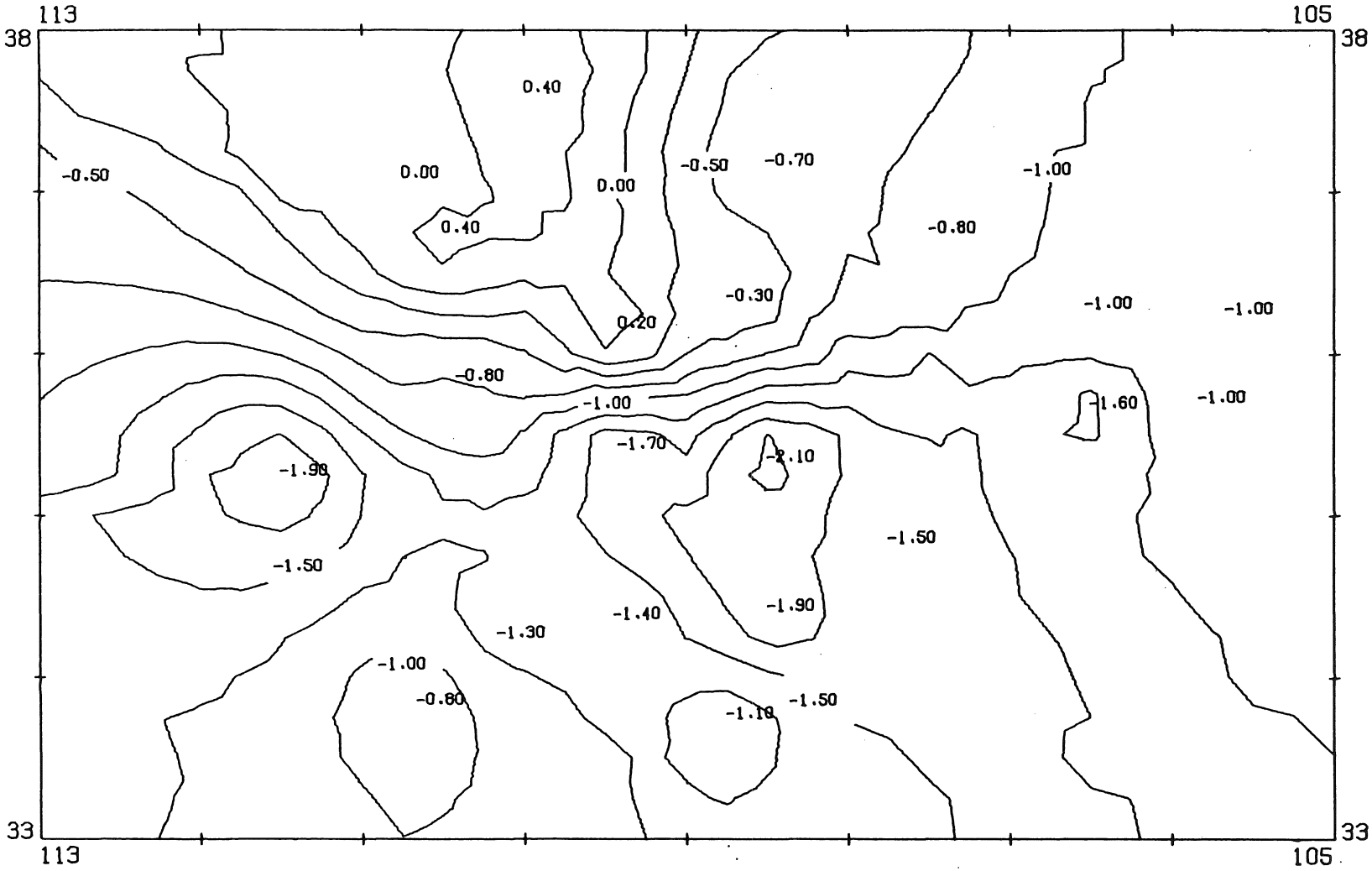
1200-1209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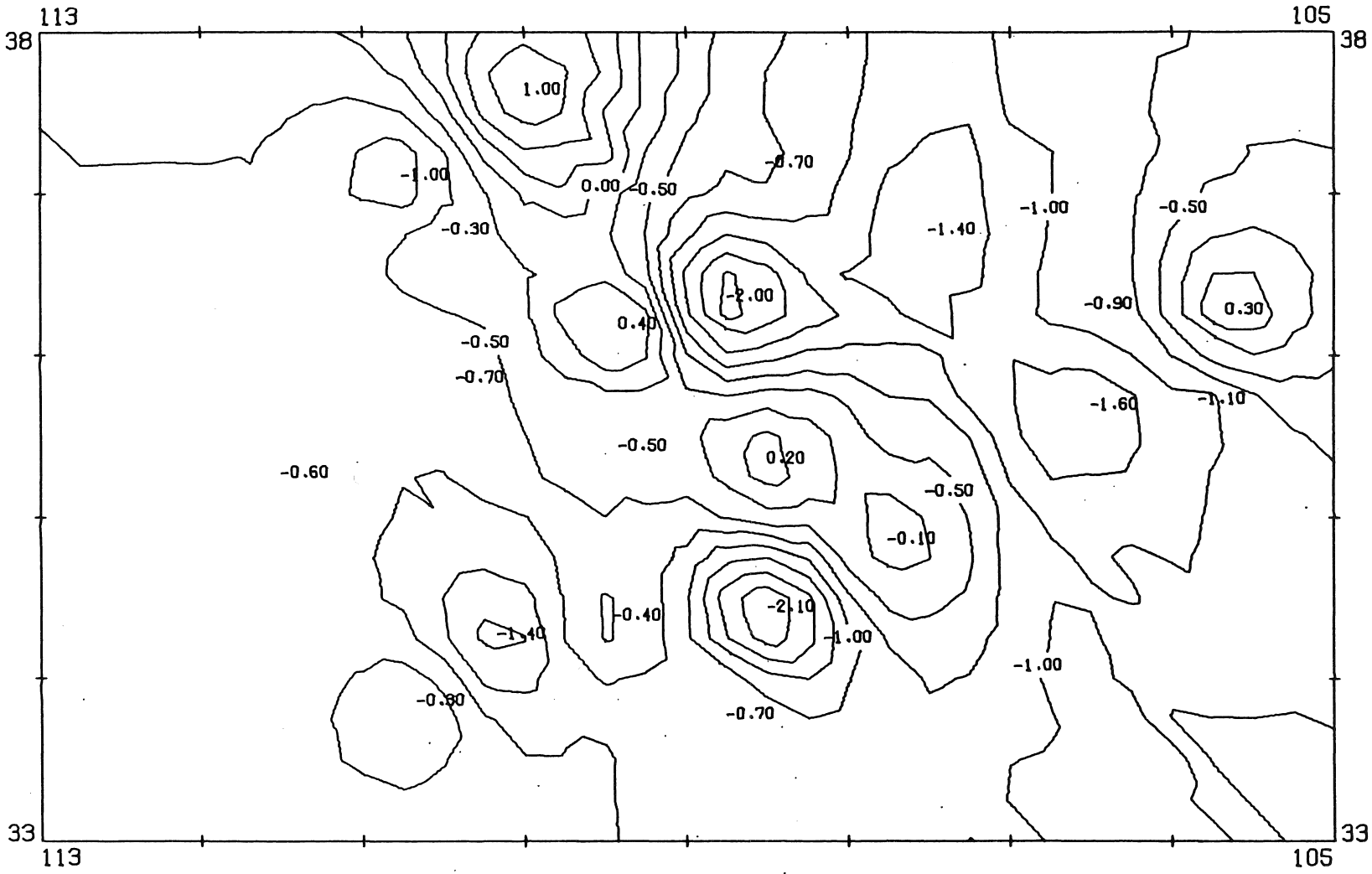
1210-1219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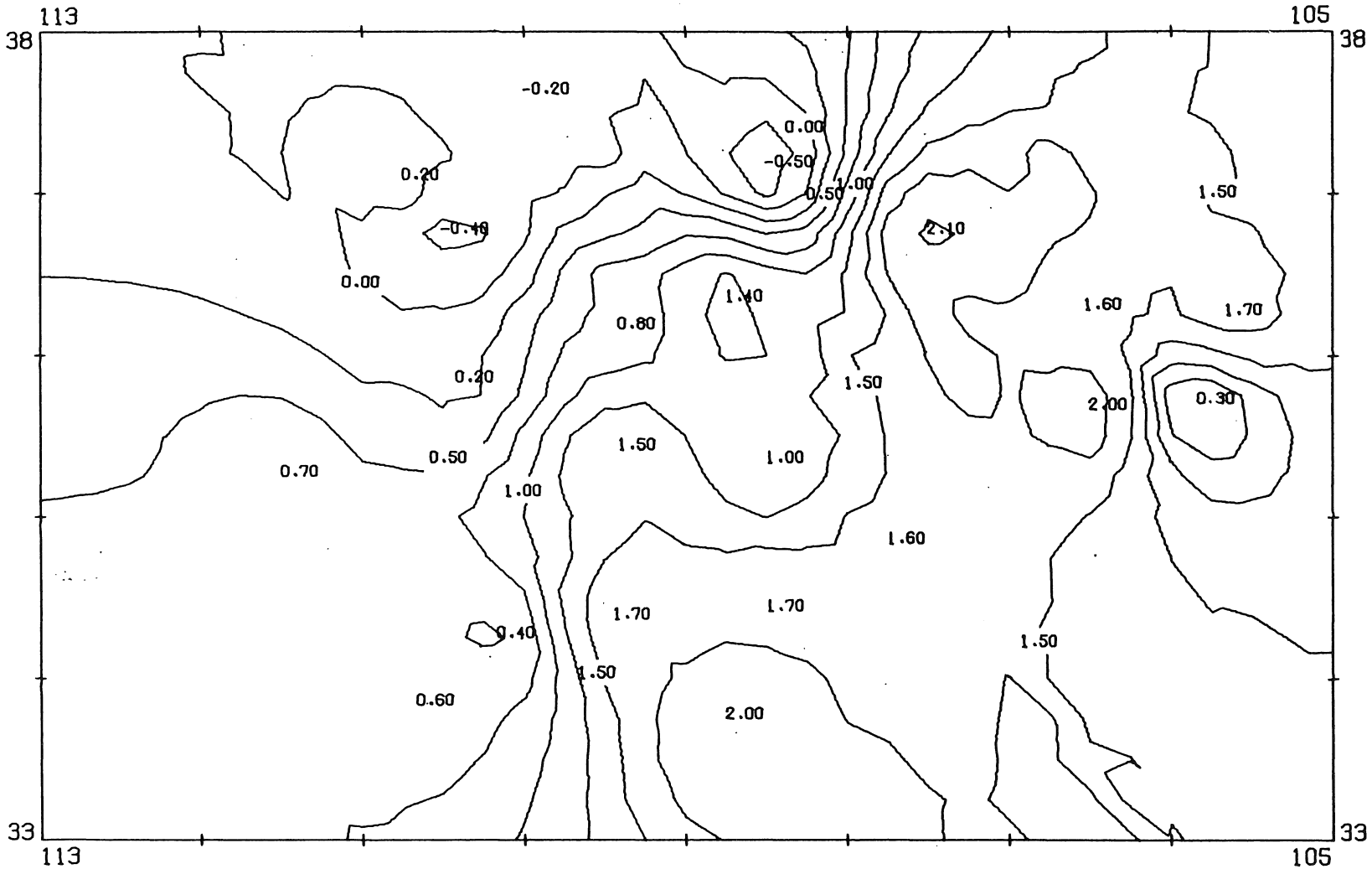
1220-1229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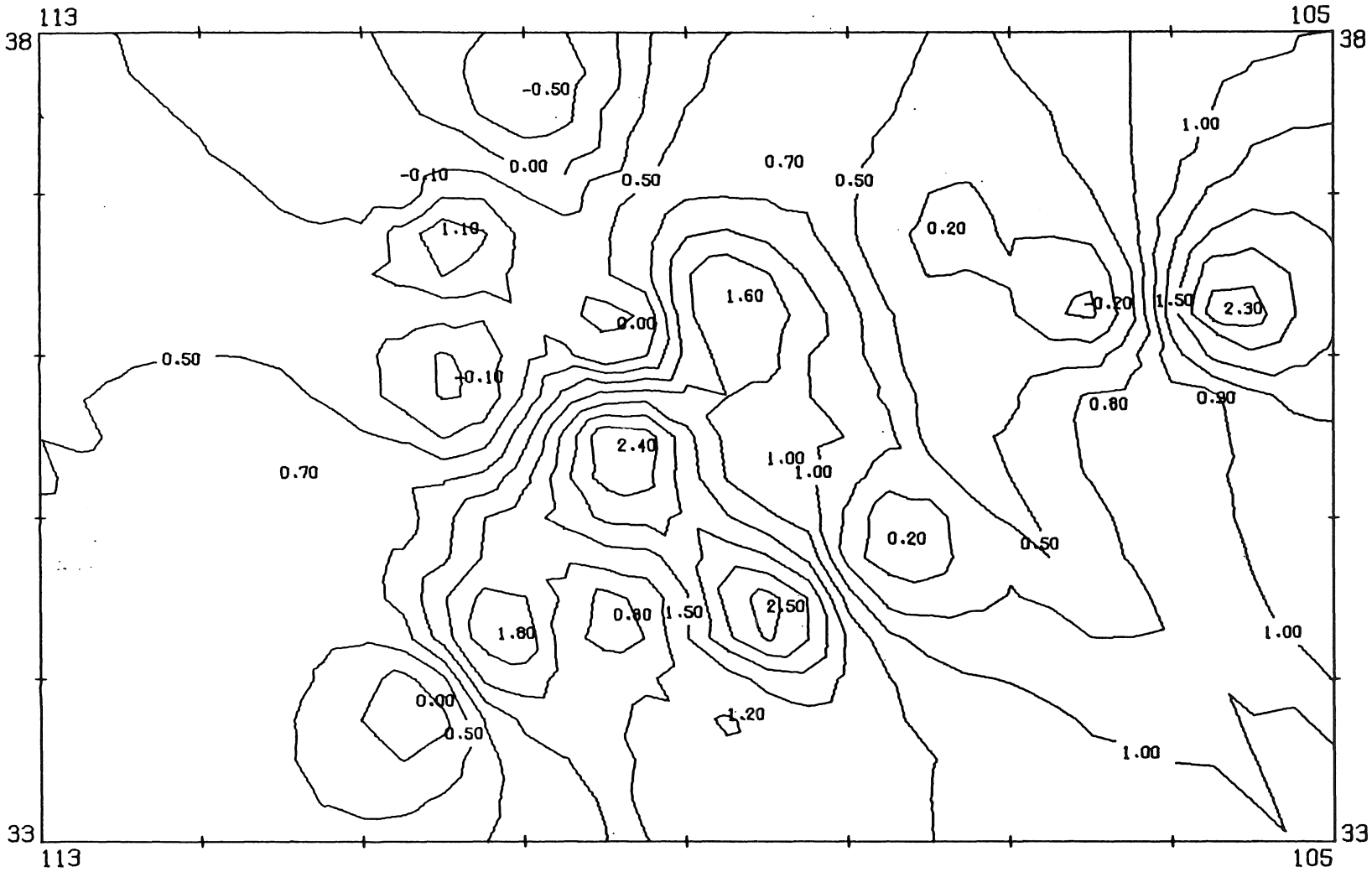
1230-1239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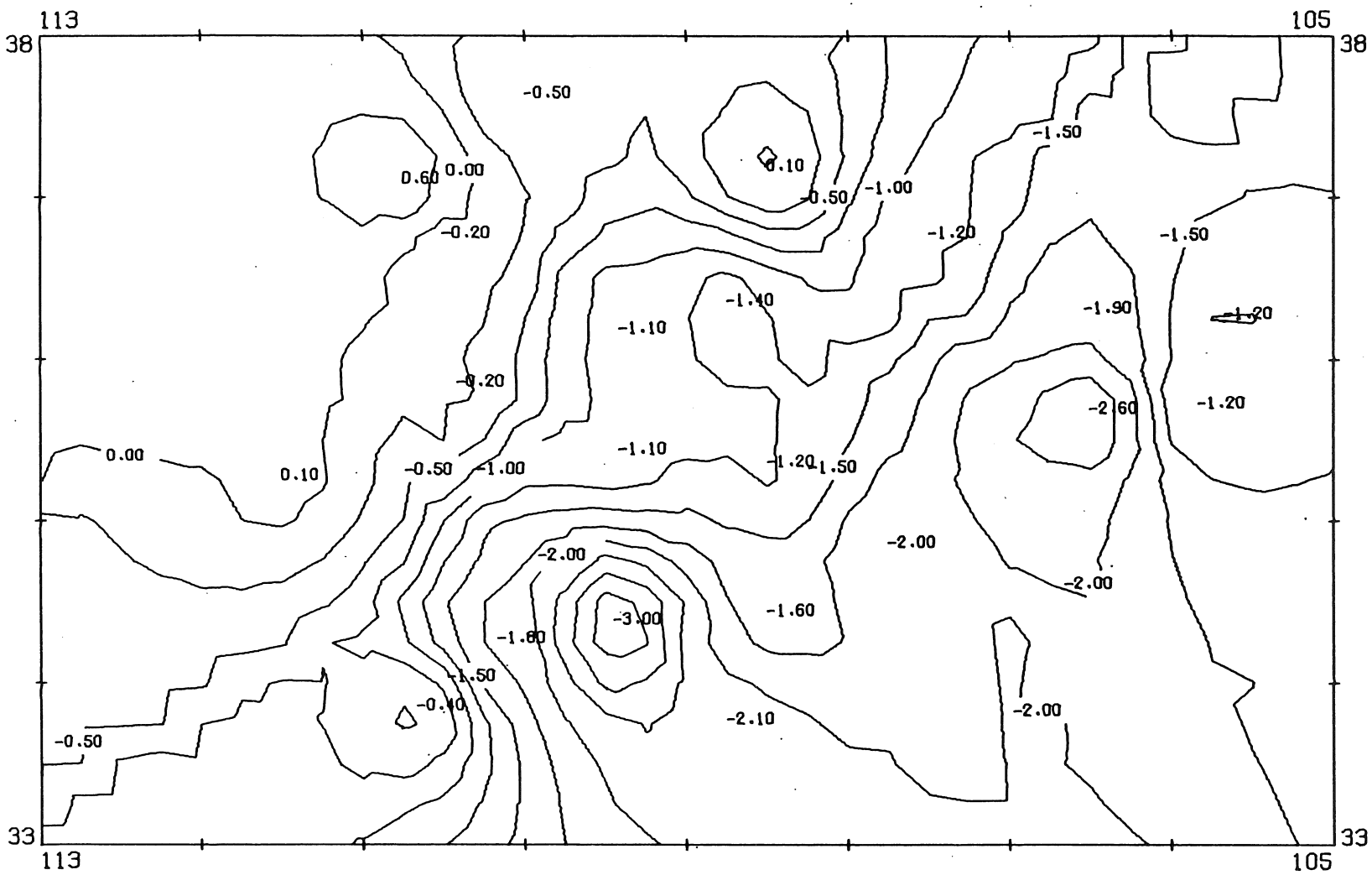
1240-1249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-1.50
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-0.20
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-1.20
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0.10
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-1.00
-1.10
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-1.50
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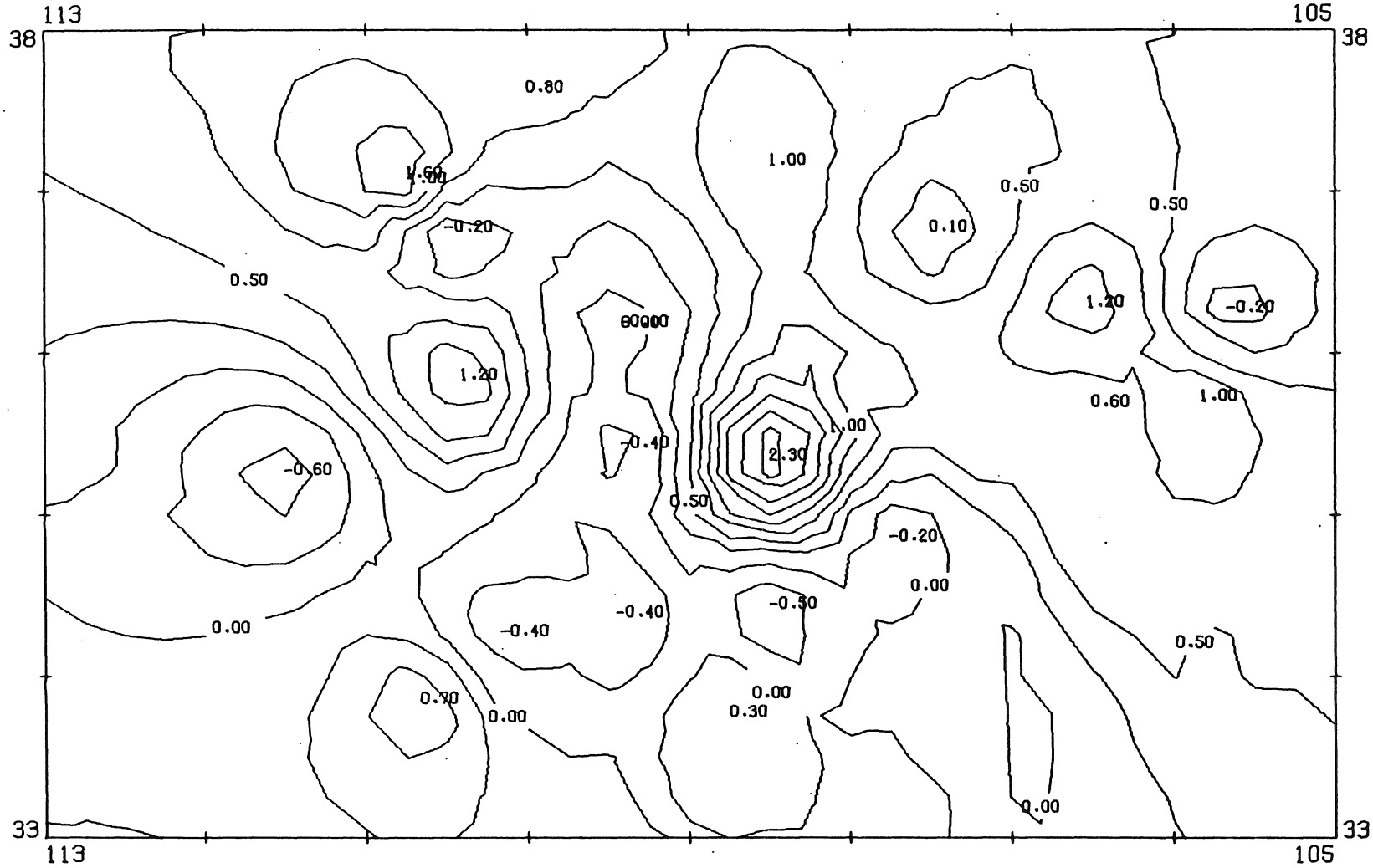
1250-1259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0.50
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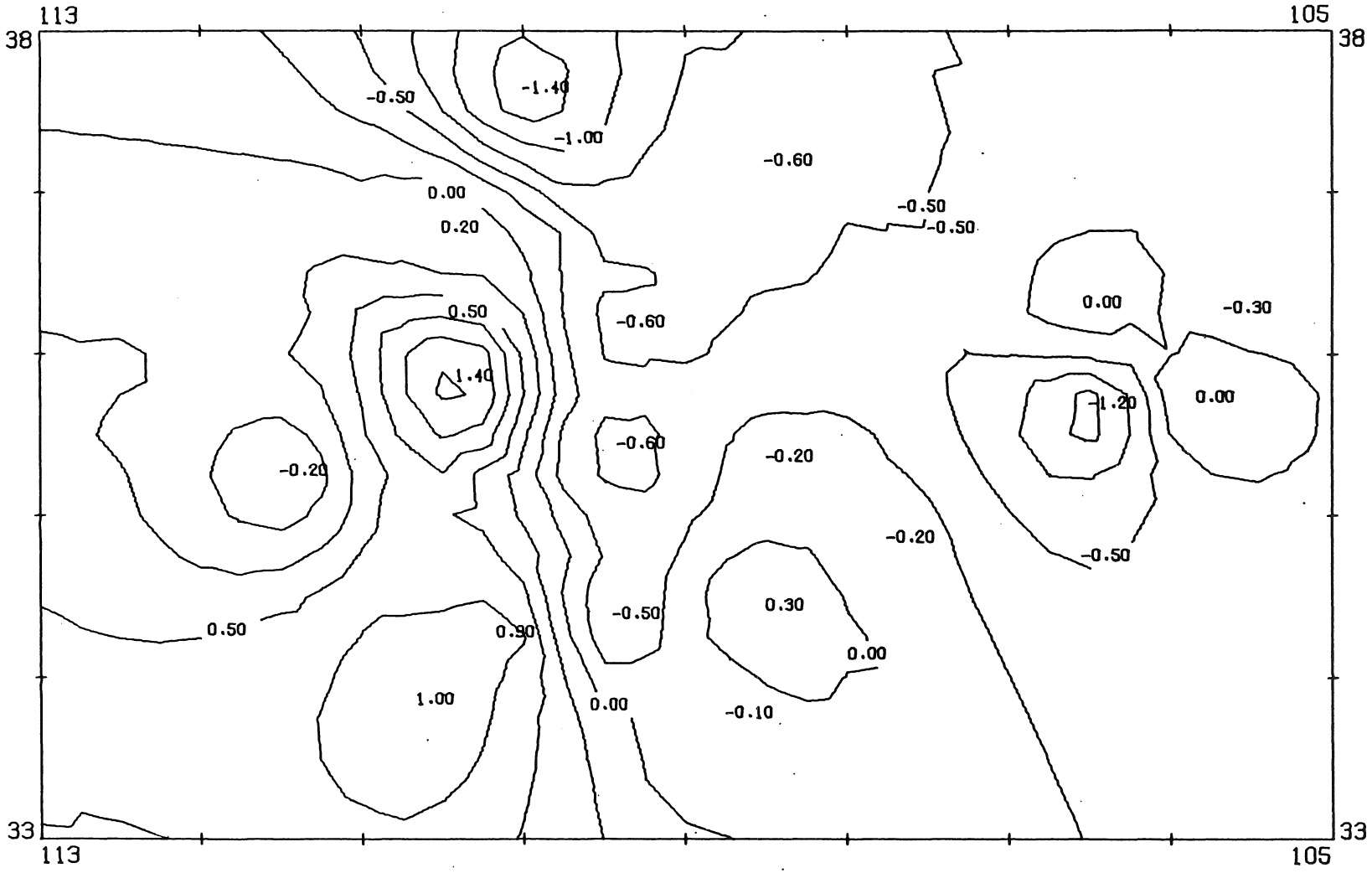
1260-1269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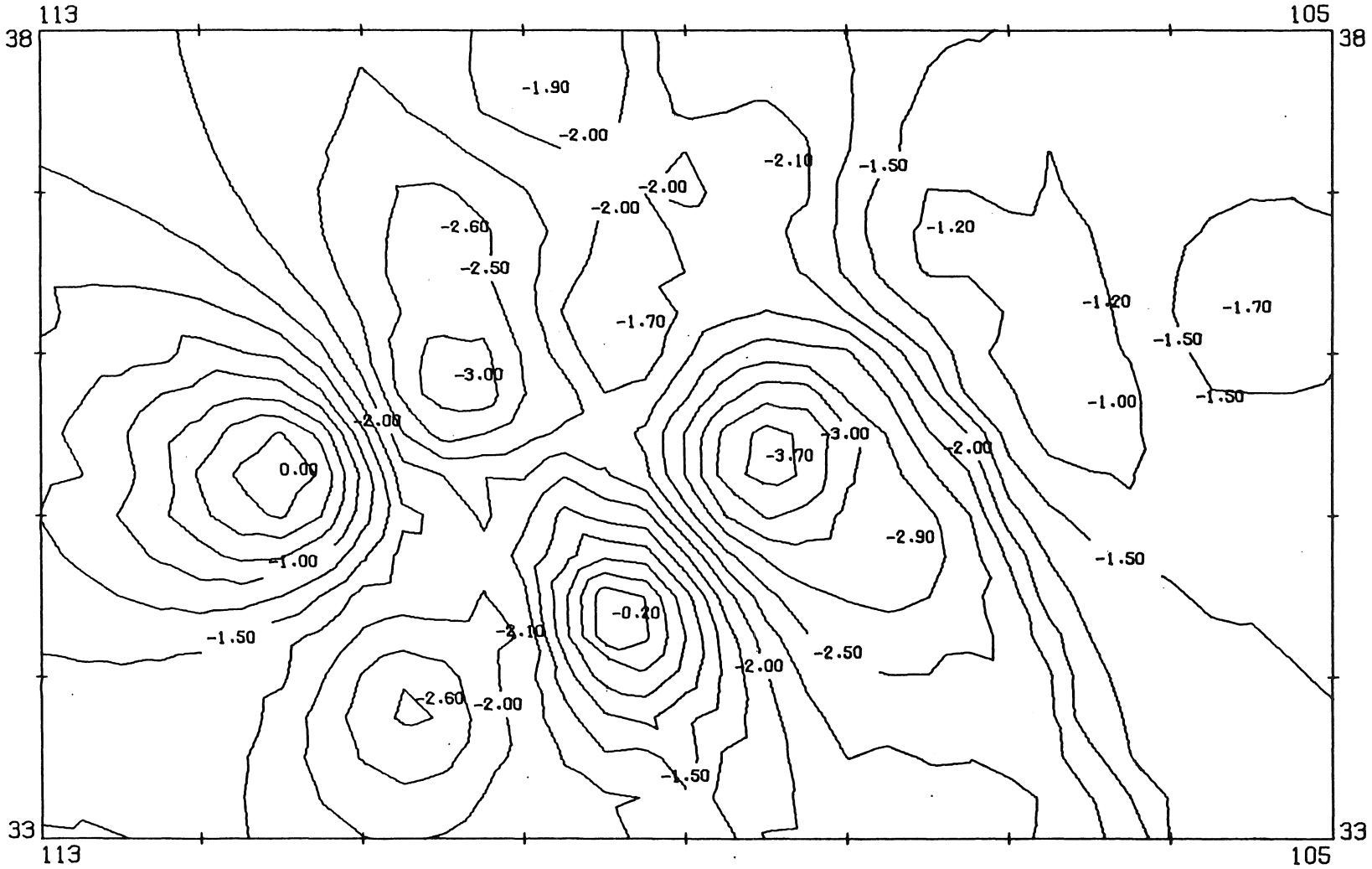
105

1270-1279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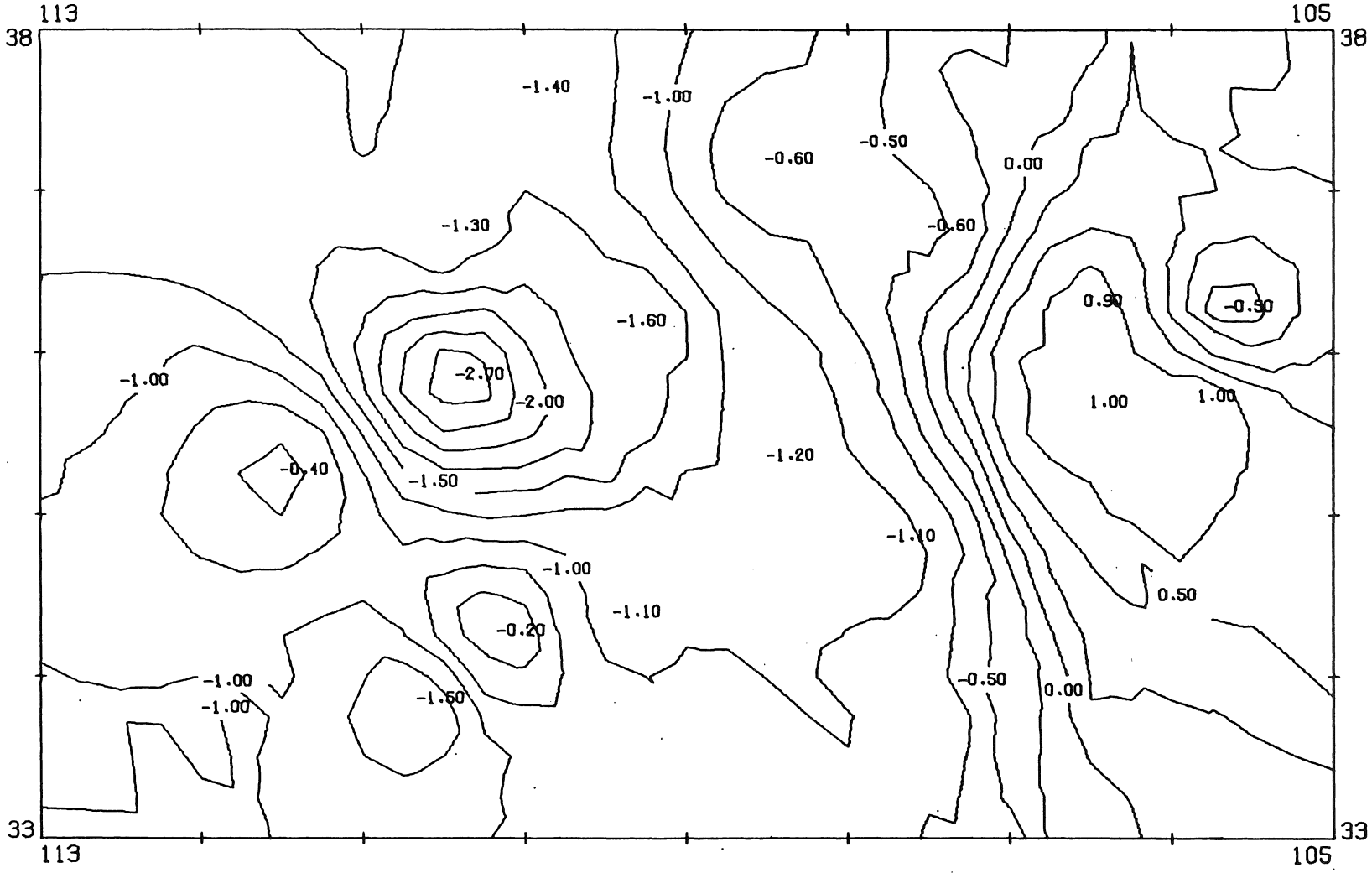
113
105

1280-1289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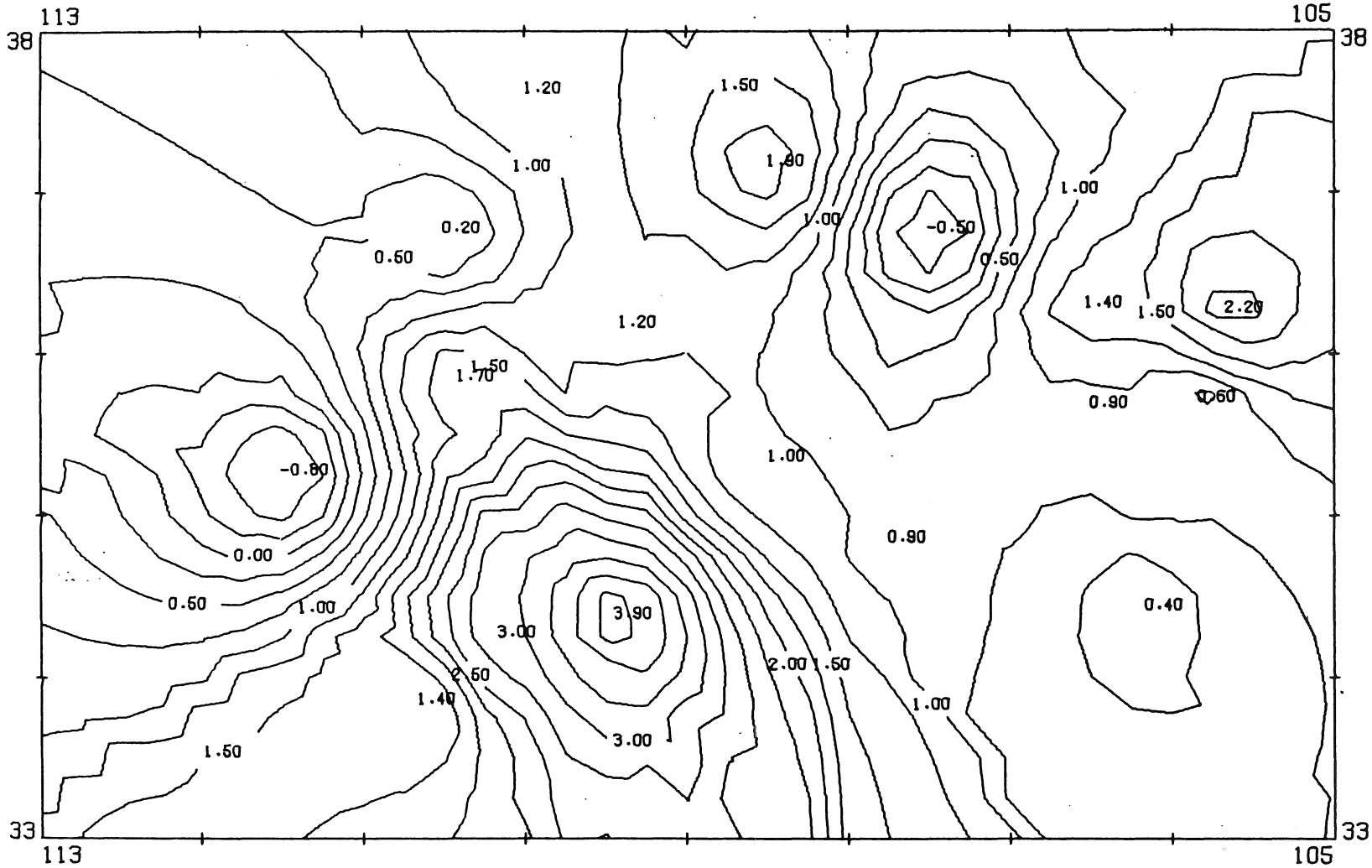
1290-1299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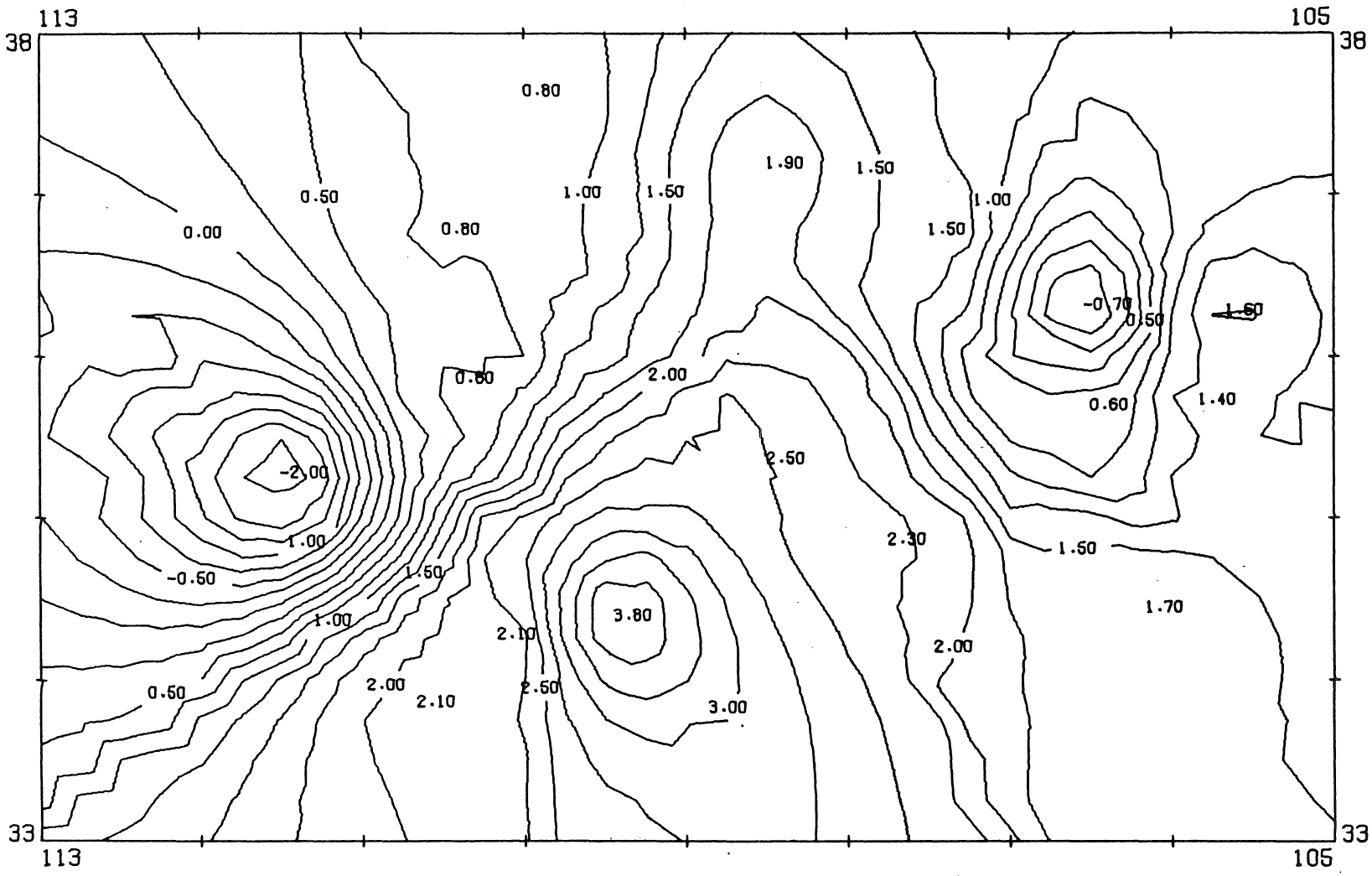
1300-1309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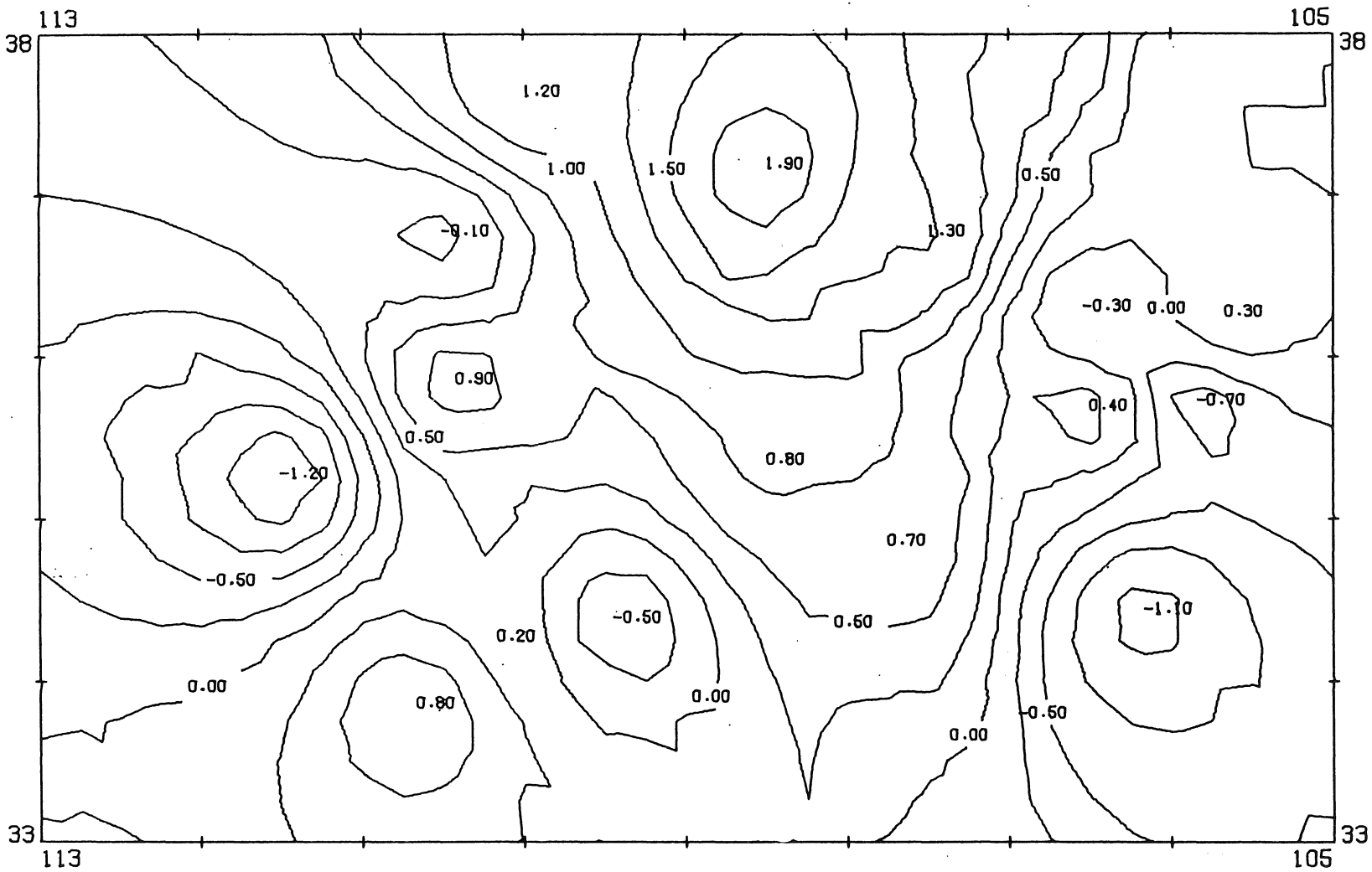
1310-1319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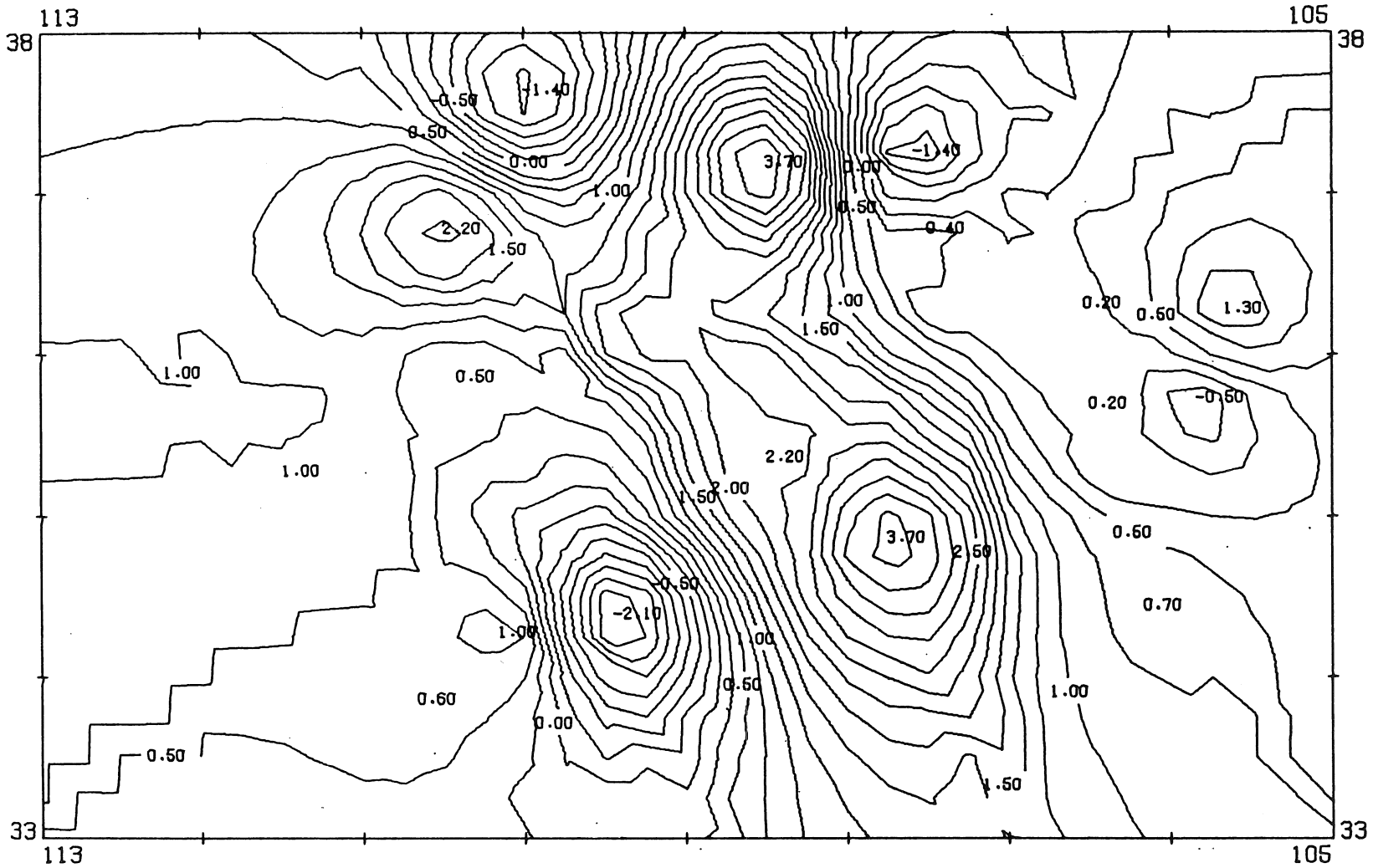
1320-1329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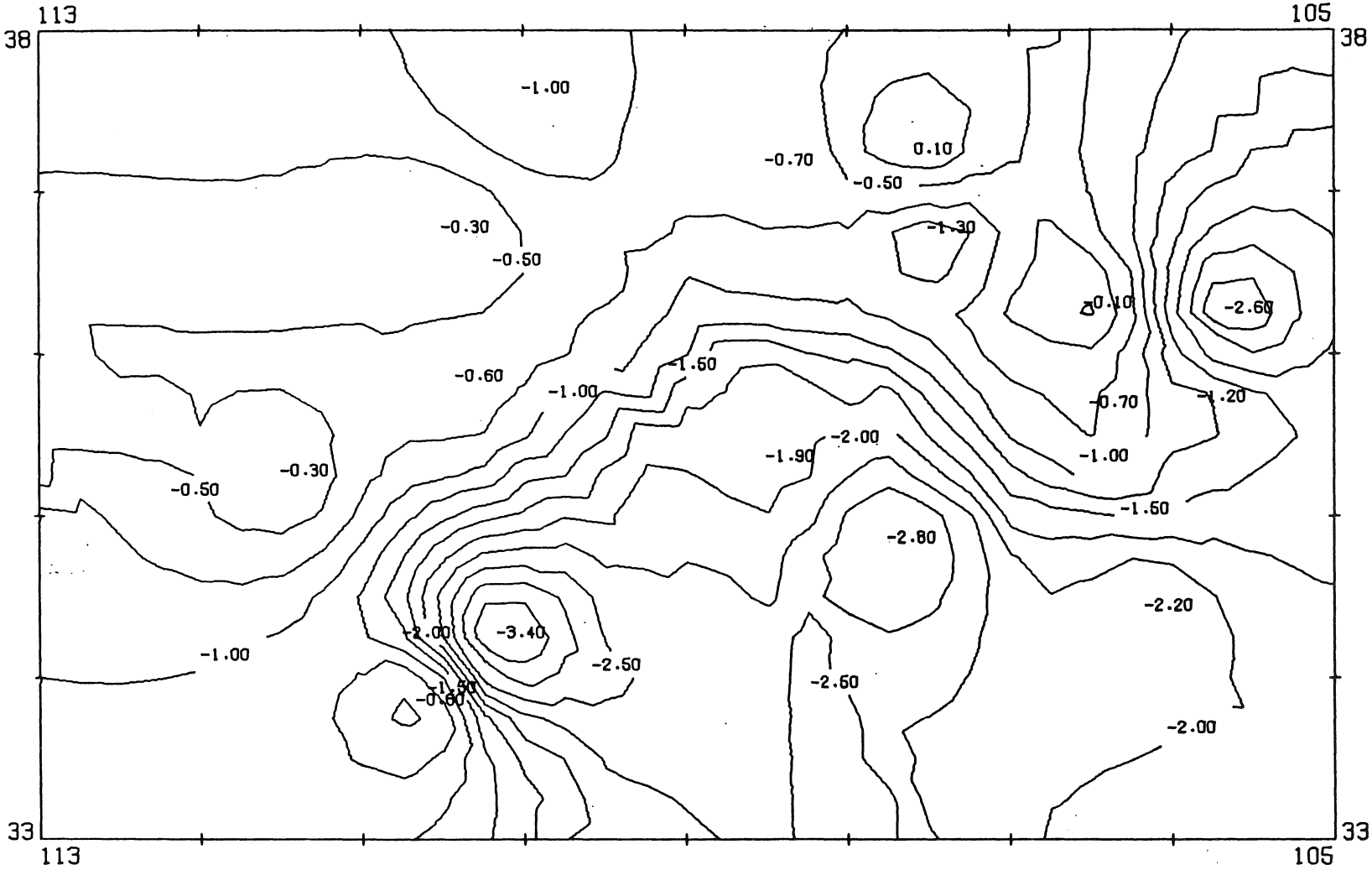
1330-1339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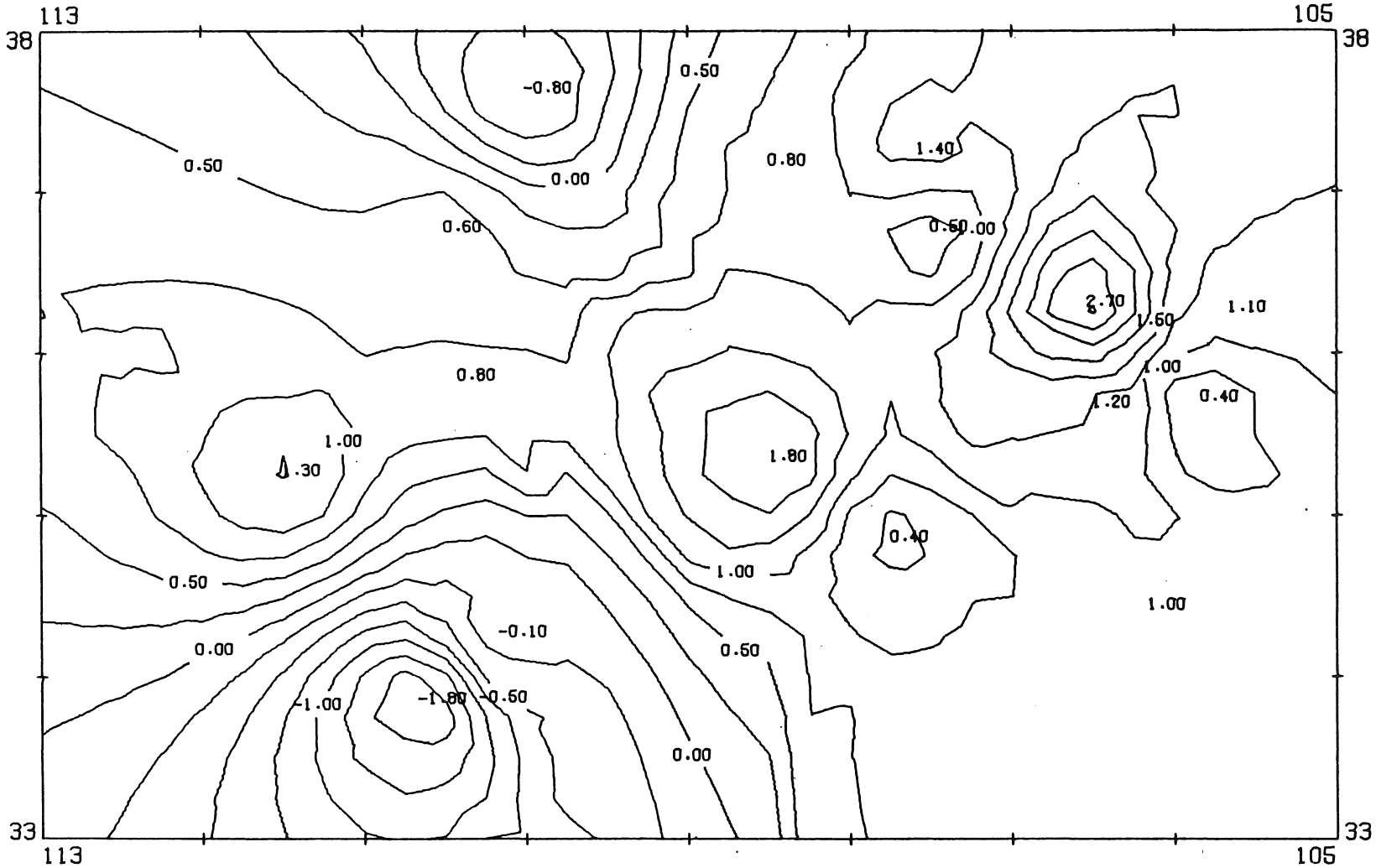
1340-1349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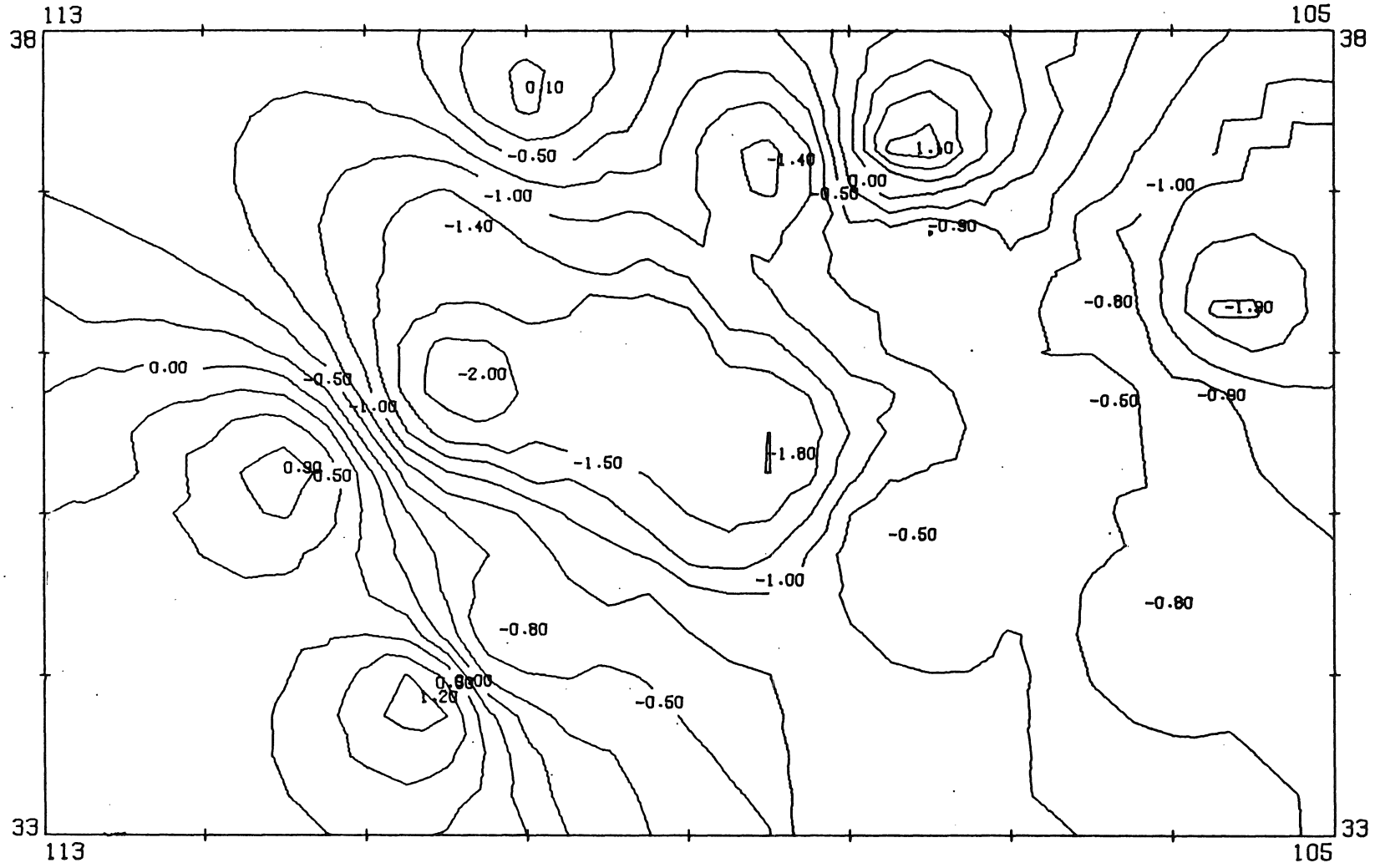
1350-1359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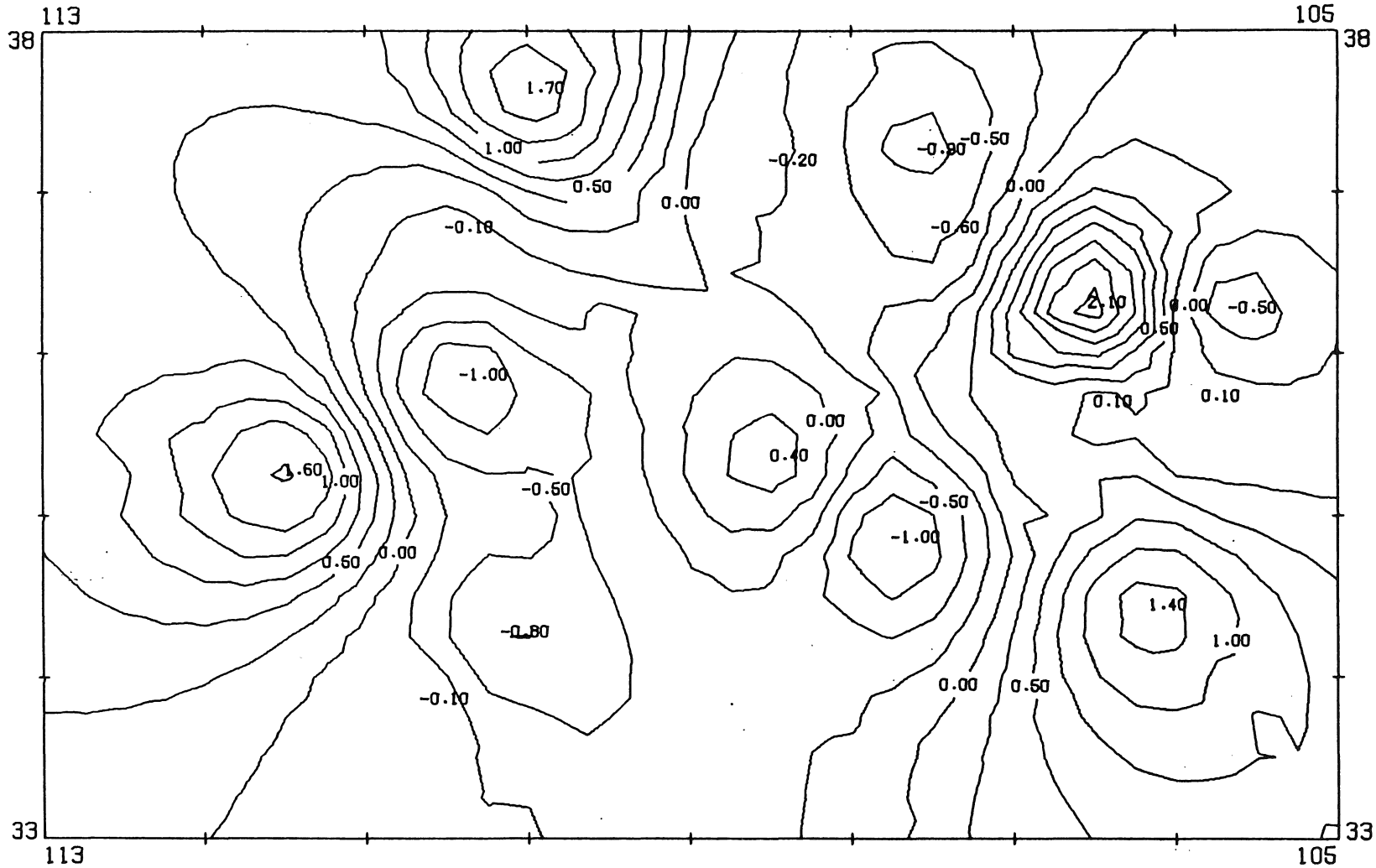
1360-1369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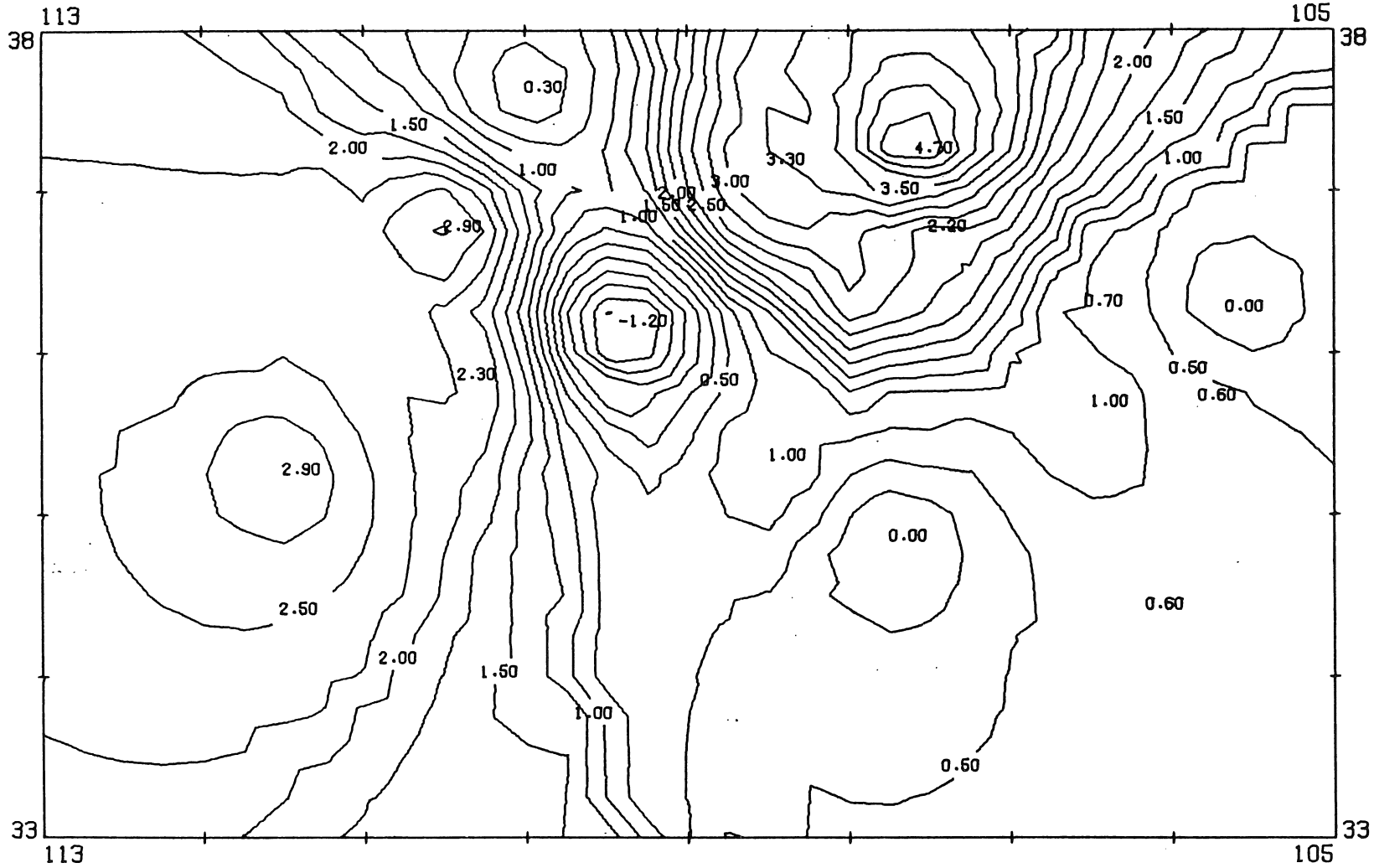
1370-1379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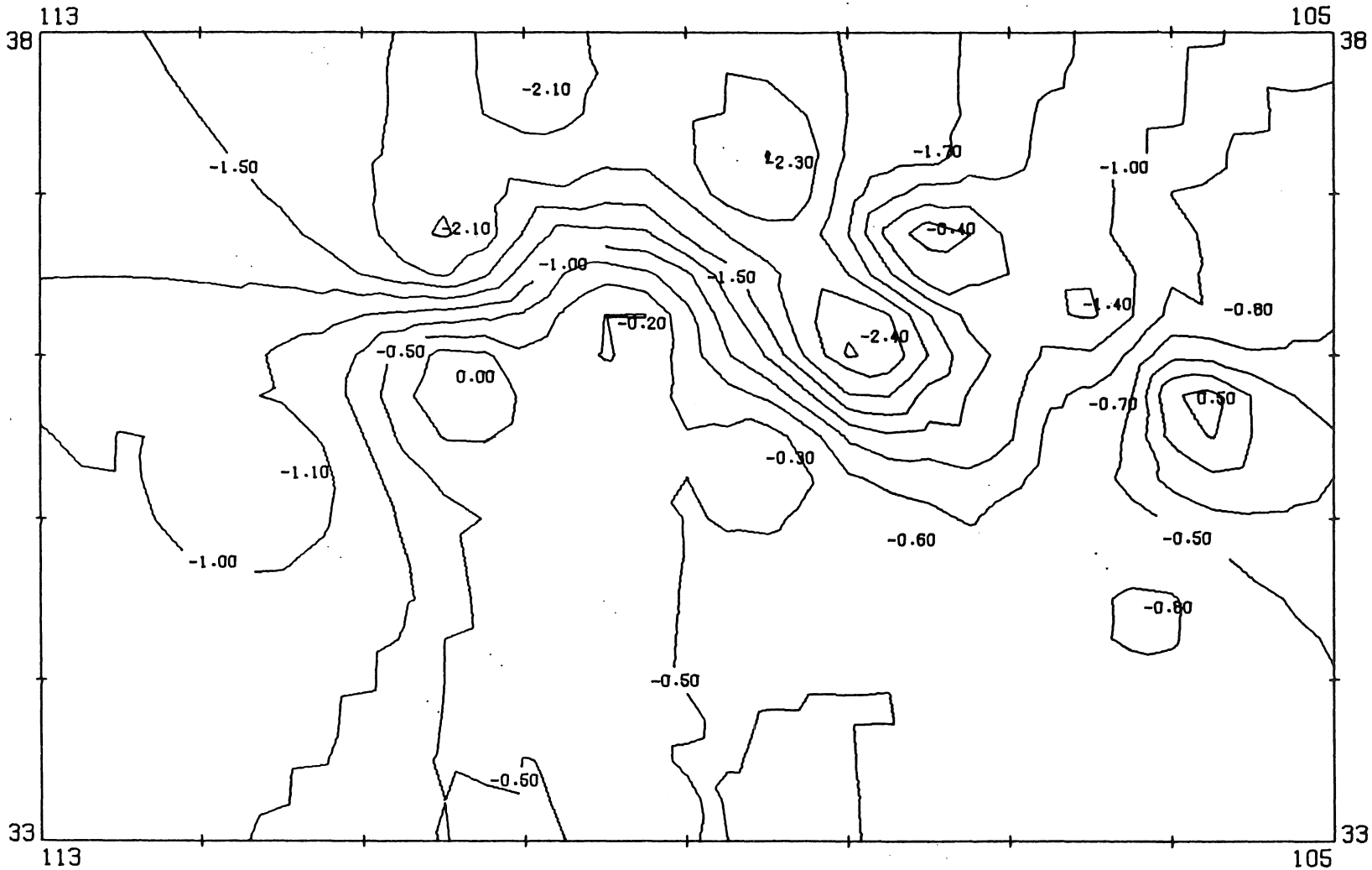
1380-1389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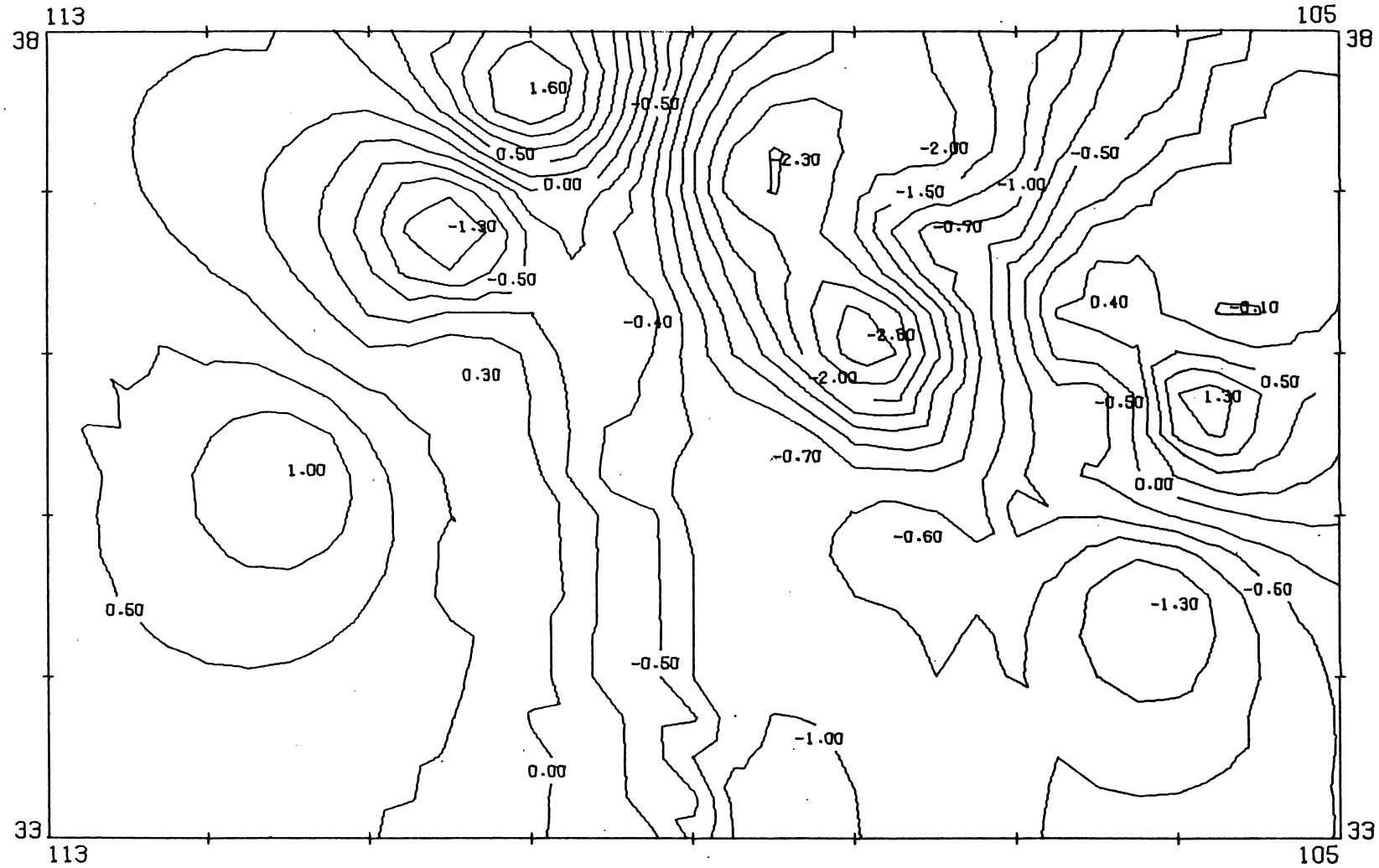
105

1390-1399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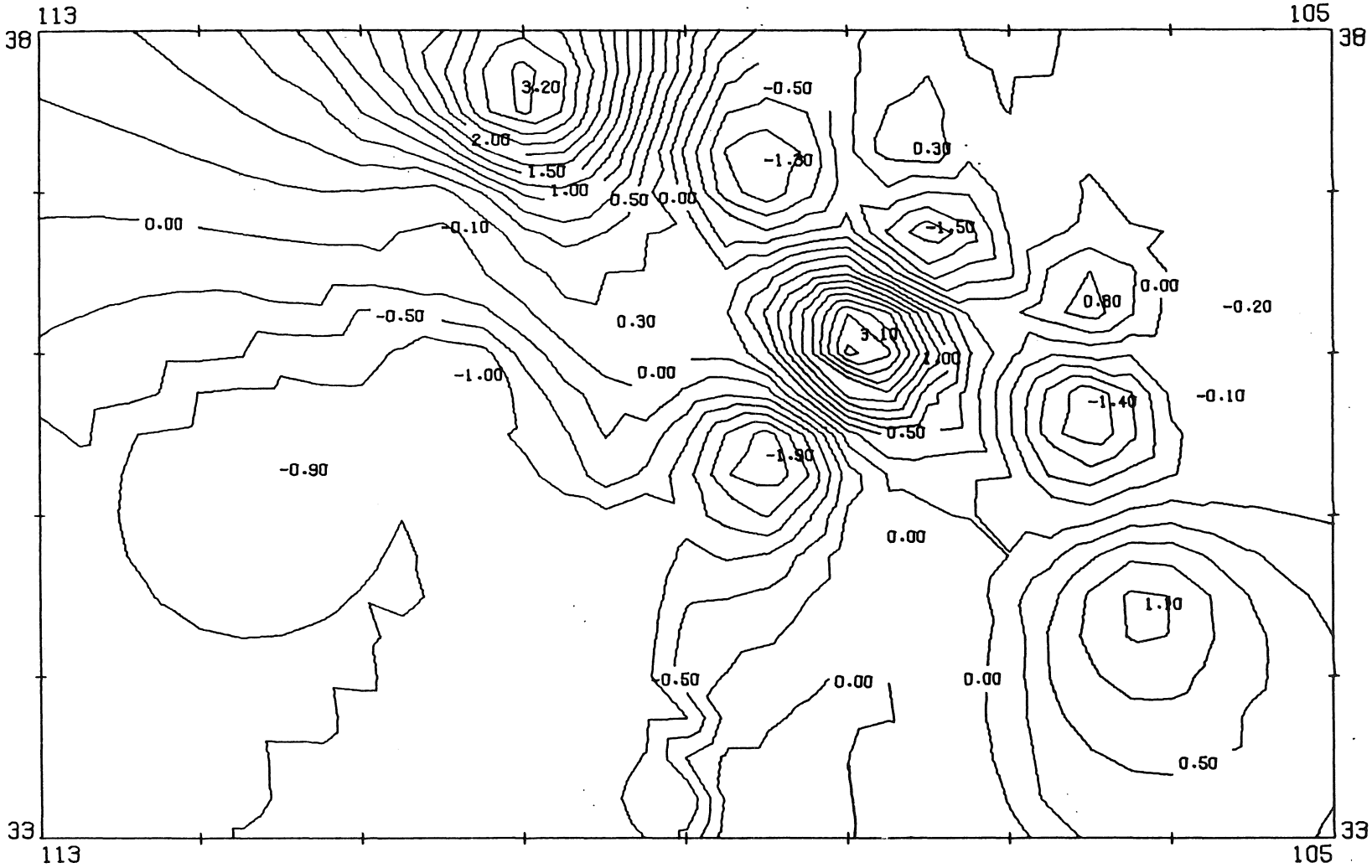
1400-1409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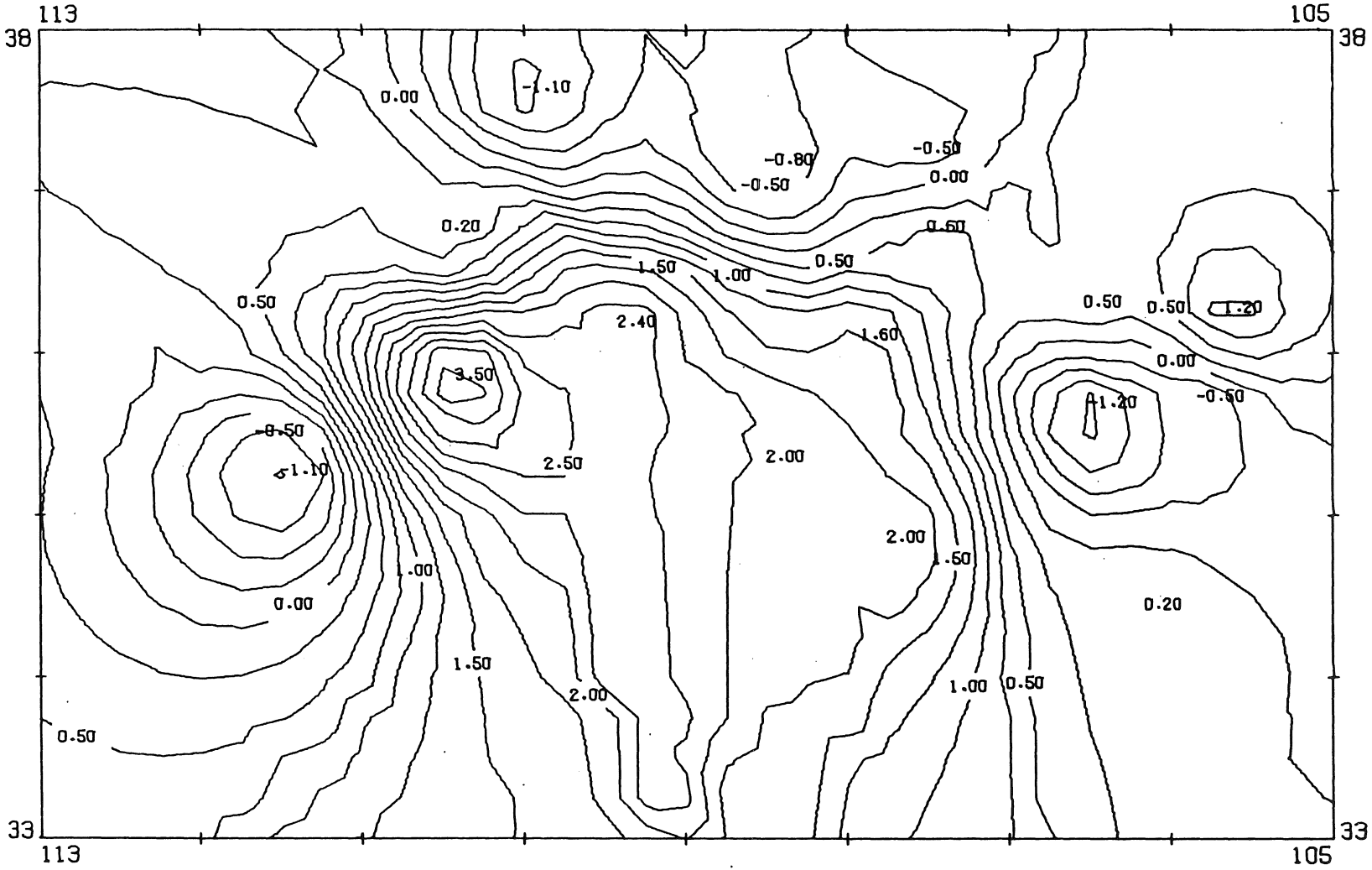
1410-1419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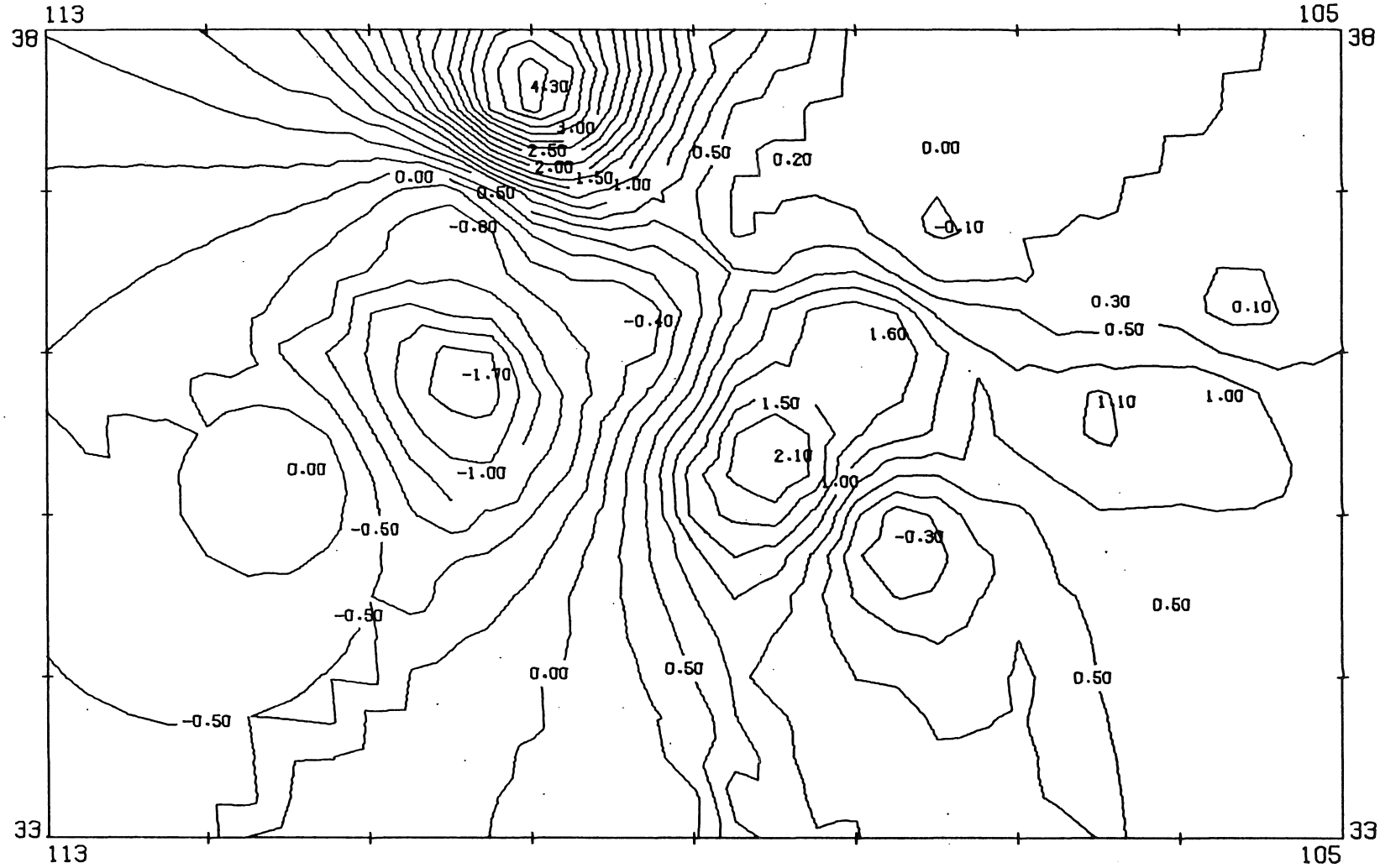
1420-1429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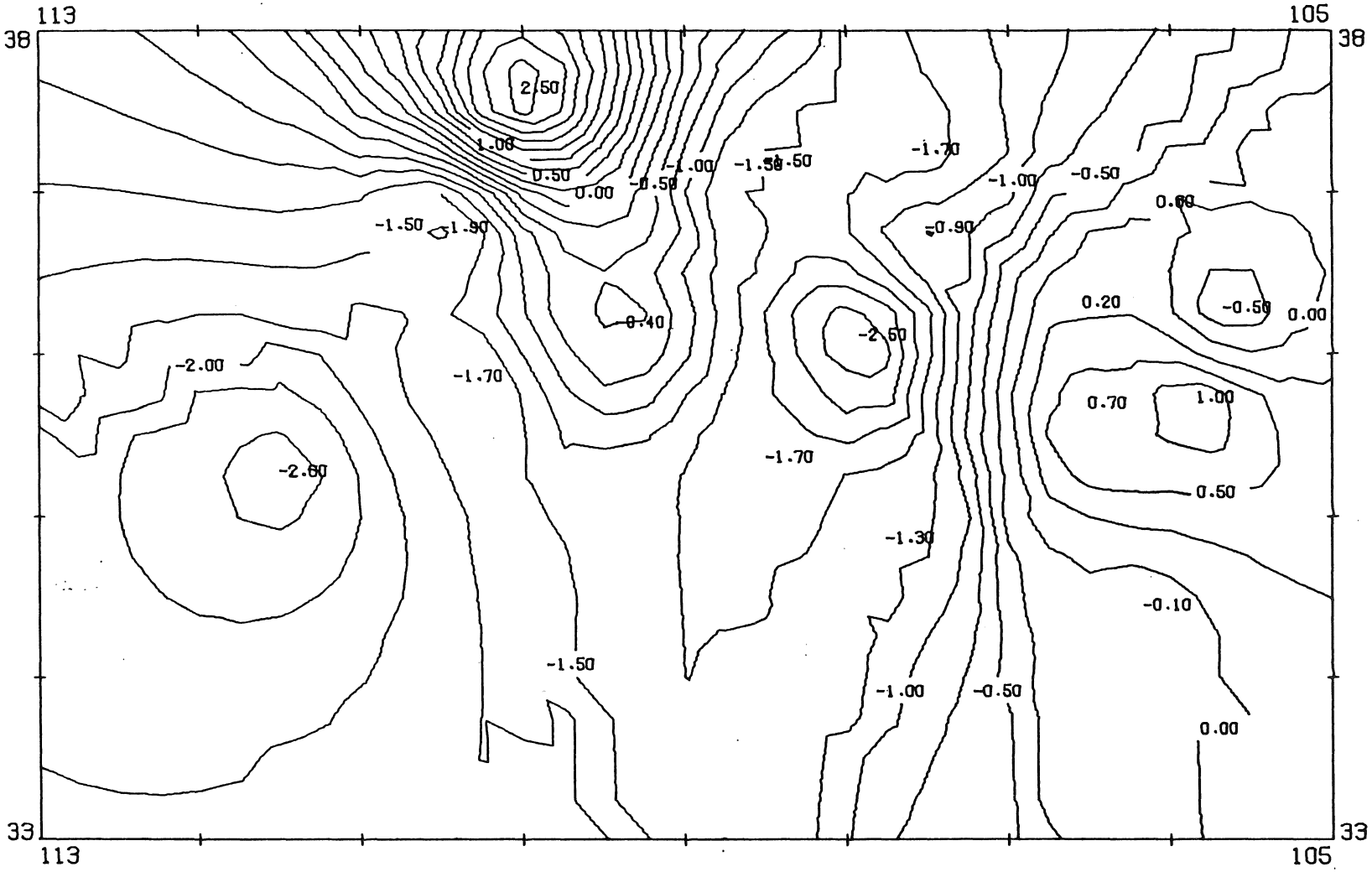
1430-1439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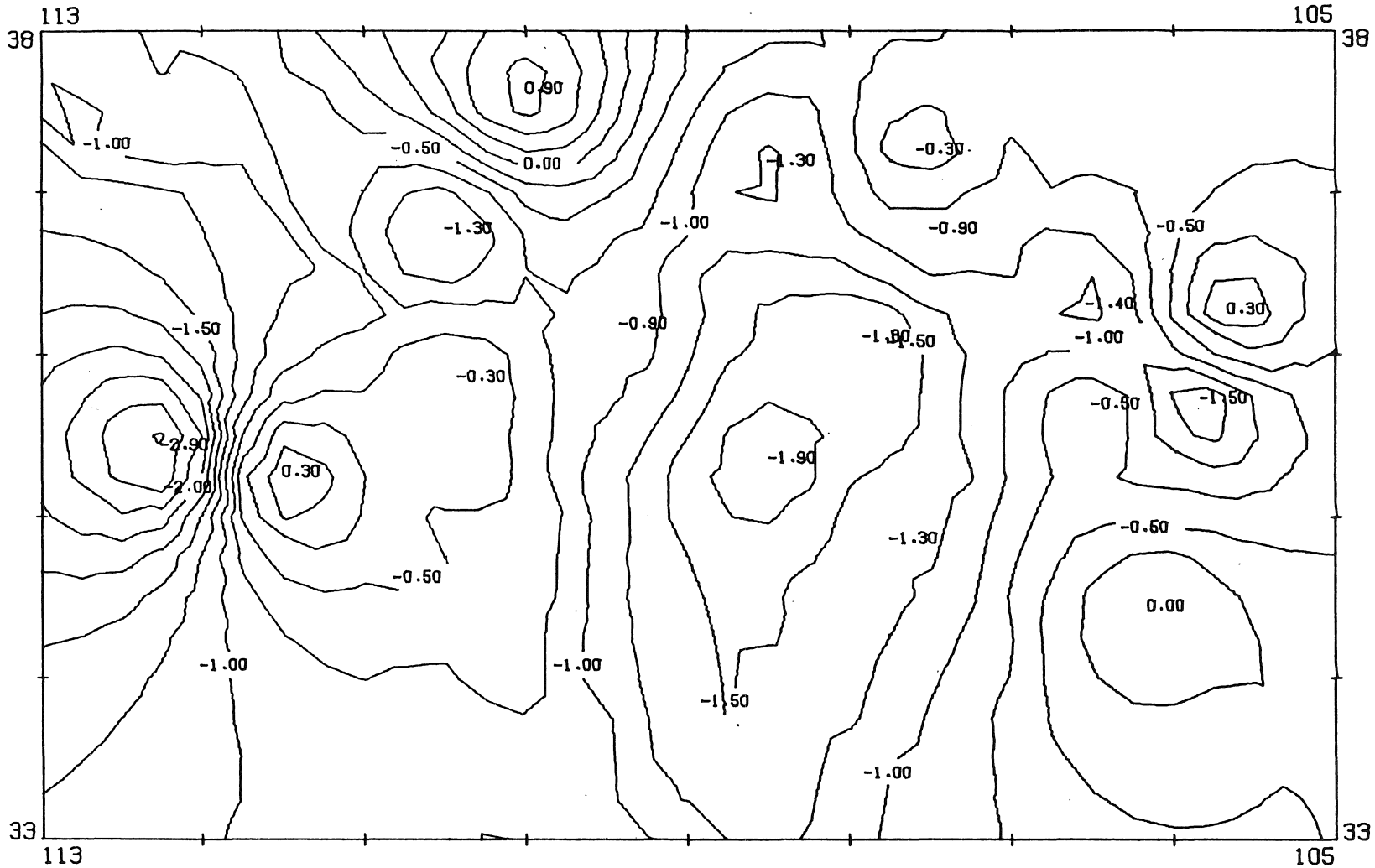
1440-1449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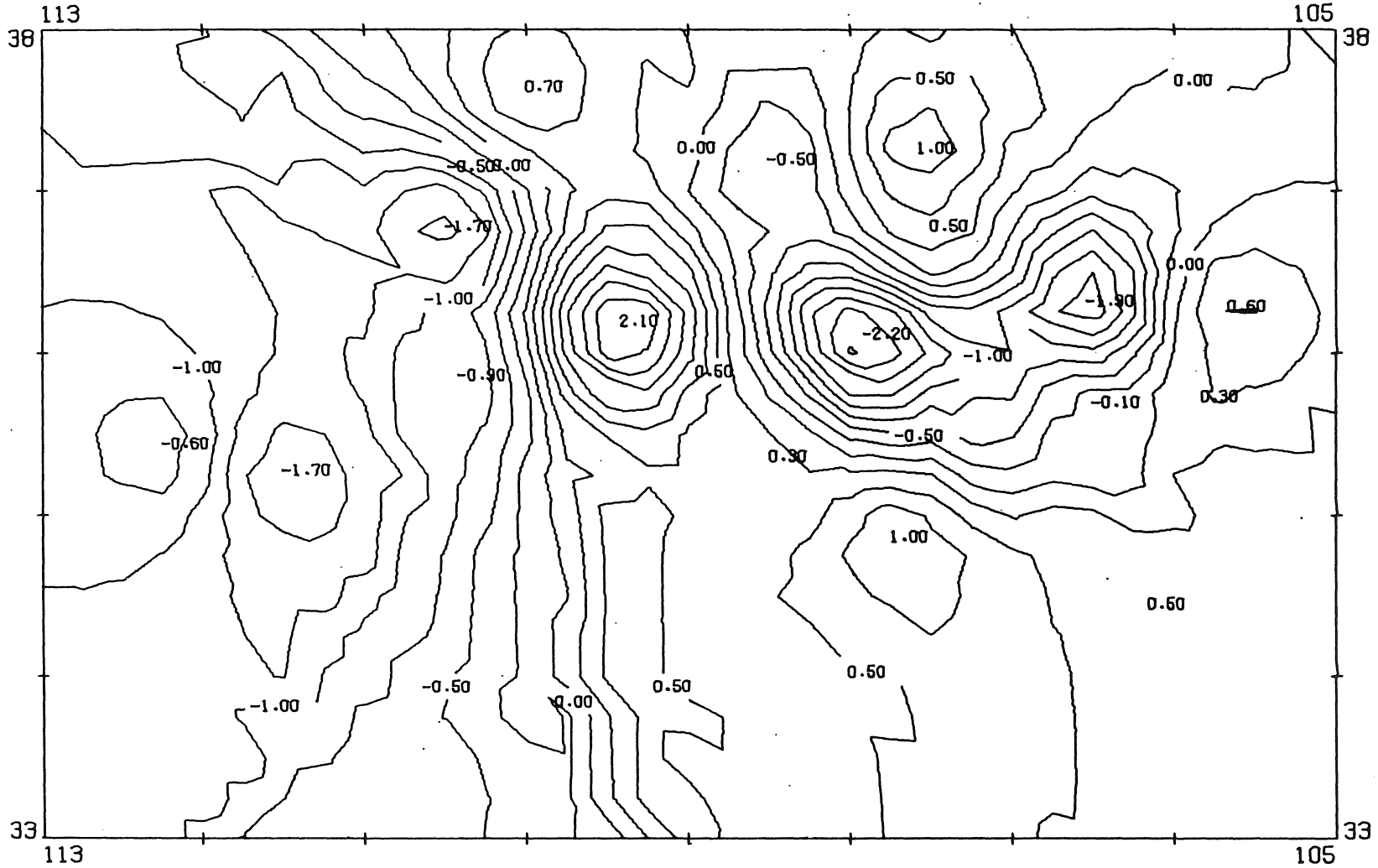
1450-1459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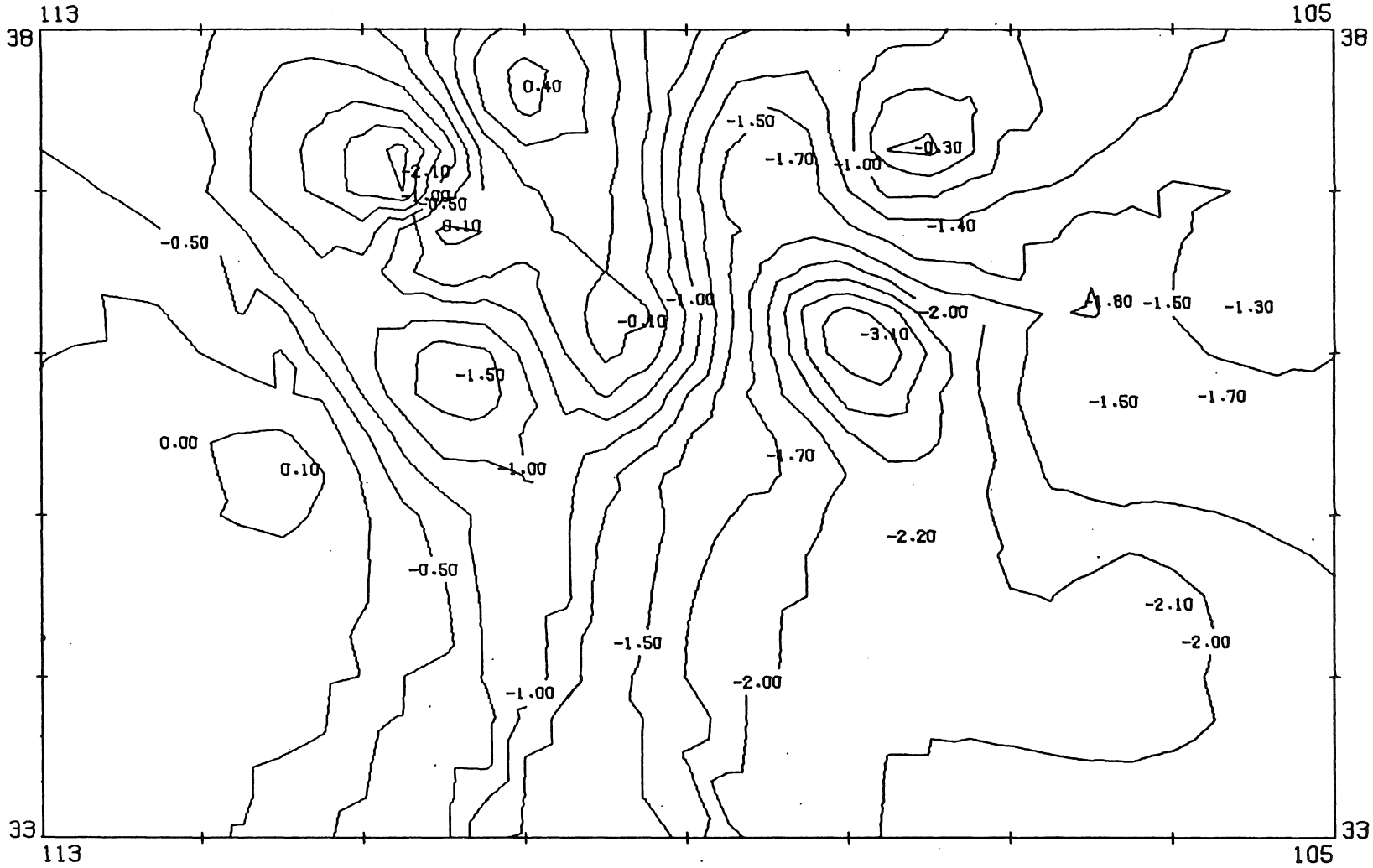
1460-1469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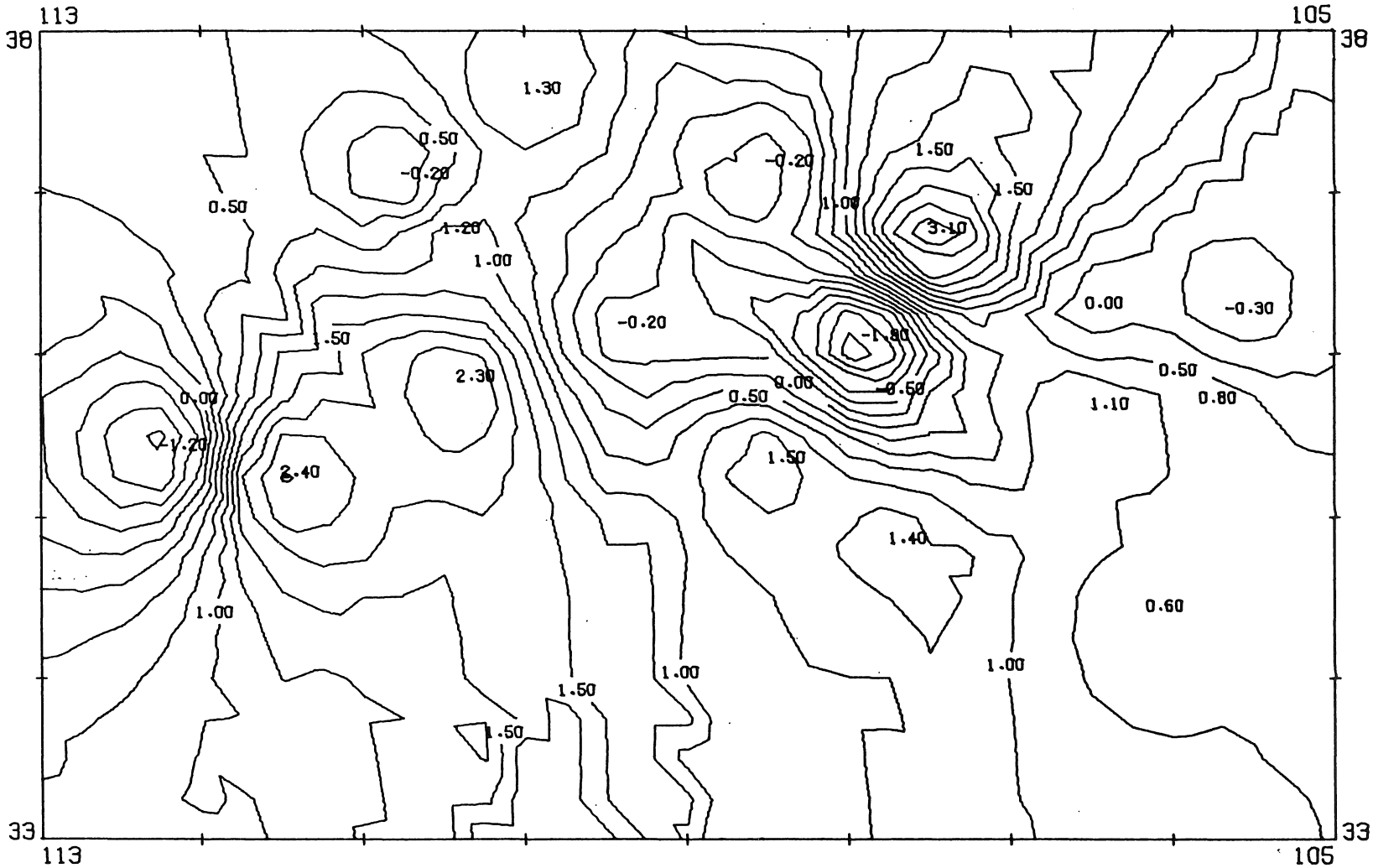
-2.00

1470-1479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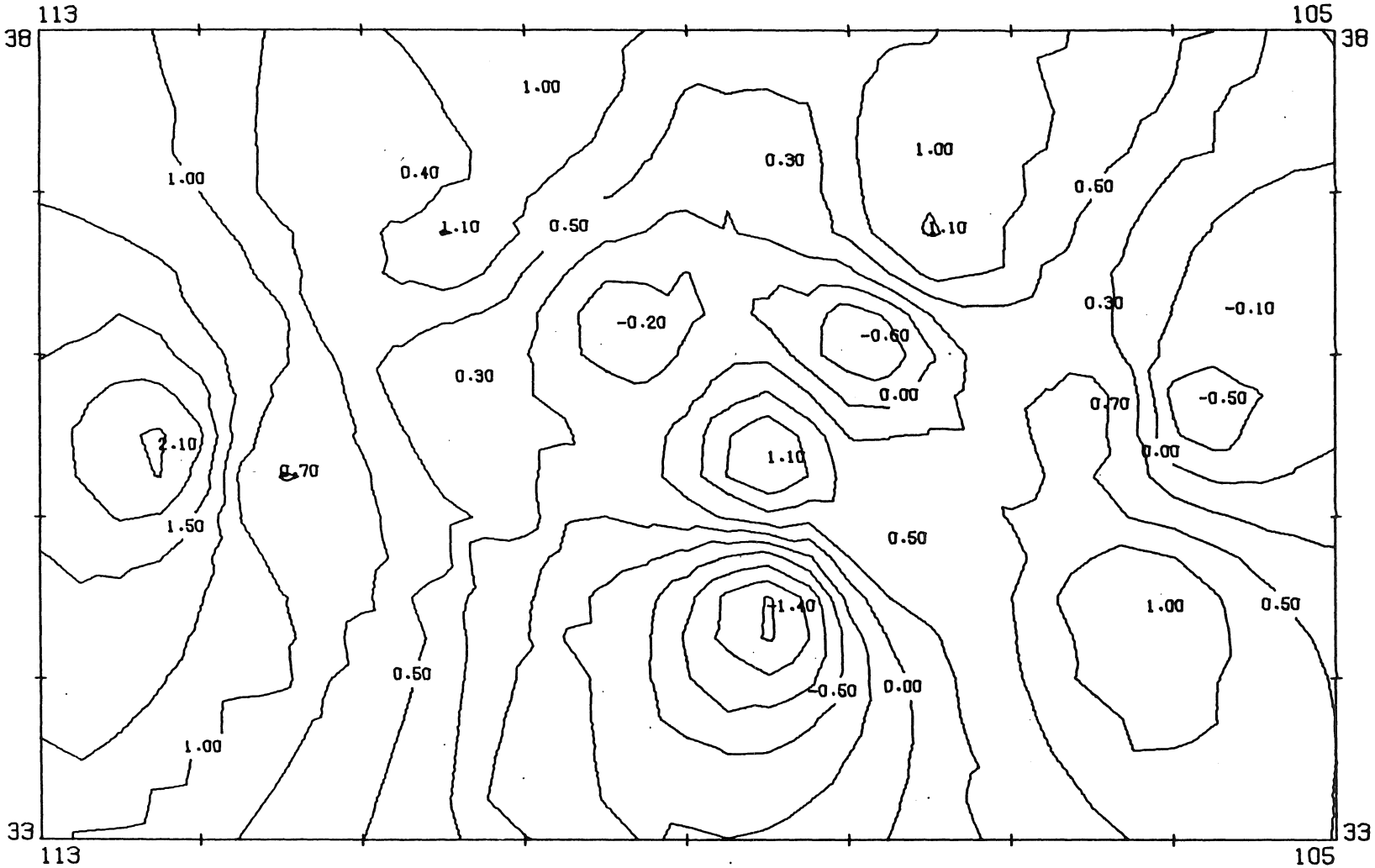
1480-1489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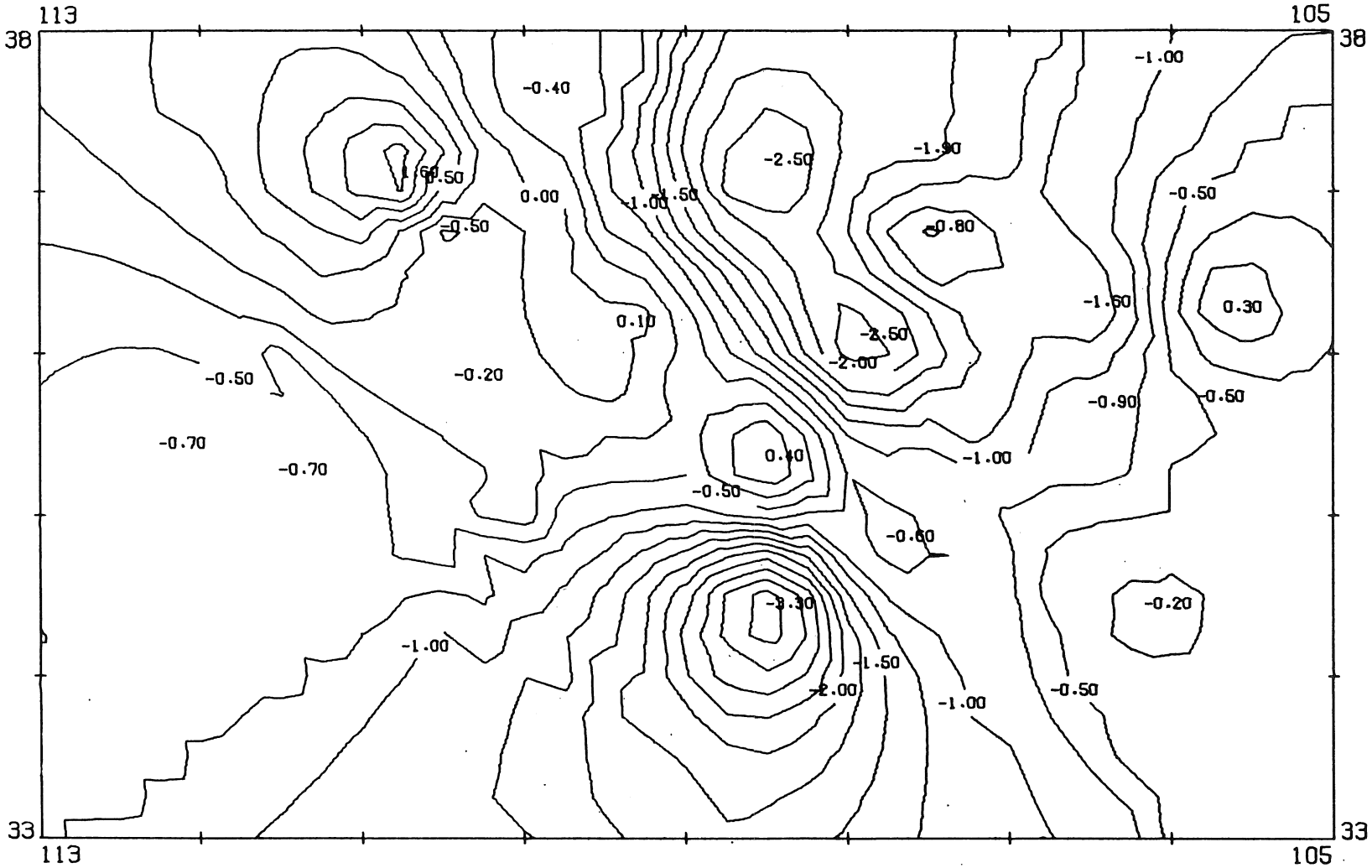
1490-1499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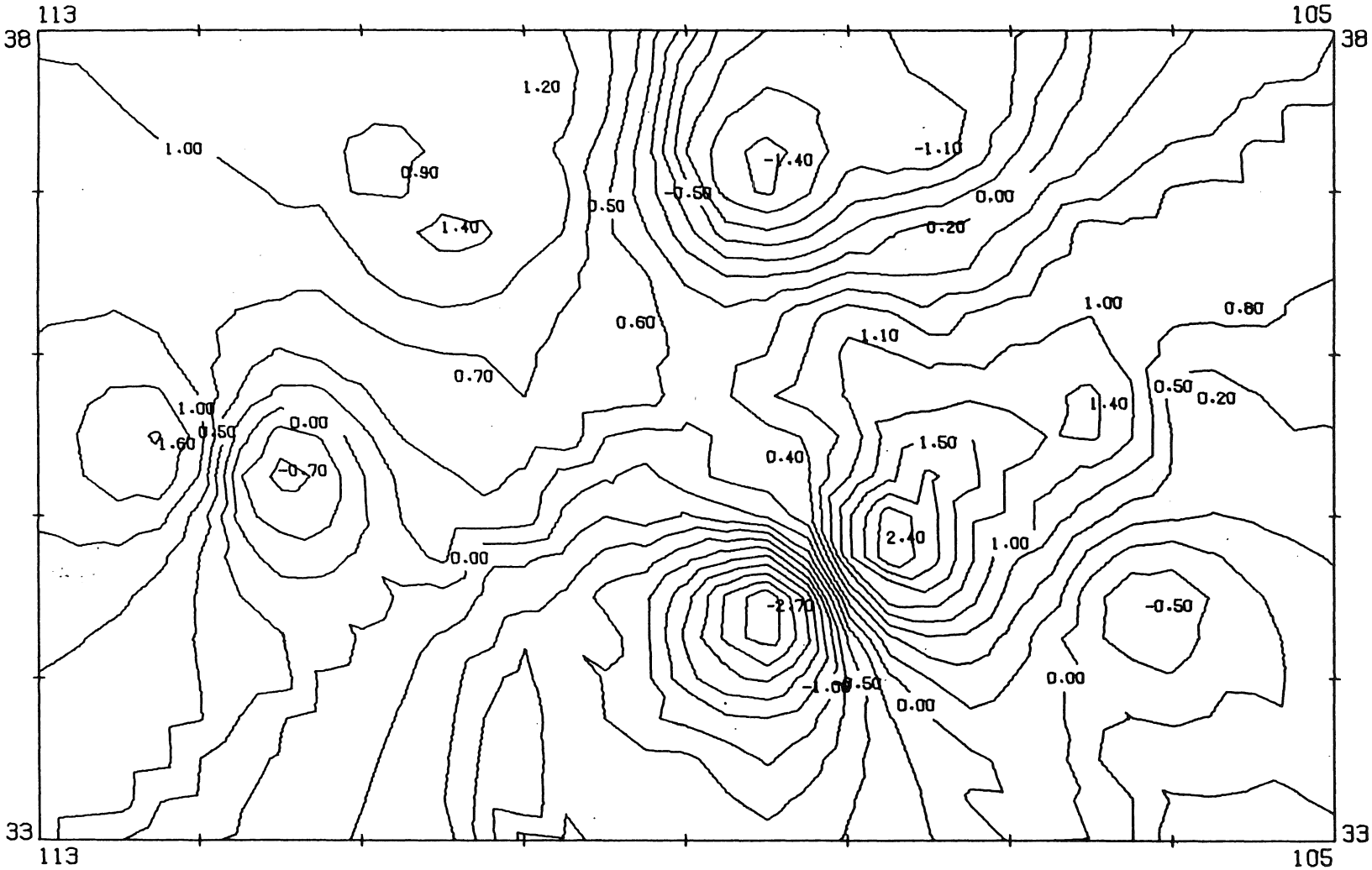
1500-1509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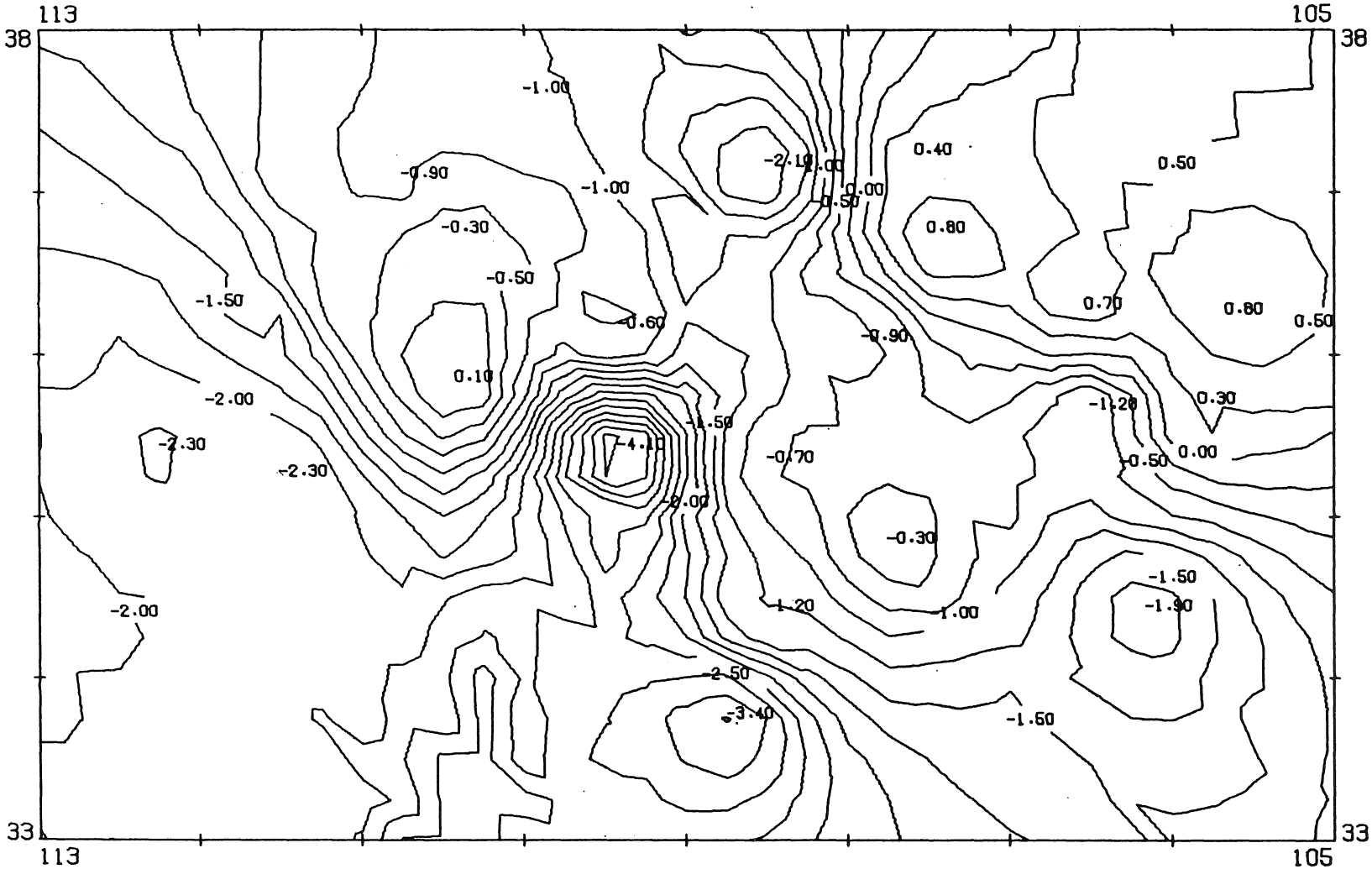
1510-1519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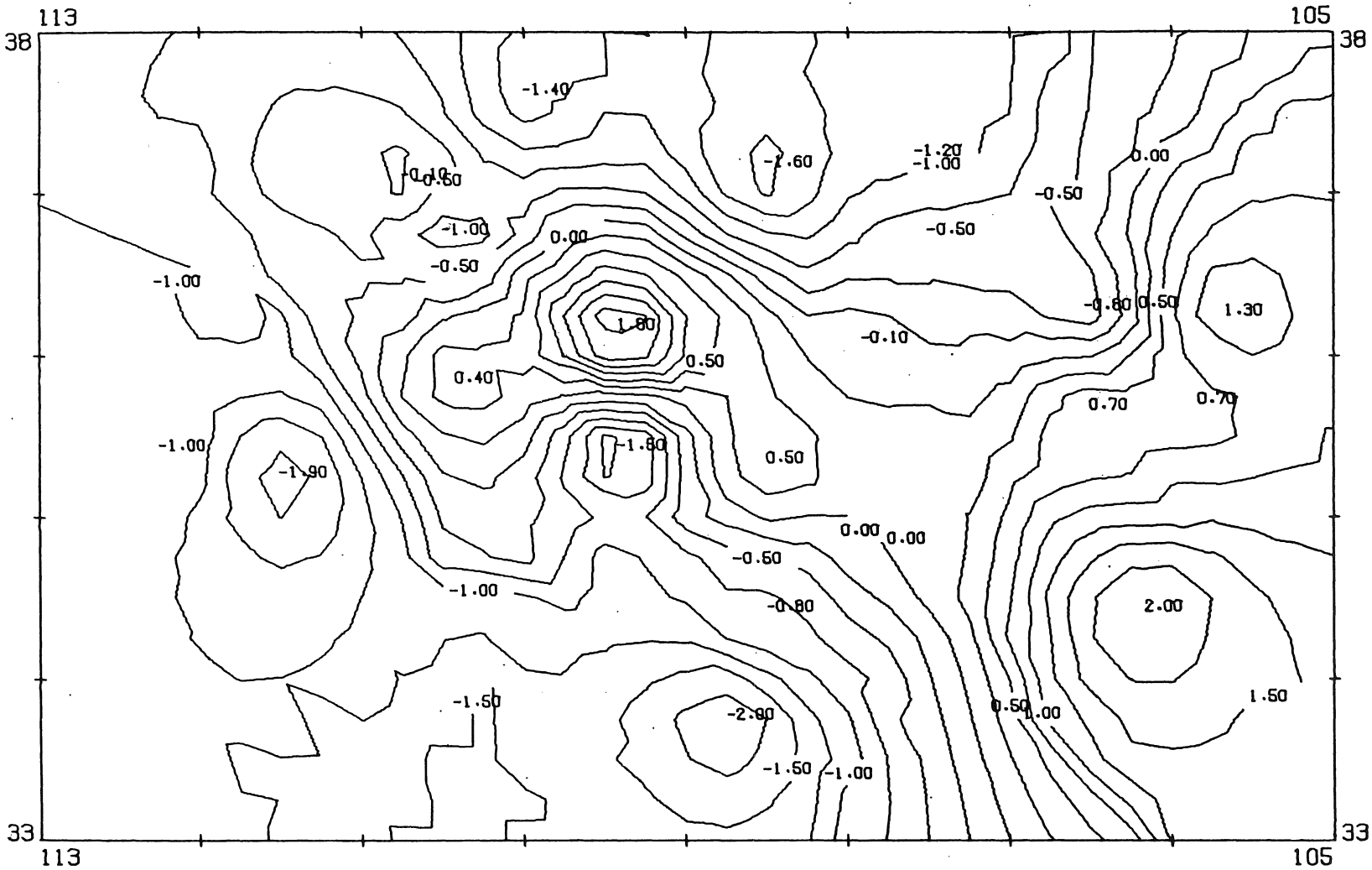
1520-1529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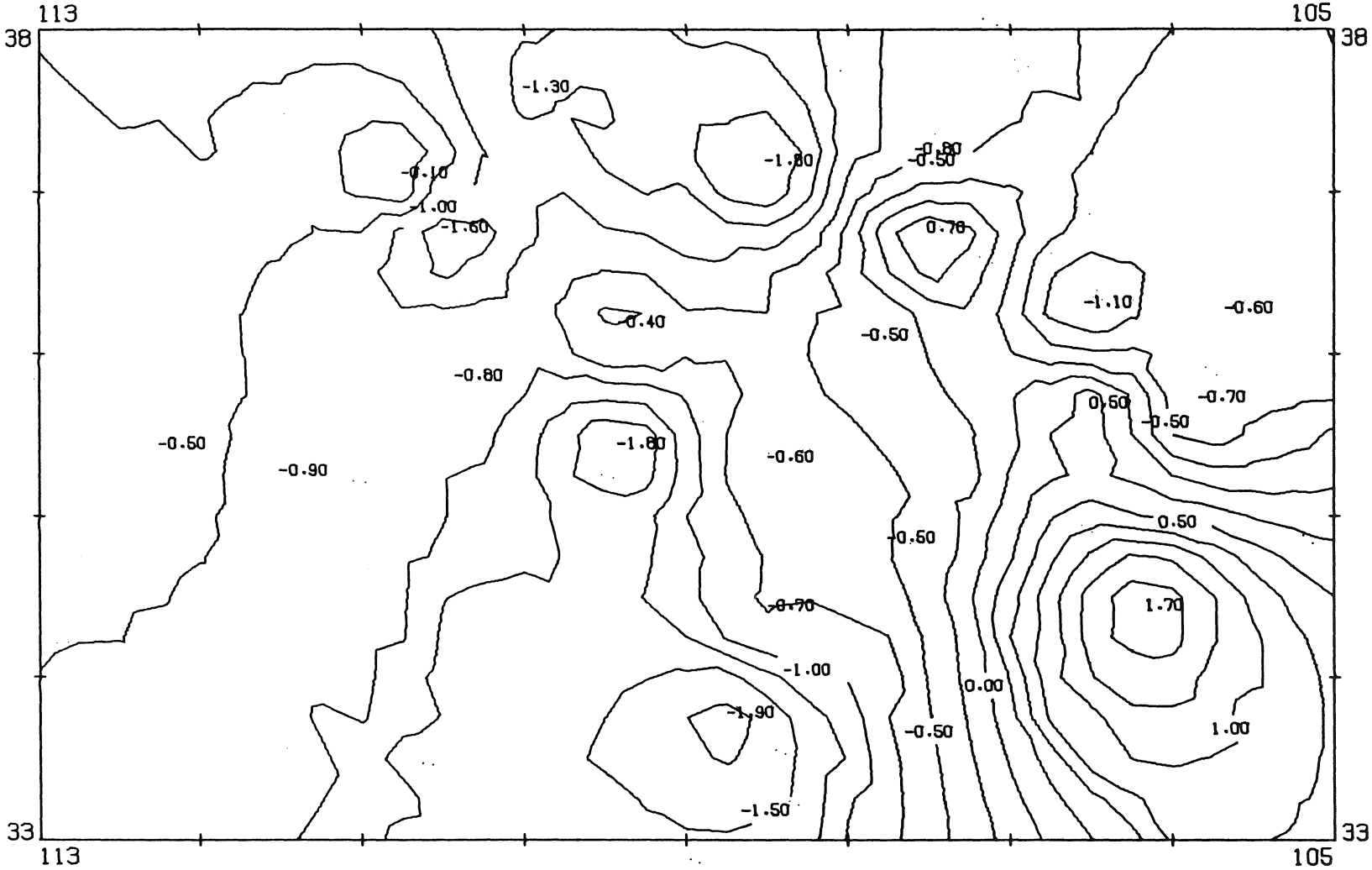
1530-1539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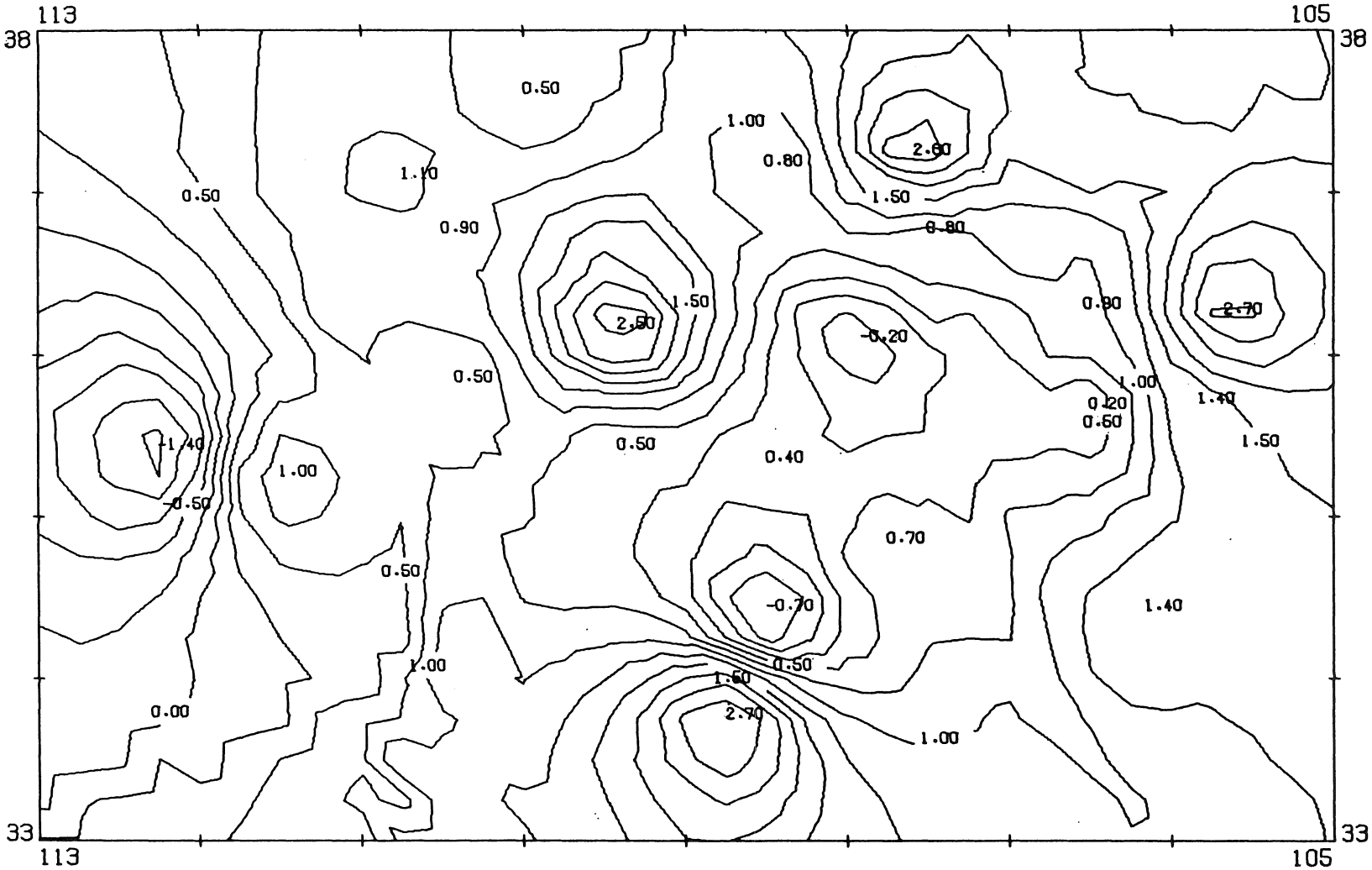
1540-1549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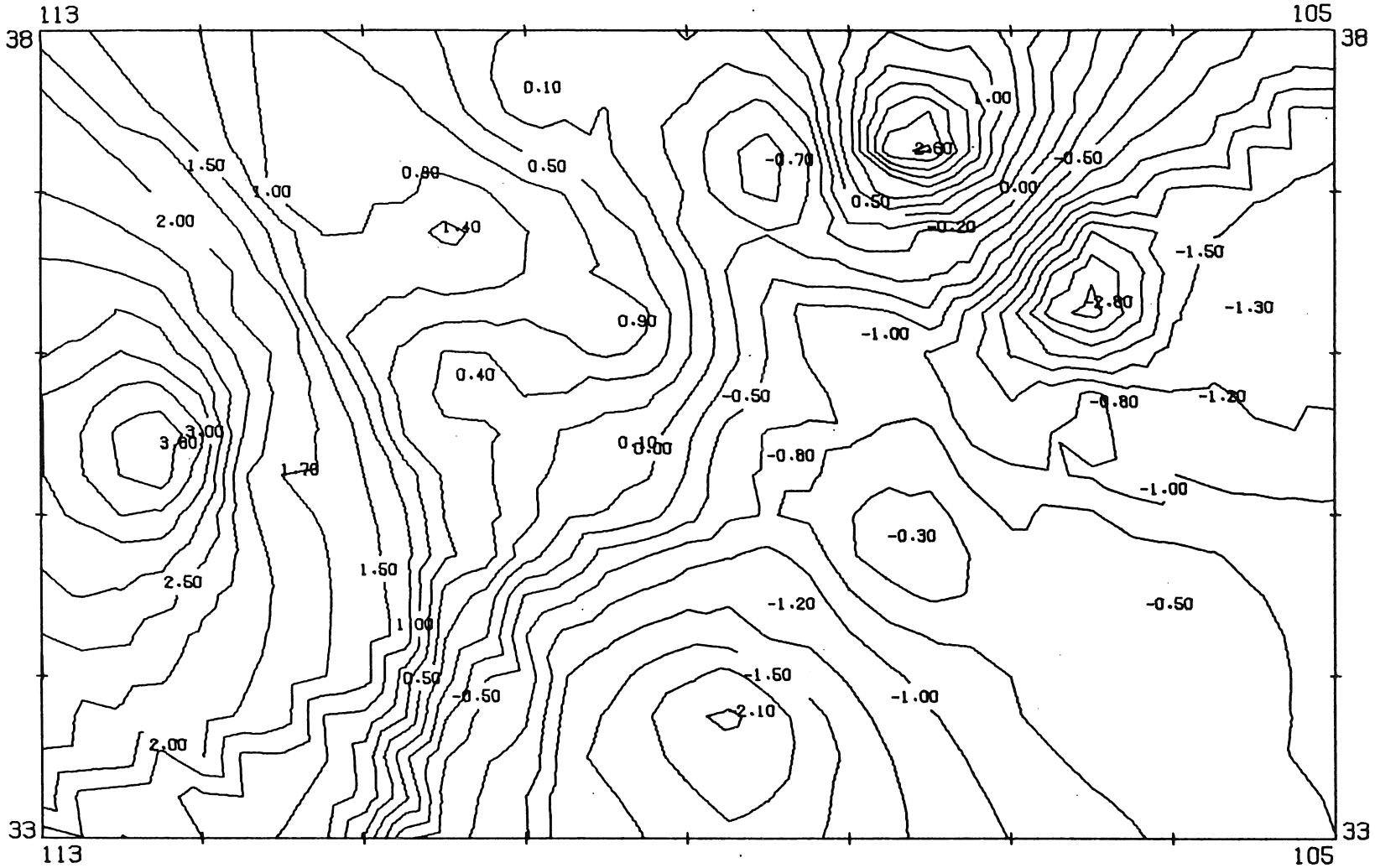
1550-1559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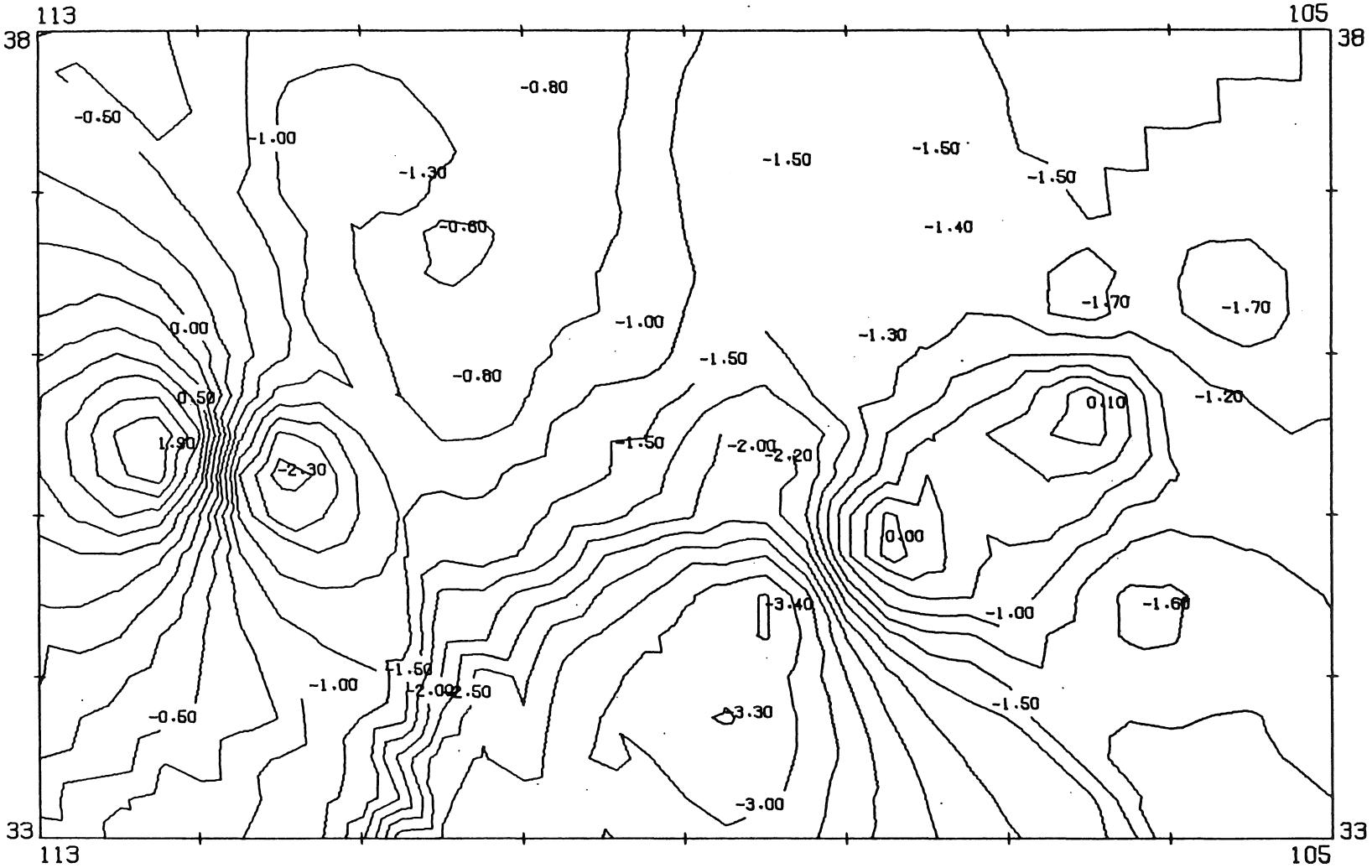
1560-1569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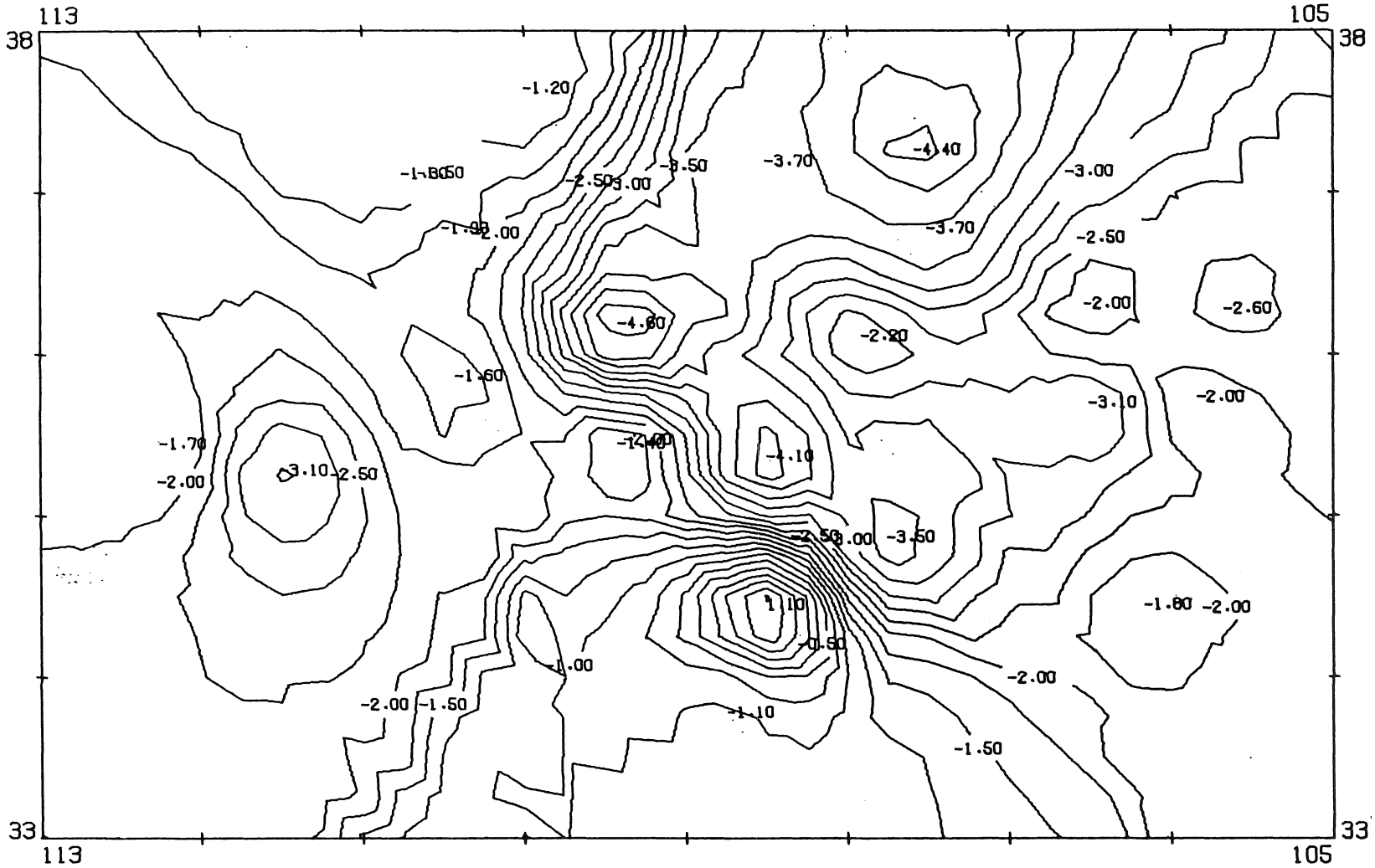
1570-1579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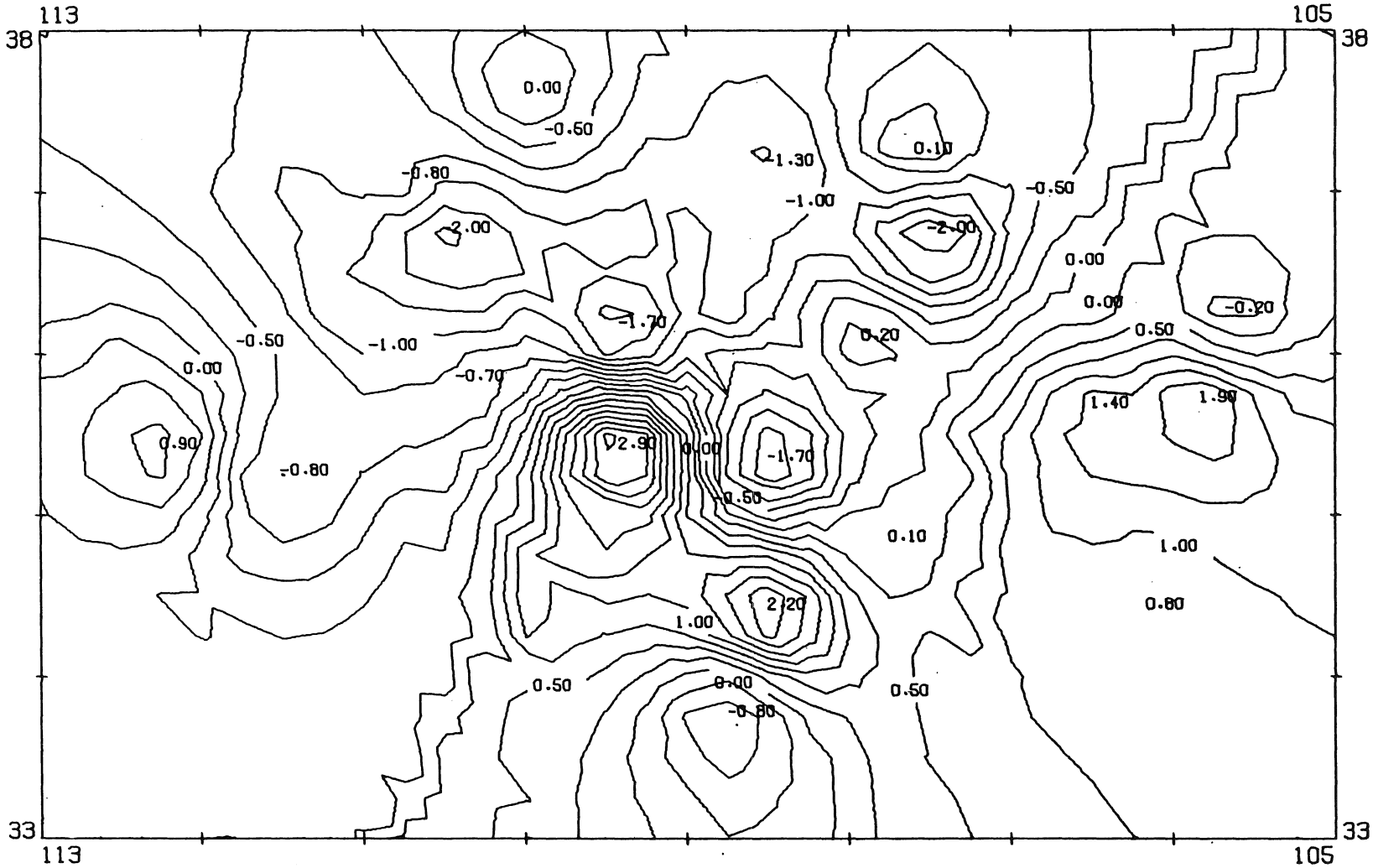
1580-1589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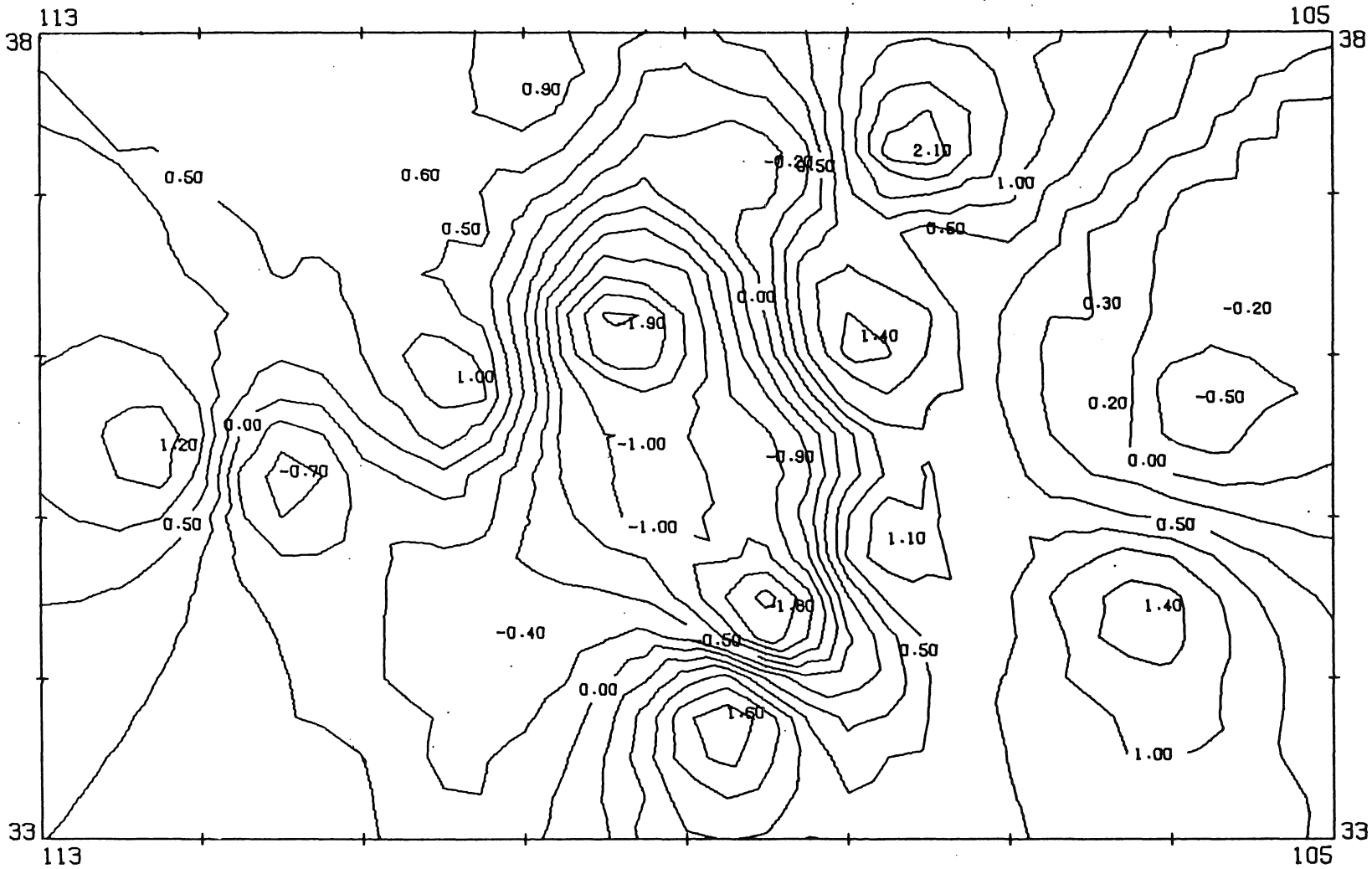
1590-1599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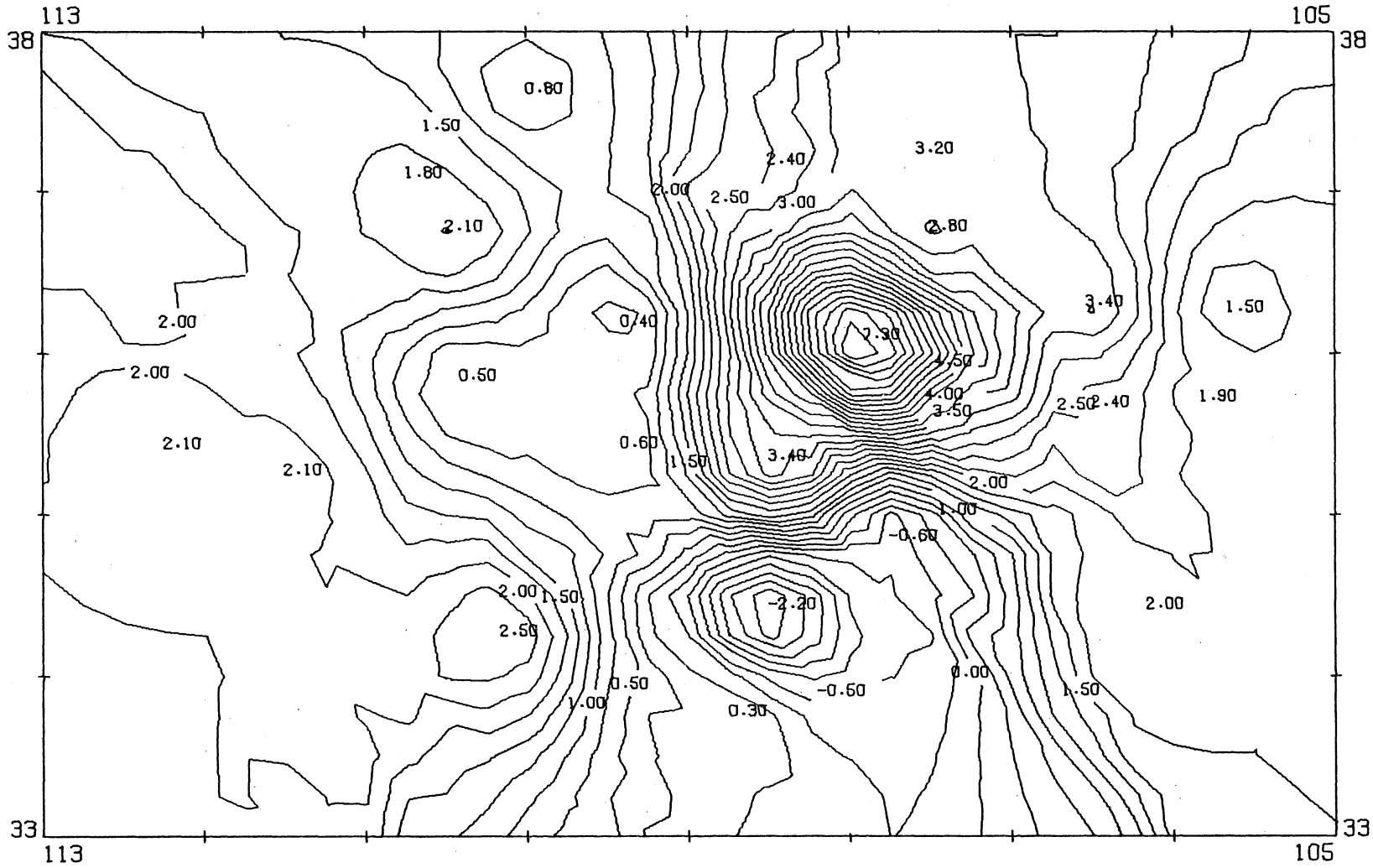
1600-1609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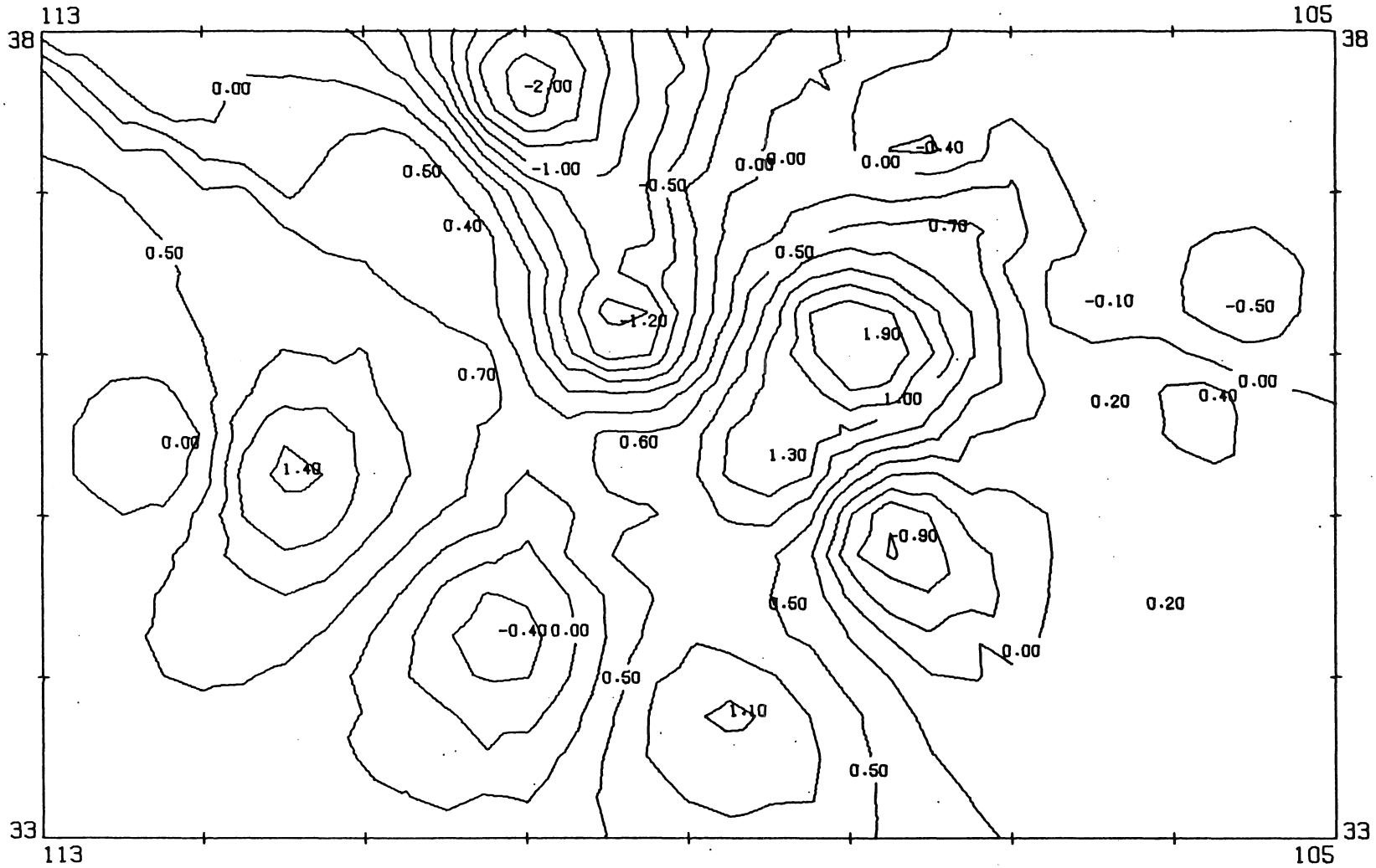
1610-1619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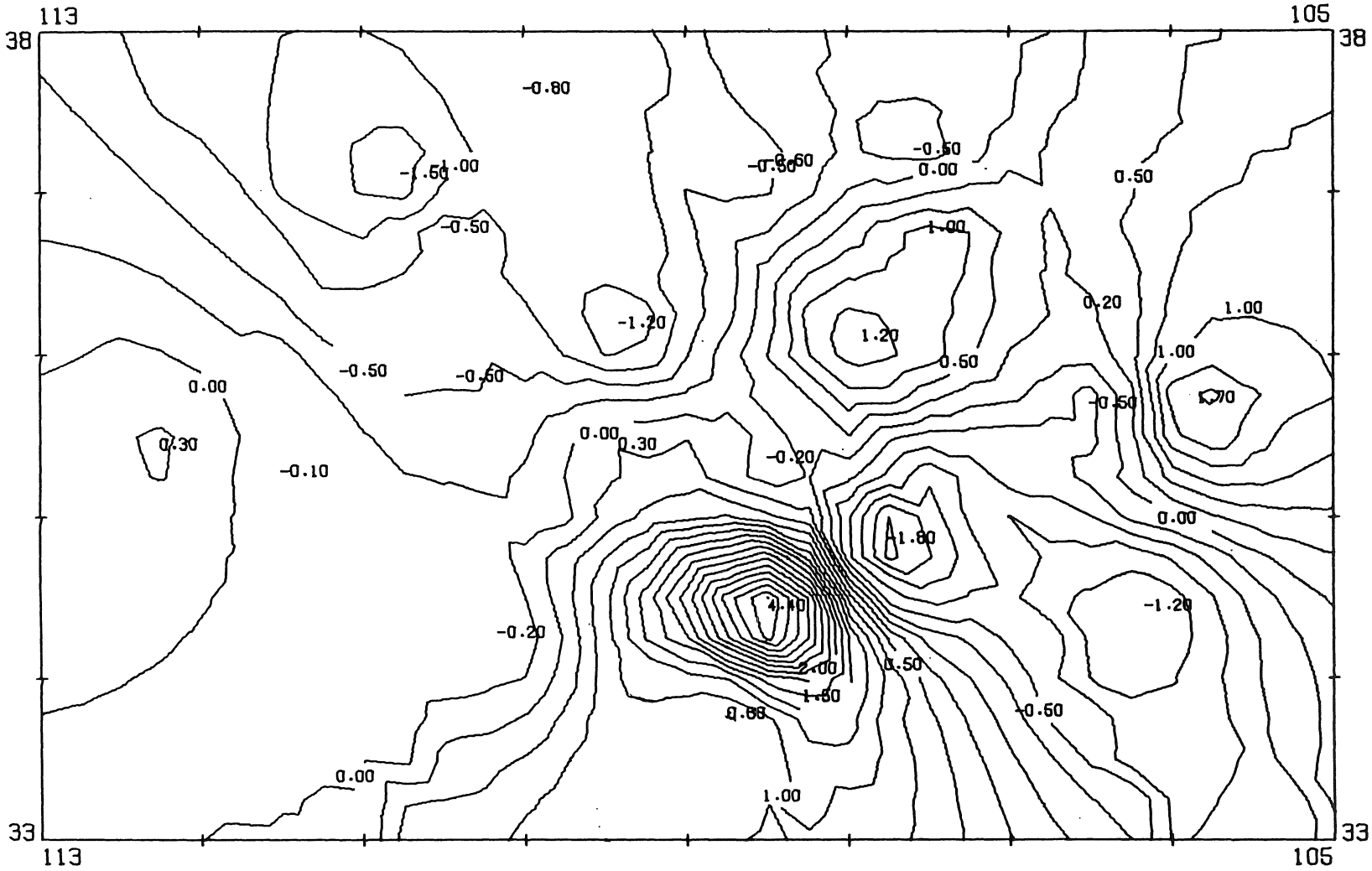
1620-1629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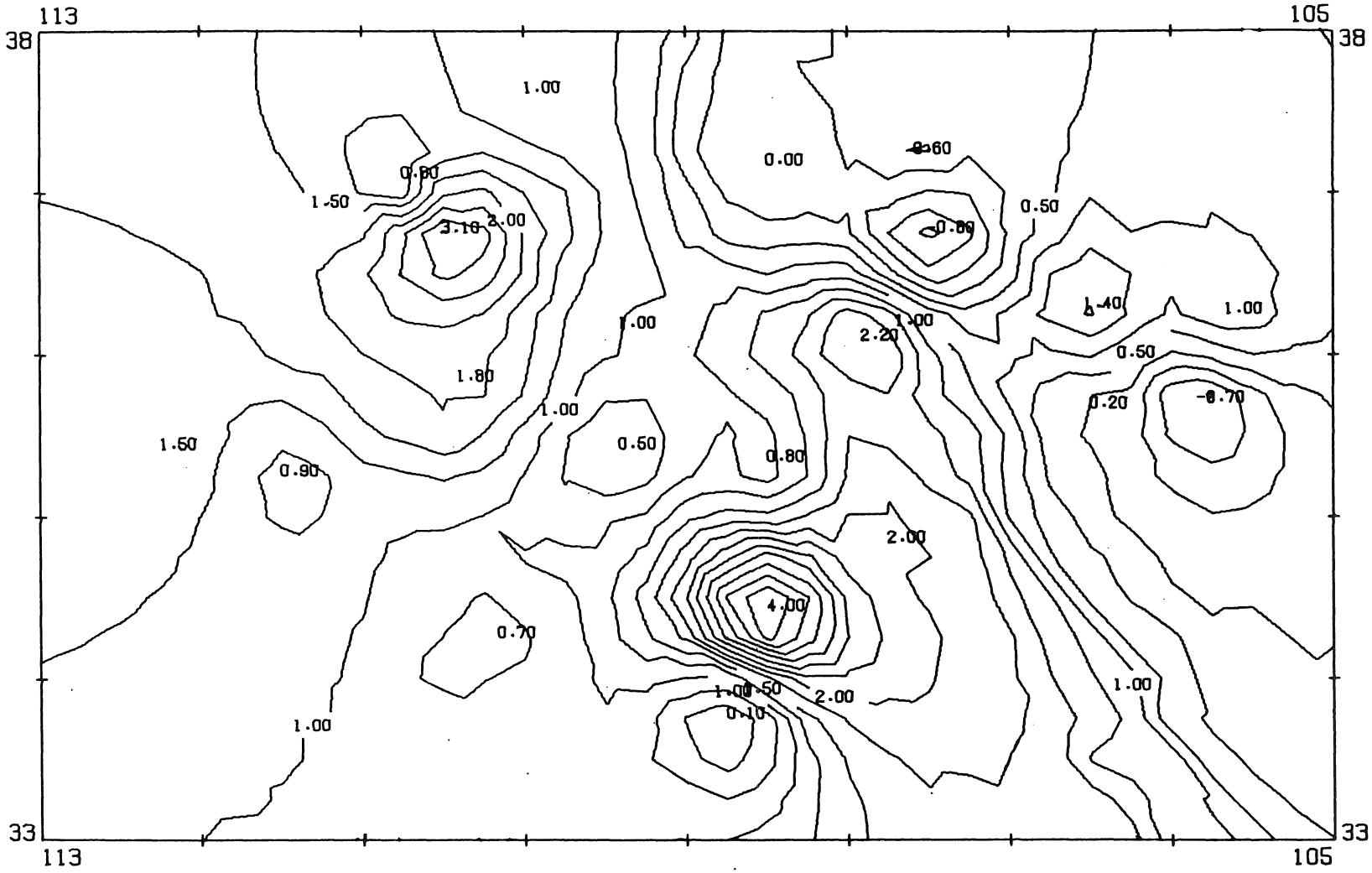
1630-1639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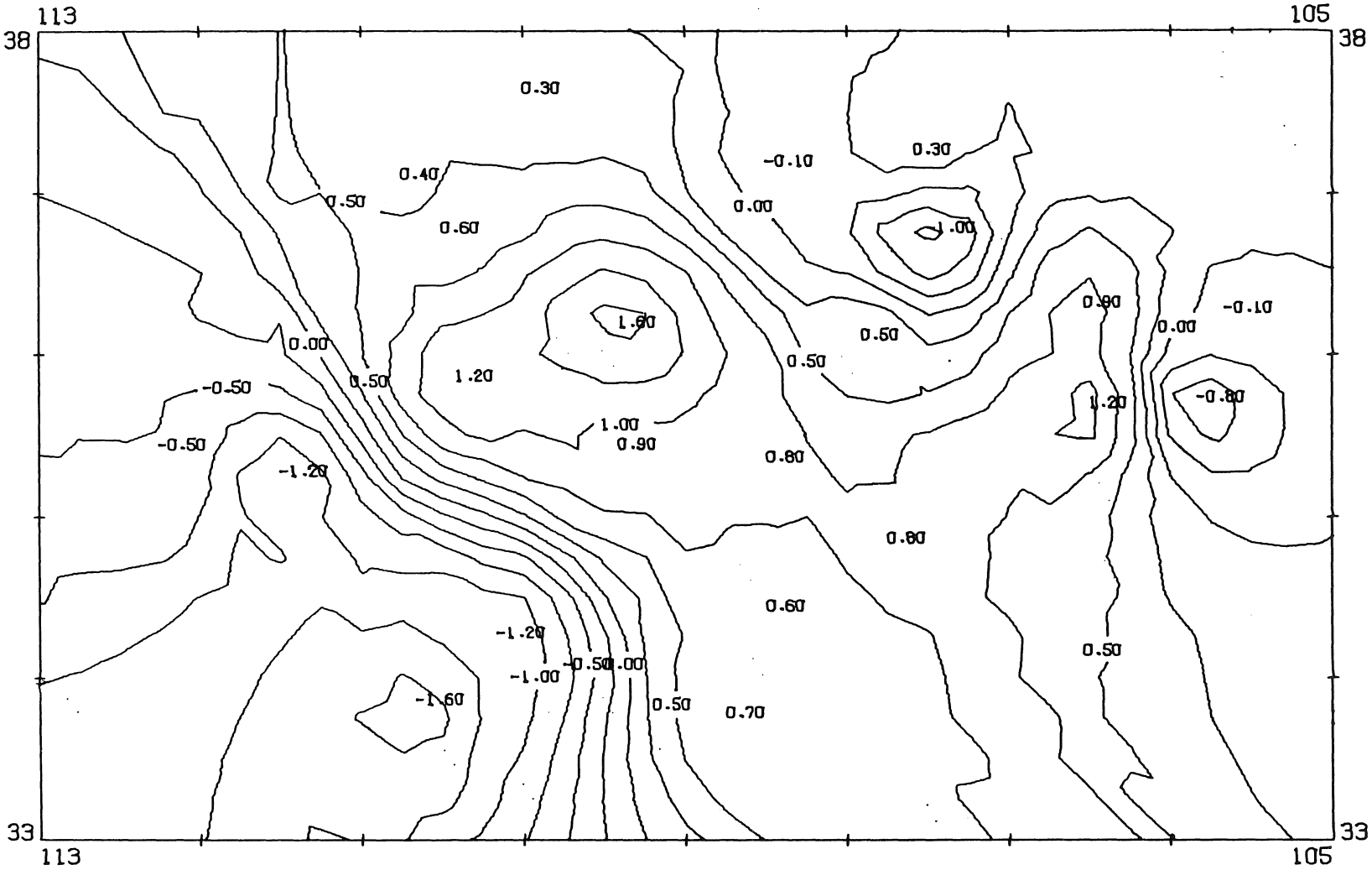
1640-1649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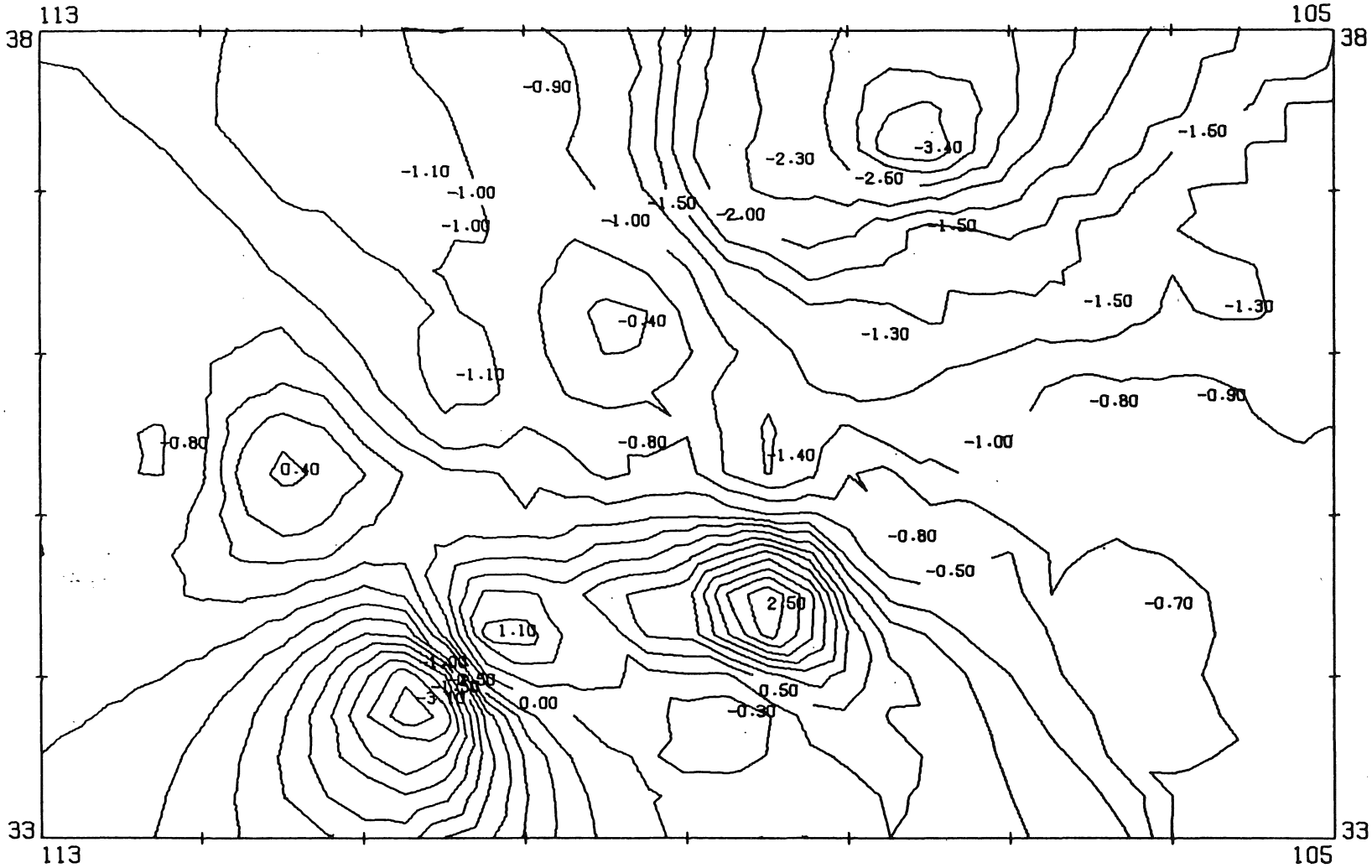
1650-1659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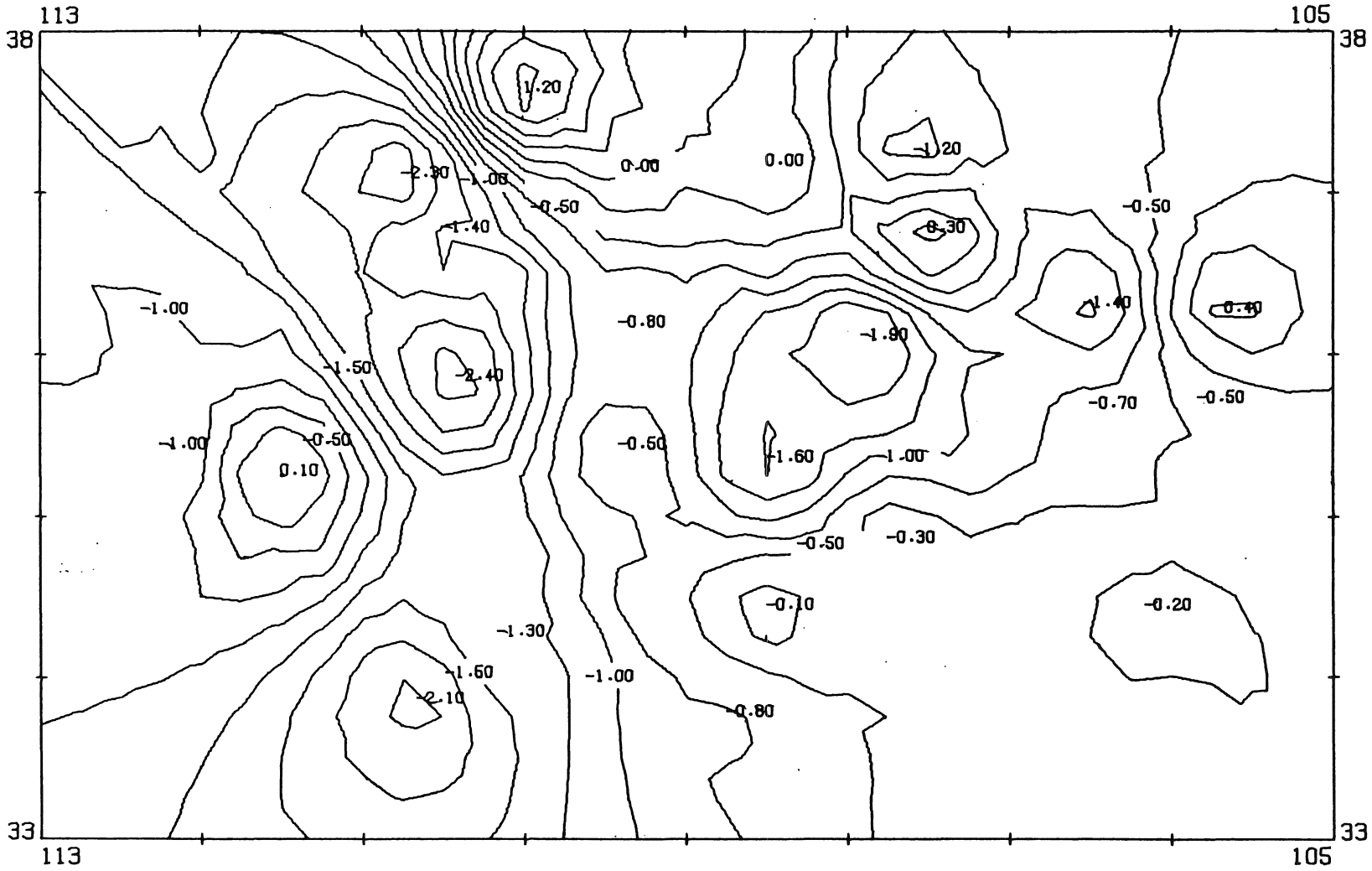
1660-1669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-1.00
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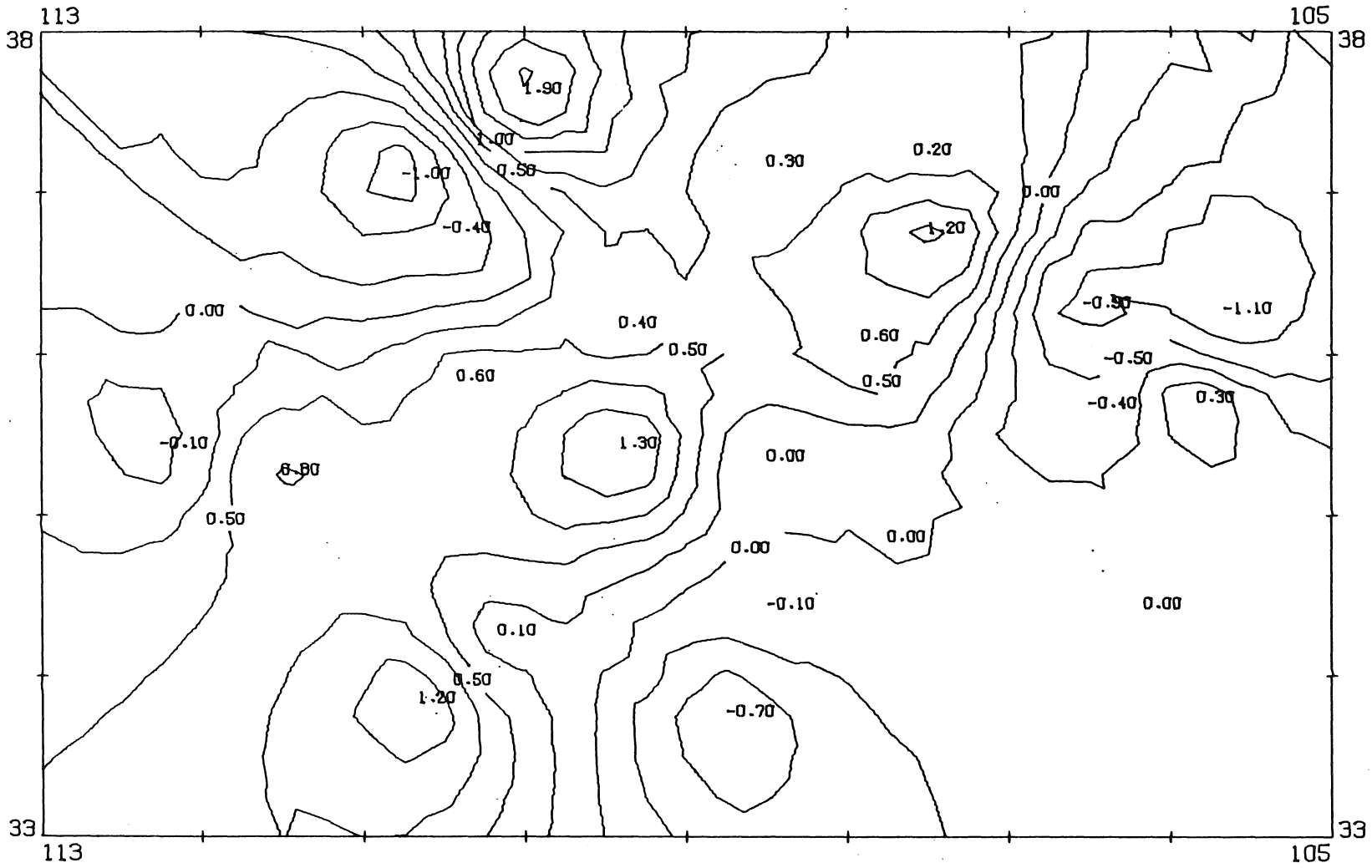
1670-1679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0.60
0.50
-0.10
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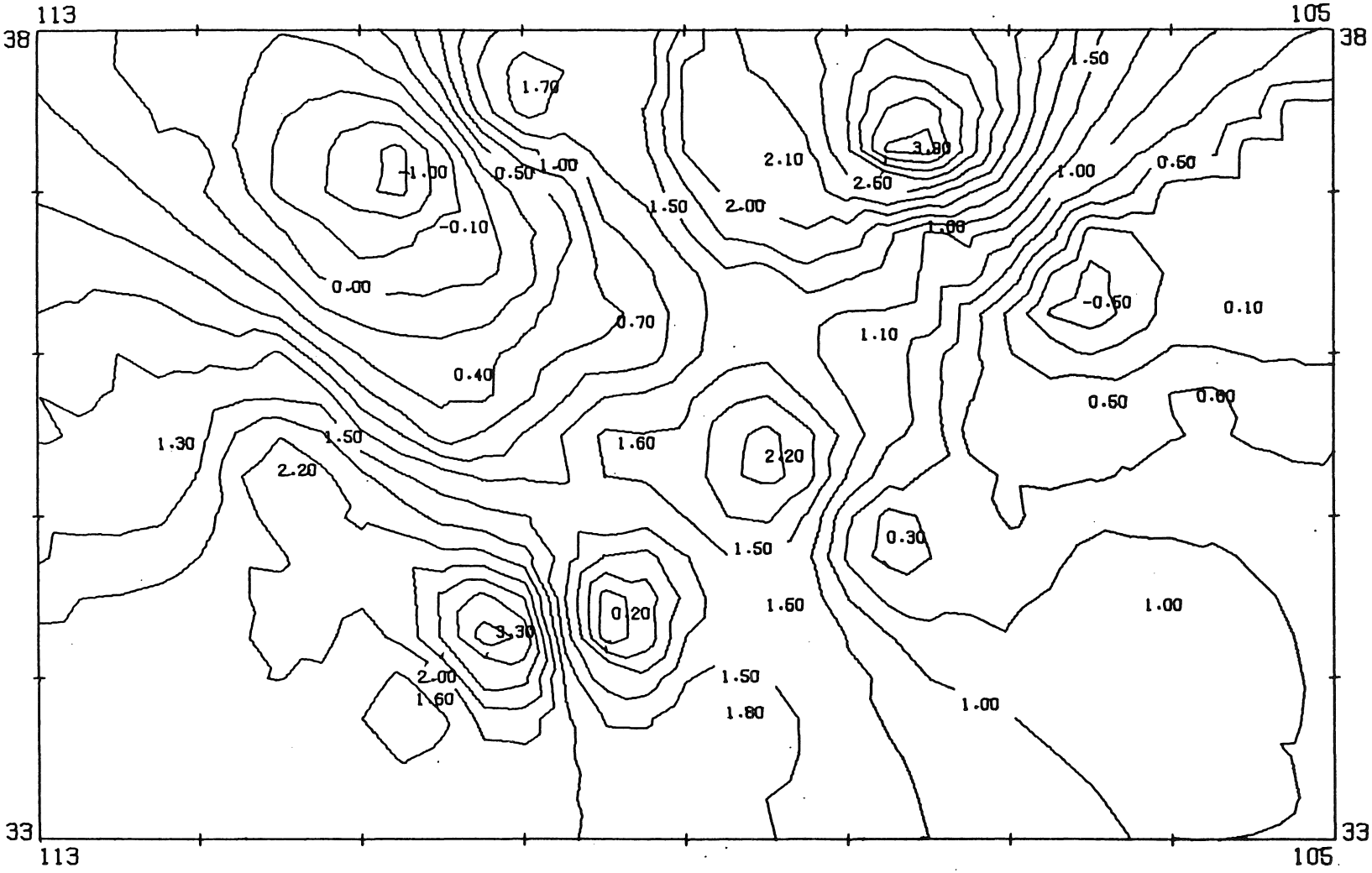
1680-1689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1.50
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3.80
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1.50
1.00
0.60
1.00
-0.50
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1.10
0.50
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1.60
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2.00
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1.50
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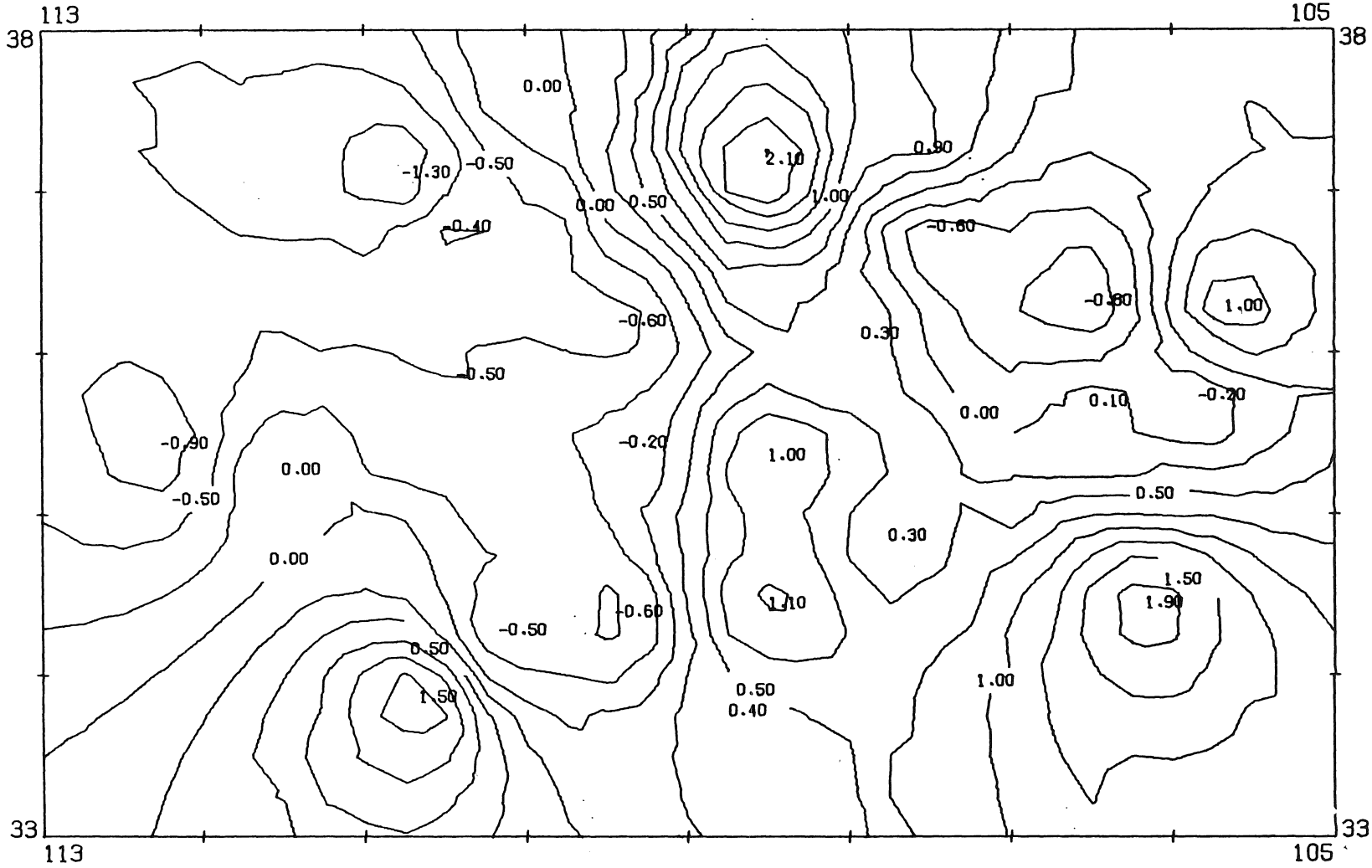
1690-1699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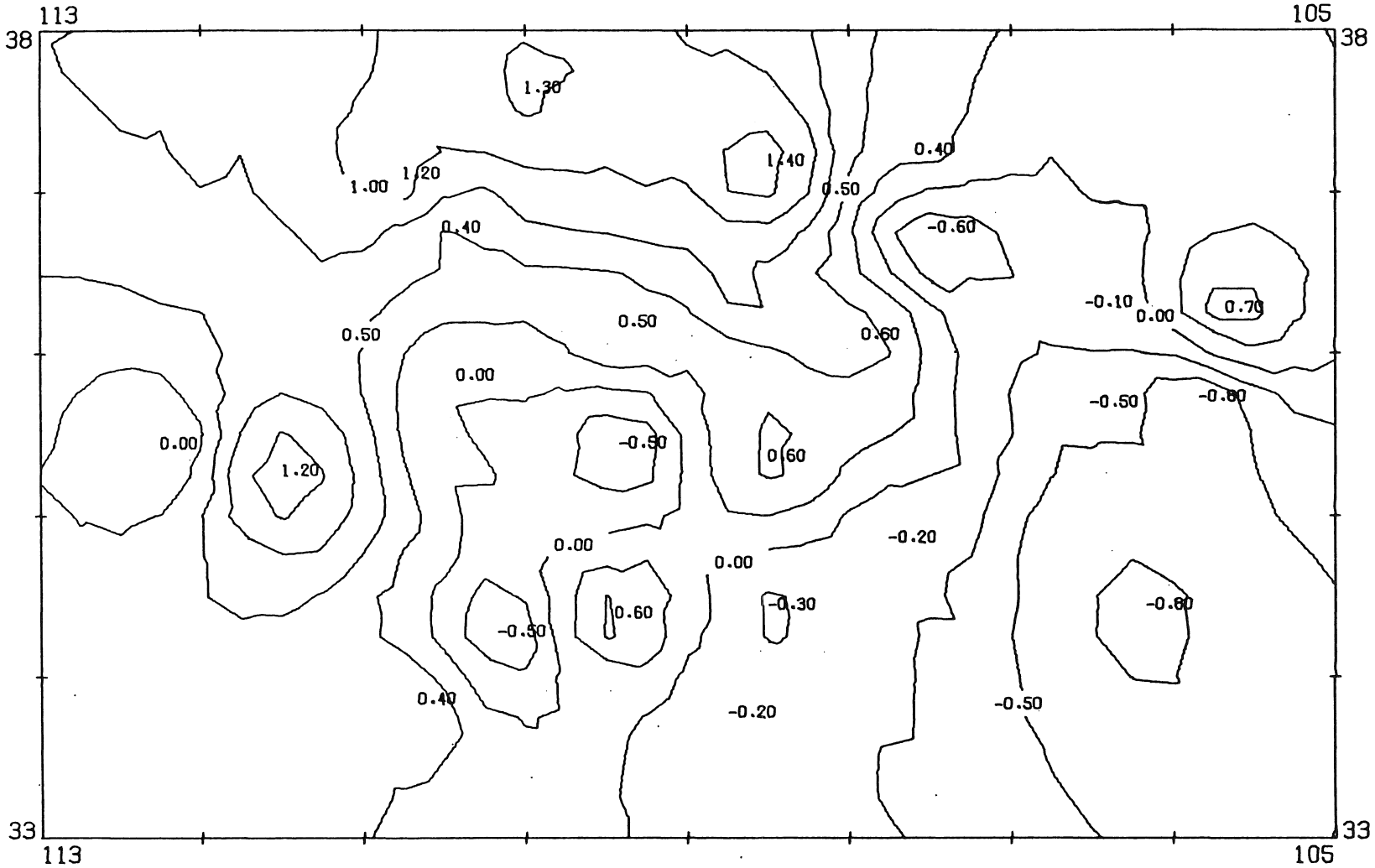
1700-1709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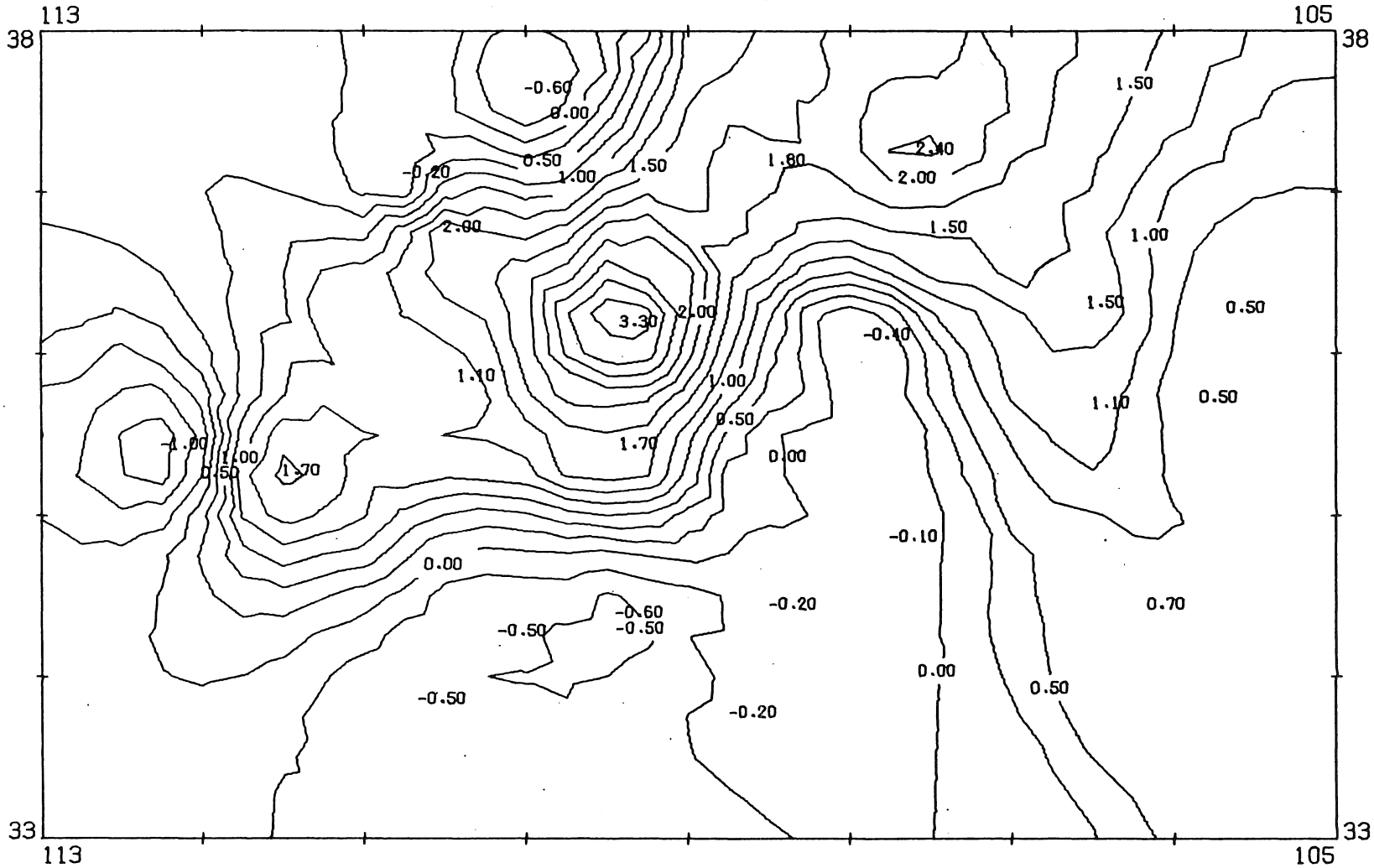
-0.50

1710-1719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2.40
2.00
2.00
1.50
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1.50
0.50
3.30
2.00
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1.10
1.00
0.50
1.10
0.50
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1.00
0.50
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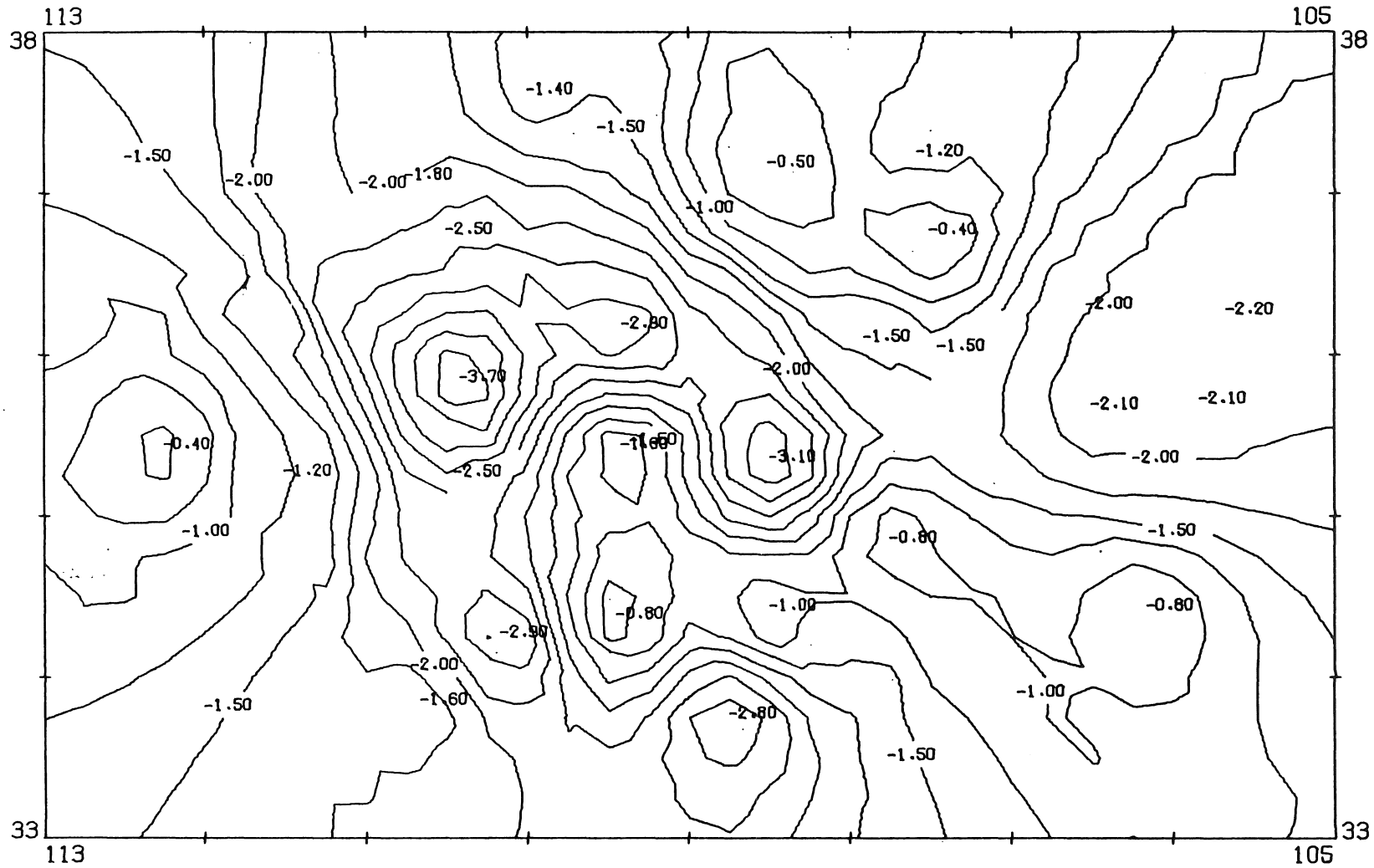
1720-1729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-1.80
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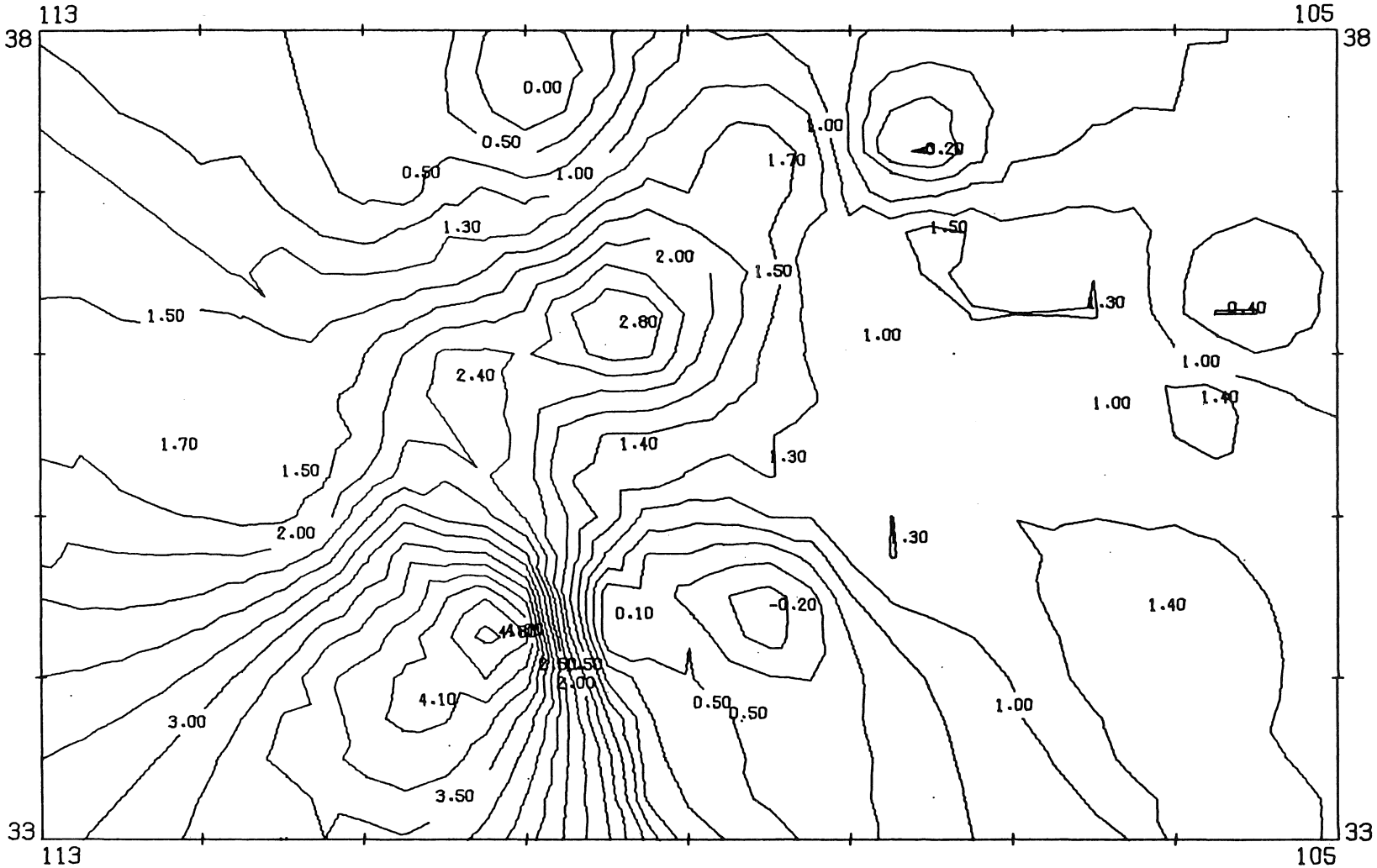
1730-1739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1.50
2.00
1.50
1.50
2.80
1.30
0.40
1.00
2.40
1.00
1.00
1.40
1.70
1.40
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1.50
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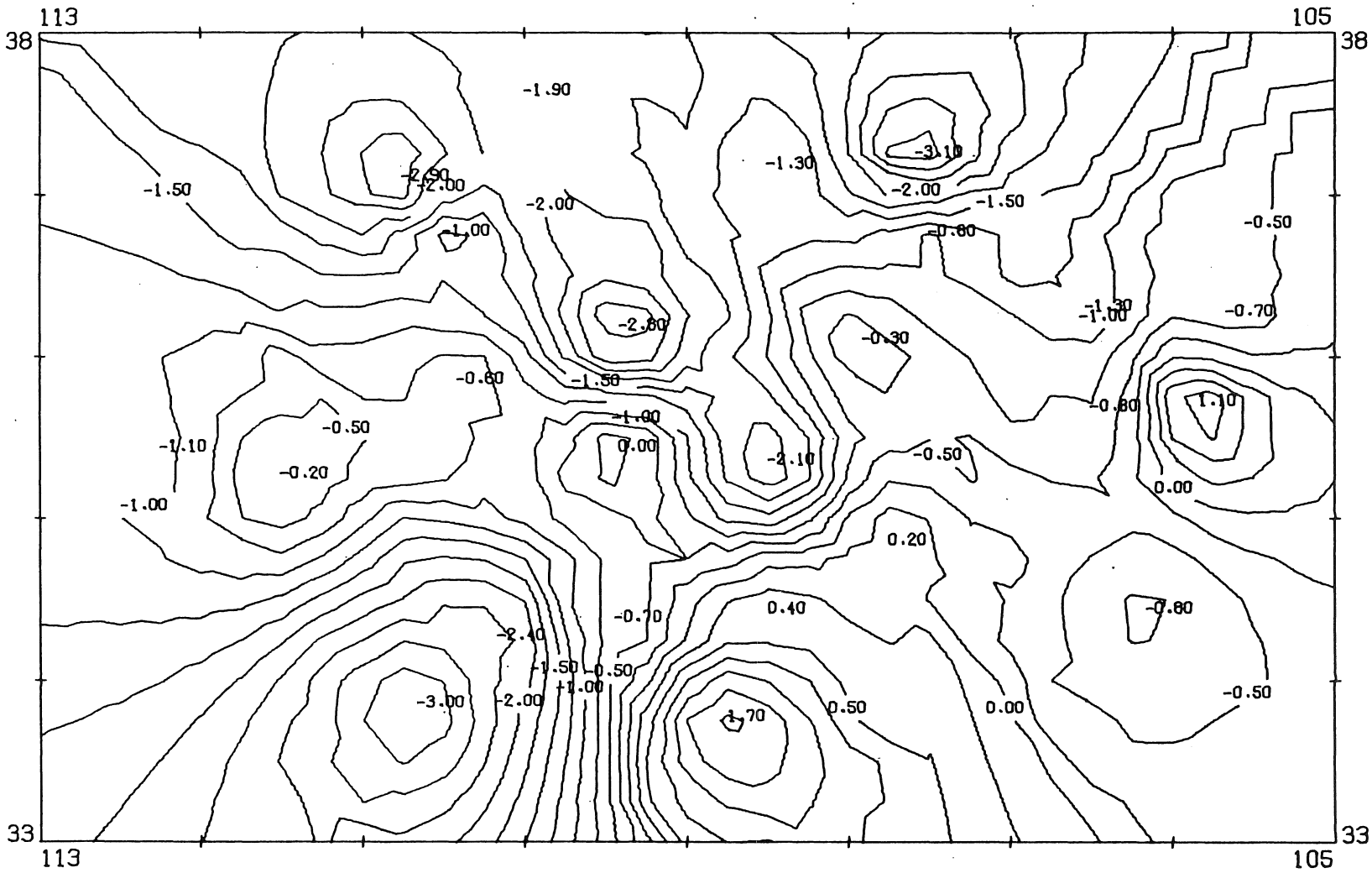
1740-1749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-2.00
-1.00
-1.30
-3.10
-2.00
-1.50
-0.80
-0.50
-2.80
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-1.00
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-0.30
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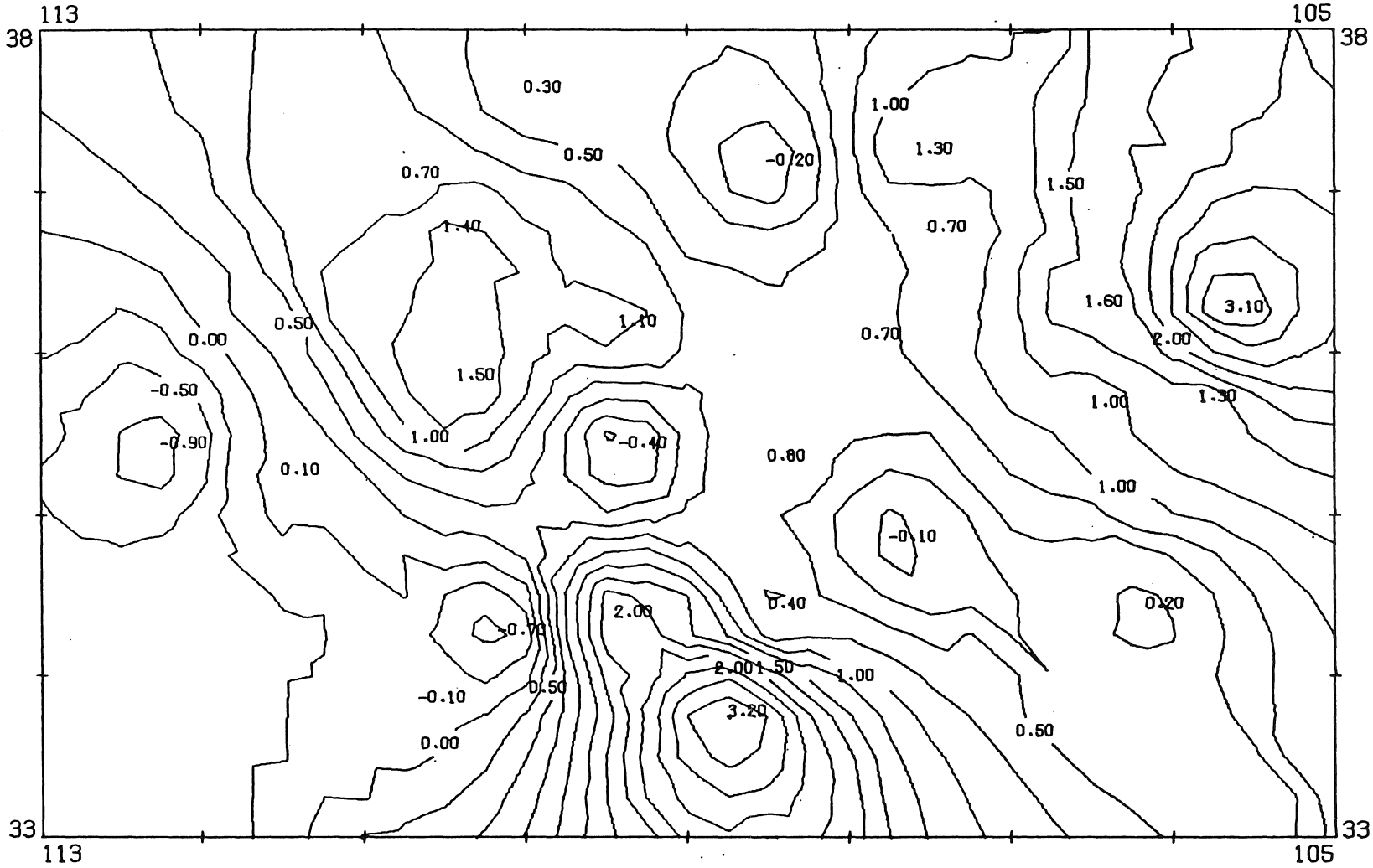
1750-1759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0.70
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0.50
1.50
-0.50
1.00
1.30
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0.80
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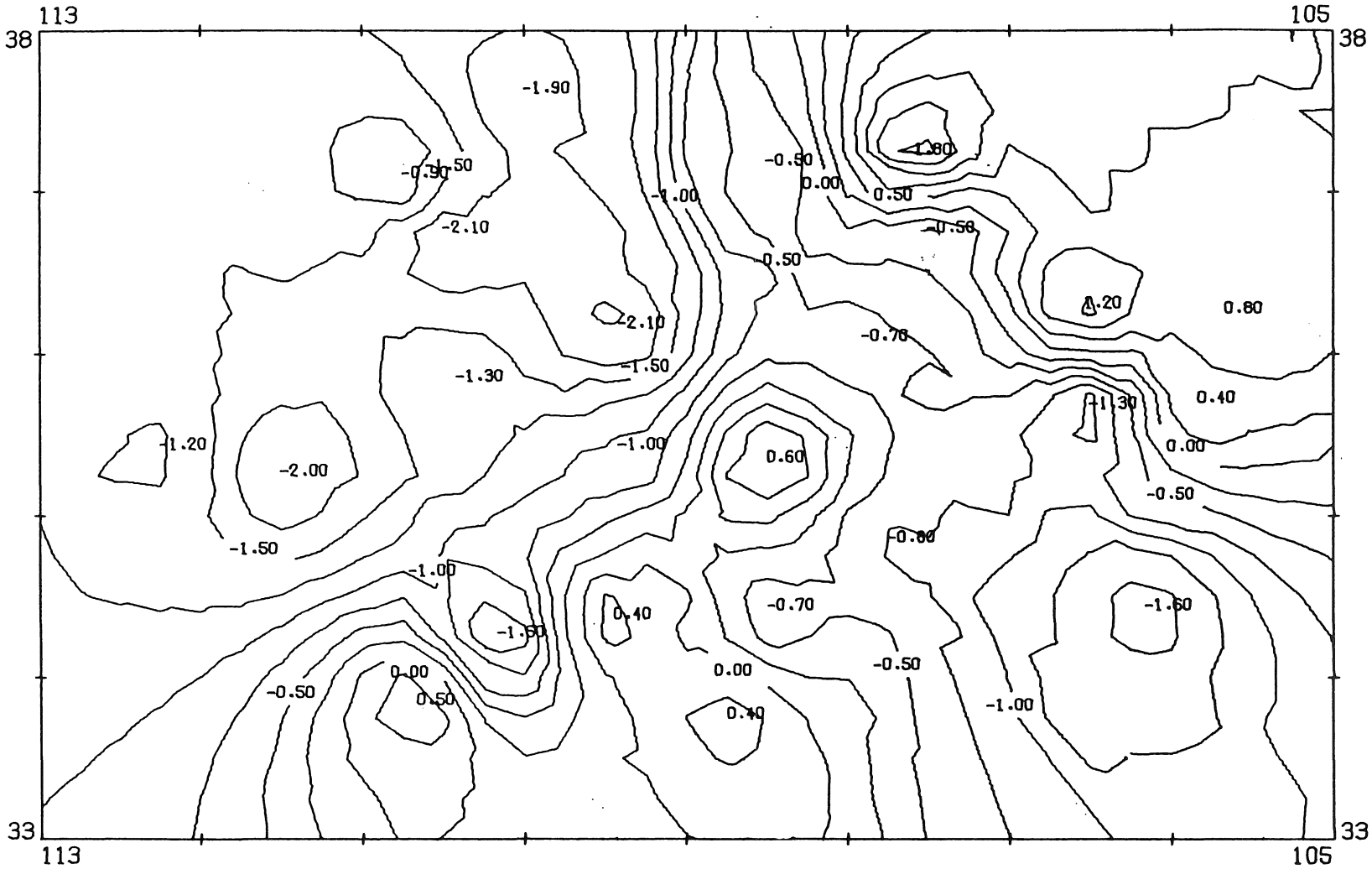
1760-1769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0.50
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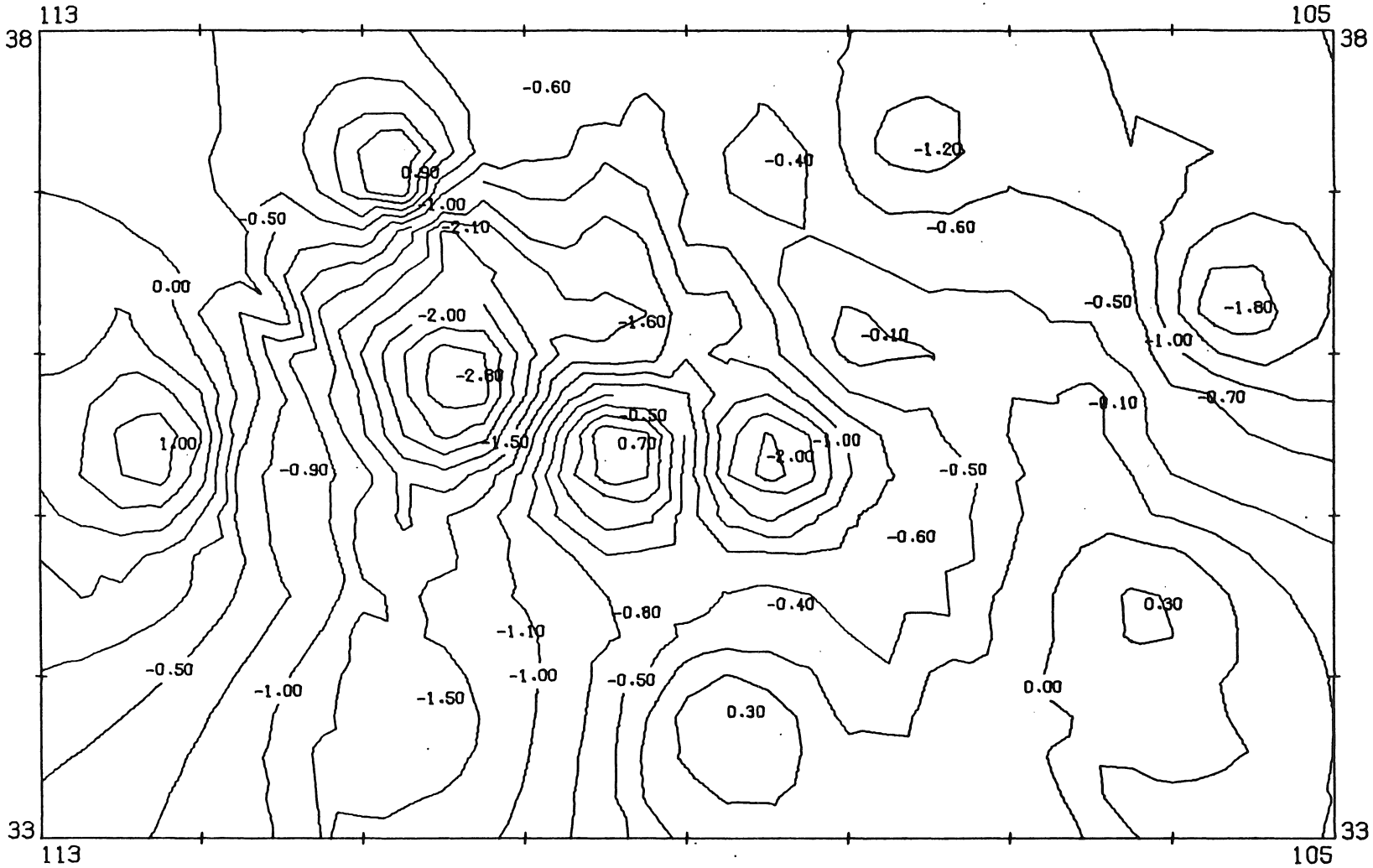
1770-1779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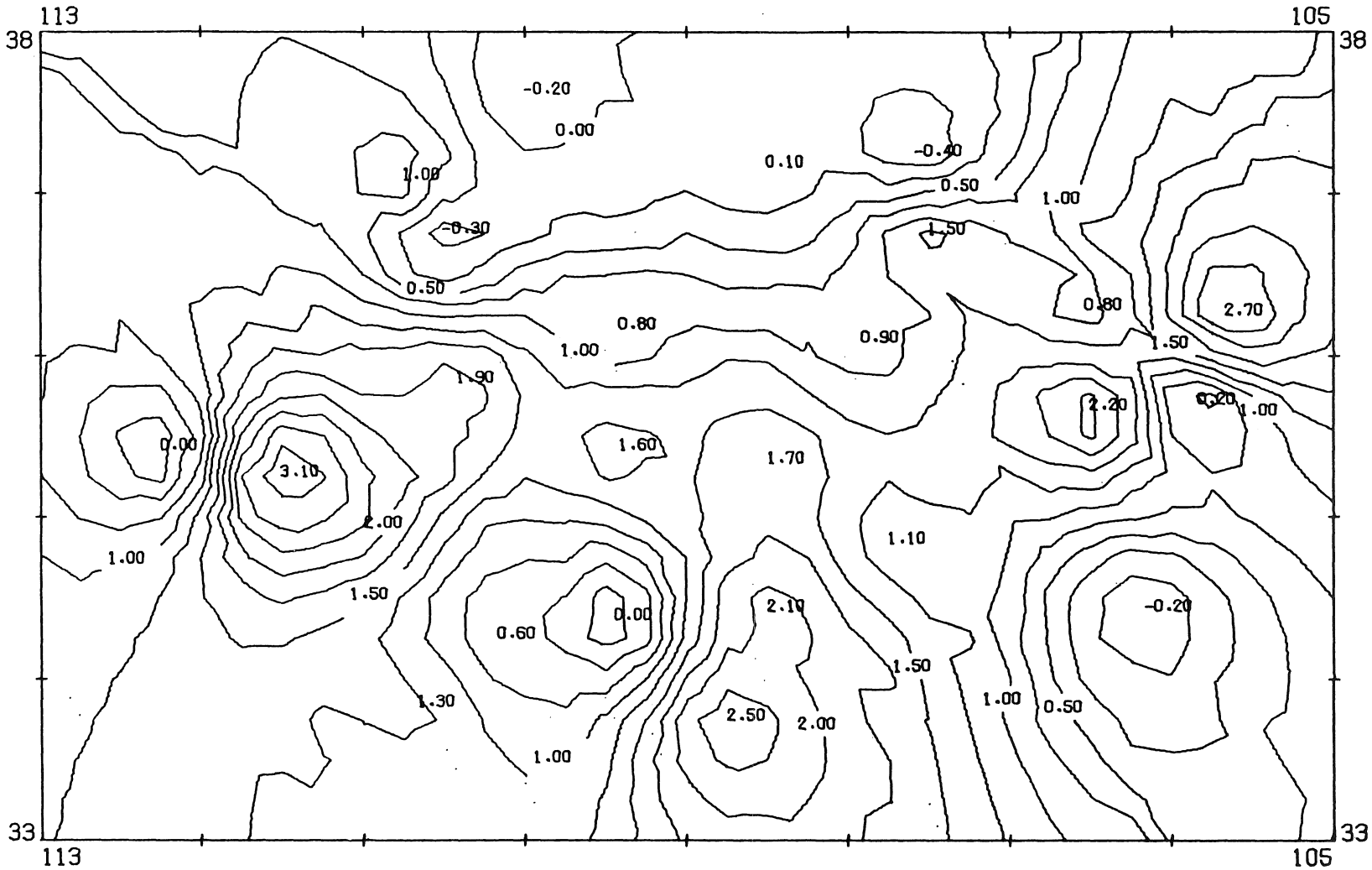
1780-1789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1.00
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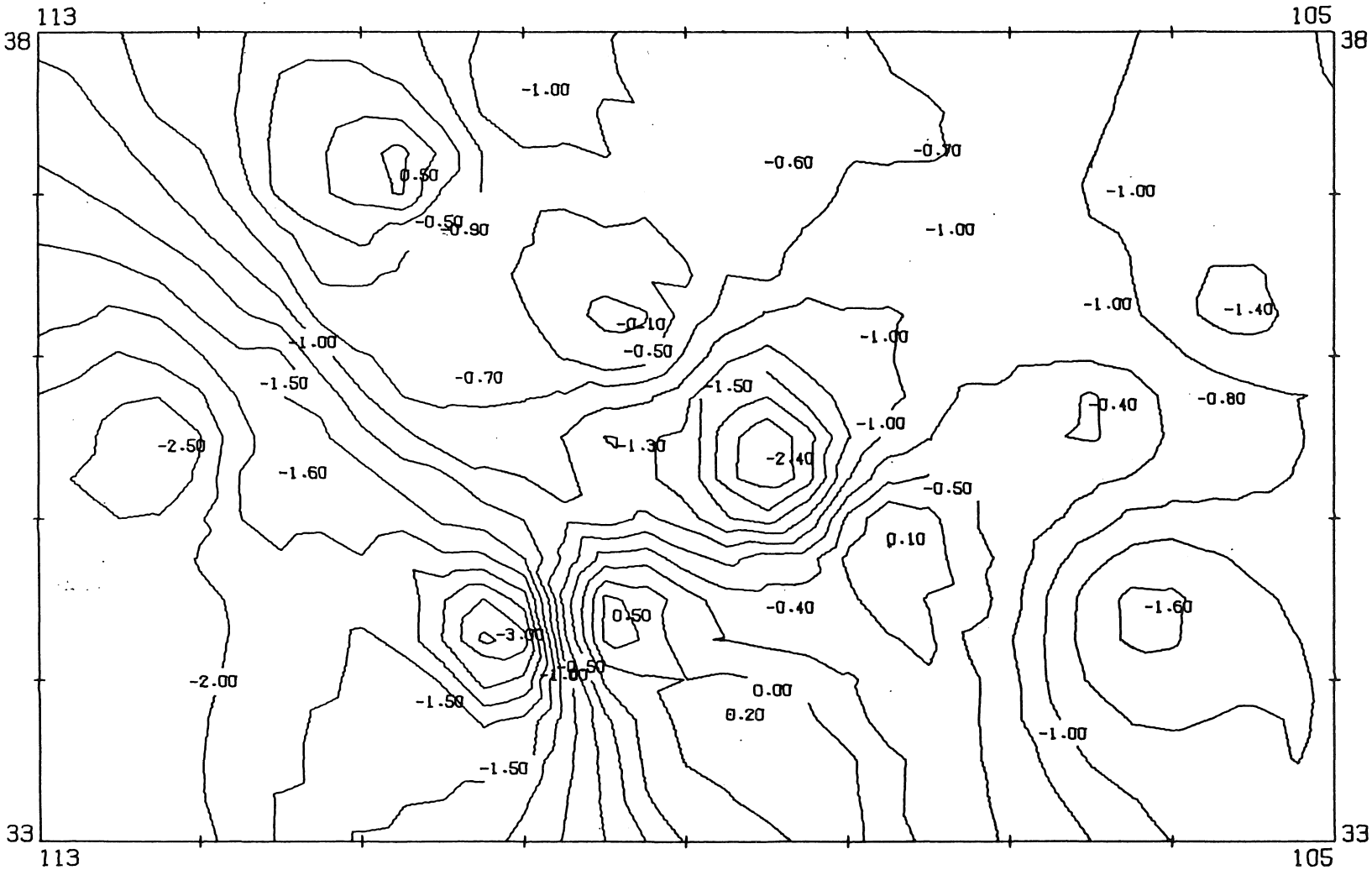
1790-1799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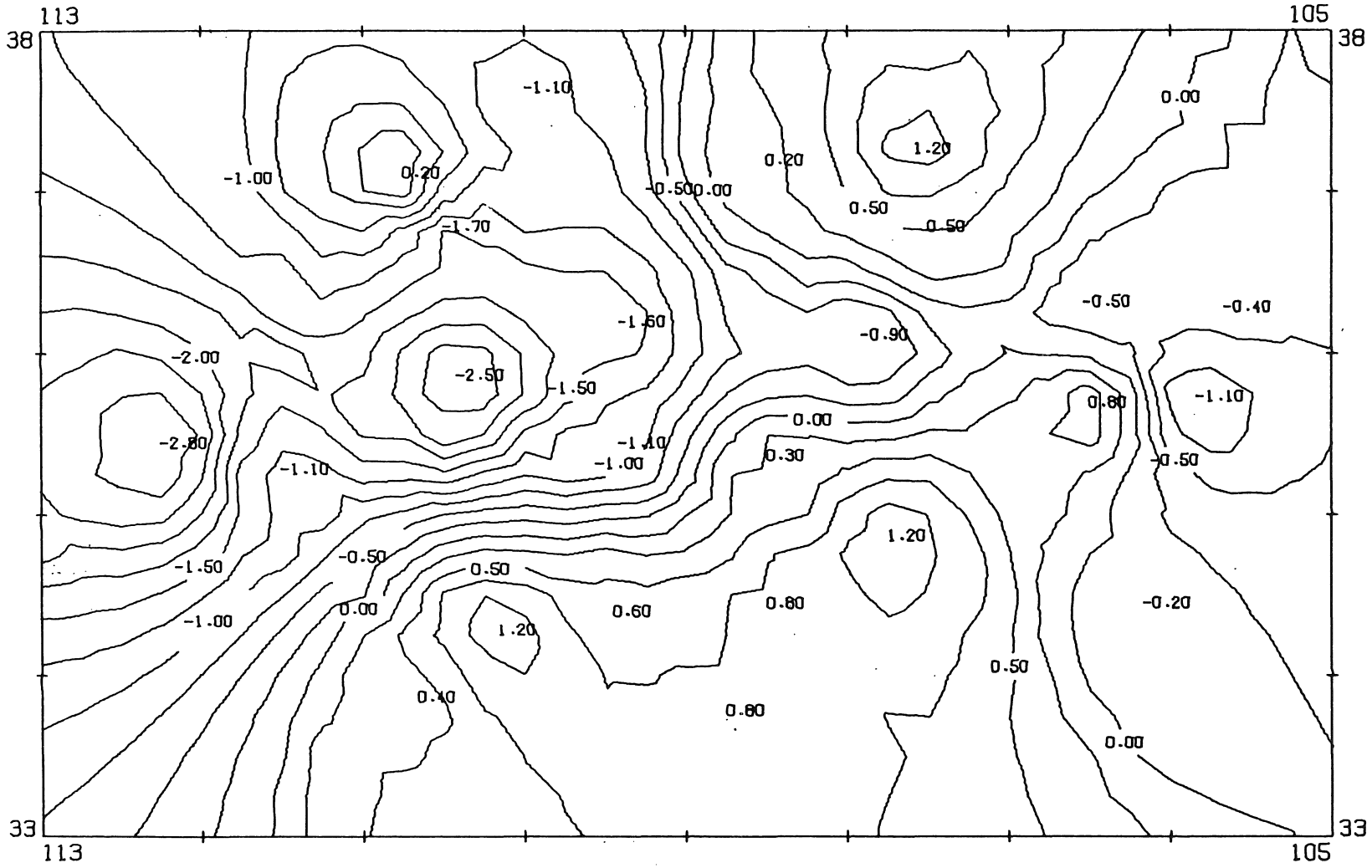
1800-1809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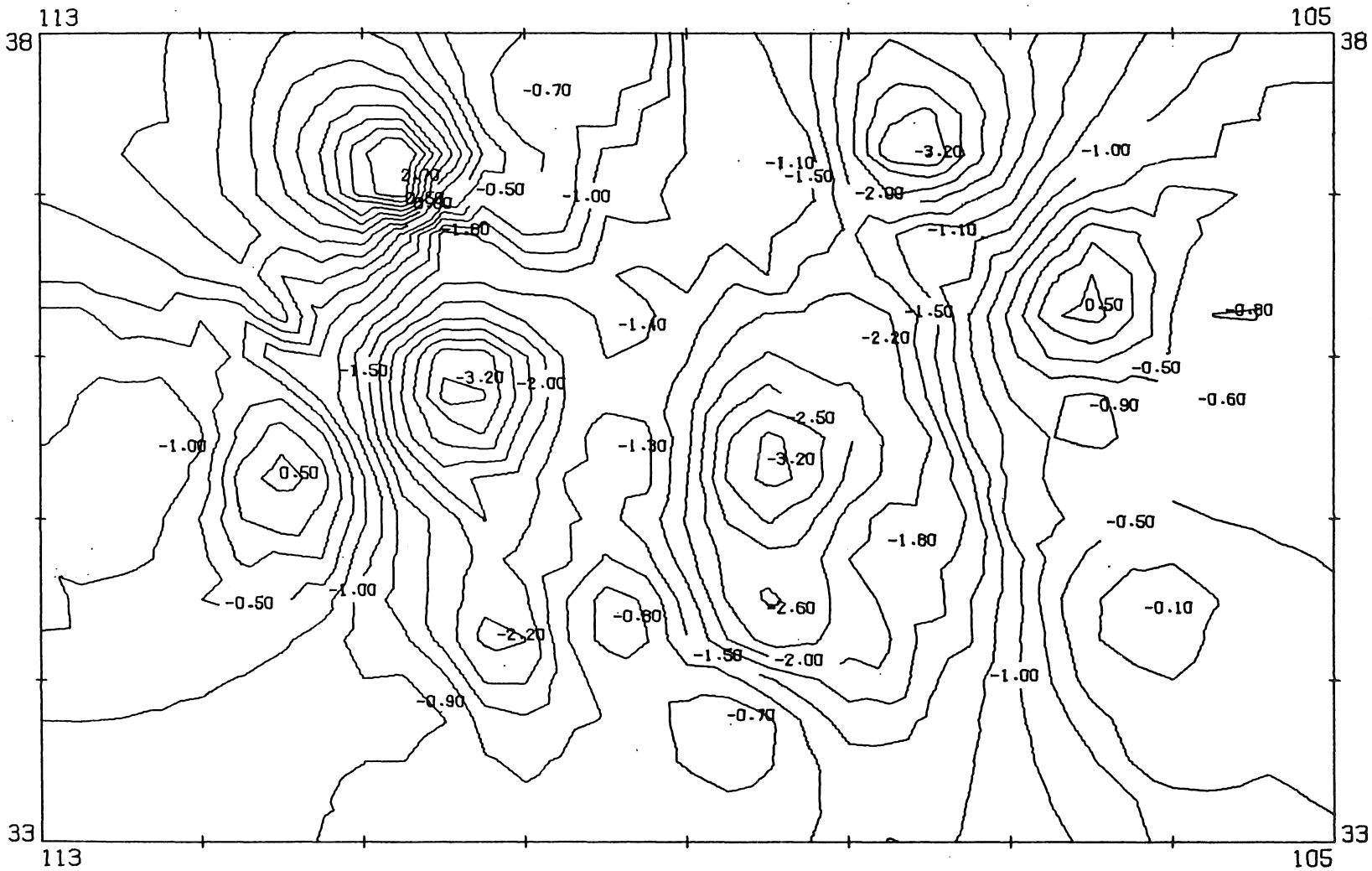
1810-1819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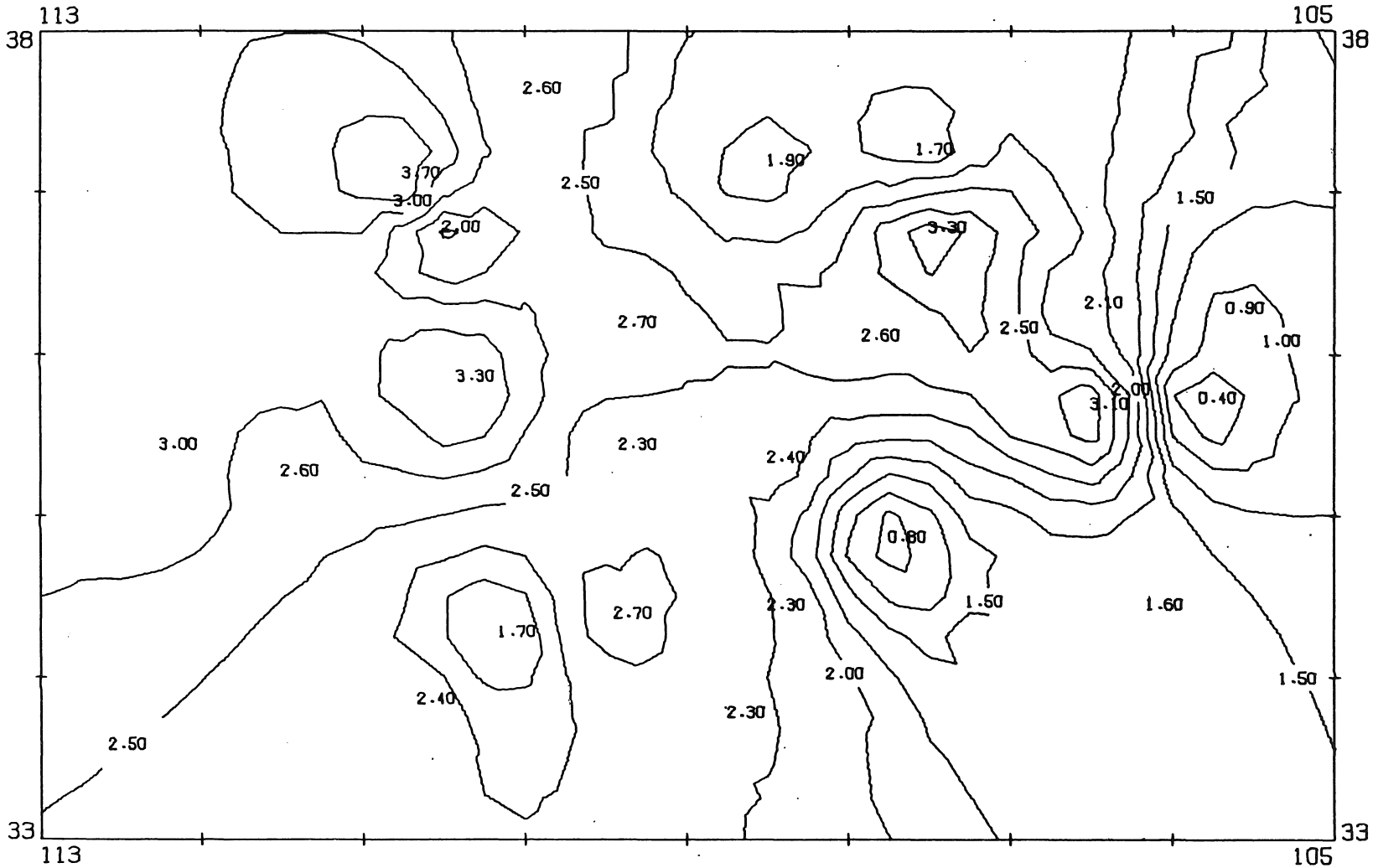
1820-1829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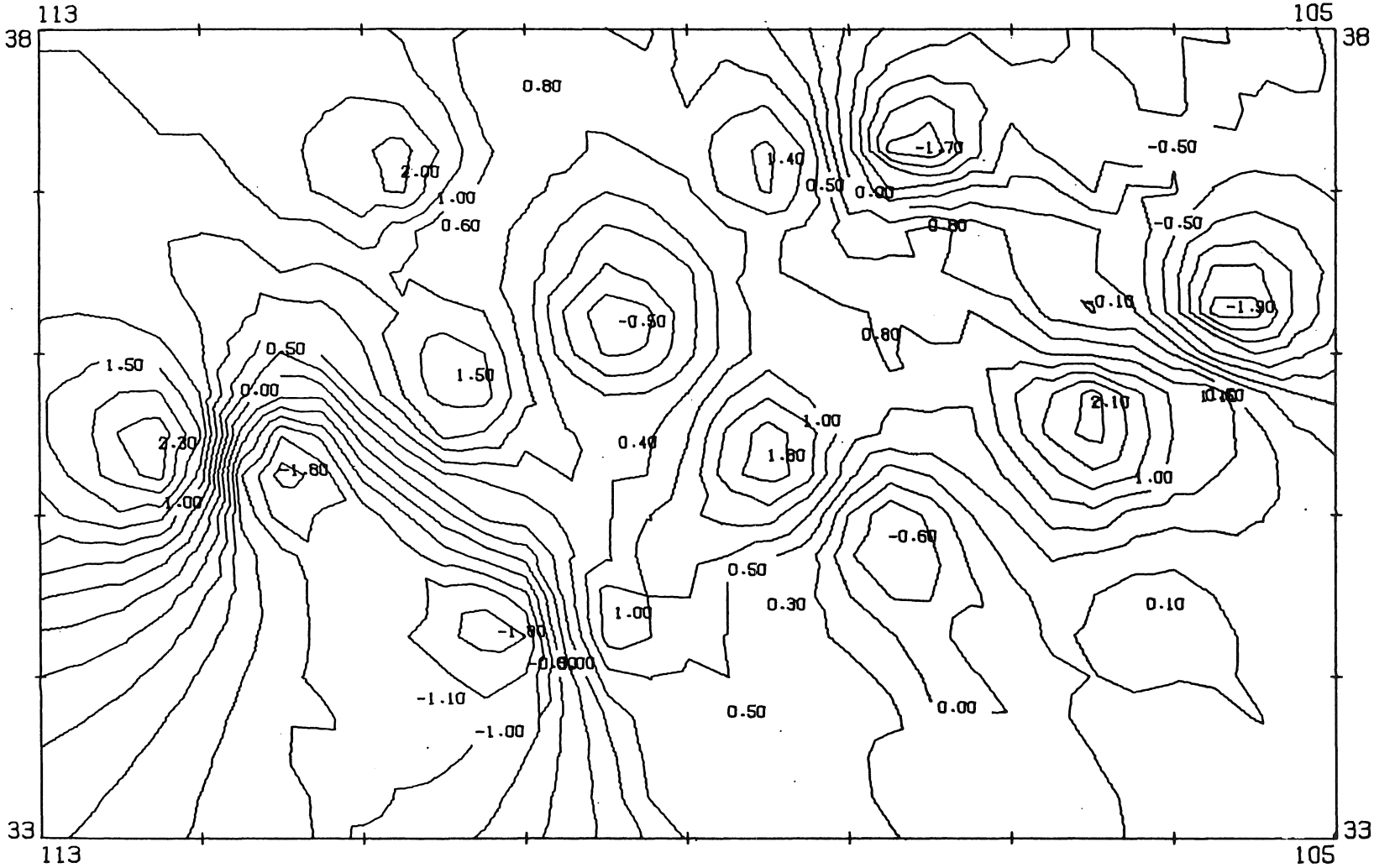
1830-1839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0.00
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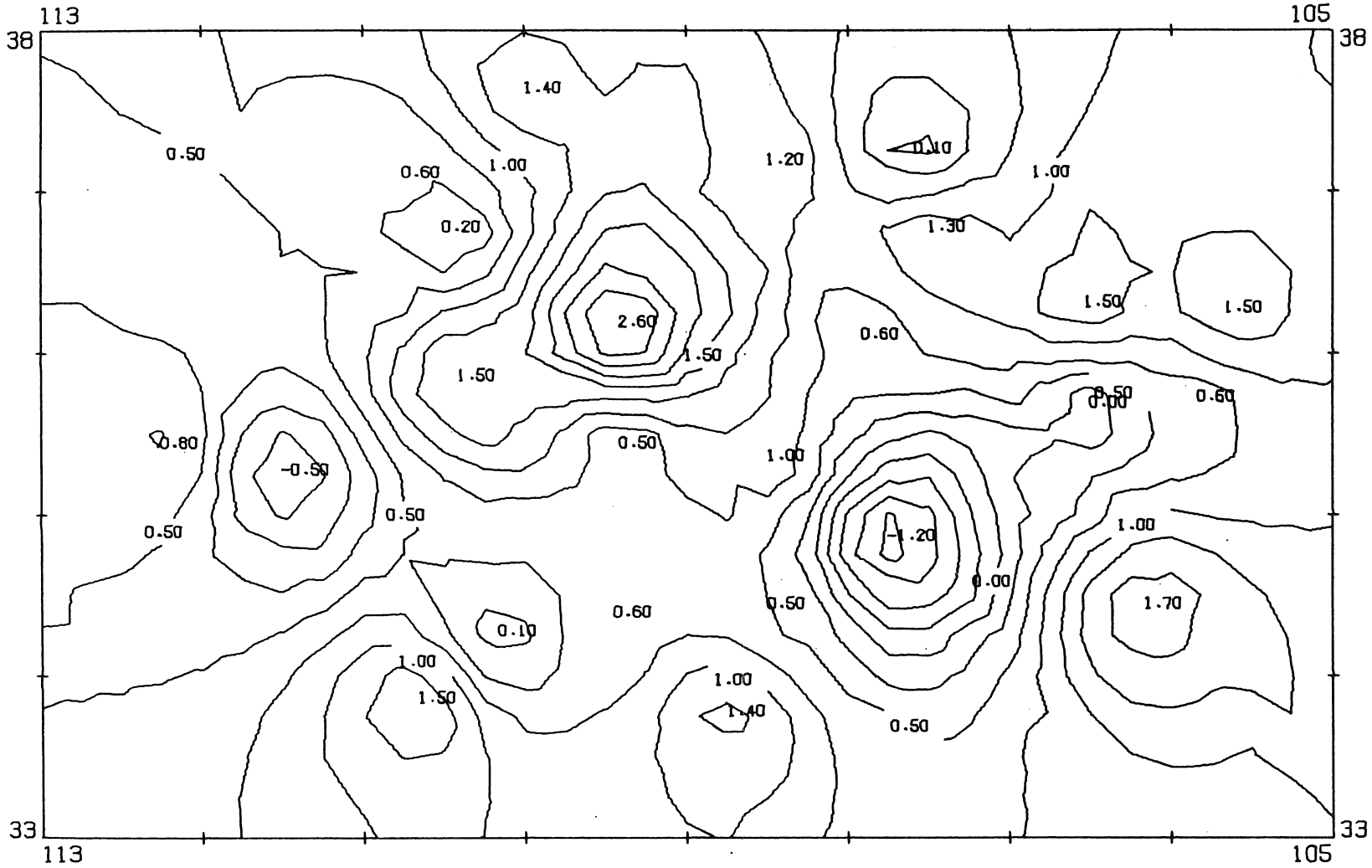
1840-1849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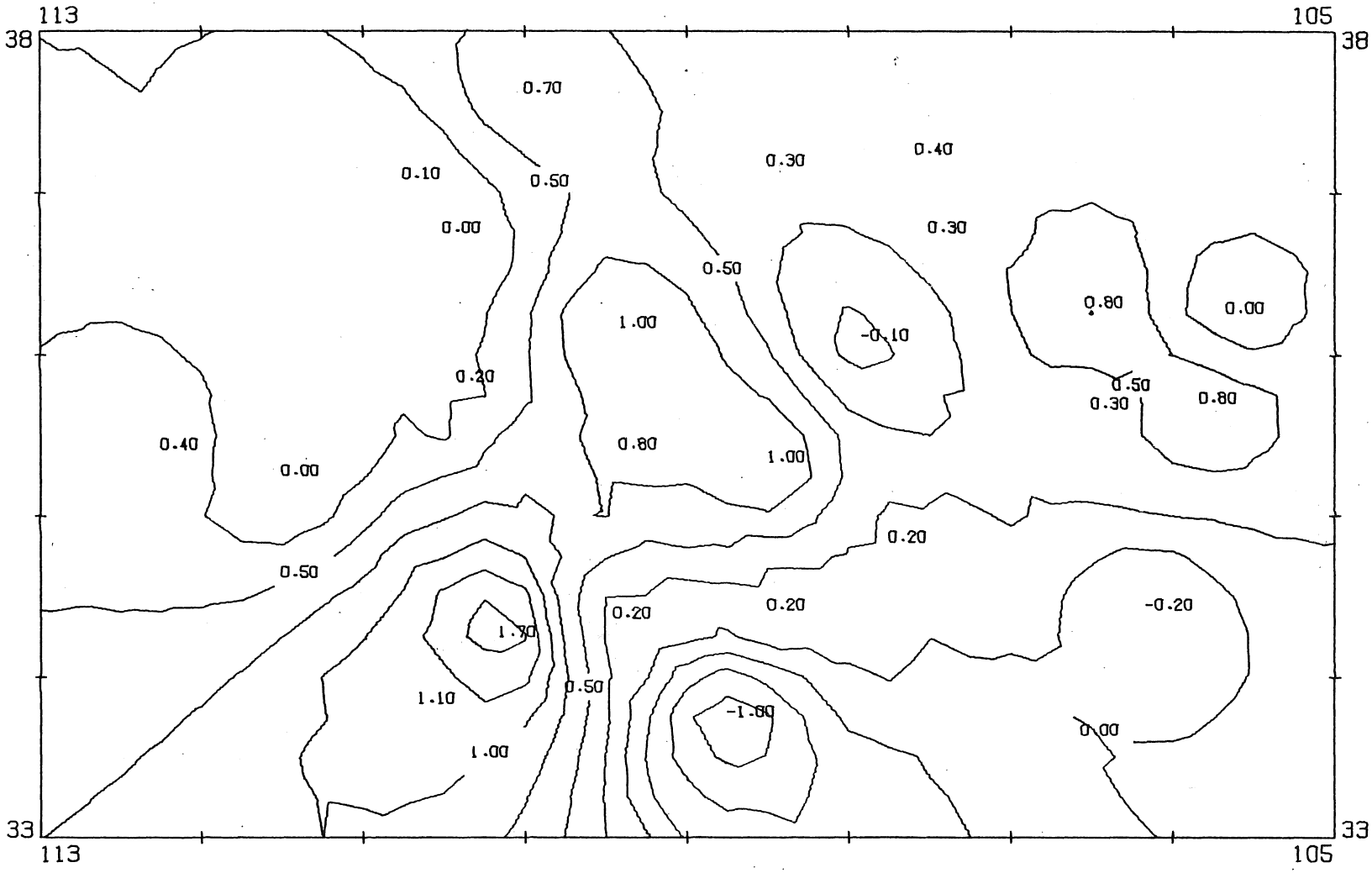
1850-1859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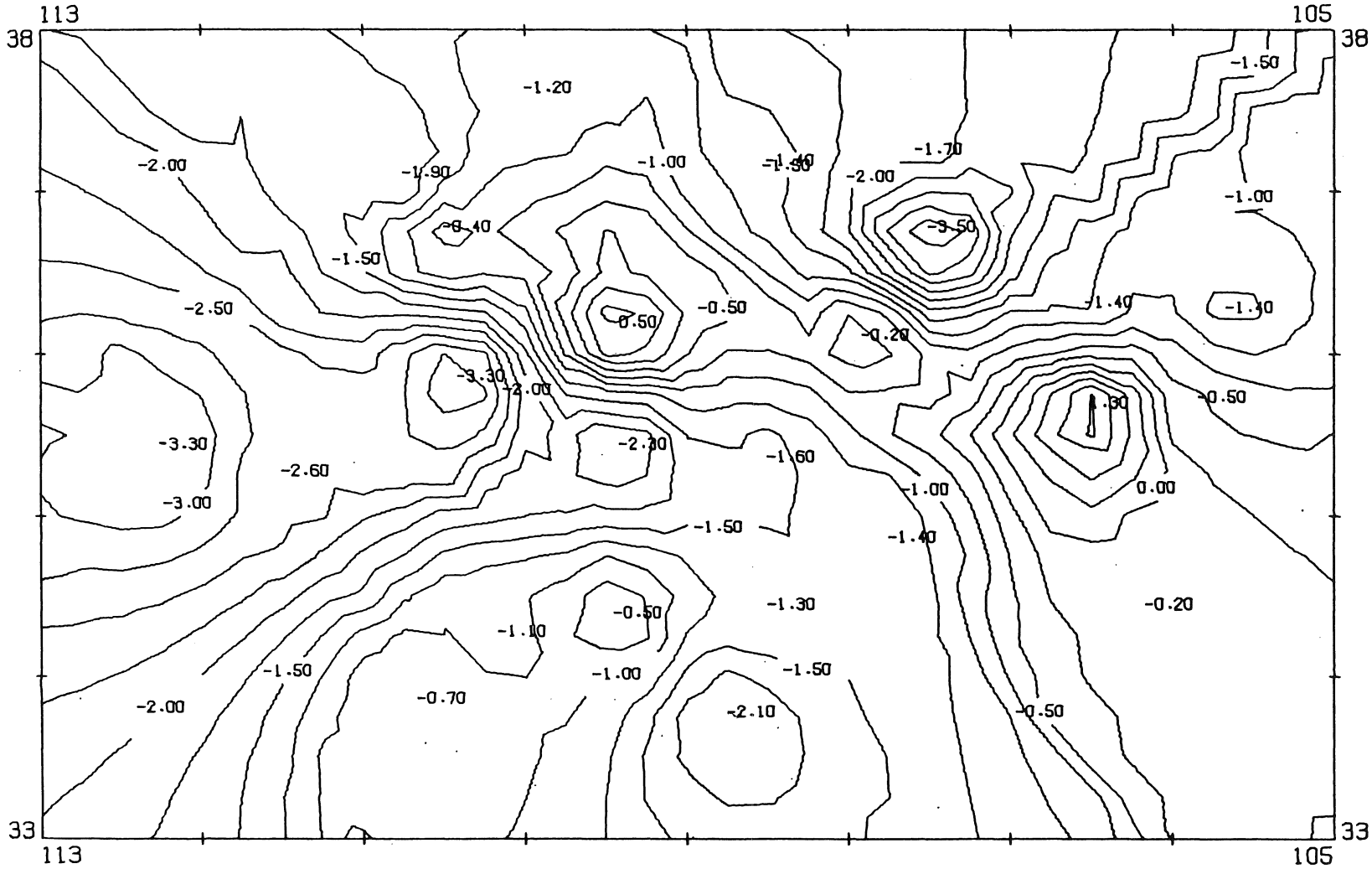
1860-1869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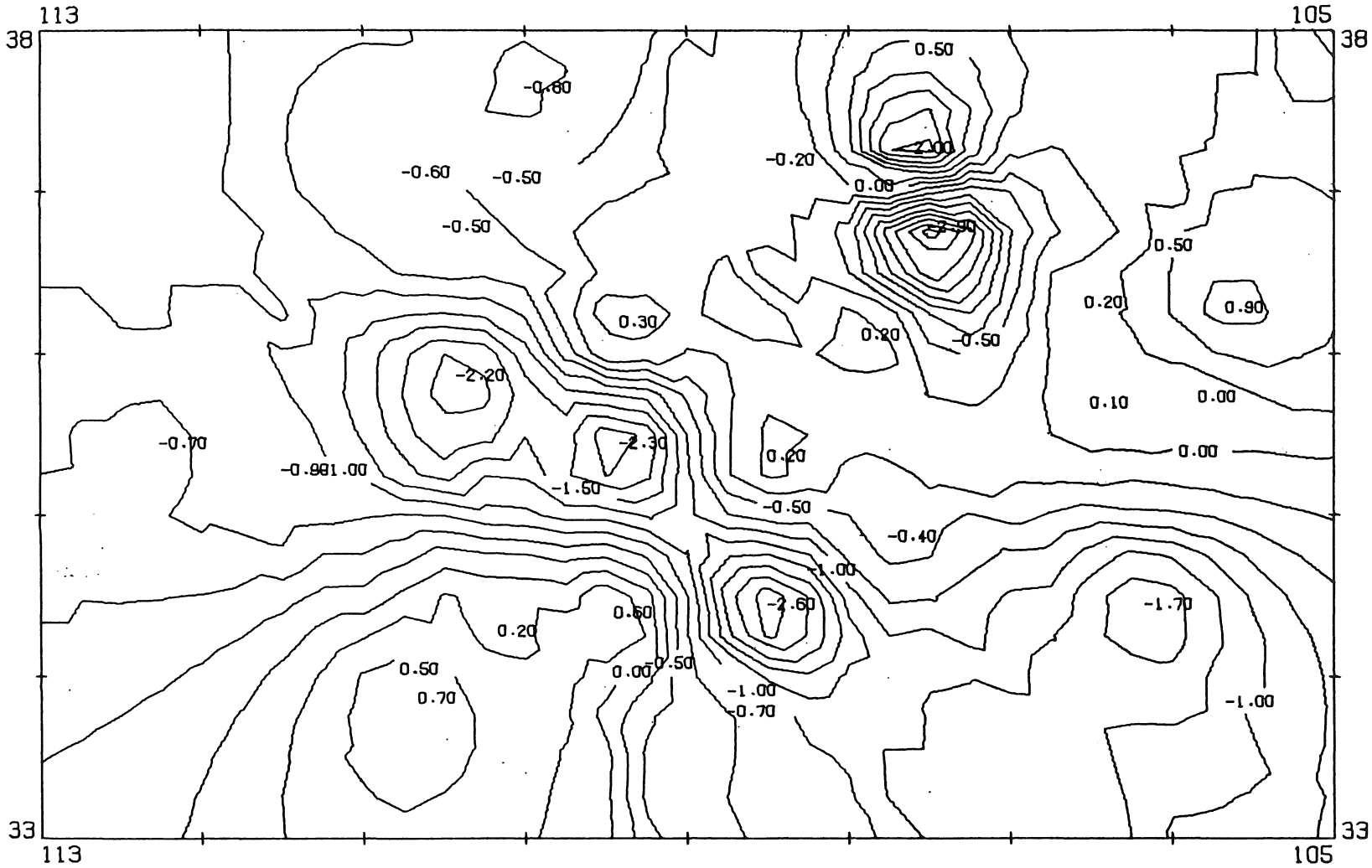
1870-1879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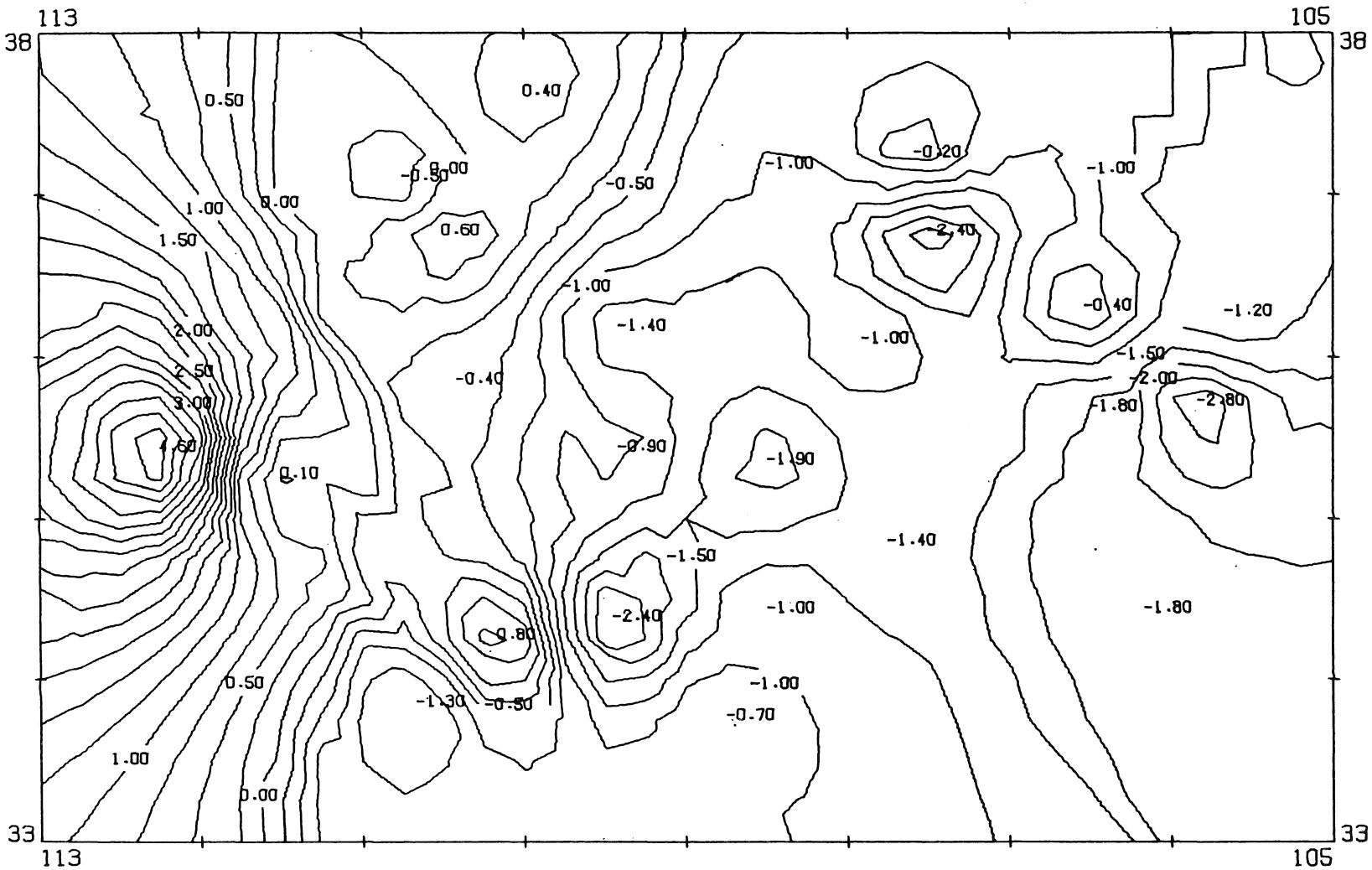
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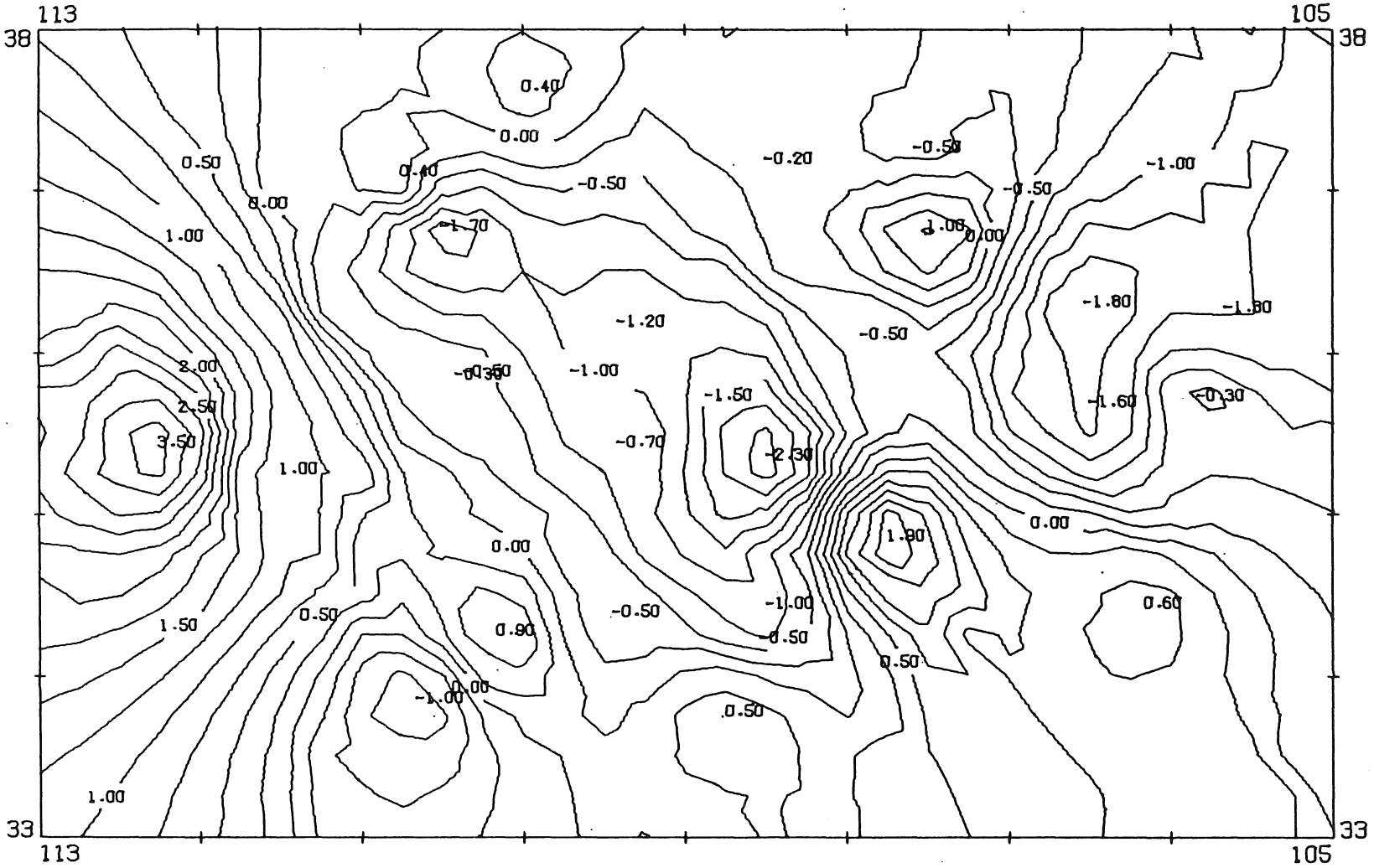
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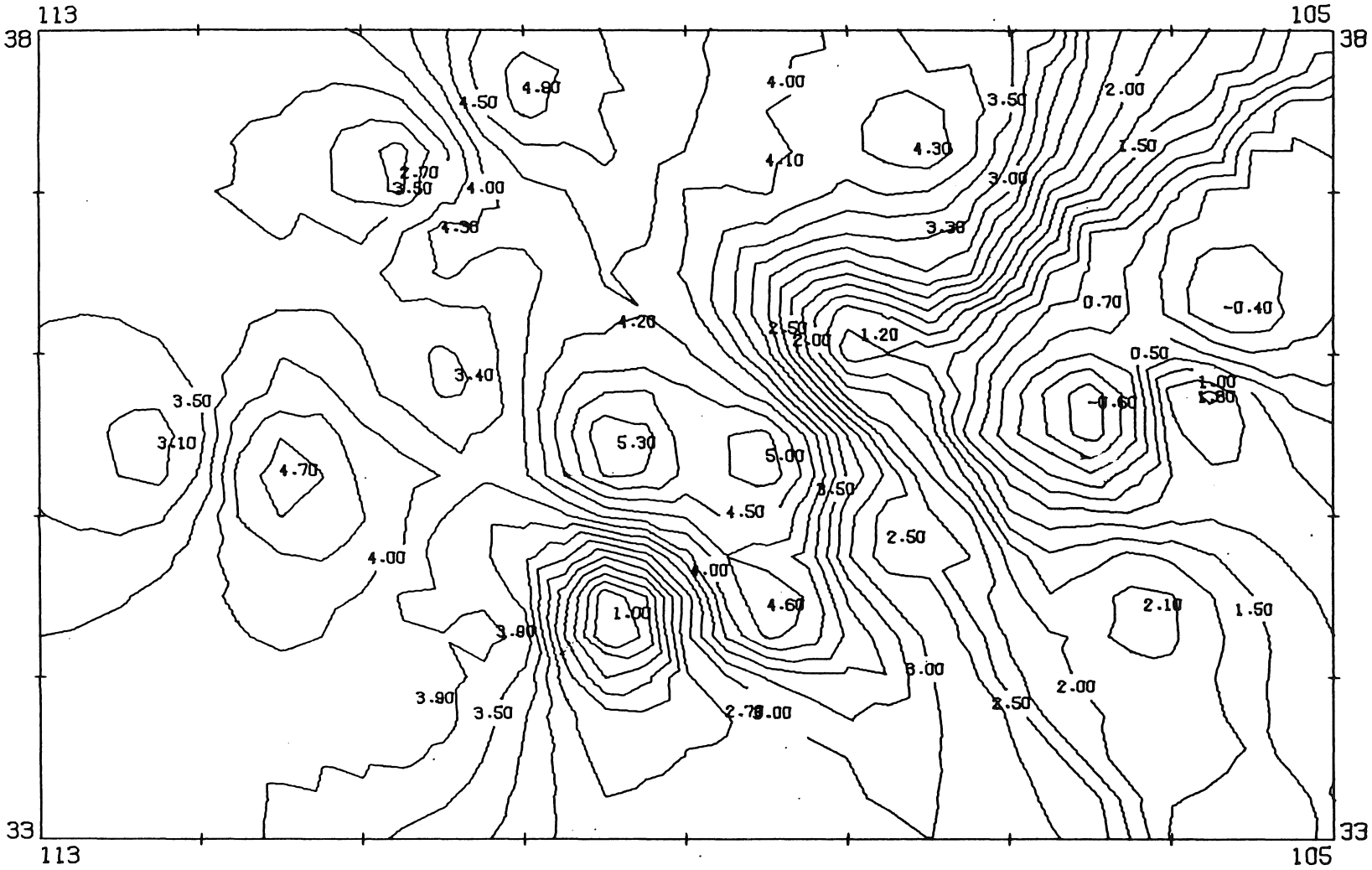
1900-1909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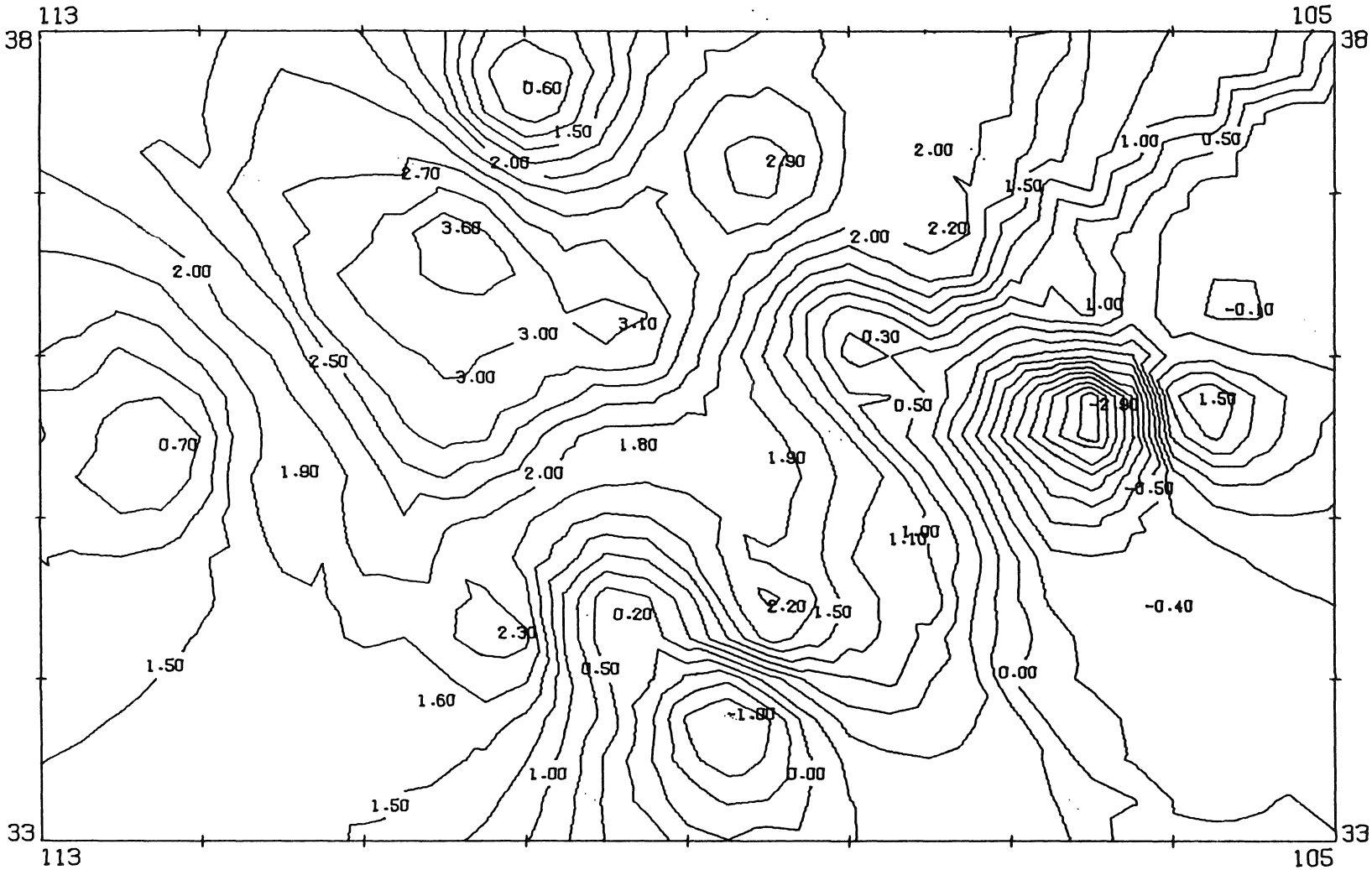
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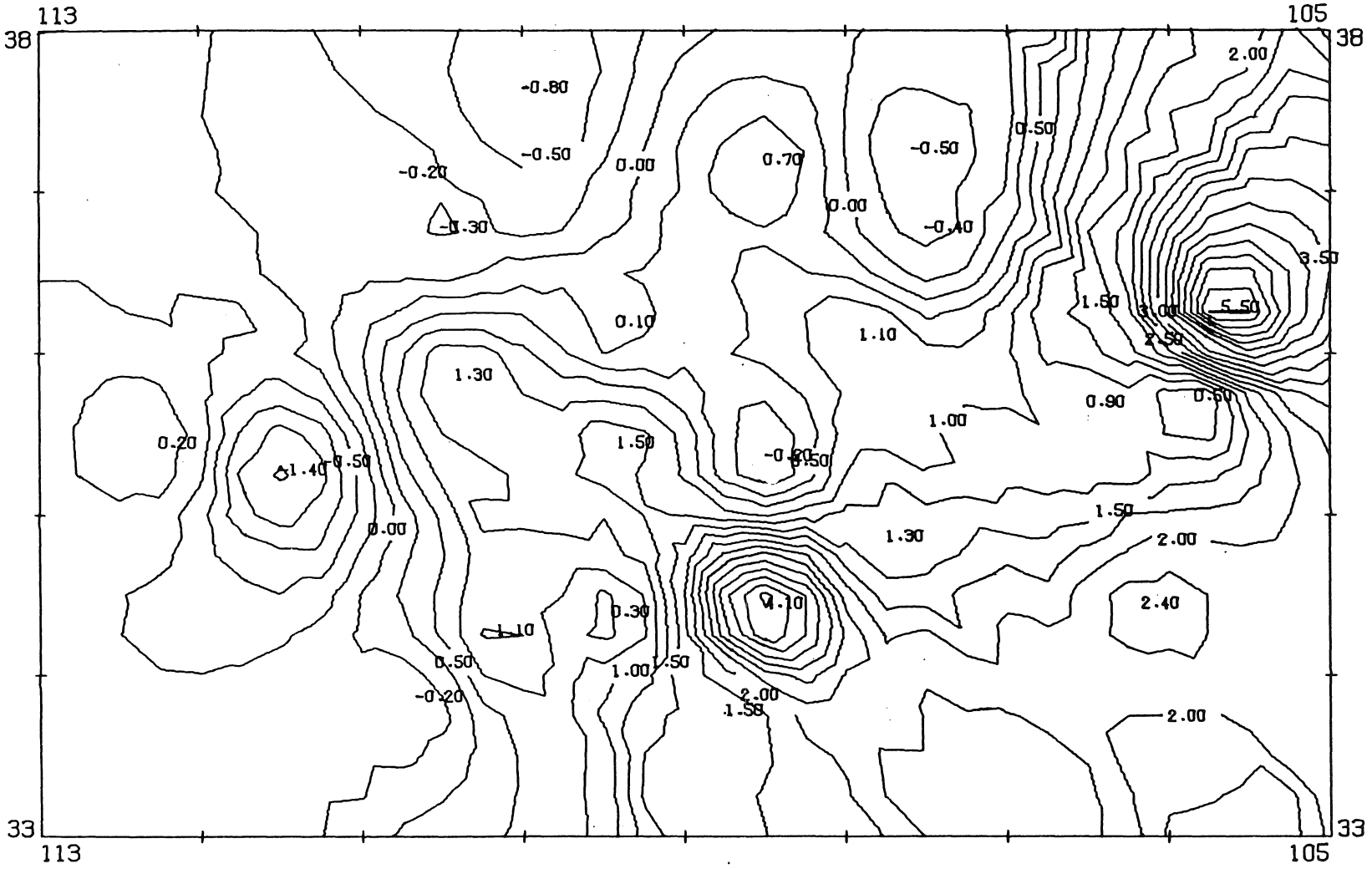
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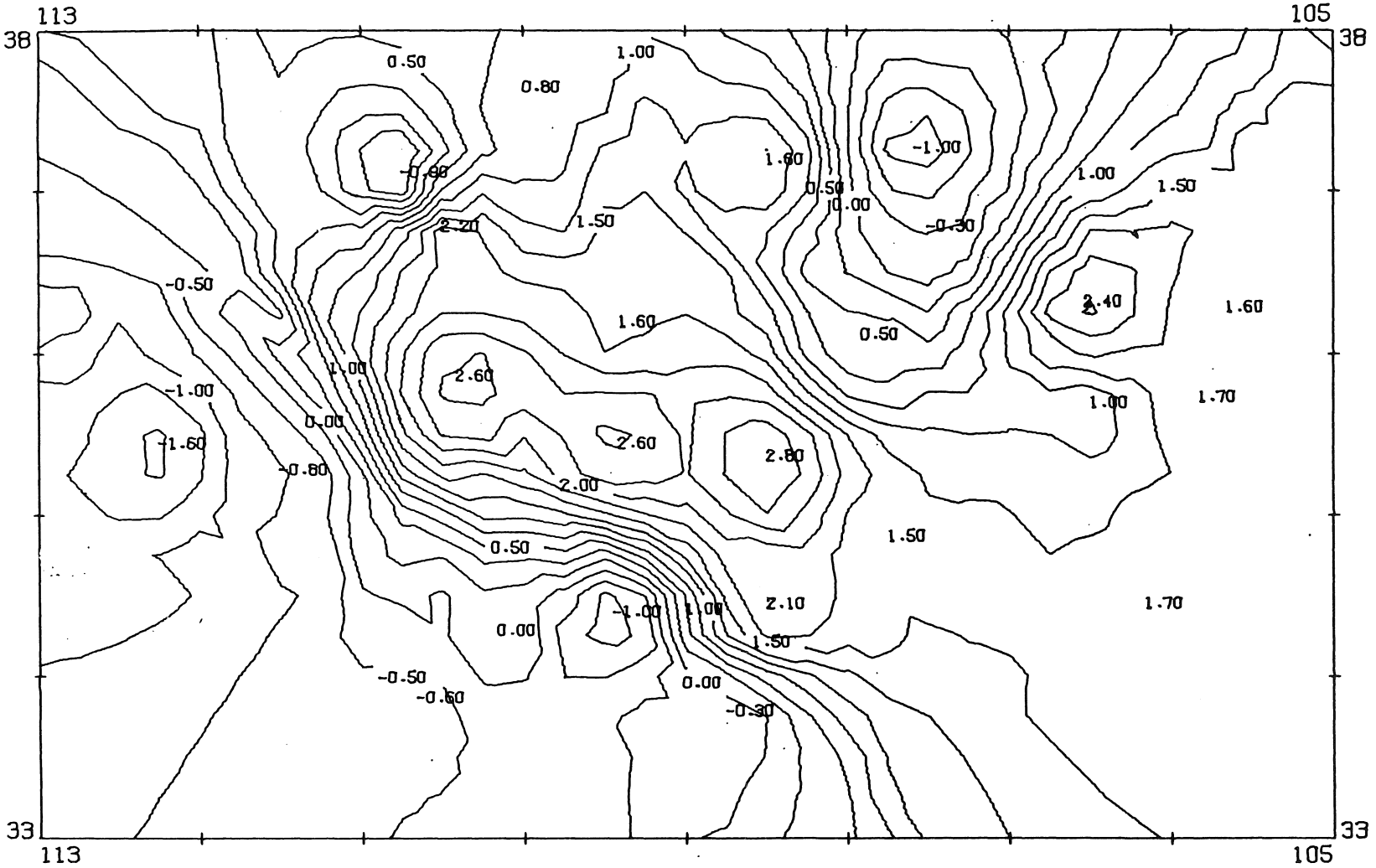
1930-1939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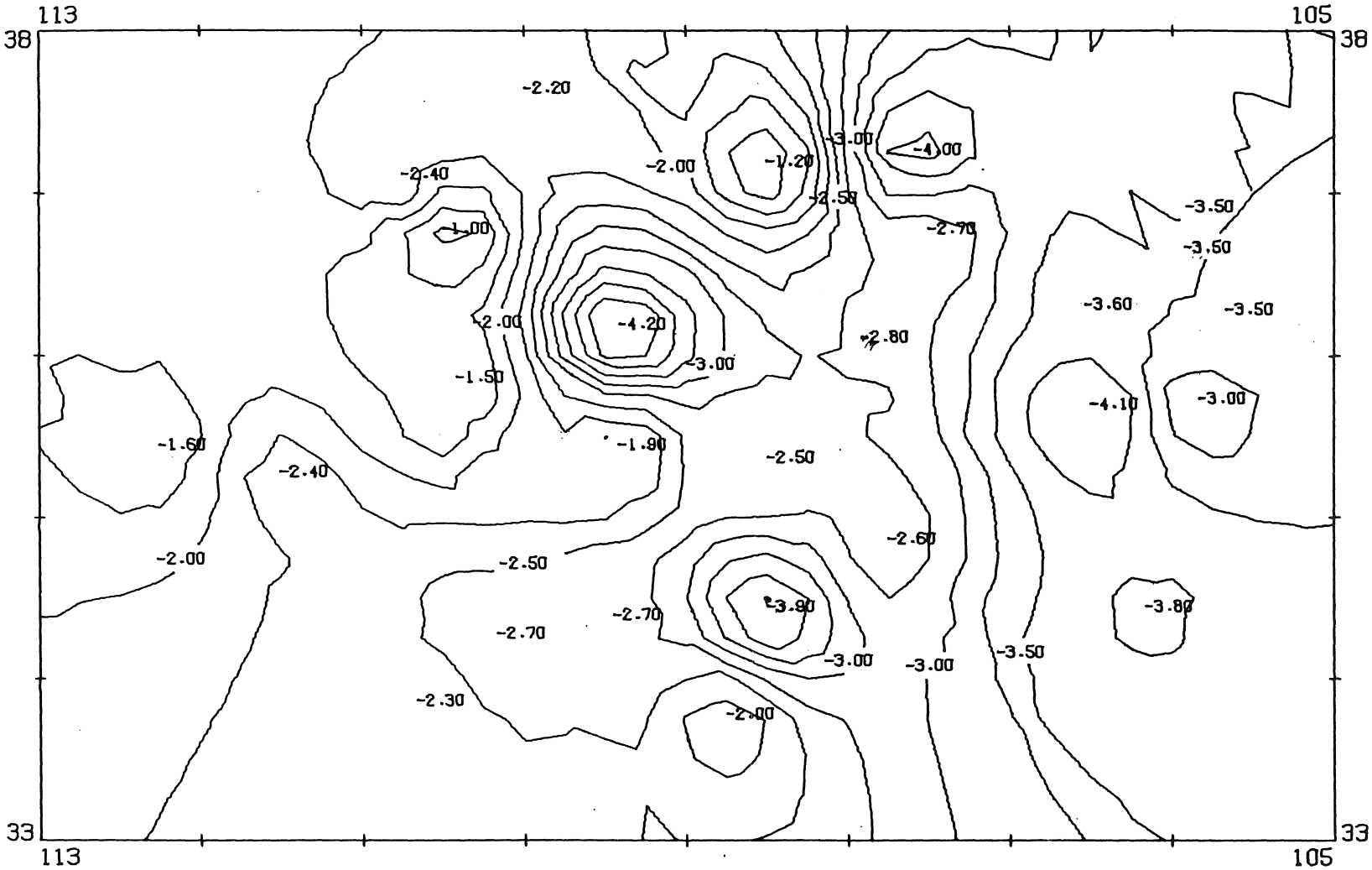
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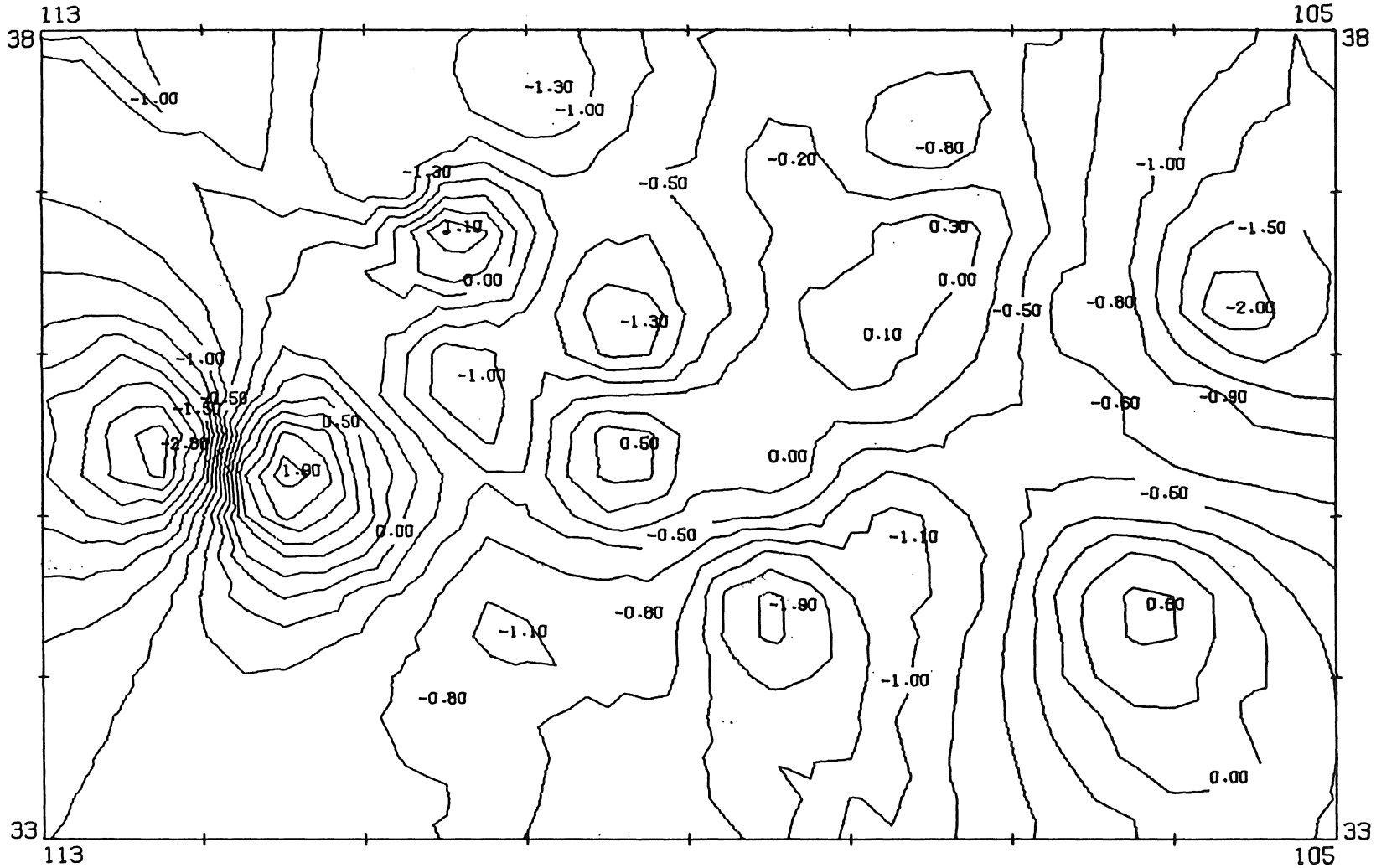
1950-1959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1960-1969