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The SYNOP Experiment: Thermocline Depth Maps for the Central Array October 1987 to August 1990

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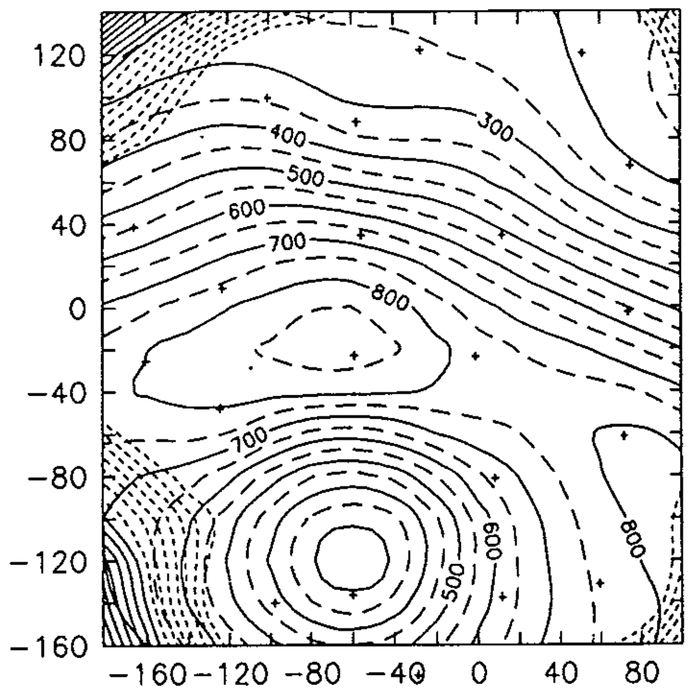

by

Karen L. Tracey and D. Randolph Watts

GSO Technical Report No. 91-5
July 1991

This research program has been sponsored by the National Science Foundation under grant number OCE87-17144 and by the Office of Naval Research under contracts N00014-87K-0235, N00014-90J-1568 and N00014-90J-1548.

Abstract

Between October 1987 and August 1990, two arrays of inverted echo sounders were deployed in the Gulf Stream northeast of Cape Hatteras as part of the SYNoptic Ocean Prediction Experiment. The "Inlet Array" consisted of 9 inverted echo sounders (IES). Centered at 74°W, the Inlet Array was designed to measure key parameters that describe the Gulf Stream path variability near Cape Hatteras. The large "Central Array" of 24 IESs was centered on the current near 68°W, about 400 km downstream of the Inlet Array. Spanning nearly 300 km in both the cross-stream and downstream directions, the Central Array was designed to monitor the thermocline structure of the Gulf Stream in the region of large meanders and frequent ring interactions.

Using objective analysis, we have mapped the Gulf Stream thermal field measured by the IESs in the Central Array. In this report, the objective analysis technique is described and the mapping parameters are documented. Daily maps of the thermocline depth field are presented for the period 26 October 1987 through 7 August 1990.

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1 Introduction

Although the Gulf Stream has been studied more than any other current system, many fundamental questions concerning the dynamics and energy balances governing its meandering still remain. To address these questions, a multi-investigator, multi-institutional research effort, entitled the SYNoptic Ocean Prediction (SYNOP) experiment, was undertaken. To accomplish the objectives, the observational phase of SYNOP was designed such that the results could eventually be integrated with numerical models of the Gulf Stream.

As one part of the SYNOP initiative, Randy Watts of the University of Rhode Island and John Bane of University of North Carolina conducted a joint field experiment in the region northeast of Cape Hatteras, NC, where the instantaneous path of the Gulf Stream is convoluted by large time-varying meanders. The study area extended from Cape Hatteras on the west to 67°W on the east. In this region, the Gulf Stream can shift laterally through an envelope which exceeds the instantaneous width of the current itself. The Gulf Stream is closely associated with the surrounding flow fields to the north and south where rings frequently form and interact with the current.

Between October 1987 and August 1990, our field program consisted of two moored arrays. The "Inlet Array" was composed of 9 inverted echo sounders (IES) and 5 deep current meters. Centered at 74°W, the Inlet Array was designed to measure key parameters that describe the path variability near Cape Hatteras as the Gulf Stream leaves the continental margin and flows into deeper water. The large "Central Array" of 24 IESs was centered on the current near 68°W, about 400 km downstream of the Inlet Array. The Central Array also consisted of thirteen tall current meter moorings, that reached from the bottom into the high-velocity Gulf Stream core. In addition, twelve IESs in the interior of the array were outfitted with bottom pressure gauges. Spanning nearly 300 km in both the cross-stream and downstream directions, the Central Array was designed to monitor the Gulf Stream thermocline structure in this region of large-amplitude meanders and ring interactions. The field phase of the program ended in August 1990.

The subsequent data processing tasks were divided among the groups at URI and UNC. The basic steps for both the current meters and IESs included transcription, editing and conversion into scientific units. The IES and bottom pressure data from both the Inlet and Central Arrays were processed at URI. These data have been documented in three technical reports [Qian *et al.*, 1990; Fields and Watts, 1991a; Fields and Watts, 1990b]. The current meter records from the Inlet Array will be documented in Pickart *et al.* [1991]. The current meter records for the Central Array, processed at UNC, will be documented separately.

After the individual IES records were scaled into thermocline depths, we combined the data for each array to produce maps of the Gulf Stream and adjacent thermal fields. This report documents the mapping procedures for the Central Array for October 1987 to August 1990. Maps of the Inlet Array for this same time period are documented separately [Tracey and Watts, 1991].

2 Central Array IES Data

From October 1987 to May 1988, the Central Array consisted of 15 IESs located on three cross-stream lines (Figure 1). During June 1988, the array was expanded to 24 IESs distributed over 5 lines. The expanded array, shown in Figure 2, was maintained until August 1990. However during

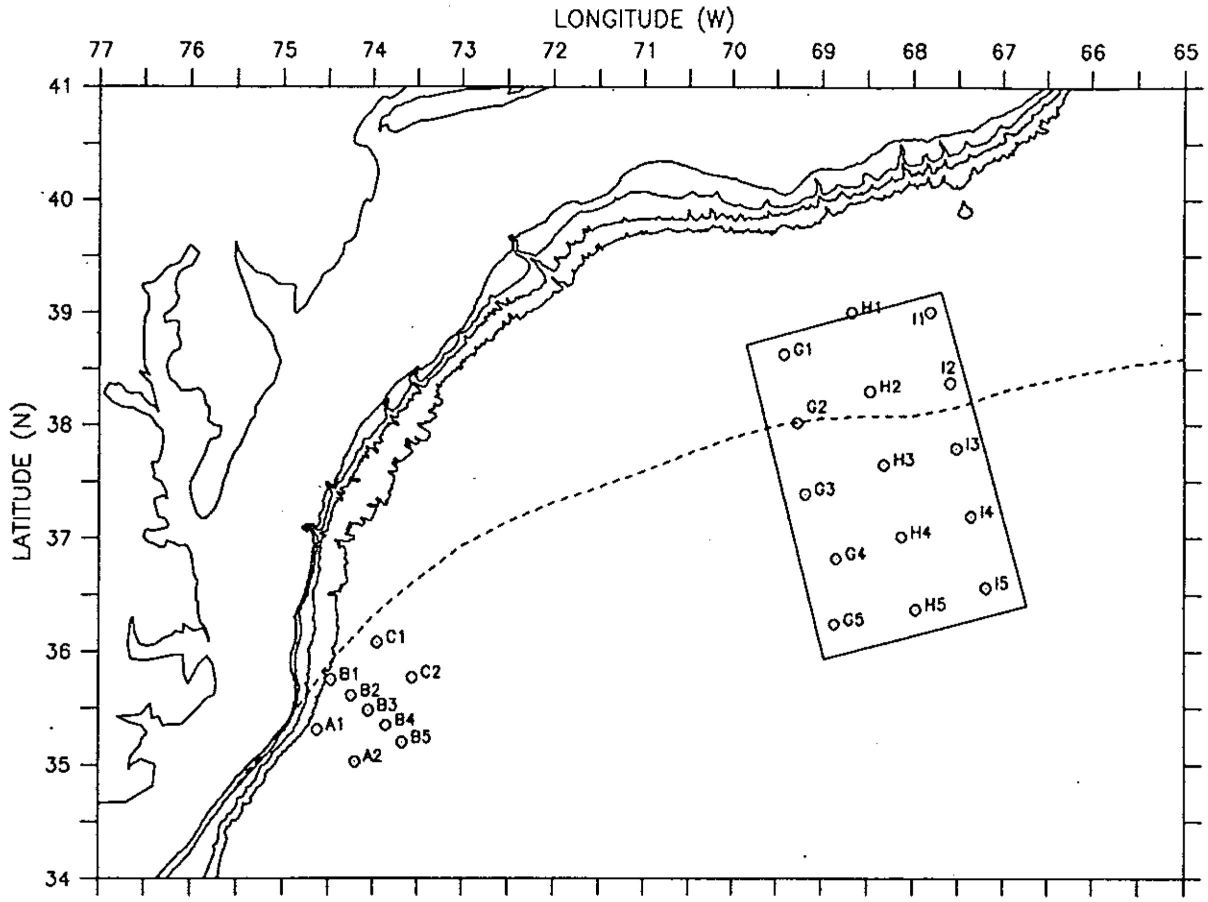


Figure 1: Inlet and Central Arrays: October 1987 to May 1988. IES sites are denoted by the open circles. The box outlines the 200 km by 320 km region of the Central Array which has been mapped by objective analysis. The dashed curve indicates the mean path of the Gulf Stream for 1975 to 1986 from Gilman and Cornillon [1990]. Bottom depths of 100, 200, 1000, 2000 m are shown.

the summer of 1989, all instruments were recovered, refurbished, and redeployed. The IES positions and durations for the three deployment periods are given in Tables 1–3. Note that the instrument at site IES89G1, deployed in October 1987 (Tables 1 and 2), actually spanned two deployment periods and was not retrieved until May 1989.

The mean spacing between the IES sites was 60 km. The array was designed so that the objectively estimated error fields would indicate accurate mapping of the thermocline topography even if isolated instruments in the array either malfunctioned or were lost. Furthermore, the instrument sites were displaced from a true rectilinear grid in order to locate many of them along the suborbital ground tracks of GEOSAT.

After recovery, the IES data were edited and calibrated using a suite of processing steps [Fields *et al.*, 1991]. Using the techniques described in Watts and Johns [1982], Tracey and Watts [1986] and Howden *et al.* [1991], the travel times measured by the IESs were scaled to thermocline depths and subsequently smoothed using a 40-hour low-pass filter to remove the inertial and tidal signals. For convenience, the thermocline depth is expressed as the depth, in meters, of the 12°C isotherm (Z_{12}). The data were subsampled at daily intervals prior to performing the objective analysis.

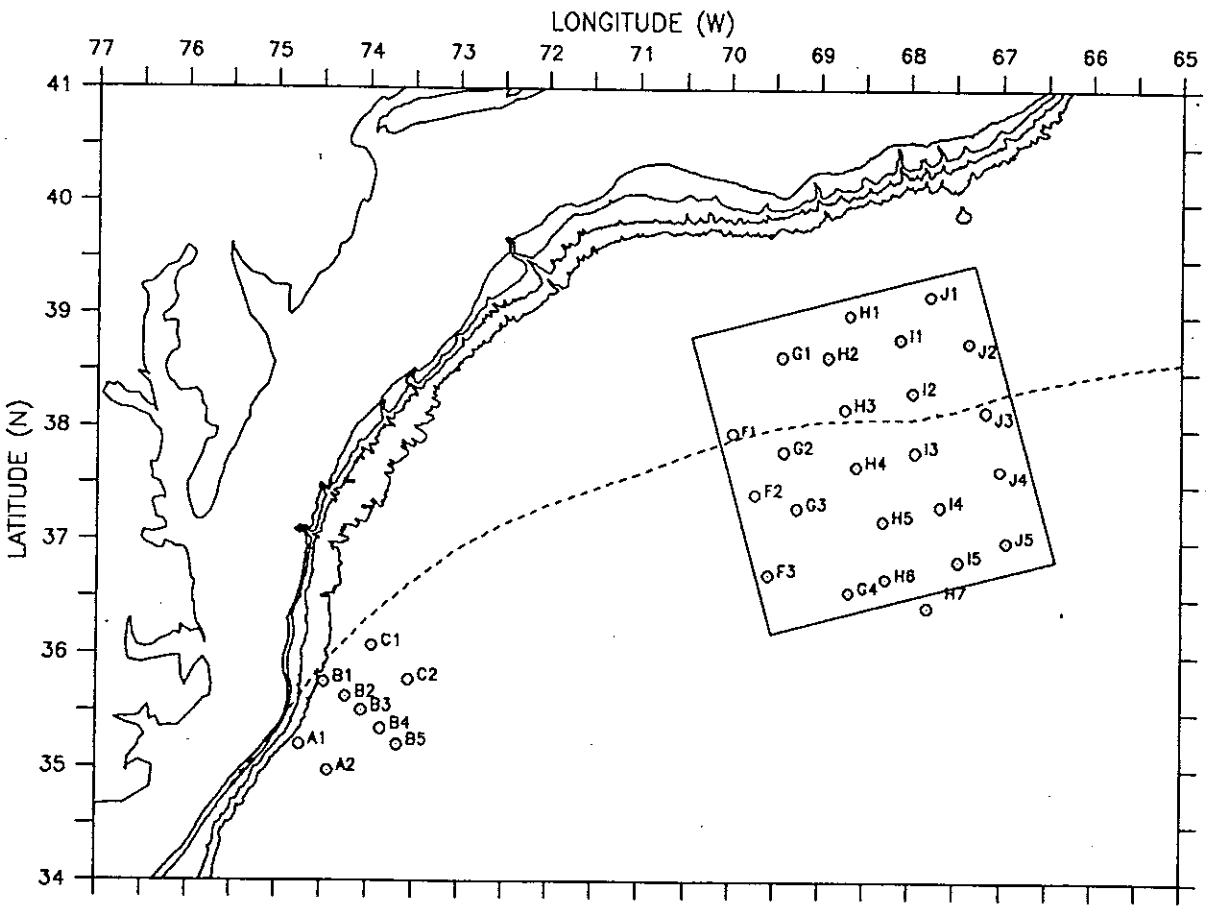


Figure 2: Same as Figure 1, except for June 1988 to August 1990. The boxed region has been expanded to 280 km downstream by 300 km cross-stream.

Table 1: **IES88 Central Array – Locations and Duration**

IES Site	Latitude (N)	Longitude (W)	Start Date	End Date
IES89G1	38° 37.64	69° 25.28	26 Oct 1987	25 May 1989
IES88G2	38° 01.00	69° 16.22	26 Oct 1987	24 May 1988
IES88G3	37° 23.34	69° 10.54	26 Oct 1987	25 May 1988
IES88G4	36° 49.80	68° 50.26	26 Oct 1987	4 Jun 1988
IES88G5	36° 14.25	68° 51.30	27 Oct 1987	21 May 1988
PIES88H1	39° 00.01	68° 40.30	**No data**	
PIES88H2	38° 18.02	68° 27.97	26 Oct 1987	23 May 1988
PIES88H3	37° 38.71	68° 19.31	25 Oct 1987	6 Jun 1988
IES88H4	37° 00.52	68° 07.74	25 Oct 1987	6 Jun 1988
IES88H5	36° 22.13	67° 58.00	25 Oct 1987	5 Jun 1988
IES88I1	39° 00.12	67° 48.70	24 Oct 1987	23 May 1988
PIES88I2	38° 22.48	67° 35.37	24 Oct 1987	23 May 1988
IES88I3	37° 47.49	67° 31.01	24 Oct 1987	6 Jun 1988
IES88I4	37° 11.18	67° 21.46	25 Oct 1987	5 Jun 1988
IES88I5	36° 33.48	67° 11.67	25 Oct 1987	5 Jun 1988

Table 2: **IES89 Central Array – Locations and Duration**

IES Site	Latitude (N)	Longitude (W)	Start Date	End Date
IES89F1	37° 56.94	69° 57.98	12 Jun 1988	4 Jun 1989
IES89F2	37° 24.40	69° 46.50	15 Jun 1988	13 Aug 1989
IES89F3	36° 42.10	69° 33.60	15 Jun 1988	13 Aug 1989
IES89G1	38° 37.64	69° 25.28	26 Oct 1987	25 May 1989
PIES89G2	37° 47.52	69° 24.33	28 May 1988	12 Sep 1989
PIES89G3	37° 17.40	69° 14.53	27 May 1988	28 May 1989
IES89G4	36° 33.19	68° 40.49	7 Jun 1988	16 Jun 1989
IES89H1	39° 00.00	68° 40.32	12 Jun 1988	1 Jun 1989
PIES89H2	38° 37.88	68° 54.20	**Instrument lost**	
IES89H2′	38° 25.80	69° 02.00	6 Jun 1989	14 Aug 1989
PIES89H3	38° 10.10	68° 43.30	12 Jun 1988	14 Aug 1989
PIES89H4	37° 39.80	68° 35.40	15 Jun 1988	14 Aug 1989
PIES89H5	37° 10.60	68° 17.00	9 Jun 1988	13 Aug 1989
PIES89H6	36° 40.45	68° 15.64	24 May 1988	3 Jun 1989
IES89H7	36° 24.53	67° 47.06	7 Jun 1988	16 Jun 1989
IES89H7′	36° 24.90	67° 48.10	18 Jun 1989	15 Aug 1989
PIES89I1	38° 47.54	68° 06.38	26 May 1988	1 Feb 1989
PIES89I2	38° 20.90	67° 59.60	10 Jun 1988	29 May 1989
PIES89I3	37° 47.55	67° 56.50	**Instrument lost**	
PIES89I4	37° 18.50	67° 39.30	9 Jun 1988	15 Jun 1989
PIES89I5	36° 49.73	67° 27.57	25 May 1988	2 Jun 1989
IES89J1	39° 10.04	67° 47.08	11 Jun 1988	30 May 1989
IES89J2	38° 45.59	67° 21.57	11 Jun 1988	30 May 1989
IES89J3	38° 09.03	67° 10.06	10 Jun 1988	6 Jun 1989
IES89J4	37° 37.84	67° 00.65	11 Jun 1988	6 Jun 1989
IES89J5	36° 59.83	66° 55.52	7 Jun 1988	15 Jun 1989

Table 3: **IES90 Central Array – Locations and Duration**

IES Site	Latitude (N)	Longitude (W)	Start Date	End Date
IES90F1	37° 56.96	69° 58.19	6 Jun 1989	19 Aug 1990
IES90F2	37° 24.62	69° 46.59	15 Aug 1989	19 Aug 1990
IES90F3	36° 42.08	69° 33.92	**Instrument lost**	
IES90G1	38° 37.63	69° 25.39	28 May 1989	19 Aug 1990
PIES90G2	37° 47.84	69° 24.31	6 Jun 1989	19 Aug 1990
PIES90G3	37° 16.99	69° 14.71	30 May 1990	18 Aug 1990
IES90G4	36° 33.00	68° 39.96	18 Jun 1989	8 Aug 1990
IES90H1	38° 59.85	68° 39.92	3 Jun 1989	14 Aug 1990
PIES90H2	38° 37.78	68° 54.90	16 Aug 1989	10 Aug 1990
PIES90H3	38° 10.09	68° 43.65	16 Aug 1989	15 Aug 1990
PIES90H4	37° 39.57	68° 35.35	16 Aug 1989	17 Aug 1990
PIES90H5	37° 10.23	68° 17.83	26 Nov 1989	17 Aug 1990
PIES90H6	36° 39.35	68° 15.70	5 Jun 1989	8 Aug 1990
IES90H7	36° 24.92	67° 47.81	17 Aug 1989	8 Aug 1990
PIES90I1	38° 47.58	68° 06.25	31 May 1989	30 Jul 1989
PIES90I2	38° 19.68	67° 58.71	2 Jun 1989	15 Aug 1990
PIES90I3	37° 47.61	67° 58.85	7 Jun 1989	9 Aug 1990
PIES90I4	37° 18.88	67° 39.58	17 Jun 1989	16 Aug 1990
PIES90I5	36° 50.19	67° 27.36	4 Jun 1989	7 Aug 1990
IES90J1	39° 10.05	67° 47.20	1 Jun 1989	11 Aug 1990
IES90J2	38° 45.90	67° 21.03	1 Jun 1989	11 Aug 1990
IES90J3	38° 09.69	67° 10.37	8 Jun 1989	9 Aug 1990
IES90J4	37° 38.77	67° 01.65	8 Jun 1989	9 Aug 1990
IES90J5	36° 00.68	66° 57.86	17 Jun 1989	7 Aug 1990

3 Objective Mapping of the Thermocline Depth Field

In order to produce gridded maps of the Gulf Stream Z_{12} field, we used objective analysis (OA) to interpolate between the irregularly-spaced observations. The interpolation is made at each output grid point as a weighted average of input values at the neighboring measurement sites. The optimal weighting was determined according to the Gauss-Markov theorem using knowledge of the space-time correlation function (see below). For our application, the correlation function was dependent on radial distance and time, $\rho(r, t')$.

The basic OA equations are clearly formulated in Bretherton *et al.* [1976] and extensions to anisotropic fields are given in Carter [1983] and Carter and Robinson [1987]. The method was further modified by Watts and Tracey [1985] and Watts *et al.* [1989] to apply the technique to the Gulf Stream frontal region. To summarize briefly, their adaptations include preconditioning the observations by removing a spatially-dependent mean thermal field and subsequently normalizing the residual perturbations by the standard deviation (STD) field. These techniques combine to produce perturbation fields which have homogeneous statistics, a requirement of objective analysis. After running the OA, both the mean and STD fields are restored to the output fields, producing maps of the Gulf Stream Z_{12} field. We used the procedures of Watts *et al.* [1989] to generate the OA maps shown in this report.

Since we have a large set of observations, we adapted programs generously provided by E. Carter (documented in Carter and Robinson [1987]) that make the computing much more efficient. We took advantage of the fact that data values which are distant (both spatially and temporally) from the output point have little influence on the estimate when compared with the nearby observations. We increased the efficiency by restricting the available data to a smaller subset prior to running the OA at each output point. First, we specified a maximum time lag ($t'_{\max}$) and maximum radial separation distance ($r_{\max}$) and eliminated observations which exceeded these restrictions. For the Central Array OA maps, we specified $t'_{\max} = \pm 1$ day and $r_{\max} = 120$ km. When determining the radial distance for each data point, we took into account downstream phase propagation of Gulf Stream meanders (discussed below) such that

$$r = \left[(x' - ct')^2 + (y')^2\right]^{\frac{1}{2}} \tag{1}$$

where the phase speed $c = 12$ km d^{-1}.

To further reduce the data around a given output grid point to use only the most influential input data, we selected a smaller subset of these restricted observations. We chose only the N points with the highest correlations to be used for the estimation at the output grid point. The choice for N is a trade off between wanting enough observations to reduce random noise and wanting fewer points to increase computational efficiency. The Gauss-Markov procedure involves inversion of an $N \times N$ matrix, repeated for each output grid point of every map. If N is too large (such that the input data are themselves not sufficiently independent) then the matrix inversions are computationally unstable and the errors actually increase. We used $N = 15$ points to produce the Central Array Z_{12} maps.

While the choices for $t'_{\max}$, $r_{\max}$, c, and N place restrictions on the data to be used for interpolation, they do not directly appear in the OA equations. Aside from the correlation function, the only user-specified parameter that is explicitly a factor in the equations is the noise level of the data (ϵ). By specifying a non-zero noise level, the interpolation scheme is not required to fit the data values exactly, and some smoothing is permitted. We specified $\epsilon = 0.05$ (in terms of percentage of the data variance), since it is our best estimate of the true error associated with the IES measurements.

3.1 The Space-Time Correlation Function

To produce the OA maps of the Central Array thermal field, it was necessary to determine a correlation function appropriate for that region of the Gulf Stream. We followed the procedures described in Watts *et al.* [1989] to calculate the spatial and temporal correlations from our observations. In all, we used Z_{12} records from over 70 IESs obtained during three separate deployment periods between 1985 and 1989. We calculated the spatial separations (x', y') between pairs of IESs within each deployment period and determined their cross-correlations for several time lags t'. Subsequently, the correlations were smoothed by a 40-km Gaussian-weighted low-pass filter to remove some of the small scale noise. Figure 3 shows the observed correlations in the full (x', y') plane for lag times of 0, 1, and 2 days.

Next, to examine the observed correlations for spatial anisotropy, we sorted the pairs into downstream, cross-stream and diagonal categories and recomputed the correlations for $t' = 0$ days. Figure 4 reveals the similarity between the three groups, indicating no significant directional dependence. Thus, we expressed the spatial decay of the correlations as a function of radial distance, rather than of both x' and y'. The best fit to the observed correlations, shown in Figure 4, was an exponential-cosine function of the form

$$\rho(r) = F_o \exp\left(\frac{-r}{A}\right) \cos\left(\frac{\pi r}{2B}\right) \qquad (2)$$

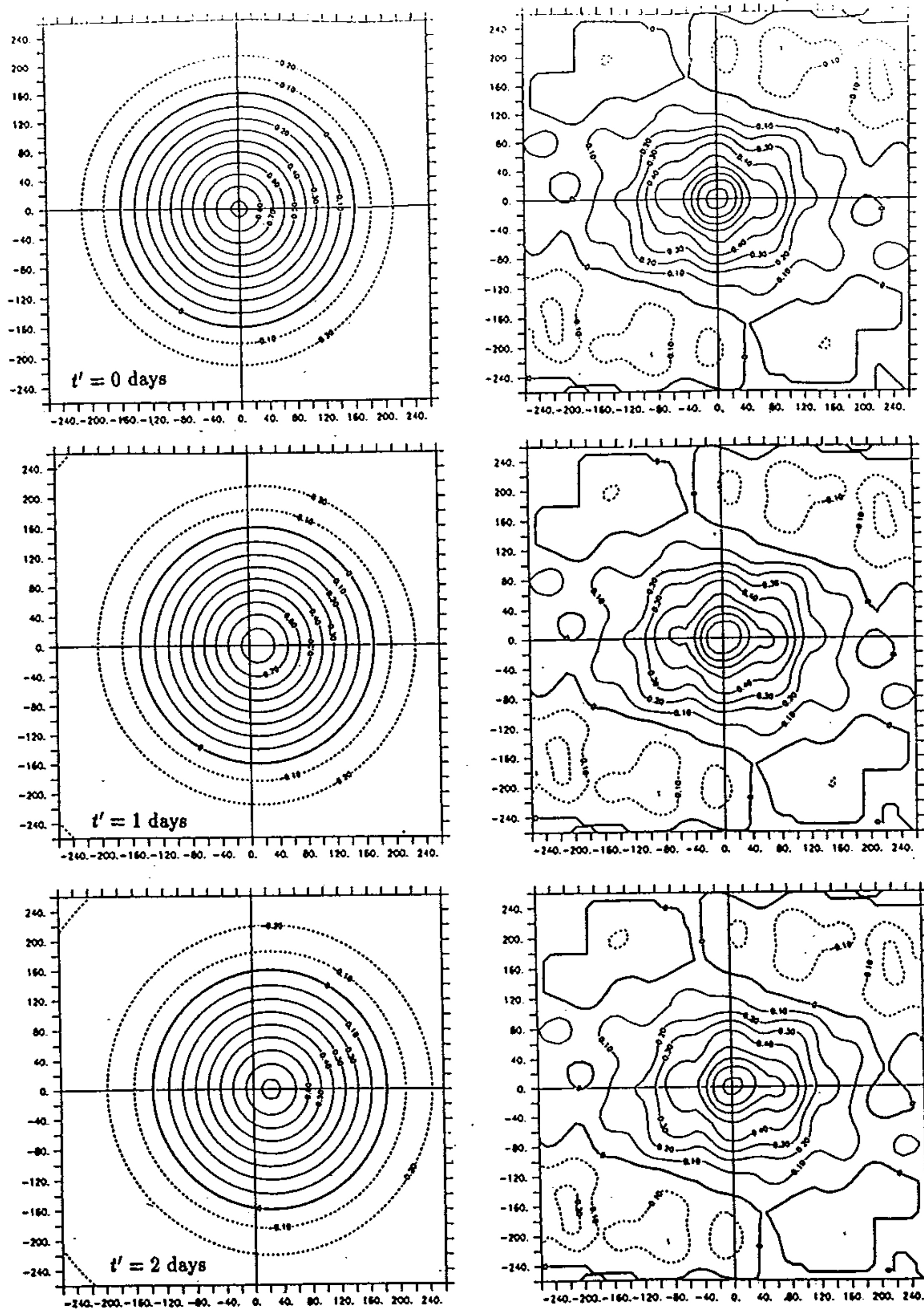


Figure 3: Two correlation functions, (right) observed and (left) analytic function $\rho_{Central}$, are contoured in plan view for time lags of 0, 1, and 2 days. The contour interval is 0.1, and negative contours are dashed. Axes tick marks indicate spatial separation distances of 20 km.

where $r^2 = (x')^2 + (y')^2$, $A = 254$ km, and $B = 160$ km. The scale factor is defined as $F_o = 1 - \epsilon$, where $\epsilon = 0.05$ is the error assoicated with the observations.

To determine the temporal decay of the correlation function, we calculated the auto-correlations of 35 IESs using positive time lags of 0 to 24 days. For this analysis, we were careful to select only IESs with long deployment periods, requiring the record length to exceed 180 days. The auto-correlations were then averaged for each time lag (Figure 5). We can express the temporal decay rate as

$$\rho(t') = \exp(-a_1 t') \cos\left(\frac{a_2 t' \pi}{180}\right) \quad (3)$$

where $a_1 = 0.05238$ d^{-1} and $a_2 = -2.2240$ d^{-1}. From symmetry requirements, the correlations for negative time lags are $\rho(-x', -y', -t') = \rho(x', y', t')$.

Subsequently, we examined the propagation of the correlation peak with time. We expected the peak to move downstream at a rate comparable to that of Gulf Stream meanders. Unfortunately, we could not accurately determine the propagation speed from Figure 3, because a lag time of 2 days was insufficient to clearly reveal the downstream movement. Instead, we selected 25 pairs of IESs which were located downstream of one another and calculated their cross-correlations for $t' = 0$ to 20 days. For each pair, we found the time associated with the maximum correlation and determined the speed based on the spatial separation between the instruments. The rates ranged from 6–23 km d^{-1}. We used an average phase speed of $c = 12$ km d^{-1} for the Central Array (cf. Equation [1]).

Finally we combined Equations [2] and [3] to obtain the full analytic expression for the correlation function of the thermocline depth in the Central Array:

$$\rho_{Central}(x', y', t') = F_o \exp(-a_1 t') \cos\left(\frac{a_2 t' \pi}{180}\right) \exp\left(\frac{-r}{A}\right) \cos\left(\frac{\pi r}{2B}\right) \quad (4)$$

where r is defined in Equation [1]. Figure 3 shows $\rho_{Central}$ in plan view for the same time lags as the observed correlations.

3.2 Mean Z_{12} and STD Fields

Watts *et al.* [1989] showed that the quality of the OA maps is influenced most strongly by the choice of mean Z_{12} field that is removed from the observations prior to performing the objective analysis (and restored later). They found that the best accuracy was obtained with a time-averaged mean field. In the past we determined the temporal mean field by fitting a third-order polynomial to the deployment-long average Z_{12} values obtained at the IES sites. Unfortunately, this method tended

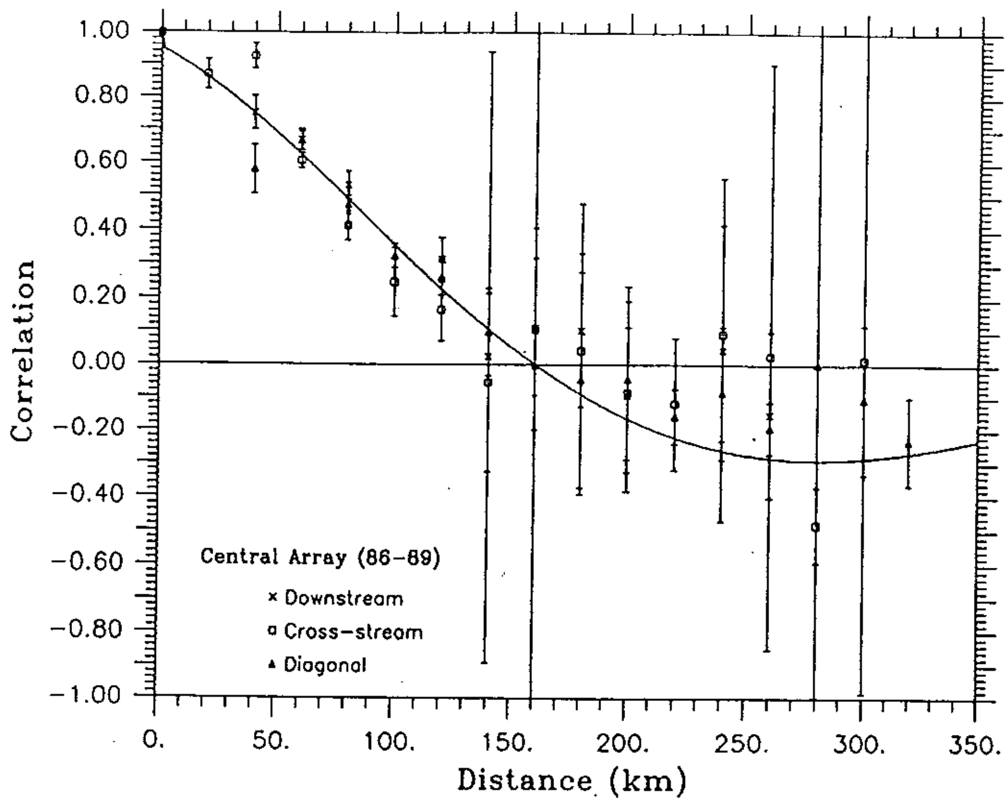


Figure 4: Correlation function for downstream, cross-stream, and diagonal IES pairs versus radial distance. The solid curve is the analytic function $\rho(r)$.

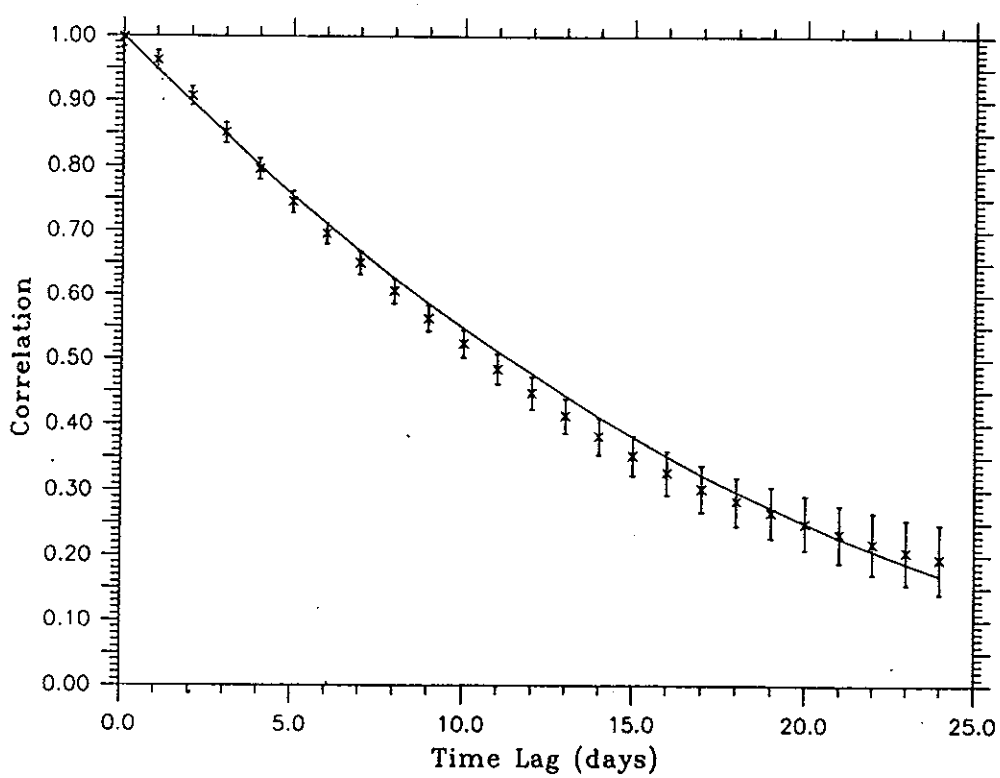


Figure 5: Average auto-correlations for 35 IESs versus lag time. The solid curve is the analytic function $\rho(t')$.

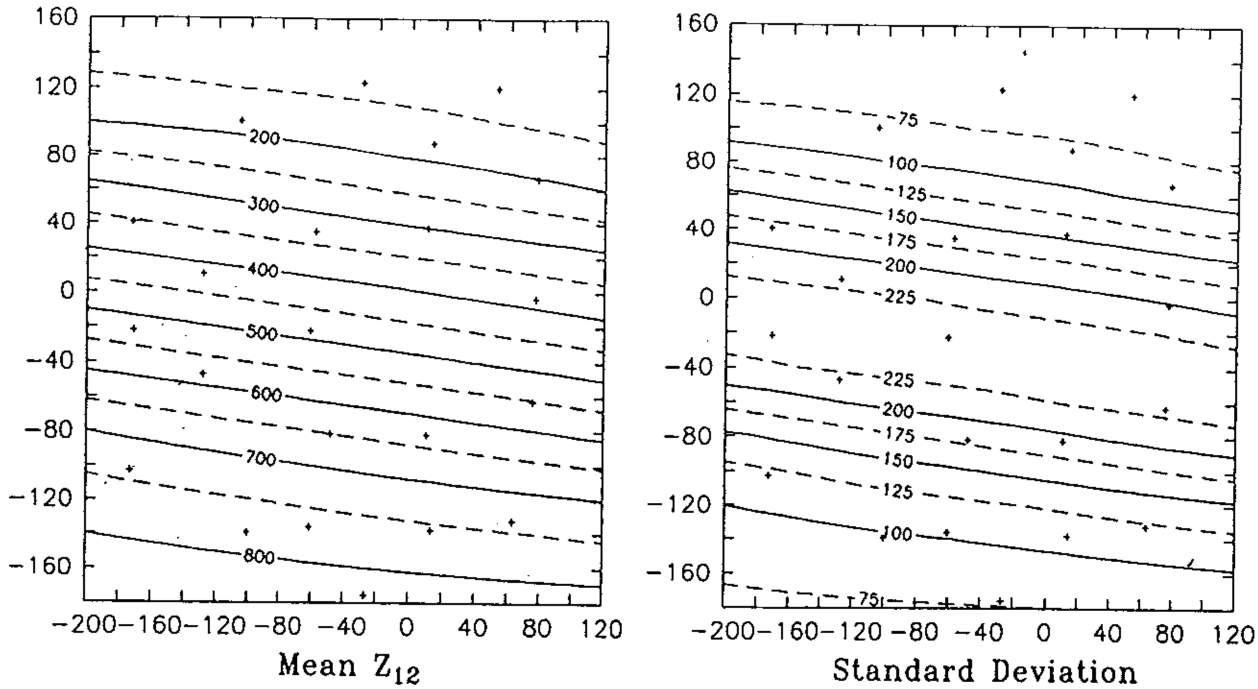


Figure 6: Mean Z_{12} (left) and standard deviation (right) fields are contoured in plan view. Contour intervals are 50 m for the mean field and 25 m for the standard deviation field. IES sites are indicated by the + marks. Axis tick marks are at 20 km intervals.

to give unrealistic values along the edges of the mapping region and we were required to tweek the inputs to obtain a smooth field. Thus for the Central Array, we elected to determine the mean Z_{12} field manually. First, we combined the Z_{12} averages for all IES sites from the three deployment periods onto a single map. Next, we picked, by eye, the relative cross-stream positions of several thermocline depths along the upstream and downstream edges of the mapping region. Then we used a cubic spline to interpolate between these positions to obtain Z_{12} values at 20 km intervals along the edges. Finally, we linearly interpolated between the two edges to fill in the remainder of the grid. The mean Z_{12} field chosen for the expanded grid (June 1988 to August 1990) is shown in Figure 6. For the smaller grid (October 1987 to May 1988), the mean field is a just a subset of that shown in Figure 6.

The standard deviations of the 61 Central Array IESs varied systematically with the mean Z_{12} value, related to the proximity of the IES sites to the mean location of the steeply sloping thermocline. This relationship is clearly shown in Figure 7. We approximated the STD field by a Gaussian function of the form

$$\sigma_{Central} = D + Ce^{-\Upsilon}$$

where $D = 40$ m and $C = 200$ m. The exponent is defined as $\Upsilon = \left[\frac{\overline{Z_{12}}(x,y)-A}{B}\right]^2$, where $A = 500$ m

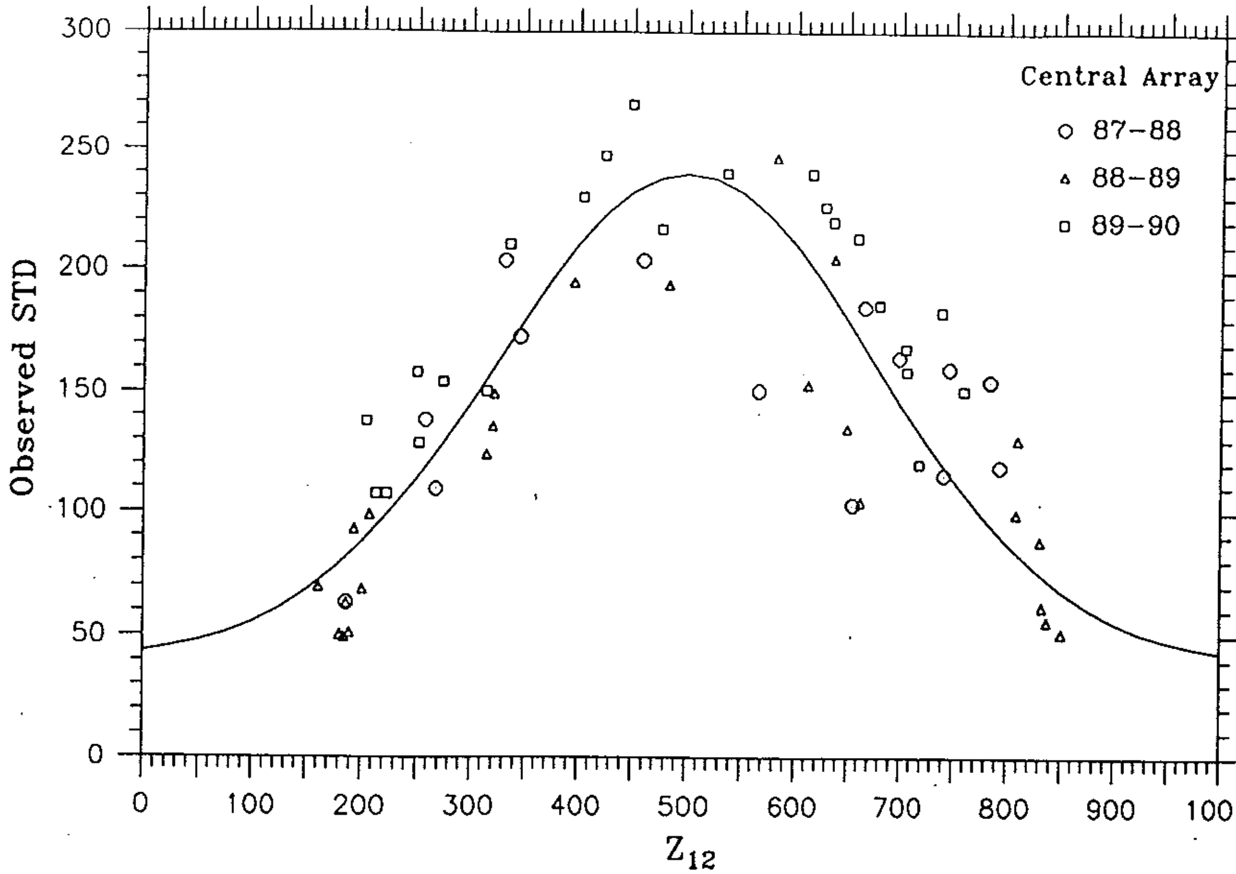


Figure 7: Observed standard deviations for 61 IESs during three deployment periods from 1987–1990 versus mean Z_{12} depth. The solid curve is the analytic function $\sigma_{Central}$.

and B = 250 m. The STD field for the expanded array is shown in Figure 6 along with the associated mean field.

3.3 Construction of the Z12 Maps

The objective analysis was performed on the "perturbation" IES Z_{12} records (i.e., the means were removed and the standard deviations normalized). The correlation function $\rho_{Central}$ was computed using Equation [4] each time a (x', y', t') triplet was specified. This resulted in a smooth, continuously changing function which produced better quality output maps than the lookup table method that we had used previously. Data restrictions were controlled by several user-specified parameters, summarized in Table 4.

The output of the objective mapping is the perturbation field on a full grid of points, with 20 km spacing. The perturbations were converted to thermocline depths by renormalizing by the STD field and restoring the mean Z_{12} field. Subsequently the Z_{12} fields were smoothed using a second-order Shapiro filter to remove small-scale ($\sim 2\Delta x$ waves) features and the outermost grid

Table 4: User-specified control parameters for OA mapping.

Parmeter	Specification
N	15 points
r_{max}	120 km
t'_{max}	±1 day
ϵ	0.05
c	12 km d^{-1}

points were dropped. The final sizes of the Z_{12} grids are 200 km by 320 km (11 by 17 grid points) for October 1987 to May 1988 and 280 km by 300 km (15 by 16 points) for June 1988 to August 1990.

4 Estimated Error Fields

Statistical estimates (percent standard deviation) of the accuracy of the output Z_{12} fields were produced during the objective analysis. The error associated with each output grid point depends only on the locations, in space and time, of the observations and the correlation function. The error is independent of the measurements themselves. Thus, the same error field applies for all daily OA maps produced from a given array of instruments.

Basically, during the 34-month-long deployment period, there were six different array configurations due to the loss or repositioning of several IESs. The corresponding error fields, along with the IES sites, are shown in Figure 8. The errors are low near the IES sites and increase with distance from those sites. There are also isolated regions of higher error due to the lack of data when an instrument failed. During the cruises to cycle the array (May-June 1989, May-June 1990 and August 1990), the array configurations changed frequently while the IESs were being recovered and redeployed. During these periods, the actual error fields associated with the Z_{12} maps changed daily. These 'transitional' error fields are not shown in Figure 8, but areas of higher error are indicated on the individual objective maps.

We use the estimated error fields to mask out portions of the OA maps where the map quality is predicted to be poor. On the Z_{12} maps, regions with predicted error 30–48% are shaded by dashed contours, and larger errors are indicated by solid contours. Based upon analogies drawn from Watts *et al.* [1989], our preliminary estimate is that the dimensional uncertainty of the Z_{12} field is less than 50 m within the mapping region for which the predicted error is less than 30%. We have used 50 m as the contouring interval for the subsequent maps of the Z_{12} field.

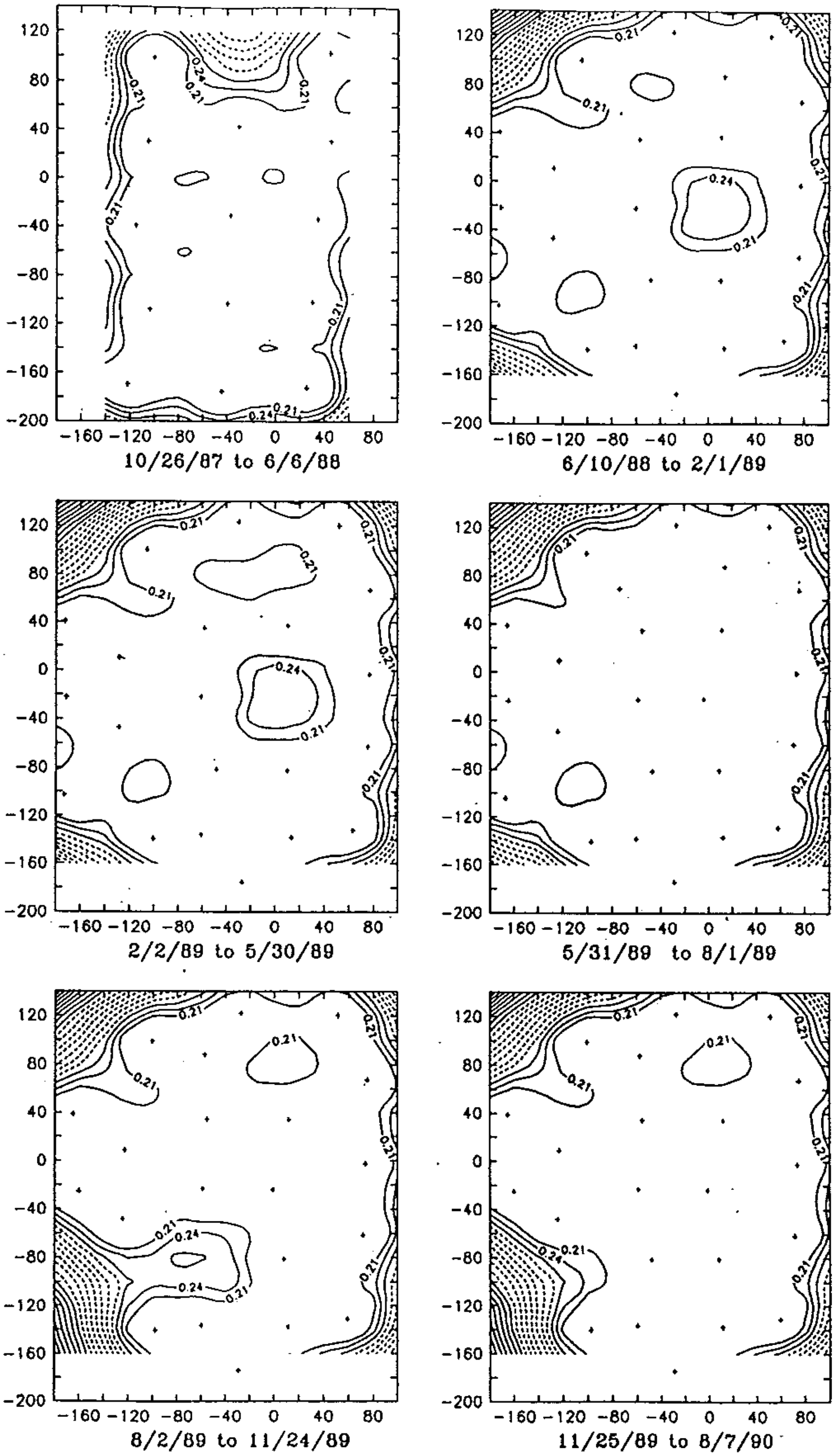


Figure 8: Estimated error (percent STD) fields for six different array configurations apply to the Z_{12} fields for the dates shown. Errors greater than 0.21 are contoured at intervals of 0.03. For clarity, errors between 0.30 and 0.48 are indicated by dashed contours. IES sites are shown by the '+' marks. The common plotting grid was chosen for the six arrays out of convenience.

5 Average Z_{12} Maps

To produce average maps of the Z_{12} field in the Central Array, we summed the maps (presented in the following section) by grid point and then divided by the number of maps. We averaged two ways, by deployment period and by season. The deployment-long average Z_{12} fields for the three periods are shown in Figure 9 with the averaging dates indicated below each map. Next, we divided the maps into twelve groups of approximately 90 days, corresponding to the four seasons. Two of the groups were for shorter time periods due to the timing of the start and end dates; the group for October-December 1987 consisted of 67 days and the July-August 1990 group of only 38 days. Average Z_{12} maps were produced for each group and these are shown in Figure 10.

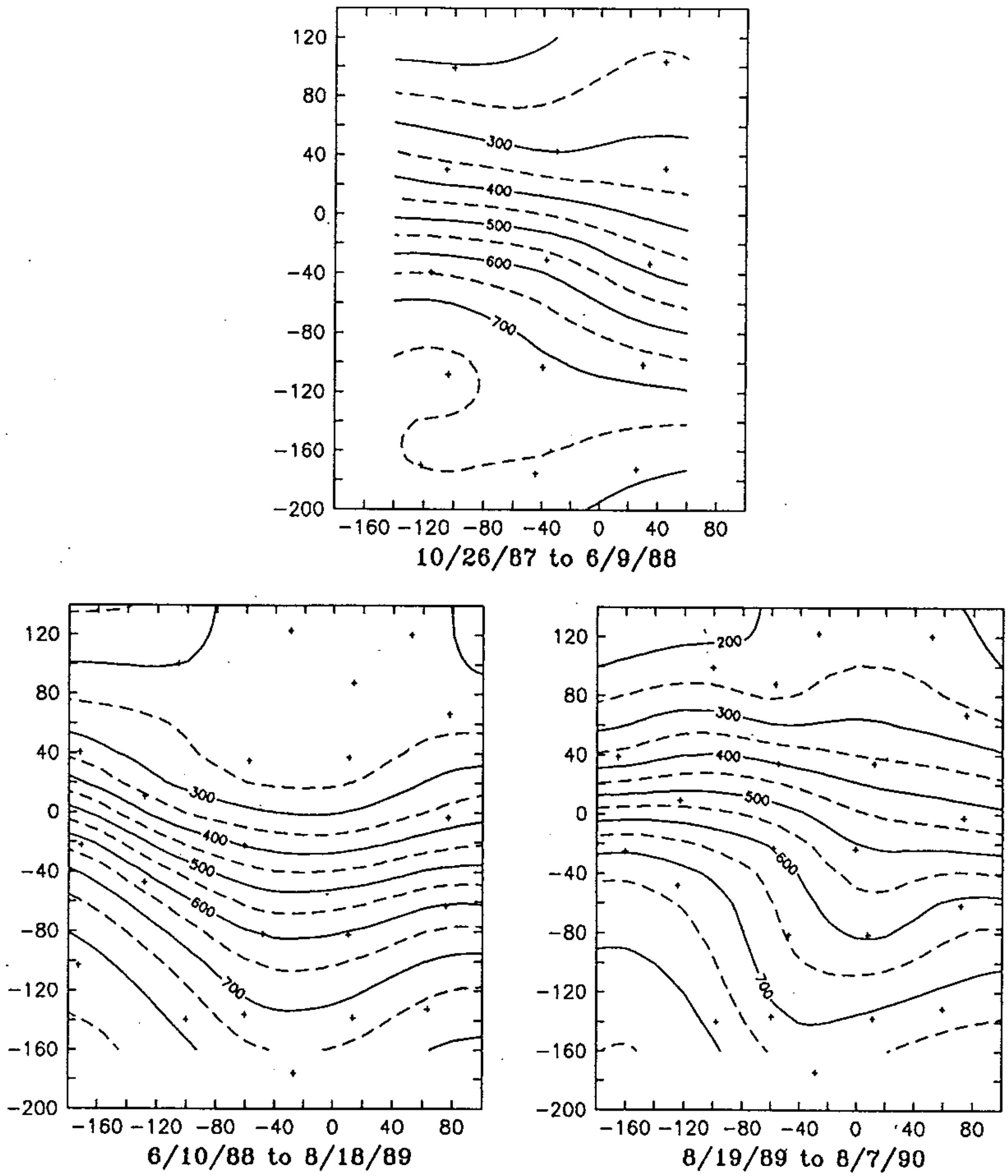


Figure 9: Z_{12} fields averaged, by grid points, for the three deployment periods. Averaging periods are indicated below each map. Depth contours are in meters. Distances on the axes are in kilometers.

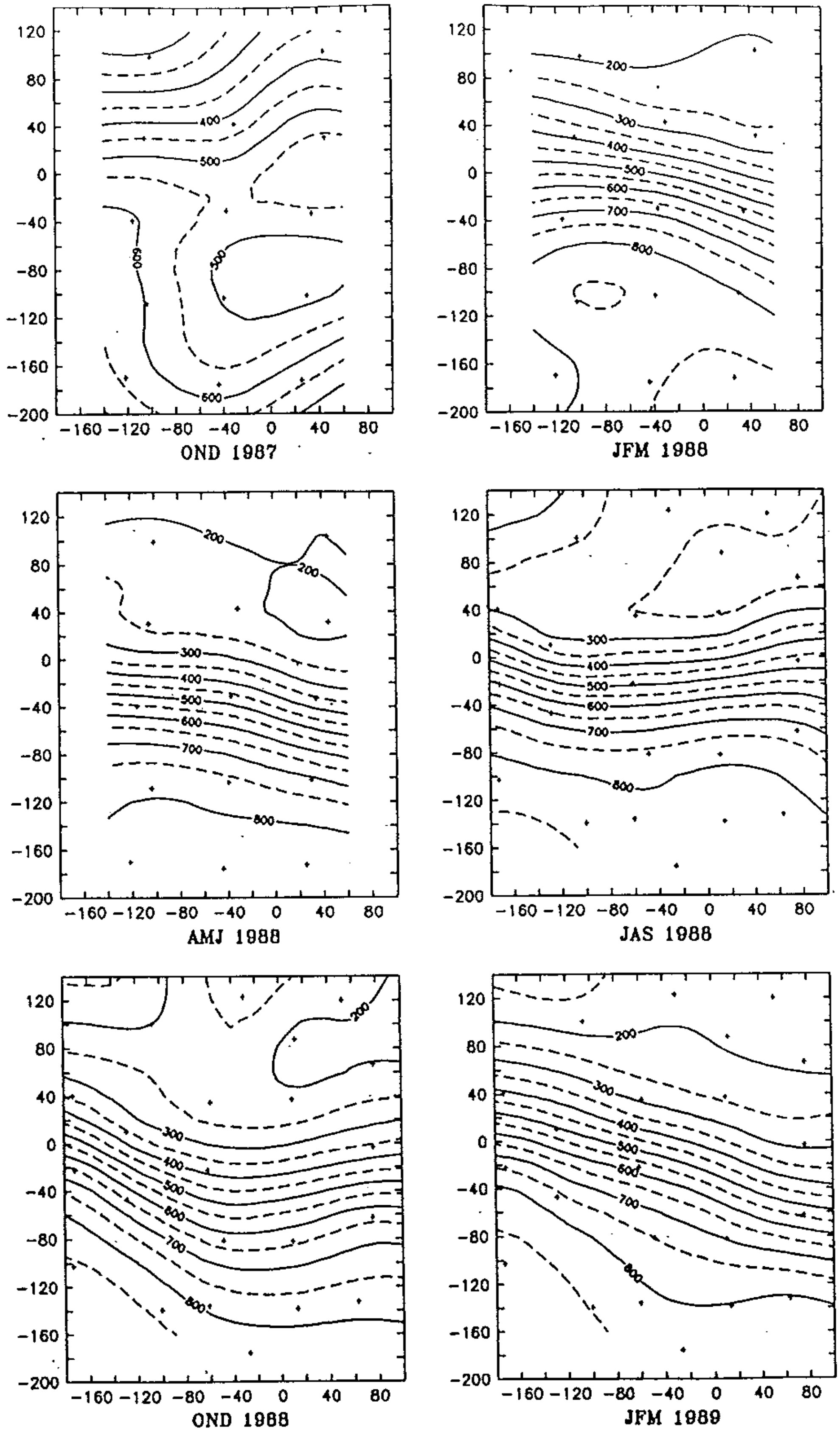


Figure 10: Seasonally-averaged Z_{12} fields. The months and year are indicated below each frame. Depth contours are in meters. Distances on the axes are in kilometers.

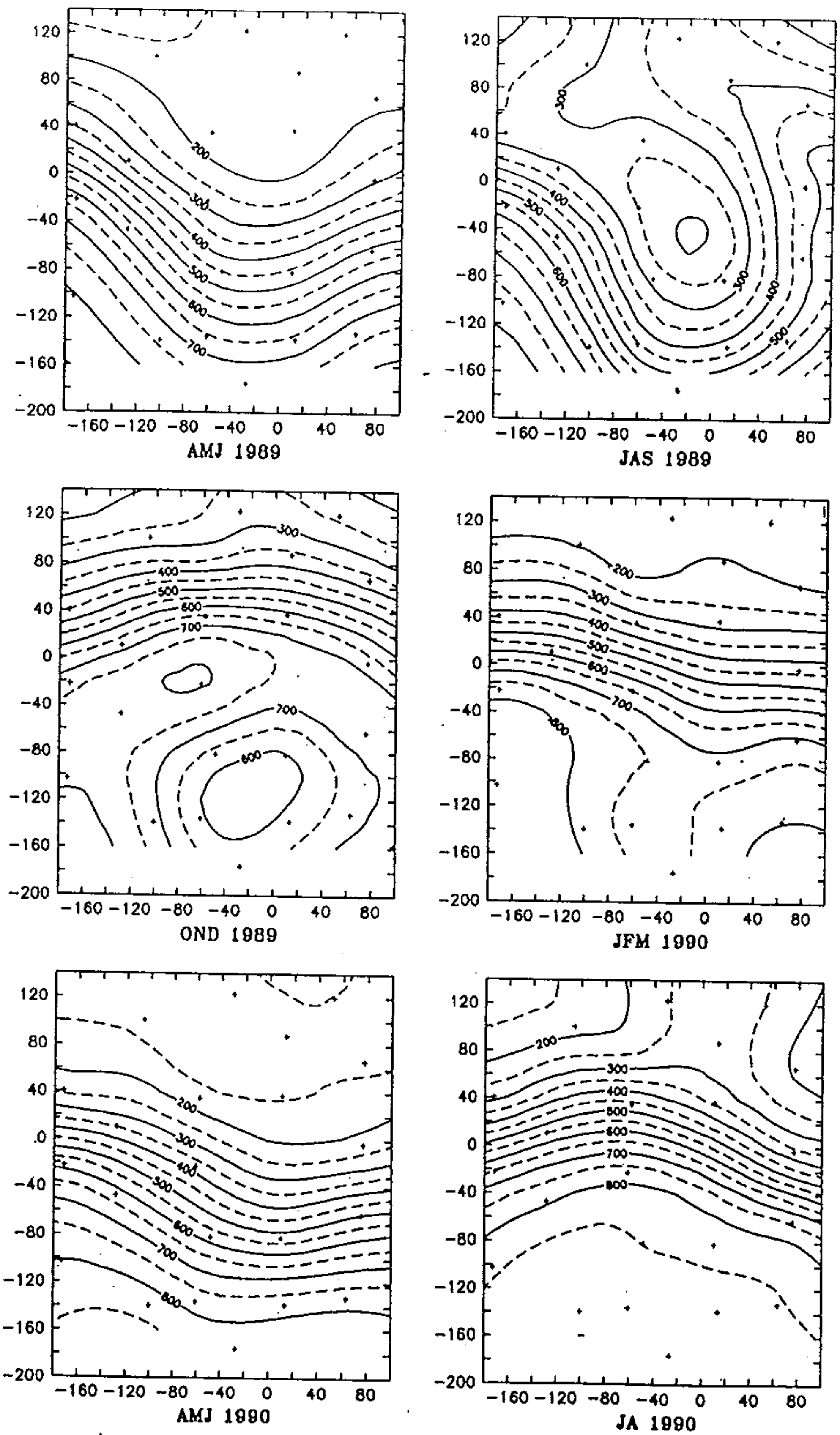


Figure 10: Continued.

6 Daily Z_{12} Maps for the Central Array

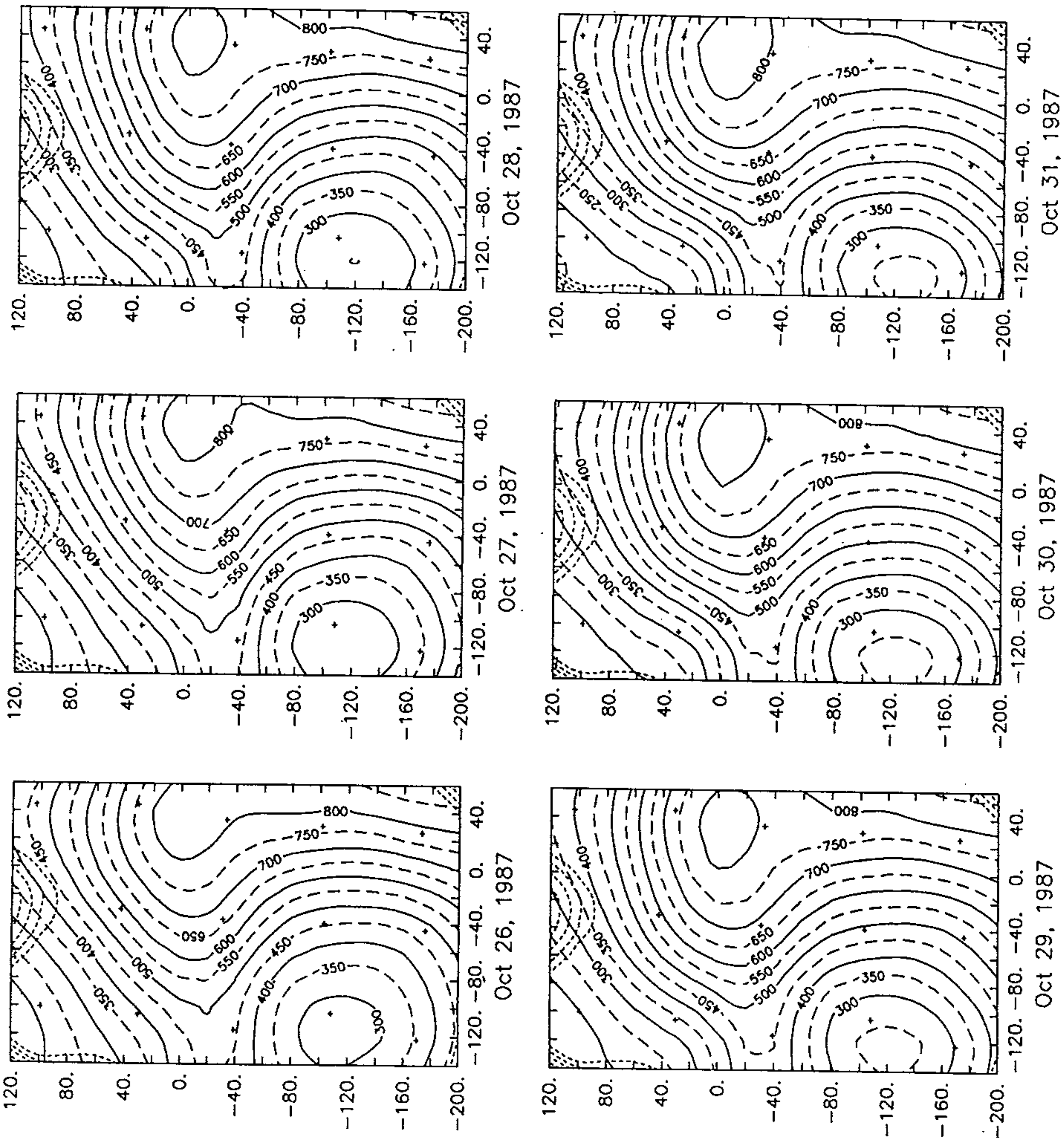
Objective maps of the Gulf Stream thermal field were produced at daily intervals for October 26, 1987 through August 7, 1990. The maps are shown for 1200 UT on the dates indicated below each frame.

The frames correspond to the boxed regions shown in either Figure 1 or 2 depending on the IES array configuration. The actual IES sites are indicated by the '+' marks and the positions are listed in Tables 1–3. Each IES position was converted to grid coordinates using scale factors of 111 km per degree latitude and 82.263 km per degree longitude; distances were referenced to the grid origin at 38°N, 68°W. Subsequently the grid was rotated 15° so that the base was oriented 075°T. This rotation was done prior to running the objective analysis for plotting convenience, not as a requirement of the OA technique. The latitude-longitude positions of the grid corners are listed in Table 5.

The Z_{12} field is contoured at 50 m intervals. Extrapolated regions of the OA maps have been masked out where the the estimated errors are high; errors of 30–48% are indicated by dashed contours and higher errors by solid contours. The contour interval of the estimated errors is 3%.

Table 5: Corner Positions of Mapping Regions

Map Dates: 26 October 1987 to 9 June 1988				
Corner	x (km)	y (km)	Latitude (N)	Longitude (W)
Upper Left	-140	+120	38° 43.07	69° 55.66
Lower Left	-140	-200	35° 55.99	68° 58.05
Upper Right	+60	+120	39° 11.05	67° 41.29
Lower Right	+60	-200	36° 23.97	66° 43.68
Map Dates: 10 June 1988 to 7 August 1990				
Corner	x (km)	y (km)	Latitude (N)	Longitude (W)
Upper Left	+140	-180	38° 47.91	70° 26.14
Lower Left	-180	-160	36 11.28	69 32.13
Upper Right	+100	+140	39° 27.09	67° 18.02
Lower Right	+100	-160	36° 50.45	66° 24.01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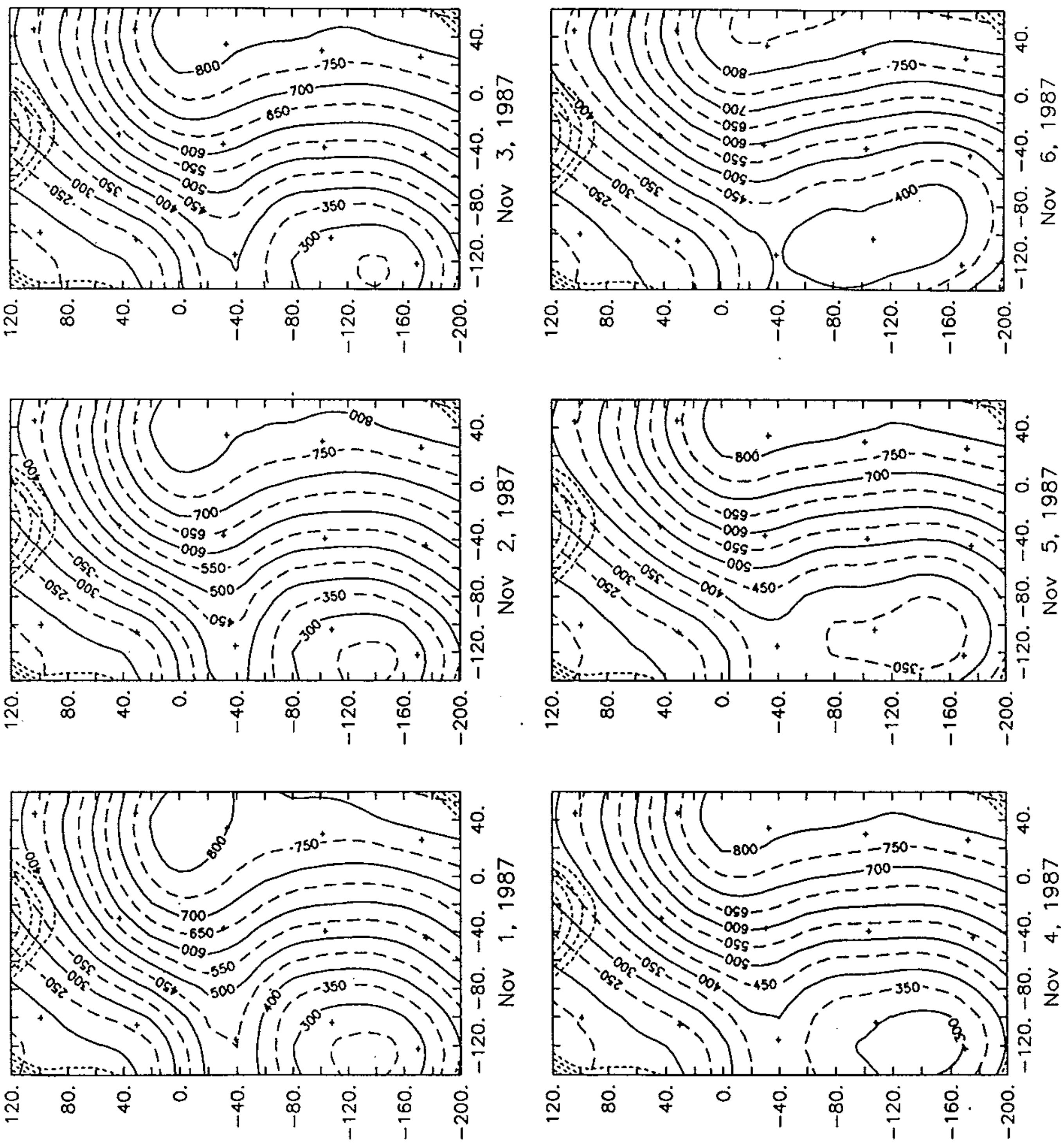
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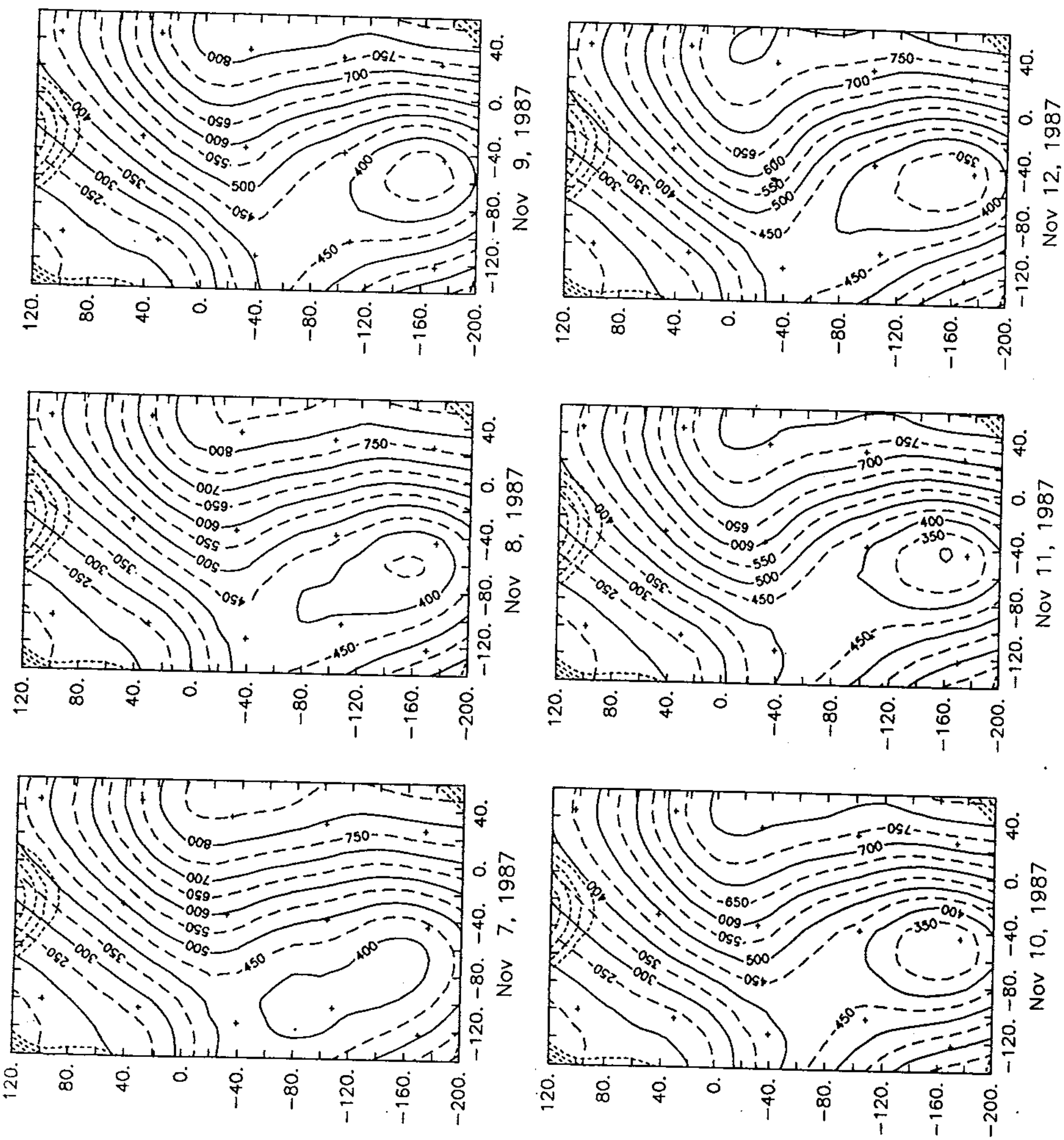
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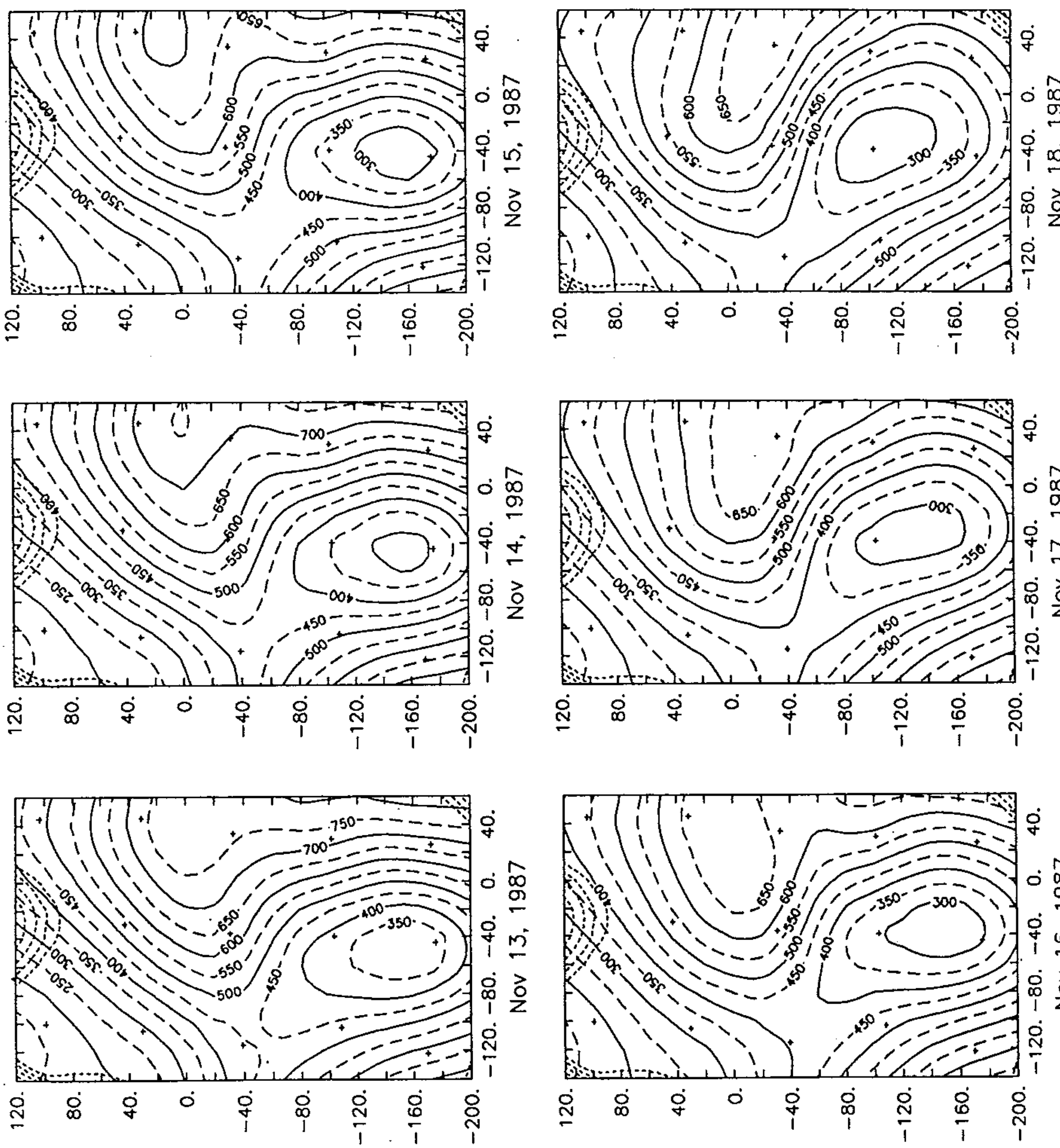
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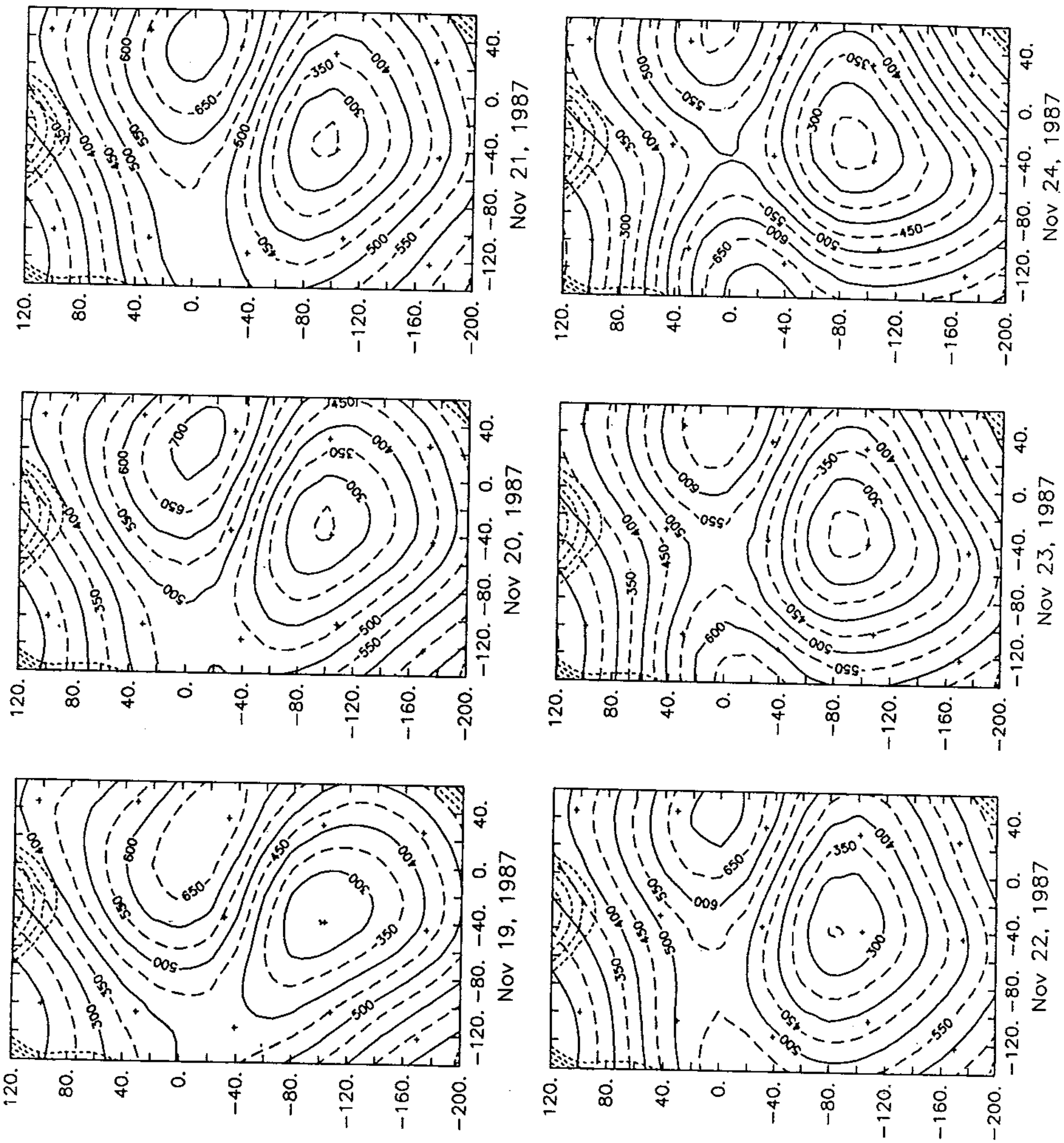
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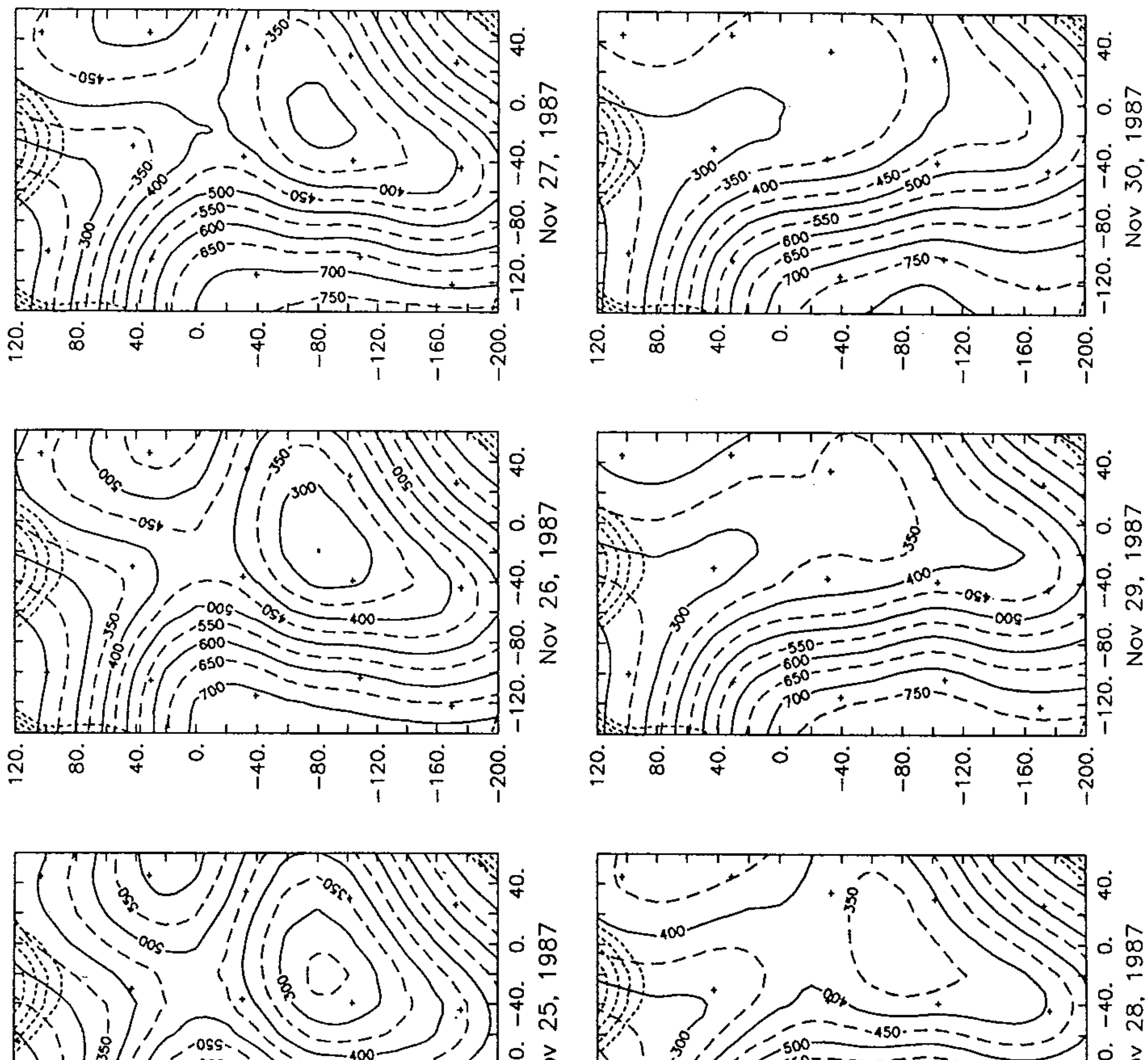
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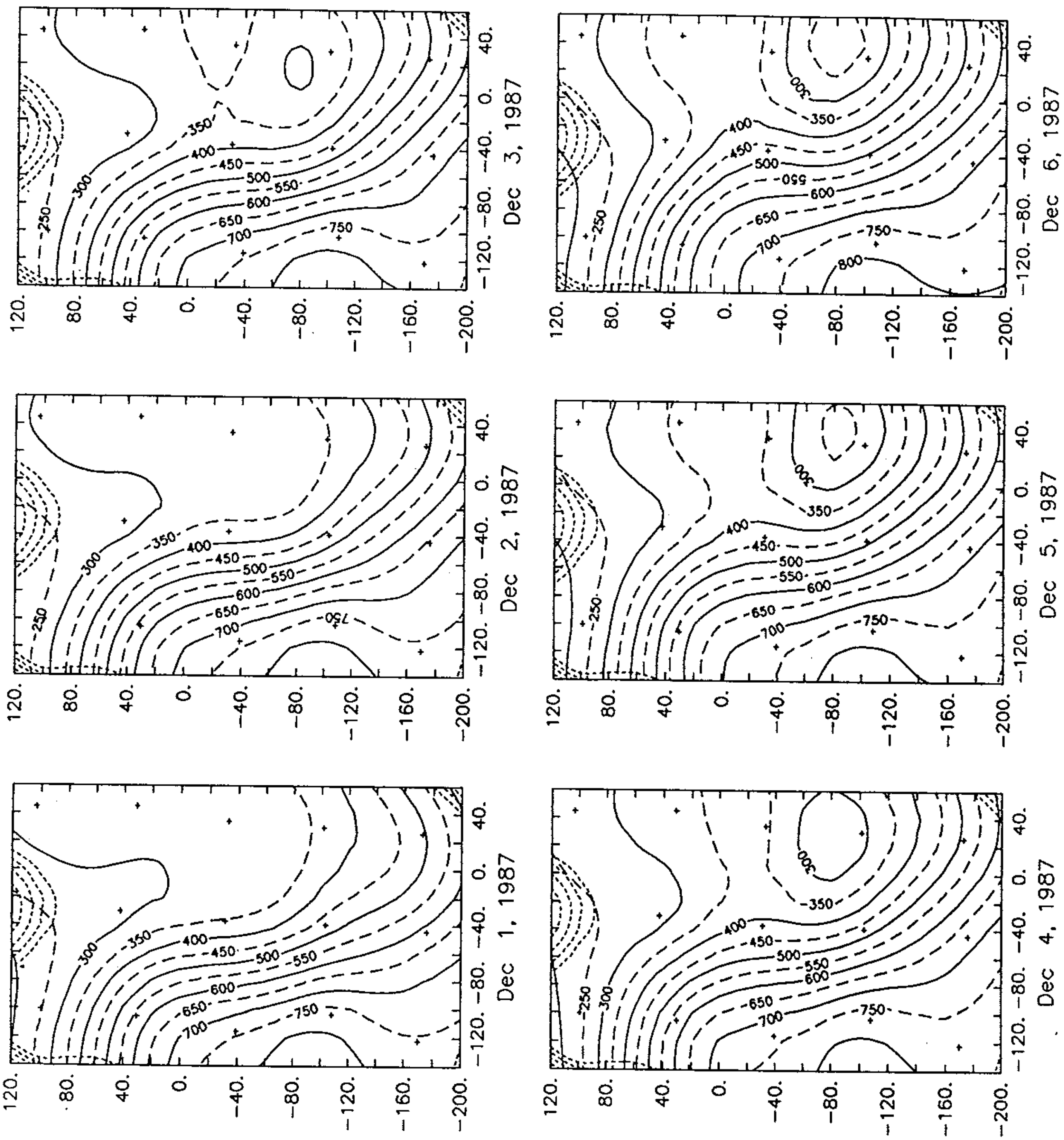
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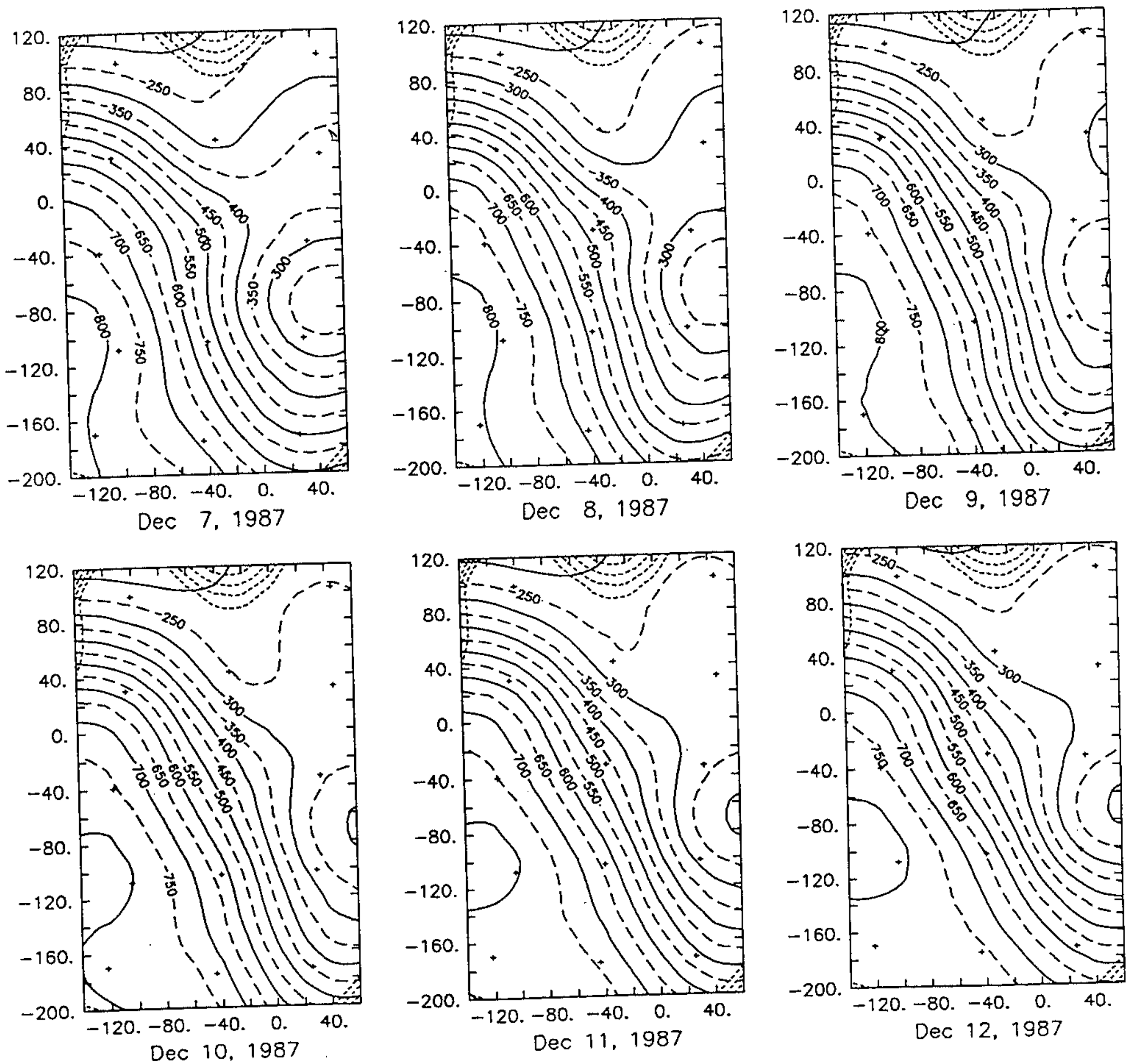

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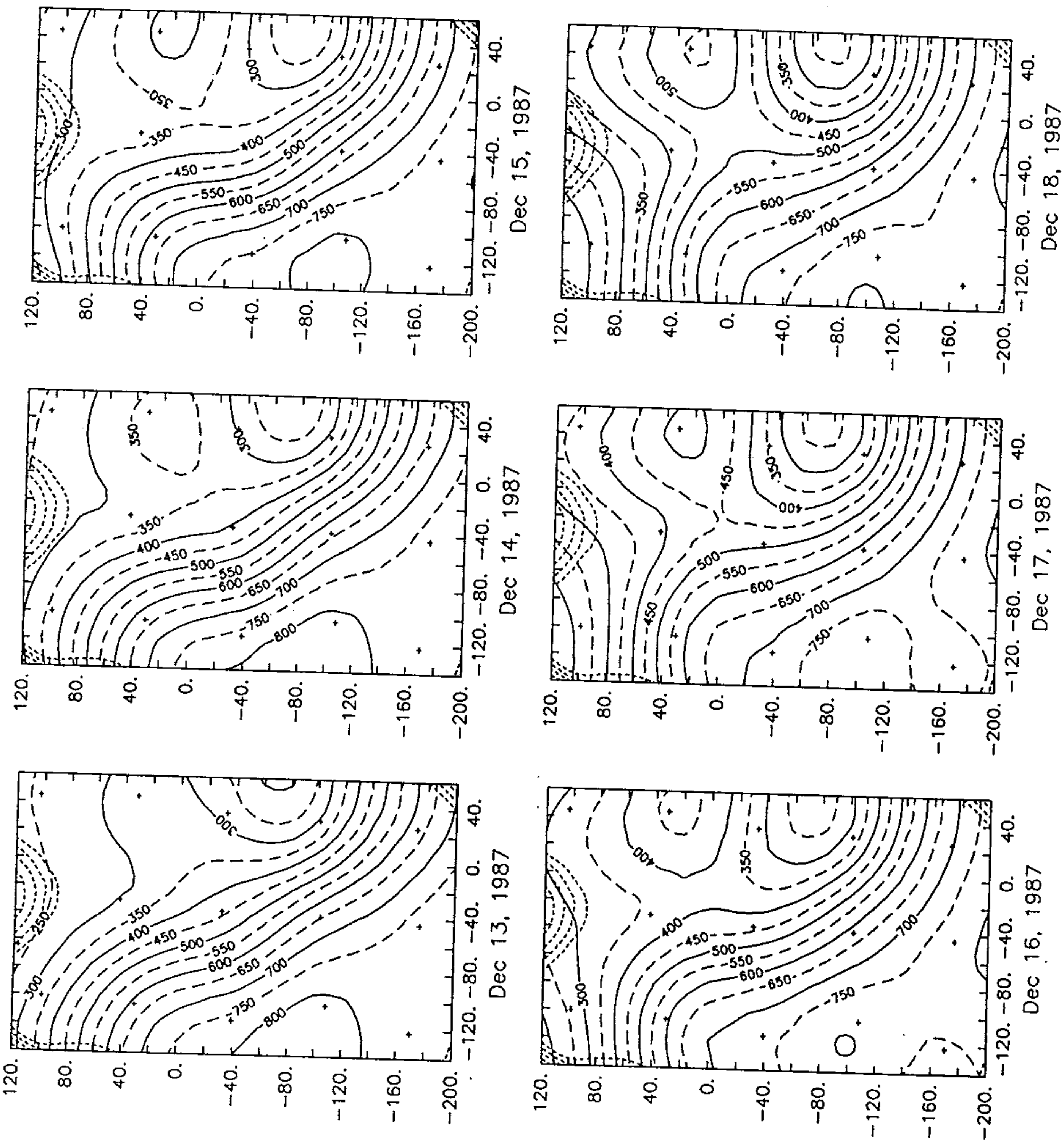
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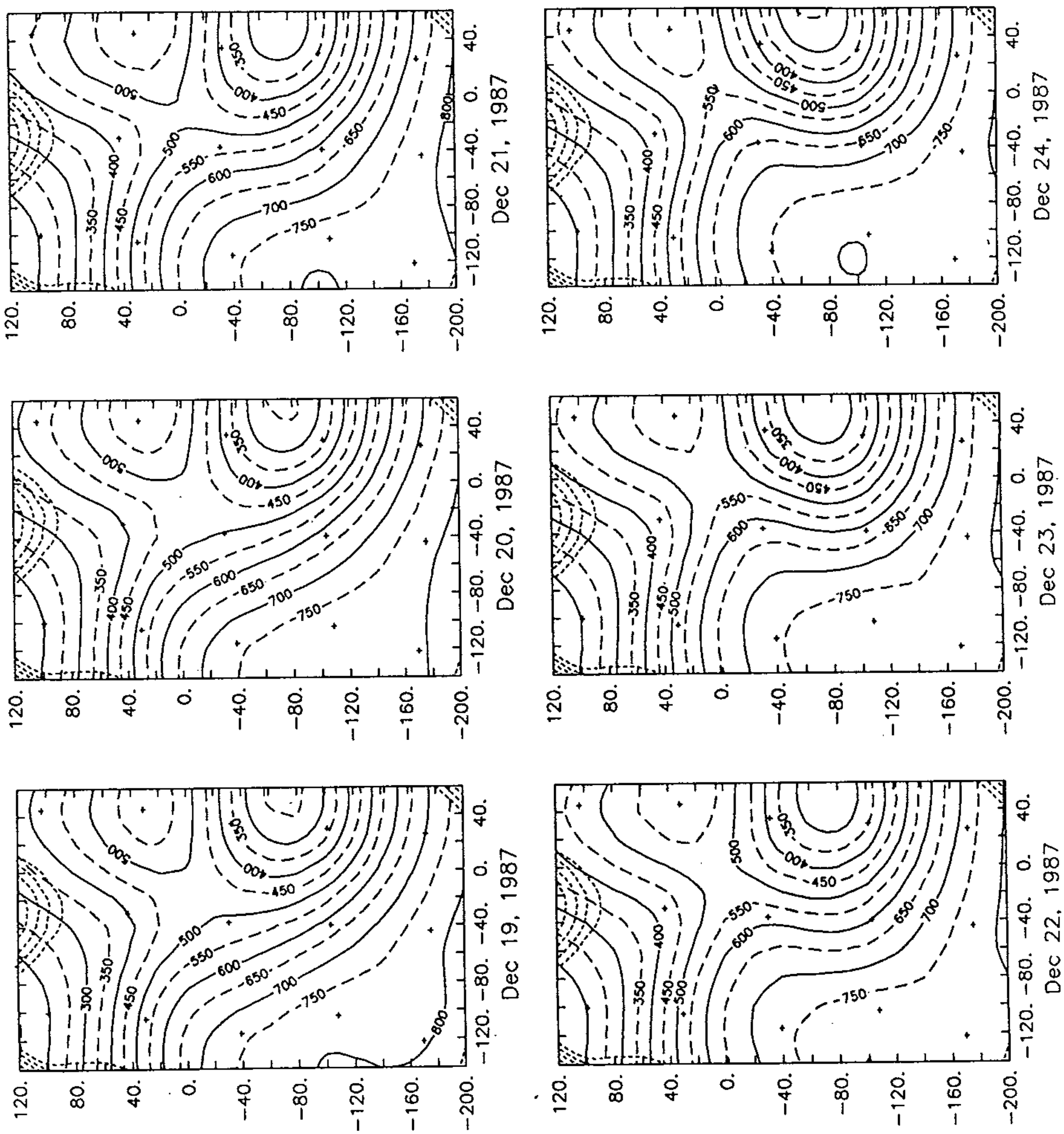
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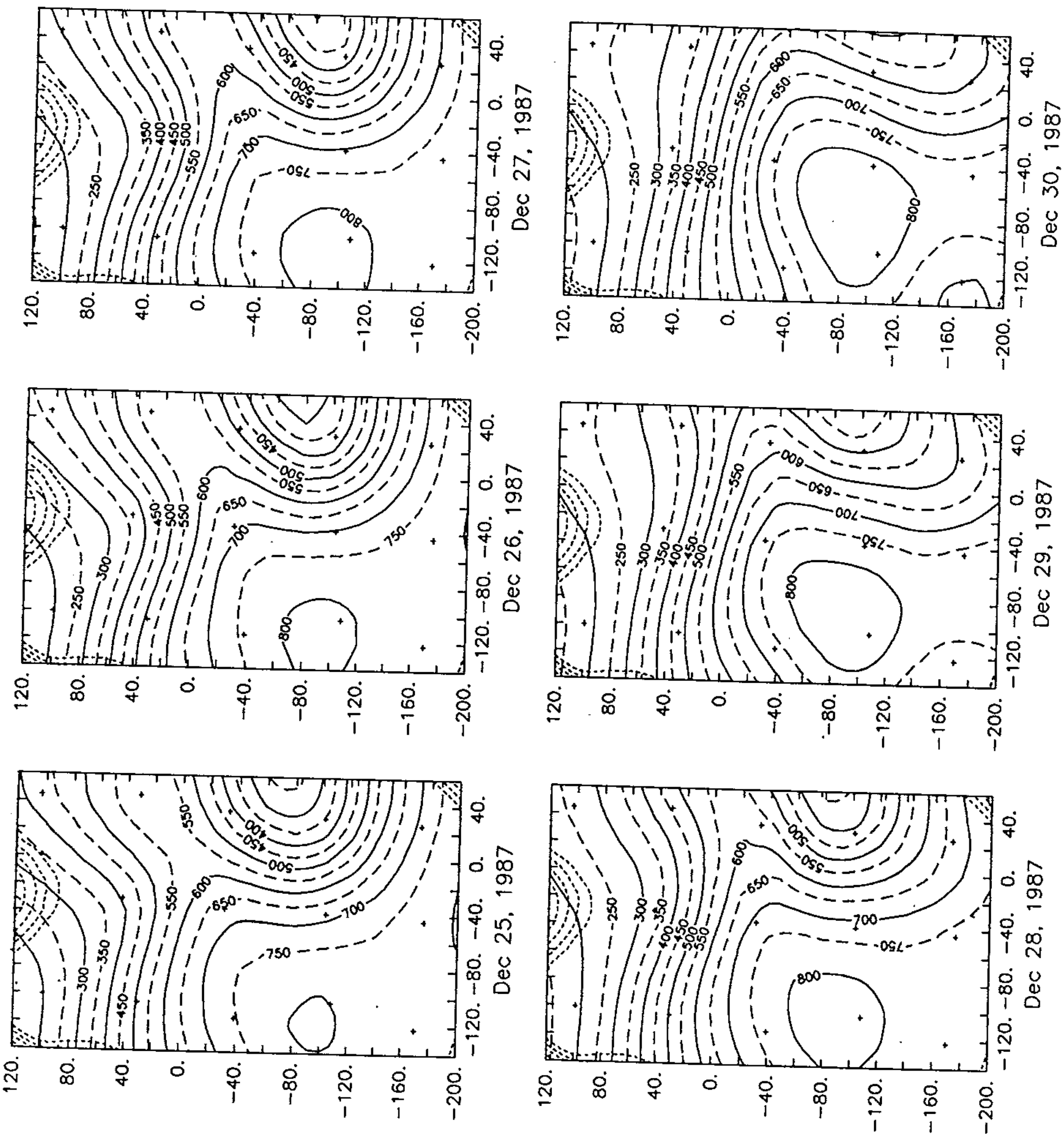
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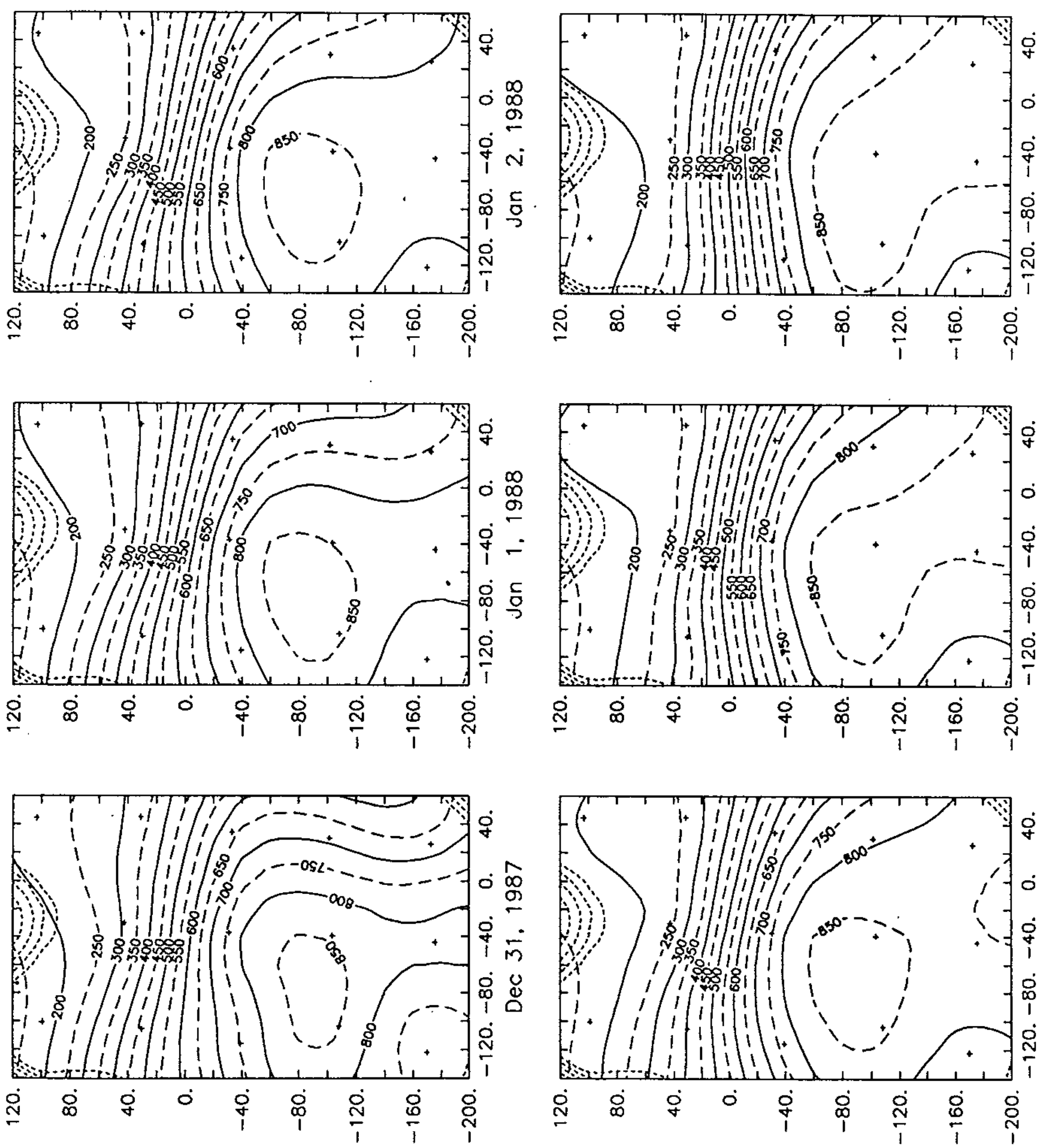
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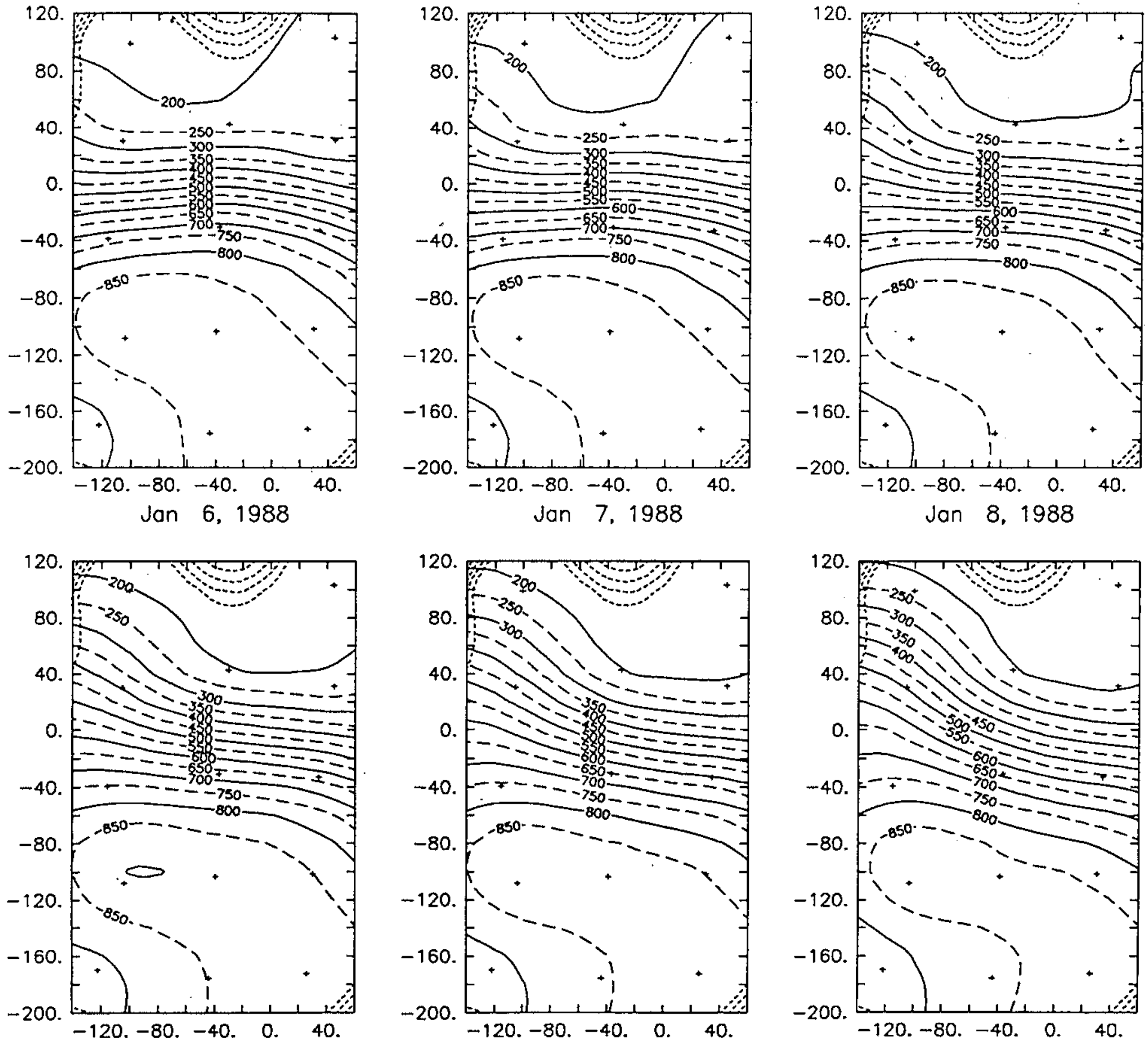
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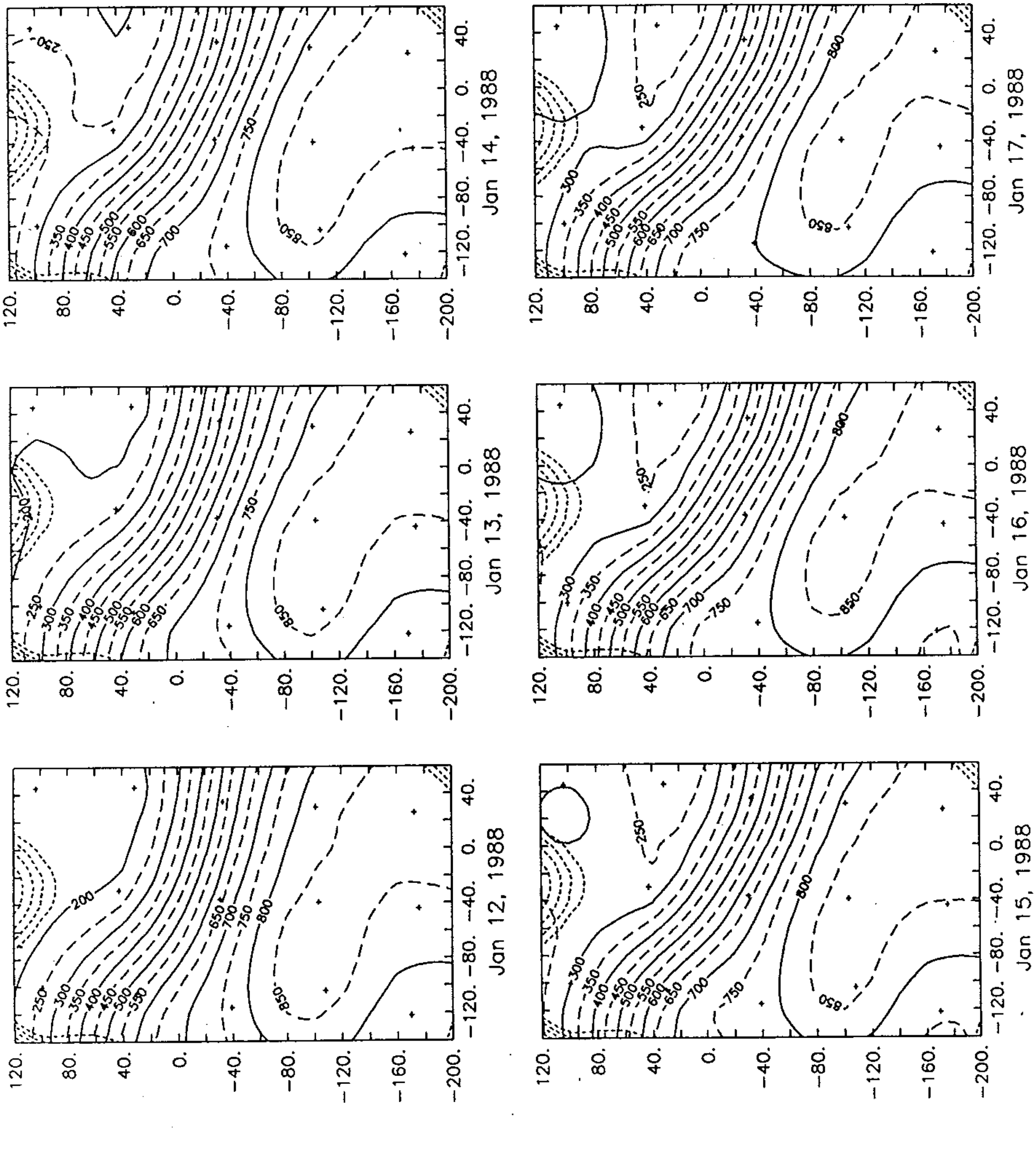
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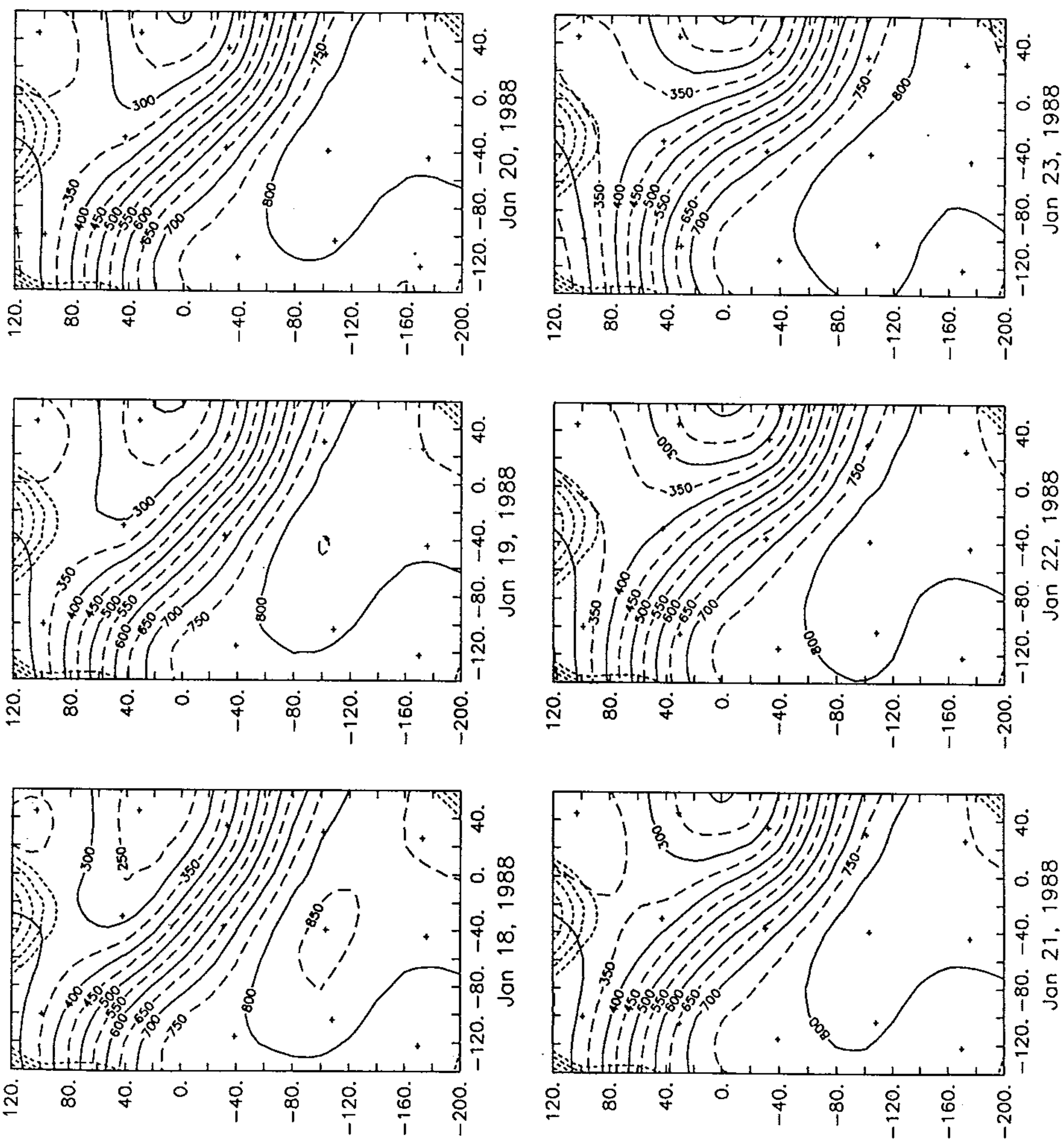
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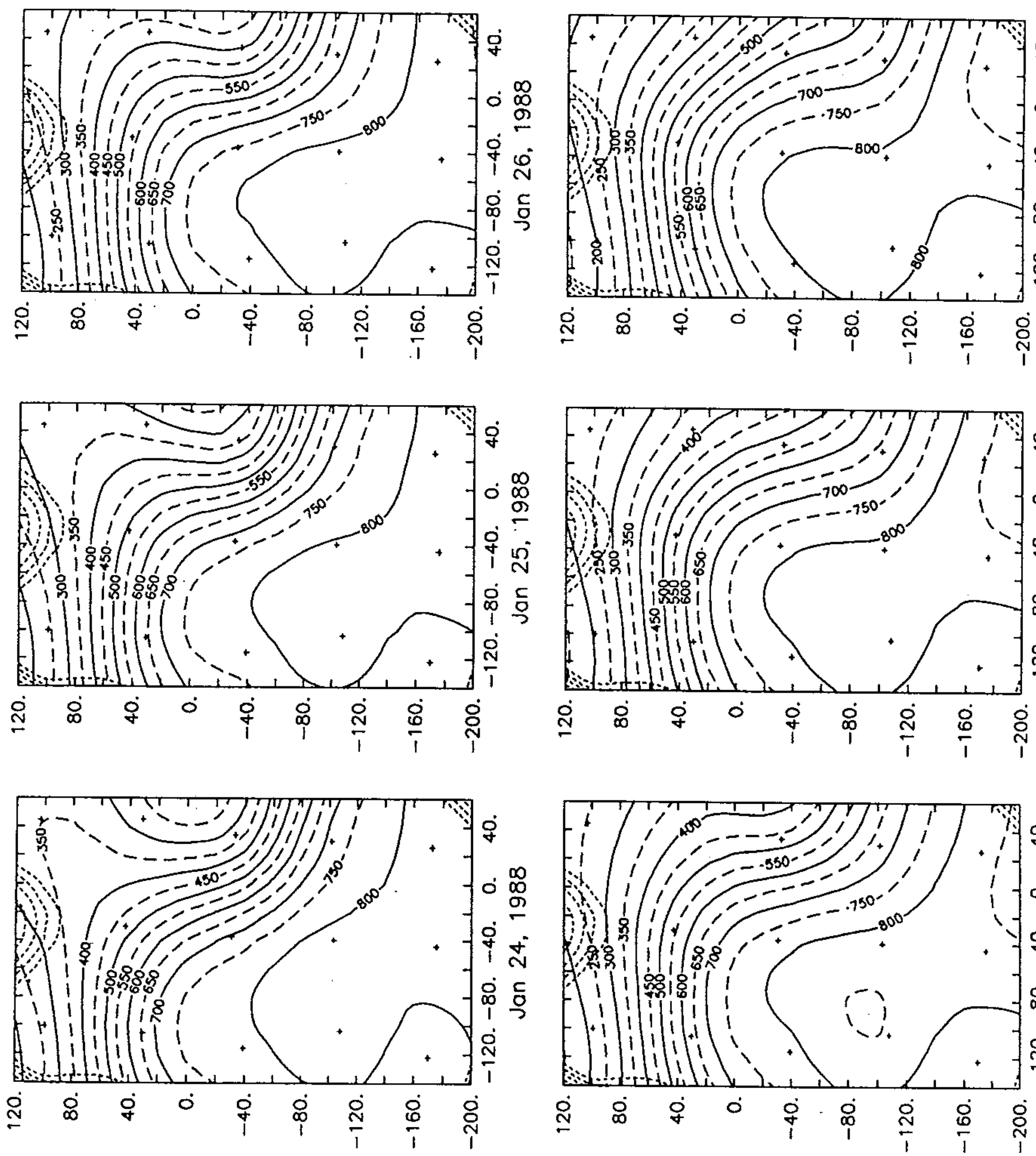
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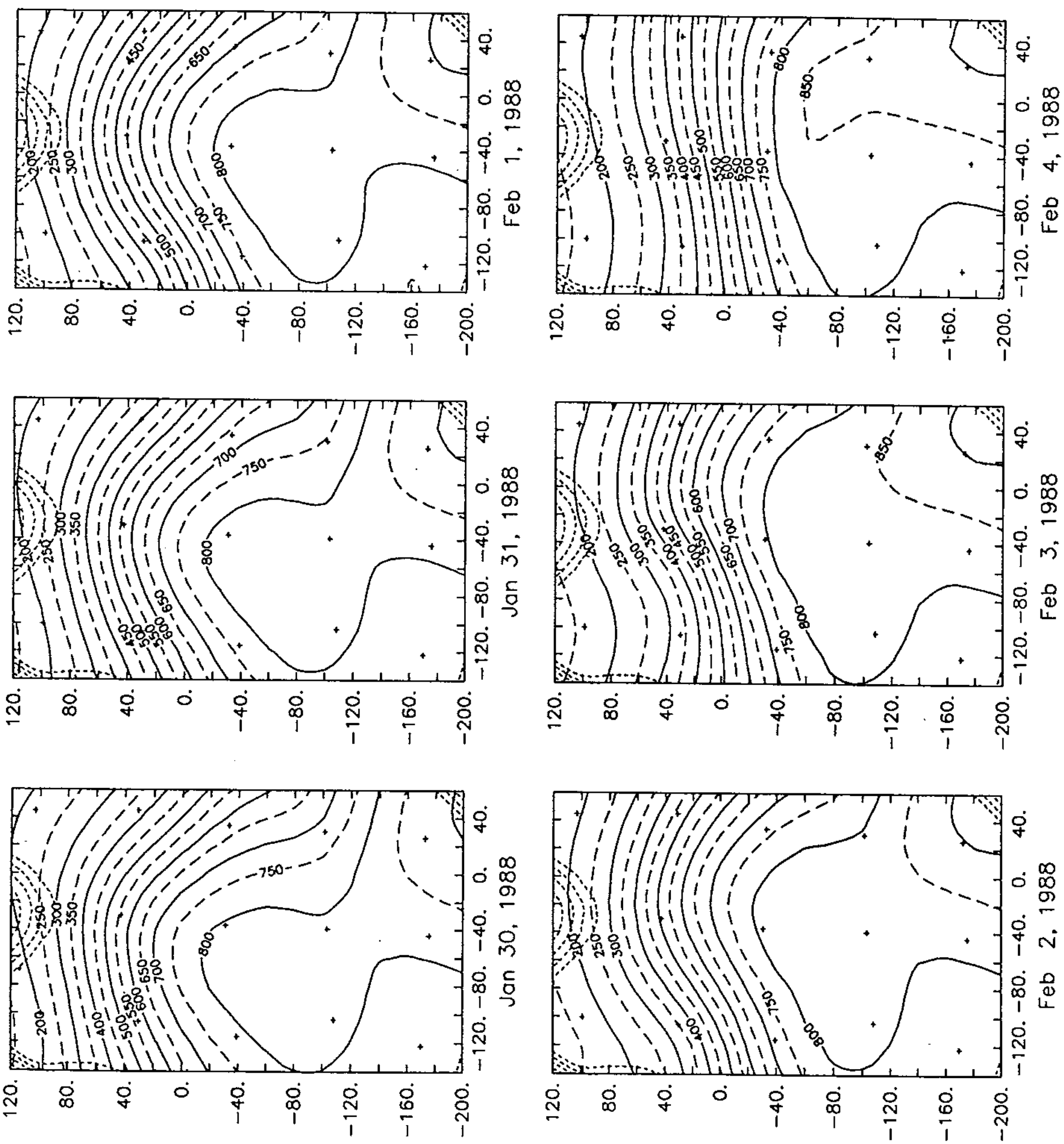
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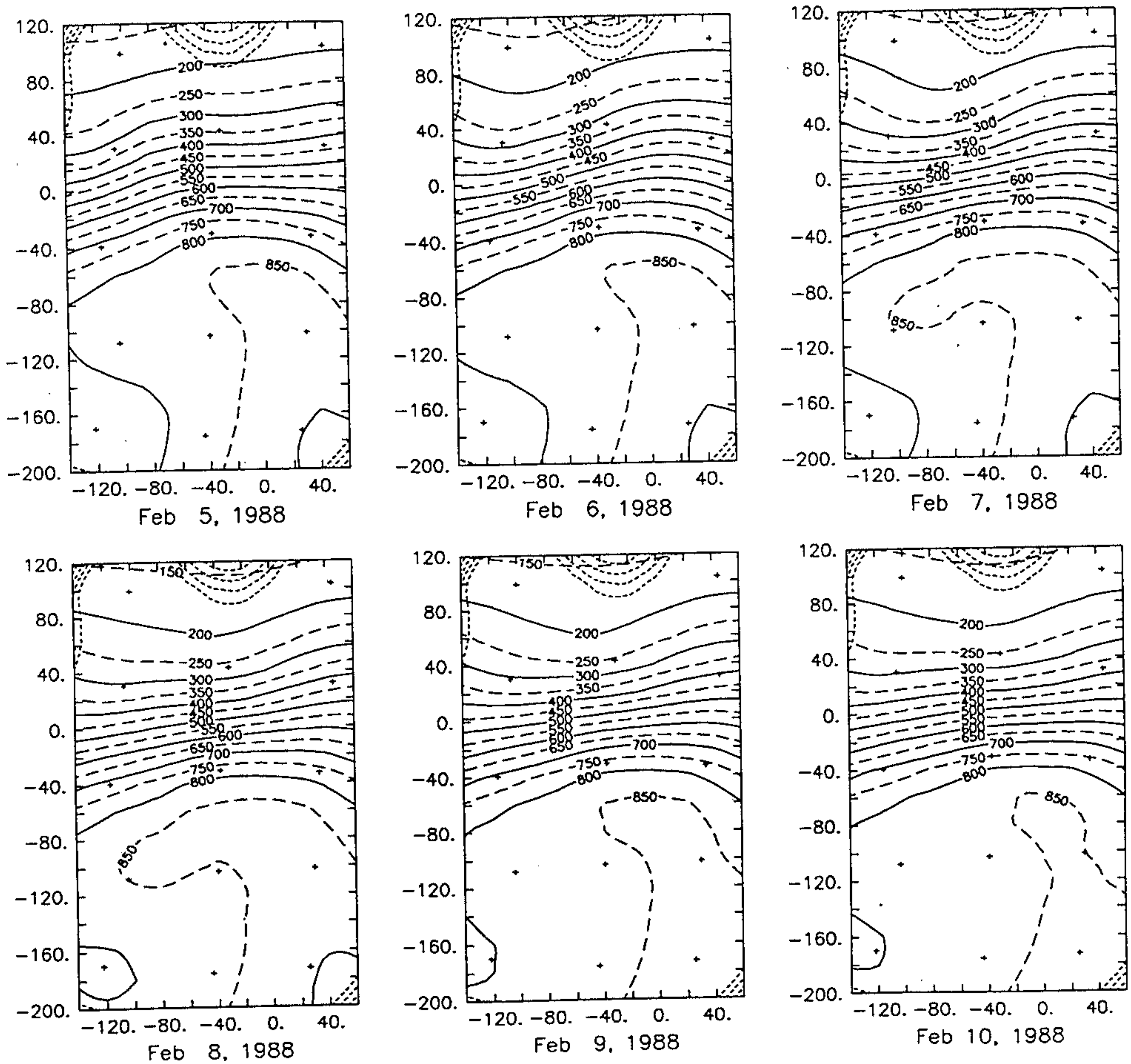
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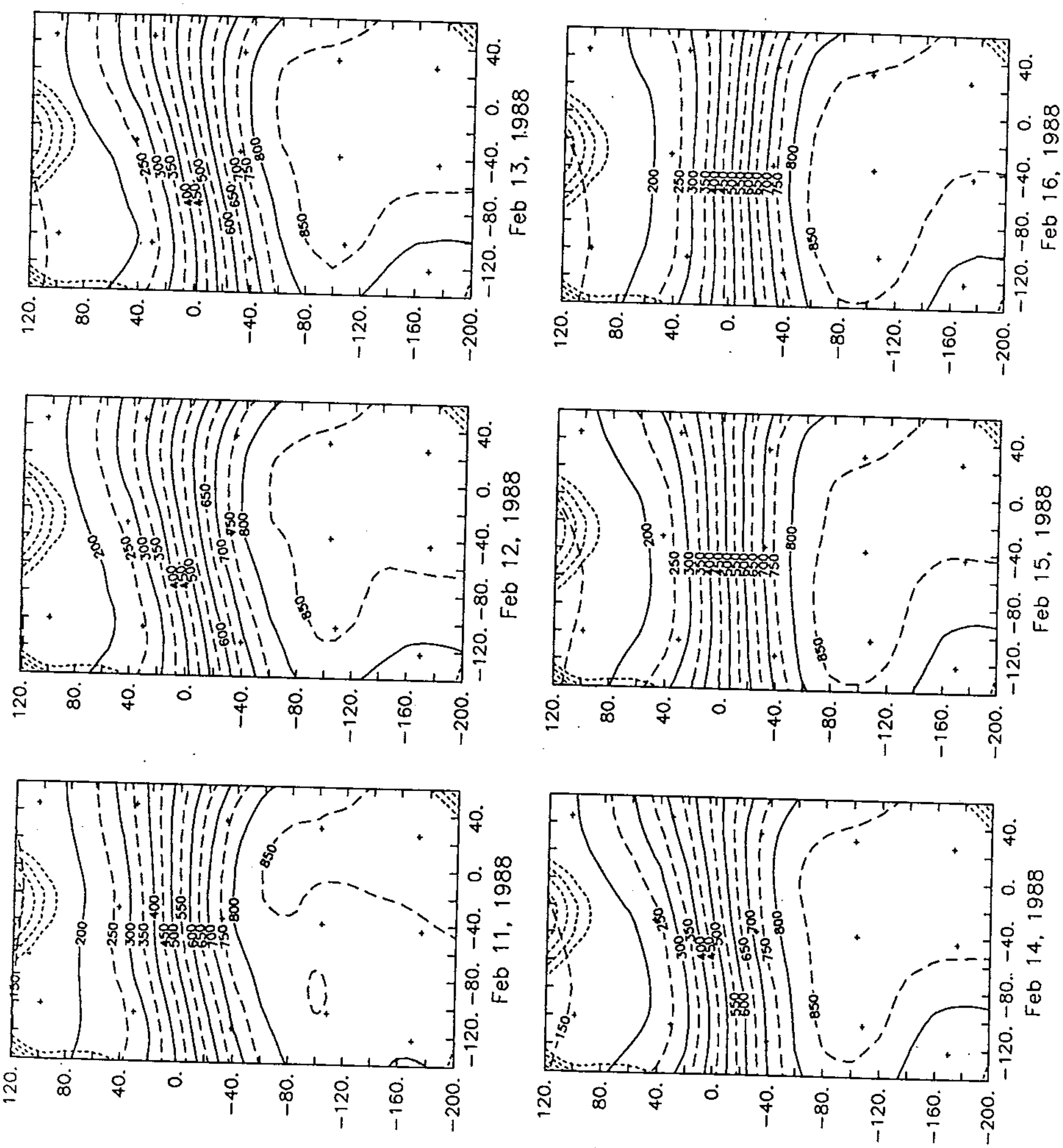
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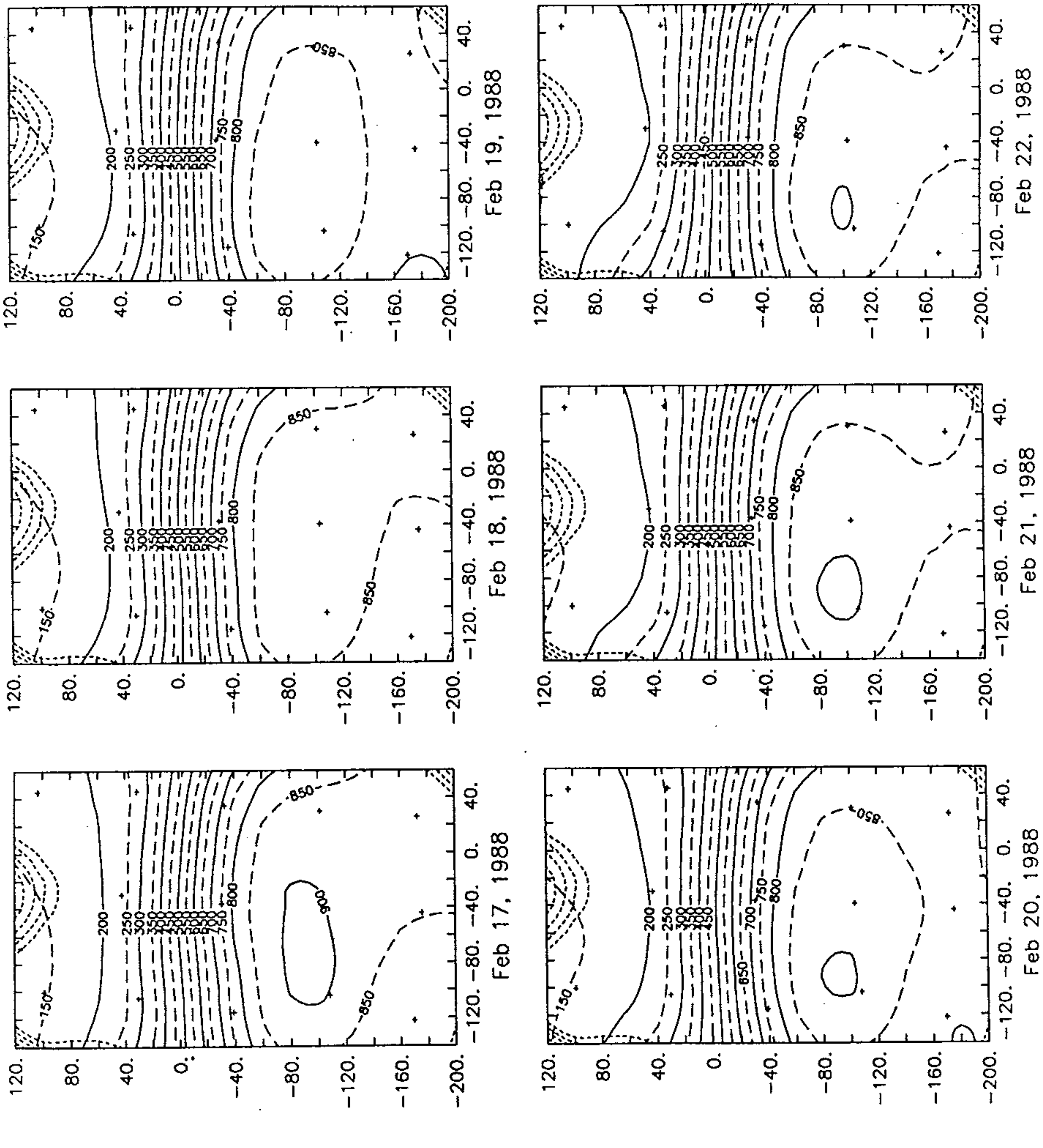
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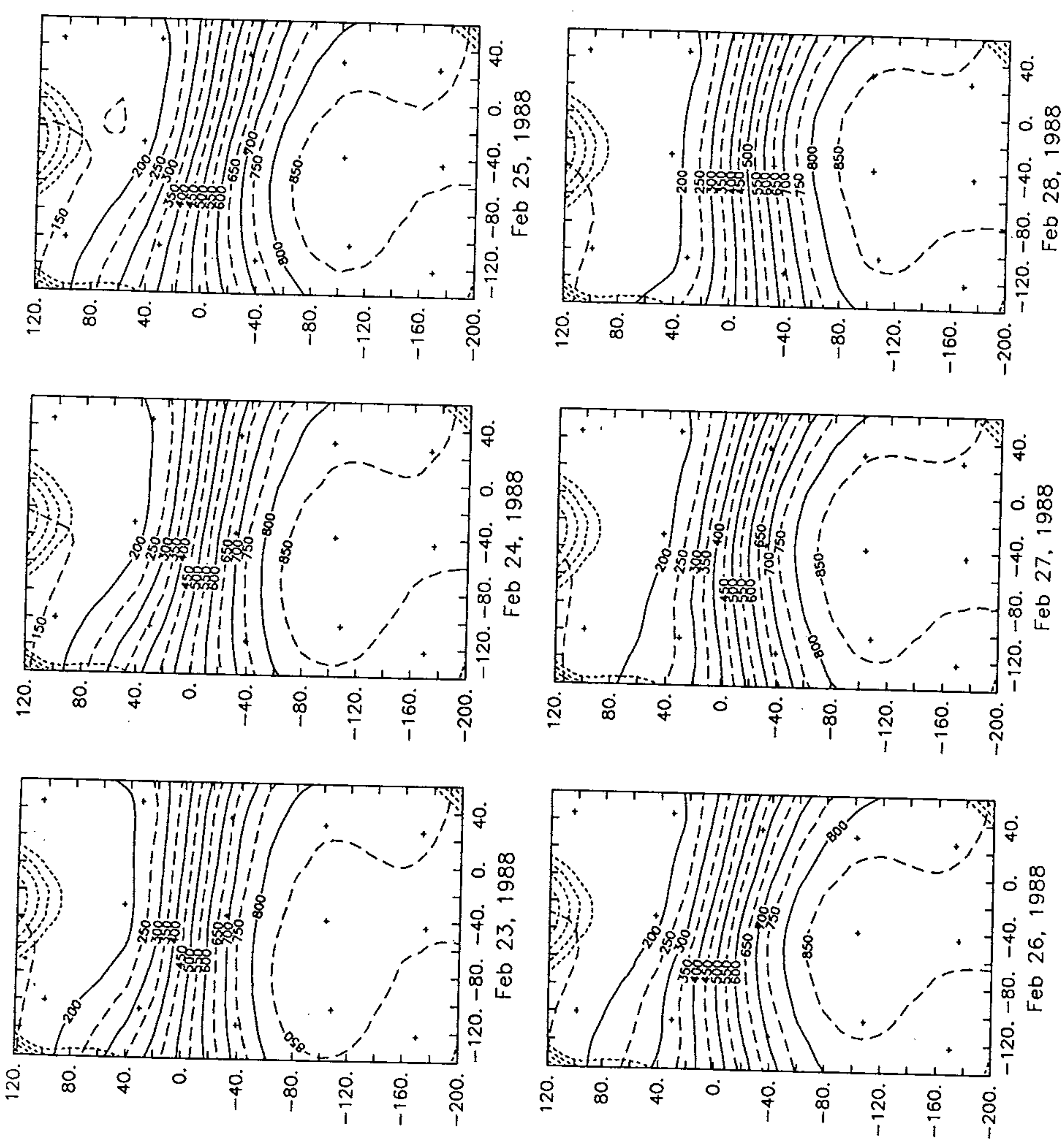
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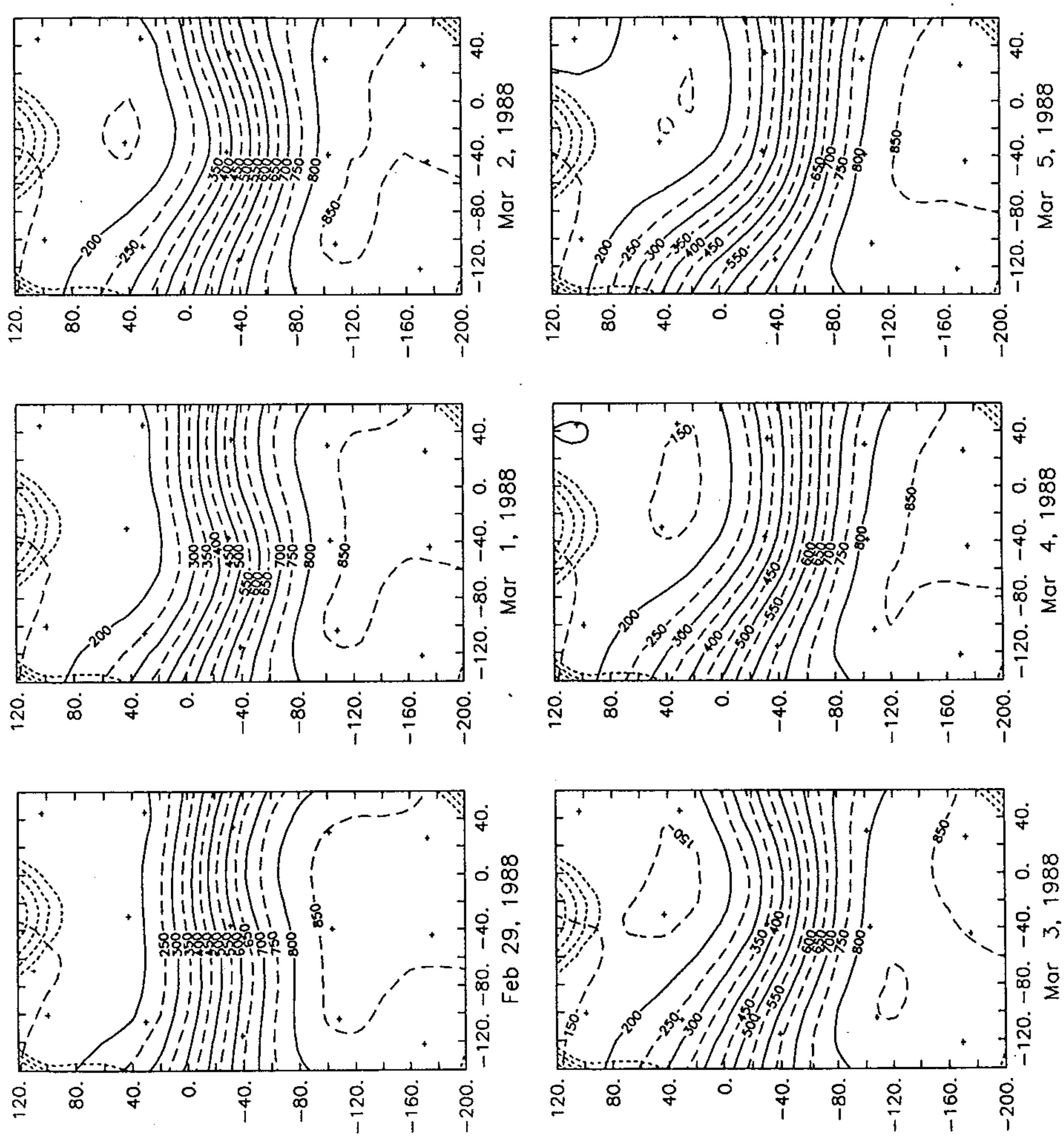
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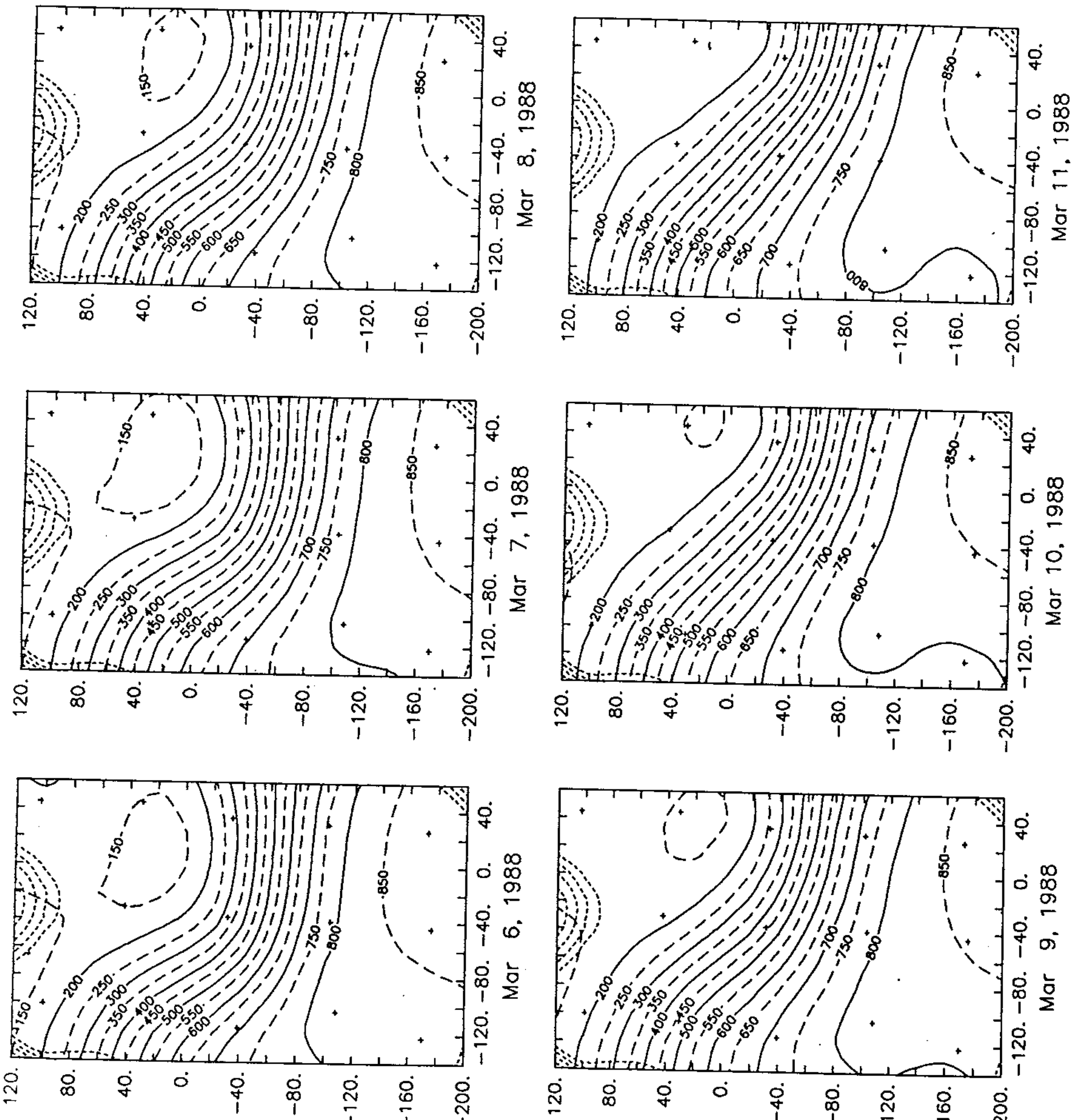
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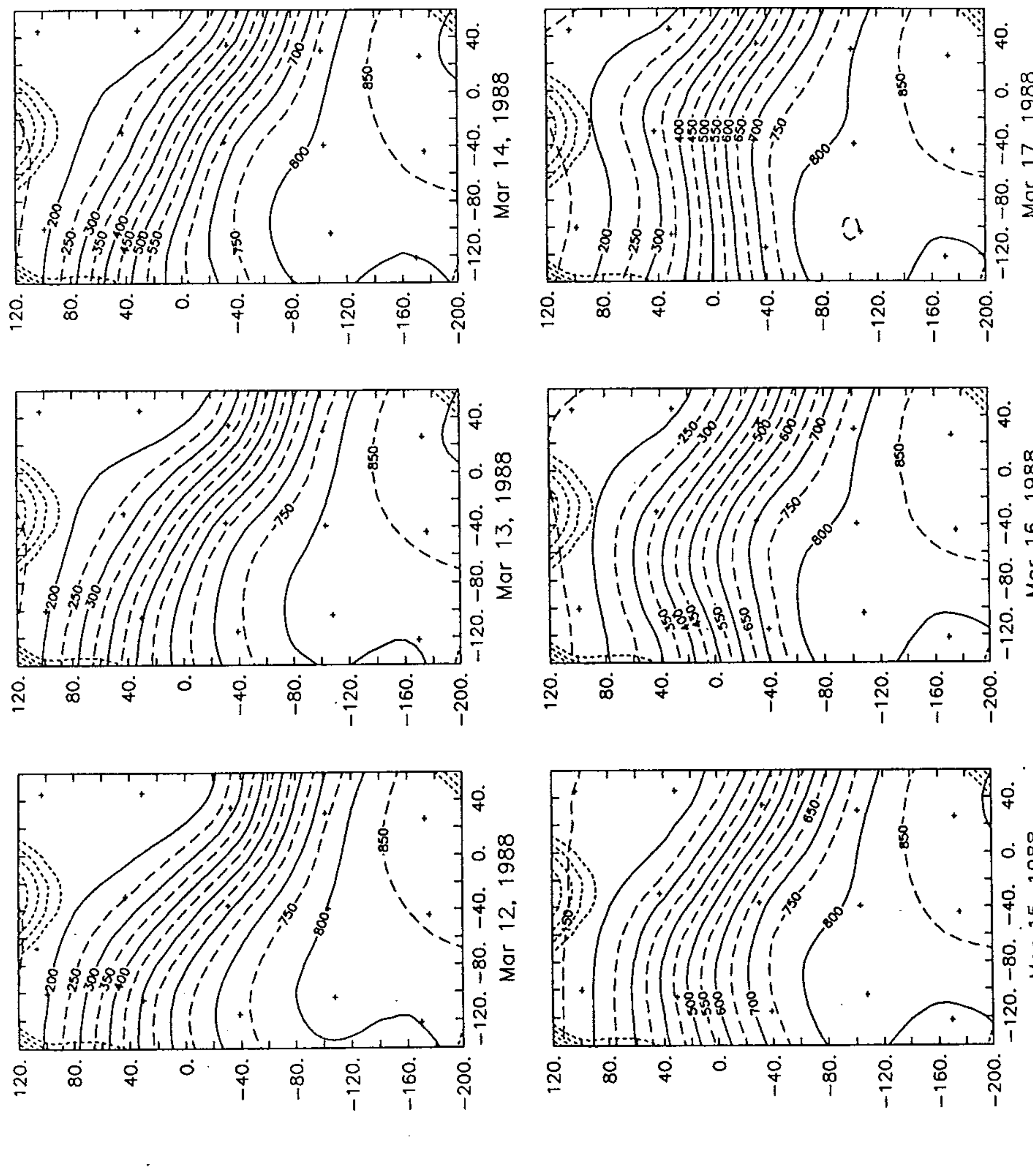
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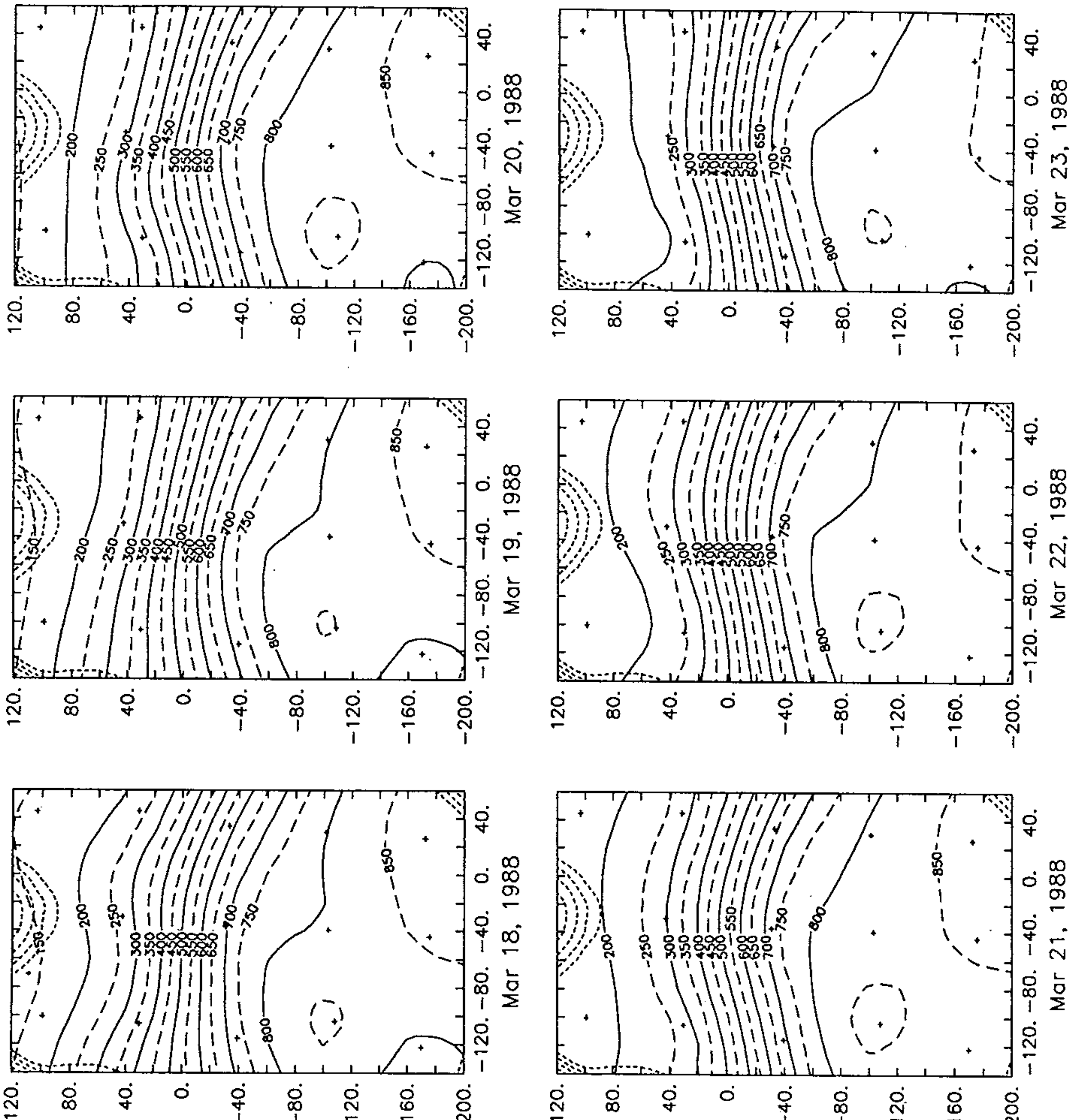
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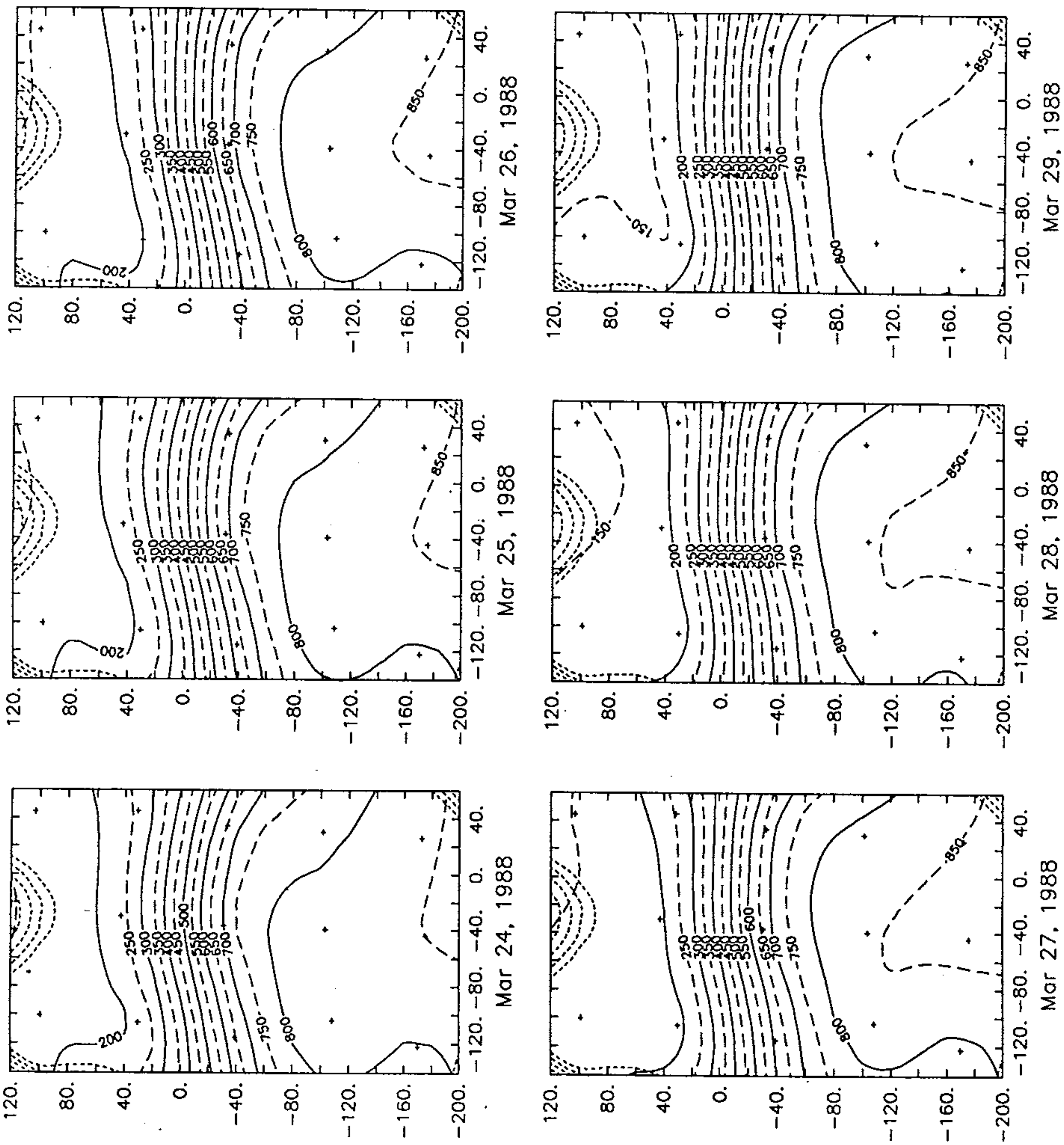
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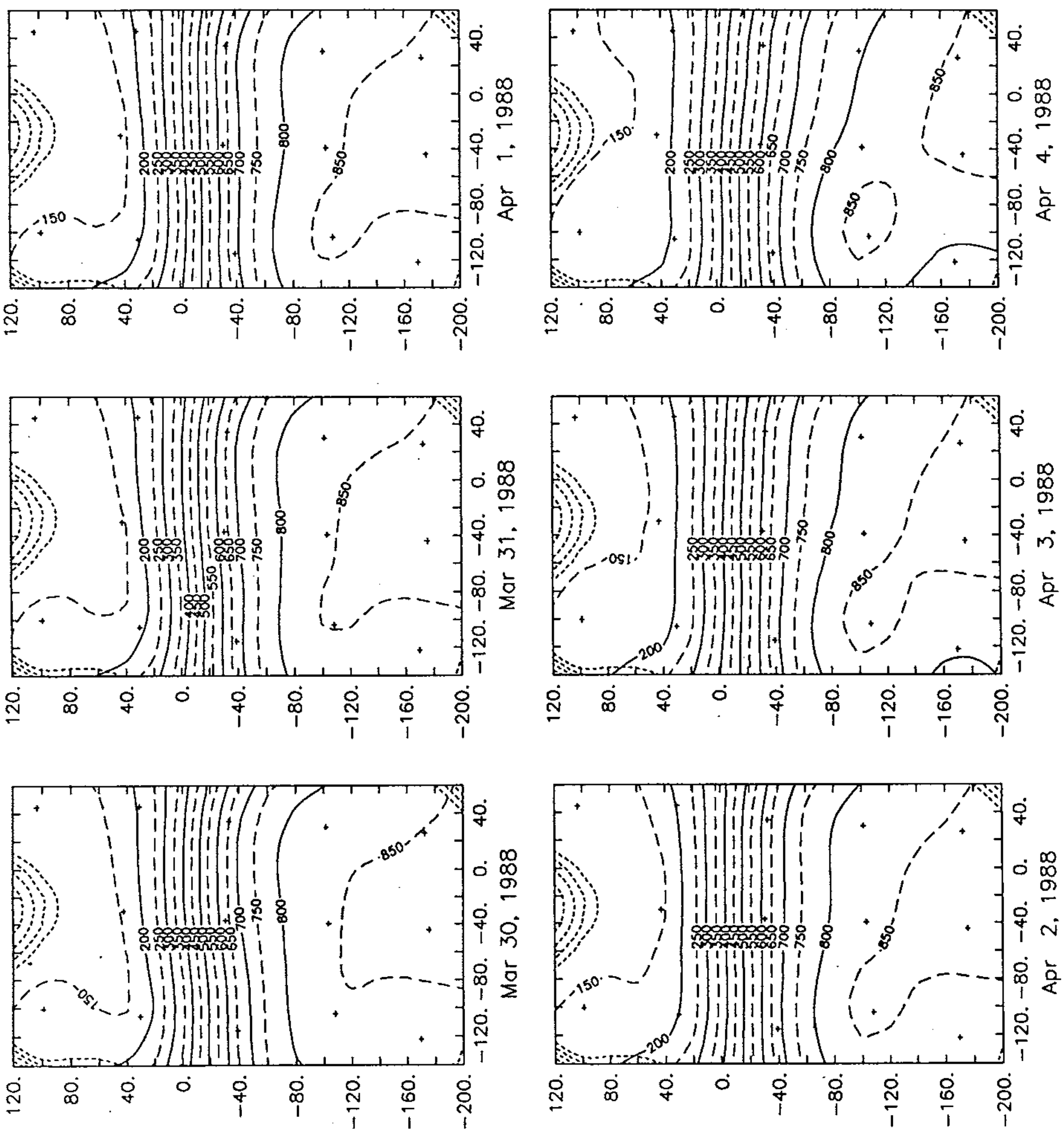
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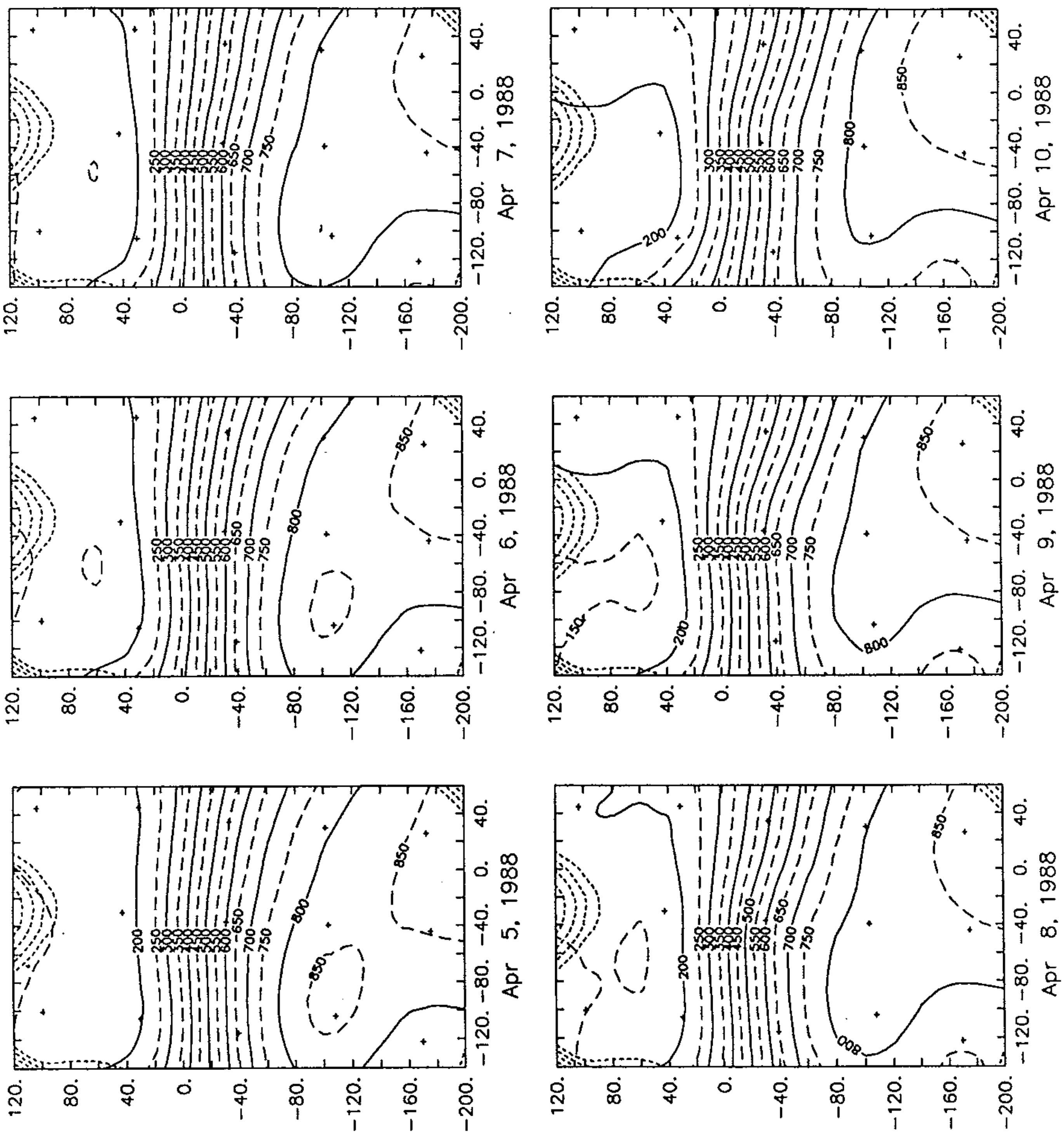
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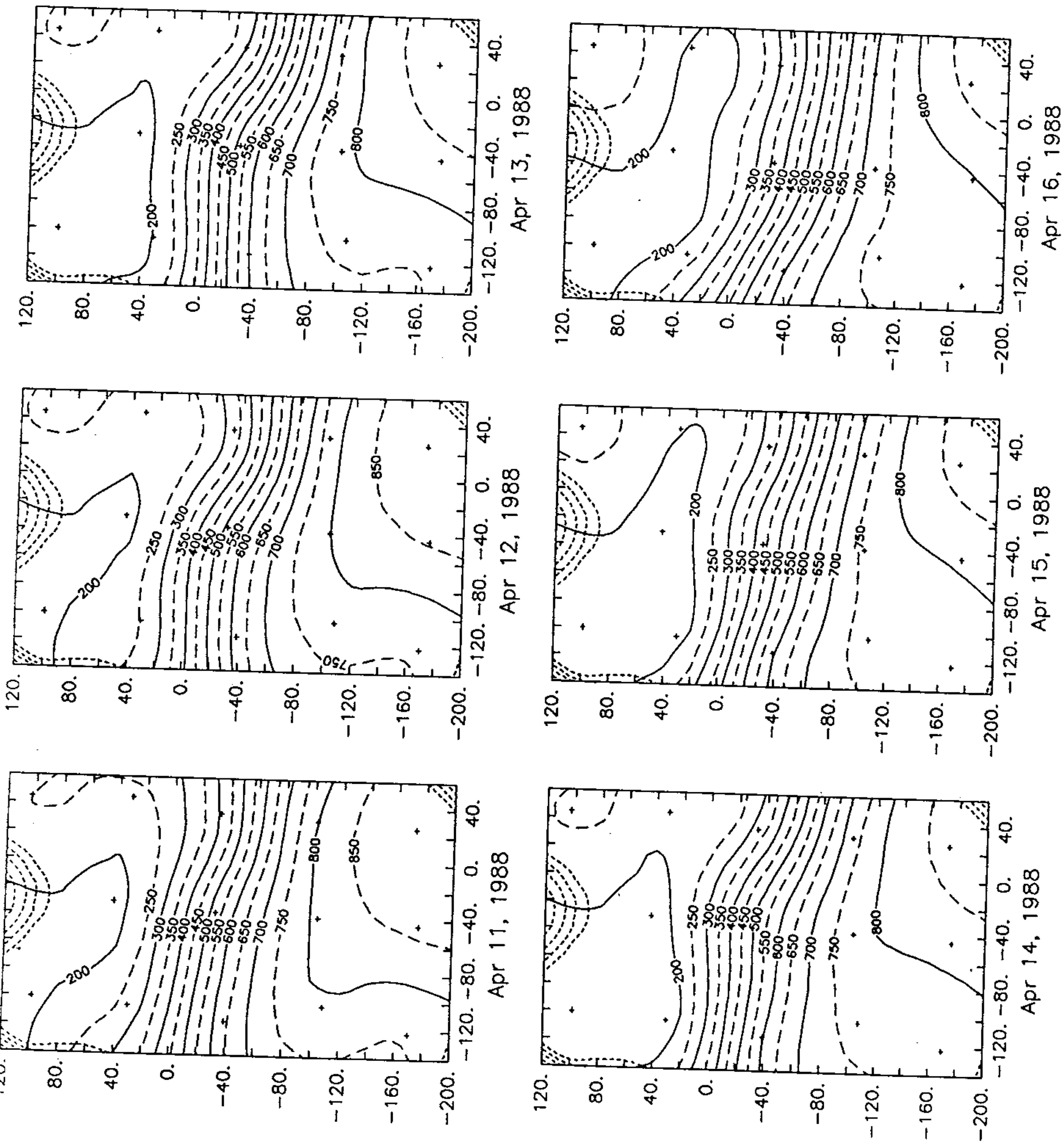
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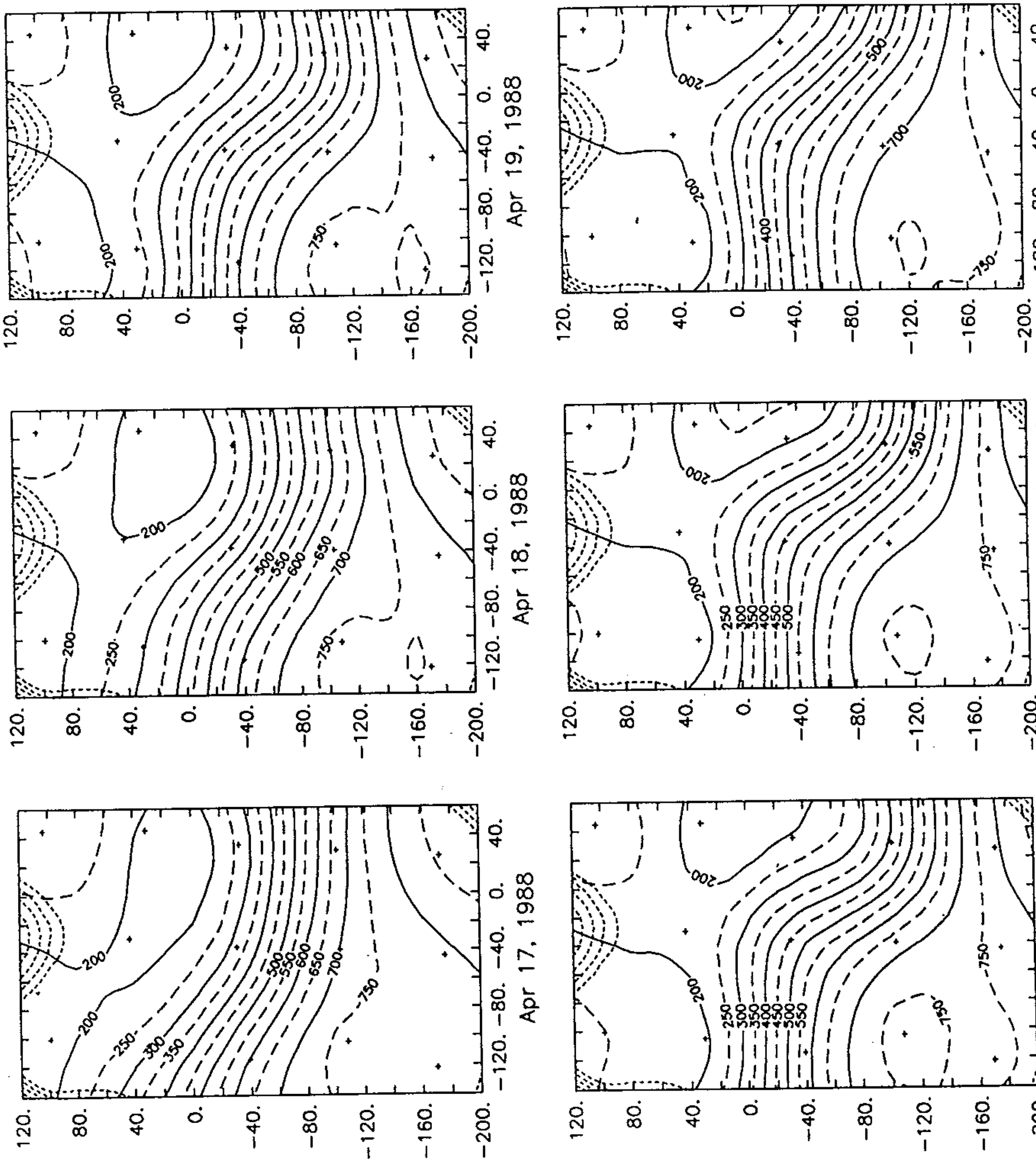
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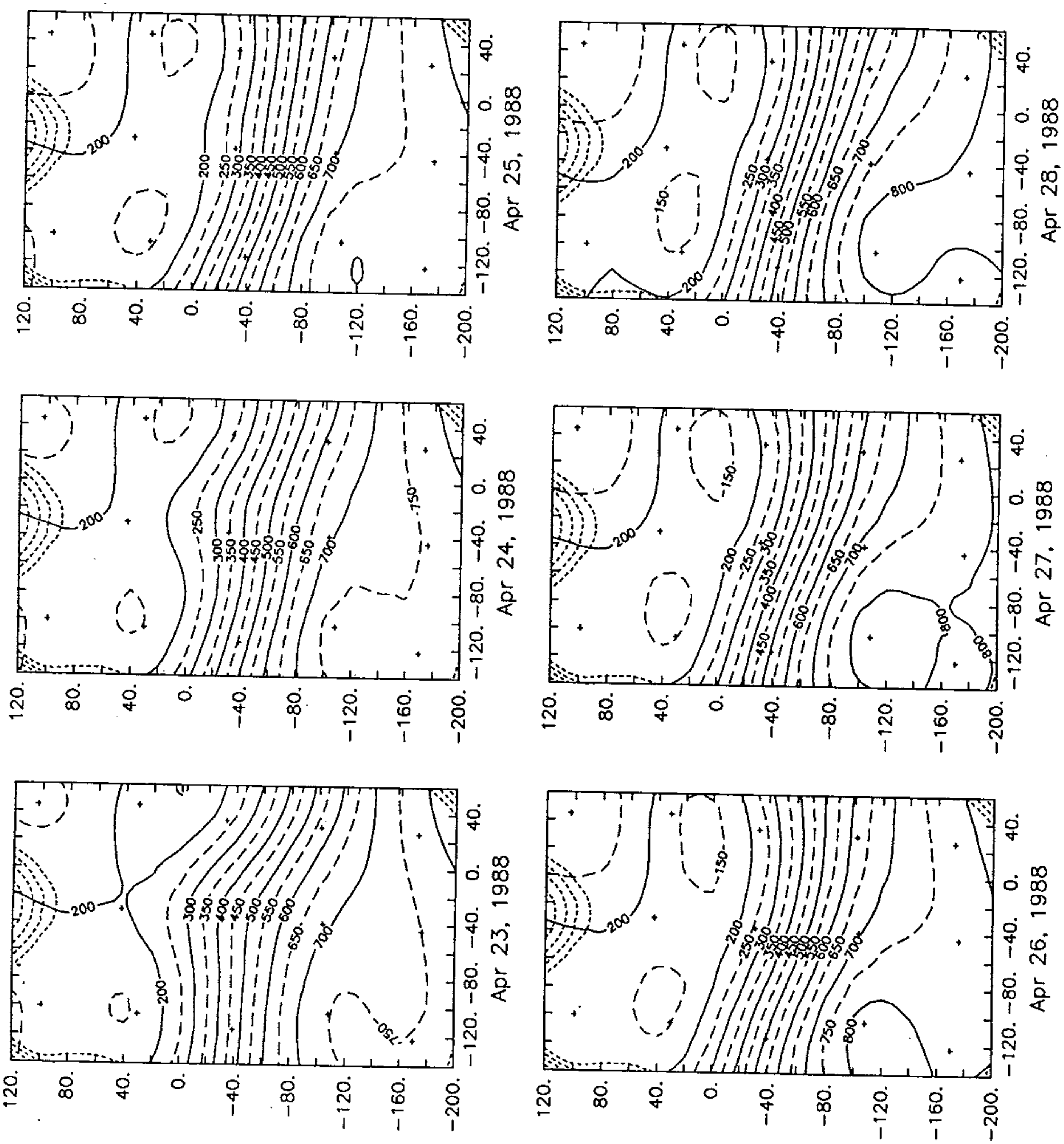
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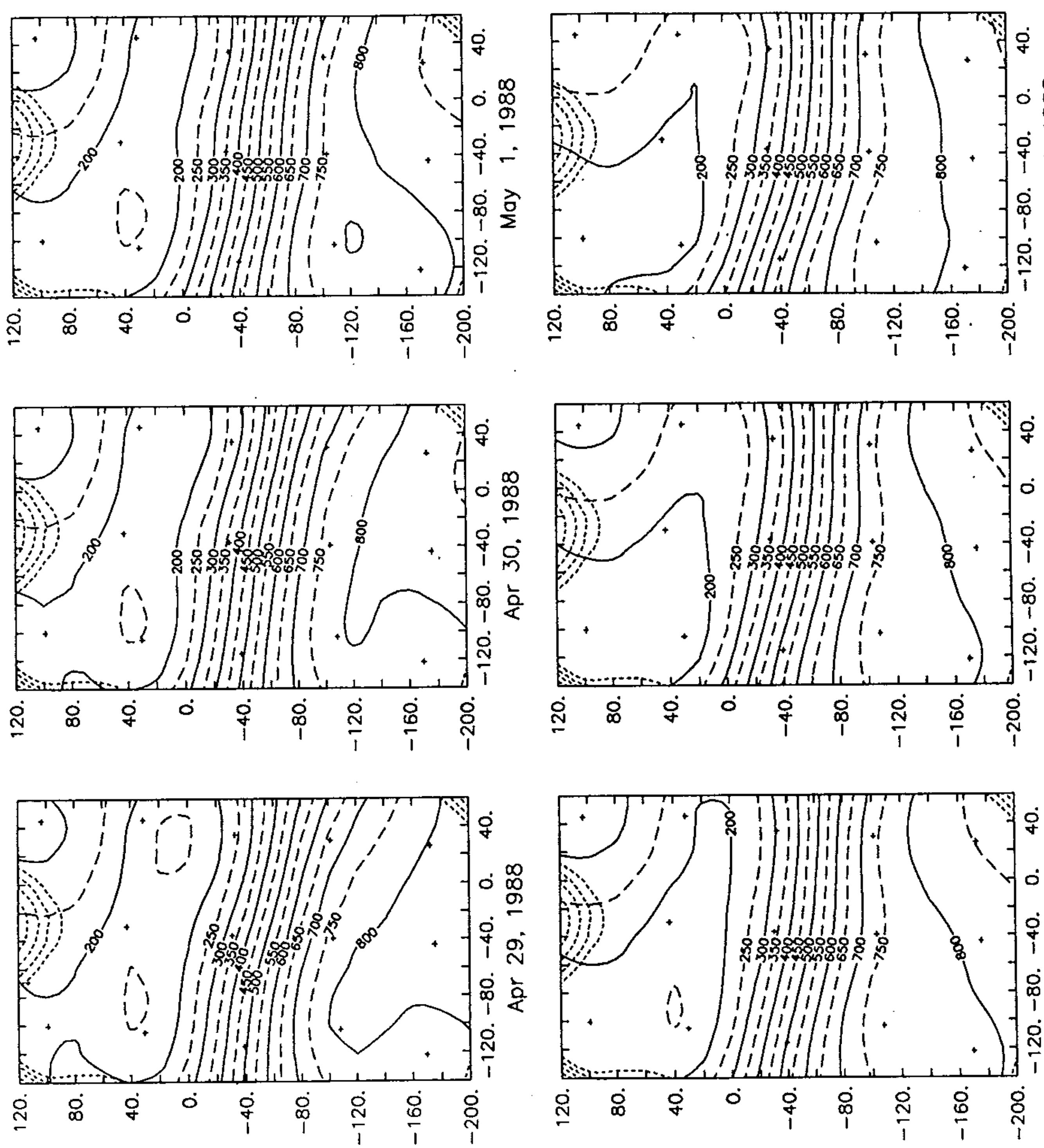
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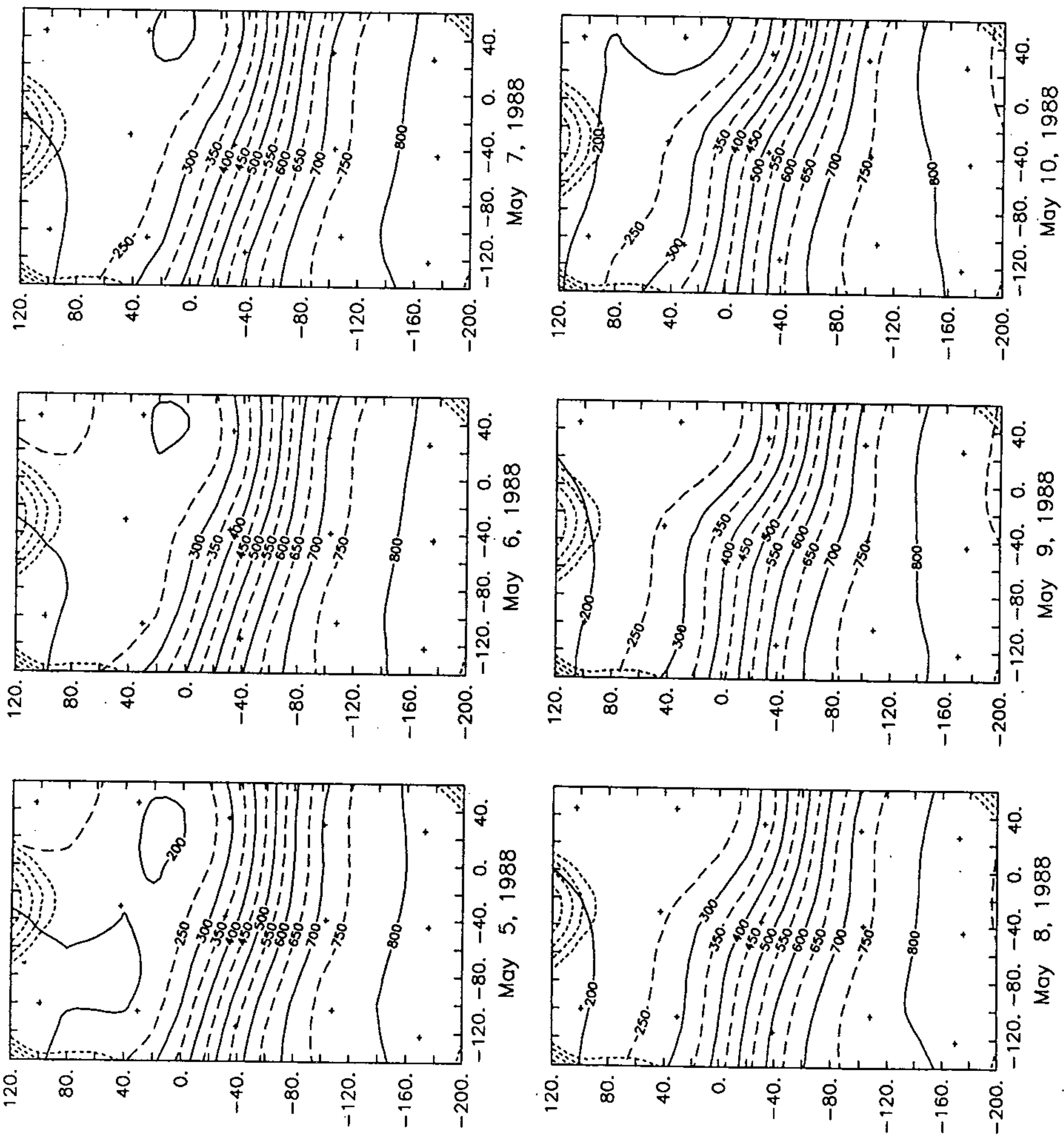
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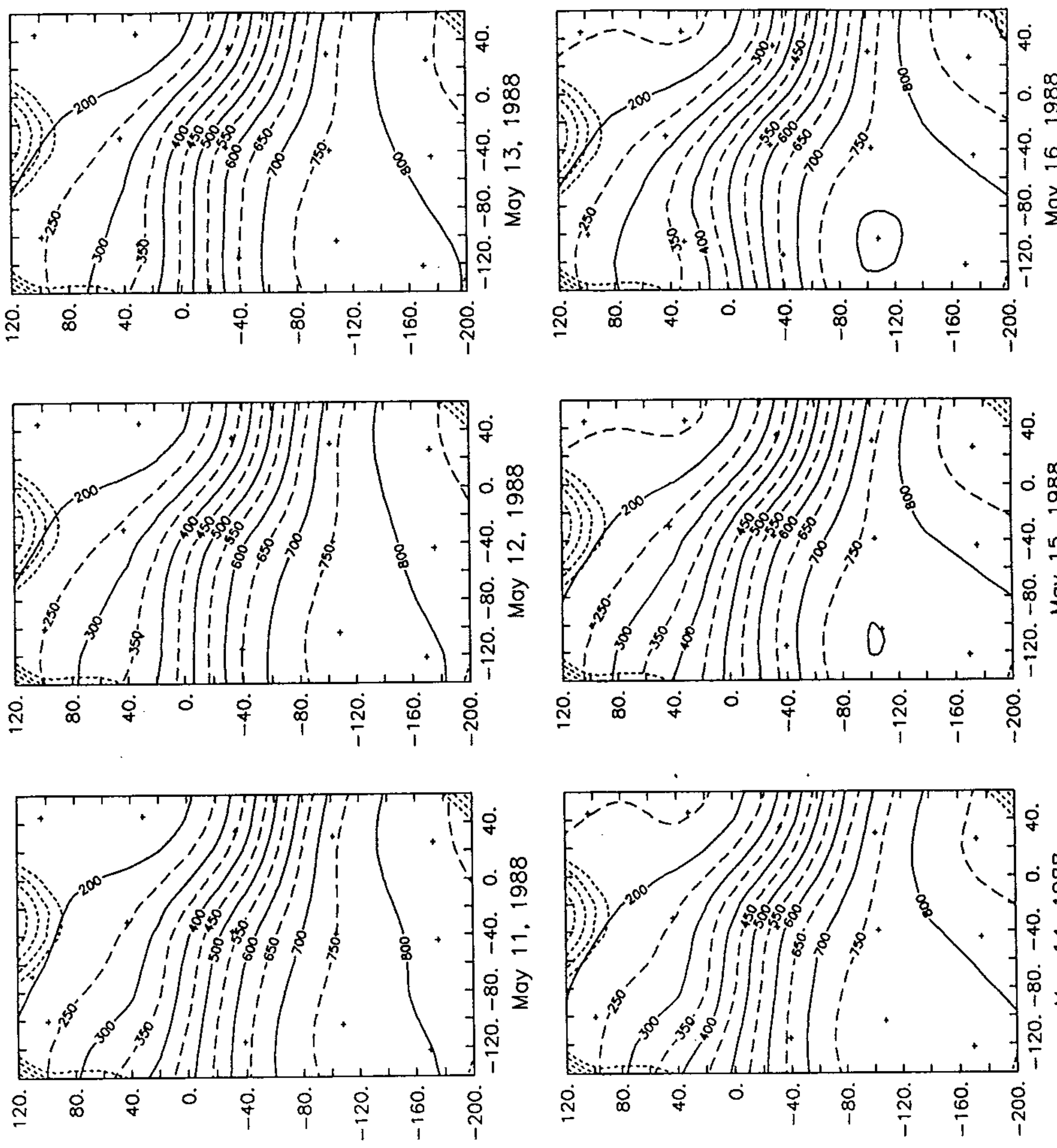
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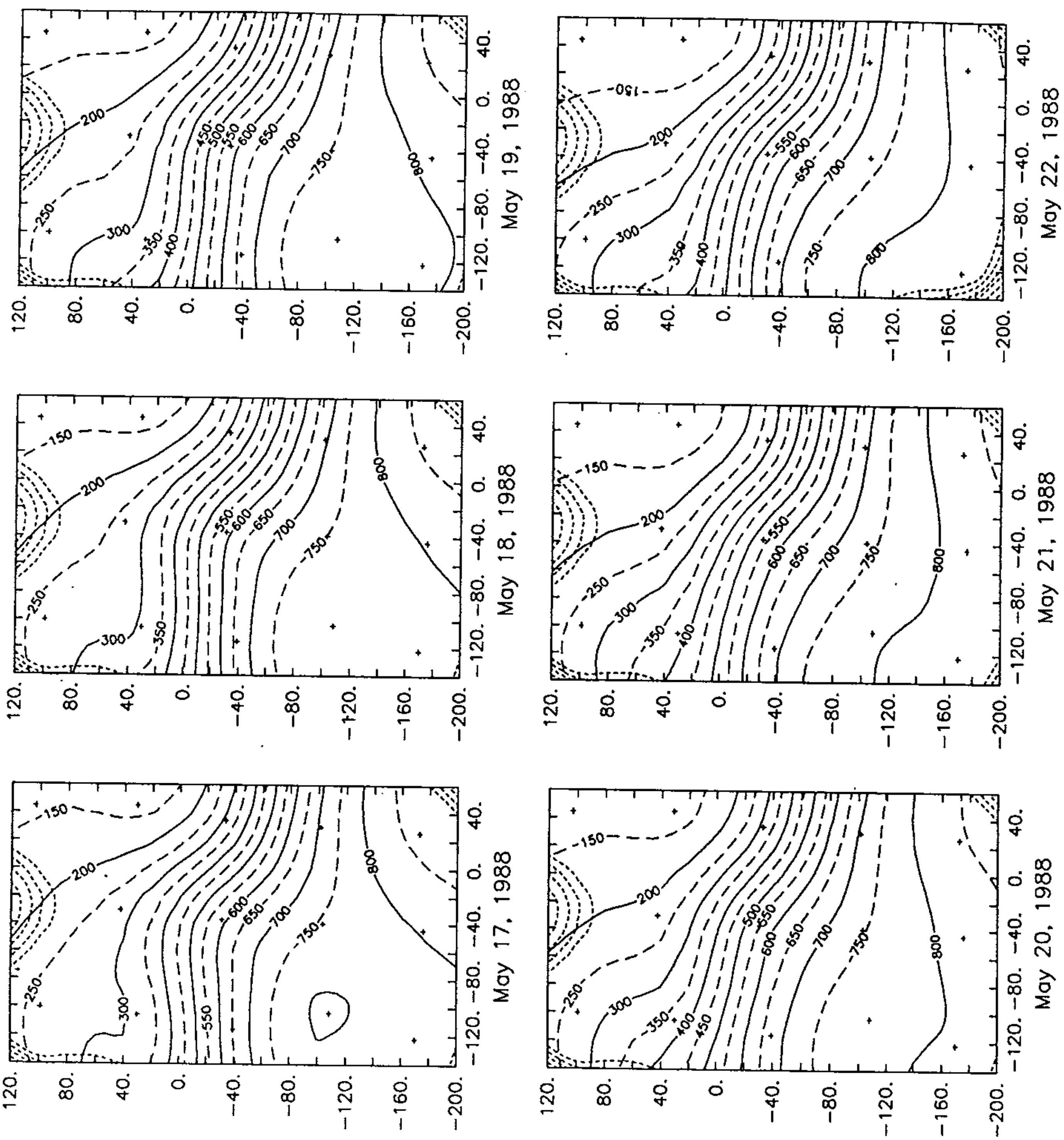
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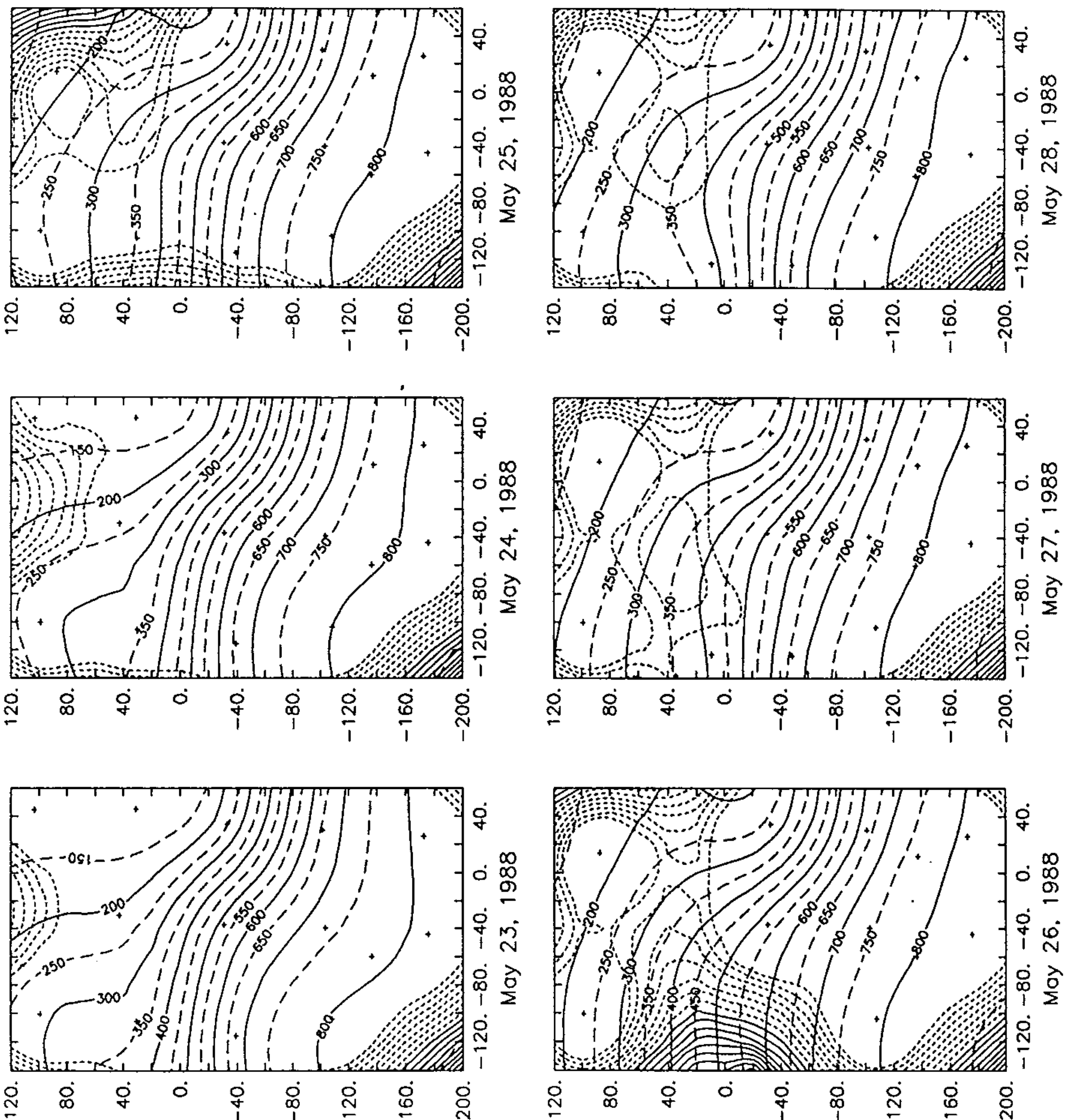
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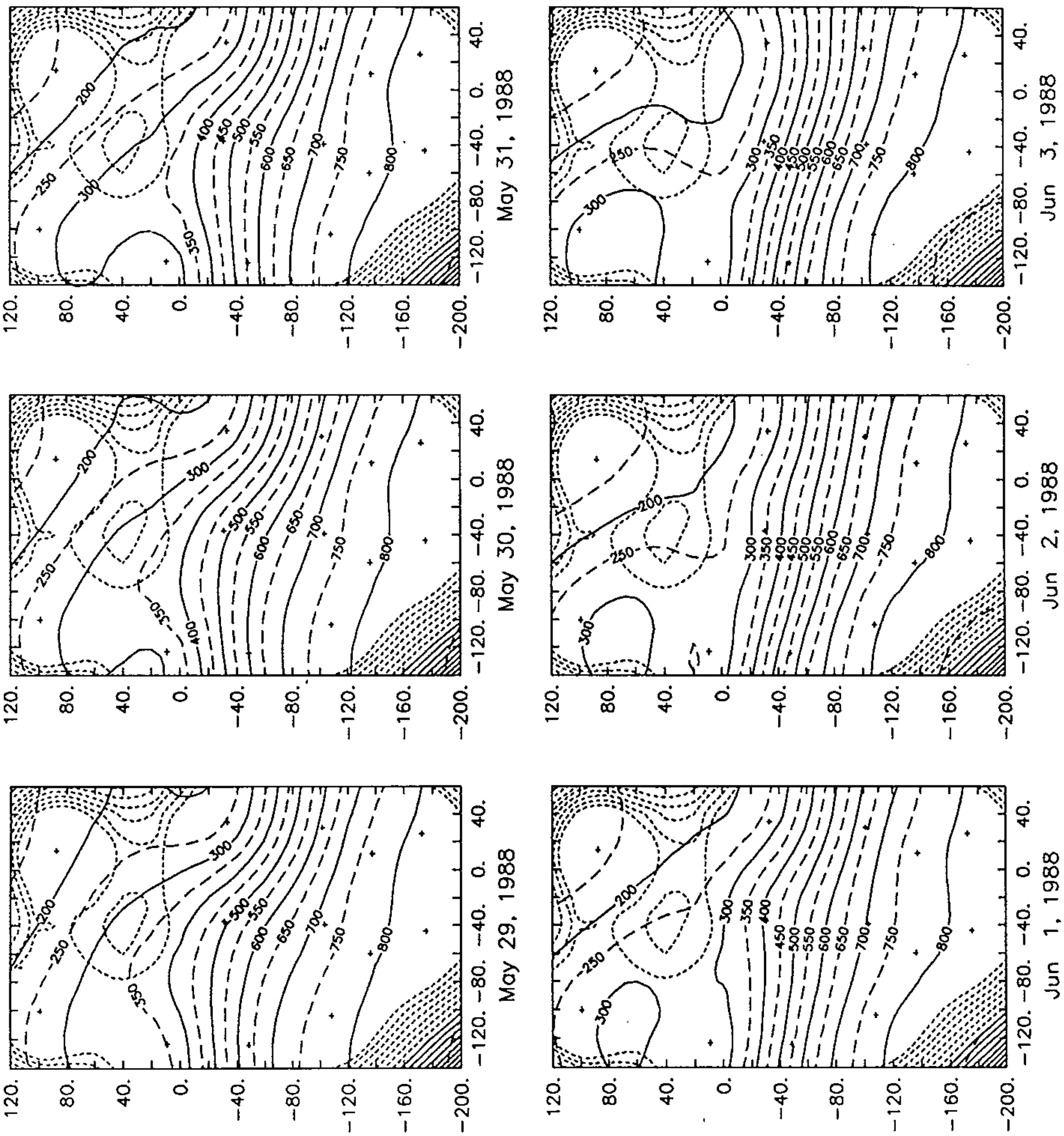
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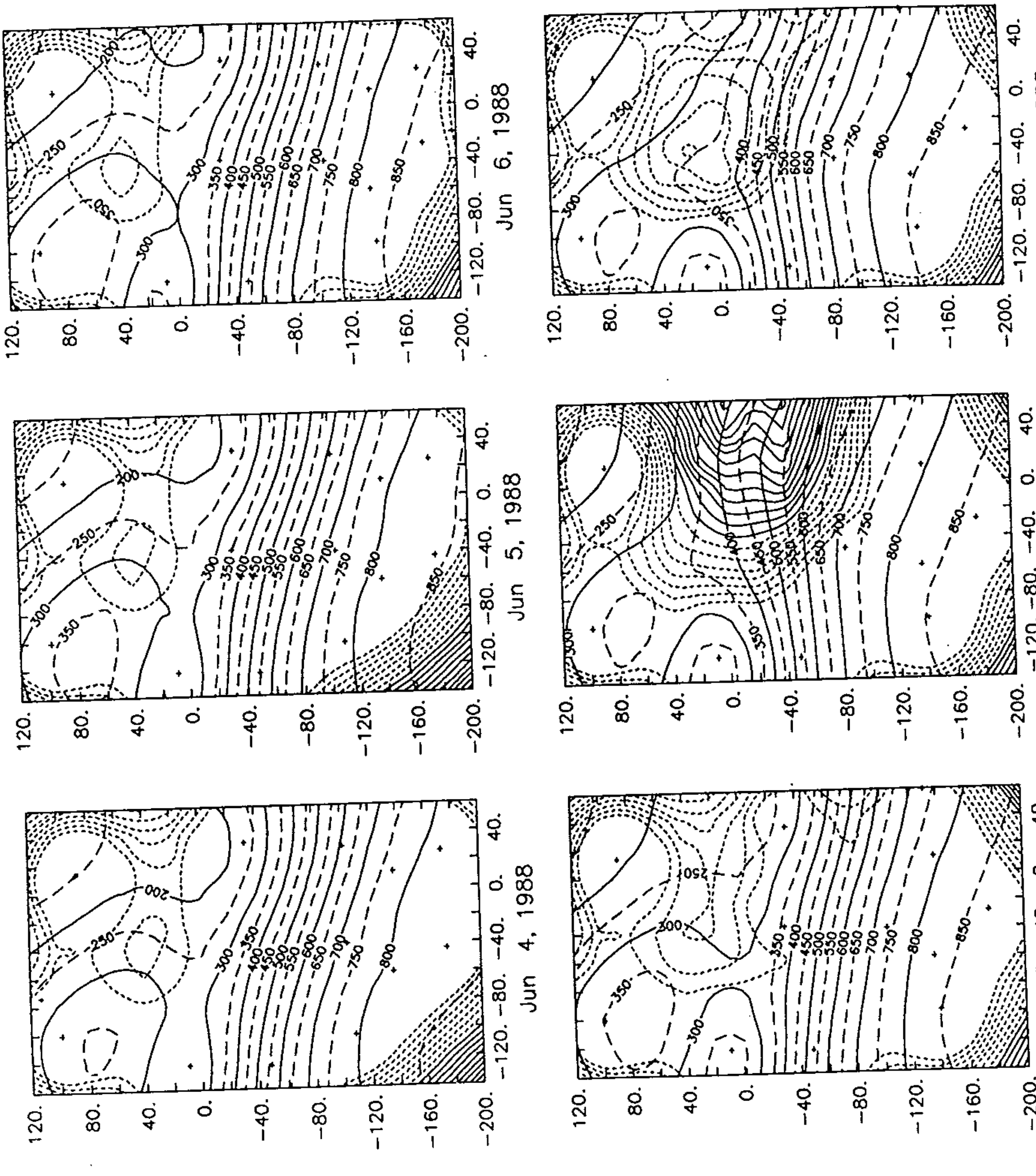
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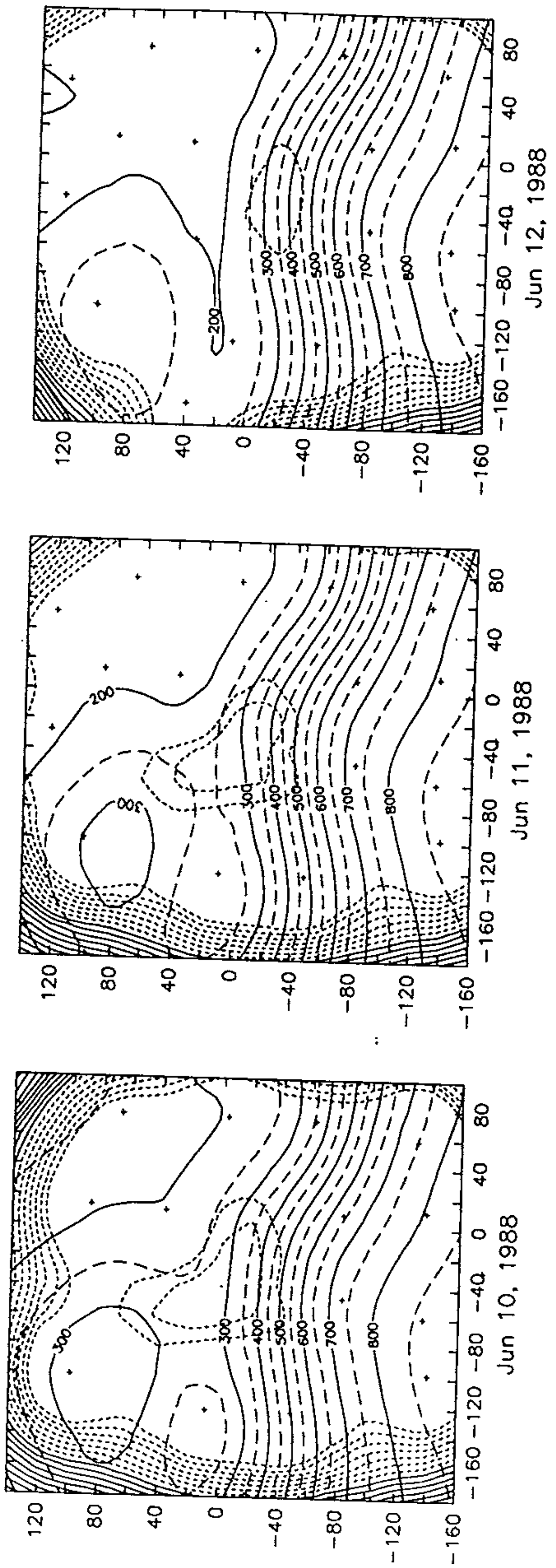
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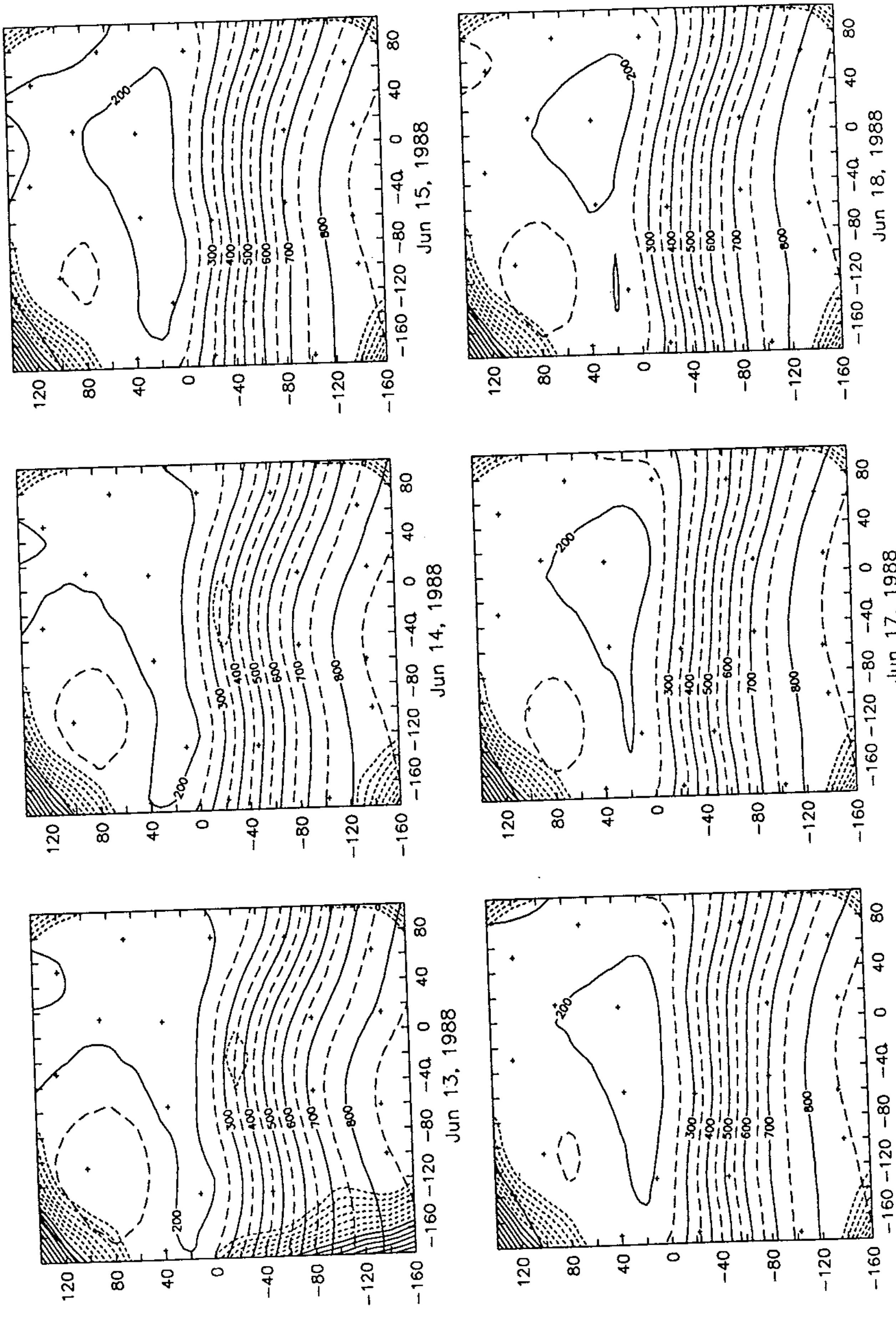
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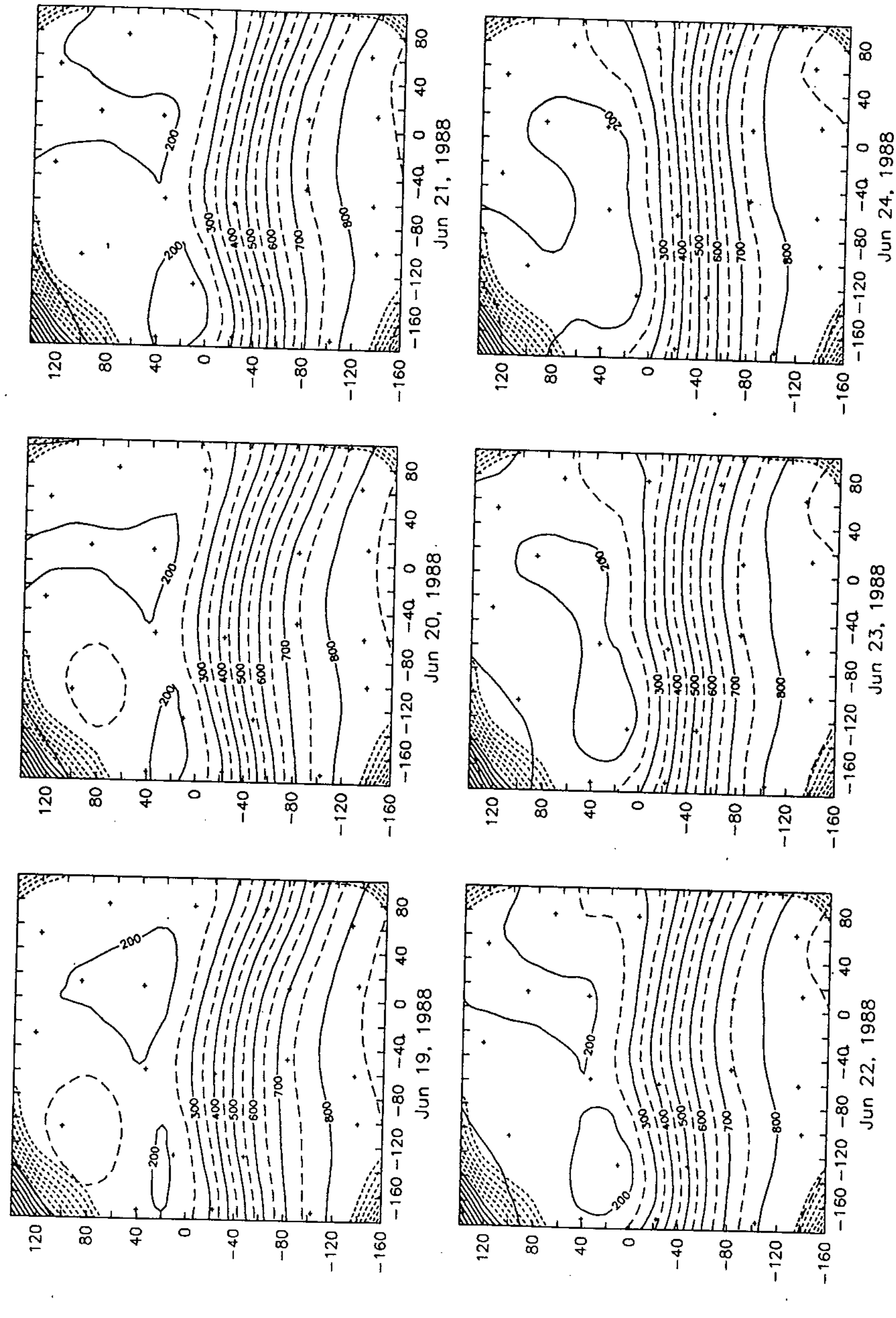
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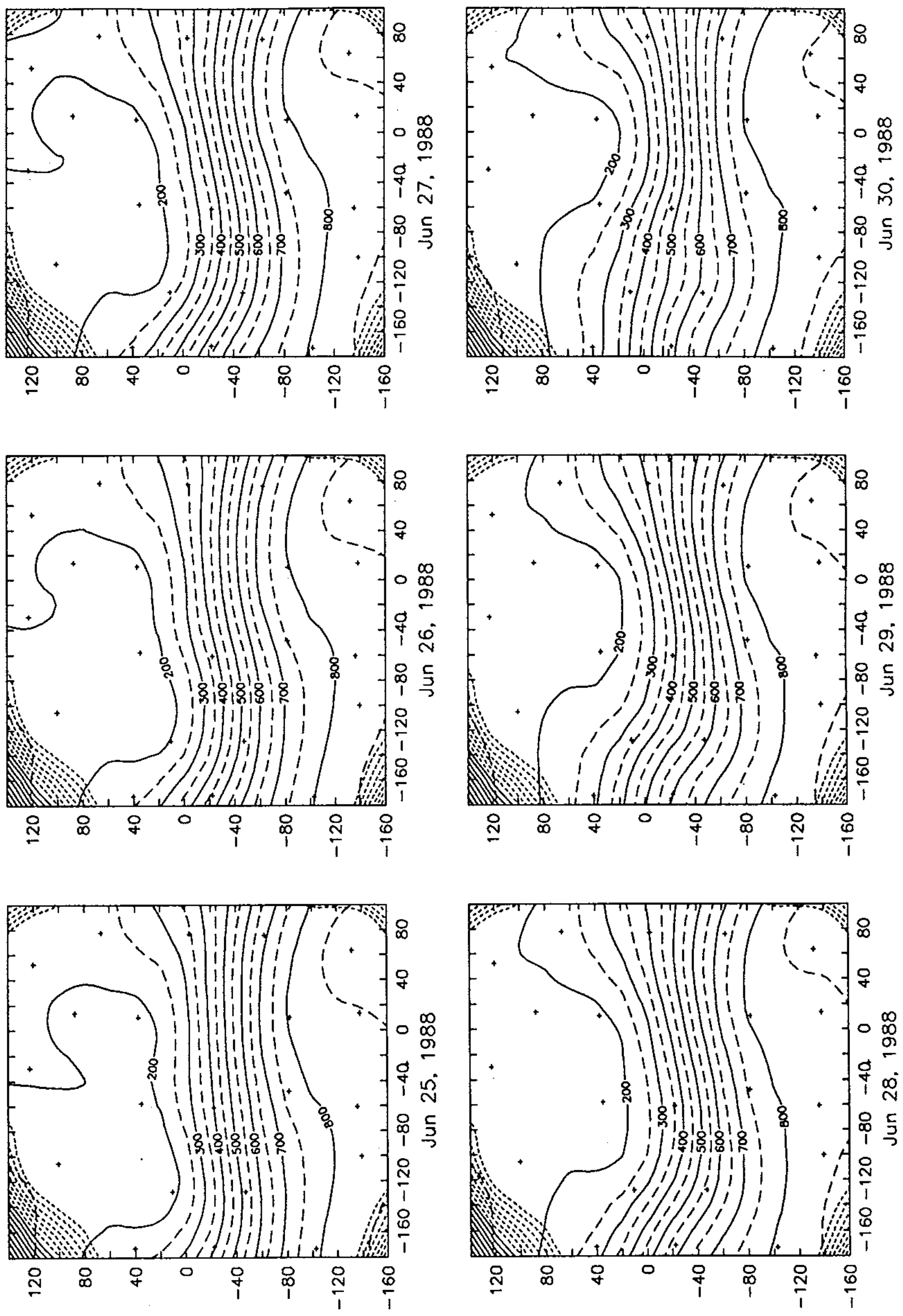
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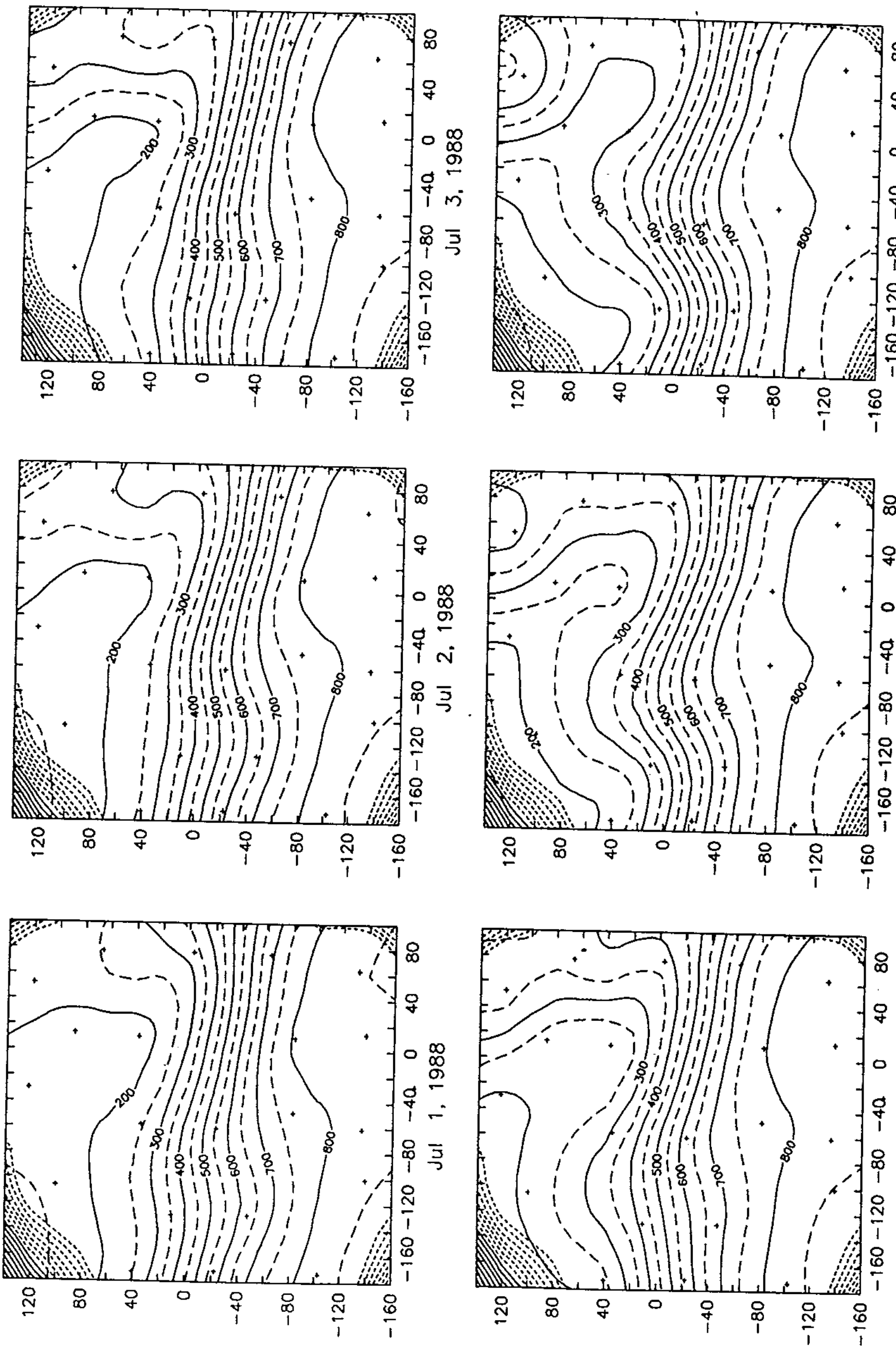
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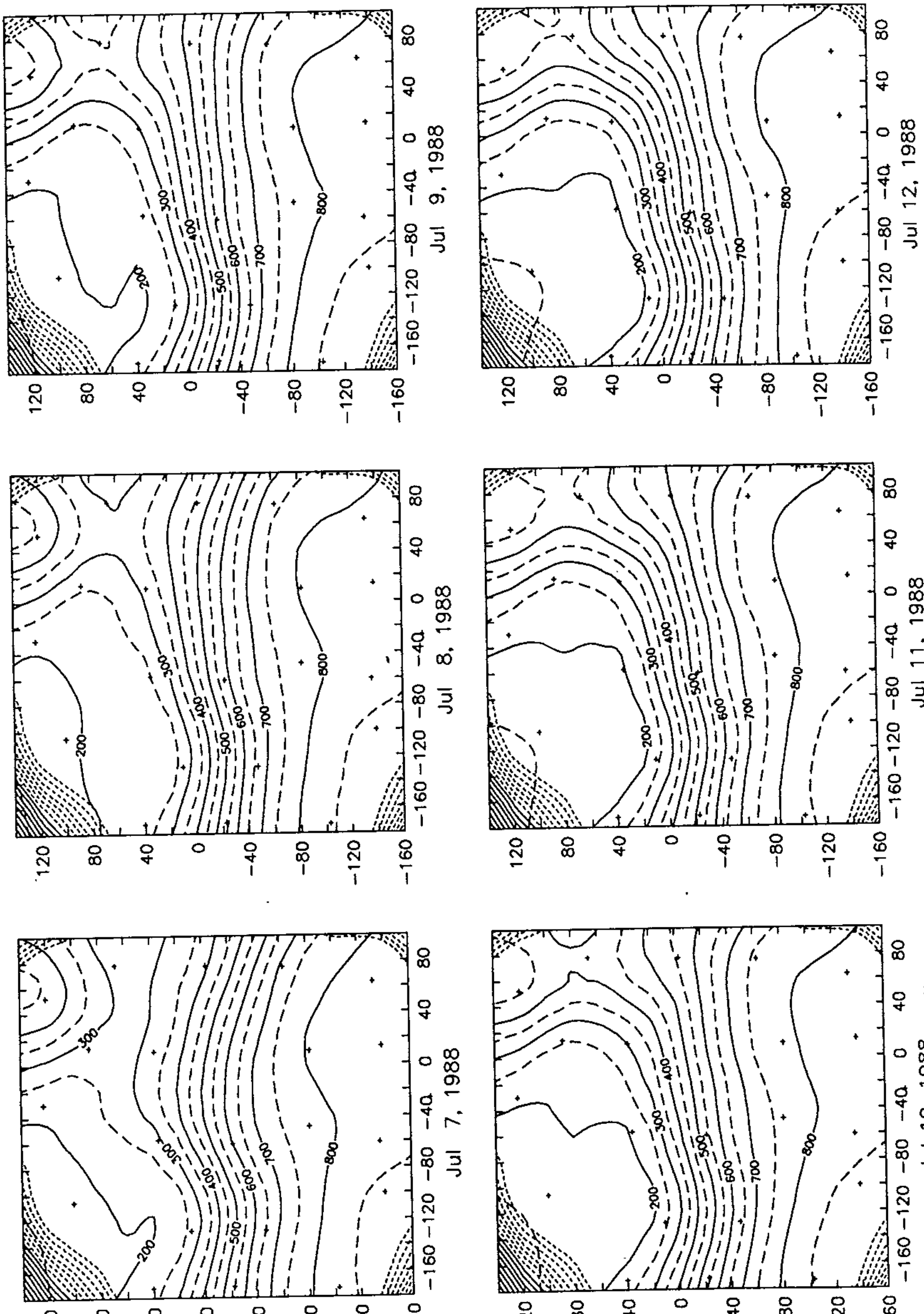
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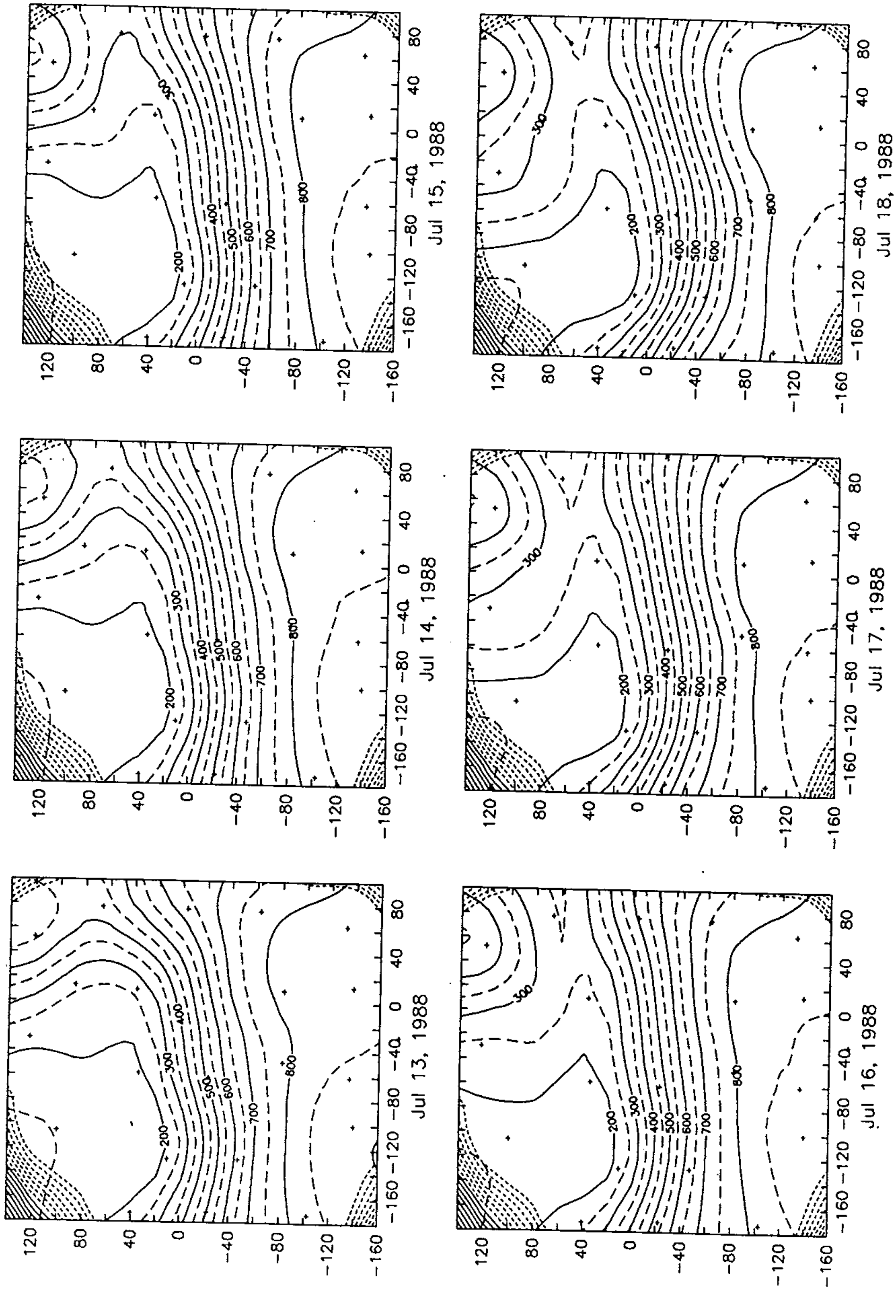
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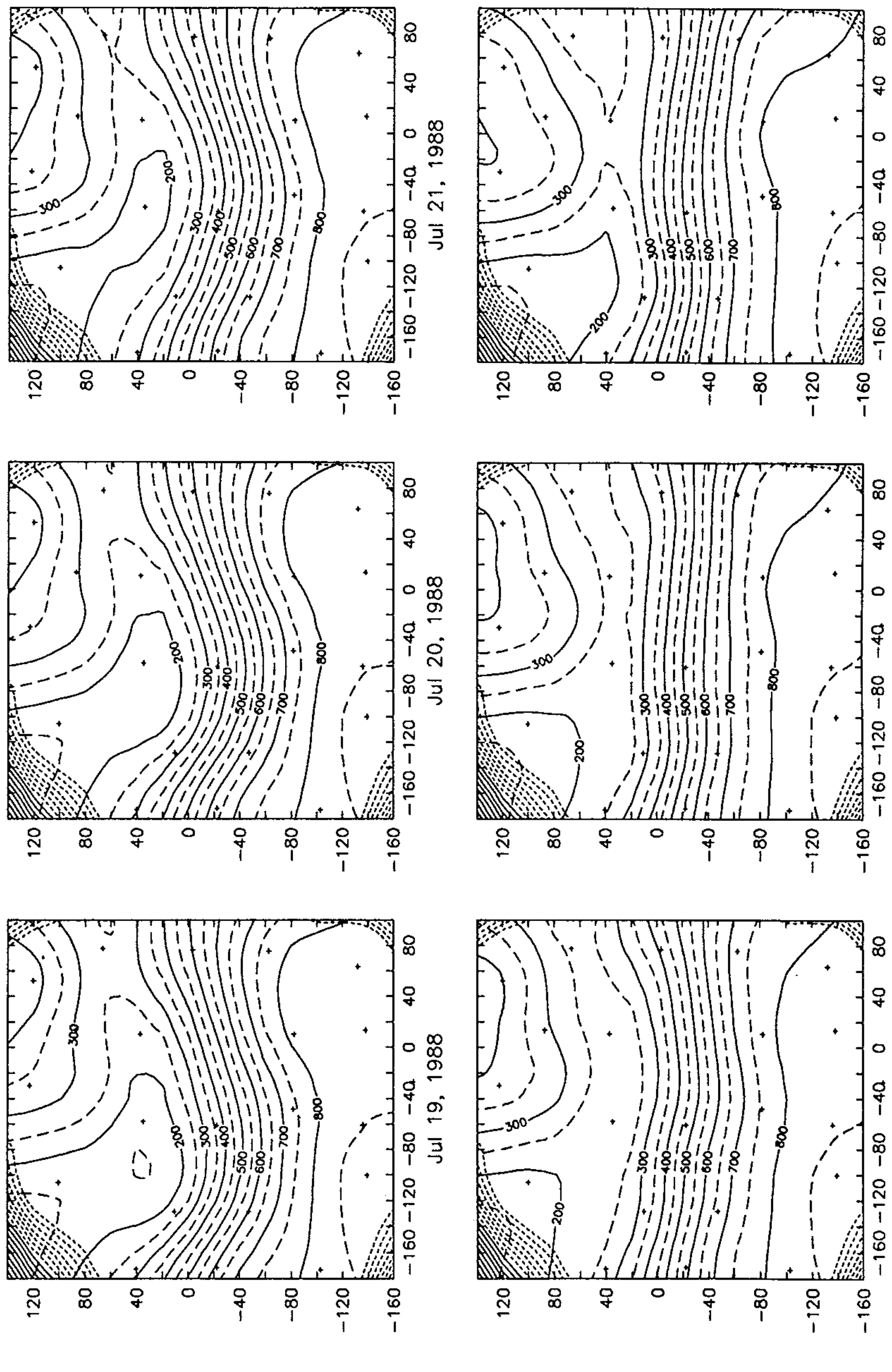
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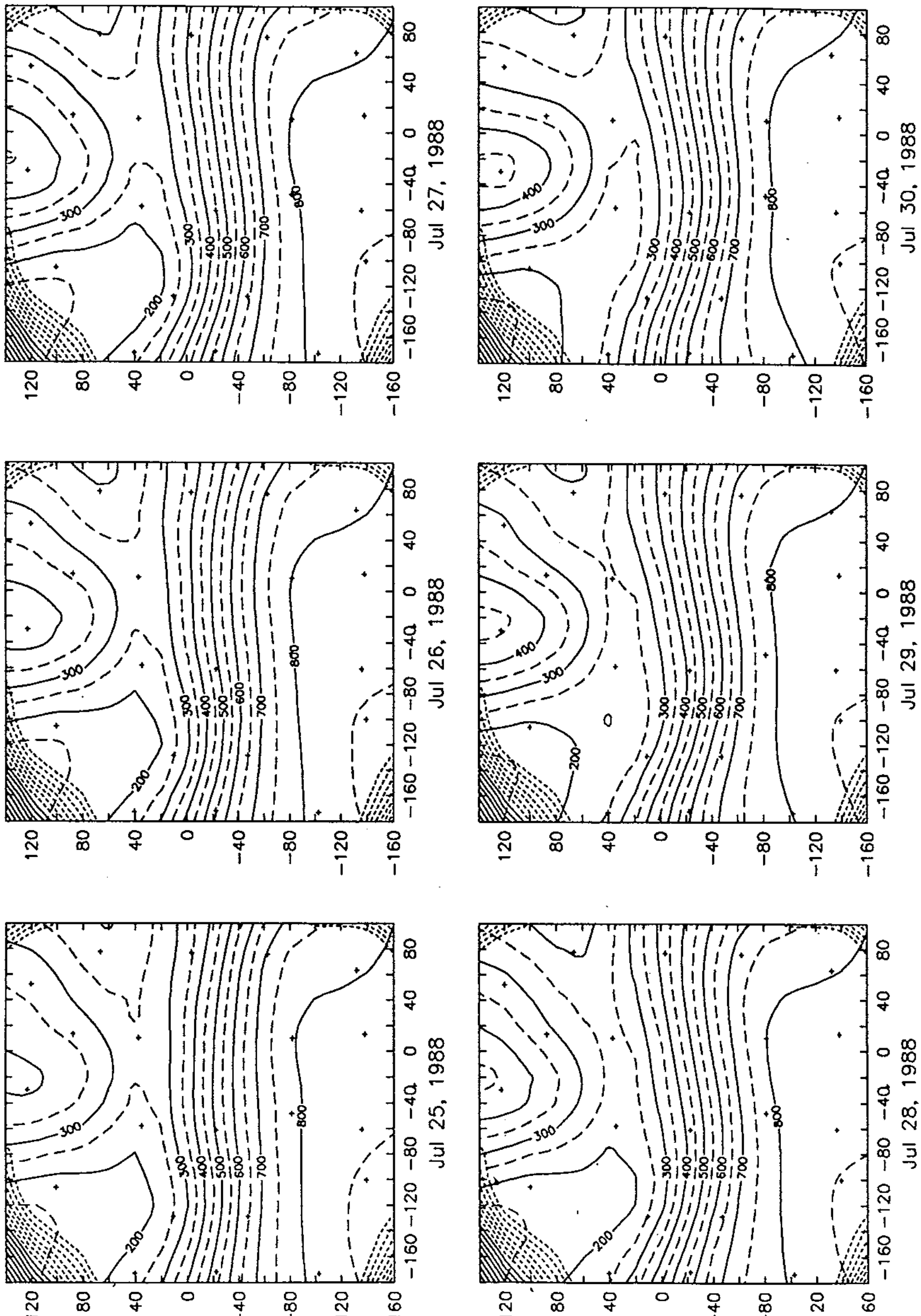
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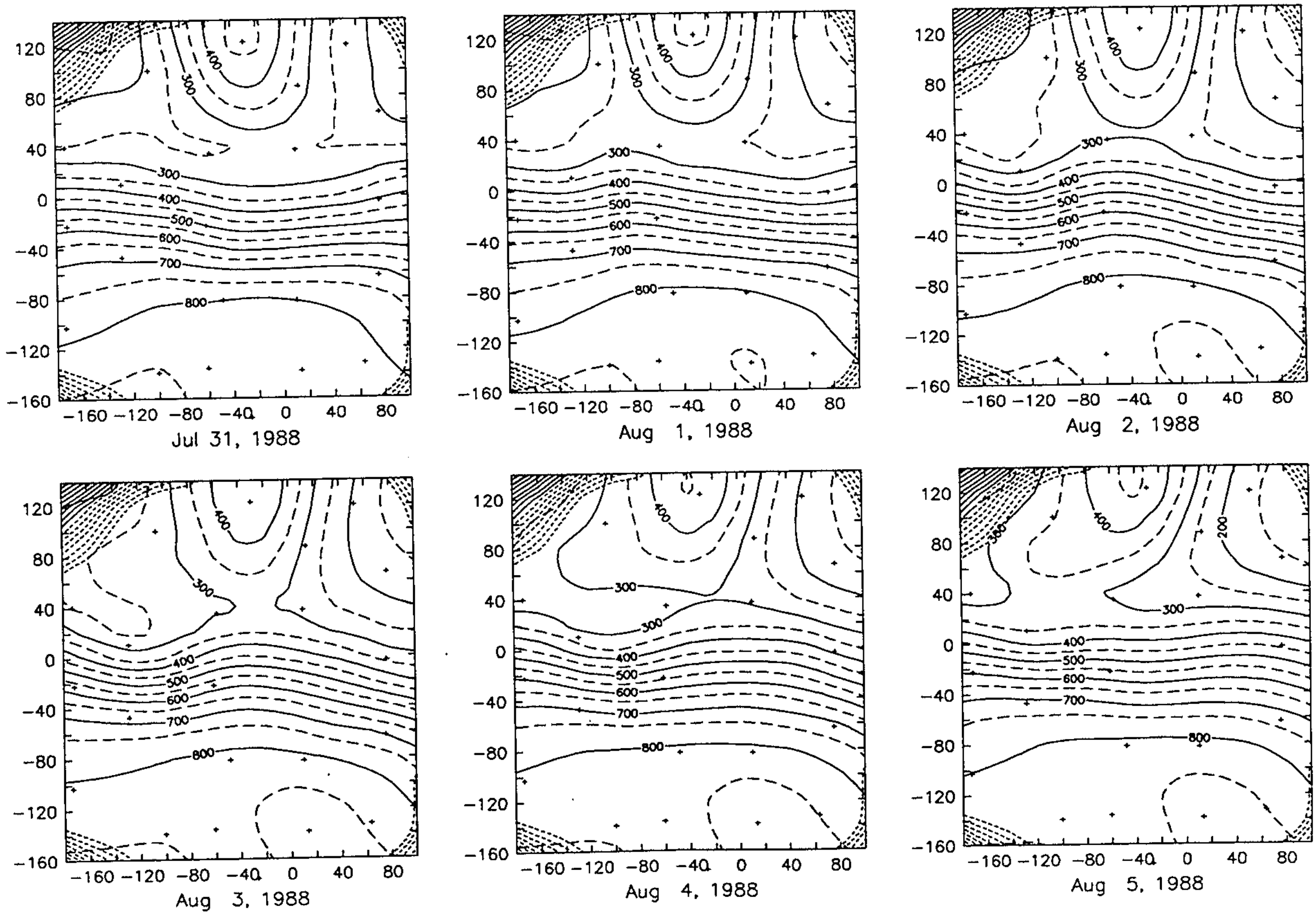
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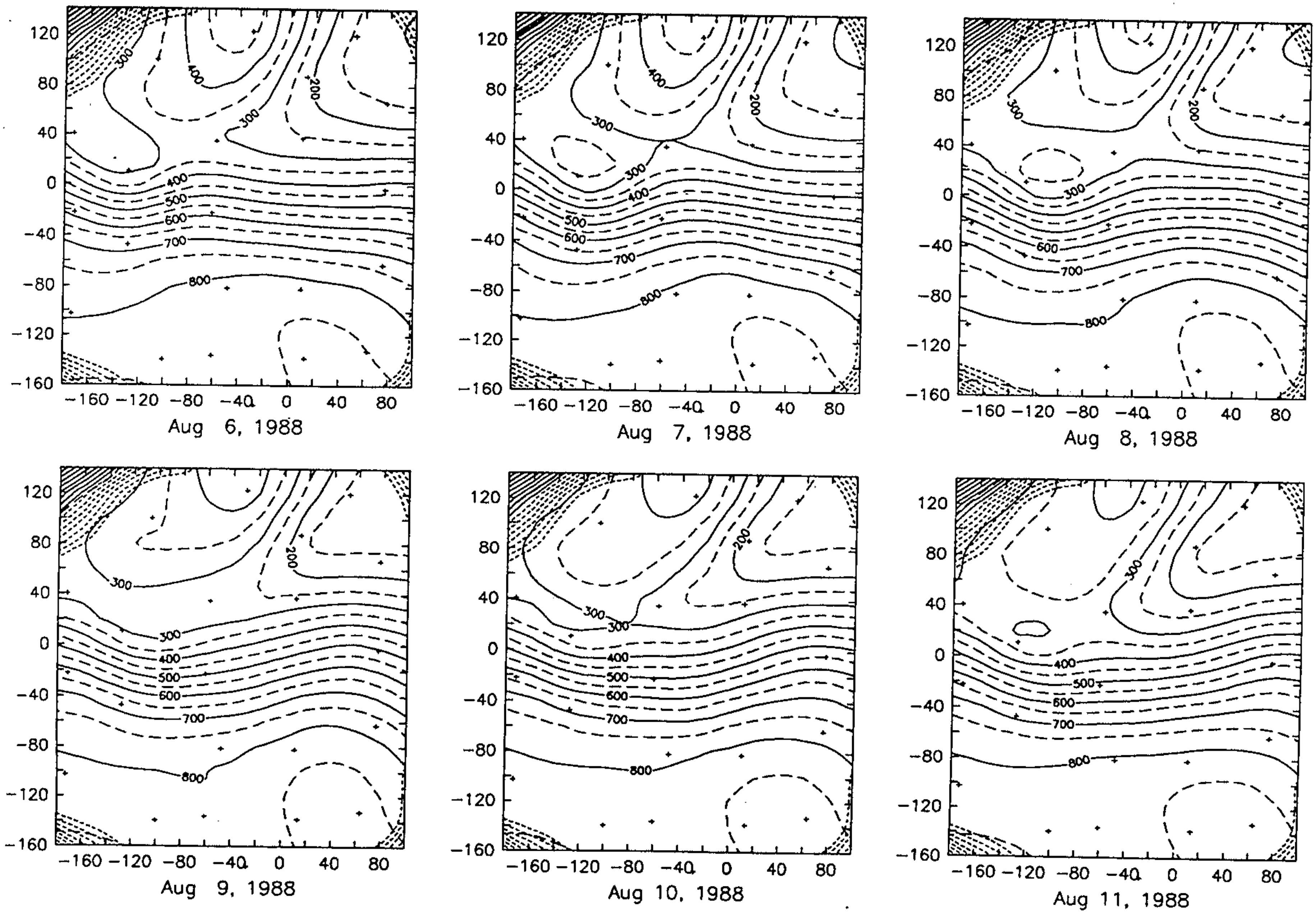
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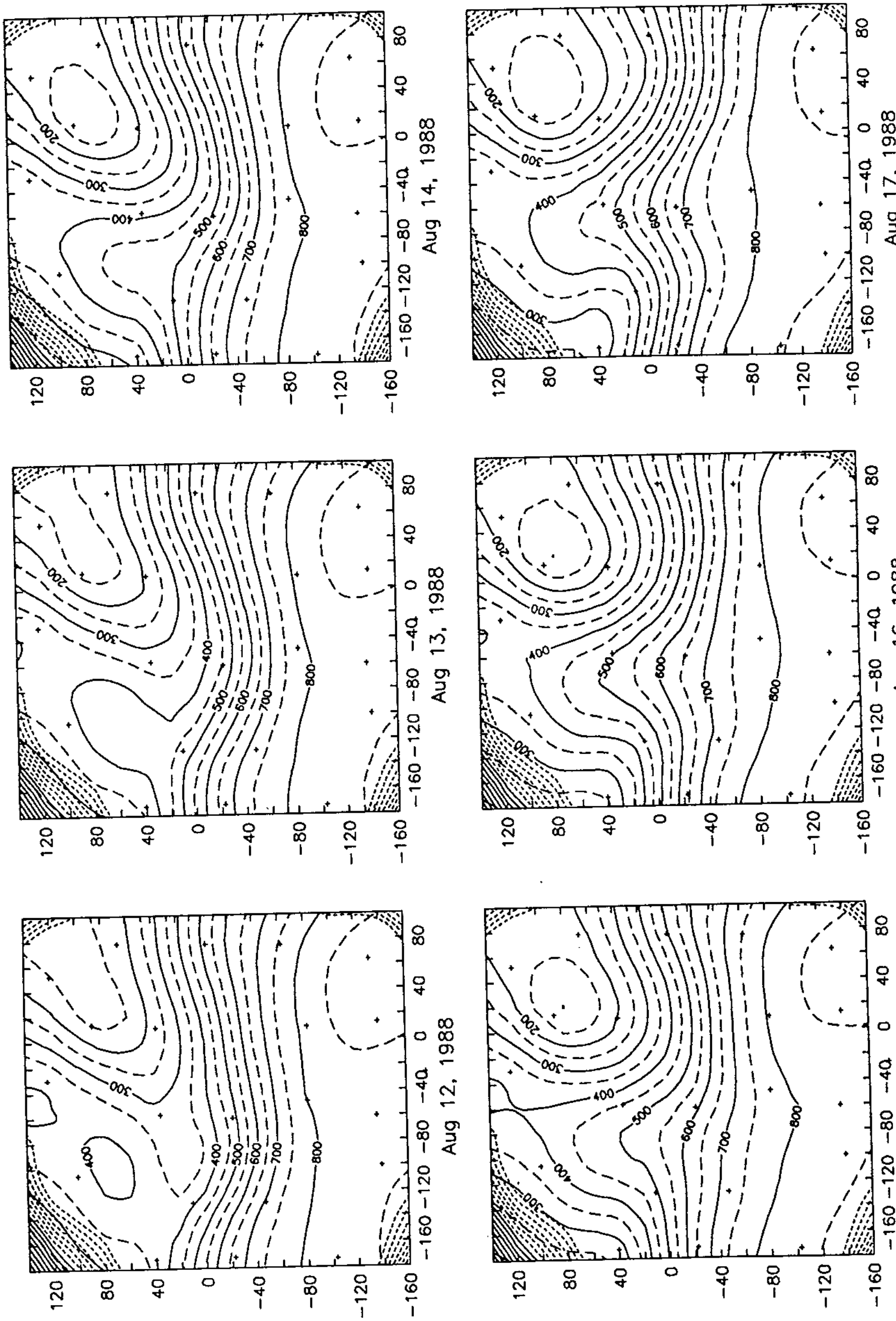

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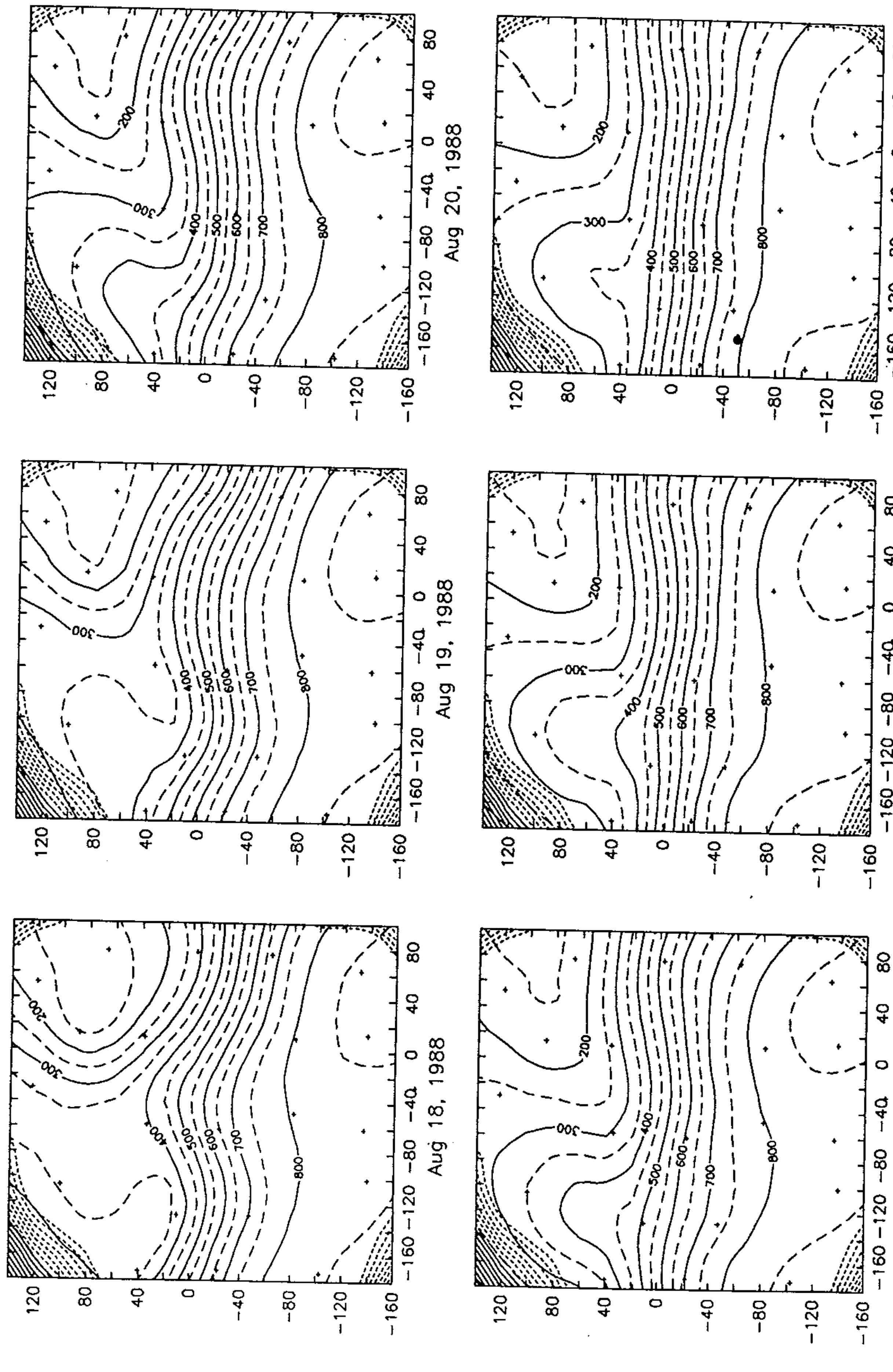
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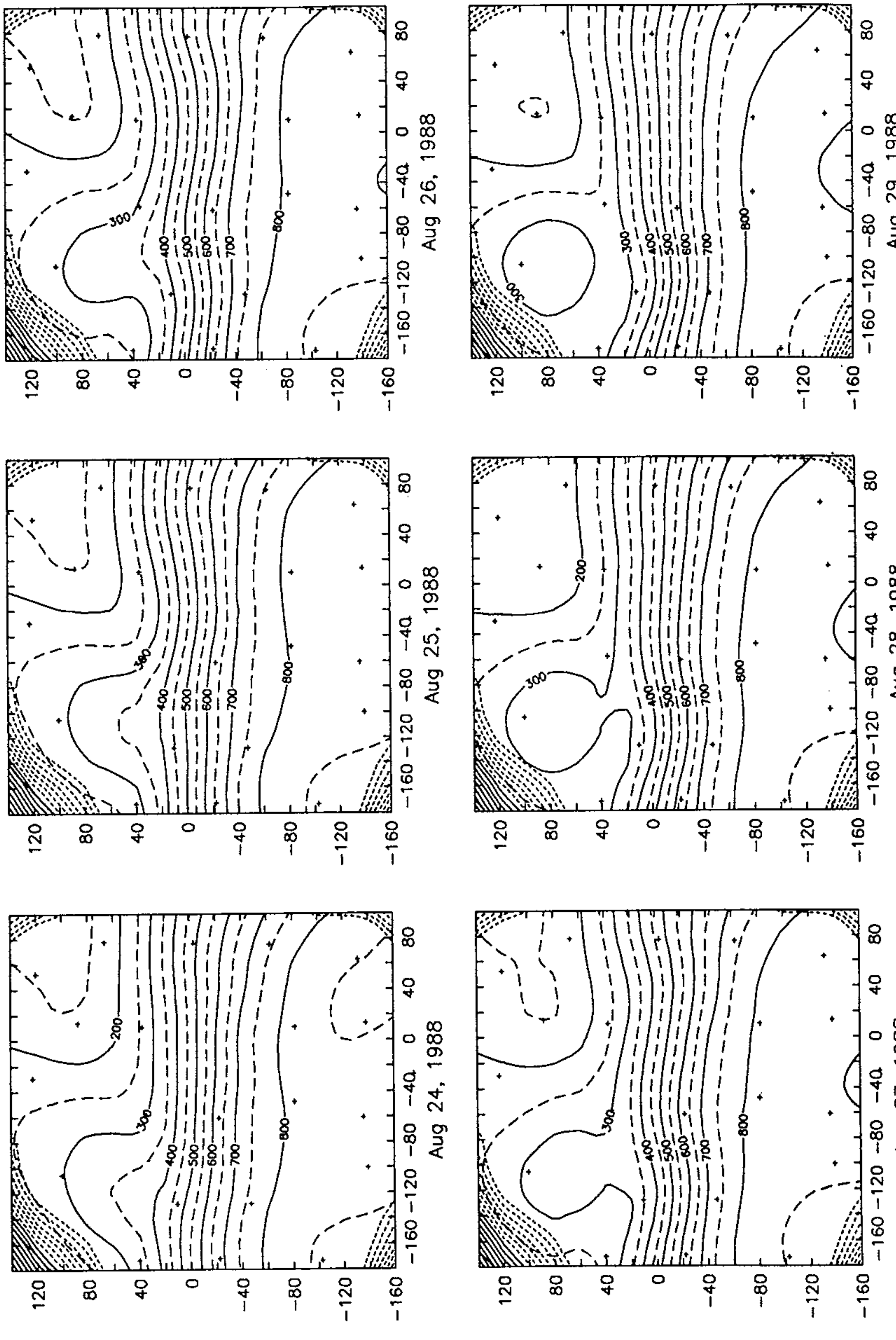
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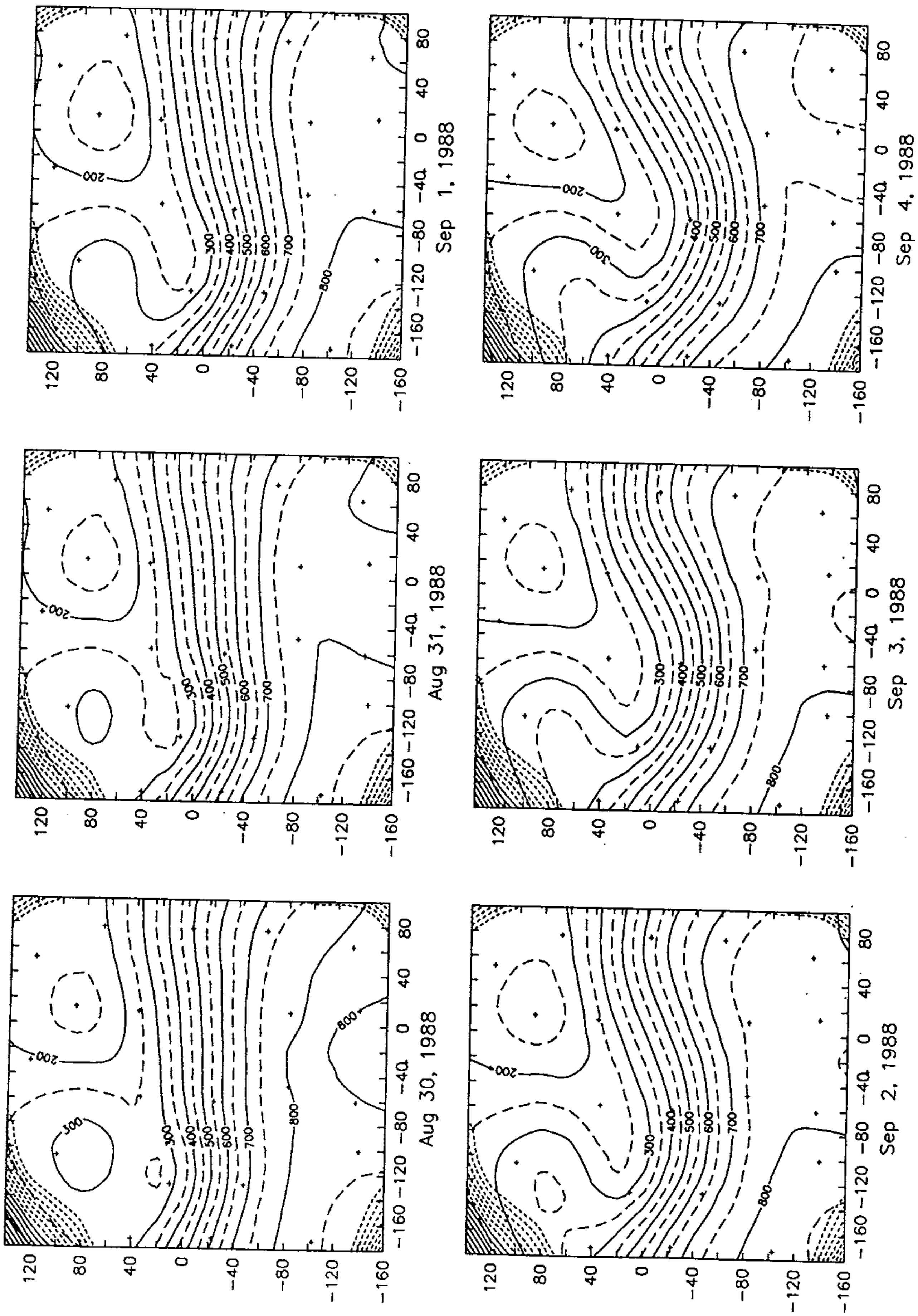
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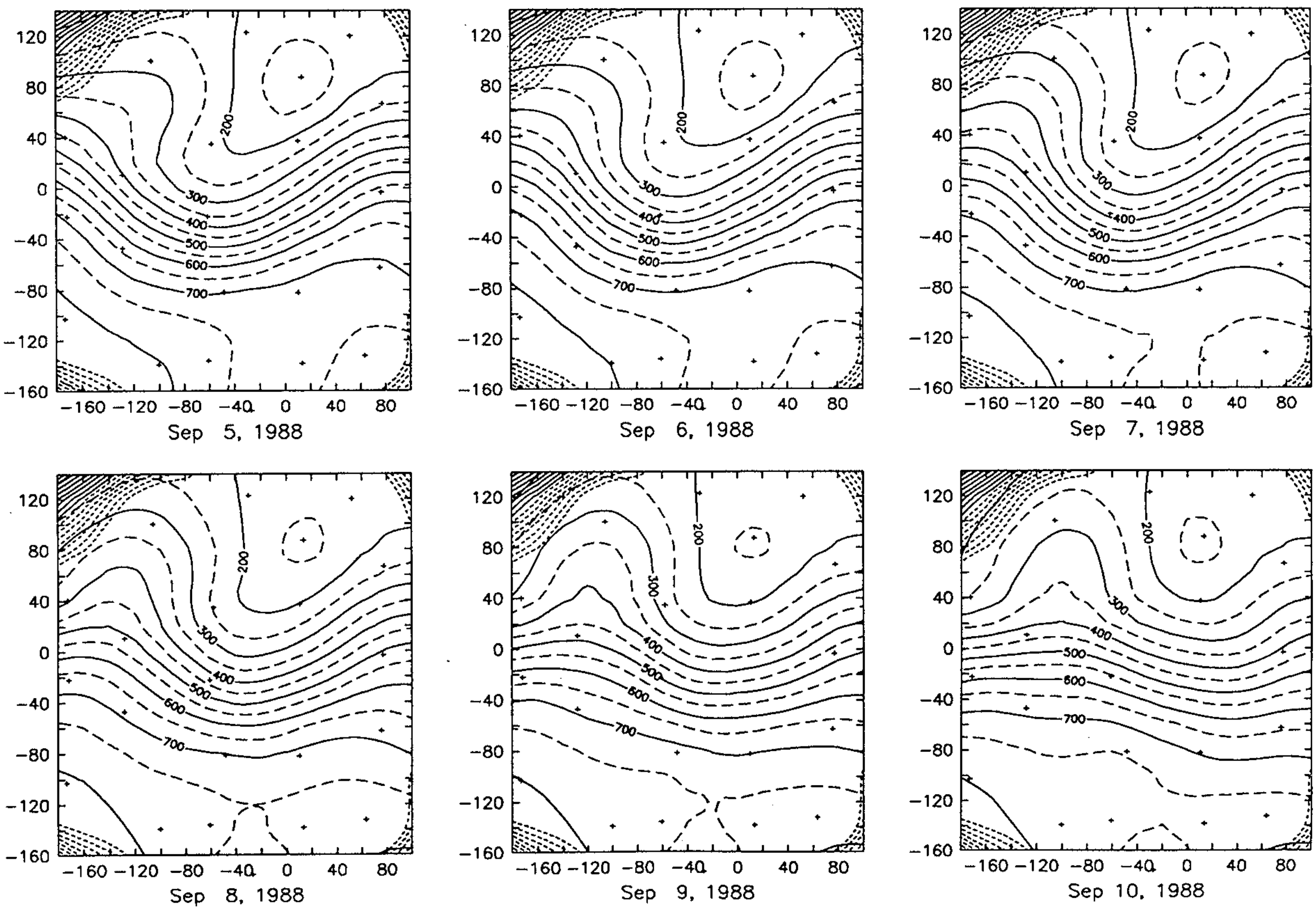

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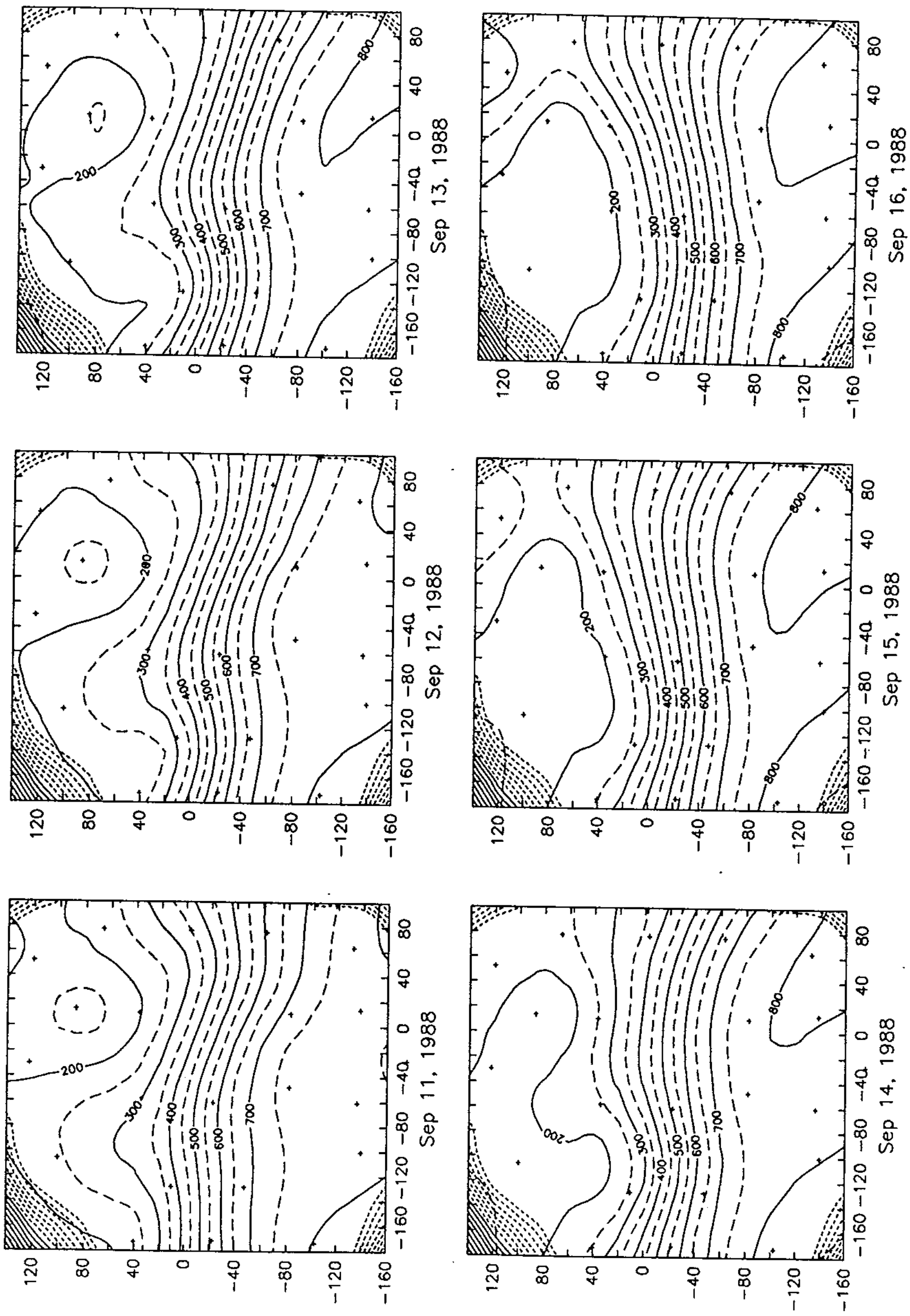
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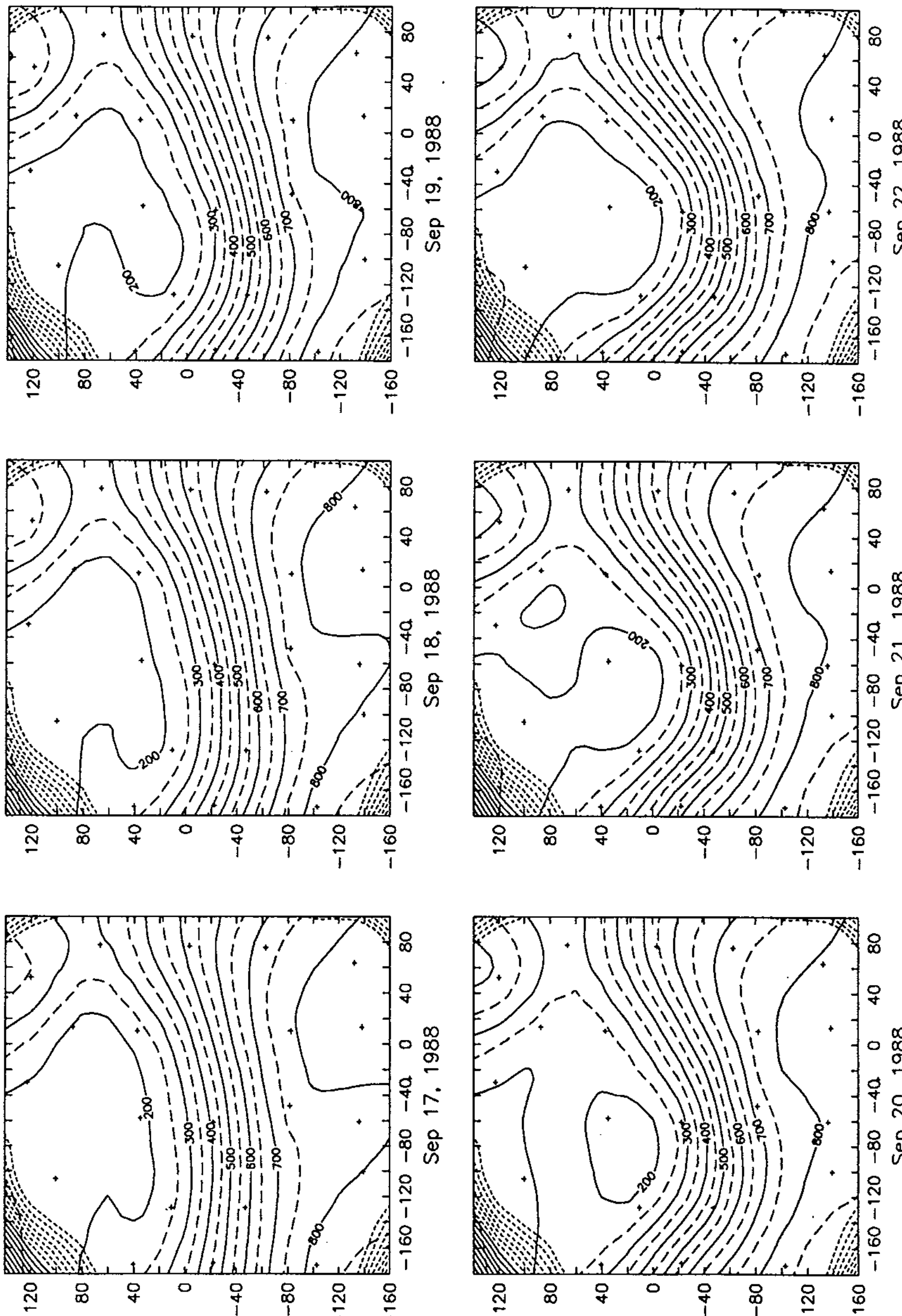
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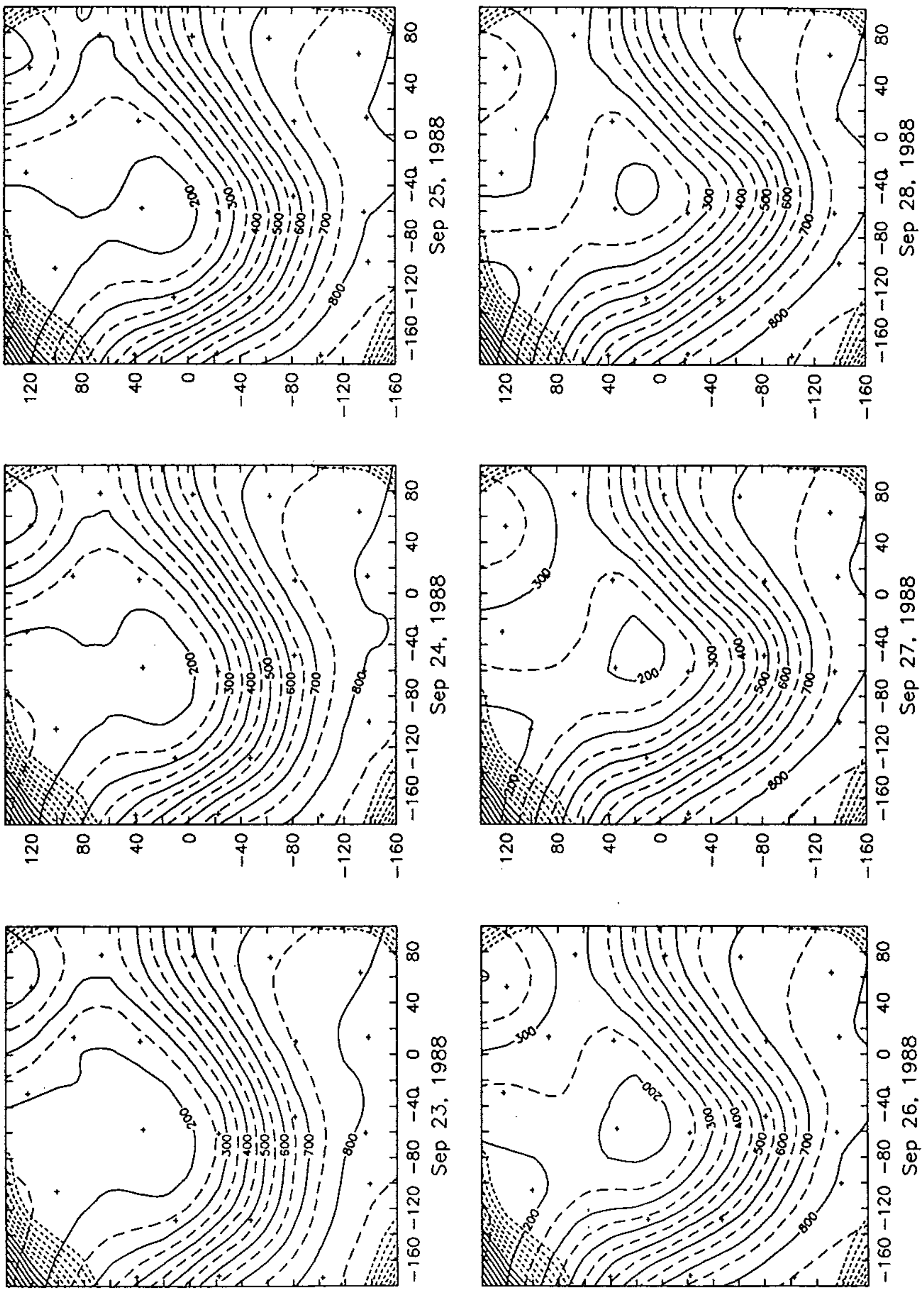
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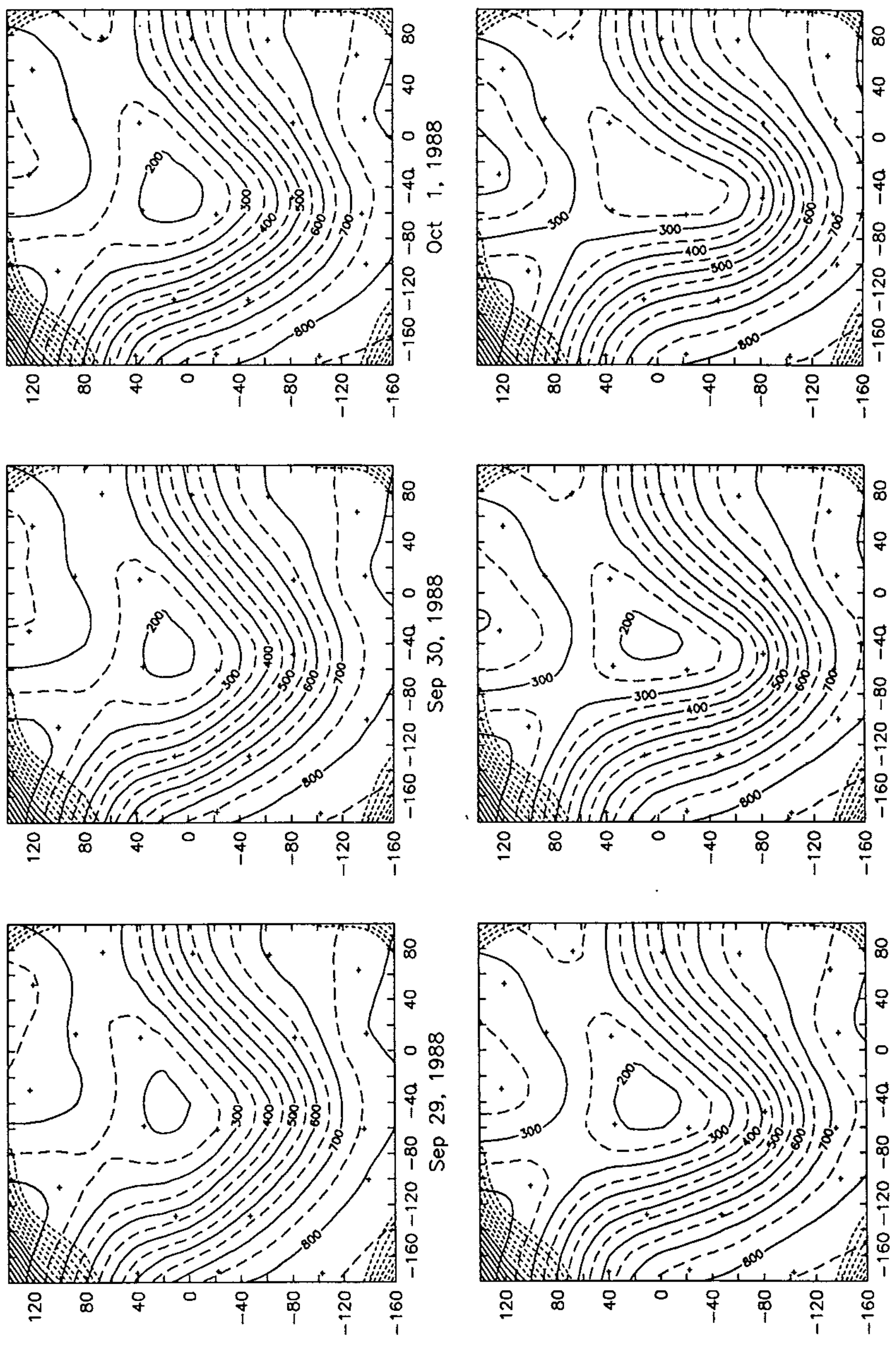
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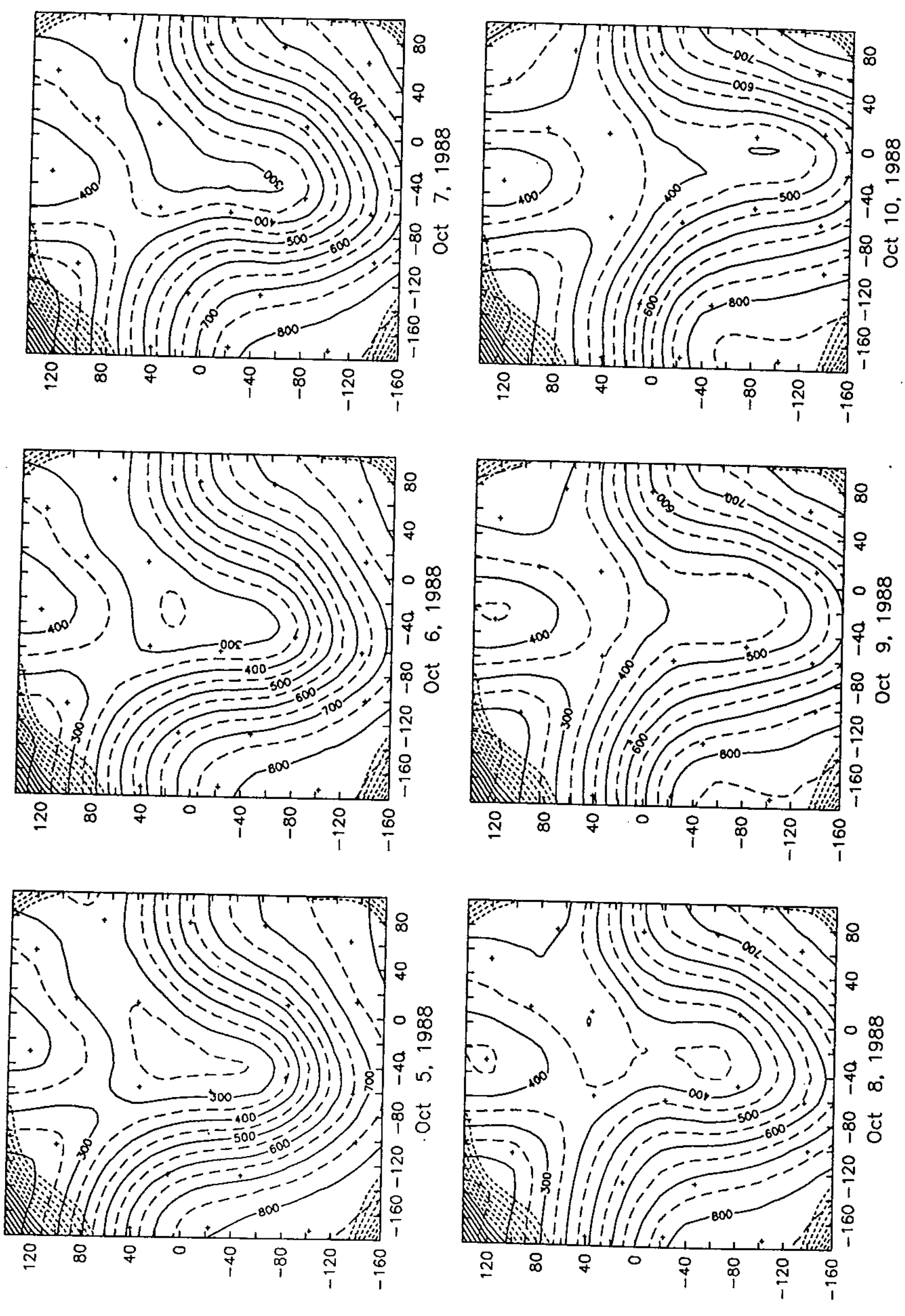
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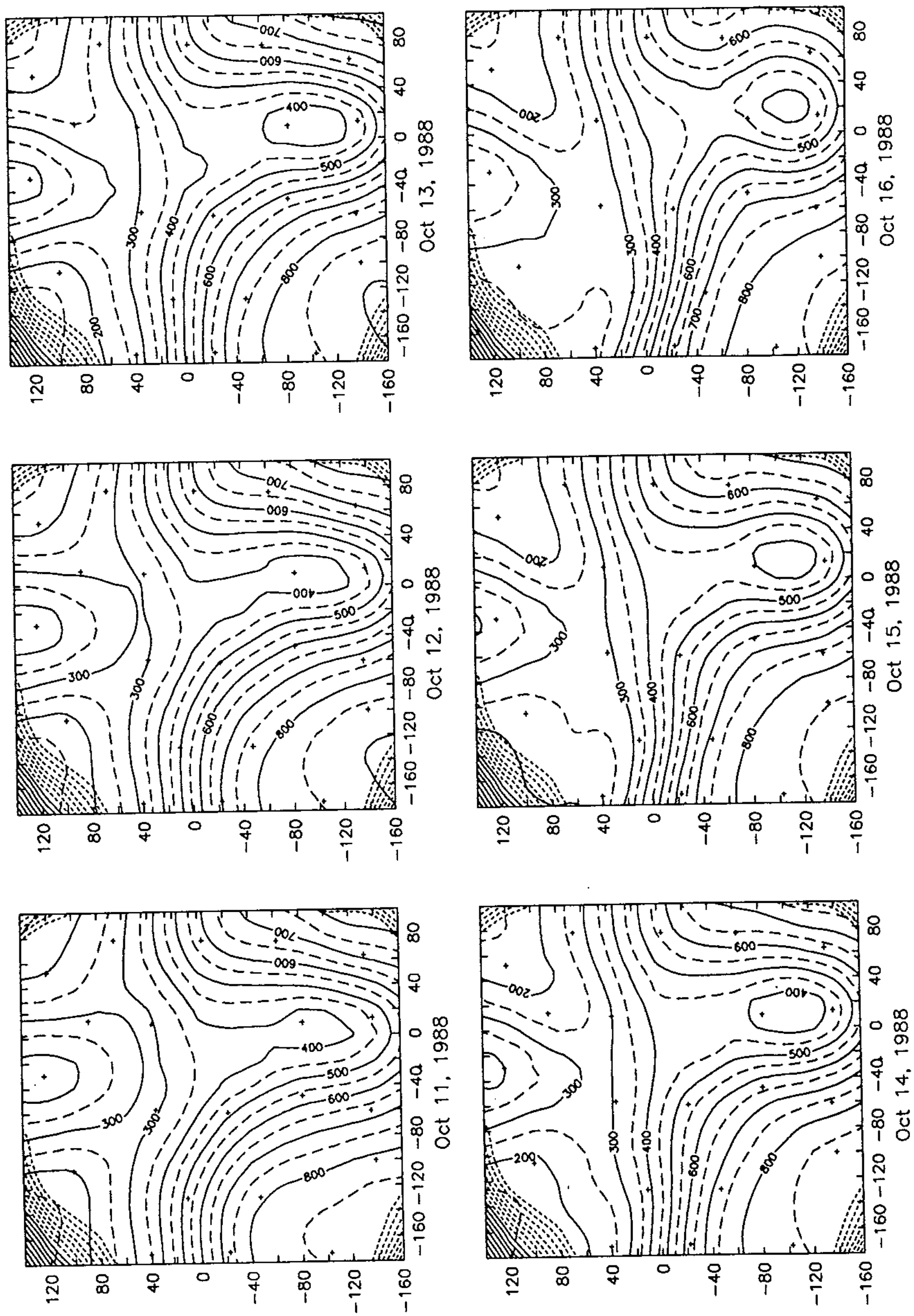
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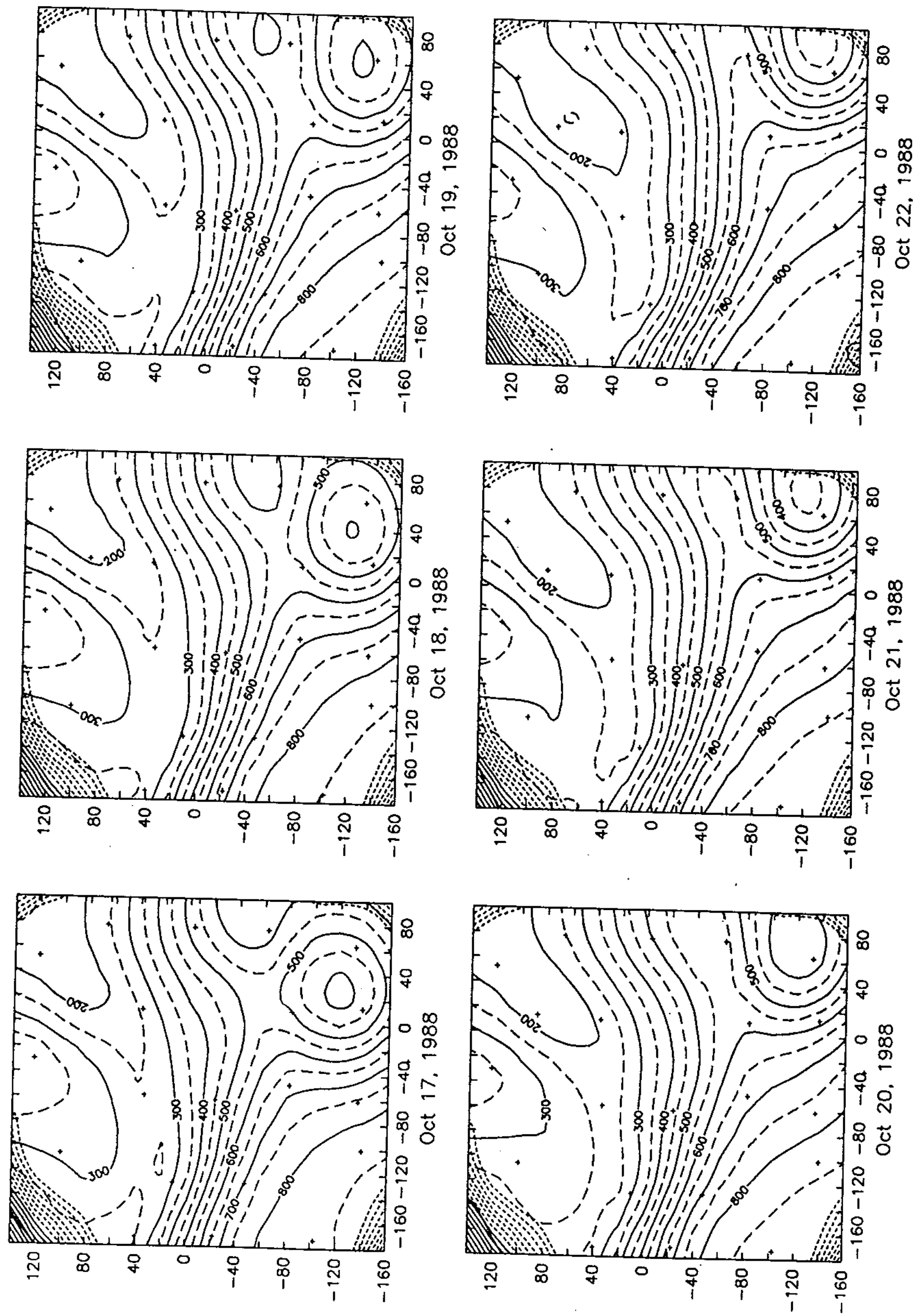

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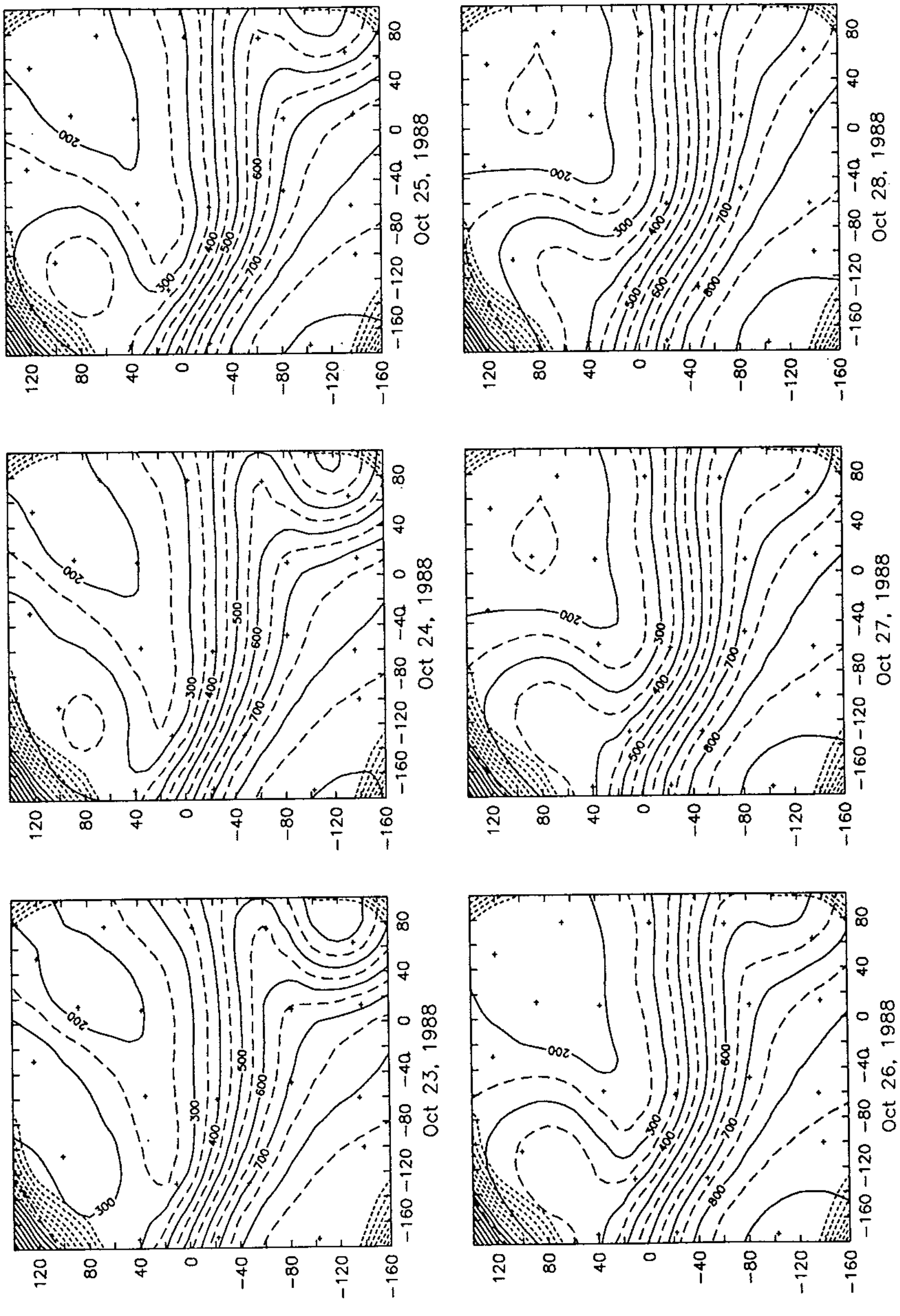
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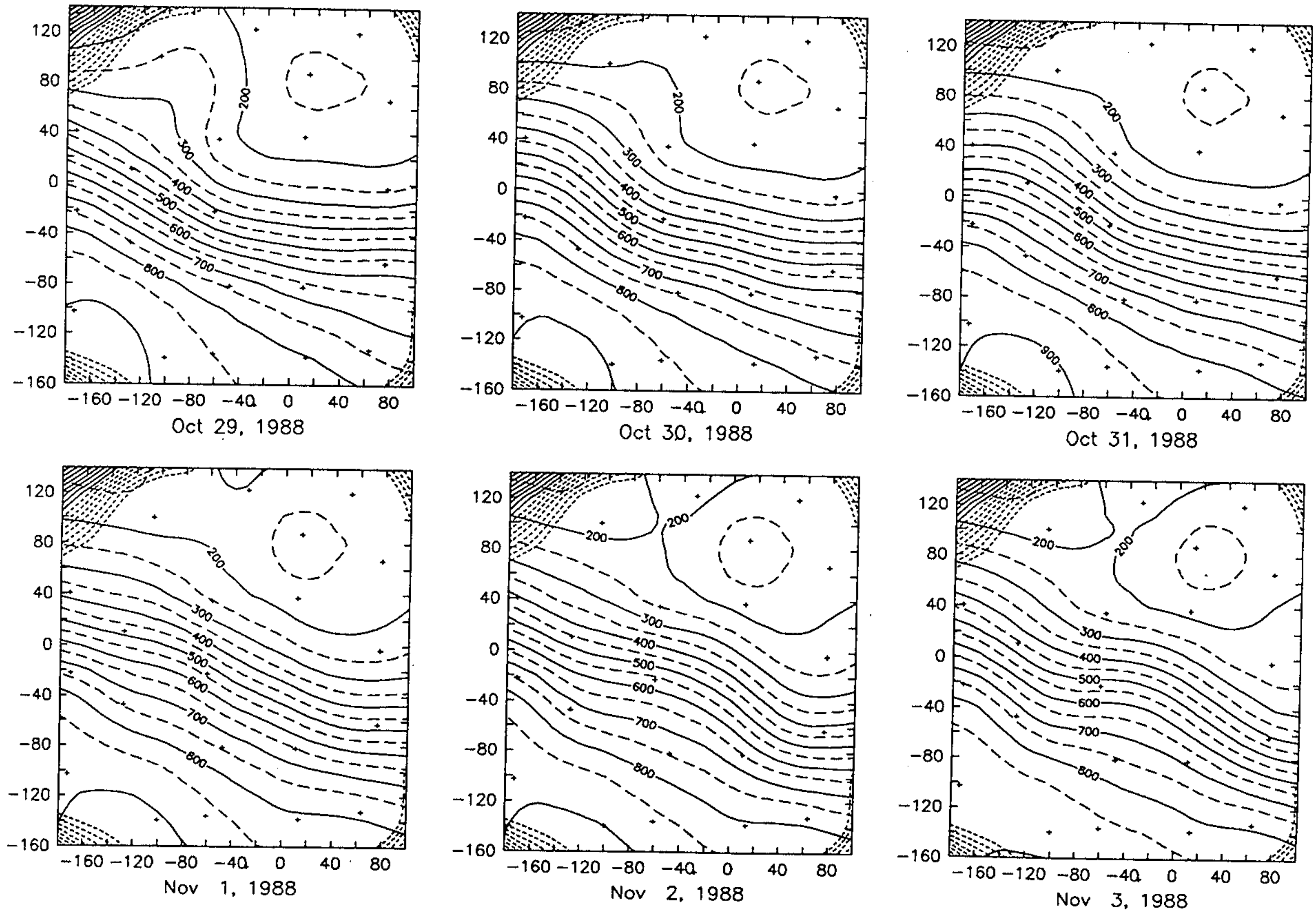
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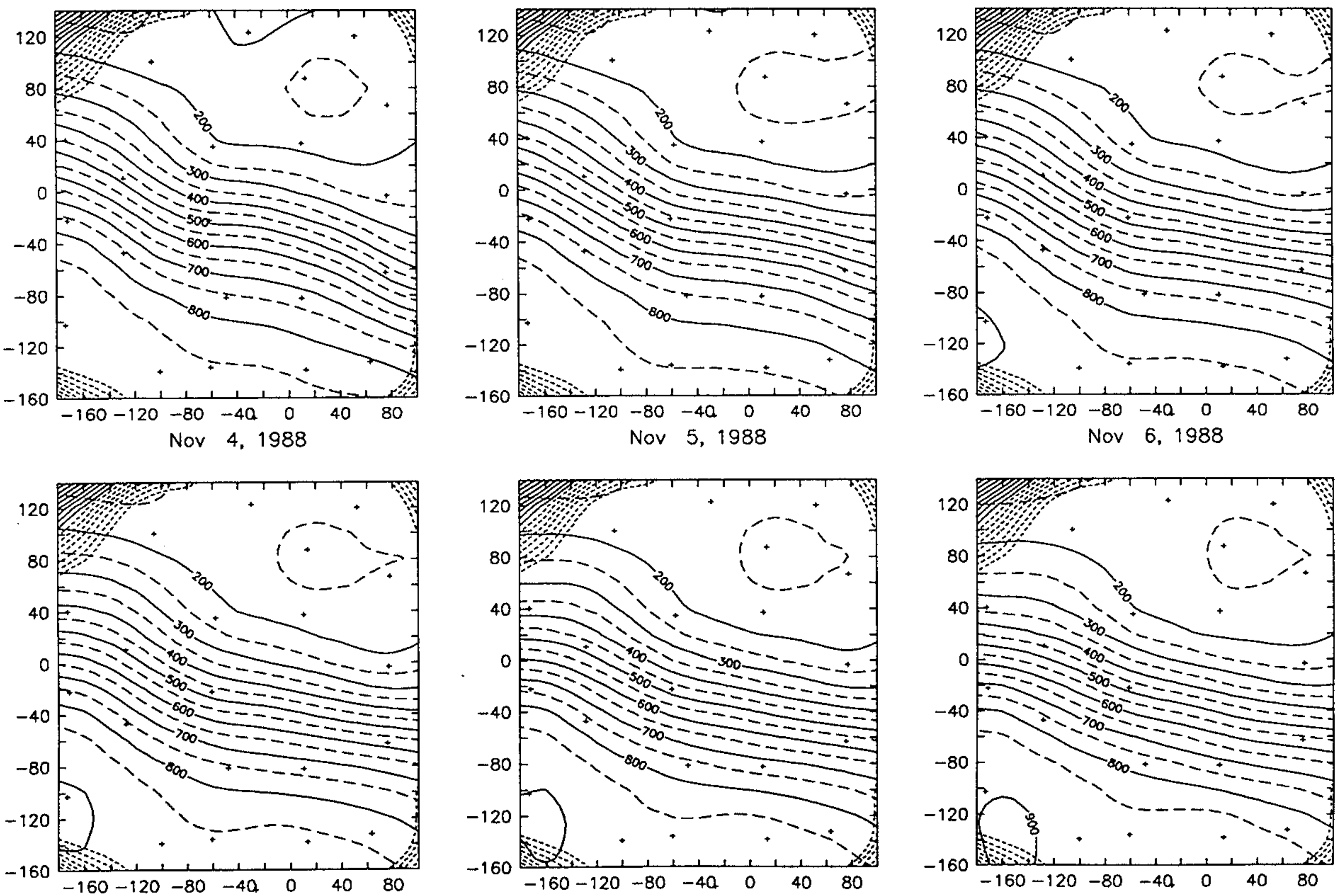

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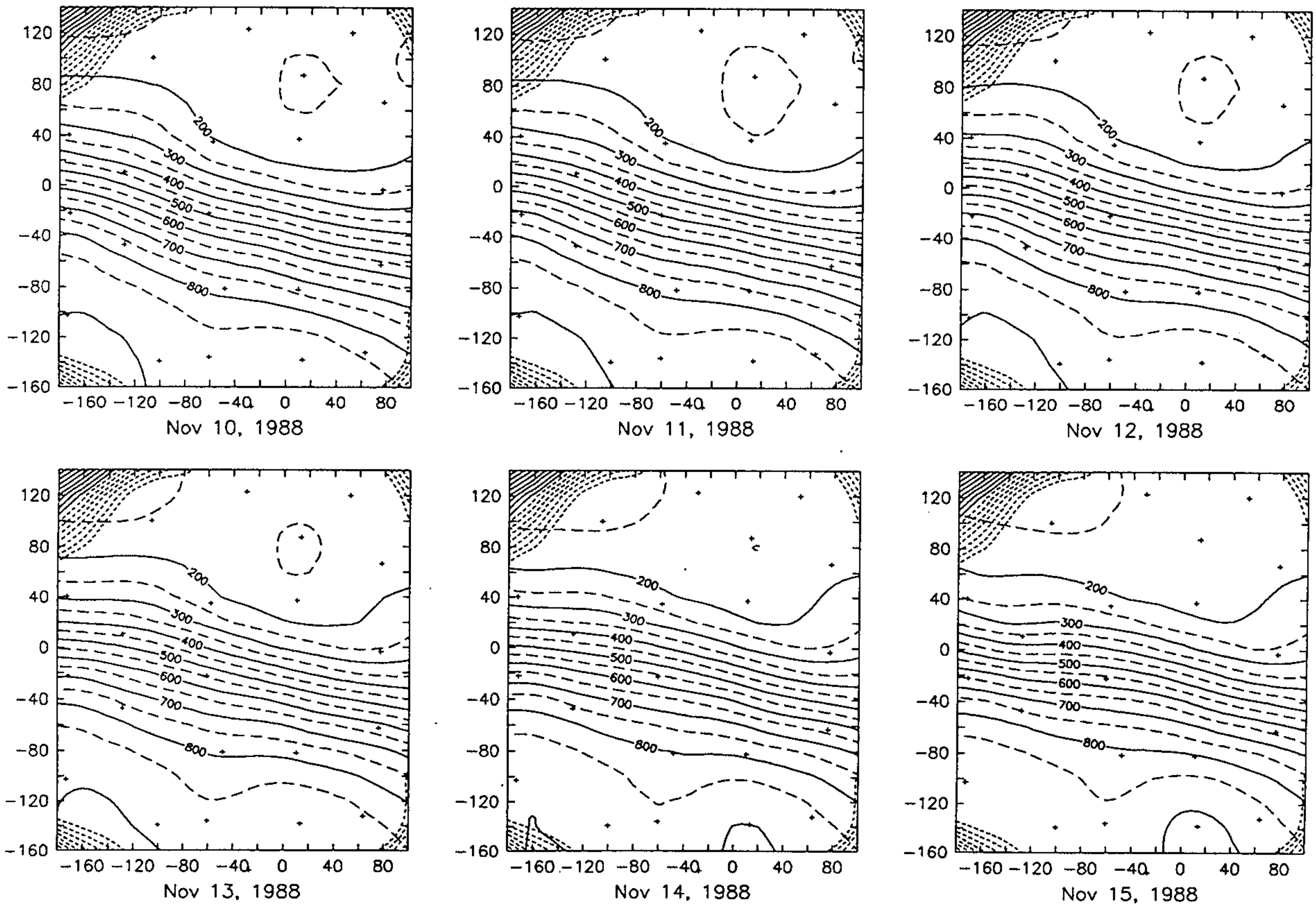
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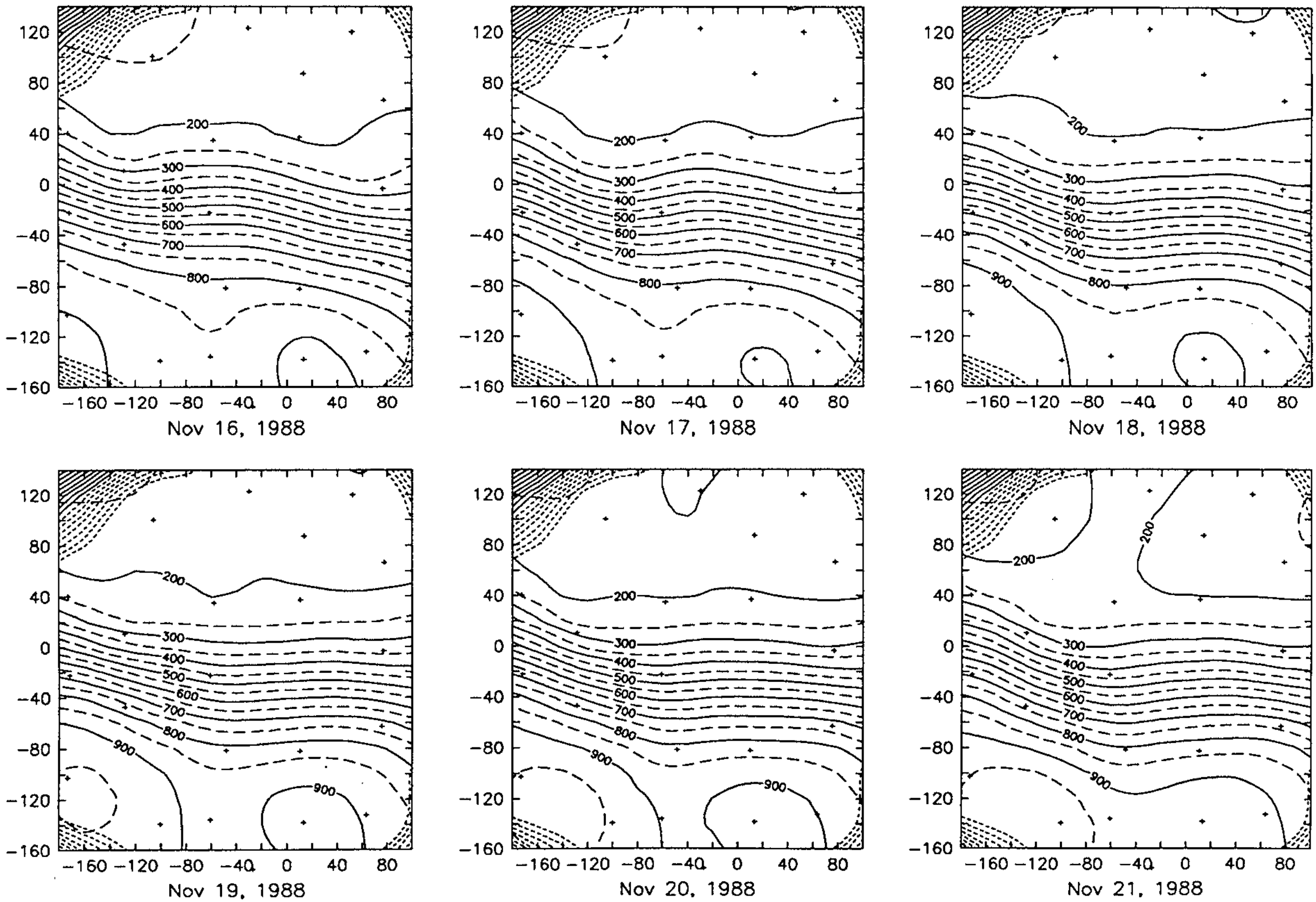
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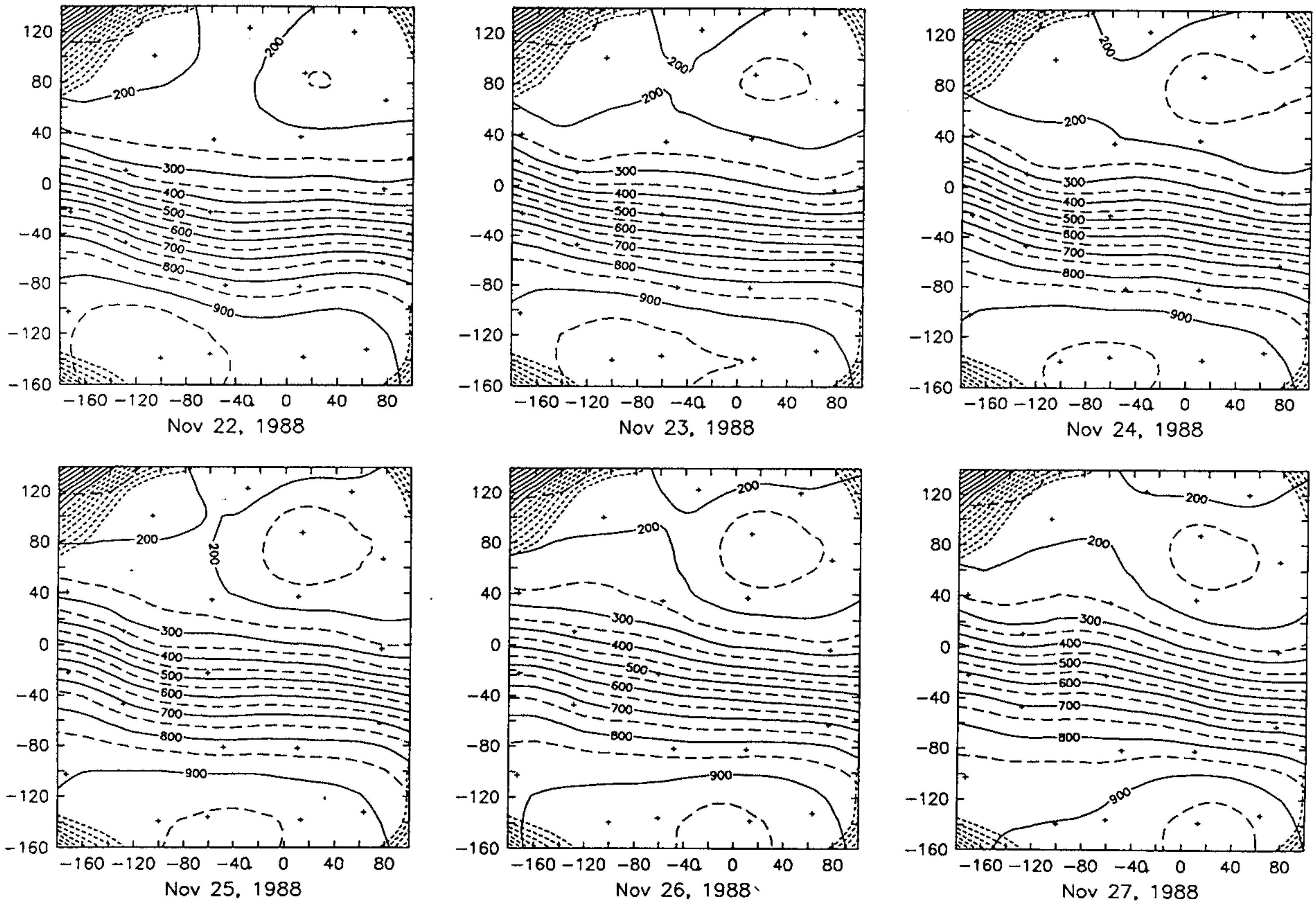
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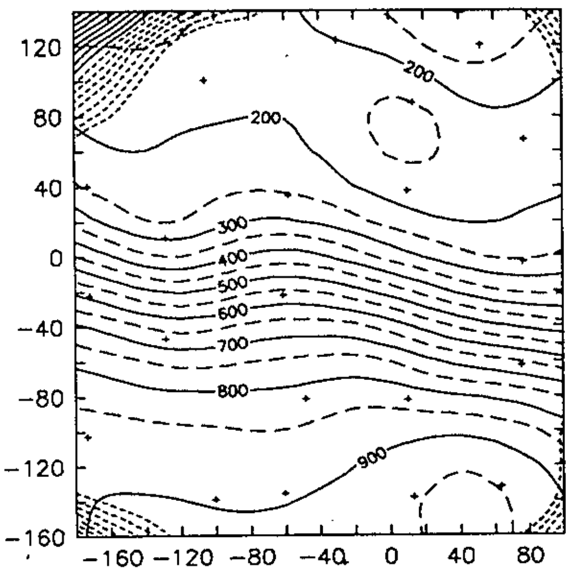

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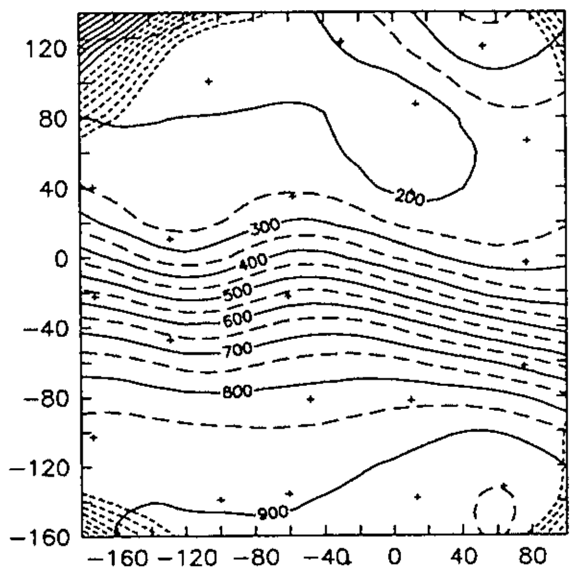

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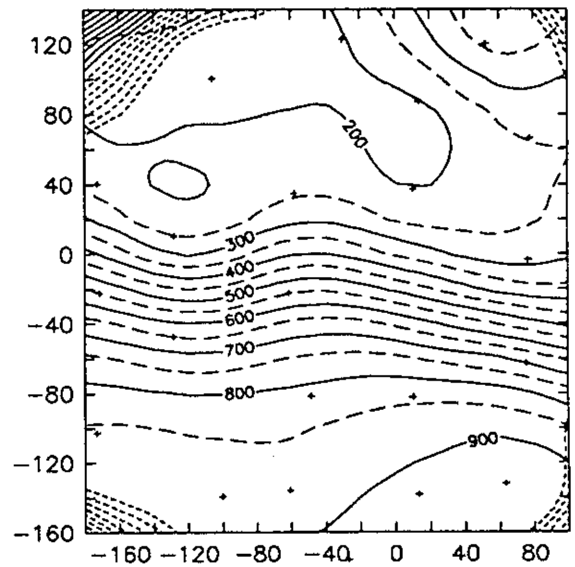

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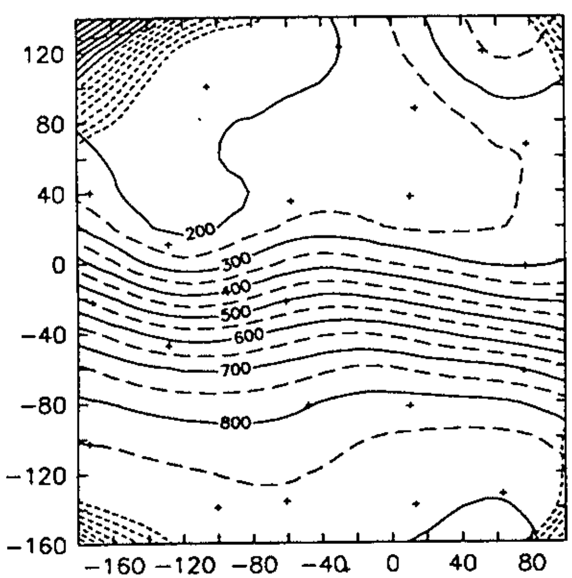

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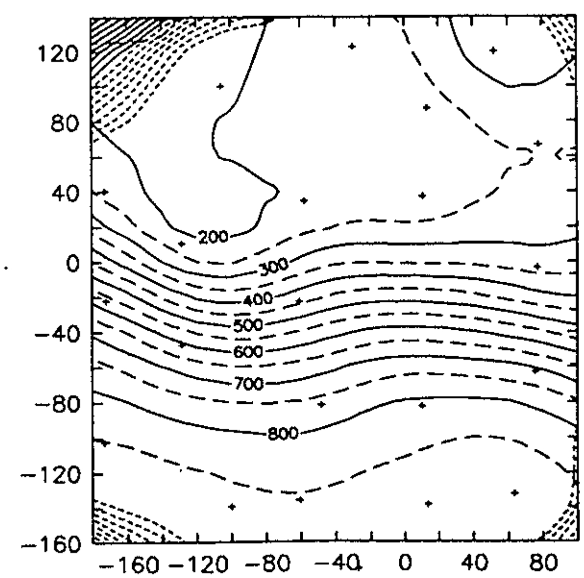

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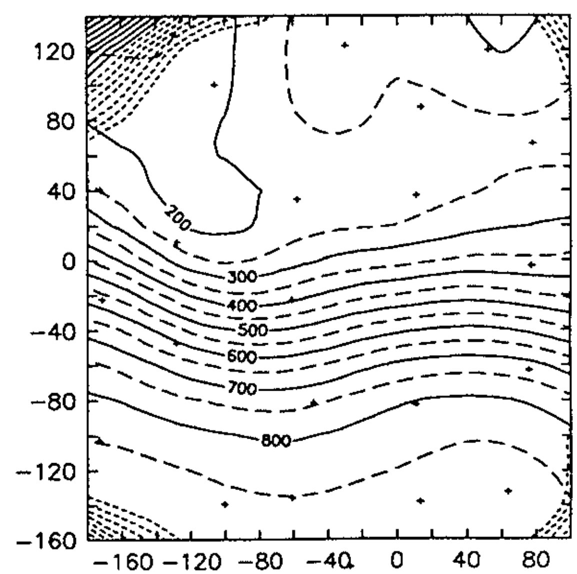

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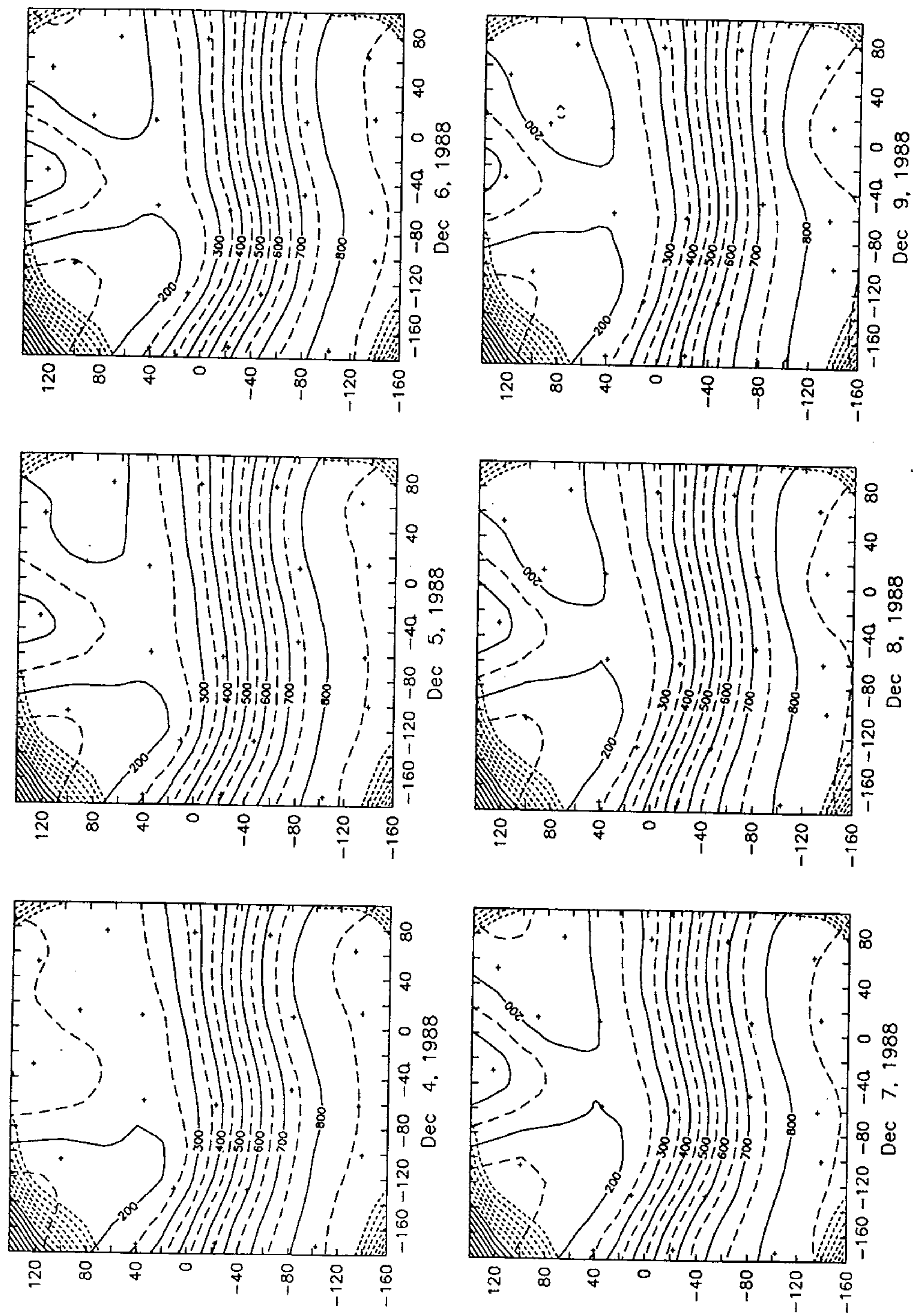
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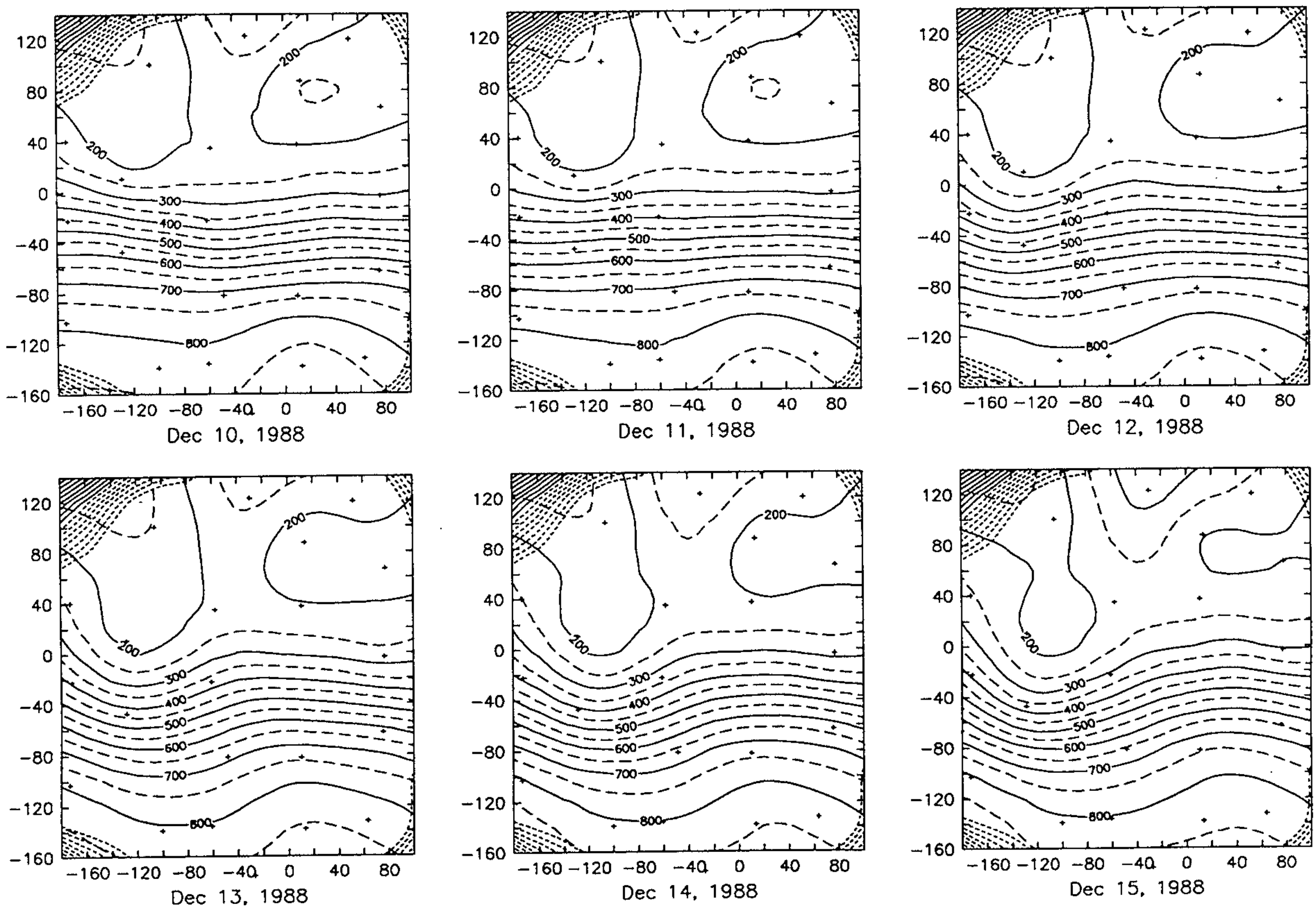
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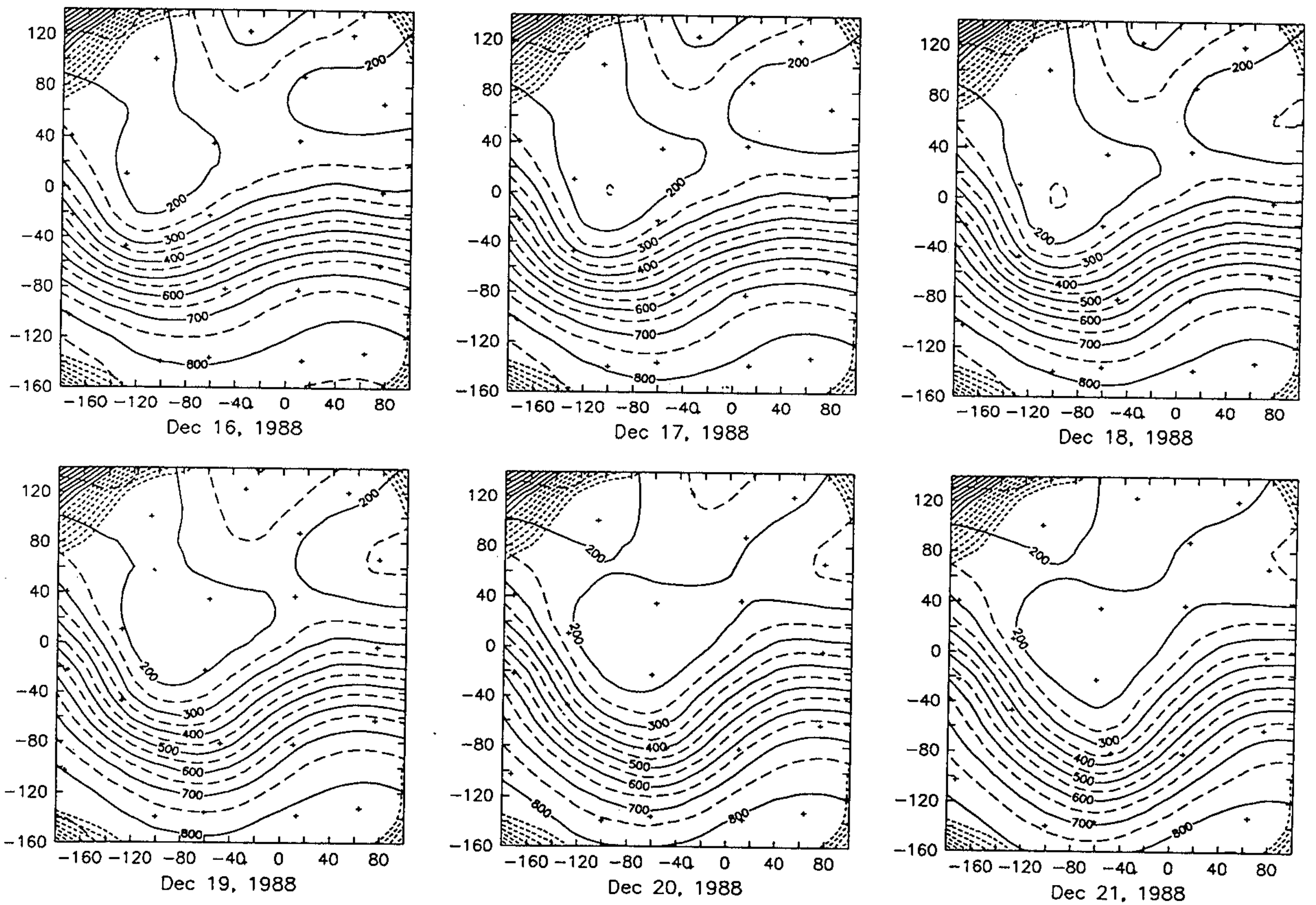
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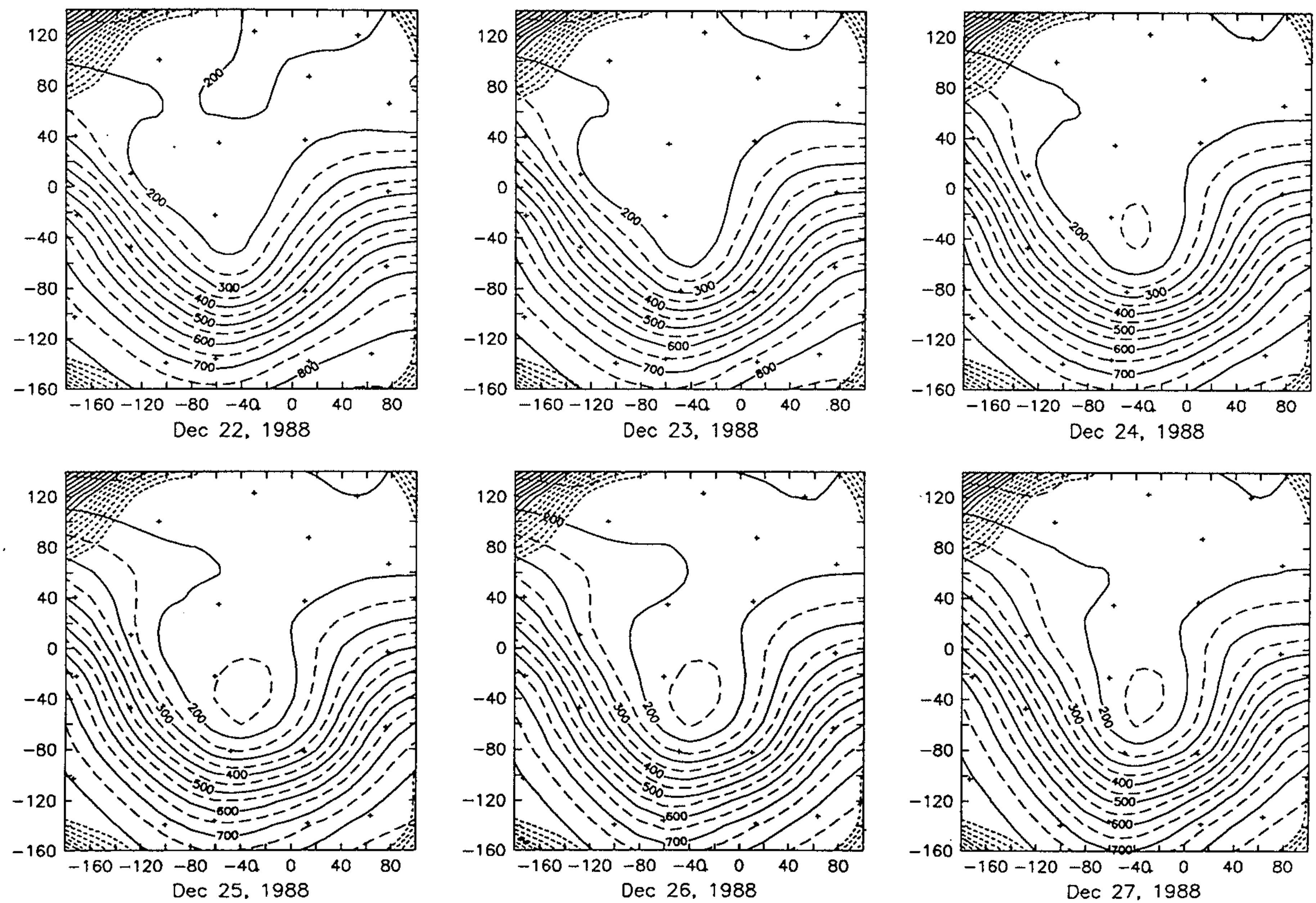
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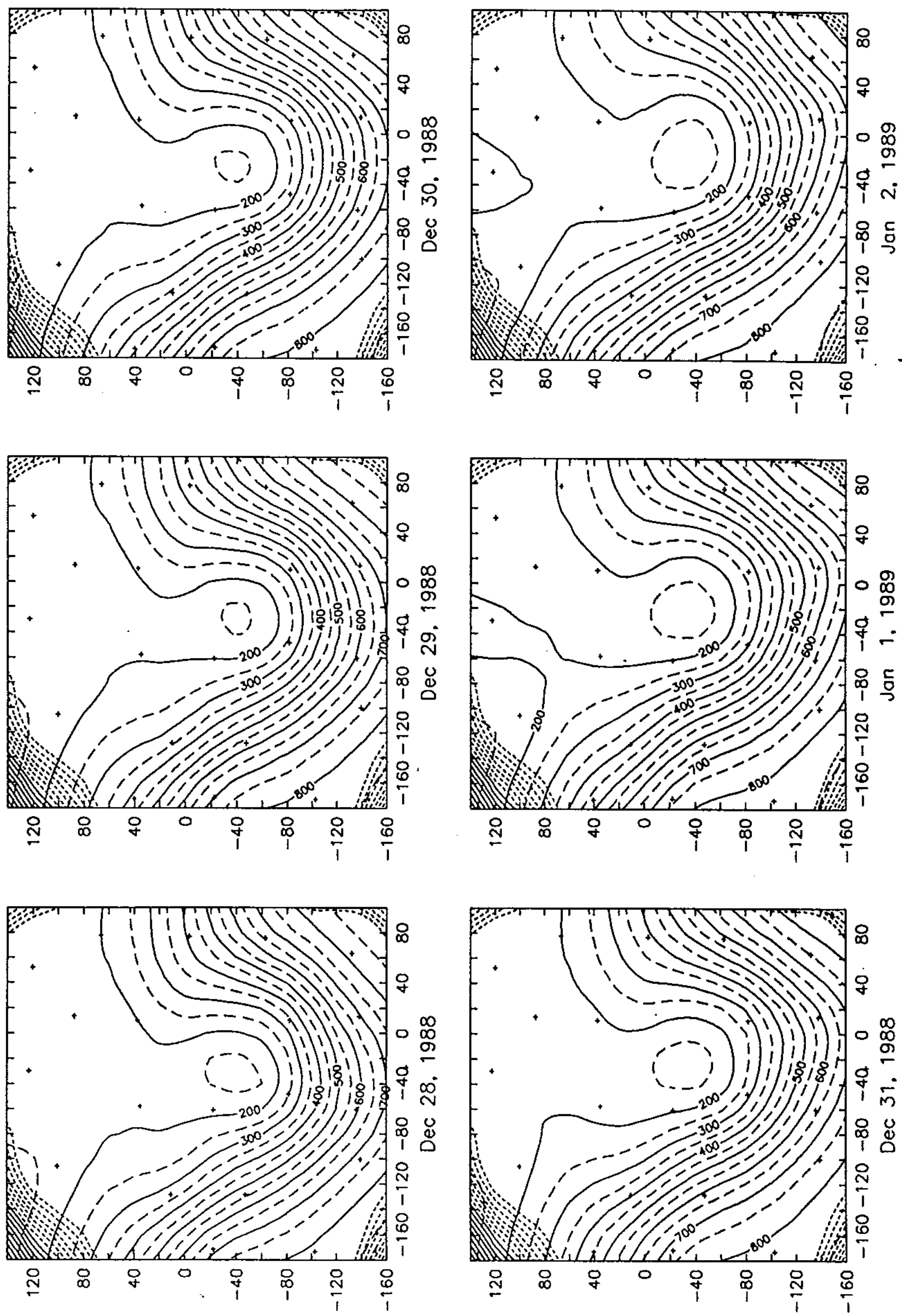
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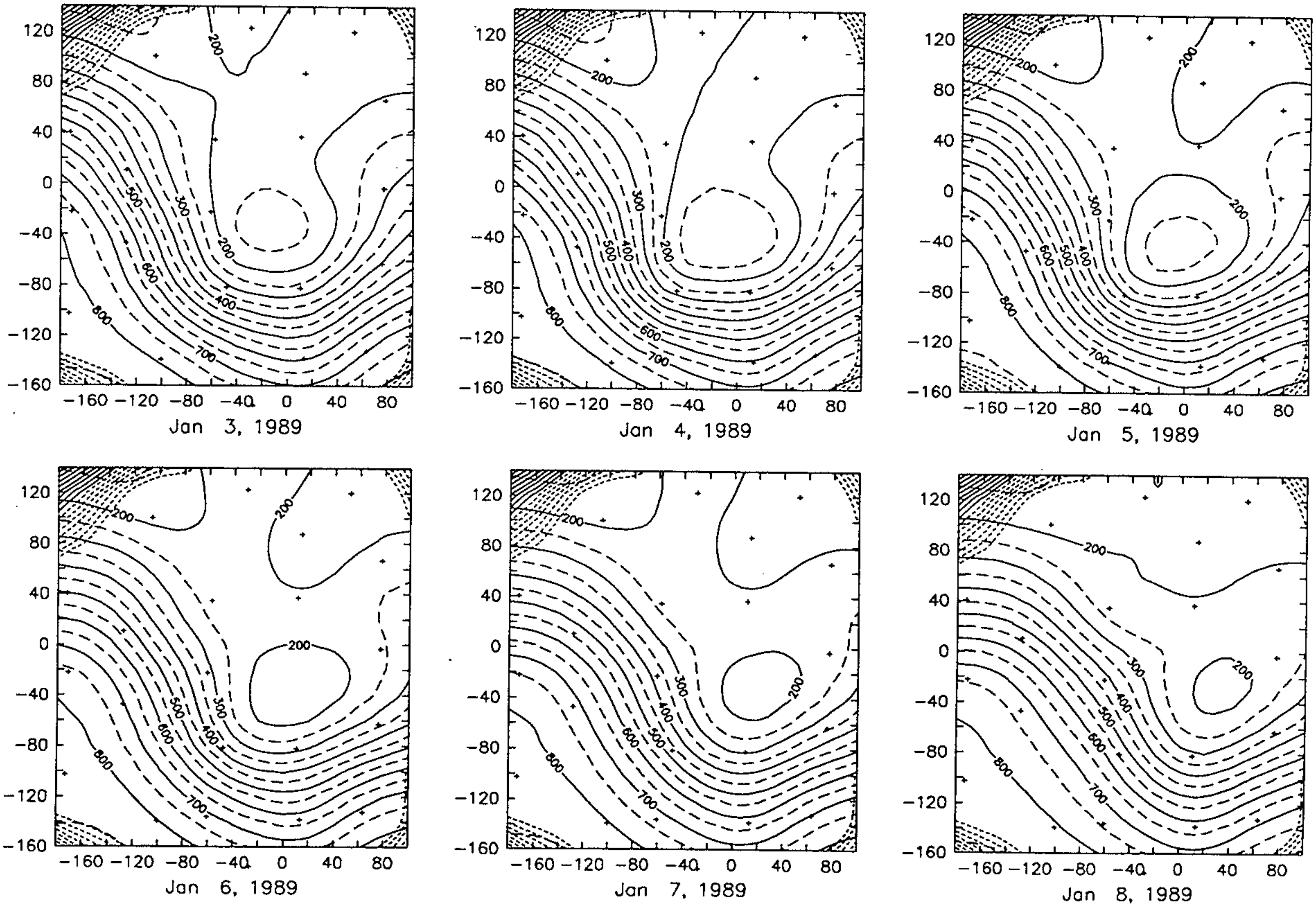
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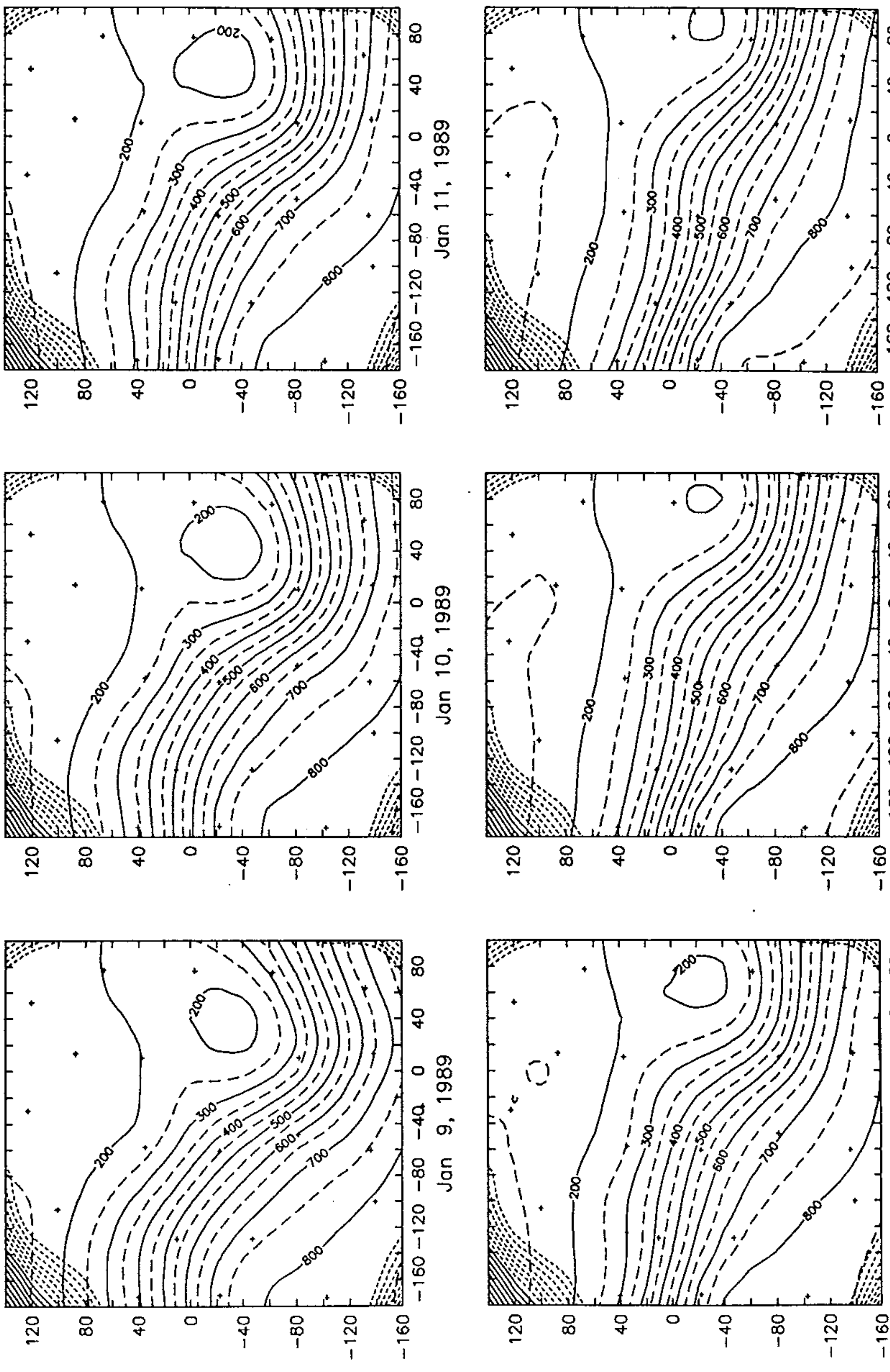
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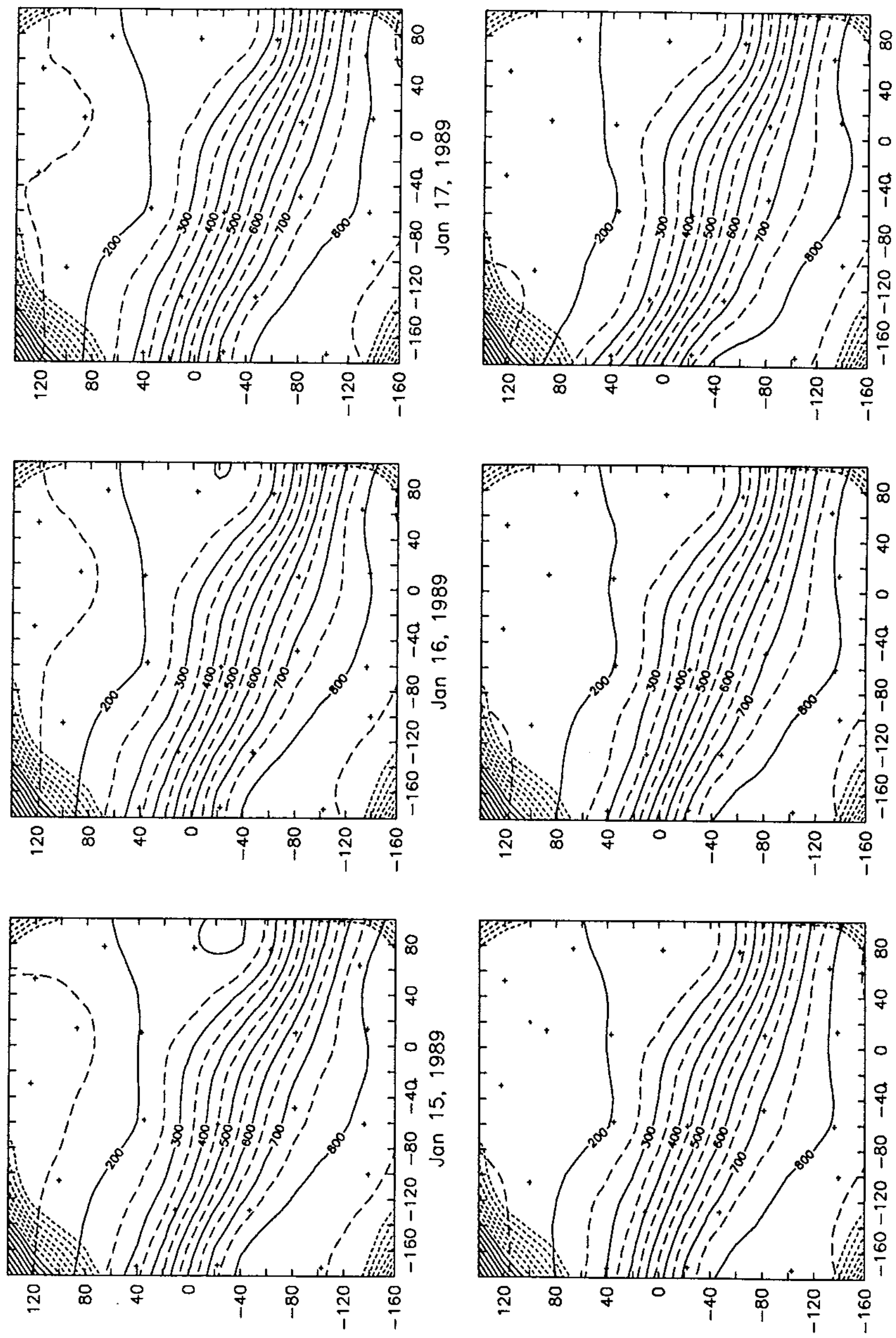
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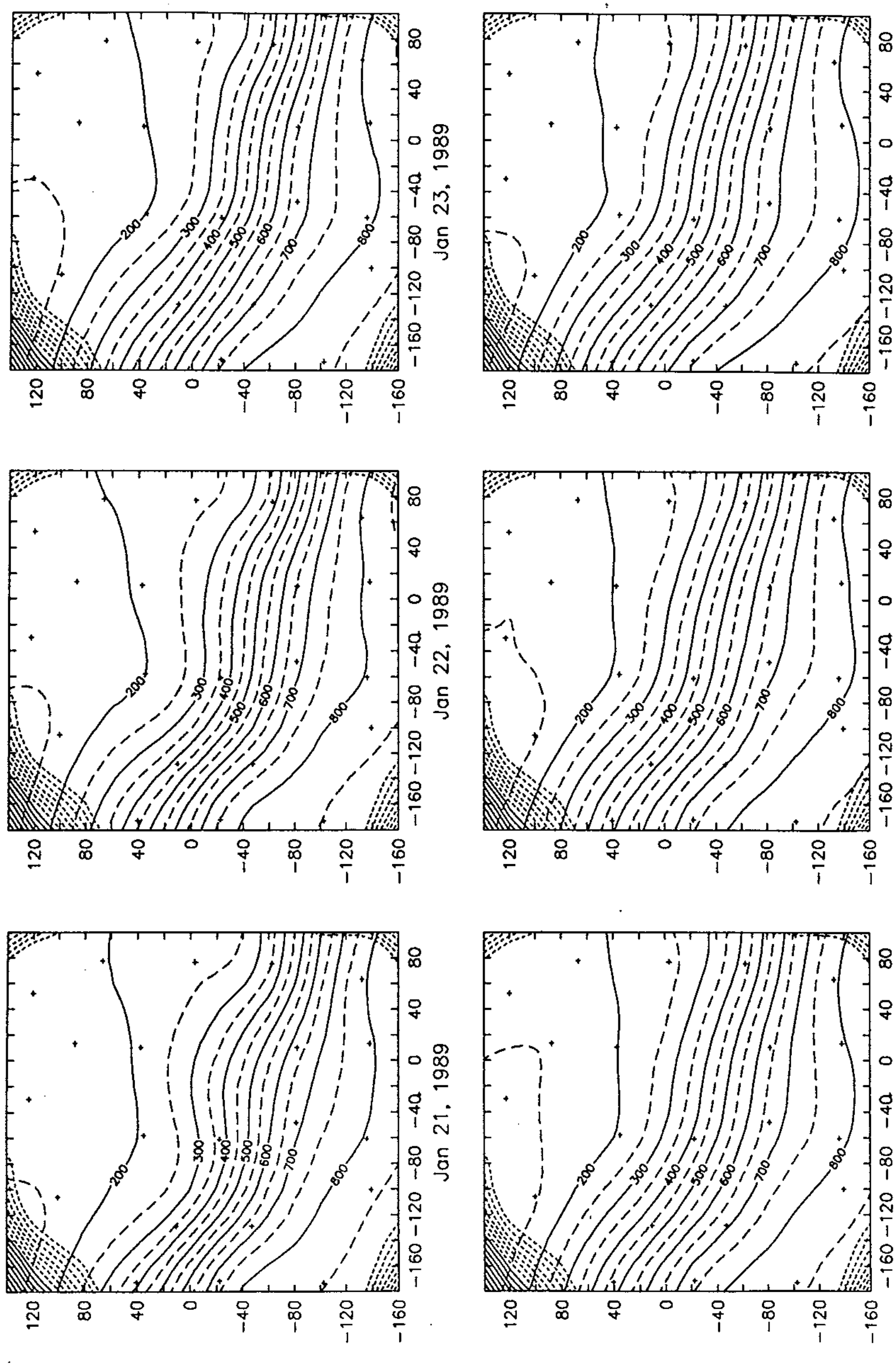
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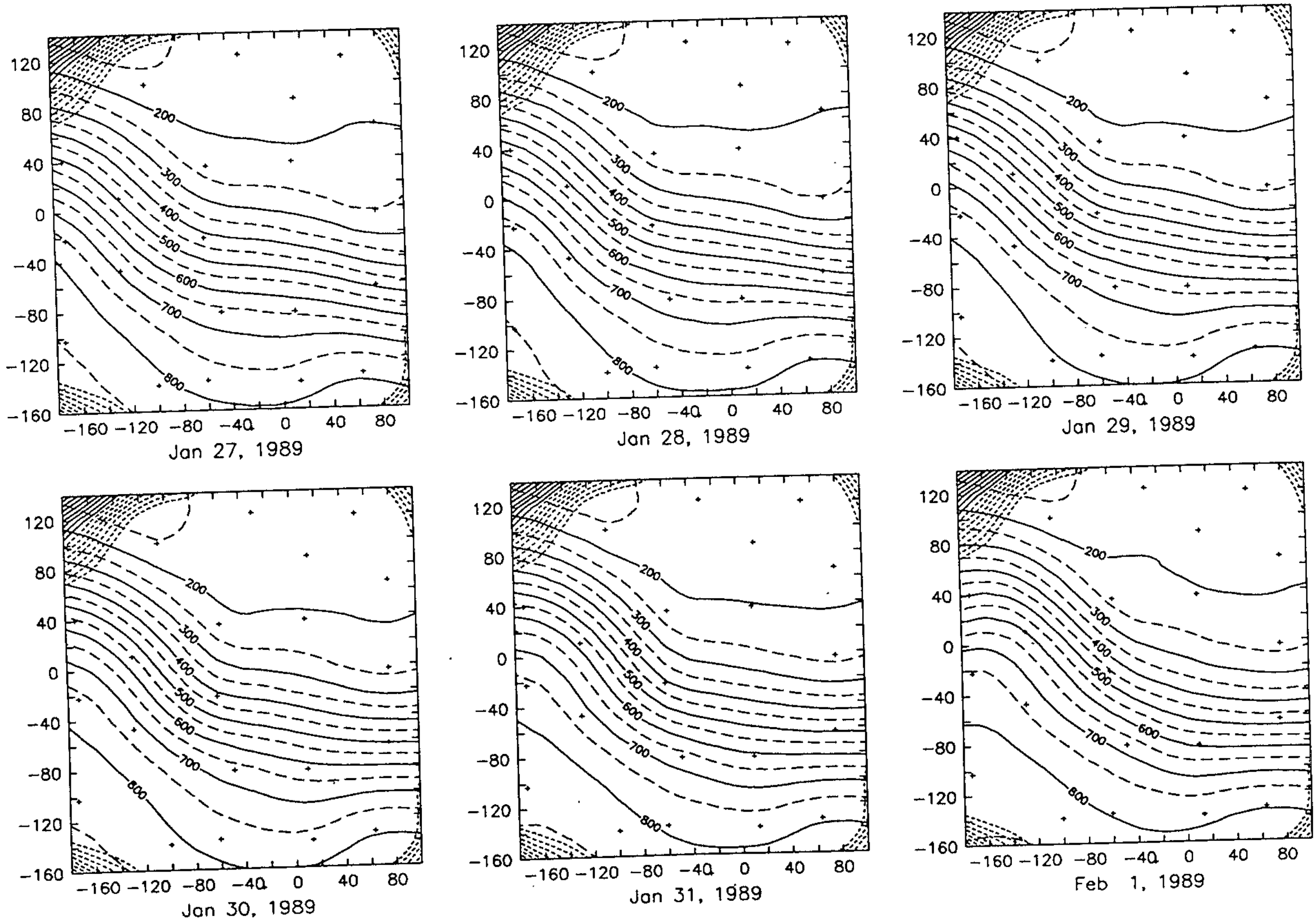
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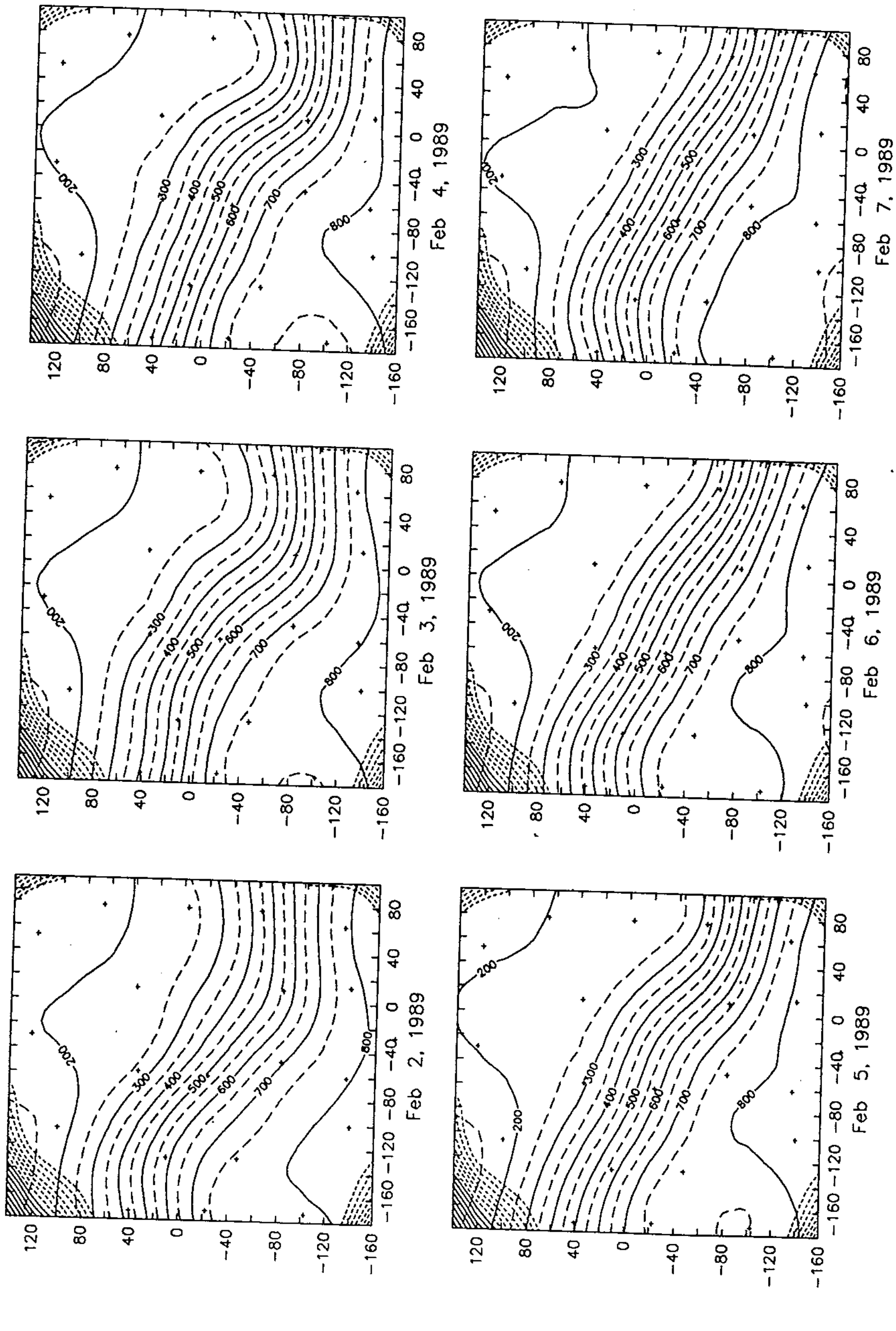
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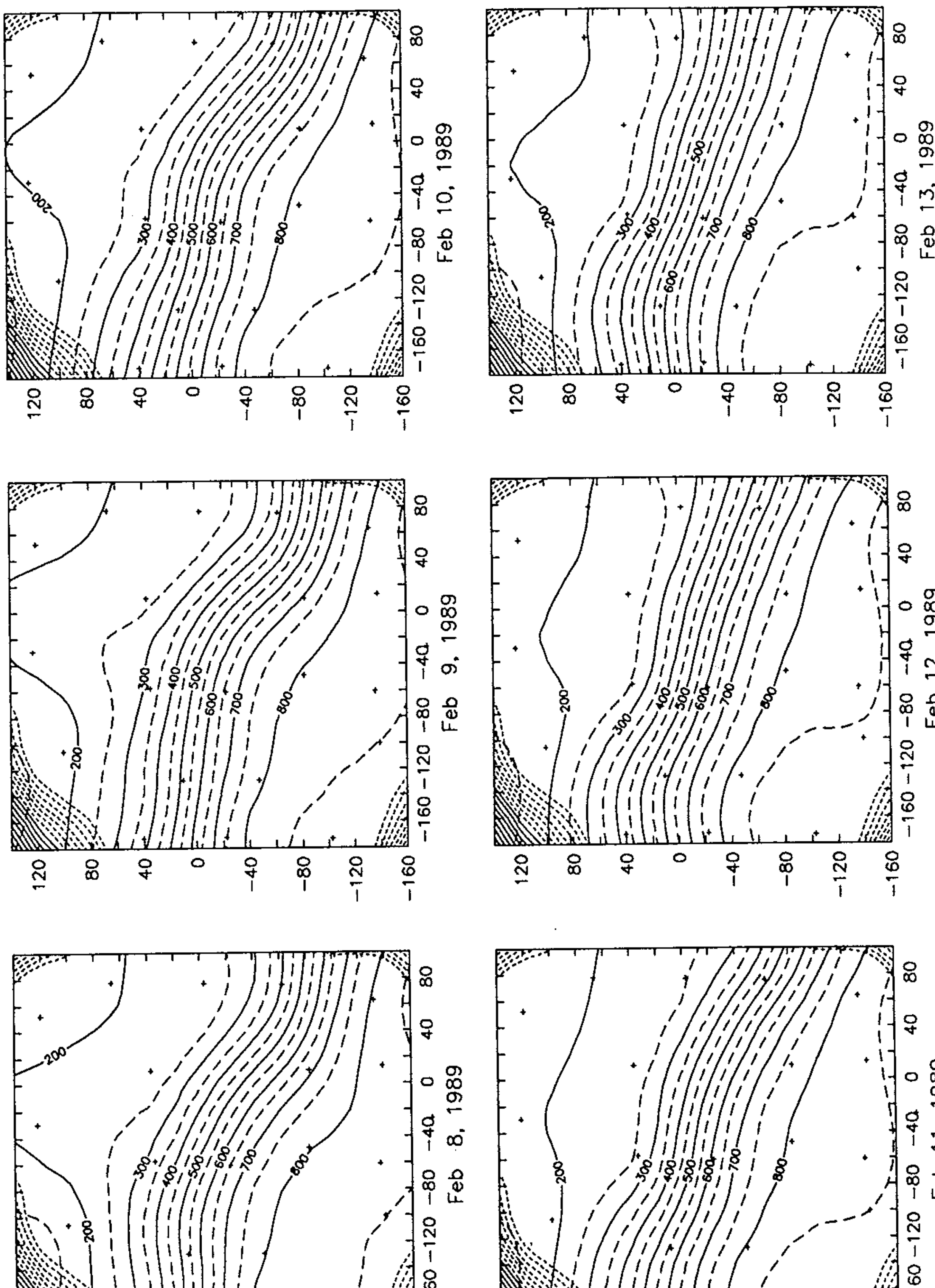
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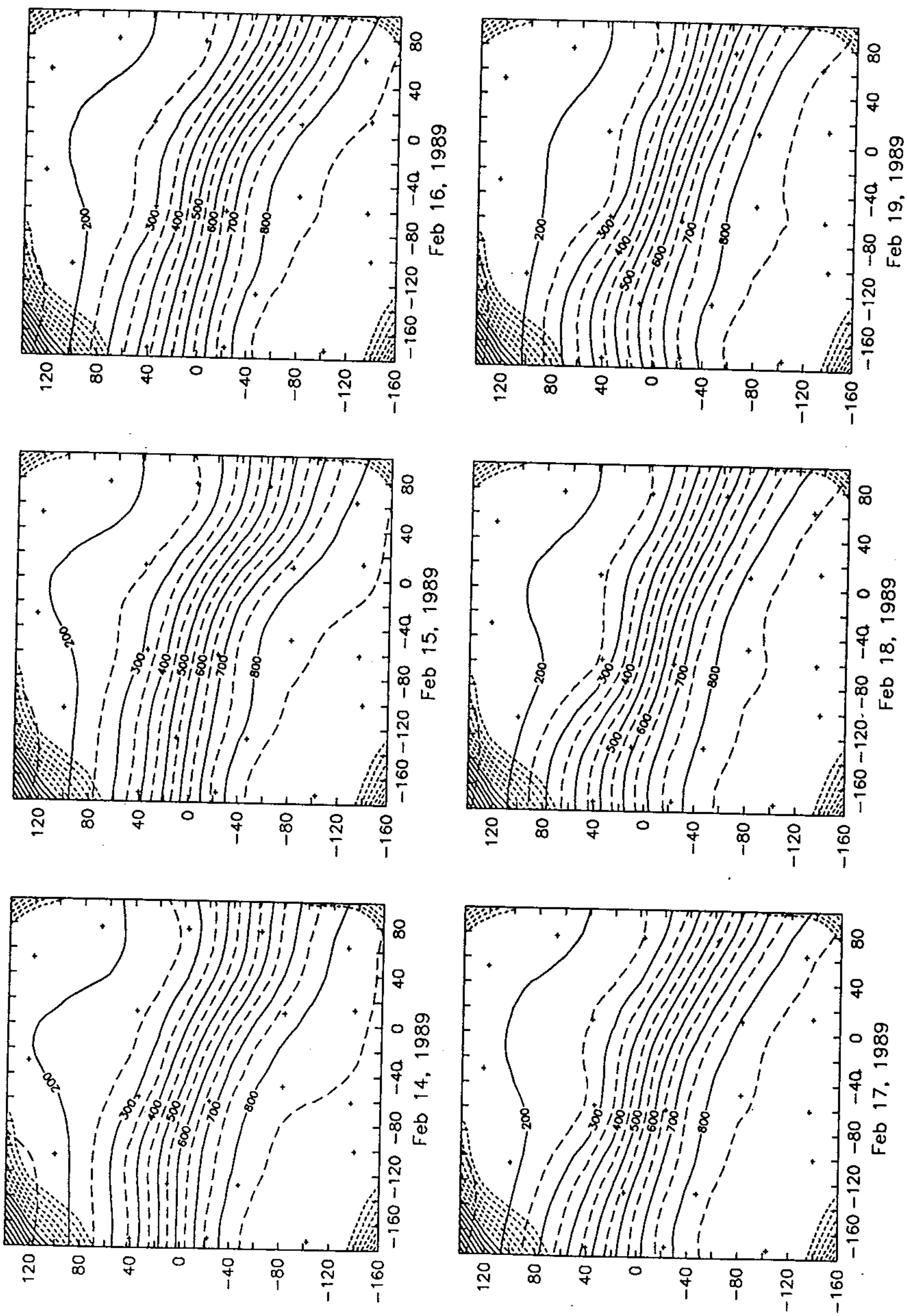
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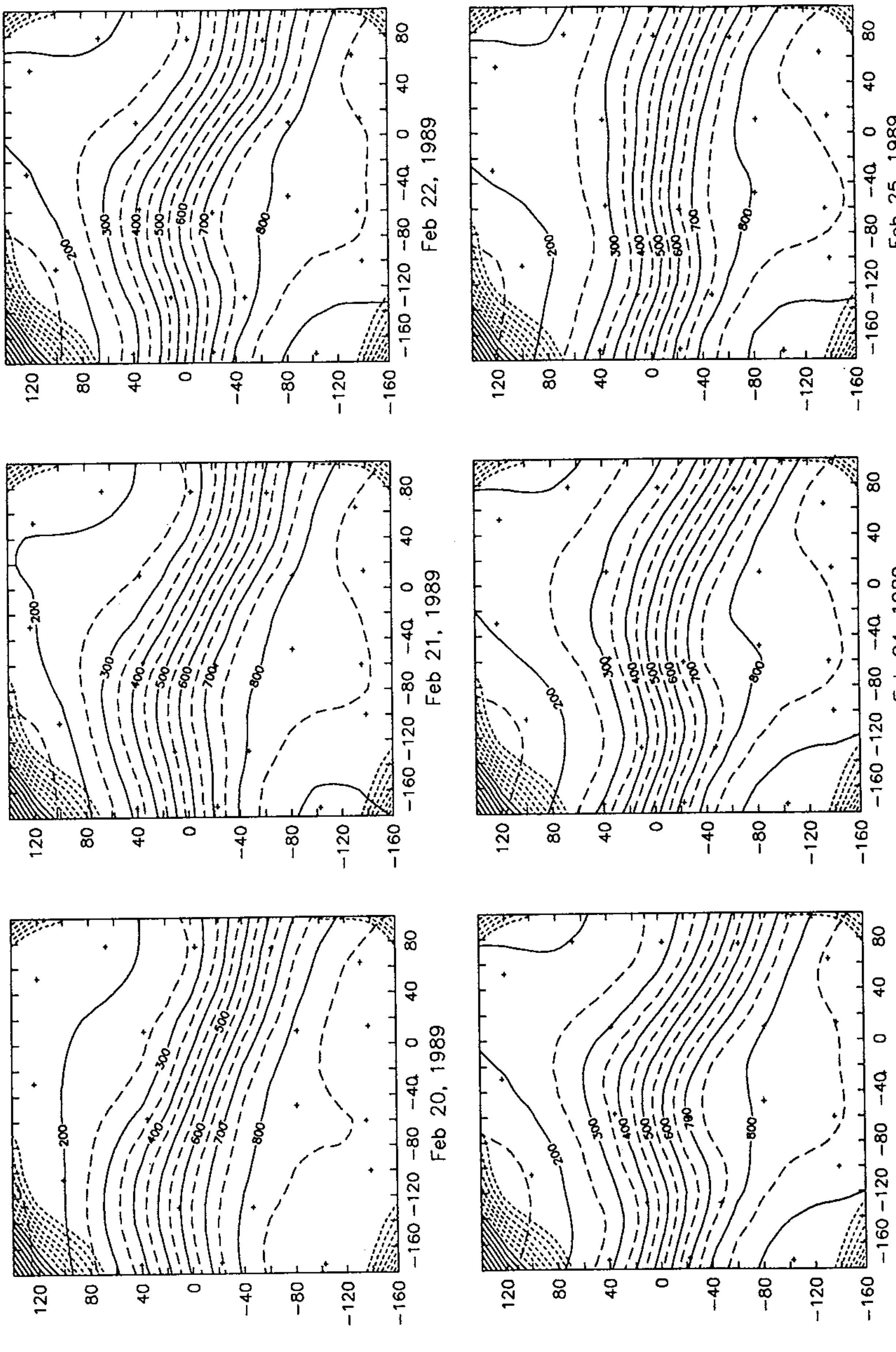
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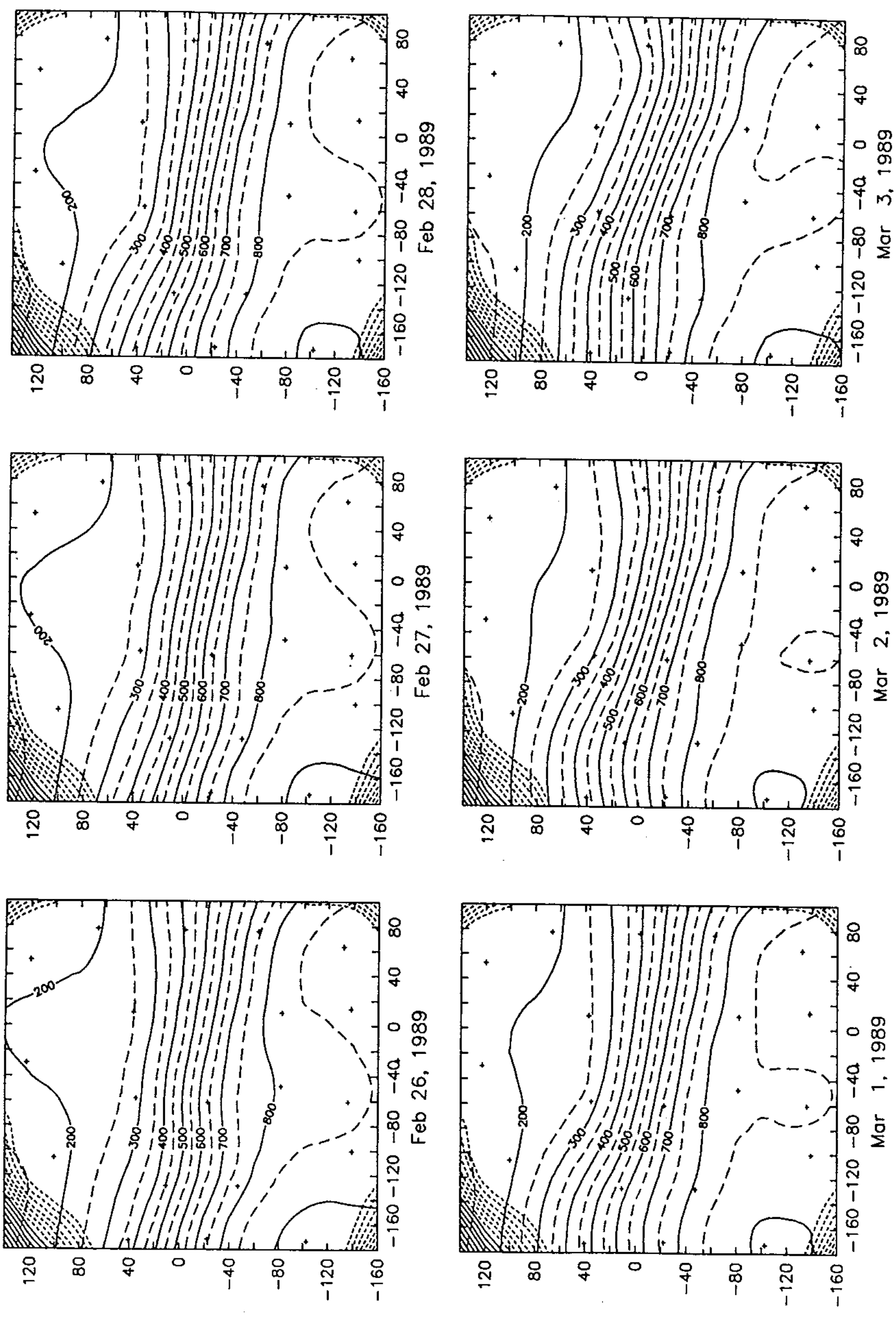
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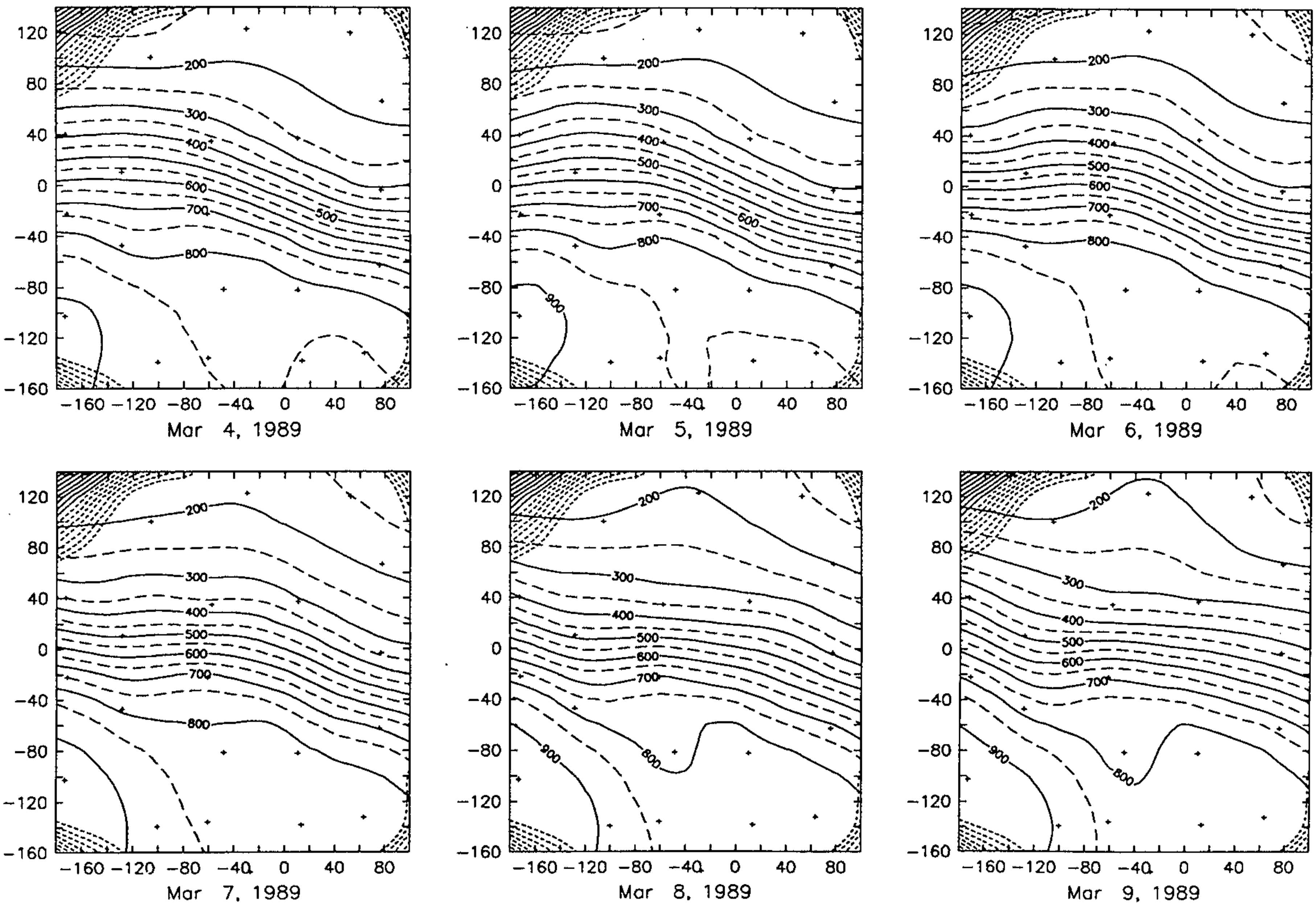
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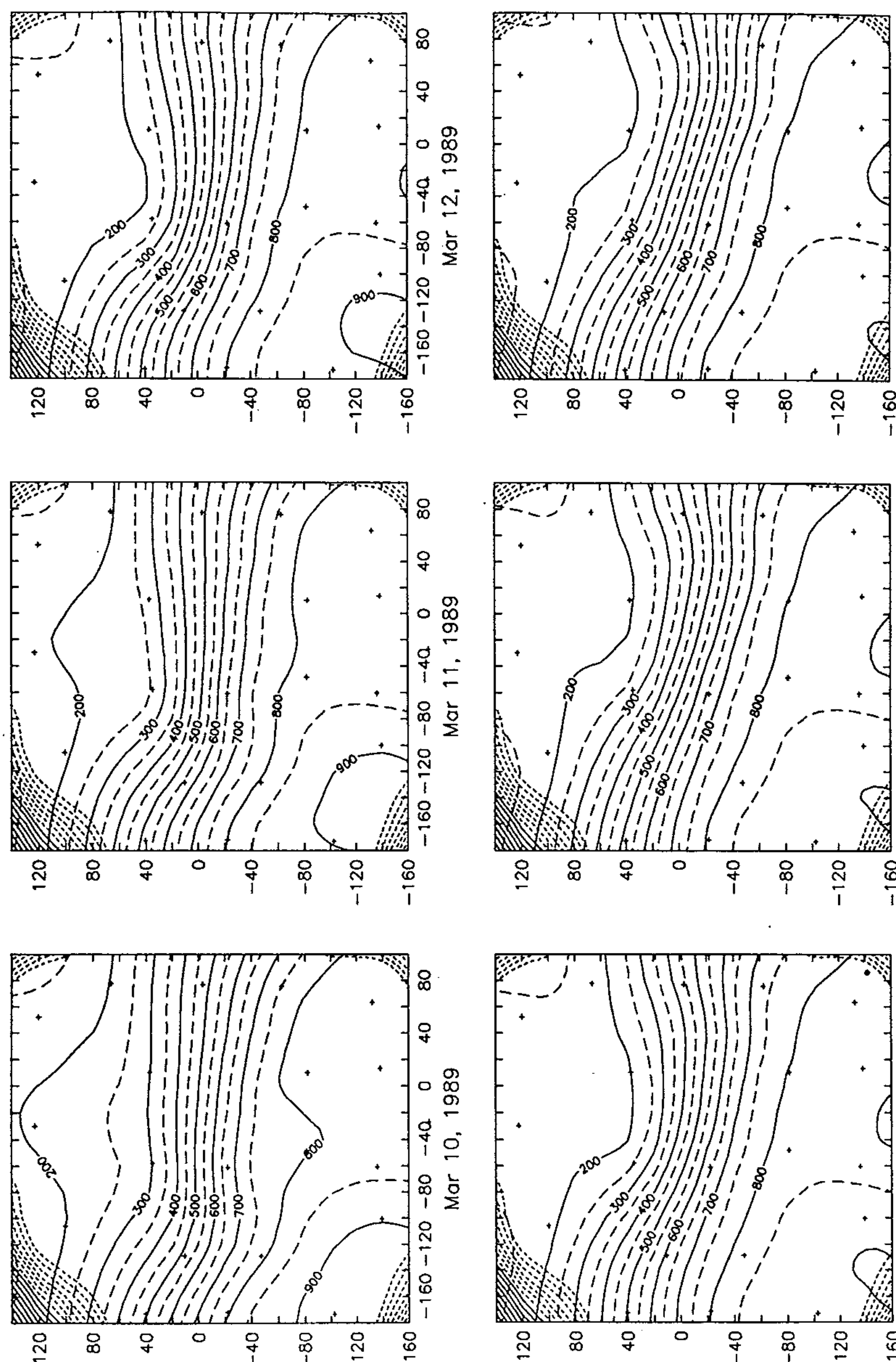
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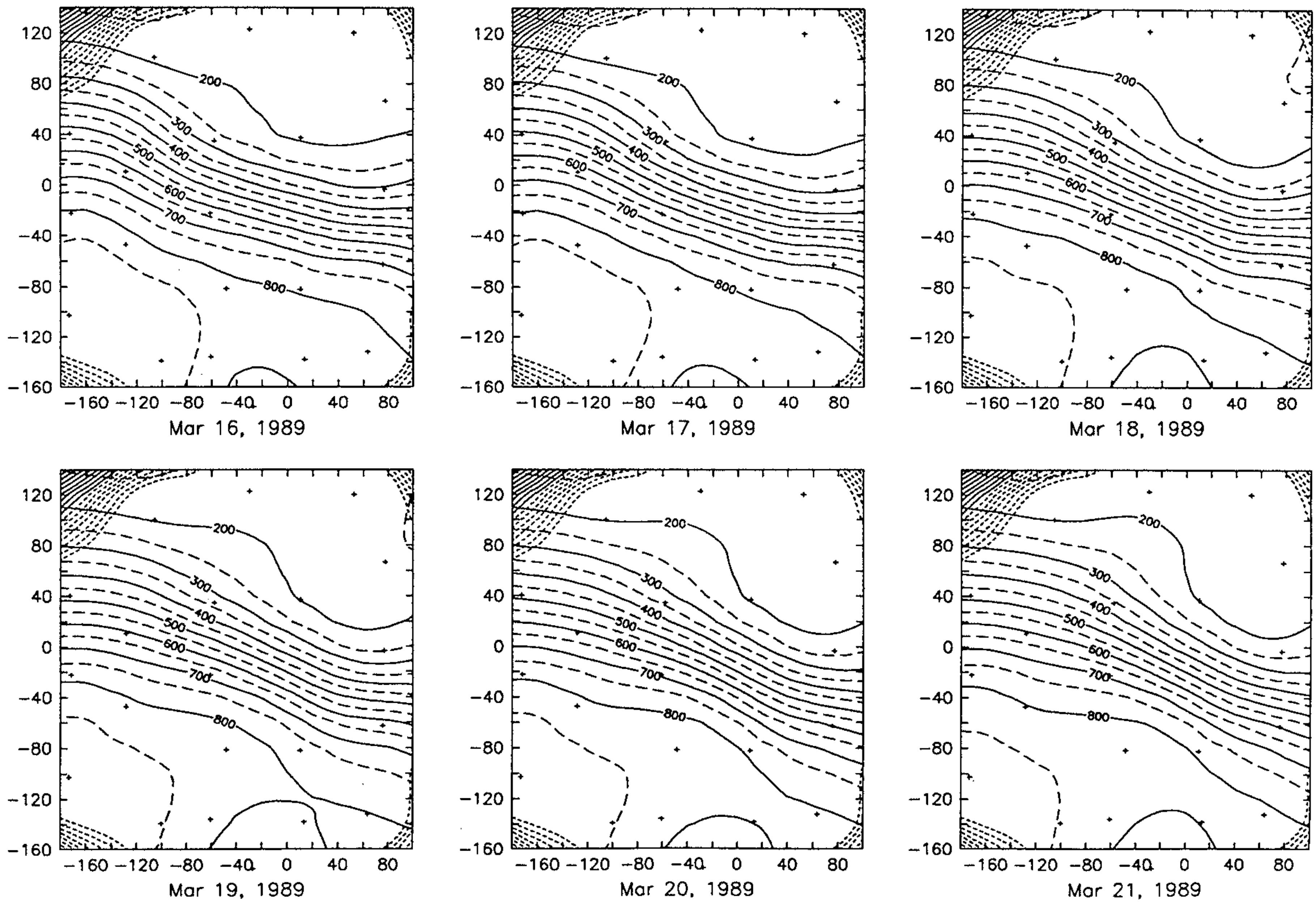

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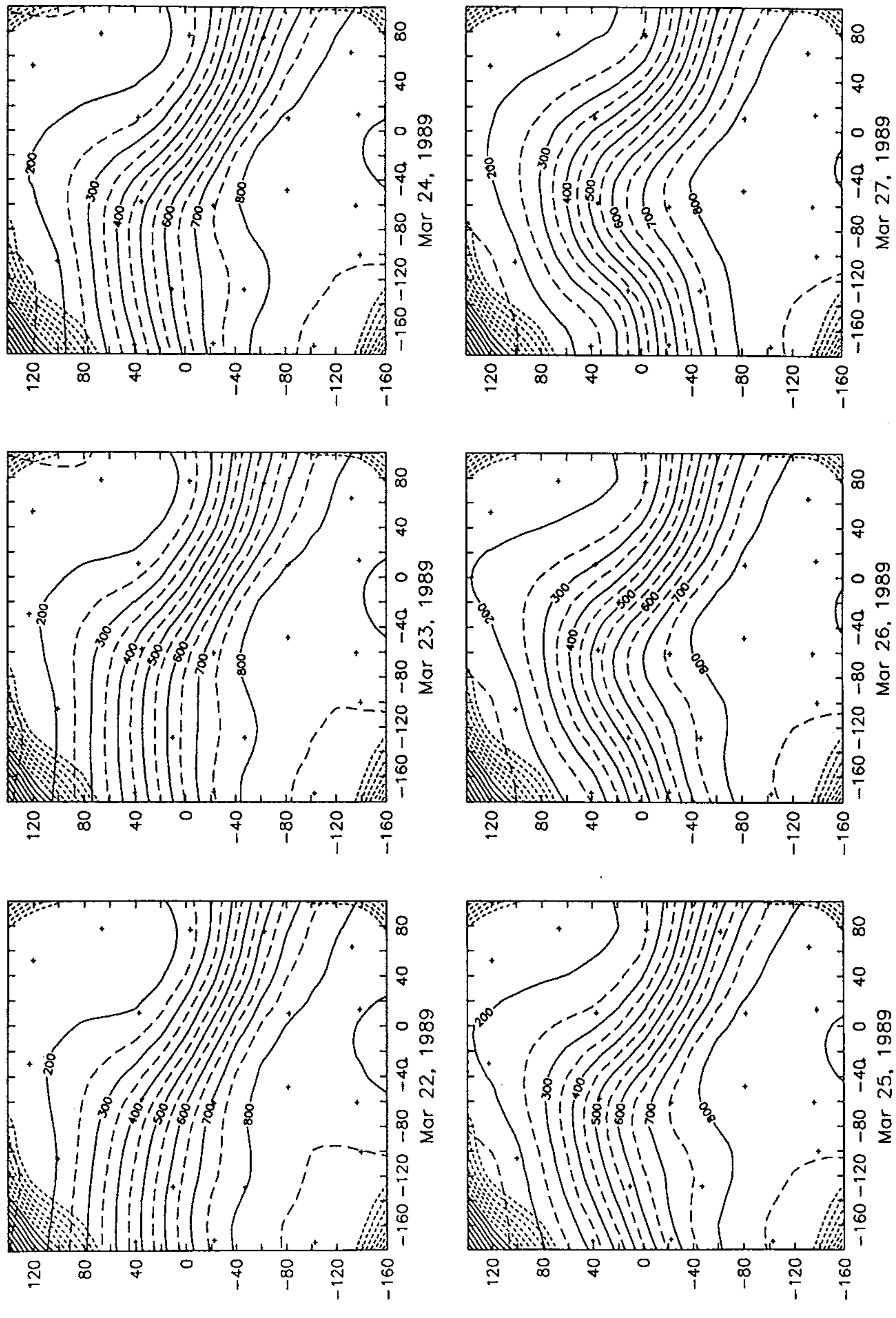
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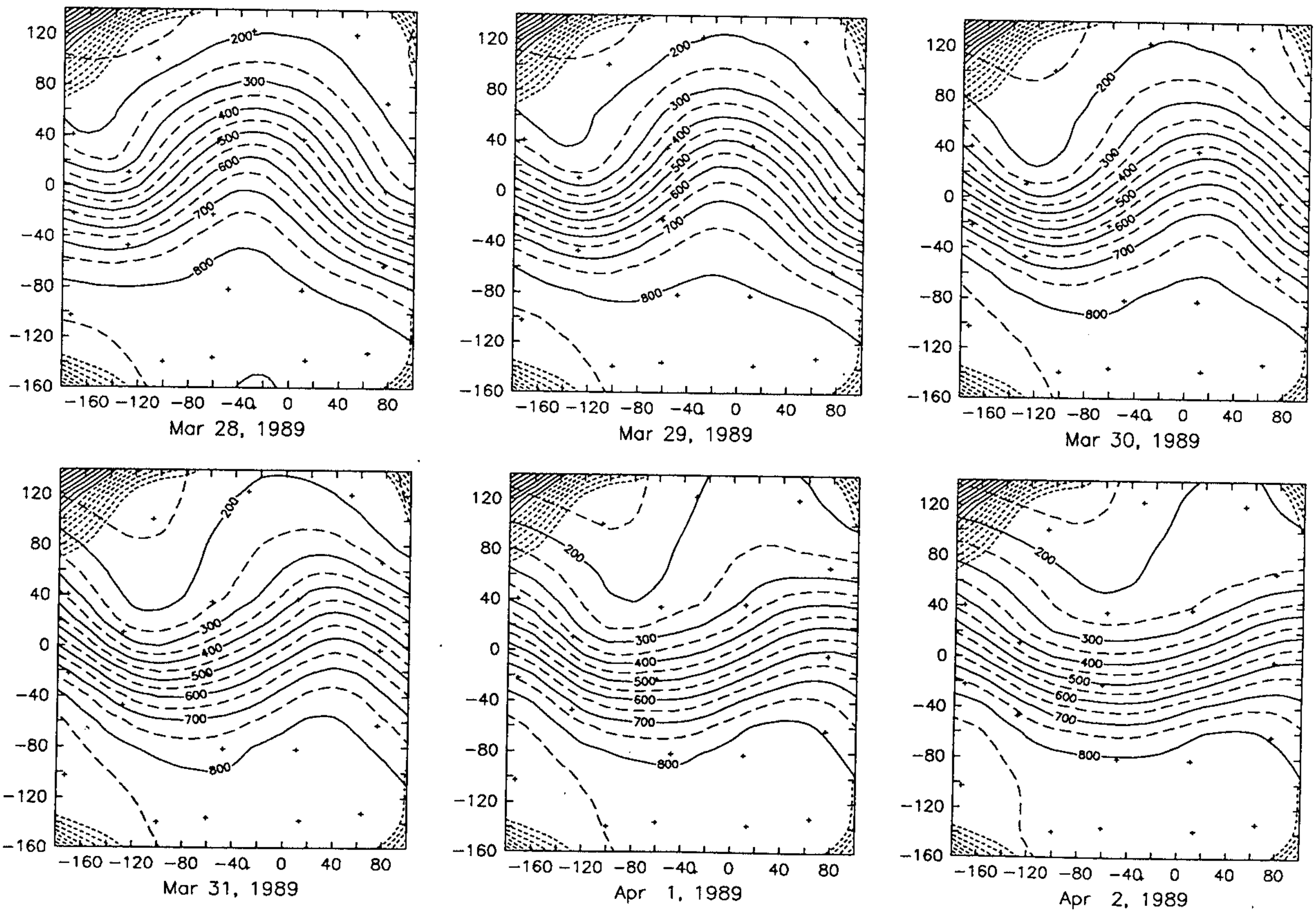
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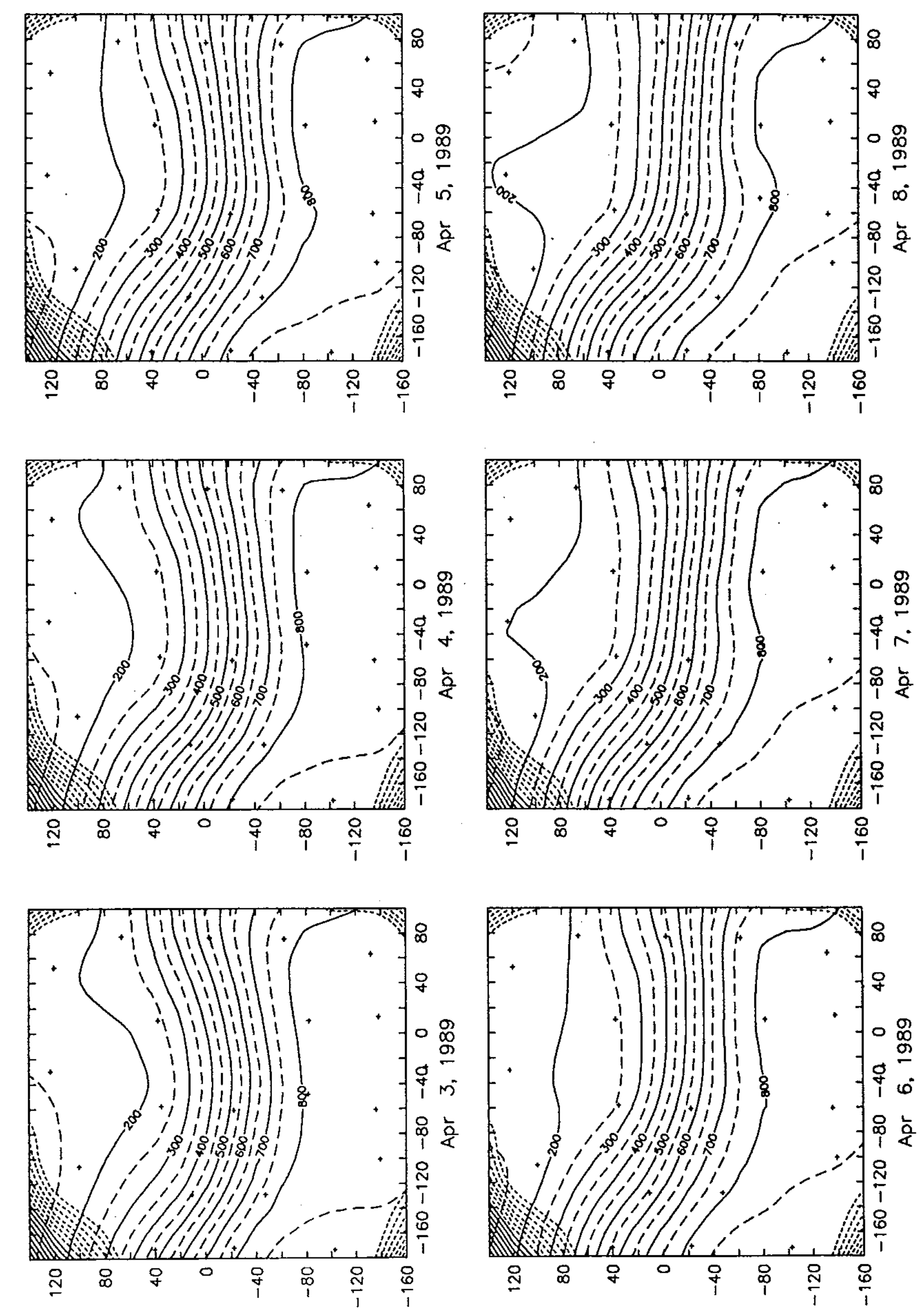
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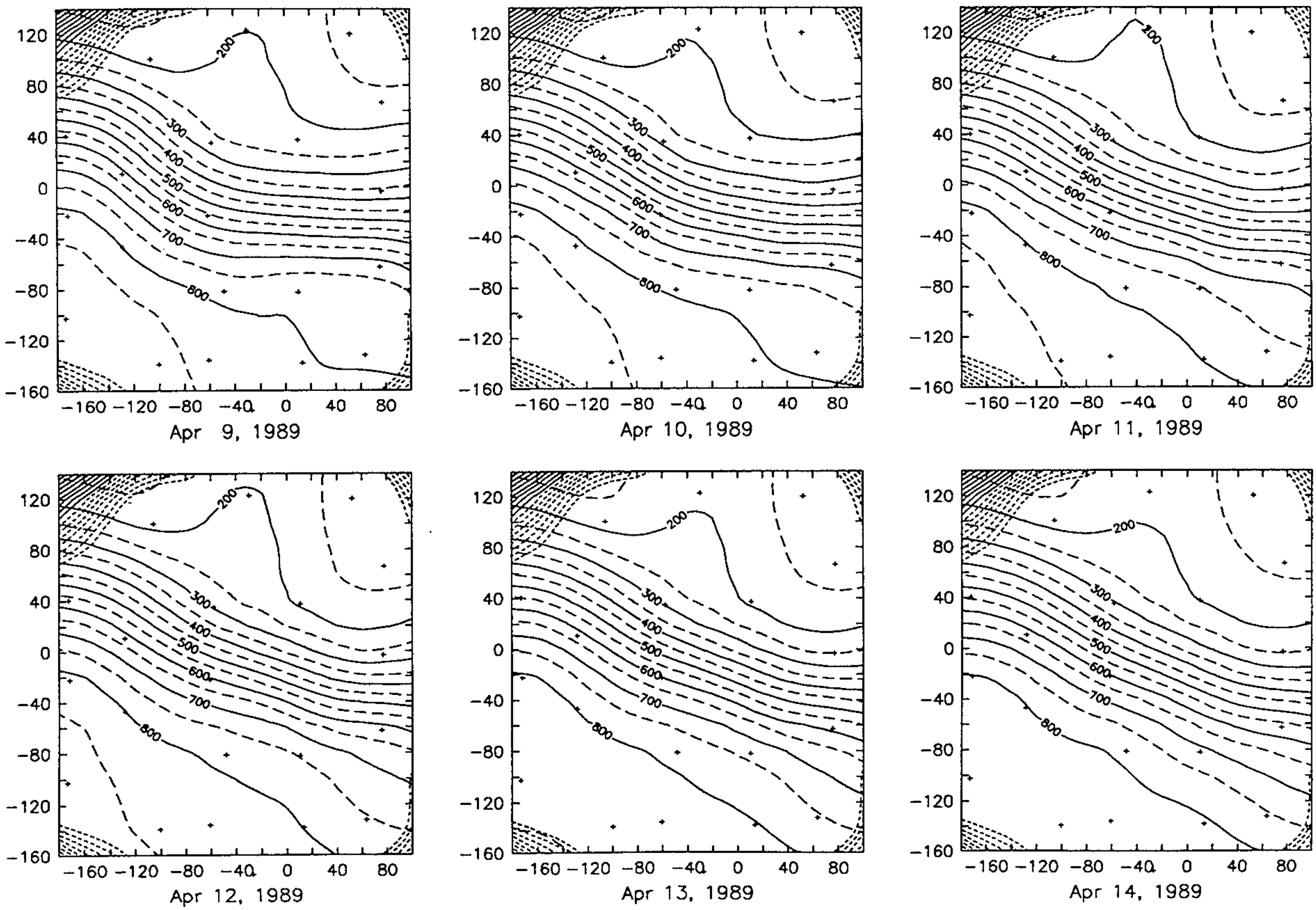

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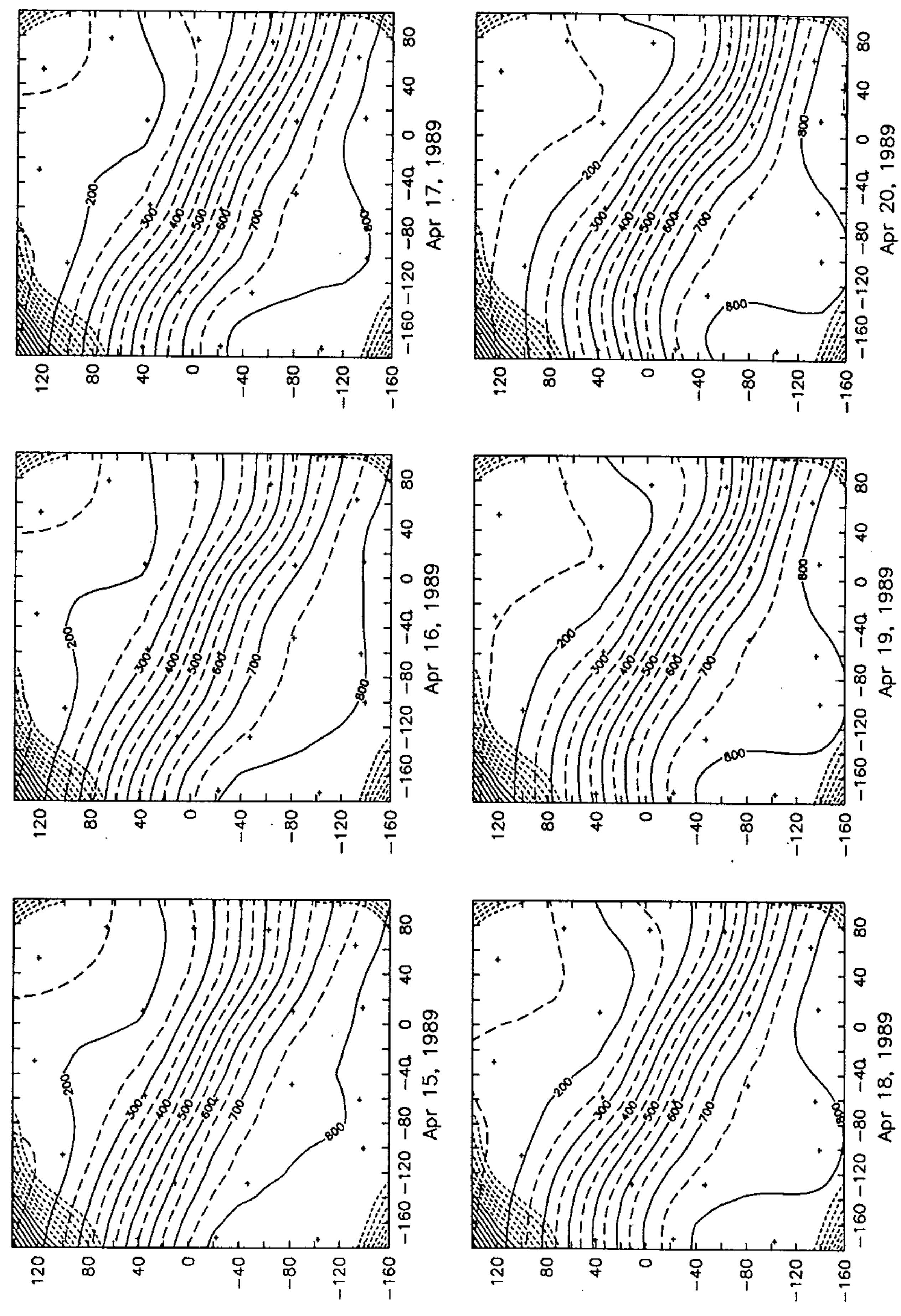
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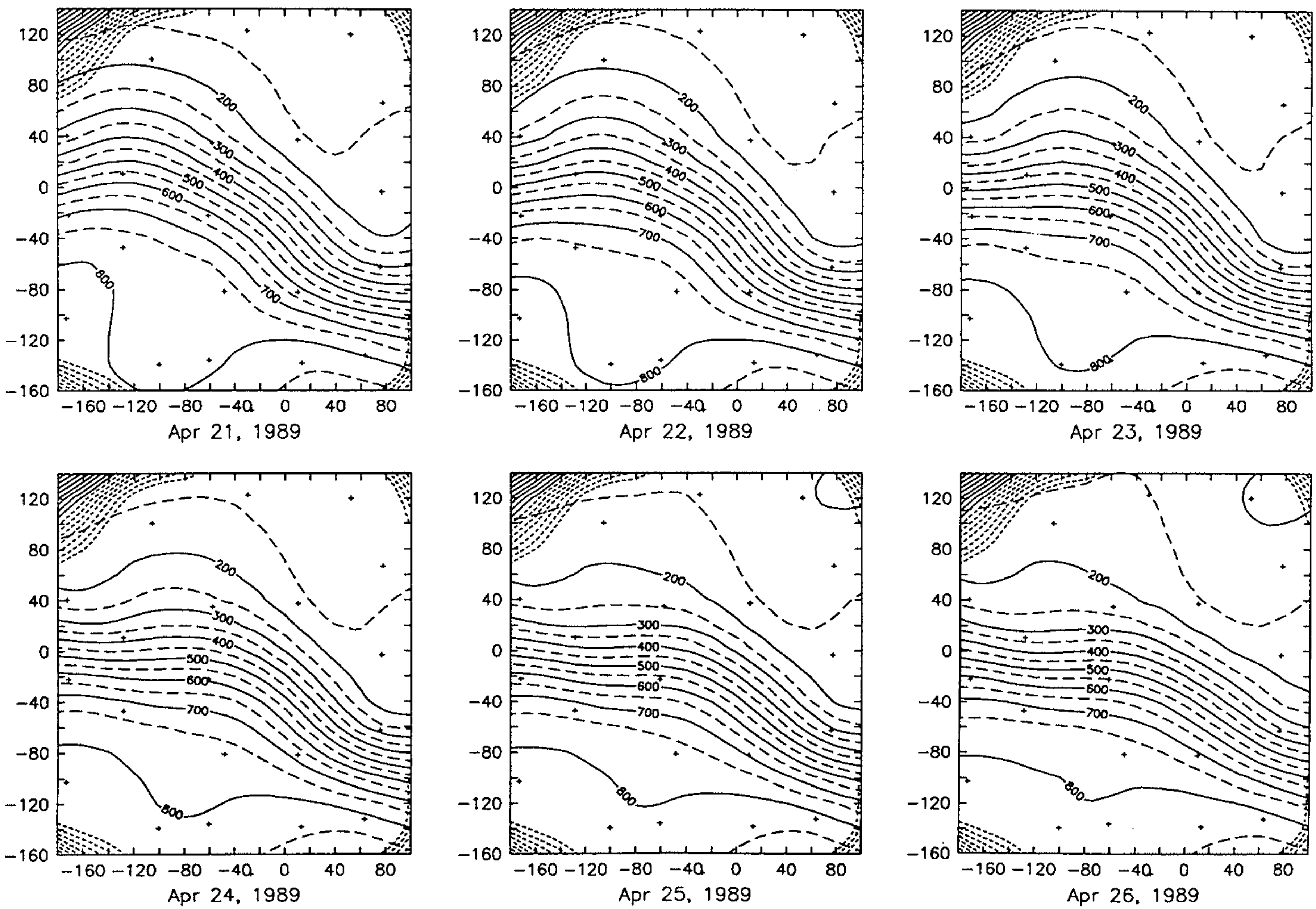
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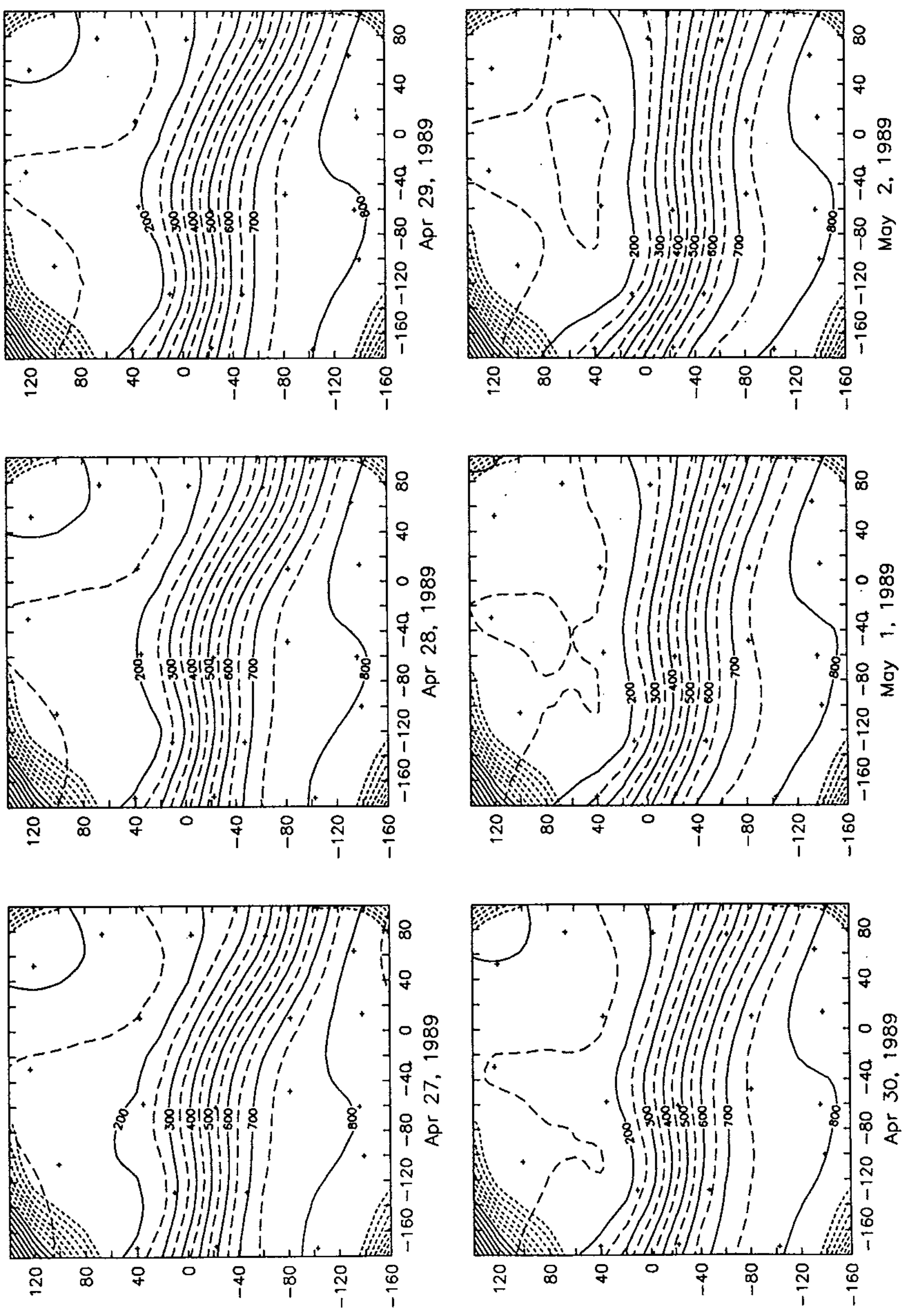
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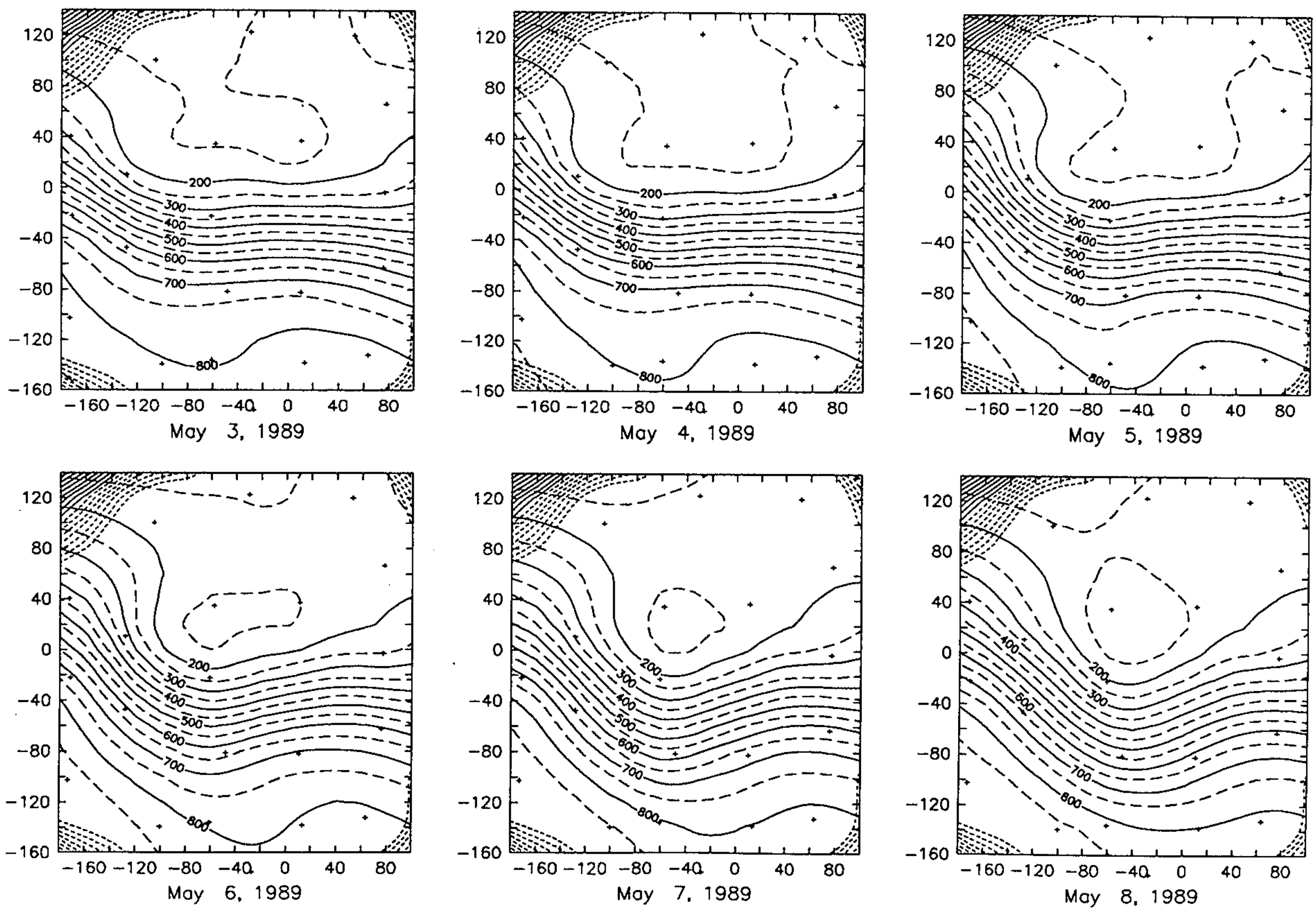
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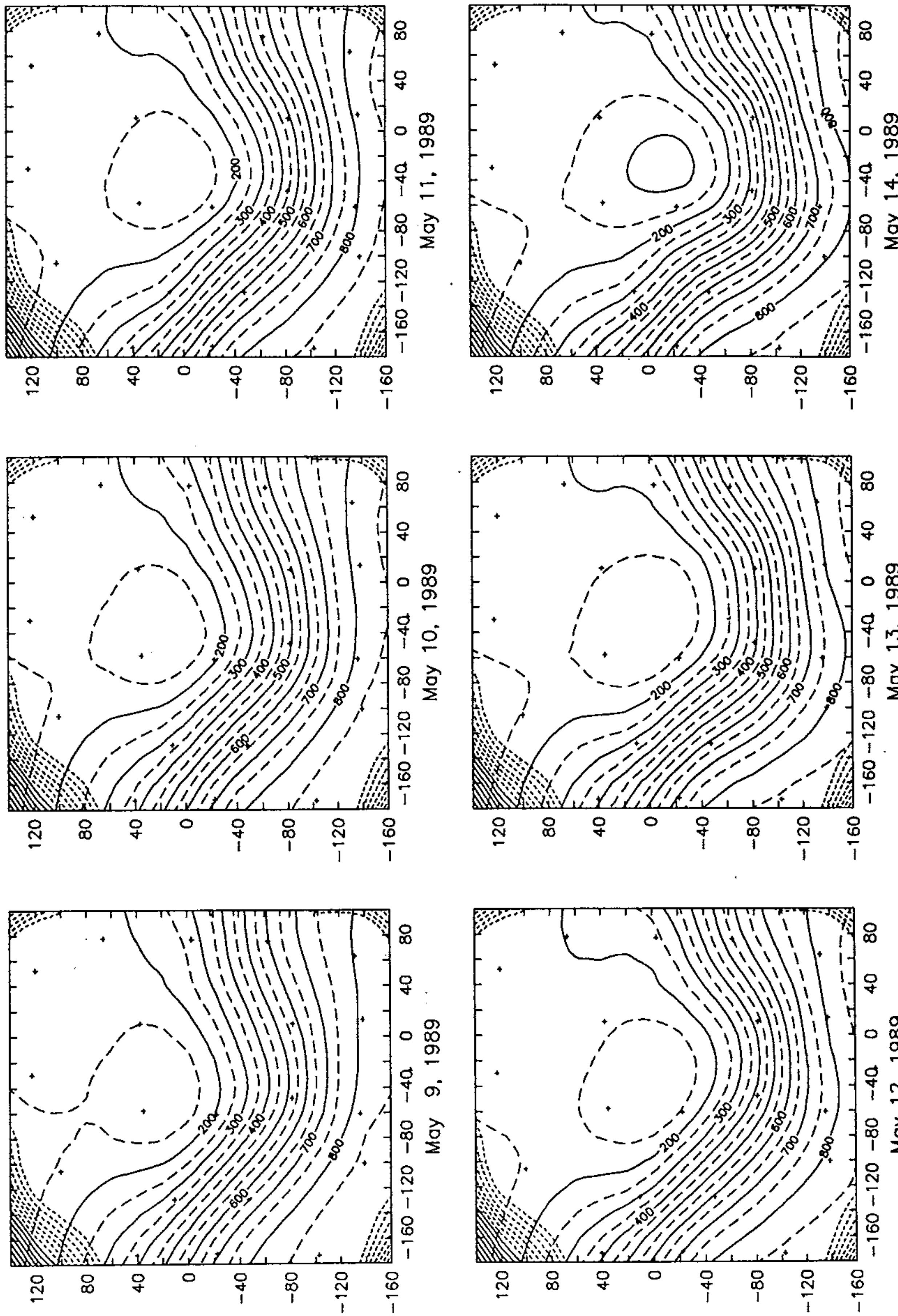
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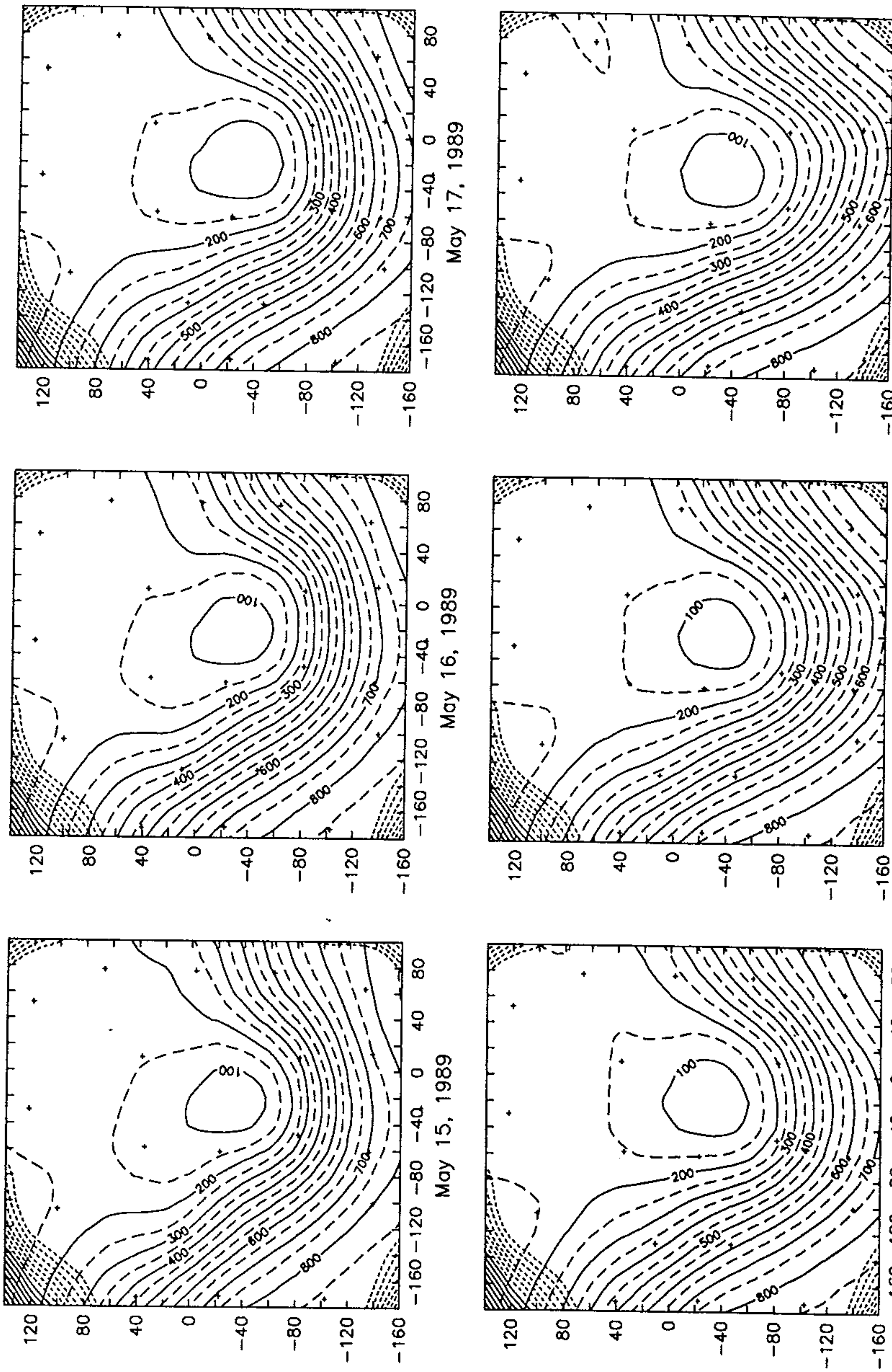
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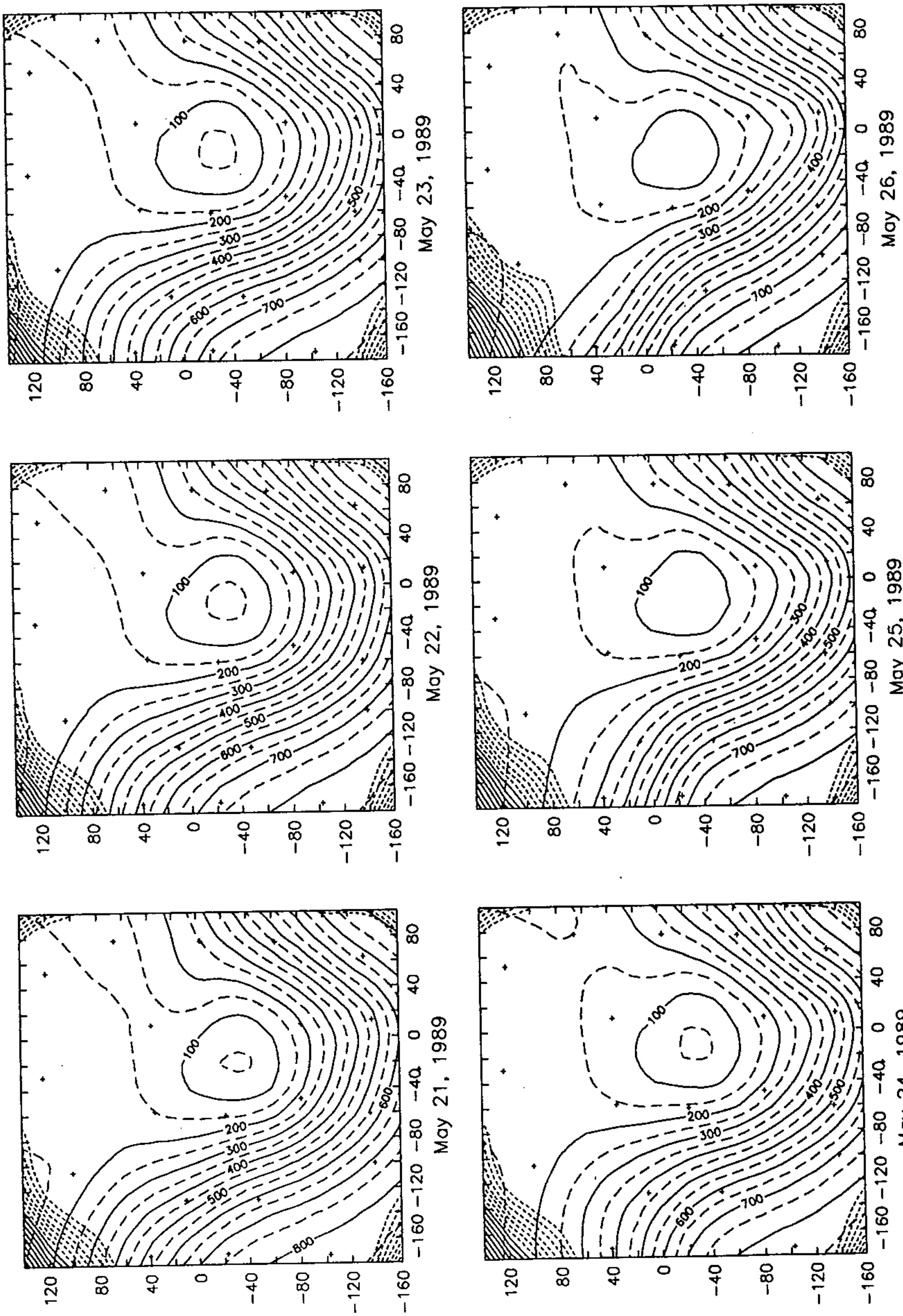
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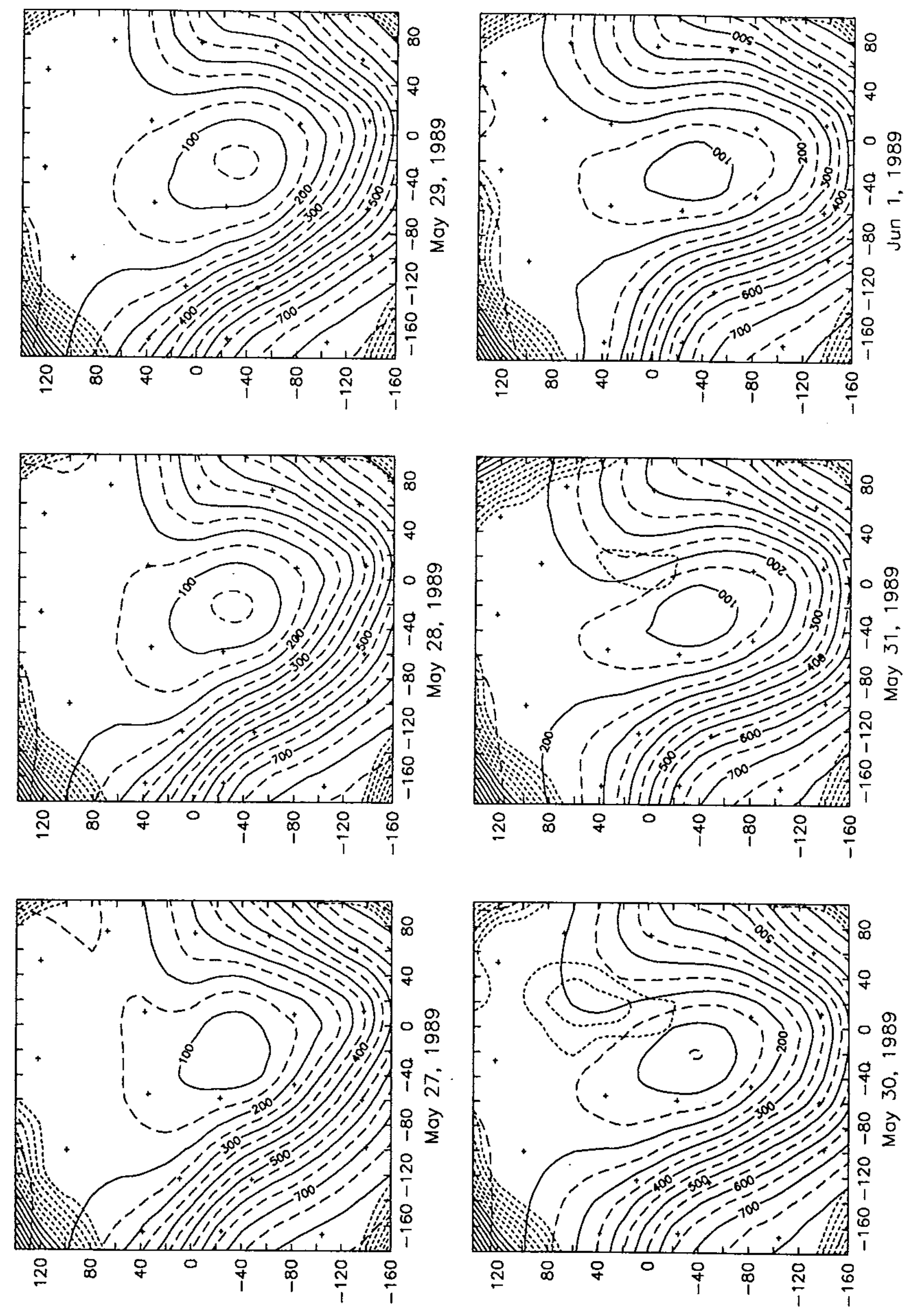
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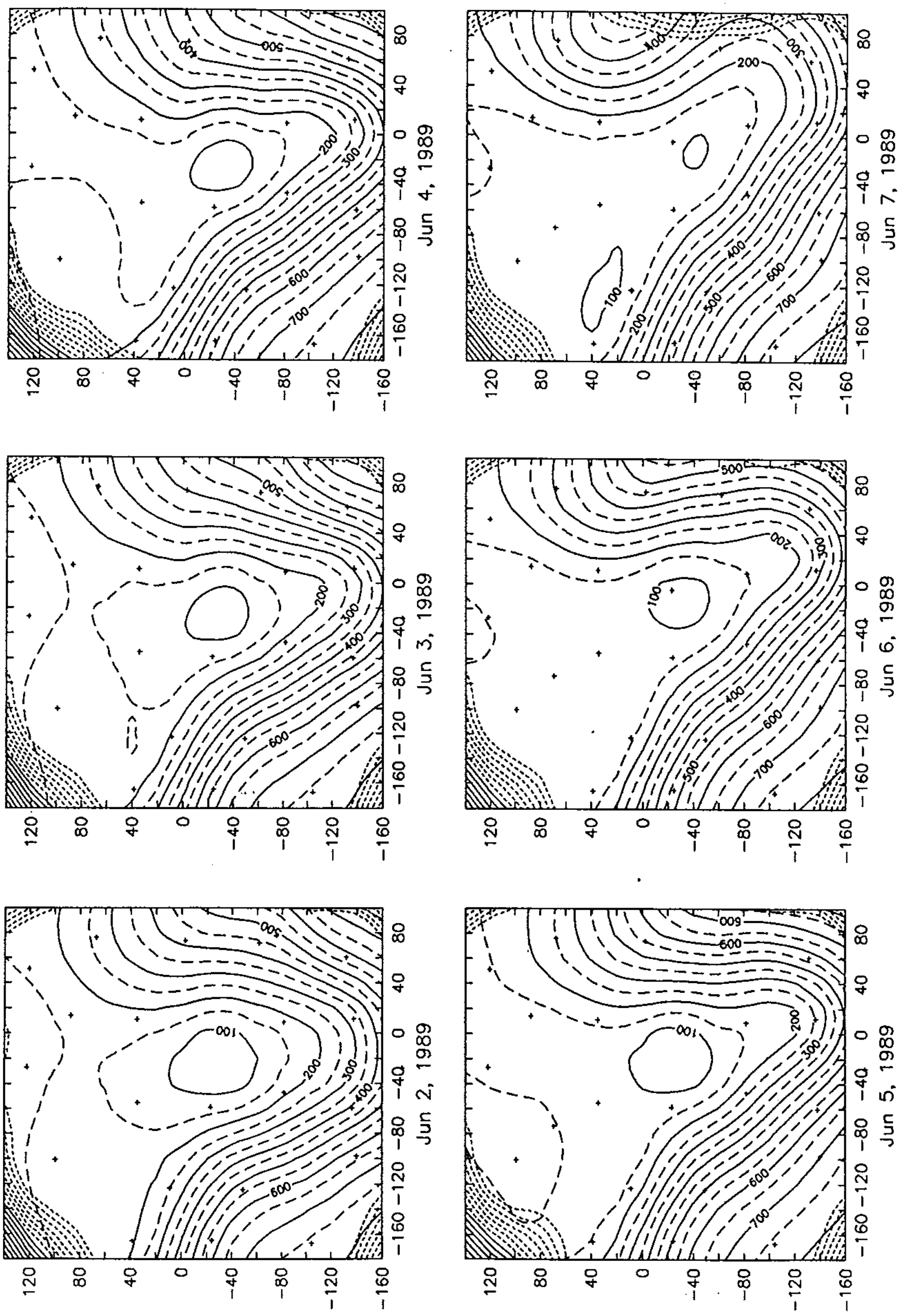
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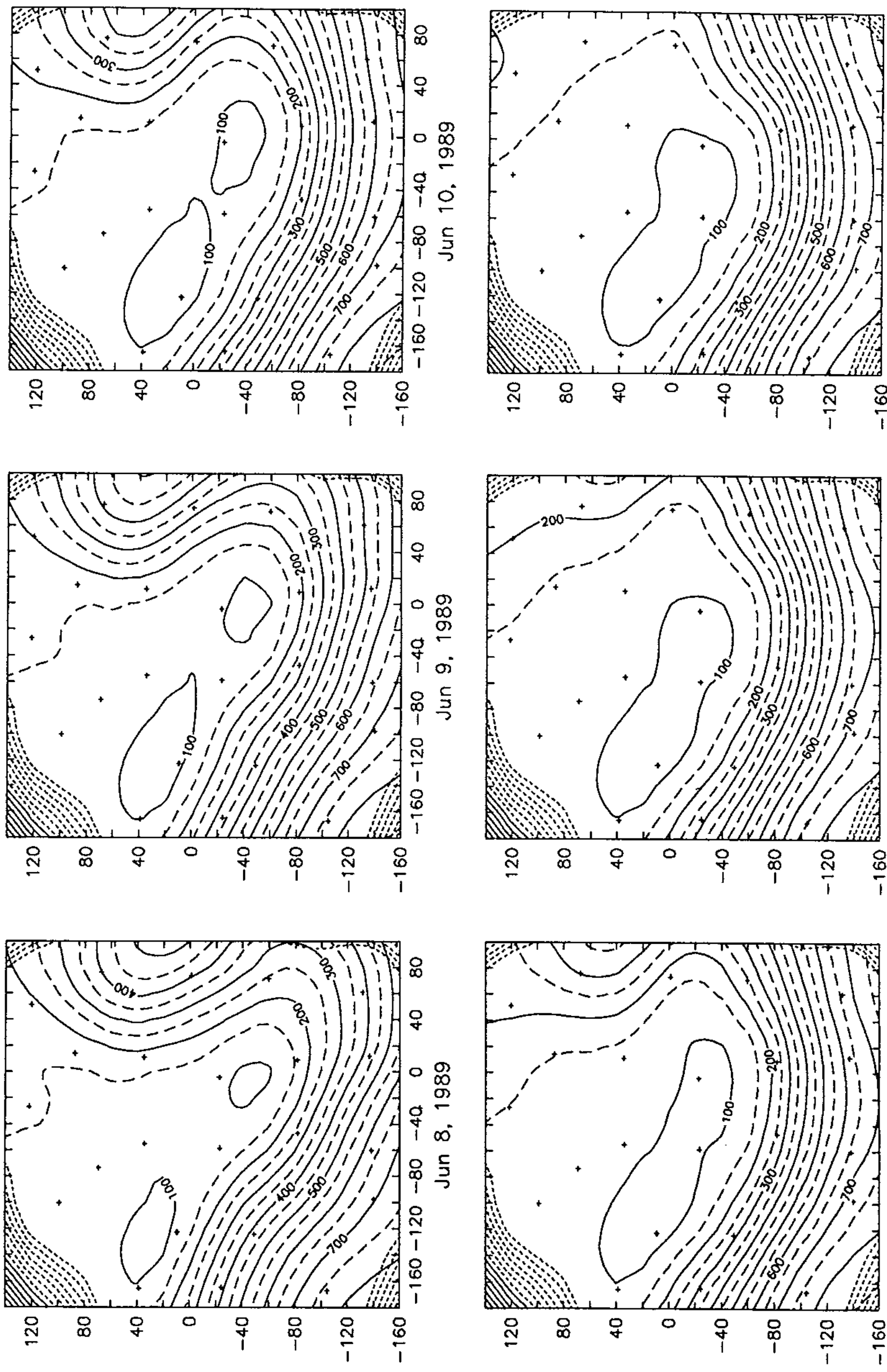
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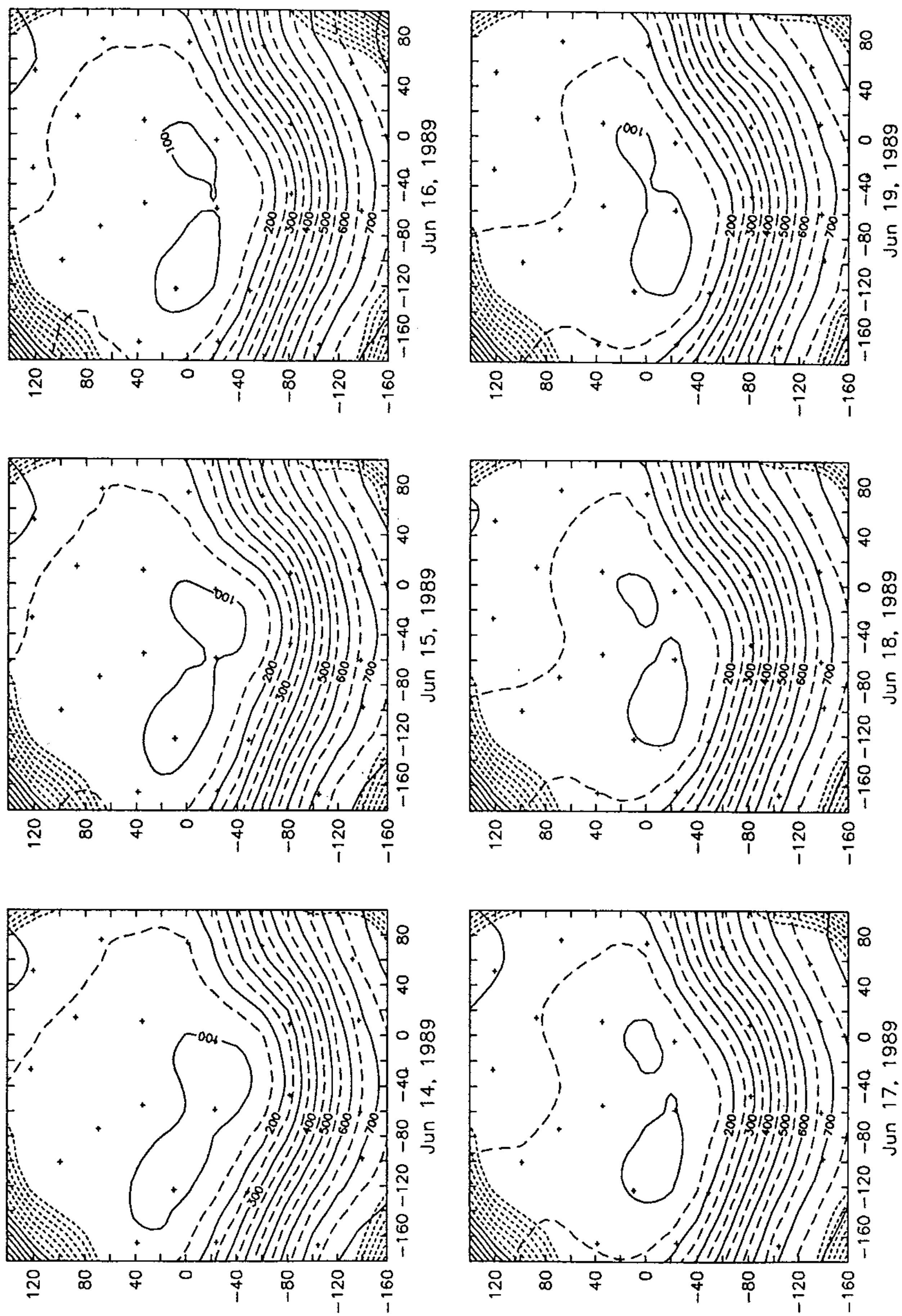
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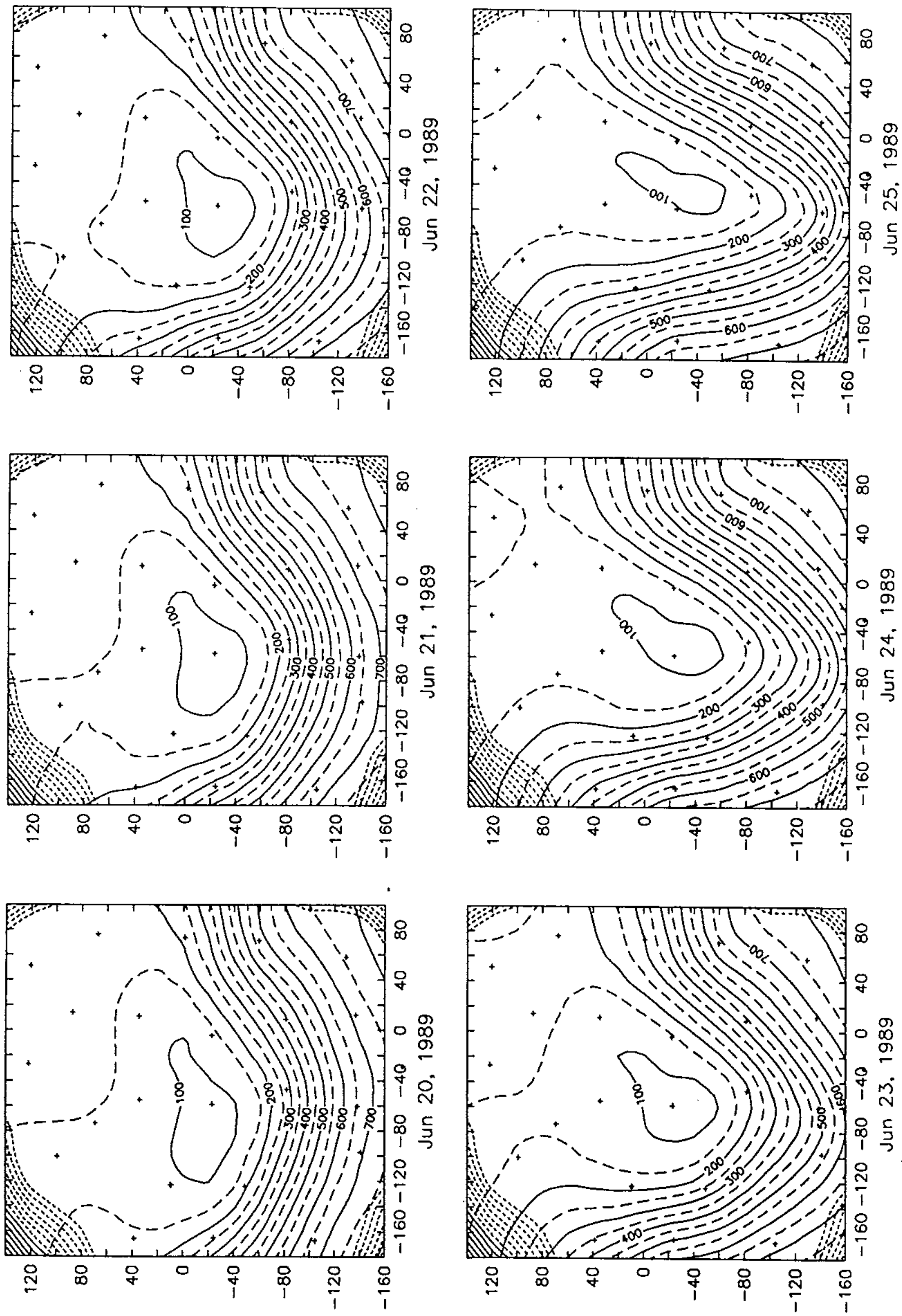

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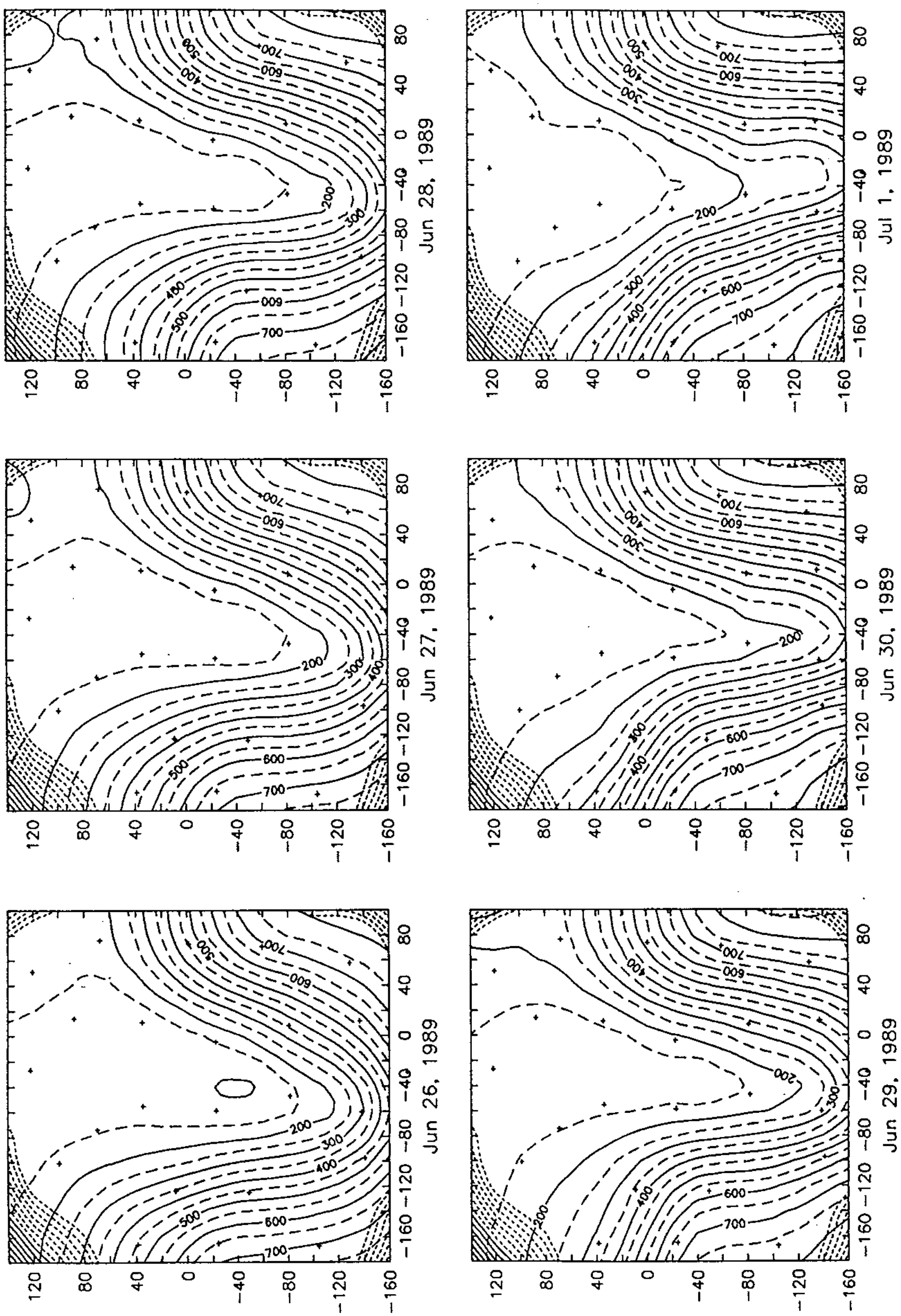
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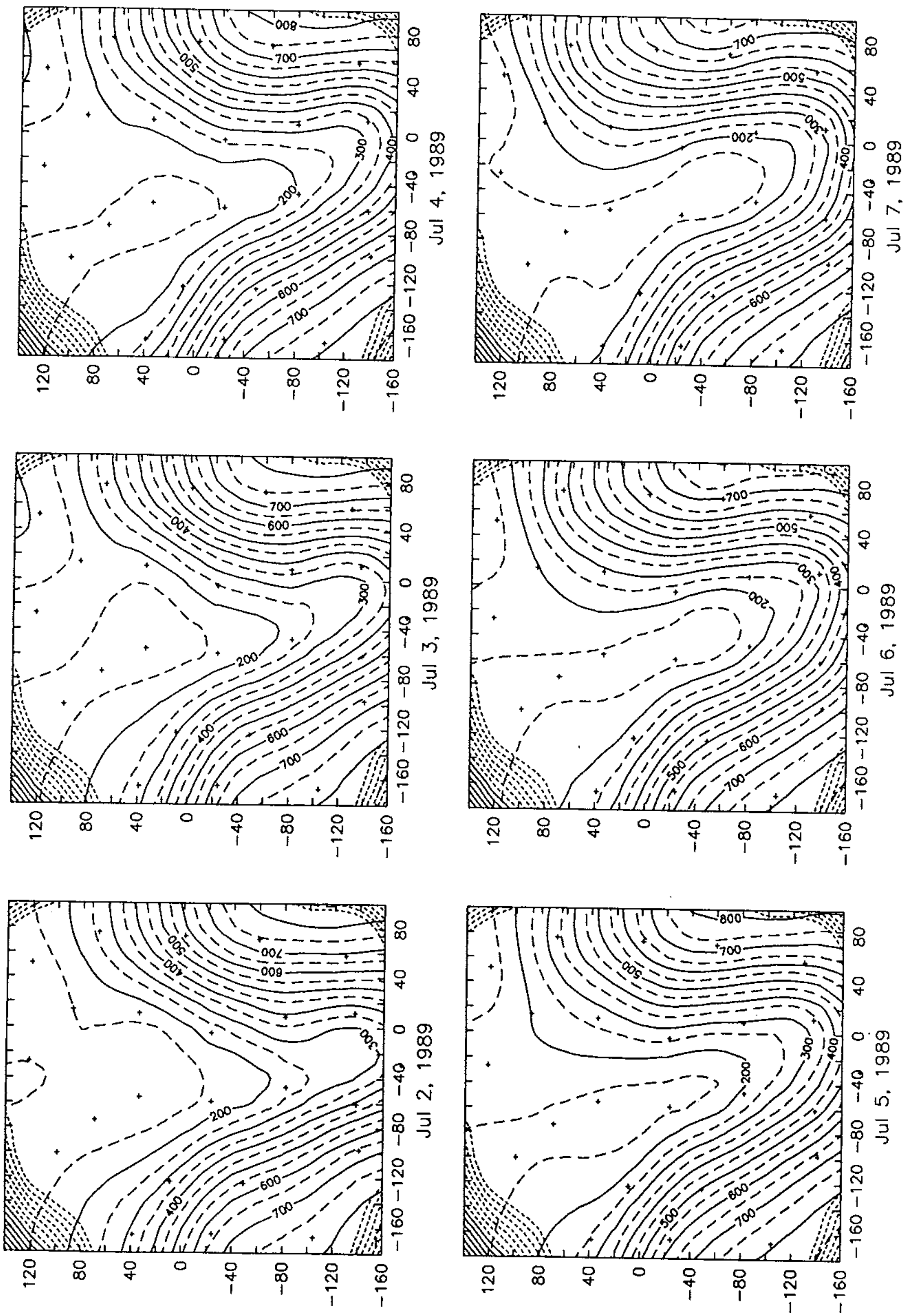
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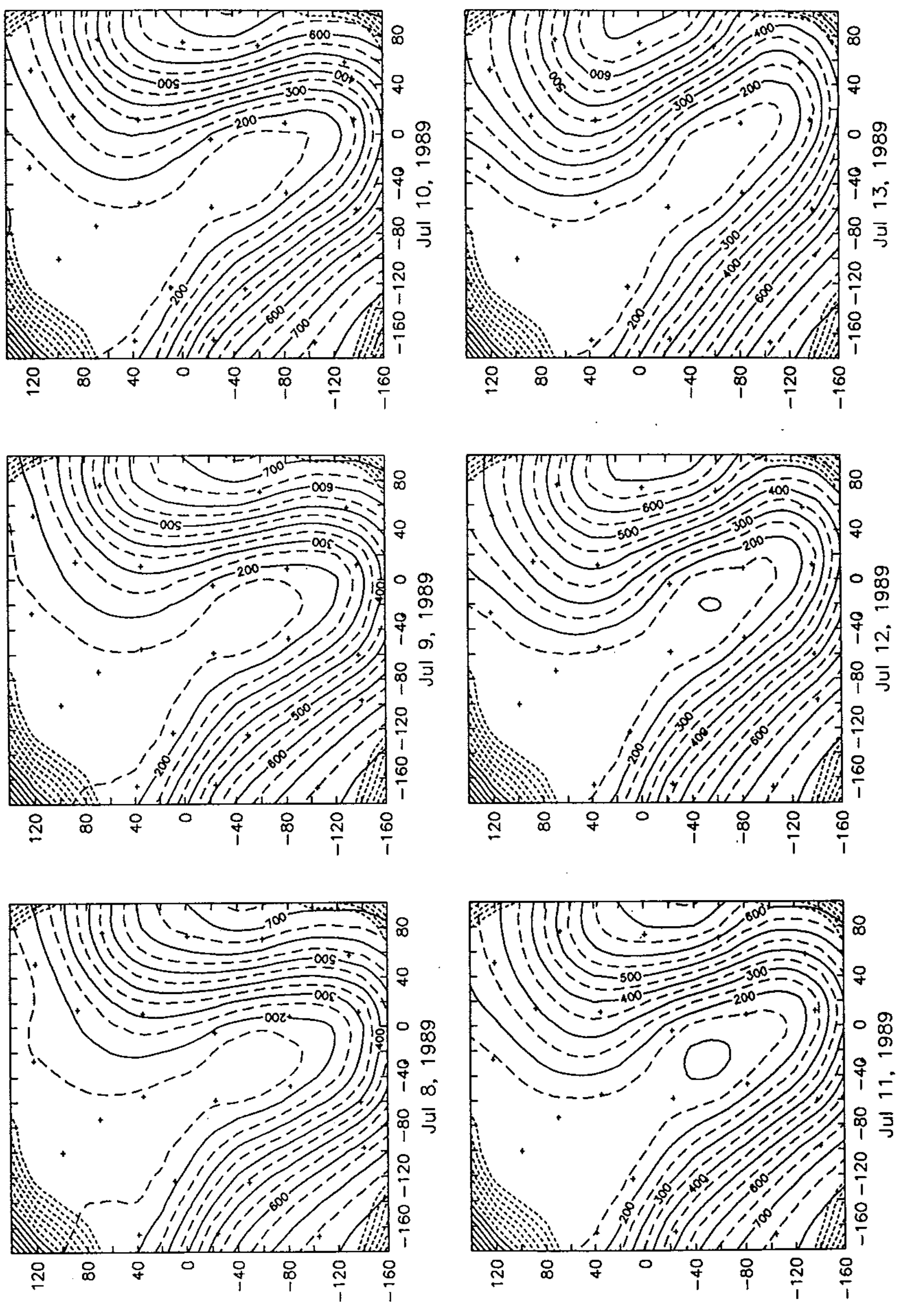
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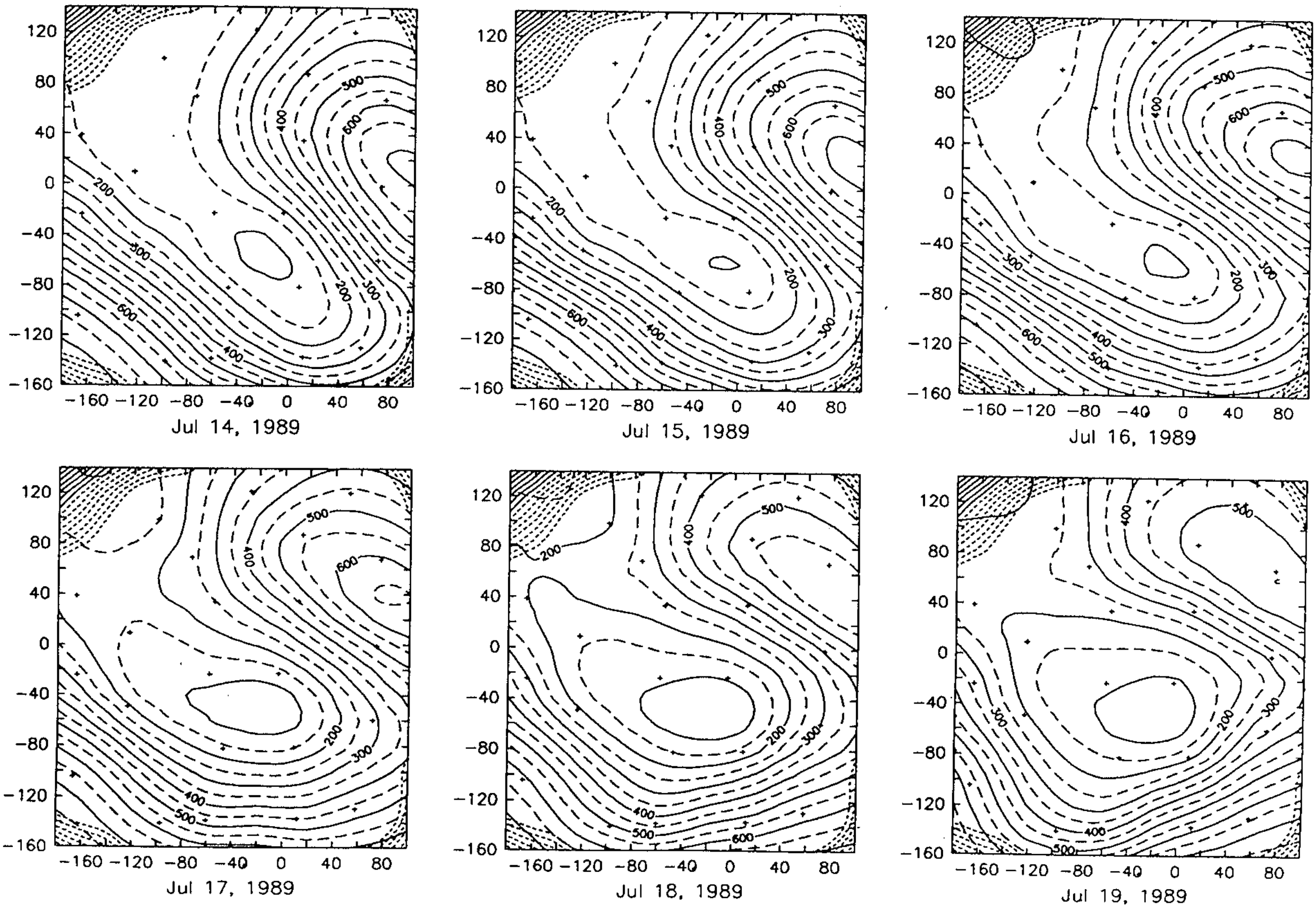

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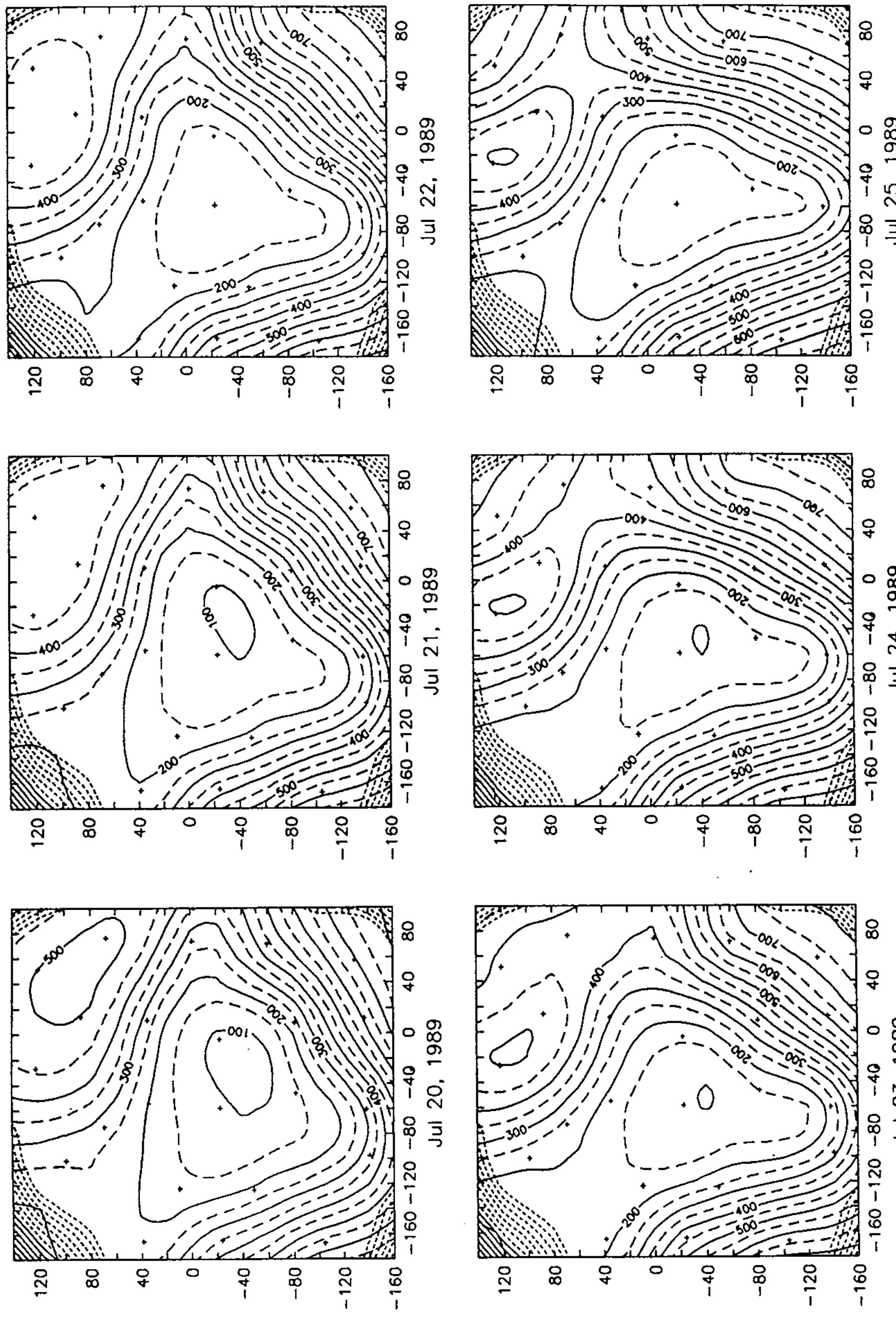
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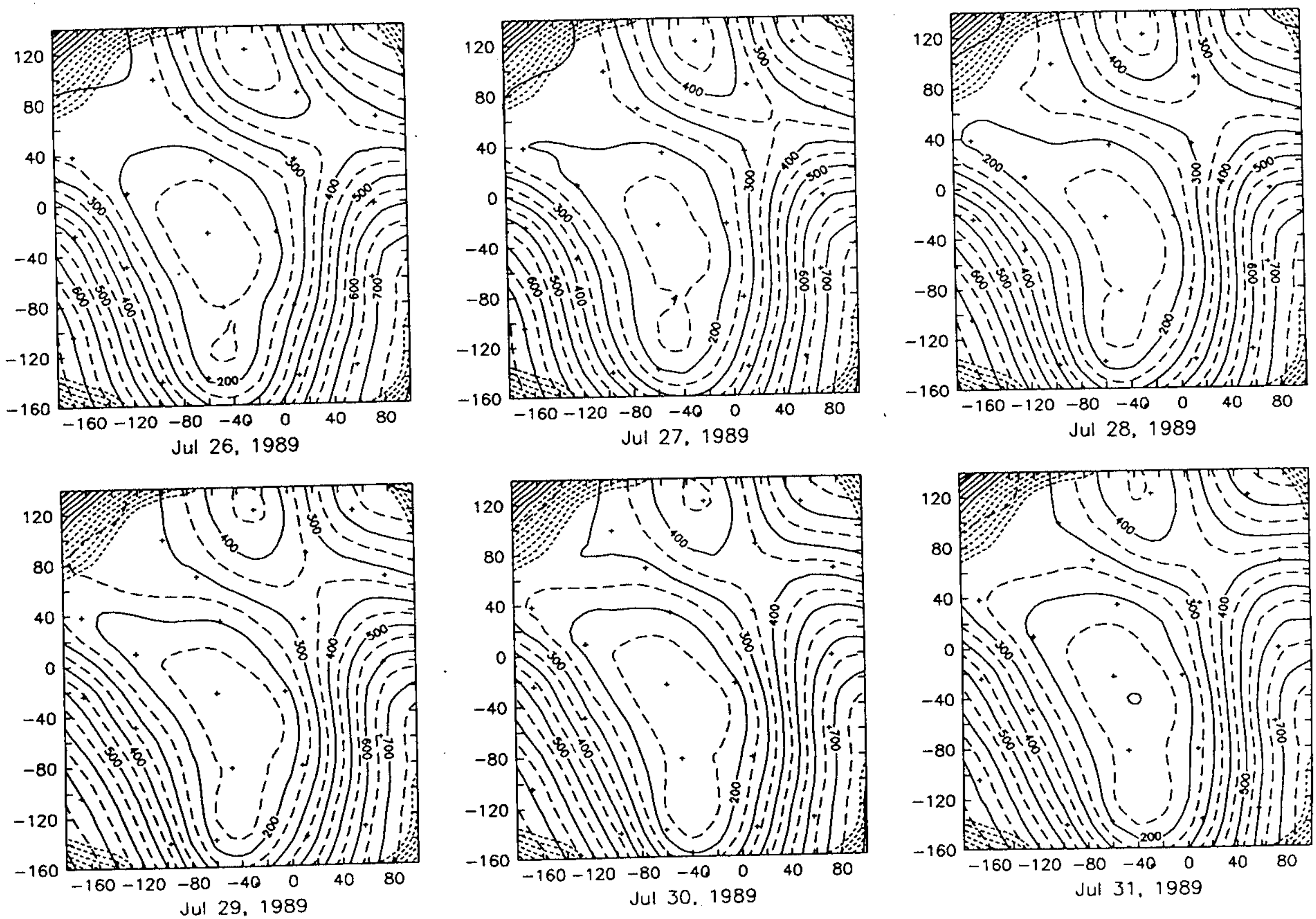
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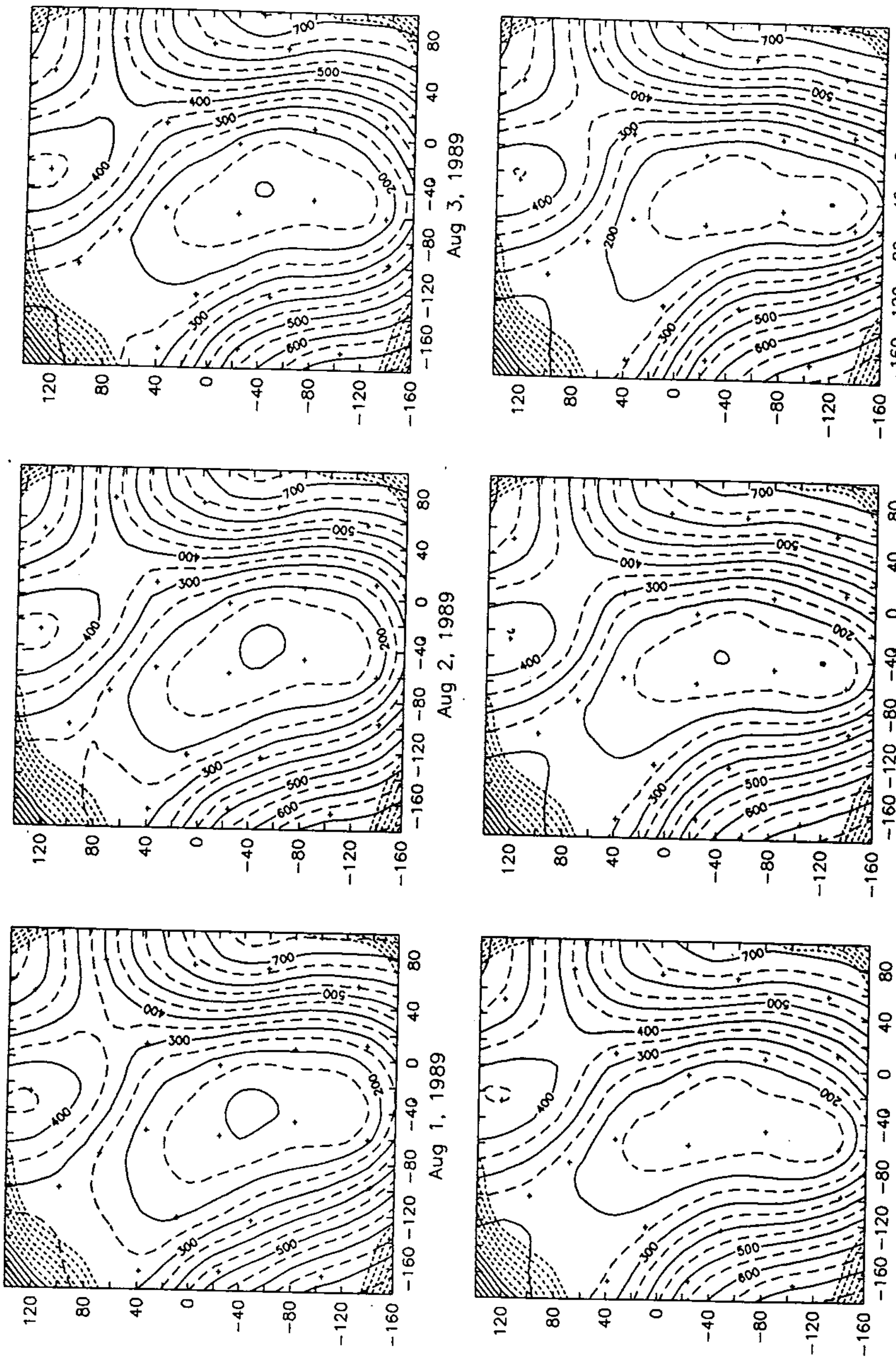
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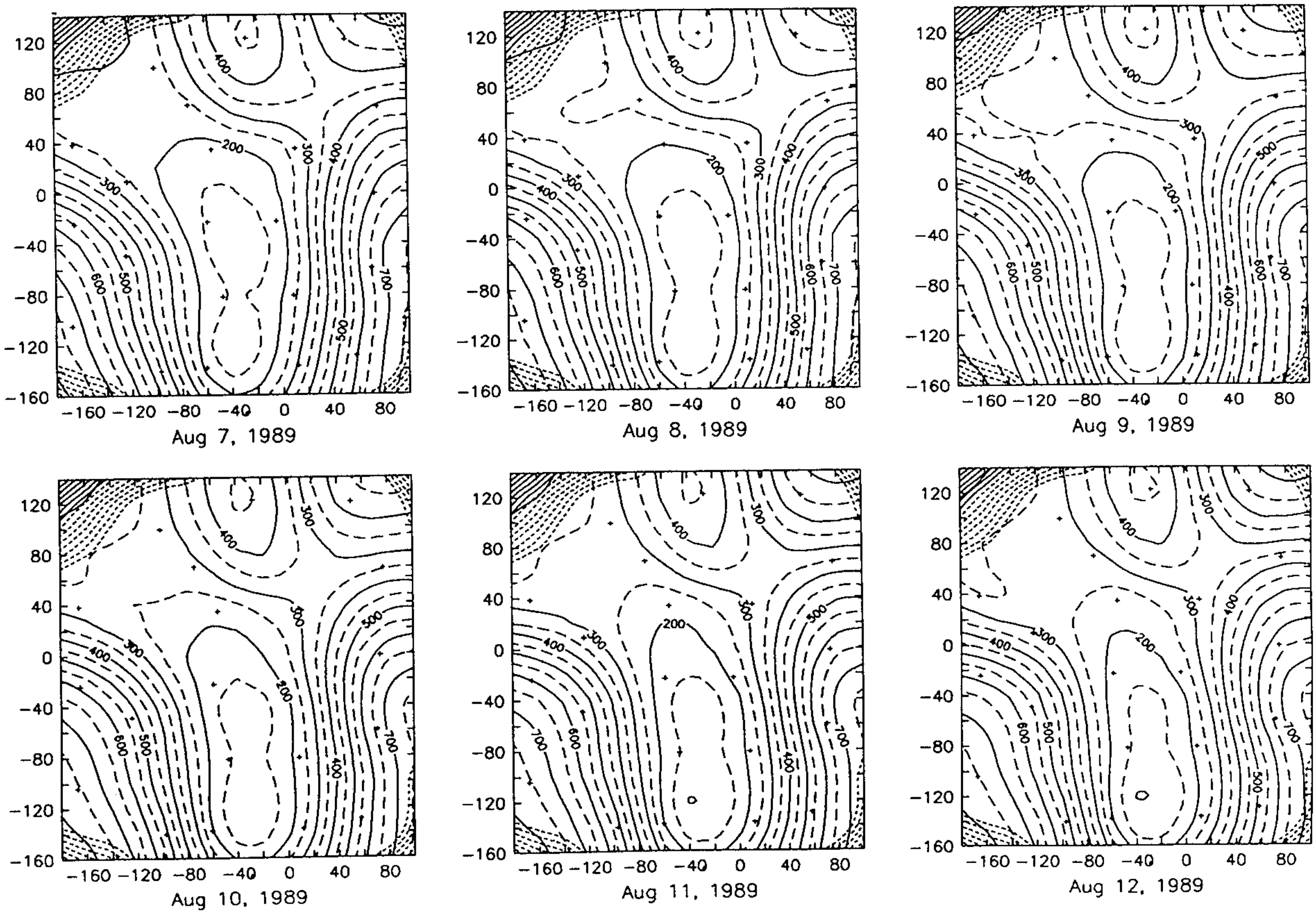
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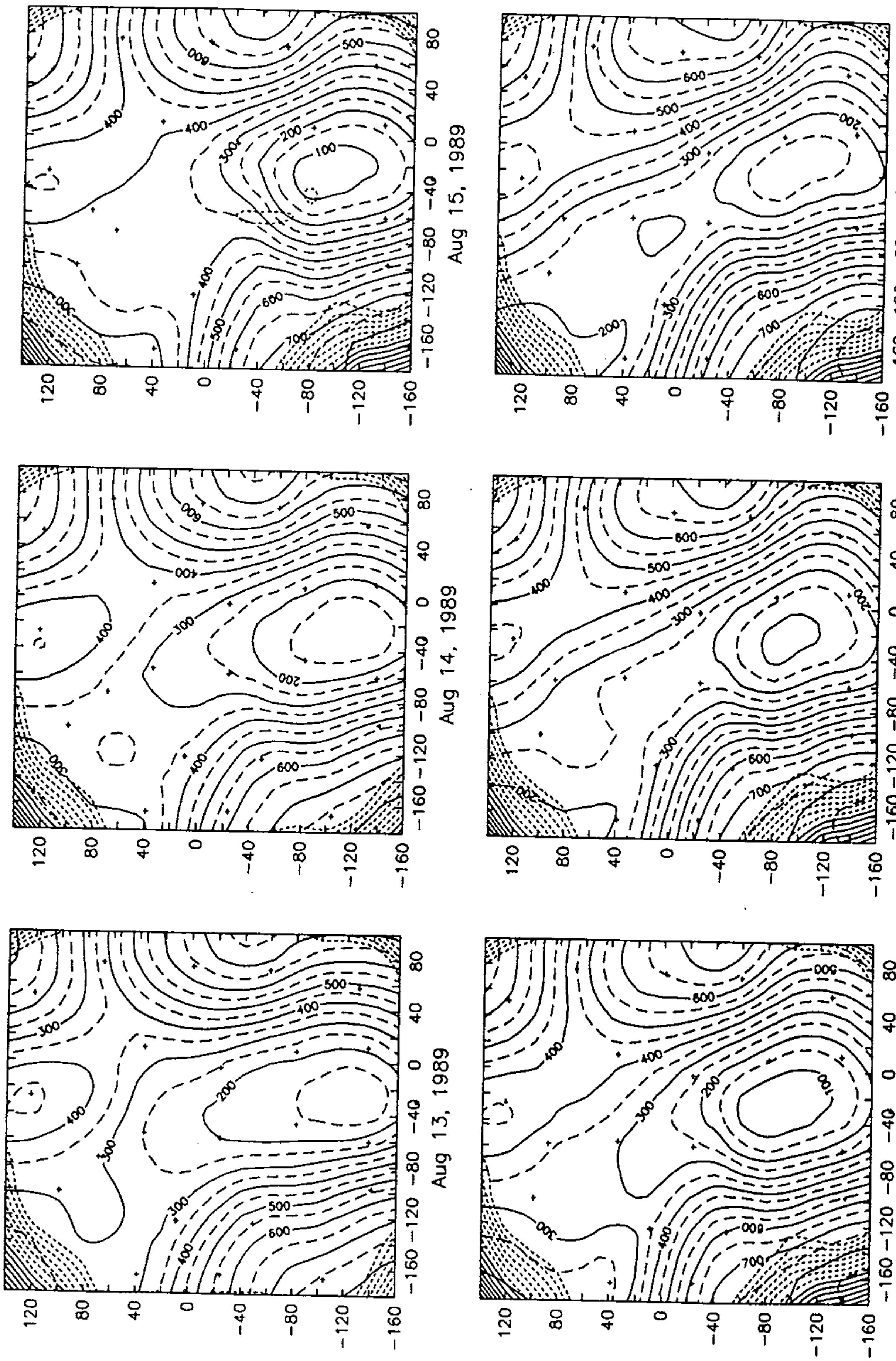
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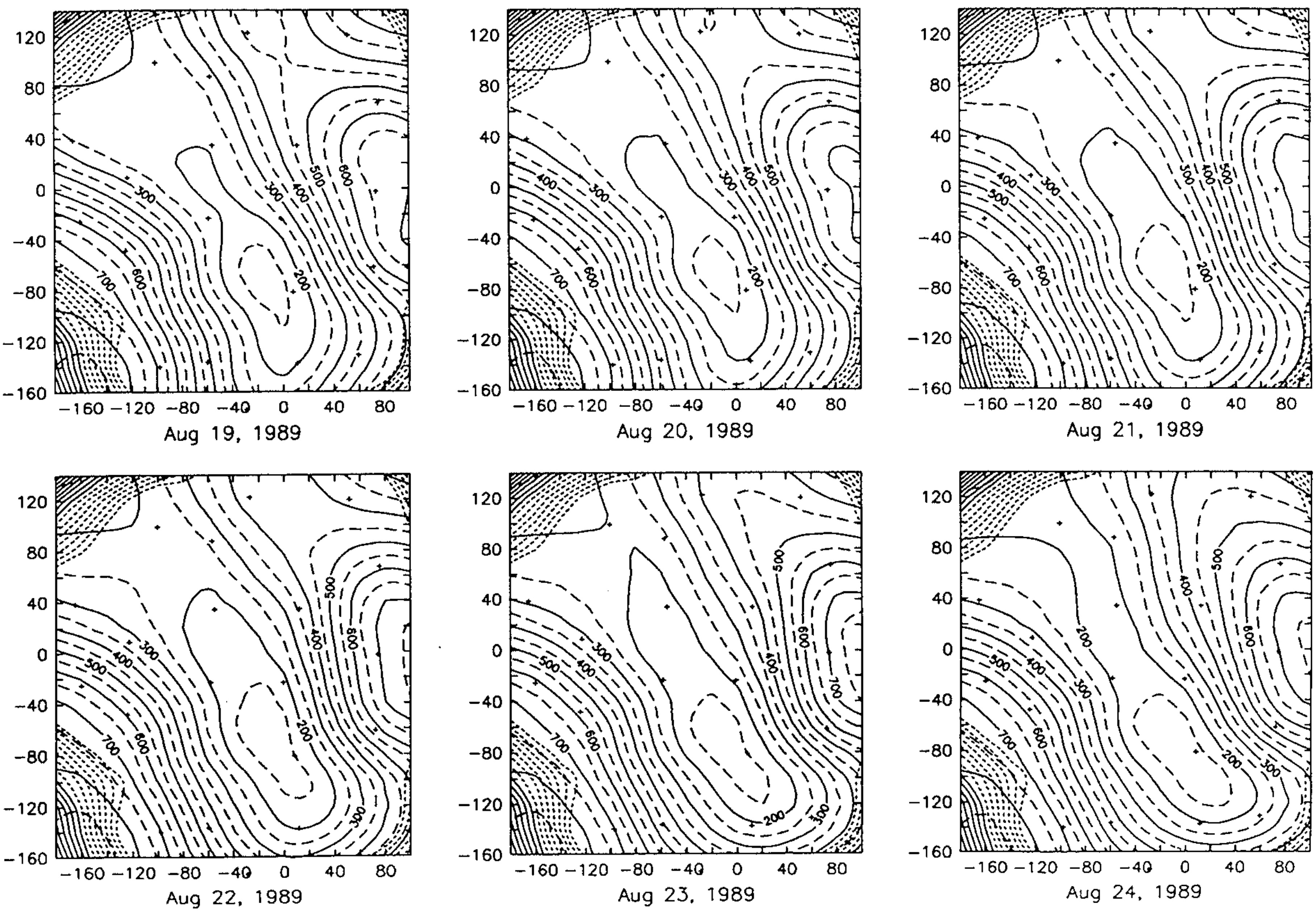

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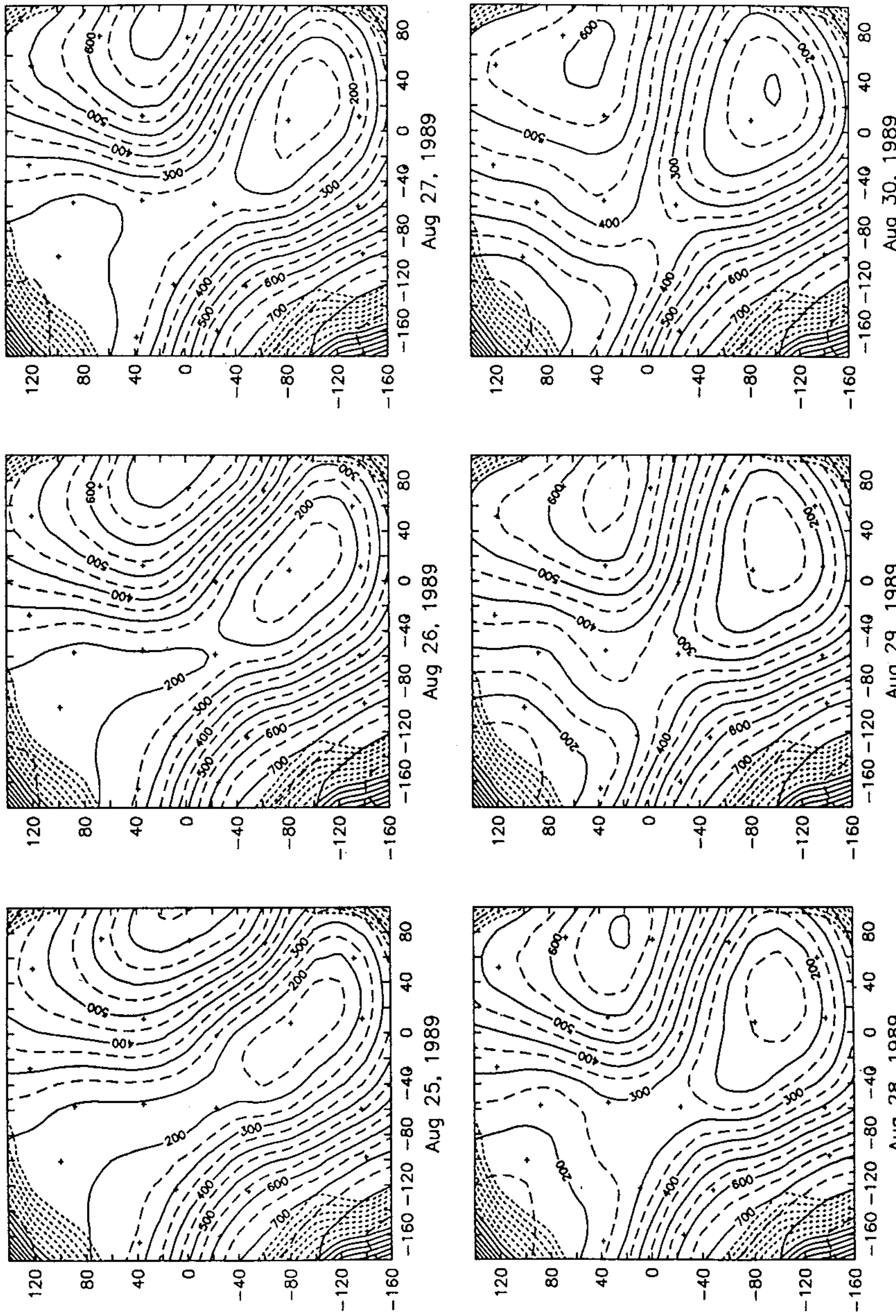
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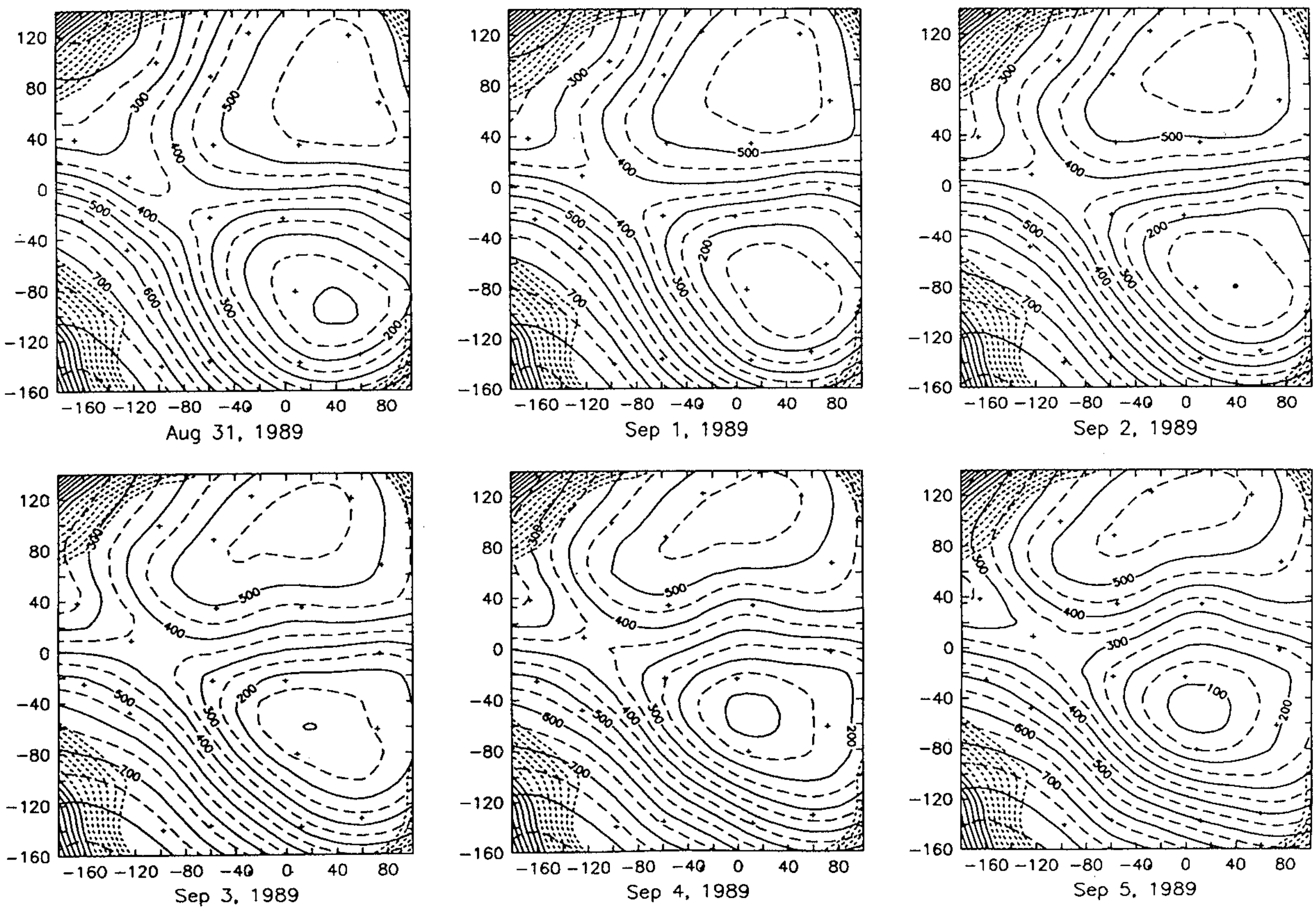
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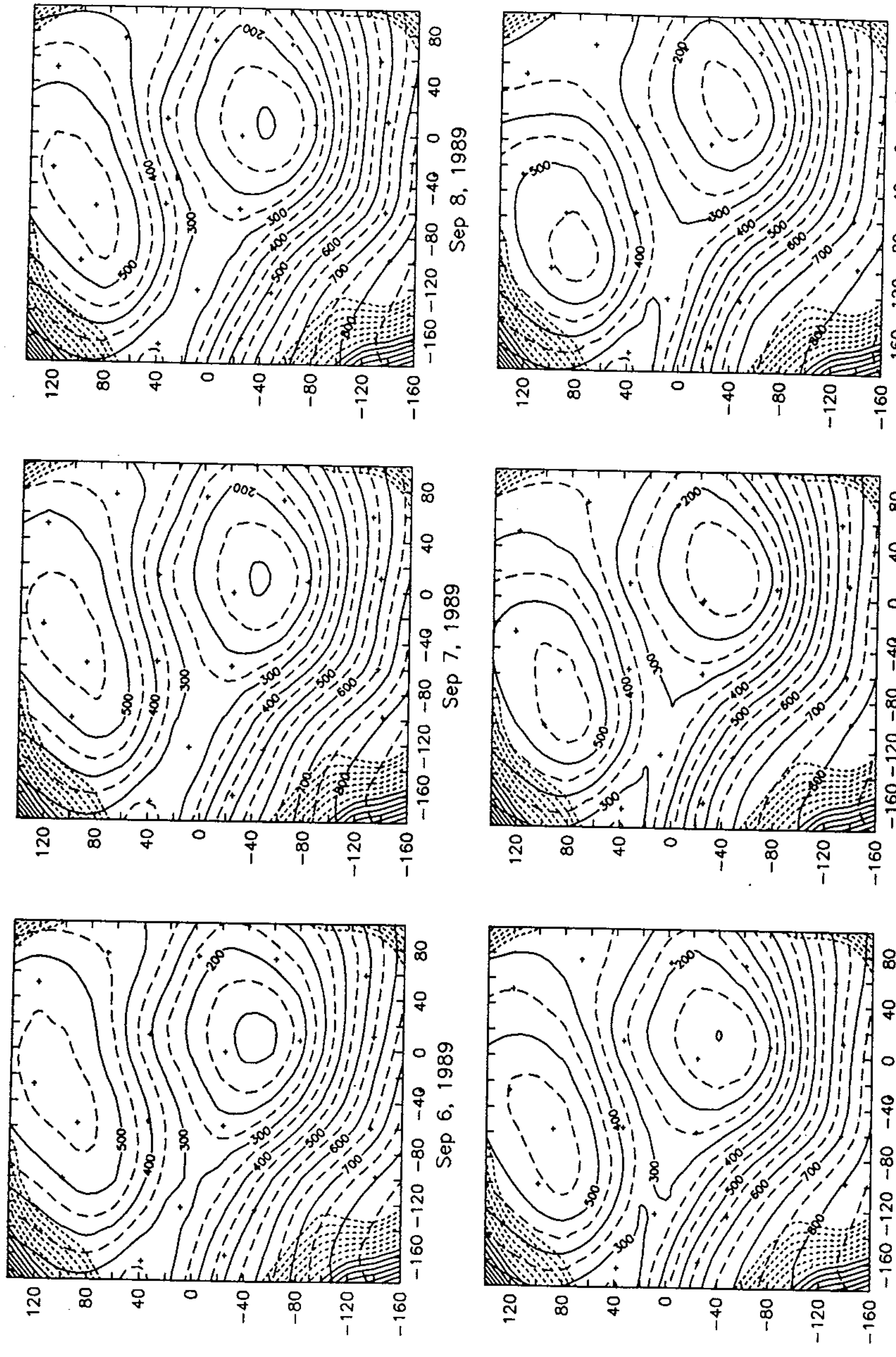
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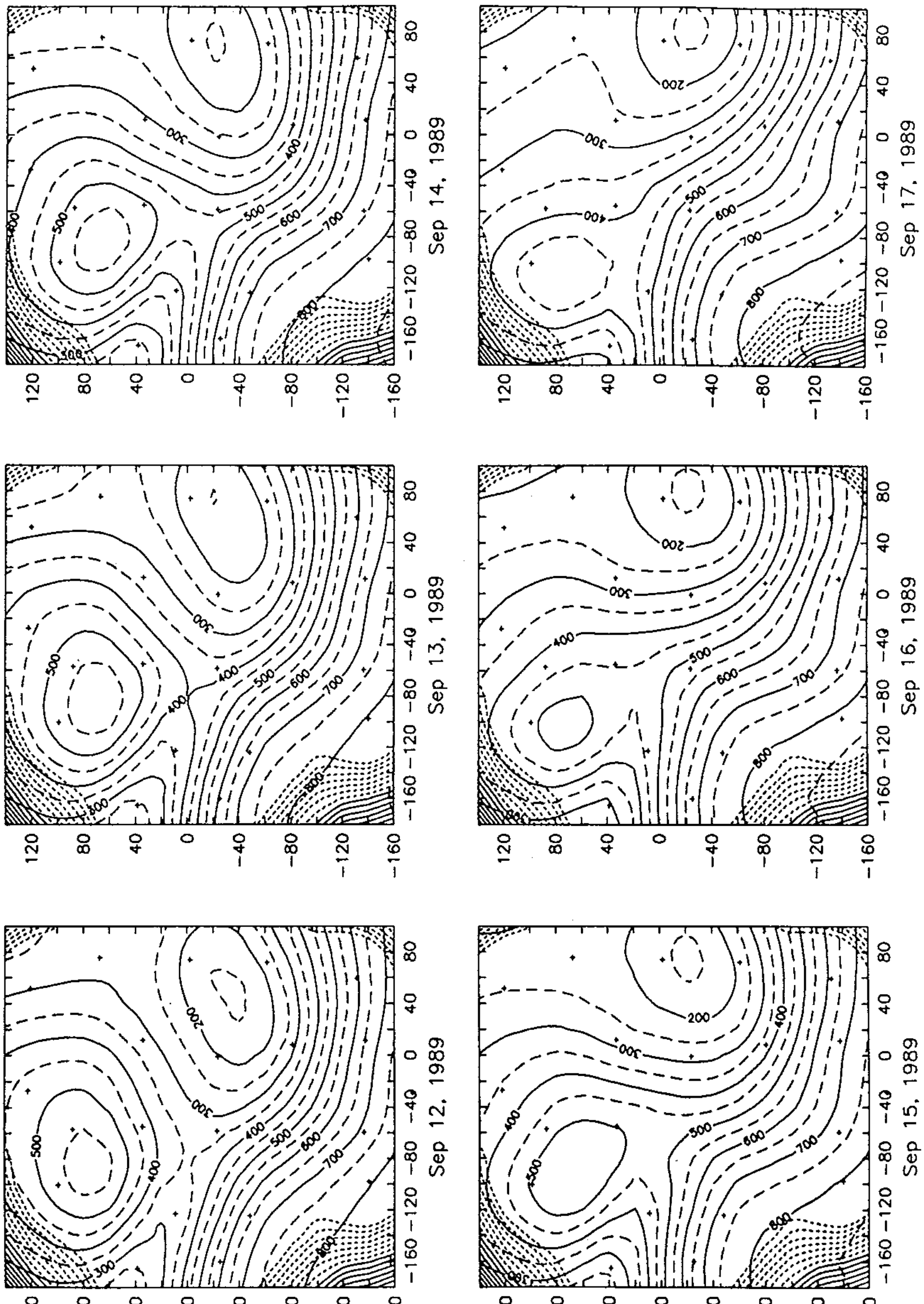
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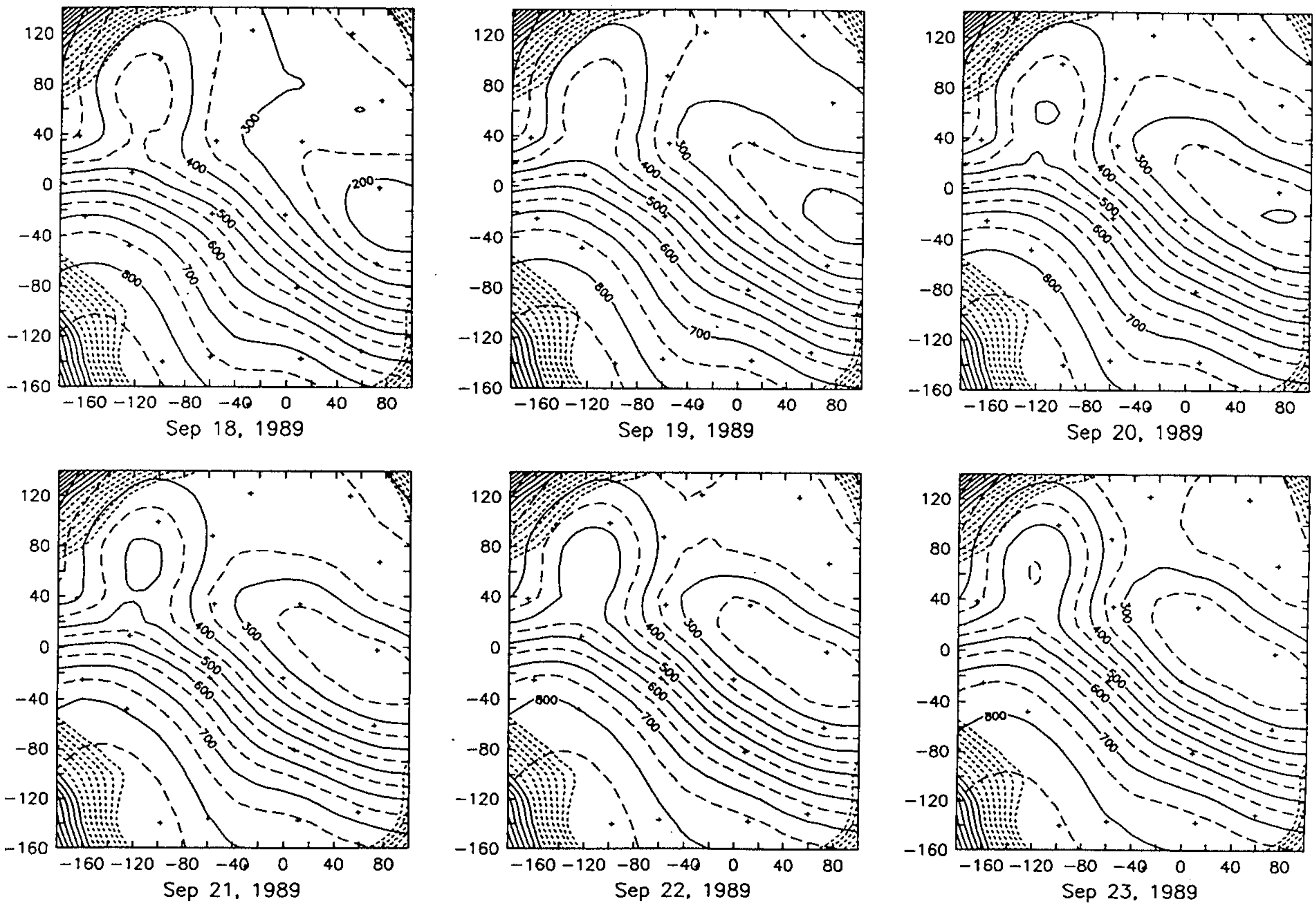
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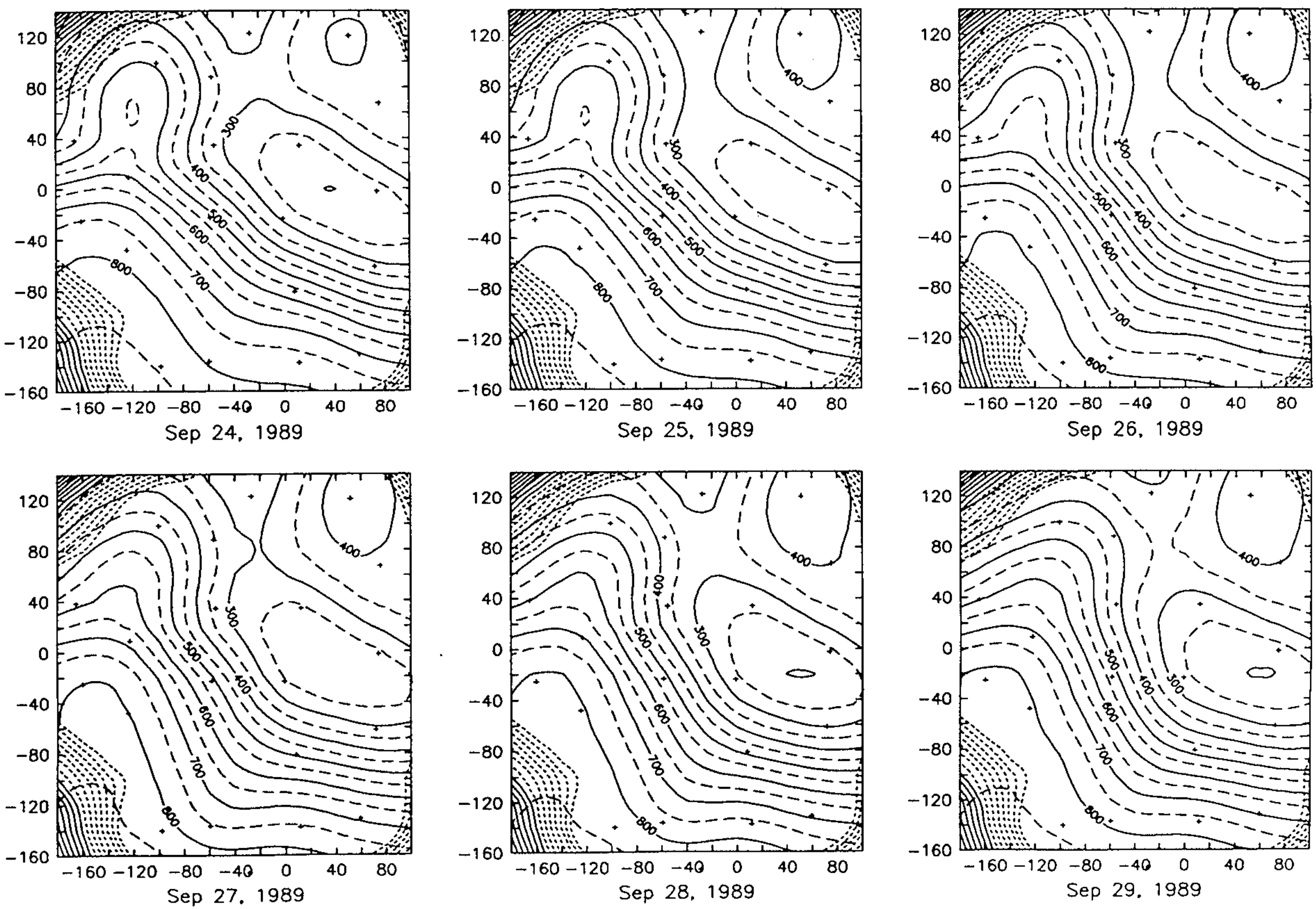
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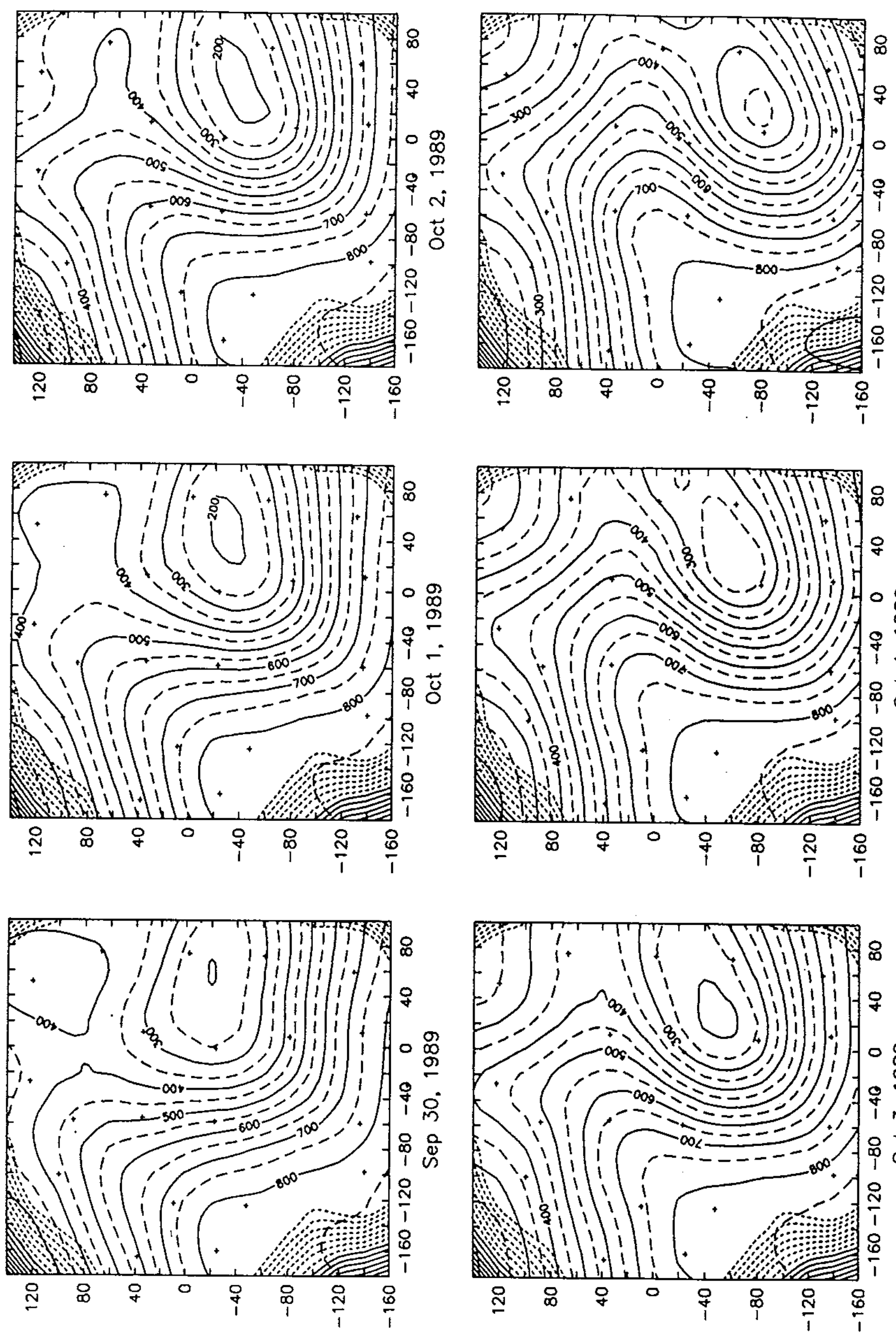
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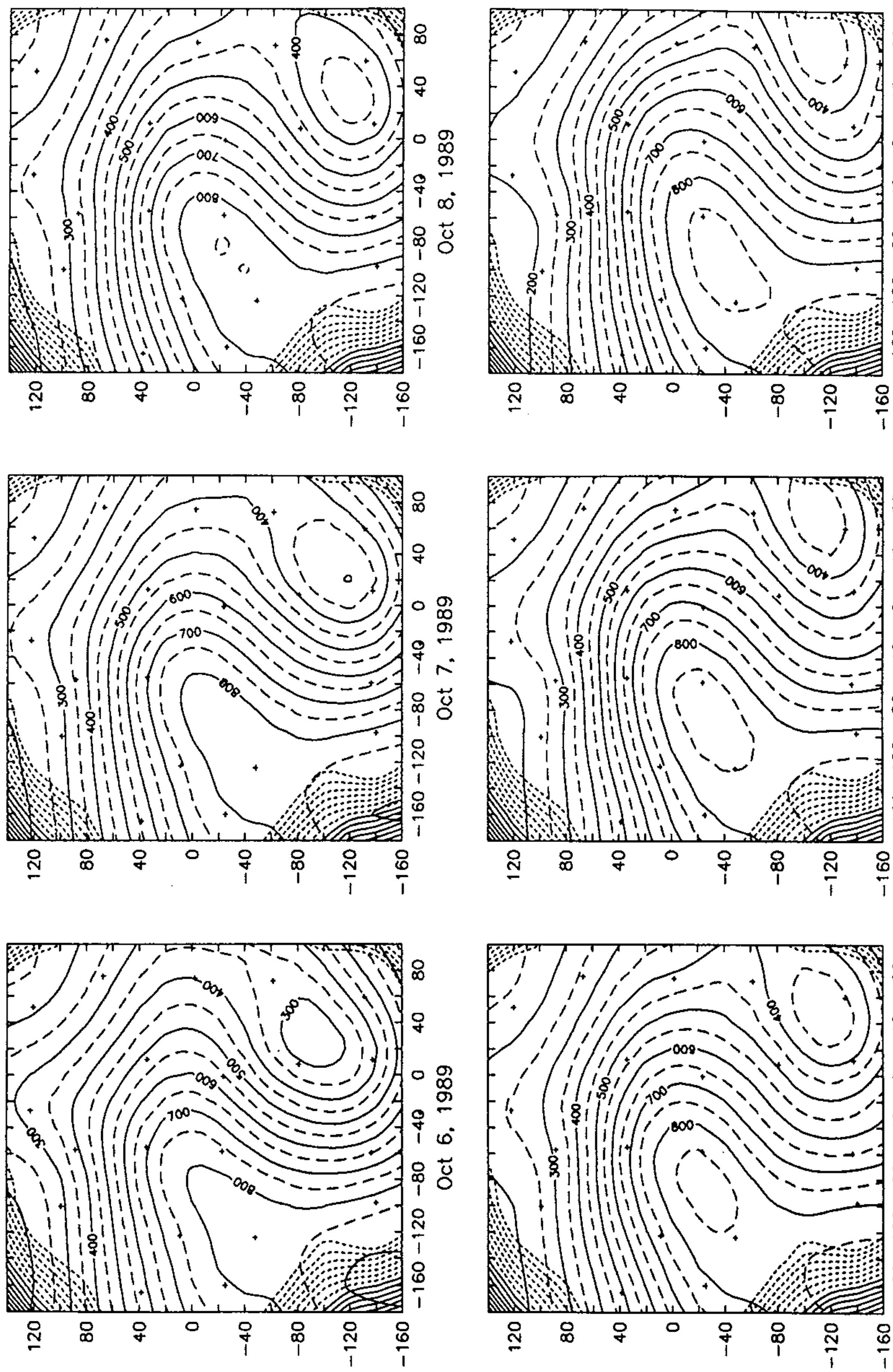
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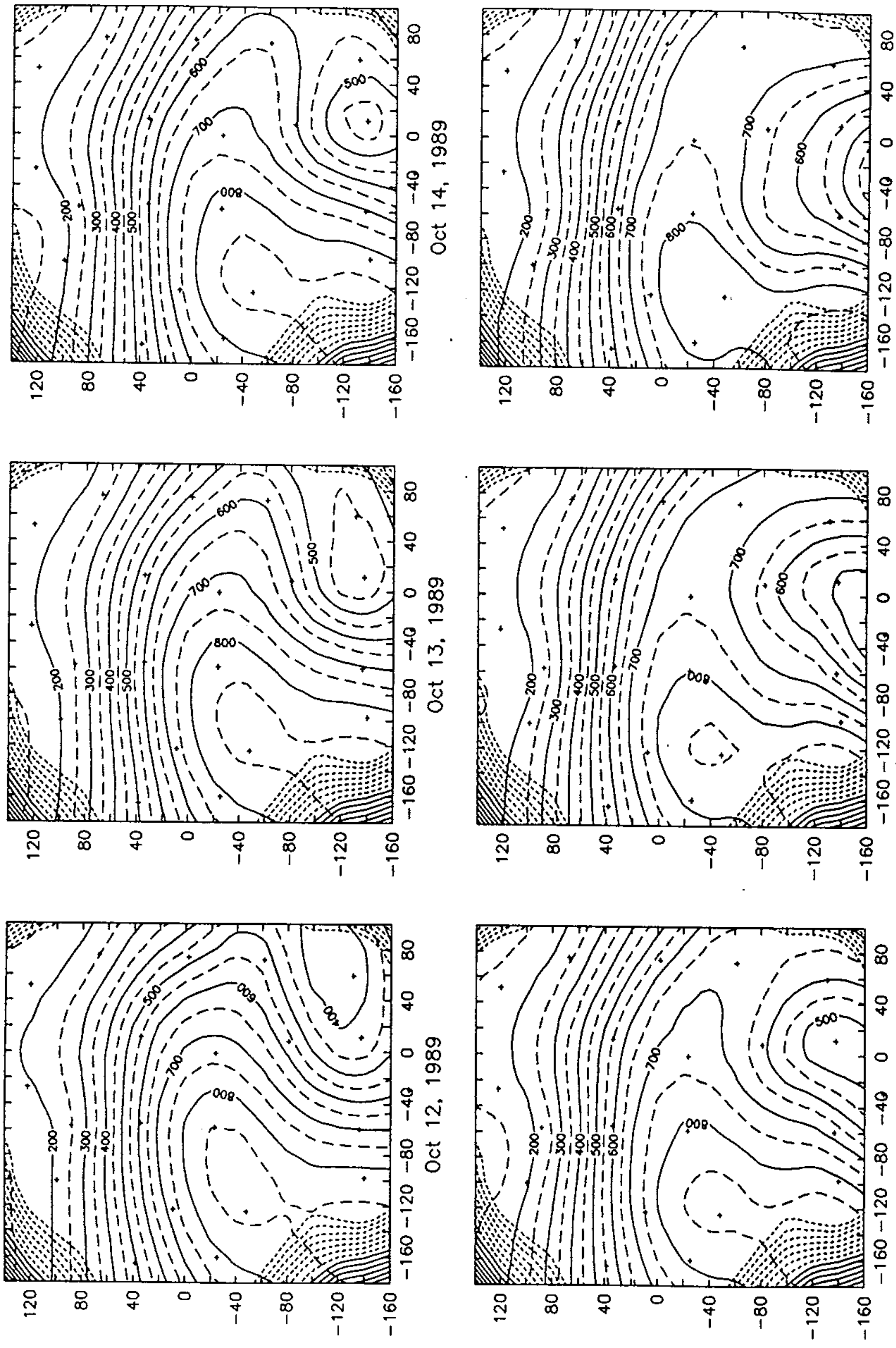
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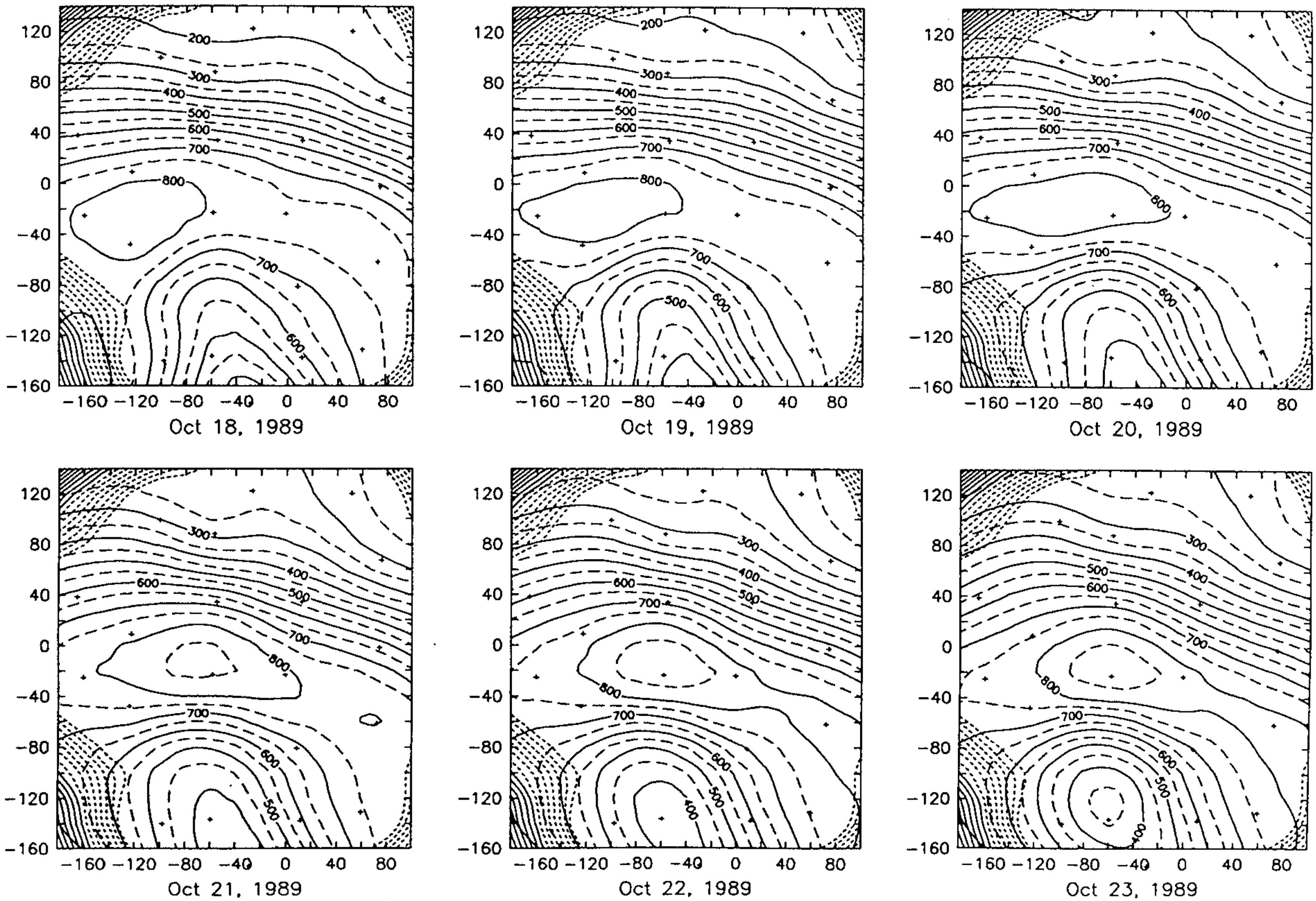
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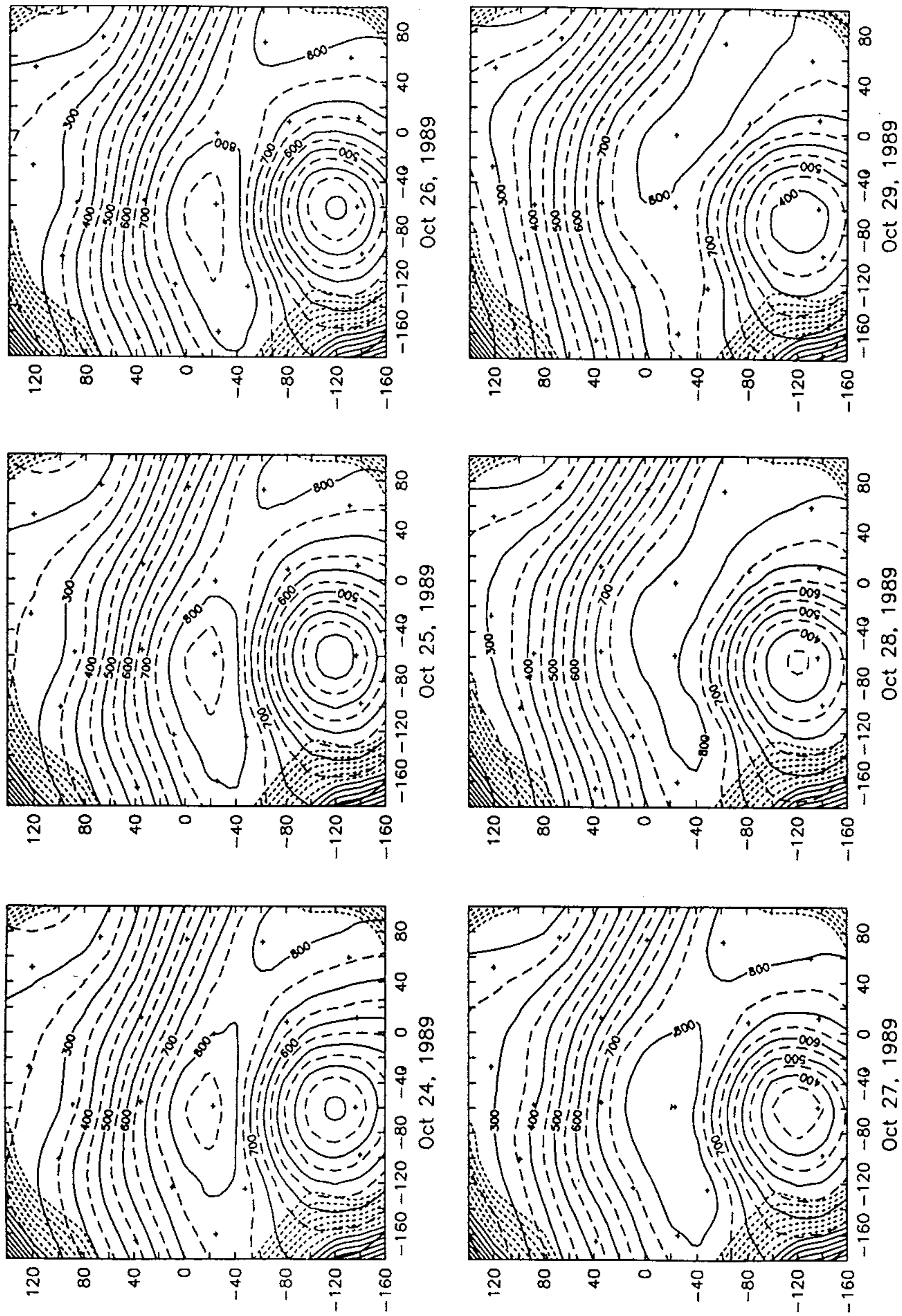
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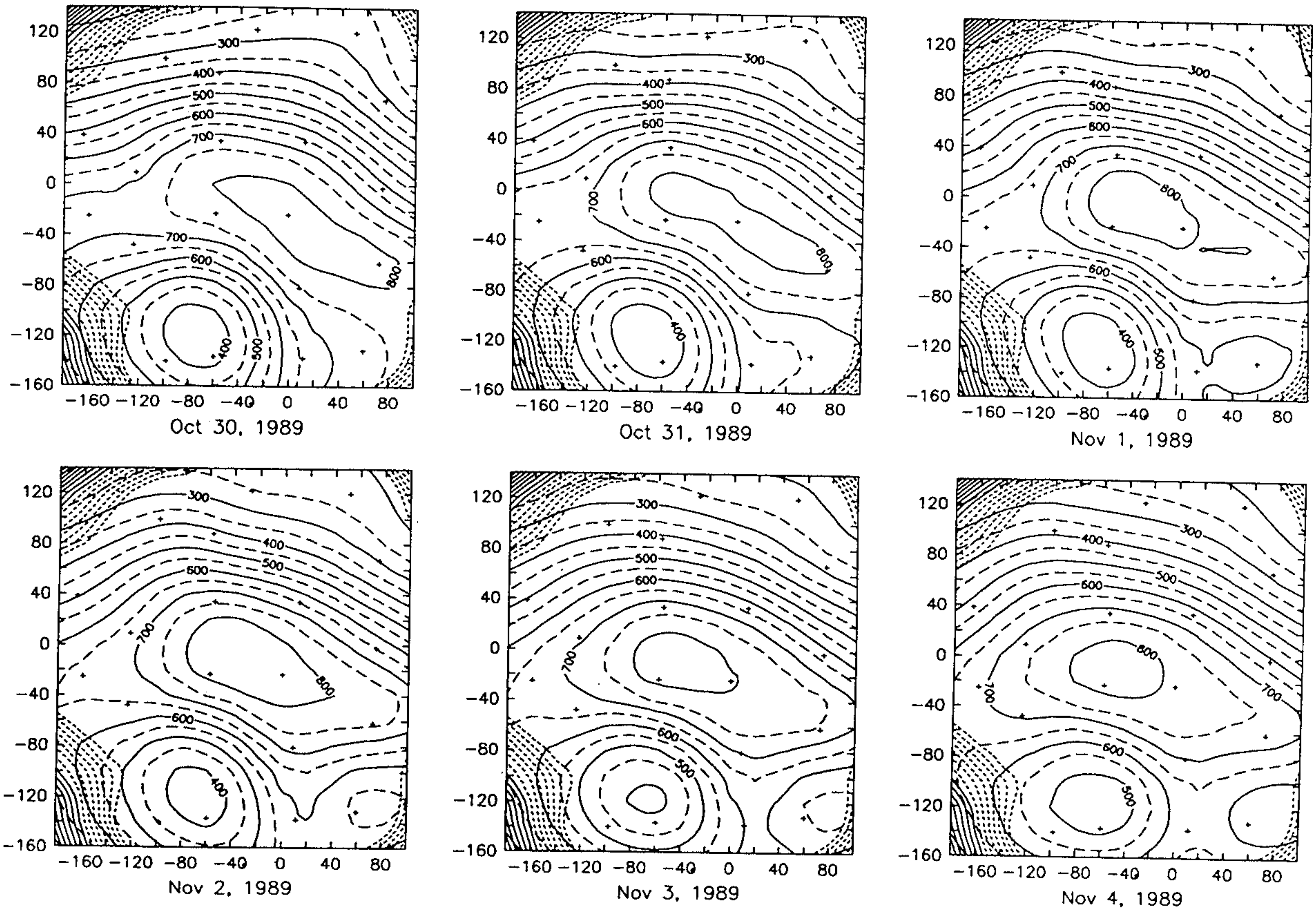
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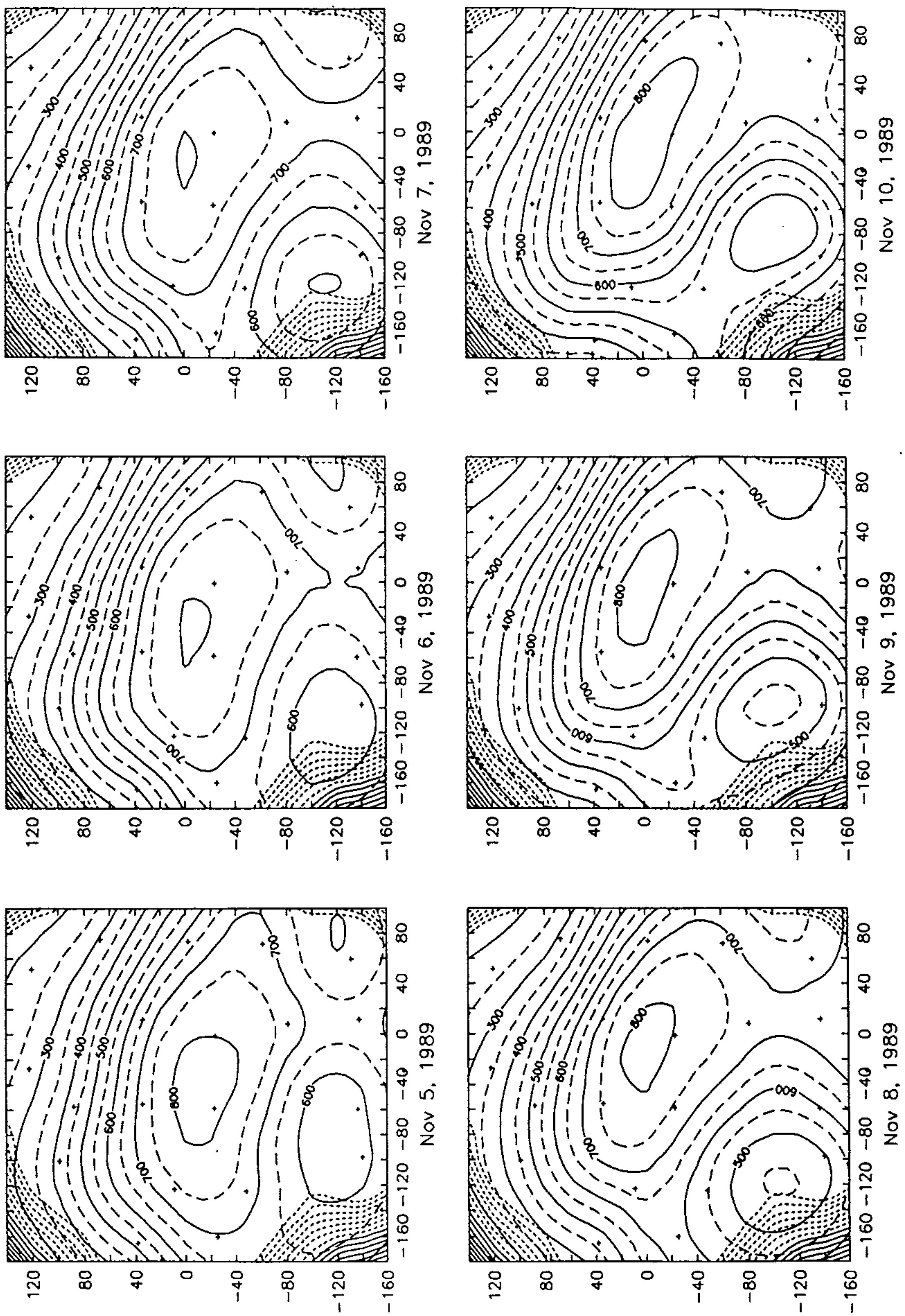
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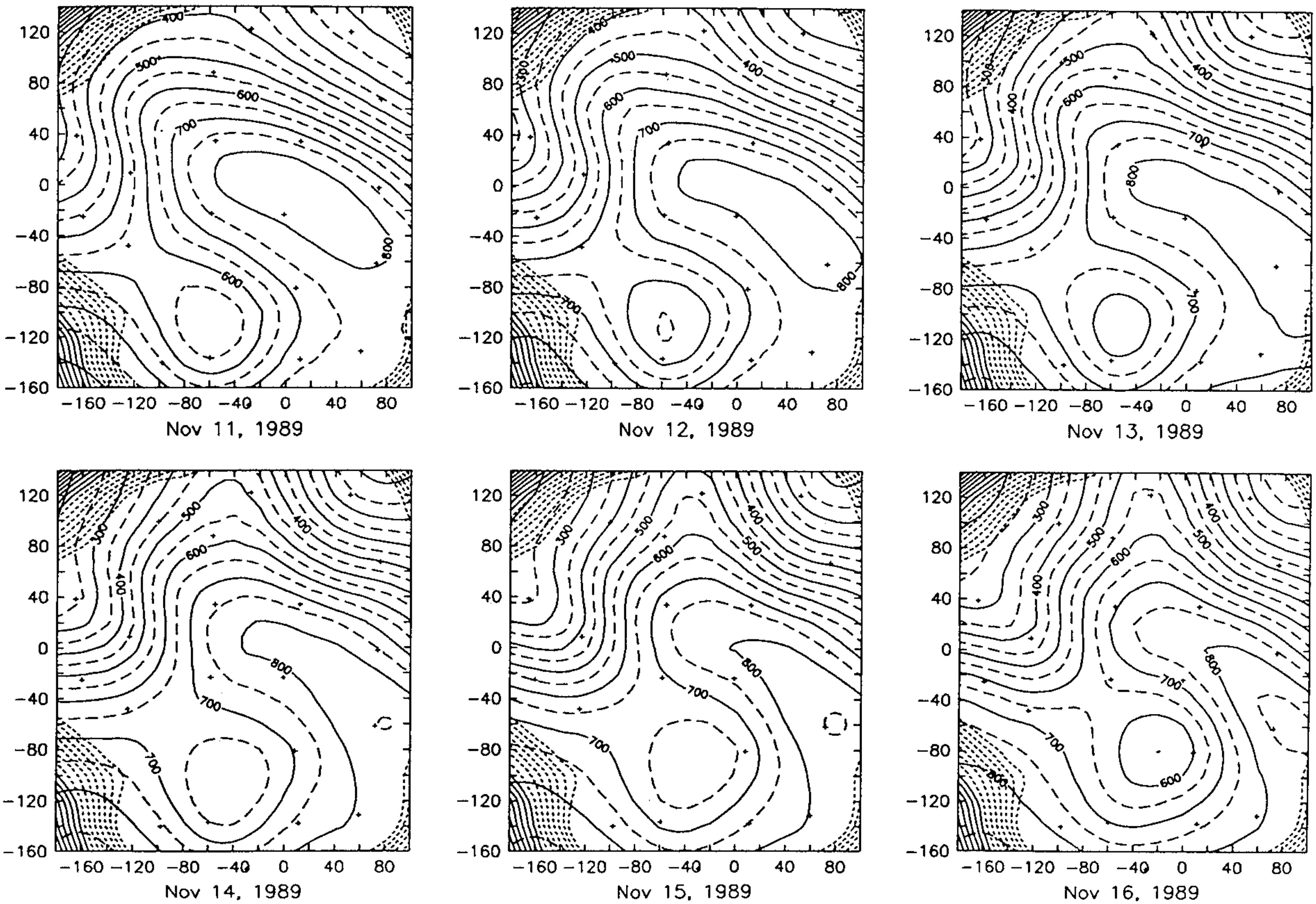
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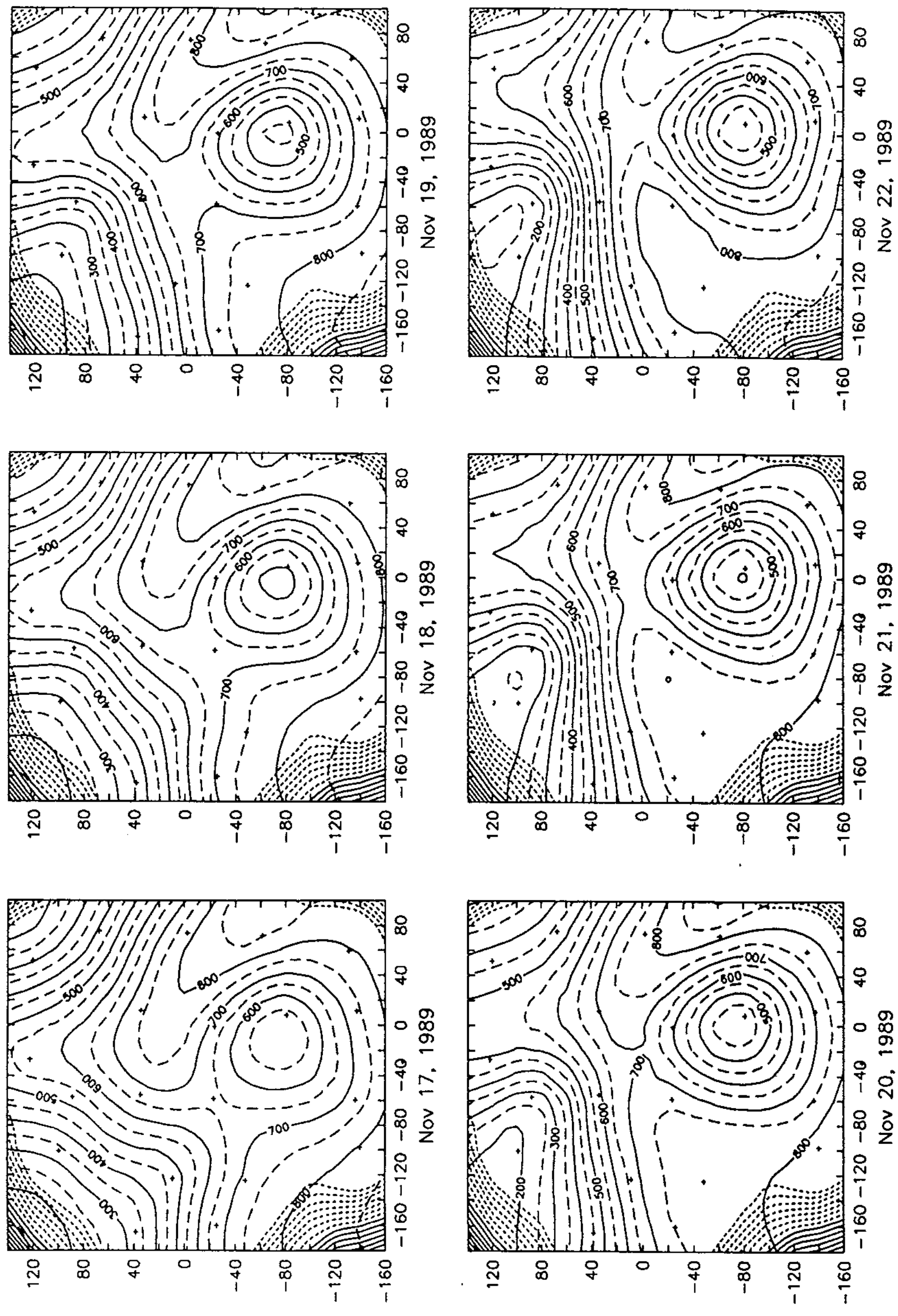
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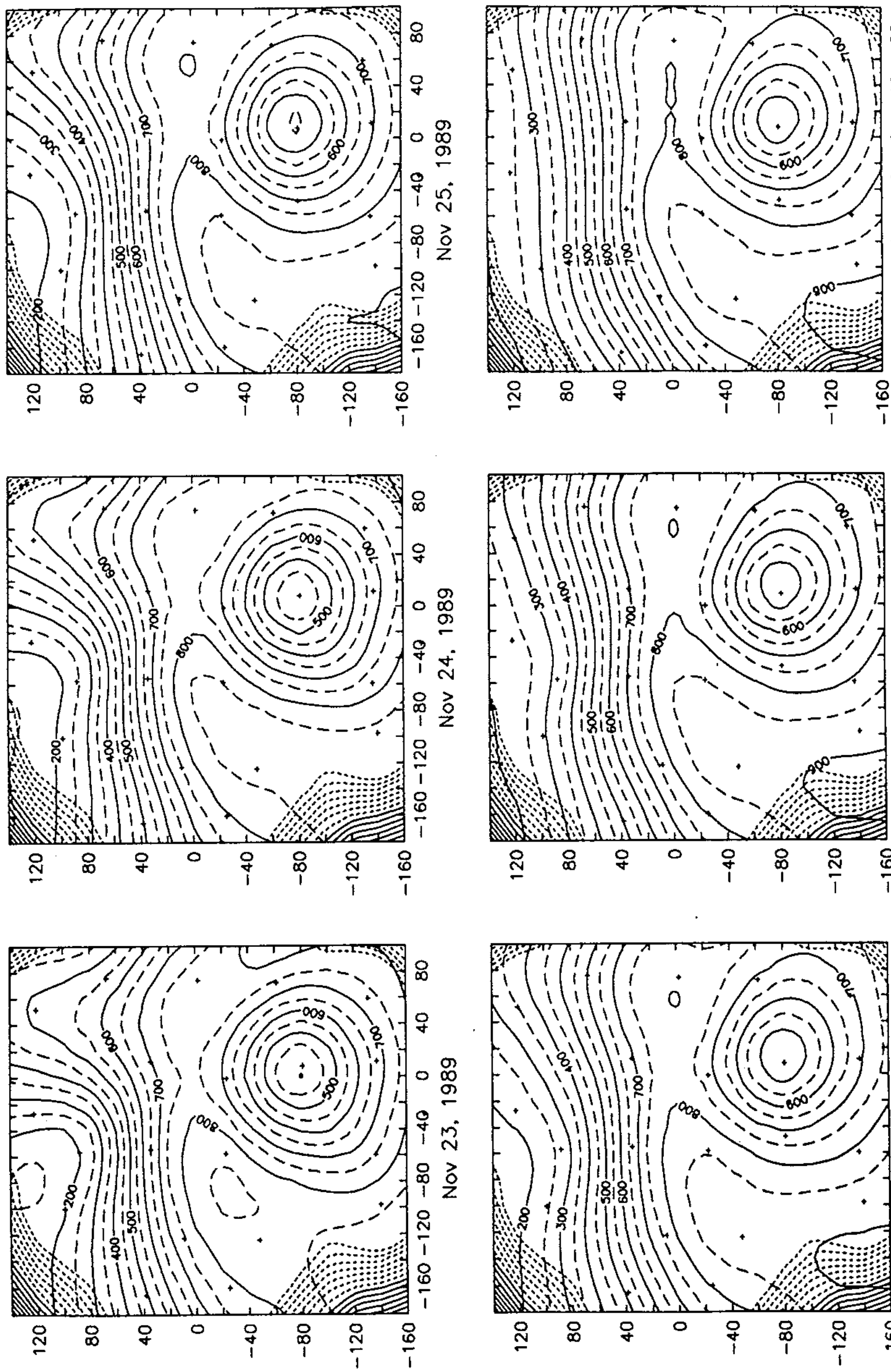
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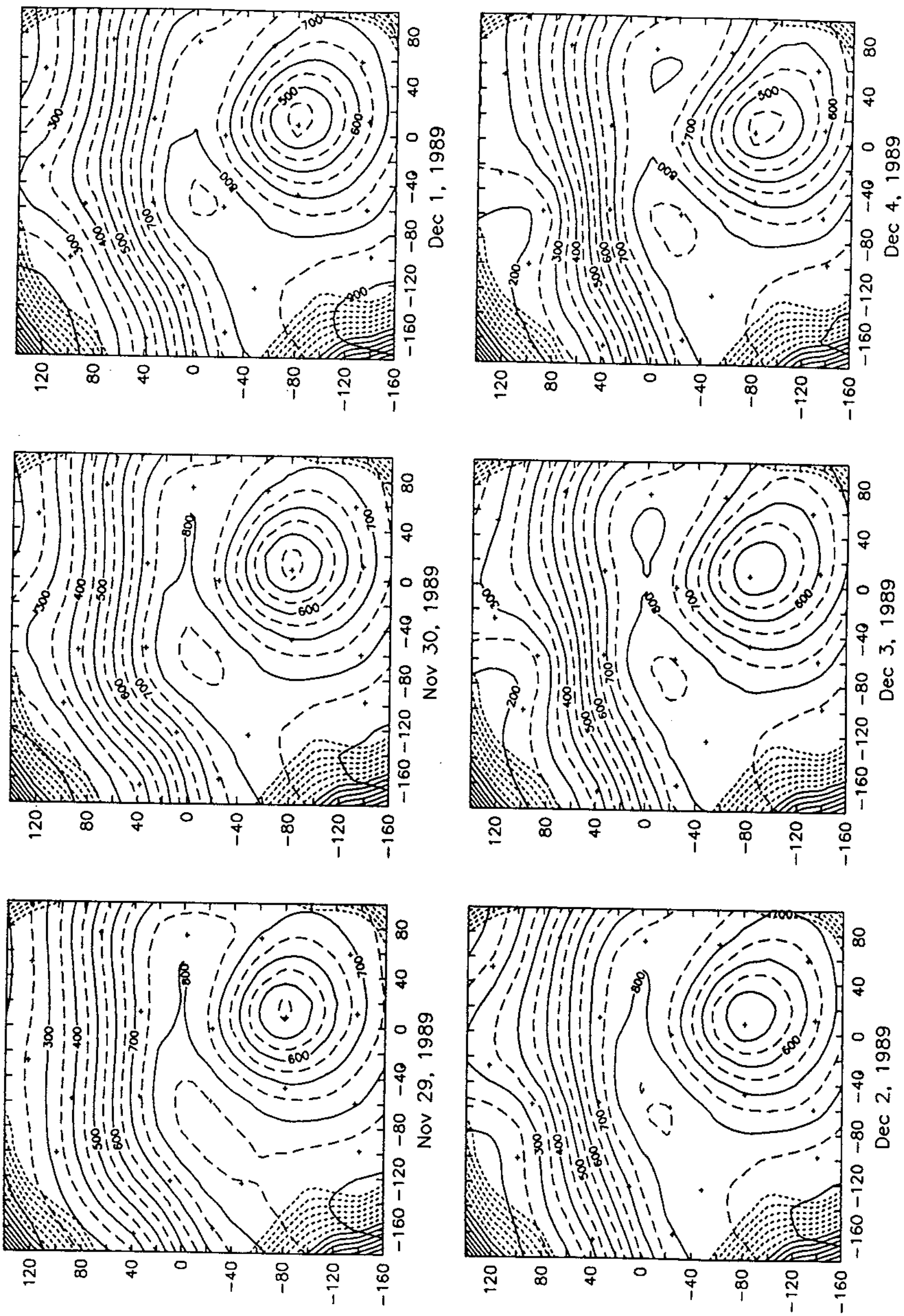

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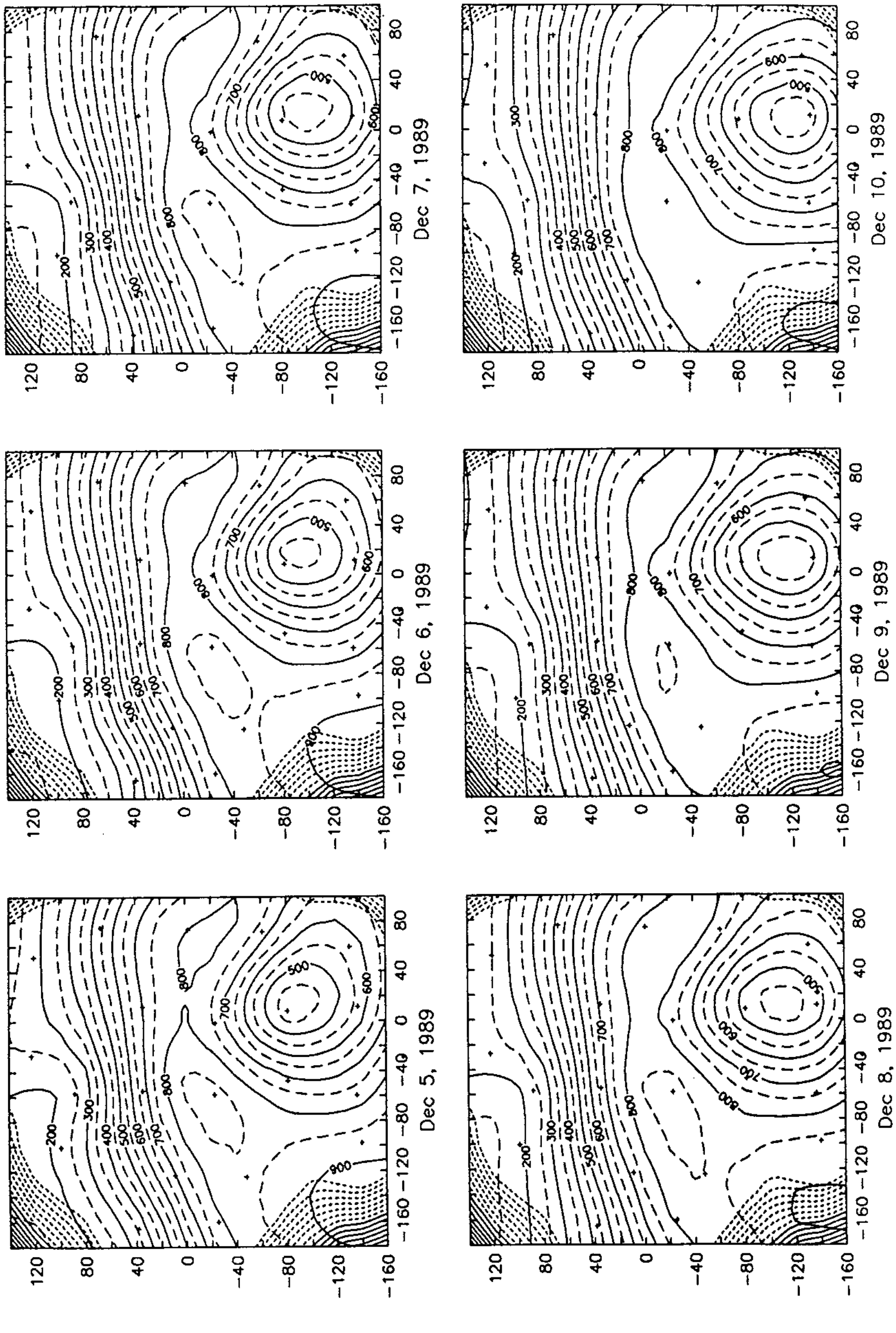
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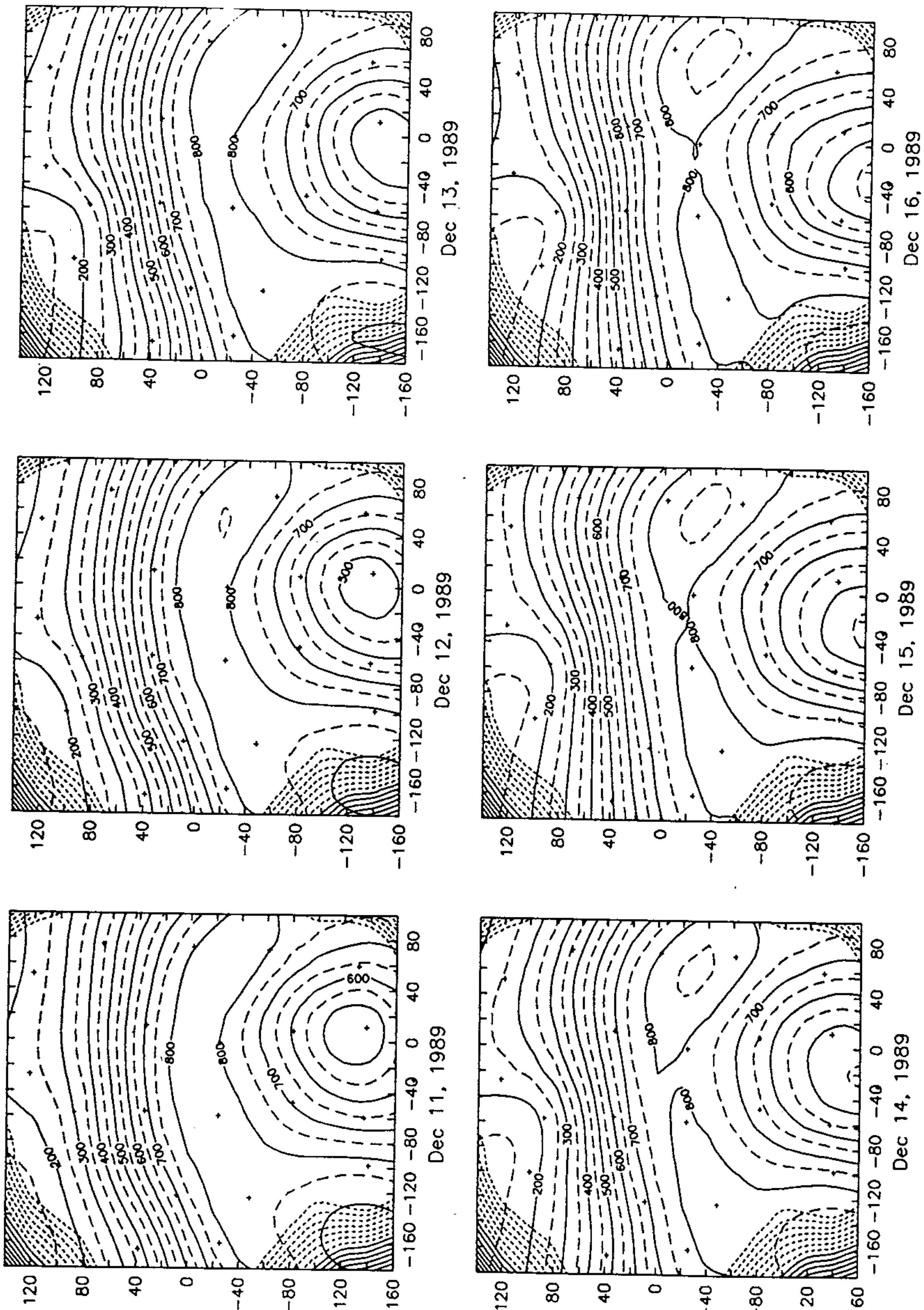
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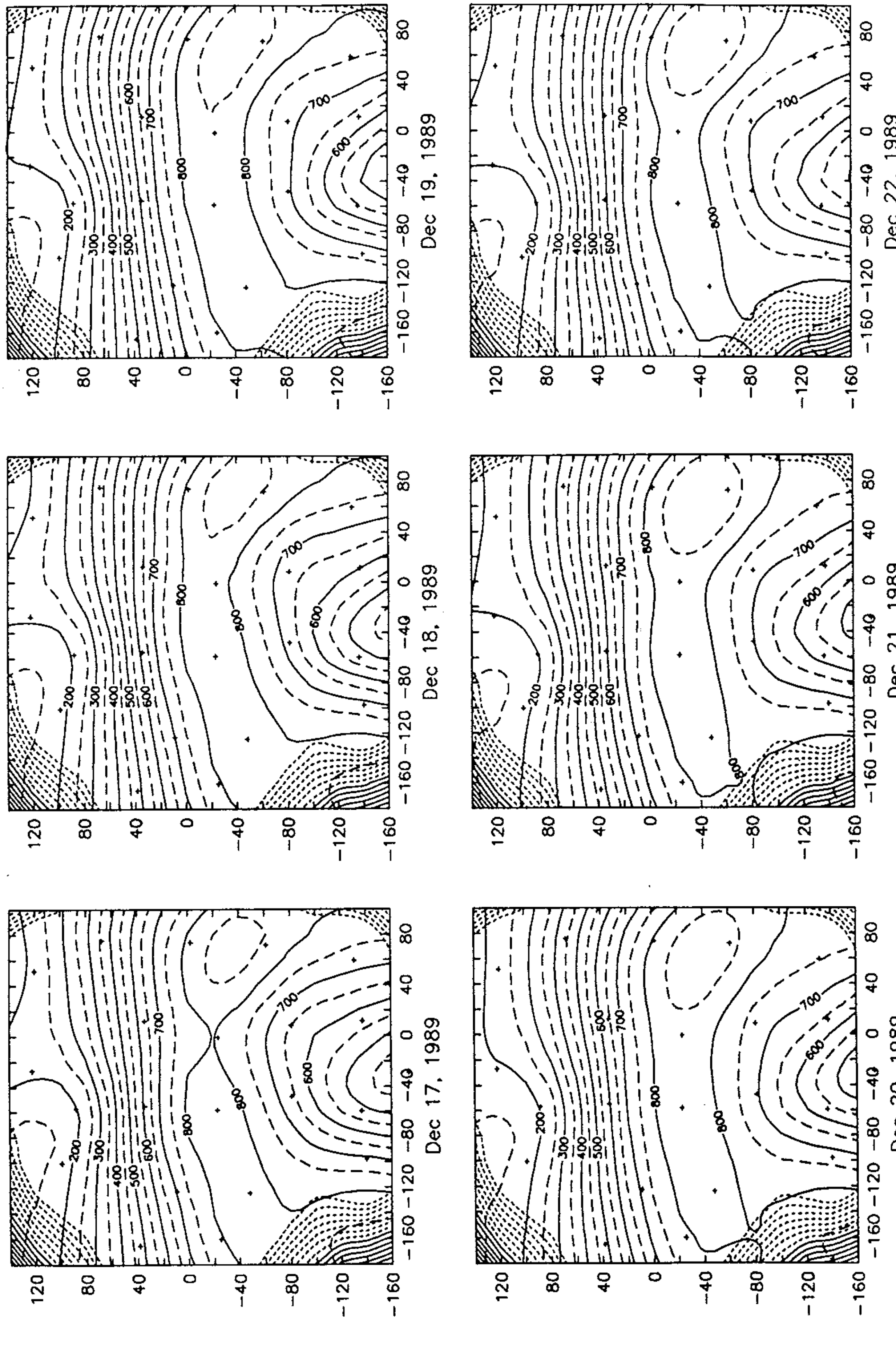

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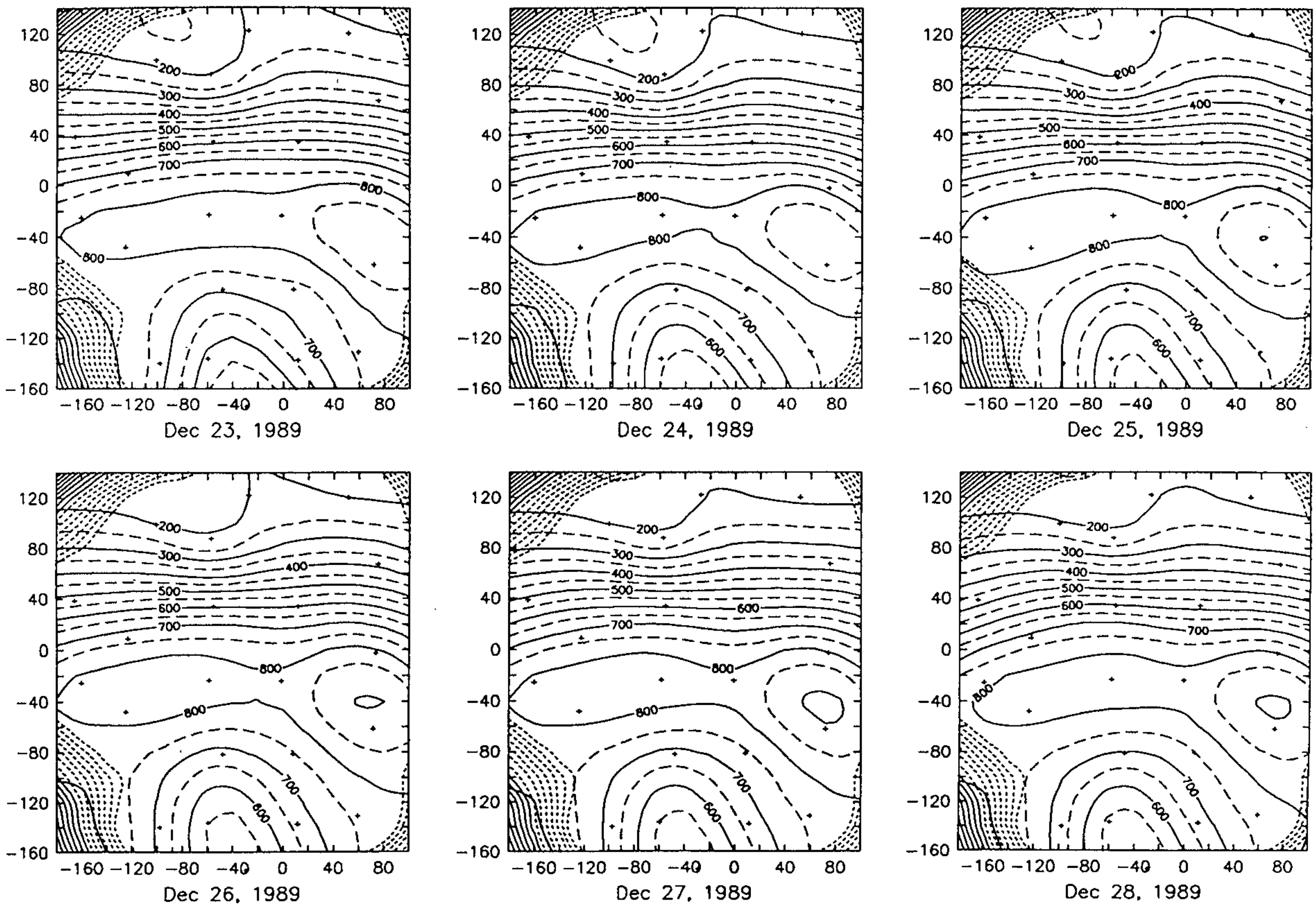
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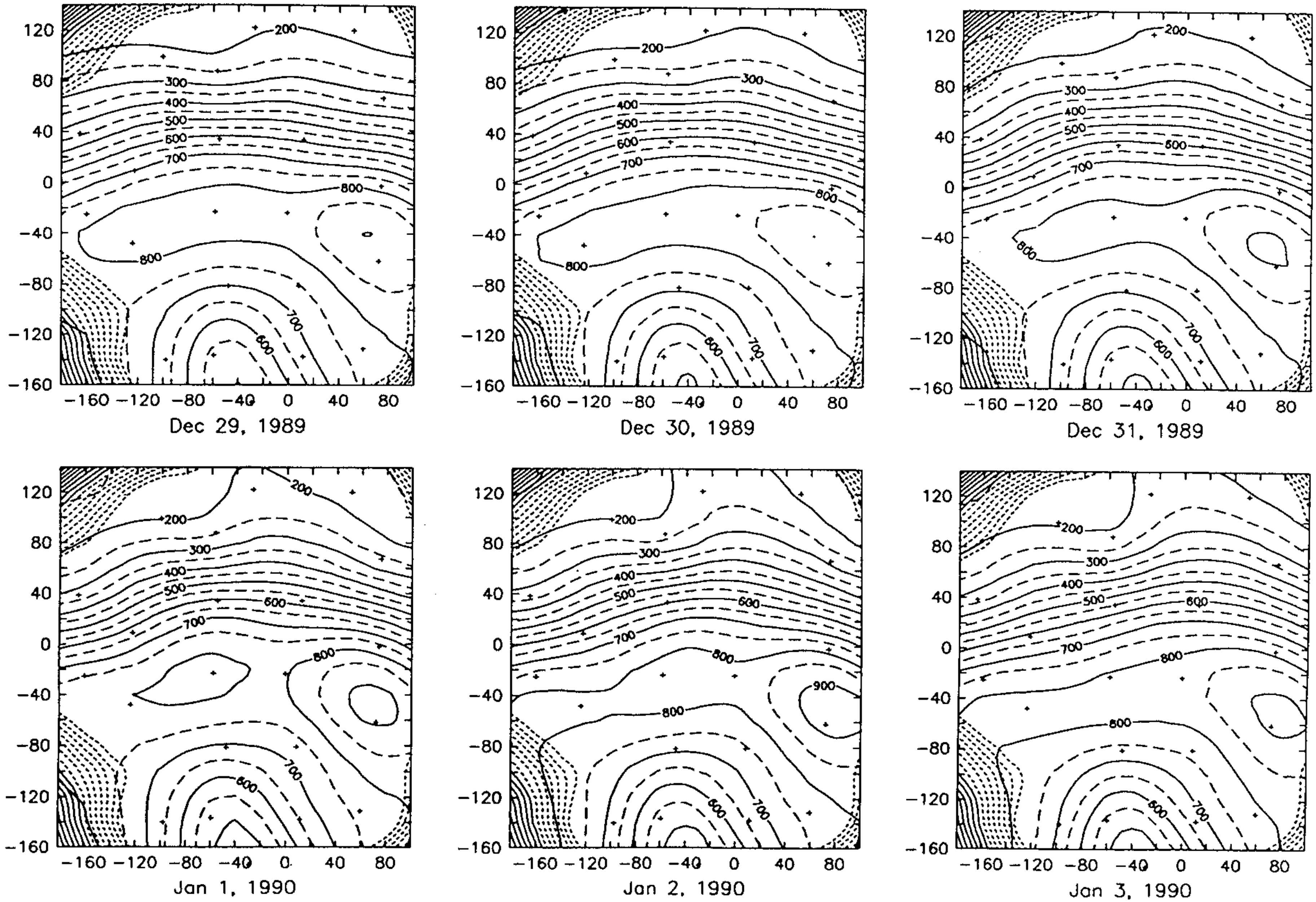
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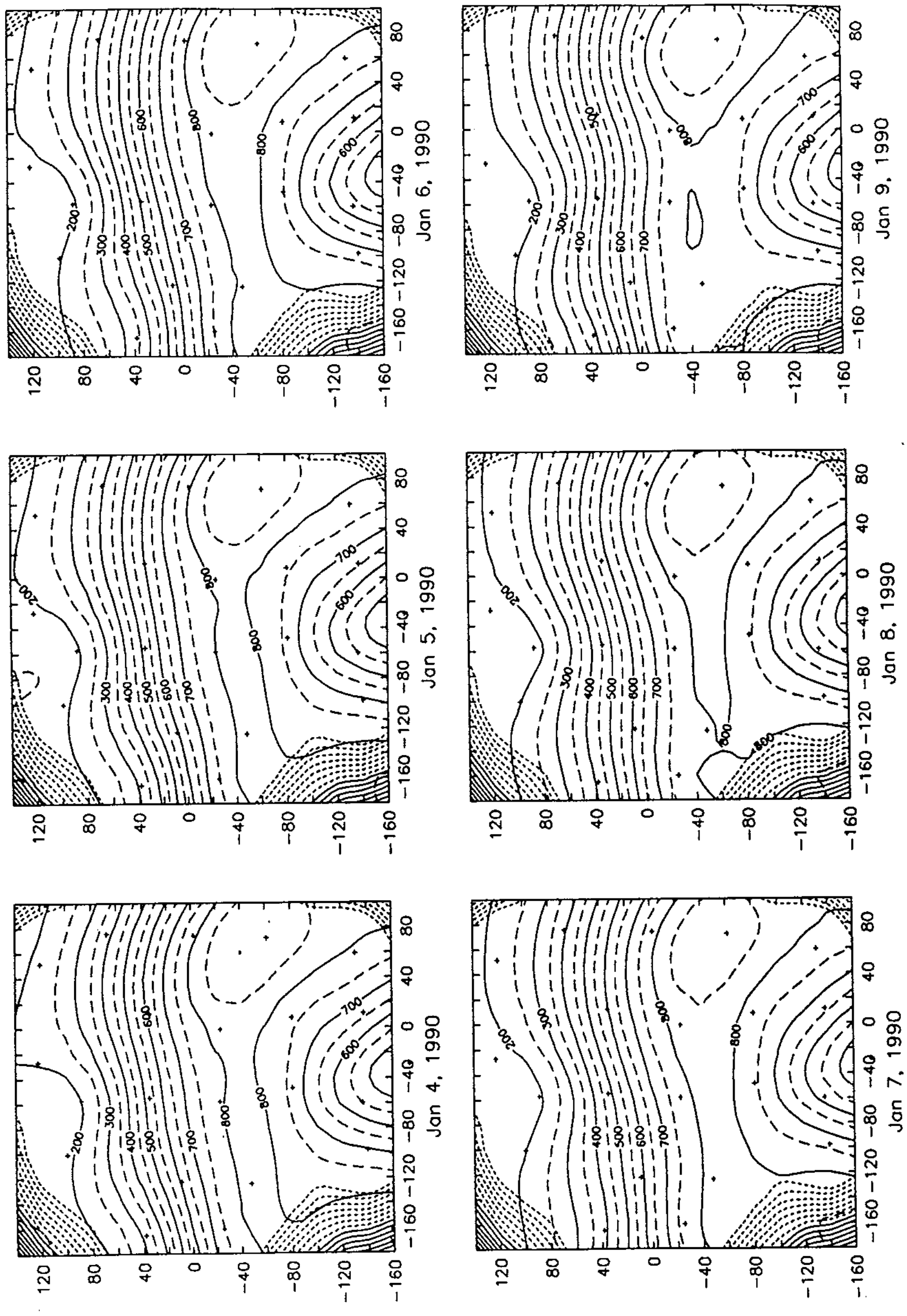
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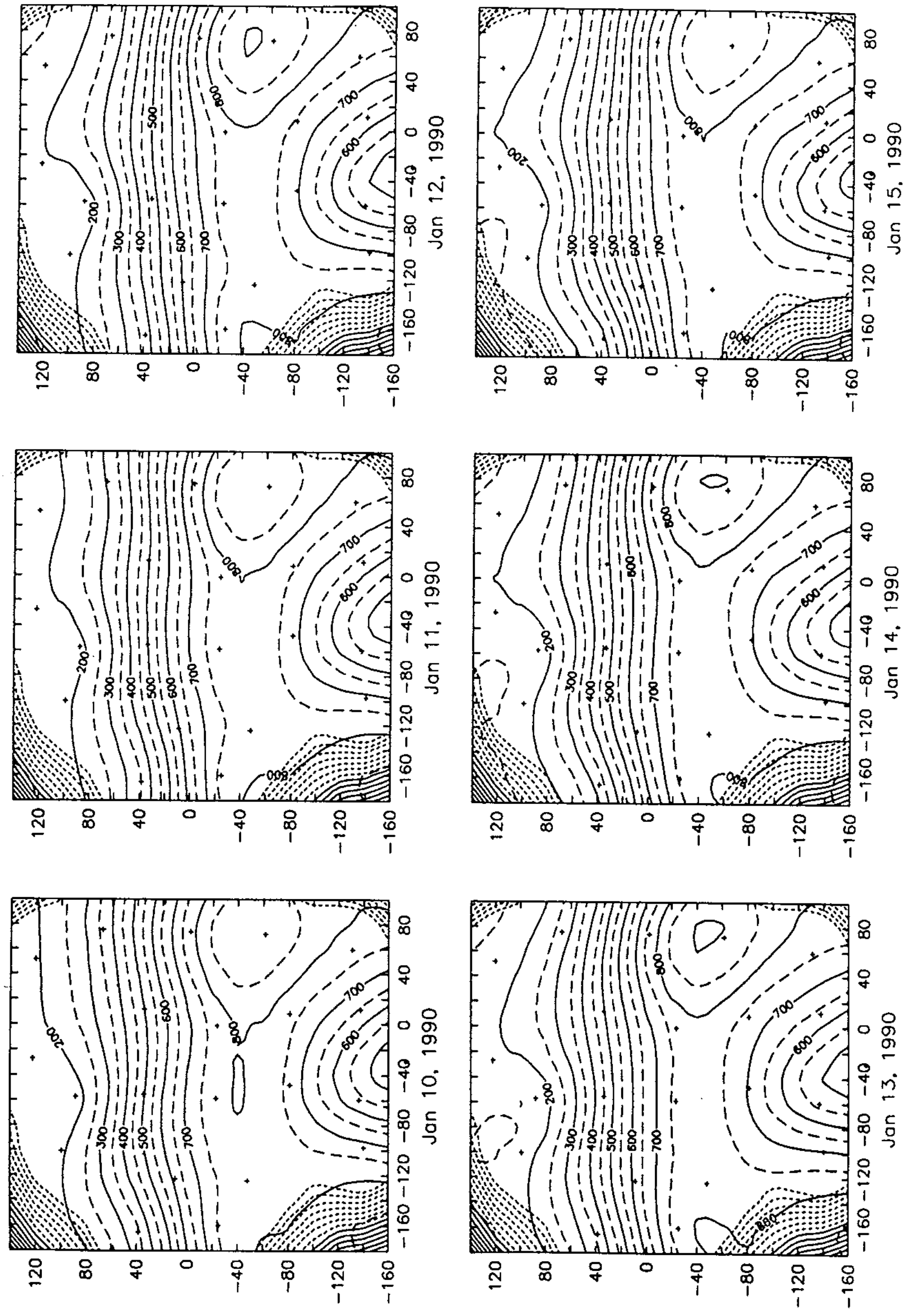
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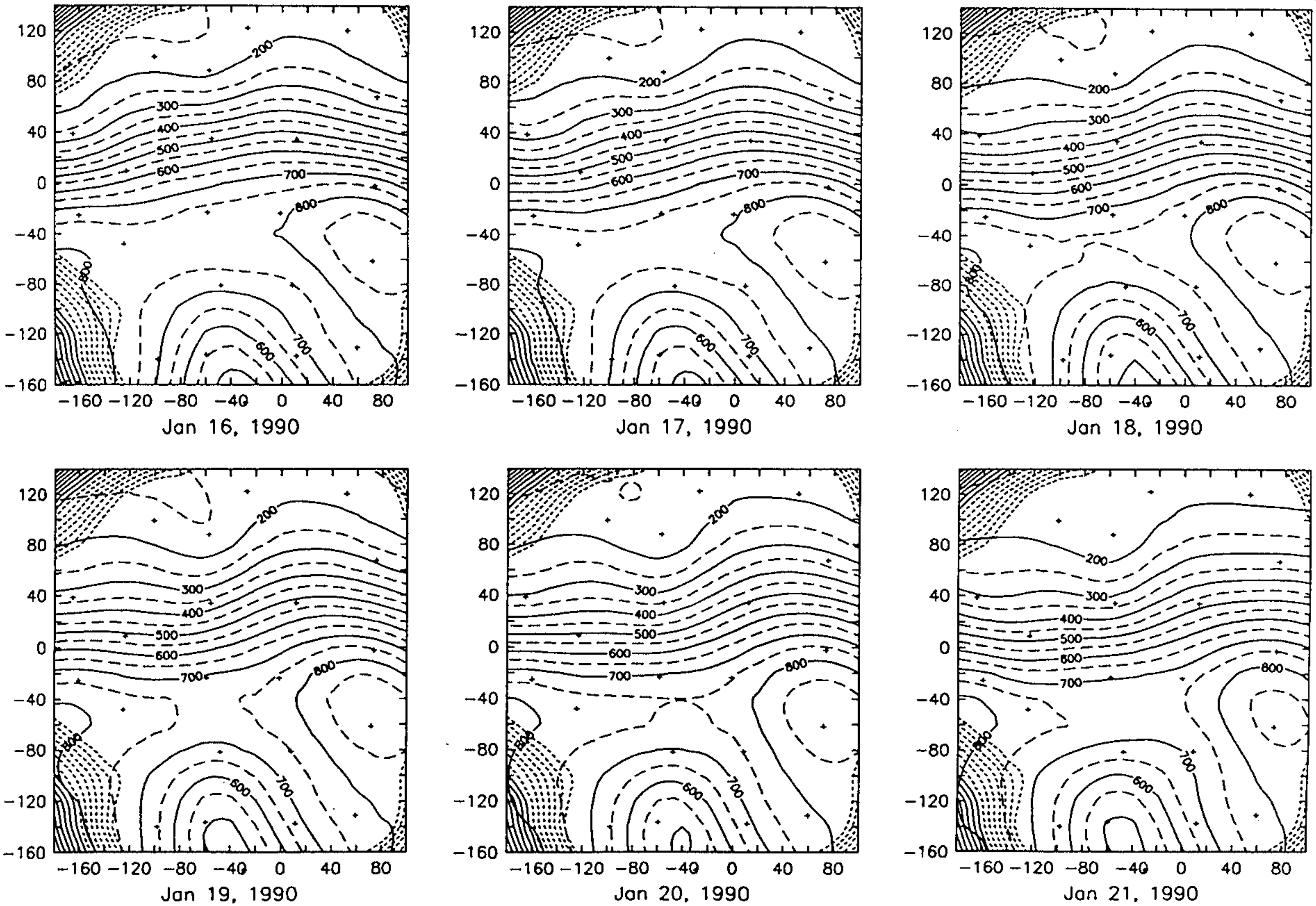
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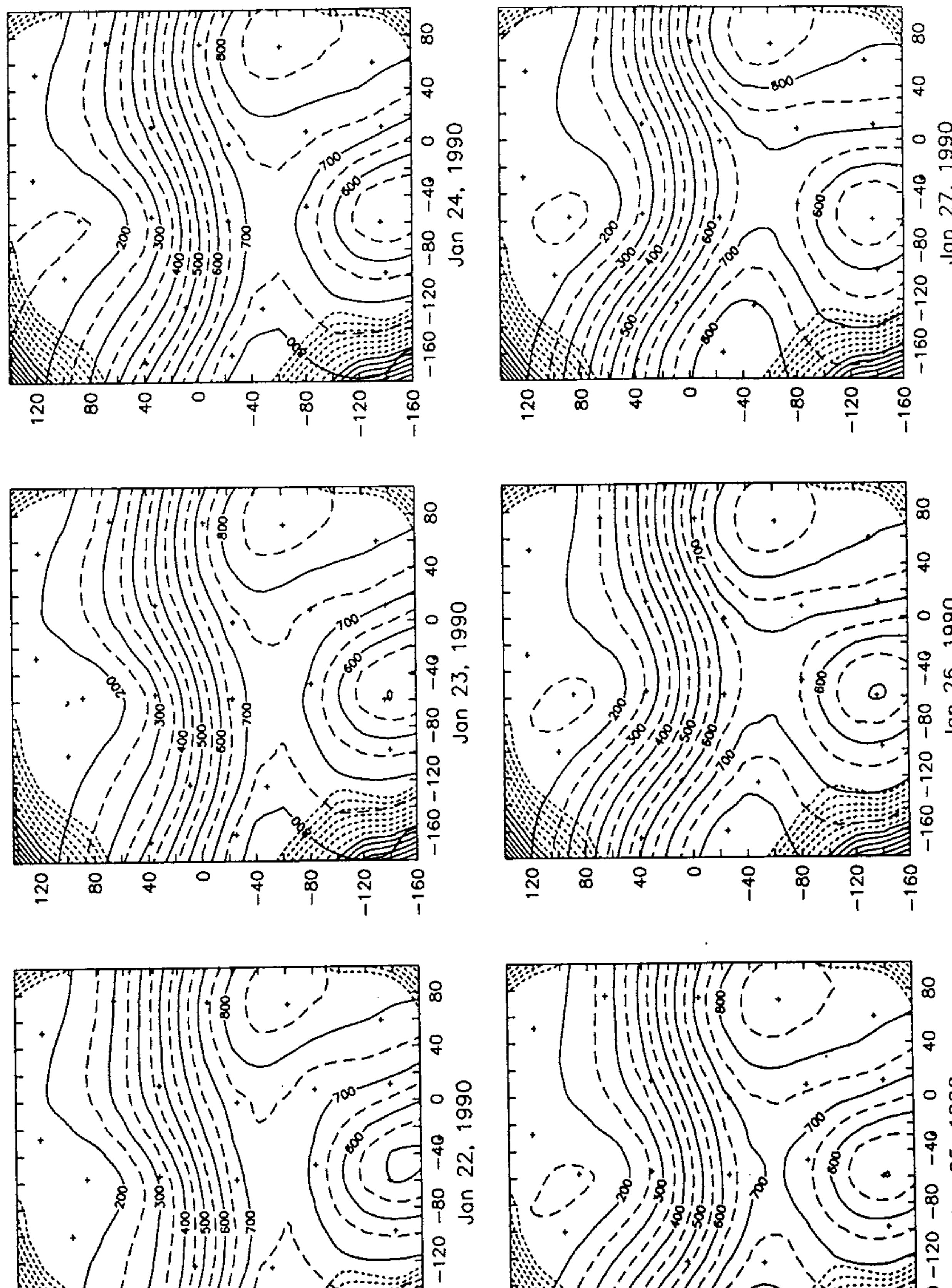

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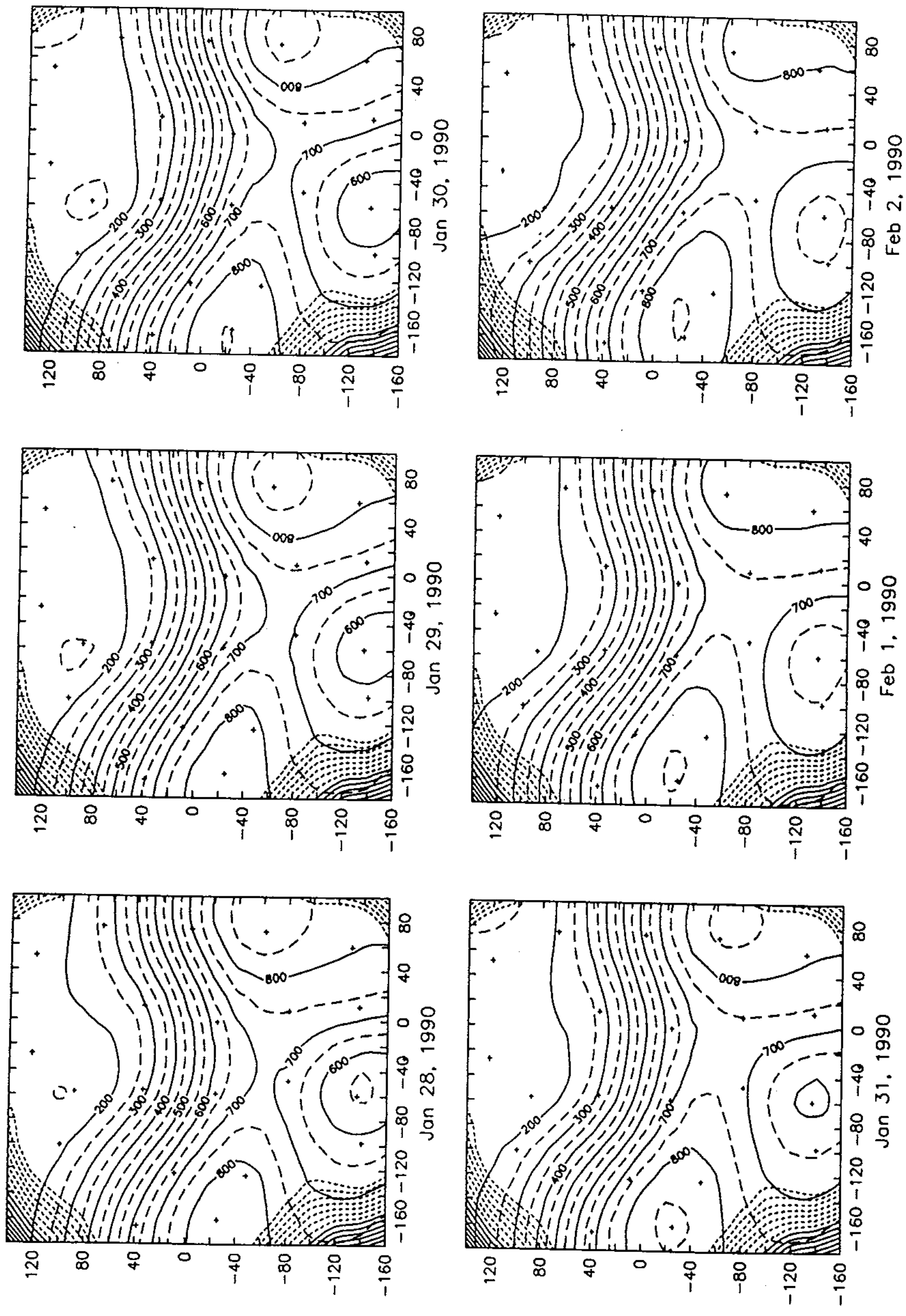
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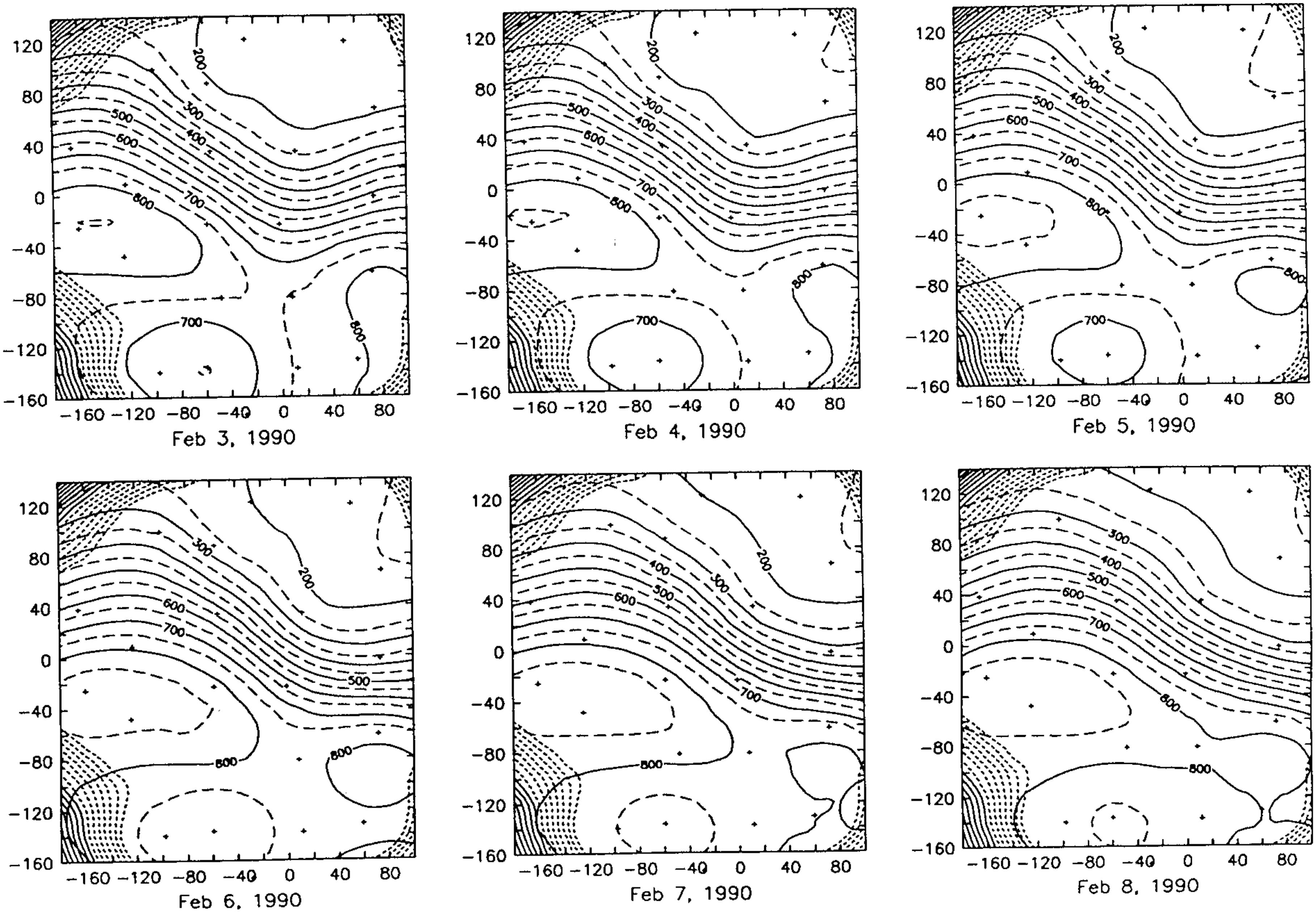
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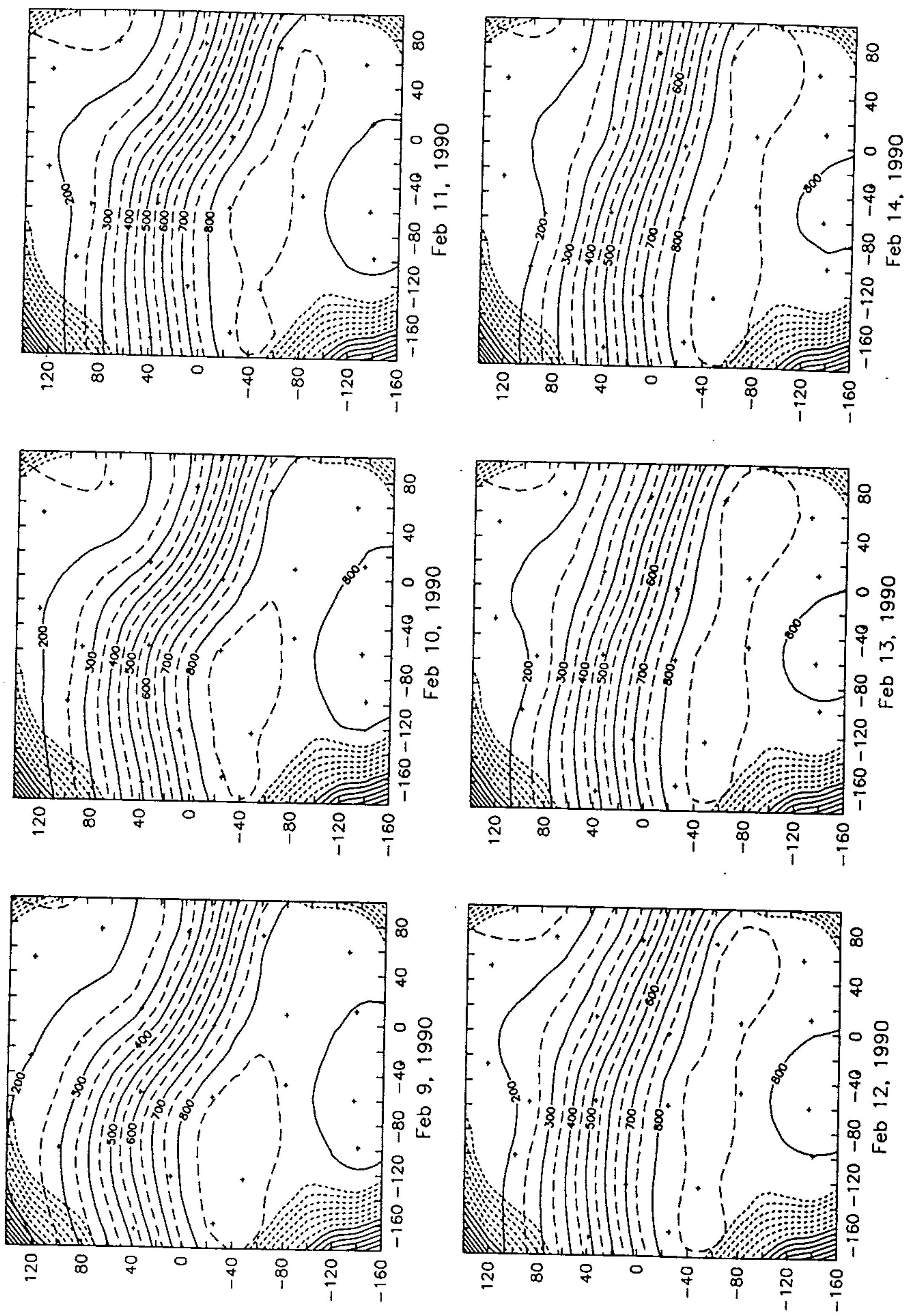
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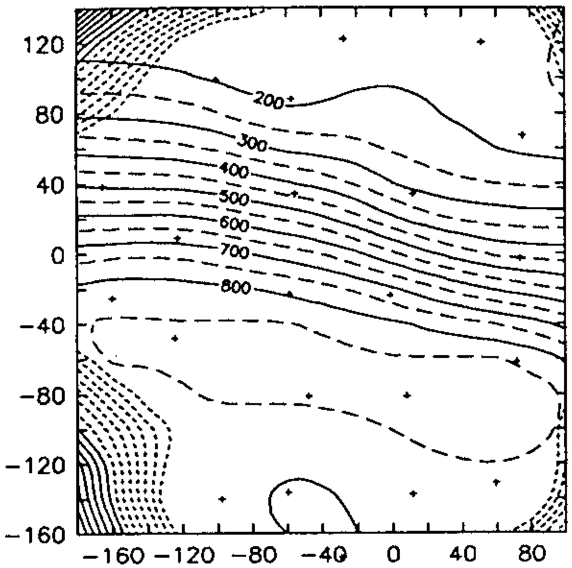

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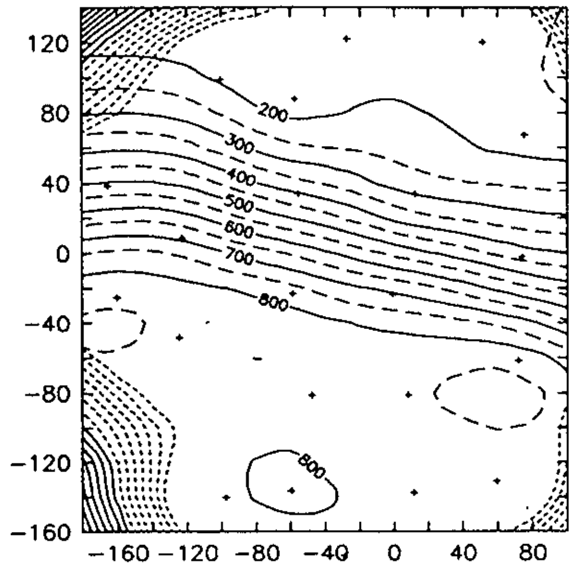

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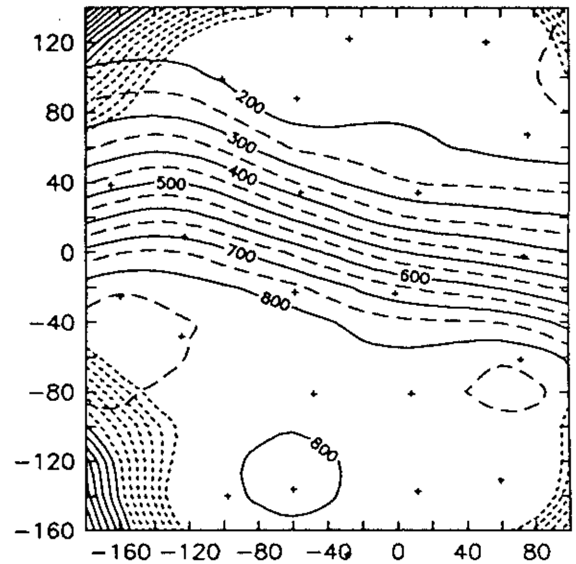

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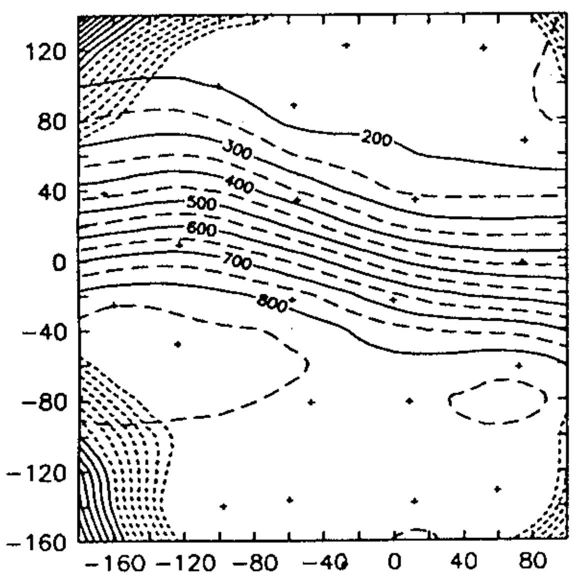

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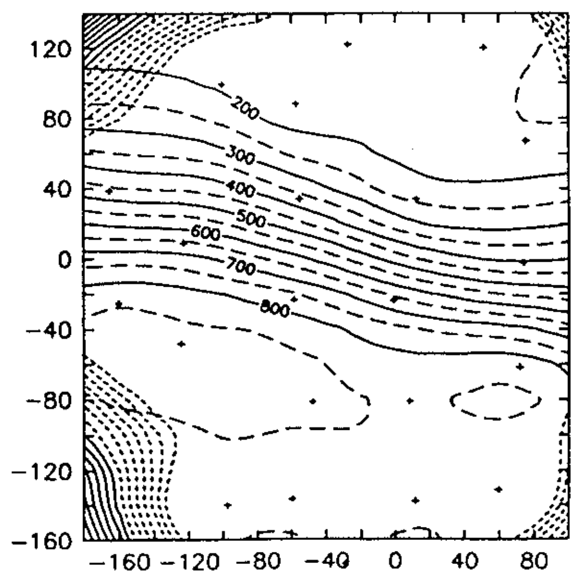

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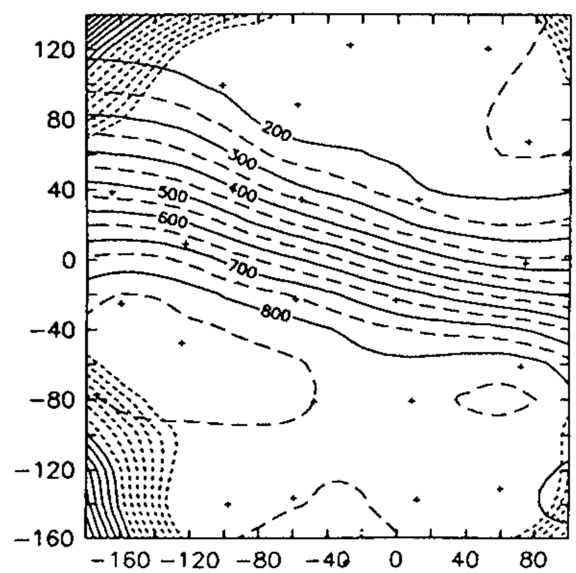

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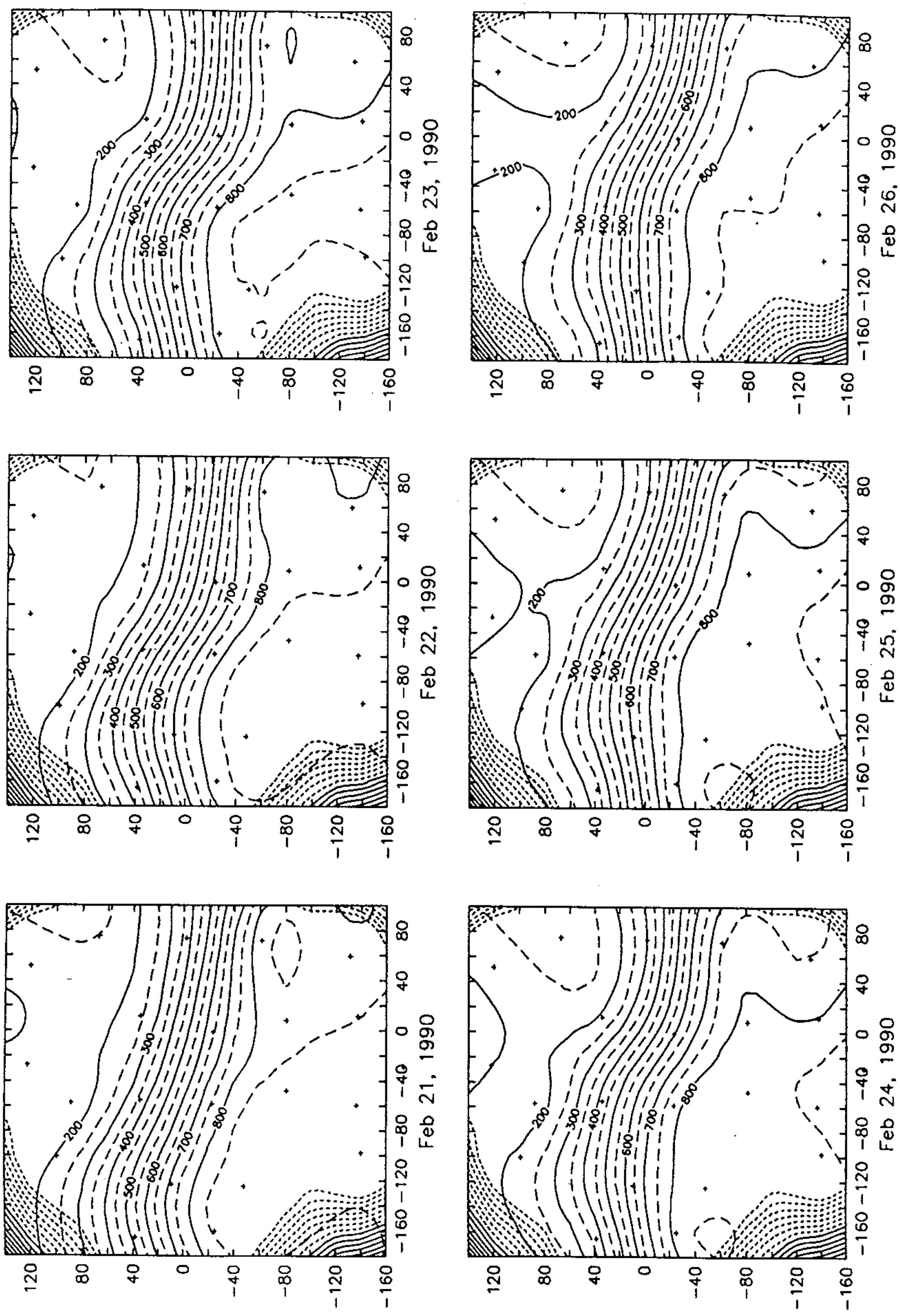
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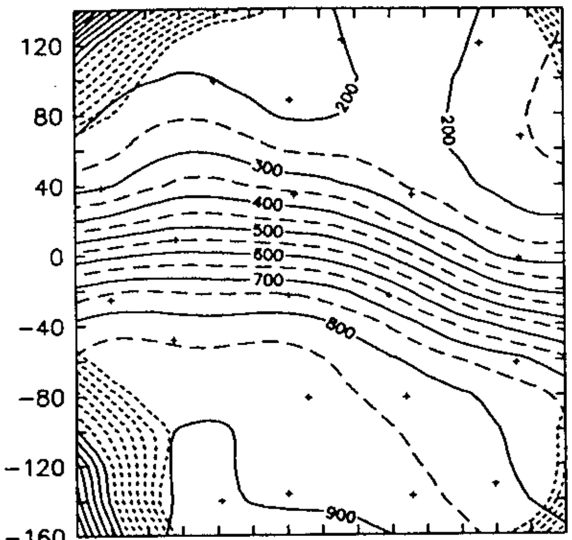

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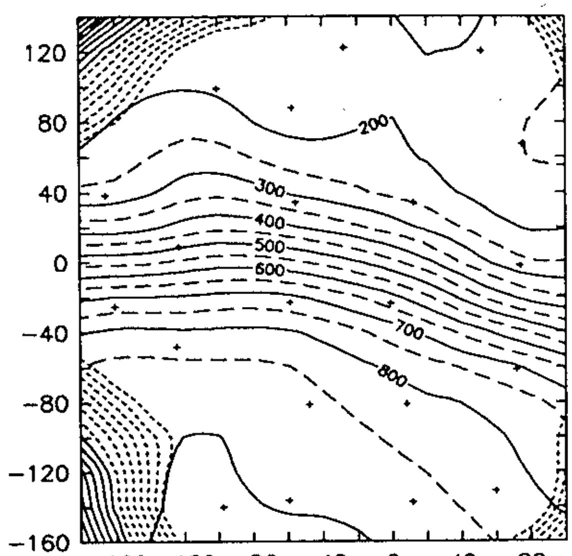

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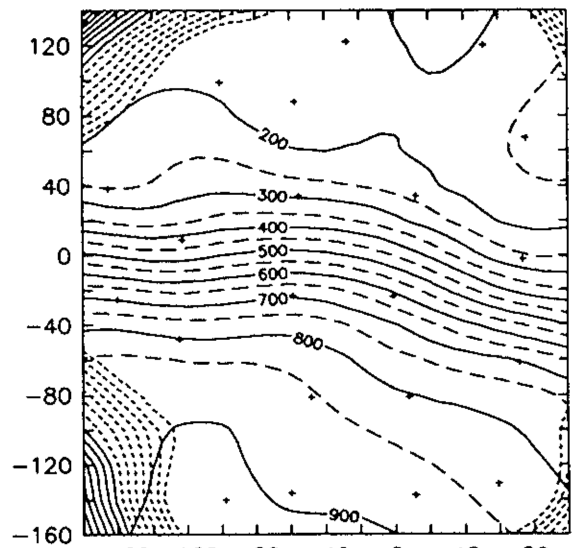

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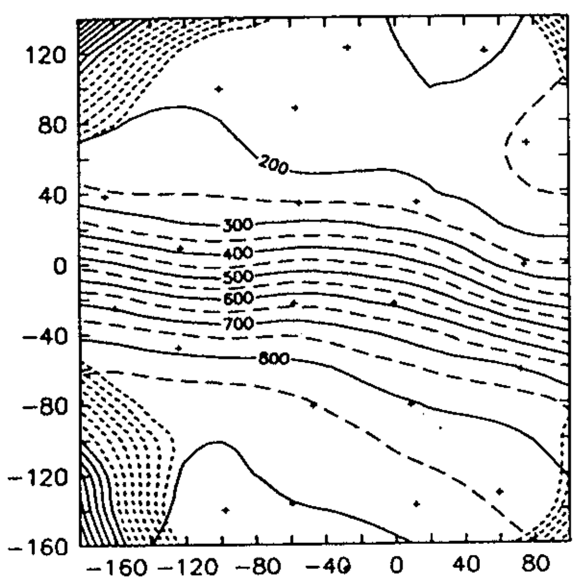

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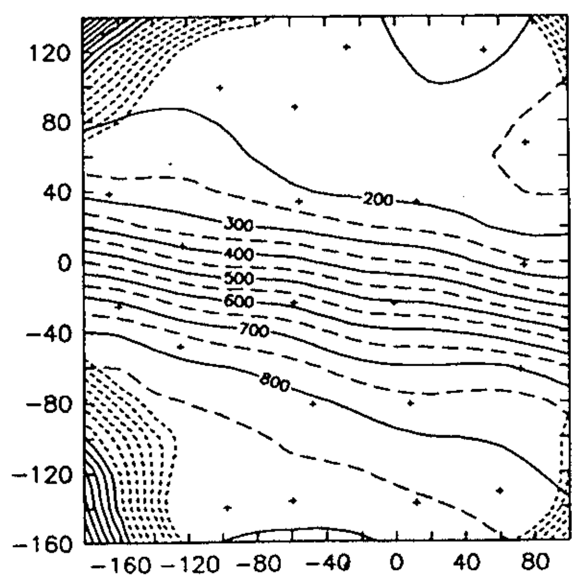

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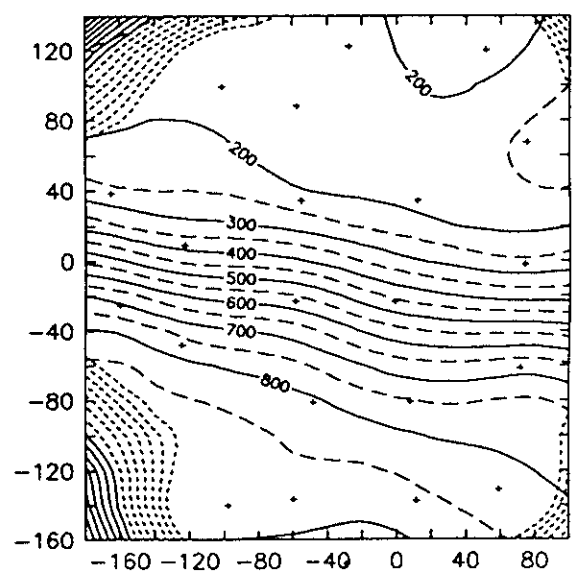

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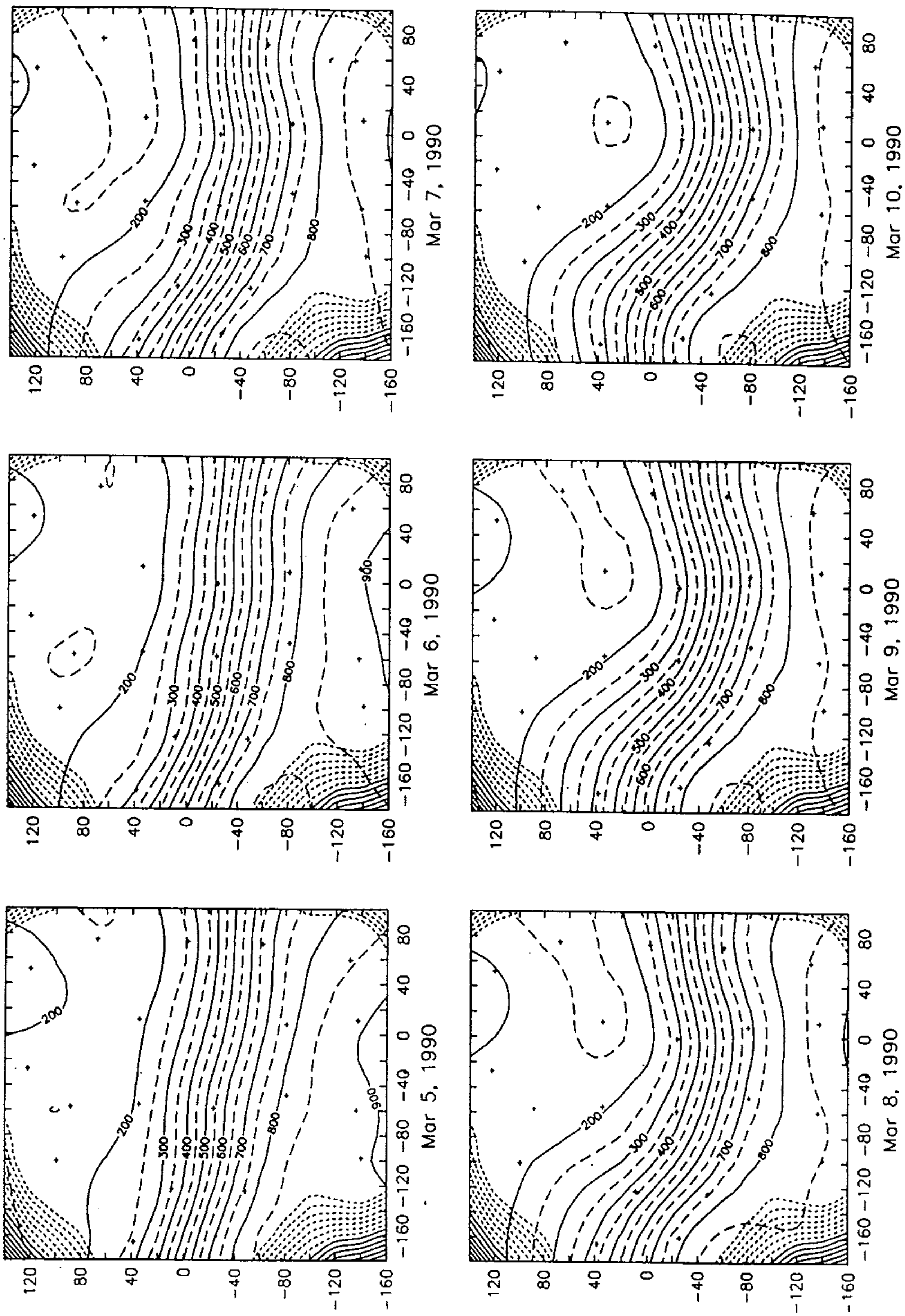
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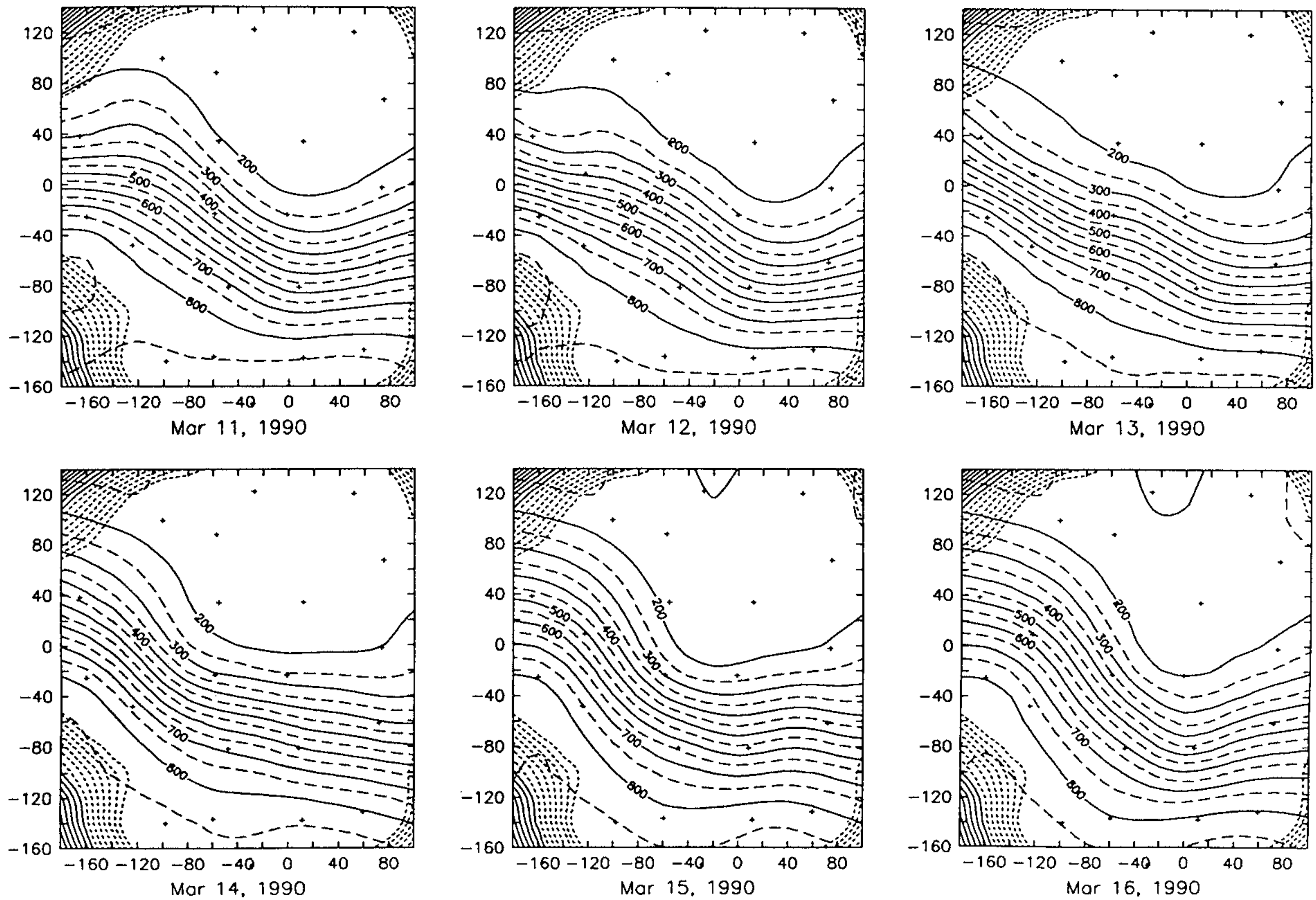
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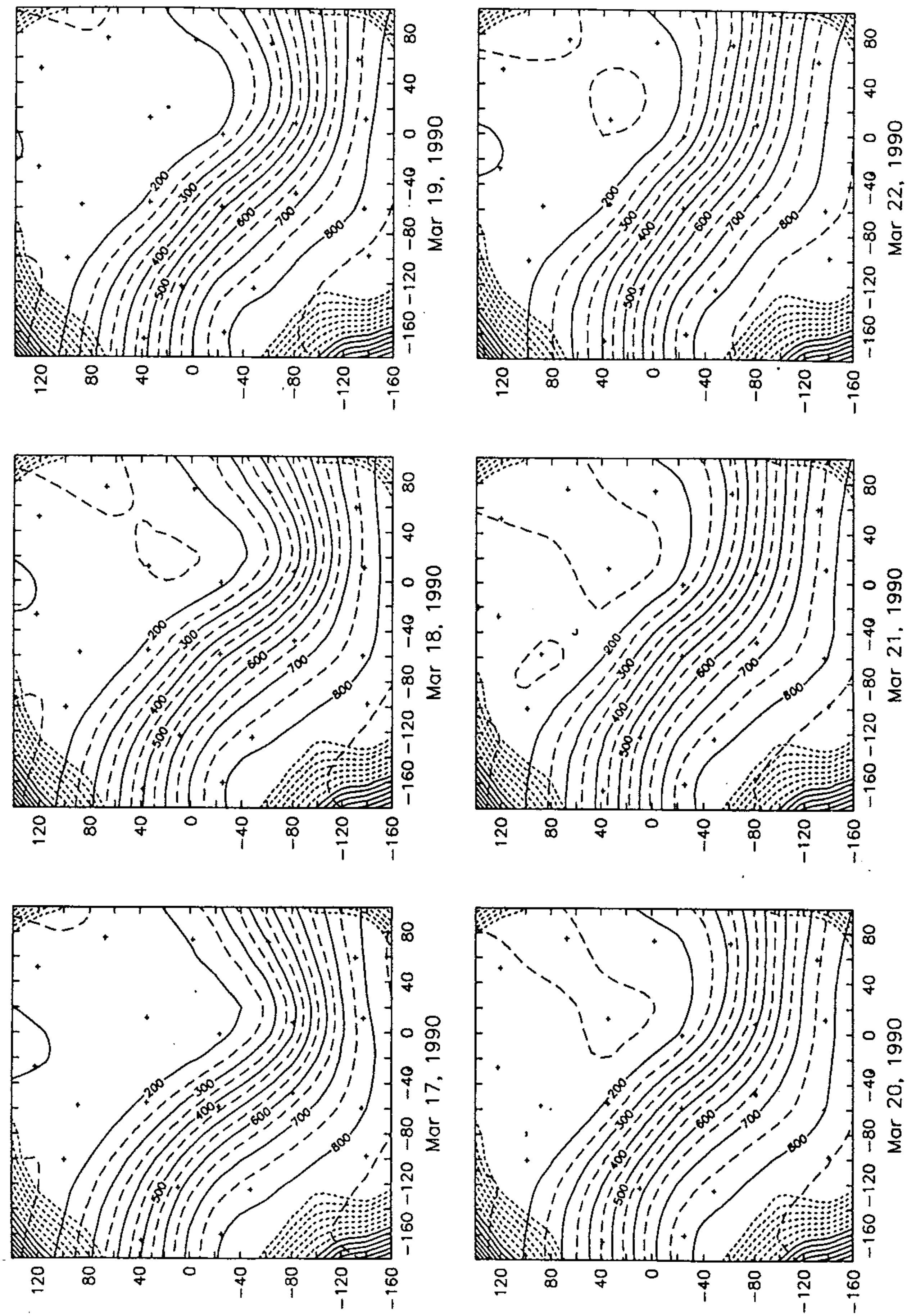
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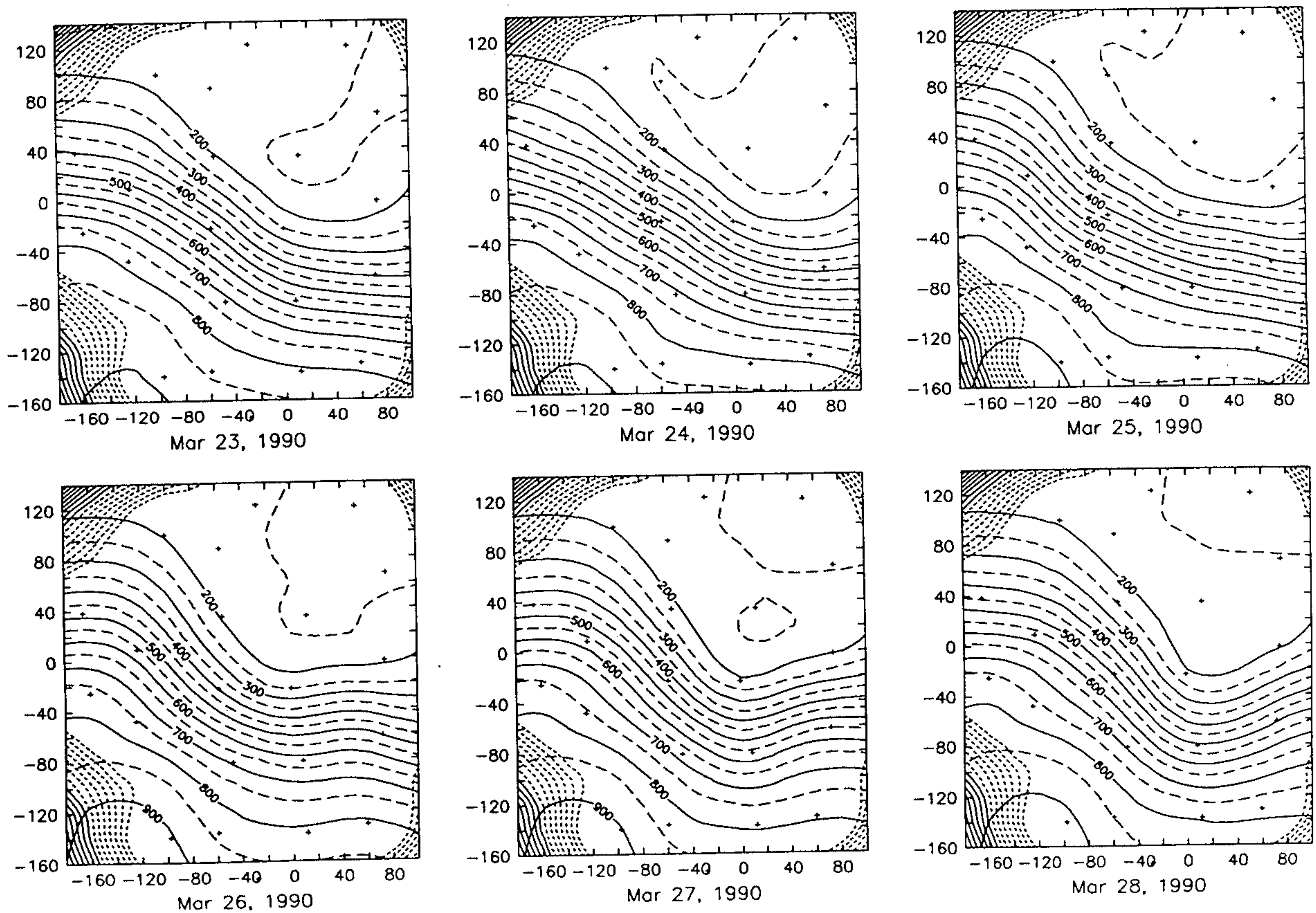
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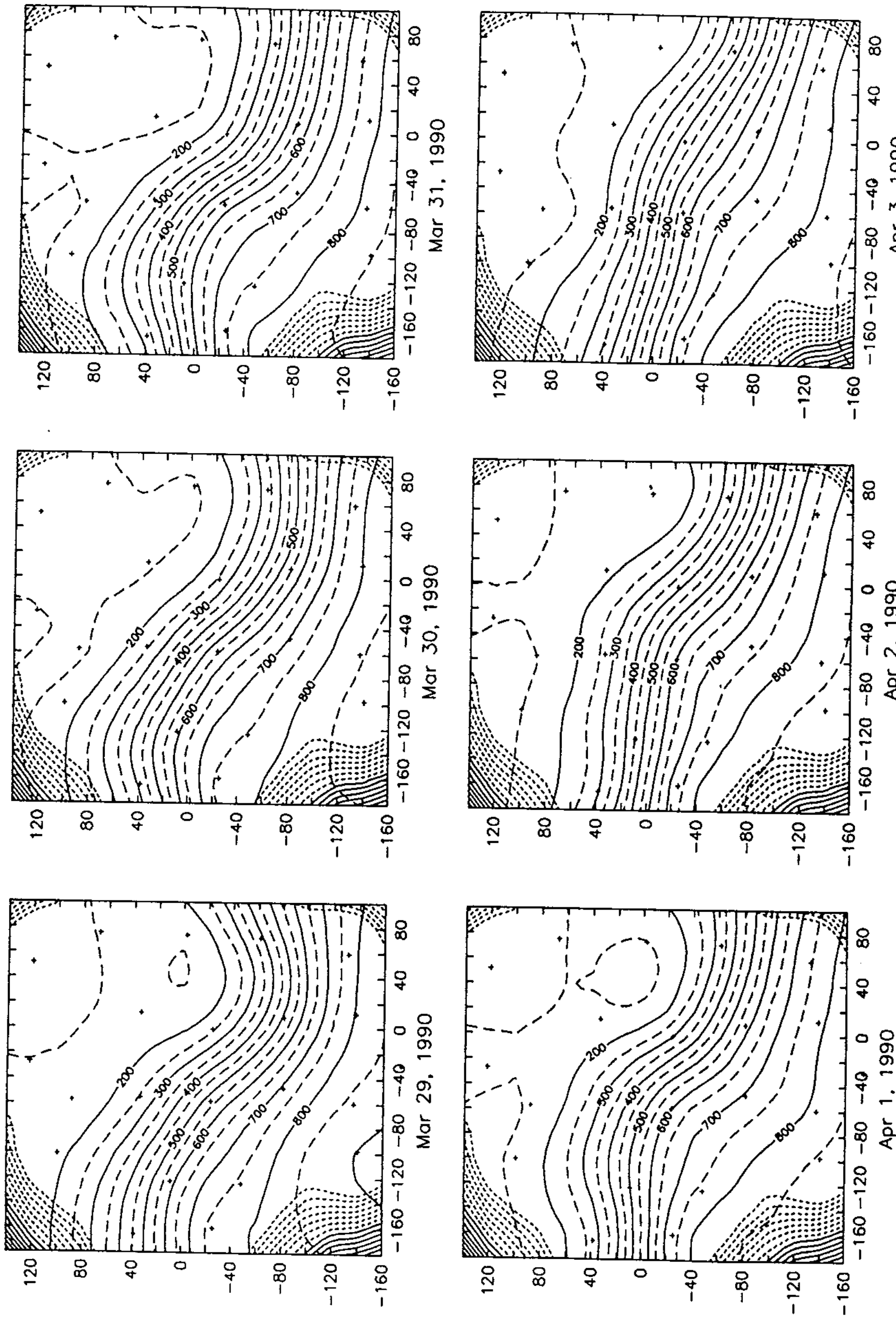
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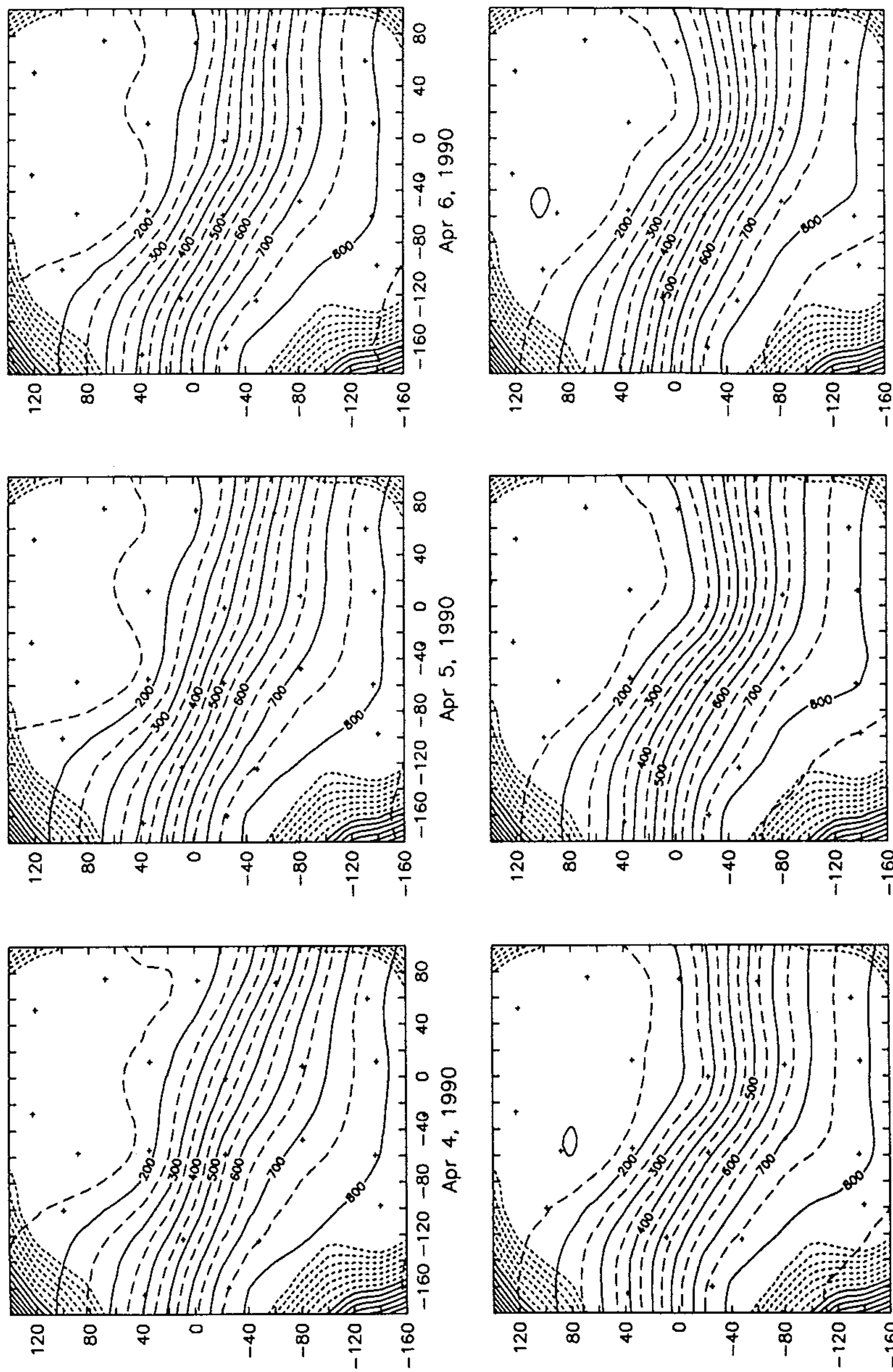
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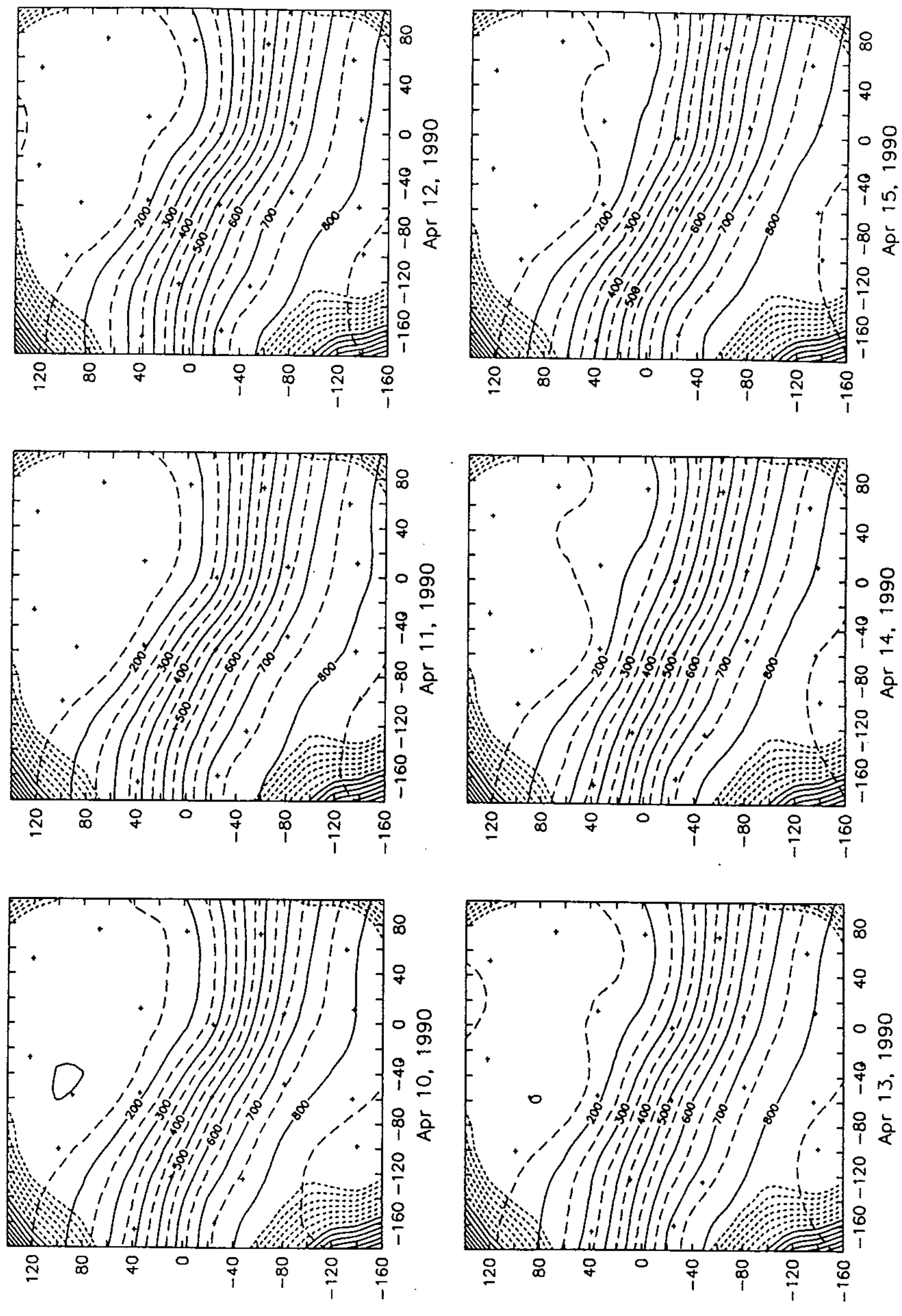
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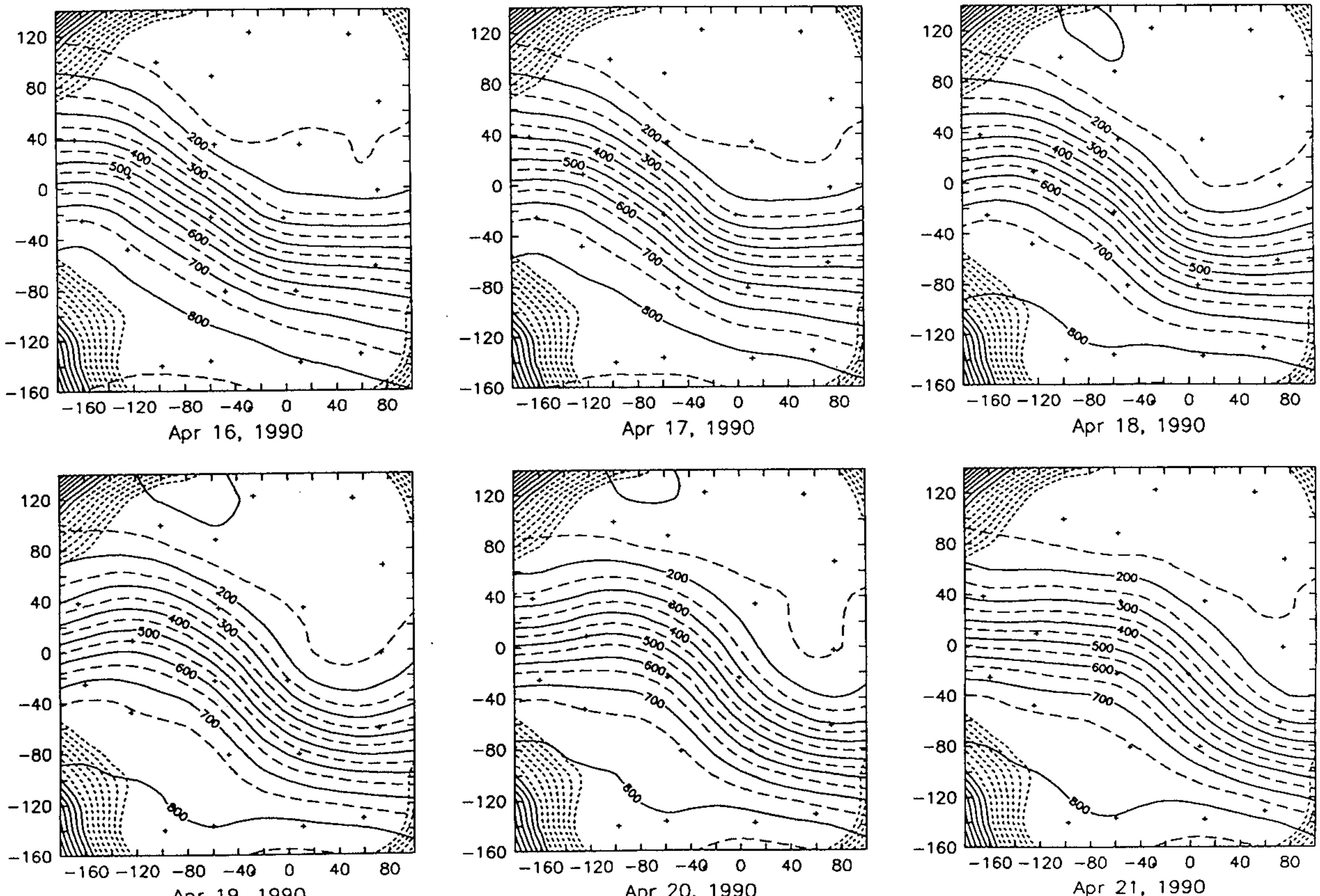
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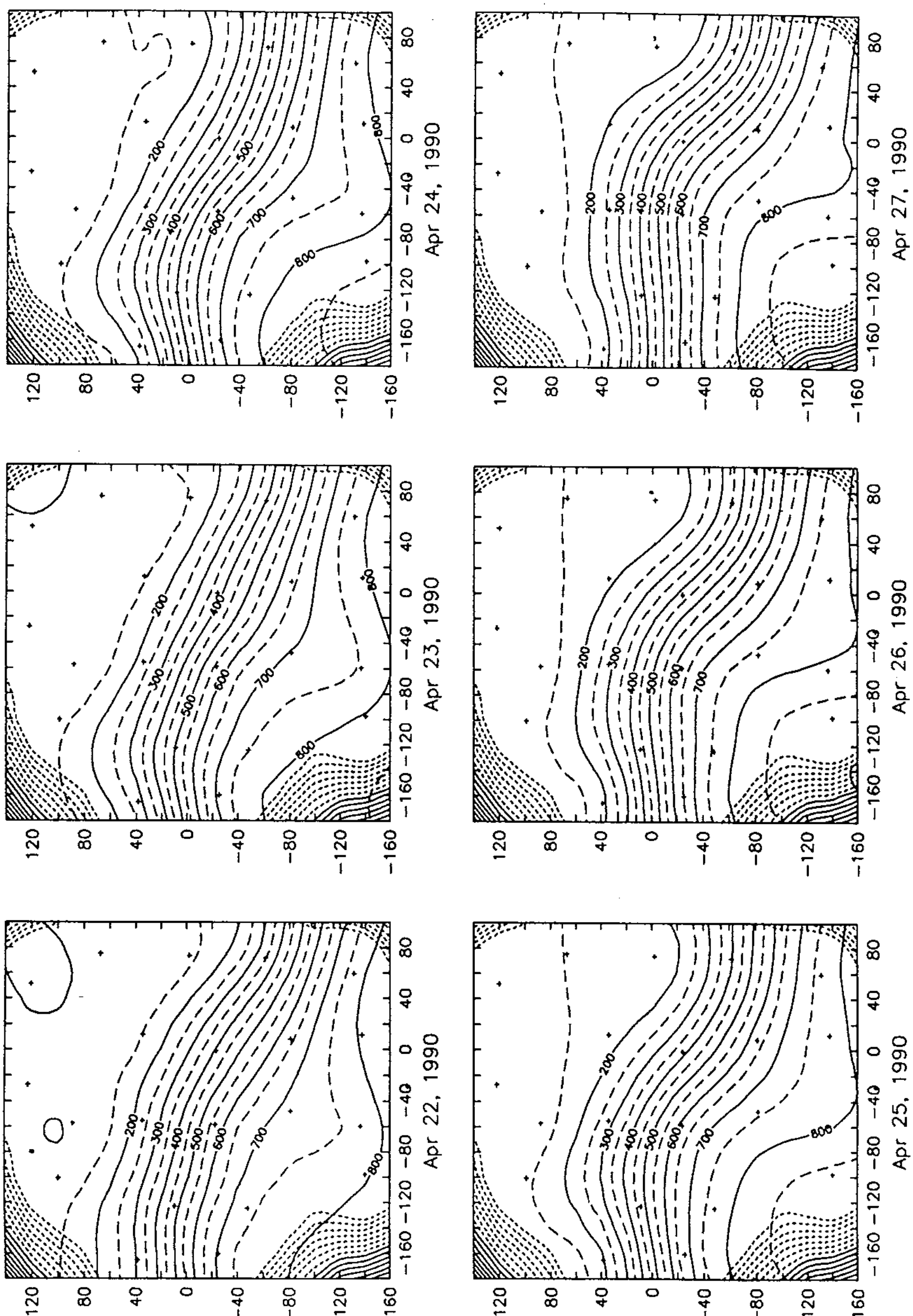
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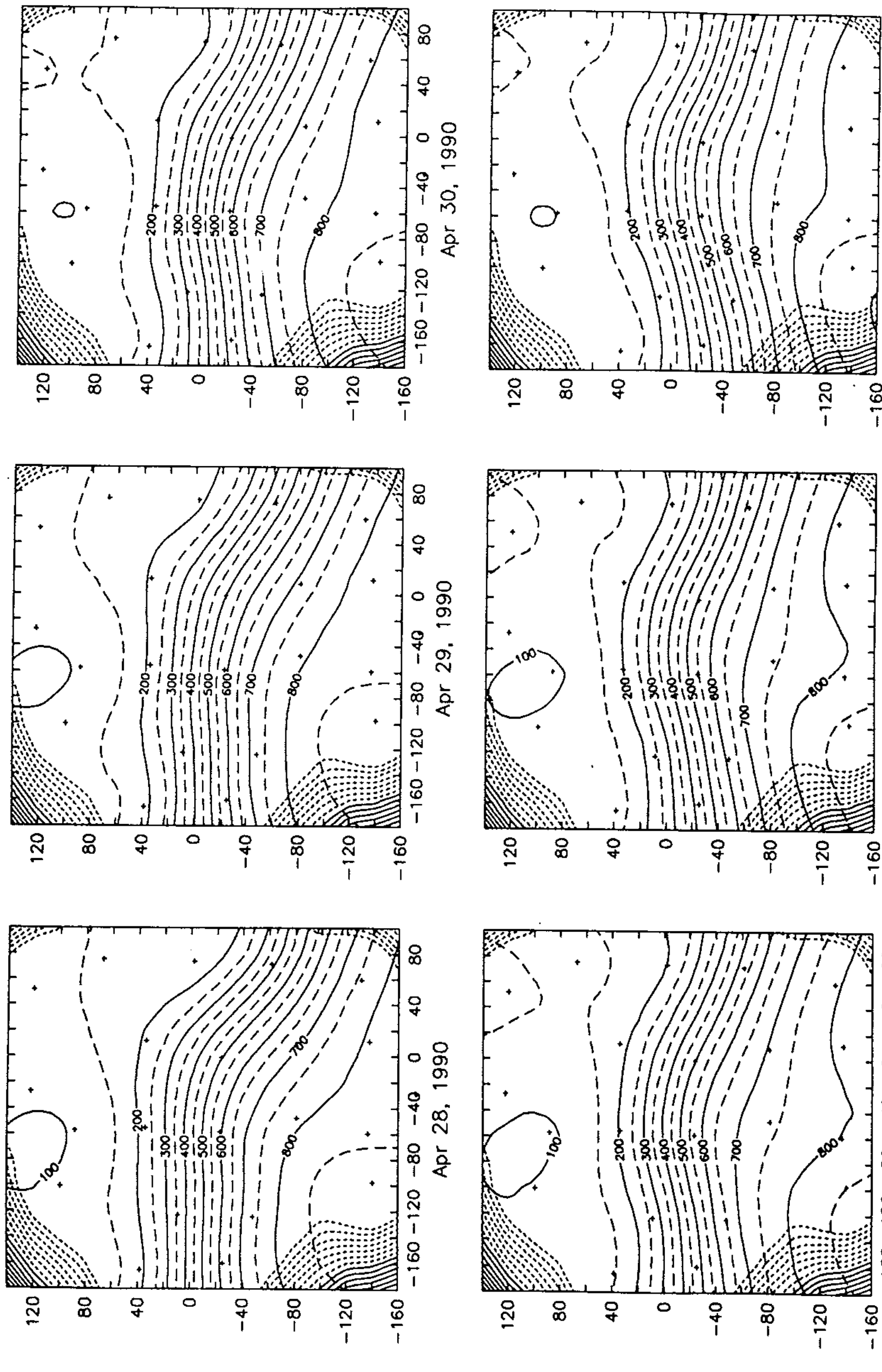
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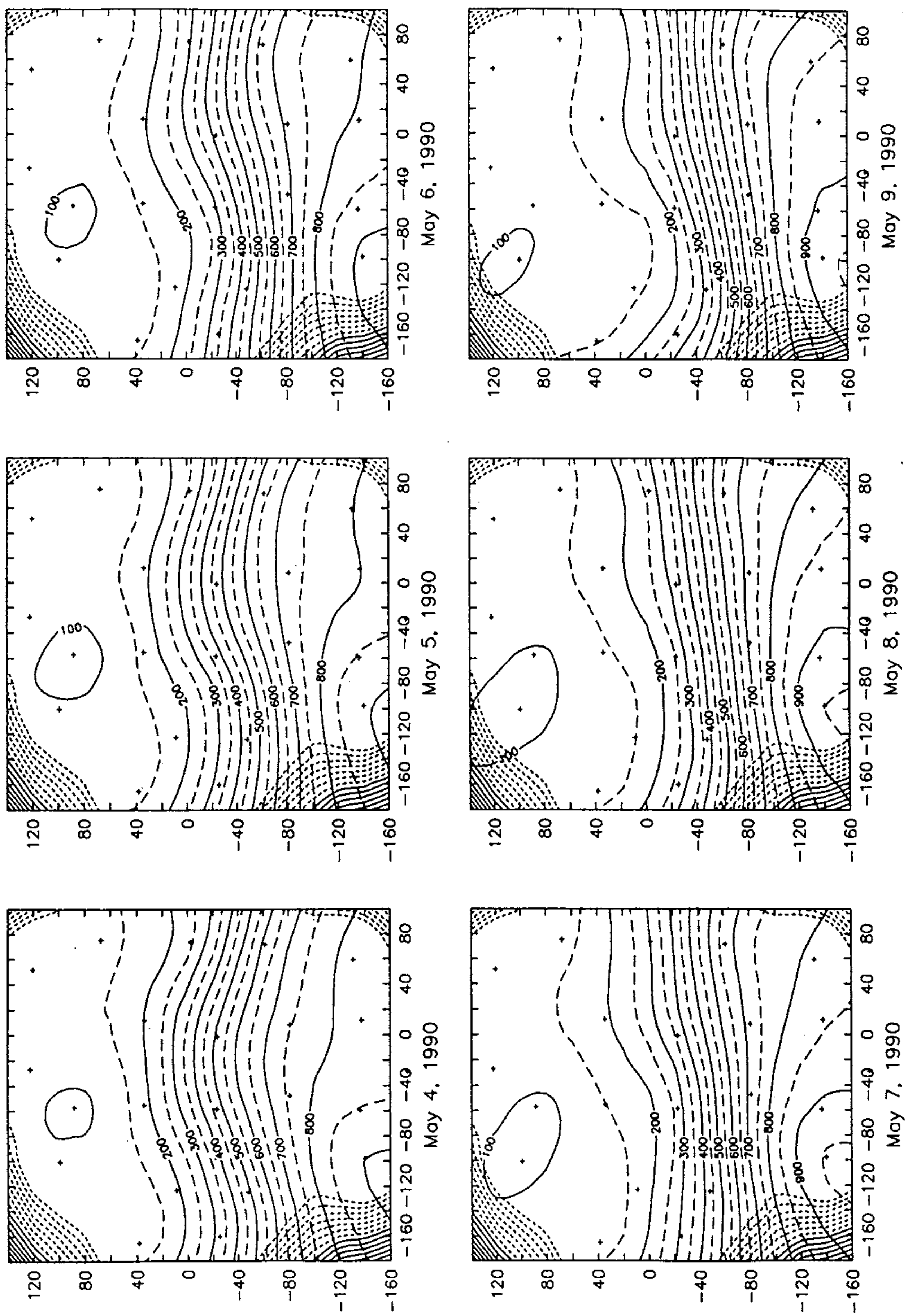
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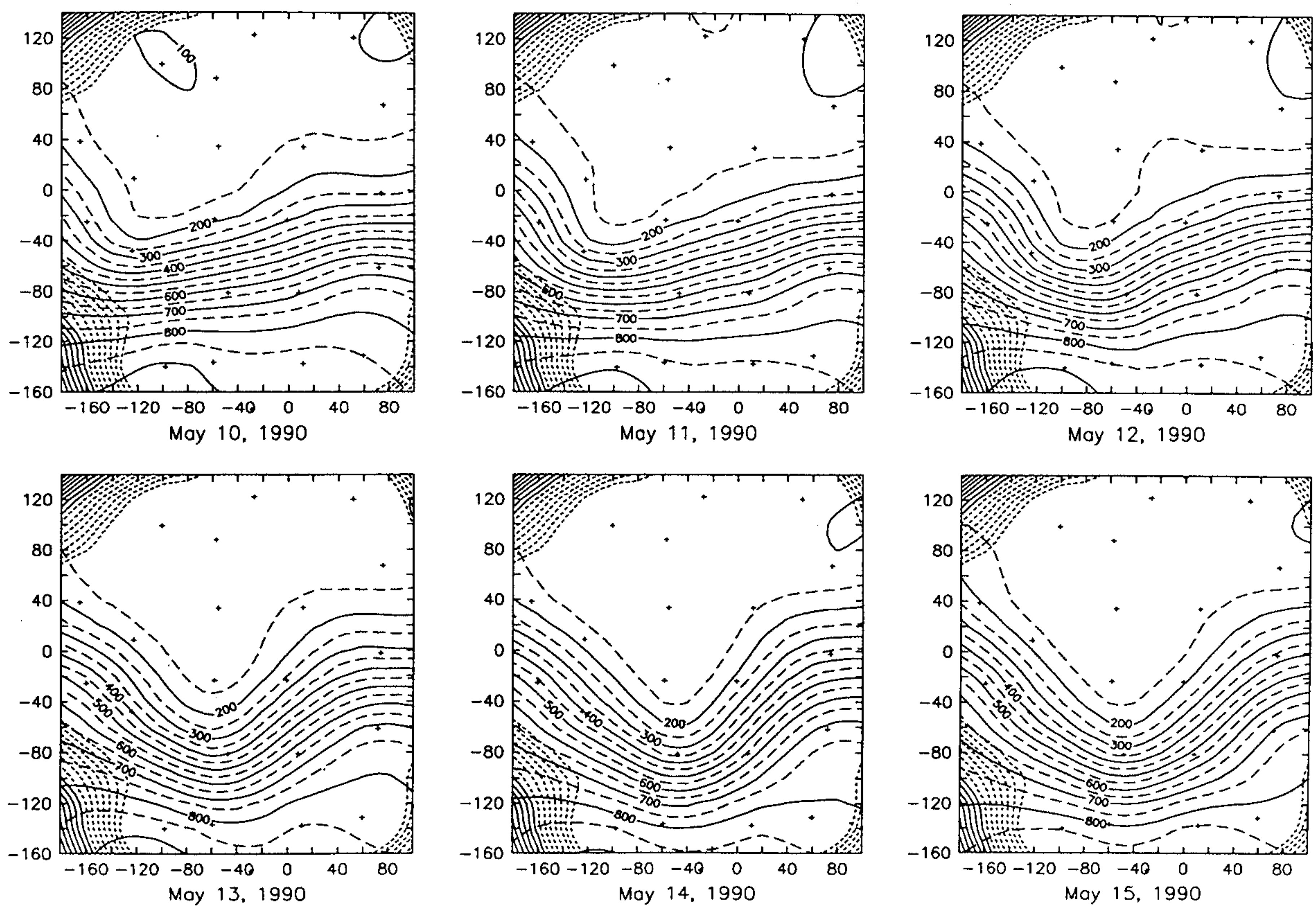
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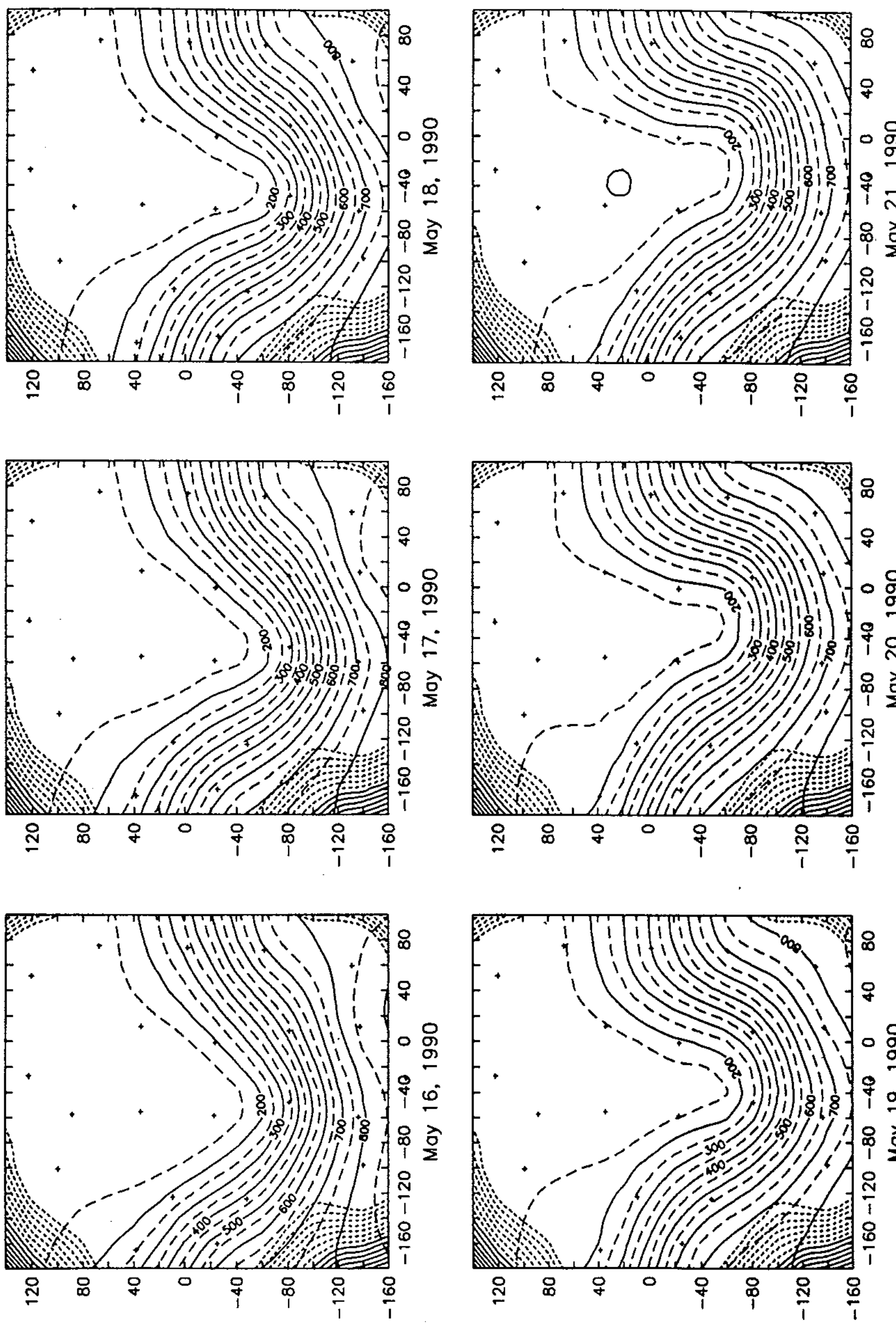
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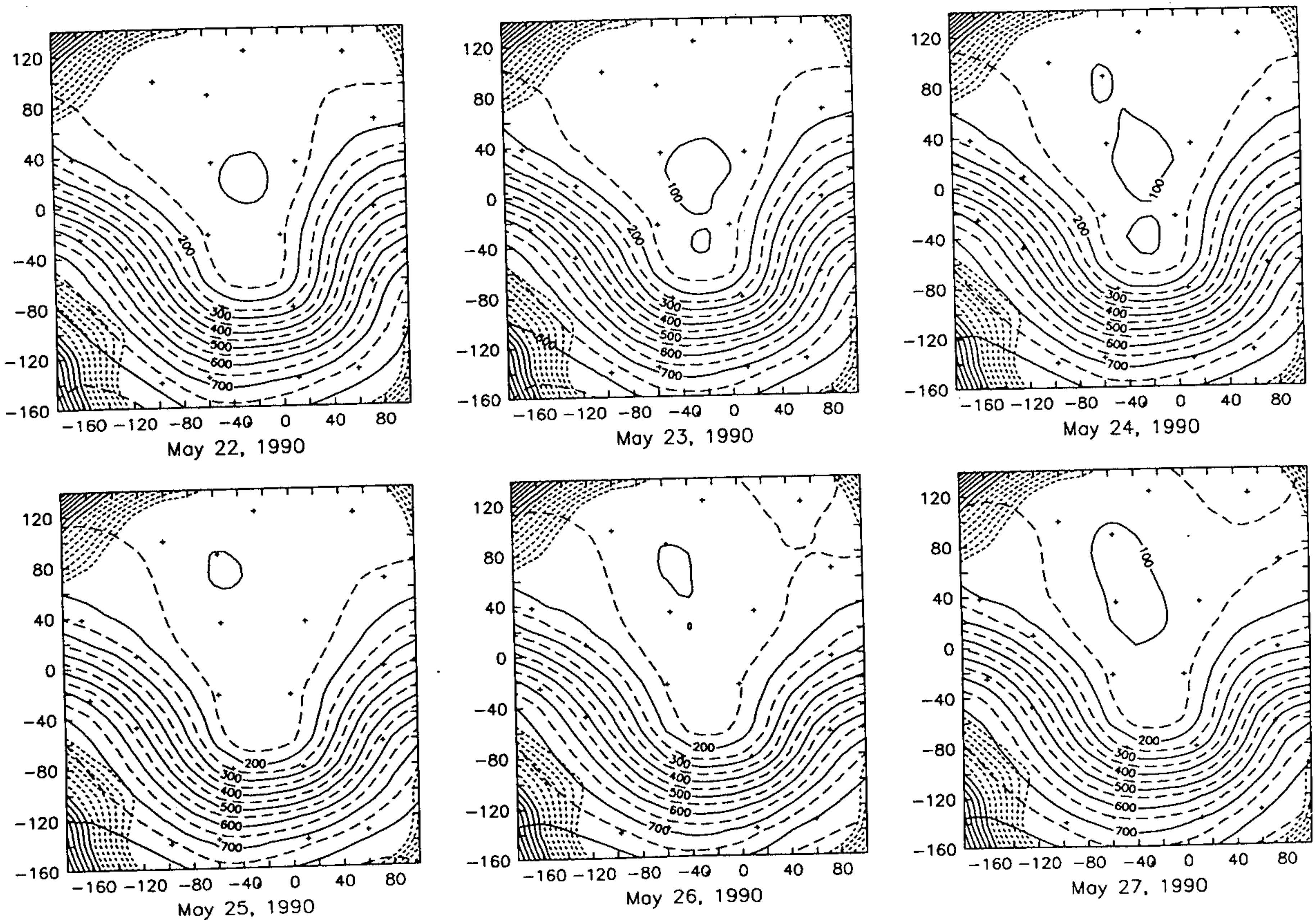
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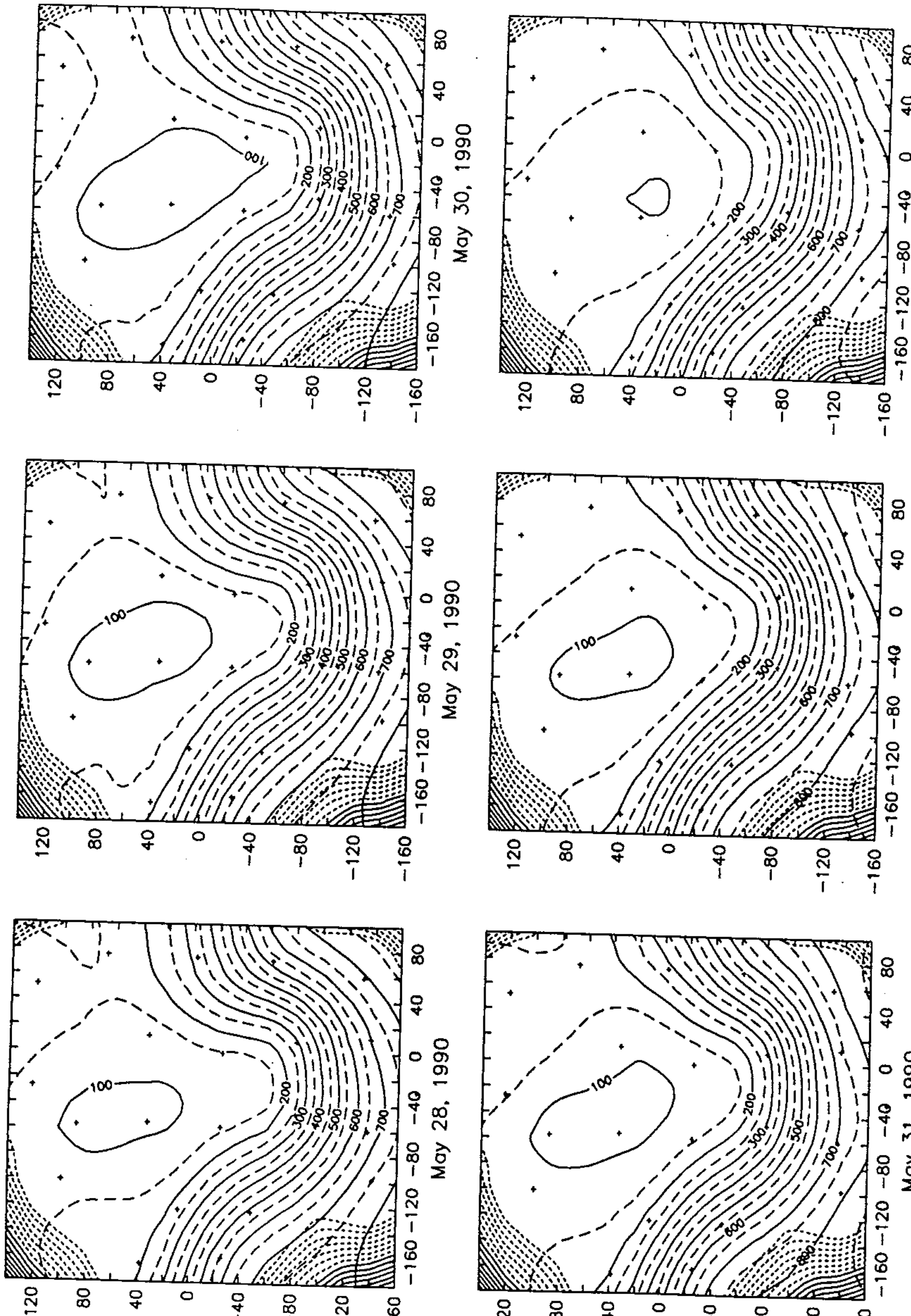
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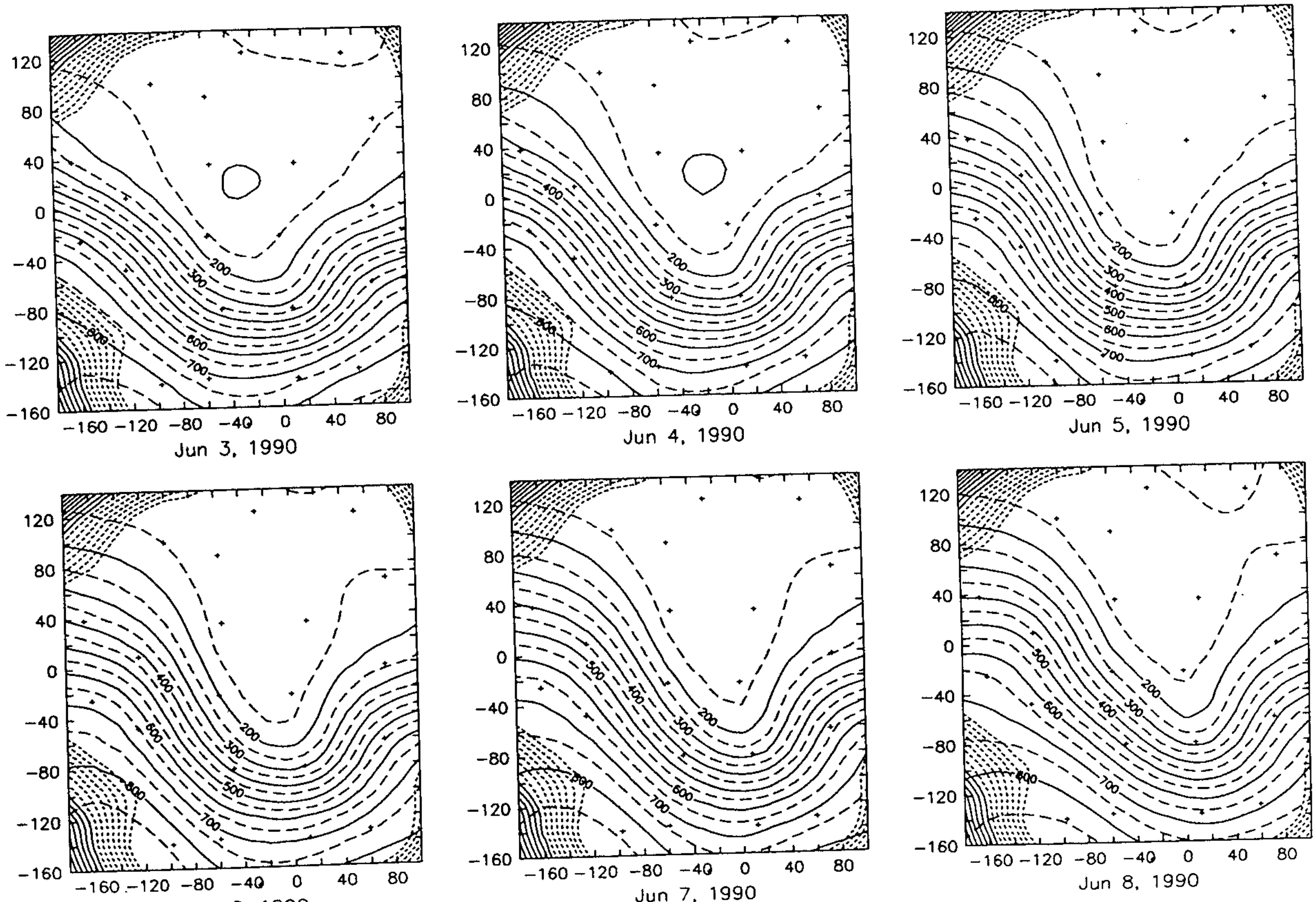
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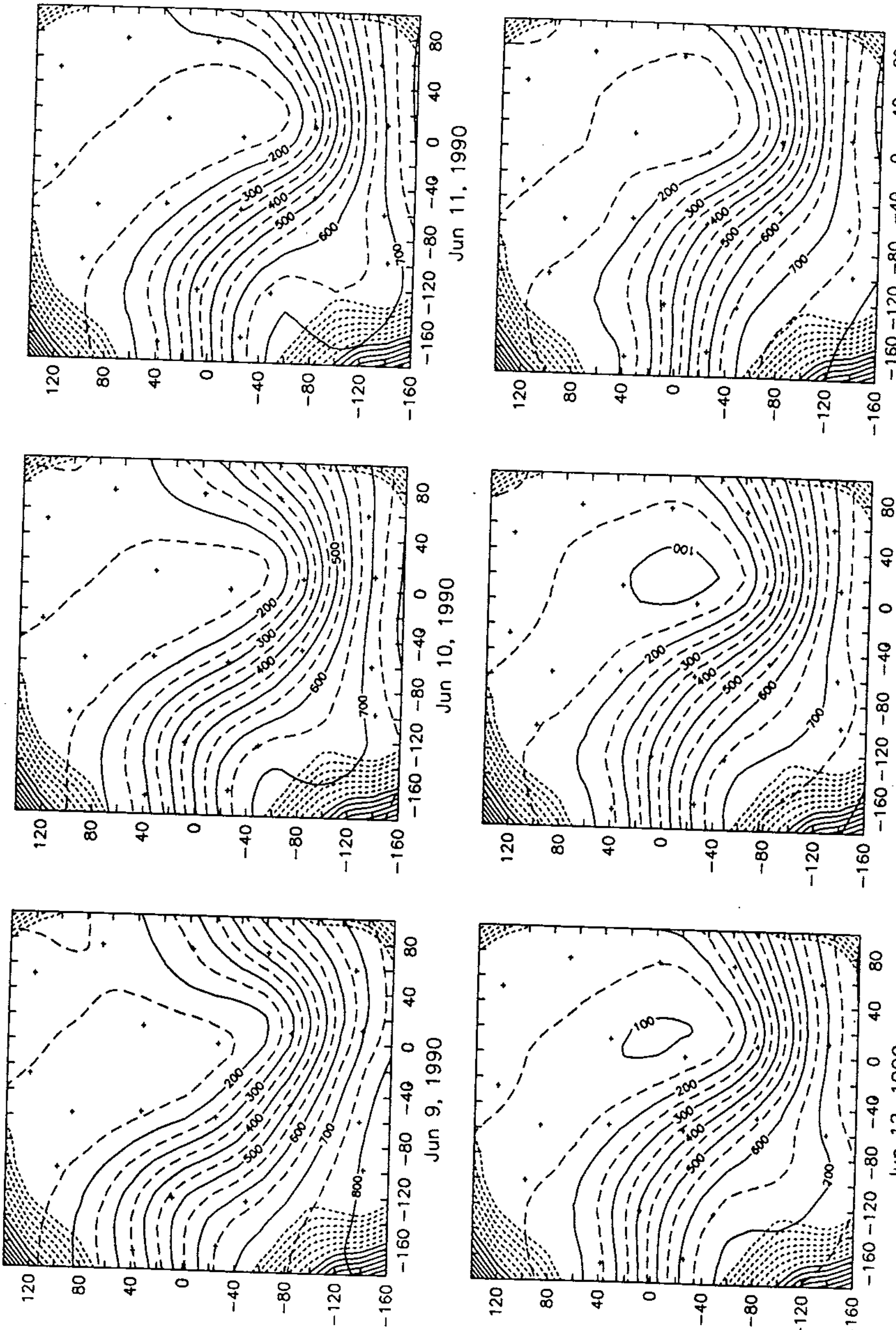
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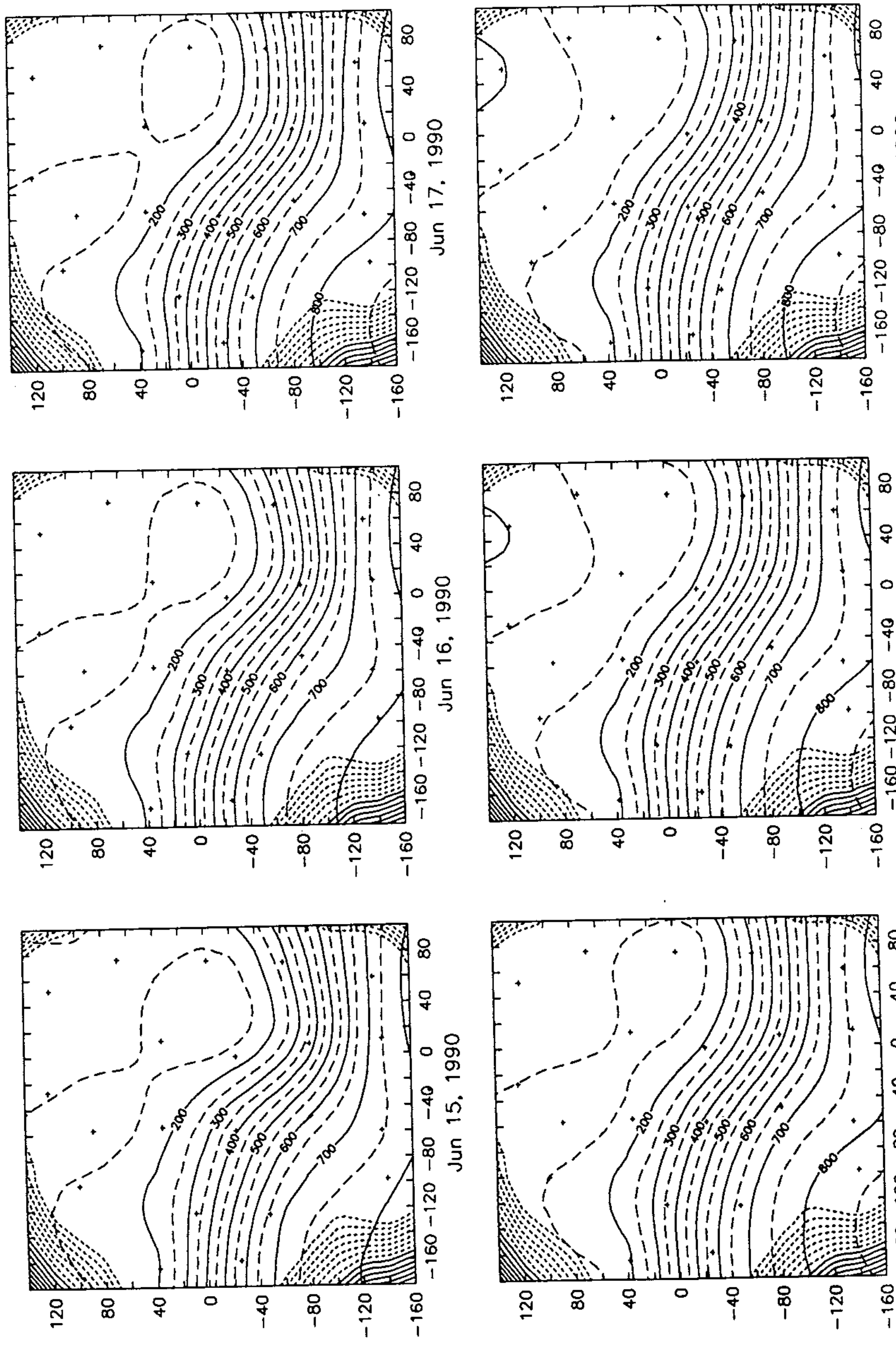
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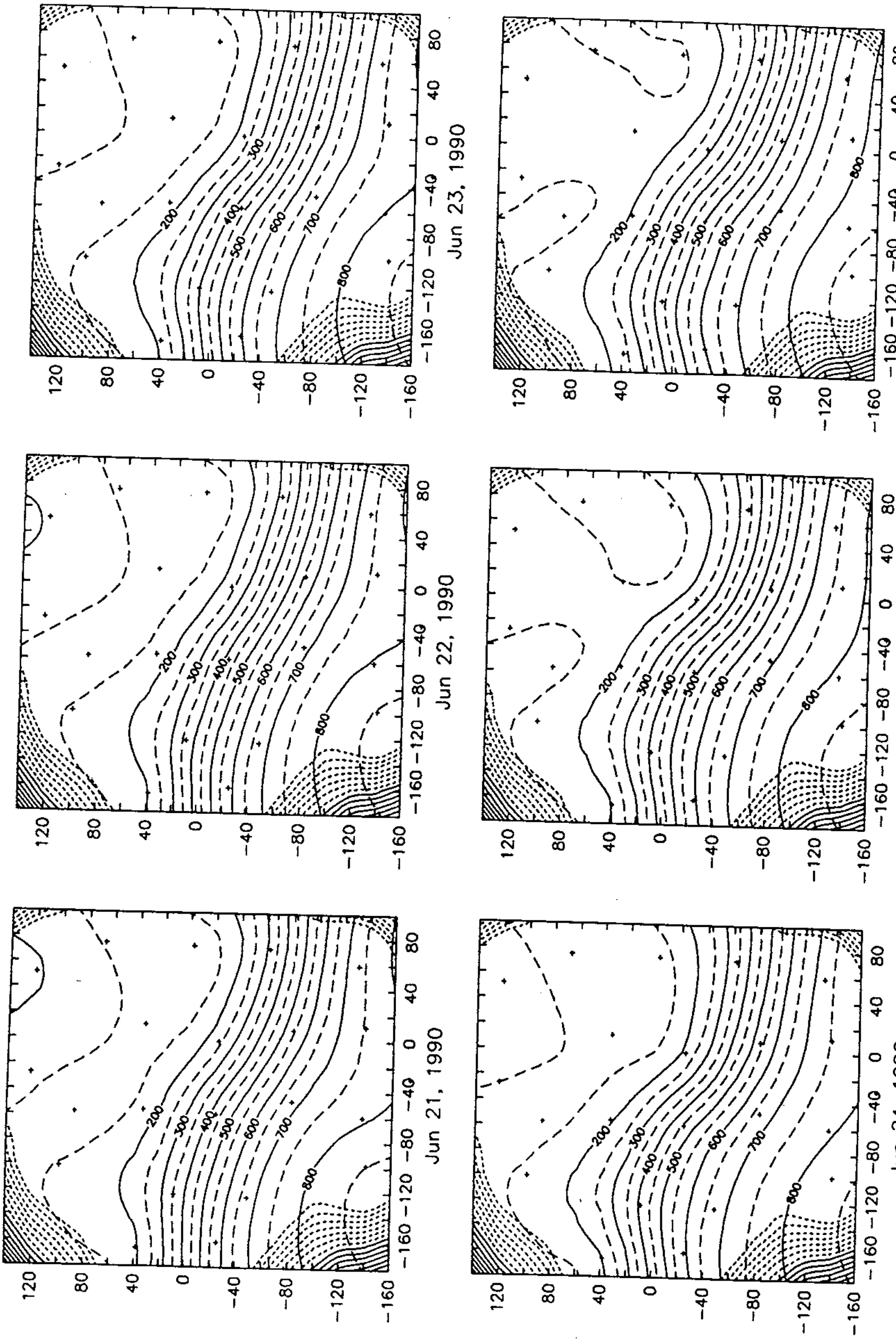
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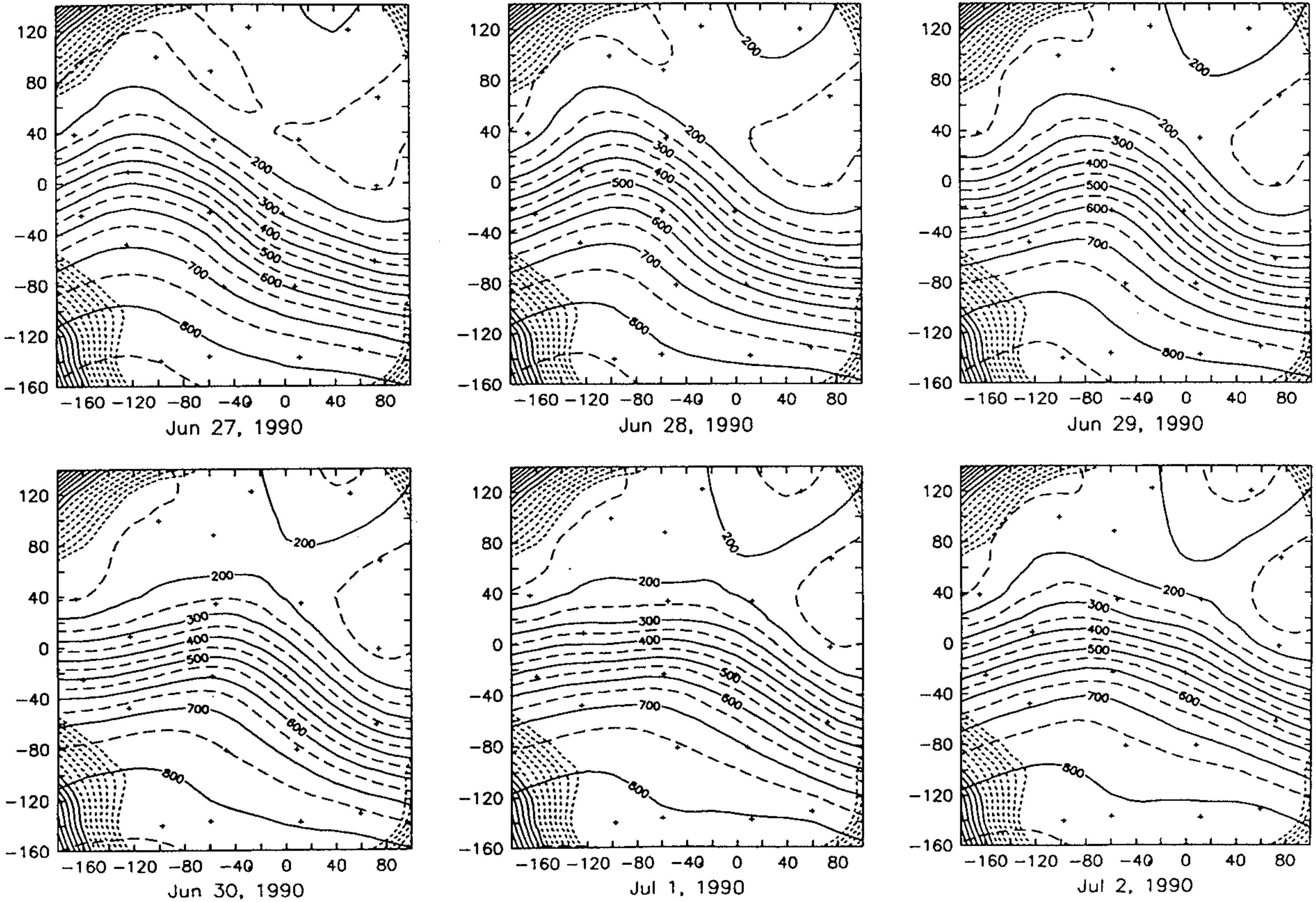
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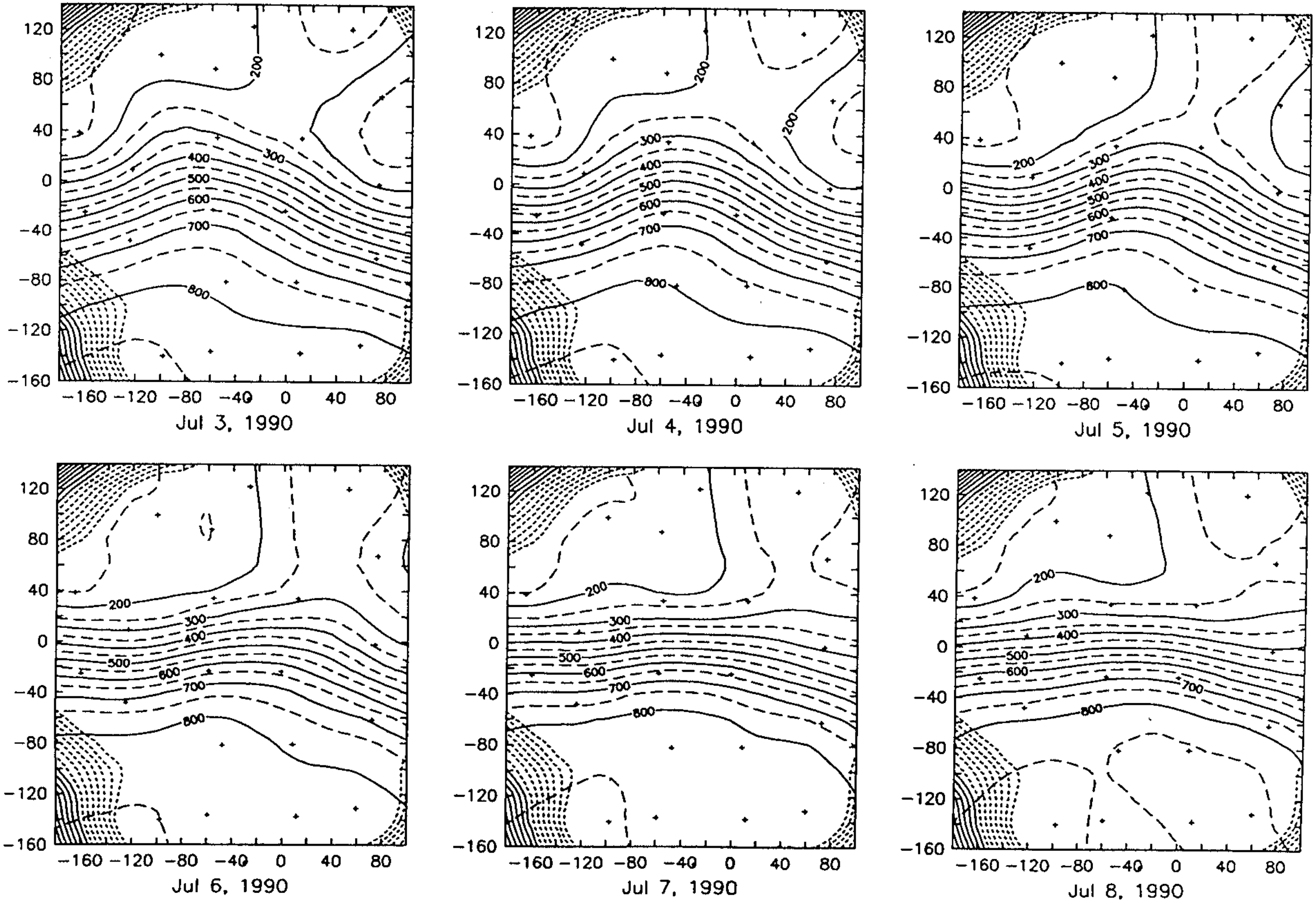
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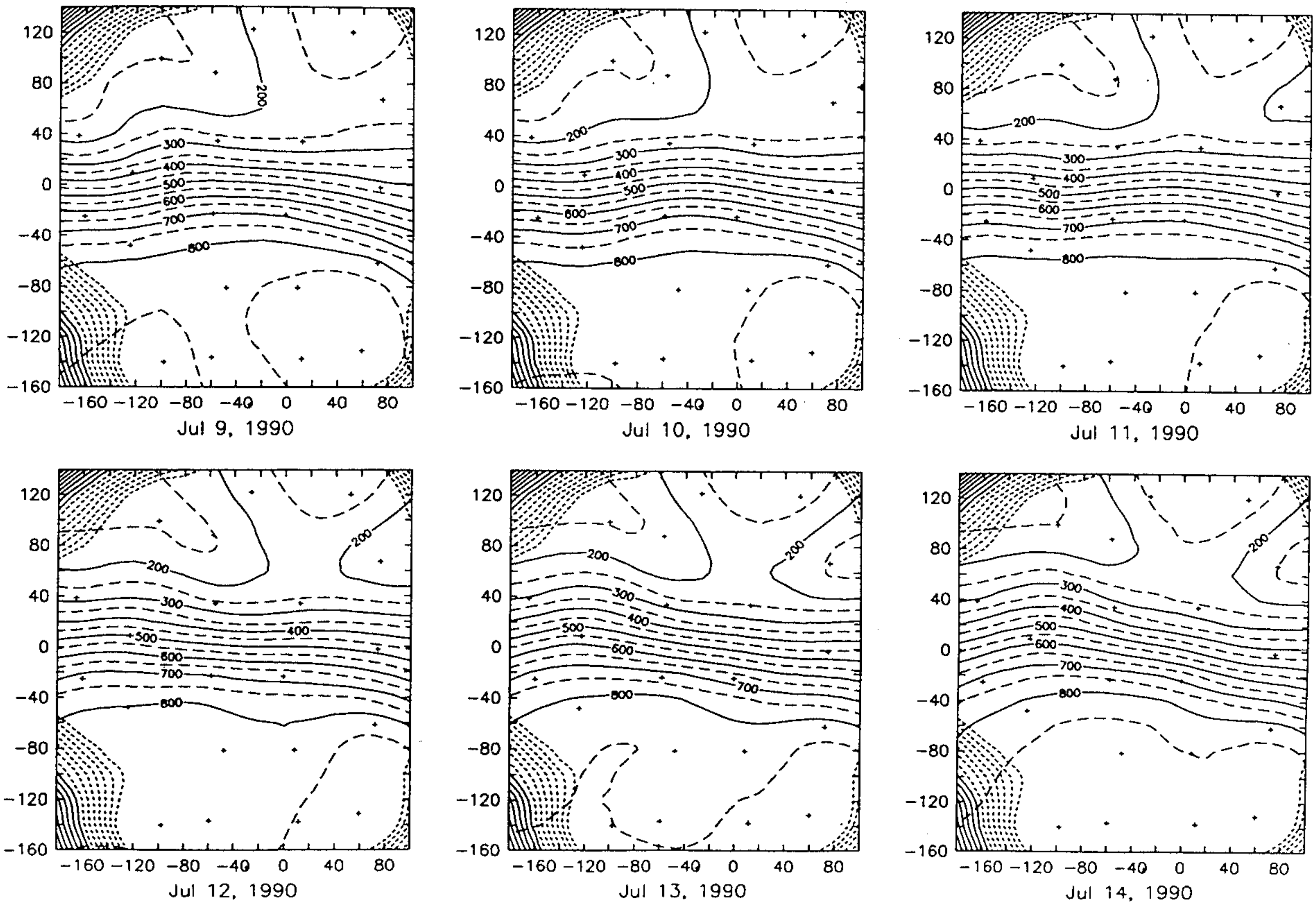
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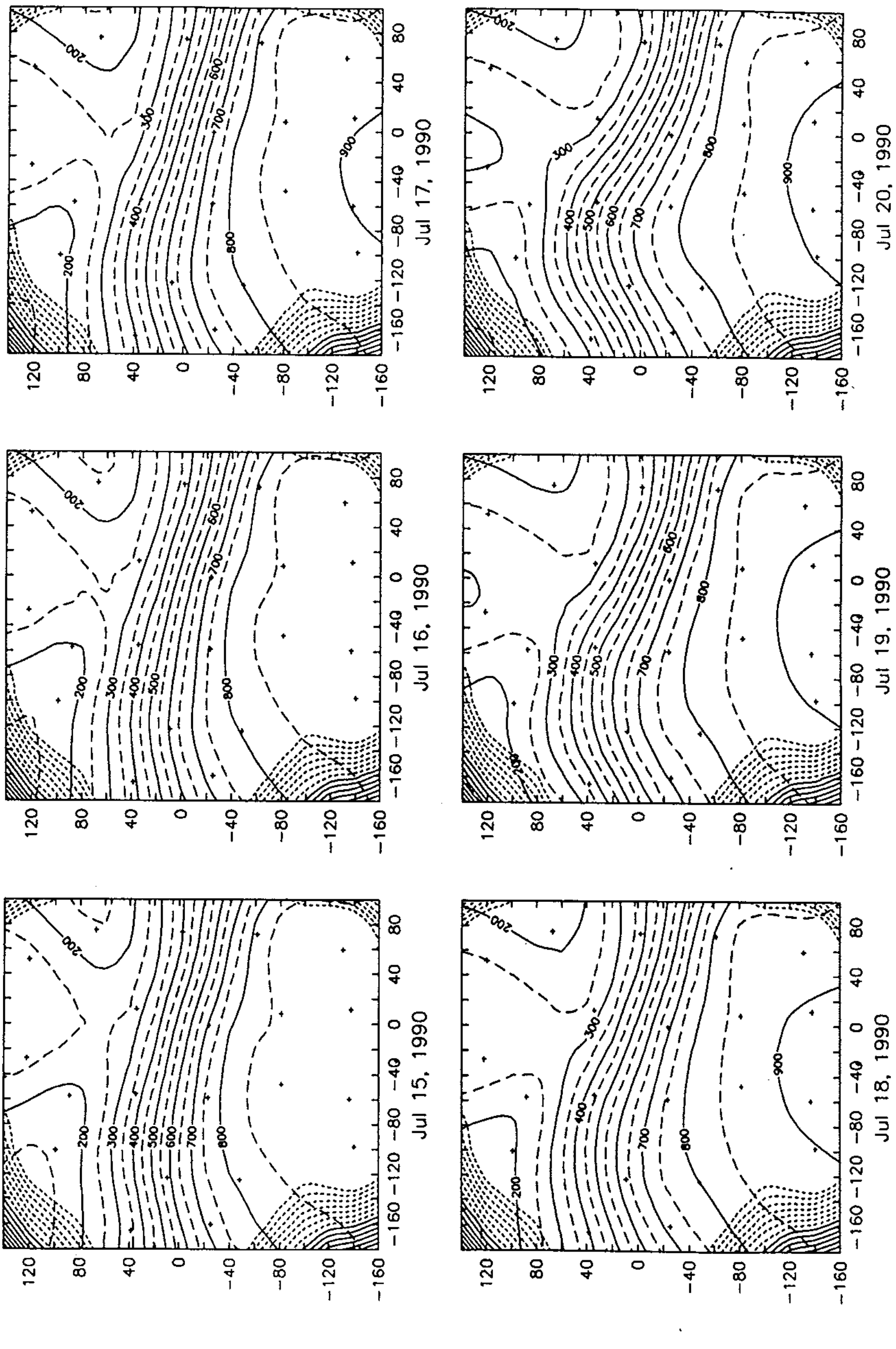
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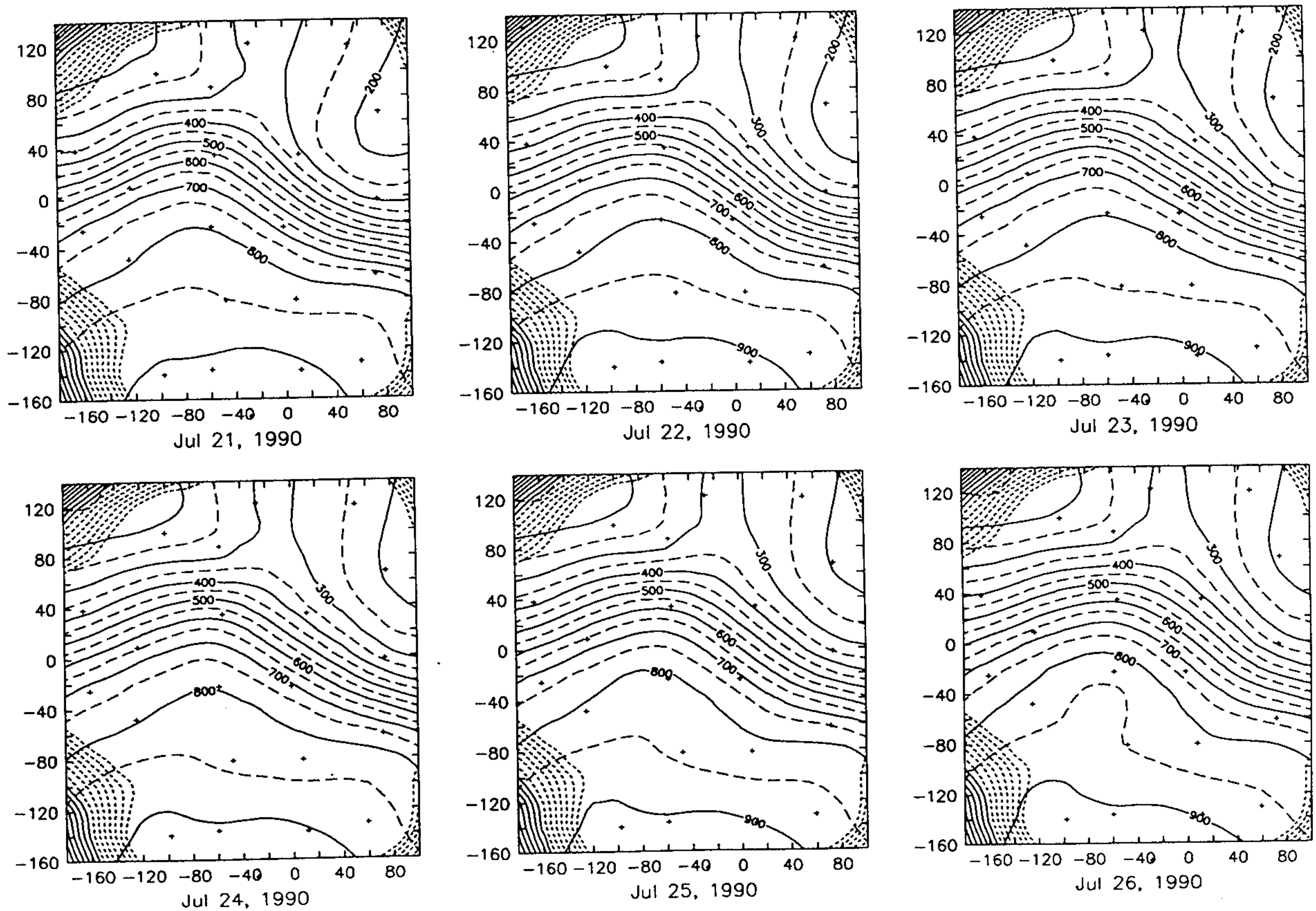

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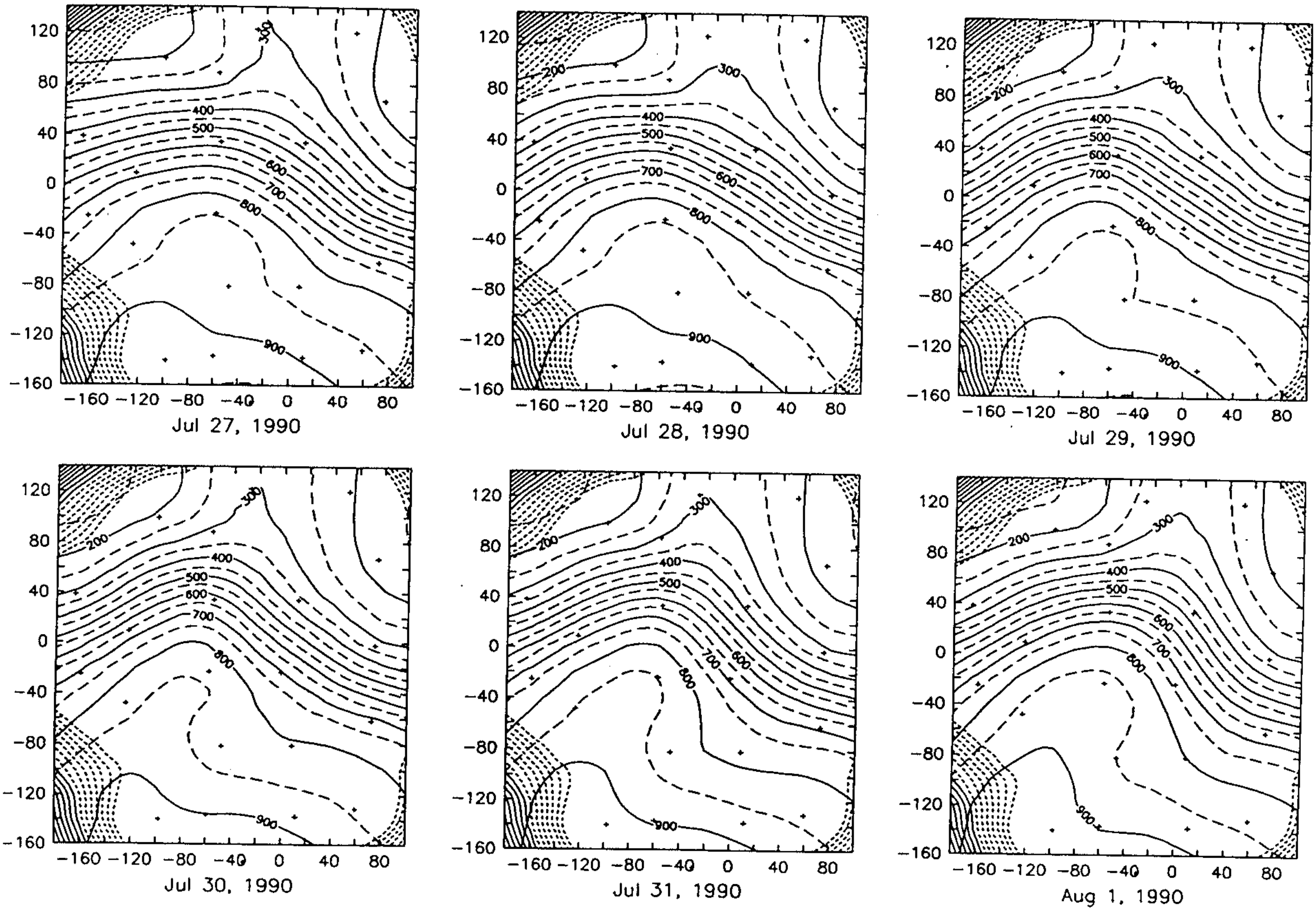
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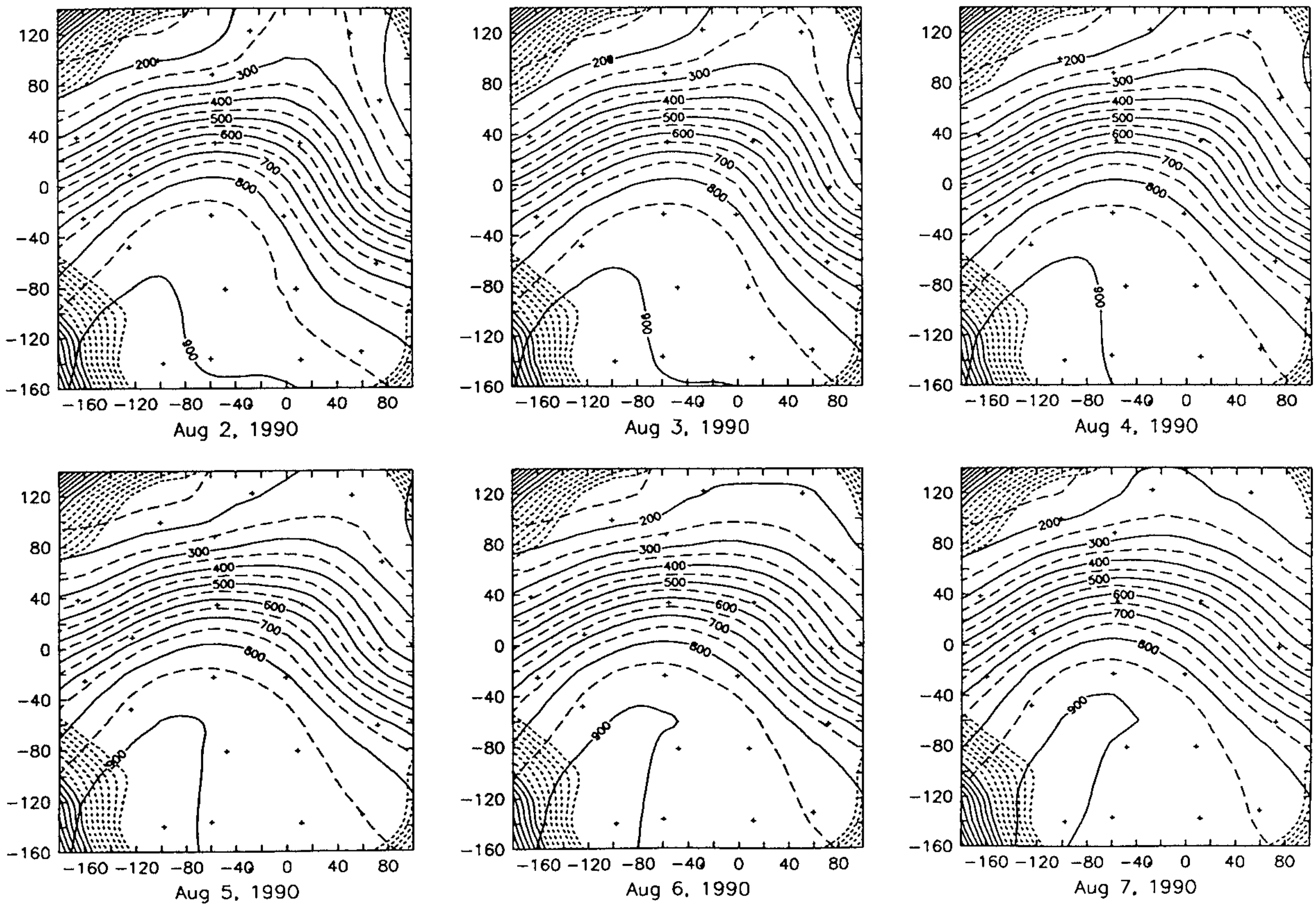
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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE:

3. DISTRIBUTION/AVAILABILITY OF REPORT: Distribution for Public release; Distribution is unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S): University of Rhode Island, Graduate School of Oceanography, GSO Technical Report 91-5

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION: Univ. of Rhode Island, Grad. School of Oceanography

6b. OFFICE SYMBOL (If applicable): 1122 PO

7a. NAME OF MONITORING ORGANIZATION:

6c. ADDRESS (City, State, and ZIP Code): South Ferry Road, Narragansett, RI 02882

7b. ADDRESS (City, State, and ZIP Code):

8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Office of Naval Research; National Science Foundation

8b. OFFICE SYMBOL (If applicable):

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER:

8c. ADDRESS (City, State, and ZIP Code): 800 N. Quincy St., Arlington, VA 22217; 1800 G. St., N.W., Washington, DC 20550

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification): THE SYNOP EXPERIMENT: Thermocline Depth Maps for the Central Array October 1987 to August 1990

12. PERSONAL AUTHOR(S): Karen L. Tracey and D. Randolph Watts

13a. TYPE OF REPORT: summary

13b. TIME COVERED: FROM 10/87 TO 8/90

14. DATE OF REPORT (Year, Month, Day): July 1991

15. PAGE COUNT: 194

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Gulf Stream, SYNOP, Inverted Echo Sounders and Thermocline Depth Maps

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Between October 1987 and August 1990, two arrays of inverted echo sounders were deployed in the Gulf Stream northeast of Cape Hatteras as part of the SYNoptic Ocean Prediction Experiment. The Inlet Array" consisted of 9 inverted echo sounders (IES). Centered at 74°W, the Inlet Array was designed to measure key parameters that describe the Gulf Stream path variability near Cape Hatteras. The large "Central Array" of 24 IESs was centered on the current near 68°W, about 400 km downstream of the Inlet Array. Spanning nearly 300 km in both the cross-stream and downstream directions, the Central Array was designed to monitor the thermocline structure of the Gulf Stream in the region of large meanders and frequent ring interactions.

Using objective analysis, we have mapped the Gulf Stream thermal field measured by the IESs in the Central Array. In this report, the objective analysis technique is described and the mapping parameters are documented. Daily maps of the thermocline depth field are presented for the period 26 October 1987 through 7 August 1990.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION:

22a. NAME OF RESPONSIBLE INDIVIDUAL:

22b. TELEPHONE (Include Area Code):

22c. OFFICE SYMBOL:

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted.

SECURITY CLASSIFICATION OF THIS PAGE