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Objective Daily Maps of Thermocline Depth for the SYNOP Eastern Array

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ABSTRACT

A major component of the field activities for the northwest Atlantic Regional Energetics Experiment (REX) is focused on the acquisition and analysis of data from inverted echo sounders (IESs). This technical note describes an analysis of data records from nine IESs deployed in an array near 40° N, 55° W. IES acoustic travel-time data were converted to thermocline depths, which were in turn objectively interpolated and contoured, resulting in daily maps. These maps provide a useful tool for studying the evolution of mesoscale features in the area of the experiment.

Acknowledgments

Thanks are extended to Dr. Amy Bower of the Woods Hole Oceanographic Institution for providing the correlation function used in the analysis. This work was supported by the Office of Naval Research under Program Element 0601153N, Dr. H. C. Eppert, Jr., Program Manager, as part of the basic research project "Extended GEOSAT Mission."

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OBJECTIVE DAILY MAPS OF THERMOCLINE DEPTH FOR THE SYNOP EASTERN ARRAY

Introduction

The final phase of NOARL's (Naval Oceanographic and Atmospheric Research Laboratory) Regional Energetics Experiment (REX) coincided with the beginning of ONR's (Office of Naval Research) SYNOP (Synoptic Ocean Prediction) program, which was conducted between Cape Hatteras and the Grand Banks in the Gulf Stream region. The SYNOP field experiments extended from late 1987 through most of 1990 and consisted of extensive moored and hydrographic measurements of oceanographic parameters in three regions: the Inlet Array (near Cape Hatteras), the Central Array (near 68° W) and the Eastern Array (near 55° W and further east). The REX component consisted chiefly of an array of 13 inverted echo sounders (IESs) deployed in a pattern to complement SYNOP current meter moorings in the eastern array. Figure 1 shows the location of the IESs in perspective, and Figure 2 shows the details of IES and current meter mooring positions. Superimposed on Figures 1 and 2 are GEOSAT-ERM groundtracks. The IES data (as well as CTD and XBT data) acquired during this experiment are described by Teague et al. (1990). IES logistics are listed in Table 1; four of the instruments were not recovered.

The purpose of the REX field programs (as well as one of the main objectives of SYNOP) was to monitor fluctuations of the Gulf Stream and to describe its variability and dynamics. Results from REX field efforts are described by Hallock et al. (1989, 1991) and Teague and Hallock (1990).

In this technical note we describe the conversion of time series of IES-measured acoustic travel times to time series of thermocline depth (in particular, Z12, the depth of the 12° isotherm) and, subsequently, objective mapping of the Z12 data over the SYNOP Eastern Array, producing a series of daily maps of Z12. The daily maps thus produced appear following the description of the method.

Conversion of IES travel times to Z12

The REX-SYNOP IESs in the Eastern Array yielded 9 records of approximately 260 days of acoustic travel time (tau). These data were low-pass filtered (with half-amplitude point at 40 hrs) to remove tidal and higher frequencies. Changes in tau (tau') about record means were converted to changes in Z12 (Z12') using regression coefficients based on historical CTD data from the region of the Eastern Array. To obtain Z12 from Z12' a reference point for each record was established using "calibration" XBTs launched at the IES position just prior to recovery (Watts and Johns, 1982). In particular, with CTD data from the Eastern Array region in summer 1983 (Hogg et al., 1985) and in early spring 1988 (Hall and Fofonoff, 1991) regression of calculated Z12' on calculated tau' yielded:

$$Z12=23.1(tau'-tau_0')+Z12_0$$

where tau', tau_0' are in milliseconds, tau_0' is tau' at the end of the record and $Z12_0$ is Z12 from calibration XBTs. The overall uncertainty in the resulting Z12 is about 30 m (this is essentially the error-of-fit of the CTD-based tau'-Z12' regressions). Table 2 lists basic statistics of the Z12 time series.

Objective mapping of Z12

Objective analysis (OA) (Bretherton et al., 1976; Watts et al., 1989) was used to interpolate the IES Z12 data to produce a series of daily maps of Z12 for the Eastern Array. In this method, the original observations, Z_j (j=1,9 here), at points X_j, are interpolated to points X_k to form a regular grid that can be contoured. This interpolation is effected with a weighting function, A_{ik}, such that

$$Y_k = \sum_j A_{jk} Y_j \qquad (1)$$

In the OA method the weighting function is based on the covariances of the variable to be interpolated and is given by

$$A_{ik} = \sum_j C_{ij}^{-1} C_{jk} \qquad (2)$$

where $C_{ij} = C(Y_i,Y_j)$ is the normalized covariance matrix. An estimate of the normalized error in variance associated with each interpolated point can be calculated

$$e_k = 1 - \sum_i \sum_j A_{ik} A_{jk} C_{ij} \,. \qquad (3)$$

In this analysis, the covariance function, C, is assumed to be homogeneous and isotropic (dependent only on the distance between points), i.e., $C(X_i,X_j) = C(|X_i-X_j|) = C(r_{ij})$. This assumption may not always be justified in the vicinity of features such as the Gulf Stream, as pointed out by Hogg (SYNOPtician 2(6), December 1991).

The OA first required the removal of a mean field and normalization by a standard deviation (sd) field. Since the NOARL- IES spatial distribution was quite sparse and the instruments were deployed for only about 9 months, the mean and sd fields suggested by Bower and Hogg (SYNOPtician 2(3), June 1991; henceforth BH) were used; these were based on over 2 years of observations in the Eastern Array.

Since the BH functions are for temperature at 500 m (not Z12) they were scaled in amplitude prior to use in the analysis. This was done by least squares fitting the BH functions,

$$\text{mean} = a - b \tanh \left(\frac{y - 50}{100.8}\right)$$

$$\text{sd} = c \exp \left[- \left(\frac{y - 50}{259}\right)^2\right] \qquad (4)$$

to the sample Z12 means and sd's (those appearing in table 2). The values of the coefficients were found to be:

a = 453 m
b = 336 m
c = 133 m.

For the same reasons given above, a correlation function developed by BH was also used. Correlations calculated with the actual Eastern Array IES records showed considerable scatter but bracketed the function used by BH:

$$C(r) = S_0 \exp \left[- \left(\frac{r}{S_2}\right)^2 \right] \cos (2\pi r / S_1) \qquad (5)$$

where

$S_0 = 0.902$
$S_1 = 610$ km
$S_2 = 141$ km

(Bower, personal communication).

A 10 x 13 grid (dx=dy=25 km) was selected and daily maps of Z12 were generated by calculating Y_k (eq. 1) for each grid point. The Y_k were then redimensionalized by multiplying by the sd and adding back the mean (eq. 4). Actual mean and sd fields were calculated with the gridded data and contoured and appear as figures 3 and 4. Figure 5 is the set of daily maps of Z12 starting on page 11. The error field is superimposed on each of the daily maps. The error contours are in increments of 10%; the dotted contour near the center of each map is 10%, the dashed contour is 20% and the remaining solid contours are 30%, 40%, . . ., etc. Beyond 30% the results become questionable.

Table 1. Times and locations of the IES/PGs.

IES No.	Latitude (N)	Longitude (W)	Depth (m)	Deployed	Recovered
IES87001	34°23.2	55°03.2	5454	13 Sept 87	27 June 88
IES87002	38°58.5	53°55.4	5412	14 Sept 87	28 June 88
IES87003	38°58.9	54°40.3	5393	13 Sept 87	27 June 88
IES87004	38°59.0	55°24.1	5409	13 Sept 87	26 June 88
IES87005	39°33.8	55°46.0	5369	15 Sept 87	26 June 88
IES87006	39°33.7	55°01.1	5367	14 Sept 87	30 June 88
IES87007	39°33.2	54°18.1	5351	14 Sept 87	29 June 88
IES87008	Not Recovered				
IES87009	Not Recovered				
IES87010	Not Recovered				
IES87011	40°07.3	55°23.5	5324	15 Sept 87	5 July 88
IES87012	40°41.0	55°01.7	5213	16 Sept 87	4 July 88
IES87013	Not Recovered				

Table 2. Statistics of Z12 series.

IES No.	Min.	Max.	Mean	Sd.
87-001	459.	859.	671.	81.
87-002	455.	882.	718.	67.
87-003	362.	921.	762.	67.
87-004	447.	866.	730.	72.
87-005	200.	860.	642.	105.
87-006	272.	901.	630.	143.
87-007	177.	832.	563.	192.
87-011	63.	806.	403.	184.
87-012	-147.	522.	191.	131.

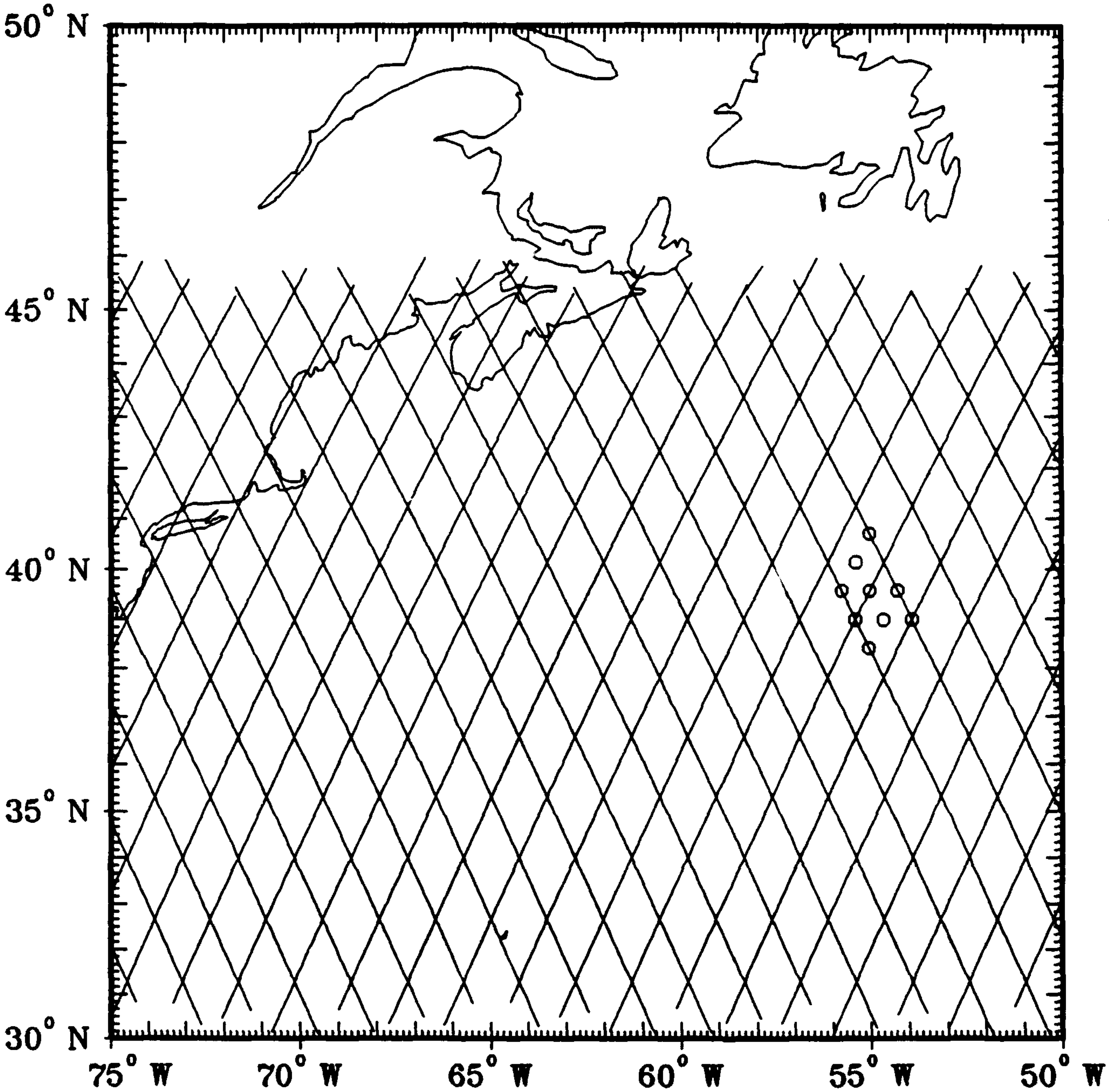


Figure 1. Location of NRL IES array deployed from September 1987 to June 1988. GEOSAT groundtracks are superimposed.

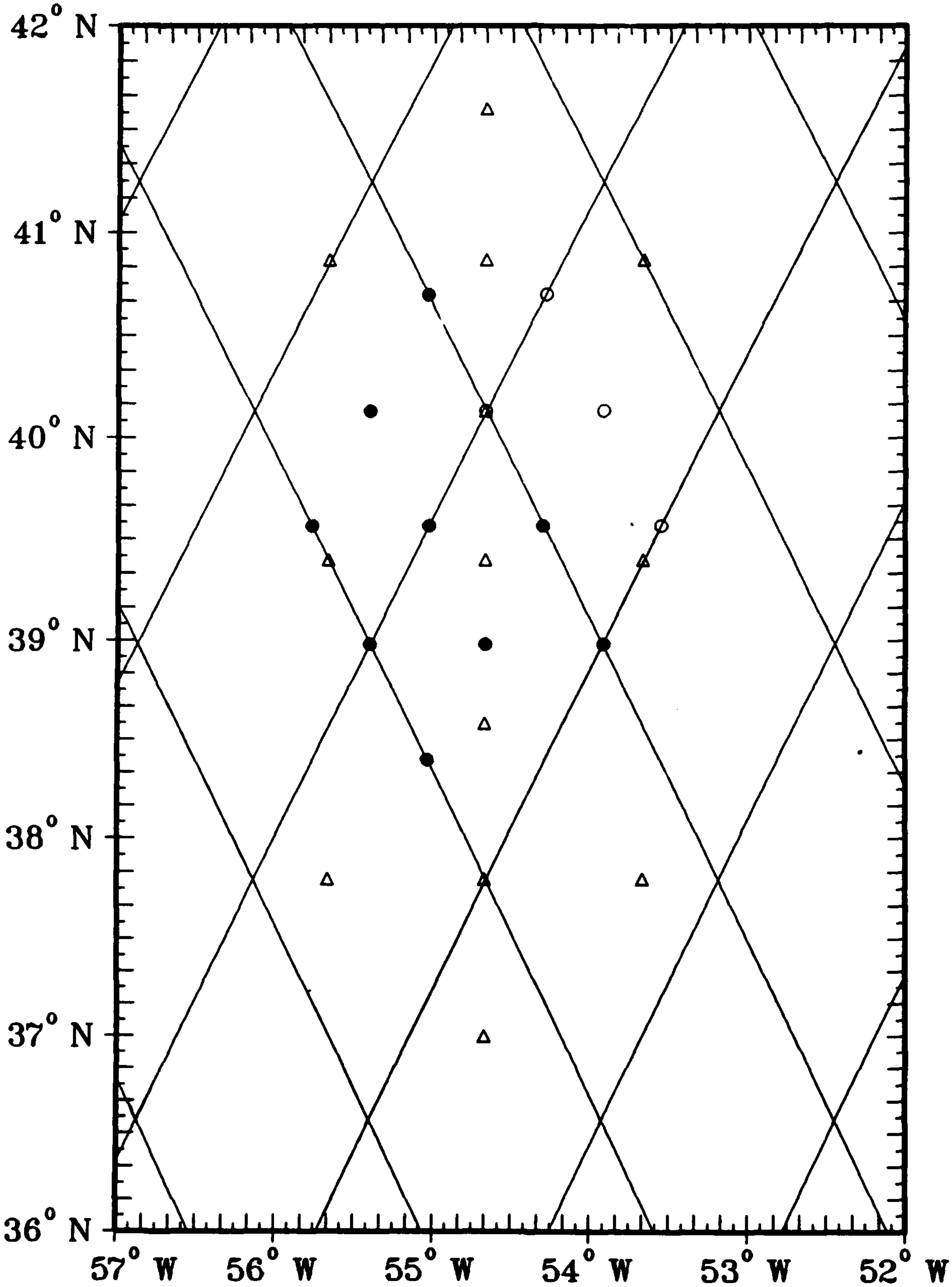


Figure 2. Detail of IES locations (circles; open circles indicate instruments not recovered) and Woods Hole current meter mooring locations (triangles). GEOSAT ground tracks are superimposed.

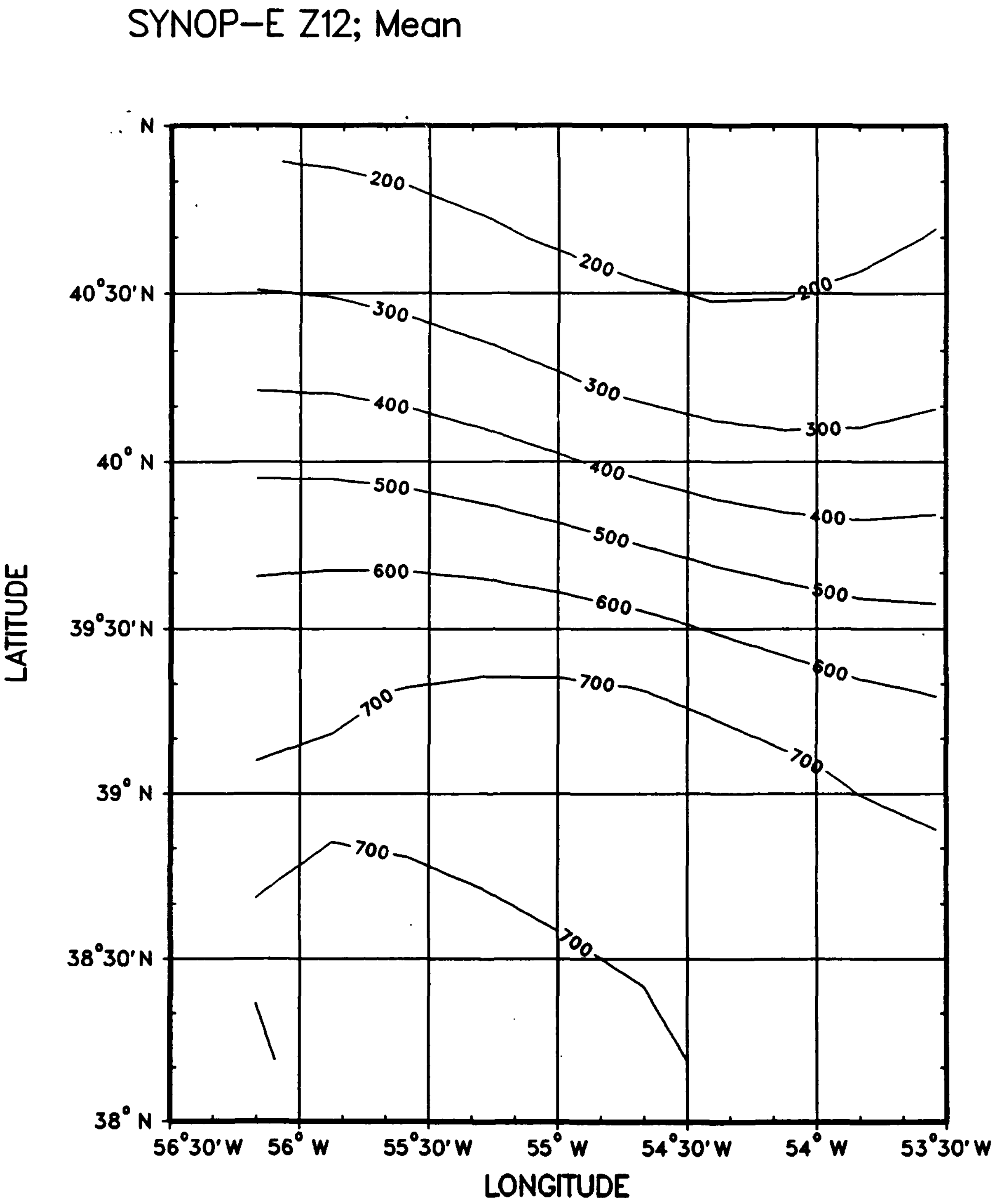


Figure 3. Map of mean Z12 calculated using the objectively interpolated, gridded data.

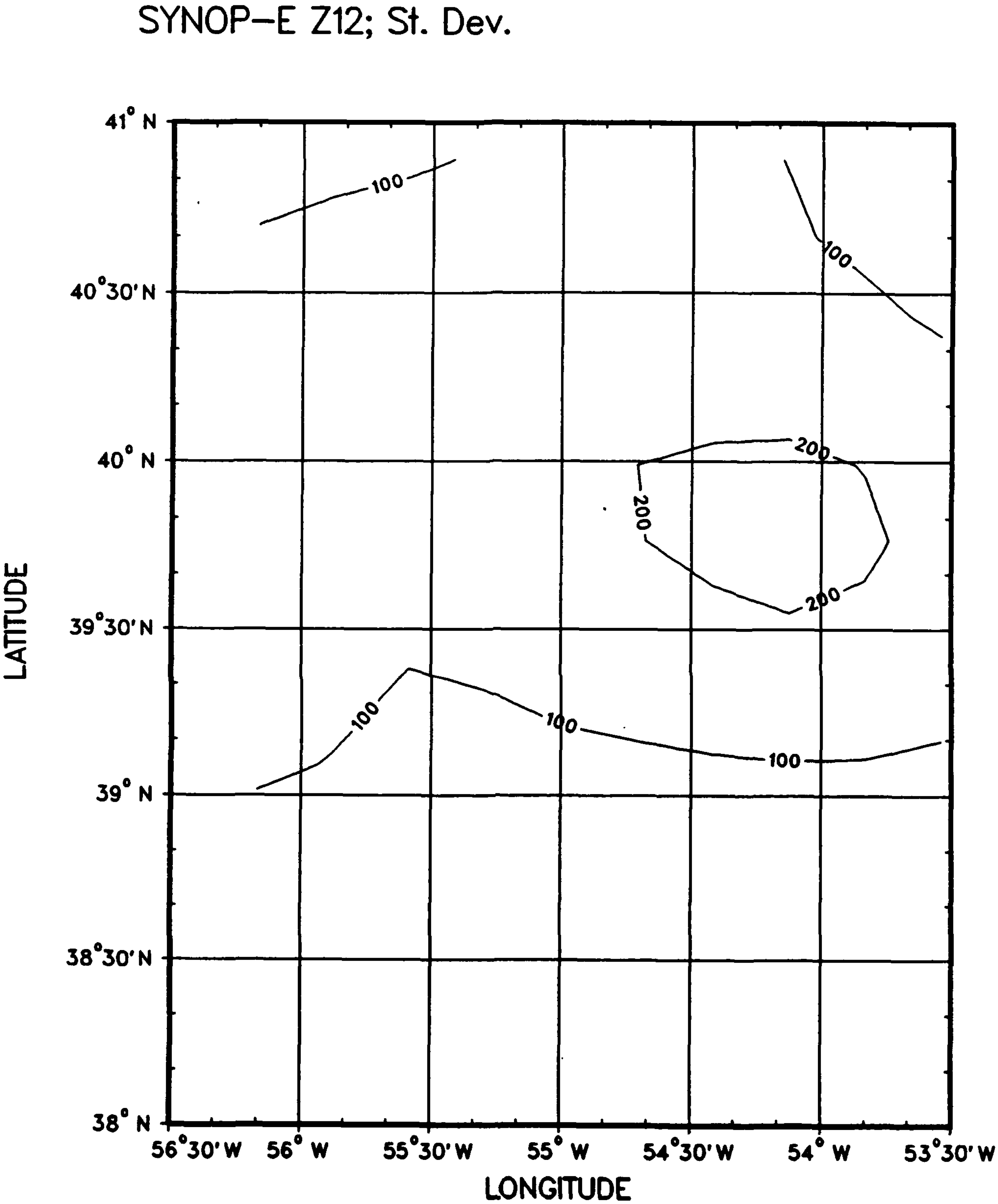
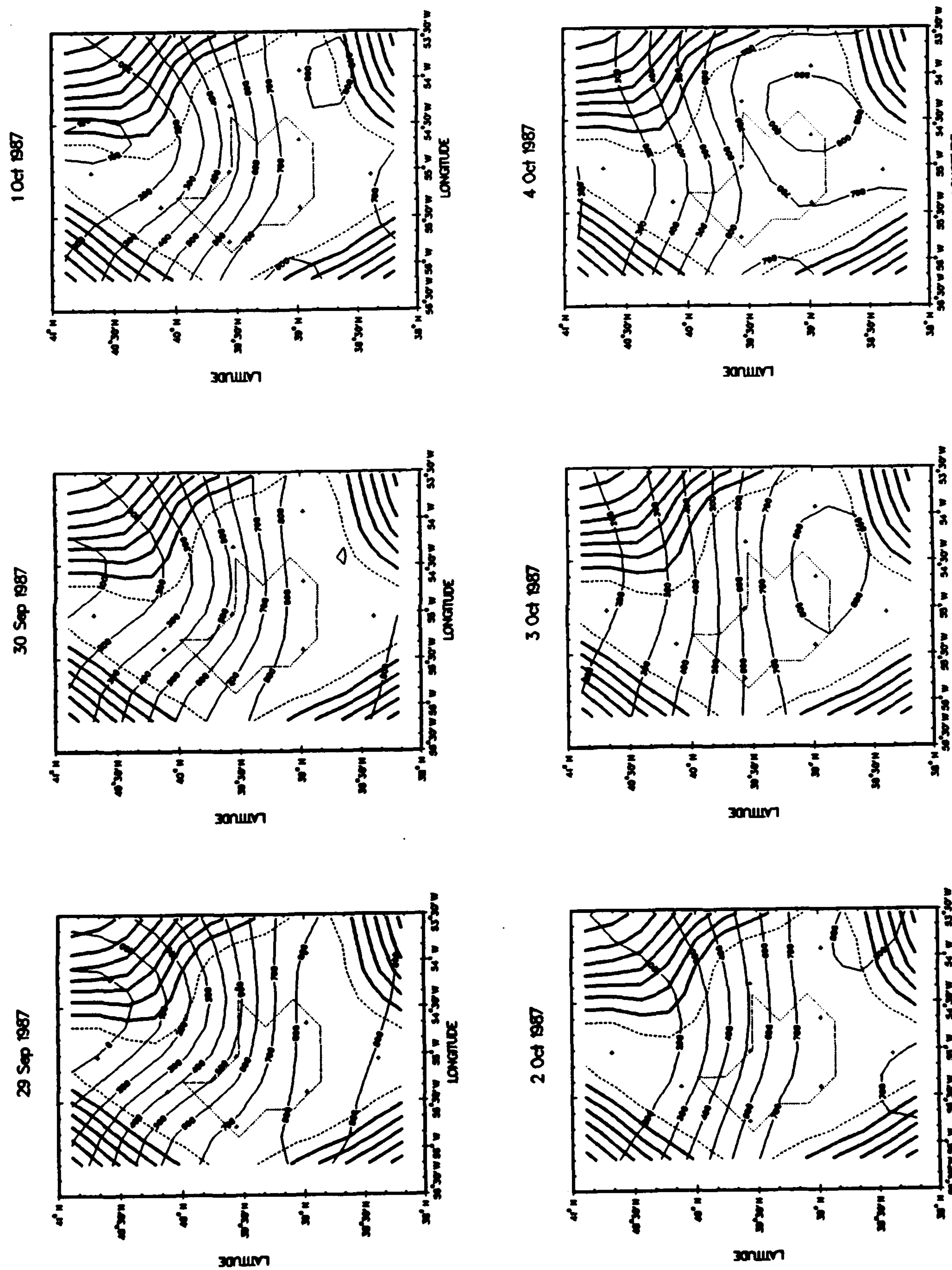


Figure 4. Map of standard deviation of Z12 about the mean shown in Figure 3.

Figure 5. Objective maps of Z12 in SYNOP Eastern Array for 29 September 1987 to 11 June 1988. Percent error variance contours superimposed on Z12 maps: dotted-10%, dashed-20%, heavy solid-30% and higher. IES positions marked by +.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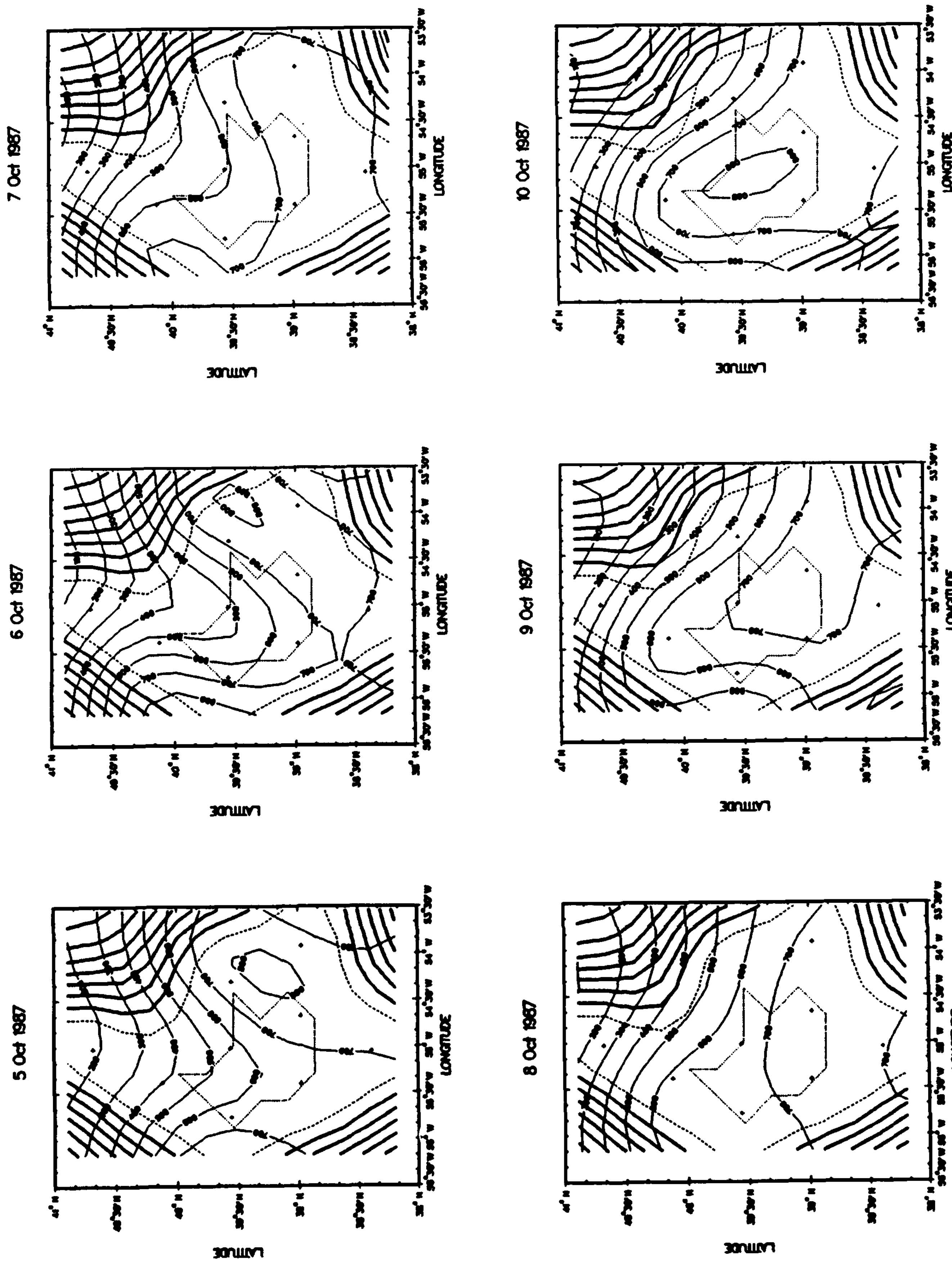
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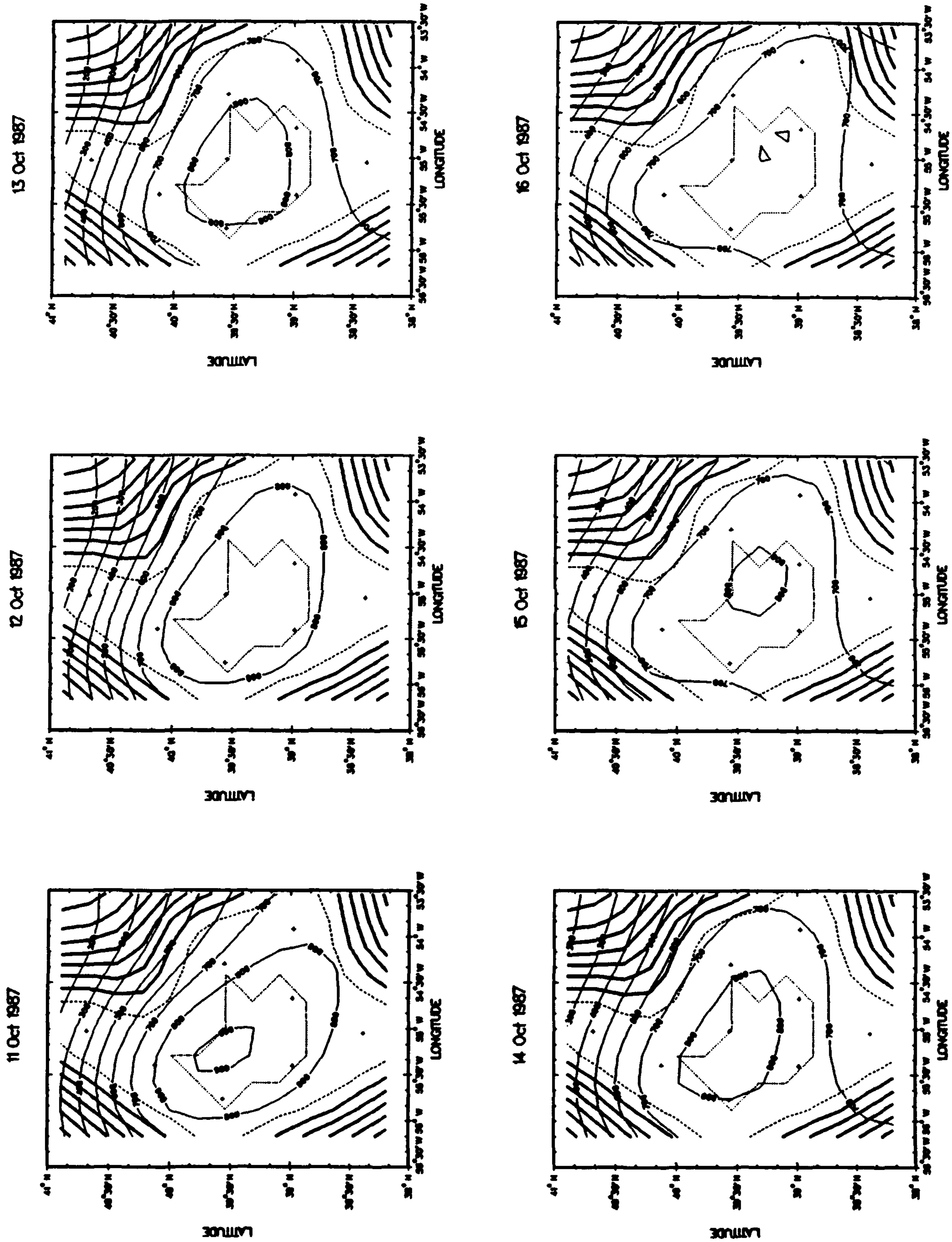
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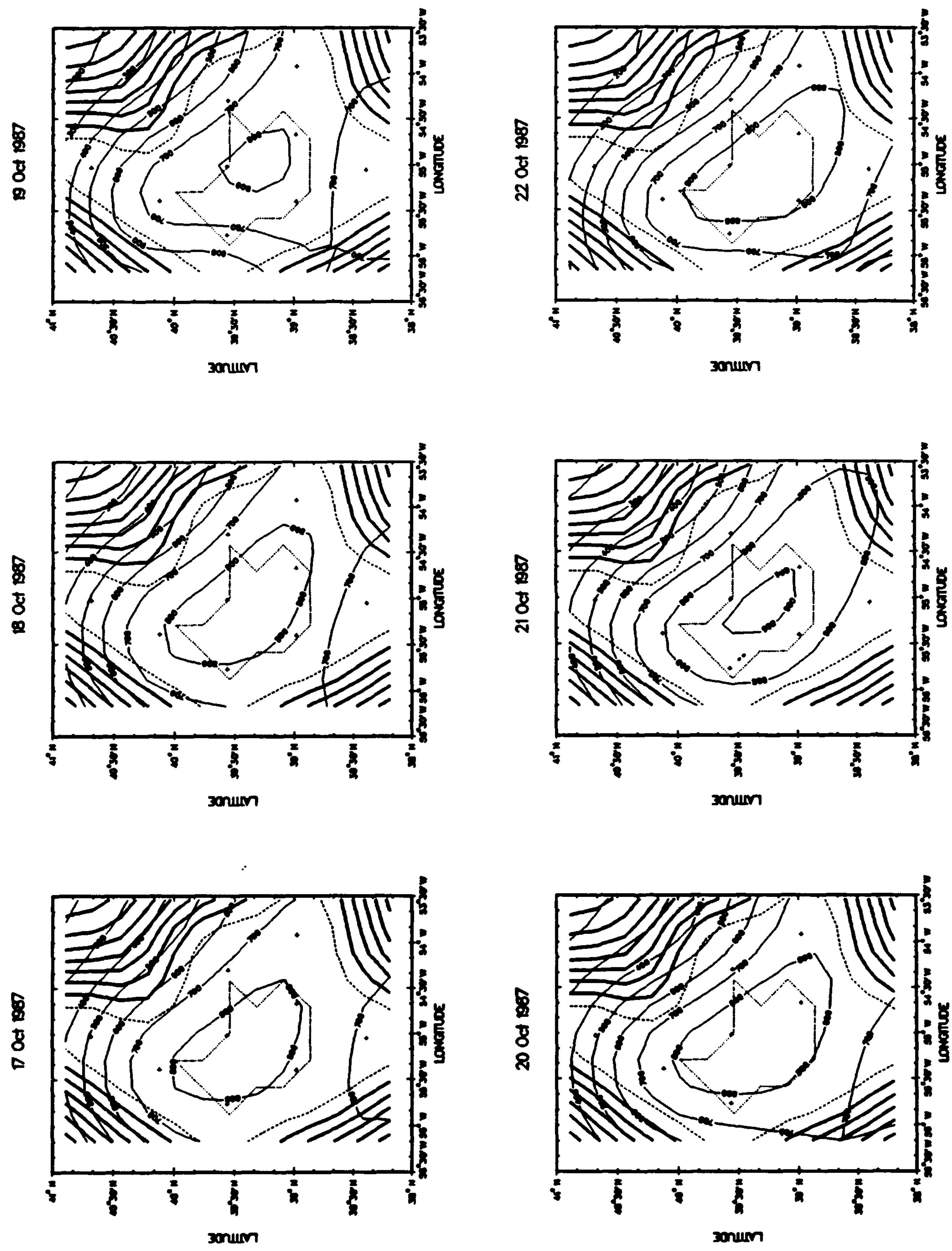

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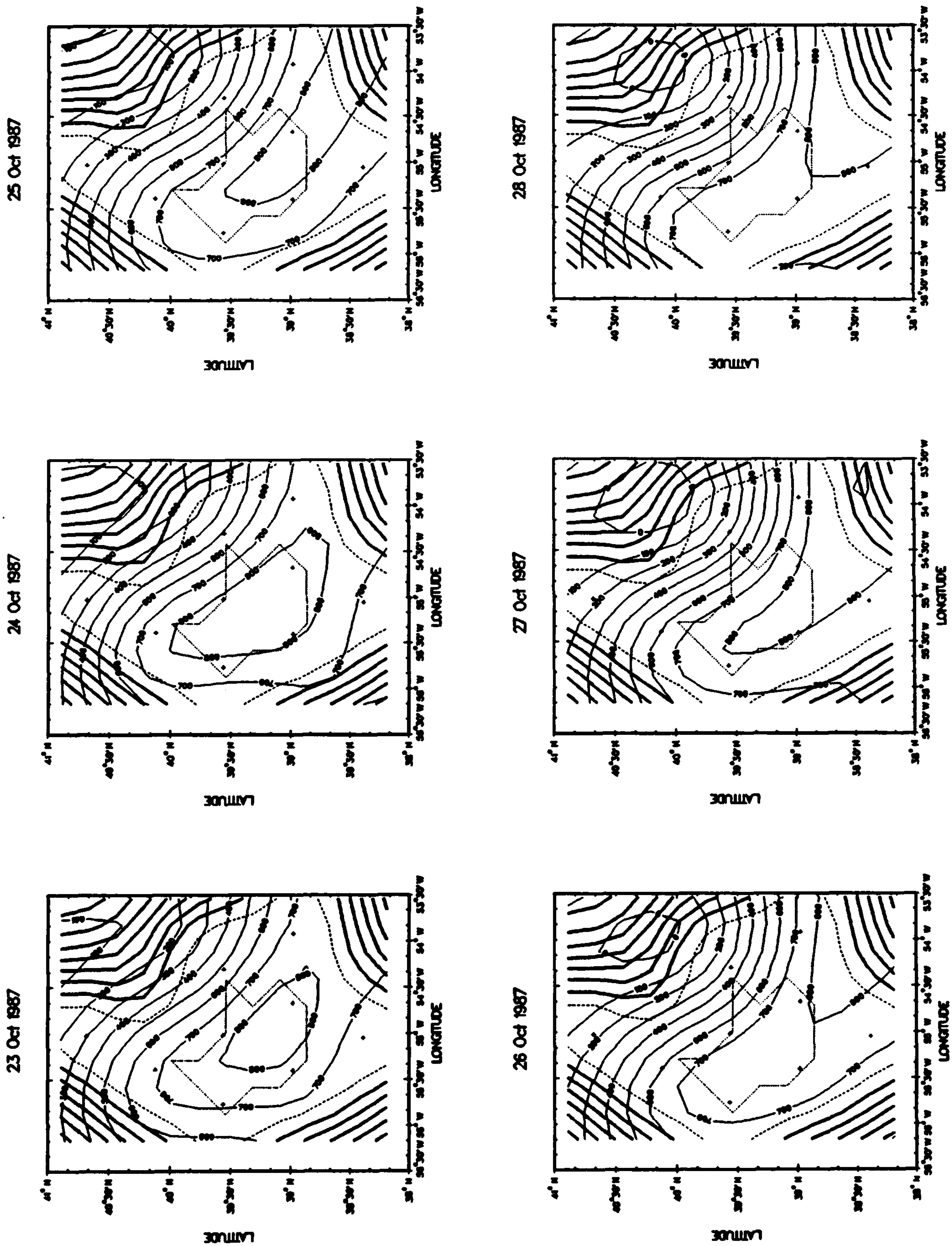
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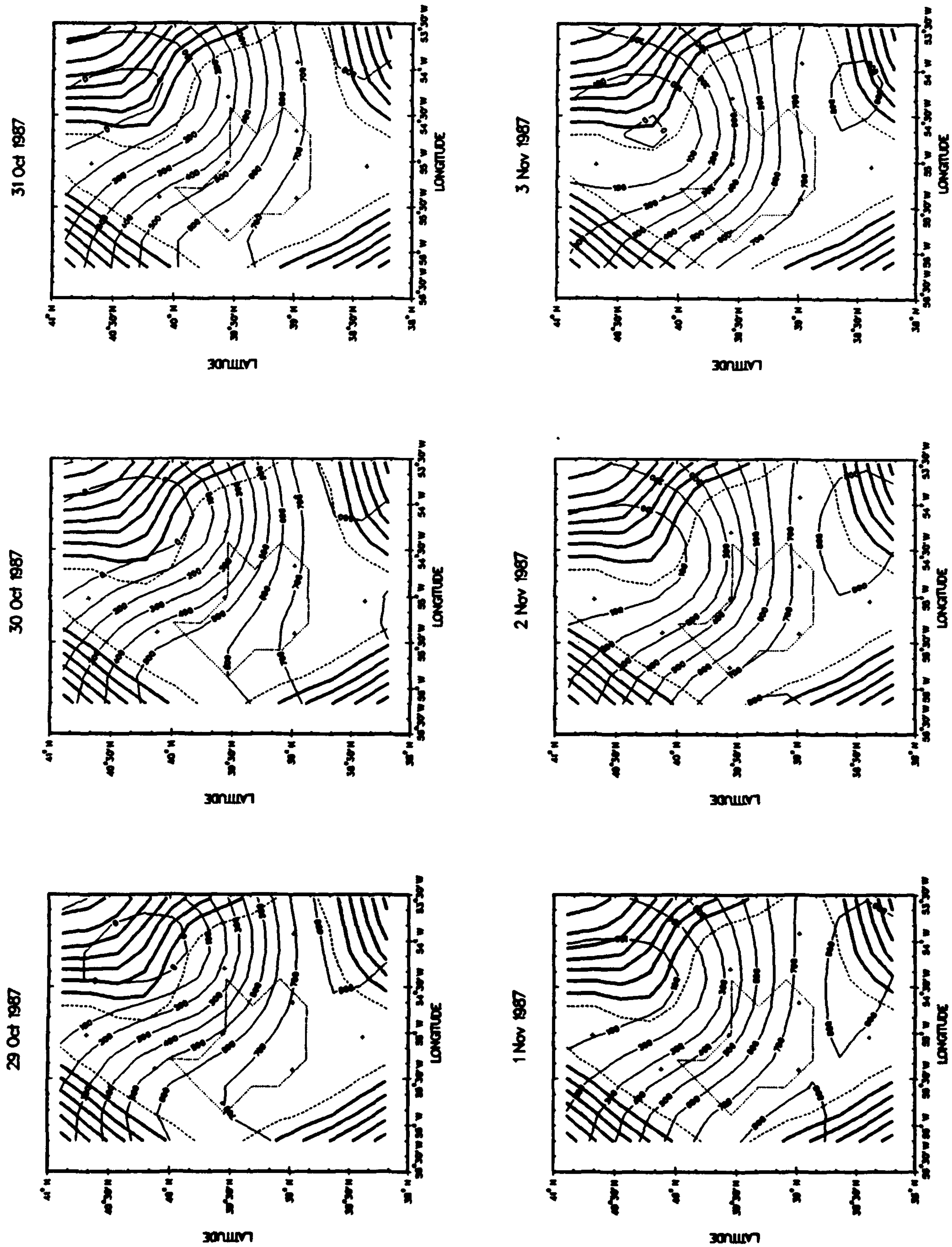
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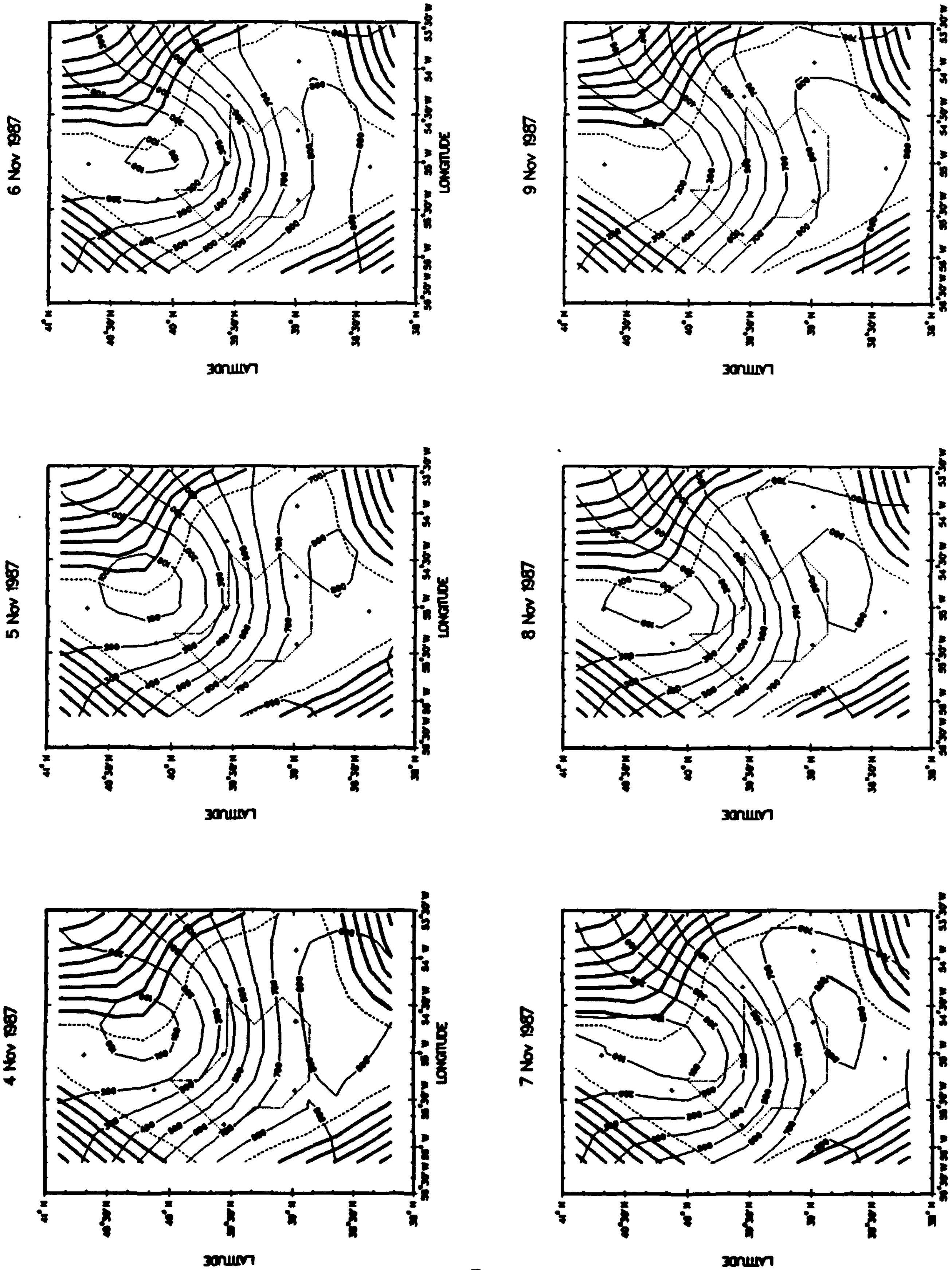

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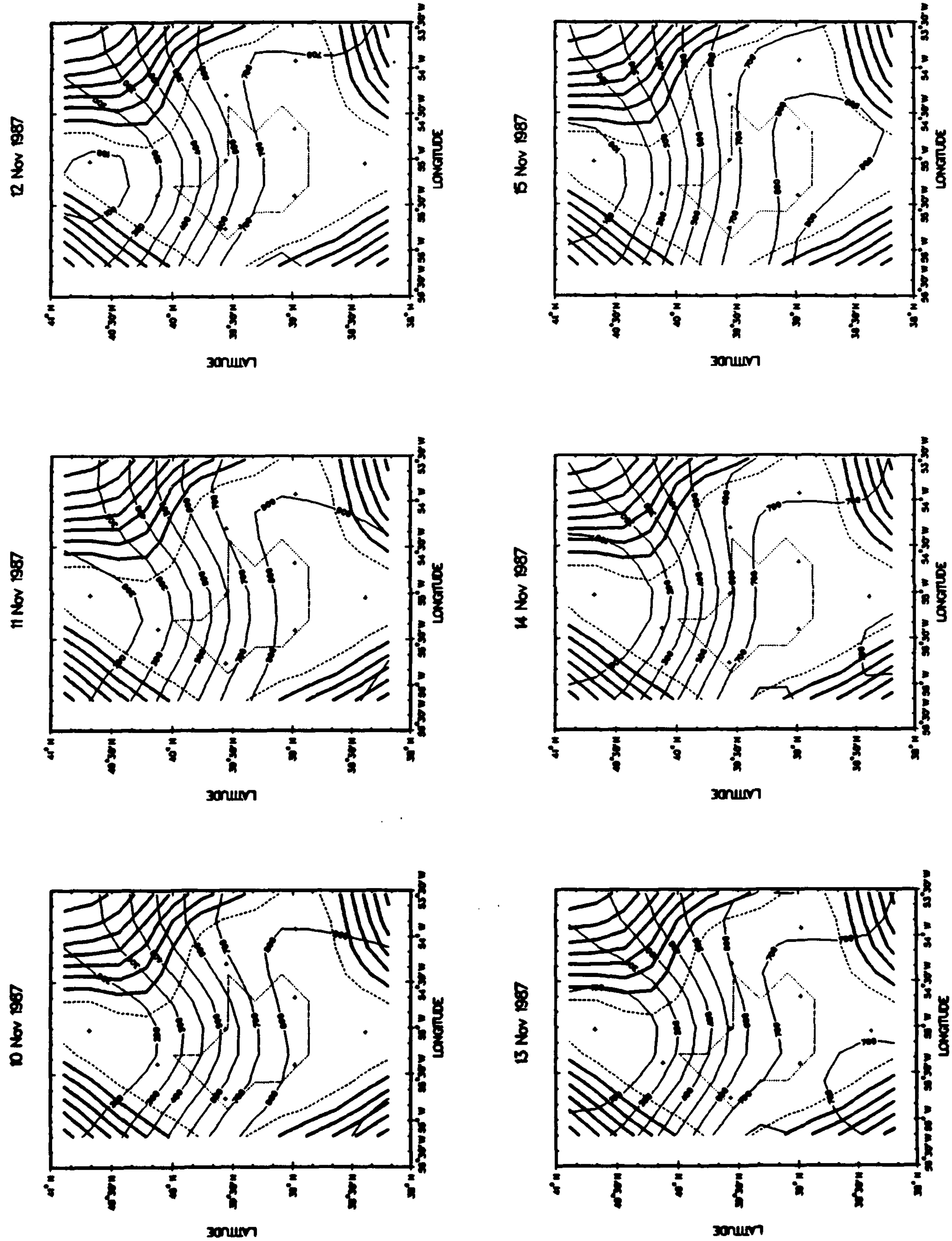
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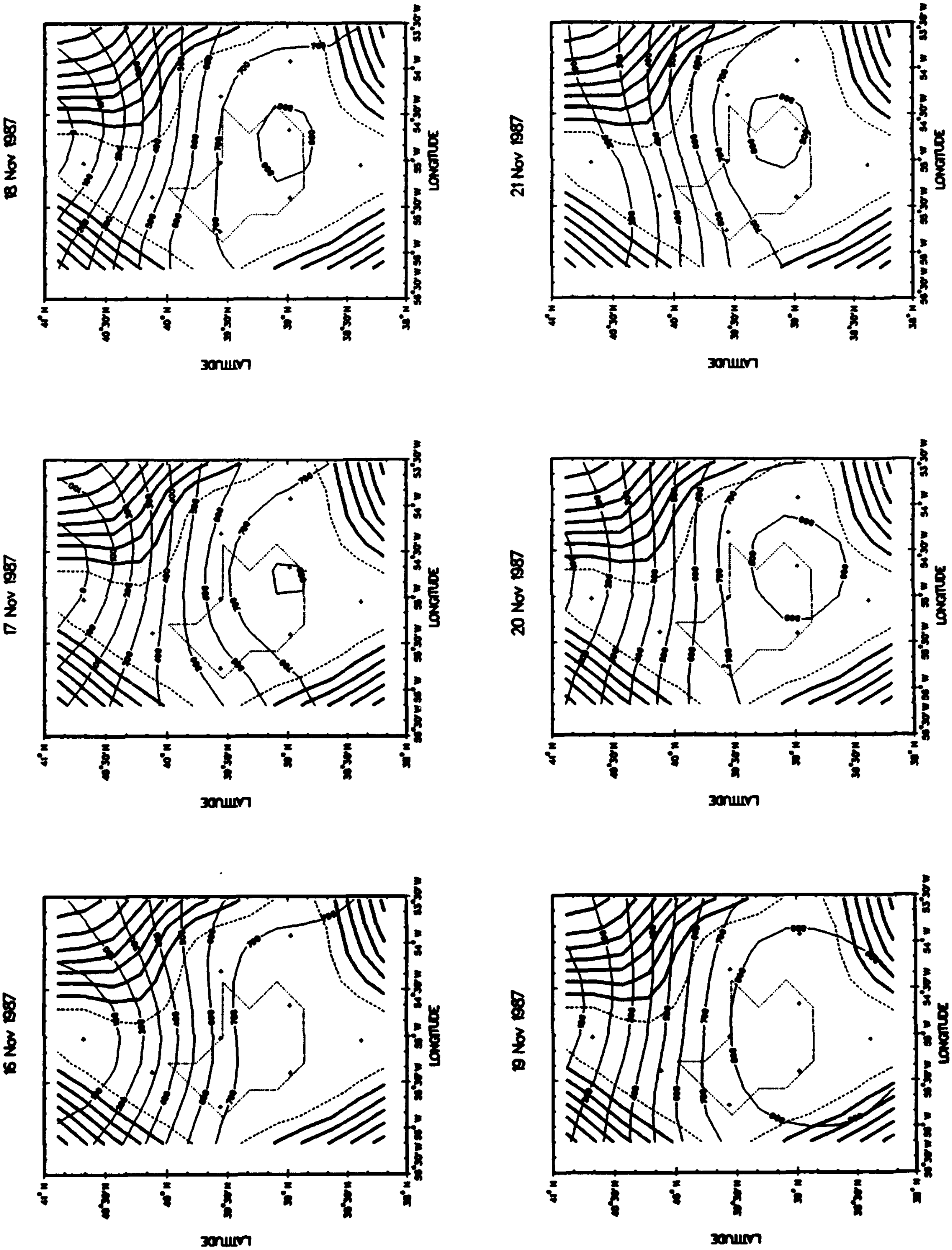
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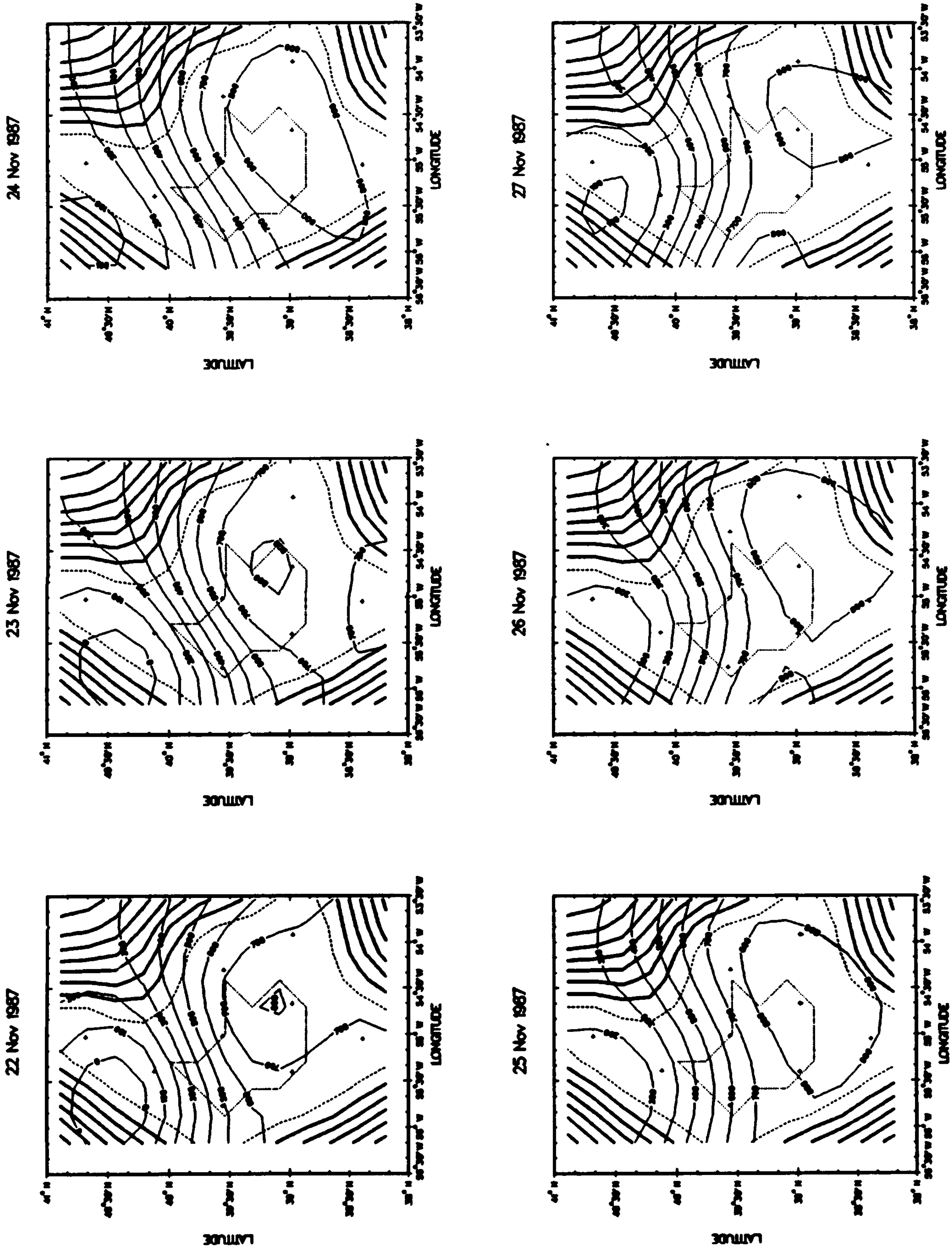
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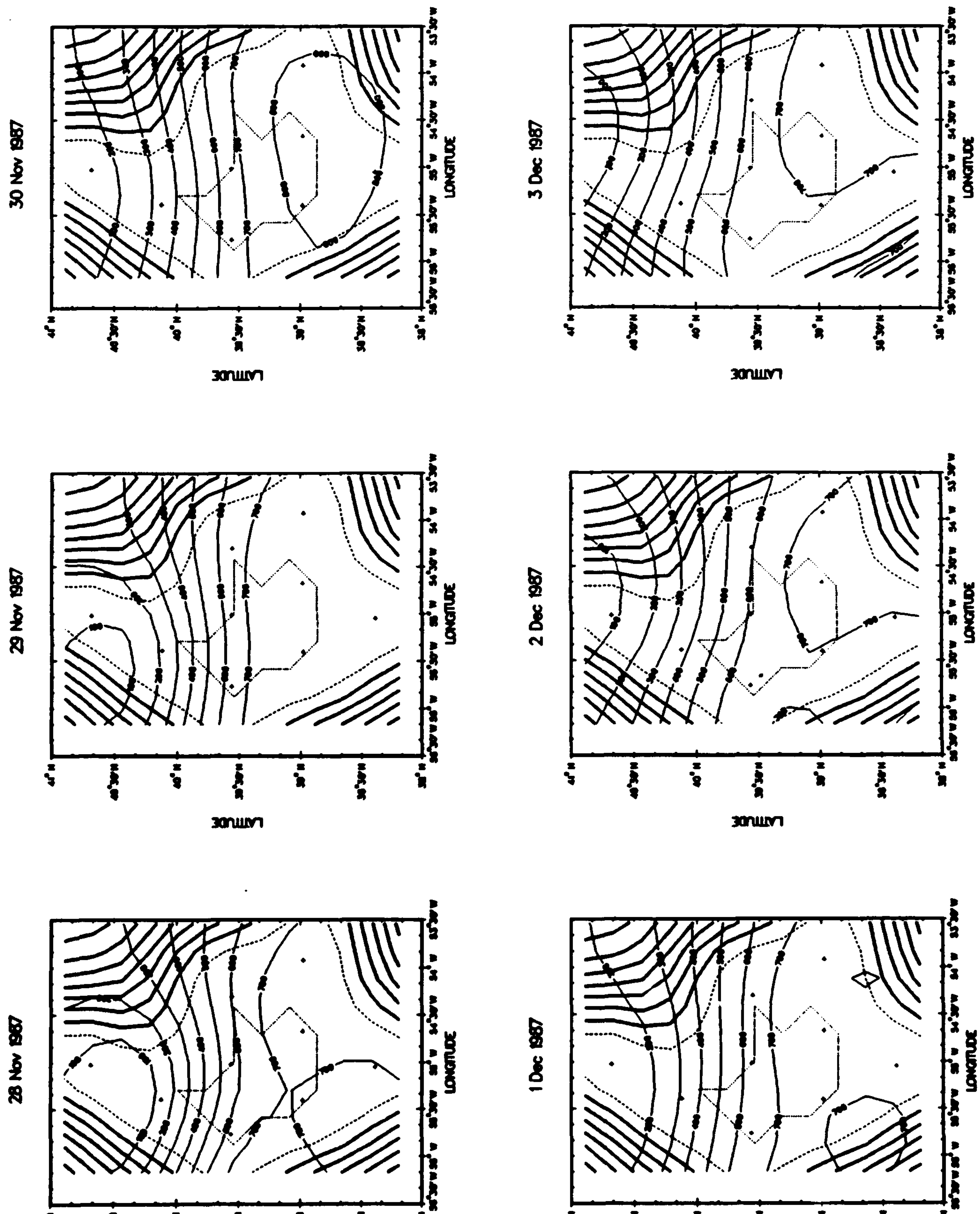

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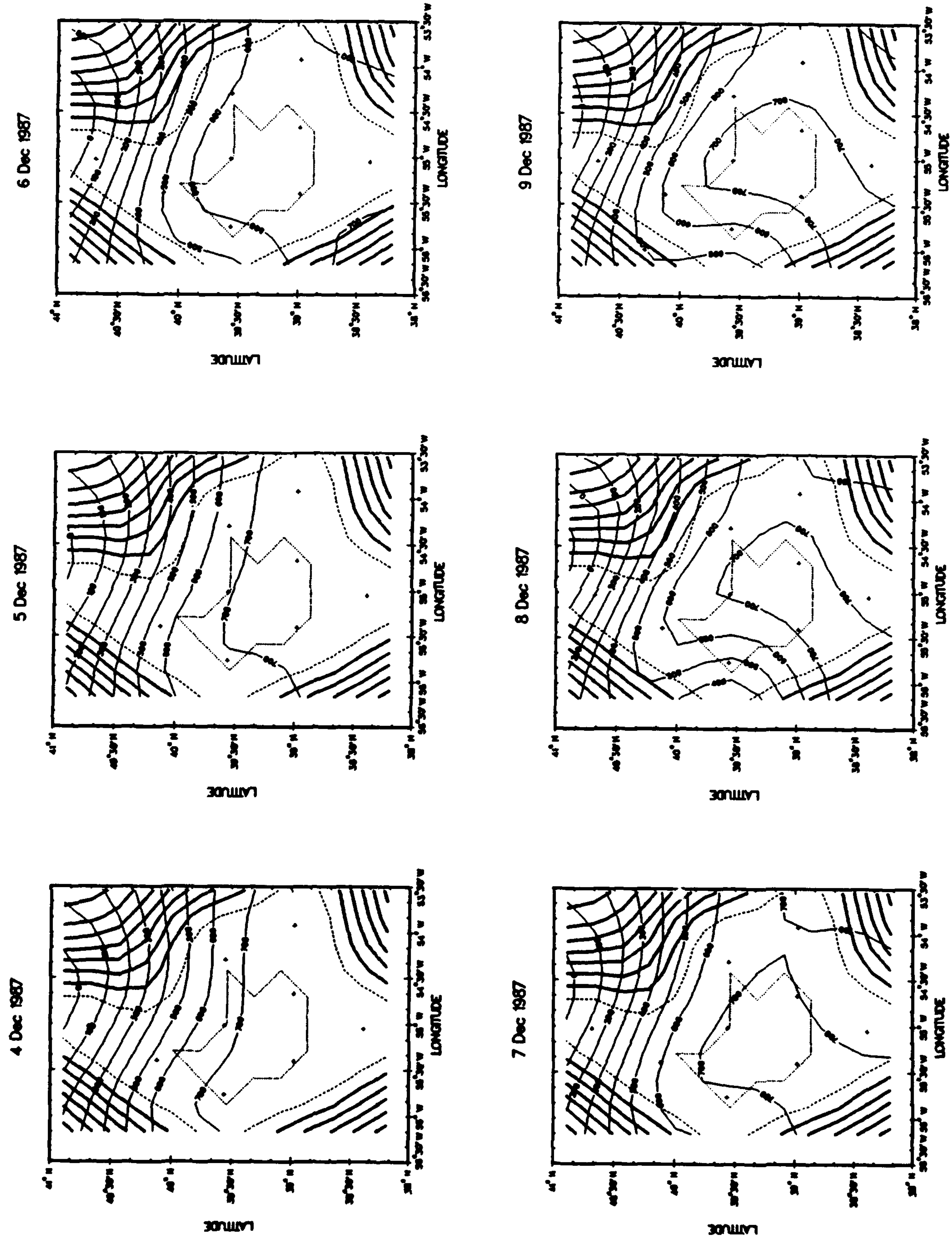

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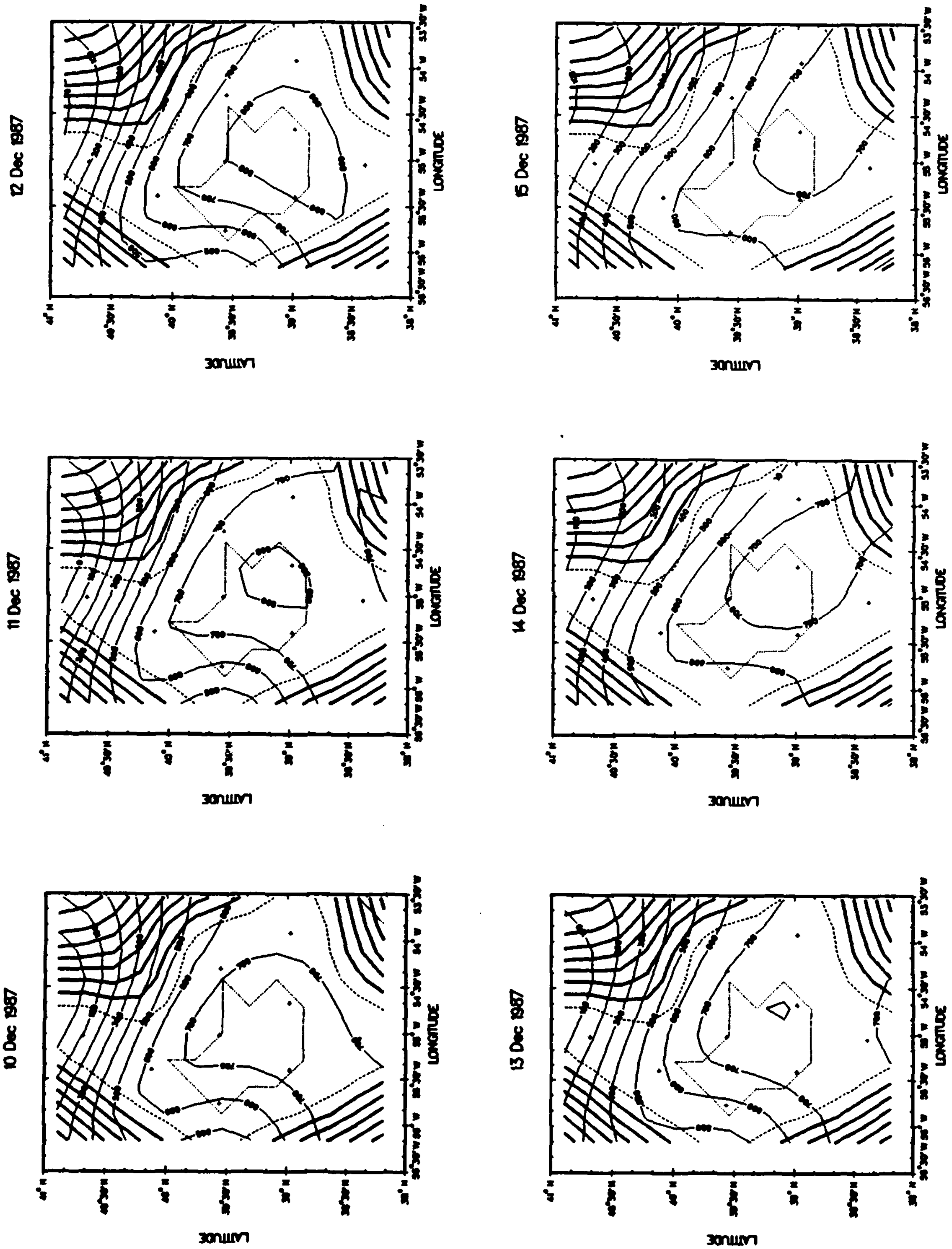
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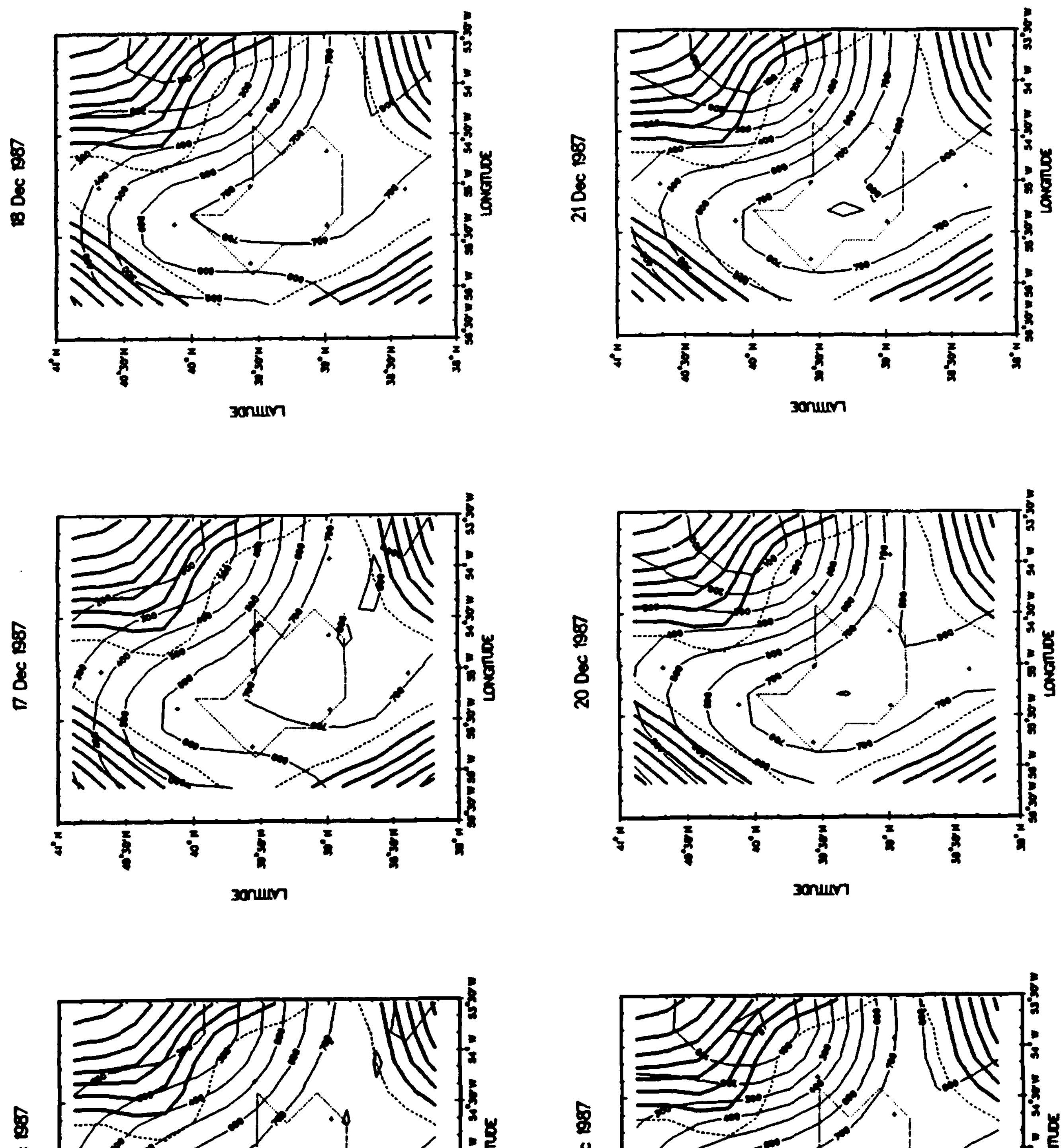
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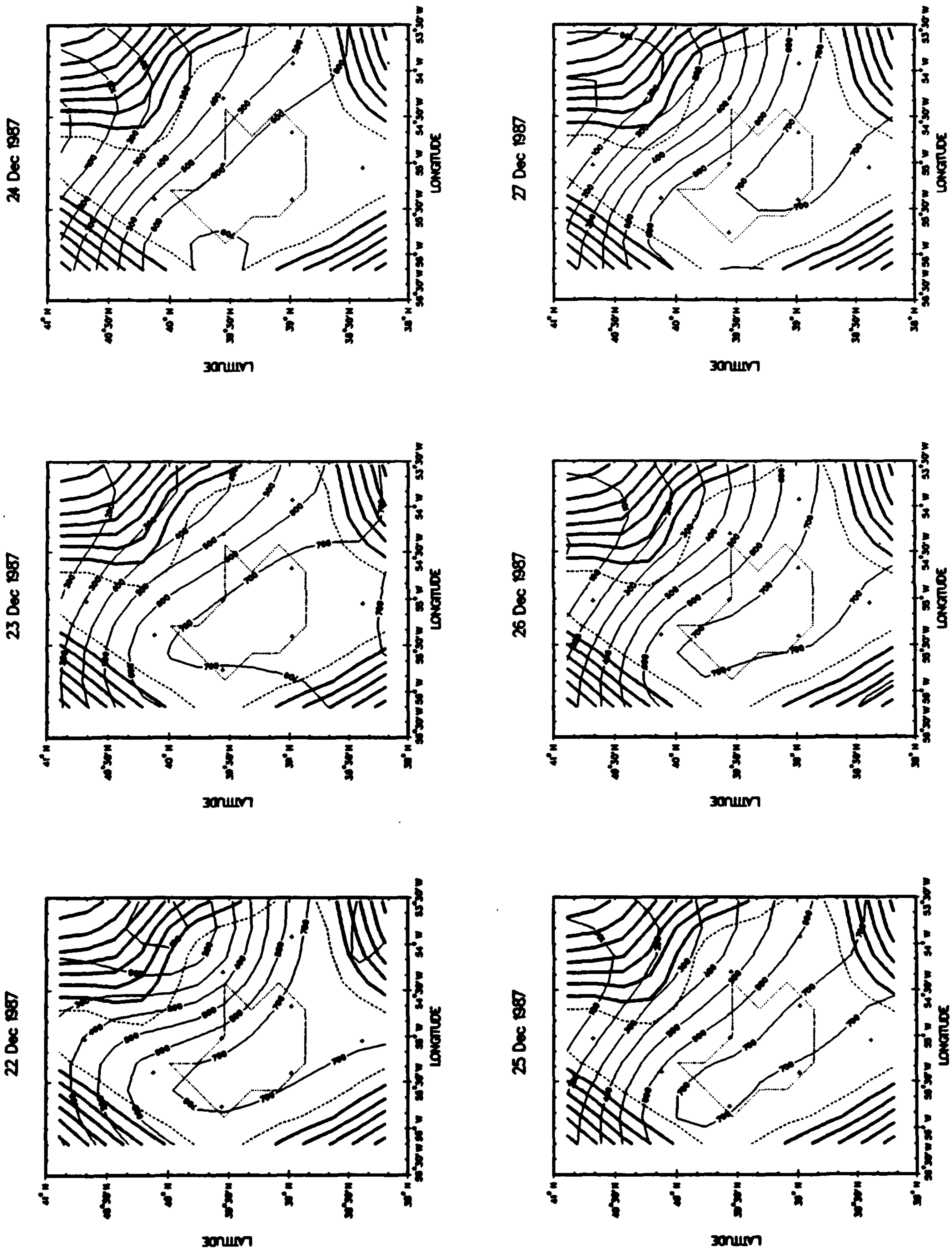
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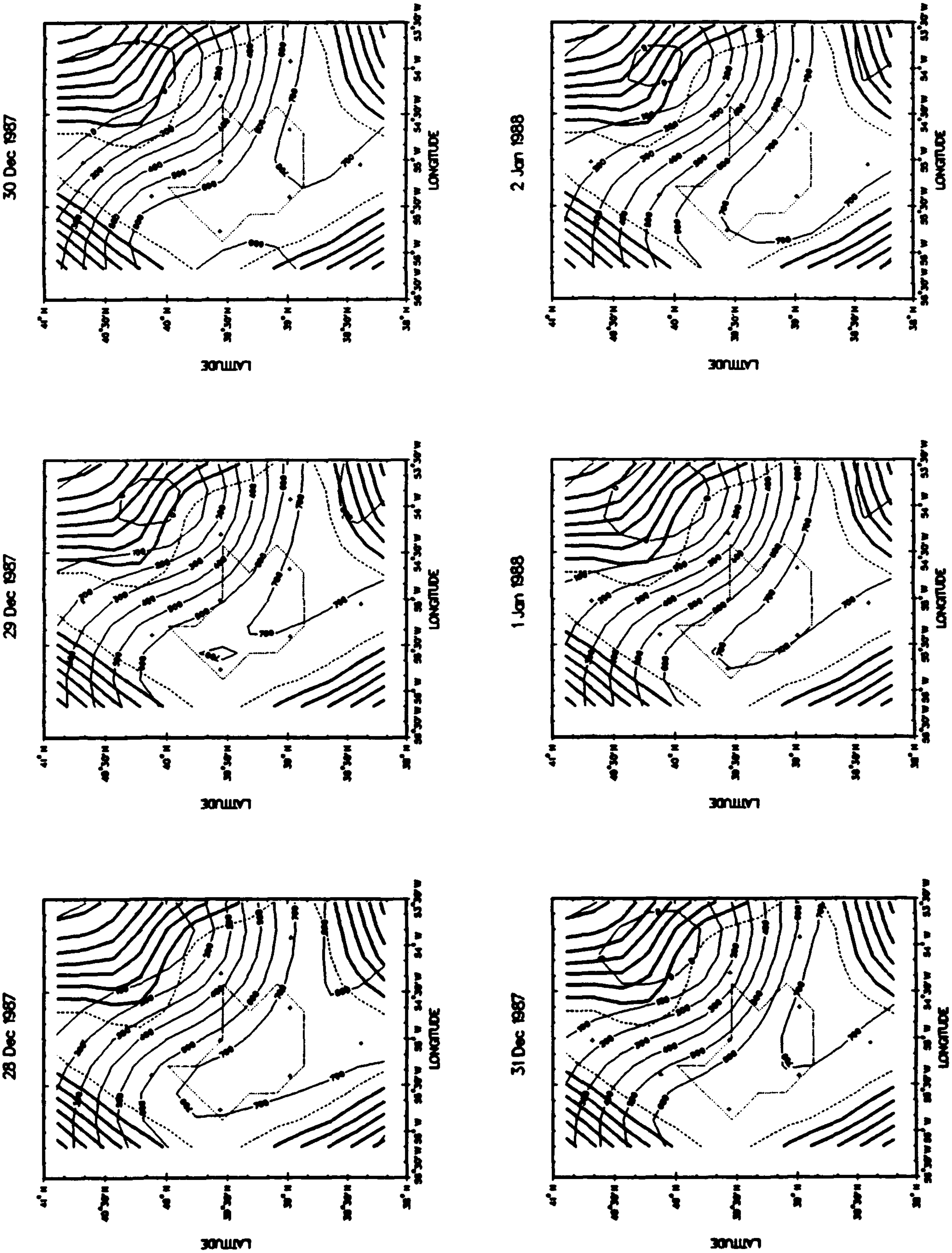
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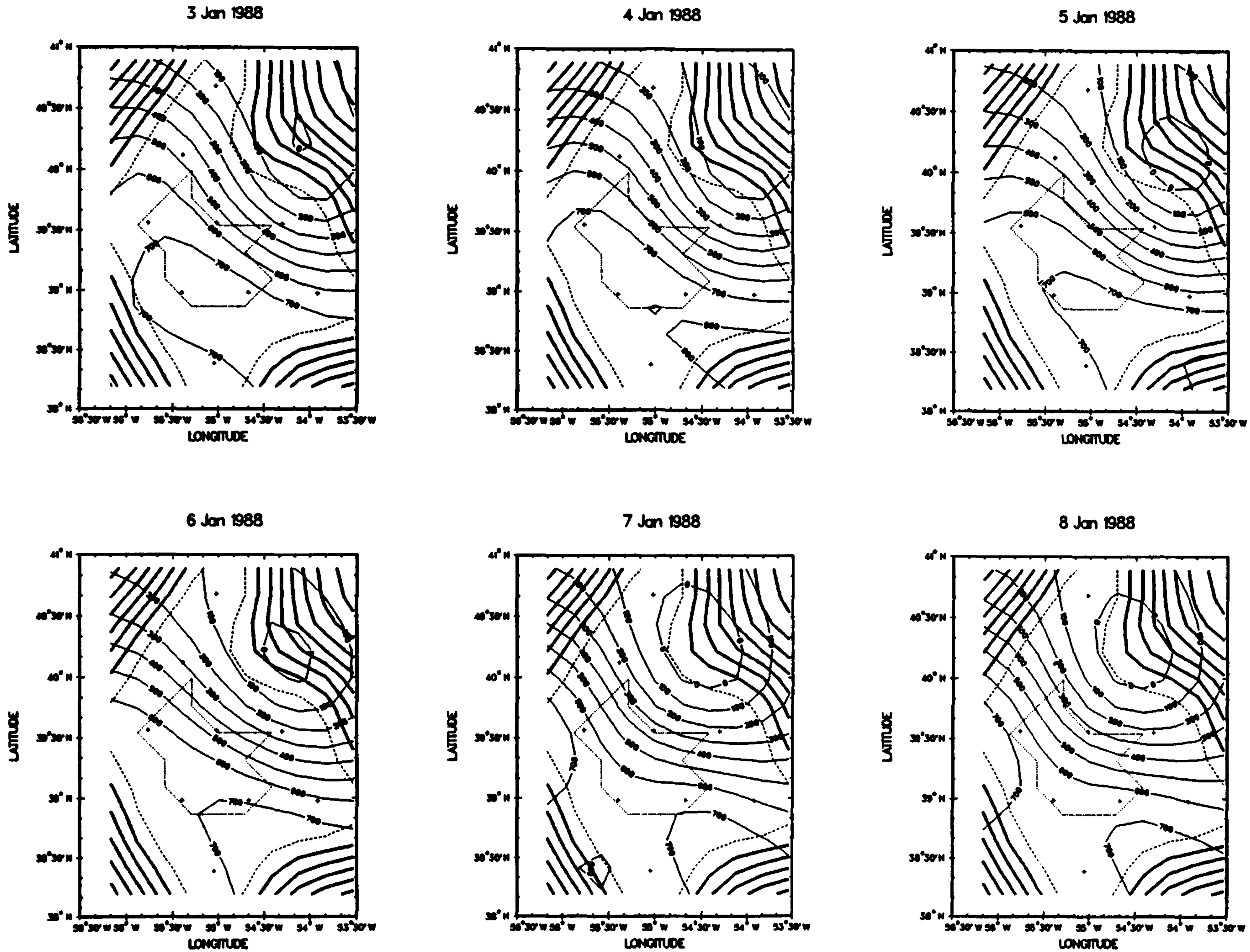
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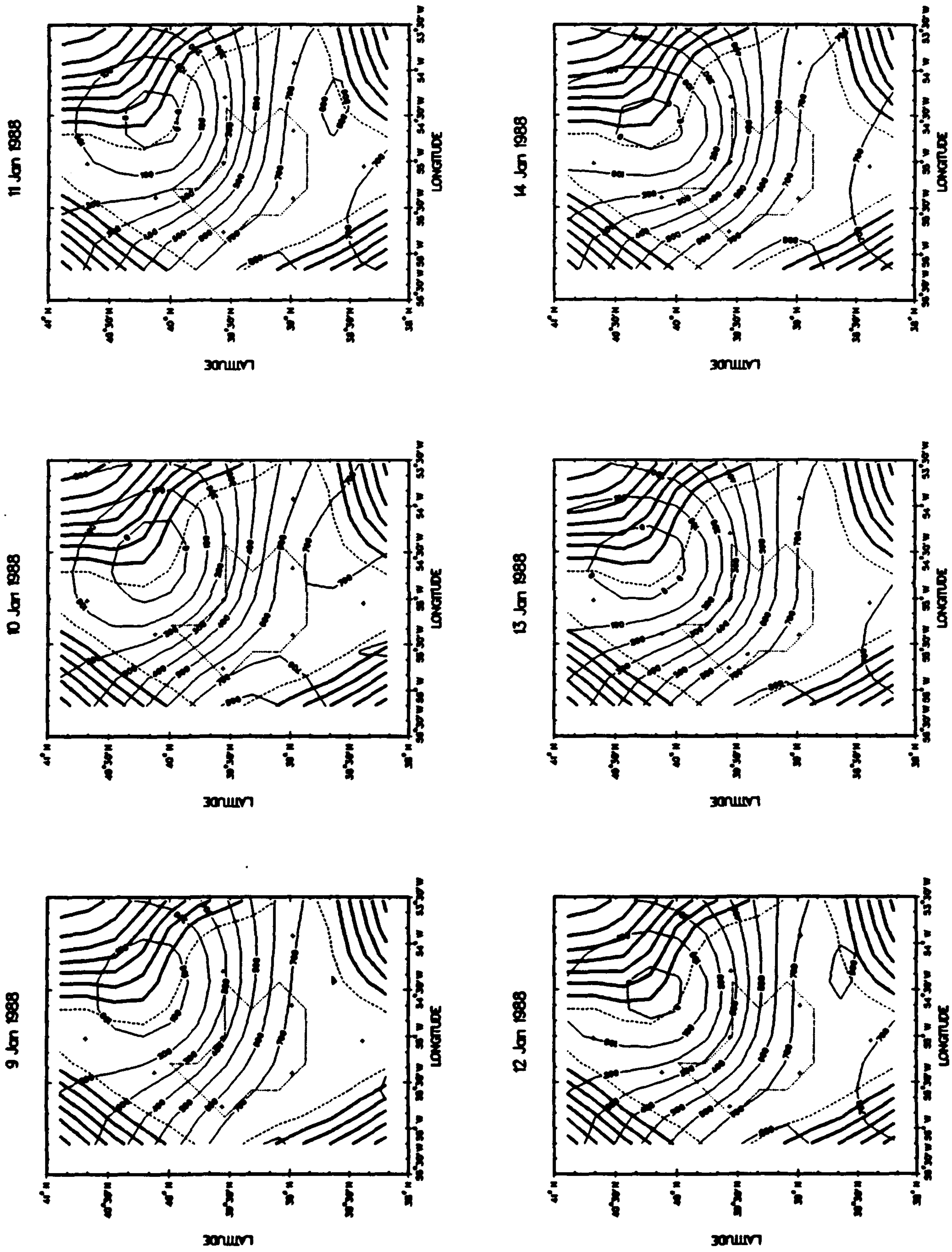
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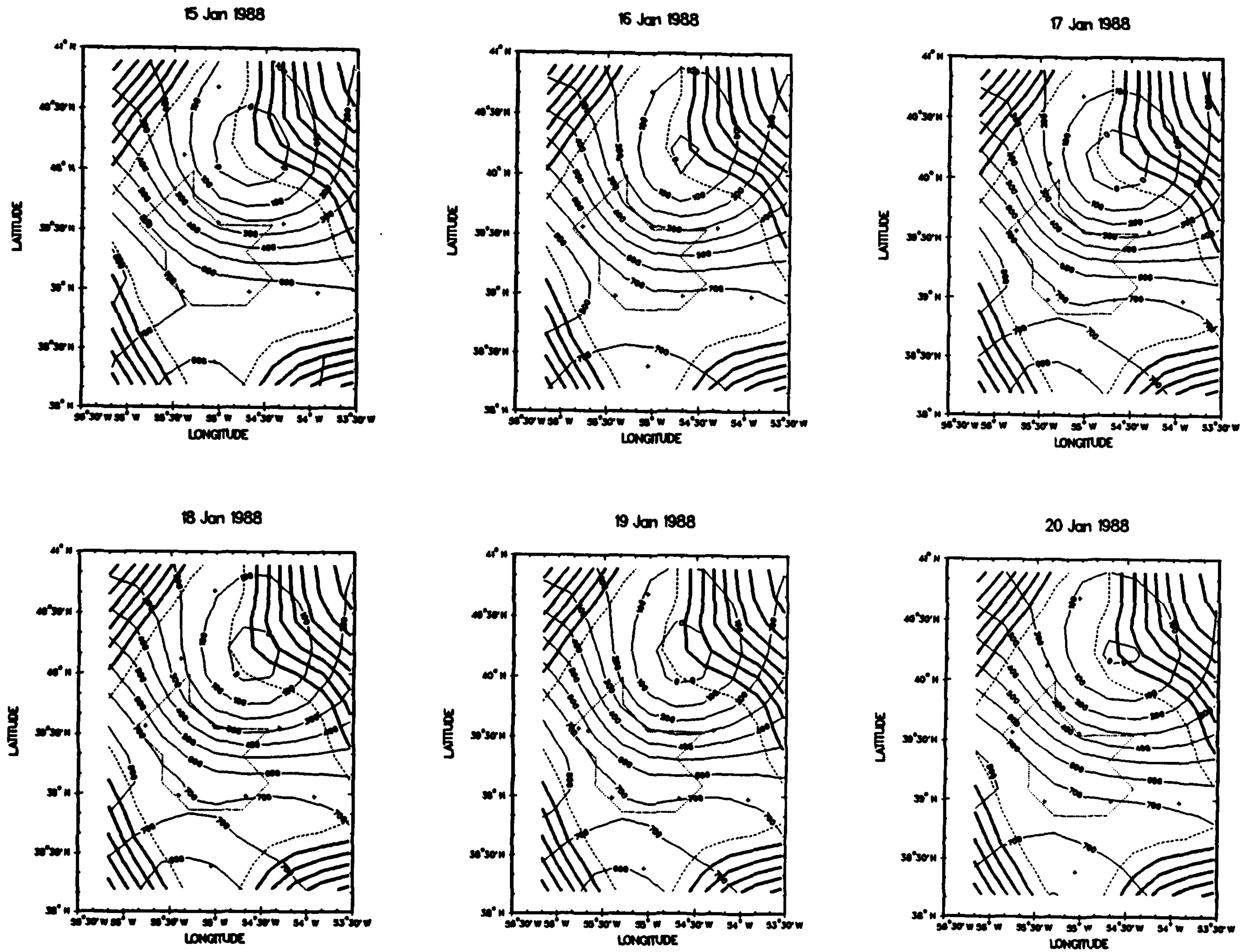
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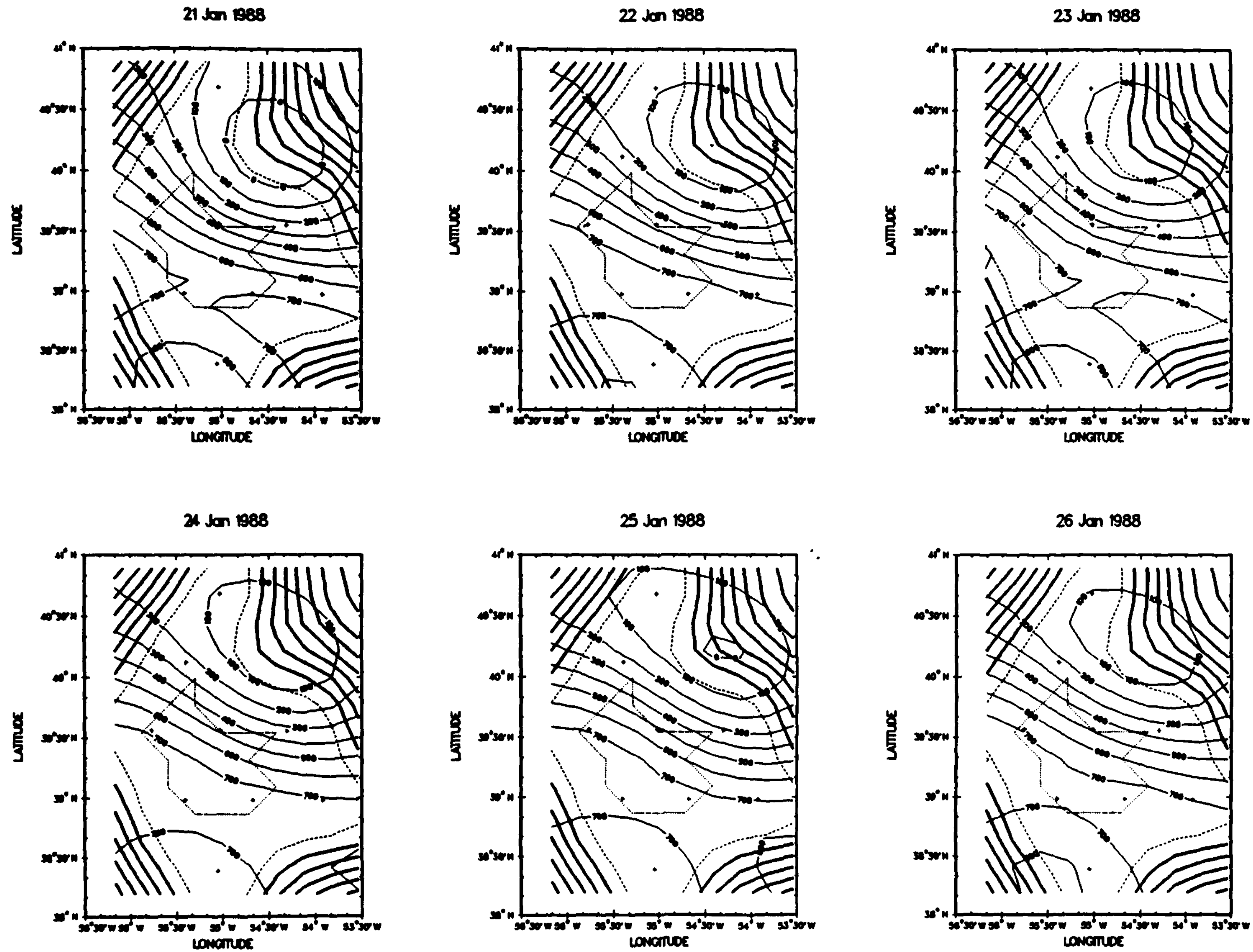
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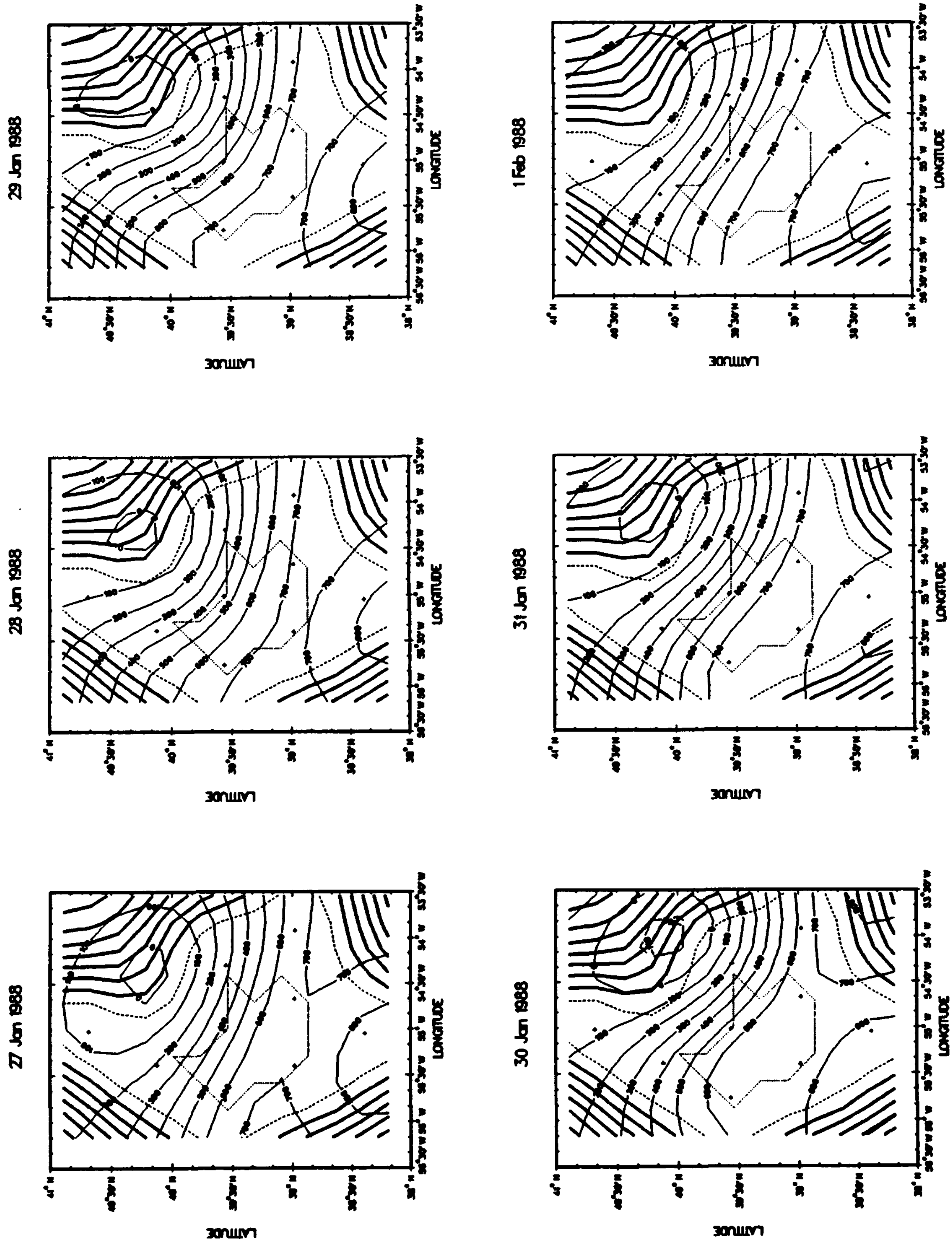

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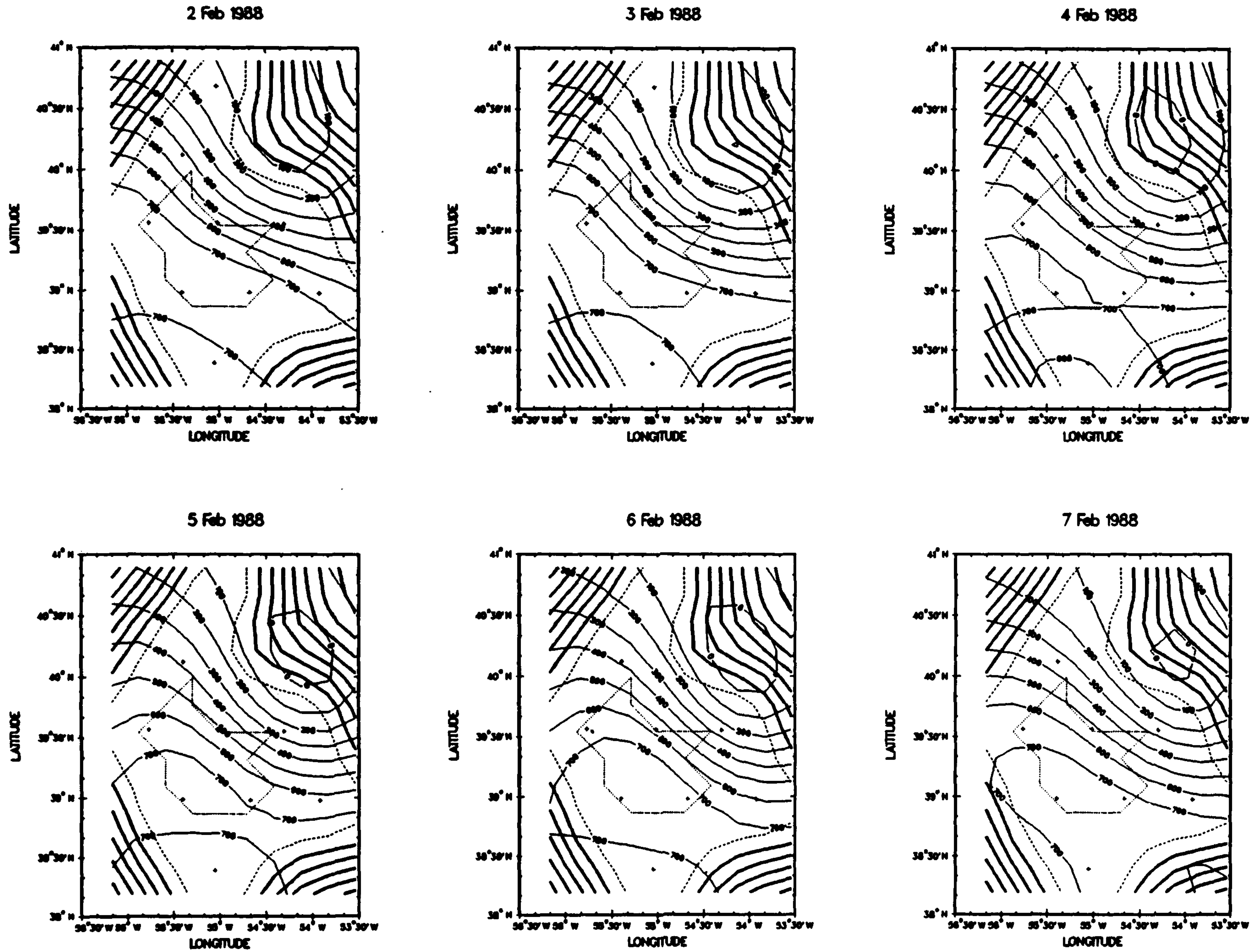
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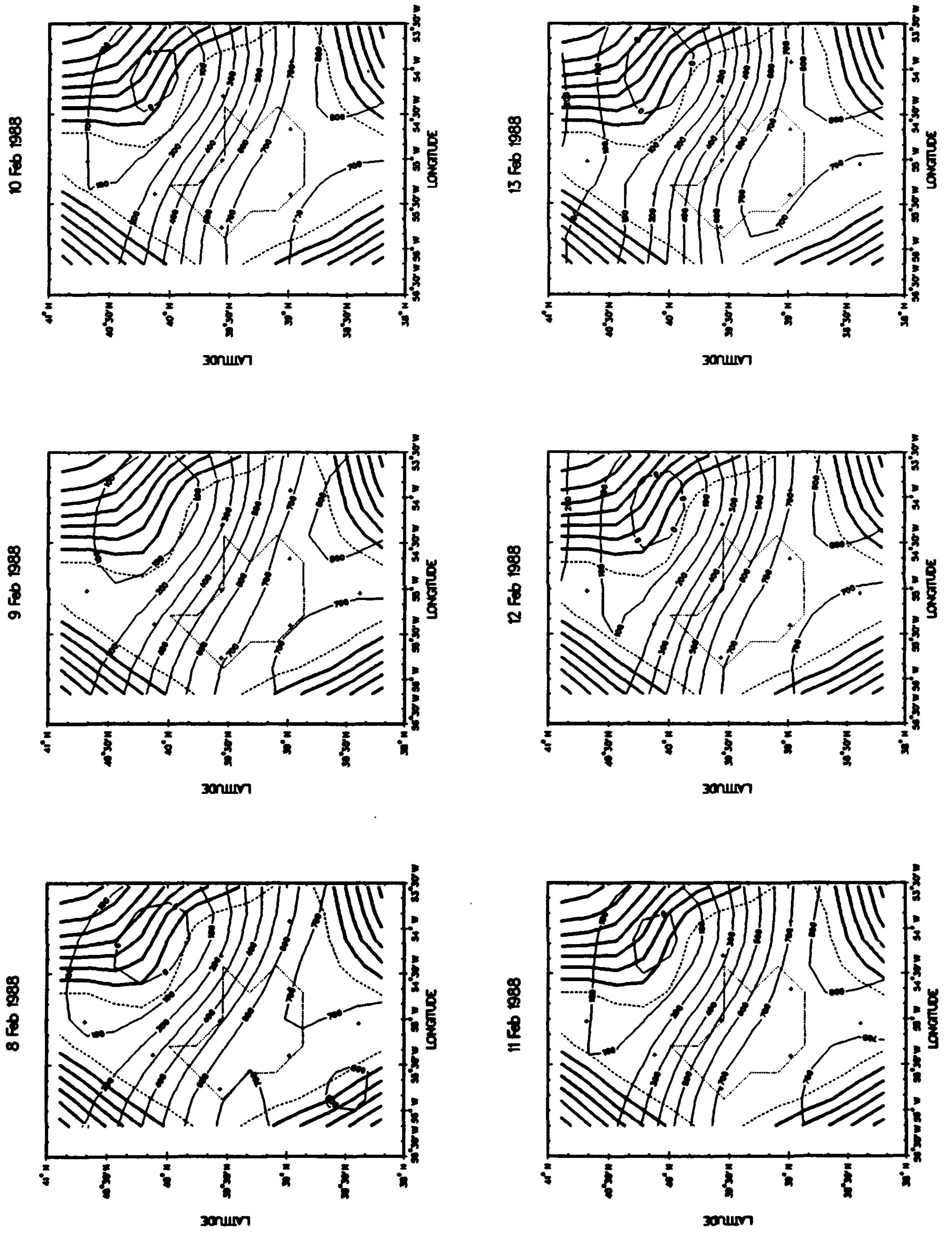
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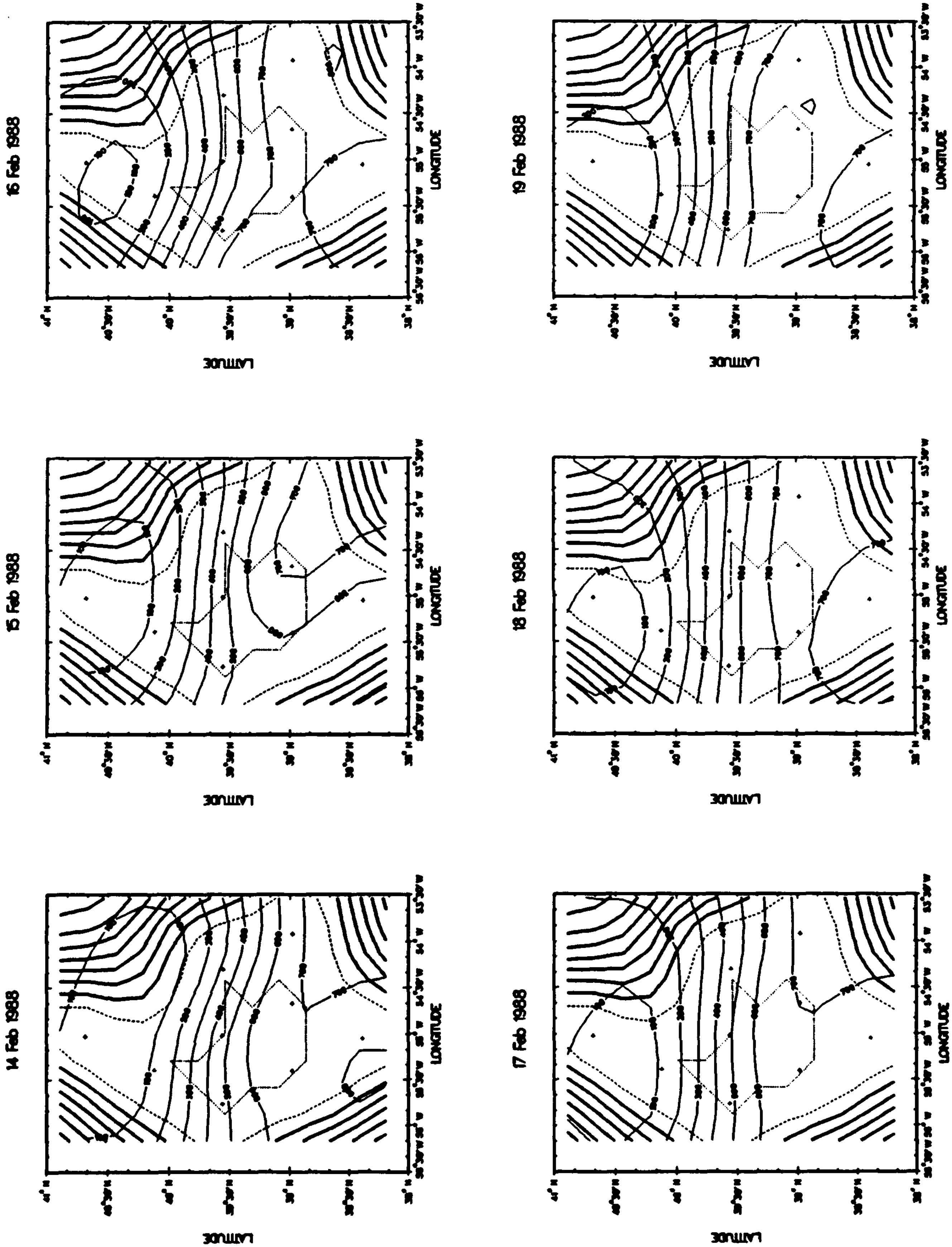
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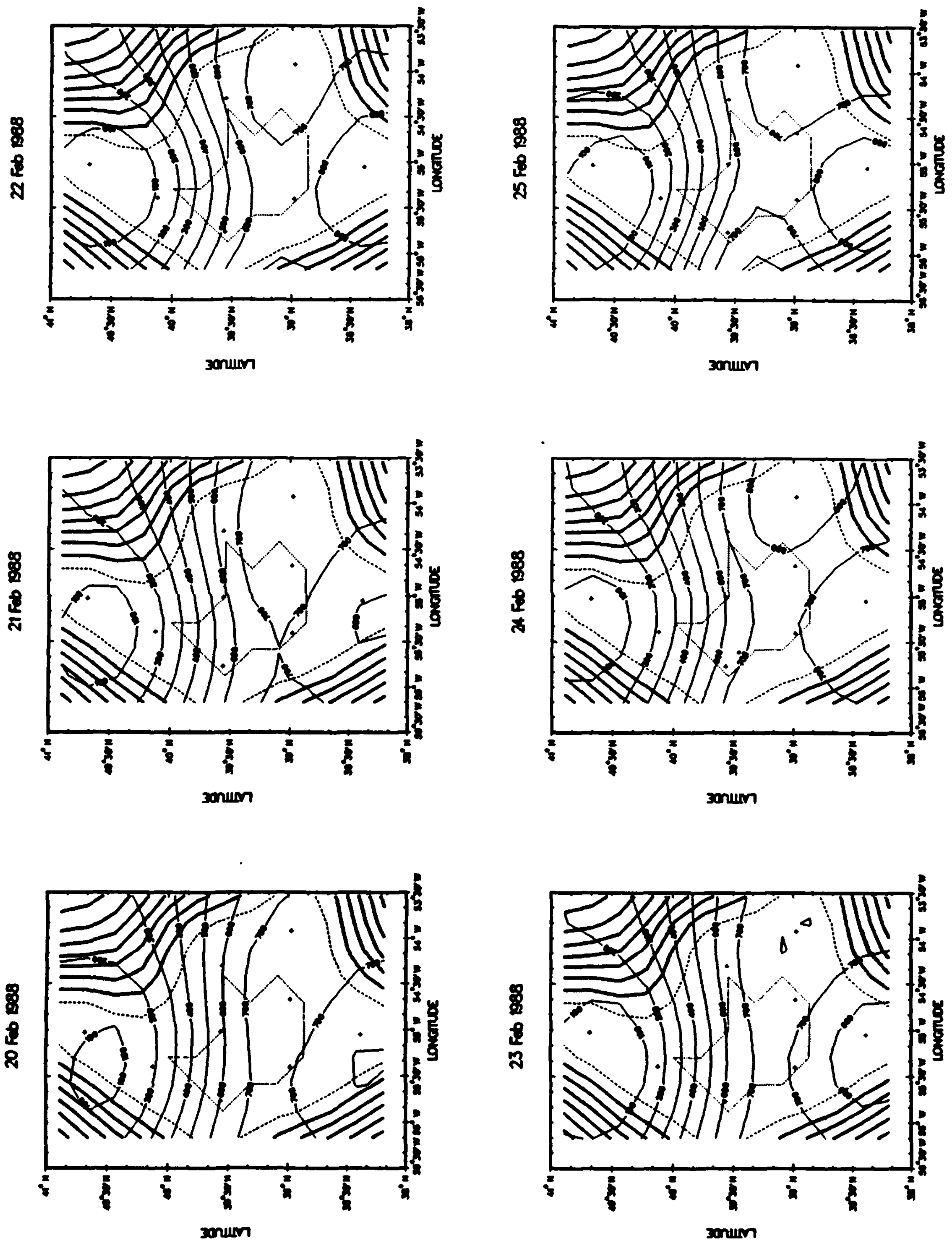
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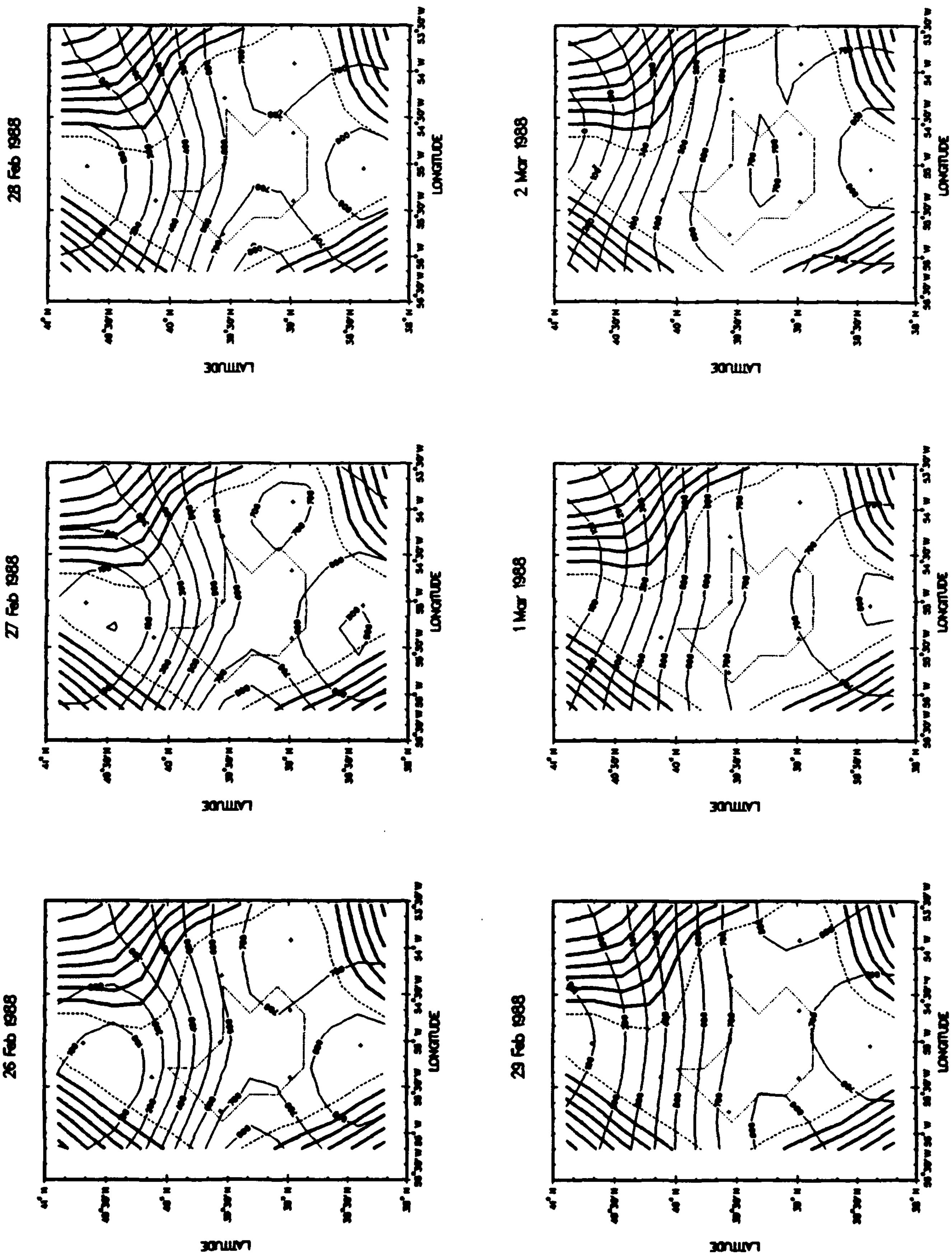
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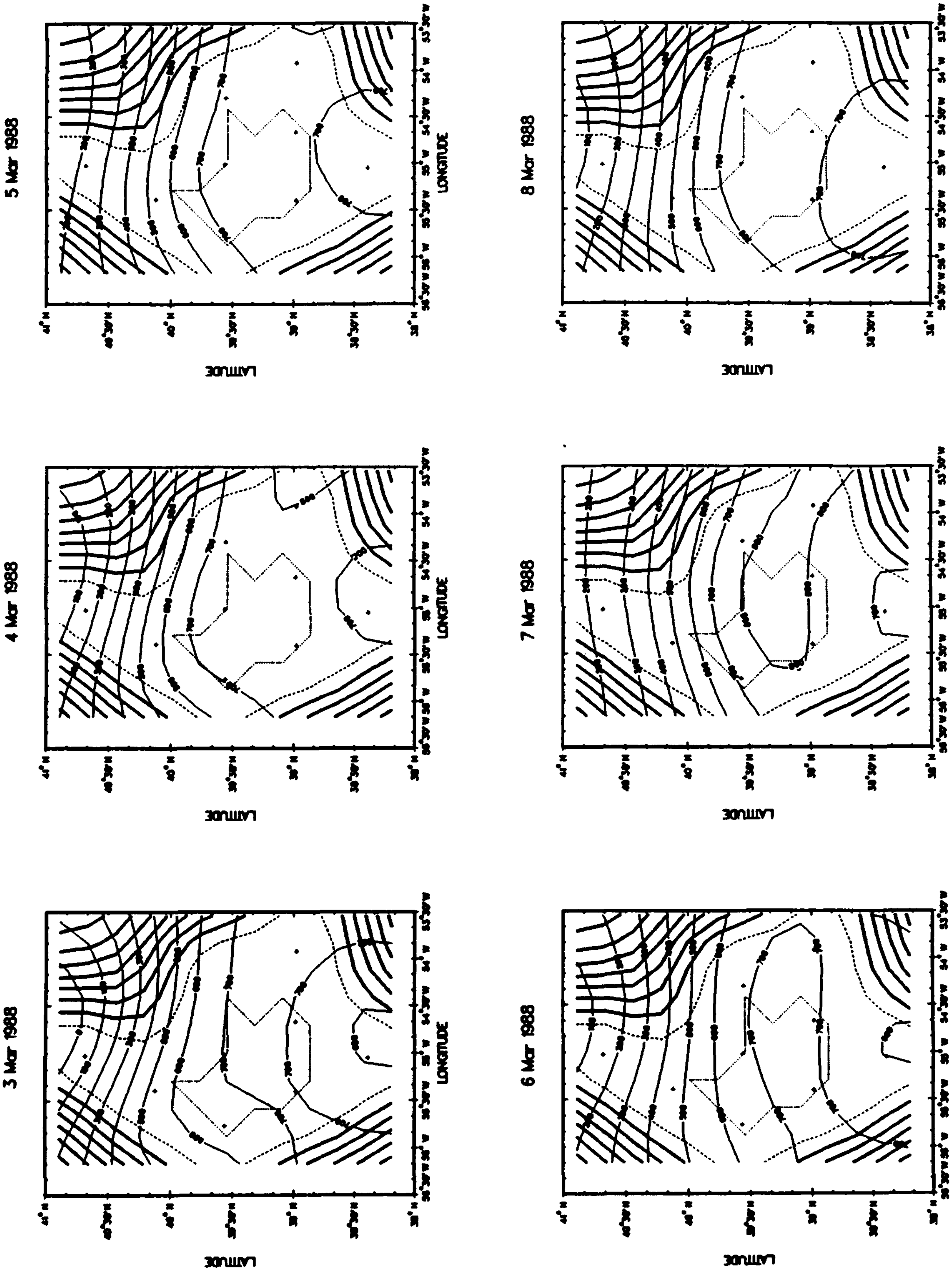

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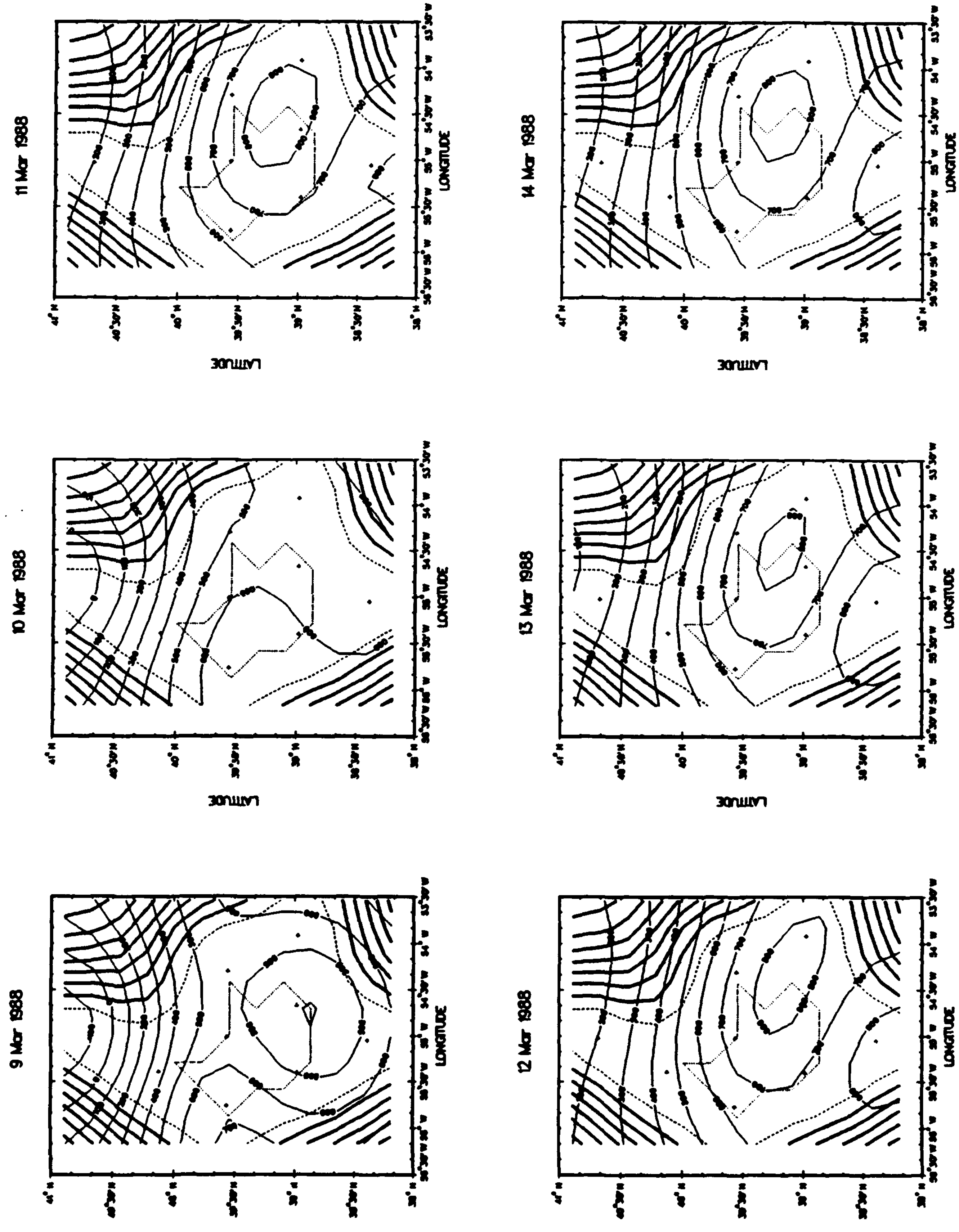

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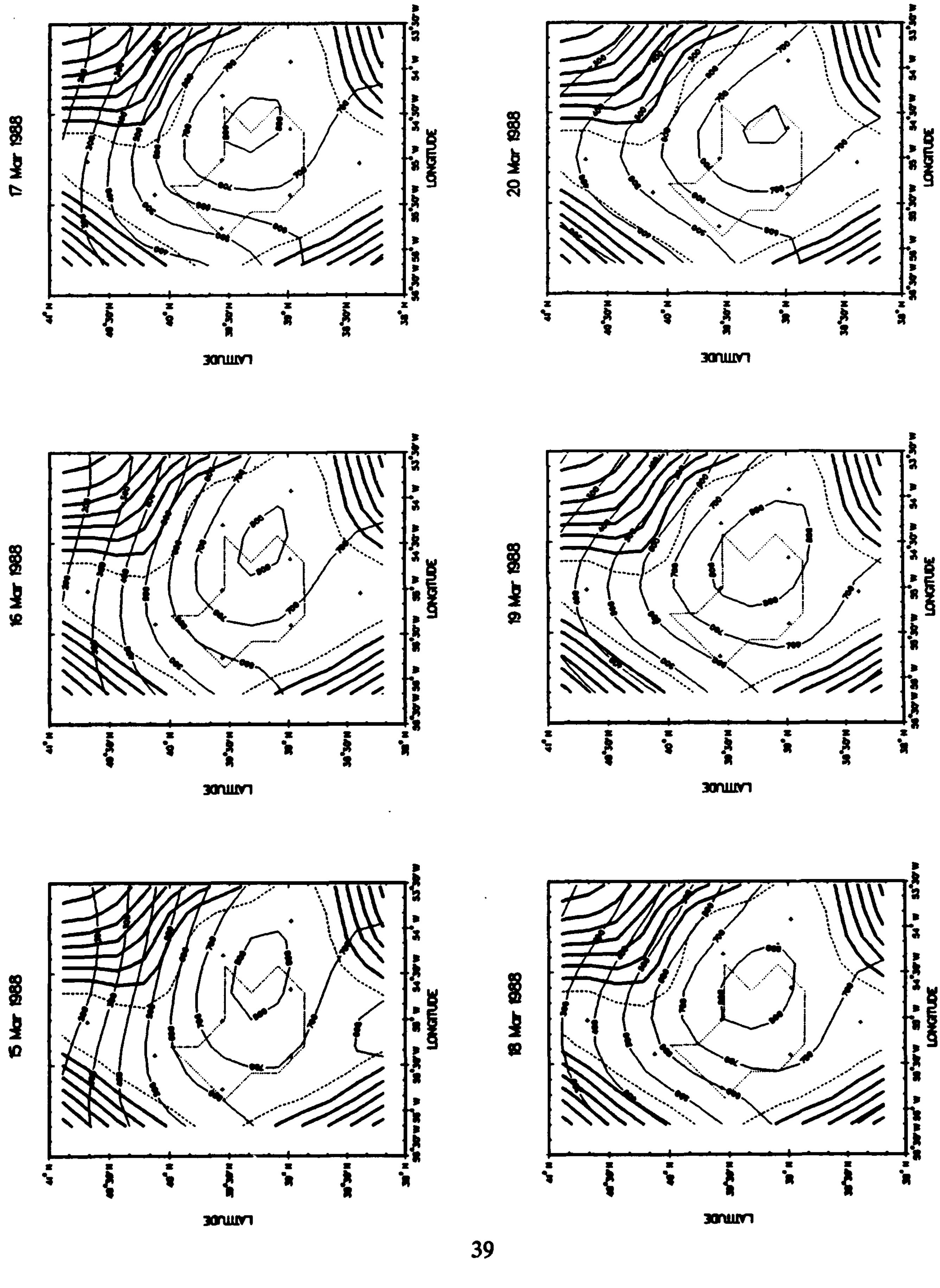
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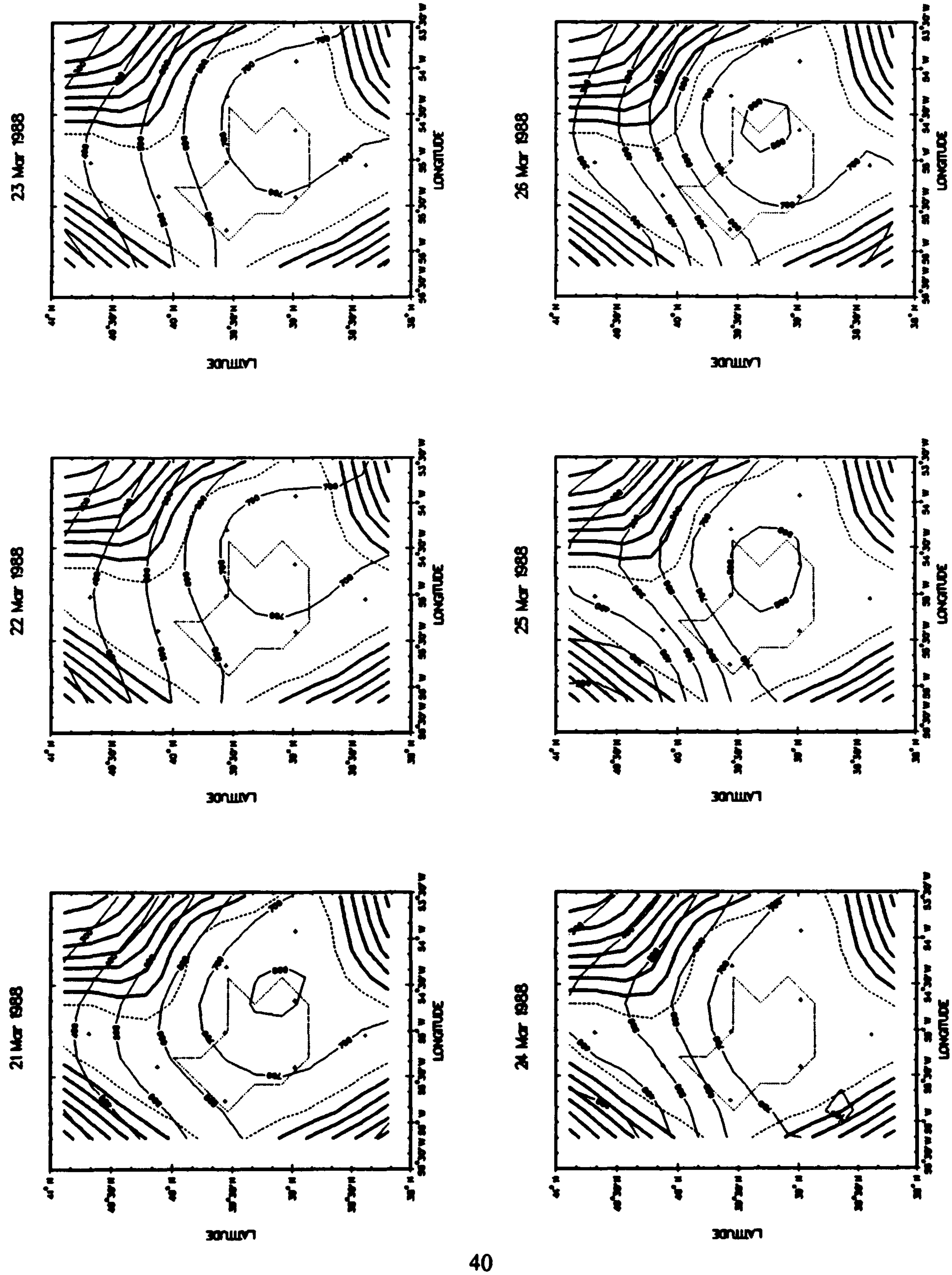
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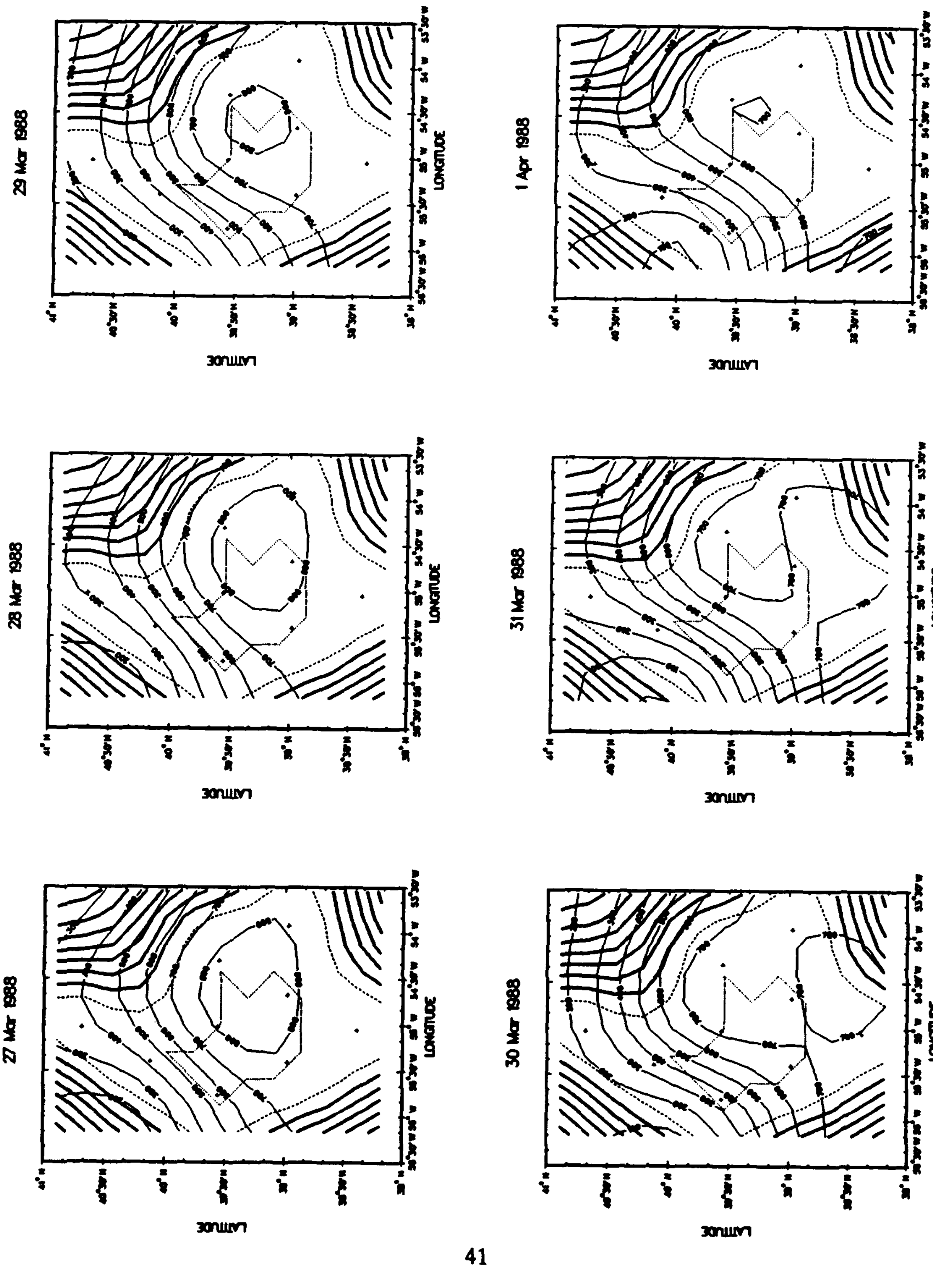
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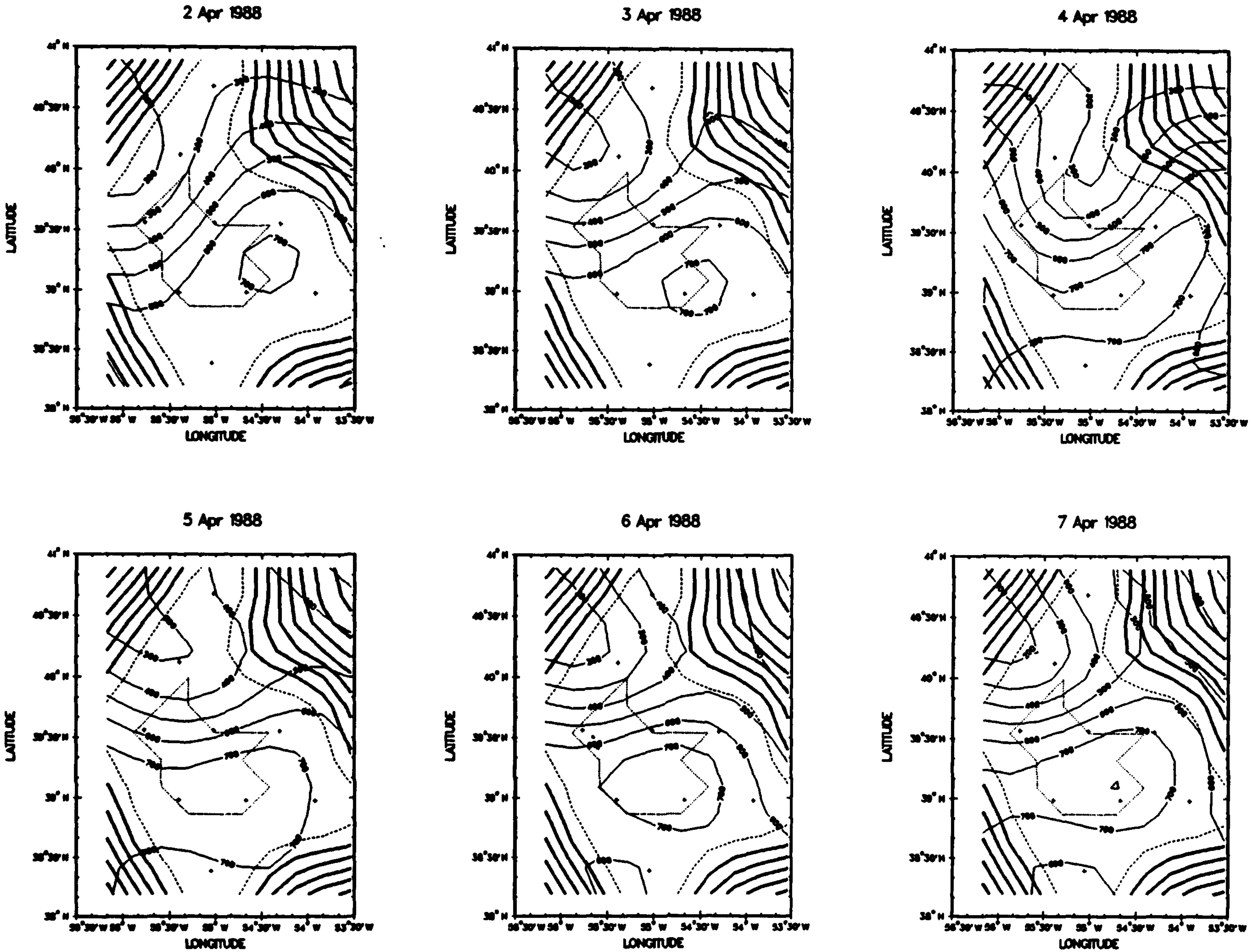
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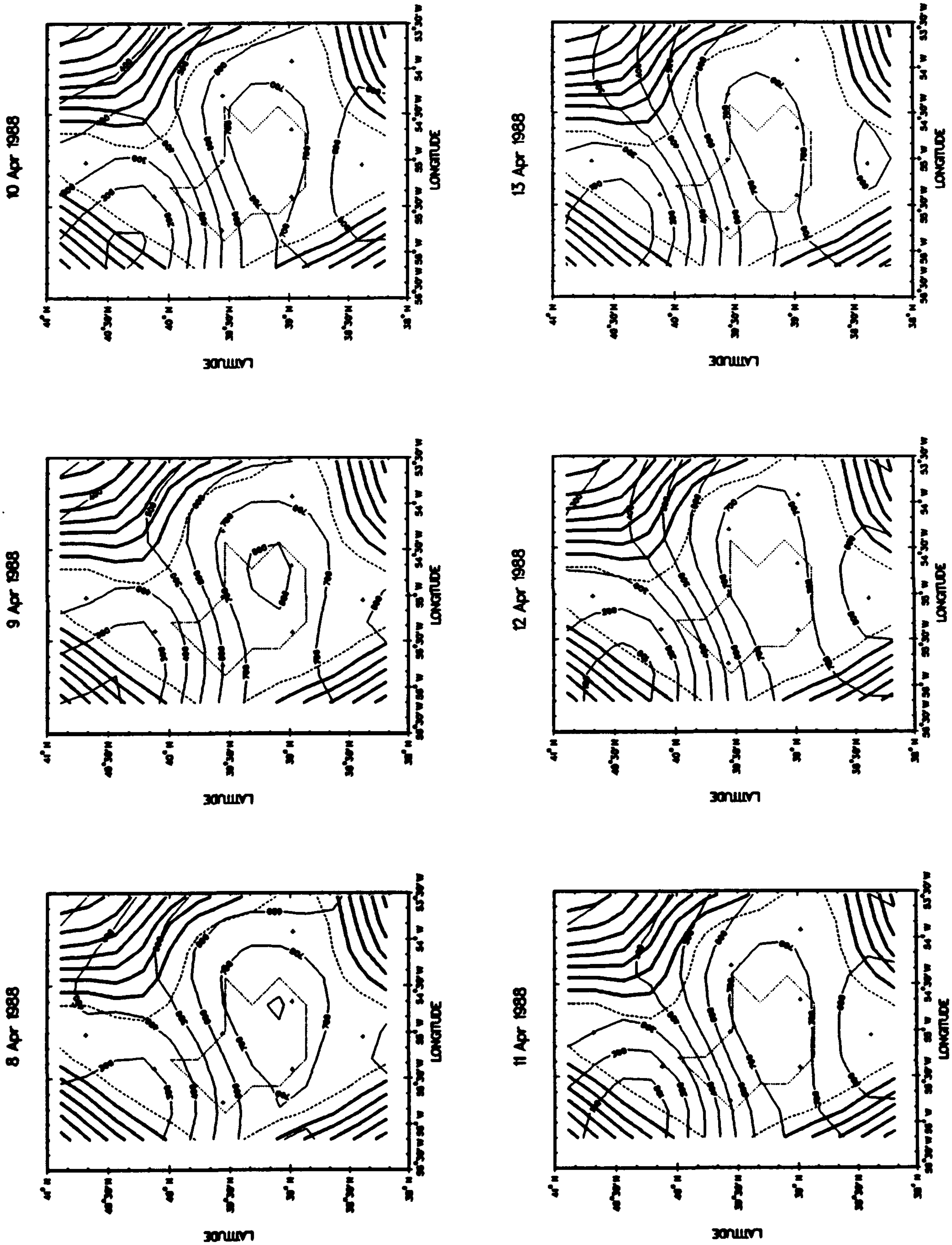
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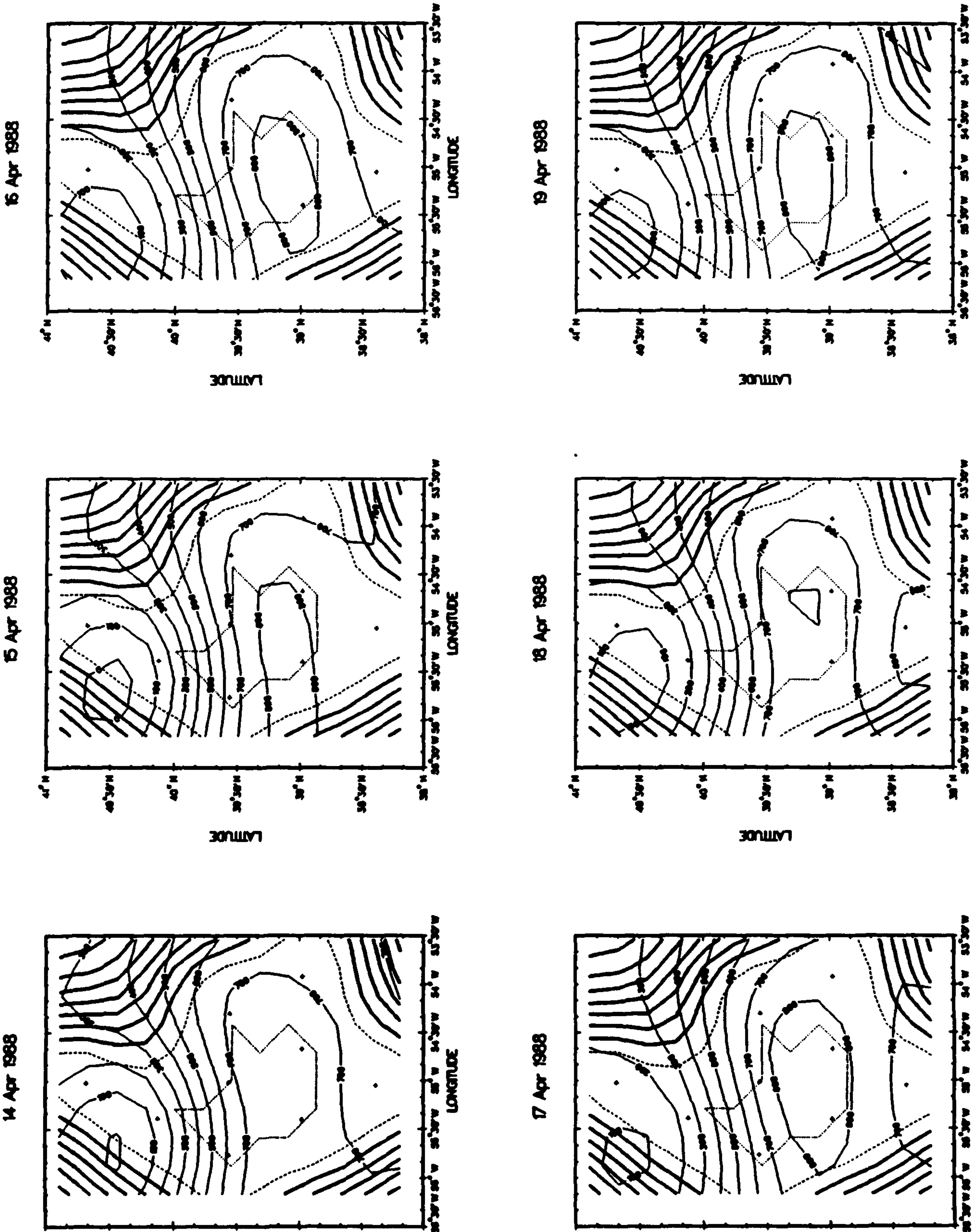
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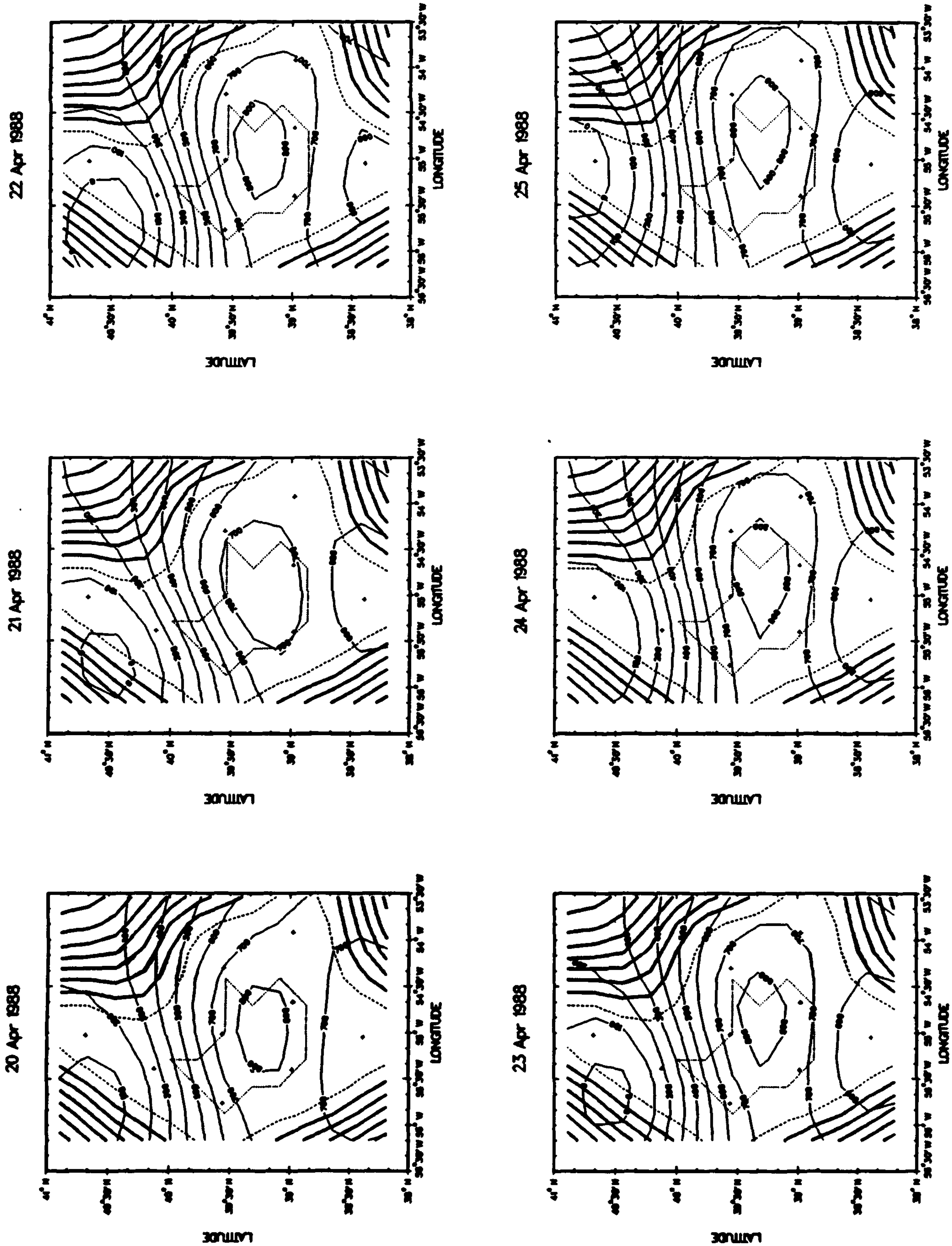
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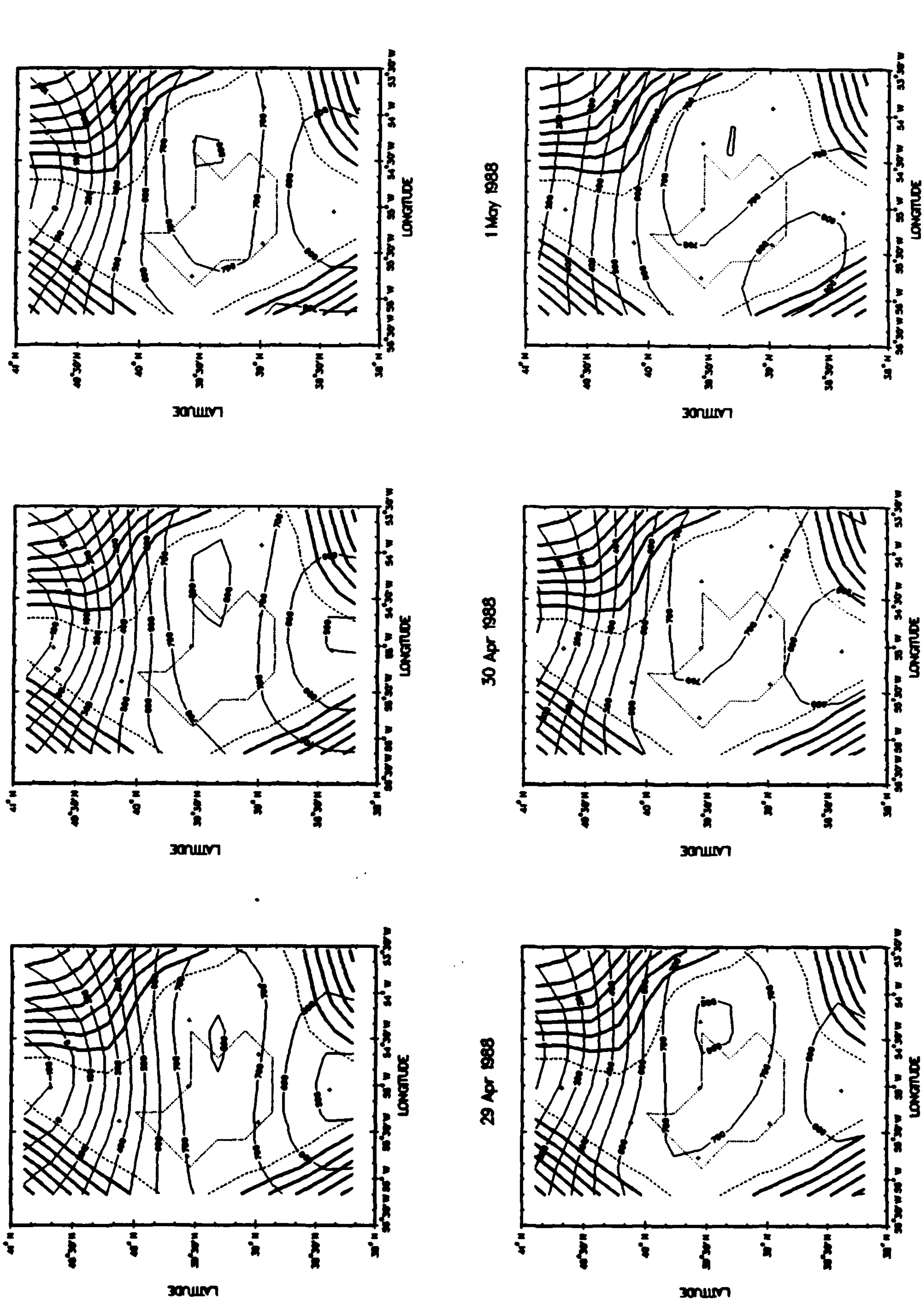

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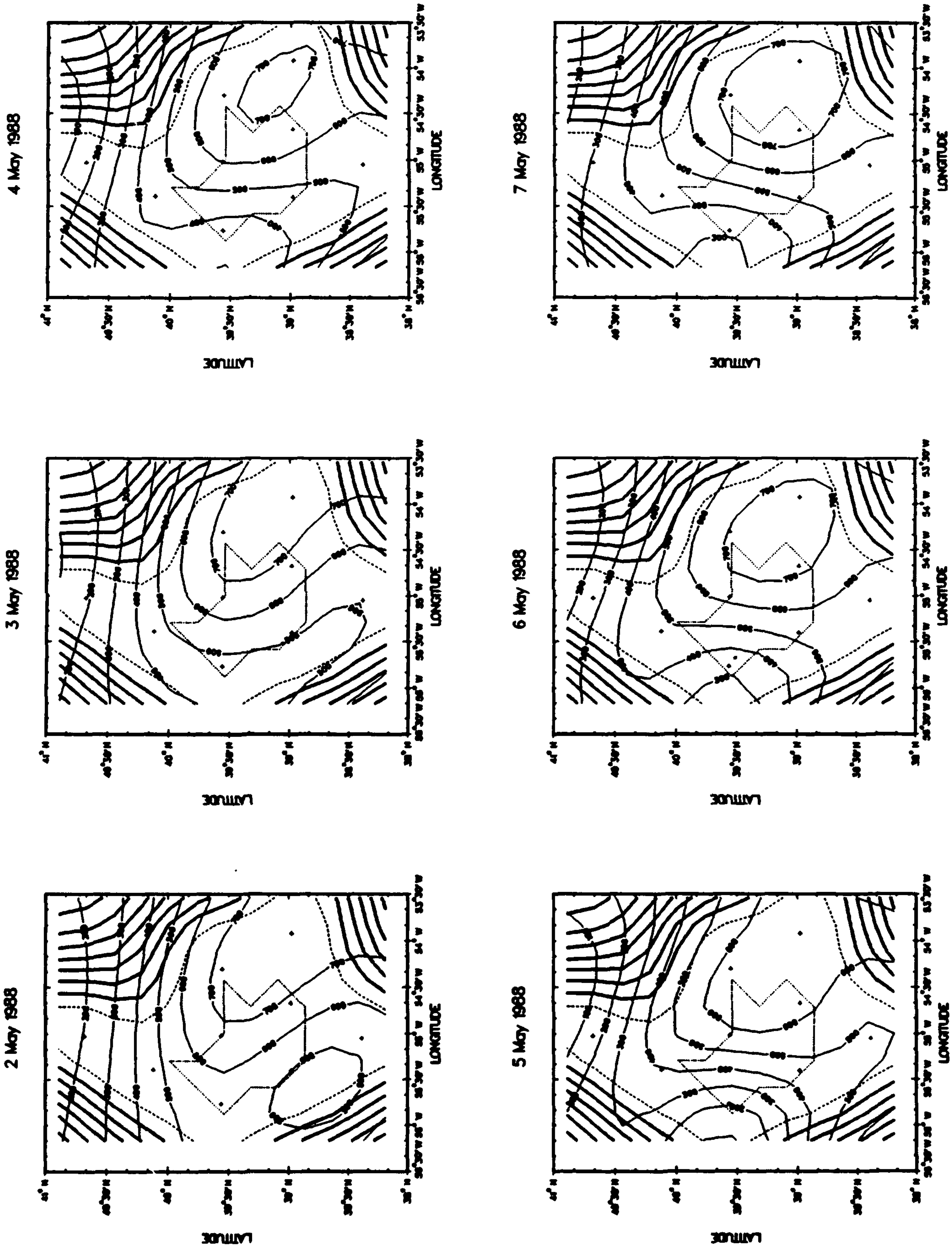
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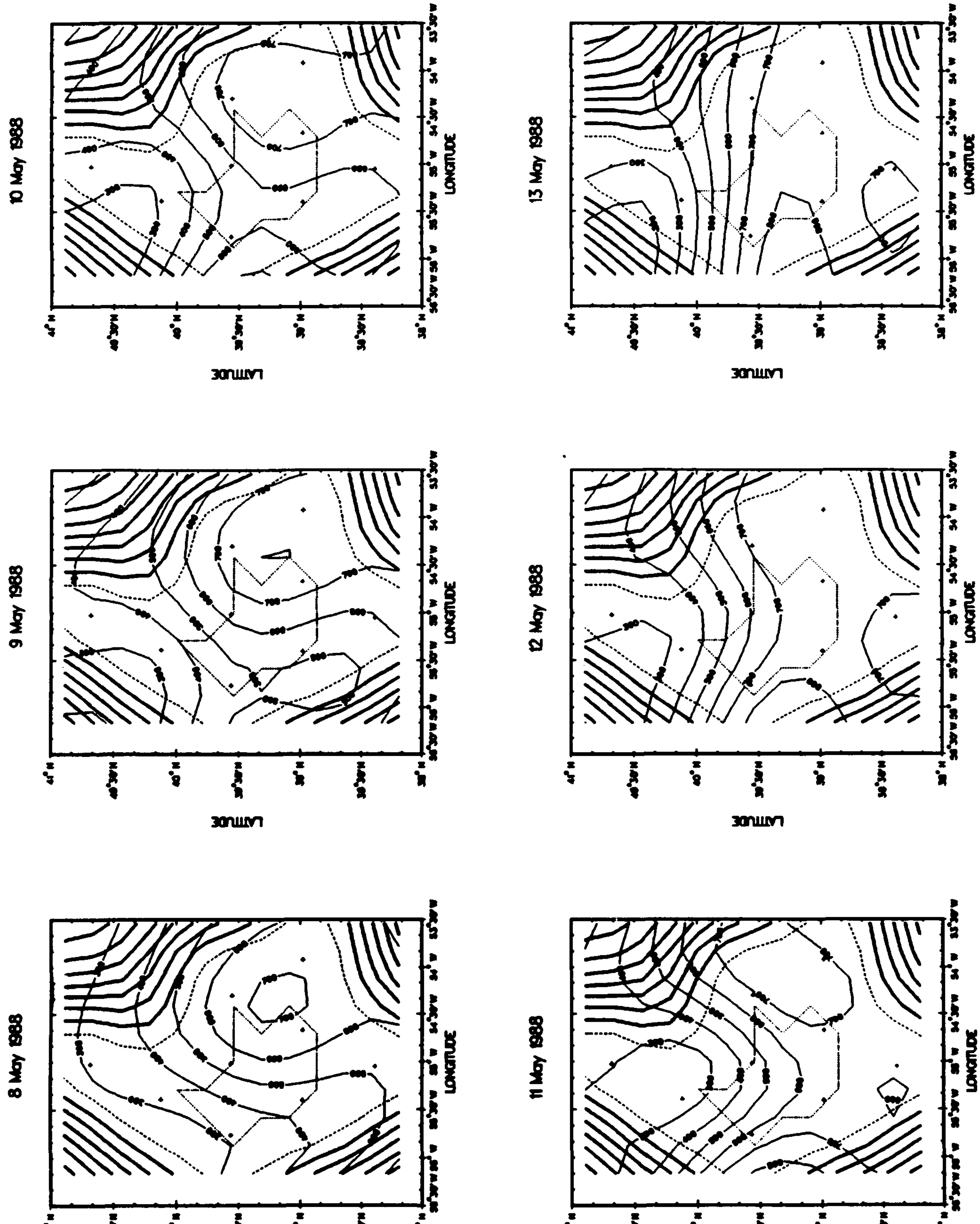

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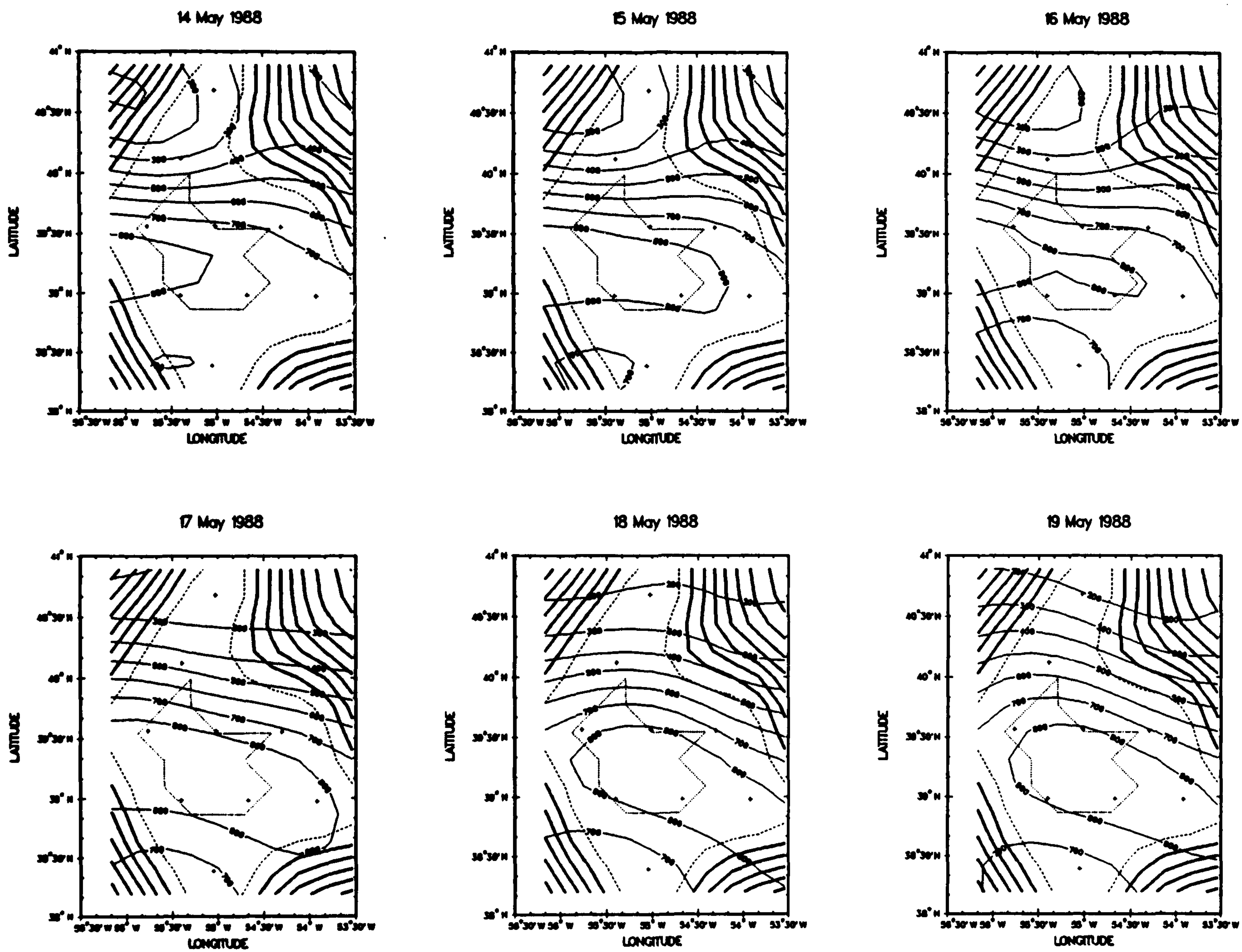
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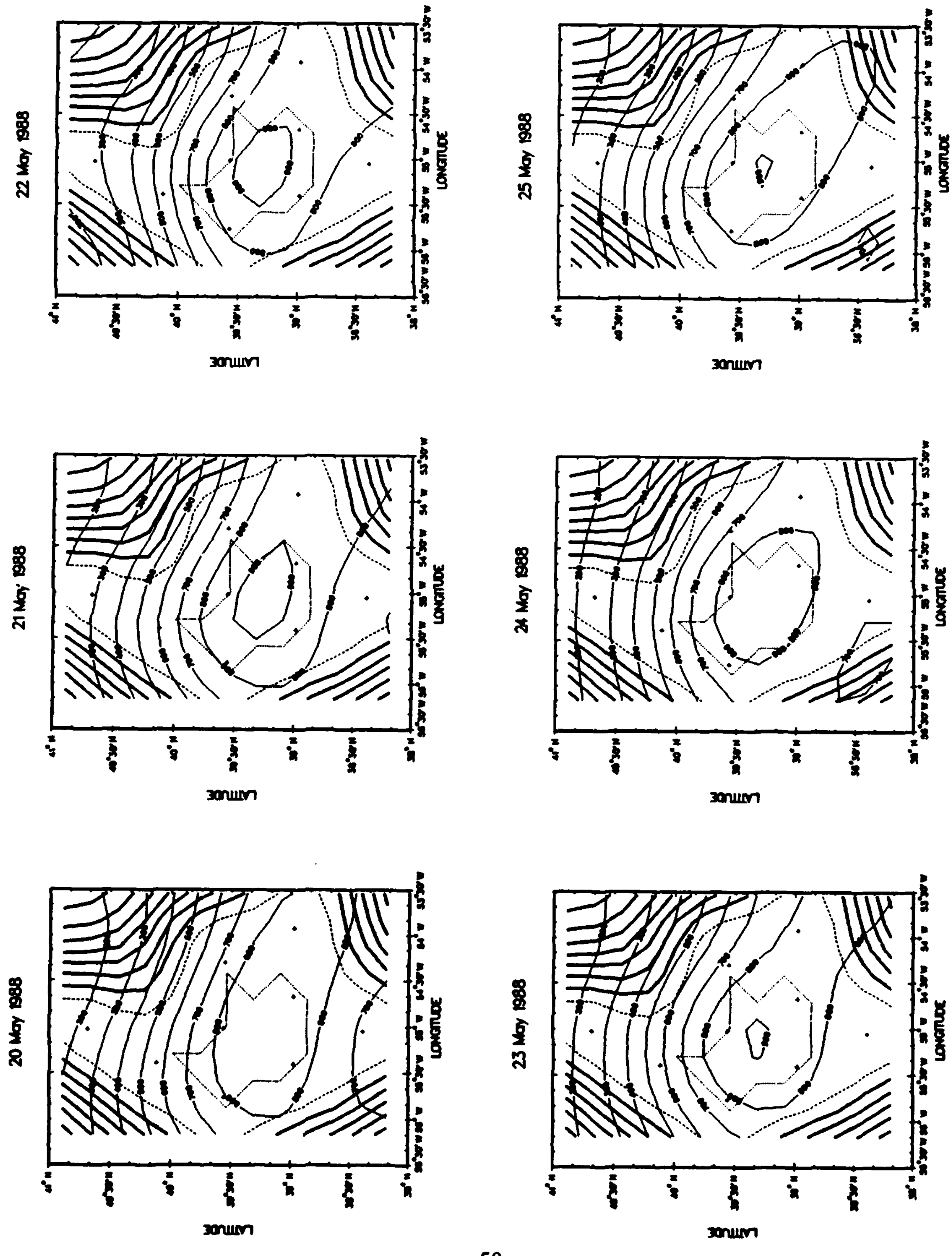
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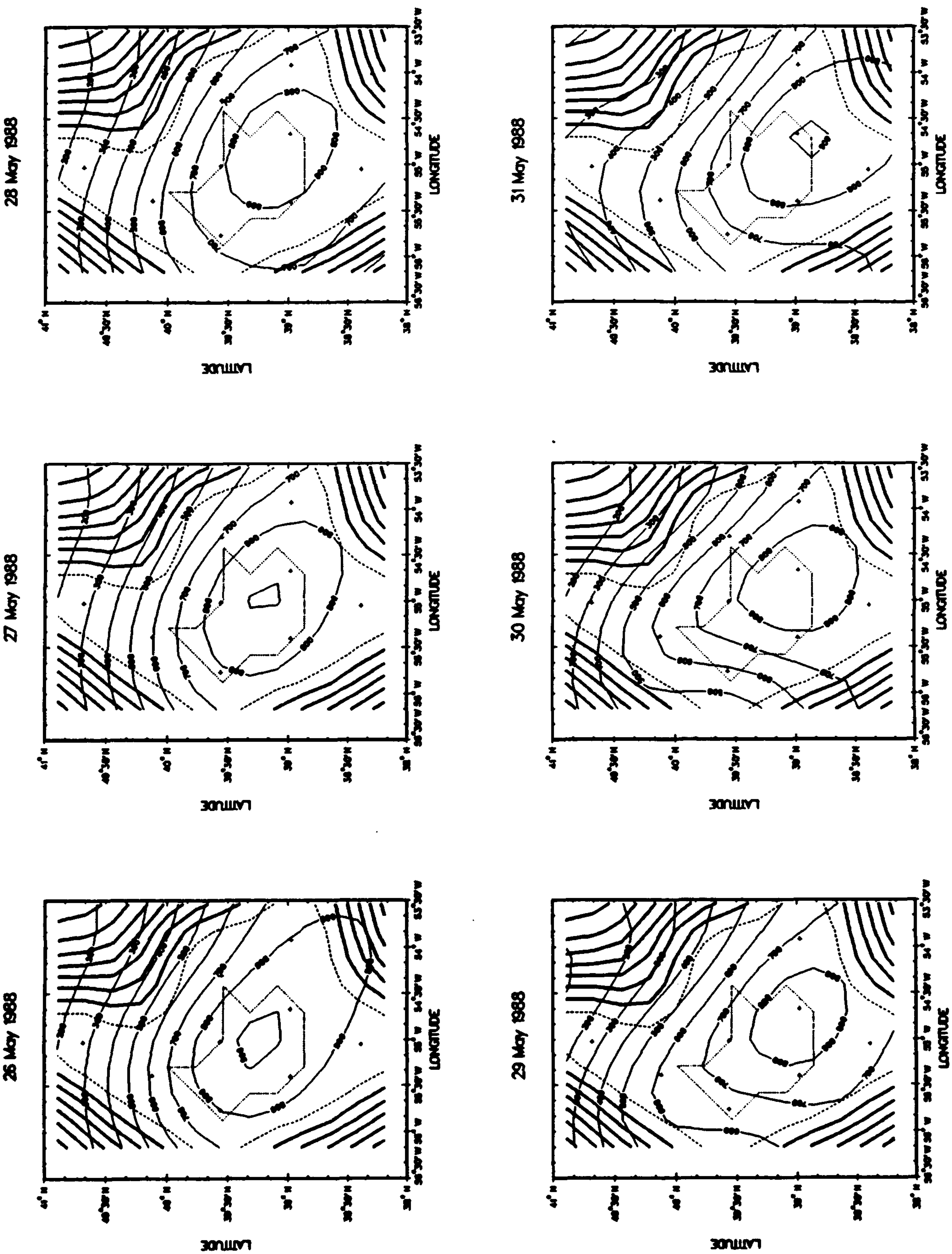
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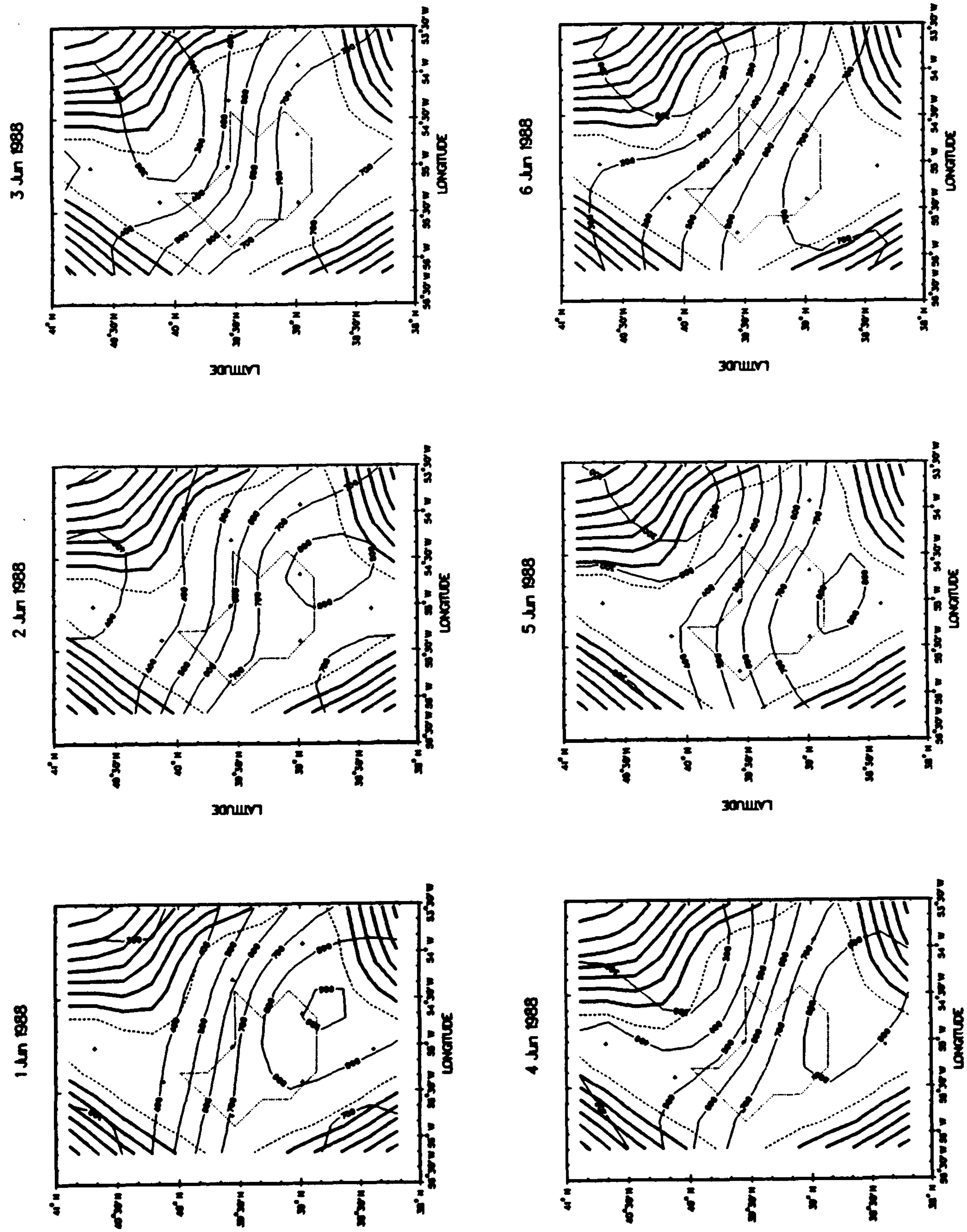
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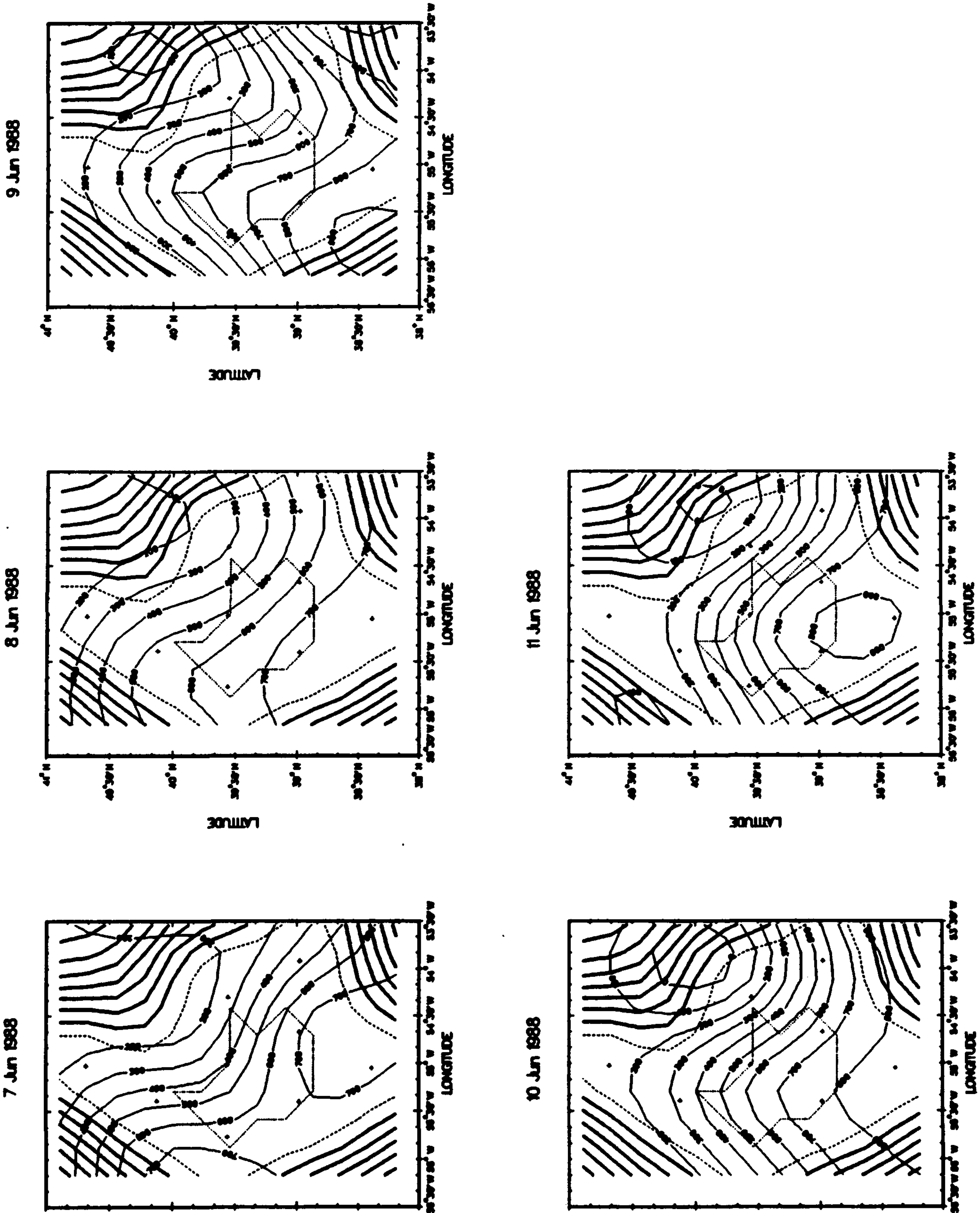
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A major component of the field activities for the northwest Atlantic Regional Energetics Experiment (REX) is focused on the acquisition and analysis of data from inverted echo sounders (IESs). This technical note describes an analysis of data records from nine IESs deployed in an array near 40°N, 55°W. IES acoustic travel-time data were converted to thermocline depths, which were in turn objectively interpolated and contoured, resulting in daily maps. These maps provide a useful tool for studying the evolution of mesoscale features in the area of the experiment.

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