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UPPER TROPOSPHERIC JET STREAMS OVER NORTH AMERICA DURING SUMMER 1988

A Thesis

by

DAVID EDWARD LANDERS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfuillment of the requirements
for the degree of

MASTER OF SCIENCE

August 1991

Major Subject: Meteorology

DEDICATION

I dedicate this thesis to Mr. Hyo-Sang Chung for his endless patience and assistance during its preparation.

ACKNOWLEDGEMENTS

I acknowledge the excellent support provided by the instructors of the Department of Meteorology at Texas A&M University, specifically Dr. Dusan Djuric, Dr. James McGuirk, Dr. Joe McFarland, and Dr. Lee Panetta. Without their patience and guidance this work would not have been completed.

I thank The United States Air Force, Air Force Institute of Technology for allowing me the opportunity to obtain my M.S. in Meteorology.

Finally, I thank my wife Lee who put up with me during the lengthy and rocky course of my research.

ABSTRACT

Upper Tropospheric Jet Streams over North America during Summer 1988. (August 1991)

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B.S., Florida International University

Co-Chairs of Advisory Committee: Dr. Dusan Djuric
Dr. James McGuirk

Much has been written describing the jet stream. Most previous works dwell on the characteristics of the winter jet stream, when jets are faster and more easily discerned. This paper will instead focus on the jet streams over North America during the summer of 1988.

During July 1988 the predominant jet regime over North America (70% of the observations at 250 mb) was that of a single jet along the United States/Canada border. During August 1988, however, the single jet regime was only present 26% of the time, with a two jet regime occurring 53% of the time.

The southern jet during August appeared in a location similar to the winter season subtropical jet, but generally had the characteristics of a polar front jet stream.

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CHAPTER I

INTRODUCTION

The existence of two major jet streams in the Northern Hemisphere is well established during the winter half of the year. Conversely, during the summer, there is believed to be routinely only one upper tropospheric jet stream.

Weather development is likely to differ depending on the jet stream regime. It was shown that severe storms have a preference for occurrence in the space between the subtropical and the polar jet streams (Whitney, 1977; Uccellini, 1987).

Formation of cyclones, rain and various other phenomena are either enhanced by the kinetic energy of, or steered by, the jets. Therefore, knowledge of the jet regime (one or two) is of basic importance in the description and forecasting of the weather.

Climatological summaries often blur the separate existence of the subtropical and the polar front jet streams and at times the jet streams merge, most often at the east coasts of North America and Asia, where the greatest zonal wind maxima tend to be observed (Riehl, 1990).

The style is that of the *Monthly Weather Review*.

There is a great deal of literature defining and analyzing different aspects of jet streams. But most works focus on the winter hemisphere where jets are faster and more easily identified. Some of these studies are described in the next section.

The goal of this study is to separate the cases during the summer months when there are one or two jet streams. Attention will be paid to possible transitions between the two regimes. Weather development will be described, with the intention of showing the differences if they exist, between the jet stream regimes.

To accomplish this goal three tasks must be completed. They are: finding the favored number of jet streams over North America during the data period, computing descriptive horizontal and vertical statistics of the jet stream,and quantifying differences in weather regimes and circulation patterns associated with the presence of single or multiple jet streams.

Based on the literature, (Palmen and Newton (1969); Reiter (1961)), the pressure levels from which to draw most of the information about jet streams during summer are 250, 200, and 150 mb. *The Glossary of Meteorology* (1959) defines the threshold speed of the jet stream as 50 kt. Since the u and v source data are given in metric units, 25 m s^{-1} (actually 49.21 kt) was selected as an appropriate threshold speed for jet stream study.

The domain of this study, 60°W to 130°W and 0°N to 90°N, was selected to observe the atmosphere over Mexico, the contiguous 48 United States and Canada.

It is expected that significant differences may occur in comparing the meteorological elements of this data set to those of previous climatological studies for two reasons. First, the chosen data represents only a small portion of the earth, and second, the 1988 summer season over most of North America was one of the hottest and driest of the 20th century (while the weather over parts of the Desert Southwest was considerably wetter than usual (Ziemianski, 1988; Ludlum, 1988; and Heim, 1988)).

CHAPTER II

BACKGROUND

Reiter (1961, p. 221) states that "The pronounced baroclinity in the lower troposphere is probably the reason the polar front jet stream was discovered first...." (The term "polar front jet" (PFJ) may be somewhat misleading. Djuric states the polar front is routinely used to separate air masses of different properties and that the terms "polar" and "tropical" are used to describe the different *sides* of the front, not the air masses themselves.)

The subtropical jet stream (STJ) was first encountered during the Second World War when Allied air-crews ran into "...head-winds commensurate with their airspeed." (Reiter 1961, p. 2) during the bombing campaign against the Japanese mainland. Study of the both the polar and subtropical jet streams advanced during the 1950s after a more elaborate world-wide rawinsonde network was established.

Palmen (1951) proposed a simple meridional circulation model for the general circulation of the atmosphere in winter (Fig. 1). He believed that the earth's energy balance was maintained by the Hadley cell in the tropics and by transient disturbances to the north. His Northern Hemisphere winter model shows a thermal equator near 0°N, with the rising air turning to the north and beginning to descend near 27°N.

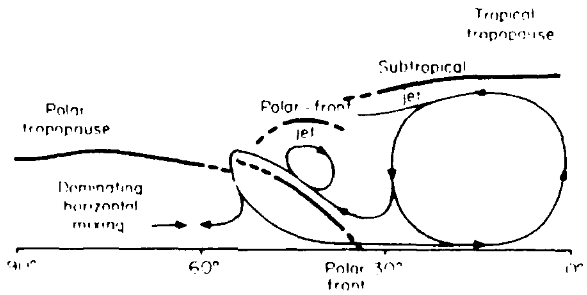


FIG. 1. The Palmen mean winter meridional circulation model, showing principal tropopauses and jet streams. (After Palmen, 1951).

Palmen theorized that the northward transfer of equatorial momentum, in conjunction with the upper-level baroclinity caused by the clash of tropical Hadley cell /mid-latitude Ferrel cell air masses was the justification for the existence of the westerly subtropical jet stream, whereas the polar jet was associated with the baroclinity and momentum transfer in the vicinity of the polar front.

With respect to description of the upward branch of the Hadley cell, Rasmusson (1990, p. 13) points out that time-averaged tropical precipitation regimes are the sum of the contributions of individual cloud clusters. When zonally averaged, the upward mass transport by the convective systems "constitutes the upward mass flux of the Hadley cell."

Sadler (1975) charted values of wind speed for standard reporting levels around the earth, between 50°S and 50°N latitude. The source data were from averaged RAWINs and

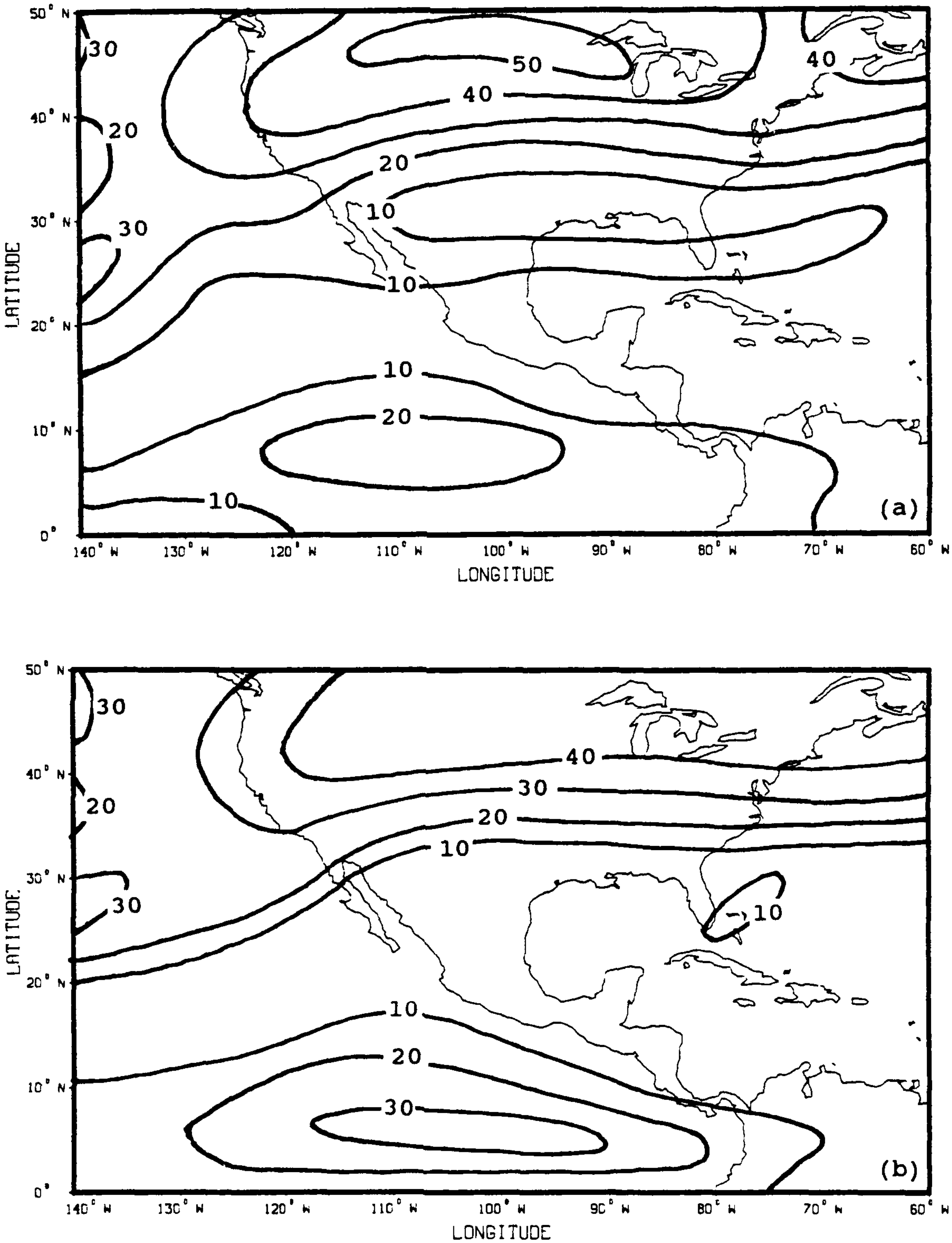


FIG. 2. Average Northern Hemisphere 200 mb winds during: (a) July; (b) August. Heavy solid lines: wind speed (kt). (After Sadler, 1975).

pilot reports taken during the period 1960-1973. A Northern Hemisphere 200 mb chart for the month of July (Fig. 2a) shows some of his results. Two branches of wind maxima are seen in the eastern Pacific (with a gap between). There is a single broad jet with a maximum of 50 kt along the United States/Canada border, with speeds decreasing southward to less than 10 kt along the Gulf Coast.

Fig. 2b, the August Northern Hemisphere 200 mb chart, shows likewise, double jets in the eastern Pacific, and a single speed maximum (40 kt) along the central United States/Canada border, slowing to less than 10 kt along the Gulf Coast.

Hoskins et al. (1989), based on ECMWF model analyses for the period 1979-1989, show similar summertime jet locations, but with much lower average speeds. In the June-July-August 250 mb wind speed analysis (Fig. 3), a 15 m s^{-1} isotach is nearly continuous around the Northern Hemisphere, centered at about 40° N. There are tributaries (5 m s^{-1}) in both the east-central Pacific and east-central Atlantic, in both cases feeding into the primary jet axis from the south. Over North America, the area enclosed by the 15 m s^{-1} isotach averages about 1600 km in width.

The ECMWF model shows vertical sections of the average zonal components of wind (u) in Fig.4. During summer (Fig. 4c), a 20 m s^{-1} isotach is centered at about 42°N at 200 mb. In the same diagram, a slight indication of another jet,

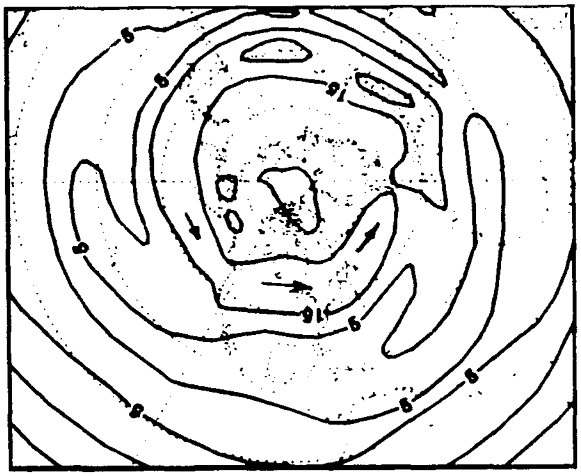


FIG. 3. Average Northern Hemisphere wind speed at 250 mb for June-July-August (m s^{-1}). (After Hoskins et al., 1989).

poleward of the primary axis, is seen in the kink of the 5 m s^{-1} isotach at 71° N. The ECMWF winter, spring, and fall analyses (Figs. 4a, 4b, and 4d) show no such kink.

The ECMWF zonally averaged meridional circulation charts for winter, spring, and fall, (Figs. 5a, 5b, 5d), agree well with the Palmen (1951) model described previously. The June-July-August chart (Fig. 5c), however, shows a strong Southern Hemisphere Hadley cell with a barely discernible Northern Hemisphere Hadley cell.

Oort and Rasmusson (1971) found a Northern Hemisphere Hadley circulation (Fig. 6) oriented similarly to the ECMWF summer chart. A five-year average stream-function of summer meridional circulation shows that the latitude of maximum upward vertical motion occurs just north of the Equator, with flow turning to the south above the 300 mb level.

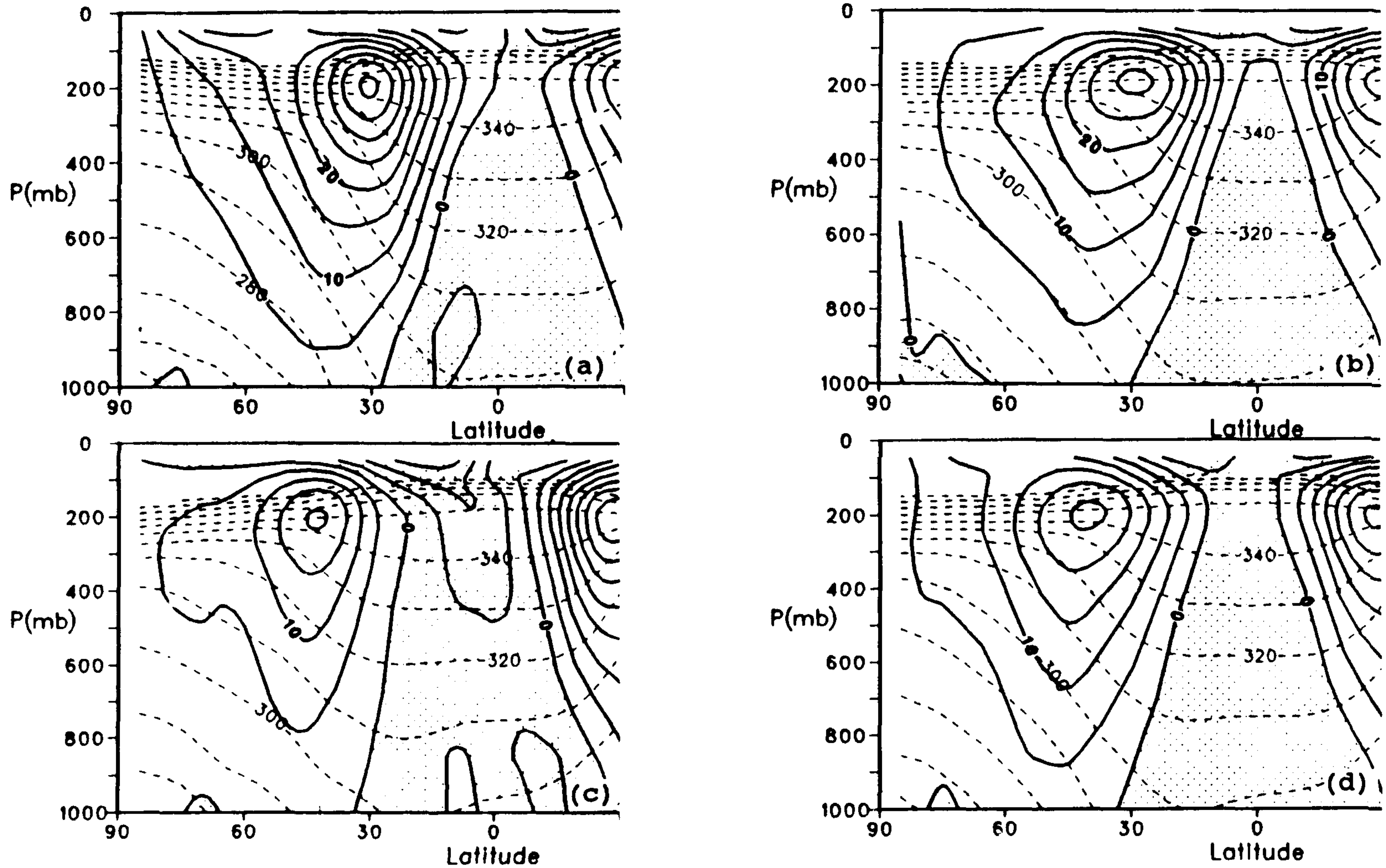


FIG. 4. Hemispheric zonally averaged u (m s^{-1}) and potential temperature (K) between 90°N and 30°S during: (a) December-January-February (b) March-April-May; (c) June-July-August; (d) September-October-November. (u contour increment 5 m s^{-1}; θ contour increment 5 K). (After Hoskins et al. 1989).

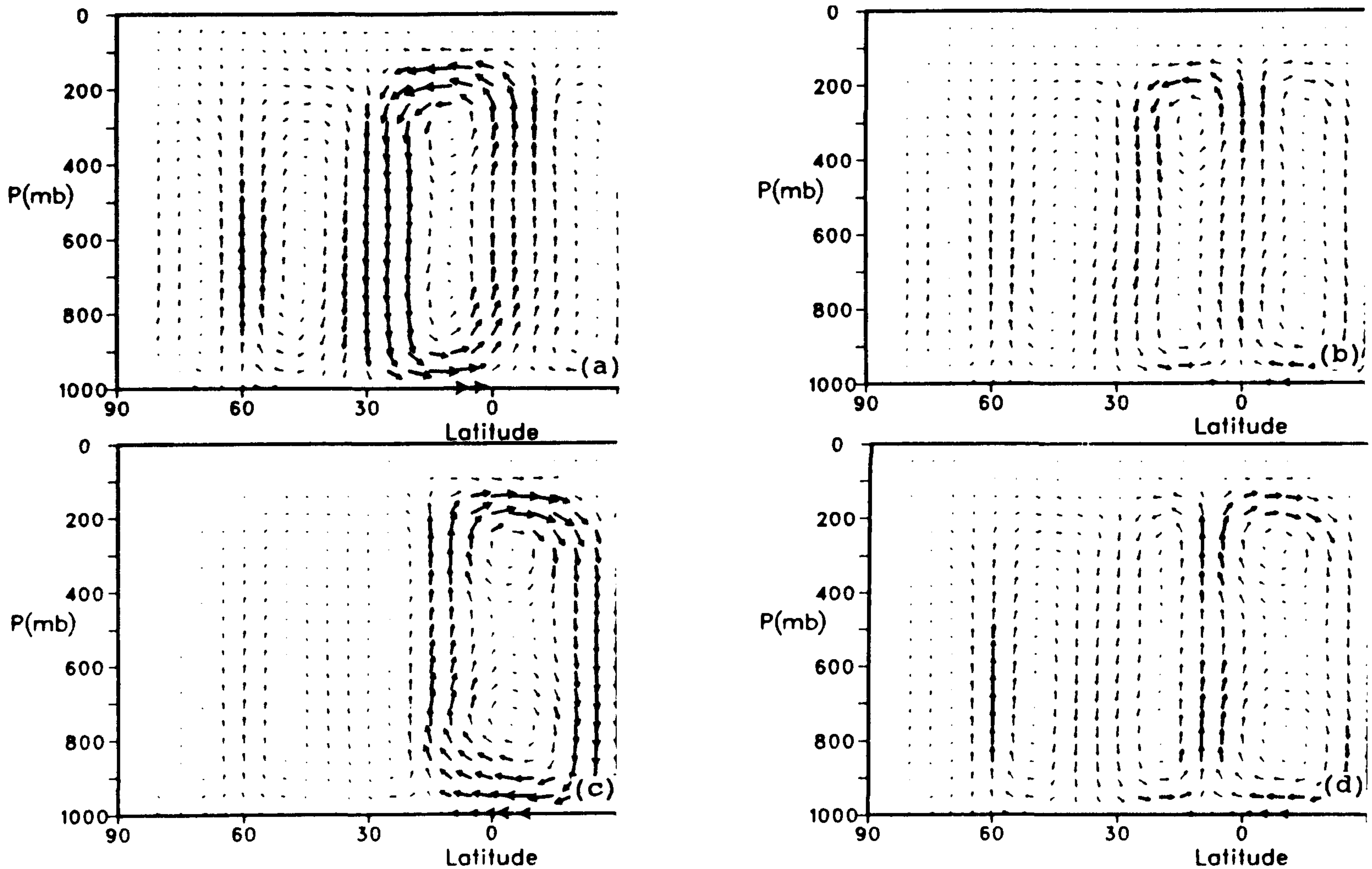


FIG. 5. Hemispheric zonally averaged meridional circulation between 90°N and 30°S during: (a) December-January-February; (b) March-April-May; (c) June-July-August; (d) September-October-November. (After Hoskins et al. 1989).

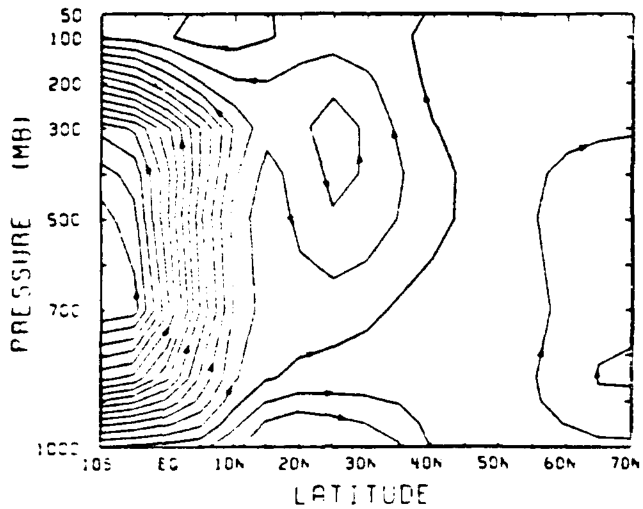


FIG. 6. Five-year stream-function of summer circulation. Contour interval: 7.5 X 10^{16} m^2 s Pa. (After Oort and Rasmusson, 1971).

Lindzen (1991) says that the circulation of the winter Hadley cell is much stronger than that of the summer cell. Comparing average Northern Hemisphere jet location in the winter to the summer location, he states that with no effective Hadley flux (summer) the average jet location occurs at 40° N. When Hadley flux is strong (winter), the average jet location is at 30°N.

Applying Palmen's momentum/heat transfer theory during Northern Hemisphere summer, the strongest westerly Hadley (subtropical) jet should occur in the Southern Hemisphere, centered at about 26°S, with an extremely weak, nonexistent or possibly even easterly subtropical jet in the Northern Hemisphere. This is shown in Figs. 7a (after Mechoso, et al., 1985), and 7b (after Mintz, 1948). Thus the argument is made that over North America, during summer, there should be only one jet stream - the polar front jet.

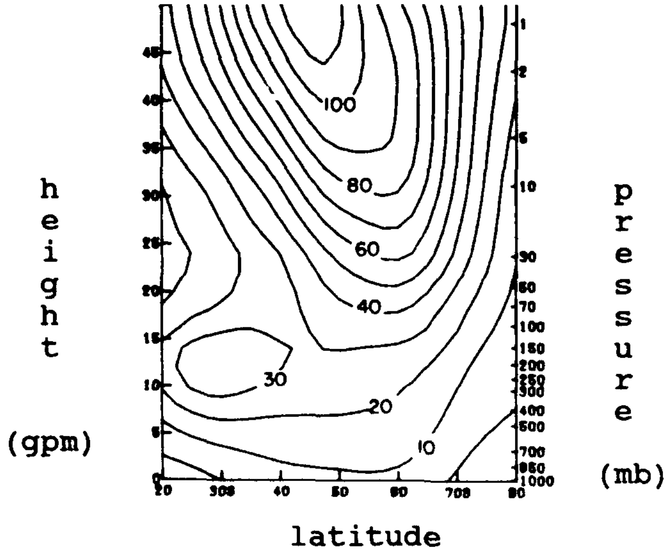
With respect to the transition periods from a single to a multiple jet regime, Reiter (1961, p. 161) states:

> Since, during a high-index stage, the meridional exchange of heat and momentum is impeded, it may be understood at least qualitatively, that during such a circulation stage, vorticity as well as positive (negative) heat energy will be stored in subtropical (polar) regions. This leads to acceleration of zonal circulation until a critical value is reached, which brings about a breakdown of the circulation. A low-index stage will then be established with increased meridional exchange.

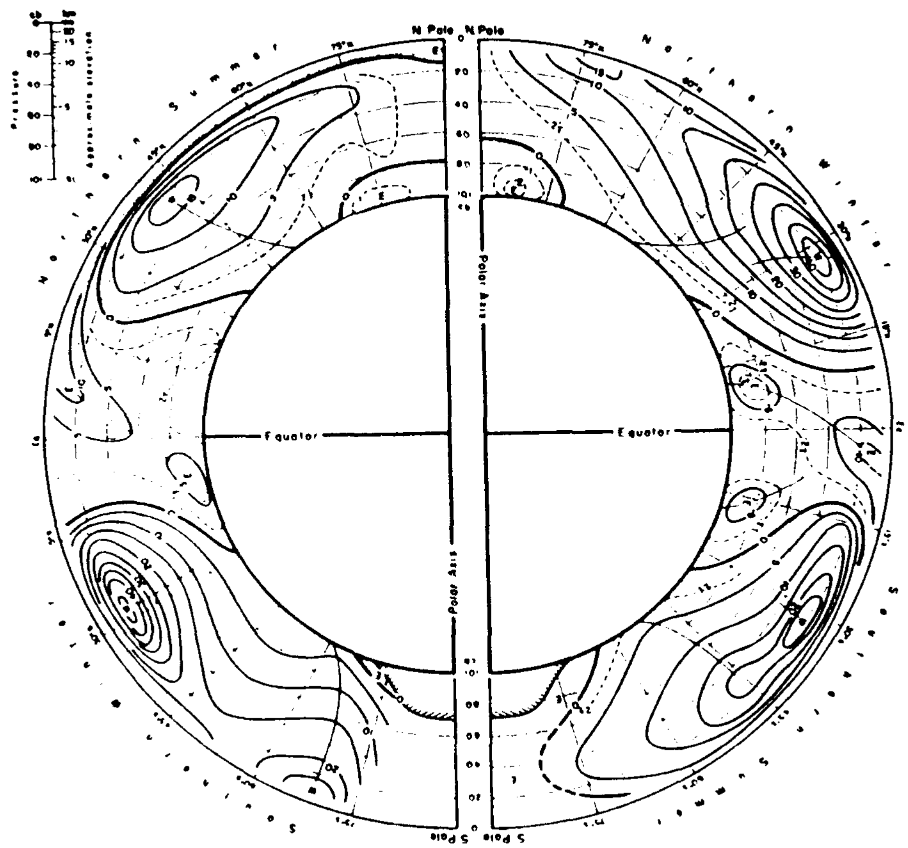
At that time, the existence of jets about the eddies, together with the primary jet could show what appears to be multiple jet stream regime.

Various authors have attempted to show differences between the polar front jet and the subtropical jet stream. Some of the differences described include the following:

1. Location and permanence. The subtropical jet is considered to be a more constant feature of the general circulation with respect to location than the polar



a.



b.

Fig. 7. Average zonal wind during July (m s^{-1}) in: (a) the Southern Hemisphere. (After Mechoso et al., 1985); (b) both hemispheres. (After Mintz, 1948).

jet,because the latter migrates with the polar front (Reiter, 1967, p. 232).

2. Speed. Highest observed jet stream winds occur in the subtropical jet stream during the winter season. Both Reiter (1967, p. 8) and Palmen and Newton (1969, p. 212) quote observed winter season subtropical jet speeds in excess of 200 kt.

3. Depth of atmosphere through which the jet exists. The subtropical jet, believed to be the result of upper level baroclinity and poleward export of angular momentum, is commonly described as a shallow feature, the primary vertical wind shear zone often less than 100 mb deep. The polar front jet, on the other hand, is usually observed through a significantly greater depth of the atmosphere, commonly to below 500 mb. As a consequence, the aspect (width-to-height) ratio of the subtropical jet is greater than that of the polar front jet (Palmen and Newton, 1969, p. 212; Reiter, 1967, p. 222).

4. Height of the jet core. Height varies somewhat with season but the subtropical jet core is usually found at and above 200 mb (Reiter, 1969, p. 224), in keeping with the increased height of the tropopause in the tropics. The polar front jet core is commonly located at the 300 mb or 250 mb level.

5. Potential vorticity signatures. Jet streams commonly occur adjacent to the breaks in the tropopause.

Since stratospheric air commonly has much higher potential vorticity than tropospheric air, several studies (described in a later chapter) have used potential vorticity analyses to identify the tropopause. Knowledge of the level of the tropopause break should assist in describing which jet stream is present (Reiter, 1967, p. 97).

6. Jet cirrus signatures. The high tropospheric clouds that occur in the vicinity of the polar front jet usually have their axes collinear with the jet axis. The high clouds near the subtropical jet are commonly observed arrayed in bands transverse to that jet's axis, especially in winter.

If multiple jet streams are observed, the above characteristics will be used to attempt to describe them as polar front jets or subtropical jet streams.

CHAPTER III

THE NUMBER OF JETS OVER NORTH AMERICA DURING SUMMER 1988

A. Data

The National Center for Atmospheric Research (NCAR) provided National Meteorological Center (NMC) global gridded analyses used in this study. The period was July and August 1988, with observation sets daily at 0000 and 1200 UTC. The source data for the NMC analyses were surface observations, radiosondes, pilot balloons, pilot reports, satellite derived wind data, and satellite vertical temperature profiles.

The data set was complete for the 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, and 70 mb pressure levels, at 2.5 ° longitude and latitude spacing. It consisted of the following meteorological elements:

u - zonal wind component [m s^{-1}]

v - meridional wind component [m s^{-1}]

RH - relative humidity [%]

T - temperature [K]

Z - Height [gpm]

B. Jet Count

Jet streams were counted along meridians, at 10° intervals, on the individual, twice-daily upper-level (250, 200, and 150 mb) charts to see if there were a "favored" number of jets at different longitudes, during the observation period. The following routine was used:

1. Only areas of wind speed greater than or equal to 25 m s^{-1} *and* over 1000 km in length were counted. (The decrease of latitudinal degree length approaching the pole was taken into account.) No jets were counted if they occurred north of 80° N, nor were any temporal qualifications applied.

2. Counting was done along meridians because zonal elongation of isotach maxima was usually greater than meridional.

3. Care was taken to record occurrences of eddies cutting off from the primary *axis of* the jet. Existence of eddies was established with the aid of geopotential height fields (contoured at 100 gpm intervals) from the same level. If a zonal jet and an eddy jet were observed along a single meridian, each was considered a separate jet stream. An eddy jet was counted if the height chart showed at least one closed contour around the eddy, *and* local wind speed about the eddy met the criteria under 1. above.

4. When confluent (diffluent) branching of the jet stream was observed, each branch was considered a separate jet stream if the length of the branch itself was at least 1000 km, upstream (downstream) from the confluent (diffluent) area. Vector winds plotted with the isotachs

showed where branches merged (split).

After all the charts of a particular pressure surface were analyzed, the number: none; one; or more than one jet stream was counted on each meridian and the results recorded. Tables 1-3 summarize jet count findings.

Jet Count Summary by Month and Season

The tables indicate that July 1988 was a "one jet" month, while during August 1988 there were many more double jet occurrences (with the exception that the August 60°W longitude band still showed preference for a single jet stream). Palmen (1969, p. 76) noted:

> These two wind systems (polar and subtropical jet streams) most nearly touch each other at the longitude of the semi-permanent troughs of the mid-latitude westerlies where they are close enough together to appear as one maximum when averaged over a large number of situations.

Jet count was lower at 150 mb than at 250 or 200 mb. North of the sub-tropics the 150 mb level is in the stratosphere where wind speeds decrease upward from the jet speed winds near the tropopause. It should be noted however that even though the 150 mb count was lower, there were still more multiple jet stream observations during August than

Table 1. Summary of the number of upper tropospheric jet streams observed over North America during July 1988.

250 mb - July, 1988

Longitude	130	120	110	100	90	80	70	60
No jets	6	3	4	4	4	6	2	3
One jet	49	51	49	43	39	37	36	44
Eddy	3	1	0	0	3	5	6	6
One jet with eddy	0	0	0	0	0	4	5	2
Two jets	4	7	9	15	16	9	12	7
Two jets with eddy	0	0	0	0	0	1	1	0
Three jets	0	0	0	0	0	0	0	0
Total	62	62	62	62	62	62	62	62

200 mb - July, 1988

Longitude	130	120	110	100	90	80	70	60
No jets	4	2	6	6	5	4	0	0
One jet	52	51	45	44	44	42	45	49
Eddy	1	1	0	0	0	3	4	4
One jet with eddy	0	0	0	0	0	3	6	7
Two jets	5	8	11	12	13	10	6	1
Two jets with eddy	0	0	0	0	0	0	1	1
Three jets	0	0	0	0	0	0	0	0
Total	62	62	62	62	62	62	62	62

150 mb - July, 1988

Longitude	130	120	110	100	90	80	70	60
No jets	20	18	19	25	21	10	5	11
One jet	42	44	43	36	39	49	54	50
Eddy	0	0	0	0	0	1	1	1
One jet with eddy	0	0	0	0	0	0	0	0
Two jets	0	0	0	1	2	2	2	0
Two jets with eddy	0	0	0	0	0	0	0	0
Three jets	0	0	0	0	0	0	0	0
Total	62	62	62	62	62	62	62	62

Table 2. Summary of the number of upper tropospheric jet streams observed over North America during August 1988.

250 mb - August, 1988

Longitude	130	120	110	100	90	80	70	60
No jets	0	0	0	0	0	0	1	0
One jet	24	13	9	12	9	8	17	37
Eddy	2	2	0	0	0	2	1	1
One jet with eddy	2	3	5	5	11	10	6	4
Two jets	29	37	38	38	36	36	32	16
Two jets with eddy	2	3	5	5	2	4	3	2
Three jets	3	4	5	2	4	2	2	2
Total	62	62	62	62	62	62	62	62

200 mb - August, 1988

Longitude	130	120	110	100	90	80	70	60
No jets	1	0	1	1	0	0	1	4
One jet	31	26	14	15	18	18	27	38
Eddy	0	0	0	0	0	0	0	0
One jet with eddy	3	2	4	4	6	8	6	5
Two jets	24	30	37	39	37	35	28	15
Two jets with eddy	0	1	0	1	0	0	0	0
Three jets	3	3	6	2	1	1	0	0
Total	62	62	62	62	62	62	62	62

150 mb - August, 1988

Longitude	130	120	110	100	90	80	70	60
No jets	33	21	12	7	3	3	5	11
One jet	27	33	37	37	47	48	49	49
Eddy	0	2	0	0	0	0	0	0
One jet with eddy	1	5	8	6	3	2	1	0
Two jets	1	1	5	12	9	9	7	2
Two jets with eddy	0	0	0	0	0	0	0	0
Three jets	0	0	0	0	0	0	0	0
Total	62	62	62	62	62	62	62	62

Table 3. Summary of the number of upper topopspheric jet streams observed over North America during summer 1988.

250 mb - July and August, 1988

Longitude	130	120	110	100	90	80	70	60
No jets	8	6	5	4	5	7	3	3
One jet	71	57	55	61	60	54	69	93
Eddy	7	7	3	3	4	2	1	1
One jet with eddy	2	2	4	2	1	4	7	4
Two jets	31	45	49	47	49	52	38	21
Two jets with eddy	0	0	0	0	0	0	0	0
Three jets	5	7	8	7	5	5	6	2
Total	124	124	124	124	124	124	124	124

200 mb - July and August, 1988

Longitude	130	120	110	100	90	80	70	60
No jets	5	2	7	7	5	4	1	4
One jet	83	77	59	59	62	60	72	87
Eddy	1	1	0	0	0	3	4	4
One jet with eddy	3	2	4	4	6	11	12	12
Two jets	29	38	48	51	50	45	34	16
Two jets with eddy	0	1	0	1	0	0	1	1
Three jets	3	3	6	2	1	1	0	0
Total	124	124	124	124	124	124	124	124

150 mb - July and August, 1988

Longitude	130	120	110	100	90	80	70	60
No jets	53	39	31	32	24	13	10	22
One jet	69	77	80	73	86	97	103	99
Eddy	0	2	0	0	0	1	1	1
One jet with eddy	1	5	8	6	3	2	1	0
Two jets	1	1	5	13	11	11	9	2
Two jets with eddy	0	0	0	0	0	0	0	0
Three jets	0	0	0	0	0	0	0	0
Total	124	124	124	124	124	124	124	124

during July.

Table 3 indicates that during summer 1988, taken as a whole, a single jet regime was clearly favored at 130°W, 70°W and 60°W, at both 250 mb and 200 mb, with the other longitudes showing nearly as many two jet occurrences as single jets. Jet count analyses for the individual months showed considerably different results.

CHAPTER IV

DESCRIPTION OF THE SUMMER 1988 JET STREAM

The 250, 200, and 150 mb pressure levels during summer 1988 were then analyzed for maximum and average wind speed and the number of occurrences of wind speeds in excess of the defined threshold (25 m s^{-1}).

A. Maximum Speed

This analysis was performed to test the adequacy of the chosen threshold jet stream speed. During July, the highest observed upper tropospheric wind speeds were observed at the 250 mb level (67 *m* s^{-1}), with maximum observed wind speeds lower above that level. Fig. 8 shows the July 250 mb maximum wind chart.

During August, highest observed speed was nearly the same at 250 and 200 mb (Fig. 9), with the speed again slower at the 150 mb level.

The selection of the 25 m s^{-1} threshold for jet definition was considered satisfactory because, in both July and August the maximum observed wind speed at each analysis level was at least twice the chosen threshold.

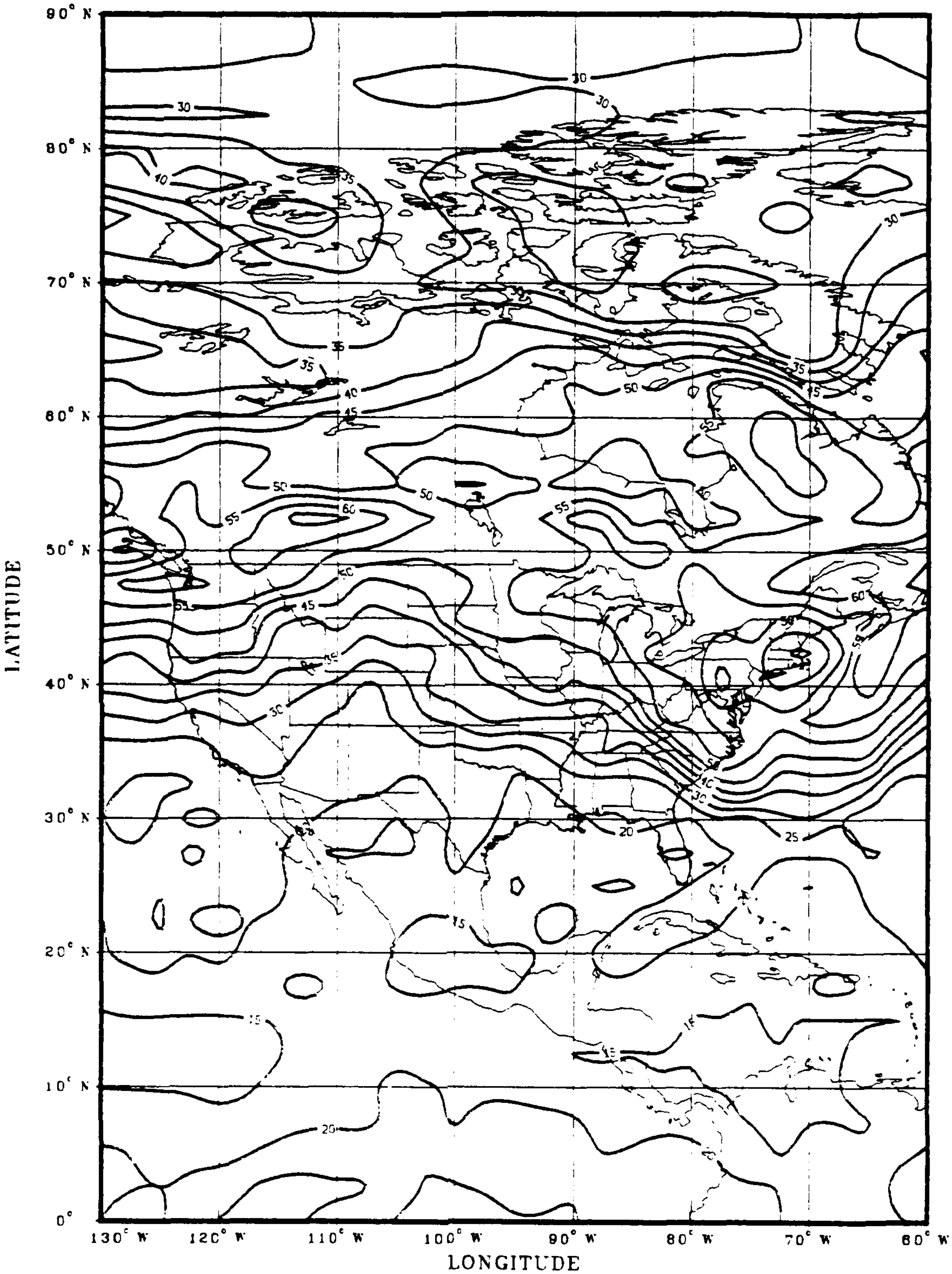


FIG. 8. Maximum analyzed wind speed at 250 mb at each grid point during July 1988 (m s^{-1}). Contour increment: 5 m s^{-1}.

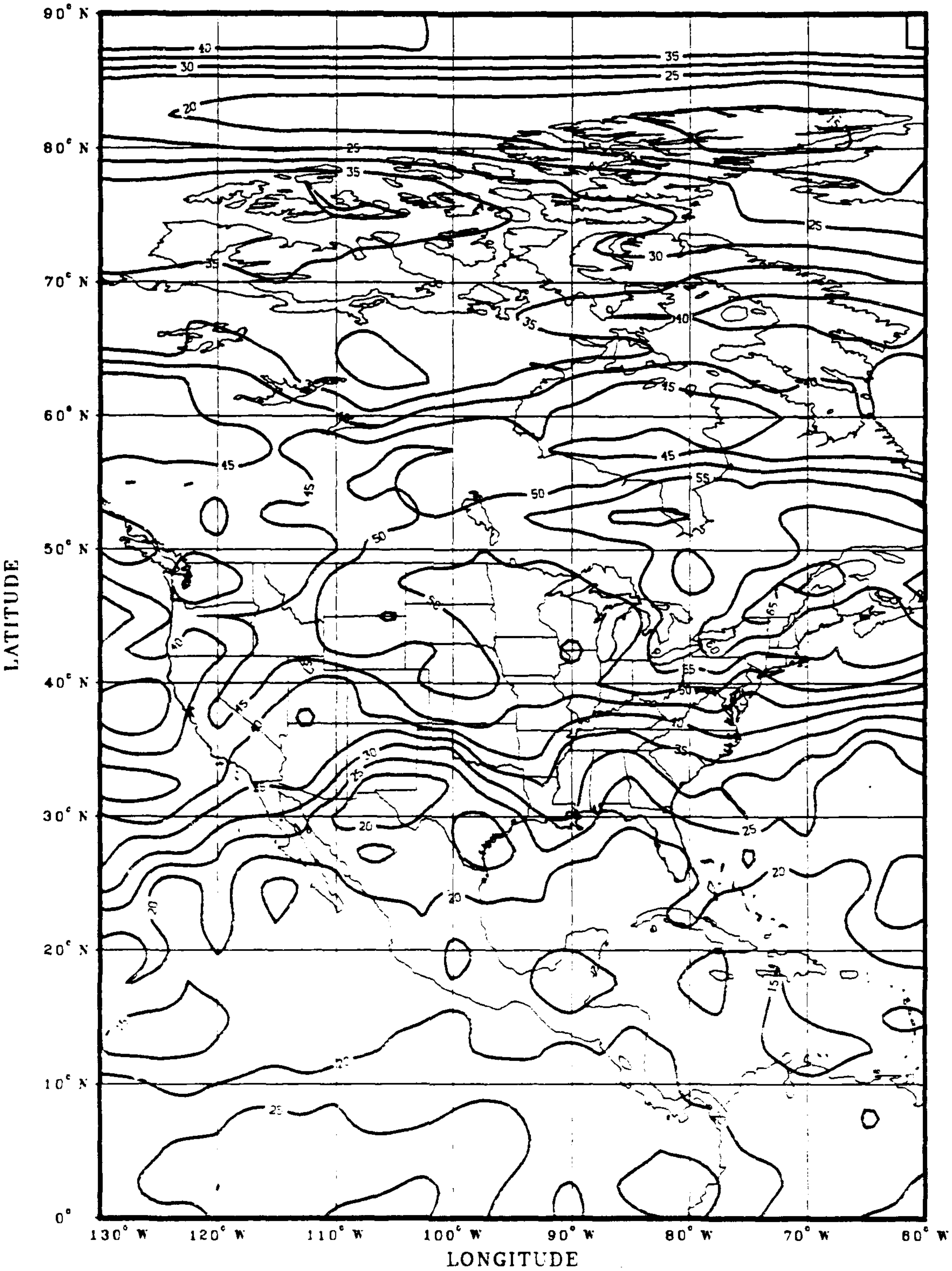


FIG. 9. Maximum analyzed wind speed at 200 mb at each grid point during August 1988 (m s^{-1}). Contour increment: 5 m s^{-1}.

B. Average Speed

Averaging the observed wind speeds at specified pressure levels was performed to identify those areas where higher wind speeds were most often located. In addition, the average upper level winds during summer 1988 could be compared to previous studies, noting similarities and differences.

July average 250 mb wind speed (Fig. 10) shows the jet occurring as a broad band near the U.S/Canada border, with a slight anticyclonic bend (Based on wind vector orientation) between Pacific and Atlantic Coasts. Maxima of the July 250 mb averages are seen in the 30 m s^{-1} isotach stretching from Vancouver Island, British Columbia eastward to south central Saskatchewan, and another 30 m s^{-1} isotach from south-central Quebec province, broadening eastward over the Gulf of St Lawrence. The area encompassed by the 25 m s^{-1} average wind isotach occurs from the eastern Pacific eastward, with slight anticyclonic curvature to 49°N, 60°W. This isotach band, about 1000 km in width in the west, broadens to about 1500 km in the east (the broadening due to the eddies and non-zonal jets that occurred more often in the eastern half of the grid domain during July.

The average wind isotachs of the 200 mb and 150 mb (Figs. 11, and 12) jet streams are quite similar in both shape and location, to those at the 250 mb level, with the exception that average speeds decrease at higher pressure

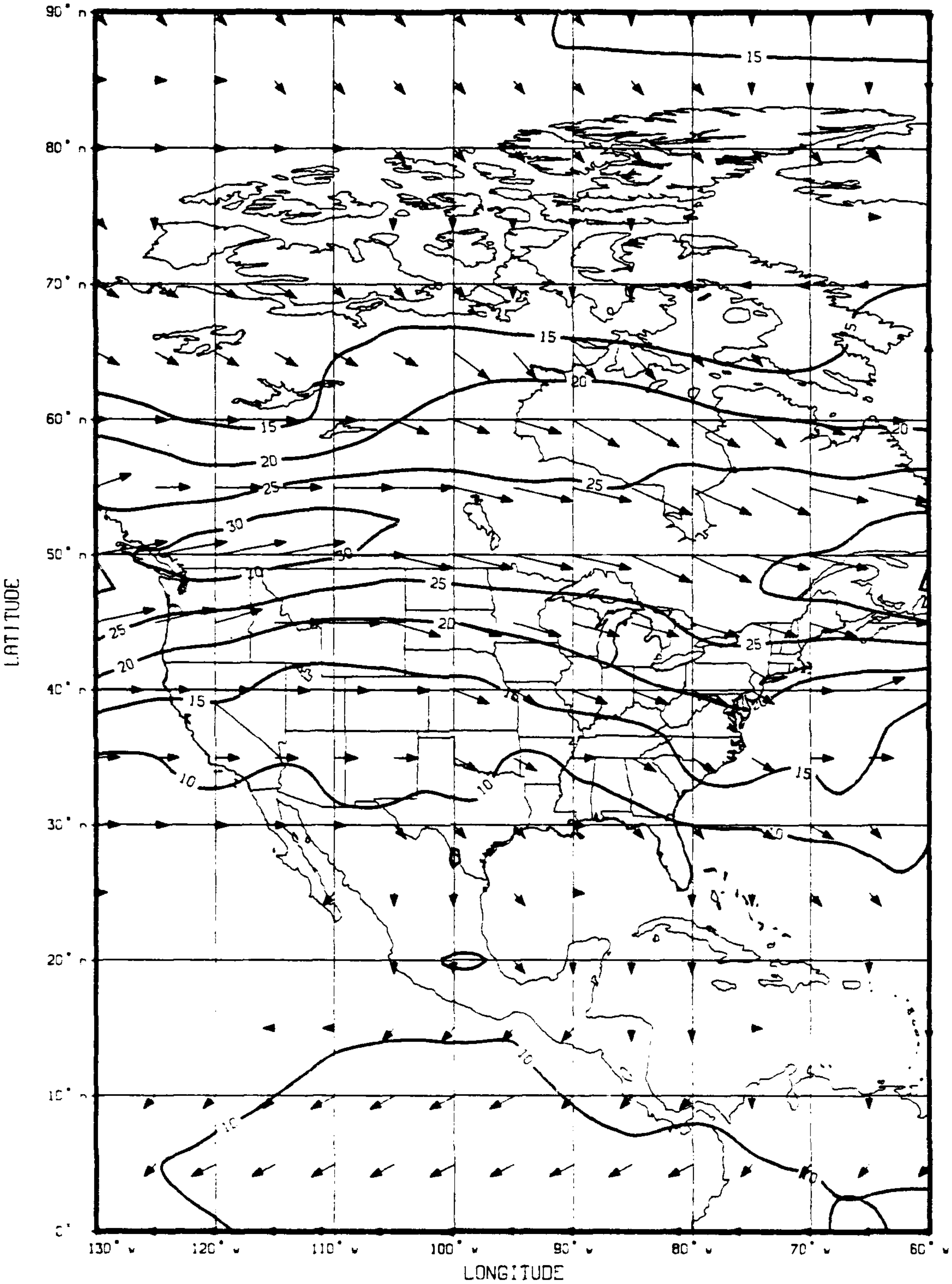


FIG. 10. Average wind speed at 250 mb during July 1988 (m s^{-1}), with average direction denoted by vectors. Speed contour increment: 5 m s^{-1}.

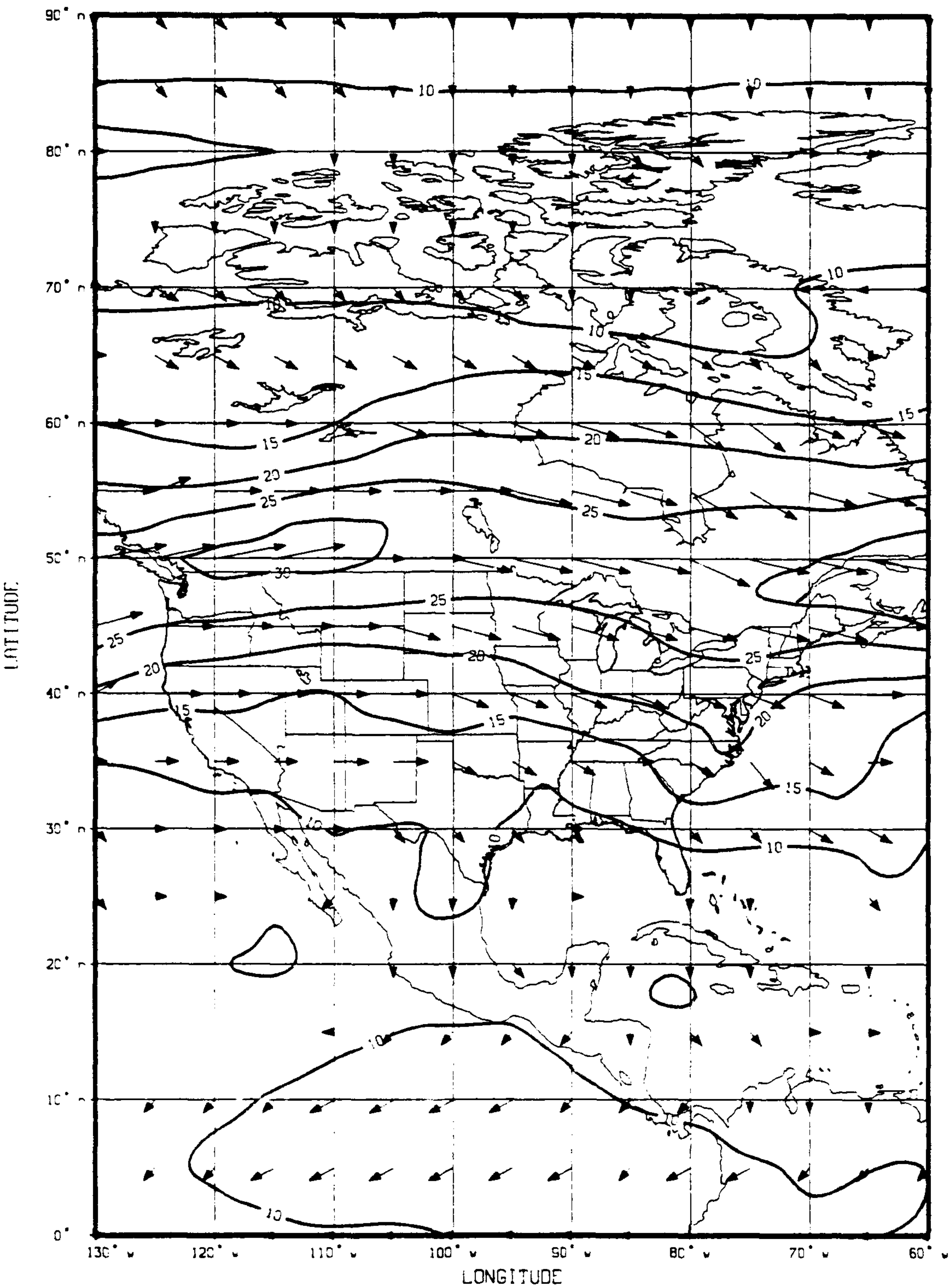


FIG. 11. Average wind speed at 200 mb during July 1988 (m s^{-1}), with average direction denoted by vectors. Speed contour increment: 5 m s^{-1}.

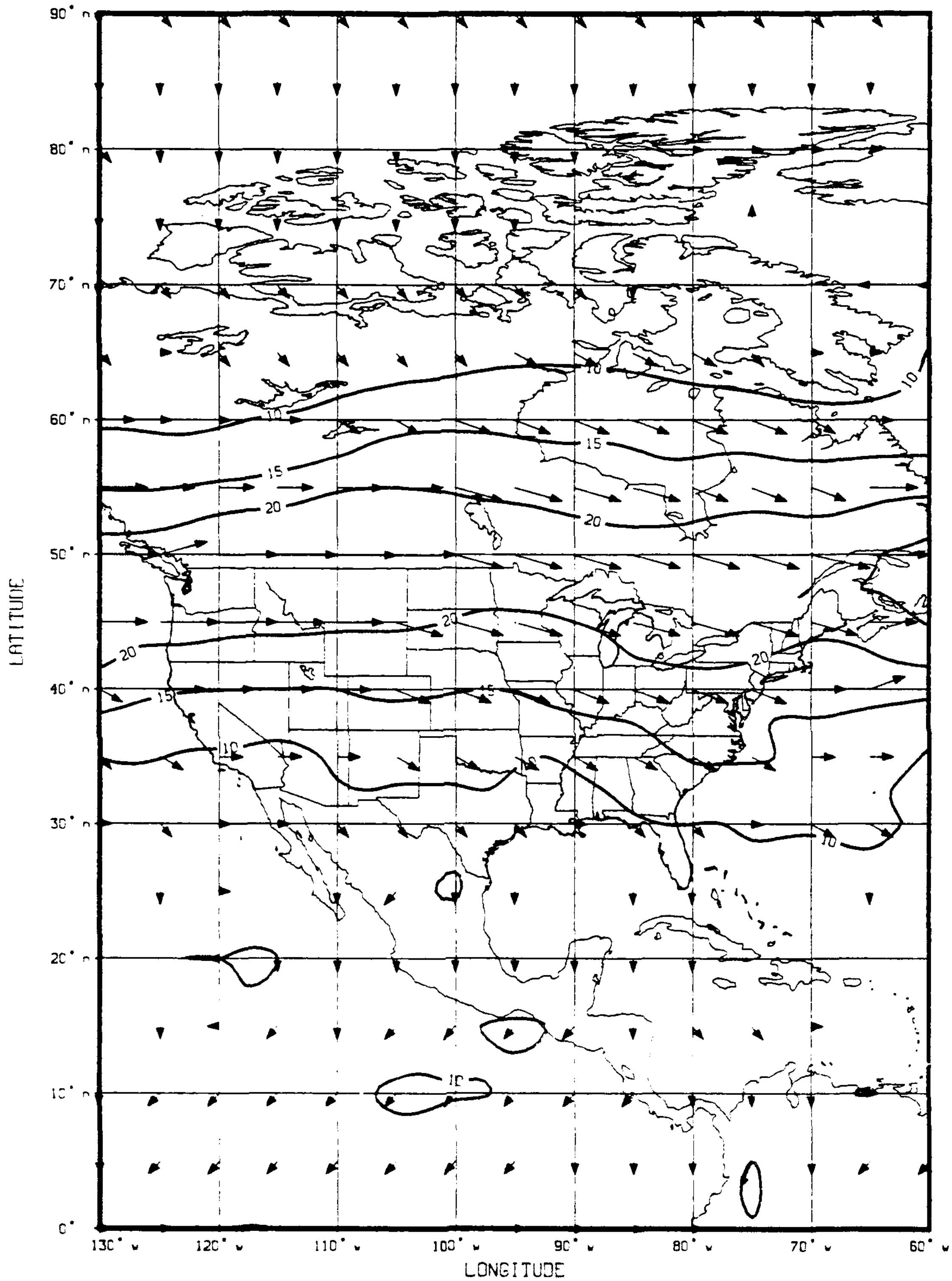


FIG. 12. Average wind speed at 150 mb during July 1988 (m s^{-1}), with average direction denoted by vectors. Speed contour increment: 5 m s^{-1}.

levels.

During August, (Fig. 13), the highest 250 mb average wind speed (30 m s^{-1}) occurred along the Minnesota/Ontario border and in an area from southern Quebec eastward. The 30 m s^{-1} isotach observed in western Canada during July is not seen on the August chart. Instead, the 25 m s^{-1} isotach starts eastward from about 112°W, averaging about 1500 km in width. At 200 mb (Fig. 14), the greatest August average wind occurred in locations similar to those of the 250 mb chart for the same period, with the exception that the 30 m s^{-1} isopleth over the north central United States was larger, oriented differently, and centered farther west.

The 150 mb average August winds (Fig. 15) showed a pattern similar to those of the lower levels with speed lower by about 5 m s^{-1}. The southern jet was slightly more predominant, judging by the shape of the 20 m s^{-1} isotach.

Summary of Jet Stream Average Speeds

The major difference between the average wind fields of July and August is the shape of the third fastest isotach at each level (20 m s^{-1} at 250 mb and 200 mb, and 15 m s^{-1} at 150 mb). During July, these isotachs occur as zonal bands, while in August, there is a split in the on-shore flow pattern in the west, and a broadening of these isotachs in the eastern half, reflecting more variability in jet speed and orientation.

The apparent split jet off the California/Oregon coast

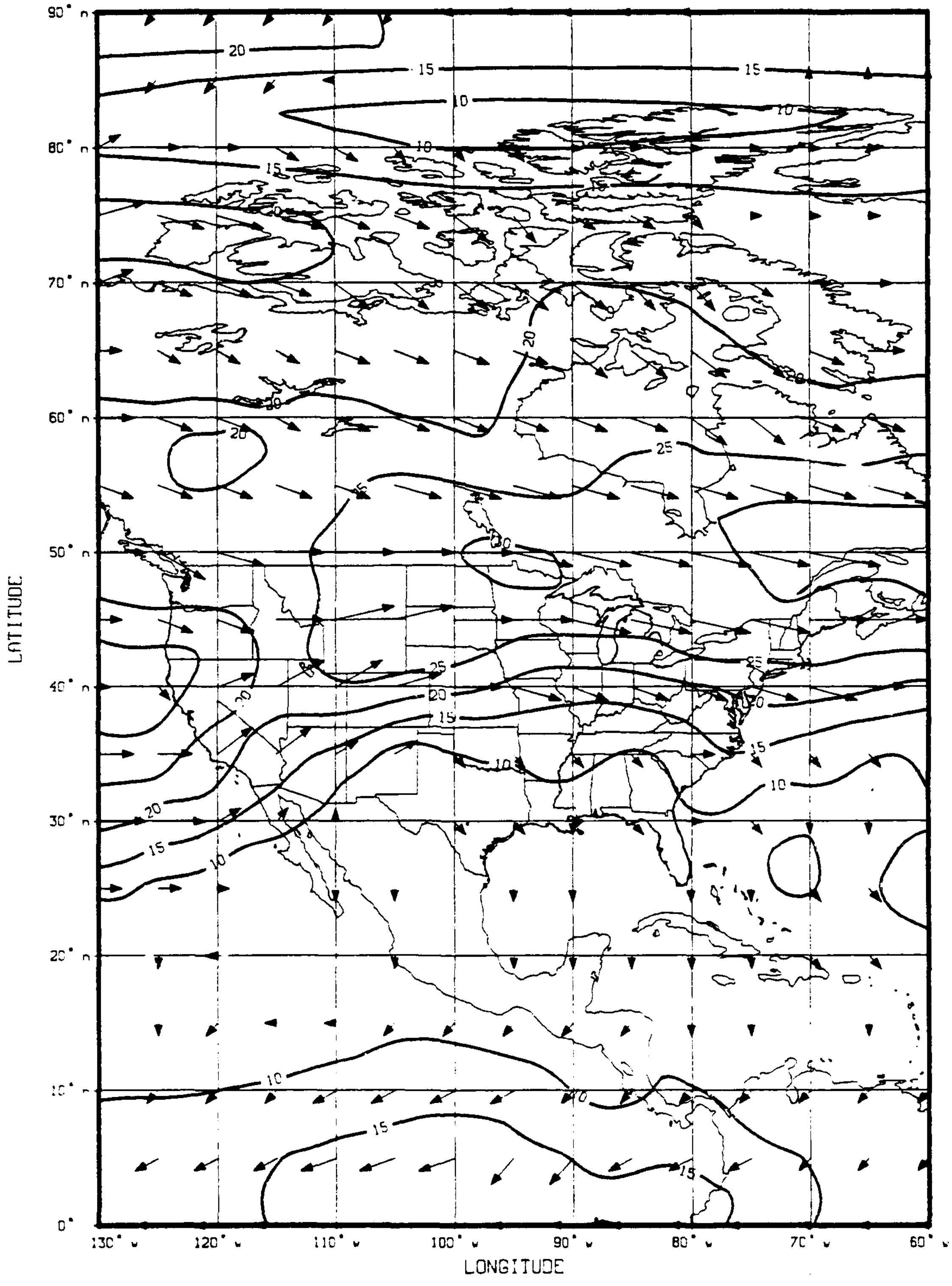


FIG. 13. Average wind speed at 250 mb during August 1988 (m s^{-1}), with average direction denoted by vectors. Speed contour increment: 5 m s^{-1}.

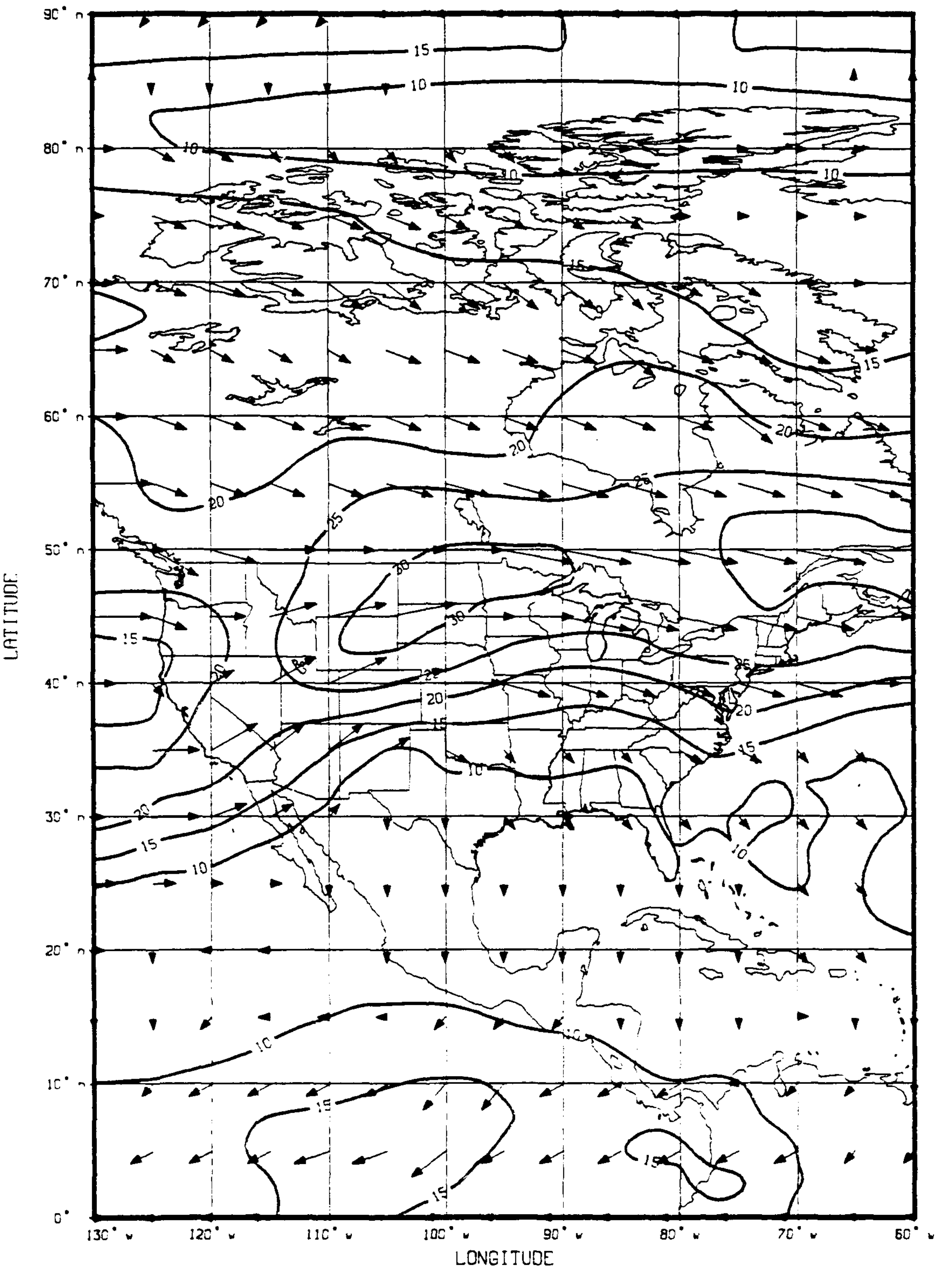


FIG. 14. Average wind speed at 200 mb during August 1988 (m s^{-1}), with average direction denoted by vectors. Speed contour increment: 5 m s^{-1}.

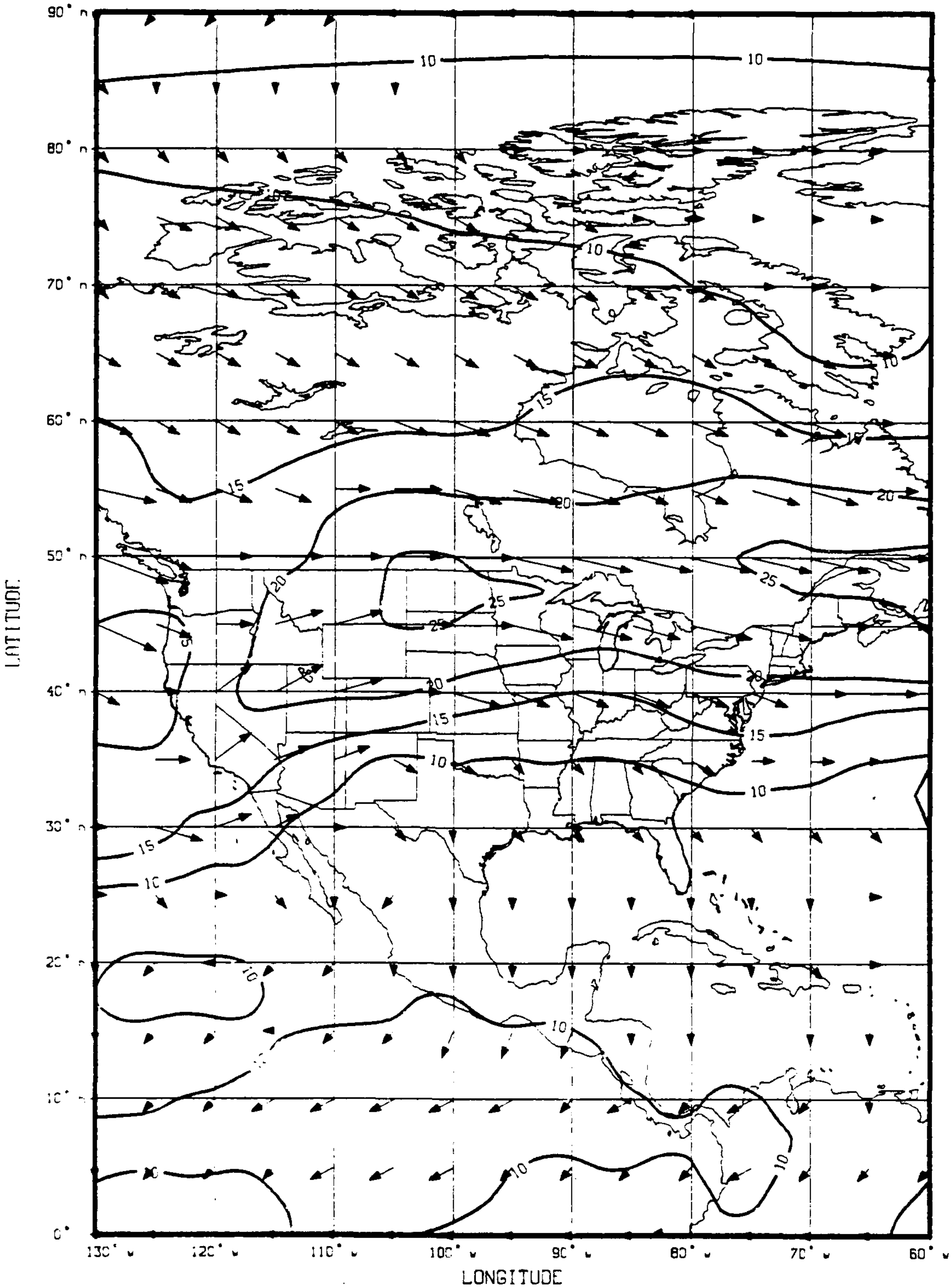


FIG. 15. Average wind speed at 150 mb during August 1988 (m s^{-1}), with average direction denoted by vectors. Speed contour increment: 5 m s^{-1}.

during August (where average wind speed decreases to about 12 m s^{-1}) verifies the double jet structure noted in Chapter III, section B.

The shape and orientation of the August 25 m s^{-1} average wind isotachs west of 110°W show that the two branches were of near equal strength at 250 mb, while the southern branch was apparently stronger at 200 mb. The orientation of the 20 m s^{-1} average wind isopleth at 150 mb shows the southern branch also somewhat stronger at that level. In addition, the map location where the southern branch entered the coast resembled that of the winter-season subtropical jet.

The speed of the southern jets was not however significantly greater than the northern jets. The ability to use relative speeds to describe the jet streams during summer was therefore judged untenable.

In the east, the area enclosed by the 30 m s^{-1} isotach was broader than during the previous month, showing, if not two separate jet streams, at least more variability in a single jet.

The 200 mb July and August average wind speeds were compared to those analyzed by Sadler (1975) (Figs. 2a, and b). In July 1988, the wind distributions compare quite favorably in both speed and isotach shape (anticyclonic over the center of the continent, cyclonic along the Eastern Seaboard.)

During August however, significant differences are observed. Wind speed was higher in August 1988, and the lull over, and off the West Coast is found about 25° farther east than in Sadler's (1975) climatology.

The observed winds, averaged for the entire two-month period (Figs. 16, 17, 18) blur the differences in jet regimes observed during the individual months. At each level analyzed, the highest average winds appear in southeastern Canada. At 250 mb, some evidence of the August double jet structure in the west is seen in the kink of the 15 m s^{-1} isotach west of Santa Barbara, California. This double structure is more apparent at the 200 mb level (with a distinct lull between the branches off the West Coast), but again, is only slightly evident on the 150 mb July-August average wind chart.

The 250 mb wind analysis for the full two month period was compared to the ECMWF analysis (Fig. 3)(Hoskins et al. 1989). Differences were expected for previously described reasons as well as the fact that the ECMWF and NMC analysis schemes differ.

Highest average speeds are considerably greater over North America in this data set than in the ECMWF data. The shape of the southern edge of the 15 m s^{-1} isotach does show a similar kink at 120°W but the width of that isotach was broader during summer 1988 than in the ECMWF analysis.

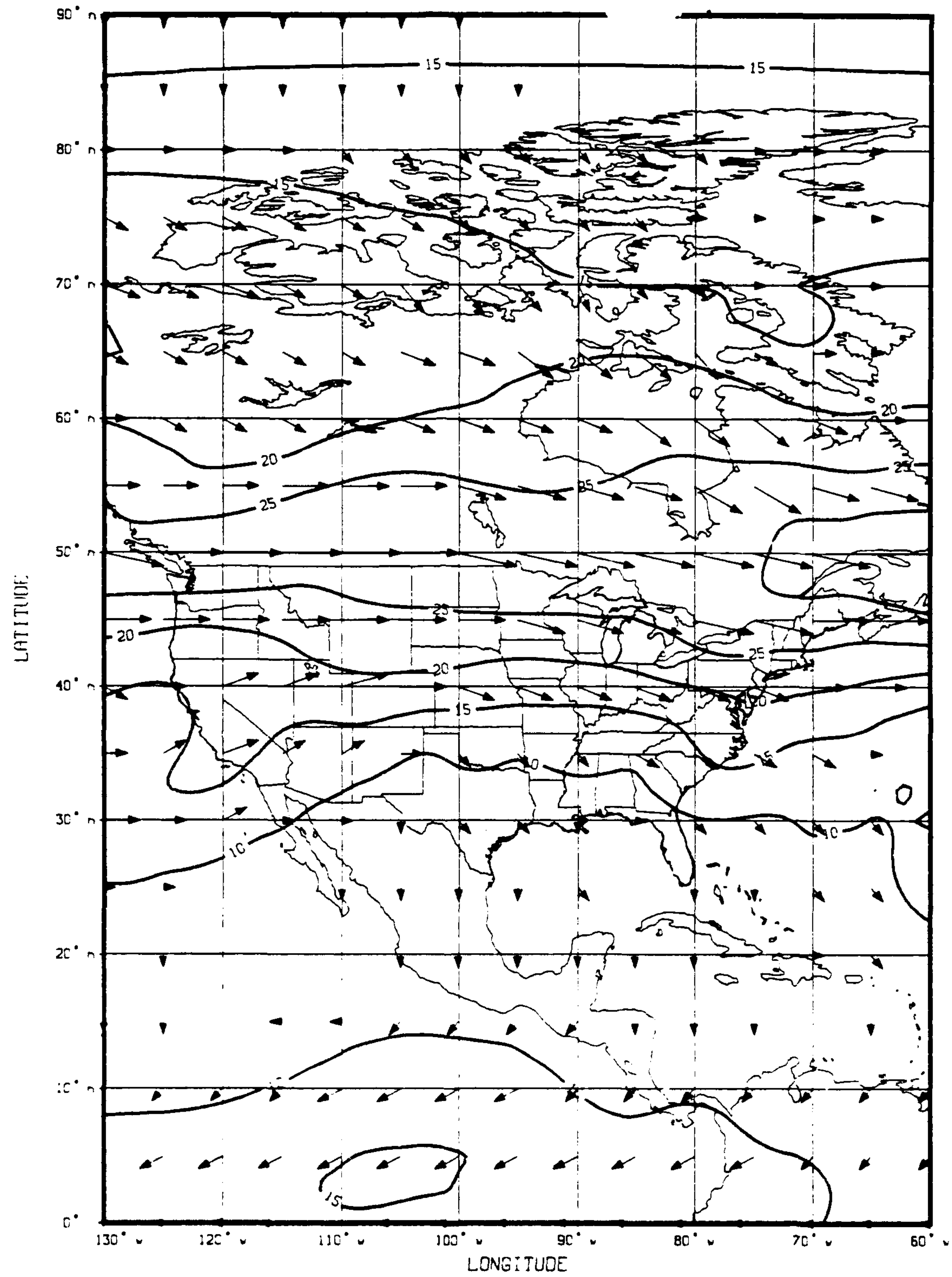


FIG. 16. Average wind speed at 250 mb during summer 1988 (m s^{-1}), with average direction denoted by vectors. Speed contour increment: 5 m s^{-1}.

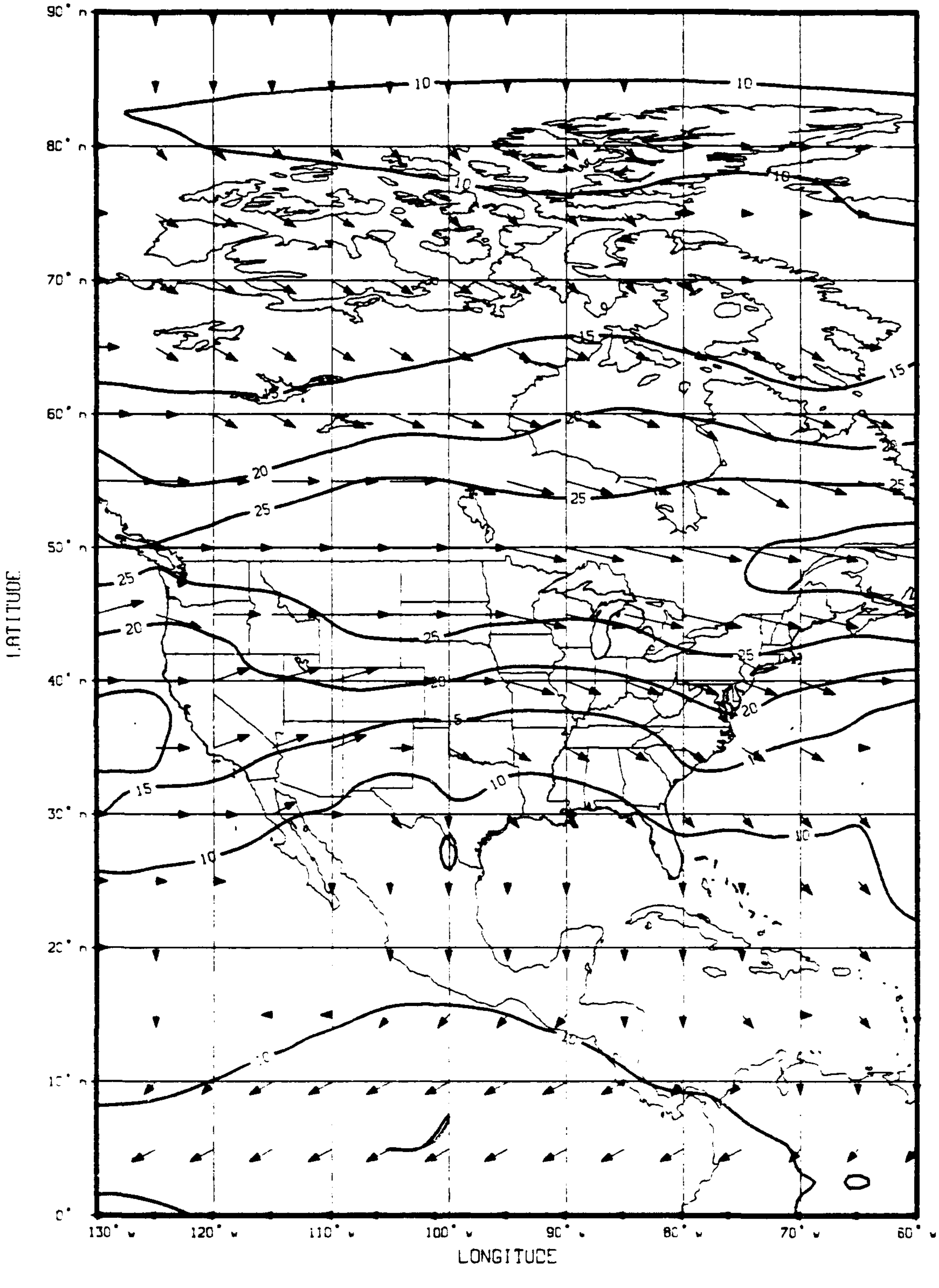


FIG. 17. Average wind speed at 200 mb during summer 1988 (m s^{-1}), with average direction denoted by vectors. Speed contour increment: 5 m s^{-1}.

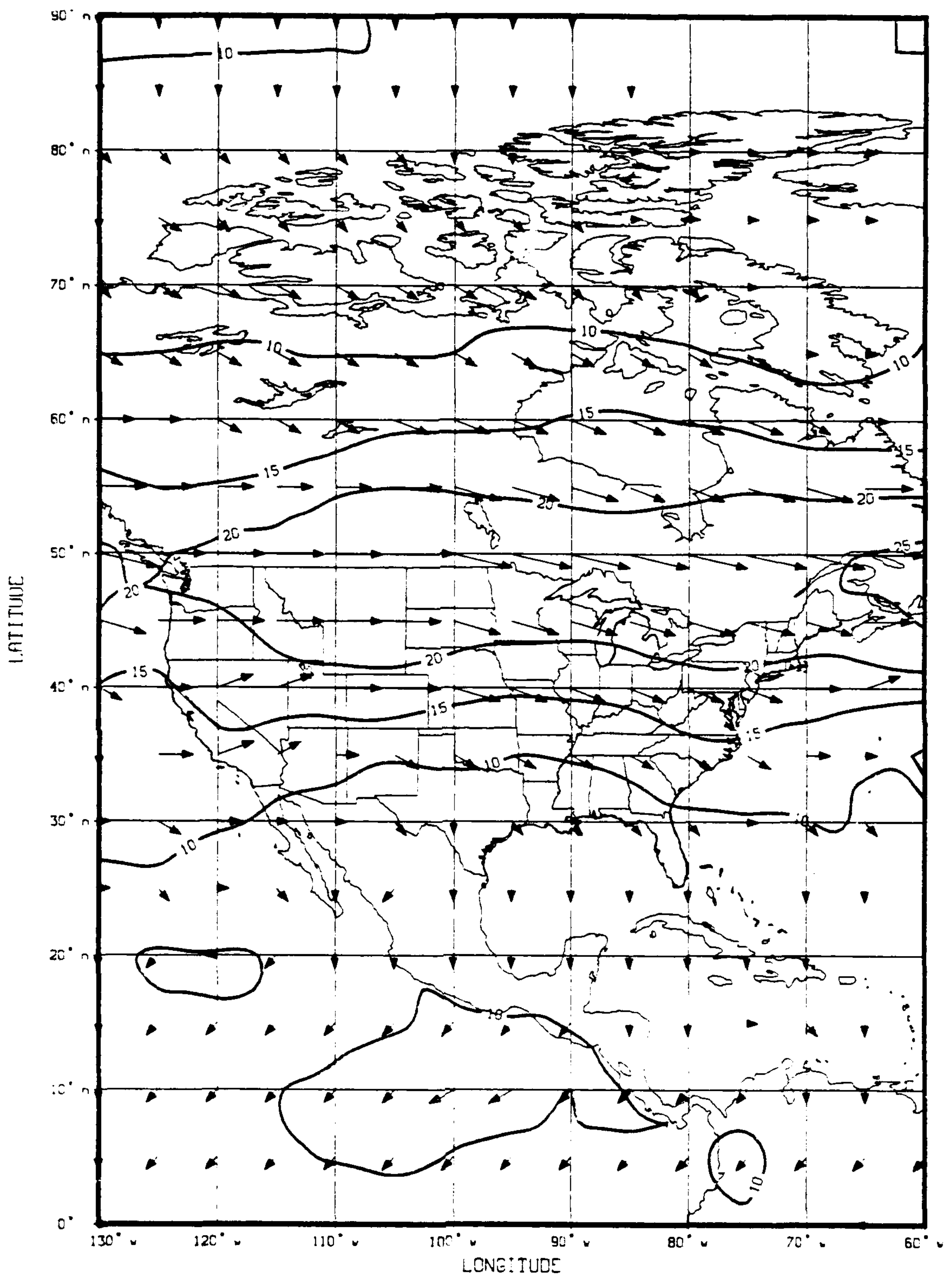


FIG. 18. Average wind speed at 150 mb during summer 1988 (m s^{-1}), with average direction denoted by vectors. Speed contour increment: 5 m s^{-1}.

C. Persistence

The number of observations of wind greater than the threshold jet speed (25 m s^{-1}) provides still more information toward finding the climatologically favored position of the jet stream during the analysis period. The 250 mb jet frequency chart for the month of July (Fig. 19) shows the jet stream occurring as a zonal band with slight anticyclonic curvature through southern Canada (in good agreement with the previously described 250 mb average wind speed chart and July jet count tables). The jet occurred most often (40 to 44 times) in a zonal swath from the eastern Pacific to south central Saskatchewan province, and 40 to 46 times over the Gulf of St Lawrence.

At higher levels (Figs. 20 and 21), the July frequency of jet occurrence is similar to the 250 mb chart in both shape and location, with the exception that the relatively lower wind speeds observed at 150 mb gave fewer jet occurrences.

The location of the August 250 mb jet stream (Fig. 22) shows considerably more variability than during the previous month. There were four separate (smaller) areas where jets were observed more than 40 times; one in southern Saskatchewan Province, one from central Wyoming, east-north-eastward to over Lake Superior; another over south-central Quebec province, and finally one over southeastern Quebec and southern Labrador. Similar to the average wind speed

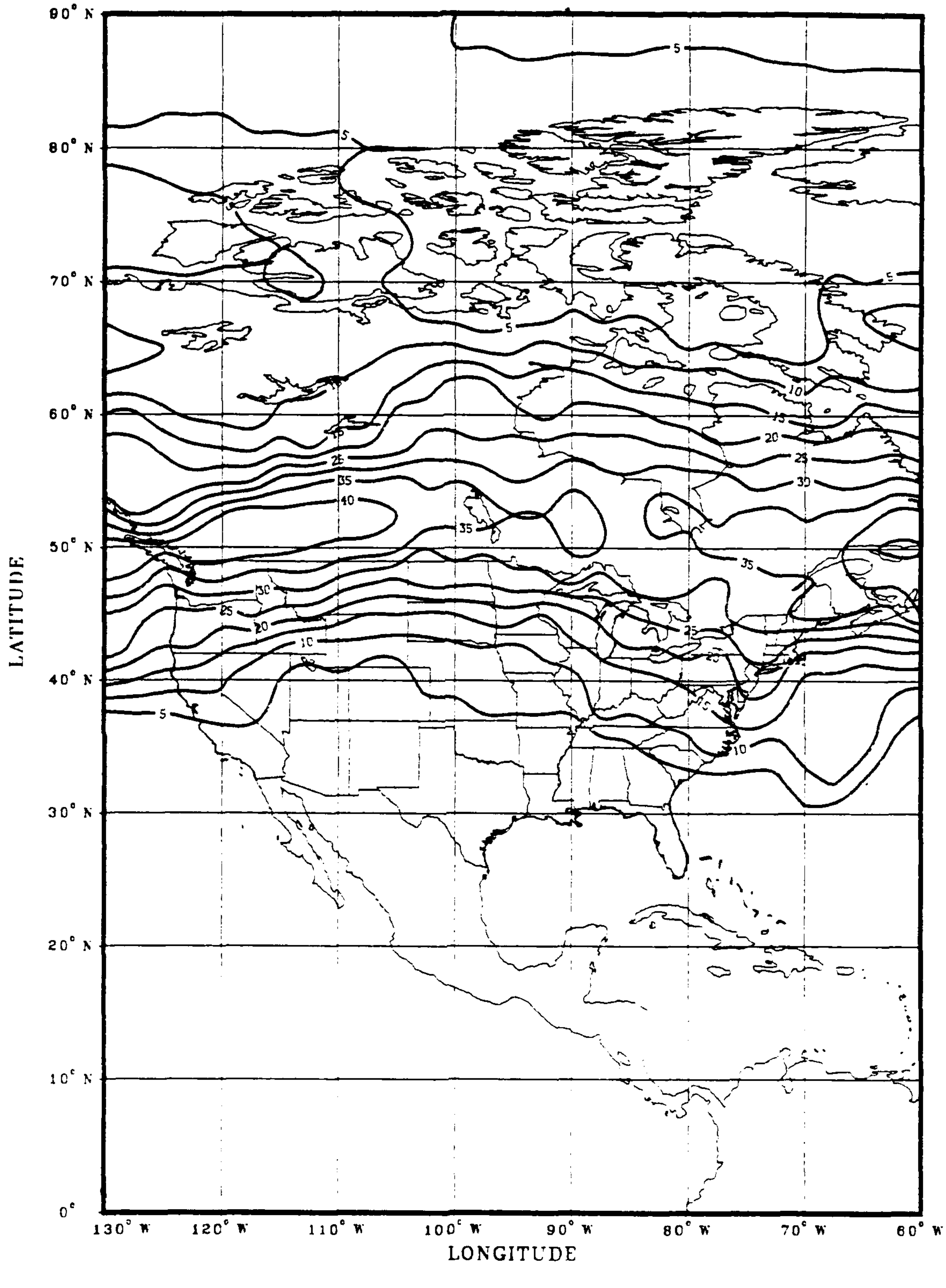


FIG. 19. Frequency of occurrence of wind greater than 25 m s^{-1} (of 62 possible) at 250 mb during July 1988. Contour increment: 5 occurrences.

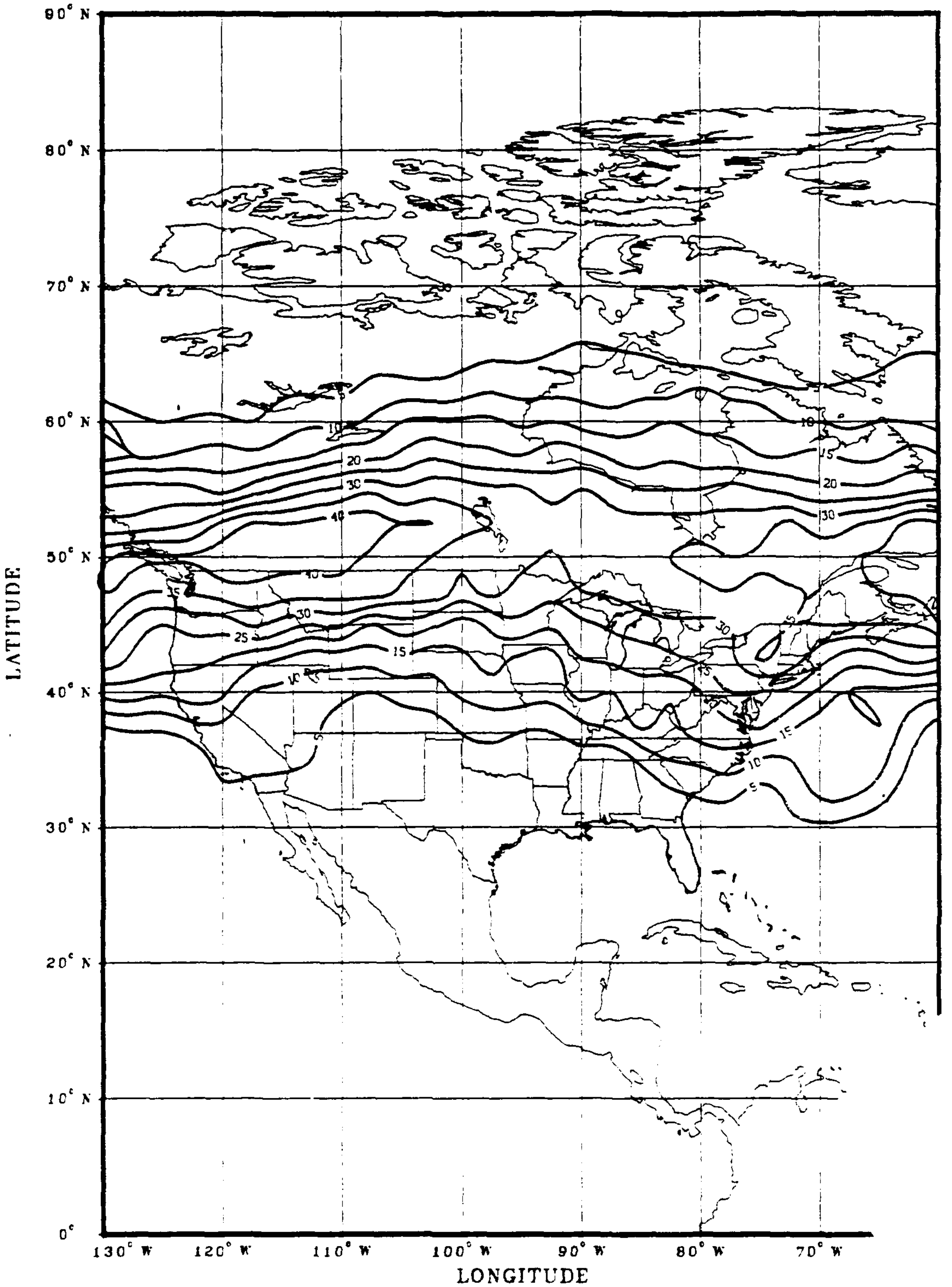


FIG. 20. Frequency of occurrence of wind greater than 25 m s^{-1} (of 62 possible) at 200 mb during July 1988. Contour increment: 5 occurrences.

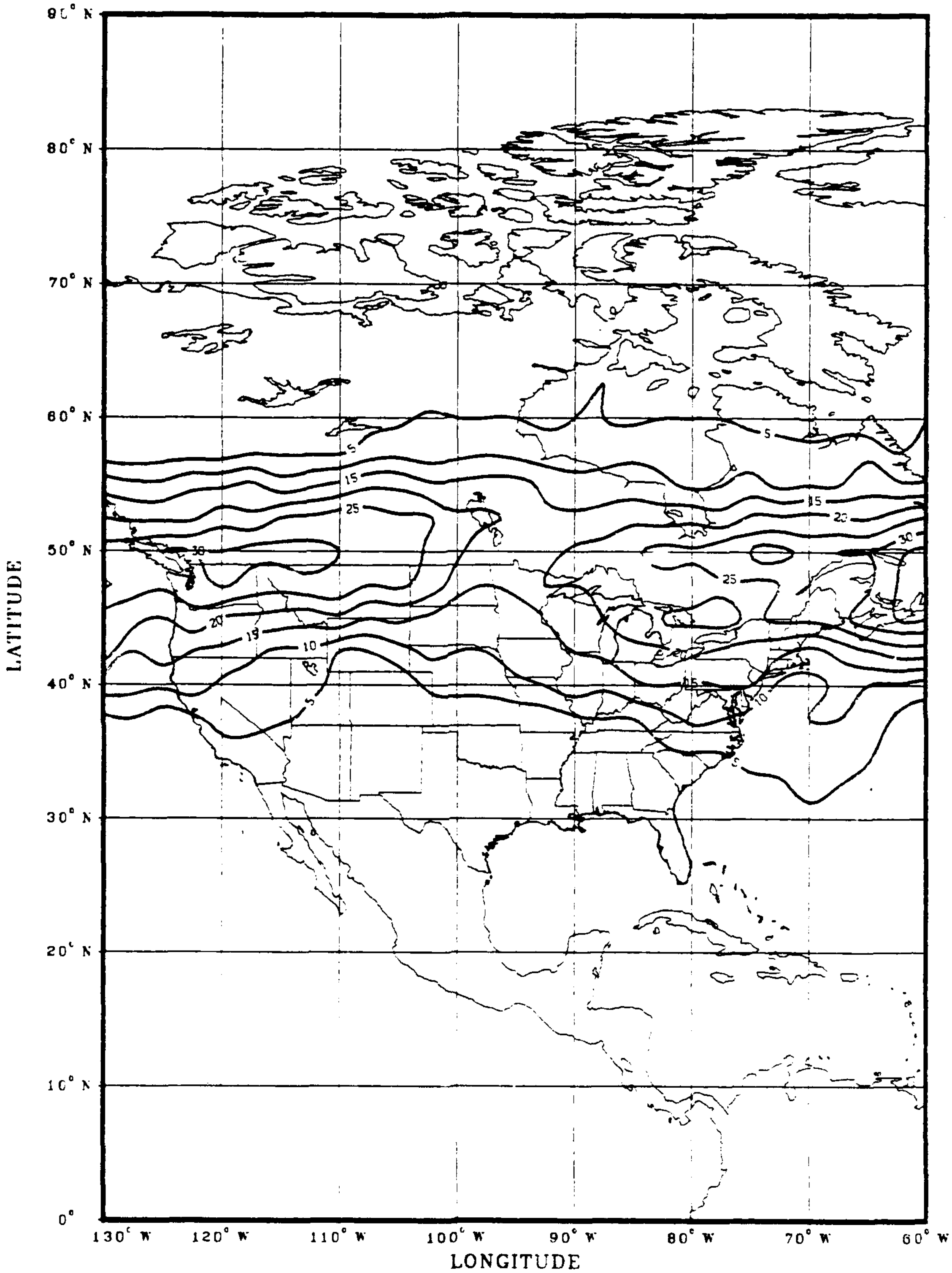


FIG. 21. Frequency of occurrence of wind greater than 25 m s^{-1} (of 62 possible) at 150 mb during July 1988. Contour increment: 5 occurrences.

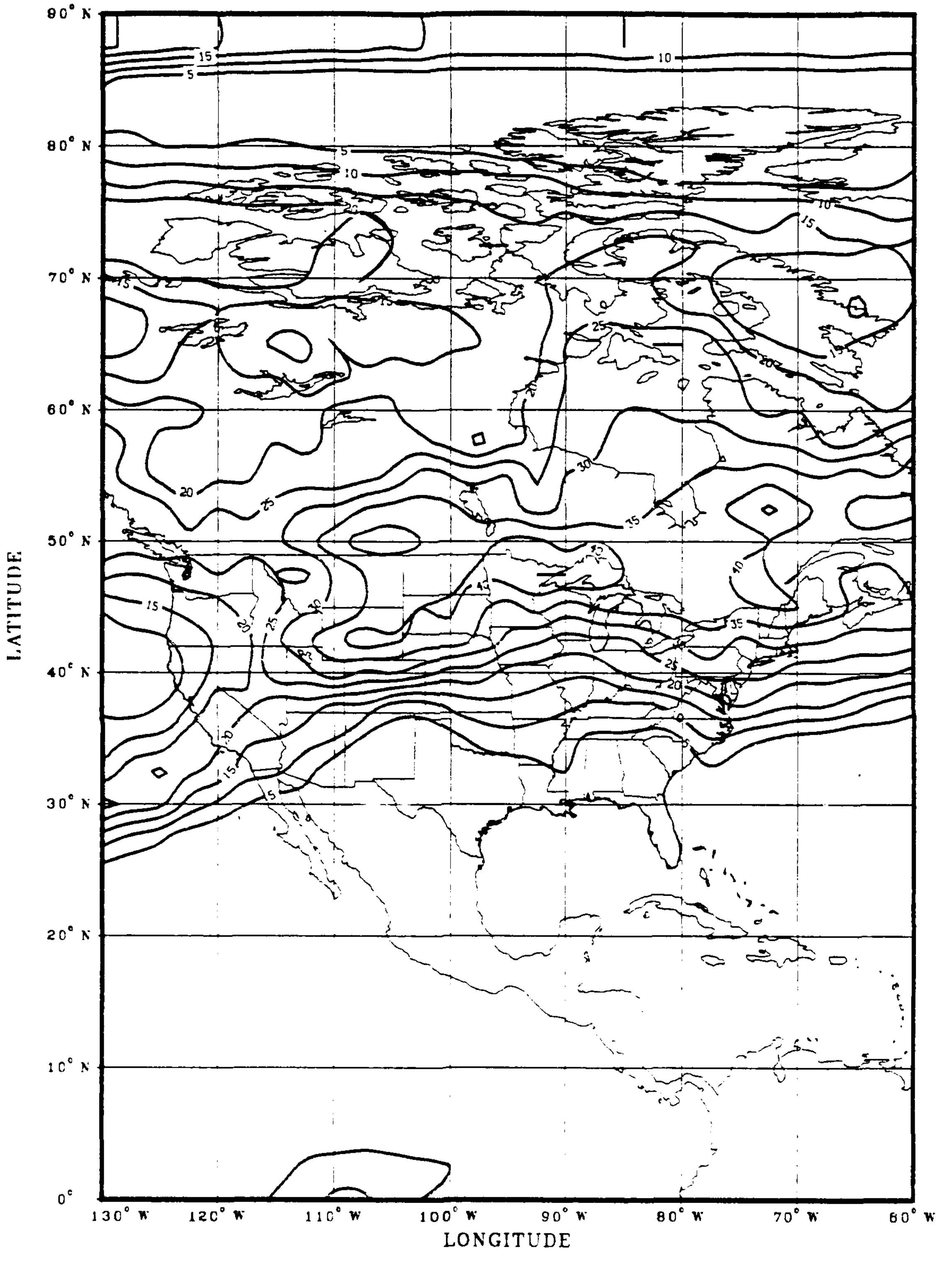


FIG. 22. Frequency of occurrence of wind greater than 25 m s^{-1} (of 62 possible) at 250 mb during August 1988. Contour increment: 5 occurrences.

data, the 25 occurrence isopleth is considerably broader in the east than in July. Again, branching of the jet stream is seen off the West Coast with one slightly more persistent branch coming ashore over Vancouver B.C. (maximum: 30 occurrences) and the other over southern California (maximum: 26 occurrences). There is a minimum (five occurrences) between these two West Coast maxima.

August 200 mb jet persistence (Fig. 23) is quite similar to that of the 250 mb level. At this level, the maximum jet frequency of both the north and south branch, (off the West Coast) is equal at 28 occurrences. The shape of the surrounding isotachs appears, however, to favor the southern jet.

At 150 mb (Fig. 24), August jet frequency is similar in shape to the lower levels, with the number of occurrences slightly less. At this level, however, the southern branch off the West Coast is more persistent than the northern branch, confirming the previous finding that the southern branch was a higher level phenomenon.

During the 1988 summer season, the most frequent location of the jet stream over North America was along the United States/Canada Border (Figs. 25, 26, 27). There is weak evidence of a second jet, seen in the 20 occurrence isopleth at 250 mb, and the 25 occurrence isopleth at 200 mb. These latter numbers appear small but were influenced primarily by the August jet frequency data.

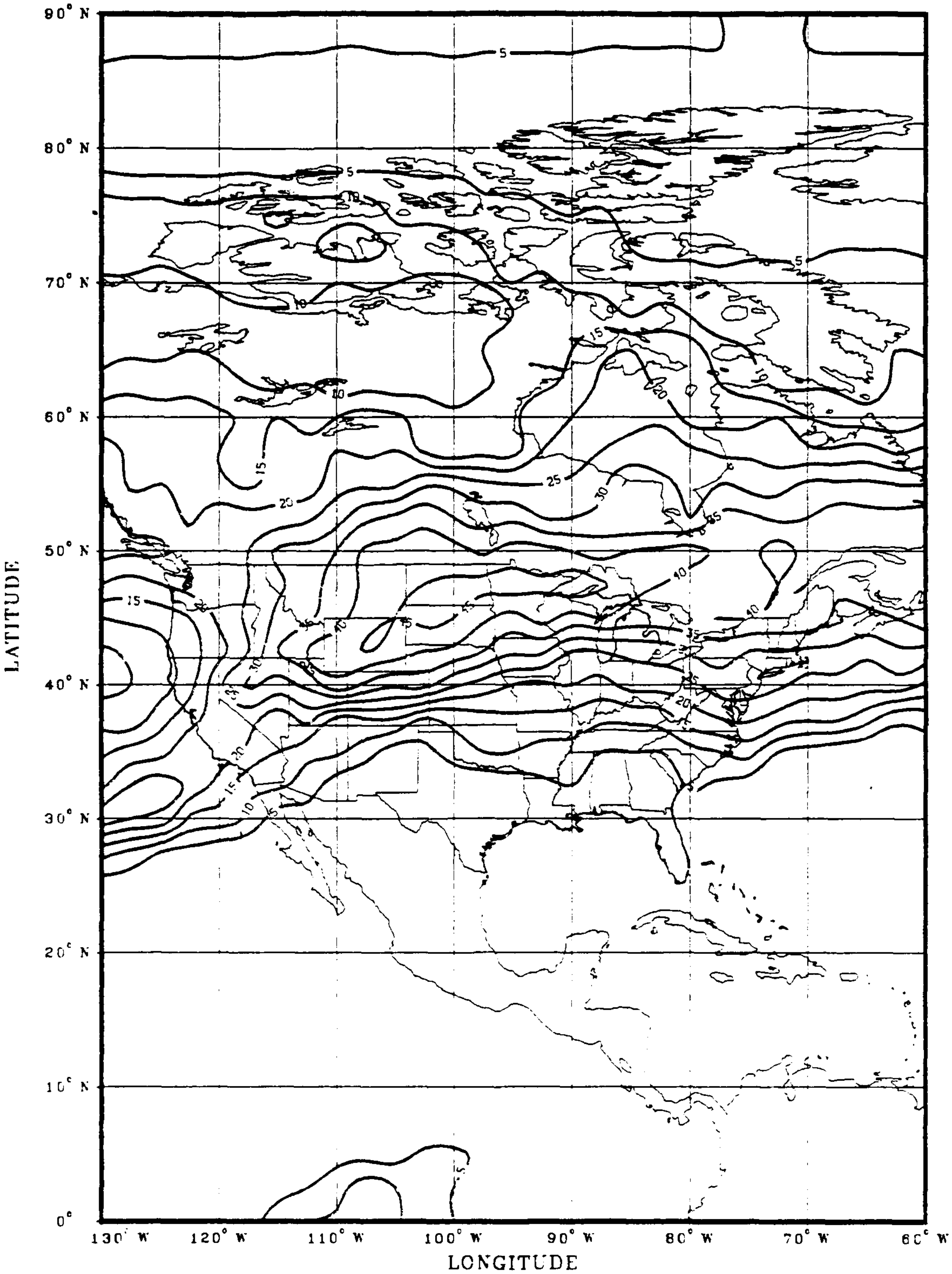


FIG. 23. Frequency of occurrence of wind greater than 25 m s^{-1} (of 62 possible) at 200 mb during August 1988. Contour increment: 5 occurrences.

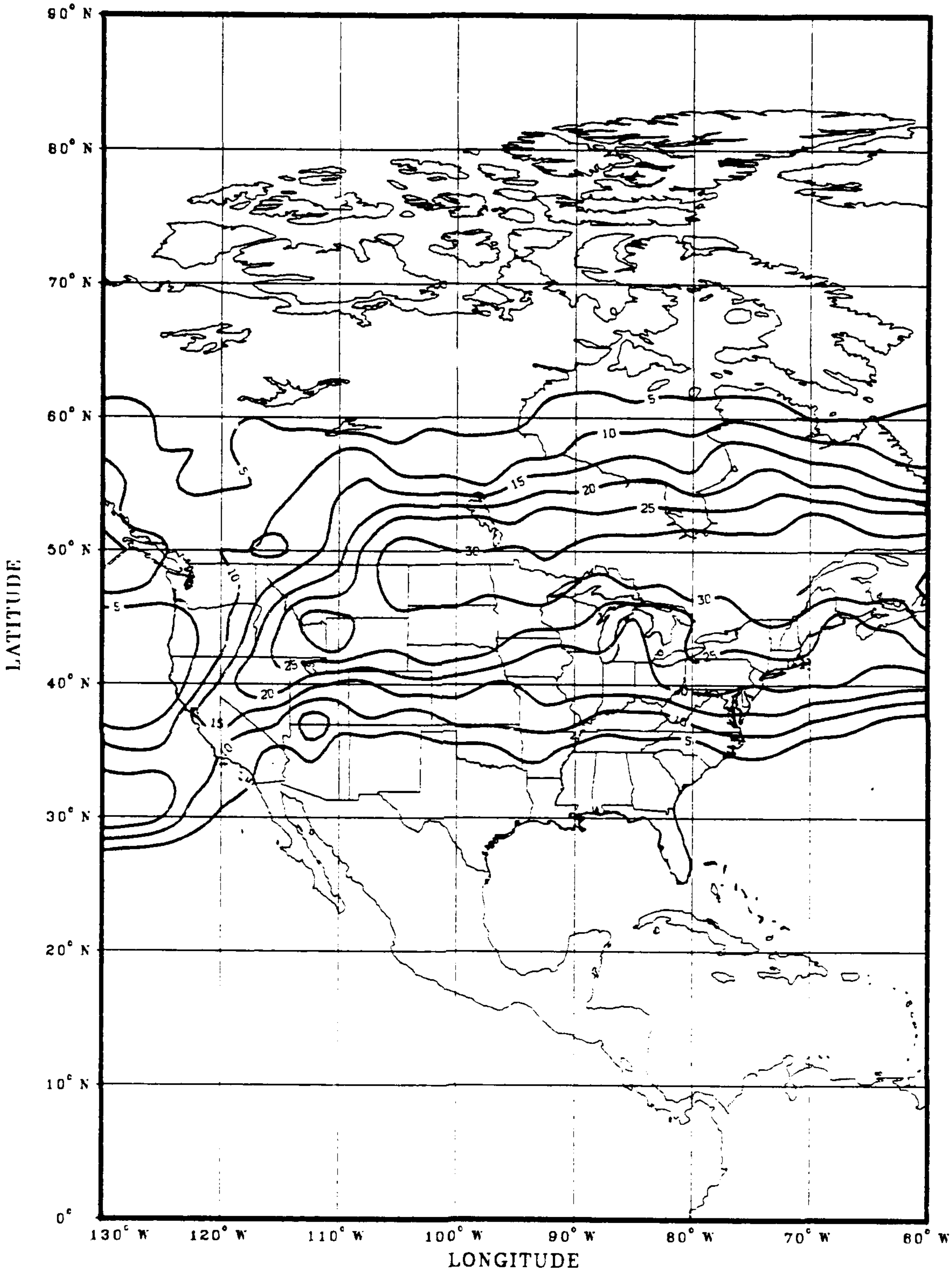


FIG. 24. Frequency of occurrence of wind greater than 25 m s^{-1} (of 62 possible) at 150 mb during August 1988. Contour increment: 5 occurrences.

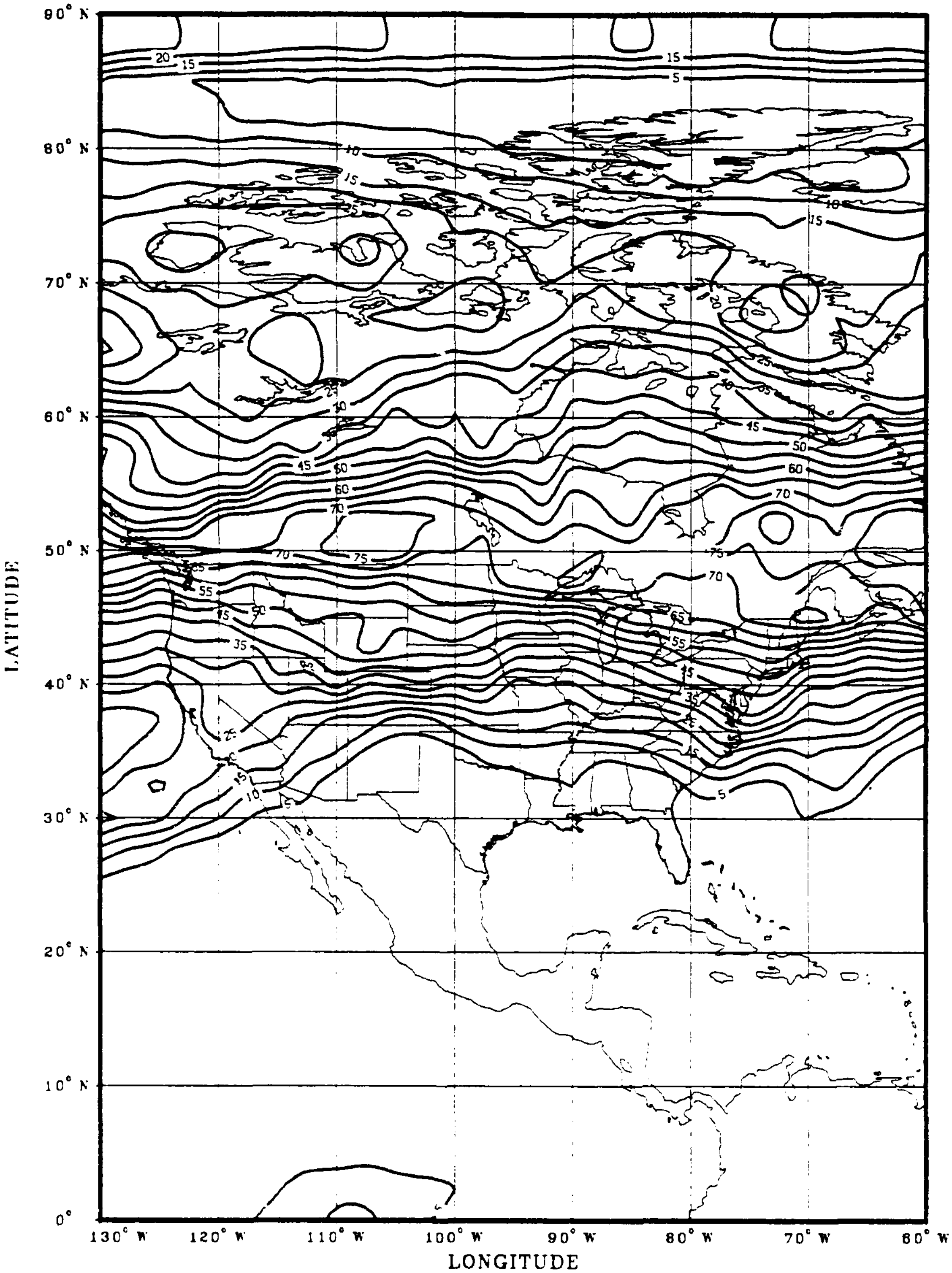


FIG. 25. Frequency of occurrence of wind greater than 25 m s^{-1} (of 124 possible) at 250 mb during summer 1988. Contour increment: 5 occurrences.

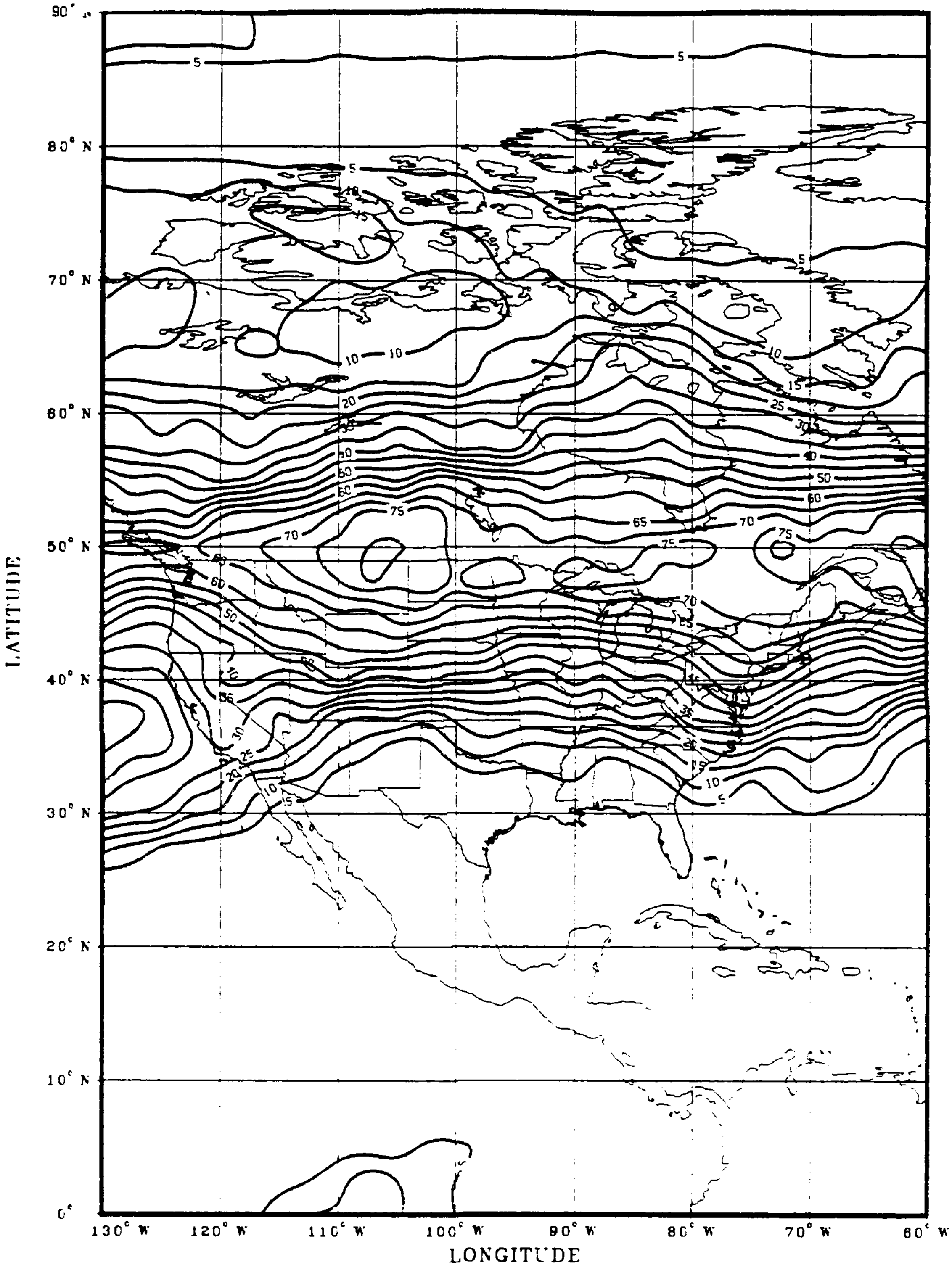


FIG. 26. Frequency of occurrence of wind greater than 25 m s^{-1} (of 124 possible) at 200 mb during summer 1988. Contour increment: 5 occurrences.

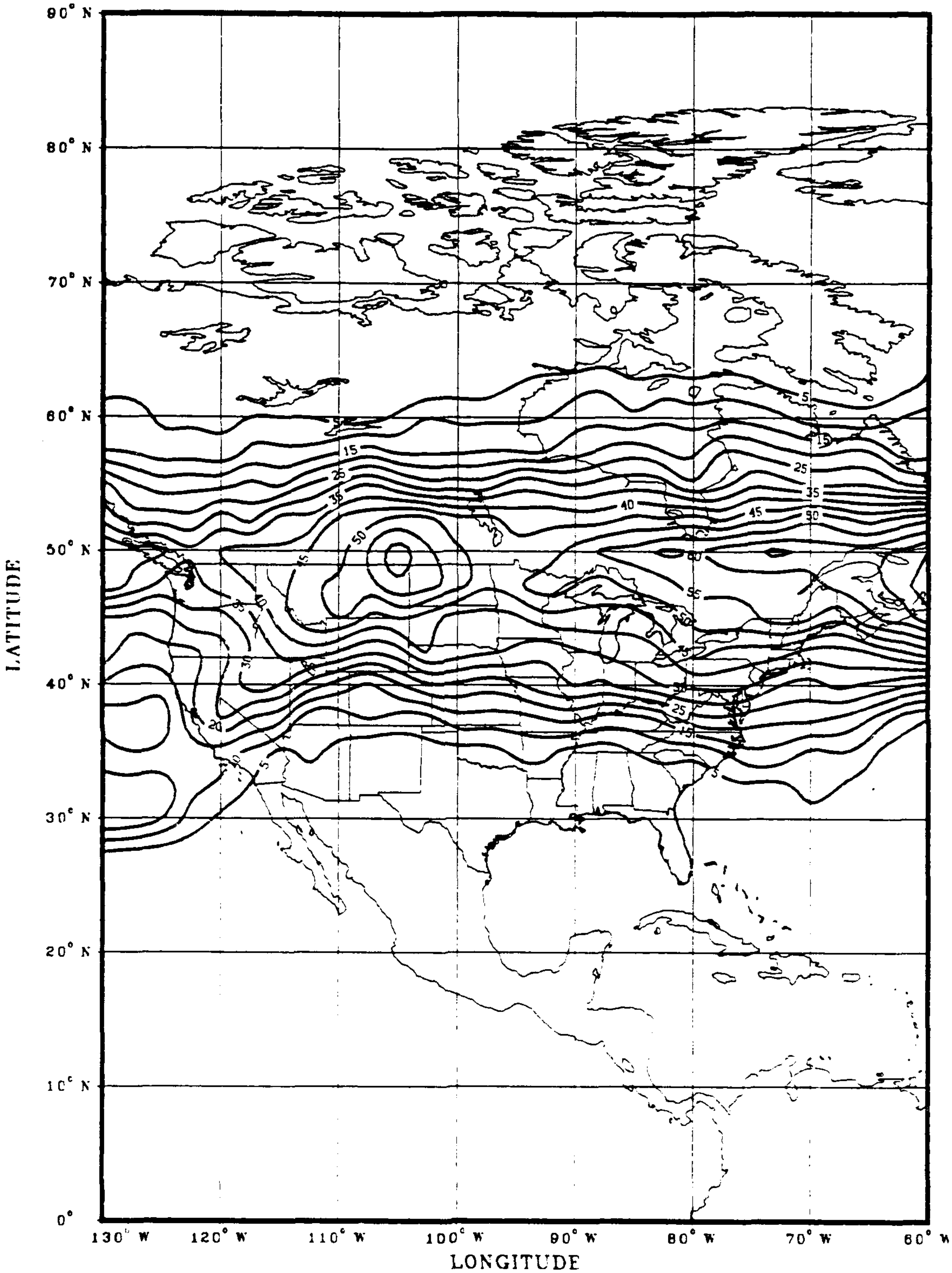


FIG. 27. Frequency of occurrence of wind greater than 25 m s^{-1} (of 124 possible) at 150 mb during summer 1988. Contour increment: 5 occurrences.

D. Height Fields

The monthly and seasonal height fields were analyzed to see if there were systematic differences to account for the differences in the jet streams of July and August. The results are shown in Figs. 28-36. In summary, average heights at all three levels agree well with the speed, number, and location of jet streams observed, a reflection of the geostrophy of the upper troposphere.

The June-July-August height from the ECMWF model (Fig. 37) was compared to the composite July-August 250 mb height field from this study (Fig. 34). The shapes of the contours are very similar. Though the closed 11000 gpm contour in this data set was not seen in the ECMWF data, the 10900 gpm contour does show weak ridging over the Midwest and troughing off the Eastern Seaboard in both studies. During summer 1988, that isopleth occurred about three degrees north of the ECMWF location (a reflection of the high pressure pattern over the United States). To the north, the 10400 gpm isopleth shows a similar west-northwest-to-east-southeast orientation and its physical location was nearly identical between the two studies.

Day by day comparison of the 200 mb height field was made with the 200 mb wind field. During July, when there was commonly a single jet stream over North America (see Chapter III for jet count procedure), the height field was rather uncomplicated with low pressure over northern Canada

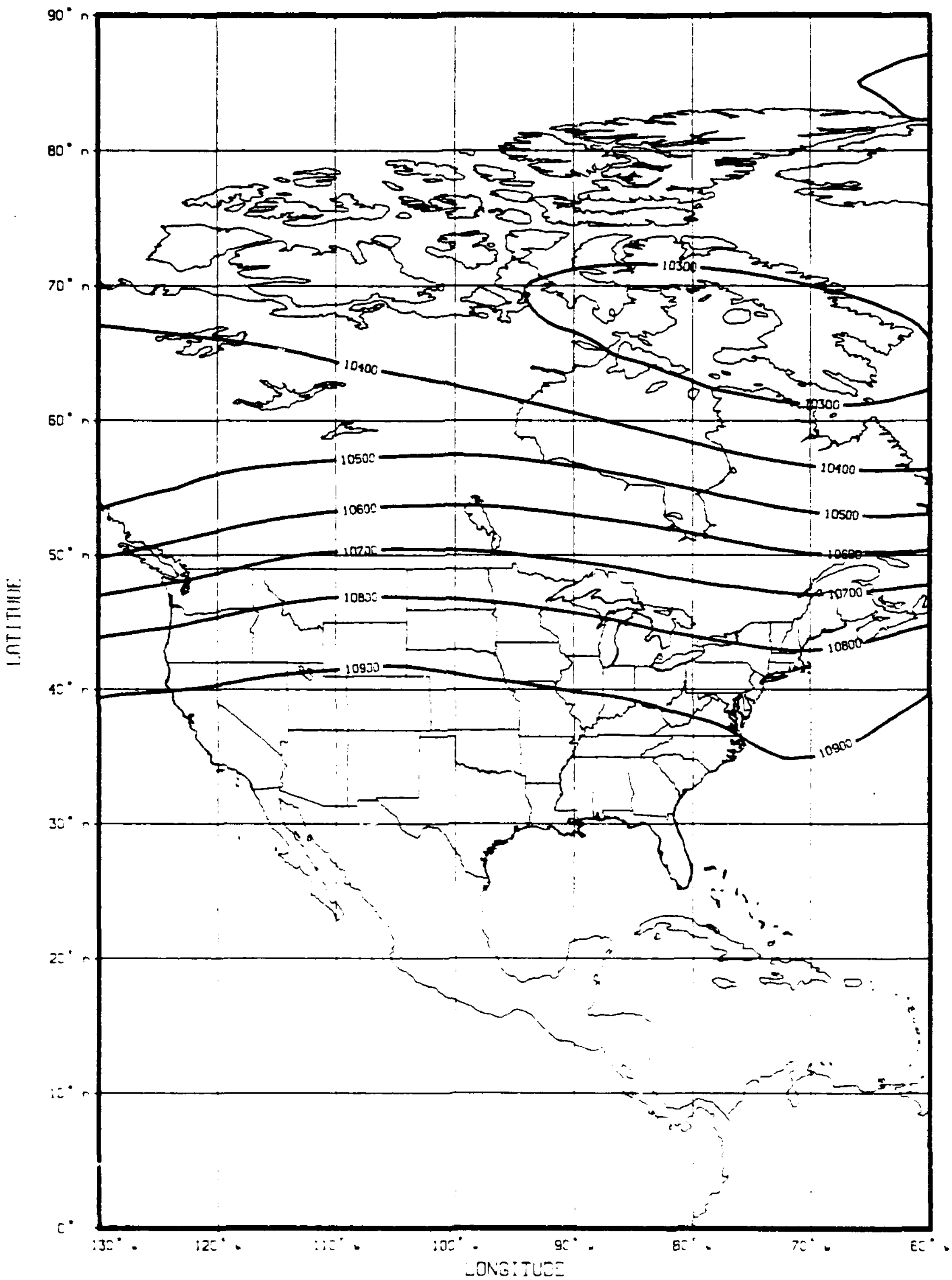


FIG. 28. Average 250 mb height field (gpm) during July 1988. Contour increment: 100 gpm.

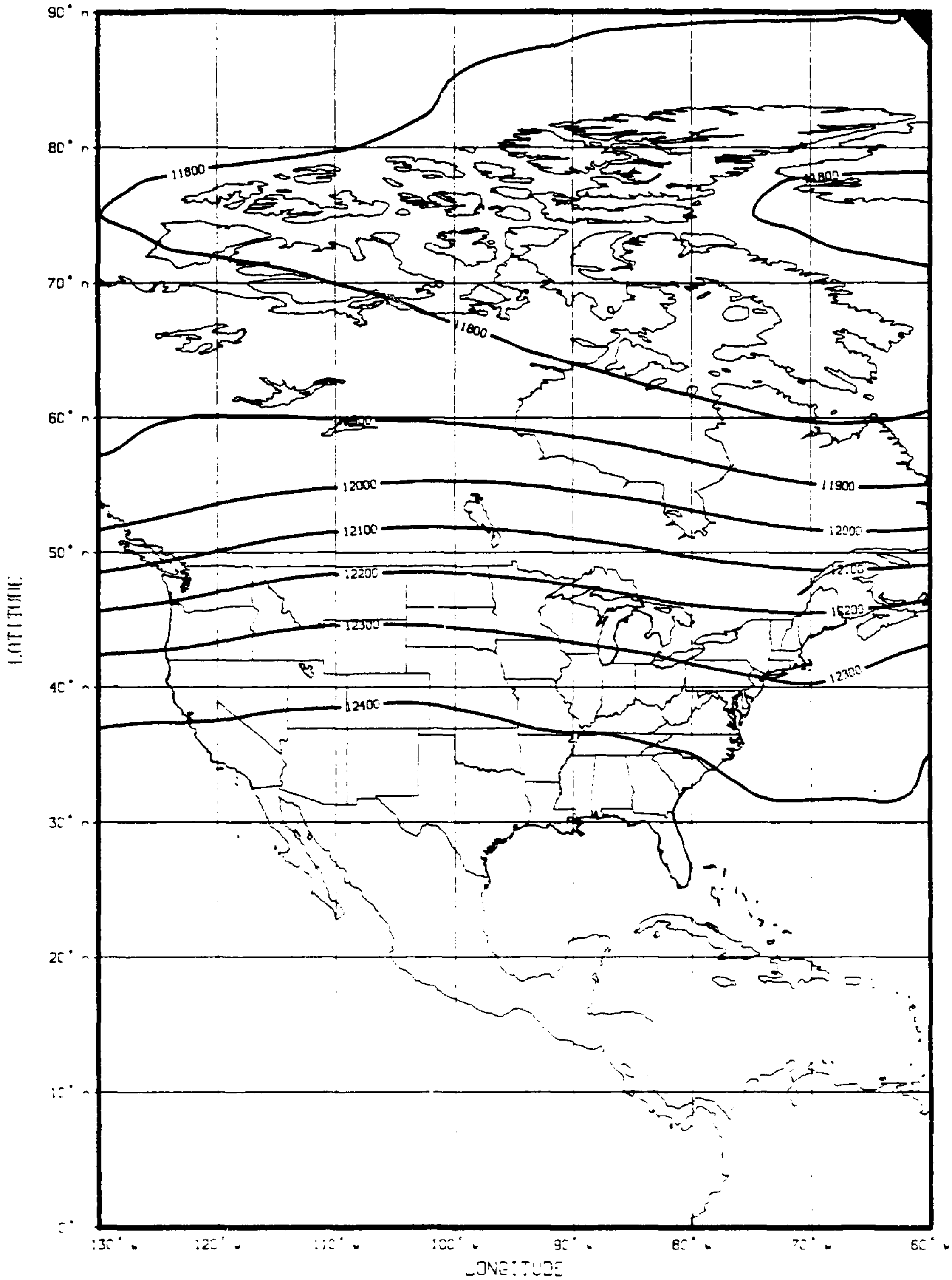


FIG. 29. Average 200 mb height field (gpm) during July 1988. Contour increment: 100 gpm.

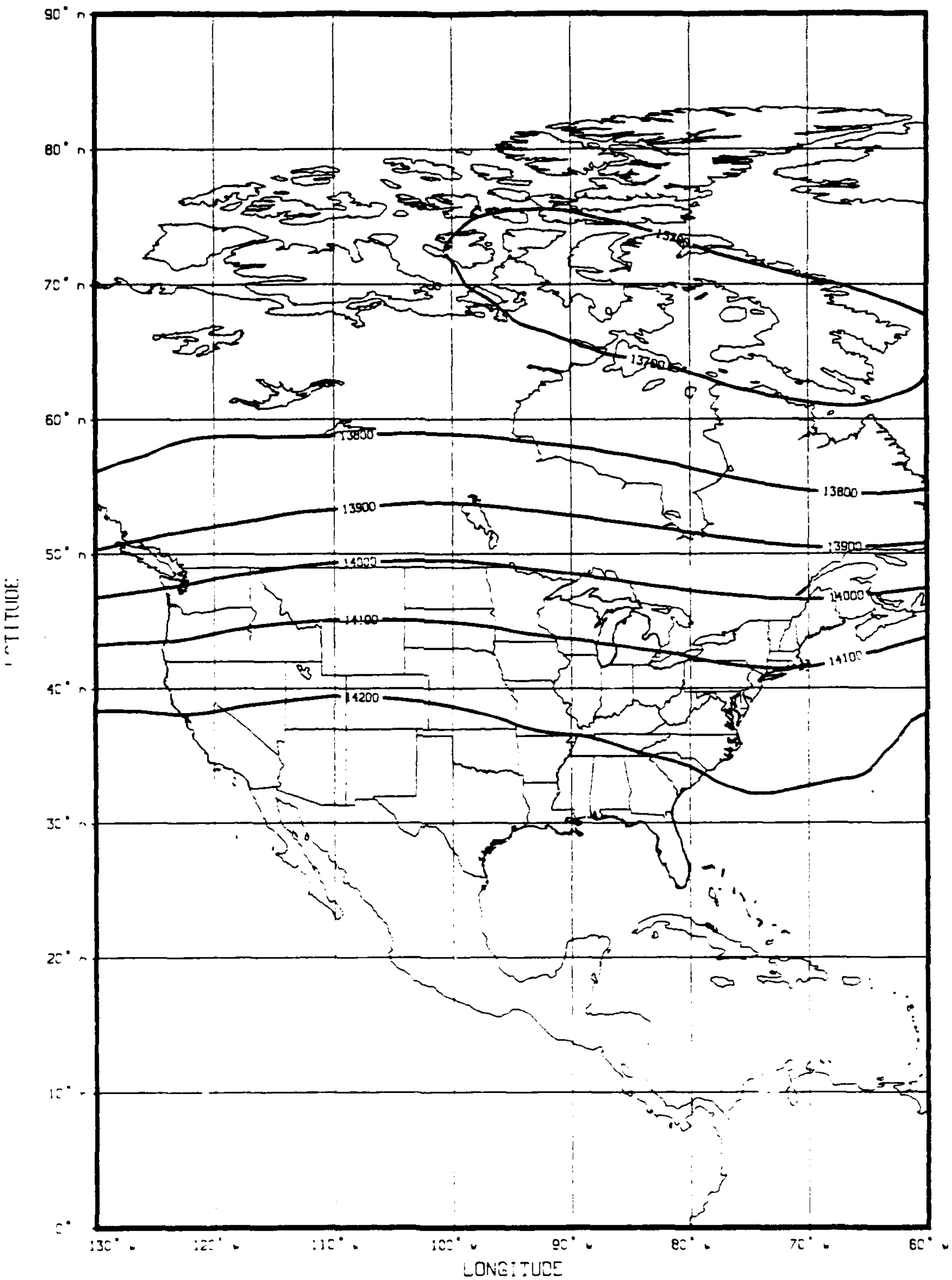


FIG. 30. Average 150 mb height field (gpm) during July 1988. Contour increment: 100 gpm.

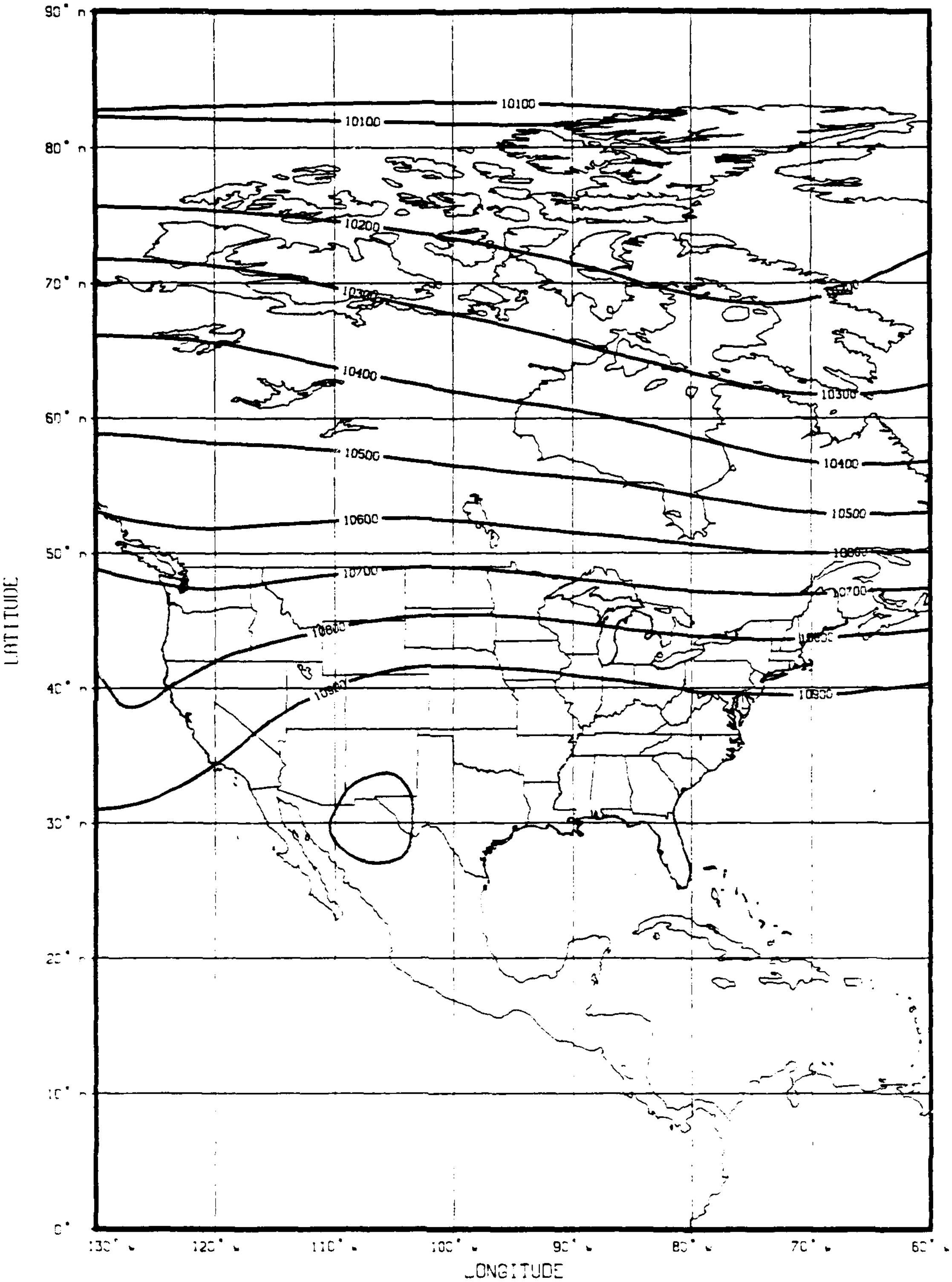


FIG. 31. Average 250 mb height field (gpm) during August 1988. Contour increment: 100 gpm.

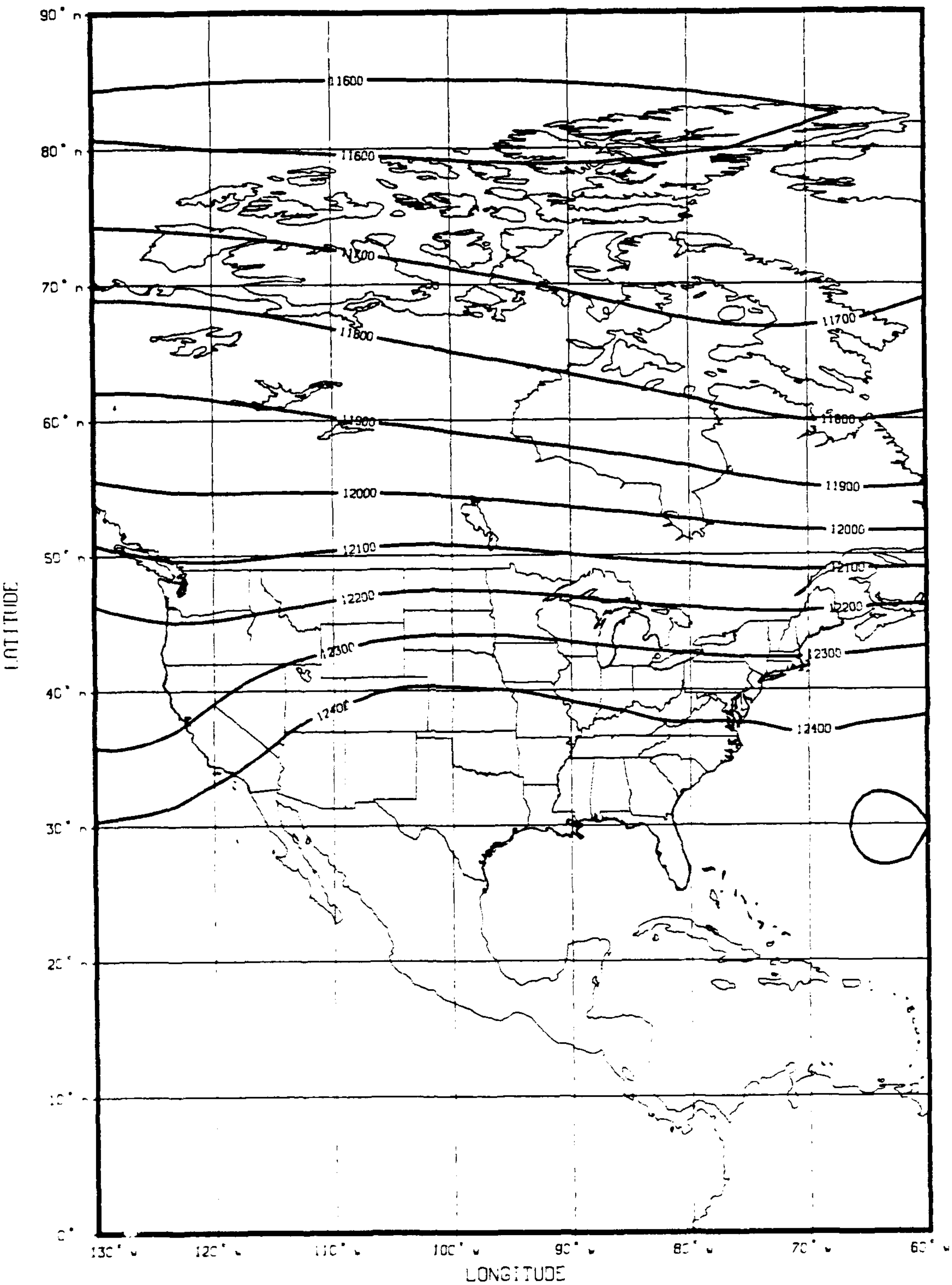


FIG. 32. Average 200 mb height field (gpm) during August 1988. Contour increment: 100 gpm.

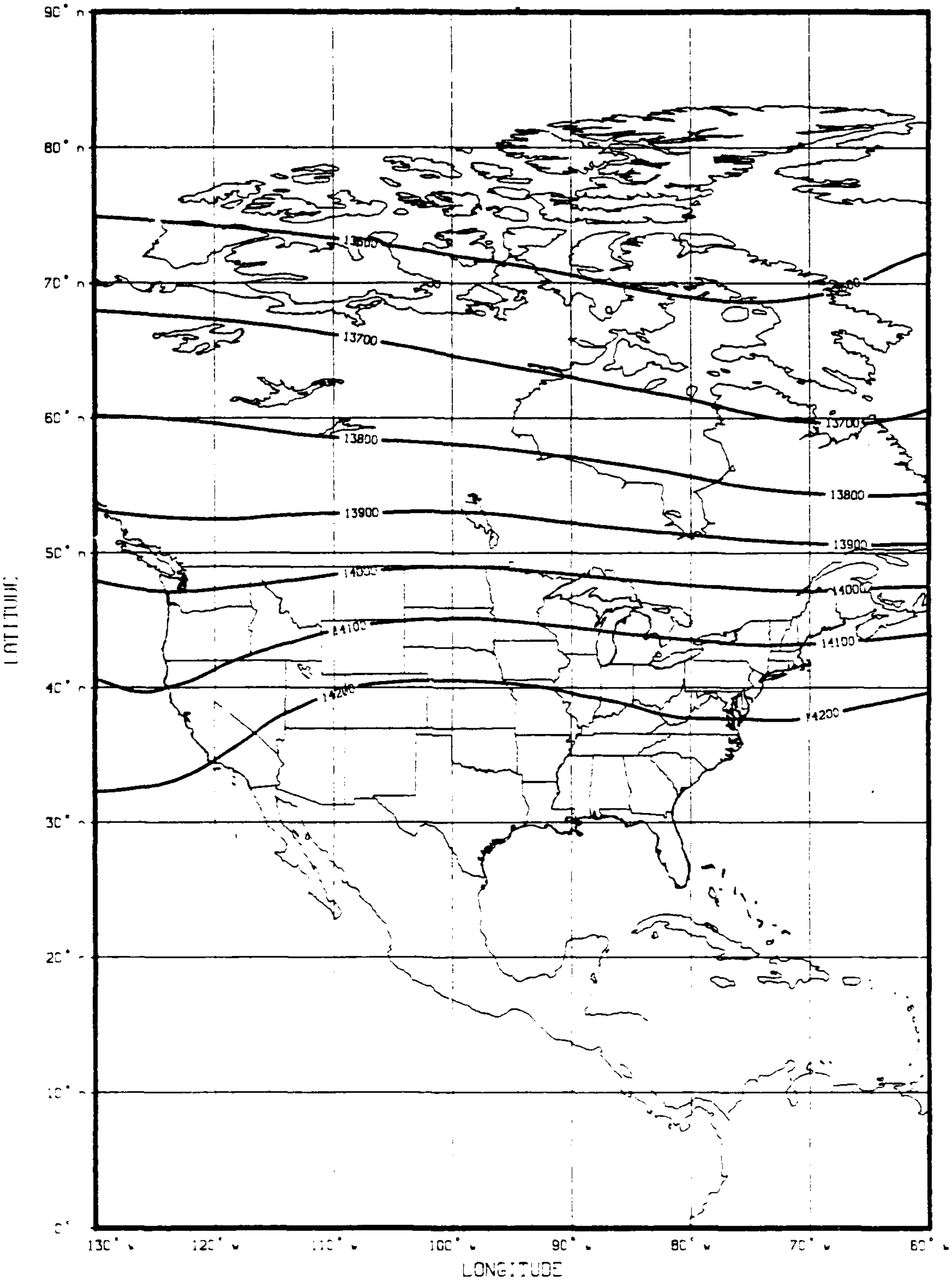


FIG. 33. Average 150 mb height field (gpm) during August 1988. Contour increment: 100 gpm.

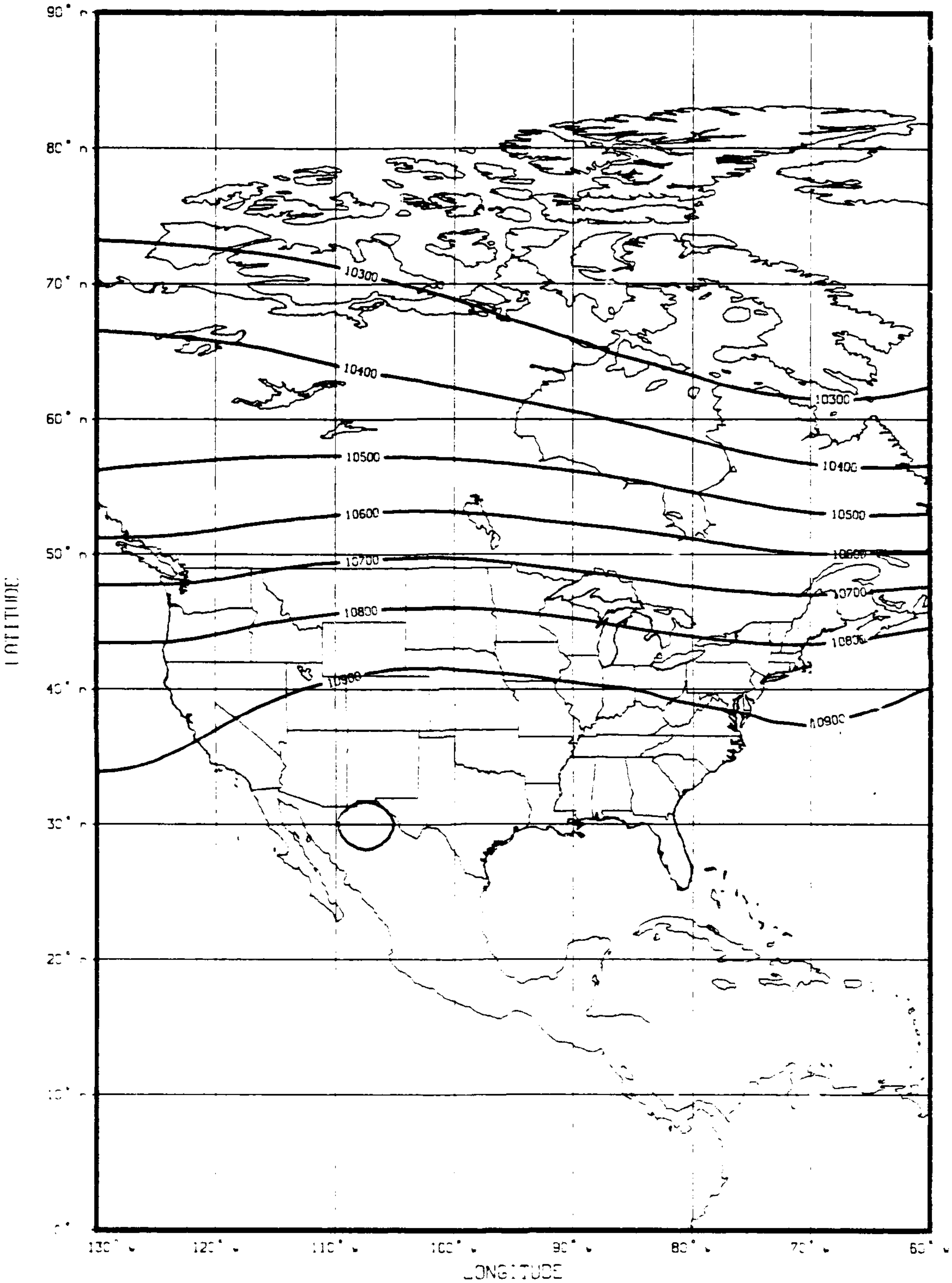


FIG. 34. Average 250 mb height field (gpm) during summer 1988. Contour increment: 100 gpm.

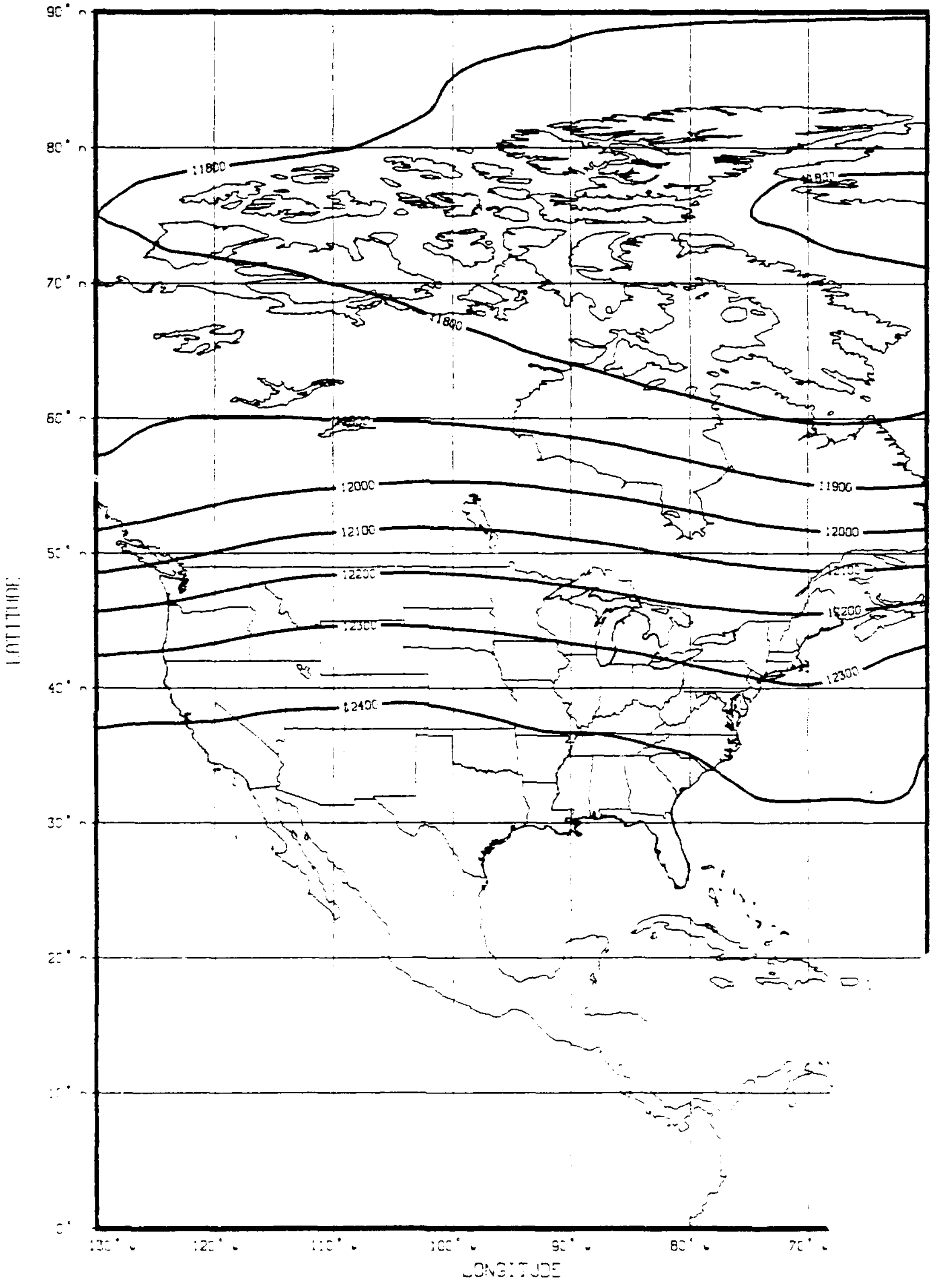


FIG. 35. Average 200 mb height field (gpm) during summer 1988. Contour increment: 100 gpm.

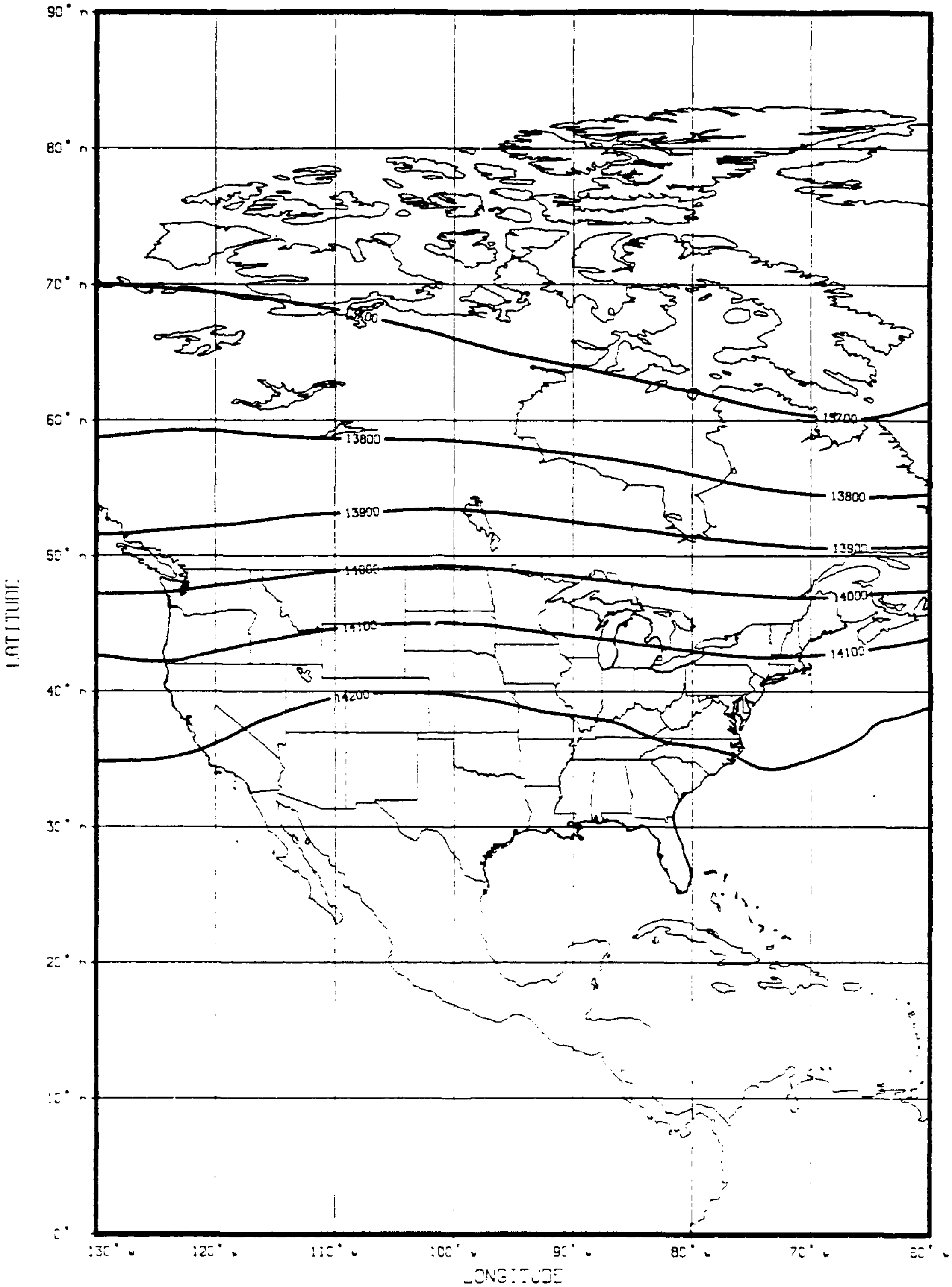


FIG. 36. Average 150 mb height field (gpm) during summer 1988. Contour increment: 100 gpm.

FIG. 37. Average Northern Hemisphere 250 mb height field during June-July-August. Contour increment 100 gpm. (After Hoskins et al., 1989).

and high pressure over the continental United States, a high index stage (as described by Reiter (1961)). During August (a multiple jet stream month) however, the daily height field showed much more variability, with exaggerated ridging and troughing (low index stage).

The upper level height field on those days when there was more than one jet present over North America usually occurred in one of two regimes. The more common regime (Fig. 38) had two centers of the same sign with no intervening (opposite sign) center; that is, two low pressure centers without a high pressure center between them, or two highs without an intervening low. There was no favored orientation (eg., N-S or NE-SW) of the same sign centers.

The other regime (Fig. 39) had a symmetric arrange-

ment of high and low centers with each flow axis independent (upstream) of the other. The example shows high pressure center north of a low pressure center in the western part of the domain, with a low pressure center north of a high pressure center downstream. The downstream couplet represents a Bergeron (1928) geostrophic confluence/difluence area.

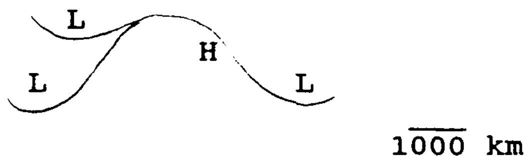


FIG. 38. Orientation of pressure centers of the same sign during multiple jet occurrences.

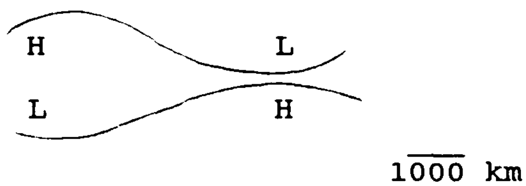


FIG 39. Symmetric orientation of pressure centers during multiple jet occurrences.

E. Vertical Sections

Vertical section (1000 mb to 70 mb) charts were constructed, graphing the magnitude of wind speed against potential temperature for those times and locations where one jet was observed, and likewise for the times when multiple jets occurred. The goal was to identify, if possible, which jets were present (polar front jet, subtropical jet, or some combination of the two), by the signatures described previously. The cross sections were taken, wherever possible, through the longitude where jet speeds were highest.

Fig. 40 shows a section through a typical single jet. The highest closed isotach (45 m s^{-1}) occurs between 200 and 280 mb at about 50°N, and the layer where wind speed is more than half the maximum observed speed is 320 mb thick. A weak but deep easterly wind zone occurs at about 17°N. The maximum gradient of the θ isopleths appears at θ=330 K north of the jet, and at θ=360 K south of the jet, showing the "isentrope hump" south of the jet, described by Reiter (1967, p. 101). (The apparent gradient of the θ isopleths above the 100 mb level is an artifact of the contouring program.)

In the double jet section (Fig. 41), the northern jet's layer of maximum wind (35 m s^{-1}) occurs between 330 and 440 mb at about 64°N, and the half speed layer is 540 mb thick. The southern jet is centered at about 51°N, with a layer of maximum speed 140 mb thick, and a half-speed layer 440 mb thick. An easterly stratospheric wind zone appears centered at 20°N. The tropopause in this diagram can be defined by θ=315 K, north of the northern jet; θ=330 K between the jets; and θ=360 K south of the southern jet.

In all the sections analyzed, when more than one jet

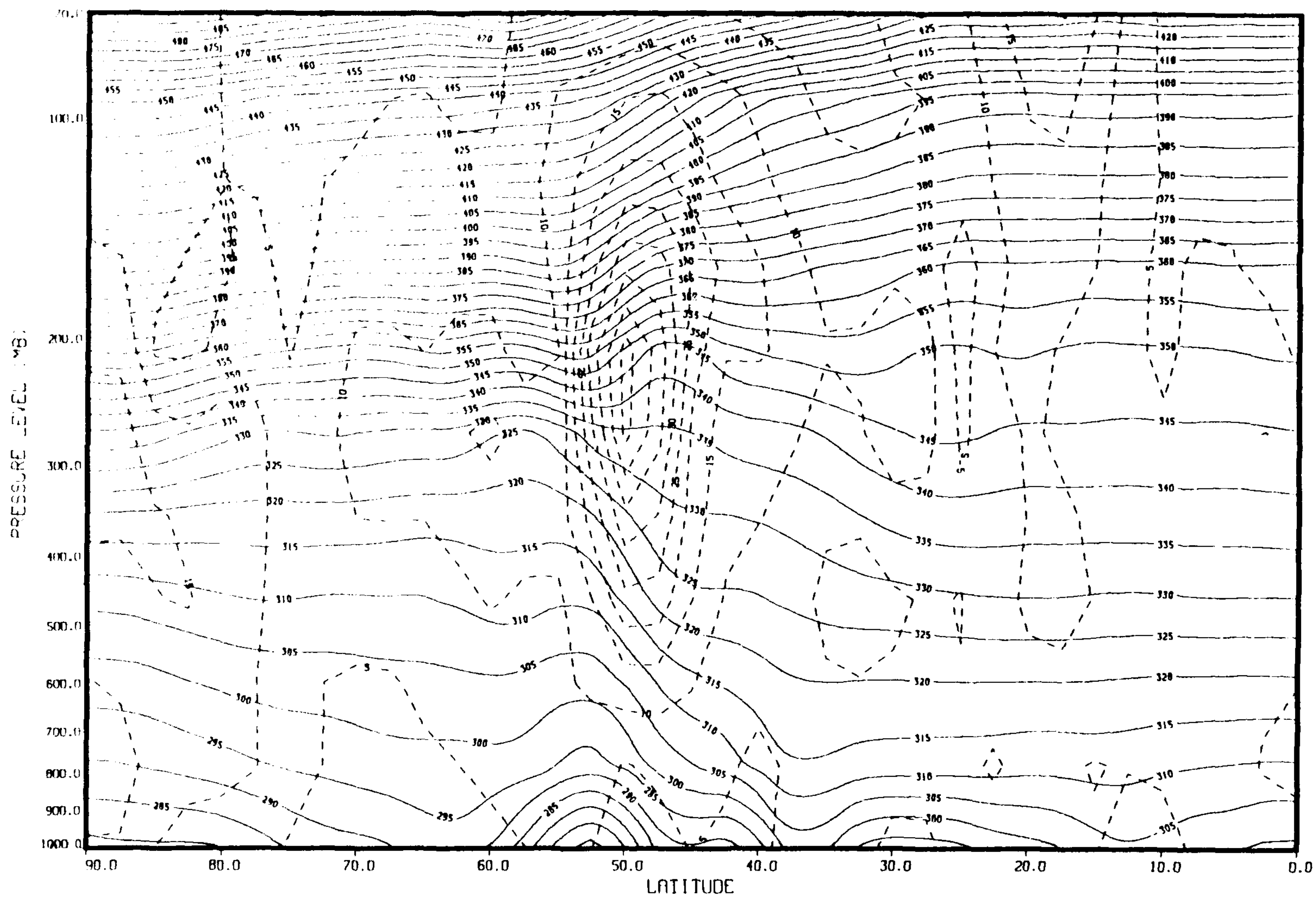


FIG. 40. Section through a typical single jet (1200 UTC 16 July 1988 at 70°W) showing wind speed (m s^{-1}), and potential temperature (K). Wind contour increment 5 m s^{-1}; potential temperature contour increment 5 K.

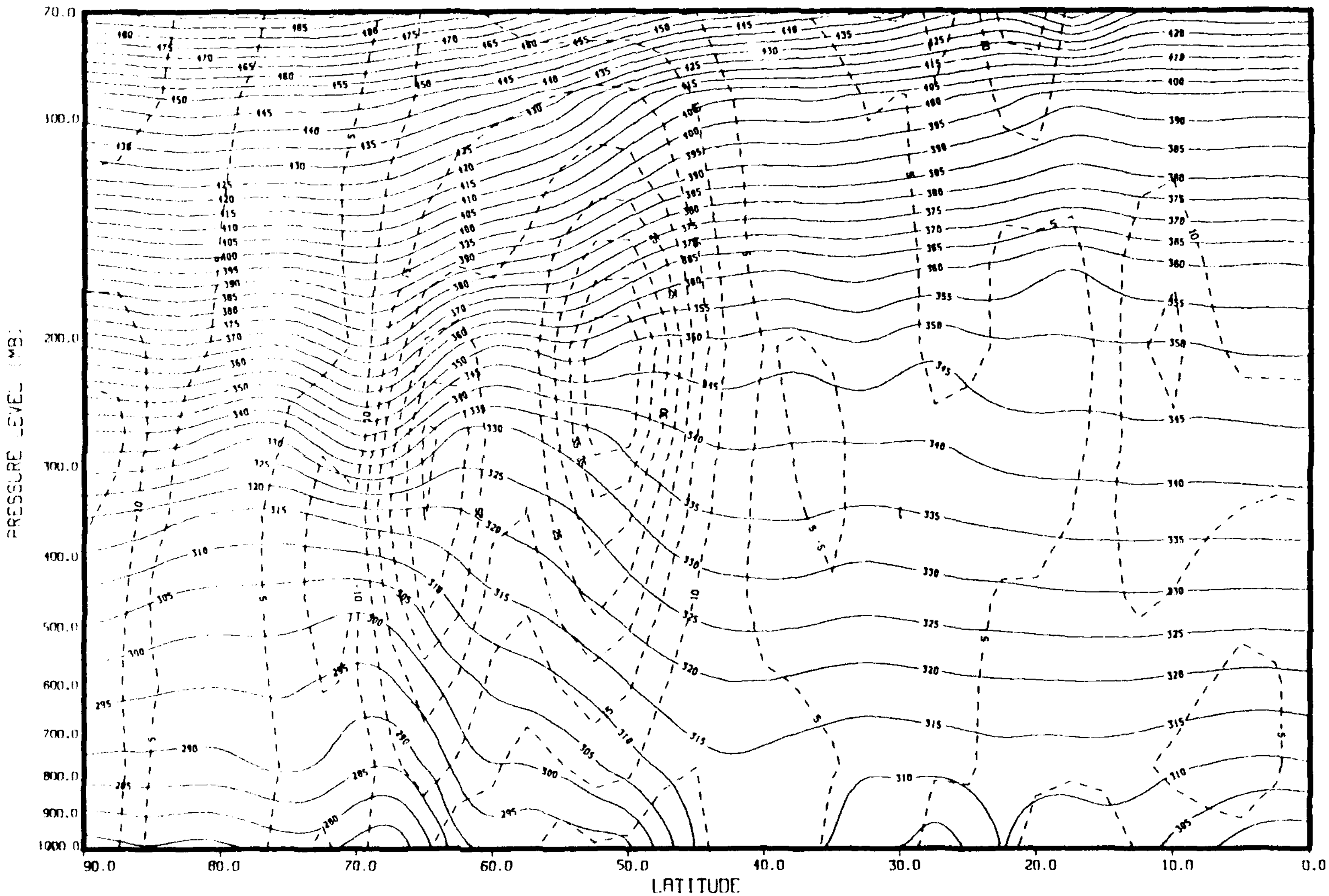


FIG. 41. Section through a typical double jet (1200 UTC 3 August 1988 at 93°W) showing wind speed (m s^{-1}), and potential temperature (K). Wind contour increment 5 m s^{-1}; potential temperature contour increment 5 K.

was present, each had great vertical extent. The lower level at which wind speeds decreased to less than half the maximum speed observed in the core of the jet usually occurred below 500 mb (unlike the subtropical jet, which exists in the high tropospheric baroclinic zone present near the upper extent of the Hadley circulation). Though the levels of maximum wind of the southern jets were near the heights at which the subtropical jet is usually found (partially a function of latitude, since the tropopause slopes up toward the equator), their "half speed" layers were too deep to fit the STJ thickness characteristic proposed by Palmen and Newton (1969). Based on that jet signature alone, the multiple jets observed were branches of the polar front jet.

F. Zonally Averaged Wind Components

Though the zonal averaging of meteorological elements usually obscures the day-to-day changes in the fields, it was performed in order to further describe the broad-scale features affecting, and affected by, the jet stream during the summer of 1988. In addition, the averaged fields could be compared to previous climatological studies, specifically the elaborate analysis performed by Hoskins et al. (1989).

Zonal Flow

During July 1988 (Fig. 42), the primary westerly zonal

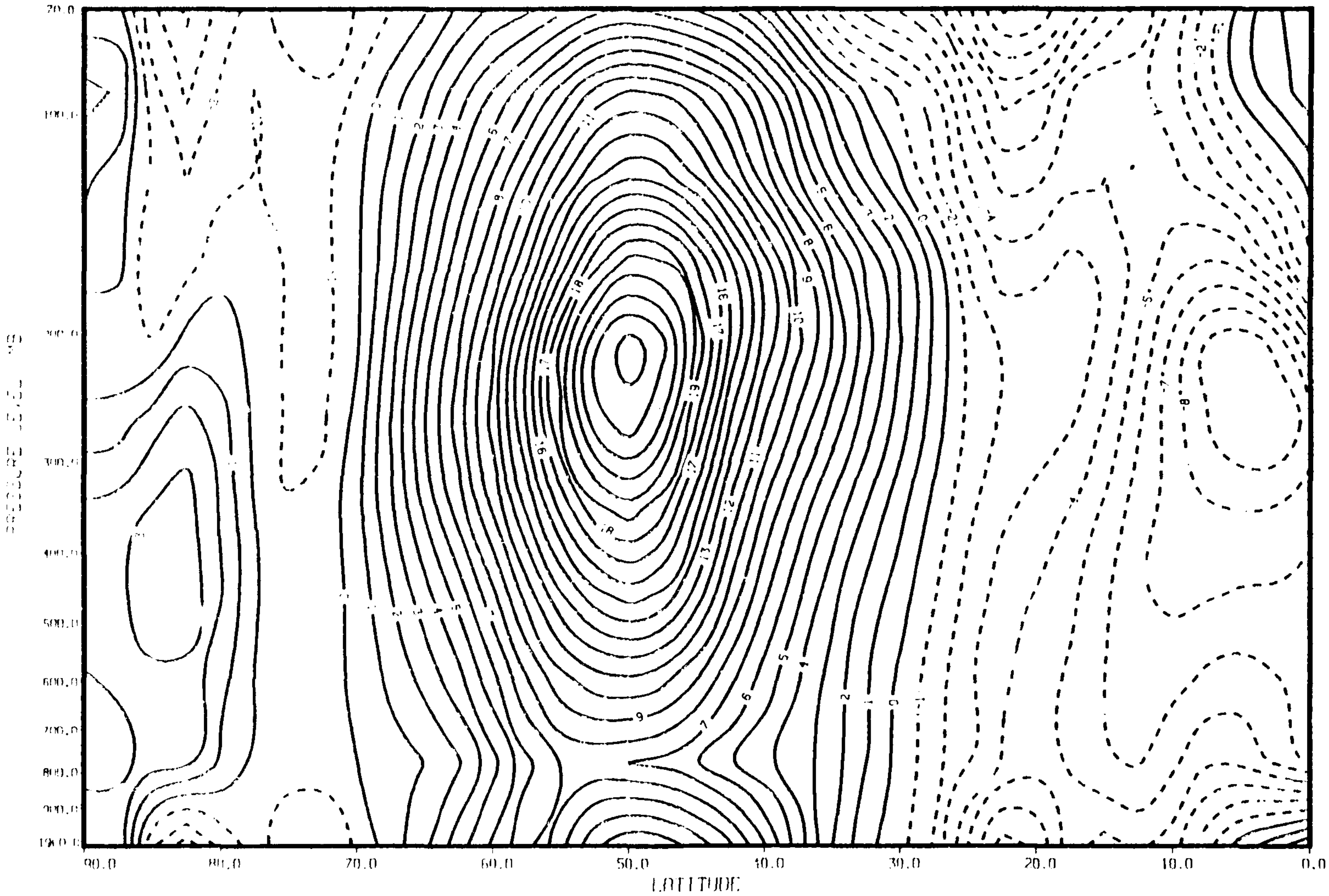


FIG. 42. Northern Hemisphere zonally averaged u between 130°W and 60°W, during July 1988. Contour increment: 1 m s^{-1}.

wind axis (maximum speed: 24 m s^{-1}) appears centered near 50°N, at about 220 mb. The surrounding u isotachs describe a (nearly) symmetric ellipse, with the minimum closed isotach (8 m s^{-1}) occurring between 34°N and 63°N, and verti-cally, between 850 mb and 70 mb.

Easterly winds occur on average, through the depth of the atmosphere south of about 30°N. There is one maximum equatorward of 8°N, centered near 230 mb, and another stratospheric jet at the 70 mb level centered at about 22°N.

In August (Fig. 43) the westerly maximum is similar in speed to that of July but occurs about 2° farther south, and a few mb higher in the atmosphere than during July.

Of greater interest, the August zonal isotachs are highly skewed left with a spike near 280 mb, the result of the increased jet activity in central and northern Canada.

Tropical easterly flow has increased as seen in the 12 m s^{-1} easterly isotach, equatorward of 10°N, at about 280 mb. The stratospheric easterly wind zone has the same speed and level as July, but has moved north to about 25°N.

The zonal flow during summer 1988 was compared to that of ECMWF (Fig. 4c). The distinct upward kink in the ECMWF 5 m s^{-1} isotach at about 65°N (Fig. 4c), hinting at the existence of a separate jet north of the primary jet is not seen in the July 1988 data. The level of maximum westerly wind is the same between the two but ECMWF shows it about 10° south of the July 1988 location. The easterly winds in

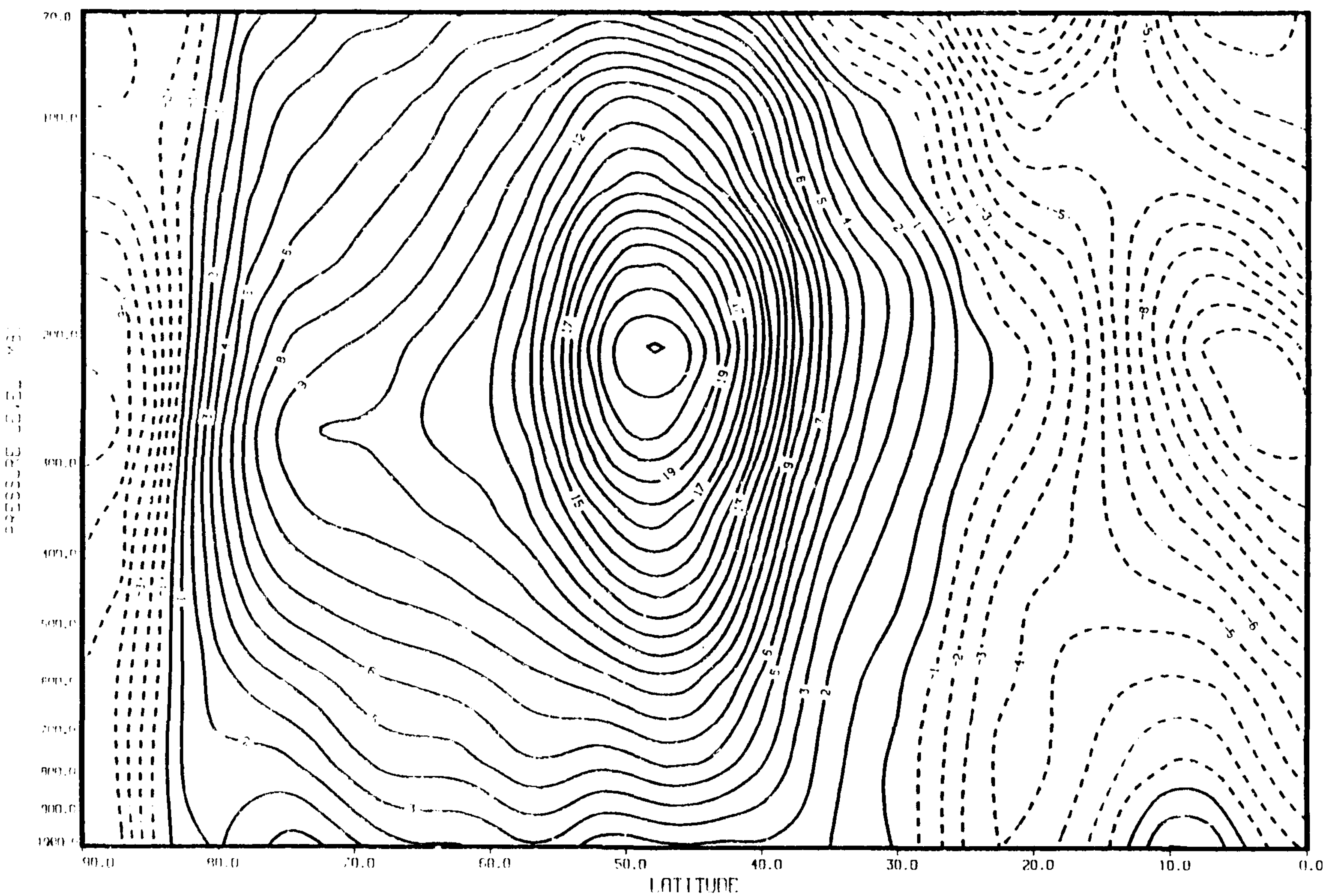


FIG. 43. Northern Hemisphere zonally averaged u between 130°W and 60°W, during August 1988. Contour increment: 1 m s^{-1}.

the tropics and subtropical stratosphere are, however, quite similar between the July data and ECMWF.

August 1988's average zonal wind bears closer resemblance to ECMWF chart (Fig. 4c). Levels of maximum wind are the same for both studies, and there is some evidence of a transitory jet north of the primary axis. The primary August westerly axis is 2° further south than in July, but still about 6° north of that depicted by the ECMWF (displaced northward, coincident with the height field, mentioned earlier. The shape of the August 0 m s^{-1} isotach mimics exactly that of ECMWF and there is even a near-surface tropical westerly wind zone at the same latitude.

Summer 1988 zonal flow (Fig. 44) bears less resemblance to the ECMWF than the August 1988 data alone, because of the lack of significant July jet activity north of the primary jet axis.

Meridional Flow

During July (Fig. 45), northerly winds occur through much of the atmosphere north of about 40°N. The maximum in this zone occurs at about 64°N and 400 mb. The Hadley circulation can be visualized in the weak southerly winds from the equator northward in the lower levels of the troposphere and the northerly return flow in the high middle troposphere equatorward of 38°N. The maximum northerly component (3 m s^{-1}) in the upper branch of the Hadley cell appears equator-

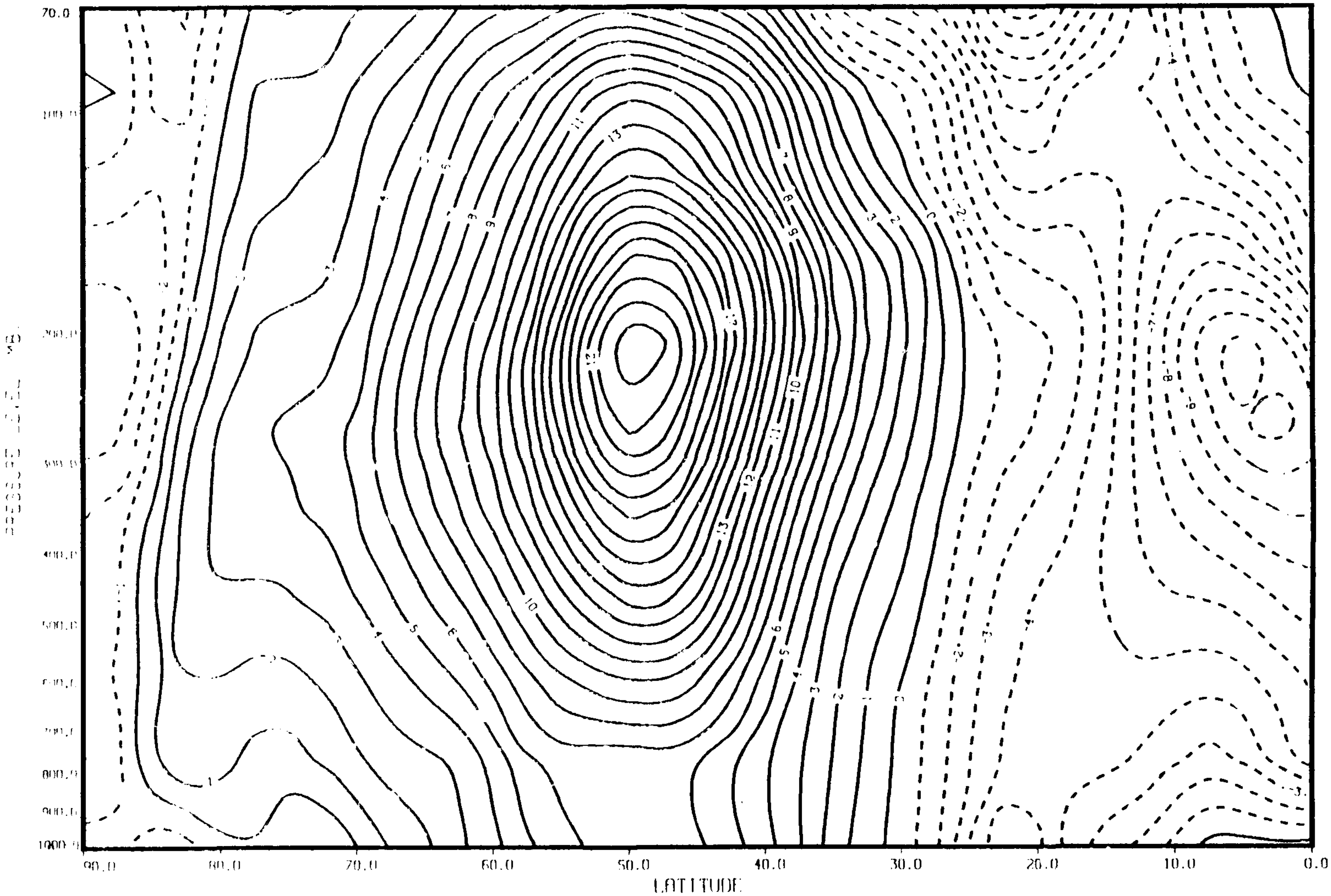


FIG. 44. Northern Hemisphere zonally averaged u between 130°W and 60°W, during summer 1988. Contour increment: 1 m s^{-1}.

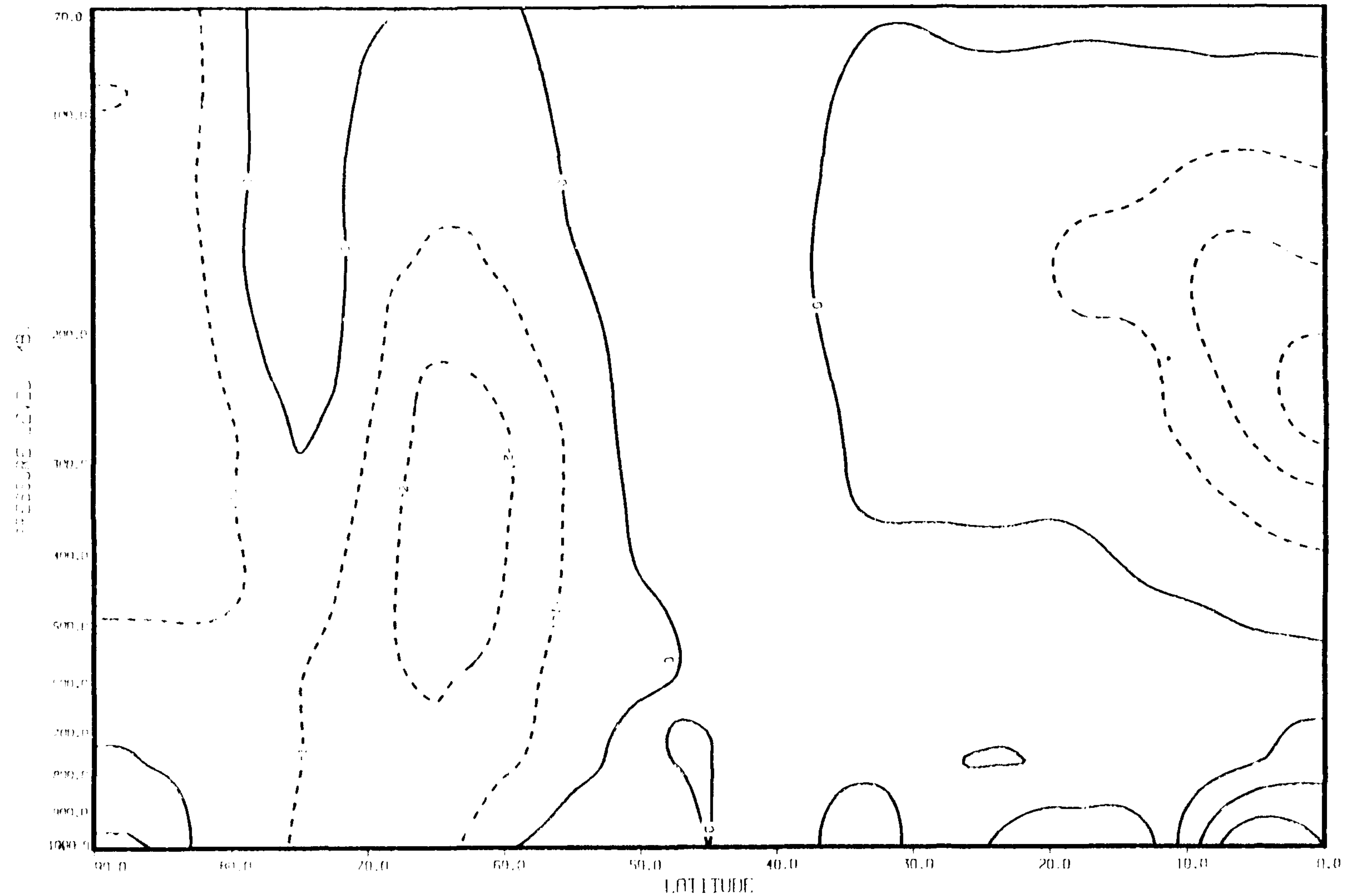


FIG. 45. Northern Hemisphere zonally averaged v between 130°W and 60°W, during July 1988. Contour increment: 1 m s^{-1}.

ward of 5°N.

During August (Fig. 46), low-level southerly winds (lower Hadley branch) are still observed from the equator northward, as is the upper level northerly Hadley return flow. But while the strength of the upper Hadley branch appears to be the same as July, (+3 m s^{-1}), it starts from further south (31°N) and occurs through a deeper layer of the troposphere. The mid-latitude northerly flow is stronger and deeper than July, and meridional flow has reversed in the polar region.

The most obvious difference in meridional flow regimes between July (Fig. 45) and August (Fig. 46) is the zone of southerly winds through the depth of the domain, centered at about 37°N during August. The maximum winds (2 m s^{-1}) occur between 160 and 310 mb.

The monthly and seasonal data were compared to the ECMWF summer meridional flow chart (Fig. 5c). The ECMWF convergence zone at about 15°N (northern extent of the Hadley cell) is seen at about 35°N in the July chart and at about 28°N in August. The pressure level at which the upper northerly branch starts is however, similar.

The northern ECMWF convergence zone (at about 60°N) is much more similar to the zones of convergence of July and August 1988.

It is coincident that enhanced poleward flow existed in the subtropics during August, when there was a preponderance

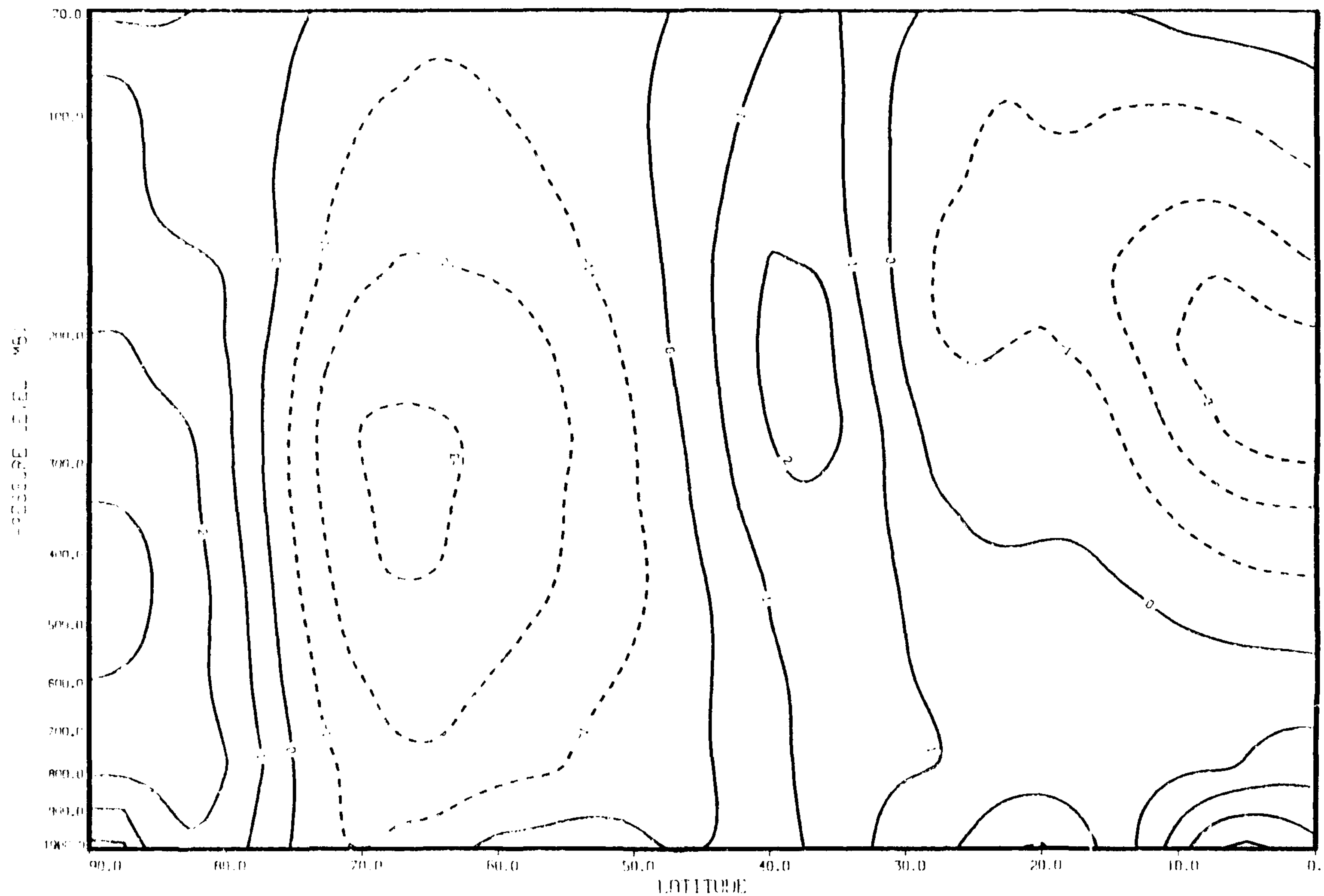


FIG. 46. Northern Hemisphere zonally averaged v between 130°W and 60°W, during August 1988. Contour increment: 1 m s^{-1}.

of multiple jet observations, but did not during July when there was commonly a single jet.

Avila and Clark (1988), in referring to the tropical storms of 1988, state that "rather strong easterly upper-tropospheric flow sheared much of the convection" generated by African (easterly) waves between June and late August. This caused a lack of tropical storm development in the western Atlantic during the period. But weakening of the easterlies from late August to November allowed some of the waves to develop into tropical storms and hurricanes.

Fig. 46 may show the onset of the enhanced poleward export of angular momentum to fuel a Northern Hemisphere westerly subtropical jet, at the expense of the upper tropospheric easterlies, as described by Avila and Clark. This jet, when averaged in with the location of the polar front jet, displaced the average August zonal jet location a few degrees to the south.

Fig. 47 shows the July-August 1988 composite meridional motion field. The northerly upper-tropospheric southerly wind zone that appeared in the August data is present but weaker, as are the branches of the Hadley cell.

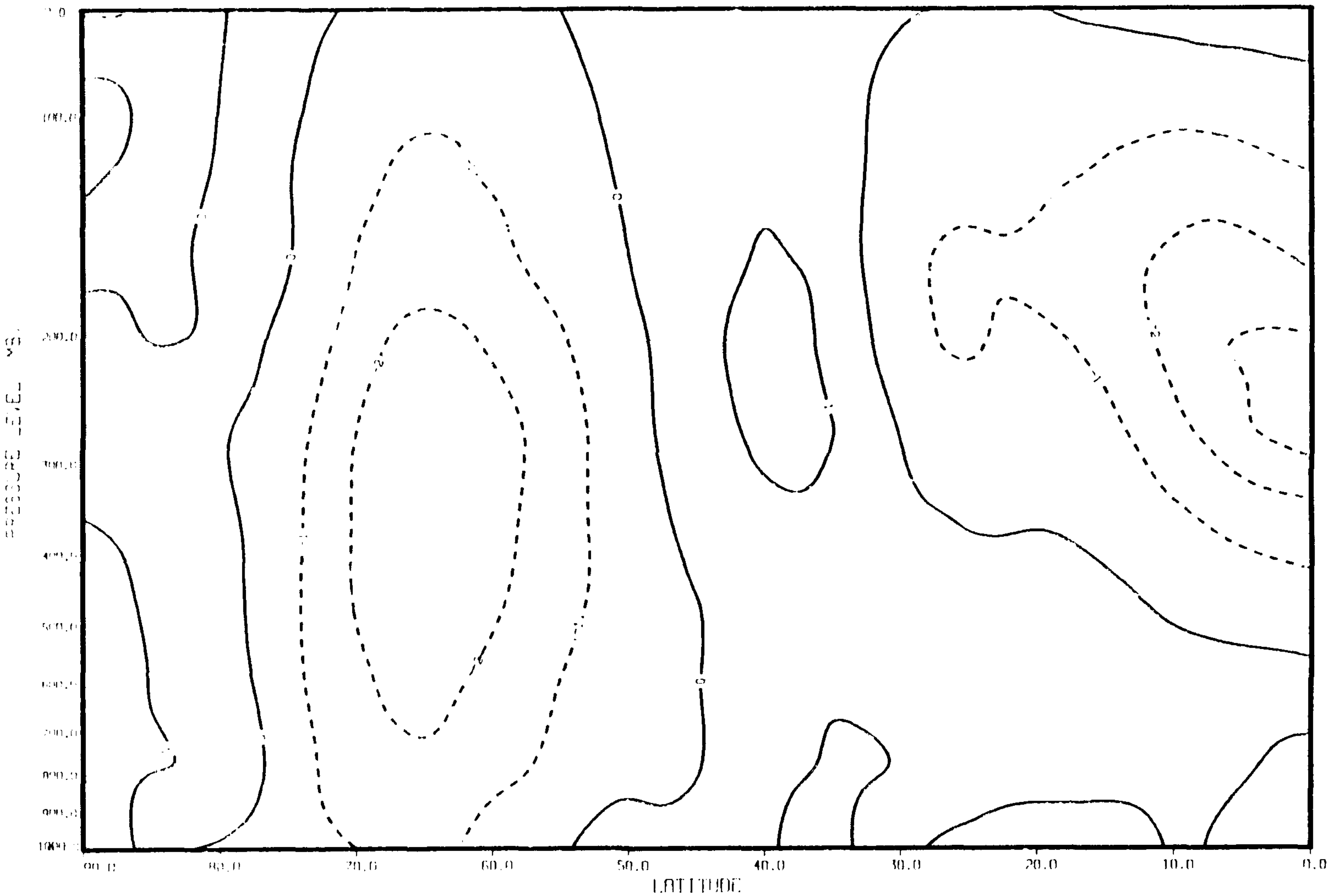


FIG. 47. Northern Hemisphere zonally averaged v between 130°W and 60°W, during summer 1988. Contour increment: 1 m s^{-1}.

CHAPTER V

JET REGIME SIGNATURES

In addition to the representative statistics already described, Q-vector analysis, and potential vorticity analysis, were performed in order to further describe the different jet stream regimes of summer 1988. In addition, GOES satellite images were perused for the signatures of polar and subtropical jets.

A. Q-vector

Though numerous authors have attempted to apply corrections to the continuity equation to enhance its usefulness in the estimation of vertical motion (Lateef, 1967; O'Brien, 1970; McFarland and Sasaki, 1977), it has generally lost favor. It uses the addition of horizontal wind derivatives, usually of opposite sign, to find vertical velocities. Because the magnitude of vertical motion is usually smaller than the input winds by orders of magnitude, a 10% error in horizontal wind measurement can easily yield a 100% error in the estimation of divergence, and vertical velocity (Holton, 1979, p. 73). This study will utilize the Q-vector equations devised by Hoskins et al. (1978) to infer vertical motion. These equations are based on the omega equation.

Though the omega equation is also somewhat subject to term cancellation, Hoskins replaced those terms in such a way potential cancellation is avoided:

$$(\sigma\nabla^2+f_0^2\frac{\delta^2}{\delta p^2})\,\omega=-2\nabla\bullet Q$$

As stated by Sanders (1989), "The Q-vector itself indicates the horizontal gradient of vertical motion and the vertical gradient of the ageostrophic wind component." Q-vector divergence shows the *forcing function* in the quasi-geostrophic omega equation, ie. vertical motion tends to be upward when the Q-vector is convergent.

The Q-vector analysis level, 500 mb, was picked because, *being near the level of non-divergence*, vertical velocities should be most apparent. Though ideally, the equations should use geostrophic wind components, for a synoptic scale analysis the use of the given u and v fields suffice.

The 500 mb Q-vector distribution and 200 mb wind speed maxima for the single jet case of 1200 UTC 15 July 1988 are shown in Fig. 48. West of Lake Winnipeg in central Manitoba, the Q-vector points generally north. This indicates that the ageostophic motion is northward in the mid troposphere beneath the jet, while above the jet the ageostrophic motion is southward (since in the upper tropospheric ageostrophic motion occurs in opposite direction

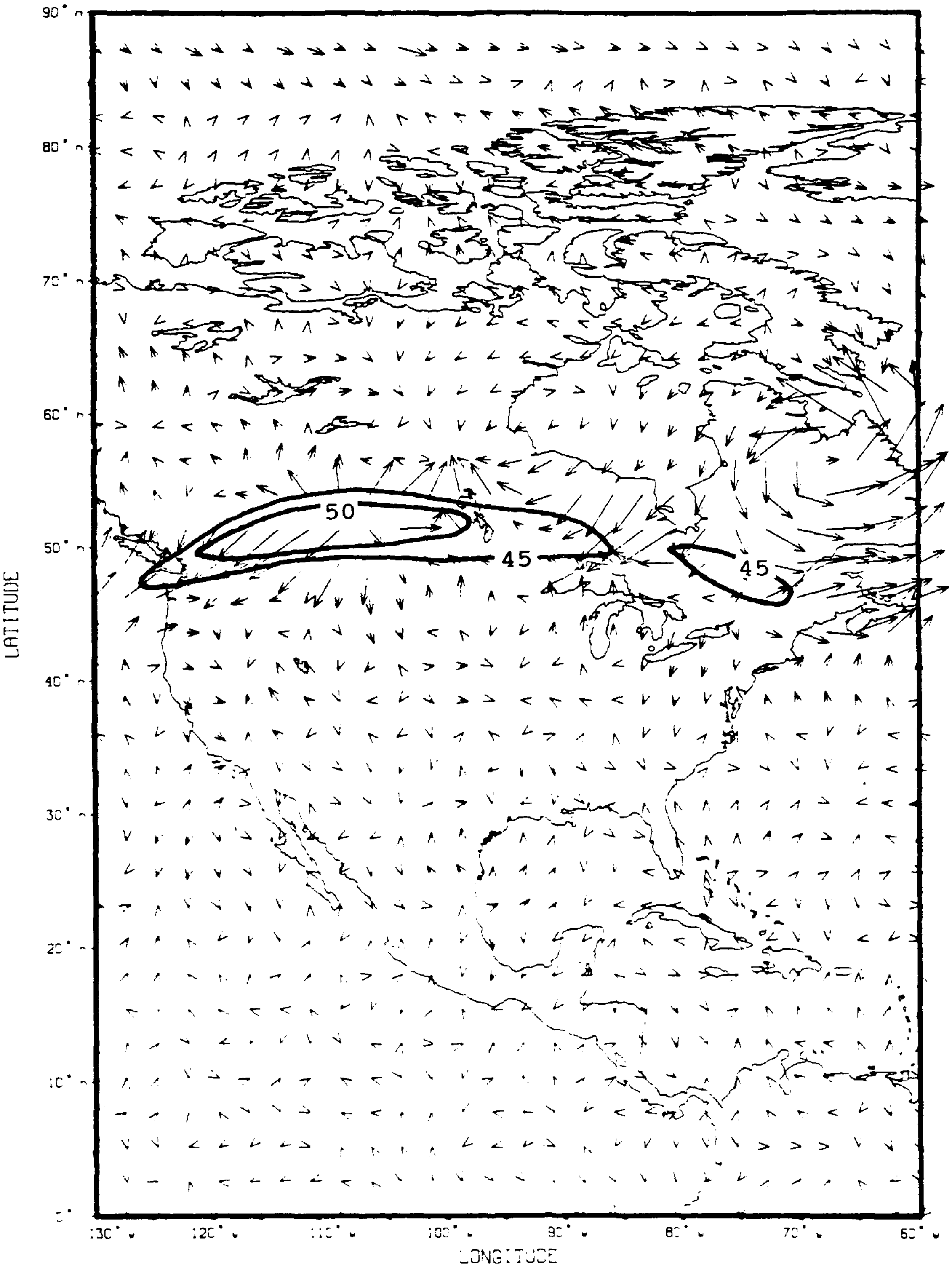


FIG. 48. The Q-vector distribution at 500 mb with 200 mb wind maxima traced, for 1200 UTC 15 July 1988. Relative magnitude of Q is indicated by arrow length, wind in m s^{-1}.

to that of the Q-vector (Sanders, 1989). This illustrates the classic example of counter-clockwise (looking downstream) "indirect" circulation at the exit of the jet streak.

The "direct" circulation field at the entrance region of this jet is seen in the Q-vector that points southwest, just east of Vancouver Island, British Columbia. Here, the mid-tropospheric flow is in the same direction as the Q-vector (southwest), while above the jet, ageostrophic flow is to the northeast. The jet-entrance ageostrophic flow is therefore counter-clockwise looking downstream, with warm air rising, south of the jet entrance, and cold air sinking north of it. A similar ageostrophic flow pattern is seen near the jet streak southeast of James Bay.

The 500 mb divergence of Q (Div-Q) diagram for the same period (Fig. 49) confirms the vertical motion suggested by the Q-vector analysis, and the convergence/divergence pattern near a jet streak (Reihl et al. 1952). There is upward vertical motion over Vancouver Island and northwest of Lake Winnipeg, near the right-rear, and left-front portion of the jet streak, respectively. Conversely there is sinking over central British Columbia, at the left entrance of the streak; and over North Dakota and Montana, at the right front of the streak; with a maximum beneath the center of the streak. Further downstream, a similar pattern of lifting and sinking occurs about the jet streak in southern

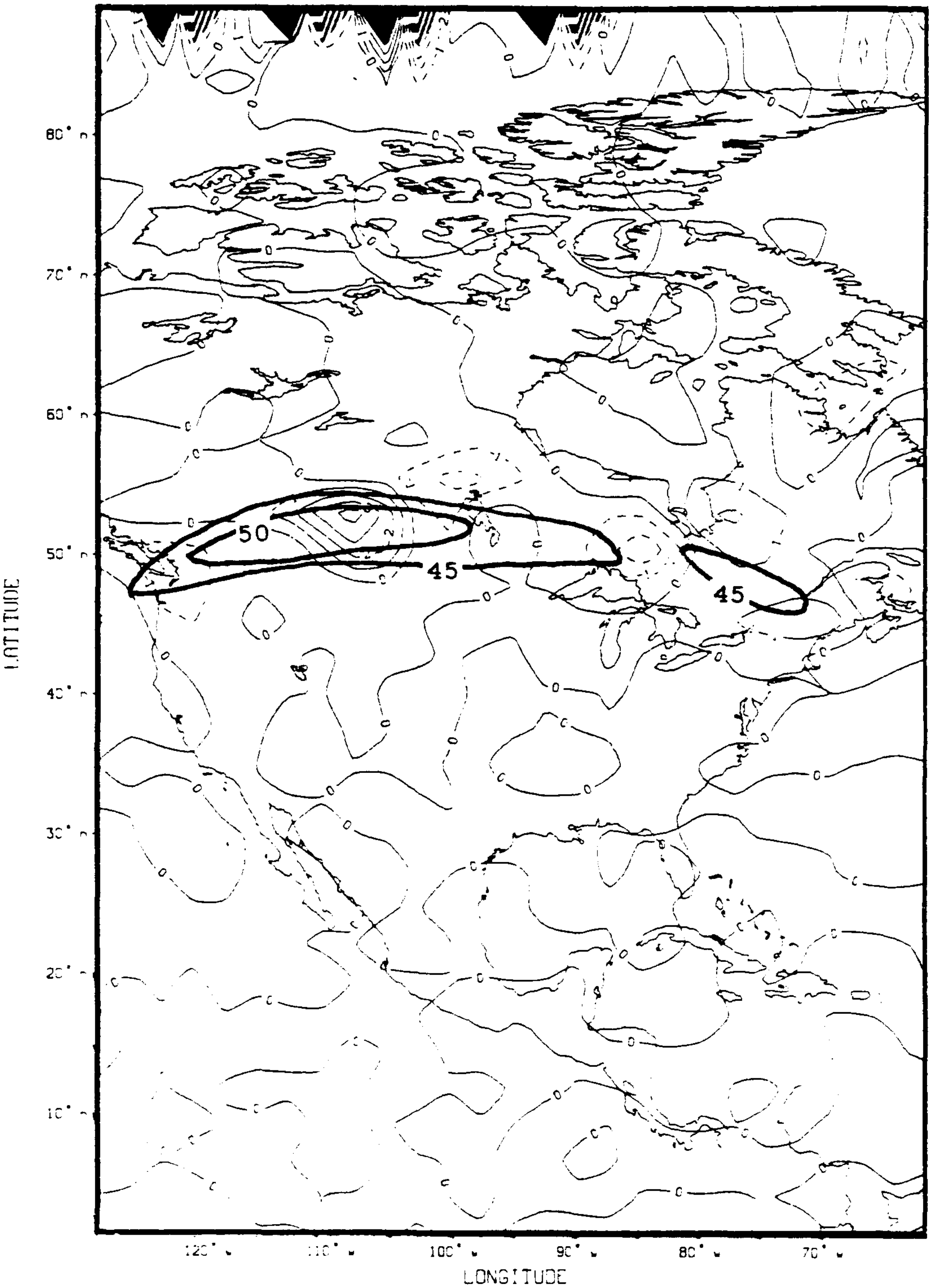


FIG. 49. The Div-Q distributi‹n at 500 mb with 200 mb wind maxima traced, for 1200 UTC 15 July 1988,. (Thin solid lines show sinking, thin dashed lines show lifting and heavy solid lines show wind speed in m s^{-1}).

Ontario and Quebec Provinces. (Note: the data spikes near 90°N are a function of source data array and not an atmospheric phenomenon.)

An interesting feature appears between the two streaks, possibly due to their orientation with one another. A lifting region (convergence of Q) occurs directly between the left-front of the upstream jet streak, and the right-rear of the downstream jet streak.

An example of the Q-vector field for a double jet case (0000 UTC 22 August 1988) is shown in Fig. 50. On this date there was a deep, sharp trough over western Canada with jet speed winds about it. Over the United States, another more zonally oriented, jet stream was occurring. The agestrophic circulations fit the text-book circulations about a small speed maximum southwest of Santa Barbara California, as well as at the exit of the jet streak in southern Alberta.

At the apparent confluence of the jets, over northern Montana, a similar direct/indirect ageostrophic pattern is observed at the entrance/exit regions of the merger, respectively (though the direct circulation appears stronger). On the eastern side of the trough between Lake Athabasca and Lake Winnipeg, another lifting/sinking couplet occurs about the 25 m s^{-1} isotach.

Large ageostrophic flows (long Q-vector) occur west of Lake Winnipeg, and larger still, off the Eastern Seaboard.

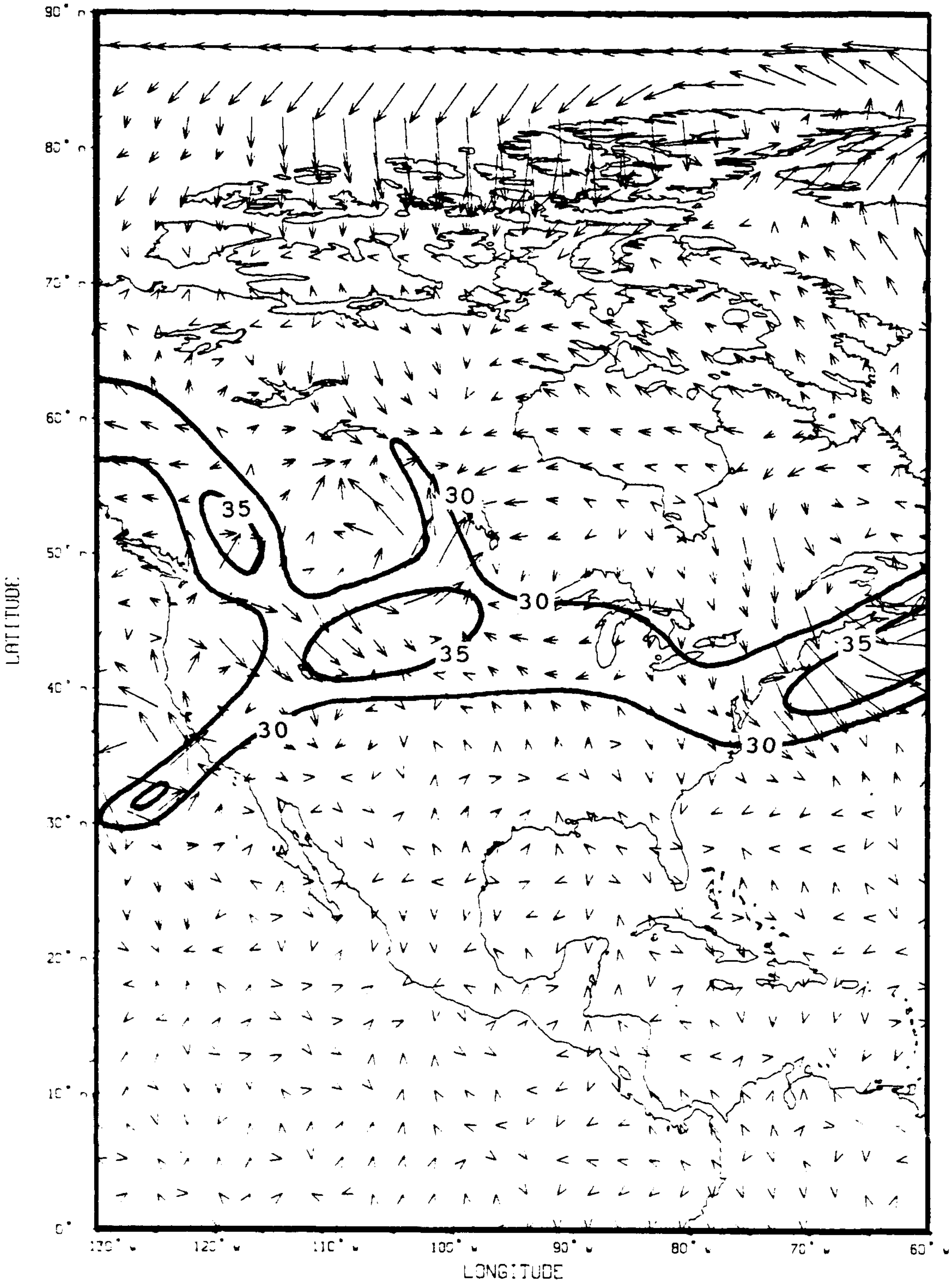


FIG. 50. The Q-vector distribution at 500 mb with 200 mb wind maxima traced, for 0000 UTC 22 August 1988. Relative magnitude of Q indicated by arrow length, wind in m s^{-1}.

The Div-Q chart for the same period (Fig. 51) shows an area of vertical motion occurring north of the Montana/Alberta border. This could be an area with the potential for severe weather (Whitney, 1977; Uccellini, 1987; McNulty, 1978), and the GOES satellite image from the same observation time shows a large complex of thunderstorms northeast of the diffluence of the jets.

Shapiro (1983, p. 3-9) states that secondary circulations may deviate from the classical direct and indirect circulations when jet front systems are imbedded within sharp upper tropospheric waves, but in most cases analyzed in this data set, correlation of jet location with Q-vector convergence/divergence were quite good.

There were no significant differences noted in either the Q-vector nor Div-Q fields between the single and double jets analyzed, except when the jets were close enough together that their ageostrophic flow fields interacted.

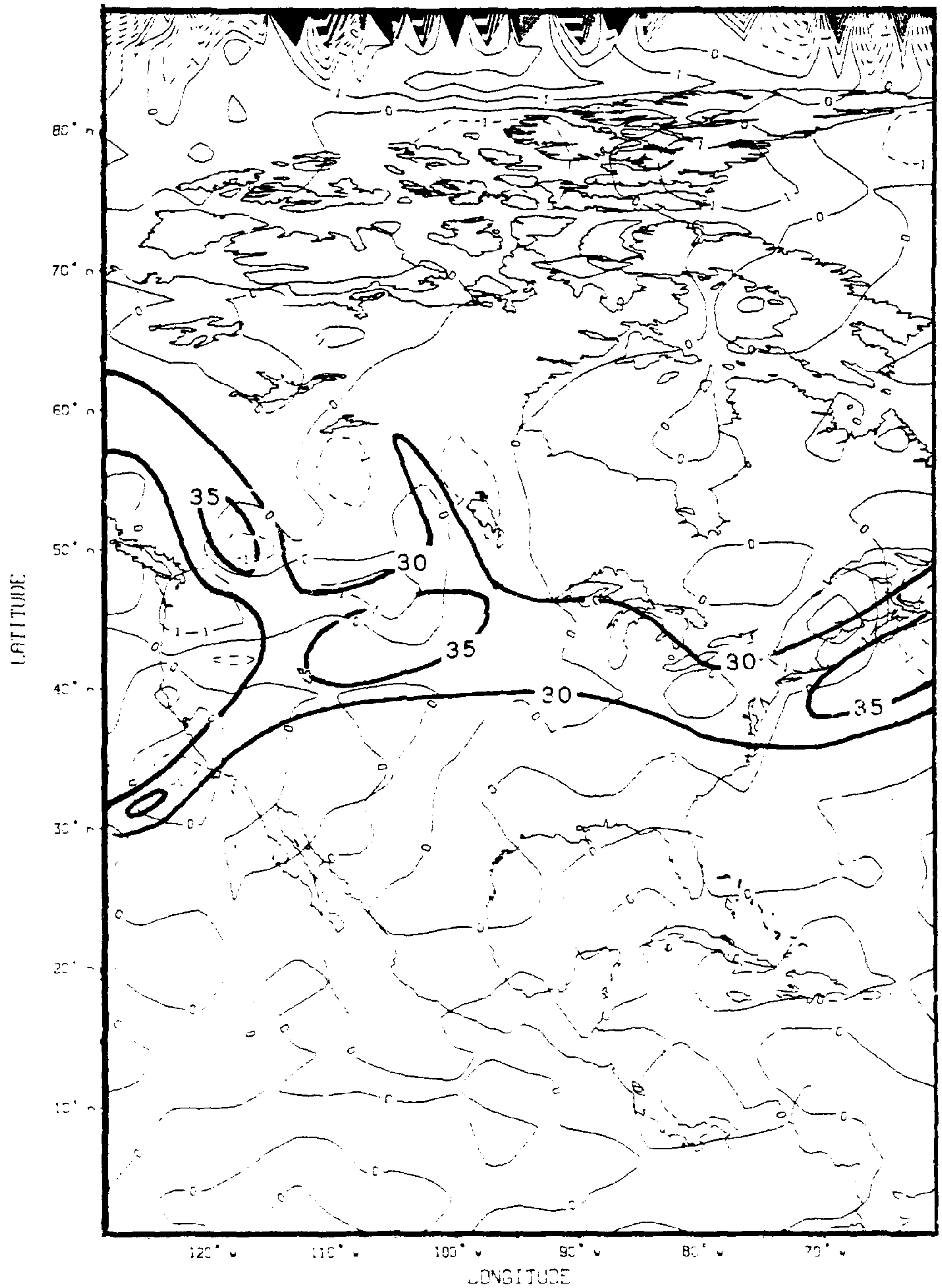


FIG. 51. The Div-Q distribution at 500 mb with 200 mb wind maxima traced, for 0000 UTC 22 August 1988. (Thin solid lines show sinking, thin dashed lines show lifting and heavy solid lines show wind speed in m s^{-1}).

B. Potential Vorticity

Isentropic potential vorticity (IPV) is usually defined as:

$$P=-g\zeta_{a_\theta}\frac{\delta\theta}{\delta p}$$

Boyle and Bosart (1986) suggested potential vorticity was more useful in defining the tropopause than conventional lapse rate of temperature. Similarly, Hoskins et al. (1985) defined $1X10^{-6}$ K kg^{-1} m^2 s^{-1} as a "potential vorticity (PV) unit" and found that in the troposphere, typical PV unit values were generally less than 1.5, while at and above the tropopause, the values were typically in excess of four units. In a later work, *Hoskins (1990)* stated, "From the pole to about 25°N, the 2 X 10^{-6} K m^2 kg^{-1} s^{-1} surface corresponds to the tropopause." His accompanying diagram (Fig. 52) suggests that PV values vary from 0 to 10 PV units south of about 25°N.

Unlike the procedure used by Hoskins (1985), potential vorticity values for the vertical sections shown in this study are computed with respect to standard pressure levels.

$$PV=-g\zeta_a\frac{\delta\theta}{\delta p}$$

This allows comparison with other vertical sections plotted

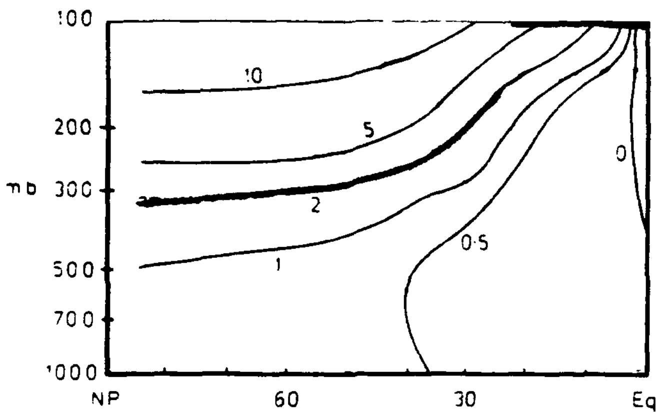


FIG. 52. Zonally averaged Northern Hemisphere potential vorticity distribution. PV contour increment: 1X 10^{-6} K kg-1 m^2 s^{-1}. PV tropopause: heavy line. (After Hoskins, 1990).

This allows comparison with other vertical sections plotted with respect to pressure level.

Shown in Figs. 53 and 54 are vertical sections of potential vorticity for the single jet case of 1200 UTC 16 July, and the double jet case of 1200 UTC 3 August.

On both diagrams, the lowest value at which the PV isopleths begin to pack is 2.0 X 10^{-6} K m^2 $kg^{-1}s^{-1}$. However, the 4.0 X 10^{-6} K m^2 $kg^{-1}s^{-1}$ isopleths fit better with the jet cores observed, to describe the tropopause (keeping the jet cores in the tropospheric air). Note: the packing above the 100 mb level is an artifact of the contouring routine used and should not be construed as an atmospheric phenomenon.

In both cases, there are troughs in the potential vorticity tropopause (as low as 400 mb at about 68°N on the 13 August chart), which show tropopause folding on the cyclonic side of the jet streams present that day. The tropopause as defined by the 4.0 X 10^{-6} K m^2 $kg^{-1}s^{-1}$ potential

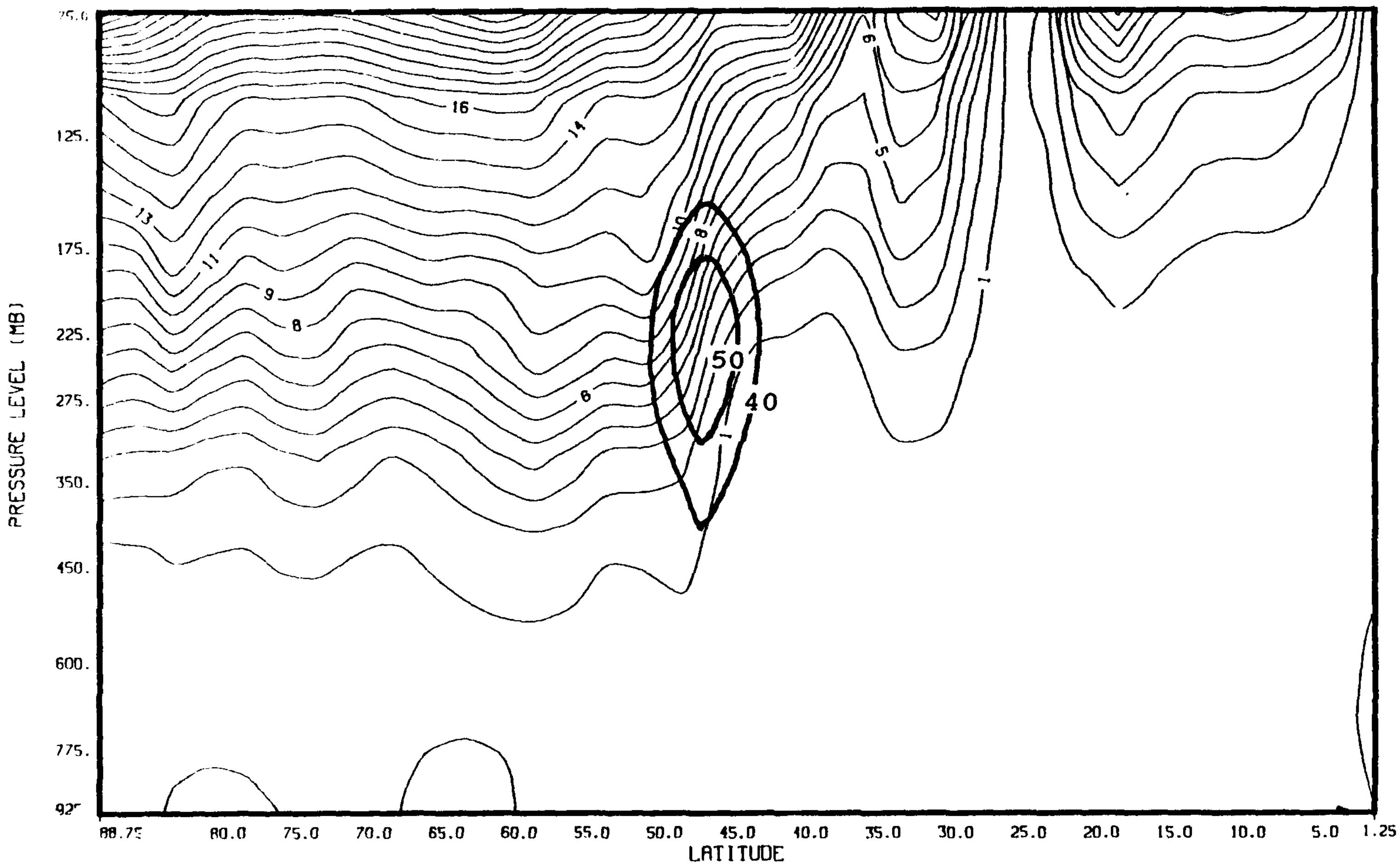


FIG. 53. Section through a typical single jet (1200 UTC 16 July 1988 at 70°W), showing jet core and distribution of potential vorticity. Jet core: heavy solid lines in m s^{-1}; potential vorticity: thin solid lines in increments of 1 $X10^{-6}K\ kg^{-1}\ m^2\ s^{-2}$.

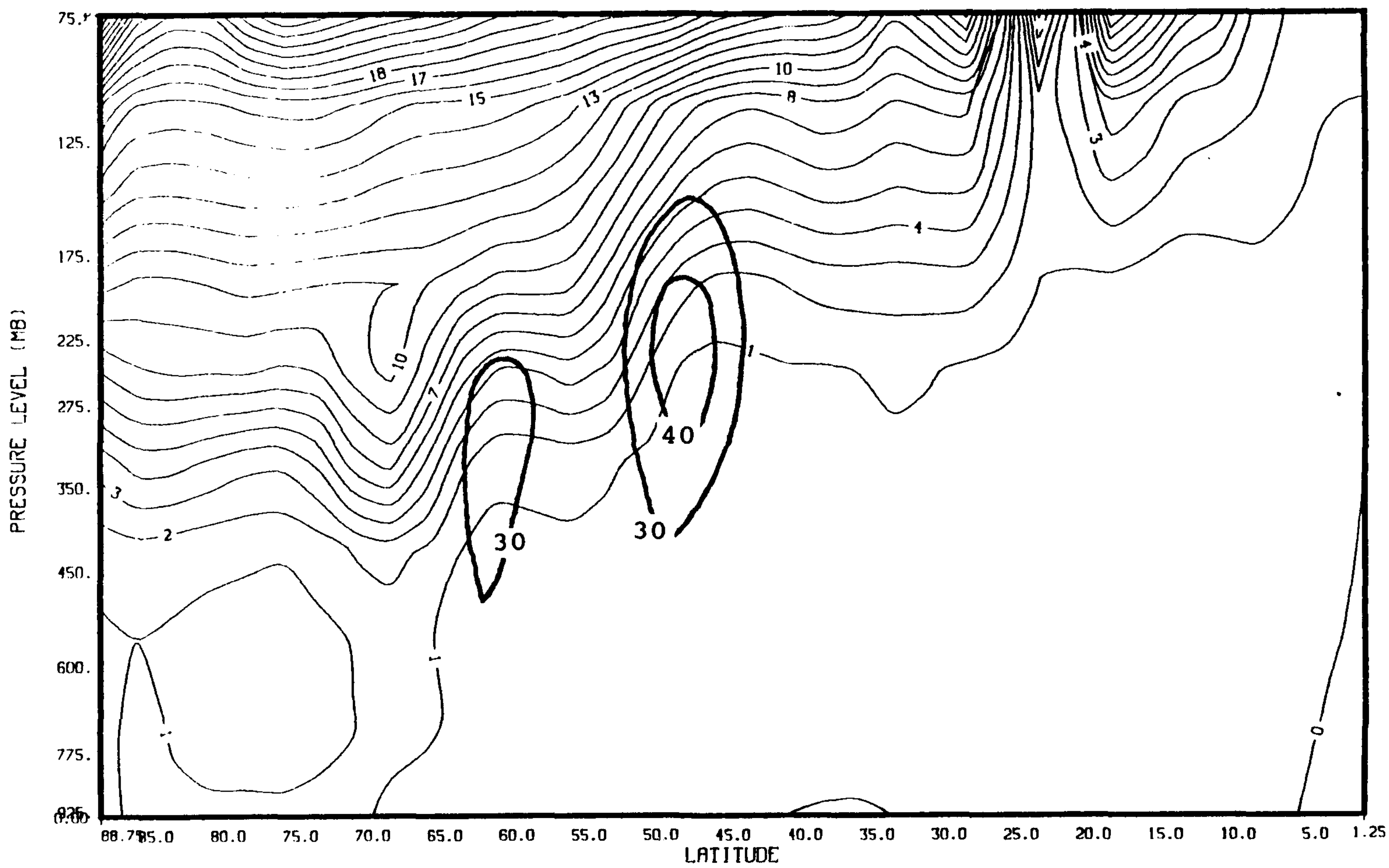


FIG. 54. Section through a typical double jet (1200 UTC 3 August 1988 at 93°W), showing jet cores and distribution of potential vorticity. Jet cores: heavy solid lines in m s^{-1}; potential vorticity: thin solid lines in increments of 1 $X10^{-6}K$ kg^{-1} m^2 s^{-2}.

vorticity isopleth is similar, in level, to the tropopause described earlier with respect to potential temperature (Figs. 40 and 41). There is more detail however in the potential vorticity tropopause, due to the method of its computation, ie. using the *gradient* of potential temperature and absolute vorticity.

The reversal of the sign of potential vorticity in the vicinity 23°N on 16 July at the 85 mb level (dashed isopleth), corresponds to the anticyclonic vorticity on the poleward side of an upper level easterly wind zone (seen as a 15 m s^{-1} isopleth, centered at 18°N above 100 mb in Fig. 40). The magnitude of anticyclonic relative vorticity in this areas is slightly greater than the Coriolis parameter, *making the absolute vorticity negative. This in turn makes* the potential vorticity in the area slightly negative. The final result is a "notch" in the potential vorticity tropopause. This feature is not depicted on the schematic provided by Shapiro in Fig. 55 (After Shapiro et al., 1987.), which shows a smooth pole-to-equator tropopause with folds at the fronts. Nor was it shown in Fig. 52, the climatological average potential vorticity chart (After Hoskins et al., 1990.).

Shapiro (1983, p. 3-25) does mention negative upper tropospheric potential vorticity generating transverse wave fronts and turbulence in the mid-troposphere. In this case no turbulence features were observed nearby on the GOES

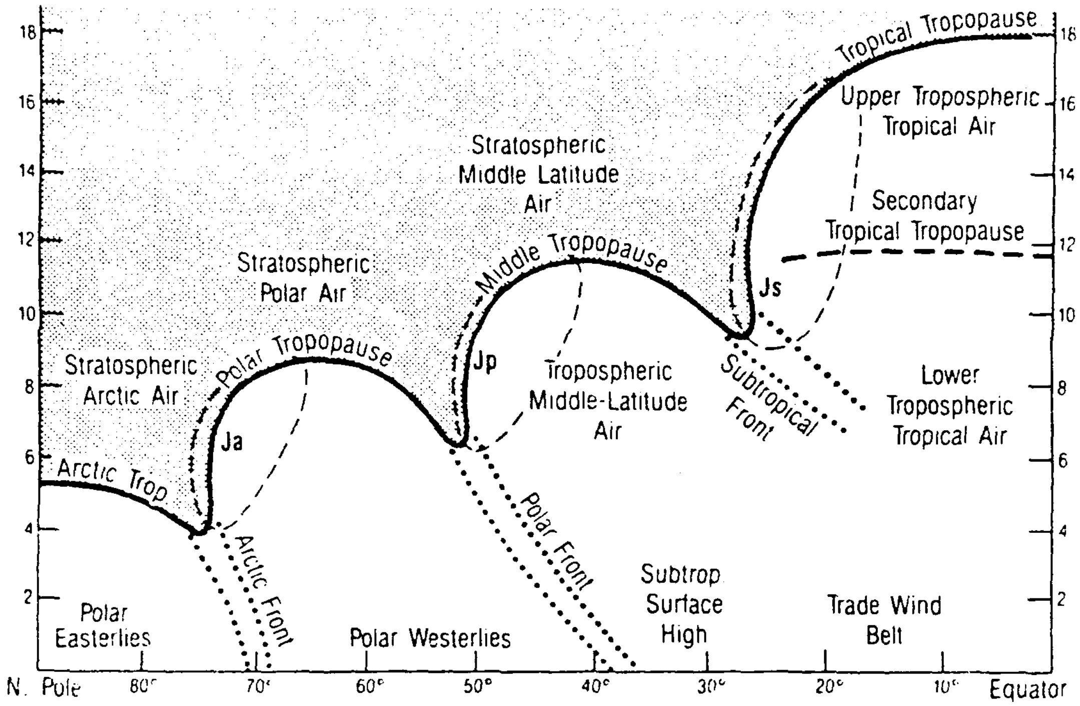


FIG. 55. Schematic of the potential vorticity tropopause between the North Pole and Equator. (After Shapiro, 1987).

tropospheric potential vorticity generating transverse wave fronts and turbulence in the mid-troposphere. In this case no turbulence features were observed nearby on the GOES images. But based on the climatological location and speed of the summer stratospheric easterly wind zone in the tropics, this notch in the potential vorticity troposphere may be a common feature.

C. Satellite images

Often the polar front jet can be discerned from the subtropical jet stream by the pattern of coincident cirrus clouds. The cirrus associated with the polar front is usually oriented collinear with the PFJ axis. Conversely, high clouds that occur with the subtropical jet are often cirrocumulus, oriented in bands, perpendicular to the jet axis (especially in winter when horizontal and vertical wind shears are greater).

Though during the month of August, the jet stream over the Southwest occurred in a common *wintertime* location of the subtropical jet stream, there were no observed instances during the two month period when the jet cirrus over North America was arrayed in transverse bands. The few times when transverse banding was observed, it occurred off the Eastern Seaboard (Fig. 56) or in the western Atlantic.

Either no subtropical jets were present over North America during the observation period, or transverse banding could be a winter-only signature of the subtropical jet stream.

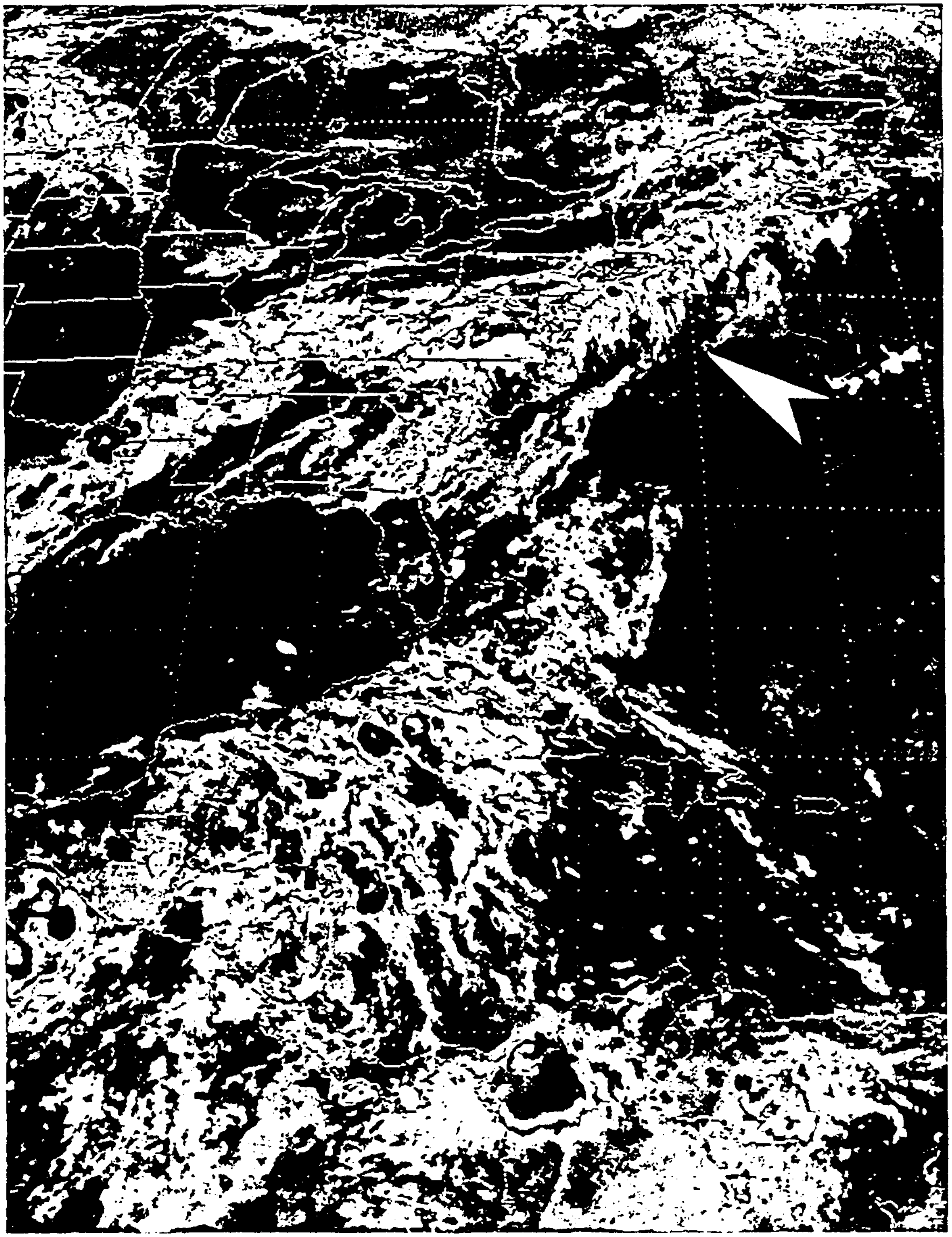


Fig. 56. Transverse jet cirrus banding as seen from GOES East, 1201 UTC 12 July 1988.

CHAPTER VI

SUMMER 1988 WEATHER DESCRIPTION

This season was characterized by anomalously warm and dry weather over the greater part of North America. While not as extreme as the "dust bowl" days of the 1930s, many locations set new records for drought and high temperatures.

During June 1934, at the height of the dust bowl, "the greatest disaster in American history attributable to meteorological factors." (Heim, 1988), drought affected over 61% of the country. By mid-July 1988 about 45% of the country was experiencing severe to extreme drought.

The 1988 drought had its beginning as early as 1987. Trenberth et al. (1988) suggest the 1987 El Nino event as a possible cause of the drought. They show that as a result of a strong ridge of West Coast high pressure during winter 1986/1987, the jet split off the West Coast. The southern branch of the split jet (that often brings wet weather to the Southwest) was weak during the last half of the winter season and the northern branch was displaced northward into Canada. As a result, there was a lack of storm tracks across the United States. A similar pressure anomaly pattern during the winter of 1987/1988 set up the drought of summer 1988.

Concurrent with the drought of 1988, average temperature over North America was anomalously high. Trenberth et al. (1988) state that insolation from the sun is usually partitioned into evapotranspiration and sensible heat, but that during drought conditions, with little moisture to evaporate, most heating is manifested in temperature increases. Heim states that during the summer, "nearly 2000 daily temperature records were set in the Northern and Central Plains, Midwest, Ohio Valley, Great Lakes, and Northeast," with daytime high temperature over 100° during nearly 1/3 of the days in June over much of the Central Plains.

Jet Stream Location and the Weather of Summer 1988

Northern Washington State and the northern portions of Idaho and Montana had areas where rainfall was 150% of normal, near the 40 occurrence isopleth of the July 250 mb jet stream frequency chart.

Over Canada, "Monthly (rainfall) totals near twice the normal were observed in the Maritime Provinces (New Brunswick, Prince Edward Island and Nova Scotia", (again under the 40 occurrence isopleth at 250 mb));"along the northwest coast of British Columbia and Vancouver Island" (40); "in central Alberta" (40); "and in the central parts of the Yukon Territory..." (Ludlum, 1988).

The western United States south of the Oregon-California border, experienced normal to below normal precipitation during the month of July, coincident with an area of less than 5 jet stream occurrences. Over the central portion of the country some of the rainfall was generated by nocturnal mesoscale convective complexes, (events that are negatively correlated with jet streams.) In the South, rainfall maxima occurred in central and west Texas. A squall line on 11 July dropped ten inches of rain on portions of west Texas.

The July jet stream while lingering in southern Canada, brought no relief to the sweltering lower 48 states, where July average temperatures were above normal over more than half the country (four to six degrees (F) above normal over much of the west, north-central and northeastern part of the country.)

In southern Canada, average July temperature was about two degrees above normal. Southern Ontario, south of the average jet frequency axis had the hottest July in thirty years (Heim, 1988).

Unlike July, higher than normal rainfall totals occurred from extreme southern California northeastward, as well as in central Nevada. These locations were coincident with the more common location of the southern, August jet. Between 5 and 11 August, a tropical disturbance off the west coast of Mexico (south of the southern jet), provided the source moisture for at least some of the anomalously high rainfall in the Desert Southwest.

During August, though average temperature was anomalously high over a greater portion of the United States than in July, the departures from normal were not as pronounced. Extreme southern California, central Nevada and central Utah were influenced by more jets than in July and temperatures were closer to normal than in the previous month, a result of cooler and more moist airmasses transported by the jet.

Over Canada, the first half of August was about two degrees cooler than normal from Saskatchewan west (on the cyclonic side of the jet), and four to six degrees warmer than usual in the east (on the anticyclonic side of the jet).

This scenario reversed during the second part of August with the west warmer, and eastern Canada cooler than normal. A warm ridge entering British Columbia on 20 August, tracked eastward to central Manitoba by 30 August. Concurrently, a northwesterly jet ahead of the ridge brought cooler polar air to the eastern part of the country. (The influence of the Canadian jets shows up in the spike near 300 mb on Fig. 41).

Comparison of the *Daily Weather Maps*, the individual significant weather events from *Weatherwise,* and the individual days' 250 mb charts usually showed upper tropospheric wind in excess of 15 m s^{-1} near the high precipitation/ severe weather locations (most usually to the northwest).

In summary, jet stream locations during summer 1988 were highly correlated with temperature, and precipitation patterns. During July when the jet was most often near the US/Canada border, the southern provinces of Canada had cool moist weather, while most of the US, especially the upper-Midwest, sweltered under hot dry conditions. The conditions changed in August when a double jet regime moderated temperatures over the US. Coincident with the change, rainfall decreased over the northwestern United States, while higher than normal rainfall amounts occurred in portions of the Desert Southwest.

CHAPTER VII

SUMMARY

Much literature exists describing the jet stream, but most authors concentrate on the winter jet. This study was performed to describe the jet stream during a summer season, particularly, summer 1988. The July regime was that of a single jet while August's showed multiple jet streams.

Conflicting properties of the August regime make it difficult to describe which jets were present that month. The northern jet always fit the classic description of a polar front jet. The southern jet however, had some polar front characteristics as well as some of the subtropical jet. In depth and satellite signature, it resembled a polar front jet; but in altitude, map location, and meridional circulation, it more resembled a subtropical jet.

The author's conclusion is that after the high index stage of circulation during July broke down toward the end of that month, enhanced meridional circulation generated separate systems whose individual jet streams, in conjunction with the primary jet axis near the United States/Canada border, gave the appearance of a multiple jet regime.

The latitudinal location and baroclinic properties of the southern jet streams provided characteristics that were in some respects polar and in others subtropical.

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