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(FOURTH NUMBER, VOLUME XIV)

MEAN STREAMLINES AND ISOTACHS AT  
STANDARD PRESSURE LEVELS OVER THE  
INDIAN AND WEST PACIFIC OCEANS AND  
ADJACENT LAND AREAS

BY

R. FROST, B.A. and P. M. STEPHENSON, M.Sc.



LONDON: HER MAJESTY'S STATIONERY OFFICE

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# MEAN STREAMLINES AND ISOTACHS AT STANDARD PRESSURE LEVELS OVER THE INDIAN AND WEST PACIFIC OCEANS AND ADJACENT LAND AREAS

## SUMMARY

In order to facilitate analysis at the British forecast offices in the Indian Ocean area mean streamlines and isotachs have been prepared for the standard pressure levels from 700 mb to 200 mb for the mid-season months and these are presented here.

The main features of the flow patterns are discussed and a simple explanation is suggested of certain salient features which have no parallel elsewhere in the Tropics, namely:

- (i) The low-level equatorial westerlies lying between the low-level equatorial troughs of both hemispheres at all seasons,
- (ii) the progress of the Asiatic summer monsoon,
- (iii) the high-level transequatorial flows in January and July.

## INTRODUCTION

On arrival in tropical and equatorial latitudes meteorologists accustomed to chart analysis in temperate latitudes find themselves in areas where the conventional pressure and contour analyses with which they are familiar are no longer applicable and where the main tools of analysis are streamline-isotach charts.

As a matter of historical interest direct wind analysis was used by V. Bjerknes *et alii*<sup>1</sup>\* for temperate latitude forecasting in the early part of this century but pressure analysis which requires less skill later replaced this and in a discussion of the relative merits of the two techniques of analysis Shaw<sup>2</sup> even went to the extent of claiming that given a map of the distribution of pressure over an area a map of the winds could be derived which would be more effective than one based on actual winds.

This somewhat sweeping assertion, even if true in temperate latitudes, is certainly not valid in the Tropics where the pressure patterns are weak and ill defined at the surface and non-existent at higher levels, see for example Heastie and Stephenson,<sup>3</sup> and the pressure-wind relationship which is an essential prerequisite for finding the wind flow is not known. Meteorologists working in low latitudes were accordingly forced back to first principles and Palmer<sup>4</sup> applied Bjerknes's streamline-isotach technique to tropical forecasting.

In this technique of analysing the wind field two sets of lines are used. The first set called streamlines are tangential to the wind direction at all points and the second set called isotachs are lines of equal wind speed. The former disclose a series of patterns such as outflows, inflows, neutral points and axes of maximum curvature whilst the latter disclose patterns of wind speed maxima and minima. In regions where the geostrophic pressure-wind relationship holds the above streamline patterns correspond with the main features of a pressure chart namely highs, lows, cols, ridges and troughs respectively. Near the equator, however, whilst these basic wind patterns are still found the corresponding pressure patterns are missing.

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\* The index numbers refer to the bibliography on page 5.

Apart from their value in analysis, streamline-isotach charts give a direct representation of the wind flow and, over areas from which data are scanty or missing, mean streamline-isotach charts are invaluable. They can be used not only to ensure continuity between daily charts but also, as shown by Lavoie and Wiederanders,<sup>5</sup> in conjunction with a current streamline chart, to predict the future wind field with an accuracy greater than that possible at present by any other means.

The only streamline-isotach or other wind charts currently available for the Far East are those of (a) Heastie and Stephenson<sup>3</sup> which are on too small a scale for detailed use in a given area and which in the Tropics have been invalidated to some extent by later data, (b) Bunnag and Buajitti<sup>6</sup> which are limited to the 5000 and 10,000 foot levels, (c) Wiederanders<sup>7</sup> for the Pacific which only touches the fringe of the Indian Ocean and (d) the India Meteorological Department's Climatological Atlas for Airmen edited by Normand<sup>8</sup> whose upper air charts only extend to the 26,000 foot level and are based entirely on pilot-balloon winds.

The charts presented here depict mean streamlines and isotachs covering the Indian and west Pacific Oceans and adjacent land areas for the four mid-season months (January, April, July and October) at standard pressure levels 700 mb, 500 mb, 300 mb and 200 mb. Streamlines are shown as continuous lines and isotachs as dotted lines. Mean vector winds have been plotted using barbed arrows with the normal convention that a half barb represents 5 knots, a full barb 10 knots and a solid triangular barb 50 knots. Calms are represented by a small circle enclosing the station. Mean vector winds from aircraft are shown with pecked lines.

#### OBSERVATIONAL DATA

All currently available rawind data have been used including those given in the references 6, 7, 9, 10, 11, 12 and 13 together with data for India, the Andaman Islands and Korea supplied by the Indian and Hong Kong Meteorological Services and data for Singapore, Gan, Colombo, Djakarta and Surabaya computed by Meteorological Office staff in the Far East Air Force Command. A list of rawind stations, together with periods of observation (where known) and sources of the data used is given in the Appendix.

Use was also made of mean vector winds over 5 or 10 degree legs and 5000 foot height bands computed by the Meteorological Office from wind observations made by high-flying aircraft on routes from Singapore to Gan and Gan to Aden over five years, and from Singapore to Darwin and Singapore to Ceylon over two years. The number of observations over a given leg varied between 10 and 99. Where fewer than 10 observations were available mean winds were not computed. (The locations of the air routes and of the rawind stations whose data have been used in this analysis are shown in Figure 1.)

In order to give as complete coverage as possible the above data were supplemented by pilot-balloon observations from Malaya,<sup>14</sup> India,<sup>5</sup> Indonesia<sup>15</sup> and islands in the Indian Ocean.<sup>16</sup> Data for China supplied by the Hong Kong Meteorological Service and for Diego Garcia and Lhasa (held in manuscript form in the Meteorological Office, Headquarters, Far East Air Force) were also used.

It will be noted that the data are inhomogeneous both in period and type of observation. However, inspection of short- and long-period means of rawind observation from Singapore, Aden, Nairobi and Bahrain suggests that three or four year averages give a very close approximation to eight to ten year averages which agrees with the conclusion of Ramage<sup>9</sup> based on observations in the tropical Pacific suggesting that any errors from the inhomogeneities of period of rawind data are unlikely to be significant. Pilot-balloon data are known to be biased in favour of fair weather conditions and this was borne in mind when drawing the charts. In the event, however, it was found possible to maintain continuity and to fit virtually all the observations without producing inconsistent patterns and it is considered that these charts give as reasonable a representation as possible of the mean flow patterns in the area.



## SALIENT FEATURES

Only the salient features of the charts are discussed here, the details being best obtained by reference to the charts themselves.

The features which are common in all months apart from their change in position following the march of the sun are:

- (i) The subtropical ridges of both hemispheres (defined as the axes through which the extratropical westerly winds change to tropical easterly winds). *Note*—The subtropical ridge lines at 700 mb and 500 mb are non-existent over Asia in July.

Examination of the mean charts shows that these subtropical ridges, which are broken up into semi-permanent cells, have an equatorward slope with height up to about 300 mb and at all levels reach their extreme northerly and southerly positions in July and January respectively. At 300 mb and 200 mb the winter subtropical ridge lines are positioned at 10°N in January and 10°S in July. They show very little evidence of any northward or southward displacement in April or October but in July and January they reach their extreme positions as summer ridge lines at about 30°N and 13°S respectively. In October the northern ridge line is located at about 18°N at 300 mb and 200 mb.

The displacements of the ridge lines from winter to summer whilst following the march of the sun are not gradual. Inspection of the daily charts shows that the largest displacement of the northern ridge lines takes place in late May and early June which agrees with the observational evidence—Yin,<sup>17</sup> Frost<sup>18</sup> and others—that the change from pre-monsoon to summer monsoon conditions is abrupt. The movement of the ridge lines southwards from their extreme positions which are reached in late August, however, is gradual.

- (ii) The low-level equatorial troughs of both hemispheres (defined as the axes through which the tropical easterly winds change to equatorial westerly winds).

These two equatorial troughs, which appear on the 700 mb charts between longitudes 60°E and 140°E approximately are positioned at about 3°N and 10°S in January and 5°N and 5°S in April. In July they reach their most northerly positions of 22°N from 70°E to 110°E and about 2½°S respectively whilst in October the two troughs lie at about 10°N and 3°S. The troughs in the mean are broken up into eddies which rotate anticlockwise in the northern hemisphere and clockwise in the southern hemisphere. These eddies frequently appear on daily charts in much the same positions as shown on the mean charts especially to the south of Gan, west of Sumatra and near Borneo and may in this respect be considered almost a quasi-permanent feature of the equatorial circulation in this region. Inspection of daily charts also shows that the mean slope of the trough lines from the surface to 700 mb is of the order of 1 in 150 towards the poles.

- (iii) The meandering belt of low-level equatorial westerlies between the equatorial troughs.

This belt is always present from the surface to above 700 mb and in the northern summer extends to 500 mb. It is at its broadest and strongest in July extending from just south of the equator to 20°N and reaching an average speed of 20 to 25 knots at 700 mb. It is at its weakest in April with an average speed of only 5 knots at the same level.

- (iv) The high-level equatorial easterlies between the subtropical ridges.

These easterlies are strongest in July with average speeds of about 50 knots at 200 mb and are weakest in April with average speeds of about 15 knots at the same level.

- (v) The extratropical westerlies which occur at all levels on the poleward sides of the subtropical ridges.

The northern hemisphere westerlies at 200 mb attain their greatest speeds of about 90 knots over India at 25°N and about 140 knots over Japan at about 32°N in January. In the southern hemisphere the westerlies at 200 mb reach maximum speeds of about 110 knots over Australia at 25°S in July. The westerlies are weakest at all levels in the northern hemisphere in July and in the southern hemisphere in January when at 200 mb speeds of only 40 to 50 knots are reached.

Two other features which occur in the northern hemisphere summer and which have no parallel elsewhere in the world are (a) a monsoonal inflow in July which over India and Burma extends from the surface to above 500 mb and (b) a strong transequatorial east-north-east current between longitudes 70°E and 140°E at 300 mb and 200 mb. An examination of the flow patterns on provisional charts for 150 mb and 100 mb, which are not reproduced here, shows that this trans-equatorial flow is at its maximum at about 150 mb and is absent at 100 mb.

A similar low-level monsoonal inflow occurs on a smaller scale in the southern hemisphere summer over north Australia and there is evidence of a corresponding high-level transequatorial east-by-south flow between the same longitudes.

#### DISCUSSION OF THE SALIENT FEATURES

Wagner's maps of the mean circulation over India at 8 km which are reproduced as Figures 10.15 and 10.16 in Riehl's "Tropical Meteorology" have been used by Yin<sup>17</sup> to provide an explanation of the spectacular 'burst' of the monsoon over India. These maps, which are based on pilot balloon observations, show two troughs over northern India, one at 90°E in winter and the other at 75°E in summer, and Yin suggests that these troughs are determined orographically by the flow of the westerlies around the Himalayan massif. According to this argument the westerlies circle the southern rim of the Himalayas in winter and spring and, as prescribed by the contours, give rise to a trough at 90°E whilst in early summer the westerlies weaken and suddenly retreat to the north of the Himalayas resulting in the formation of a trough at 75°E just west of the bulk of the mountains.

No reason is given why the streamlines at 8 km should follow the contours of the Himalayas at about 4 km and the present streamlines give no support to this. Thus the streamlines at both 500 and 300 mb in winter and spring and at 300 mb in summer do not show any suggestion of a trough over India at any longitude whilst at 500 mb in summer there are two cyclonic circulations at about 85°E and 95°E. It is clear that the explanation of the 'burst' of the monsoon as the simple westward shift of an ill-defined, if not non-existent, orographically determined trough is unsatisfactory and an alternative explanation suggested by the flow patterns presented in this paper is given later.

In a draft survey of the "Problems of Tropical Meteorology" Alaka states that the region between the circulatory regions of the northern and southern hemispheres has been variously called the Intertropical Front, the Intertropical Convergence Zone, the Equatorial Front and the Equatorial Convergence Zone. He points out that this reflects the great diversity of views which have been advanced to account for its structure and suggests that as this region is neither frontal nor invariably convergent the name Equatorial Trough is more appropriate. It would seem that this new definition adds to the semantic confusion. Over most of the world there is one clearly delineated region between the north-east and south-east Trades which on a streamline chart appears as an asymptote of convergence. Over the Indian Ocean, however, between longitudes 60°E and 140°E approximately, steady westerly winds are found at all times of the year at the equator and on streamline charts the transitions between these and the Trades take place via two axes of curvature which, by analogy with pressure patterns, may be called trough lines. With the disappearance of the westerlies, the trough lines merge into an asymptote of convergence at a neutral point. It is suggested, therefore, that the term Equatorial Trough should be restricted to those regions where the trade winds meet the equatorial westerlies and that the term Equatorial Convergence Zone should be used for all other regions.

Various explanations of the equatorial westerlies have been attempted. According to the classical hypothesis the Trades are drawn towards the heated continents and after their passage across the equator are deflected by the Coriolis force. This explanation is, however, incompatible with the observed fact that the equatorial westerly winds over the eastern Indian Ocean occur at all times of the year on both sides of the equator.

Fletcher<sup>19</sup> put forward a theory that the equatorial westerlies are caused by radiative cooling from the cloud tops on the two trough lines observed over the Indian Ocean but it is not clear on this theory whether the trough lines are cause or effect. Freeman<sup>20</sup> has suggested an explanation for the east Pacific based on the idea of hydraulic jumps under an inversion whilst Palmer<sup>21</sup> considered that the equatorial westerlies in the central Pacific were a statistical result of the equatorial eddies. Whilst Palmer's and Freeman's theories may be valid for the Pacific where the equatorial westerlies are variable in time and space they cannot explain the constant equatorial westerlies of the Indian Ocean.

It is suggested that the simplest explanation of the observed belt of low-level westerlies and reversed easterlies aloft is that they form part of a simple circulation cell which has an ascending branch over the heated land mass of Indonesia and a descending branch over the equatorial Indian Ocean at about longitude 60°E. The broadening of the equatorial westerlies could result from additional heating of the land masses of south-east Asia and India in May and June.

Inspection of the surface charts for the Indian Ocean<sup>22</sup> shows that the equatorial flow is slightly north of west between about 60°E, Java and north Australia in January and is almost due west in April. In May there is a broad west-south-westerly sweep of surface air across the equator which affects Malaya and Burma whilst the air which reaches India is from the west or north-west and is of North African or Arabian origin. In June and July the transequatorial flow becomes more south-westerly and affects both India and Burma. At 700 mb the flow is also slightly north of west between about 60°E and Java and Australia in January and almost due west in April and in July. Inspection of the charts at 200 mb shows that between Indonesia and 60°E the flow in January is slightly south of east and in April is almost due east, whilst in July there is a strong transequatorial flow from the east-north-east. The fact that the flow in the mid-season months at the surface is about 180° out of phase with the flow at 200 mb suggests a simple circulation model with a sink more or less fixed over the Indian Ocean at the equator at about 60°E and an energy source which, following the march of the sun, moves northwards over Indonesia, Malaya, Thailand and Burma. In late May temperatures over Thailand and Burma reach their peak, but at this time a vigorous heat low develops over north-west India and Pakistan due to the intense insolation with clear skies and by early June this low becomes the area of maximum heating. The circulation cell which, until then, has been rotating slowly around the sink thus shifts abruptly from a west-south-west to a south-west orientation. For the early months of the Indian monsoon Koteswaram<sup>23</sup> suggested a model similar to the final stages of the above with an energy source over northern India and a sink to the south over the equatorial Indian Ocean and suggested that as the energy source shifted later to Tibet the circulation over India broke up with the advance of the circumpolar westerlies. The mean pressure gradients between Gan (which is near to the site of the suggested sink) and Indonesia, Malaya, Thailand and India and the massive cumulonimbus development in turn over Indonesia, Malaya, Thailand and India following the march of the sun and the dryness of the air at Gan at all levels are also in conformity with the simple model.

#### ACKNOWLEDGEMENT

The authors are indebted to Mr. B. J. G. Binge for his assistance in drawing the charts.

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## APPENDIX—LIST OF RAWIND STATIONS USED

Station	Latitude	Longitude	Period of observation	Source or Ref. No.
Aden	12°49'N	45°02'E	1948-55	12
Alice Springs	23°48'S	133°53'E	1950-55	10
Allahabad	25°27'N	81°44'E	1953-60	India Met. Dept.
Amsterdam Island	37°50'S	77°34'E	1951-55	16
Bahrain	26°16'N	50°37'E	1951-55	12
Bangkok	13°44'N	100°30'E	1955-60	7
Benina	32°05'N	20°16'E	1951-55	12
Bombay	19°05'N	72°53'E	1954-60	India Met. Dept.
Brisbane	27°26'S	153°05'E	1956-58	10
Broome	17°57'S	122°13'E	1950-55	10
Calcutta	22°39'N	88°27'E	1952-60	India Met. Dept.
Cape Town	33°58'S	18°36'E	1954-58	11
Charleville	26°25'S	146°17'E	1956-58	10
Chiangmai	18°47'N	98°59'E	1955-60	7
Clark Field	15°10'N	120°34'E	1949-58	9
Cloncurry	20°40'S	140°30'E	1952-55	10
Cocos Island	12°05'S	96°53'E	1952-55	10
Colombo	06°54'N	79°52'E	1956-57	H.Q., F.E.A.F.
Daly Waters	16°16'S	133°23'E	1950-55	10
Darwin	12°26'S	130°52'E	1952-55	10
Djakarta	06°11'S	106°50'E	1959-62	H.Q., F.E.A.F.
Durban	29°58'S	30°57'E	1957-59	11
Forrest	30°51'S	128°06'E	1956-58	10
Gan Island	00°41'S	73°09'E	1959-62	H.Q., F.E.A.F.
Gauhati	26°05'N	91°43'E	1955-60	India Met. Dept.
Giles	25°02'S	128°18'E	1957-58	10
Guam	13°34'N	144°55'E	1949-58	9
Habbaniya	33°22'N	43°34'E	1951-55	12
Hobart	42°50'S	147°30'E	1953-55	10
Hong Kong	22°19'N	114°10'E	1950-59	H.Q., F.E.A.F.
Honiara	09°25'S	159°58'E	1957-60	7
Iwojima	24°47'N	141°20'E	1949-59	9
Jodhpur	26°18'N	73°01'E	1956-60	India Met. Dept.
Kadena	26°21'N	127°45'E	1949-59	9
Kagoshima	31°38'N	130°26'E	1952-58	9
Kalgoorlie	30°46'S	121°27'E	1950-55	10
Khartoum	15°36'N	32°33'E	1953-55	12
Koror	07°21'N	134°29'E	1950-58	9
Lae	06°44'S	147°00'E	1956-59	7
Madras	13°00'N	80°11'E	1951-60	India Met. Dept.
Marcus Island	24°17'N	153°58'E	1952-58	9
Maun	19°59'S	23°25'E	1953-58	11
Melbourne	37°44'S	144°54'E	1950-55	10
Nagpur	21°09'N	79°07'E	1953-60	India Met. Dept.
Nairobi	01°18'S	36°45'E	1948-62	11 & 13
Naze	28°23'N	129°33'E	1955-58	9
New Delhi	28°35'N	77°12'E	1950-60	India Met. Dept.
Nicosia	35°09'N	33°17'E	1951-55	12
Oodnadatta	27°33'S	135°27'E	1950-55	10
Osan	37°06'N	127°02'E	Not known	R. Obsy, Hong Kong
Perth	31°56'S	115°57'E	1954-55	10
Ponape	06°58'N	158°13'E	1951-58	9
Port Blair	11°40'N	92°43'E	1956-60	India Met. Dept.
Port Hedland	20°23'S	118°37'E	1951-55	10
Pretoria	25°45'S	28°14'E	1952-58	11
Saigon	10°49'N	106°40'E	1956-58	7
Salisbury	17°50'S	31°01'E	1951-59	11
Singapore	01°21'N	103°54'E	1951-60	H.Q., F.E.A.F.
Surabaya	07°13'S	112°43'E	1959-62	H.Q., F.E.A.F.
Songkhla	07°11'N	100°37'E	1955-60	7
Tananarive	18°54'S	47°32'E	1953-59	11
Tateno	36°03'N	140°08'E	1952-58	9
Torishima	30°29'N	140°18'E	1956-58	9
Townsville	19°15'S	146°46'E	1954-55	10
Trivandrum	08°29'N	76°57'E	1956-60	India Met. Dept.
Truk	07°27'N	151°50'E	1951-58	9
Veraval	20°54'N	70°22'E	1957-60	India Met. Dept.
Williamtown	32°49'S	151°50'E	1952-55	10
Woomera	31°09'S	136°48'E	1950-55	10
Yap	09°31'N	138°08'E	1950-58	9
Yonago	35°26'N	133°21'E	1952-58	9

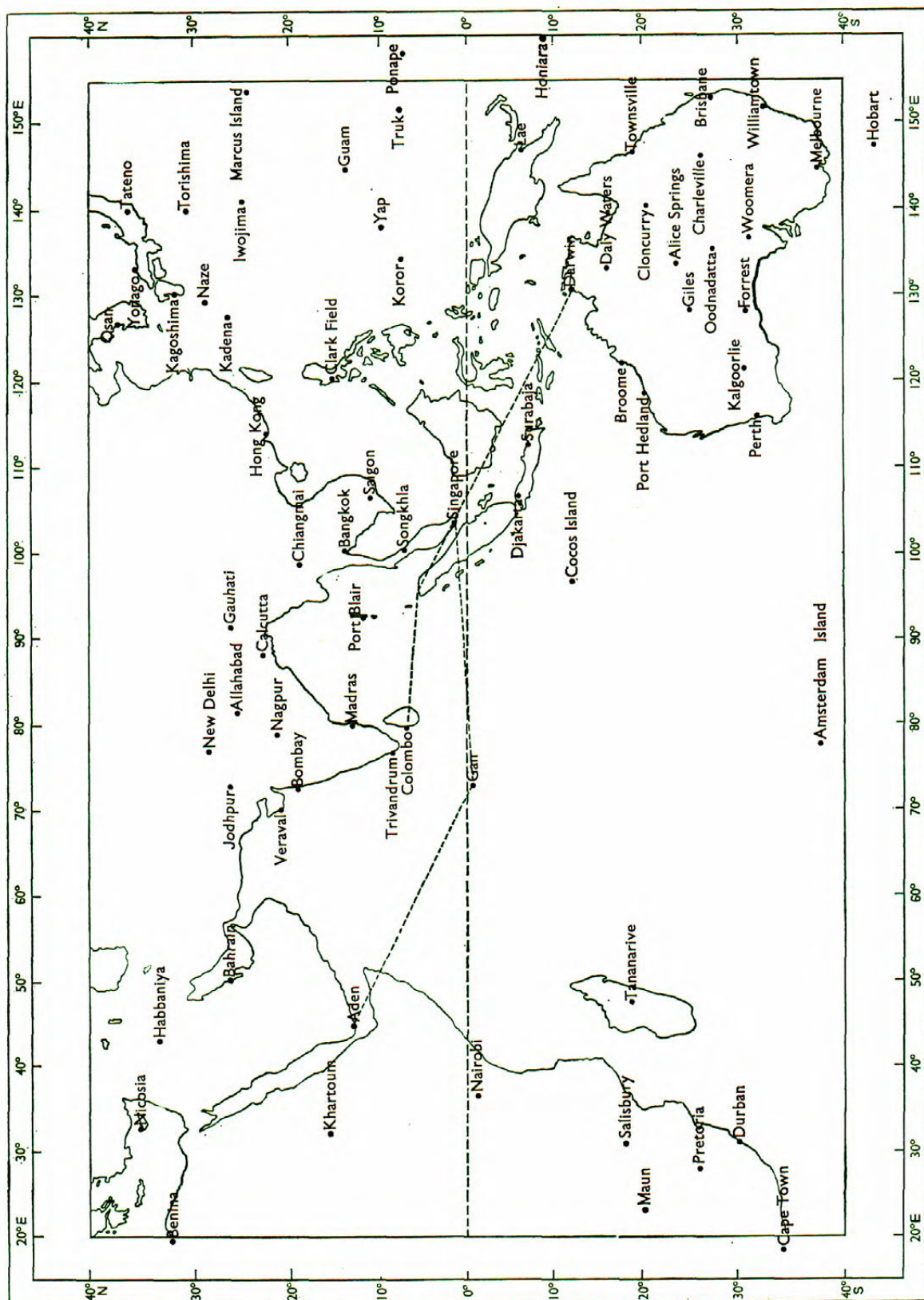


FIGURE 1—AIRCRAFT ROUTES AND RAWIND STATIONS USED IN UPPER AIR STREAMLINE ANALYSIS



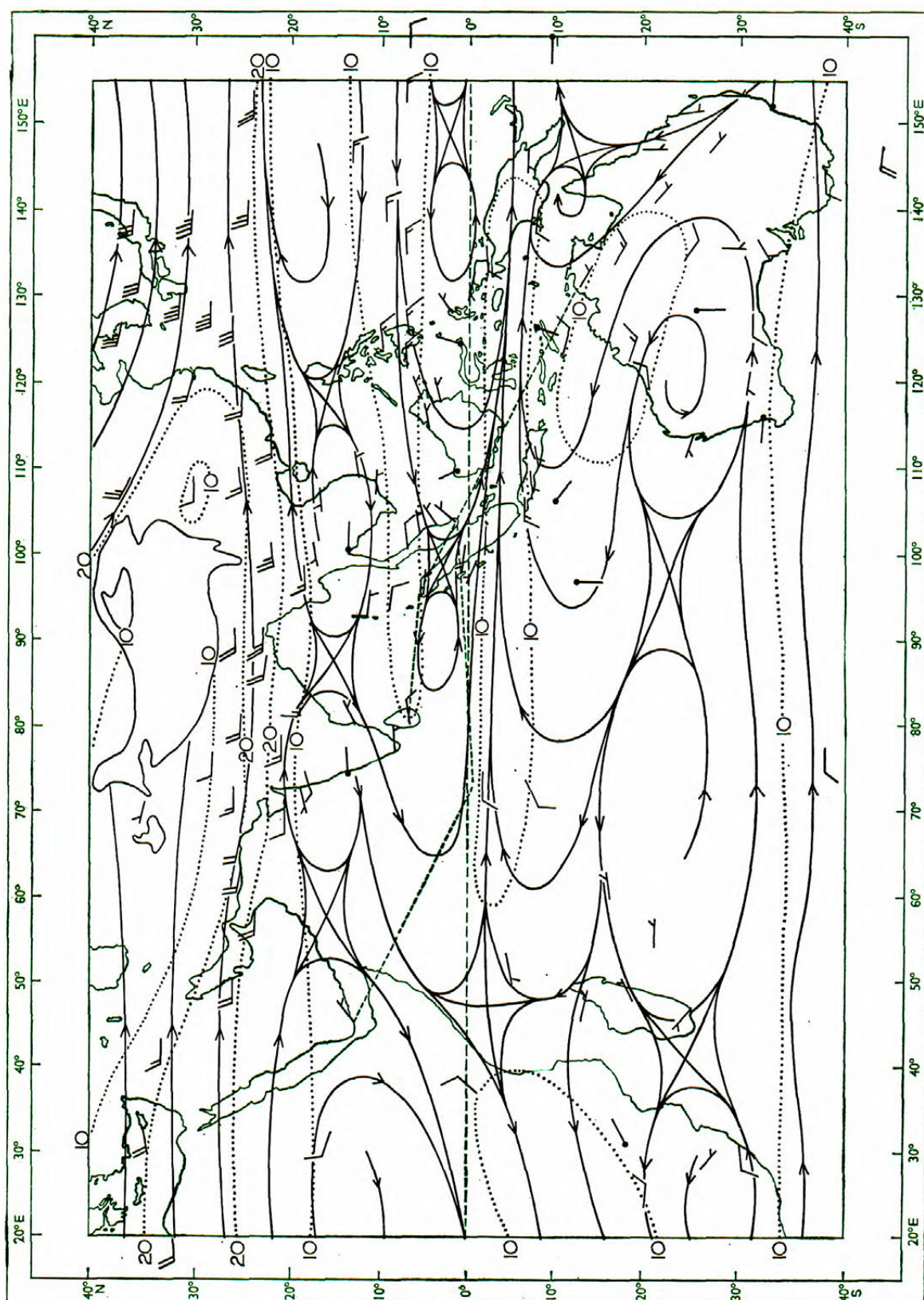


FIGURE 2.—700 MB STREAMLINES AND ISOTACHS (KNOTS)—JANUARY



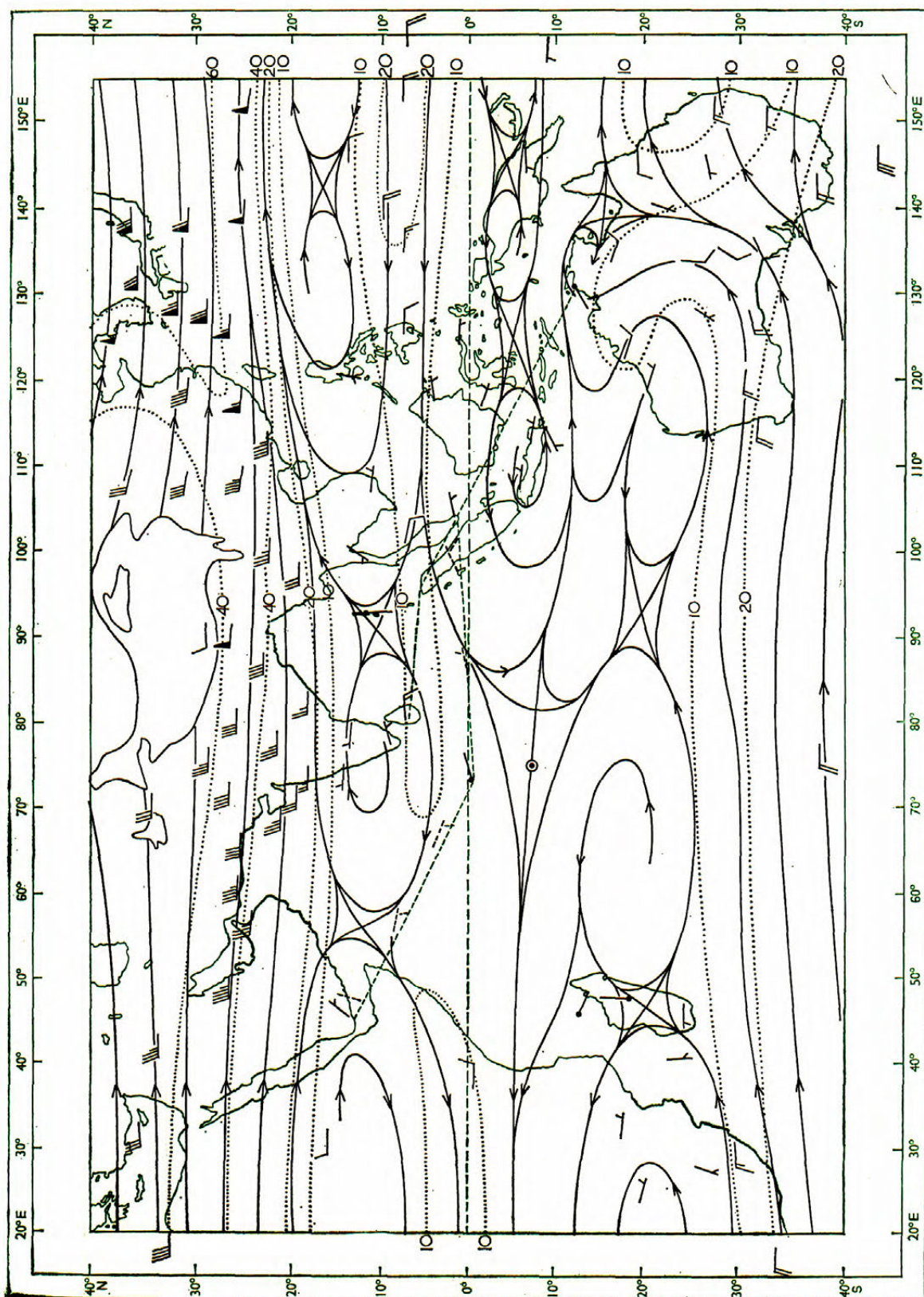


FIGURE 3—500 MB STREAMLINES AND ISOTACHS (KNOTS)—JANUARY



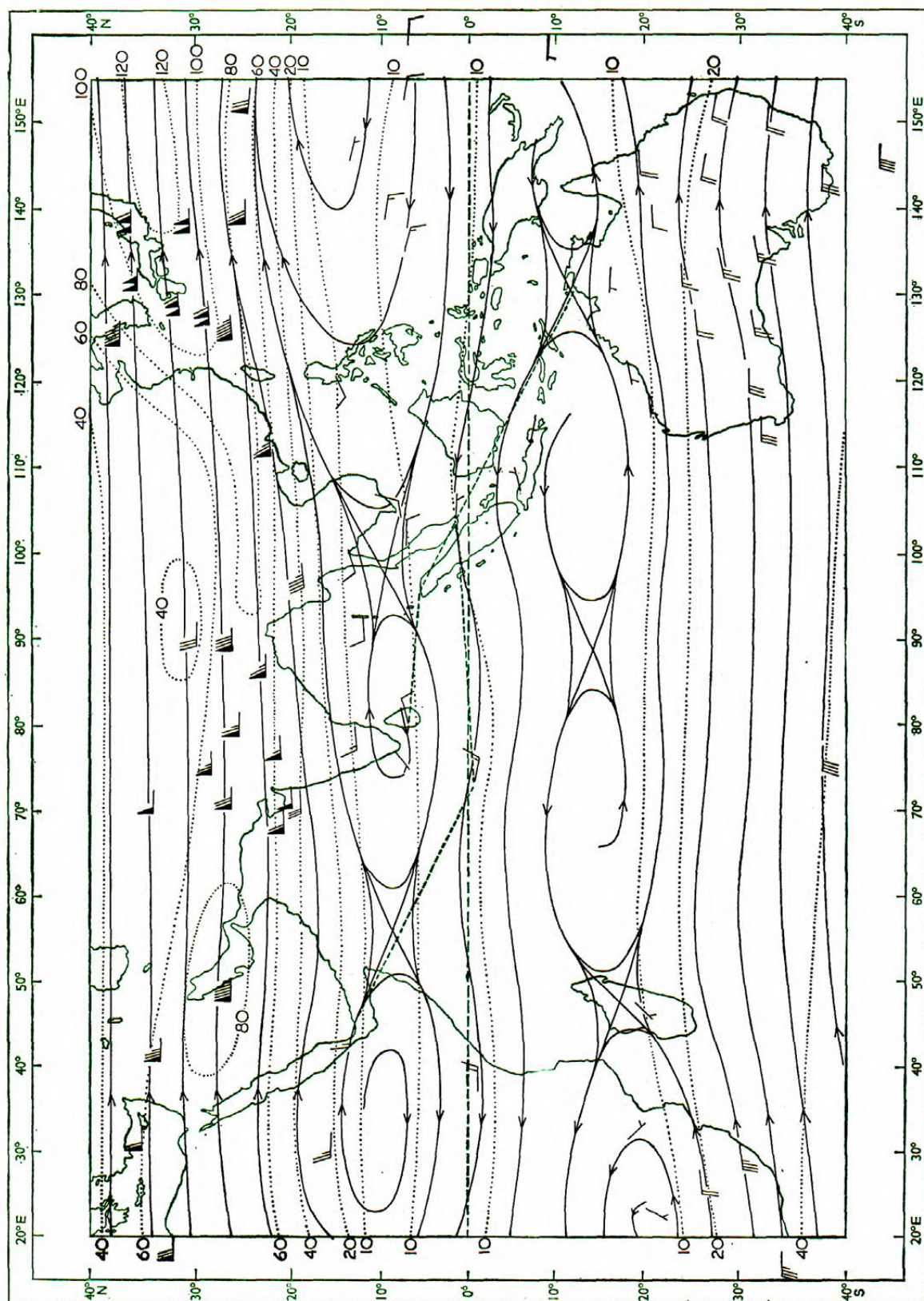


FIGURE 4—300 MB STREAMLINES AND ISOTACHS (KNOTS)—JANUARY



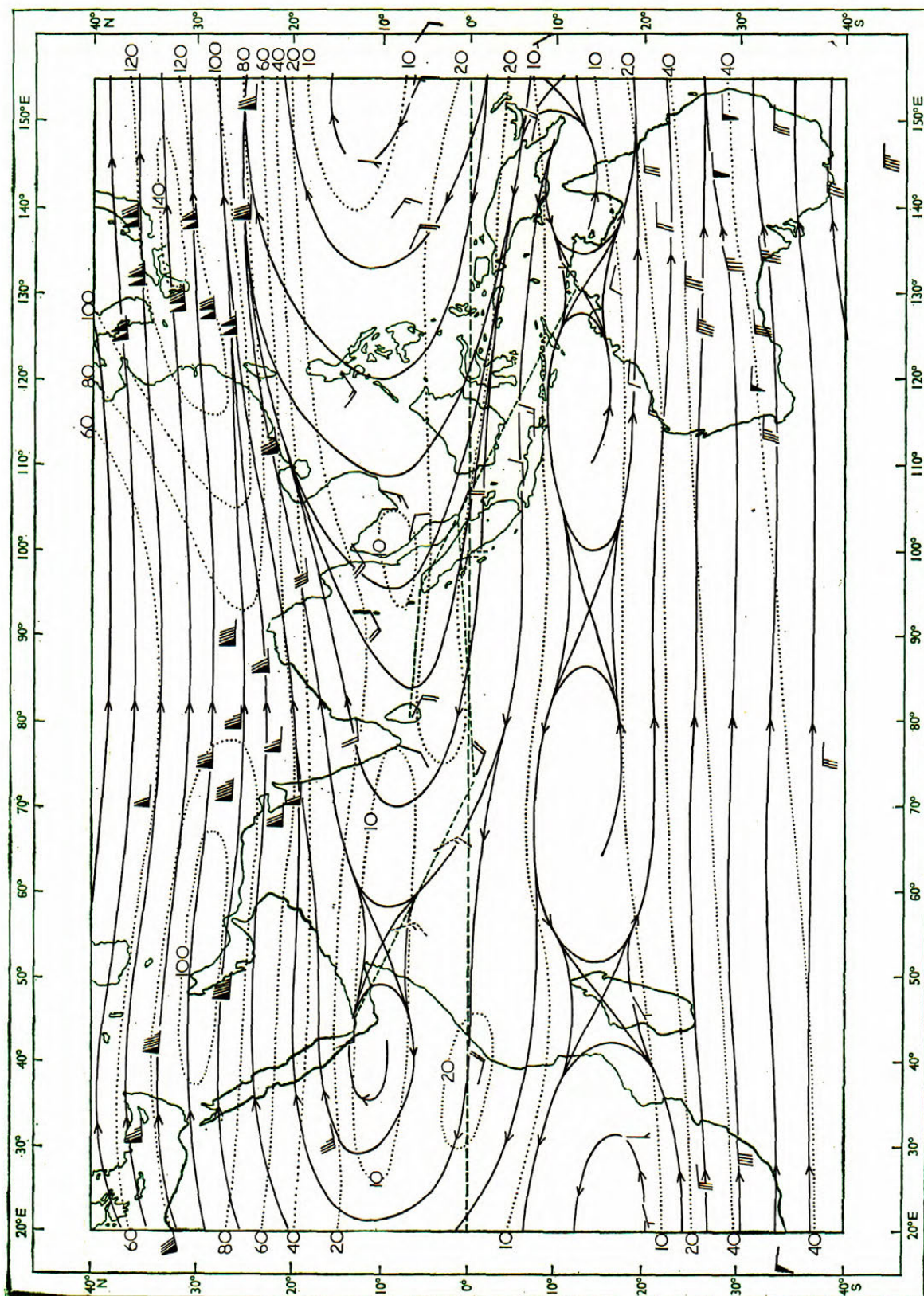


FIGURE 5—200 MB STREAMLINES AND ISOTACHS (KNOTS)—JANUARY



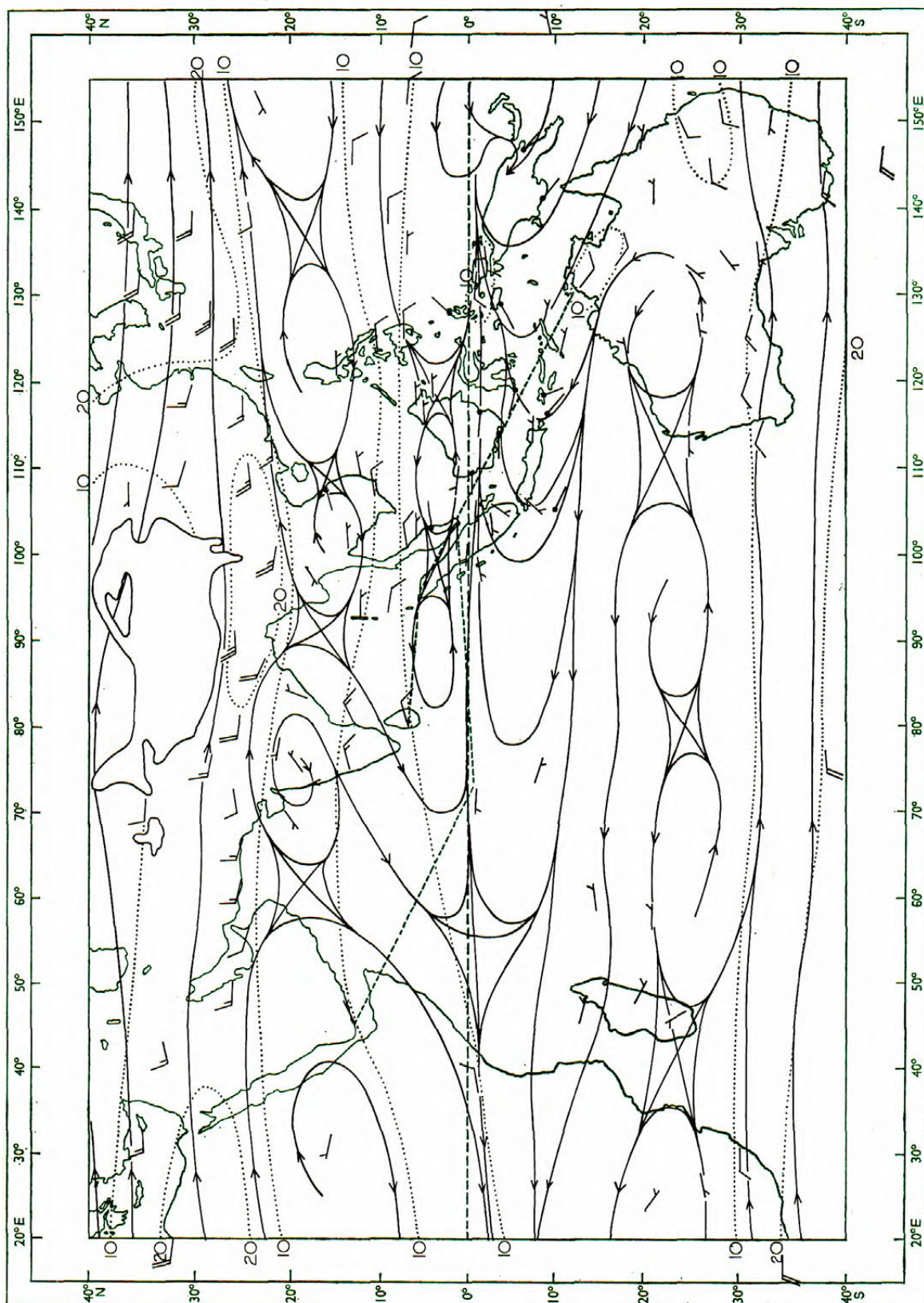


FIGURE 6—700 MB STREAMLINES AND ISOTACHS (KNOTS)—APRIL

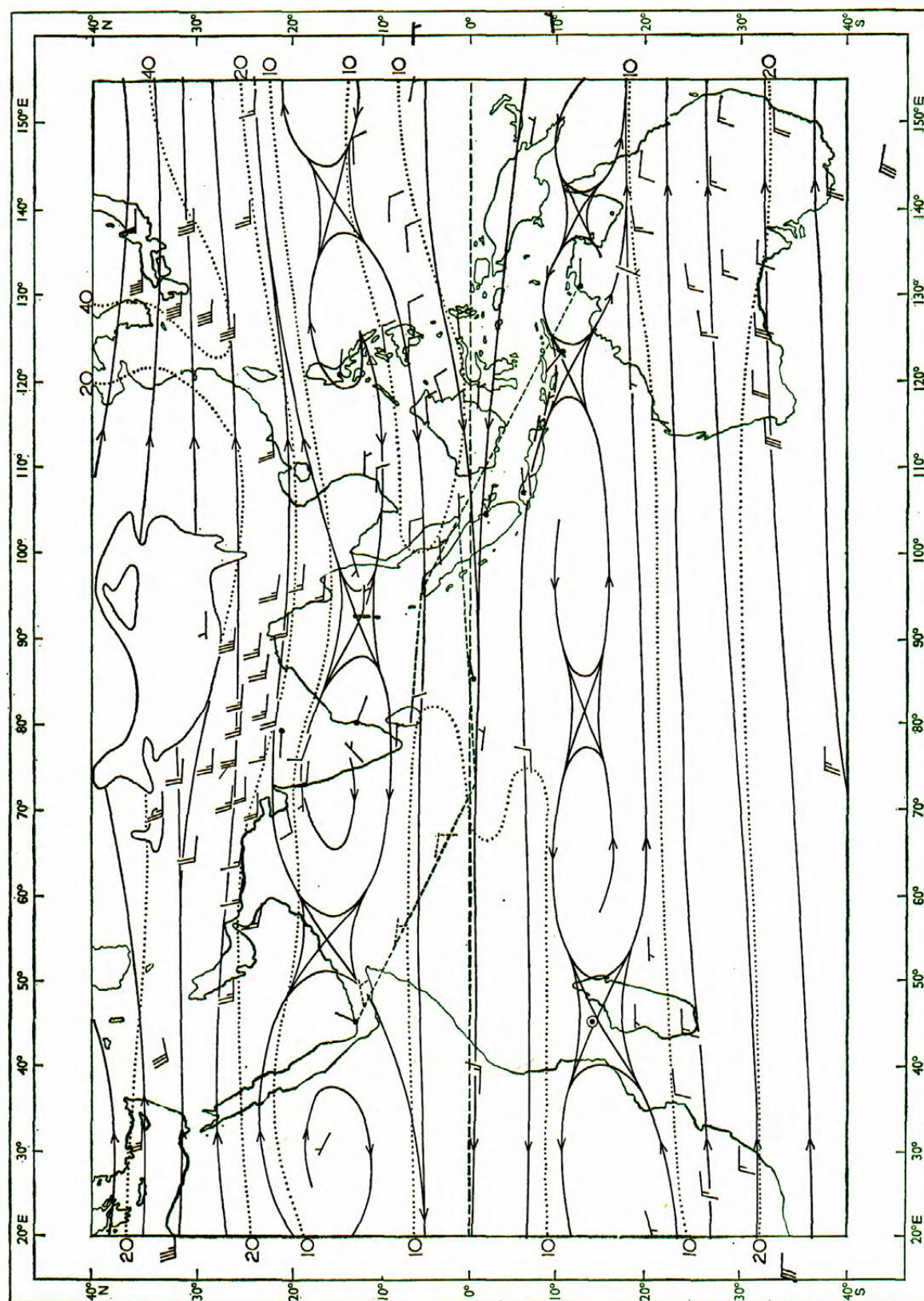


FIGURE 7—500 MB STREAMLINES AND ISOTACHS (KNOTS)—APRIL



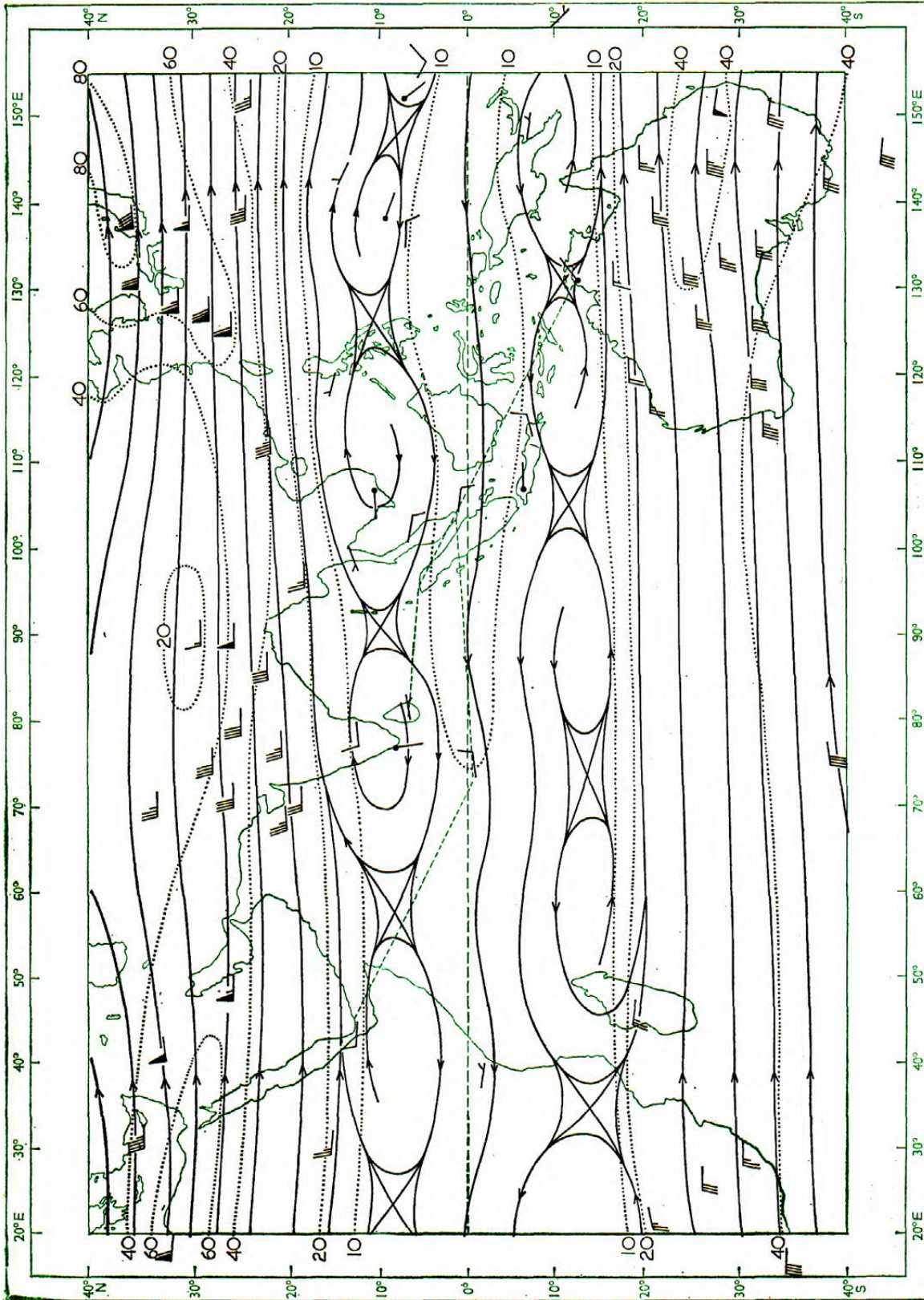


FIGURE 8—300 MB STREAMLINES AND ISOTACHS (KNOTS)—APRIL



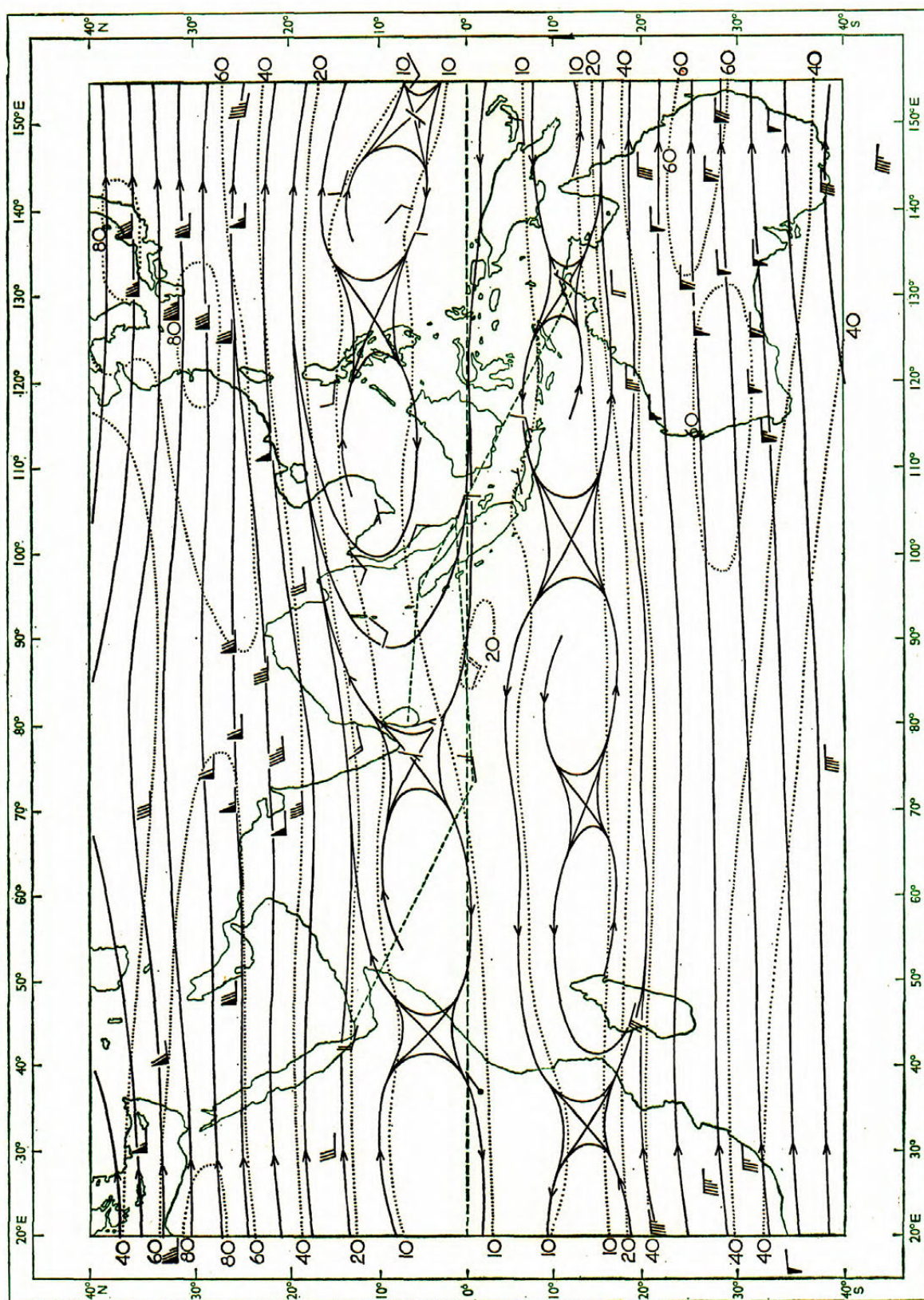


FIGURE 9—200 MB STREAMLINES AND ISOTACHS (KNOTS)—APRIL



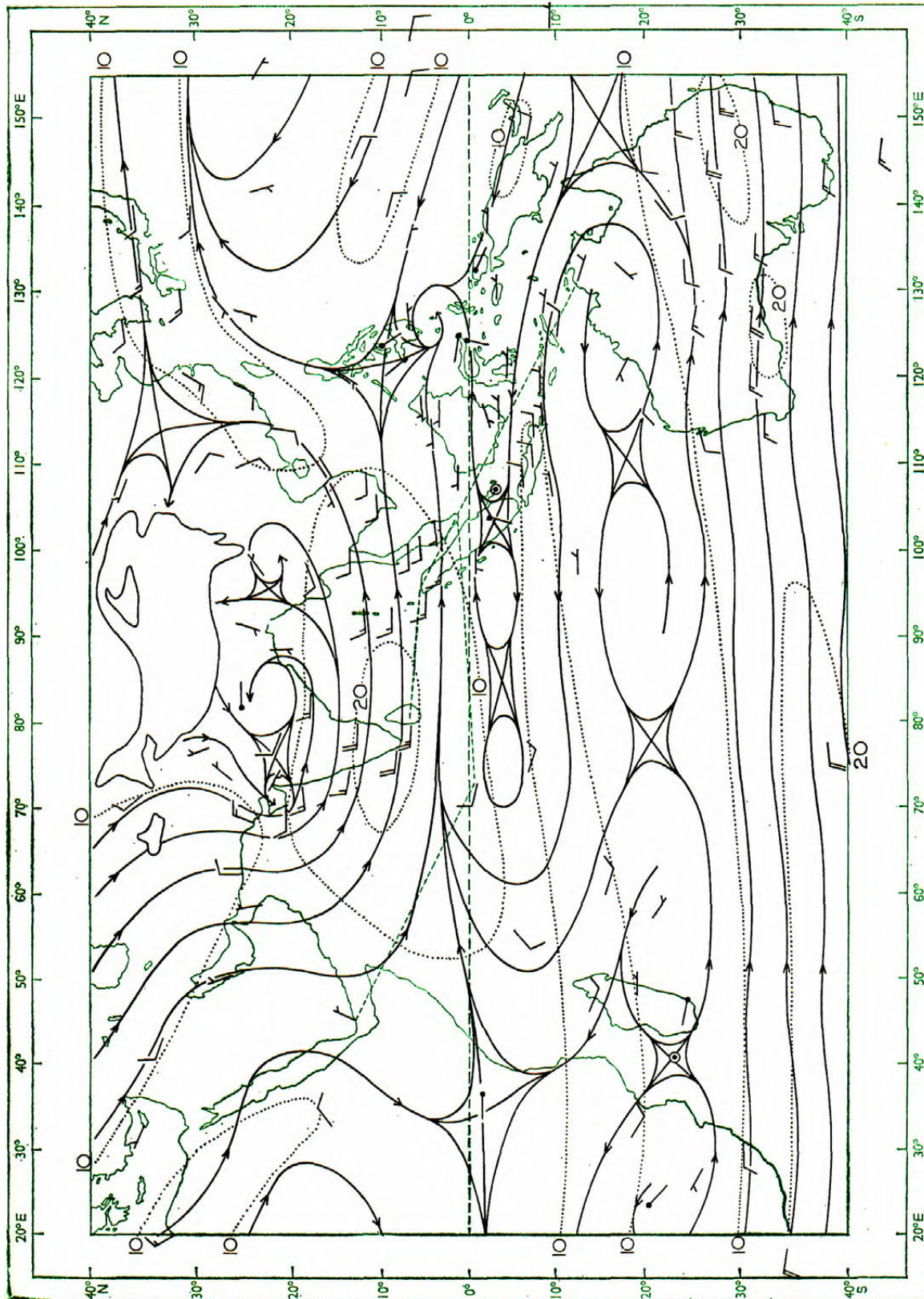


FIGURE 10—700 MB STREAMLINES AND ISOTACHS (KNOTS)—JULY



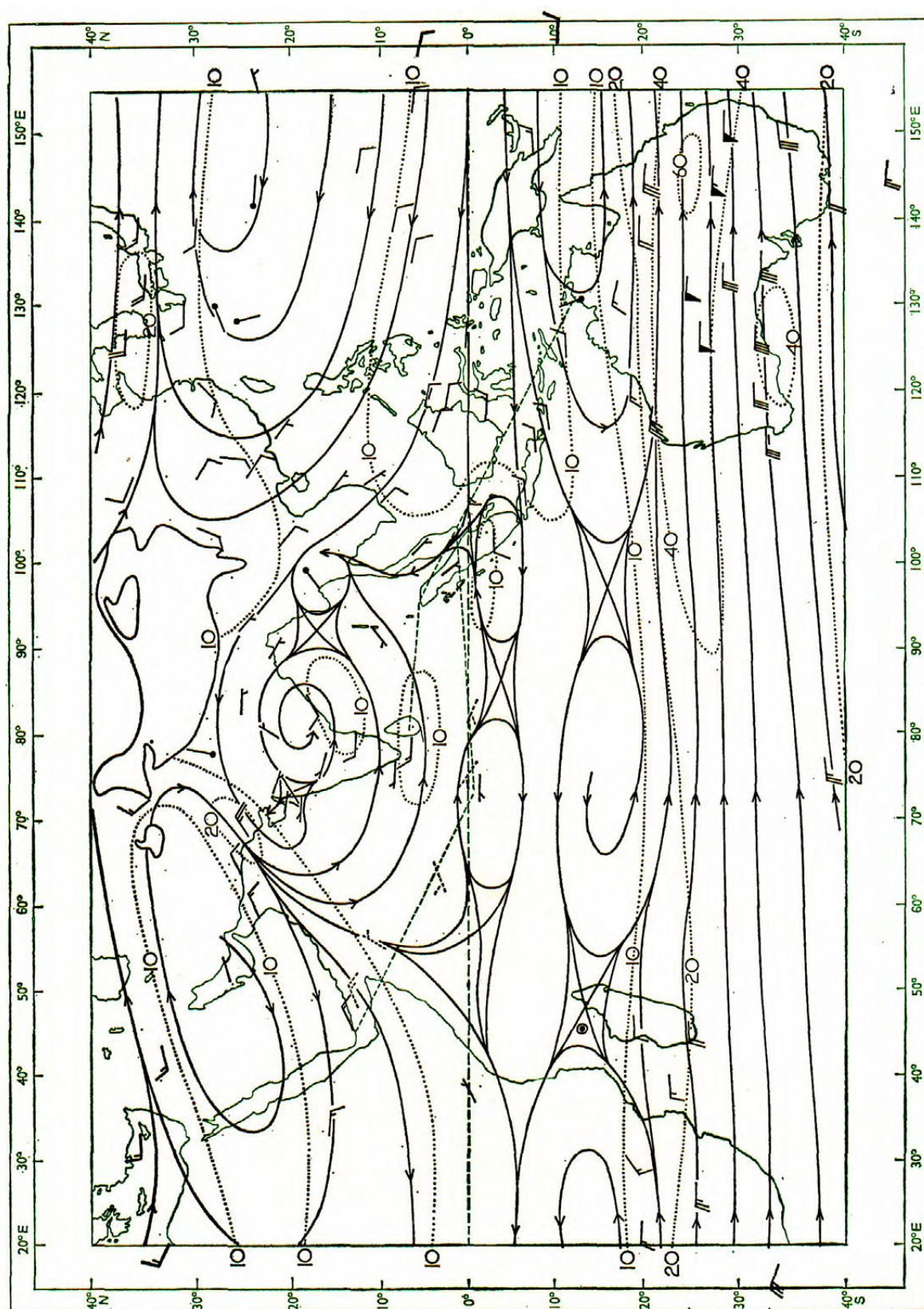


FIGURE 11—500 MB STREAMLINES AND ISOTACHS (KNOTS)—JULY





FIGURE 12—300 MB STREAMLINES AND ISOTACHS (KNOTS)—JULY



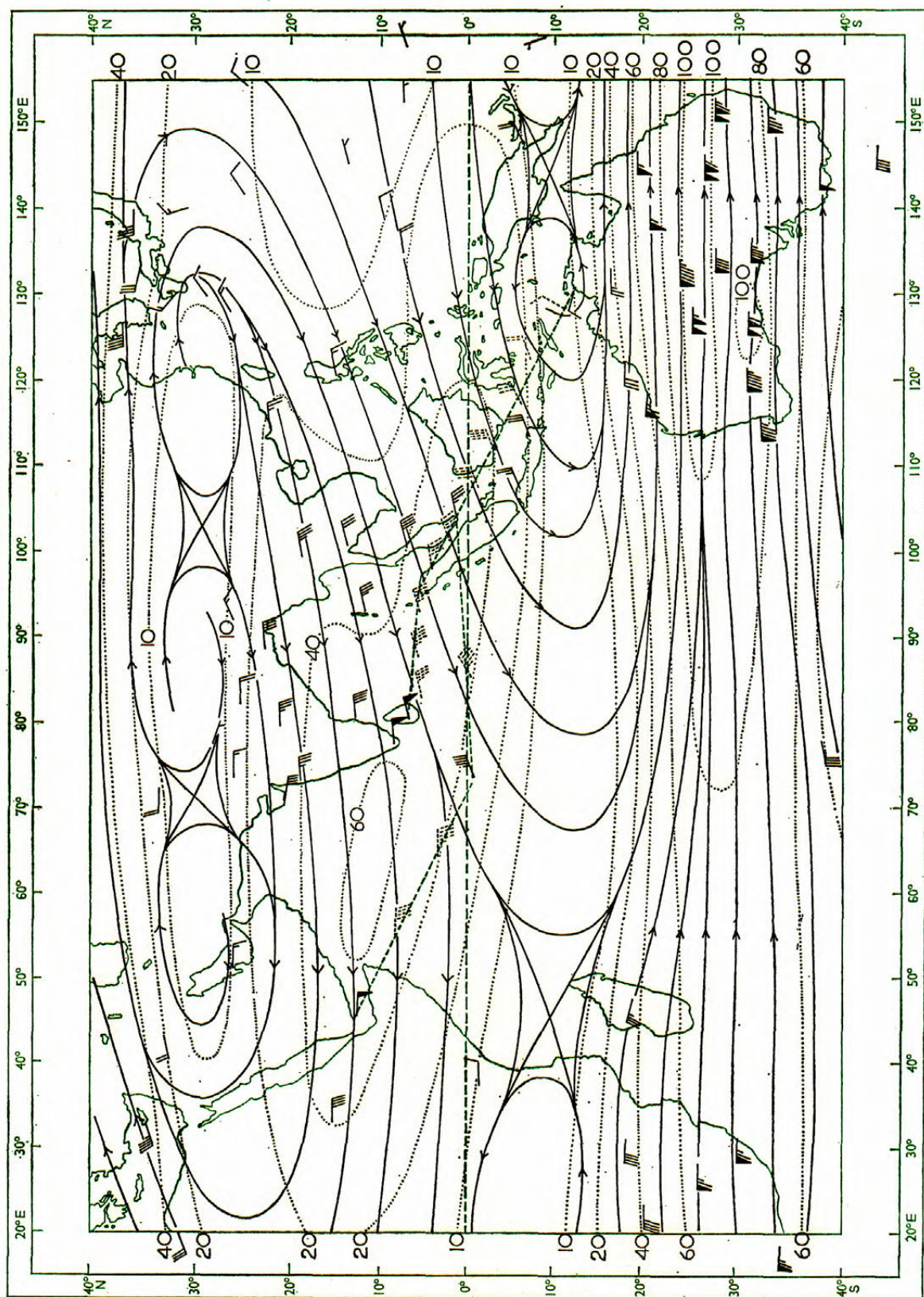


FIGURE 13—200 MB STREAMLINES AND ISOTACHS (KNOTS)—JULY





FIGURE 14—700 MB STREAMLINES AND ISOTACHS (KNOTS)—OCTOBER



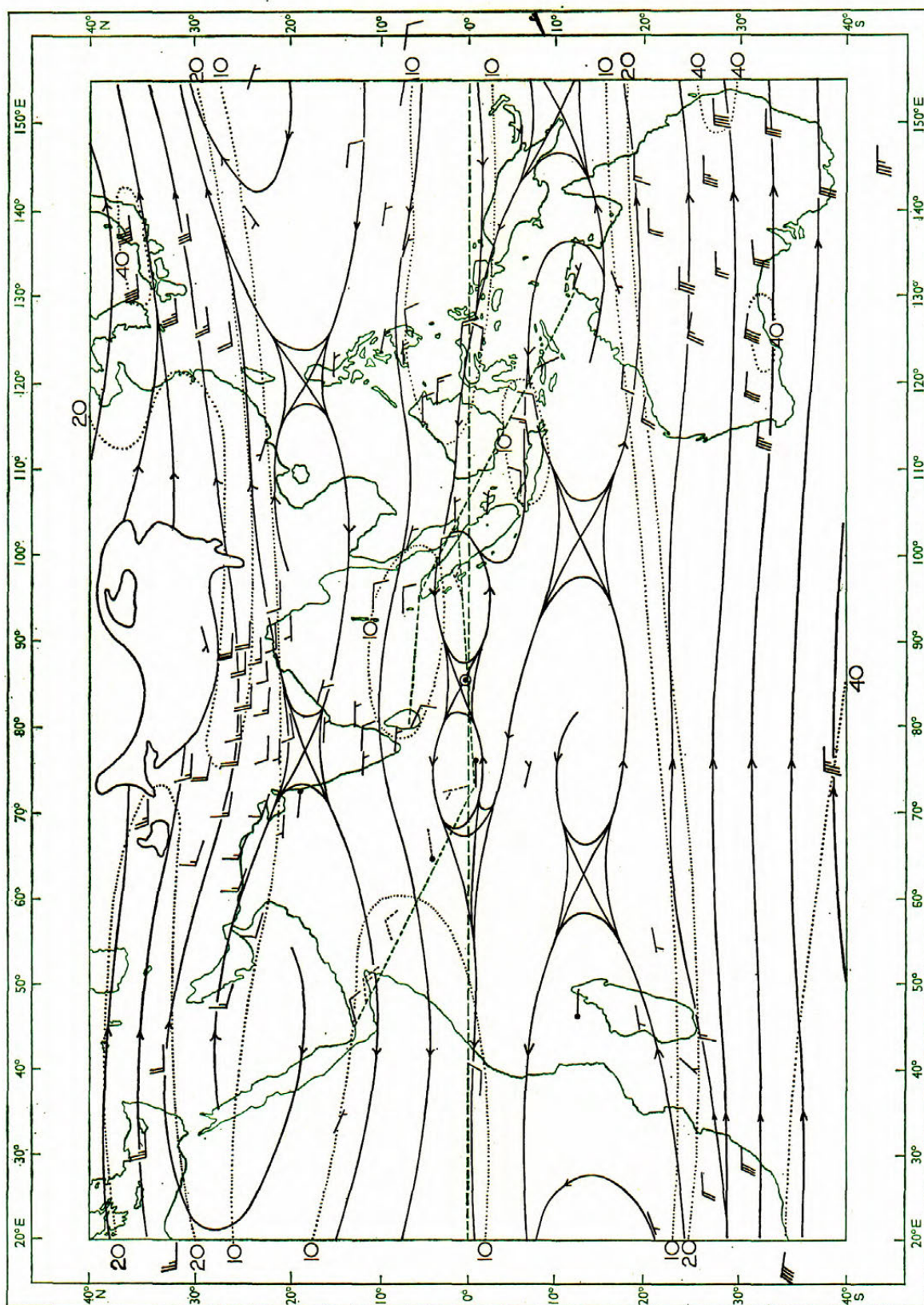


FIGURE 15—500 MB STREAMLINES AND ISOTACHS (KNOTS)—OCTOBER



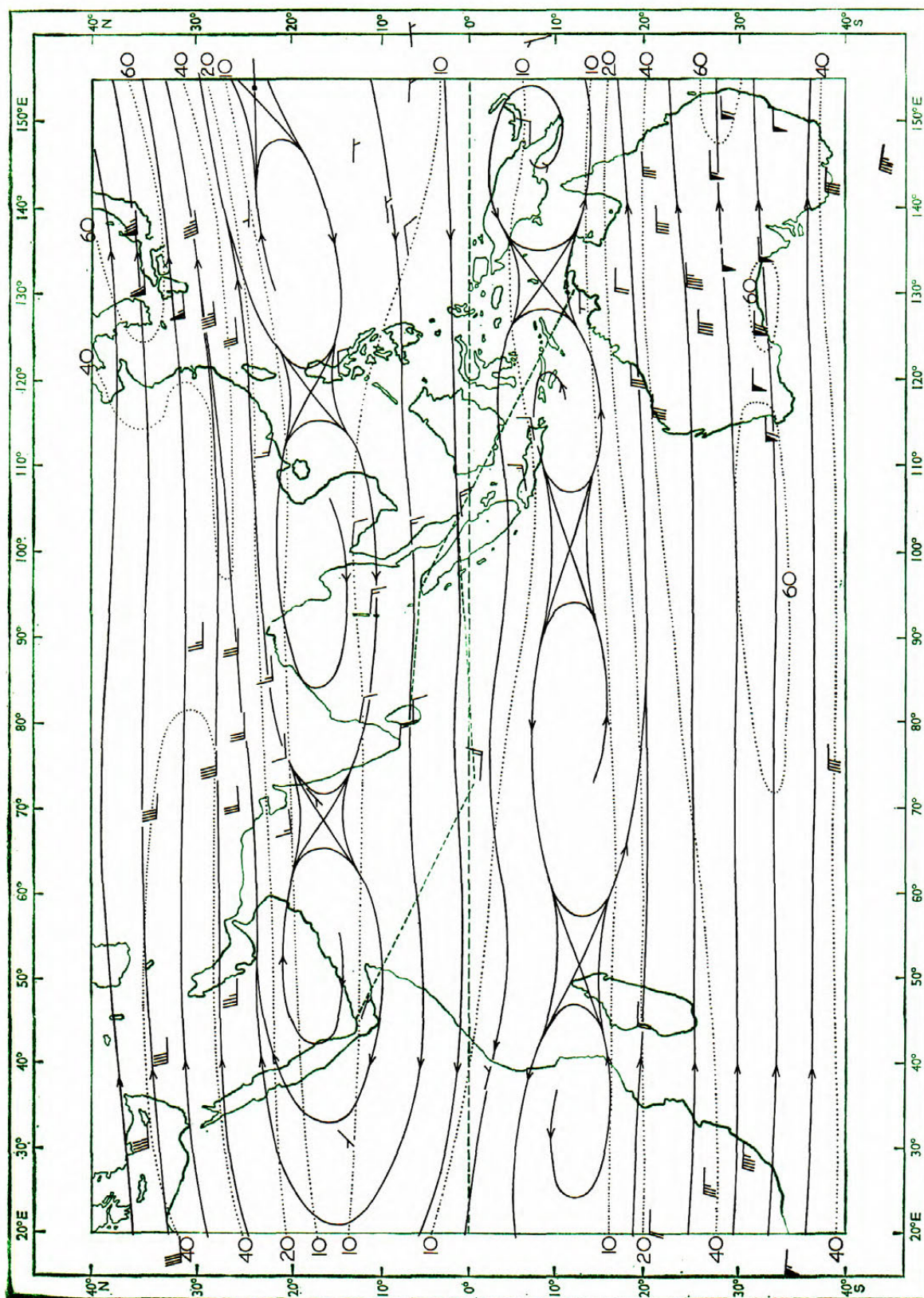


FIGURE 16—300 MB STREAMLINES AND ISOTACHS (KNOTS)—OCTOBER



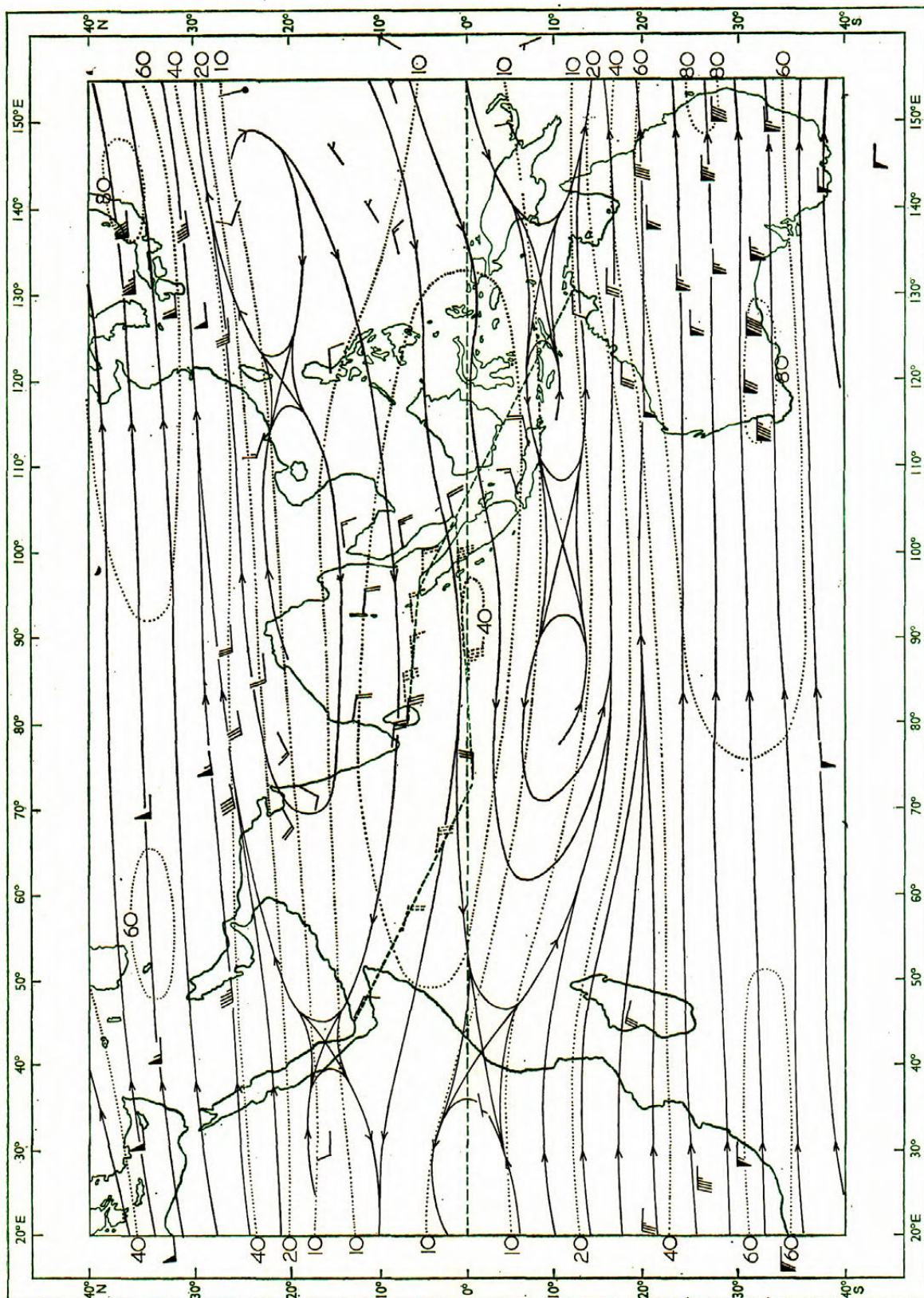


FIGURE 17—200 MB STREAMLINES AND ISOTACHS (KNOTS)—OCTOBER



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