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METEOROLOGICAL OFFICE

Geophysical Memoirs No. 114
(FOURTH NUMBER, VOLUME XV)

CIRCULATION PATTERNS AT 850, 700, 500 AND 200 MILLIBARS OVER THE EASTERN HEMISPHERE FROM 40°N TO 40°S DURING MAY AND JUNE

BY

P. B. WRIGHT, B.Sc. AND M. W. STUBBS, B.Sc.

LONDON: HER MAJESTY'S STATIONERY OFFICE

PRICE £3 0s. 0d. NET

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1971

U.D.C. 551.513:
551.515.5:
551.577.33

Geophys. Mem., London
15, No. 114, 1970

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CIRCULATION PATTERNS AT 850, 700, 500 AND 200 MILLIBARS OVER THE EASTERN HEMISPHERE FROM 40°N TO 40°S DURING MAY AND JUNE

§1 – INTRODUCTION

This memoir has been produced to supplement the information given in *Geophysical Memoirs* No. 103[1*] and 109[2] which presented streamline/isotach charts for various levels of the upper atmosphere for the mid-season months of January, April, July and October. In many parts of the world it is possible to interpolate the patterns that might be expected in the intermediate months but in the monsoon areas of the tropics the changes that occur between April and July are considerable and non-uniform.

Because the changes take place over quite a short period, usually less than a month, it was found that monthly mean streamline/isotach charts (such as those published by the International Meteorological Centre[3]), although very useful in many ways, do not illustrate the changes in sufficient detail. It was therefore decided to divide the period into 10-day periods, i.e. decads (*D*), and to use decad means throughout the study. A selection of the charts and cross-sections which were prepared are presented in this memoir and it is hoped that they will be of assistance in the interpolation of wind flow patterns in the troposphere over a large part of the tropical zone during the period between April and July.

A preliminary study of the 200-mb level was made by Lockwood.[4] The main project of this memoir was planned by M.W. Stubbs who also organized the extraction and computation of the original data. These data and the computed results were then analysed and the text of the memoir was prepared by P.B. Wright.

The area for which the investigation was carried out extends from 40°N to 40°S and from 20°W through India to 150°W. The levels studied were 850, 700, 500 and 200 mb. Data for the months of May and June for the years 1956-60 were analysed, and 5-year streamline/isotach charts were prepared. It was decided that the most useful charts to present in this memoir were those for the middle decad of May (11th-20th), *D*14, and the middle decad of June (10th-19th), *D*17. Mean flow charts and vertical cross-sections of wind for individual decads were also prepared, and these showed that the period of transition varies from year to year; for example in early June 1956 over India the main part of the change in the circulation patterns had already taken place whereas at the same time in 1958 it had not yet started. It was decided to present in this publication some of the charts and cross-sections for decads of individual years, in order to illustrate the patterns to be expected while the changes are taking place and to highlight some of the differences between the years.

For the 700-mb level a complete analysis was made for each decad of May and June in each of the years 1956-60. A more limited time and space coverage was afforded to the 200-mb and 850-mb levels. Charts for 500 mb for individual years were not prepared, because the pattern at this level was usually found to be transitional between the more pronounced patterns above and below, and would therefore provide little useful information that was not apparent from charts of either the 700-mb or the 200-mb level.

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*The index numbers refer to the bibliography on p. 38.

PART I – THE STREAMLINE/ISOTACH CHARTS AND WIND CROSS-SECTIONS: THEIR PREPARATION AND USEFULNESS

§2 – THE DATA

All available data from radar-wind stations in the area were used. Except in a few areas where the coverage was good, these data were supplemented by pilot-balloon observations. The numerous sources of data are listed in Appendix I (p. 40).

Use was also made of winds measured from aircraft, using Doppler methods; these winds were obtained from RAF and civil aircraft observations collected in the Meteorological Office from British-operated airfields. For the year 1959 there were 270 observations relevant to the area and the period under study and for 1960 there were 300. All of these observations were extracted but because they were so widely distributed, both in space and in time, they provided data for only a few of the analyses, and these mainly at the 200-mb level.

§3 – CALCULATION OF THE MEAN WINDS

The decads of the year are numbered consecutively from *D*1 (1-10 January), but 29 February is ignored when it occurs. Thus, for example, 1-10 May is *D*13 and 31 May-9 June is *D*16. The period under study in the present memoir consists of *D*13-*D*18 inclusive. In parts of the text the decads are subdivided into 5-day periods, i.e. pentads (*P*); these are also numbered from 1 January and so 1-5 May is *P*25, and 25-29 June is *P*36.

For each radar-wind and pilot-balloon station the Meteorological Office Mercury computer was used to calculate the mean winds for each decad. At stations where more than one observation was made on any day, only one was used in the calculation, usually that nearest to 0000 GMT. For the majority of the calculations, especially those for the higher levels and for pilot-balloon stations, observations were available from less than 10 separate days and in many instances the number was less than 5. In every instance the mean of the available observations was found and then the mean wind and the number of observations for each station were plotted on the relevant chart.

The 5-year vector mean wind for each decad was calculated as a weighted mean V of the decad mean winds for each year (v_{56}, v_{57}, v_{58}, v_{59}, v_{60}), defined by:

$$V = \frac{a_{56}\,v_{56} + a_{57}\,v_{57} + a_{58}\,v_{58} + a_{59}\,v_{59} + a_{60}\,v_{60}}{a_{56} + a_{57} + a_{58} + a_{59} + a_{60}}$$

where a_r = 1 if there were at least 4 observations in that decad in year r,

= 0.75 if there were 3 observations,

= 0.50 if there were 2 observations,

= 0.25 if there was 1 observation,

= 0 if there were no observations.

The weighted vector mean wind V was then plotted on the chart on which the 5-year mean pattern would be drawn; the number of years in which at least 1 observation for the decad was made and the total number of observations used from all 5 years combined were also plotted.

§ 4 – ANALYSIS OF THE CHARTS FOR INDIVIDUAL DECADS

The decad mean wind observations were analysed by drawing streamlines and isotachs. During this process amendments were made to the lines, where necessary, to maintain an approximately non-divergent wind field, except where there was good evidence to the contrary. Few of the calculated mean values had to be completely rejected; the means constructed from radar-wind observations were given more weight than those from pilot-balloon data, and attention was also paid to the numbers of observations that contributed to the mean values.

Amendments were made to the analyses to take account of the aircraft observations (see § 8) and of the cross-sections along 75°E which were constructed (see § 9). Alterations were also made to a few analyses in the light of a study of winds over east Africa [10, 11, 12] (see § 16).

The charts were compared with each other to ensure reasonable consistency, particularly in areas of sparse data coverage. Comparisons, in order of importance, were made between:

(i) charts of different levels for the same decad,

(ii) charts of the same level for different decads of the same year, and

(iii) charts of the same level for the same decad of different years.

Two of the points looked for were: a balance between convergence and divergence through the troposphere, and, near the equator, a balance between meridional flows through the troposphere (see § 20).

Reference was also made to other available charts of the area, in particular those by Raman and Dixit[5] and Wiederanders.[6]

§ 5 – ACCURACY OF THE ANALYSES FOR INDIVIDUAL DECADS

The details of the flow patterns are most complex at 850 mb and simplest at 200 mb, so a greater density of observations is necessary to depict the detail at lower levels.

Of the 5 years' charts studied, those for 1958 are likely to be the most accurate because:

(i) That year was included in the period of the International Geophysical Year, when more stations than usual made upper-air observations, and data were more readily available.

(ii) A larger number of charts have been analysed, so that there was greater opportunity for checking their consistency.

It is considered that the patterns depicted on the charts for individual decads of 1958 are unlikely to be seriously in error except over the limited areas denoted, by a cross (X), in Table I. In those areas it is possible that substantial errors may be present on some charts.

TABLE I – AREAS WHERE SUBSTANTIAL ERRORS MAY BE PRESENT IN SOME OF THE CHARTS FOR INDIVIDUAL DECADS OF 1958

Area		Pressure level		
		850 mb	700 mb	200 mb
East Atlantic Ocean	(east of 20°W)	X	X	X
Sahara	(20°N to 30°N)	X		
Sahara	(around 20°N)		X	
East Africa	(10°N to 10°S)			X
Arabia		X		
Arabian Sea and Indian Ocean				X
Arabian Sea and Indian Ocean except the south-west quadrant		X	X	
Indonesia				X
West Pacific Ocean	(north of 30°N)	X	X	X
West Pacific Ocean	(180° to 150°W)	X	X	
West Pacific Ocean	(south of 10°S and 180° to 150°W)			X

X denotes that substantial errors may be present in that area on some of the charts for that level.

§6 – ANALYSIS AND ACCURACY OF THE 5-YEAR MEAN CHARTS

The analysis of these charts was undertaken in a similar way to that of the charts for individual decads, account being taken of both the number of years and the number of observations represented by each plot. In order to avoid biasing the 5-year mean charts in favour of the pattern for any particular year, because there were more observations for that year (usually 1958), reference was made to the analyses for individual years. A complete comparison for the 850-mb level was not possible because the only charts analysed were for 1958. The 5-year mean patterns for this level are, therefore, likely to be biased in favour of the patterns for 1958 in a few areas, especially in central and southern Africa where observations were much more plentiful in 1958 than in the other years. Similarly, a comparison was not possible for the 500-mb level, for which no charts for individual years were analysed, and consequently the patterns shown in Plates 5 and 6 are likely to be less accurate than those presented for the other levels. Finally the 5-year mean charts were compared with each other to ensure vertical consistency.

§7 – REPRESENTATIVENESS OF THE 5-YEAR MEAN CHARTS

Since 5 years is rather a short period compared with that normally used in compiling mean charts, it is important to know, where possible, how closely the charts represent the patterns to be expected in any other year chosen at random from outside the period used. It is also important to know whether linear interpolation is justified between the patterns for *D*14 and *D*17, and between these and the mean April and July patterns. When the charts are used for such purposes therefore, the following factors should be borne in mind:

(i) The time of the rapid change in the flow pattern varies greatly from year to year. The change has not usually started by *D*14, but the main part of it is usually completed by *D*17, hence the flow patterns of *D*14 and *D*17 are less variable from year to year than those of the intermediate decads.

In 1956 a large part of the change had already occurred by *D*14, consequently the flow pattern for *D*14 of 1956 is very different from those of the other years in many respects (compare Plates 15 and 27). It appears likely that this exceptional behaviour occurs only about once every 40 years (see § 18). It is suggested, therefore, that the mean pattern to be expected in D14 should be rather closer to the April pattern than is indicated on the 5-year mean charts presented here.

For southern Asia – the area where the seasonal changes are most pronounced – the progress of the changes during the transition period of each year is summarized in Tables II-V. In each table the earliness of the flow pattern in each decad is expressed by comparing the pattern with one of the 5-year mean patterns for the corresponding level.

TABLE II – THE STATE OF THE 700-MILLIBAR FLOW PATTERN OVER SOUTHERN ASIA IN EACH DECAD EXPRESSED RELATIVE TO THE 5-YEAR MEAN PATTERN FOR *D*14

Year	Decad					
	*D*13	*D*14	*D*15	*D*16	*D*17	*D*18
1956	J	H	J	J	J	J
1957	A	O	(J)	J	J	J
1958	O	O	O	(J)	J	J
1959	A	O	H	J	(J)	J
1960	(A)	O	(J)	J	J	J

See Plate 3

TABLE III – THE STATE OF THE 700-MILLIBAR FLOW PATTERN OVER SOUTHERN ASIA IN EACH DECAD EXPRESSED RELATIVE TO THE 5-YEAR MEAN PATTERN FOR *D*17

Year	Decad					
	*D*13	*D*14	*D*15	*D*16	*D*17	*D*18
1956	A	(A)	O	J	J	J
1957	A	A	A	O	O	(J)
1958	A	A	A	A	O	J
1959	A	A	A	O	A	O
1960	A	A	A	O	O	J

See Plate 4

TABLE IV – THE STATE OF THE 200-MILLIBAR FLOW PATTERN OVER SOUTHERN ASIA IN EACH DECAD EXPRESSED RELATIVE TO THE 5-YEAR MEAN PATTERN FOR *D*14

Year	Decad					
	*D*13	*D*14	*D*15	*D*16	*D*17	*D*18
1956	J	J	J	J	J	J
1957	A	A	O	J (west) O(east)	J	J
1958	O	O	O	O(west) J (east)	J	J
1959	(A)	O	J (west) O(east)	J	J	J
1960	A(west) O(east)	O	J	J	J	J

See Plate 7

TABLE V – THE STATE OF THE 200-MILLIBAR FLOW PATTERN OVER SOUTHERN ASIA IN EACH DECAD EXPRESSED RELATIVE TO THE 5-YEAR MEAN PATTERN FOR *D*17

Year	Decad					
	*D*13	*D*14	*D*15	*D*16	*D*17	*D*18
1956	O	O	J (west) O(east)	J	J	J
1957	A	A	A	A	O	O
1958	A	A	A	A	O	J
1959	A	A	O(west) A(east)	O	J (west) O(east)	J (west) O(east)
1960	A	A	A(west) O(east)	O	O	J

See Plate 8

Notes on Tables II – V.

A = The pattern in the decad concerned differed substantially from that shown on the 5-year mean chart and was closer to the April pattern than was the 5-year mean.

J = The pattern in the decad concerned differed substantially from that shown on the 5-year mean chart, and was closer to the July pattern than was the 5-year mean.

Brackets round A or J imply that the difference from the 5-year mean pattern was less than would be implied by the letter without brackets.

O = The pattern in the decad concerned was similar to that of the 5-year mean chart.

H = A hybrid pattern showing some features of early season and some of late, and difficult to compare. (The two decads marked 'H' were rather similar to each other.)

The category was subdivided into 'west' and 'east' when the state over the African sector (west) was considered to be in a different category from the state over the Pacific sector (east).

(ii) There is some suggestion that after the main change has occurred a temporary weakening of the monsoon circulation takes place in *D*17; the years 1956, 1957 and 1959 all showed a weaker equatorial westerly at 700 mb in *D*17 than in *D*16. Because insufficient evidence is available it is not possible to determine whether this temporary weakening is the effect of chance but it should, perhaps, be taken into account when the patterns to be expected in *D*16 and *D*18 are deduced.

(iii) In all 5 years there was a stronger westerly current in the lower troposphere over Burma and Indo-China in *D*16 than in *D*17. The presence of tropical storms in the Philippines/China Seas area probably contributed to the strength of this westerly in 1958 and 1960 but as the feature occurred in all the years studied it may be a seasonal singularity.

(iv) A biennial oscillation is apparent in several features of the tropical flow, notably in the strengths of the Madagascan trades and the equatorial westerly, which were greatest in the even years (see § 21). Because data for 3 even years and 2 odd years have been used the charts may thus be biased in favour of currents stronger than the long-term mean for these areas.

§8 – USE OF THE AIRCRAFT OBSERVATIONS

The aircraft observations of wind were plotted on separate charts; an example is shown as Figure 1. Close consistency between neighbouring observations is evident on most of these charts; this is particularly remarkable since most of the plotted values are of individual observations rather than averages over several days, and neighbouring values often represent different days of the decad. This emphasizes not only the high quality of the observations but also the steadiness of the patterns. The most notable exception was in *D*15 of 1959 during which large changes took place and the mean pattern was not representative of the flow on individual days.

The streamlines and isotachs deduced from the aircraft observations alone – although they were often based on data for only 1 or 2 days – are in very good agreement with those constructed from the radar-wind and pilot-balloon observations. For that reason it was considered justifiable to use aircraft observations to make corrections to the patterns drawn on the main charts. They were a particularly valuable aid to detailed analysis over eastern Africa and the Arabian Sea in the exit

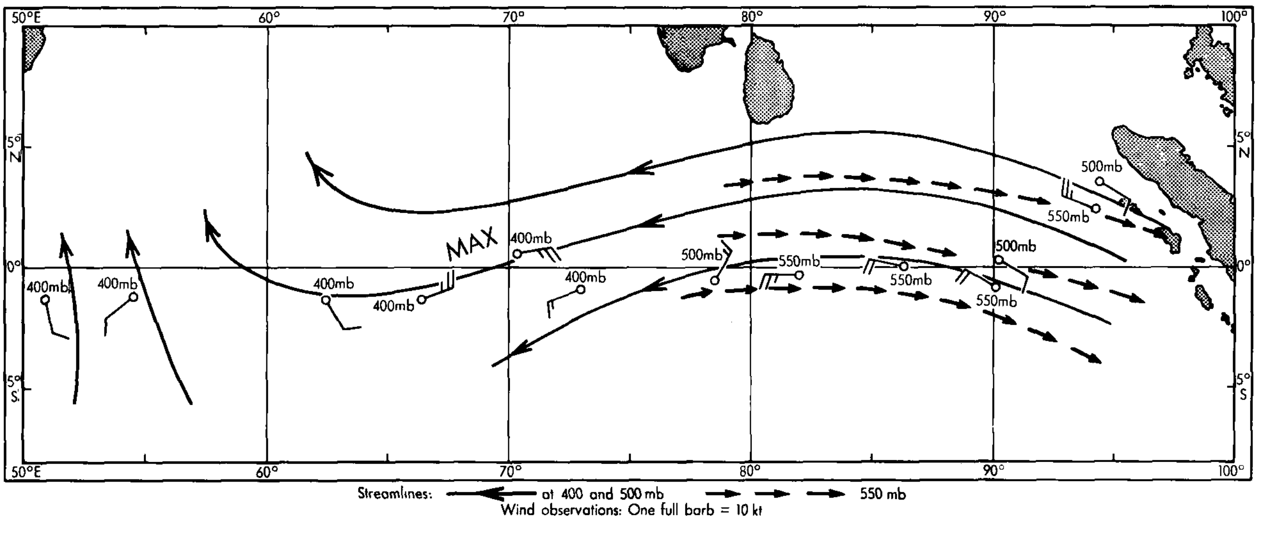

FIGURE 1. AIRCRAFT OBSERVATIONS OVER THE INDIAN OCEAN DURING *D*18 OF 1960

TABLE VI – LATITUDES OF AXES, AT 75°E, OF (a) UPPER TROPOSPHERIC NORTHERN SUBTROPICAL WESTERLY CURRENT, (b) NORTHERN RIDGE AT 200 MILLIBARS AND (c) LOWER TROPOSPHERIC INDIAN EASTERLY TRADES

(a) Latitude of axis of upper tropospheric northern subtropical westerly current

	Year				
	1956	1957	1958	1959	1960
Decad	Latitude in degrees north				
*D*13	not available	⩽26	29	41, 28	44, 31
*D*14		⩽23	29	36, 28	41, 27
*D*15		⩽27	29	34	46, 31-39
*D*16		⩽29	29	40	46, –
*D*17		⩽31	36	38	36
*D*18		⩽33	37	39	39

(b) Latitude of 200-mb northern ridge axis

	Year				
	1956	1957	1958	1959	1960
Decad	Latitude in degrees north				
*D*13	23	9	15	12	7
*D*14	21	12	15	13	14
*D*15	28	17	13	21	21
*D*16	28	17	14	25	23
*D*17	29	23	21	25	23
*D*18	28	23	26	25	27

(c) Latitude of axis of lower tropospheric Indian easterly trades

	Year				
	1956	1957	1958	1959	1960
Decad	Latitude in degrees north				
*D*13	18	9	14	10	13
*D*14	23, 12	13	14	15	15
*D*15	20	14	15	19	18
*D*16	23	16	13	22	22
*D*17	24	–	19	–	23
*D*18	24	25	24	23	25

Note: A dash (–) indicates that an axis was not well defined.

region of the 200-mb easterly flow, and substantial changes were made to the streamlines and isotachs on some charts.

A small proportion of the aircraft observations could not be fitted into the analyses because they were either in error or unrepresentative of the decad.

§9 – ANALYSIS OF THE CROSS-SECTIONS

For each individual decad of the period under study, the mean zonal wind components at several levels for a number of stations, mainly radar-wind stations, lying close to the 75°E meridian, were analysed, to form vertical cross-sections. Where necessary, the analyses were amended to ensure consistency with those charts for the standard levels which had been analysed for the corresponding decad; they were also checked for consistency with the others in the same year. To emphasize the seasonal changes, certain features were traced from the cross-sections to form continuity cross-sections, which are not reproduced here. Table VI shows, for each decad, the latitudes of these features obtained from the continuity cross-sections.

The cross-sections, reproduced as Plates 30-35, are considered to be accurate from 5°N northwards, where data were plentiful, but south of 5°N it is possible that there may be substantial errors in some places.

PART II – DESCRIPTION OF THE MAIN FEATURES OF THE CIRCULATION

§10 – INTRODUCTION

The circulation patterns in the tropical regions during the transition period (May and June) are shown in the decad mean streamline/isotach charts (Plates 1-29).

The flow at each level may conveniently be regarded as comprising several characteristic wind régimes, each occupying a zonal belt and usually extending across a wide range of longitude.

In this memoir the term 'monsoon' is restricted to the circulation patterns characteristic of the months June-September over southern Asia and the Indian Ocean.

§11 – CIRCULATION IN THE UPPER TROPOSPHERE

At levels above about 400 mb the flow patterns are typified by those at 200 mb shown in Plates 7 and 8. The main régimes at this level are:

(i) *Northern subtropical westerly current.* A jet stream, centred between 30°N and 40°N, which extends across all longitudes studied and moves northwards during the period.

(ii) *Northern ridge belt.* A zone of light winds and anticyclonic curvature of the streamlines, in the latitude range 5°N-30°N. There are usually three anticyclonic centres present, over Africa, west Asia and east Asia. This belt also moves northwards during the period, in close association with the movement of the subtropical westerly.

(iii) *Southern ridge belt.* A similar anticyclonic zone which extends from Africa to Australia. Its latitude varies from decad to decad between the equator and 15°S, and the positions of anticyclonic centres within it also vary.

(iv) *Southern subtropical westerly.* Part of a jet stream which encircles the globe near 30°S.

(v) *Upper easterly current.* This is found in equatorial regions between the two ridge belts. It is always present over the Indian Ocean and it increases greatly in strength and in area during the period. Over Africa it is weak during May but it develops and increases rapidly in strength during June; however, occasionally the ridge axes are absent and westerly winds extend to all latitudes.

The 200-mb pattern is rather different over the Pacific. There is a westerly current, centred at about 20°N, which is separated from the northern subtropical westerly current by a belt of light north-westerly winds or a weak ridge. Near the equator the axes of the northern and southern ridges can sometimes be distinguished but often these are replaced by an equatorial belt of light winds, and a westerly flow occupies nearly all latitudes. This pattern is distorted when tropical storms occur.

§ 12 – CIRCULATION IN THE LOWER TROPOSPHERE

Within the 900-600-mb layer the patterns vary little with height and are typified by those for 700 mb illustrated in Plates 3 and 4. For the zones at 700 mb it is convenient to use the same terminology as was used for the corresponding features at 200 mb, although there are several important smaller-scale variations within the zones.

At 700 mb, the northern subtropical westerly current is present over Arabia and north Africa but it has more meridional fluctuations than at 200 mb. It loses its identity over central Asia, where it is broken up by the mountain ranges, and develops again over the East China Sea. Over northern India there is a smaller westerly current–the north Indian westerly–which declines and disappears towards the end of June.

At the start of the period the northern ridge belt is usually continuous across all longitudes studied, with anticyclonic centres over Africa, Arabia, India, Indo-China and the Pacific. The Indian centre declines early in the period, and that over Arabia somewhat later. This process produces a break in the ridge belt, which is associated with the developing monsoon circulation.

The southern ridge belt extends across south Africa and the Indian Ocean in latitudes ranging from 15°S to 25°S. There are usually anticyclonic centres over south Africa and near the island of Madagascar, and probably another over the Indian Ocean, although the last of these centres is difficult to locate owing to lack of observations. Over Australia there are two preferred latitudes for the ridge axis, about 15°S and 26°S. In this area the axis is often double and is associated with markedly meridional flow or with a cut-off low near New Zealand. Over the Pacific the ridge is more constant in position, near 15°S.

The southern subtropical westerly current cannot be discussed in detail owing to the shortage of observations south of 30°S.

Between the two ridge belts easterly trade winds blow. Over Africa and the Pacific these easterlies are continuous across the equator, with confluence near the equator; over the Indian Ocean two equatorial troughs are present early in May and the trades flow around these to feed the belt of westerly winds that straddles the equator (i.e. the equatorial westerly). As the transition progresses, the northern equatorial trough moves northwards across India to become the monsoon trough, and the westerly expands and strengthens to become the monsoon westerly, which is associated with the monsoon rains of India; meanwhile the north Indian westerly, the anticyclonic cell over India and the associated branch of the trades decline and disappear.

Over the Pacific, tropical storms, when they occur, greatly distort the otherwise simple decad mean pattern of a smooth easterly flow in equatorial regions.

The 850-mb patterns are in general similar to those at 700 mb, particularly over the Pacific and Asian sectors where the only marked difference is that the anticyclonic circulation that is apparent over India at 700 mb early in the season does not occur at 850 mb. Over Africa, however, there are several important differences between the patterns at the two levels. Over central Africa the 850-mb charts show a marked trough line with cyclonic vortices and some south-westerly winds, all of which are usually absent at 700 mb during May and June. Another feature of the 850-mb pattern that is absent at 700 mb is the presence over east Africa of a strong but narrow southerly current which strengthens during the period; this will be described in detail later (see § 16).

§ 13 – CIRCULATION AT 500 MILLIBARS

In subtropical latitudes the 500-mb flow patterns are approximately the mean of those at 700 mb and 200 mb. The currents are westerly with maxima of about 30-40 knots. In the tropical zone the winds at 500 mb are generally light and the flow patterns are ill defined. This level tends to be in the layer of transition between the differing and distinct patterns of the upper troposphere and the lower troposphere. The transitional nature of the 500-mb level is well illustrated in the cross-sections along 75°E (Plates 30-35).

§ 14 – SEASONAL CHANGES

Progressive changes occur in the broad features of the flow during May and June. The changes are most marked in the northern hemisphere, where they are largest in the Asian sector and least over the Pacific.

Over Asia the northern westerly and the northern ridge in the upper troposphere move northwards through a considerable distance (about 15 degrees of latitude between *D*13 and *D*18). The movement is rather sudden, most of it taking place within two or three decads (Figure 2). At the same time the upper easterly current intensifies and also extends northwards. In the lower troposphere, as already described, the pre-monsoon pattern breaks down as the trough moves northwards and the monsoon westerly strengthens.

In the African sector a similar change occurs in the upper tropospheric features. The movement is smaller than over Asia (through about 12 degrees of latitude), but it occurs just as suddenly (Figure 2). There is also a tendency for the southern ridge to move southwards towards the end of the period (Figure 3). This movement may be associated with the rapid increase in the strength of the upper easterly current and is the only change in any of the southern hemisphere features that is as marked as those of the northern hemisphere. In the lower troposphere there is little noticeable change at 700 mb but at 850 mb the equatorial trough moves northwards and becomes broader; this movement appears to be a much steadier process than the change in the upper troposphere.

In the Pacific sector, except in the north-west Pacific which is influenced by the Asian monsoon, there is very little seasonal change from April to June.

While the year-to-year differences in the patterns are, in general, not great, there are large variations in the dates of the change (Figures 2-5). In particular, in 1956 much of the change had already occurred in all sectors by *D*13, instead of by *D*16 which is about normal. In 1958 the change over west Asia occurred about two decads later than normal, associated with a late start to the monsoon over India, but over Africa and east Asia it was about normal.

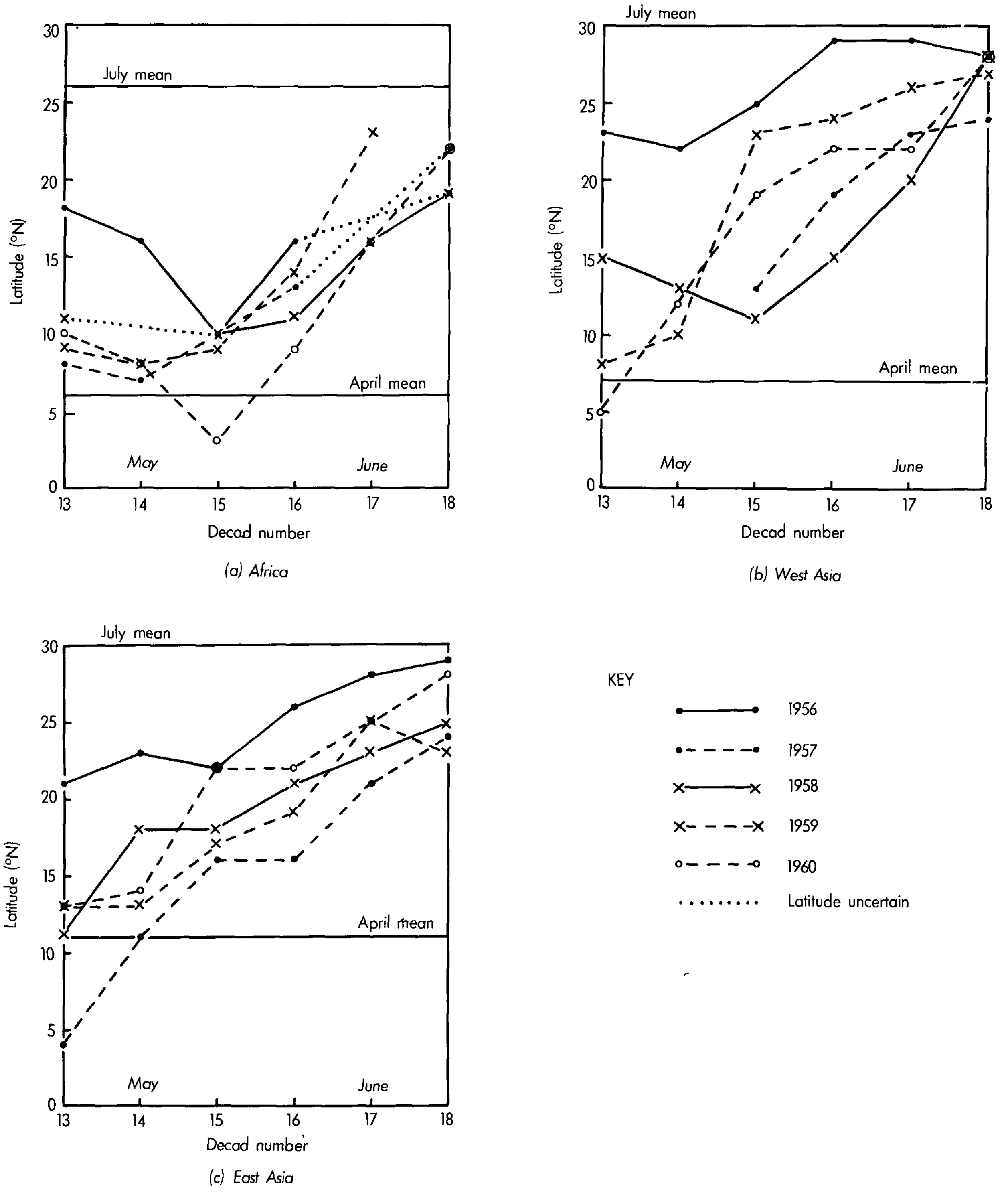

FIGURE 2. LATITUDE OF NORTHERN RIDGE AXIS AT 200 MILLIBARS DURING *D*13-*D*18 OF THE PERIOD 1956-60

(a) Africa (20°E) (b) West Asia (60°E) (c) East Asia (95°E)

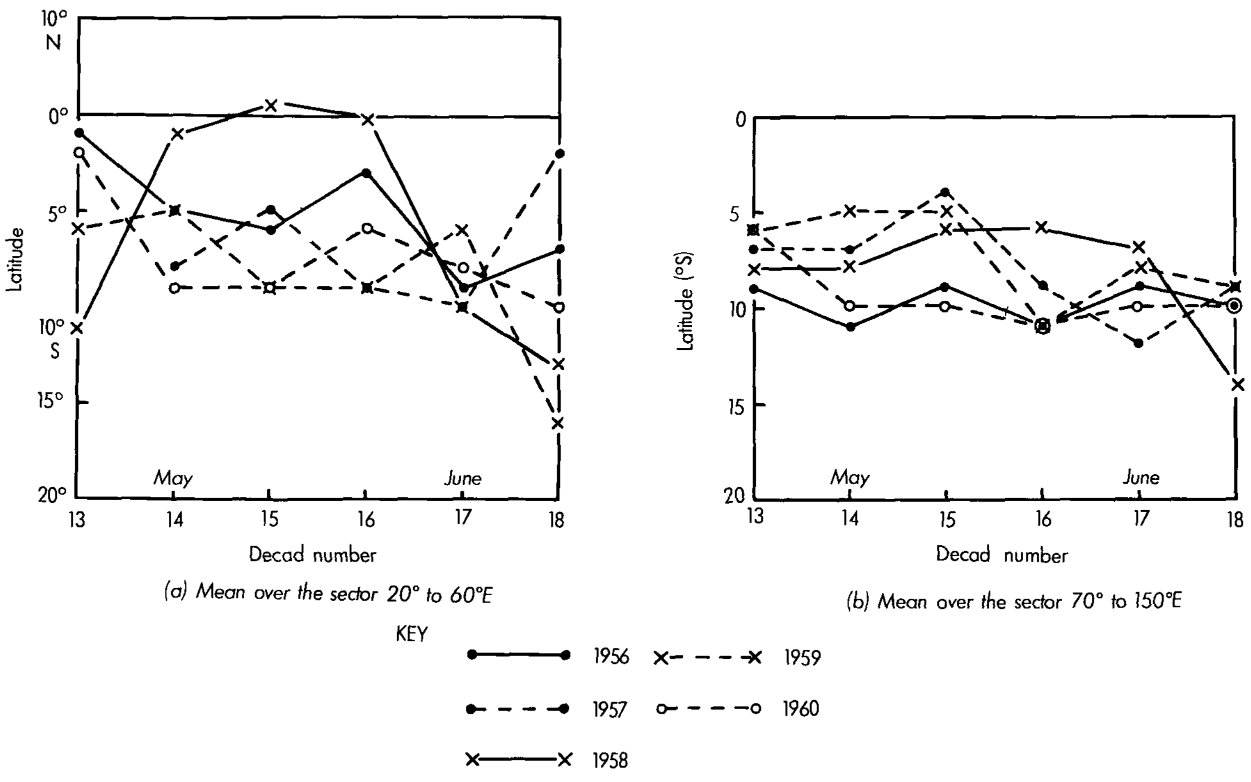

FIGURE 3. LATITUDE OF SOUTHERN RIDGE AXIS AT 200 MILLIBARS DURING $D13$-$D18$ OF THE PERIOD 1956-60

(a) Mean over the sector 20°-60°E (b) Mean over the sector 70°-150°E

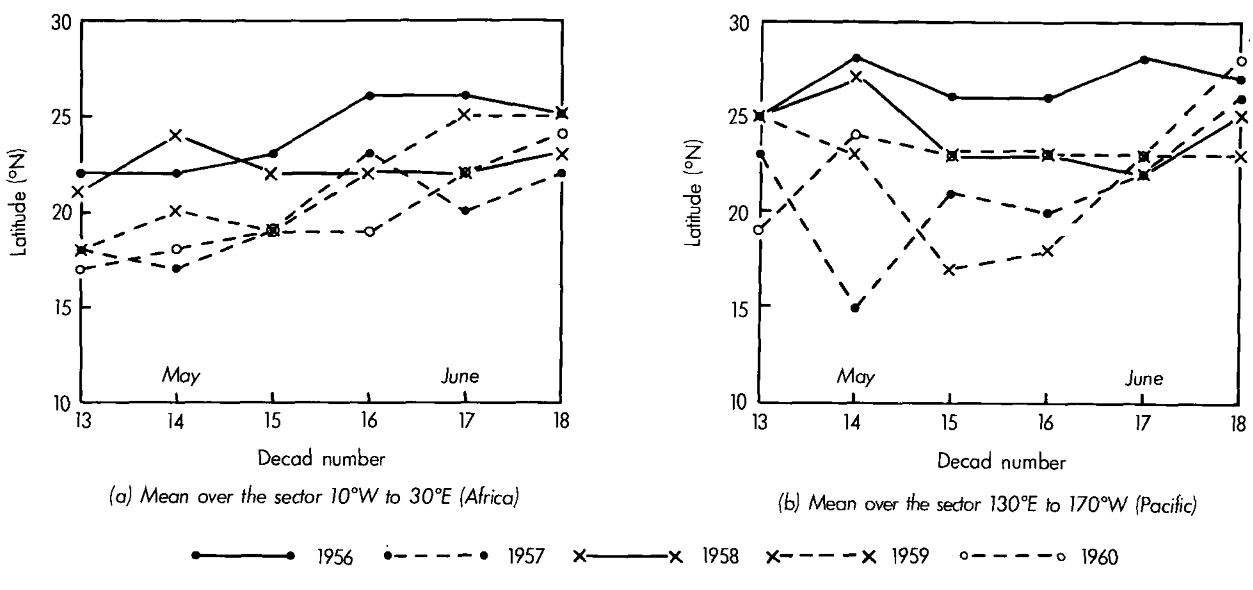

FIGURE 4. LATITUDE OF NORTHERN RIDGE AXIS AT 700 MILLIBARS DURING $D13$-$D18$ OF THE PERIOD 1956-60

Mean over: (a) African sector (10°W-30°E), (b) Pacific sector (130°E-170°W)

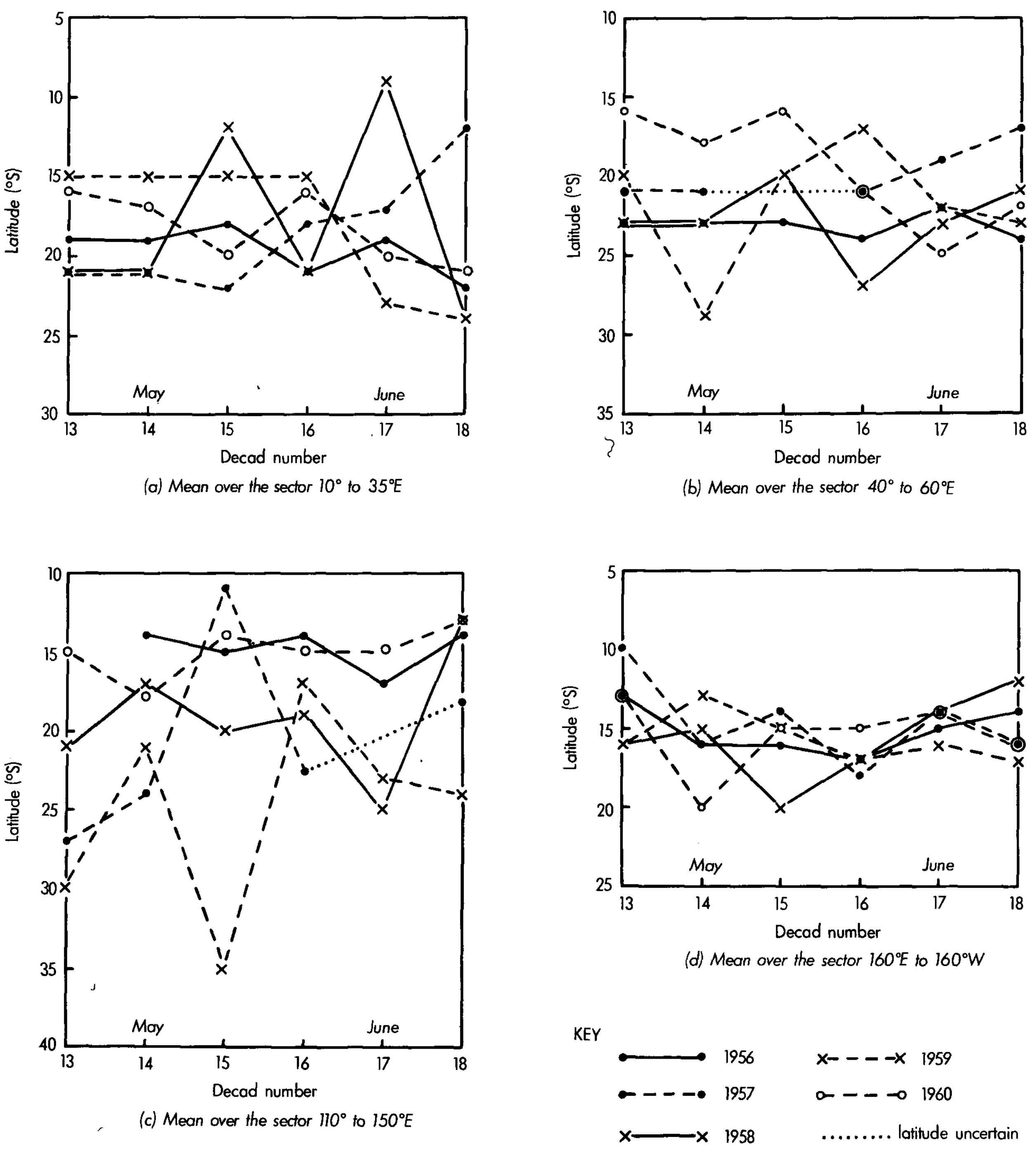

FIGURE 5. LATITUDE OF SOUTHERN RIDGE AXIS AT 700 MILLIBARS DURING *D*13-*D*18 OF THE PERIOD 1956-60

Mean over sector: (a) 10°E-35°E, (b) 40°E-60°E (c) 110°E-150°E, (d) 160°E-160°W

PART III – DETAILED STUDIES OF THE FLOW PATTERNS

§ 15 – THE ASIAN SECTOR

The patterns

The sequence of the pattern changes during May and June can be studied by reference to the charts for 1958. That year was fairly typical as far as the manner of change was concerned, although it was exceptional in that the main change occurred from *D*16 to *D*18, about two decads later than usual.

The situation prior to the onset of the monsoon circulation is illustrated by the charts for *D*13 of 1958 (Plates 9, 15 and 21) These show the northern westerly jet axis at about 30°N over north India, the northern ridge at 200 mb over south India, the northern equatorial trough at 700 mb along about 7°N with a cyclonic centre over Ceylon, and the equatorial westerly current over the Indian Ocean most marked at 850 mb over the western part of the ocean. This situation is fairly typical of early May, although in some years there is an anticyclonic centre at 700 mb over central India (for example *D*13 of 1959 and 1960) and the equatorial westerly is sometimes much weaker (for example in *D*13 of 1959 it was almost non-existent at 700 mb). The pattern is very similar to the mean April pattern shown in *Geophysical Memoirs* No. 109.[2]

The 200-mb patterns over west Asia show that in 1958 a sudden northward movement of the features in the northern hemisphere took place between *D*16 and *D*18, together with a rapid increase in speed and extent of the upper easterly over the Indian Ocean. At about the same time, at 700 mb the anticyclonic cell and north-easterly trades over India declined and the monsoon trough moved north to take their place. The anticyclonic cell over Arabia at 700 mb and the weak flow-pattern in the same area at 850 mb, which existed during *D*13-*D*16, declined and were replaced by a northerly flow in *D*17 and *D*18. This, together with the strengthening southerly current over east Africa, resulted in an increased mass flux over the Arabian Sea and an associated strengthening of the lower tropospheric westerly current, which was observed as the 'burst of the monsoon' on the west coast of India. By *D*18 of 1958 the westerly jet had moved to 37°N, the northern ridge had moved to 27°N, and the monsoon trough at 700 mb was orientated along 22°N. The monsoon westerly in the lower troposphere and the upper easterly were both well developed, and the pattern closely resembled the normal July flow pattern (*Geophysical Memoirs* No. 109[2]); it was similar also to the pattern in *D*18 of the other years studied.

The changes are also illustrated by the decad mean vertical cross-sections along 75°E. Those for 1958 (Plates 30-35) show that the westerly jet axis moved little during *D*13-*D*16 and then shifted rapidly northwards during *D*16-*D*18; the other currents also underwent their most rapid change and development during this period. The cross-sections for the other years demonstrate that the changes were usually equally rapid; the dates of the changes varied from year to year but in any particular year all the features underwent the main part of their change within a period of about two decads. The latitudes of the main features, obtained from the continuity cross-sections, have been presented as Table VI (page 8).

Variations of the evolution in different years

In 1960 the changes were more gradual than in the other years – the main change occurred during *D*14-*D*16. The Arabian anticyclone declined in *D*16 and was absent in *D*17 and *D*18. It appears likely that the equatorial westerly was stronger than usual throughout the season. In *D*13 there was a blocking situation in the subtropical flow over west Asia, the westerly current being shifted far to the north, with a blocking high over Iraq.

In 1959 the main changes in all the features occurred during *D*14-*D*16, although in *D*17 there was a temporary weakening of the monsoon westerly and a recession southwards of the subtropical westerly. An unusual feature in *D*15 was a trough over Arabia in place of the usual ridge, otherwise the Arabian anticyclone persisted throughout the season.

In 1958, as already described, the changes in the flow patterns were slight until *D*16 but were rapid thereafter. Examination of Figure 2 shows that this late change of the flow was comparatively local; over Africa and east Asia the date of change was about normal. The Arabian anticyclone declined in *D*17 and was absent in *D*18.

In 1957 the main change occurred in two stages, during *D*14-*D*15 and *D*16-*D*17, but knowledge of the upper easterly is scarce owing to lack of data. The Arabian anticyclone was absent from *D*16 onwards.

In 1956, although data from the upper troposphere were again scanty, it is clear from the charts and cross-sections that by *D*13 a substantial change had already taken place making the pattern for this decad about a month in advance of normal (compare Plates 15 and 27). Nedungadi and Srinivasan[7] noticed this exceptional earliness in connection with winds over Everest–an area in which weather is particularly sensitive to this change. Figure 2 shows that the change occurred exceptionally early over Africa and east Asia also. A further change occurred in the Indian sector during *D*14-*D*15, and the Arabian anticyclone was absent from *D*14 onwards.

In 1956, 1957 and 1959 the monsoon westerly was weaker in *D*17 than in *D*16. It was not possible to determine whether this was a chance effect or a regular occurrence because only 5 years' data were studied. The charts also suggest that, during temporary weakenings of the monsoon westerly, the direction of the current is from north of west instead of from the west or from south of west, while the upper easterly correspondingly has a component from the south, instead of from the north as is normal.

Relations between upper-tropospheric changes and the onset of the monsoon

It is clear from the foregoing description that the onset of the monsoon is one aspect of a large-scale rapid change in the flow patterns over Asia that occurs each year during May or June, in which the upper troposphere plays an important part. An investigation into the relationship between upper-tropospheric changes and the advance of the monsoon along the west coast of India, which has been described by Wright[8], is summarized below.

The monsoon usually advances in two surges separated by a pause of up to three weeks. It was found that during the period 1956-65 the date of the first of these surges was related to the date when the 200-mb westerly wind component at Bombay (19°07′N, 72°51′E) decreased permanently below 5 knots, associated with the movement of the upper ridge axis to the latitude of Bombay. The date of the second surge was similarly related to the date when the 200-mb westerly wind component at New Delhi (28°35′N, 77°12′E) began the rapid decrease that is associated with the sudden northward movement of the subtropical westerly jet.

The surges of the monsoon were found to occur with a delay (relative to these changes in the upper troposphere) that was greater in years when the equatorial westerly current was weak in early May, i.e. prior to the onset of the monsoon circulation. The dates of onset at 13°N and 22°N along 75°E, obtained from charts published in the *Indian Daily Weather Report*[9] were used for convenience to represent the two surges of the monsoon. Details of these relationships are given in Tables VII(a) and VII(b), which show that the range in values of the delays was, in general, very small. There were, however, a few exceptional values, most of which occurred in those instances when the first surge either did not extend as far northwards as 13°N, or extended beyond 22°N. Under such circumstances these two latitudes are not suitable for indicating the two surges, e.g. in 1963 the first surge extended to 23°N, which accounts for the exceptionally small delay in that year as shown in Table VII(b). In 1956, but in none of the other years studied, substantial quantities of rain fell on about 1 May in many places on the west coast of India. This fact, together with the monsoonal character of the 700-mb pattern for *D*13 of 1956 (Plate 27), suggests that a surge of the monsoon took place on or about that date.

TABLE VII – RELATIONSHIPS BETWEEN CHANGES IN THE 200-MILLIBAR FLOW PATTERNS AND THE DATES OF ONSET OF THE MONSOON AT TWO LATITUDES ALONG 75°E

(a)	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965
B	25A	25M	12J	22M	19M	20M	15M	18M	6J	25M
V_G	(2)	(4)	(12)	(2)	16	21	6	−6	22	18
B'	24A	23M	6J	21M	11M	9M	12M	21M	26M	16M
d_{13}	24M	4J	14J	4J	20M	21M	19M	4J	7J	5J
$d_{13}-B'$	30	12	8	14	9	12	7	14	12	20

A = April M = May J = June

Notes: B = date when 200-mb westerly component at Bombay fell below 5 knots

V_G = value of 700-mb westerly component at Gan (00°42′S, 73°10′E,), 1-10 May, in knots

B' = adjusted date (B - $\frac{1}{2}V_G$)

d_{13} = date when monsoon reached 13°N

$d_{13}-B'$ = delay from adjusted date

Values in brackets are estimated from charts

(b)	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965
N	19M	24M	8J	29M	25M	21M	22M	19M	24M	8J
V_G	(2)	(4)	(12)	(2)	16	21	6	−6	22	18
N'	18M	22M	2J	28M	16M	10M	19M	22M	13M	30M
d_{22}	22J	26J	22J	25J	14J	10J	17J	12J	23J	2Jy
$d_{22}-N'$	35	35	20	28	29	31	29	21	41	33

M = May J = June Jy = July

Notes: N = date when main decrease of 200 mb westerly component at New Delhi began

V_G = value of 700 mb westerly component at Gan, 1-10 May, in knots

N' = adjusted date (N - $\frac{1}{2}V_G$)

d_{22} = date when monsoon reached 22°N

$d_{22}-N'$ = delay from adjusted date

Values in brackets are estimated from charts

(c)	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965
B_1	13A	28A	18A	23A	7A	6A	13A	25A	17A	22A
d_{13}	24M	4J	14J	4J	20M	21M	19M	4J	7J	5J
$d_{13}-B_1$	41	37	57	42	43	45	36	40	51	44
d_{22}	22J	26J	22J	25J	14J	10J	17J	12J	23J	2Jy
$d_{22}-B_1$	70	59	65	63	68	65	65	48	67	71

A = April M = May J = June Jy = July

Notes: B_1 = date of start of decrease in 200 mb zonal component at Bombay

d_{13} = date when monsoon reached 13°N

$d_{13}-B_1$ = delay for first burst of the monsoon

d_{22} = date when monsoon reached 22°N

$d_{22}-B_1$ = delay for second burst of the monsoon

It was also found that in the upper tropospheric wind field during April a change occurred, identifiable by a decrease in the westerly wind component at Bombay, and that the date of the start of this change was quite closely related to the dates of both surges of the monsoon (see Table VII(c). The most marked exceptions occurred in 1958 and 1964. In these two years the first surge would have been expected to occur about 30 May, however, an examination of the graphs of zonal wind component at Bombay showed that in both years, and in none of the other years, a substantial increase in westerly wind occurred about this date. This suggests the presence of some additional factor in 1958 and 1964, which delayed the first surge of the monsoon but not the second. The exceptionally late start of the circulation changes in 1958 already mentioned, confirms this and also suggests, because the lateness occurred only in the west Asian sector, that the additional factor was both local and temporary in its influence.

Relation between the upper-tropospheric flow and the surface pressure

The mechanism by which the upper-tropospheric flow influences the monsoon probably involves the low-pressure area that deepens over north India between March and July. A representative value for the depth of this low-pressure area was obtained from the daily surface synoptic charts published in the *Indian Daily Weather Report;*[9] the value used was the value of the lowest closed isobar over north India/Pakistan drawn (at 2-mb intervals) on the 1200 GMT chart, small intense depressions being ignored. The scatter diagram (Figure 6) demonstrates that during May and June there is a close correlation between this pressure and the latitude of the upper ridge. It indicates that a northward movement of the upper ridge is associated with a fall in pressure and in particular that a movement from 16°N to 20°N, which usually takes place suddenly, is accompanied by a proportionately greater fall of pressure.

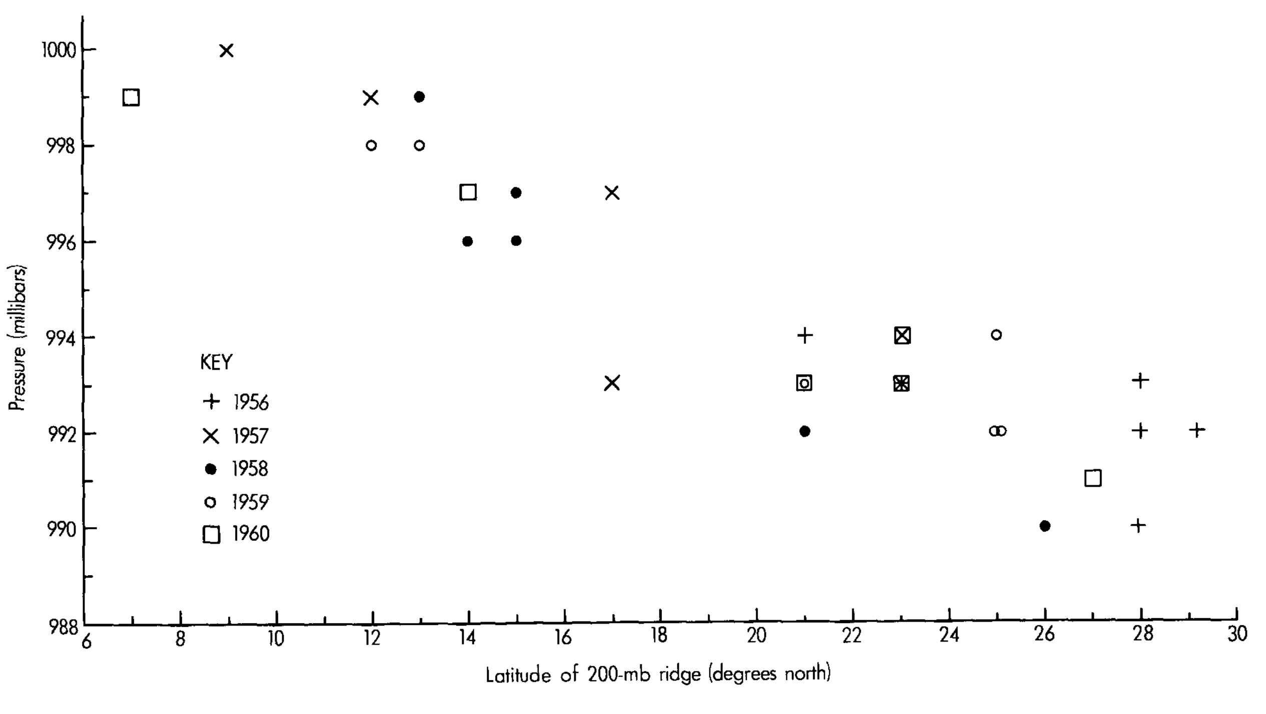

FIGURE 6. SCATTER DIAGRAM SHOWING THE ASSOCIATION BETWEEN DECAD MEAN VALUE OF LOWEST ISOBAR OVER NORTH INDIA AND THE LATITUDE OF 200-MILLIBAR NORTHERN RIDGE AXIS AT 75°E DURING MAY AND JUNE 1956-60

The association is further emphasized by a study of the changes of pressure before and after each movement of the upper ridge. Table VIII gives a list of the dates when a marked decrease in the 200-mb zonal wind component at Bombay began, as indicated on the graphs given by Wright.[8]

TABLE VIII – PRESSURE OVER NORTH INDIA/WEST PAKISTAN DURING DECREASES IN THE 200-MILLIBAR ZONAL WIND COMPONENT AT BOMBAY, 1 APRIL-10 JUNE 1956-65

Date of start of decrease (according to 5-day running means)			3-day mean values of lowest closed isobar over north India/West Pakistan during decreases	
			Mean of days	
d			*d*+1, *d*+2, *d*+3	*d*+4, *d*+5, *d*+6
			mb	*mb*
1956	April	13	1003	999
	May	22	993	991
1957	April	7	1005	1003
		16	1000	1001
		28	1002	1000
	May	23	999	994
1958	April	11	1005	1004
		18	1002	998
	May	1	997	996
		7	994	995
		30	998	994
	June	9	994	993
1959	April	5	1005	1000
		23	1001	1003
	May	8	1001	998
		16	997	997
	June	2	991	992
1960	April	7	1001	1003
		22	1001	1001
		30	1000	997
	May	15	997	993
	June	3	994	991
1961	April	5	1003	1002
		29	1000	1001
	May	26	993	993
	June	7	992	991
1962	April	13	1003	1003
	May	9	1001	999
		27	992	994
	June	4	993	987
1963	April	3	1003	1003
		13	996	1001
		25	1003	1002
	May	5	998	999
		23	995	993
1964	April	17	1000	999
	May	14	1001	995
	June	3	994	993
1965	April	4	1005	1004
		11	1003	1002
		21	1001	998
	May	23	997	994
	June	7	996	993

All substantial decreases from 1 April to 10 June each year are included.

TABLE IX – MEAN VALUE OF LOWEST CLOSED ISOBAR OVER NORTH INDIA/WEST PAKISTAN RELATIVE TO DATE (*d*) OF START OF DECREASE OF 200-MILLIBAR ZONAL WIND AT BOMBAY, 1 APRIL-10 JUNE 1956-65

Days	Mean pressure
	mb
d–8, *d*–7, *d*–6	999.7
d–5, *d*–4, *d*–3	999.3
d–2, *d*–1, *d*	999.4
d+1, *d*+2, *d*+3	998.8
d+4, *d*+5, *d*+6	997.4

Averaged over all occasions listed in Table VIII

These decreases were probably associated with northward movements of the upper ridge. Since the graphs depict 5-day running means it is possible that on some occasions the true decrease started two days later than the date given in the table. For each occasion the values of pressure during the decrease are given in Table VIII. Relative to each of the dates in Table VIII the mean value of the lowest closed isobar was calculated over five 3-day intervals; the mean values taken over all the dates are shown in Table IX. The average fall in central pressure over the period 1 April-30 June is about 0.5 mb in 3 days. Table IX shows that there was a much greater fall during the period of decrease in the 200-mb zonal wind component than before it.

Thus the sudden movement of the 200-mb ridge during May probably influences the monsoon by inducing a fall in surface pressure over north India. The resulting increased north-south pressure gradient over peninsular India then causes a steady increase in and northward movement of the equatorial westerly current, culminating in a surge of the monsoon. The stronger the westerly is at the beginning of the process, the sooner the surge occurs.

This hypothesis suggests the possibility that each surge of the monsoon current is associated with a sudden change in the flow pattern at 200 mb.

§ 16 – THE AFRICAN SECTOR

200-mb patterns

At 200 mb the main features described for Asia (the northern subtropical westerly, northern ridge belt, etc.) exist also over Africa but are nearer to the equator. Figure 2 illustrates this for the northern ridge axis. In *D*14 of 1958 the ridge belts and upper easterly were absent from the equatorial regions, and westerlies from both hemispheres extended to the equator; the charts indicate that this is probably a common state of affairs over the Atlantic. As over Asia, a marked northward shift of the northern ridge takes place towards the end of the transition season. This shift occurs at least as suddenly as that over Asia although the movement is over a lesser distance. In association with this shift the upper easterly strengthens. The southern ridge also shows some tendency towards a systematic movement during the season but its movement is southwards, opposite to the general trend at this time of year.

700-mb patterns

In the lower troposphere there are much greater differences between the African and Asian sectors. Early in the period the two subtropical ridge axes at 700 mb are situated along about 20°N and 20°S respectively; the northern ridge is usually well marked across the continent, and there is a large anticyclonic centre over the Sahara. The southern ridge usually has two centres, one over the mainland and another over or near Madagascar. Between the ridges a broad belt of easterlies covers the area. This pattern is fairly similar to that over the Asian sector but over the African sector the evolution during the transition period does not involve drastic changes of pattern, as does that over the Asian sector. The northern ridge moves northwards during the period; the movement is probably associated with the movement of the 200-mb ridge but is not nearly so large or sudden. The easterlies persist, generally with two belts of maximum winds of about 20 knots, although towards the end of the period there is, in some years, a tendency for westerlies to develop in places near the equator. Strong south-easterly trades blow across north Madagascar throughout the period. North-easterly trades blow along the south Arabian coast round the Arabian anticyclone but later in the season, as the anticyclone collapses, these trades back to north or north-west and are entrained into the monsoon circulation.

850-mb patterns

Over Africa, in contrast to Asia, the flow patterns at 850 mb show considerable differences from those at 700 mb. The charts for 1958 (Plates 9-14) indicate that at 850 mb one of the main features (much more marked than at 700 mb), was a belt of confluence situated between about 5°S and 15°N. Sometimes it was possible to identify within this belt two trough lines separated by westerlies or south-westerlies. The existence of these troughs could be confidently inferred from the observations; however, since neighbouring observations sometimes referred to different levels and since the vertical wind-shear was large, reliance should not be placed on smaller-scale details. The network of observations was dense enough to indicate that this was also a convergence zone, which broadened and moved somewhat northwards during the period. The main northward movement appeared to occur during *D*13-*D*14 but perhaps this change should be interpreted as being due to the development of the northern trough and the weakening of the southern trough. The zone appeared to become more active in *D*17, with more-prominent vortices and south-westerlies, while the northern trades decreased in strength; it was also at this time that the greatest change in the position of the 200-mb ridge occurred.

Another difference between the patterns at the two levels was in the spacing of the ridge axes; those at 850 mb were wider apart and the subtropical westerly belts correspondingly covered smaller areas of Africa. The quasi-permanent trough at 700 mb over U.A.R.(Egypt) was replaced at 850 mb by a strong north-west to north current which penetrated the anticyclonic belt. Cyclonic centres were often present over the Sudan area, probably as a consequence of the interaction between the upper trough over Egypt and the northern equatorial trough, no doubt influenced by the mountains of Ethiopia which distort the flow.

Smaller-scale features

(i) *The southern trades.* Findlater[10, 11] has described a narrow but strong southerly current often found in the lowest layers of the troposphere over Kenya during the monsoon season. It is observed most frequently during June–August but it also occurs in May. The evidence is based predominantly on data from Garissa (00°29′S, 39°38′E), where observations began in 1962. These show that the highest monthly mean wind speed at this station averages 27 knots during May–September and that it occurs near 850 mb. Core speeds of more than 50 knots occur frequently. The current does not usually extend to 700 mb, especially early in the season.

No observations from Garissa are available for the years 1956-60. Because of the concentrated nature of the current, stations a short distance away may provide little suggestion of its existence, e.g. Nairobi (01°18′S, 36°45′E), located only 200 miles from the core of the current, is little affected by it. Nevertheless, on the basis of Findlater's evidence the current has been depicted, with reasonable accuracy it is thought, on the 850-mb charts for 1958. It was particularly in evidence during *D*16-*D*18 (see Plates 12-14). The feature is shown as being less narrow and intense on the 10-day means than on daily charts, but this is to be expected owing to day-to-day variations in position and intensity. The 700-mb data confirm that the current does not extend up to that level in May.

Findlater[12] showed, from a few case studies of occasions when sufficient observations were available, that often the flow did not form a broad, uniform current but that it was banded into several narrow, concentrated wind maxima. Although the data used in the present study are not nearly sufficient in general to distinguish such bands, if indeed they are present in decad means, there is some evidence of their existence, in particular over and just north of Madagascar (see Plates 12 and 13). Because of Findlater's evidence, the observations in this area were treated as reliable and attempts were made to reproduce the banded structure. It is possible that a banded pattern persists throughout the current but in the absence of observations a uniform current has been drawn.

The western edge of the southerly current is clearly marked but the position of the eastern edge is much more doubtful owing to the lack of observational evidence. The strength of the flow past the north tip of Madagascar suggests that there must be a substantial cross-equatorial flow east of the African coast at 850 mb.

There is a quite substantial south-east to east flow across the Tanzanian plains. To the south of this, between 10°S and 15°S over Zambia, another substantial south-easterly trade wind forms the main outflow from the 850-mb anticyclone over south Africa. The branch mentioned by Findlater, which leaves the main current to flow from the south-east near Lake Rudolf, is much weaker than the other two.

The reasons for the existence of the strong low-level current are by no means obvious. The current forms part of the circulation of the monsoon cell, which causes its veering from south-east to west. Its sharp western edge is almost certainly due to the presence of the mountains which act as a barrier to the flow, especially in the region of Nairobi where they reach above 850 mb. Both north and south of Nairobi some air flows north-westwards over the lower ground. The Madagascan mountains, whose axis is perpendicular to the flow, probably also influence the current by producing the increased speeds near the north tip of Madagascar.

The east African mountains thus provide an effective western boundary to the Asian monsoon circulation at low levels.

(ii) *The northern trades.* At 850 mb there is a substantial wind flow from the north, which joins the monsoon westerly. This flow is also somewhat banded; a branch comes directly from the northern subtropical westerly over north-east Arabia, while another narrow current is deflected round the north-east African trough and thence along the Red Sea trench. Another branch of the northern trades, including the outflow from the north African anticyclone, flows southwards over Libya or Egypt and then turns westwards.

(iii) *The northern westerly.* There were considerable differences from decad to decad and from year to year in the flow over north Africa and the Mediterranean; for example, in 1958 *D*17 showed a much more zonal flow (i.e. a wind direction closer to 270°) than did *D*16. In order to study this aspect of the flow the value of the *zonality* (ratio of zonal component to meridional component of wind) was calculated for each decad.

To obtain greater accuracy, and to make it possible to compare other years in addition to 1956-60, 500-mb contour height data obtained from punched cards[13] were used as follows:

Let *zonal strength* be the mean value of the quantities

$$H\ (40°\text{N}) - H\ (30°\text{N})$$

taken along the meridians 10°W, 0°, 10°E, 20°E, 30°E,

where H = the 500-mb contour height at the position indicated.

Let *meridional strength* be the mean of the quantities

$$|\ H\ (0°) - H\ (10°\text{W})\ |,\quad |\ H\ (10°\text{E}) - H\ (0°)\ |,$$

$$|\ H\ (20°\text{E}) - H\ (10°\text{E})\ |,\quad |\ H\ (30°\text{E}) - H\ (20°\text{E})\ |,$$

taken along the 35°N parallel.

Then *zonality* = *zonal strength* × cos 35° / *meridional strength*.

The values for the period 1956-60 are given in Table X, which shows that 1960 was the most meridional year and that the odd years were notably more zonal than the even years. This biennial fluctuation in the character of the flow persisted throughout the period 1949-67 (Figure 7) with but one exception: 1954. The small variations in the mean for each decad (Table X) suggest that there is no significant seasonal change.

TABLE X – VALUES OF ZONALITY OVER THE MEDITERRANEAN FOR *D*13-*D*18, 1956-60

Decad	Year					Mean
	1956	1957	1958	1959	1960	
	Zonality *(knots)*					
*D*13	2.1	11.5	1.2	6.6	1.4	4.6
*D*14	3.9	2.6	7.1	7.8	1.7	4.6
*D*15	2.5	10.2	2.8	3.9	2.0	4.3
*D*16	6.6	4.4	2.2	8.7	2.7	4.9
*D*17	4.8	2.2	7.4	3.8	2.9	4.2
*D*18	5.2	3.4	3.8	3.8	3.6	4.0
Mean	4.2	5.7	4.1	5.8	2.4	

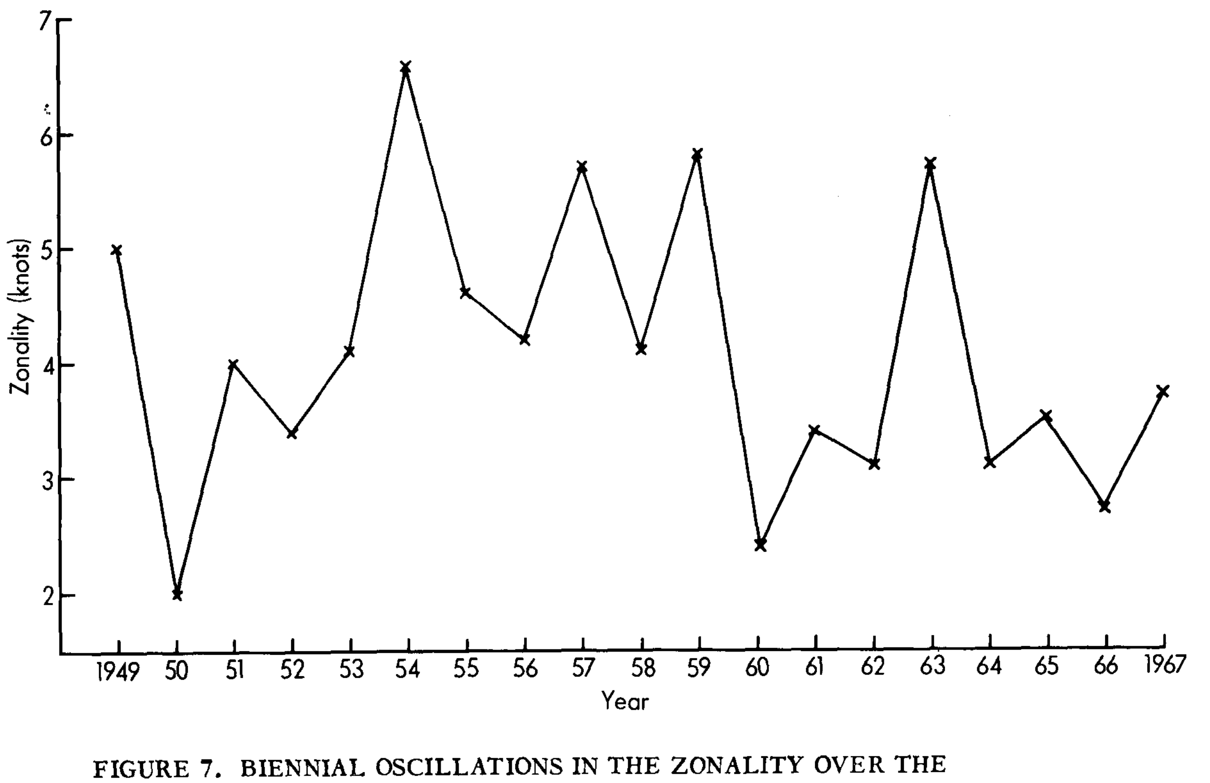

FIGURE 7. BIENNIAL OSCILLATIONS IN THE ZONALITY OVER THE MEDITERRANEAN, AVERAGED OVER MAY AND JUNE, 1949-67

Variations of the evolution in different years

In 1956 a substantial part of the northward movement of the northern ridge had already taken place by *D*13 (Figure 2), however, the ridge retreated southwards in *D*15 and subsequently proceeded northwards again. The axes of the southern ridge and the Madagascan trades at 700 mb were remarkably constant in position from decad to decad. In *D*18, the equatorial trough was well-marked at 700 mb.

In 1957 the main movement of the 200-mb ridge axis occurred, as far as can be judged, during *D*17-*D*18. The pattern at 700 mb in *D*15 was very unusual in the Madagascar area where the south-easterly trades were replaced by westerlies; it was the only decad during the period studied when this occurred (Figure 8).

In 1958 there was no ridge axis over Africa in *D*14. The main northward movement occurred during *D*16-*D*18.

In 1959 the main movement occurred during *D*15-*D*17. The pattern over much of the Indian Ocean in *D*15 was highly abnormal (Figure 9).

In 1960 the main movement occurred during *D*16-*D*18. The southern ridge axis was fairly constant in position.

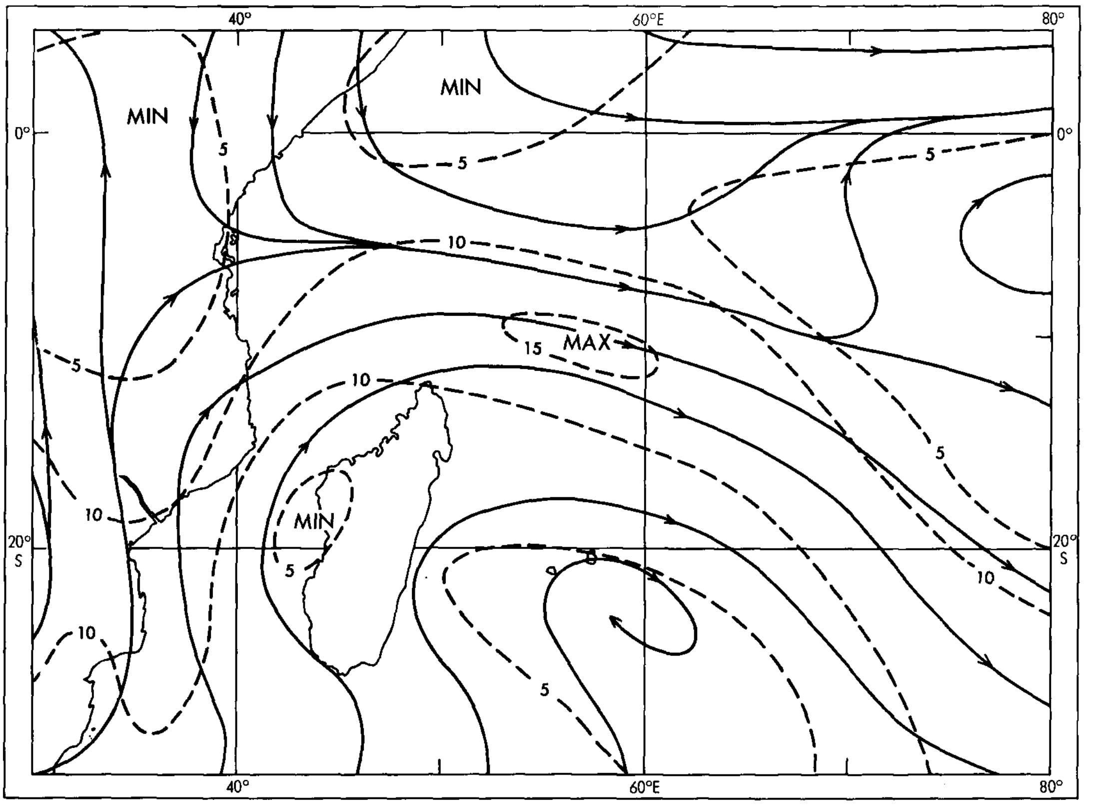

FIGURE 8. STREAMLINE/ISOTACH CHART FOR 700 MILLIBARS DURING *D*15 OF 1957

Streamlines — Isotachs at 5-knot intervals

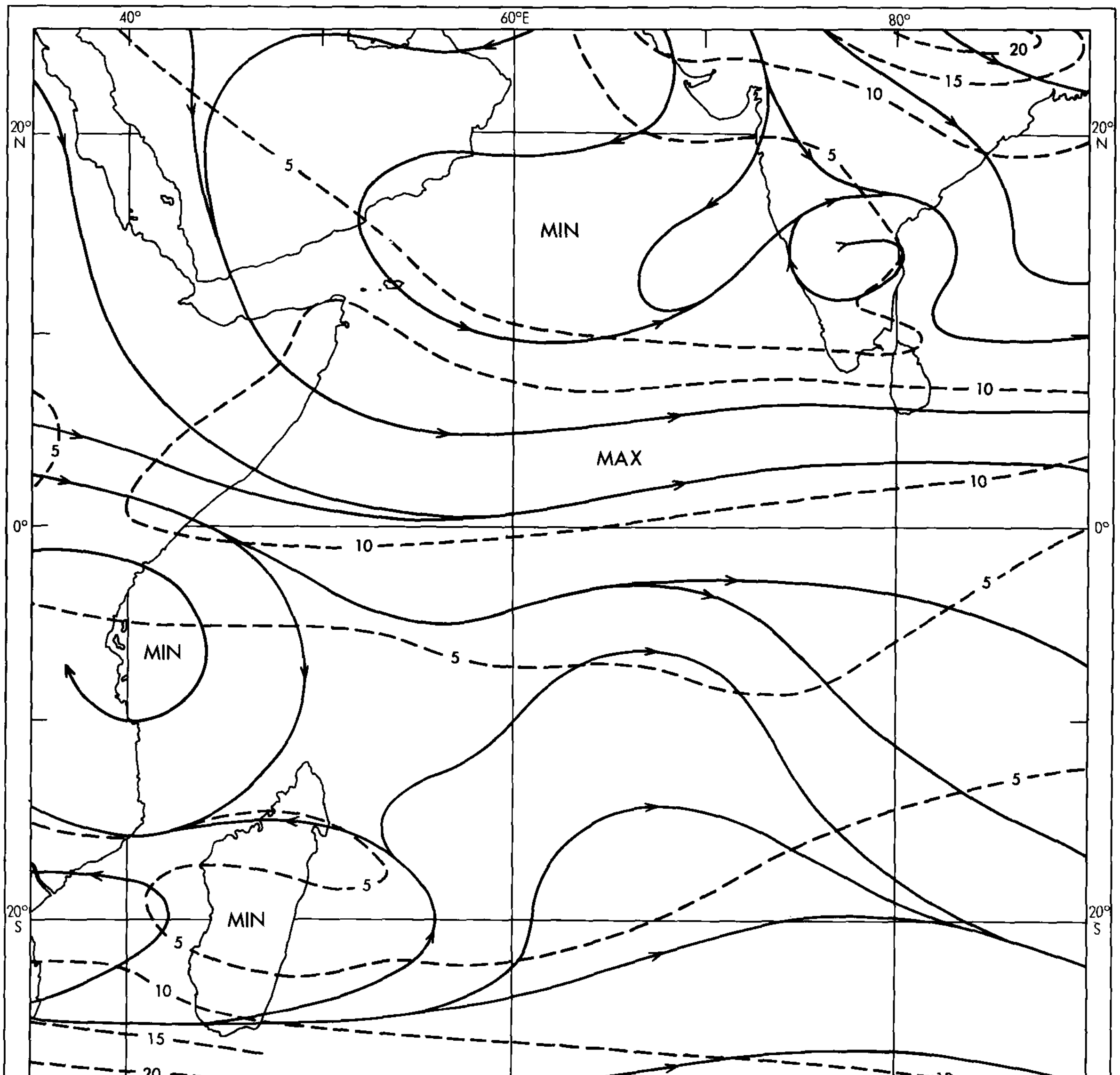

FIGURE 9. STREAMLINE/ISOTACH CHART FOR 700 MILLIBARS DURING $D15$ OF 1959

Streamlines — — — — Isotachs at 5-knot intervals

Relations between changes at the surface and those in the upper troposphere

It is of interest to see whether the northward progress of the rain area of central Africa is related to the movement of the 200-mb ridge in the same way as is that over Asia.

Climatological charts show that the rain area associated with the intertropical convergence zone moves northwards during April-July, its northern boundary moving from about 10°N in May to about 20°N in July. Thus stations in the region 10°N-15°N should best show the date of transition. Pentad mean rainfall totals were therefore examined for two stations in Nigeria—Kano (12°03′N, 08°32′E) and Sokoto (13°01′N, 05°15′E). The pentad (*P*) when the rainy season started in each year is given in Table XI(a). There was a very wide range in the dates of onset.

The 850-mb charts for 1958 (Plates 9-14) show that the northern trough crossed the stations about *P*31, when the rains started; this indicates that the rainfall was associated with the westerly belt between the troughs. Comparison of Table XI(a) with Figure 2(a) gives no indication of any association between rainfall and the position of the ridge axis at 200 mb; in particular, the unusually early 1956 season was not reflected at all in the rainfall figures.

The onset of the rains at Abeché (13°51′N, 20°51′E) in Chad, summarized in Table XI(b), showed close similarity to the dates of onset in Nigeria. The chief differences were that the rainy season started a little later at Abeché and that short rainy spells which occurred before the main season gave less rain than in Nigeria; both differences were probably consequences of the more northern latitude of Abeché. It seems then that the date of onset of the rains, although it varies widely from year to year, is the same over a wide range of longitude in any one year.

TABLE XI – COMMENCEMENT OF RAINY SEASON IN NIGERIA AND CHAD, AND CESSATION OF RAINY SEASON IN GABON, 1956-60

(a) Nigeria (start of rainy season), based on data from Kano (12°03′N, 08°32′E) and Sokoto (13°01′N, 05°15′E).

Year	Pentad in which rainy season commenced
1956	*P*31
1957	*P*25
1958	*P*31
1959	*P*27 but gradually died out, renewed *P*33
1960	*P*27 (short spell), *P*31-*P*32 (weak start), *P*34-*P*35 (main start)

(b) Chad (start of rainy season), based on data from Abeché (13°51′N, 20°51′E).

Year	Pentad in which rainy season commenced
1956	*P*33 or *P*37
1957	*P*26
1958	*P*29 or *P*32
1959	*P*33
1960	*P*34

(c) Gabon (end of rainy season), based on data from Libreville (00°27′N, 09°25′E).

Year	Pentad in which rainy season ceased
1956	*P*27 or *P*31
1957	*P*31
1958	*P*25
1959	*P*28
1960	*P*30 or *P*32

Data for two stations farther south, Pala (09°22′N, 14°55′E) and Fort Archambault (09°08′N, 18°23′E) in Chad, were studied but these were less useful as a guide because the rainy season appeared to arrive more gradually than at Kano and Sokoto. However, it is of interest that this situation is somewhat similar to that over the Indian sector, where the onset of rain is less sharp in Ceylon than at Mangalore (12°55′N, 74°53′E).

At Libreville (00°27′N, 09°25′E), Brazzaville (04°15′S, 15°14′E) and Mayumba (03°25′S, 10°39′E) a rainy season ends during the period under study. The dates of ending of the rains were quite closely related at the three places (those for Libreville, in Gabon, are given in Table XI(c)), dry weather tending to start earlier and to be more absolute at the southern stations. However, the dates appear to be unrelated to the dates of the start of the rainy season in the north and they show no obvious relation to the movements of either the northern or the southern ridge at 200 mb.

The seasonal movement of the northern ridge axis at 700 mb (Figure 4(a)) was less marked than that at 200 mb but it showed some association with the ending of the rainy season, as can be seen by a comparison of Table XI(c) with Figure 4(a). Surprisingly, the dates of onset of the rainy season in Nigeria and Chad were less closely related to the movement of the 700-mb northern ridge axis. The southern ridge axis at 700 mb over Africa was often complex in structure, and the apparently large movements implied by Figure 5 were often simply due to the decline of one ridge and the intensification of another or even to the lack of data, which made it difficult to determine the true configuration. Therefore, comparisons with Figure 5 are not justified.

These remarks suggest that the African counterpart of the Indian monsoon is a shallower and more localized phenomenon, and that its development is not related to changes in the upper tropospheric flow.

§ 17 – THE WEST PACIFIC SECTOR

200-mb patterns

The 200-mb flow patterns over the Pacific are more complex than those over the other sectors.

The most distinctive feature is a westerly current, the 'separated westerly', which prevails between about 10°N and 20°N in the eastern part of the area. This current is most pronounced in the early decads of the period when it reaches speeds above 60 knots. It is separated from the continuation of the main northern subtropical westerly by a belt of much lighter westerly or north-westerly winds (about 10-20 knots) around latitudes 25°-30°N. As the season progresses this belt tends to have more northerly winds, or even to develop anticyclonic cells, so it could perhaps be regarded as the continuation of the northern ridge belt but in a higher latitude.

There can be seen over the Pacific at 200 mb, close to the equator, a belt of diffluence (see especially *D*14 of 1958, Plate 22). The light winds near the equator and the substantial flow of air away from the equator, depicted on the charts and confirmed by the observations, suggest that this is also a belt of divergence; this suggestion is supported by the fact that in the extreme west Pacific the belt broadens into two ridges, one north and one south of the equator. It is this system of ridges and divergence zones that probably constitutes the true eastward continuation of the northern and southern ridge belts.

Thus, easterly winds are the exception rather than the rule at 200 mb over the Pacific. They develop to some extent in the west Pacific as the season progresses but part of this development is directly associated with the eastern fringe of the Asian monsoon circulation. Easterly winds were comparatively prevalent in 1956 and 1960, at least as far east as 155°E.

South of the southern ridge the flow over Australia was strong and zonal in nearly every decad.

Charts of the 200-mb level for much of the Pacific were prepared for only 1958, so a comparison of different years is not possible. However, McCreary *et alii*, [14] who produced a detailed study of the 200-mb flow patterns in the west Pacific sector for the years 1956-59, make the following interesting remark: 'The 1956 spring season is notably different from any of the years analysed previously (namely 1957, 1958 and 1959). The transition from winter to summer occurred with usual abruptness but in April rather than May'.

700-mb patterns

The flow patterns at 700 mb over the Pacific sector bear a closer resemblance to those over Africa than to those over the Indian Ocean.

The northern subtropical westerly is present; it is very constant in position and generally reaches 30 knots. It is west-south-westerly near Japan, associated with the permanent trough that lies along the eastern seaboard of Asia.

The northern ridge axis is usually north of 20°N throughout most of its length. It was in existence over the Pacific during every decad of the period under study, and in some decads, particularly in 1957 and 1959, its axis extended west-south-west to Indo-China. Before the monsoon circulation develops, the ridge is usually linked to the anticyclone over India. The ridge shows some tendency to move northwards during June (see Figure 4(b)). In 1956 once again, the ridge was consistently farther north than in the other years; it tended to be farther north in the even than in the odd years, especially in May, but the differences may not be significant.

The southern ridge axis over the Pacific is notably constant in position. It was found between 12°S and 18°S in every decad except *D*15 and *D*16 of 1958 (which were affected by deep tropical storms) and *D*14 of 1960 (see Figure 5). The ridge often extended across northern Australia, especially in 1956 and 1960. The position of the ridge axis over Australia is much more variable; it appears to have two preferred latitudes, 15°S and 25°S, and there are frequently two ridge axes, one in each of these latitudes.

Associated with the variations in the character of the ridge over Australia the southern westerlies vary greatly in latitude and zonality. In particular, when there is a double ridge the flow is usually meridional or blocked, with a deep trough or cut-off cyclone near New Zealand. The zonality of this flow along 32°S from 115°E to 160°E was calculated, in a manner similar to that for the Mediterranean but using the wind data at 700 mb from five stations: (Guildford (31°56'S, 115°57'E), Forrest (30°51'S, 128°06'E), Woomera (31°09'S, 136°48'E), Williamstown (32°49'S, 151°50'E) and Lord Howe Island (31°31'S, 159°04'E)) instead of grid-point contour heights at 500 mb. Results are shown in Table XII. A biennial variation is again apparent but

TABLE XII – VALUES OF ZONALITY OVER AUSTRALIA FOR *D*13-*D*18, 1956-60

Decad	Year					Mean
	1956	1957	1958	1959	1960	
	Zonality *(knots)*					
*D*13	1.6	1.3	4.8	0.7	5.3	2.7
*D*14	5.3	3.0	5.6	1.0	1.1	3.2
*D*15	5.3	1.6	6.7	1.2	1.4	3.2
*D*16	4.0	0.7	7.1	1.9	9.1	4.6
*D*17	6.3	0.9	0.4	1.6	1.4	2.1
*D*18	3.4	10.0	2.3	3.4	1.1	4.0
Mean	4.3	2.9	4.5	1.6	3.2	

in the opposite sense to that over the Mediterranean. There was stronger zonal flow in the even years. Examination of the even years alone shows that 1960 was markedly the weakest, as it was over the Mediterranean. The correlation between the values of the zonalities in the two areas calculated for individual decads is less noticeable, the correlation coefficient being -0.29.

Between the two ridges, as over Africa, there is a broad belt of easterlies. These are rather less strong than those over Africa: they reach a maximum of about 20 knots in each decad.

The westerlies of the Indian Ocean penetrate eastwards to varying distances at different times, and there are sometimes eddies and a narrow belt of westerly winds reaching well into the Pacific. In some decads tropical storms cause marked disturbances of the flow.

850-mb patterns

The flow pattern at 850 mb over the Pacific sector, shown on the 5-year mean charts (Plates 1 and 2) and also on the chart for *D*13 of 1958 (Plate 9) bears a close resemblance to that at 700 mb (Plate 15). There is a smooth easterly trade wind flow between two ridge axes, which are situated at somewhat higher latitudes than the corresponding features at 700 mb.

Explanations of the Pacific flow patterns

As a result of the large-scale effects of the land/sea distribution on the atmospheric circulation (to be discussed in §20) the wind and pressure belts would be expected to lie closer together over the Pacific than over other sectors and to show a smaller movement with the sun. Many features over the Pacific support this, e.g. the absence of equatorial westerlies at 700 mb, the single belt of divergence at 200 mb in place of the two ridges, and the marked constancy in latitude of the southern ridge at 700 mb. It is therefore necessary to explain the extistence of the 200-mb ridge at about 28°N, the 'separated westerly' and the northern position of the 700-mb northern ridge.

The 200-mb ridge around 28°N is not the true northern ridge of the Pacific, but is basically an extension of that over Asia. Its presence indicates that the influence of the Asian monsoon circulation, when fully developed, extends well out into the Pacific.

Yoshino[15] has discussed the 'separated westerly'. He showed that its strength is not correlated with the strengths of either the subtropical westerly over Japan or the upper easterly over south Asia. He also presented an analysis showing that a simple Hadley cell existed between 145°E and 155°W over the Pacific during July 1958, a month when the 'separated westerly' was particularly well marked; this cell had an ascending branch around 10°N, and a descending branch between 20°N and 25°N.

It is possible to account for many of the observed features of the flow in terms of such a Hadley cell mechanism, as follows. Upward motion in the lowest latitudes induces a belt of divergence in the upper troposphere near the equator, and this results in poleward flow at higher levels. In the northern hemisphere the northward-moving air acquires an acceleration from the west caused by the increase in magnitude of the Coriolis parameter from its equatorial value of zero: a westerly current results, therefore, between 10°N and 20°N. At about 20°N-25°N the descending branch of the Hadley cell is associated with convergence and, probably, low pressure at upper levels. A branch of the subtropical westerly current is deflected to flow southwards around this area of low pressure and thus reinforces the 'separated westerly'. Under the descending branch divergence occurs and a lower-tropospheric anticyclone is formed at about 23°N. (This is represented on the 700-mb chart by the northern ridge.)

The circumpolar flow is probably also a particularly powerful influence in these longitudes, because the westerly flow over the Himalayas and the west-north-westerly flow from farther north in Asia meet in a strong and persistent trough along the eastern seaboard of Asia. Rossby long-wave theory requires that this trough should induce a ridge somewhere in mid-Pacific, with a strong west-south-westerly jet between them. The upper tropospheric pattern in the area between the subtropical jet and the 'separated westerly' takes the form of a diffluent ridge and confluent trough, so the area is favourable for anticyclonic development in the lower troposphere.

Charts produced by McCreary[13] show that the 'separated westerly' was in evidence from May to October. Perhaps this implies that the Hadley cell is best-developed in those months. However, it may be true that the cell exists also during the northern winter months but then the westerly current is not evident because it is indistinguishable from the subtropical westerly which is much stronger and farther south than in the northern summer.

The complex appearance of the west Pacific upper-tropospheric flow patterns is thus seen to be the result of three distinct circulation systems: the Pacific Hadley cell, the Asian monsoon cell, and the northern subtropical westerly long-wave flow. Further complications are produced in the patterns during decads when tropical storms prevail.

Tropical storms

A study of daily surface charts shows that the North Pacific was affected by tropical storms in the following decads in 1957, *D*13, *D*14 and *D*18; in 1958, *D*15, *D*16 and *D*17; in 1960, *D*15, *D*16 and *D*18. The year 1958 showed a greater number and intensity of storms than the other years; this is illustrated by the 700-mb decad mean charts (Plates 15-20), of which particularly those for *D*15 and *D*16 show very distorted patterns.

An examination of the latitudes of the 200-mb northern ridge over east and west Asia (Figures 2(b) and 2(c) noting the decads when storms did, and did not, occur, suggests that tropical storms may be associated with a northerly position of the ridge over east Asia relative to that over west Asia.

Tropical storms in the Pacific tend to occur most frequently in the region 5°N-30°N, 110°E-155°E, where the main season is July to October, according to Luk'janov.[16] The mean annual number of observed storms is 11, of which 1 on average can be expected during May and June; however, over the past 60 years the annual total has varied greatly. Storms apparently occurred more frequently during 1957-60; more than 17 were recorded in each of these years, while in 1958 there were 36 recorded storms, more than in any other year. Storms also occur in the Pacific south of the equator but in that region they are rare during May and June; however, it is of interest that the total annual numbers in 1958 and 1959 (6 and 11 respectively, compared with the average value of 2) were higher than in any other year since 1910. This apparent increase is possibly in part due to an increase in the number of observations in the area during the International Geophysical Year.

PART IV – DISCUSSION OF OTHER FEATURES

§ 18 – THE EXCEPTIONAL NATURE OF 1956

During the discussion of the flow patterns in the various sectors (§ 15-17) the exceptional earliness of the seasonal changes in 1956 was frequently intimated. The main changes, which are most marked in the Asian sector, normally occur about the end of May, whereas in 1956 they occurred at the end of April. As a result the mean patterns in the Indian area in May 1956 were very different from the normal May patterns; in particular the central pressure of the north Indian depression (which deepens at the time of the main change, as described in § 15) was much lower than in the other years.

It was possible to establish that this behaviour was indeed exceptional, because monthly mean surface-pressure maps for May, for most years from 1899 to 1967, are available in the Meteorological Office. The depth of the north Indian depression in May each year, according to these maps, is shown in the form of a histogram in Figure 10. The histogram shows that in two of the years (1918 and 1956) the monthly mean pressure was 995 mb–well outside the usual range of 998-1005 mb. It is, therefore, suggested that the circulation patterns behave in this way infrequently, perhaps only once in 40 years.

Stehnovskij[17] produced data illustrating the variations of zonal index around the Earth in latitudes 40°N-60°N. His data showed that there was a tendency for a negative mass anomaly to be associated with an above-normal zonal index, and in particular that May 1956 had the highest zonal index of any of the months from March to September during 1955-59.

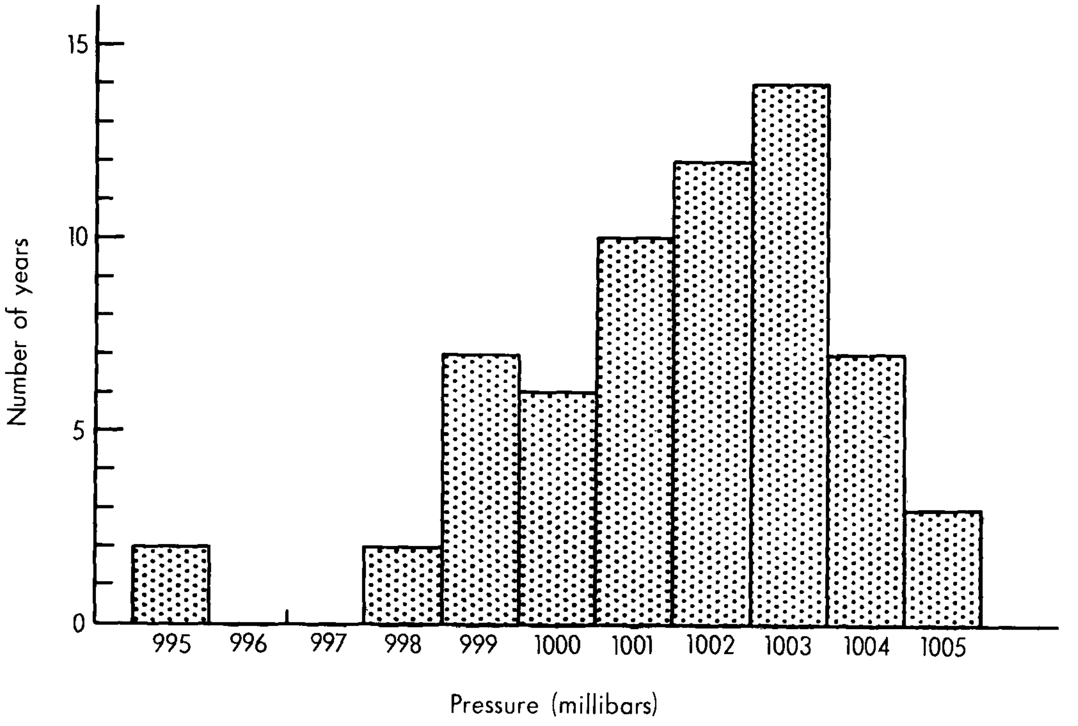

FIGURE 10. HISTOGRAM SHOWING NUMBER OF YEARS IN WHICH THE MEAN CENTRAL PRESSURE OF THE NORTH INDIAN DEPRESSION DURING MAY HAD SPECIFIED VALUES
Period 1899-1965, omitting 1945 and 1947-49

§ 19 – CELLULAR STRUCTURE OF THE SUBTROPICAL FLOW

In much of the foregoing description the area has been regarded as being divided into sectors, within each of which the flow patterns vary little with longitude.

This has been done partly for convenience and partly because the flow does indeed appear to behave in this way as far as basic patterns and seasonal changes are concerned. Each unit, or 'cell', usually shows itself in the form of an individual anticyclonic centre at 200 mb, with associated uniform positions of the ridge and jet axes. For example, in D16 of 1958 (Plate 24) there were, in the northern hemisphere, a cell over Africa, two cells over Asia and another over the Pacific; the first three cells had anticyclonic centres at 200 mb. The latitudes of the various belts (subtropical westerly jet, ridge axis etc.) are often very different in adjacent sectors, and marked meridional flow in the upper troposphere then occurs near the boundaries. This is often true, for example, between the African and west Asian cells over Arabia.

These cells appear to have a natural length of about 45-50 degrees of longitude. It is of interest to investigate whether this is the wavelength that would be expected for Rossby waves in this latitude. The expected stationary wavelength of Rossby waves on the normal flow patterns were therefore calculated. The data used were the monthly mean grid-point values of 500-mb contour height along 30°N and 40°N, averaged over the period 1949-64, between 40°W and 70°E[13] (data were not available farther east). The values obtained for the stationary wavelength at 35°N were 55 degrees of longitude in May and 52 degrees in June. Since the level of non-divergence that should be used in this calculation is normally about 600 mb and since the flow at that level is usually weaker than at 500 mb these values are probably a little too high. Thus, bearing in mind the lack of precision of the calculation, the result agrees satisfactorily with the observed wavelength and suggests that the Rossby mechanism plays a part in maintaining the stability of the cells.

The movement of the sun is the basic cause of the seasonal changes. The heating effect of the sun is more immediate over land than over sea, so greater changes would be expected over a land sector than over an oceanic one.

Also, a sector with a uniform latitudinal land/sea distribution tends to favour a uniform extent of movement of the wind belts. Conversely, in a sector where the land/sea distribution changes greatly with longitude (namely near the east or west coast of a continent) the associated temperature gradient induces a meridional flow and a tendency for differential movement of the belts.

All this implies that cells tend to position themselves over sectors with uniform land/sea distribution, and that the range of seasonal movement within a cell depends on its land/sea distribution.

It can be seen that the African sector is about the width of one Rossby wave and that the Asian sector is about twice that width. Thus it is not surprising to find, in general, one cell over the African sector and two over the Asian sector. The Pacific is of width suitable for two or more cells, but only the westernmost one has been studied here.

The seasonal changes within each of the cells are very different in extent. The flow in the cell over the west Pacific, as expected, undergoes the least seasonal change because this is a completely ocean-covered sector. A greater change takes place in the cell over the African sector which is predominantly land. Over Asia, because the land/sea distribution is fairly uniform, the two cells tend to move similar distances at about the same time, although there was in 1958 a notable exception in which the main northward movement occurred about a month earlier over east Asia than over west Asia (see Figure 2).

Although the total proportion of land over the Asian sector is less than that over Africa, the seasonal movement of the wind and pressure belts is greater over Asia. This may be due to the latitudinal land/sea distribution. If the Indian Ocean were replaced by land, thus creating a distribution similar to that in the African sector, the zone between the equator and 20°N would be hotter than at present during the northern summer. This would cause the centre of gravity of the heating zone, and its associated trough, to lie farther south, as indeed occurs over Africa. Perhaps the existing distribution of land and sea in the Asian sector, with the boundary lying near the tropic of Cancer, is nearly ideal for producing the maximum possible northward shift of the belts.

§20 – THE TWO-LAYER STRUCTURE OF THE TROPICAL TROPOSPHERE

During the preparation of the analyses it was observed that, especially near the equator, the direction of wind flow in the upper troposphere was often the reverse of that in the lower troposphere. A good example of this was in *D*18 of 1960 over the Indian Ocean. The chart for 200 mb (Plate 29) shows a mainly easterly current with a component from the north; that for 700 mb (Plate 28) shows, in the same area, a westerly current with a component from the south where the flow crosses the equator. The aircraft observations available during this decad (Figure 1) also illustrate this reversal and show that the boundary between the currents was between 500 mb and 550 mb.

This tendency for the upper and lower flows to be opposed appears, from the analyses, to be characteristic of the Indian Ocean and Pacific Ocean circulations. It suggests that these systems behave as Hadley cells, as has already been discussed for the Pacific. Over the African sector, apart from the extreme east which is influenced by the monsoon cell, westerlies exist only below 700 mb during May and June. This suggests that if a Hadley cell system exists it is confined to the lowest levels, and may explain why the movement of the 850-mb features appears to be independent of the changes in the upper troposphere.

It was found in a recent study of upper winds over the Seychelles (04°37′S, 55°27′E) by Wright and Ebdon,[18] that in most months from September 1963 to December 1964 the meridional flows cancelled out in such a way that the mean meridional mass flux integrated through the troposphere over the Seychelles was small. This tendency for the meridional components of the flow to be of opposite signs in the upper and lower troposphere appears, according to the present analyses, to be quite common at places near the equator. The effect can be observed by a comparison of the 700-mb chart with the 200-mb chart for *D*16 of 1958 (Plates 18 and 24) or *D*18 of 1958 (Plates 20 and 26), in addition to the example in *D*18 of 1960 quoted earlier.

This state should be contrasted with that of temperate latitudes, where a substantial net meridional flux of air may be maintained over a particular place for a long period.

It has been noted that near the equator in areas where data are plentiful the meridional components of the flow in the upper and lower troposphere are of opposite sign. This was assumed to be equally valid in areas of sparse data and the analyses of the equatorial regions were drawn with this in mind.

§21 – BIENNIAL OSCILLATIONS

Several features of the flow patterns in the tropics and subtropics exhibited a biennial oscillation during the period 1956-60. Two such features, the zonalities over the Mediterranean and over Australia, have already been noted and it was seen in the former case that the fluctuation was not confined to this 5-year period (Figure 7). These oscillations are fully discussed by Wright.[19]

The equatorial westerly current in the Indian Ocean is found to exhibit such a variation in strength, as was noted also by Ananthakrishnan and Thiruvengadathan.[20] This variation in strength is illustrated by the 850-mb zonal component at Singapore, where a biennial oscillation is found in the annual means and also in the mean May values (Figure 11(a)). It was previously noticed (§15) that the strength of the equatorial westerly in May is a factor in determining the date of onset of monsoonal weather in India. It is therefore suggested that the observed westerly flow in the Indian Ocean is the sum of two distinct components: a component which is present during much of the year and exhibits a biennial fluctuation, and a stronger flow which is due to the monsoon cell and is not subject to biennial variations.

The strength of the trade winds at 700 mb near Madagascar, as represented by the longitudinal extent of the 10-knot isotach shown on the decad mean charts, showed a variation during 1956-60 similar to that of the equatorial westerly (Figure 11(b)) but this is not surprising because the two currents form part of the same circulation system.

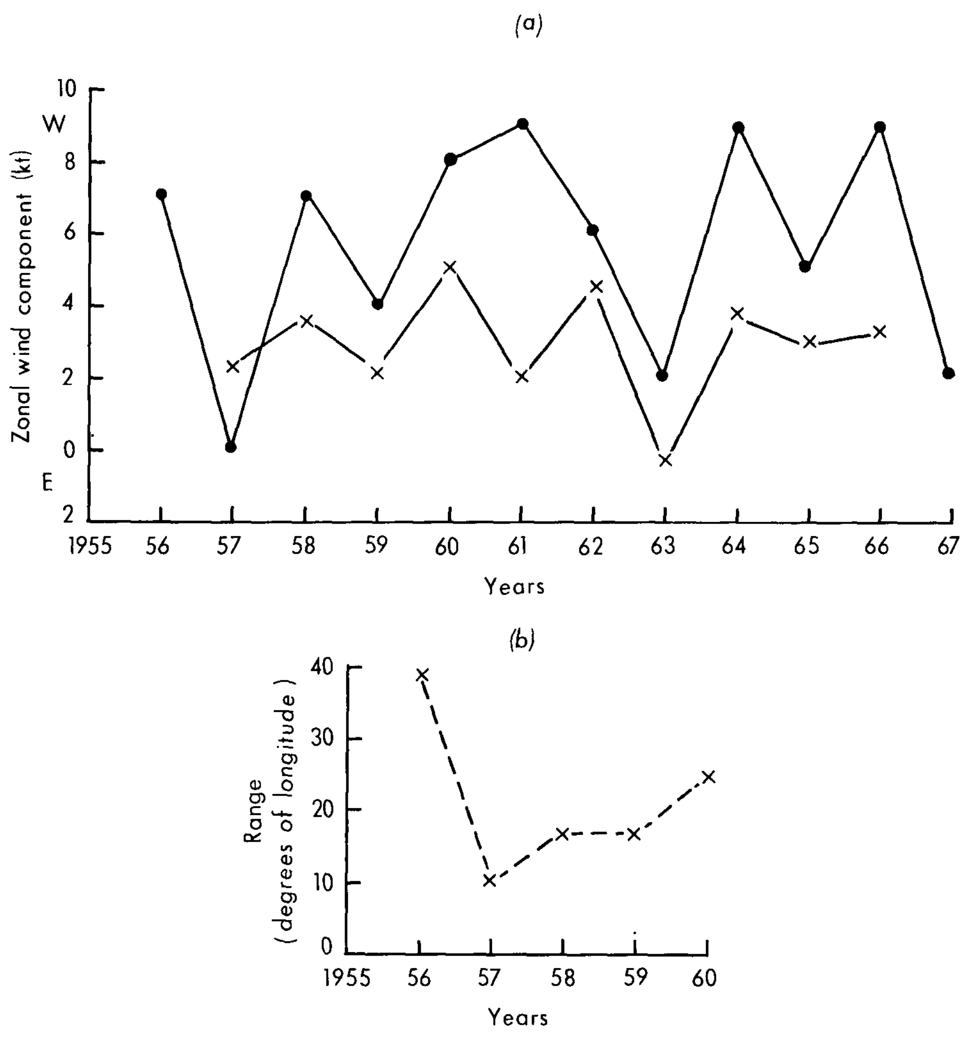

FIGURE 11. BIENNIAL OSCILLATIONS IN FEATURES OF THE CIRCULATION OVER THE INDIAN OCEAN

Components from the west are positive.

(*a*) Singapore

x———x Annual mean 850-mb zonal wind component

•———• May mean 850-mb zonal wind component

(*b*) Madagascan trades

x– – – –x Extent of 10-knot isotach at 700 mb (mean of *D*13-*D*18)

PART V – RELATIONS WITH EXTRATROPICAL FEATURES

§ 22 – MASS FLUX BETWEEN HEMISPHERES

Stehnovskij,[21,22] using the simple relationship that the mean pressure over an area is proportional to the mass of air above that area, has made calculations of the mass of air over the northern hemisphere.

Averaged over many years, the graph of daily values of mass of air over the northern hemisphere shows a well-marked annual variation, with a maximum in January and a minimum in July. The decrease from January to July is markedly non-sinusoidal and there are two periods when the decrease is steepest, 25 March-20 April and 15 May-20 June, the latter being the steeper of the two. The fact that these are also approximately the periods of the two main changes in the tropical circulation, suggests that they are the times of fundamental changes during the transition from winter to summer flow over the northern hemisphere.

In 1956 the daily values of the mass during most of May were below normal and the monthly mean mass was the lowest of those of the five Mays studied. This agrees with the suggestion made earlier (§ 18) that the flow patterns of May 1956 were closer to the normal summer patterns than is usual in May. Further evidence comes from calculations of the pressure anomaly north of 30°N, based on the 1951-64 monthly mean surface-pressure charts in the Meteorological Office. These showed that May 1956 had the largest negative anomaly of any May during this period; it was also the only exception to a biennial oscillation in which the Mays in even years showed higher pressure than the Mays in odd years.

Thus the changes in the tropical flow patterns appear to be associated with an efflux of air from the northern hemisphere. This does not necessarily mean, however, that the changes are world wide. Belinskij[23] found that the annual exchange of air between hemispheres takes place primarily in the Eurasian sector. In other sectors, during spring, decreases in the mass of air over the continents are balanced by increases over the oceans in the same hemisphere. Hence, the observed rapid depletion of mass of air over the northern hemisphere, which occurs between May and June in most years but which occurred between April and May in 1956, may be simply a reflection of the decline of the Asian anticyclone and the deepening of the Indian depression.

§ 23 – THE 500-MILLIBAR FLOW IN TEMPERATE LATITUDES OF THE NORTHERN HEMISPHERE

The movements and developments of troughs and ridges in the 500-mb flow at 40°N and 50°N were studied in order to see if there was any change that might be related to the changes in the tropics. This work has been described in detail by De la Mothe and Wright.[24] The main conclusion was that at 50°N there appear to be two major changes of régime. In the mean for the 16 years 1949-64 these occurred in early April and at the end of May – at about the same time as the two major changes in the tropical upper-tropospheric patterns (see § 15) – however, in most individual years it was difficult to identify these changes because of the dominance of smaller-scale mobile waves in the flow. It was also suggested that a study of the variations in the wavelength of the circumpolar westerly flow over Asia might provide guidance in forecasting the onset of the monsoon.

At 40°N a deep trough is found over Japan during the winter and, in the mean, this relaxes rapidly during the first half of April. In individual years however, the relaxation is interrupted by several temporary returns to the winter state. These variations do not appear to be related to tropical changes, except in one instance: in 1956, when the first relaxation took place in *P*16 (17-21 March), about 20 days earlier than normal.

This suggests (see §18) that the relaxation may be associated with the main tropical change, with the important implication that the exceptional character of 1956 could already have been deduced by late March. However, soon afterwards the trough reappeared quite strongly and did not finally relax until early May, which was later than normal; thus the relationship is by no means simple.

In 1958 and 1964, during the periods when the 200-mb upper ridge axis had moved north over east Asia but was still well south over west Asia, the ridge at 50°N was centred farther east than usual: at 110°E. This is not greatly surprising because such a configuration of the 200-mb pattern would, of necessity, induce a ridge in about that latitude; however, it is difficult to determine which is the cause and which is the effect.

PART VI – CONCLUSIONS

§24 – EXTENT OF THE CHANGES

This memoir has discussed the changes in the circulation patterns in the tropics during the transition from the northern winter to the northern summer. It has been shown that there appear to be two periods when the changes are most rapid–the first in April and the second about the end of May. The second is the more marked and has been studied in greater detail.

The main characteristic of the second set of changes is the development of the monsoon cell – a process that involves substantial changes of flow at all levels of the troposphere in the tropics from east Africa to the western fringe of the Pacific. In the northern hemisphere the effect of the changes extends westwards over Africa and eastwards across the west Pacific in the upper troposphere but the lower troposphere in these areas is probably not affected.

Each set of changes appears to be accompanied by a readjustment of the positions of troughs and ridges in the northern hemisphere 500-mb temperate-latitude flow, together with a net flux of air from the northern to the southern hemisphere.

Many of the changes occurred exceptionally early in 1956. The high value of the northern hemisphere zonal index and the very early relaxation of the 500-mb trough over Japan in that year (compared with the other four years), suggests that these two features may be significant factors associated with the process of the changes in the flow patterns in the tropical regions.

§25 – MECHANISM OF THE CHANGES

It is suggested that the mechanism of the changes can be summarized as follows.

During the winter the Asian continent north of 40°N is intensely cold and the effect of the Tibetan plateau is to extend this cold area even farther south. As the sun moves north the continent is at first slow to warm up, owing to the extensive snow cover, and the marked trough over east Asia therefore persists with little weakening. Meanwhile north India, protected by the Himalayas to the north and in a clear anticyclonic régime, warms up rather more quickly than would be expected for its latitude. These factors contribute to the retention of the main zone of strong thermal contrast, and therefore of the subtropical westerly jet, in a southern position. About early April the snow line begins to recede rapidly and, with rapid surface warming taking place, a fall of pressure occurs over the continent. This is accompanied by a flow of air out of the continent and thus accounts for the observed decrease in the mass of air. The associated weakening of the jet produces a change in the wavelength of the extratropical flow which in turn causes a rearrangement of the troughs and ridges.

Because of the land/sea distribution a large northward movement of the wind belts to their summer positions has to take place during the next three months. This is accomplished by a process similar to that already described but it is by no means clear why this change should be sudden rather than gradual. Since a northward movement of the jet is involved, it is possible that the Asian mountains play a further role by constraining the jet to remain farther south during April and May than it otherwise would be. A further change in the wave number of the westerly flow occurs, caused by the weakening of the thermal gradient. By its very nature such a change is abrupt, so it may be that this change triggers off the movement of the jet and the upper ridge over Asia; however, the existence of such a mechanism has not been established.

The development of the monsoon cell is part of the change and it occurs at the same time, although the strength of the equatorial westerly current is a factor which, if it is weak just before the change, will delay the onset of monsoon weather in a particular area.

Within the upper tropospheric flow there is a close linkage which causes the abrupt change to be apparent over both Africa and the western Pacific but the lower tropospheric flow is not affected outside the monsoon cell itself.

ACKNOWLEDGEMENTS

The authors are grateful to the following meteorological services for supplying data used in the study:

1. The Director of Meteorology, Commonwealth Bureau of Meteorology, Australia.
2. The Director, Weather Bureau, Union of South Africa.

The authors gratefully acknowledge the assistance given by Dr G. B. Tucker who prepared the computer programme for the project; also the helpful comments and assistance provided by Mr D. H. Johnson in the organization of the project and during the preparation of the final text.

Thanks go to Mrs Linda Phillips, Miss Mabel Pitt, Mrs Rosemary Smith, Mrs Pauline Tonkinson and to Messrs M. Paterson, D. Thornton and M. Walker who carried out the tasks of data extraction, preparation of data tapes and the plotting of the computed data.

BIBLIOGRAPHY

1. HEASTIE, H. and STEPHENSON, P.M.; Upper winds over the world, Parts I and II. *Geophys. Mem., London,* 13, No. 103, 1960.

2. FROST, R. and STEPHENSON, P.M.; Mean streamlines and isotachs at standard pressure levels over the Indian and west Pacific Oceans and adjacent land areas. *Geophys. Mem., London,* 14, No. 109, 1965.

3. RAMAGE, C.S. and RAMAN, C.R.V.; International Indian Ocean Expedition, Meteorological Atlas, 2, Upper air. Honolulu, University of Hawaii, International Meteorological Centre. (To be published by East-West Centre Press, Honolulu.)

4. LOCKWOOD, J.G.; Winds at the 200-mb level over the tropics and sub-tropics during the seasons of monsoon change. *Met. Mag., London,* 92, 1963, p. 75.

5. RAMAN, C.R.V. and DIXIT, C.M.; Analyses of monthly mean resultant winds for standard pressure levels over the Indian Ocean and adjoining continental areas, Parts I and II. Bombay, India Meteorological Department, International Meteorological Centre, 1964. (Limited distribution.)

6. WIEDERANDERS, C.J.; Analyses of monthly mean resultant winds for standard pressure levels over the Pacific. *Scient. Rep., Honolulu,* No. 3, 1961.

7. NEDUNGADI, T.M.K. and SRINIVASAN, T.R.; Monsoon onset and Everest expeditions. *Indian Jnl Met. Geophys., New Delhi,* 15, 1964, p. 137.

8. WRIGHT, P.B.; Changes in 200-mb circulation patterns related to the development of the Indian south-west monsoon. *Met. Mag., London,* 96, 1967, p. 302.

9. Poona, India Meteorological Department. *Indian Daily Weather Report,* 1956-65.

10. FINDLATER, J., Cross-equatorial jet streams at low level over Kenya. *Met. Mag., London,* 95, 1966, p. 353.

11. FINDLATER, J.; Some further evidence of cross-equatorial jet streams at low level over Kenya. *Met. Mag., London,* 96, 1967, p. 216.

12. FINDLATER, J.; A major low level air current near the Indian Ocean during the northern summer. *Q. Jnl R. met. Soc., London,* 95, 1969, p. 362.

13. Berlin, Deutscher Wetterdienst. Daily values of the 500-mb absolute topography at northern hemisphere grid-points, 1949-64.

14. McCREARY, F.E. Jr, *et alii*; Monthly mean upper tropospheric circulation over the tropical Pacific during 1954-1959. Joint Task Force Seven Met. Center, JTFMC TP-19, Vols 1 (1958) and 2 (1959), Pearl Harbor, Hawaii, 1960; Vols 3 (1957) and 4 (1956), University of Hawaii, Honolulu, 1961.

15. YOSHINO, M.M.; Atmospheric circulation over the northwest Pacific in summer. *Met. Rdsch, Berlin,* 20, 1967, p. 45.

16. LUK'JANOV, V.V.; Tropical cyclones of the Pacific Ocean. Moscow, *FEL'ZENBAUM, A.C. (editor).* Marine meteorological investigations. *Trudŷ Inst. Okeanol., Moscow,* Tom 72, 1963, p. 50.

17. STEHNOVSKIJ, D.I.; On the problem of the interdependence of the zonal circulation of the atmosphere in the northern and southern hemispheres. *Trudŷ tsent. Inst. Prognozov, Moscow,* Vyp. 143, 1965, p. 53.

BIBLIOGRAPHY *(contd)*

18. WRIGHT, P.B. and EBDON, R.A.; Upper air observations at the Seychelles 1963-64. *Geophys. Mem., London,* **15**, No. 111, 1968.

19. WRIGHT, P.B.; A widespread biennial oscillation in the troposphere. *Weather, London,* **23**, 1968, p. 50.

20. ANANTHAKRISHNAN, R. and THIRUVENGADATHAN, A.; Biennial oscillation in the equatorial troposphere. *Nature, London,* **212**, 1966, p. 1443.

21. STEHNOVSKIJ, D.I.; Certain problems of the interaction of the atmospheric circulation of the northern and southern hemispheres. *Trudy̆ tsent. Inst. Prognozov, Moscow,* Vyp. 137, 1964, p. 54.

22. STEHNOVSKIJ, D.I.; Large-scale pressure anomalies in the period 1955-1959. Moscow, BATJAEVA, T.F. (editor). The structure of the troposphere and stratosphere and the interdependence of the circulations of the northern and southern hemispheres. *Trudy̆ tsent. Inst. Prognozov, Moscow,* Vyp. 143, 1965, p. 24.

23. BELINSKIJ, N.A.; Use of some properties of atmospheric processes in long-range forecasting. *Trudy̆ tsent. Inst. Prognozov,* Leningrad, 1957. (Translation available in the Meteorological Office Library, Bracknell.)

24. DE LA MOTHE, P.D. and WRIGHT, P.B.; The onset of the Indian south-west monsoon and extratropical 500-mb trough and ridge patterns over Europe and Asia. *Met. Mag., London,* **98**, 1969, p. 145.

APPENDIX I – SOURCES OF DATA

1. Washington, United States Weather Bureau; *Daily series synoptic weather maps,* Washington, D.C.
2. Geneva, World Meteorological Organization; *Catalogue of IGY/ICC meteorological data.* [Microcards] WMO/OMM, No. 135, IGY/ACI. 4. Geneva, 1962.
3. London, Meteorological Office; *Daily Weather Report Overseas Supplement,* London.
4. Lisbon, Serviço Meteorológico Nacional; *Boletim Meteorológico,* Lisbon.
5. Lisbon, Serviço Meteorológico Nacional; *Anuário climatológico de Portugal,* Lisbon.
6. Karachi, Pakistan Meteorological Service; *Pakistan Daily Weather Report,* Karachi.
7. Tokyo, Japan Meteorological Agency; *Aerological Data of Japan,* Tokyo.
8. Singapore, Meteorological Services of Malaya and Singapore; Upper air data, Singapore.
9. Saigon, Direction de la Météorologie; *Résumé mensuel du temps en Indochine (Viêt-Nam),* Saigon.
10. Mauritius, Royal Alfred Observatory; Meteorological Observations and Climatological Summaries, Mauritius.
11. Tananarive, Service Météorologique; *Résumé mensuel du temps à Madagascar,* Tananarive.
12. Cairo, Meteorological Department; *Daily Weather Reports United Arab Republic,* Cairo.
13. Khartoum, Sudan Meteorological Service; *Synoptic Bulletin Sudan Weather Service,* Khartoum.
14. Brazzavile, Service Météorologique de l'Afrique Equatoriale Française; *Résumé mensuel du temps en A.E.F.,* Brazzavile.
15. Loanda, Serviço Meteorológico de Angola; *Observaçöes meteorológicas de altitude em Angola,* Loanda.
16. Lourenço Marques, Serviço meteorológico de Moçambique; *Boletím mensual das observaçöes meteorológicas organizad pelo Serviço meteorológico de Moçambique,* Lourenço Marques.
17. Wellington, New Zealand Meteorological Service; *Daily Weather Bulletin New Zealand Meteorological Service,* Wellington.
18. Manila, Philippine Weather Bureau; Pilot balloon data, Manila.
19. Lagos, Nigeria Meteorological Service; *Monthly rainfall summaries,* Lagos.
20. London, Meteorological Office; Upper air data held by Climatological Services Branch, Meteorological Office, Bracknell.

APPENDIX II – OTHER RELEVANT PUBLICATIONS

1. ALAKA, M.A.; Problems of tropical meteorology (a survey). *Tech. Notes, Wld met. Org., Geneva,* No. 62, 1964.

2. RAMDAS, L.A. *et alii;* Prediction of the date of establishment of southwest monsoon along the the west coast of India. *Indian Jnl Met. Geophys., Delhi,* 5, 1954, p. 305.

3. REIHL, H.; Tropical Meteorology. New York, London, Toronto, McGraw-Hill, 1954, p. 235.

4. FLOHN, H.; Contributions to a synoptic climatology of north-east Africa. *Tech. Notes, Wld met. Org., Geneva,* No. 69, 1965, p. 236.

5. FLOHN, H.; Comments on a synoptic climatology of southern Asia. *Tech. Notes, Wld met. Org., Geneva,* No. 69, 1965, p. 245.

6. YEH, T.-C., DAO, S.-Y. and LI, M.-T.; The abrupt change of circulation over the northern hemisphere during June and October. New York, BOLIN, B. (editor); The atmosphere and the sea in motion. (Scientific contributions to the Rossby Memorial Volume.) New York, Rockefeller Institute Press in association with Oxford University Press, 1959, p. 249.

7. SUTCLIFFE, R.C. and BANNON, J.K.; Seasonal changes in upper air conditions in the Mediterranean–Middle East Area. Rome, UGGI/IAMAP Scientific Preedings of the International Association of Meteorology, Tenth General Assembly, September, 1954 Colloque sur les problèmes de météorologie tropicale. London, Butterworths Scientific Publications, 1956, p. 322.

8. YOSHINO, M.; Four stages of the rainy season in early summer over East Africa, Pt. 1. *Jnl met. Soc. Japan, Tokyo,* 43, 1965, p. 231.

9. ANANTHAKRISHNAN, R.; General circulation of the atmosphere over the Indian Ocean and adjoining areas. Geneva, World Meteorological Organization, and Paris, United Nations Educational Scientific and Cultural Organization, Symposium on meteorological results of the International Indian Ocean Expedition, Bombay, July 1965, India Meteorological Department, Bombay, 1965, p.105.

10. KOTESWARAM, P.; The Asian summer monsoon and the general circulation over the tropics. Poona, India Meteorological Department. Symposium on Monsoons of the World, New Delhi, 19-21 February 1958, under the auspices of IUGG, WMO, IAMAP and the Government of India. Delhi, 1960, p. 105, discussion p. 262.

11. NORMAND, Sir CHARLES; Monsoon seasonal forecasting. *Q. Jnl R. met. Soc., London,* 79, 1953, p. 463.

12. GORDON, A.H. and TAYLOR, R.C.; Lagrangian dynamics and low latitude weather. Honolulu, International Indian Ocean Expedition Meteorology Program, Report No. 1, Hawaii Institute of Geophysics, University of Hawaii, Honolulu, 1966.

13. RAI SIRCAR, N.C. and PATIL, C.D.; Horizontal distribution of temperature over India in May during years of early, normal and late south-west monsoon. *Indian Jnl Met. Geophys, Delhi,* 12, 1961, p. 377.

14. PANT, P.S.; Onset of monsoon over India. *Indian Jnl Met. Geophys., Delhi,* 15, 1964, p. 375.

APPENDIX II – OTHER RELEVANT PUBLICATIONS *(contd)*

15. RAMAMURTHI, K.M. and KESHAVAMURTY, R.N.; Synoptic oscillations of Arabian anticyclones in the transition season. *Indian Jnl Met. Geophys., Delhi,* 15, 1964, p. 227.

16. LOCKWOOD, J.G.; Winds at the 200 mb level over the tropics and sub-tropics during the seasons of monsoon change. *Met. Mag., London,* 92, 1963, p. 75.

17. Geneva, World Meteorological Organization, and Paris, United Nations Educational Scientific and Cultural Organization. Symposium on meteorological results of the International Indian Ocean Expedition, Bombay, July 1965–Abstracts. Bombay, India Meteorological Department and Indian National Committee for Oceanic Research, 1965.

18. RAMASWAMY, C.; On synoptic methods of forecasting the vagaries of southwest monsoon over India and the neighbouring countries. Geneva, World Meteorological Organization, and Paris, United Nations Educational Scientific and Cultural Organization, Symposium on meteorological results of the International Indian Ocean Expedition, July 1965. Bombay, India Meteorological Department, 1965, p. 317.

19. CHANG, J.-H.; The Indian summer monsoon. *Geogrl Rev. New York,* 57, 1967, p. 373.

20. LOCKWOOD, J.C.; The Indian monsoon–a review, *Weather, London,* 20, 1965, p. 2.

21. RANGARAJAM, S.; Thermal effects of the Tibetan plateau during the Asian monsoon season. Australian Met. Mag., Melbourne, No. 42, Sept. 1963, p. 24.

22. LUK'JANOV, V.V.; Some features of the summer monsoon over the north-eastern part of the Indian Ocean. Moscow, SAMOYLENKO, V.S. (editor). Studies of atmospheric circulation and boundary-layer of the air in the Pacific and Indian Oceans. *Trudÿ Inst. Okeanol., Moscow,* Tom 78, 1965, p. 81.

23. SUBBARAMAYYA, I. and RAMANADHAM, R.; The Asian summer-monsoon circulation. *Jnl met. Soc. Japan, Tokyo,* 44, 1966, p. 167.

24. Bangkok, Meteorological Department of Thailand. Upper winds over south-east Asia and neighbouring areas; 2 vols, 1965.

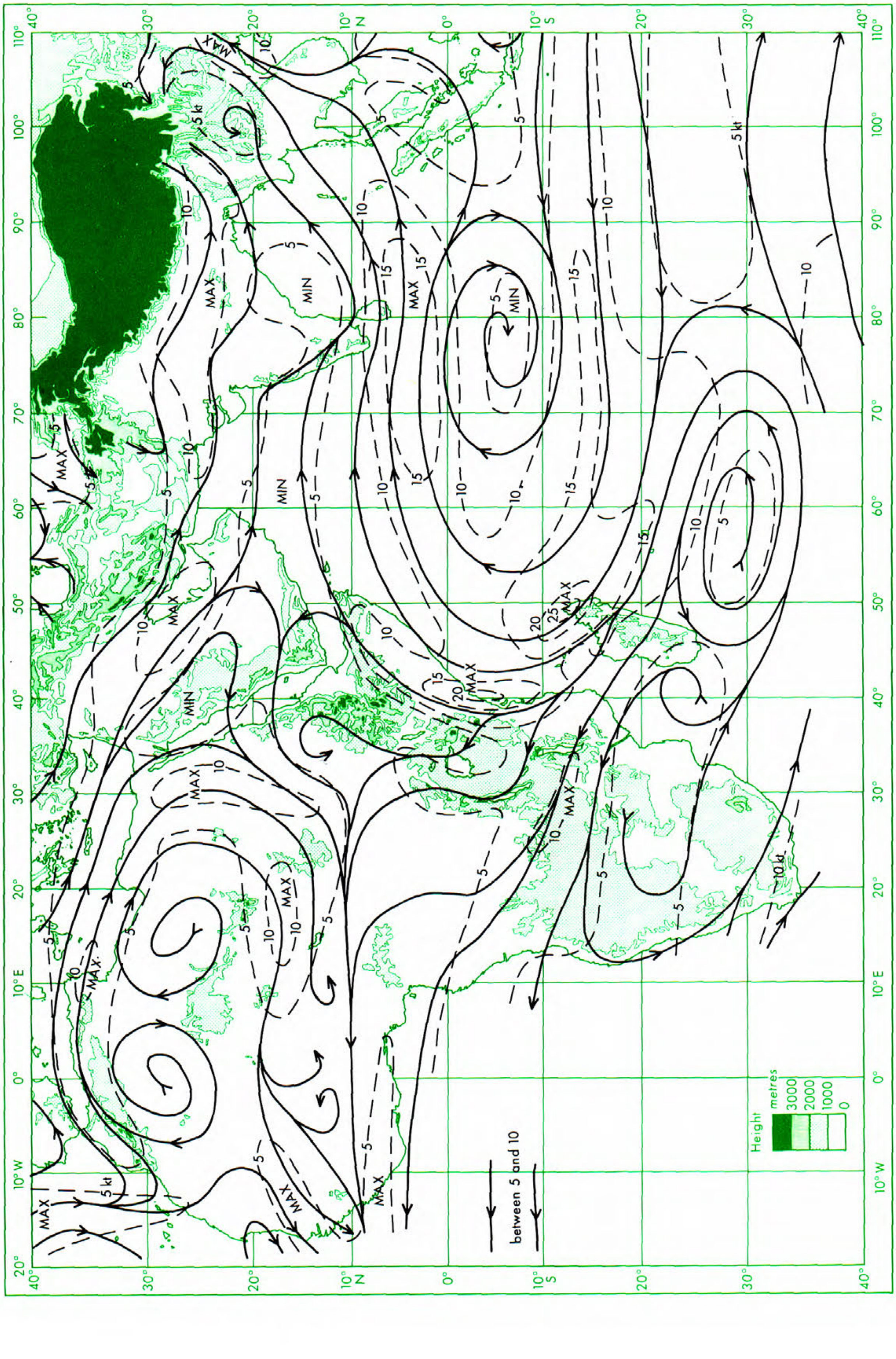

PLATE 1(a). 850-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 14 (11-20 MAY), 1956-60

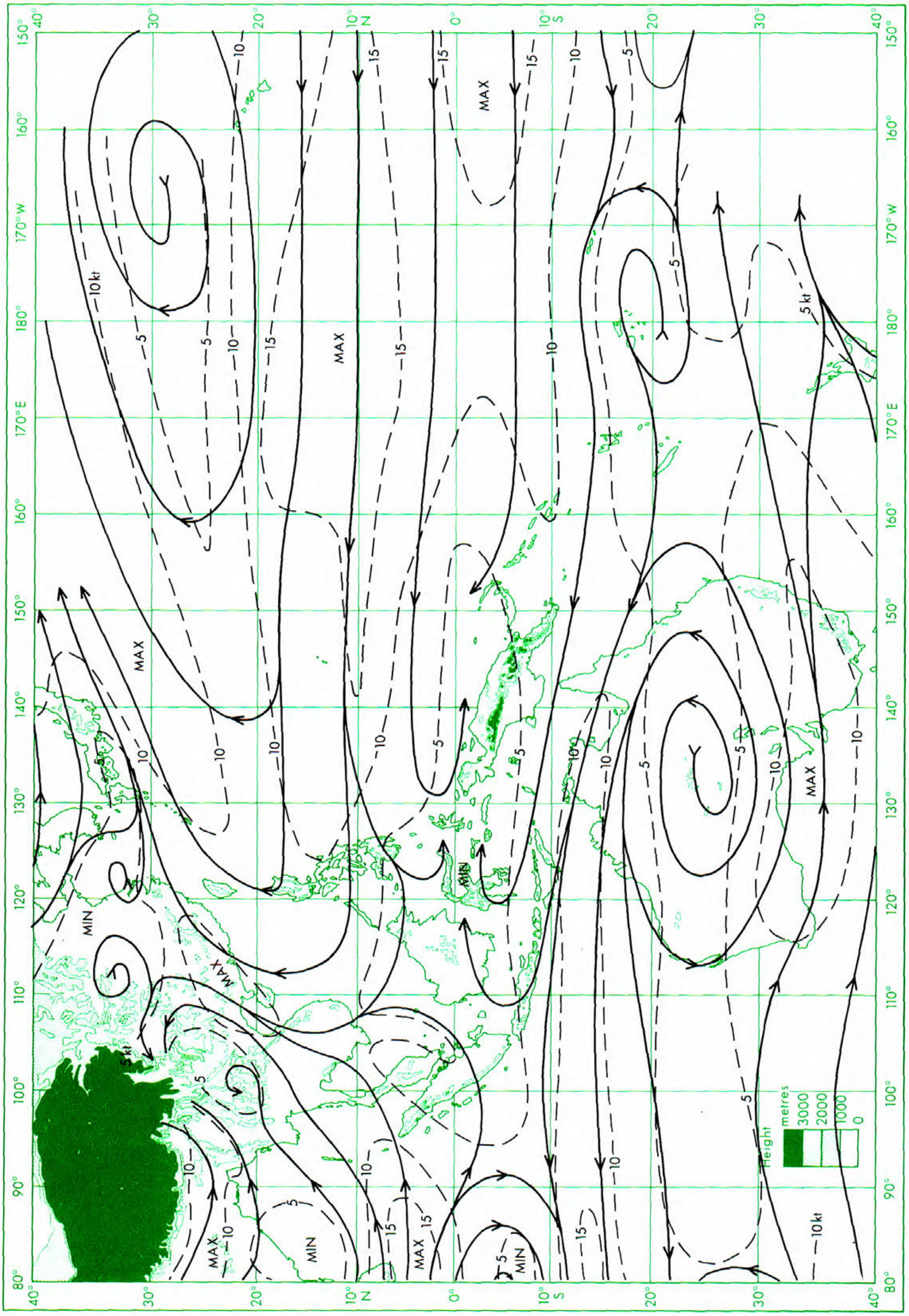

PLATE 1(b). 850-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 14 (11-20 MAY), 1956-60

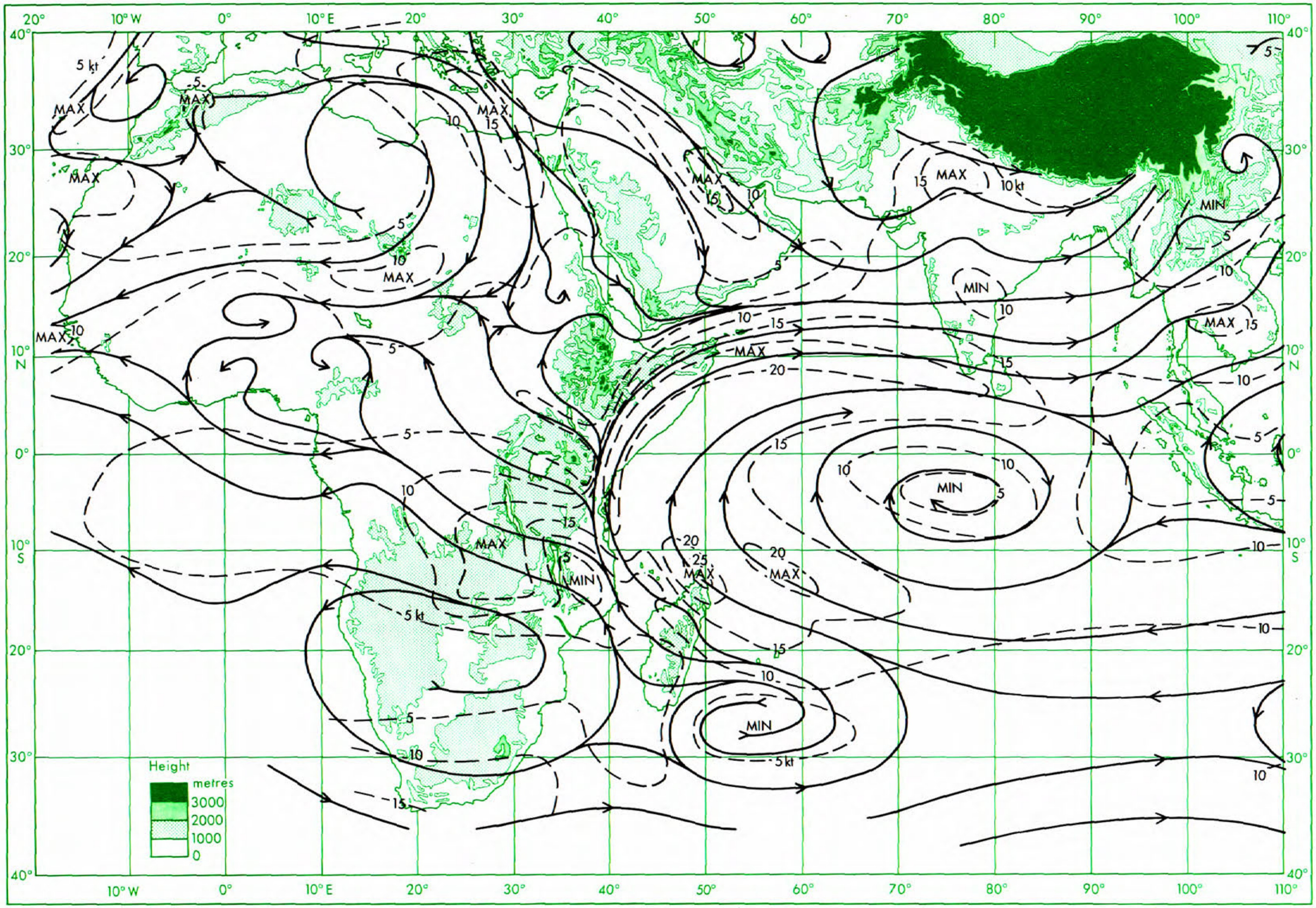

PLATE 2(a). 850-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 17 (10-19 JUNE), 1956-60

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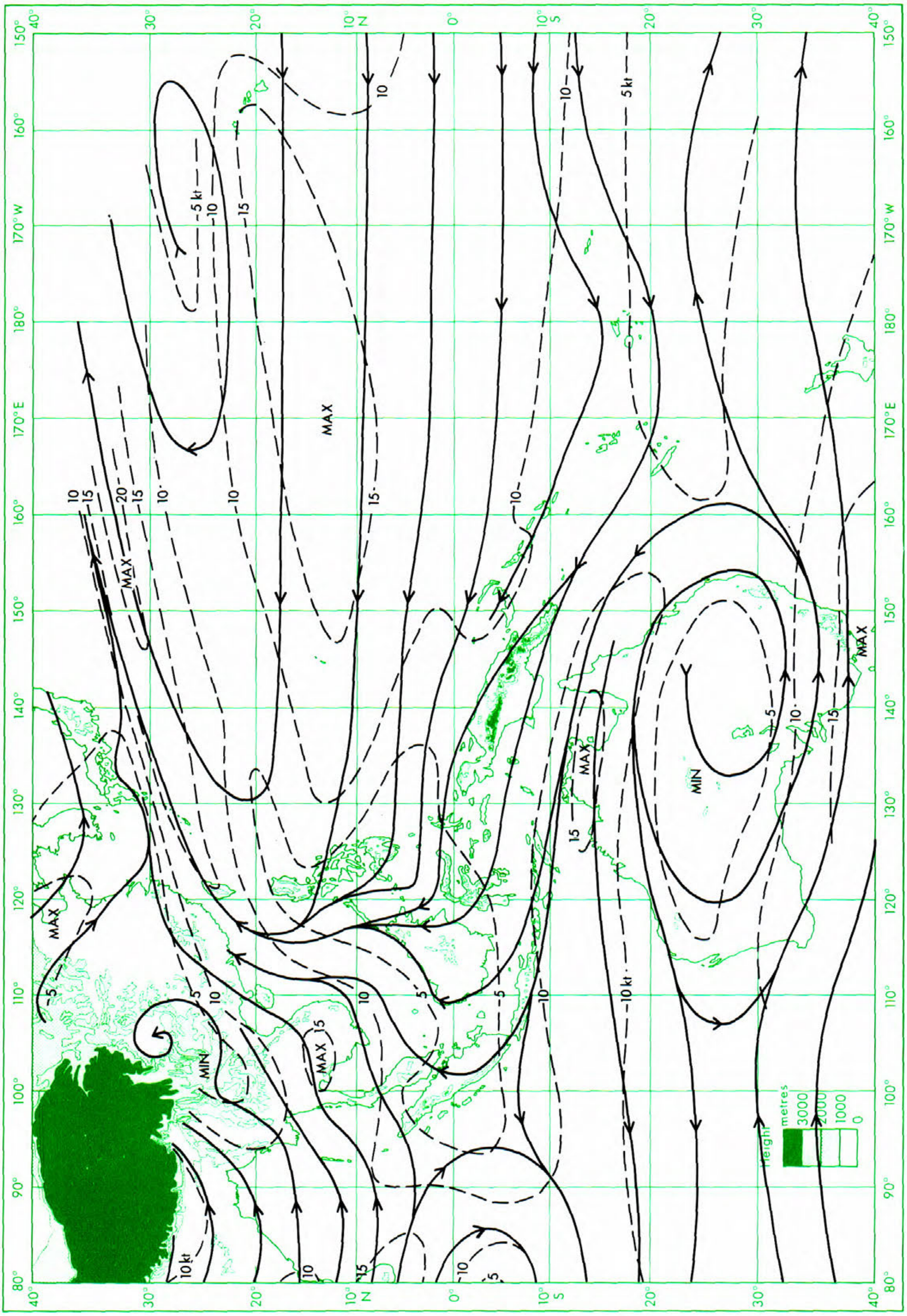

PLATE 2(b). 850-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 17 (10-19 JUNE), 1956-60

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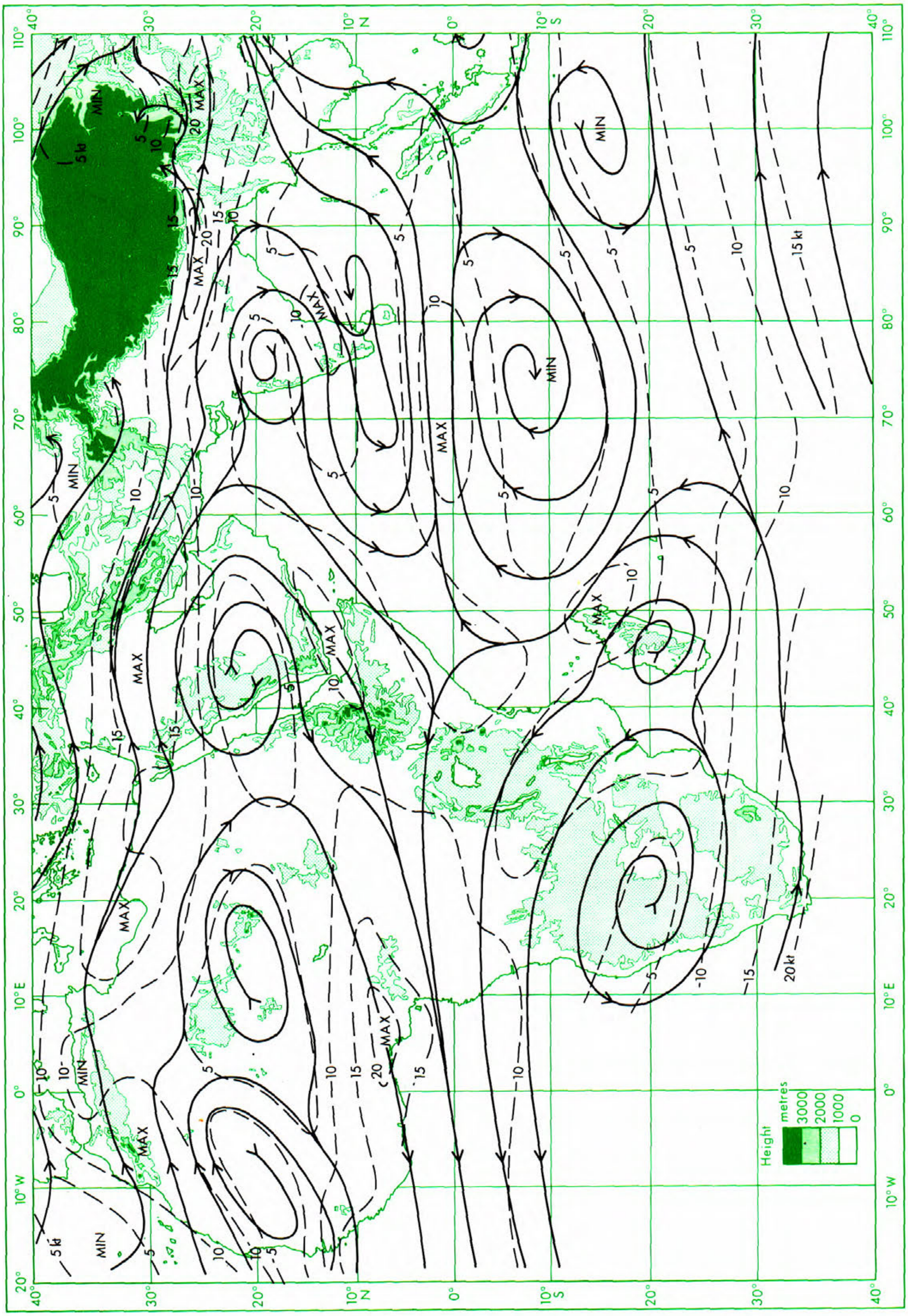


PLATE 3(a). 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 14 (11-20 MAY), 1956-60

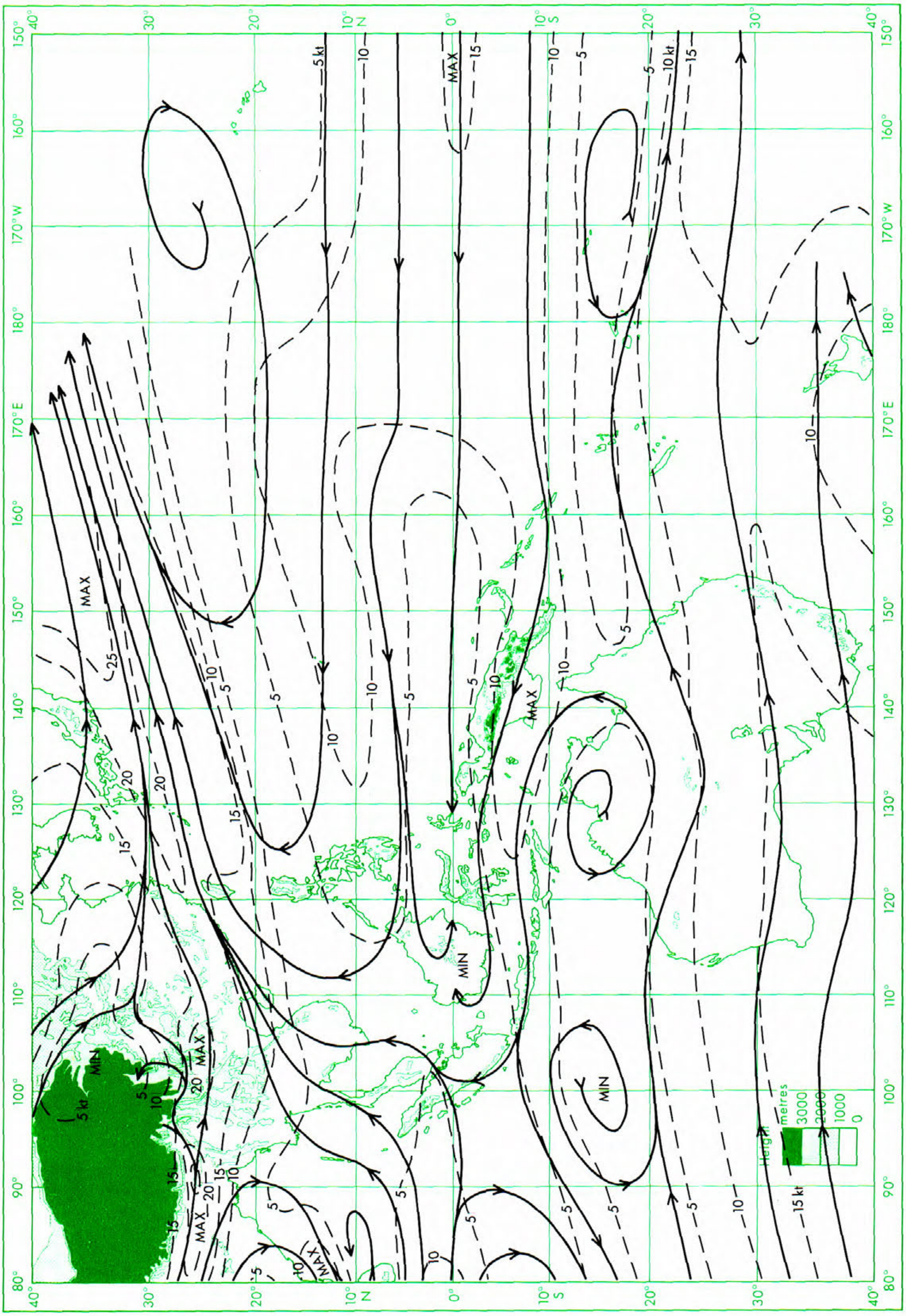
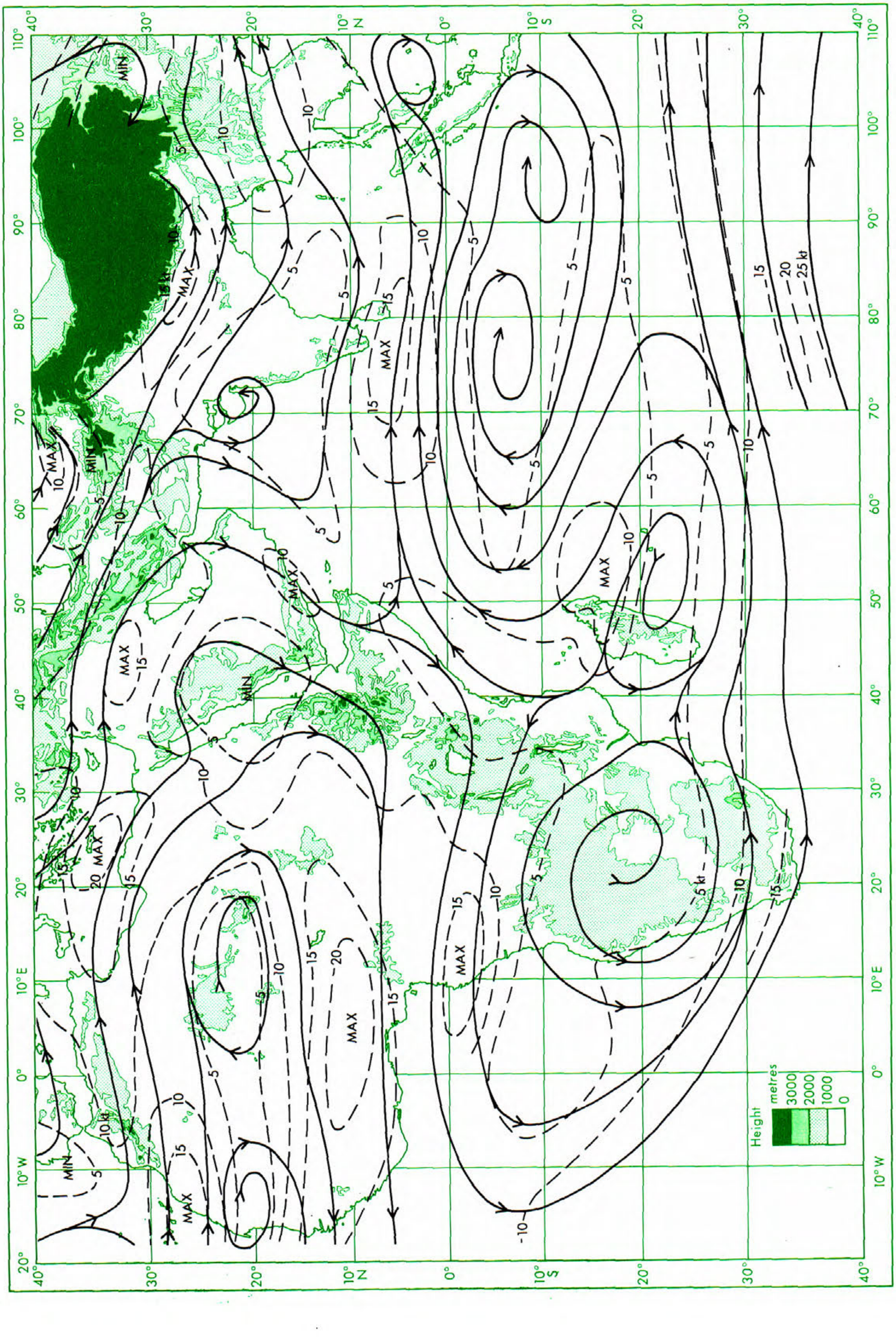


PLATE 3(b). 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 14 (11-20 MAY), 1956-60



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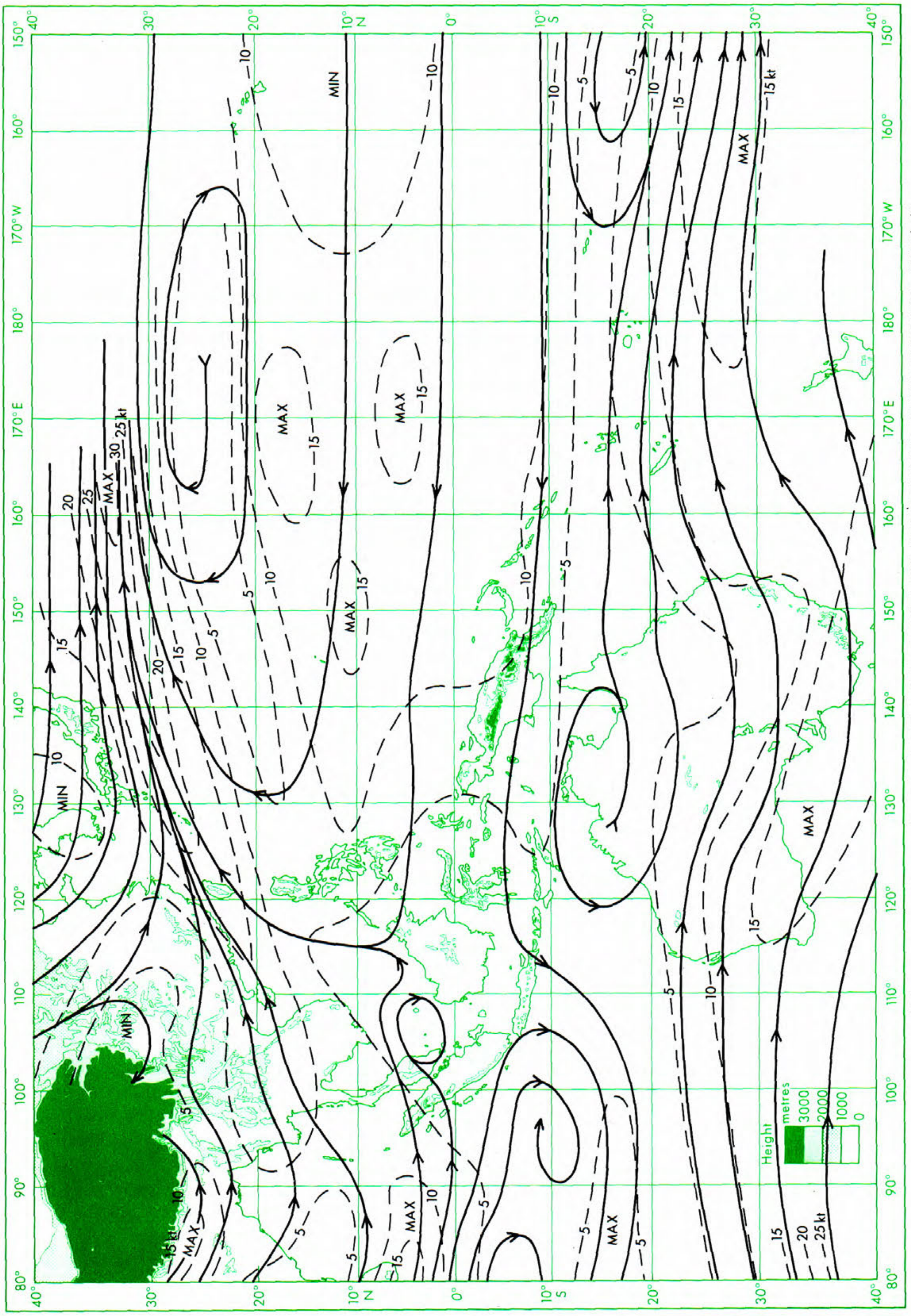


PLATE 4(b). 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 17 (10-19 JUNE), 1956-60

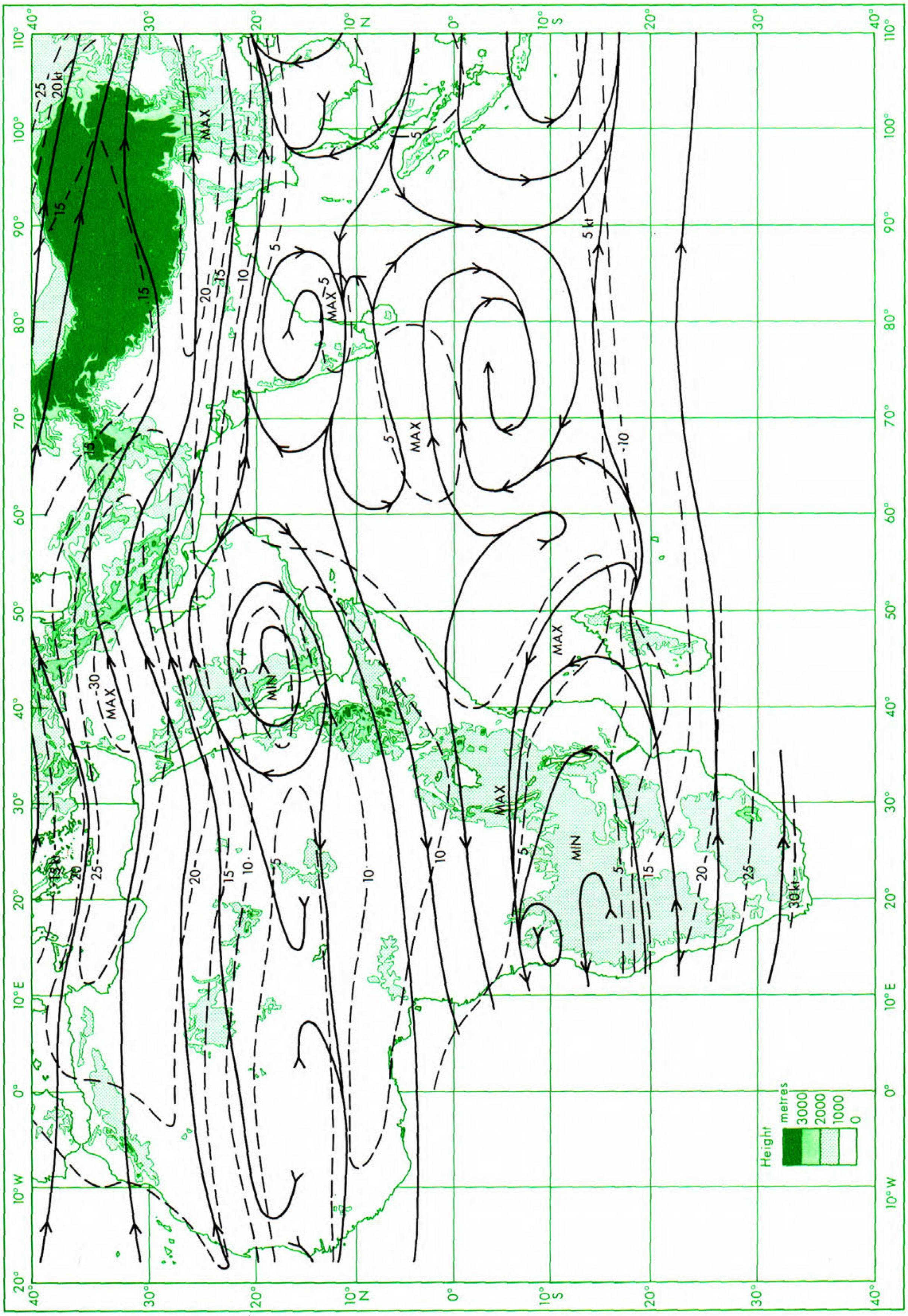


PLATE 5(a). 500-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 14 (11-20 MAY), 1956-60

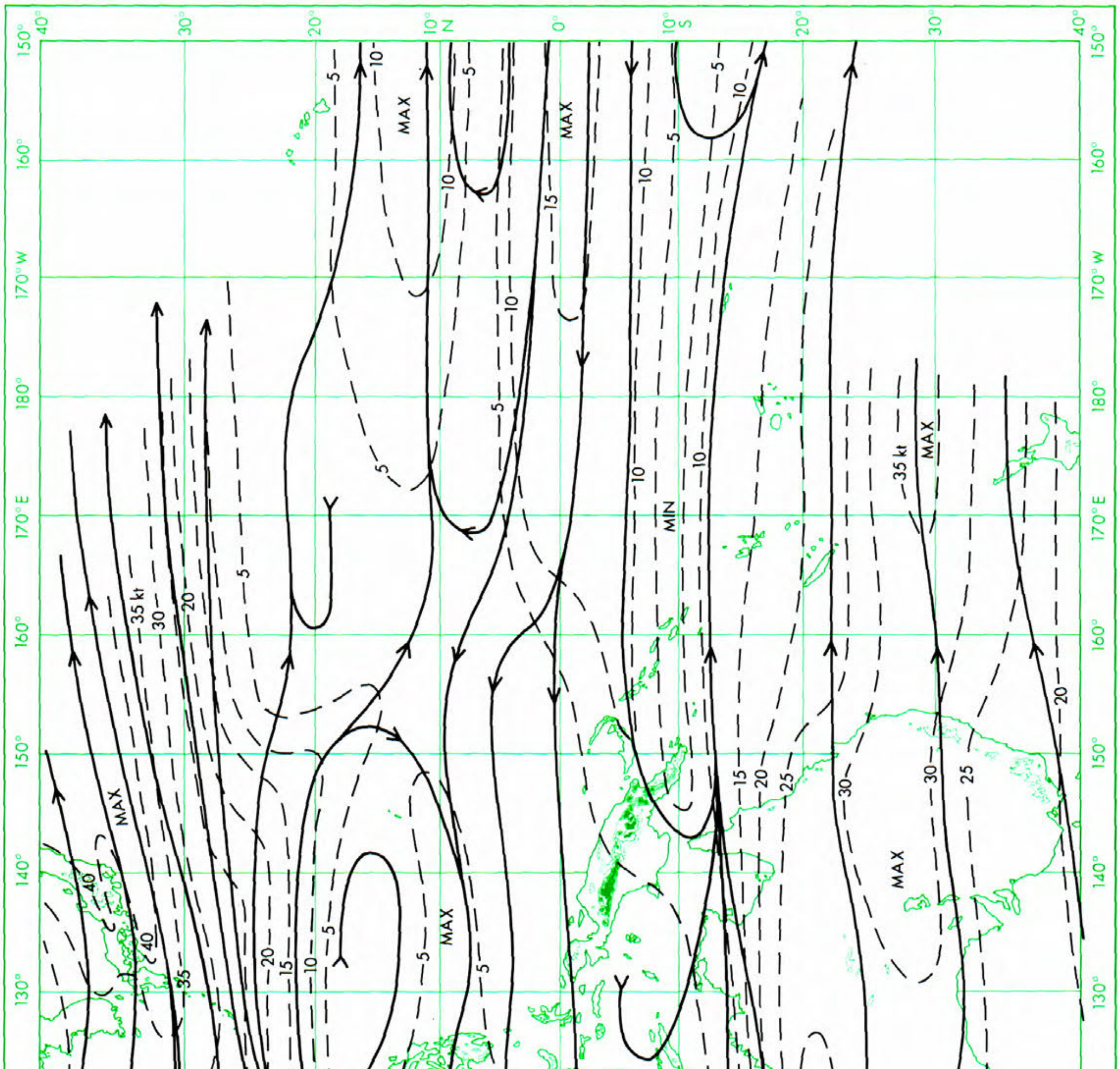
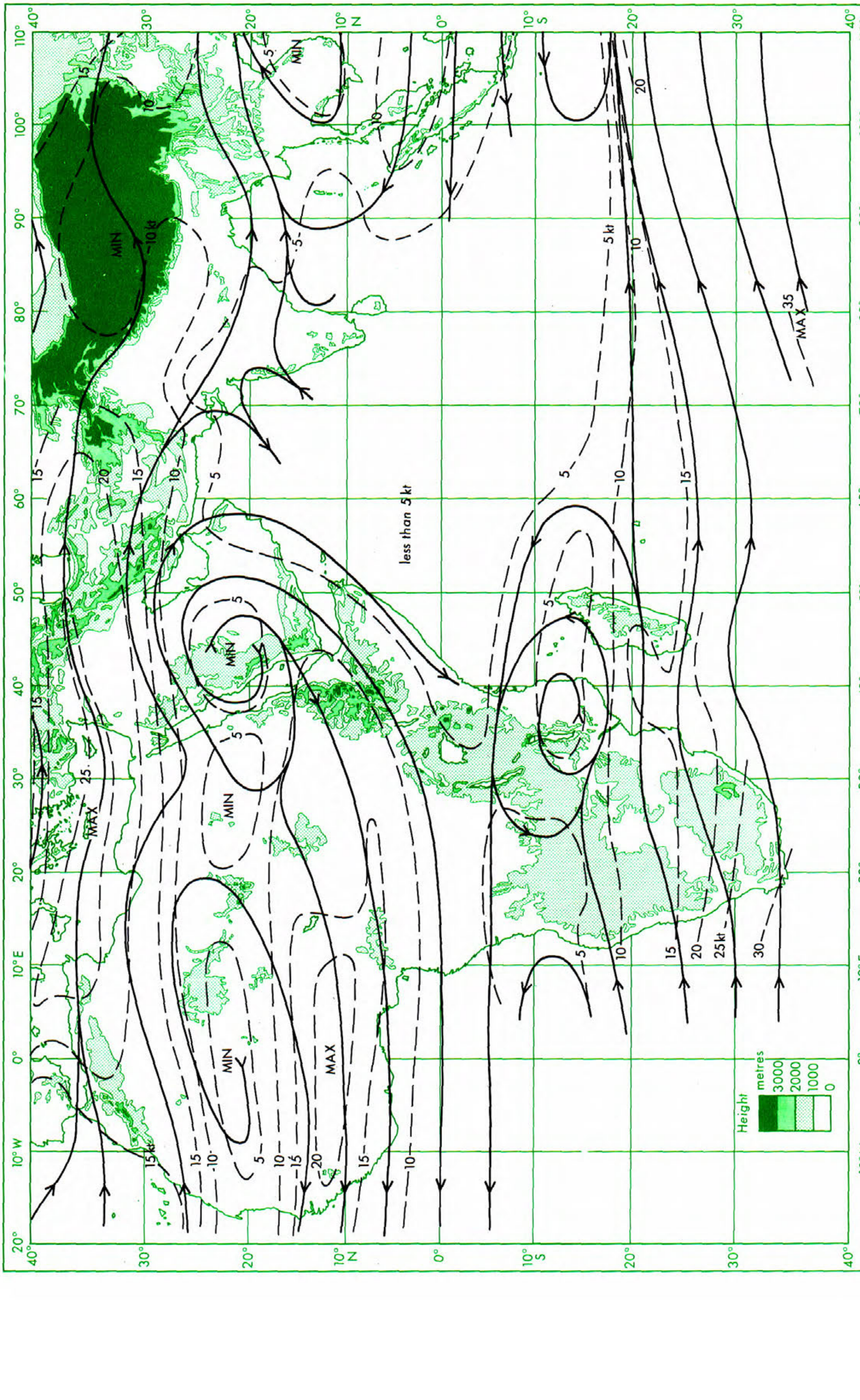


PLATE 5(b). 500-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 14 (11-20 MAY), 1956-60



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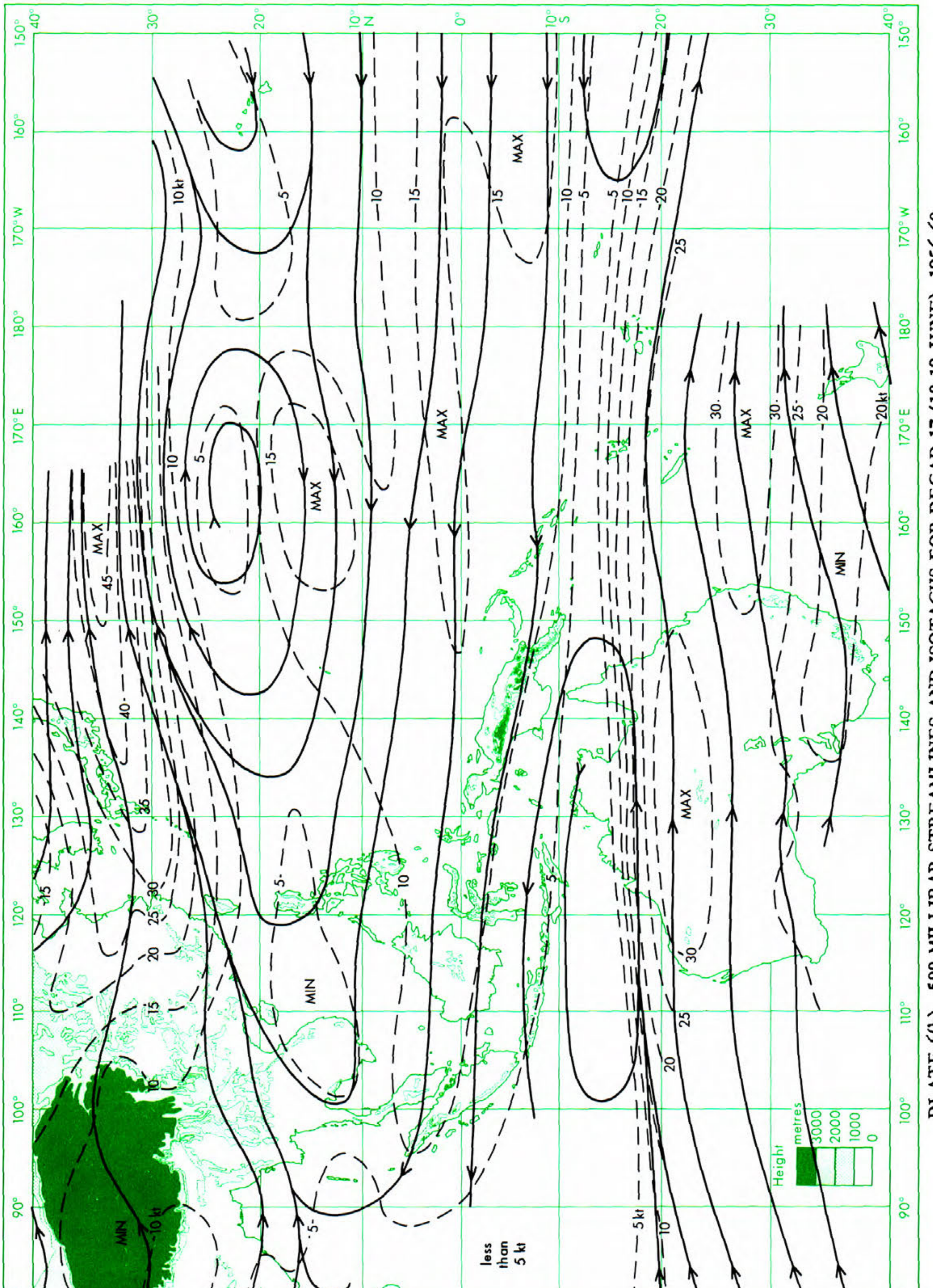

PLATE 6(b). 500-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 17 (10-19 JUNE), 1956-60

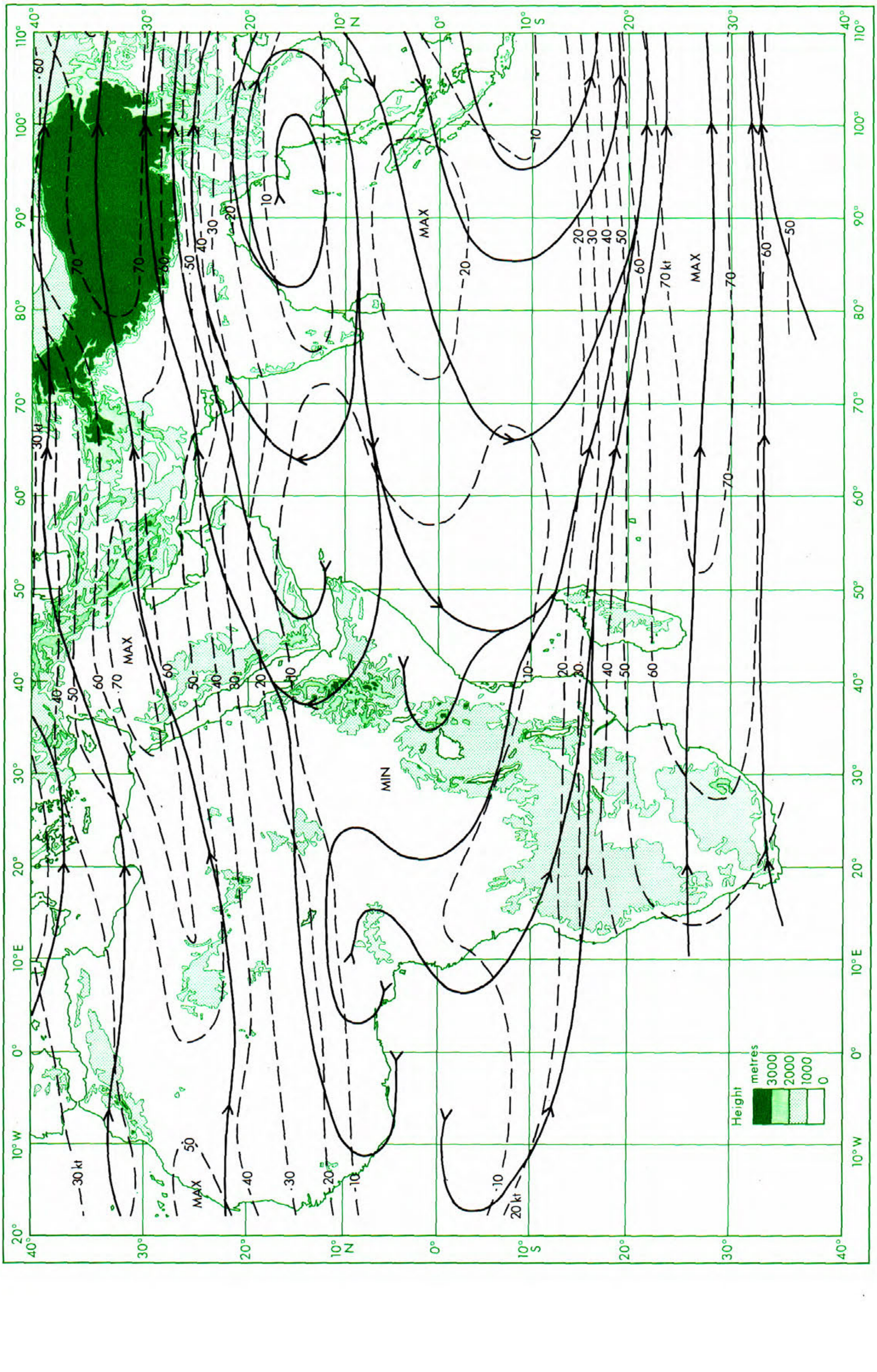

PLATE 7(a). 200-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 14 (11-20 MAY), 1956-60

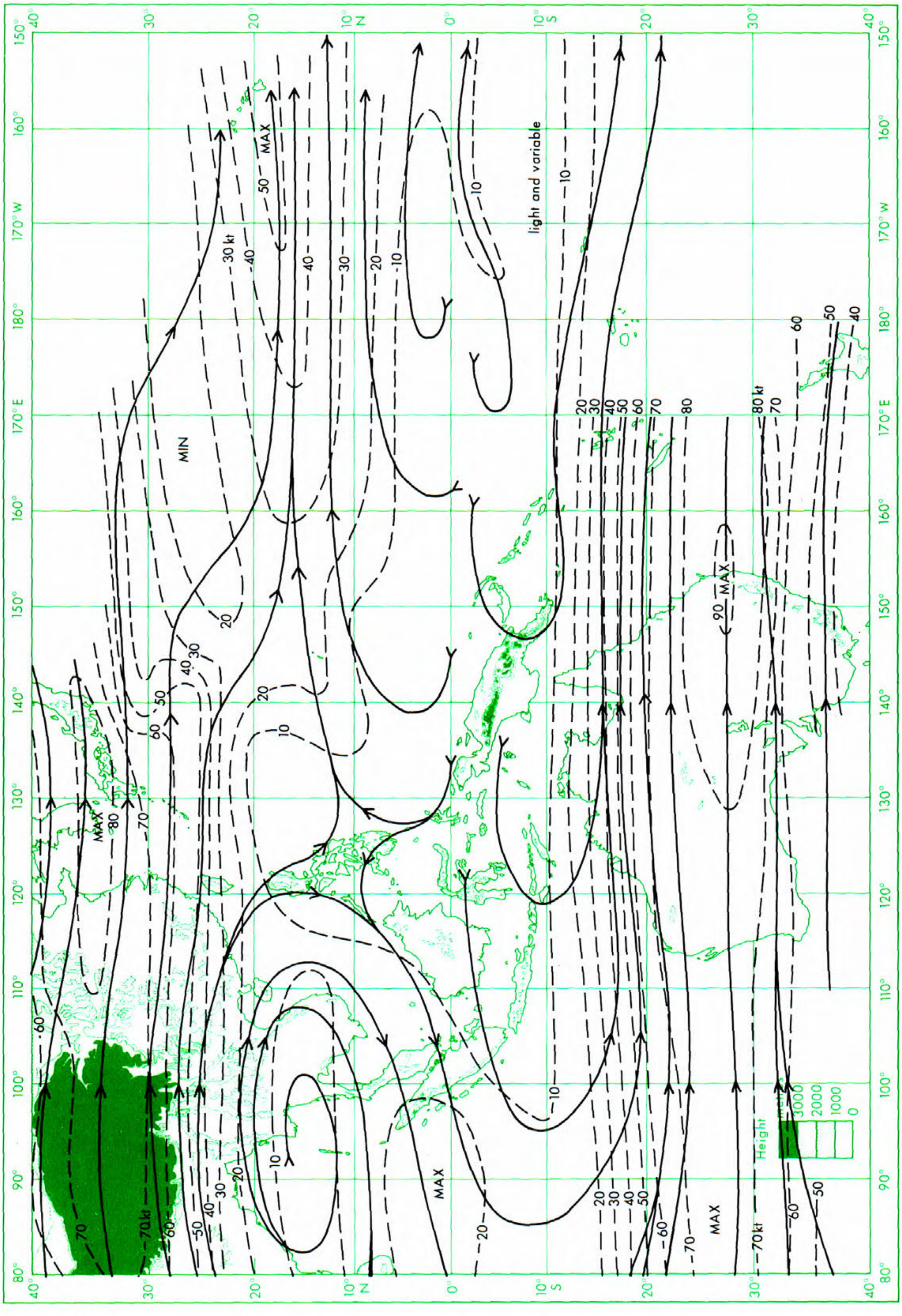

PLATE 7(b). 200-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 14 (11-20 MAY), 1956-60

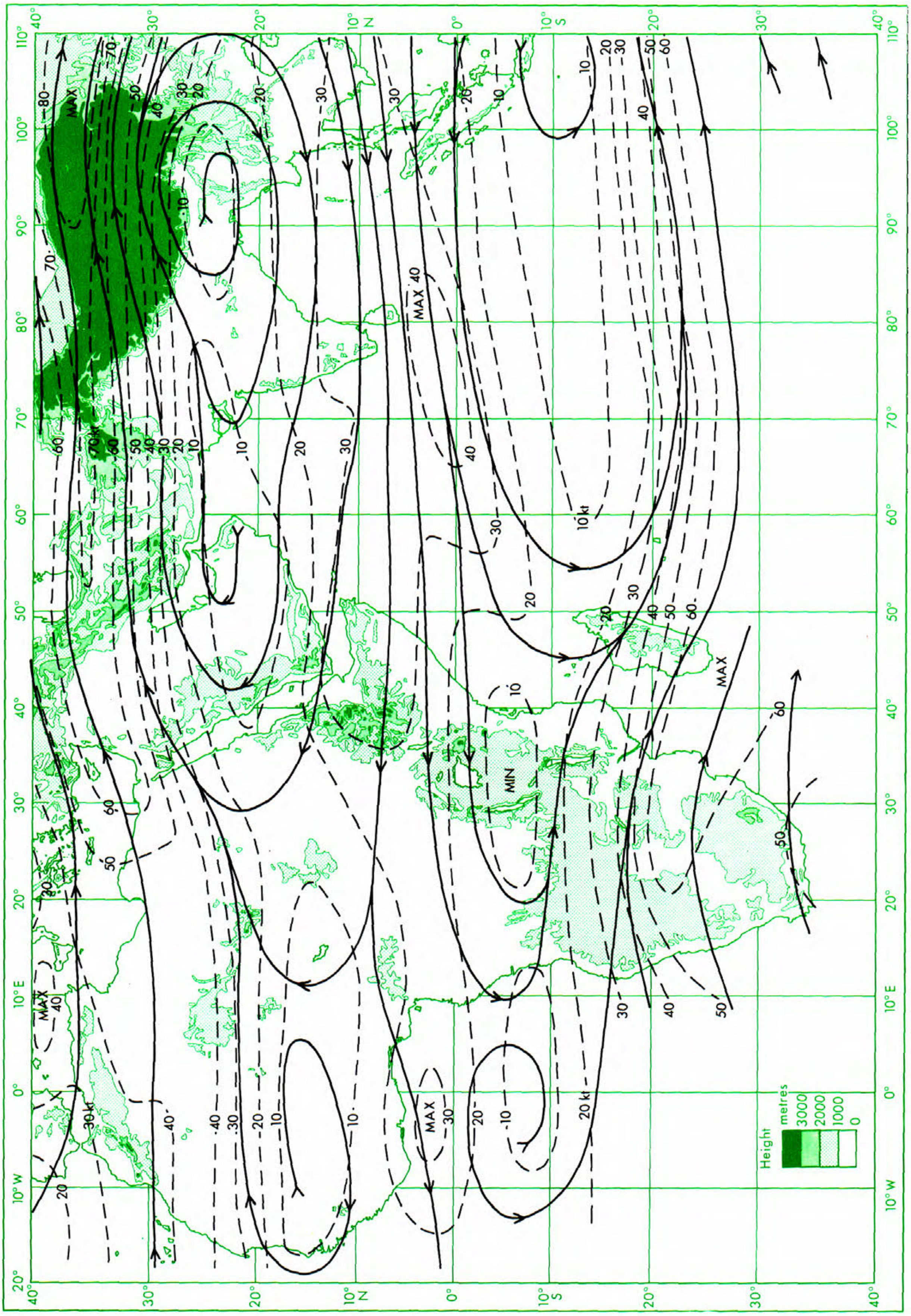

PLATE 8(a). 200-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 17 (10-19 JUNE), 1956-60

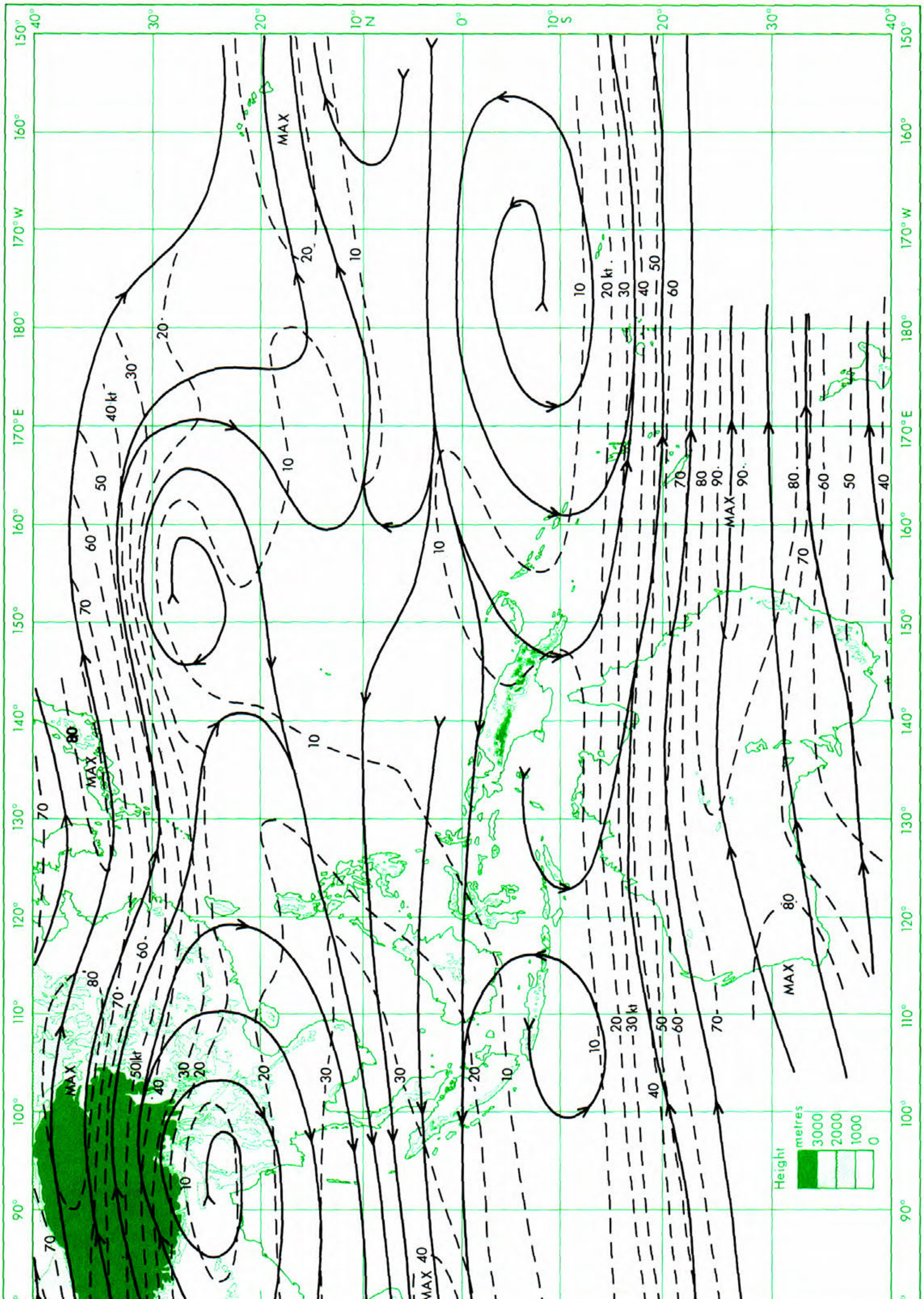

PLATE 8(b). 200-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 17 (10-19 JUNE), 1956-60

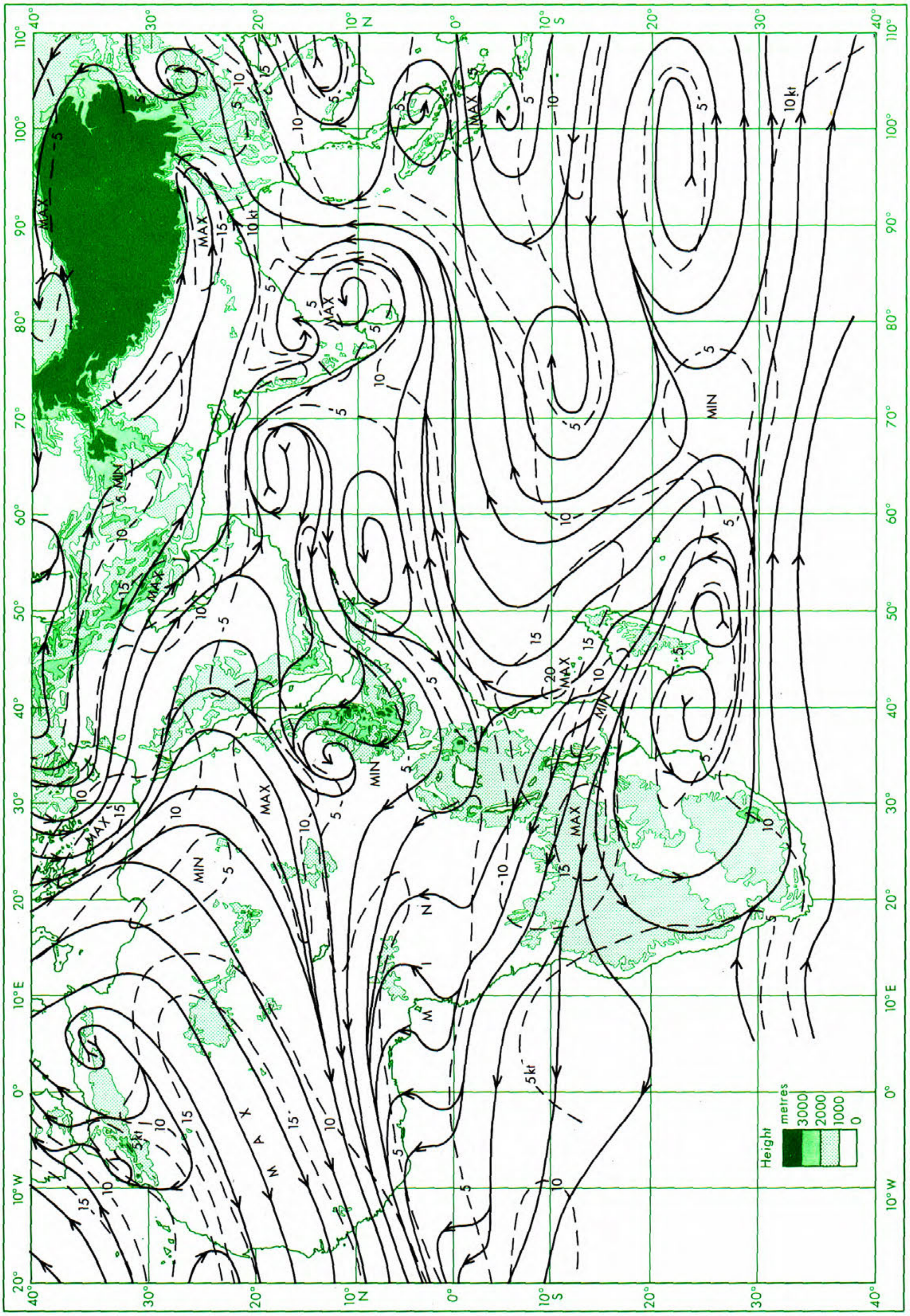

PLATE 9(a). 850-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 13 (1-10 MAY), 1958

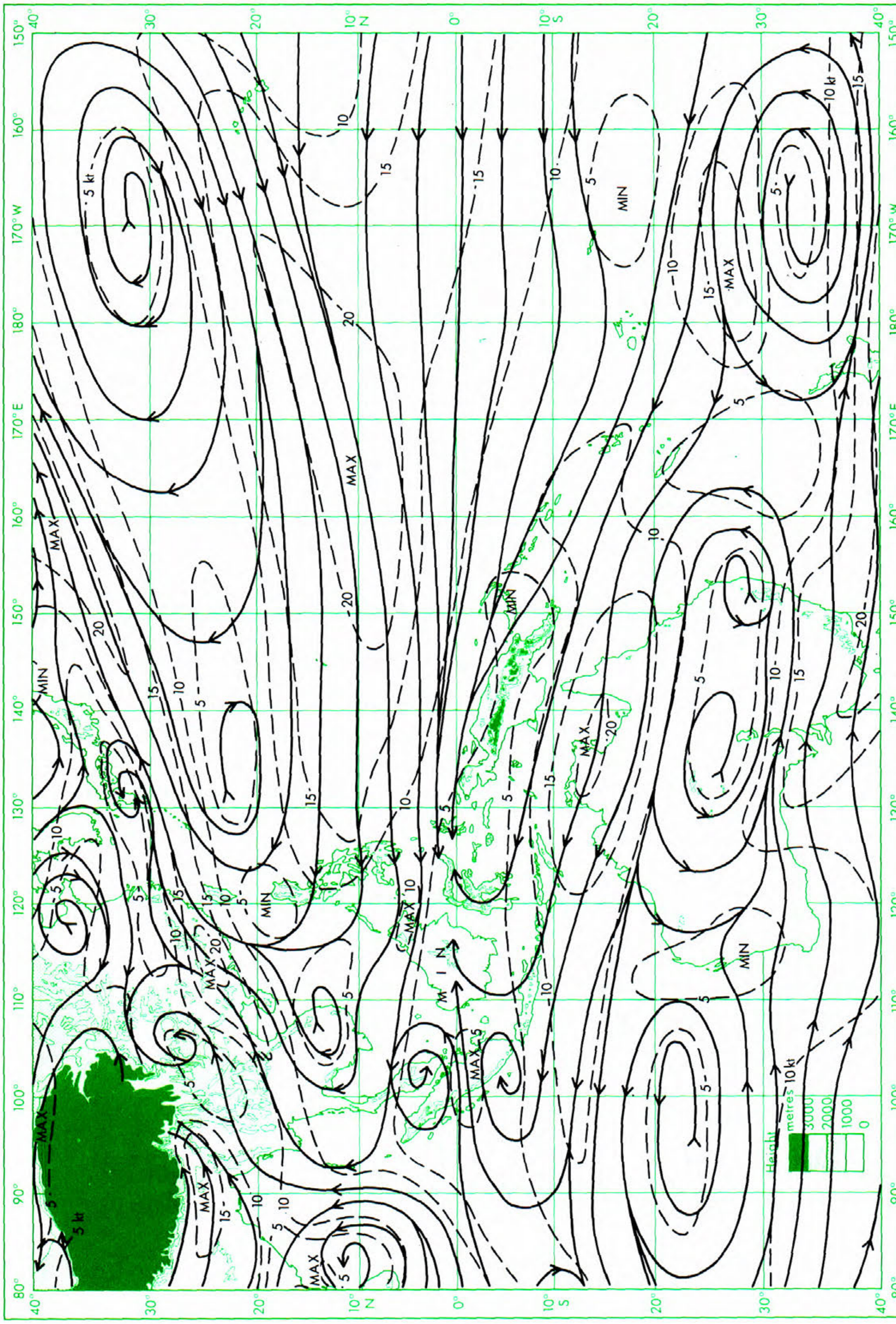

PLATE 9(b). 850-MILLIBAR STREAMLINES AND ISTOACHS FOR DECAD 13 (1-10 MAY), 1958

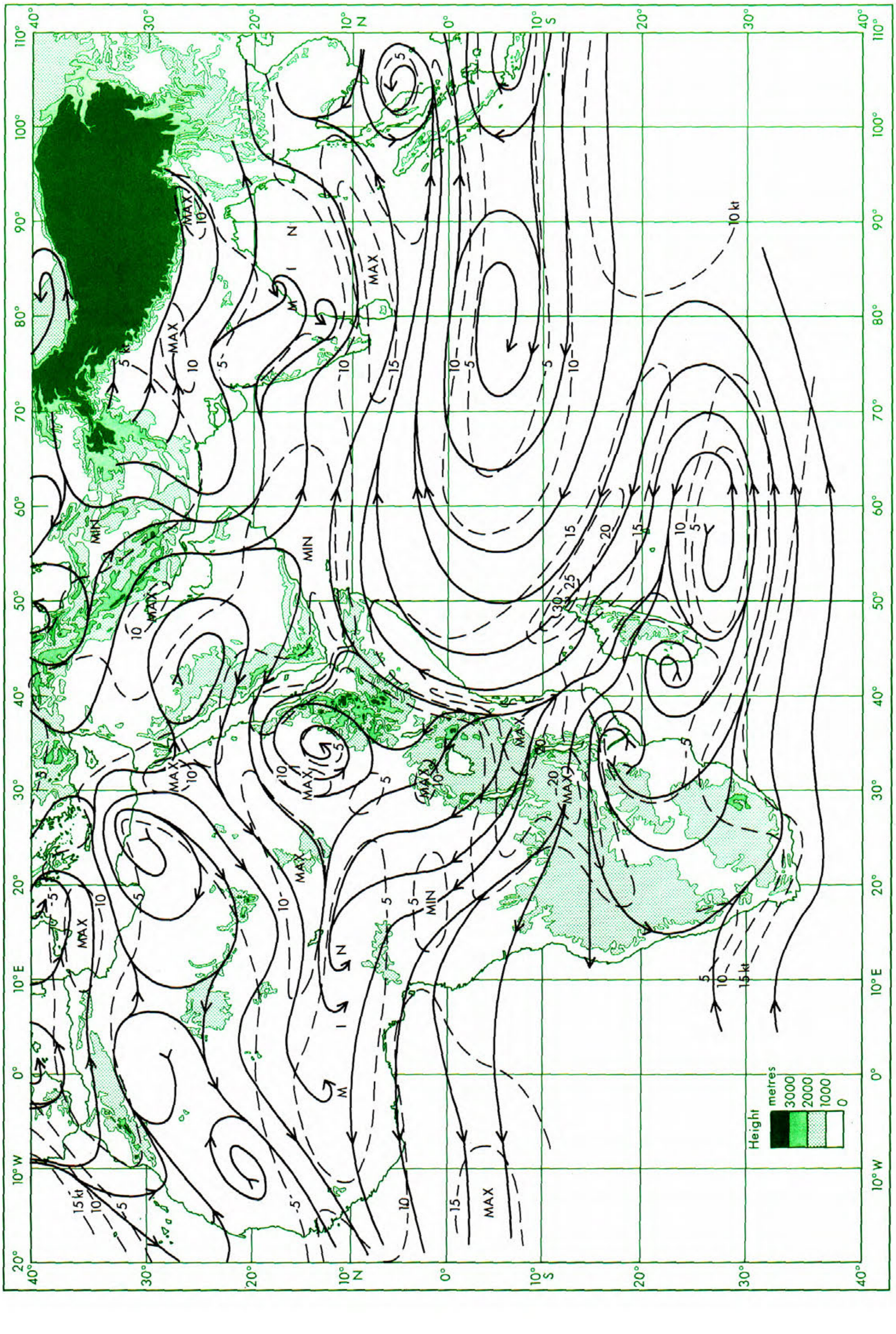

PLATE 10. 850-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 14 (11-20 MAY), 1958

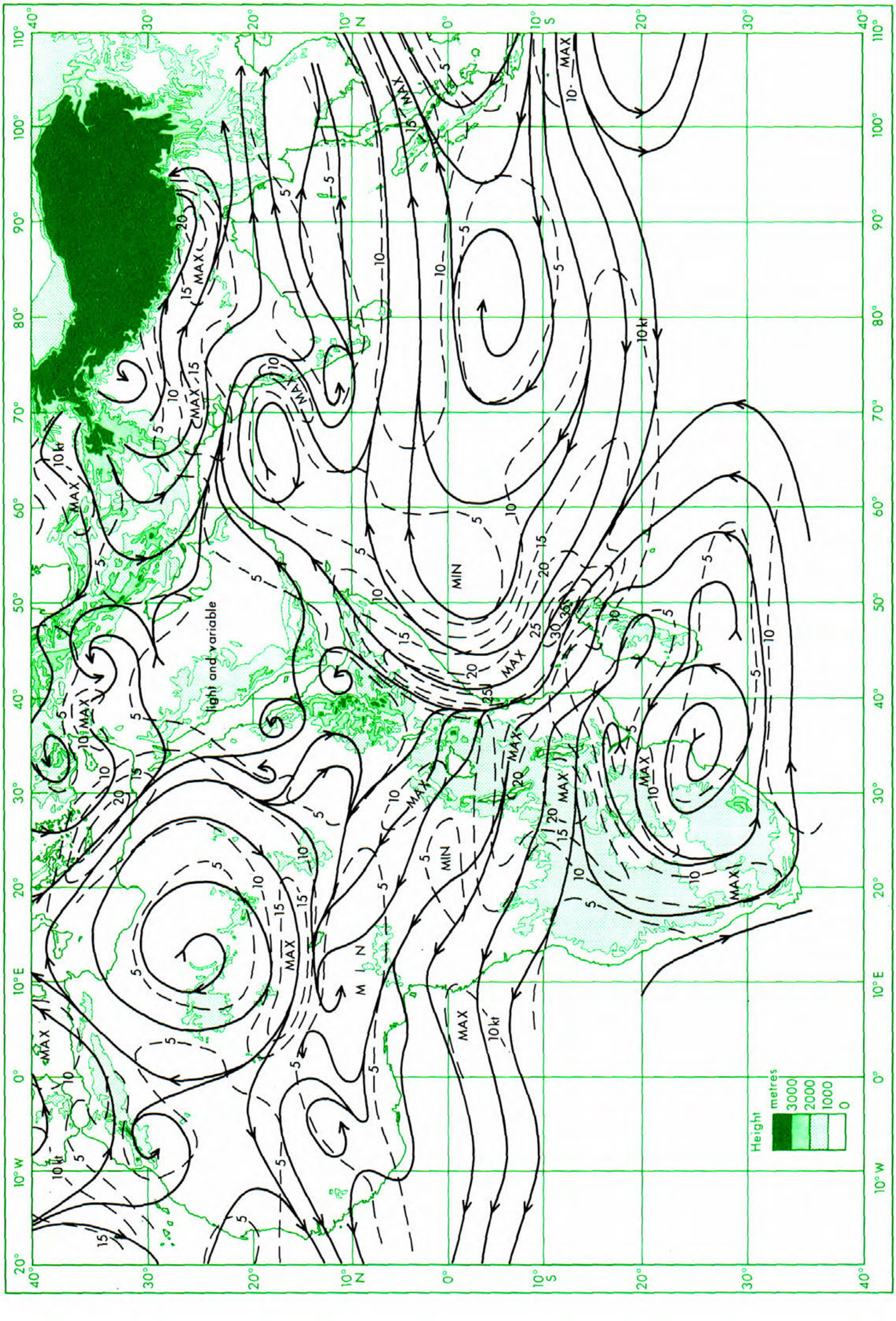

PLATE 11. 850-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 15 (21-30 MAY), 1958

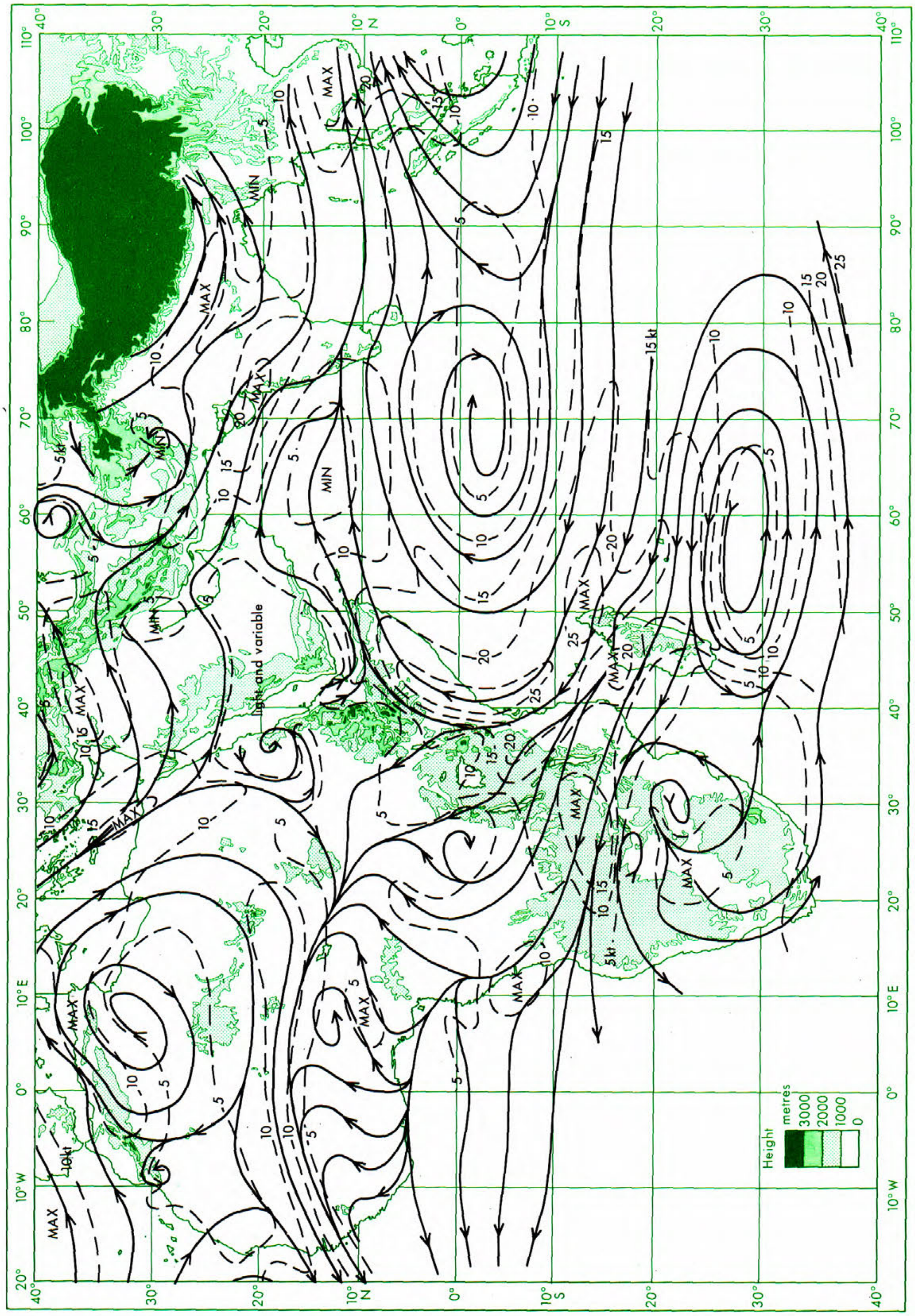

PLATE 12. 850-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 16 (31 MAY-9 JUNE), 1958

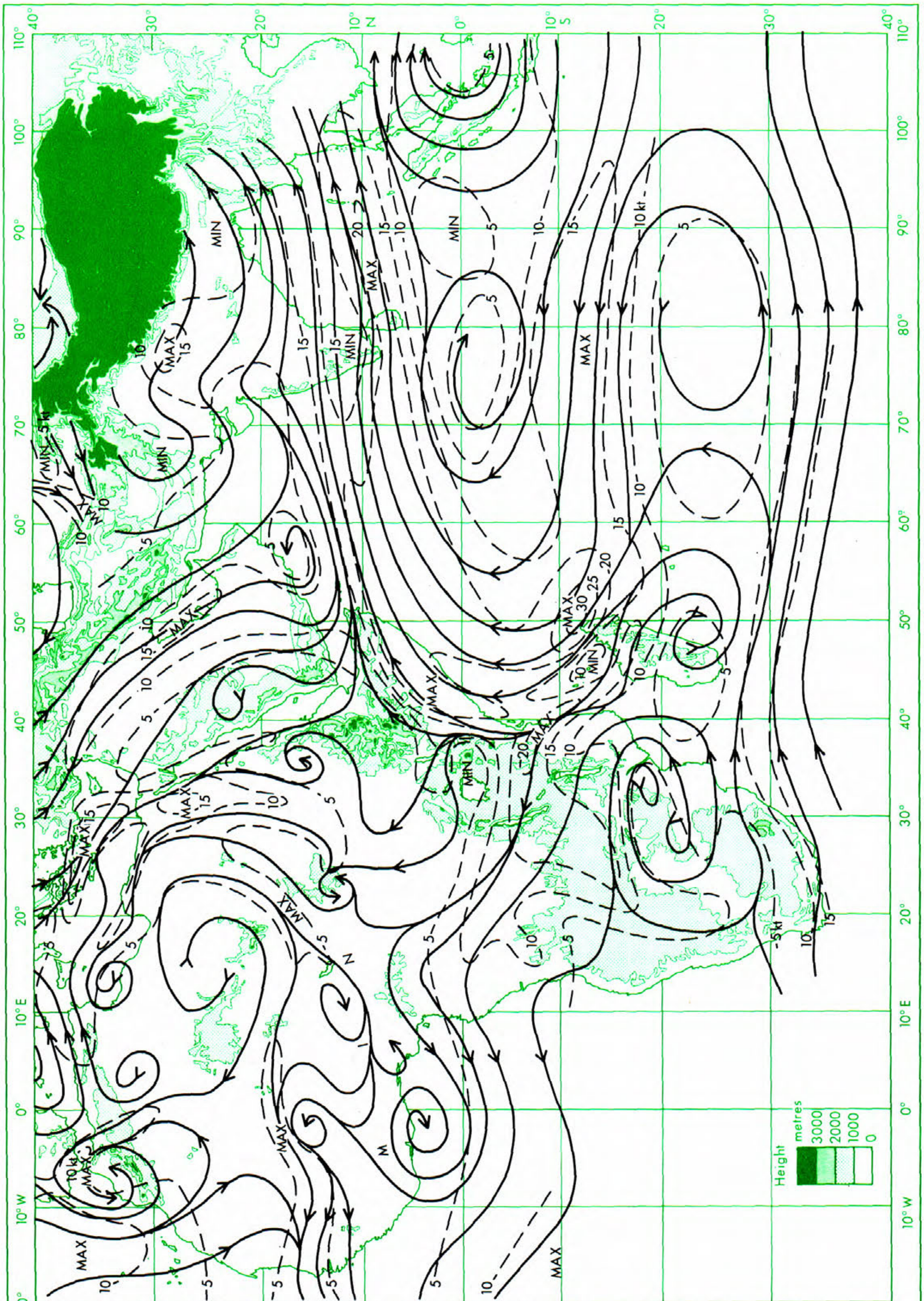

PLATE 13. 850-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 17 (10-19 JUNE), 1958

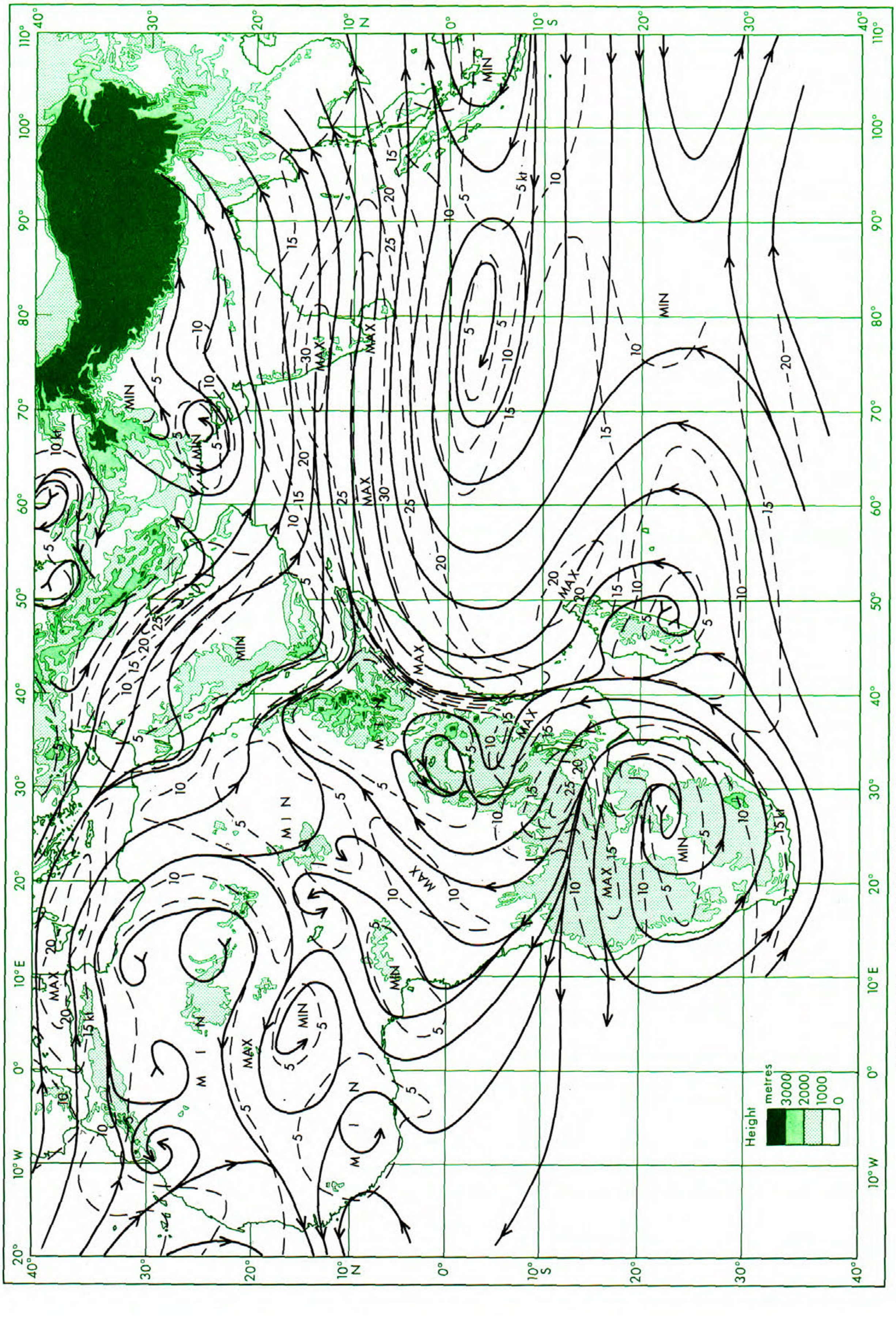

PLATE 14. 850-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 18 (20-29 JUNE), 1958

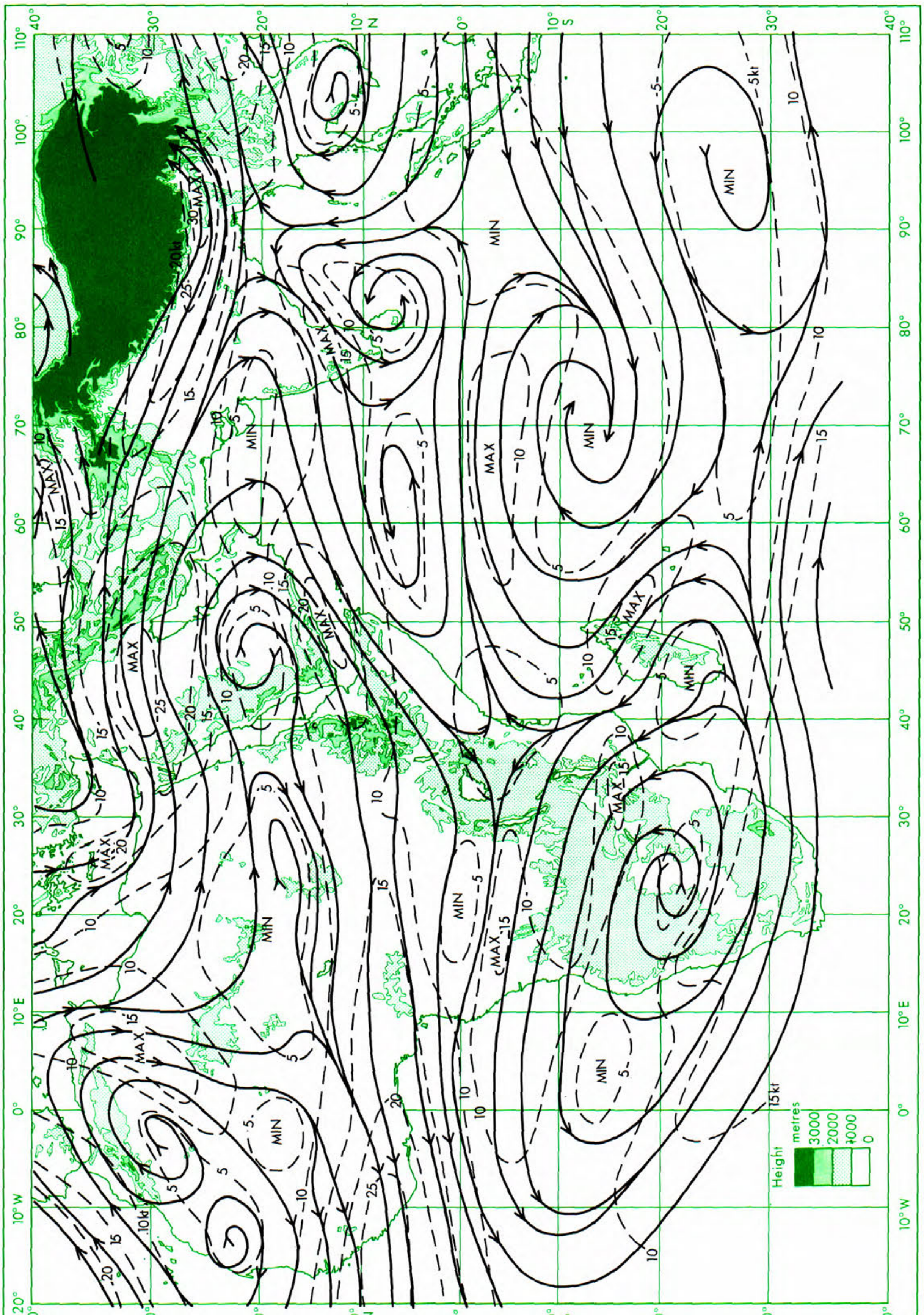

PLATE 15(a). 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 13 (1-10 MAY), 1958

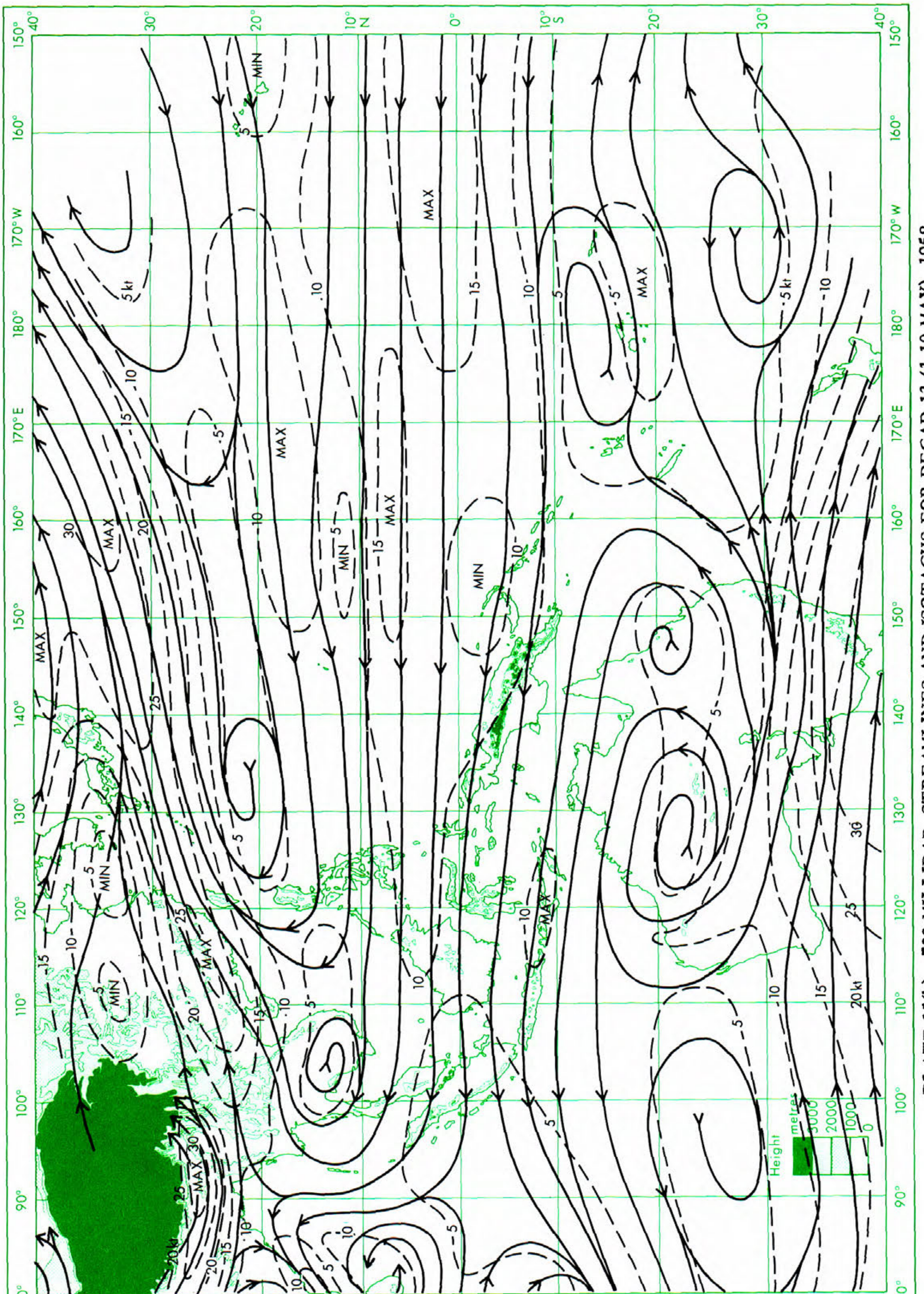

PLATE 15(b). 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 13 (1-10 MAY), 1958

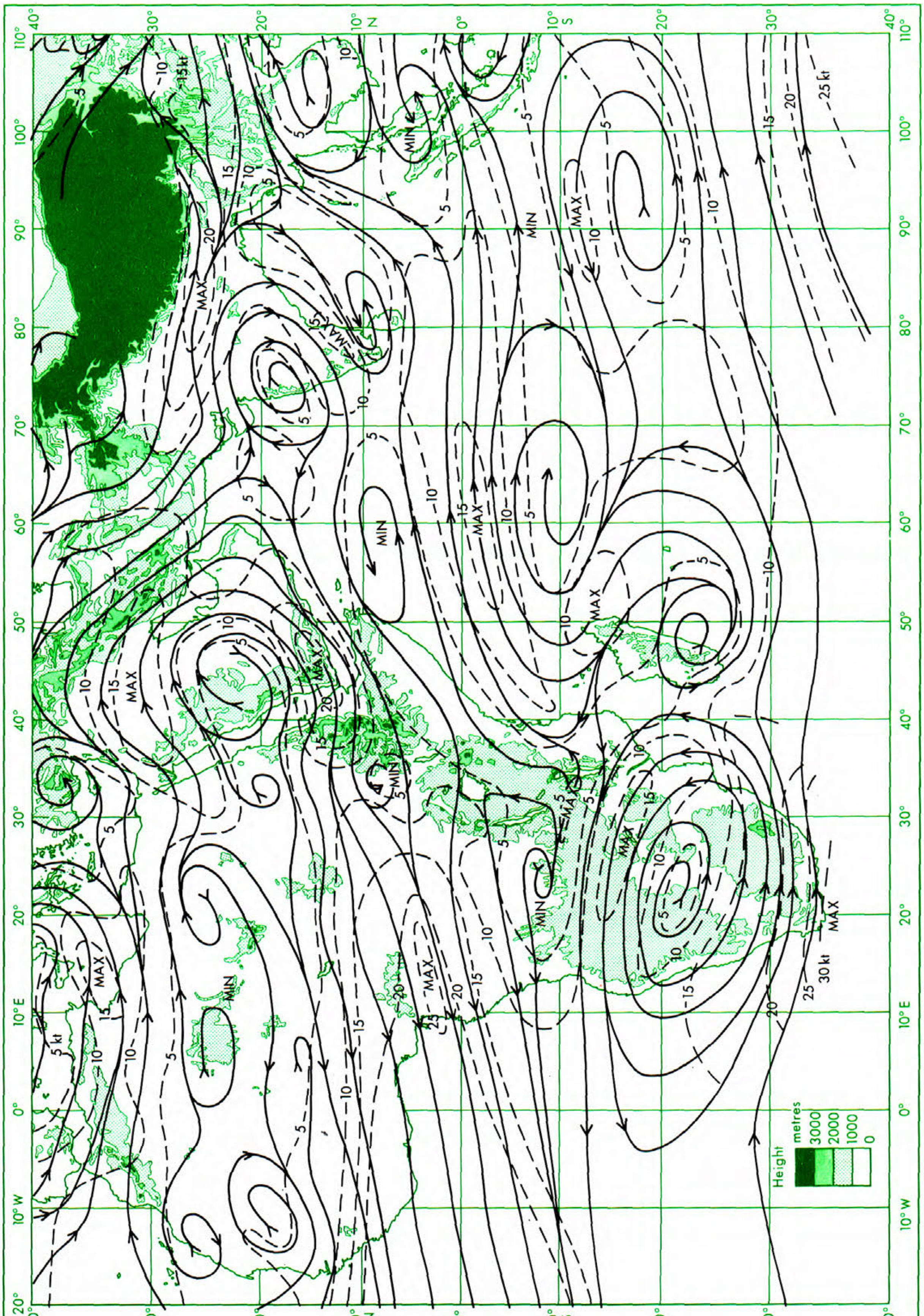

PLATE 16(a). 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 14 (11-20 MAY), 1958

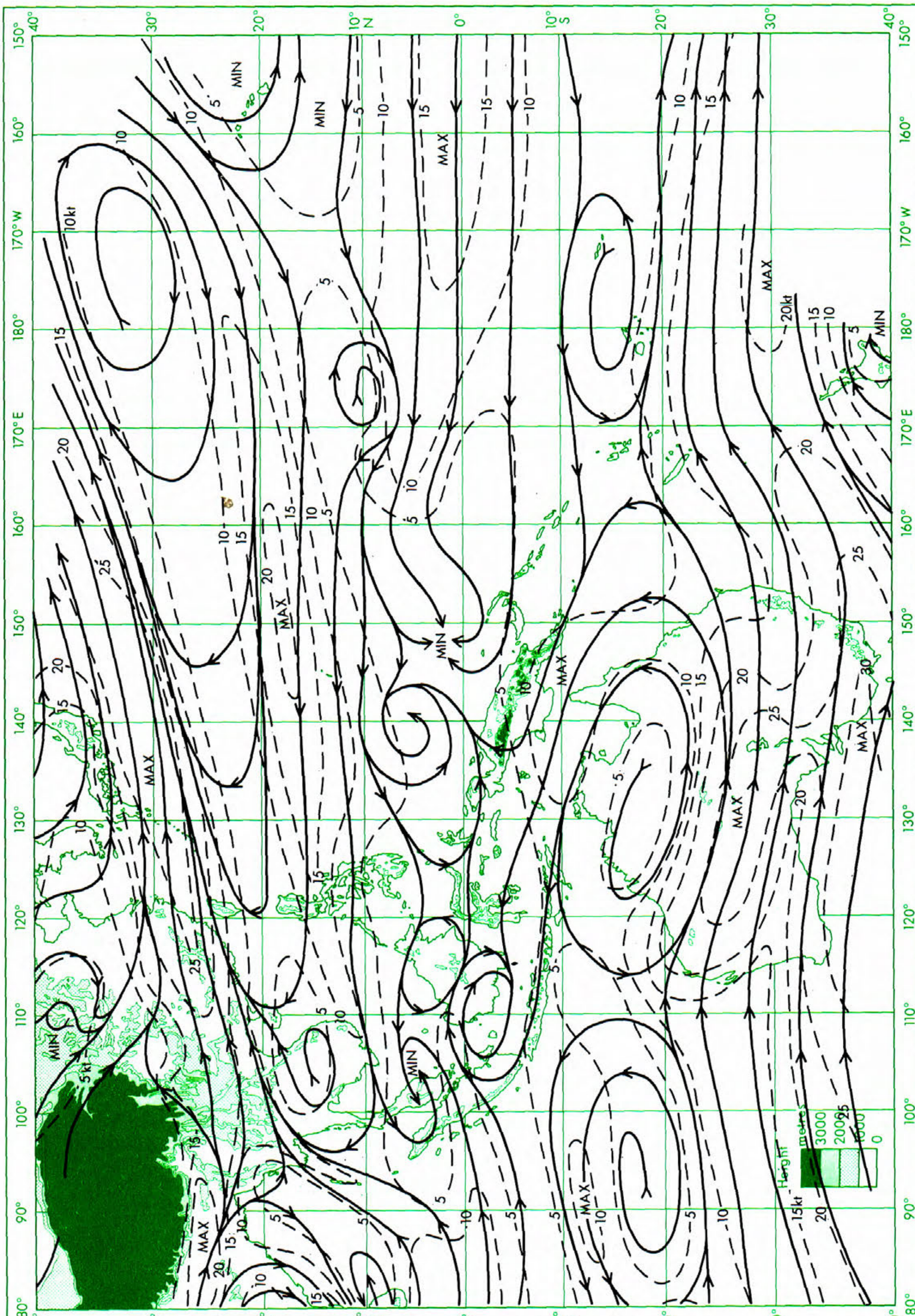

PLATE 16(b). 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 14 (11-20 MAY), 1958

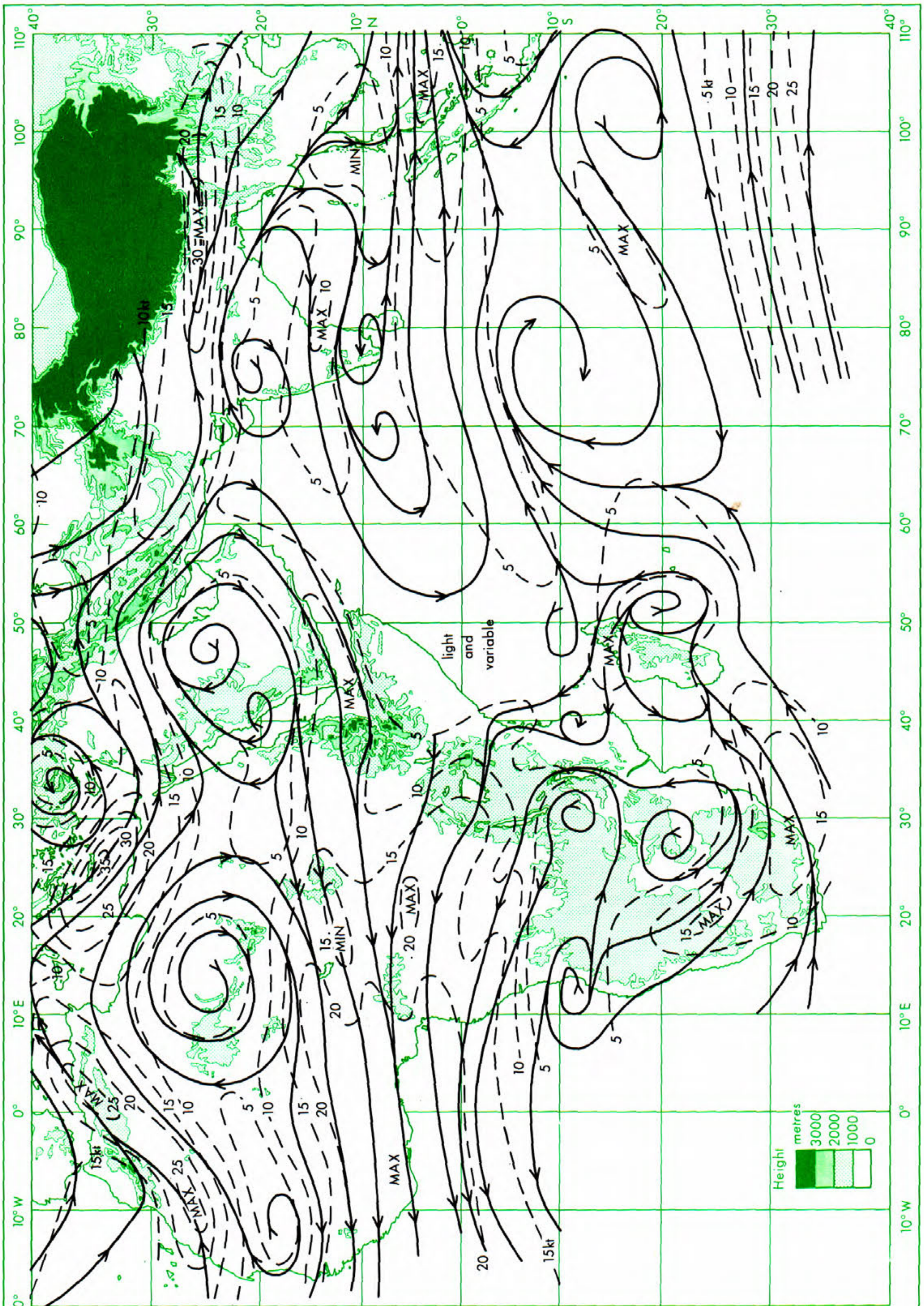

PLATE 17(a). 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 15 (21-30 MAY), 1958

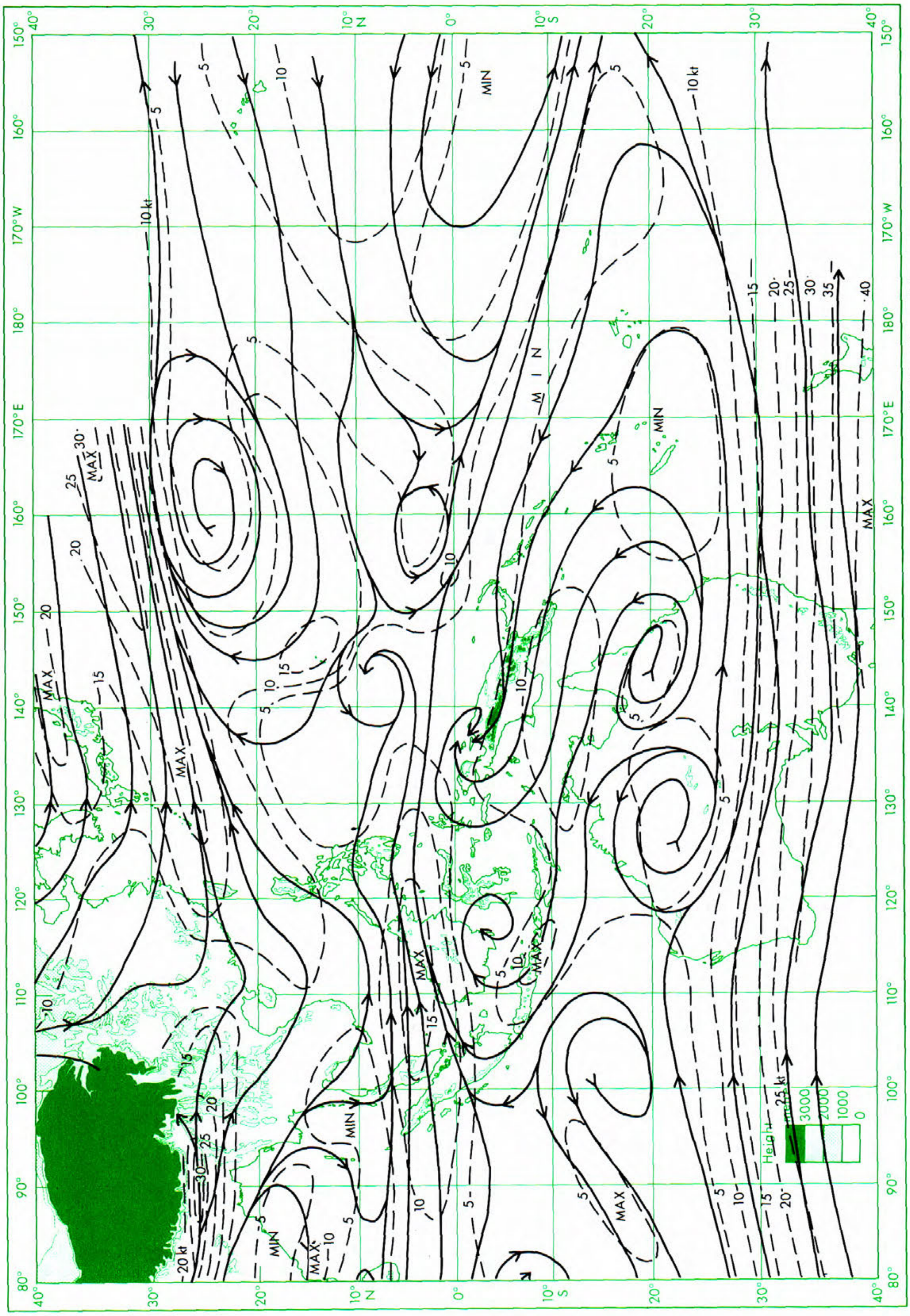

PLATE 17(b). 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 15 (21-30 MAY), 1958

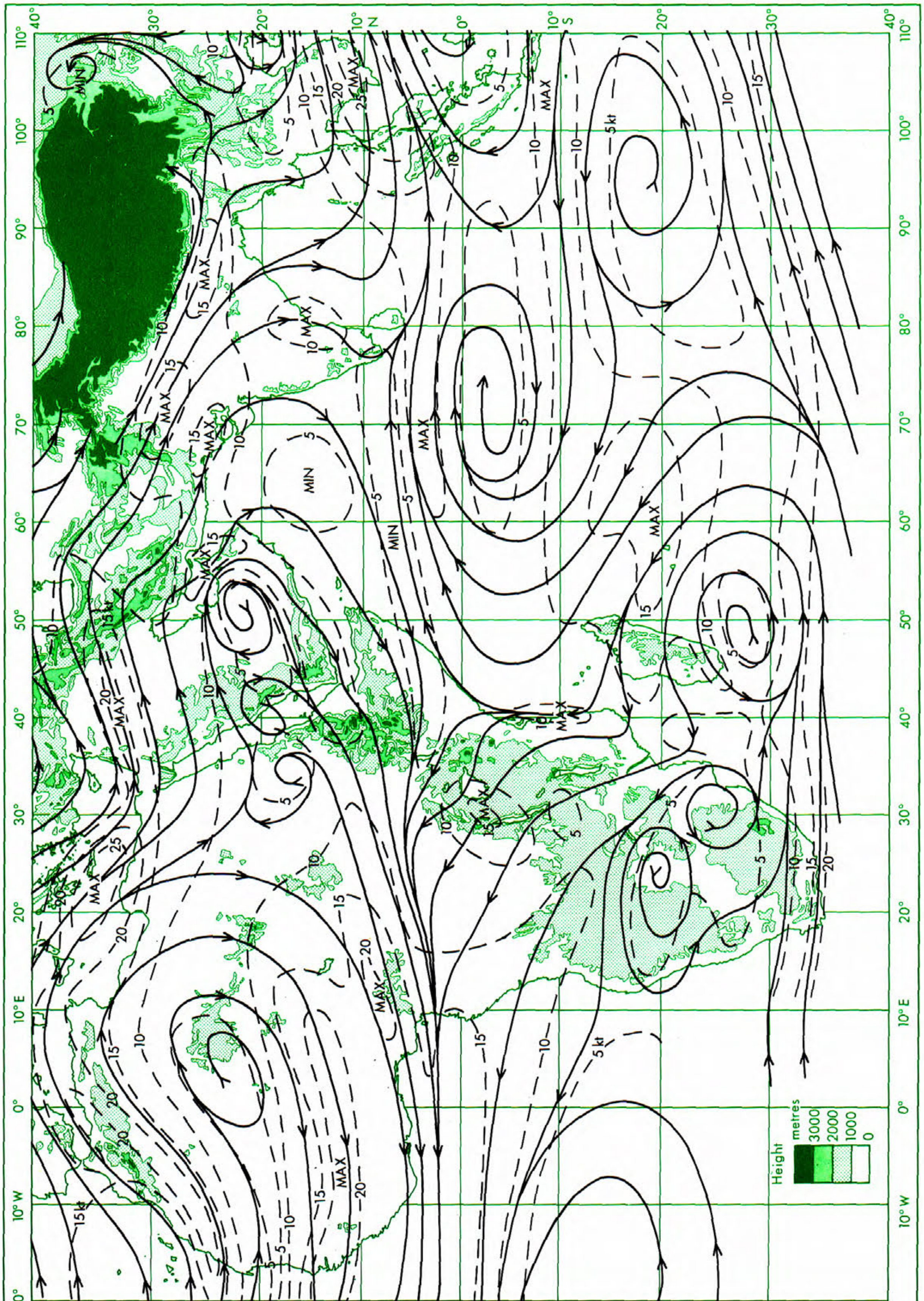

PLATE 18(a). 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 16 (31 MAY-9 JUNE), 1958

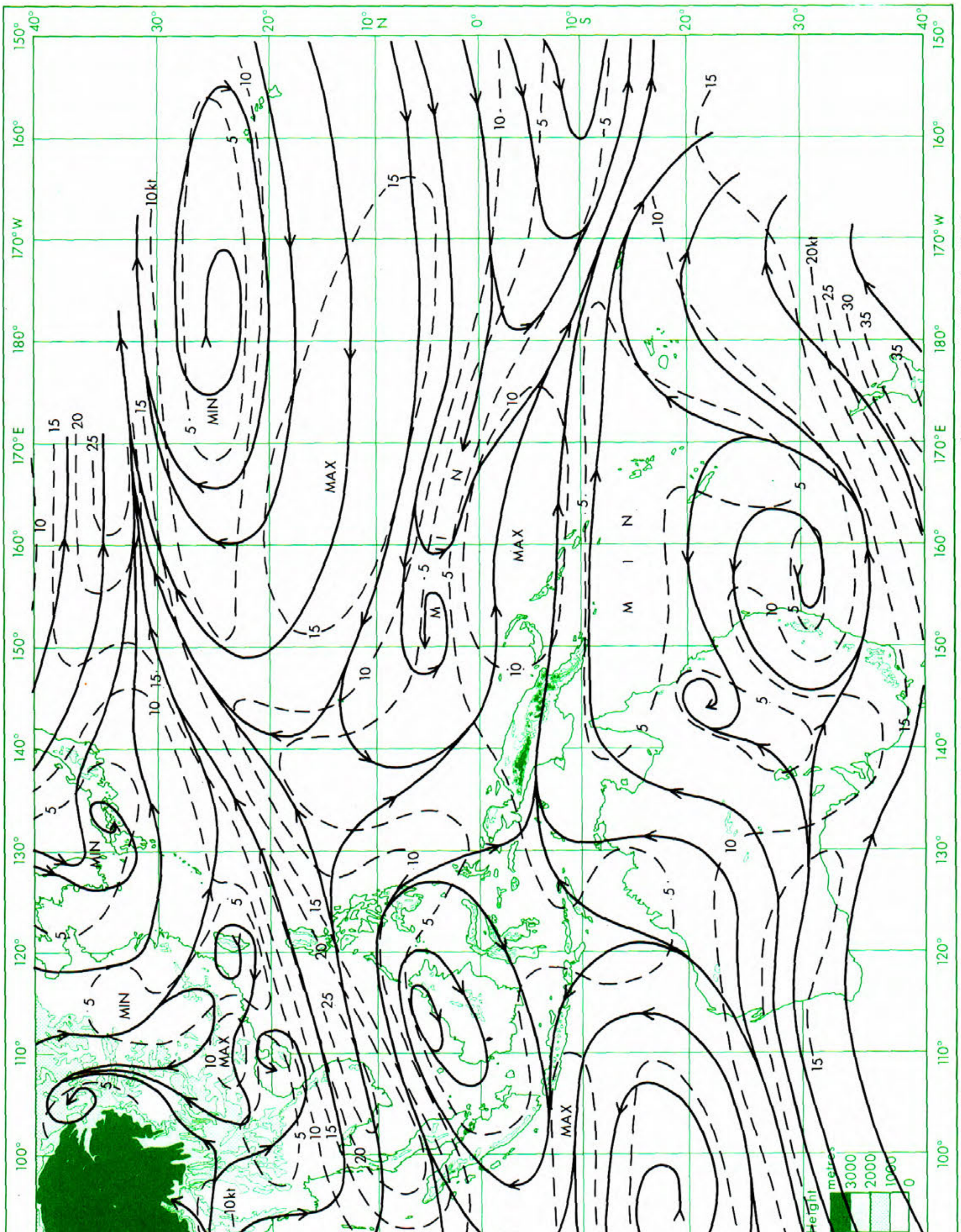

PLATE 18(b). 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 16 (31 MAY-9 JUNE), 1958

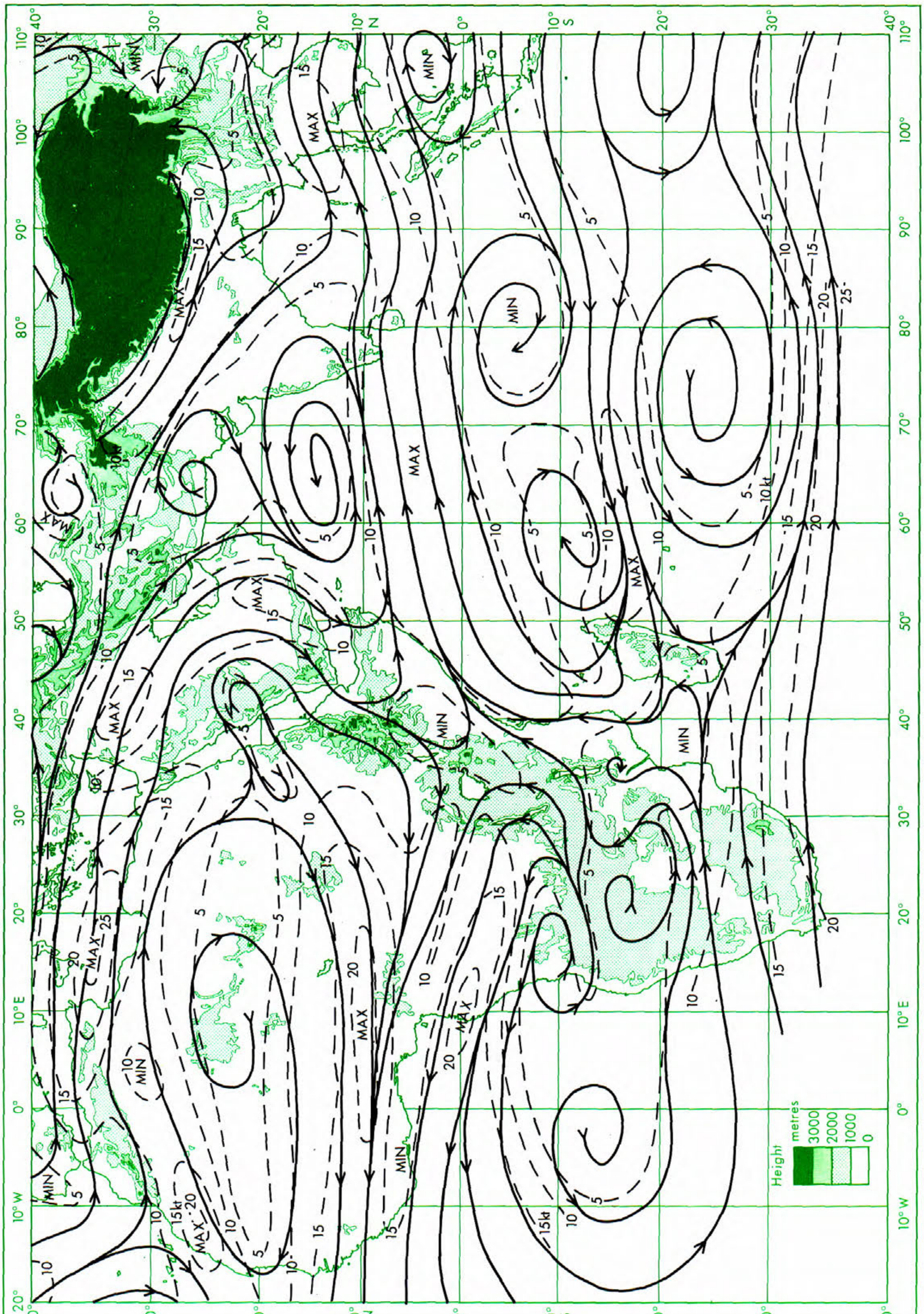

PLATE 19(a). 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 17 (10-19 JUNE), 1958

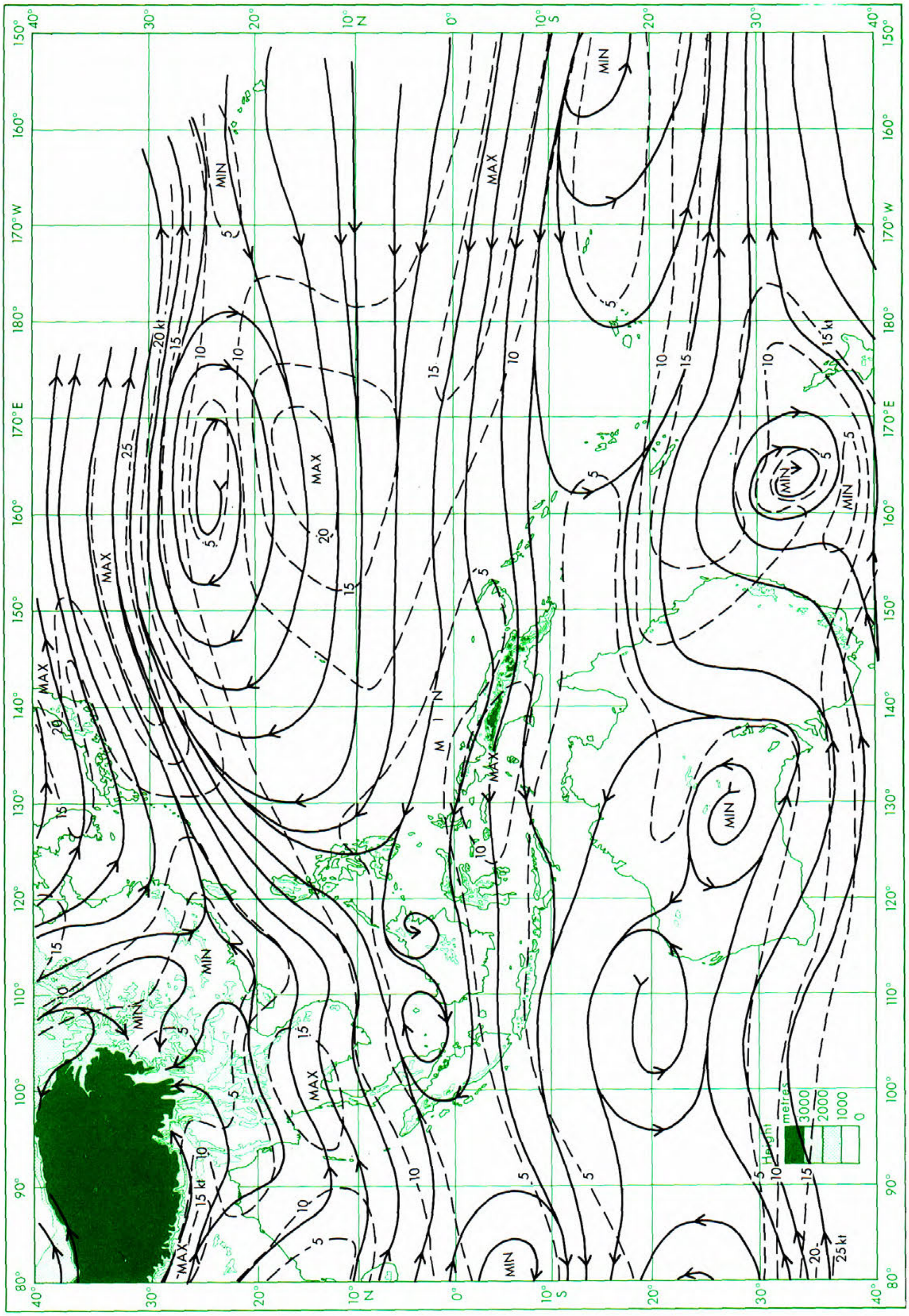

PLATE 19(b). 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 17 (10-19 JUNE), 1958

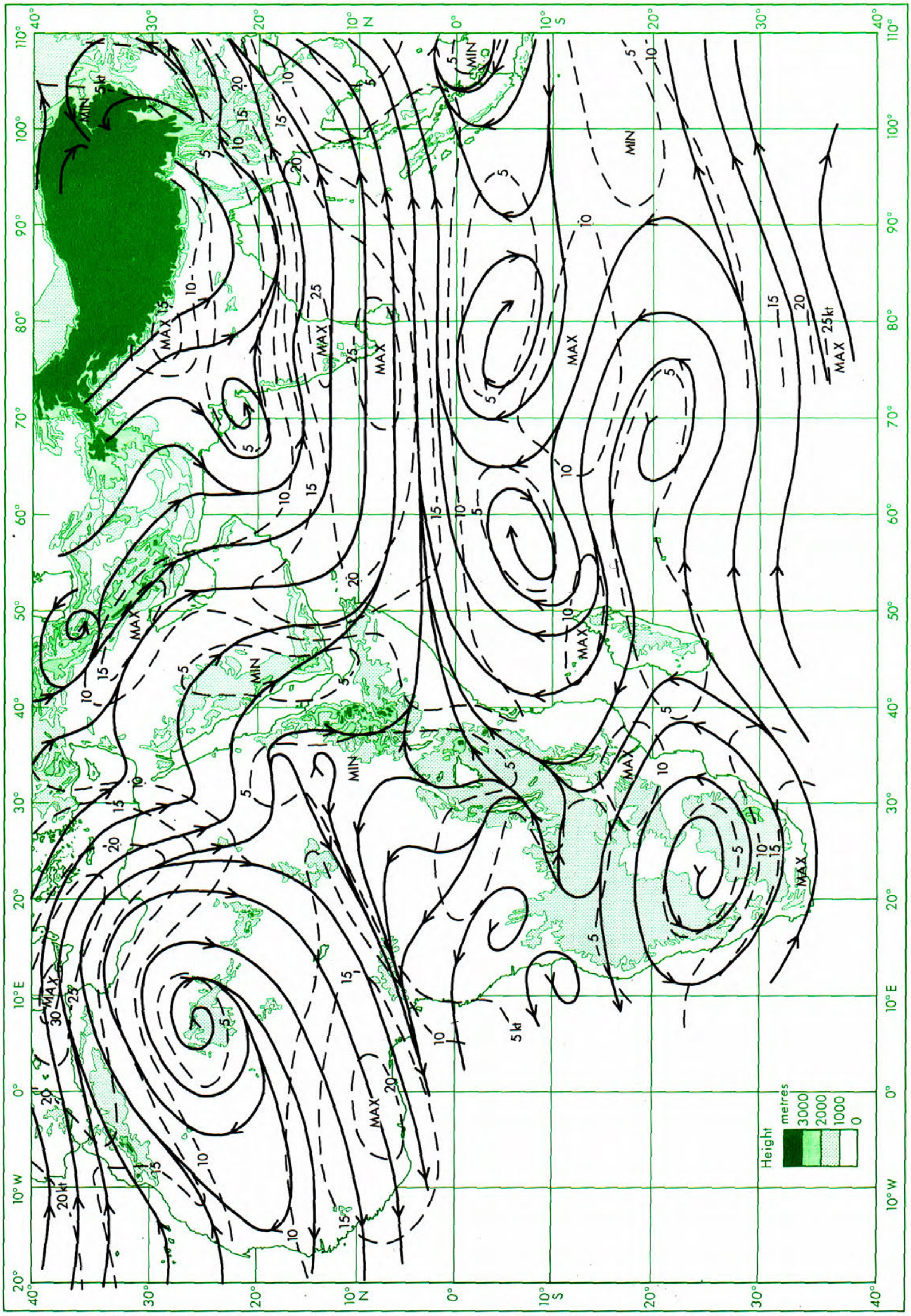

PLATE 20(a). 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 18 (20-29 JUNE), 1958

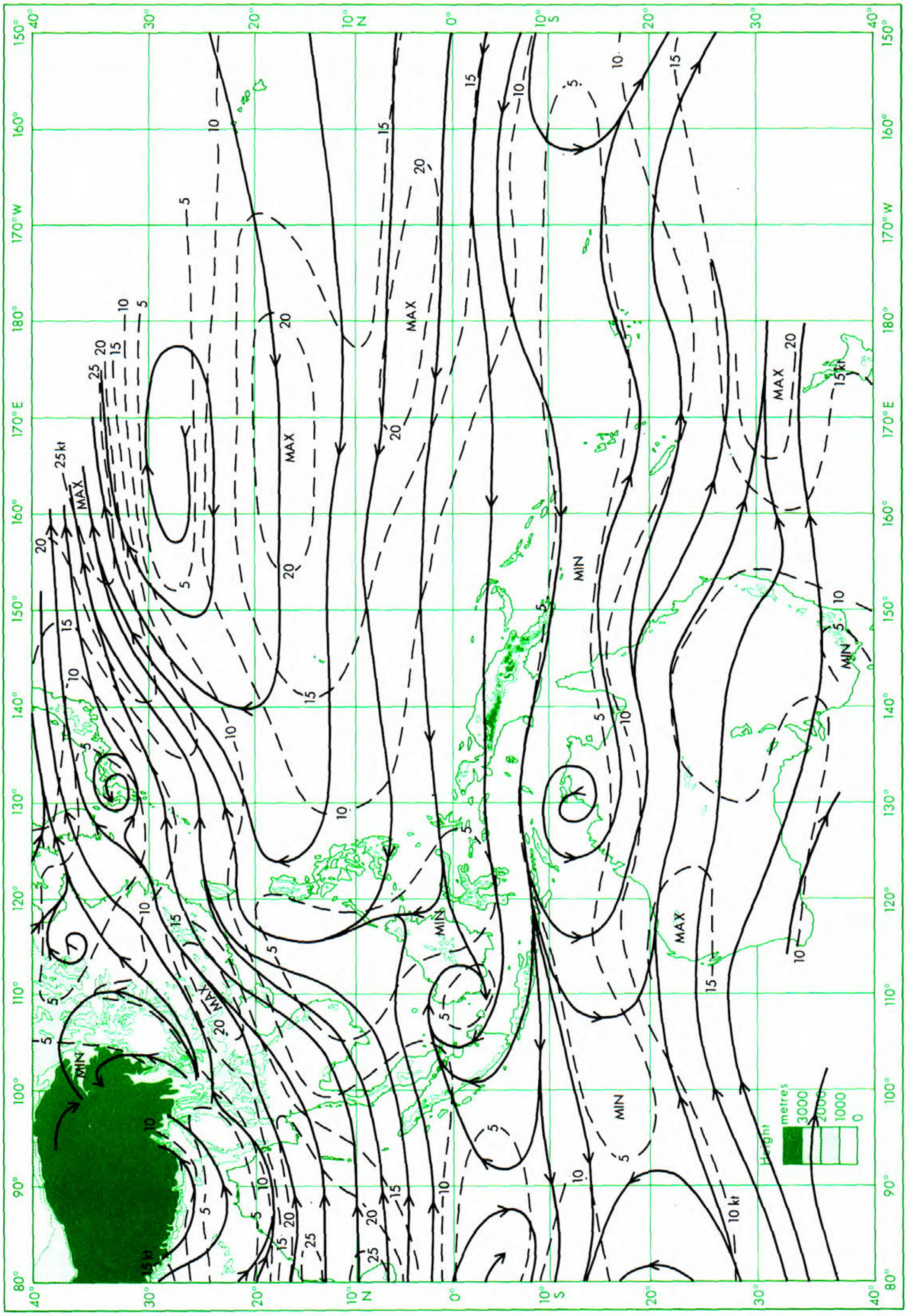

PLATE 20(b). 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 18 (20-29 JUNE), 1958

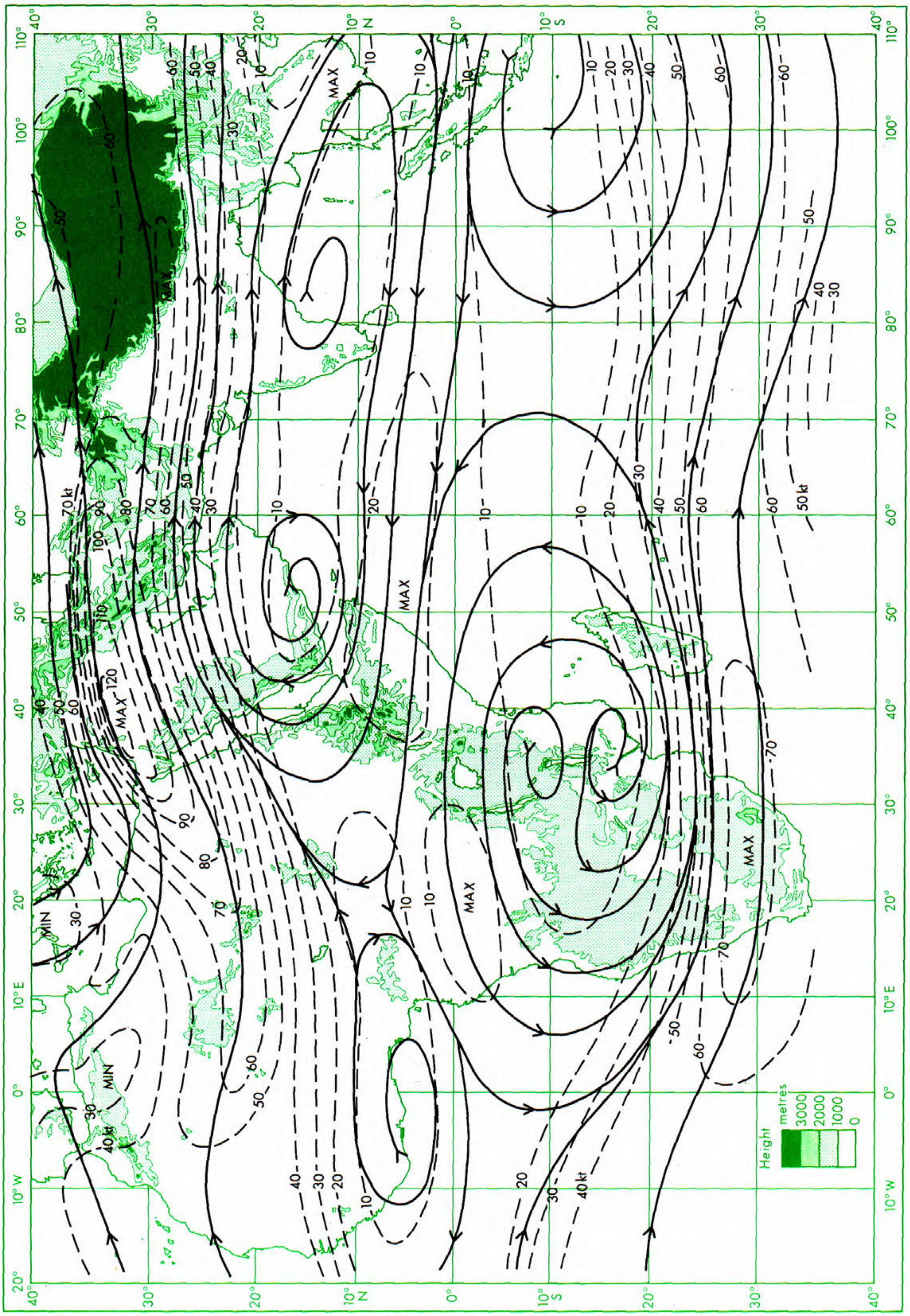

PLATE 21(a). 200-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 13 (1-10 MAY), 1958

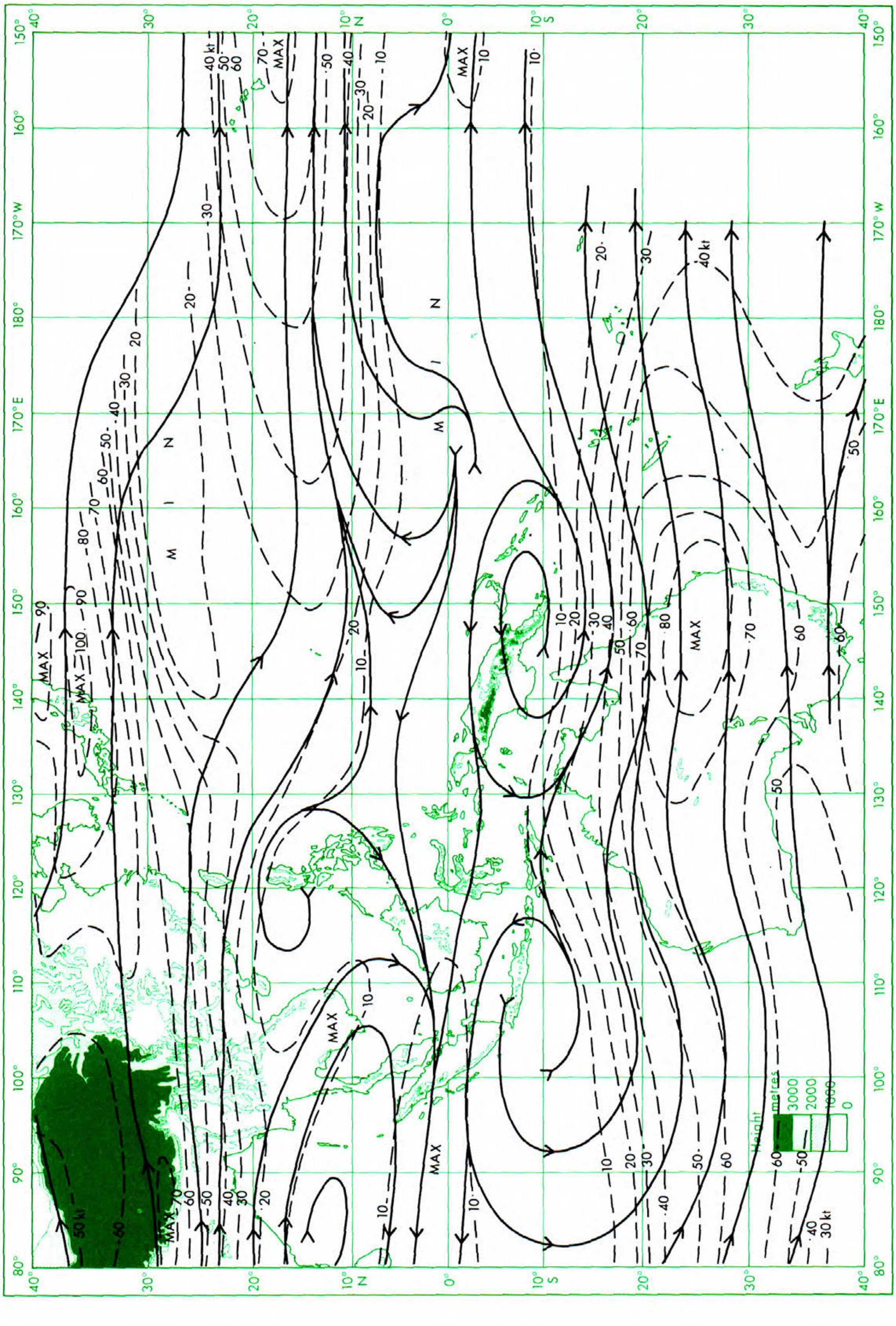

PLATE 21(b). 200-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 13 (1-10 MAY), 1958

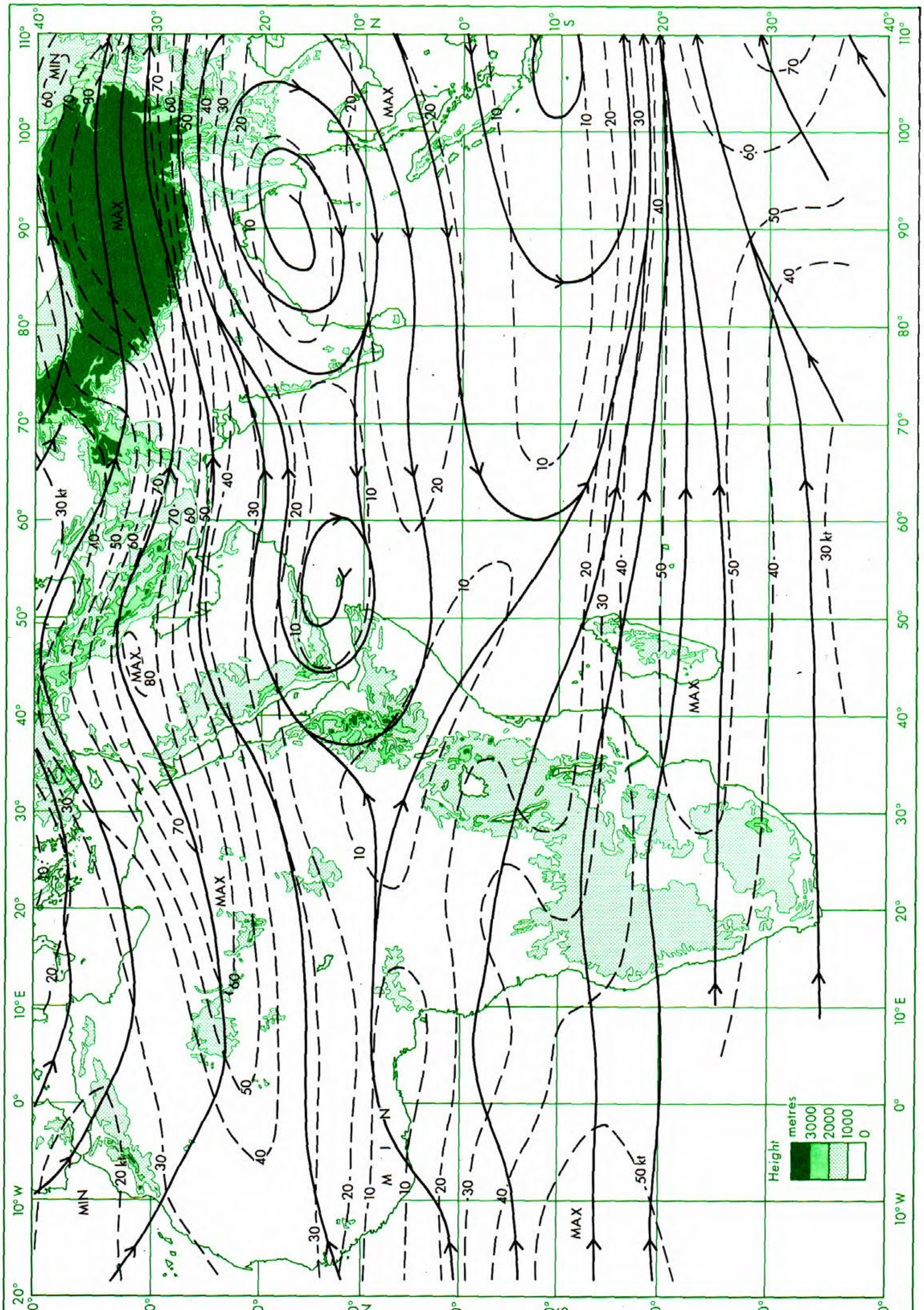

PLATE 22(a). 200-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 14 (11-20 MAY), 1958

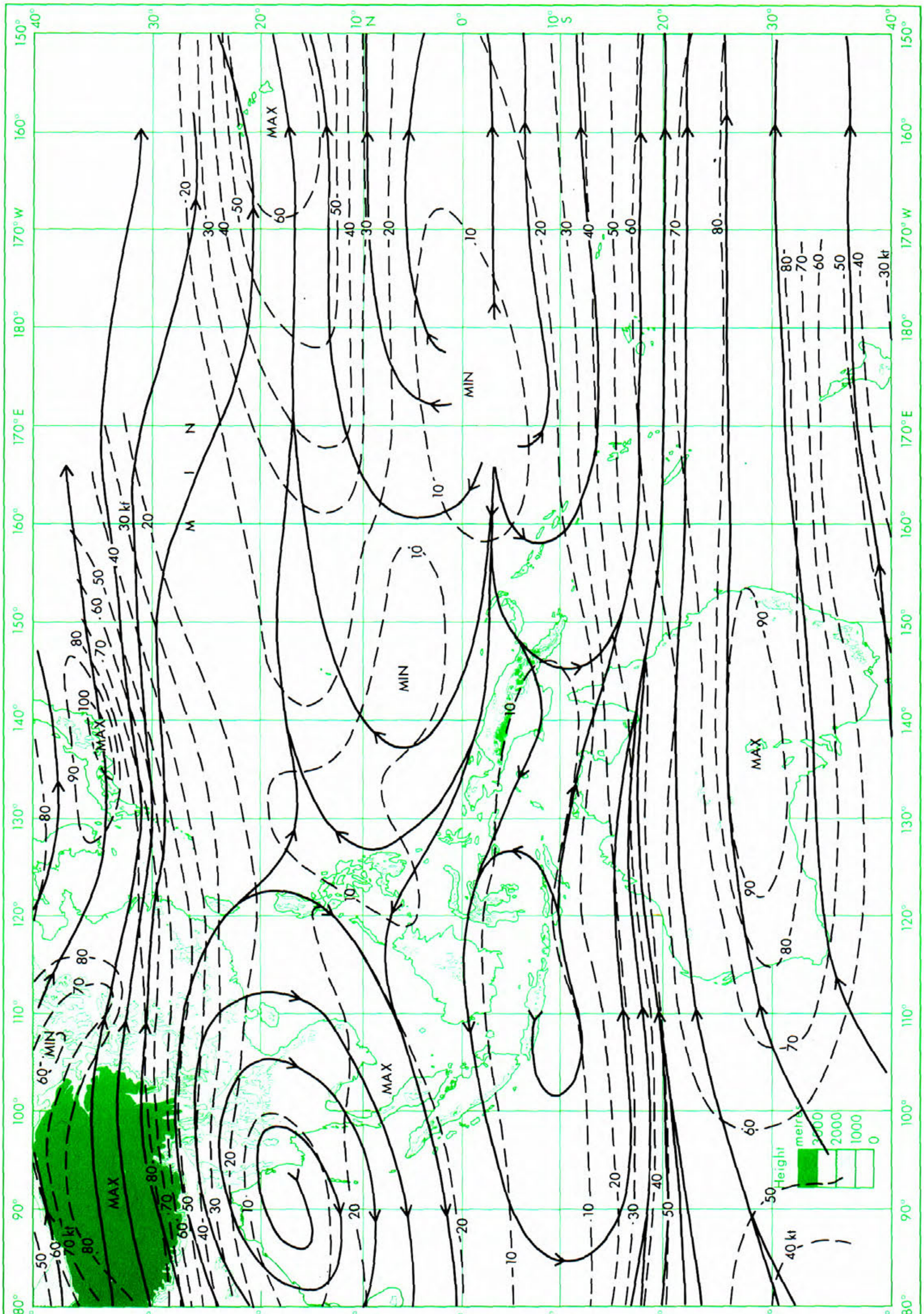

PLATE 22(b). 200-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 14 (11-20 MAY), 1958

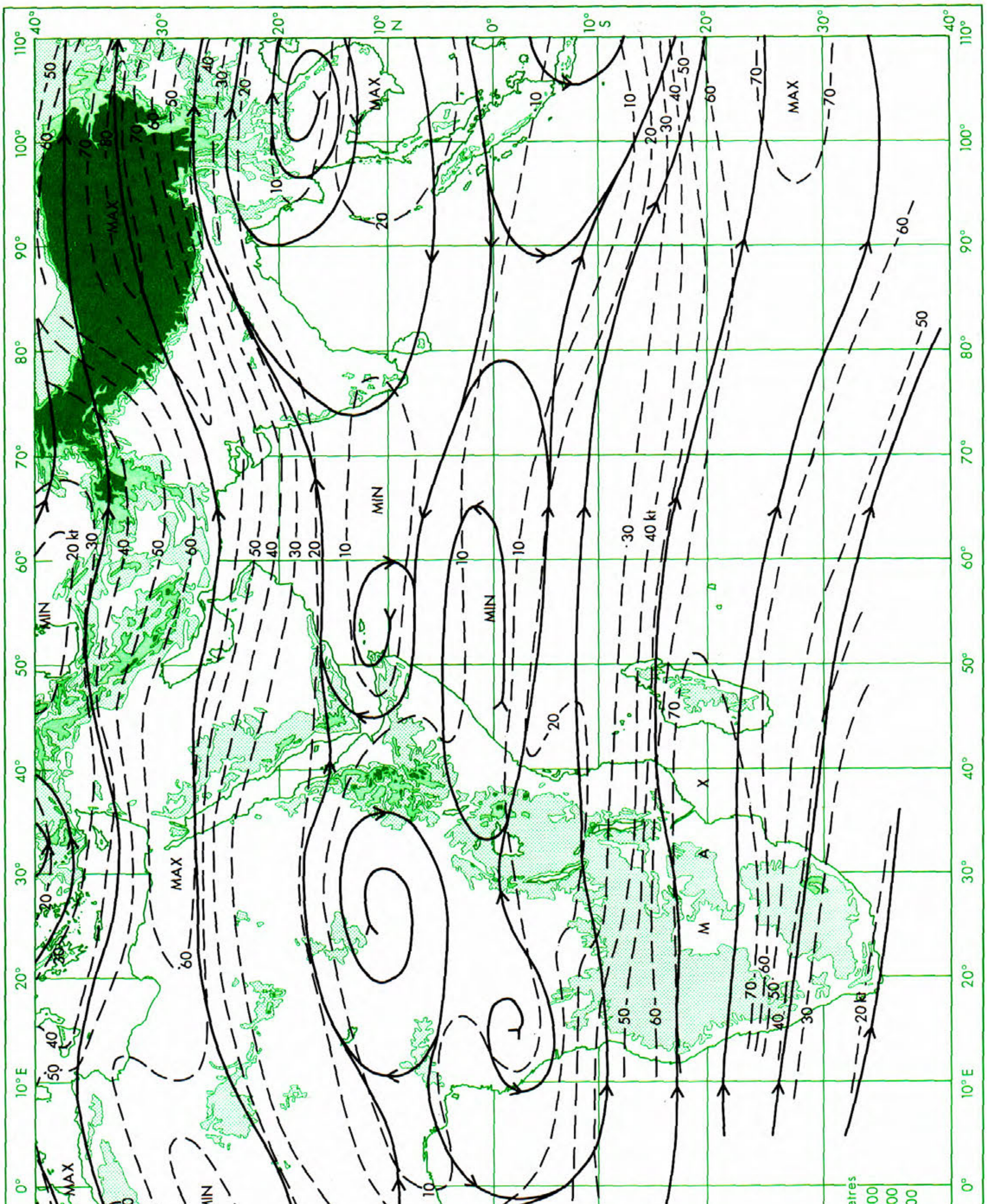

PLATE 23(a). 200-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 15 (21-30 MAY), 1958

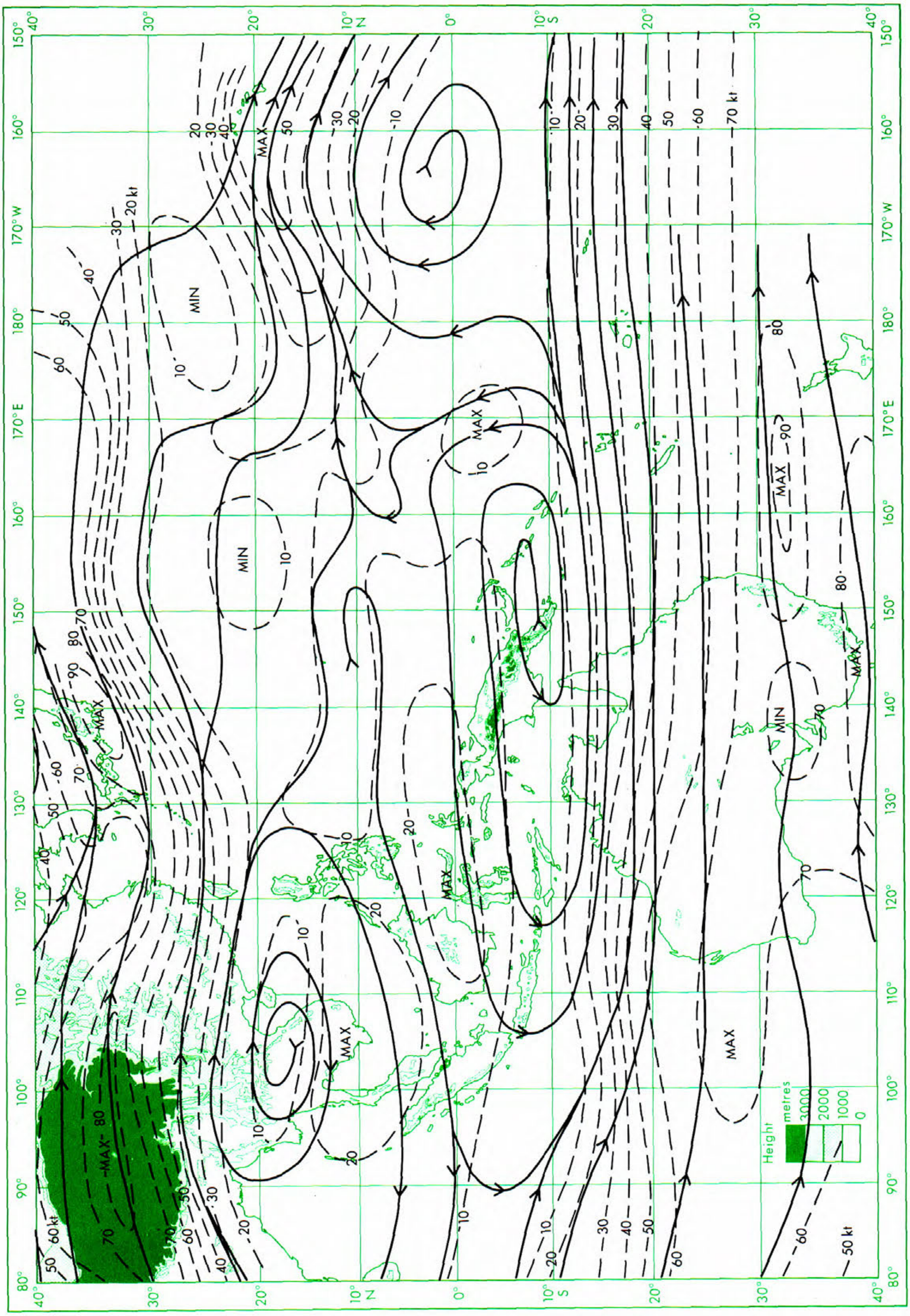

PLATE 23(b). 200-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 15 (21-30 MAY), 1958

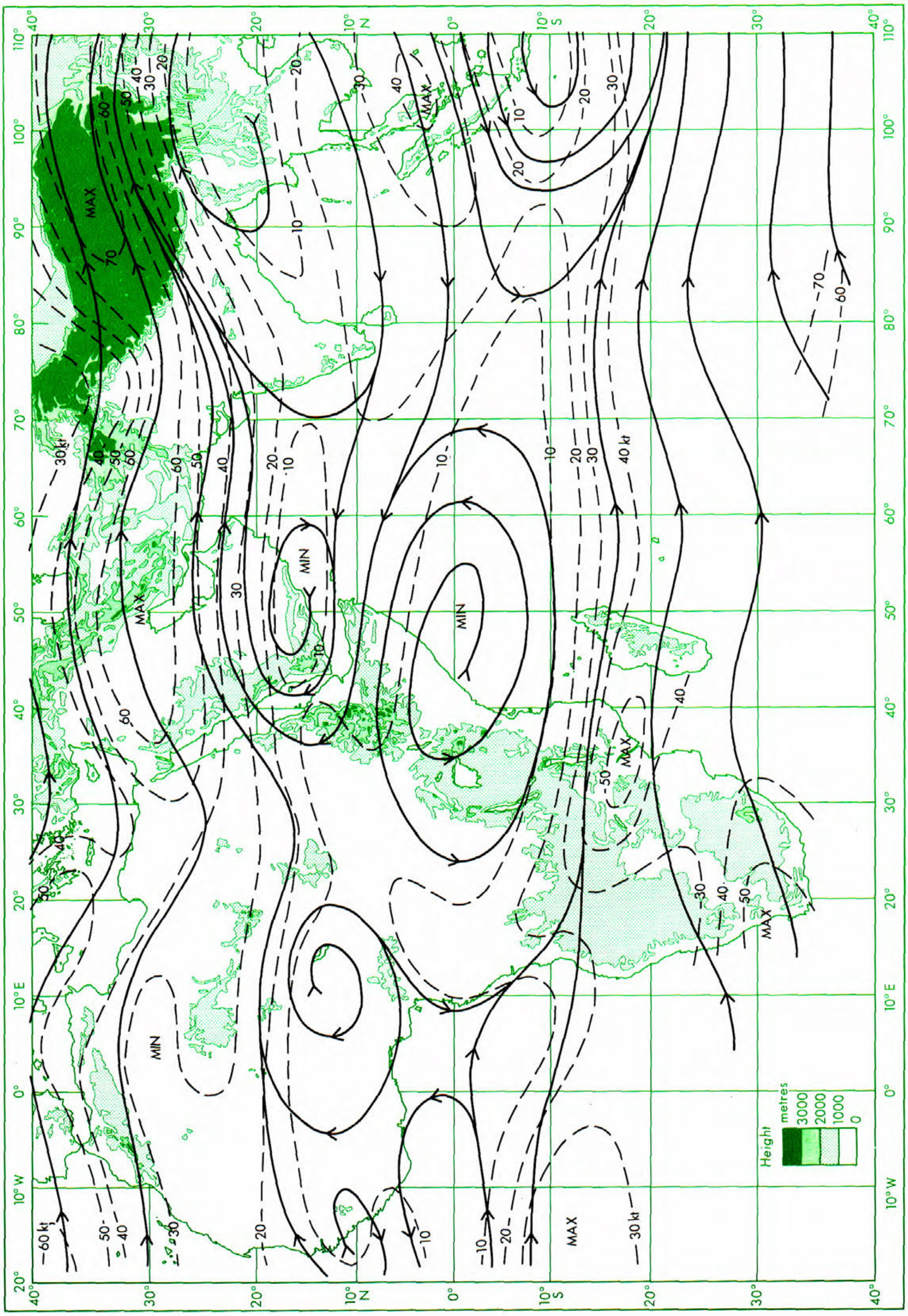

PLATE 24(a). 200-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 16 (31 MAY-9 JUNE), 1958

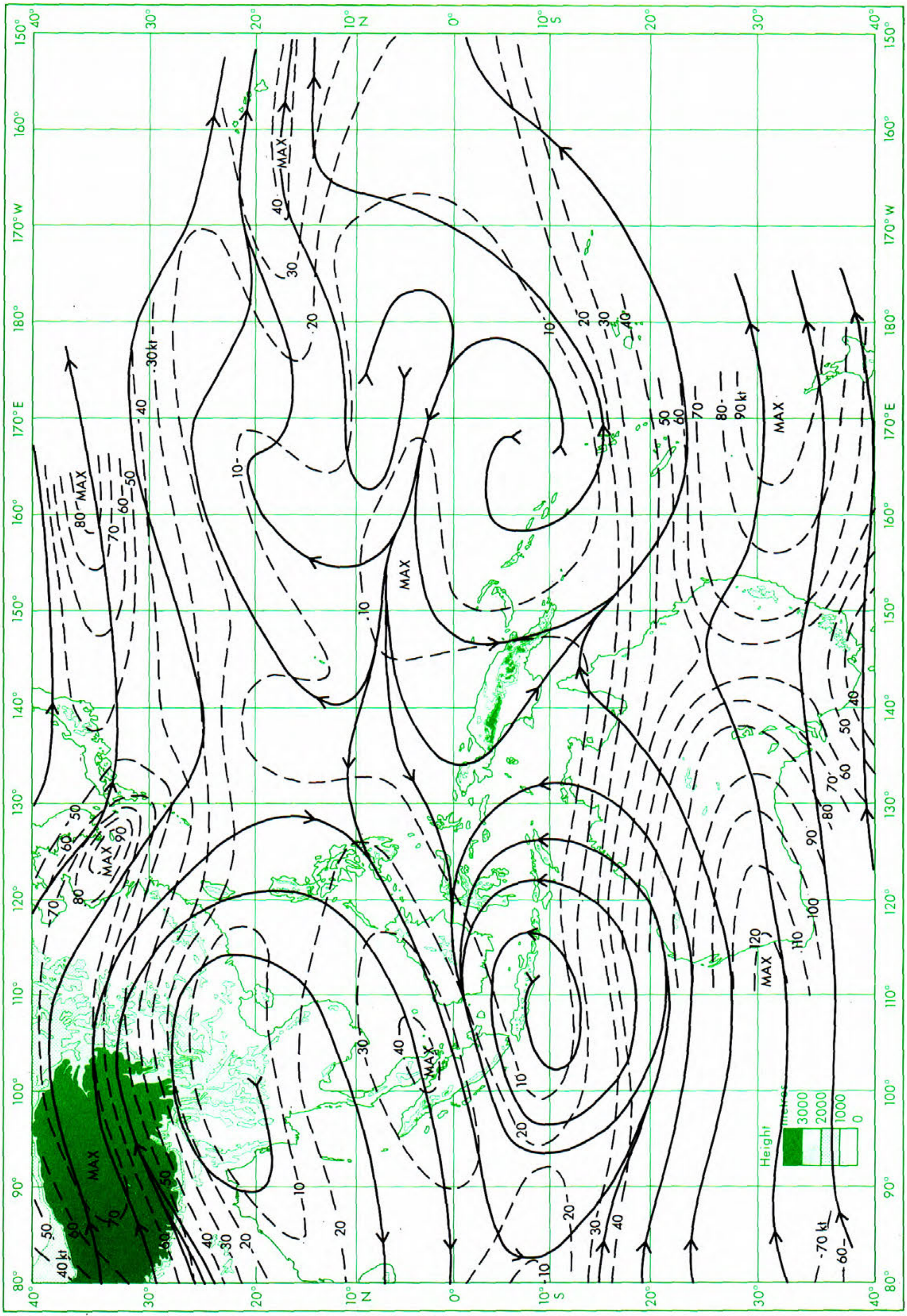

PLATE 24(b). 200-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 16 (31 MAY-9 JUNE), 1958

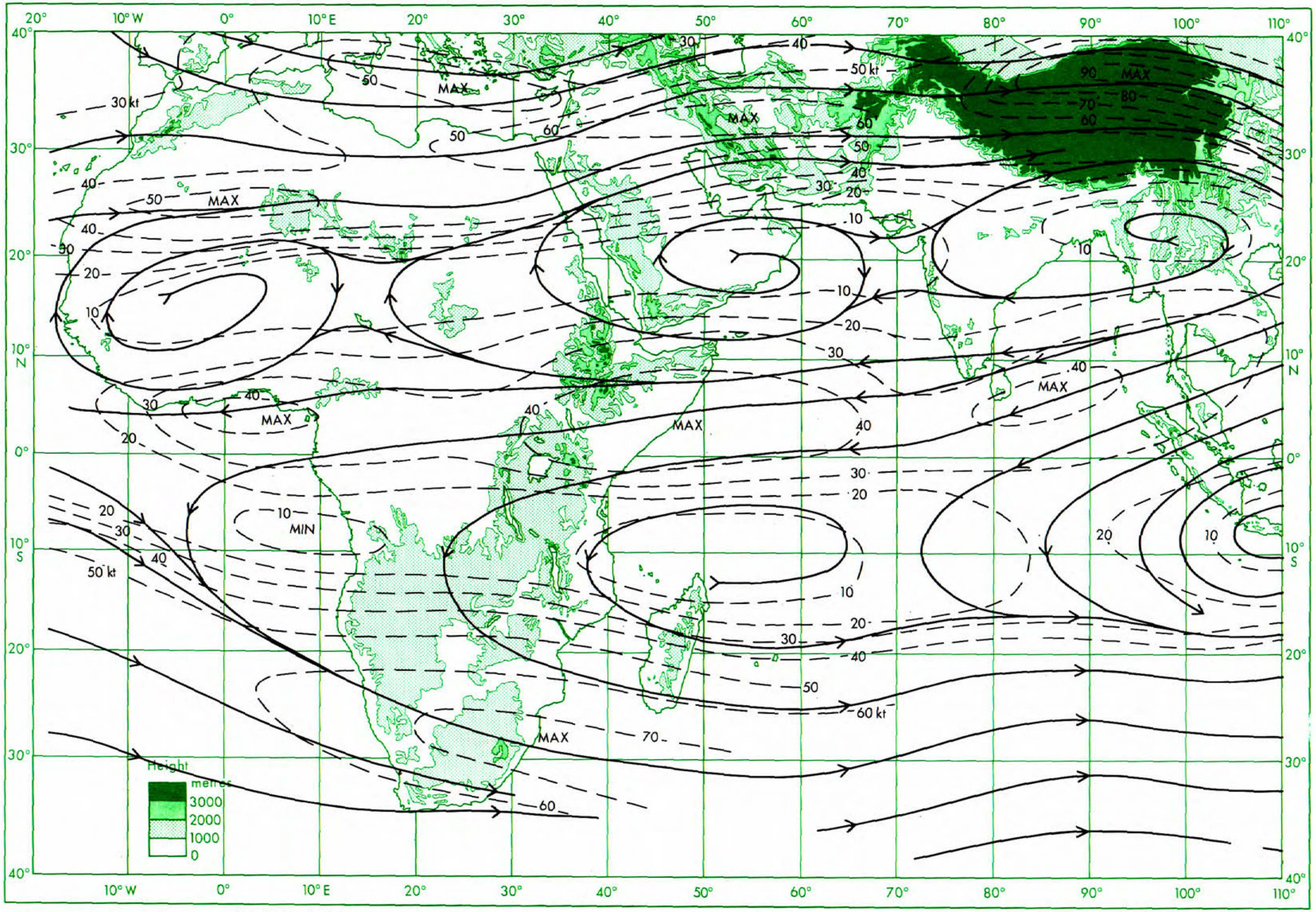

PLATE 25(a). 200-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 17 (10-19 JUNE), 1958

In order to avoid overcrowding of streamlines on some areas of the chart, several streamlines have been left open-ended on this figure.

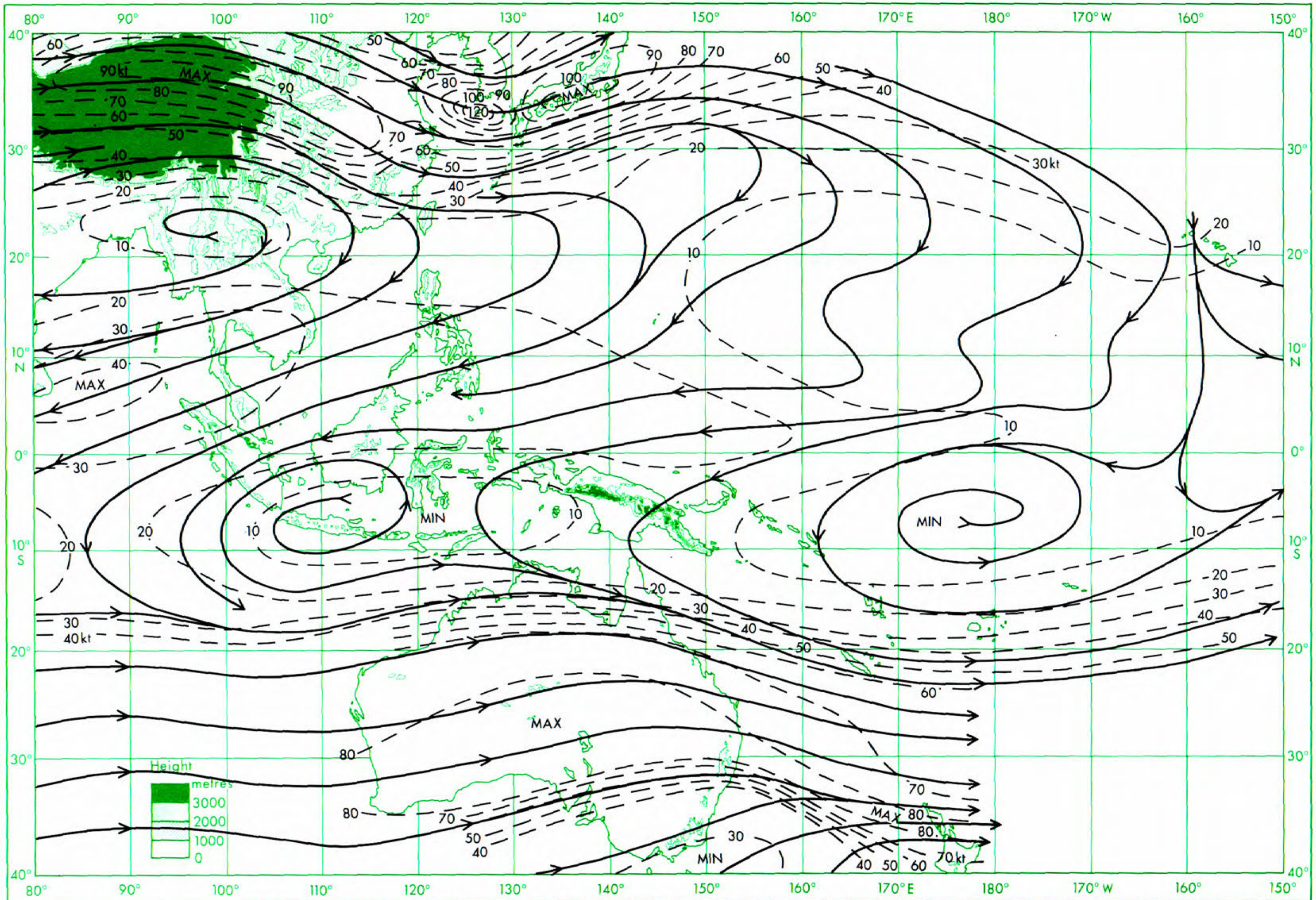

PLATE 25(b). 200-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 17 (10-19 JUNE), 1958

In order to avoid overcrowding of streamlines on some areas of the chart, several streamlines have been left open-ended on this figure.

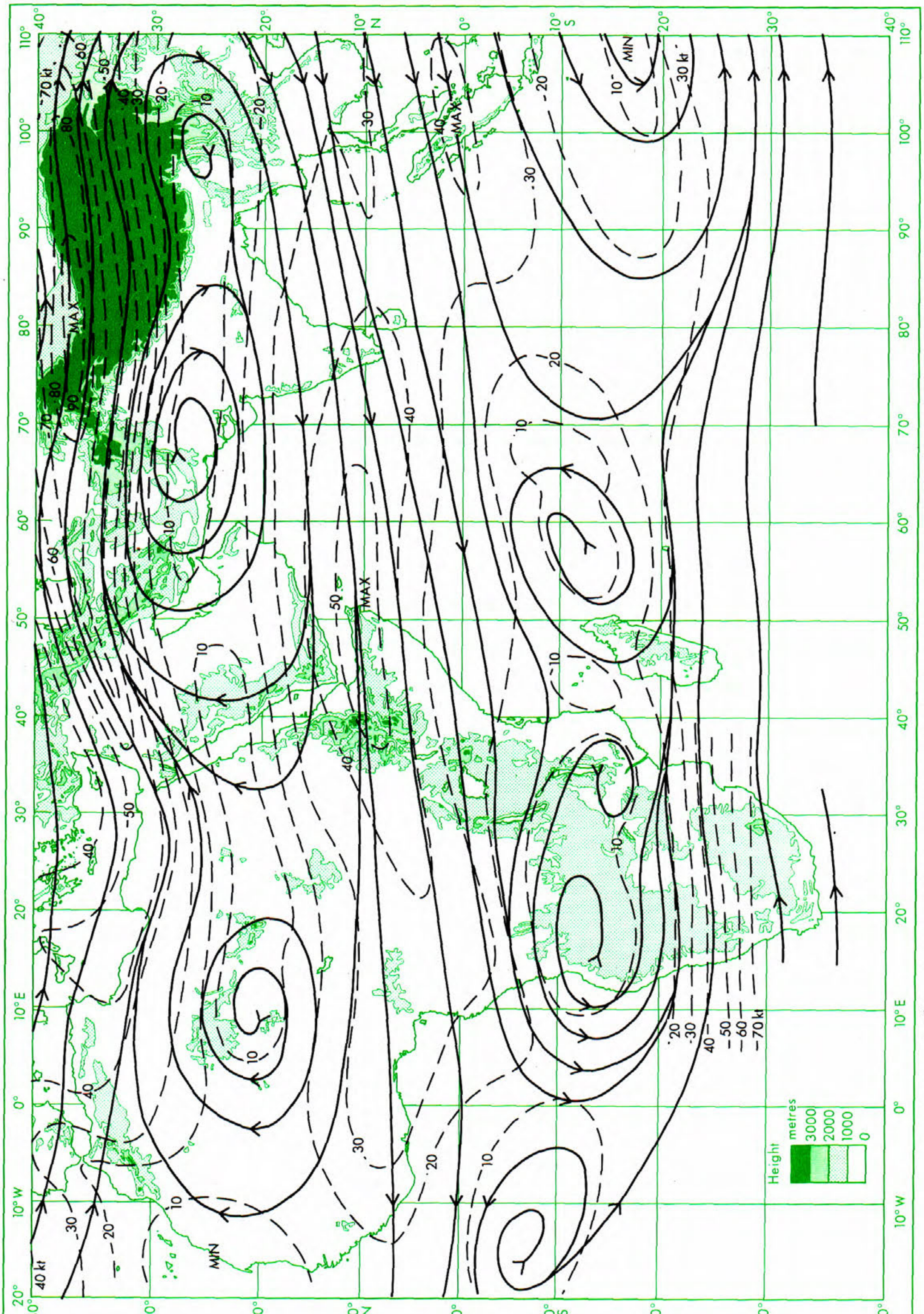

PLATE 26 (a). 200-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 18 (20-29 JUNE), 1958

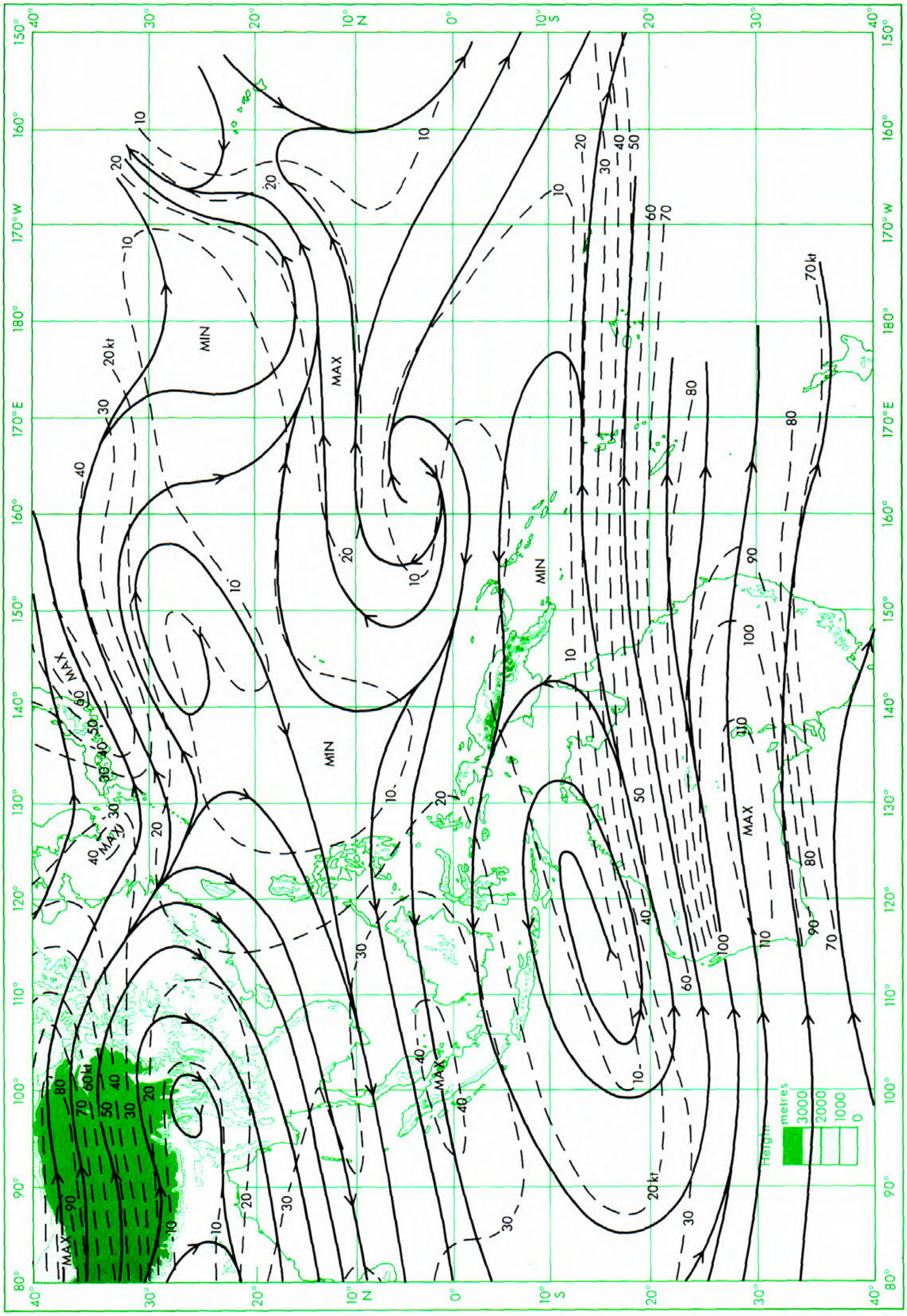

PLATE 26(b). 200-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 18 (20-29 JUNE), 1958

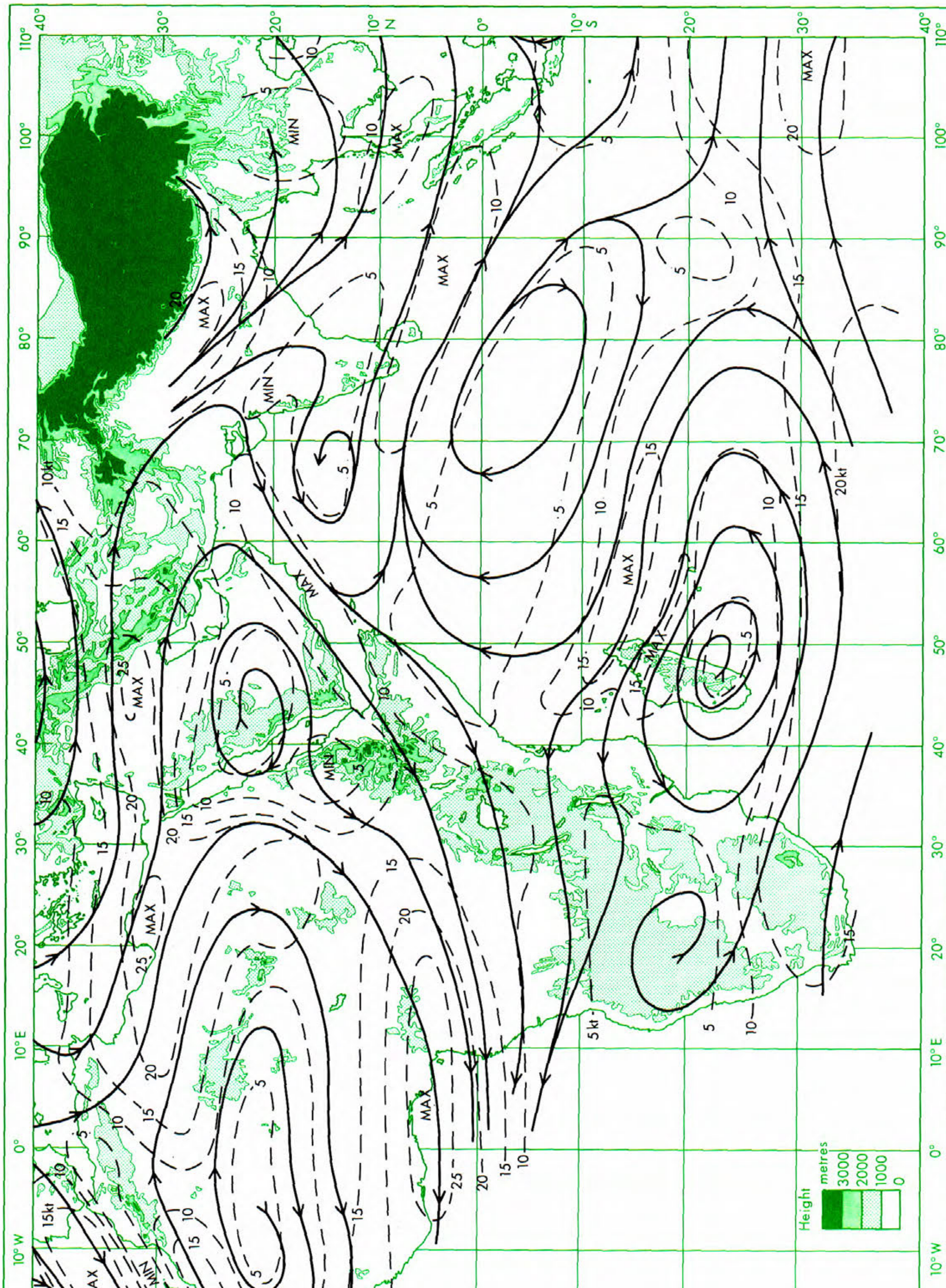

PLATE 27(a). 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 13 (1-10 MAY), 1956

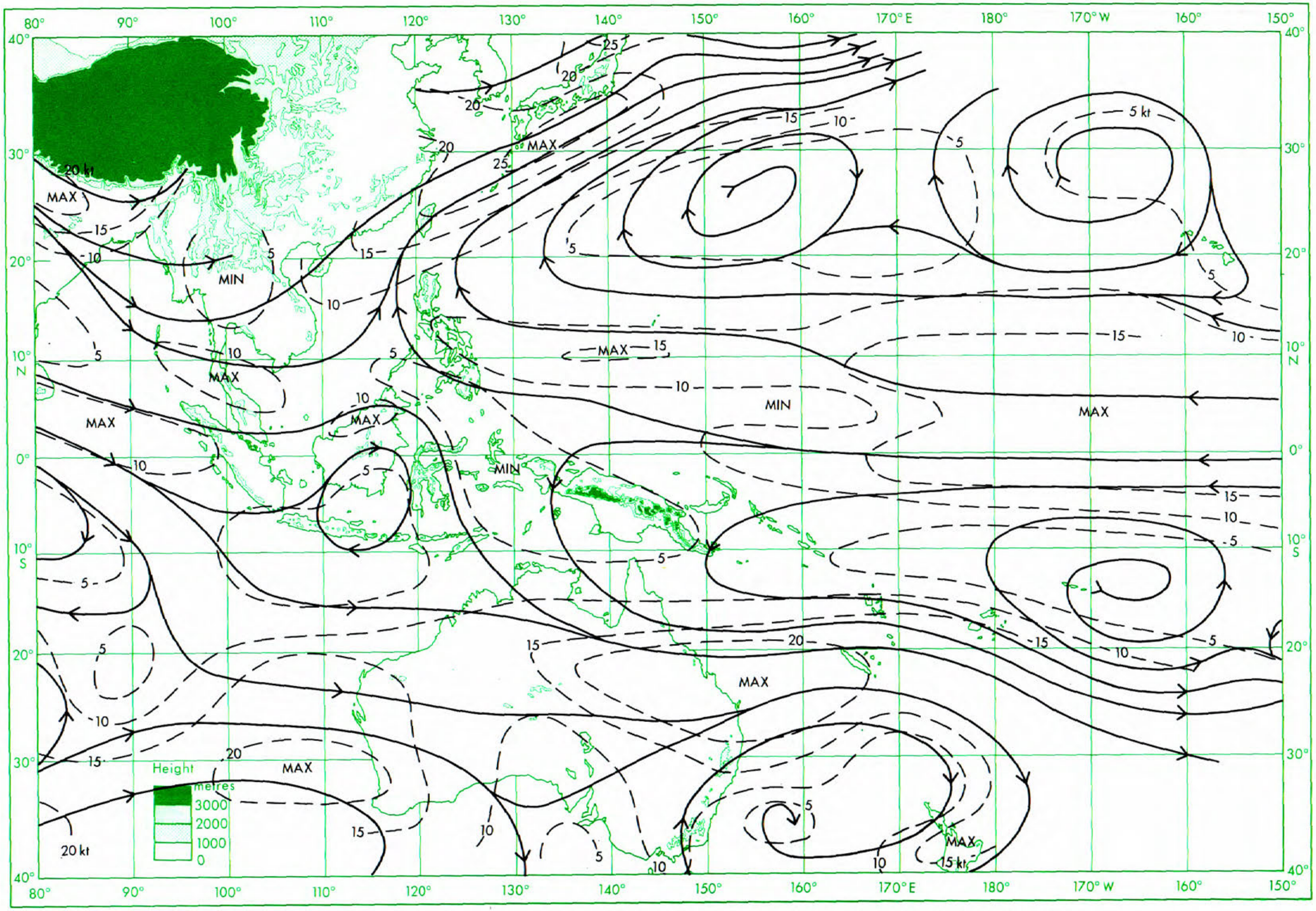

PLATE 27 (b). 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 13 (1-10 MAY), 1956

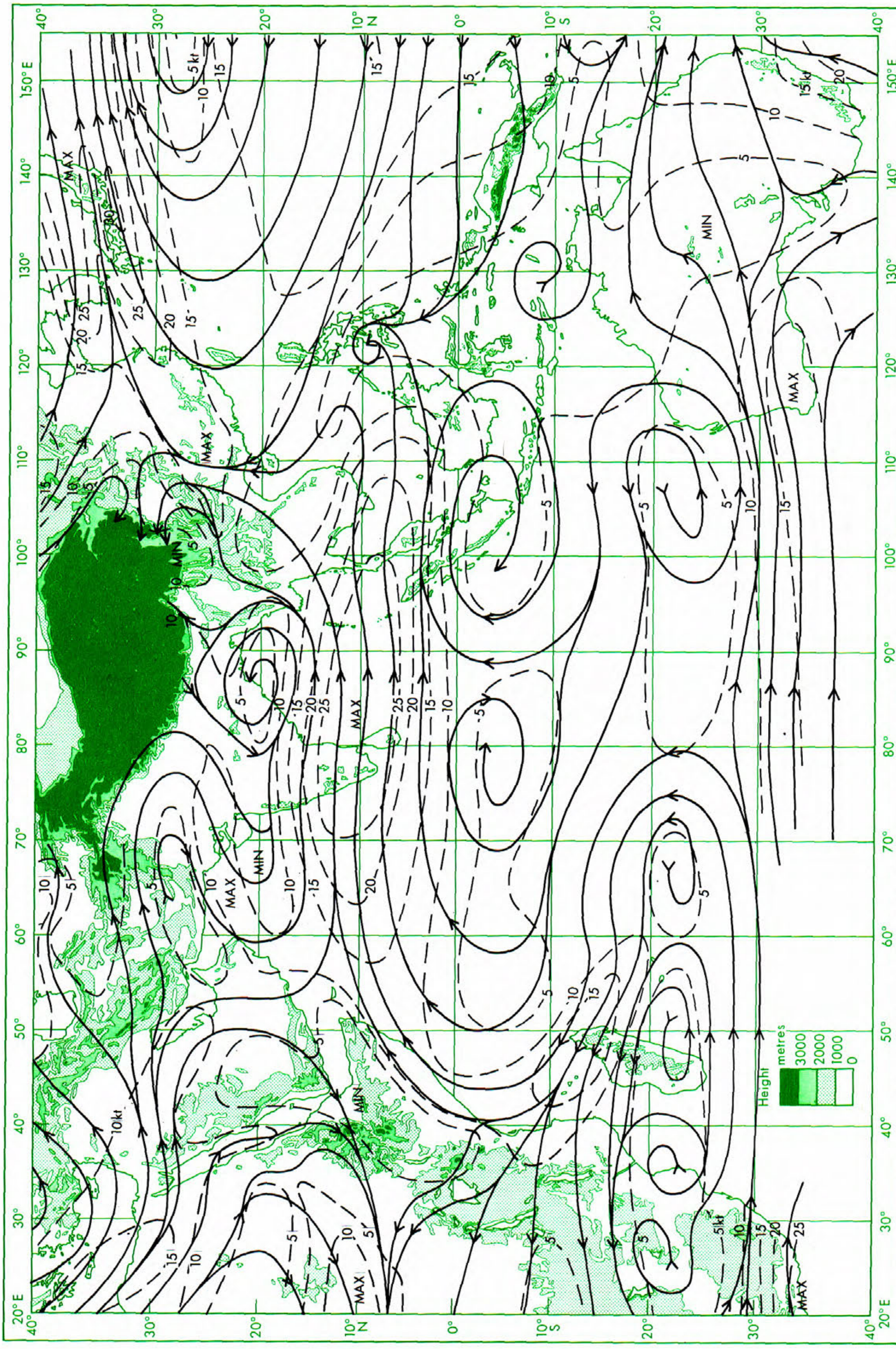

PLATE 28. 700-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 18 (20-29 JUNE), 1960

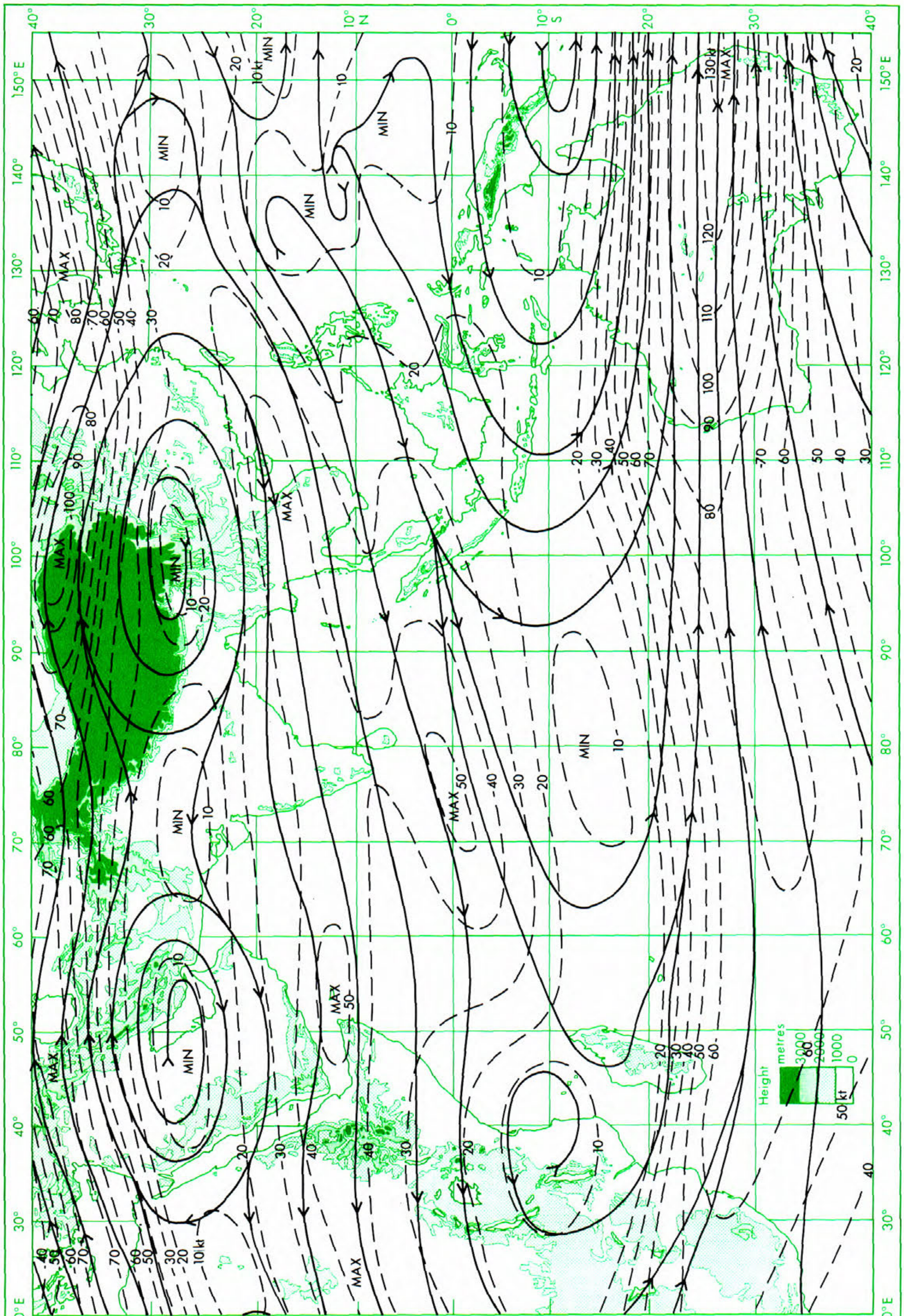

PLATE 29. 200-MILLIBAR STREAMLINES AND ISOTACHS FOR DECAD 18 (20-29 JUNE), 1960

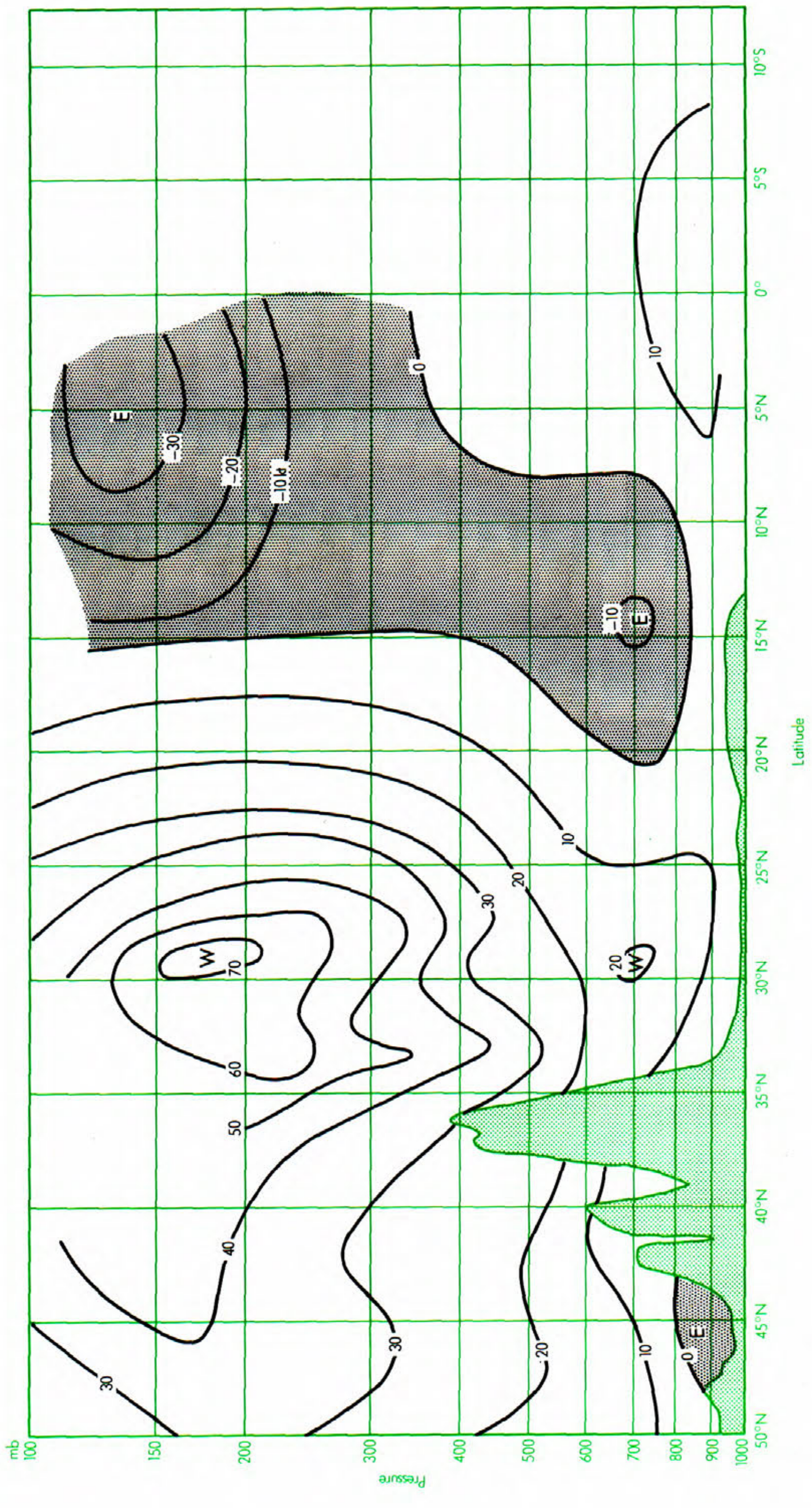

PLATE 30. DECAD MEAN VERTICAL CROSS-SECTION ALONG 75°E, FROM 50°N TO 5°S, FOR *D*13 (1-10 MAY), 1958

Black stippling is used to emphasize easterly wind components.

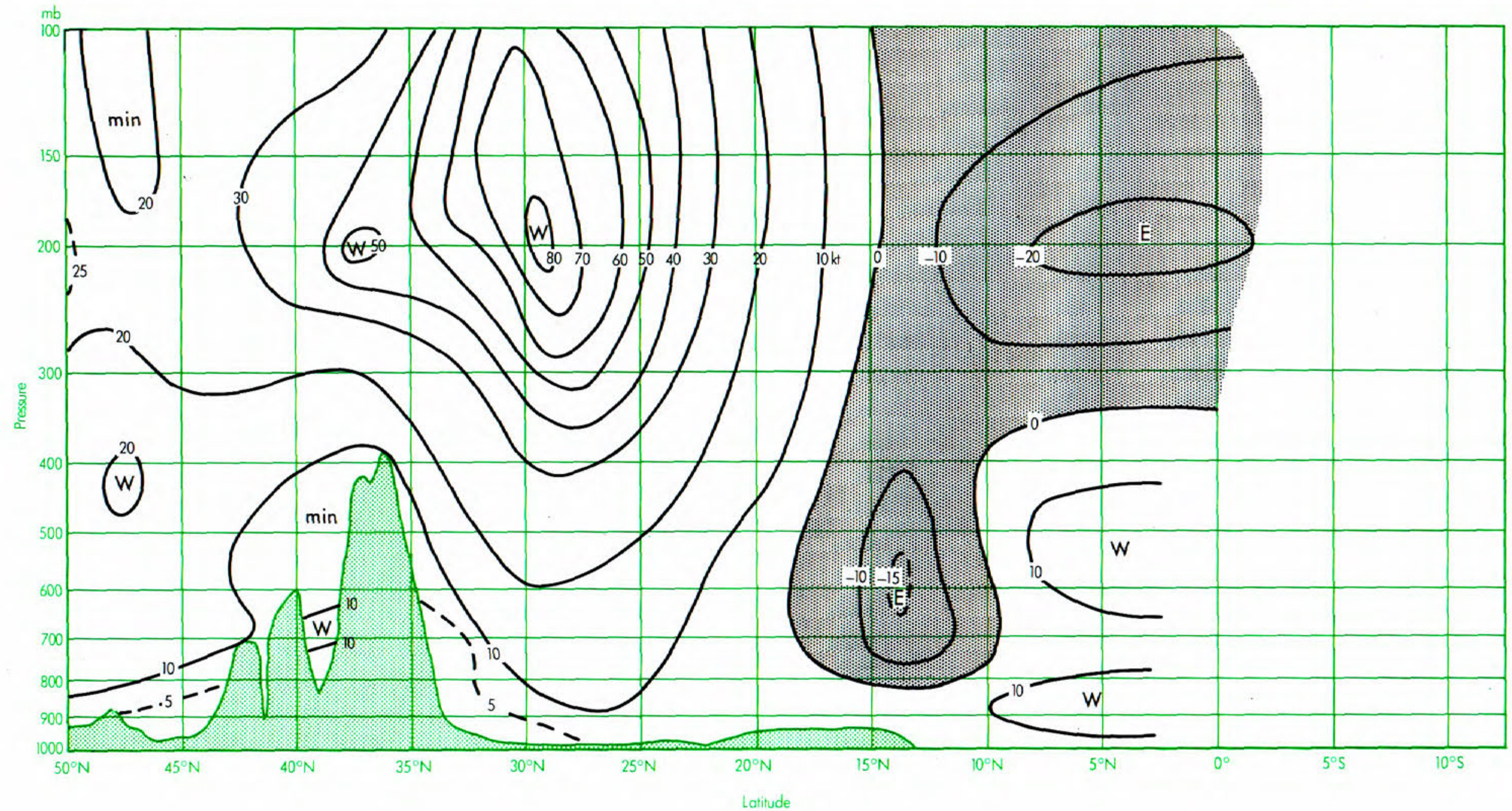

PLATE 31. DECAD MEAN VERTICAL CROSS-SECTION ALONG 75°E, FROM 50°N TO 5°S, FOR *D*14 (11-20 MAY), 1958
Black stippling is used to emphasize easterly wind components.

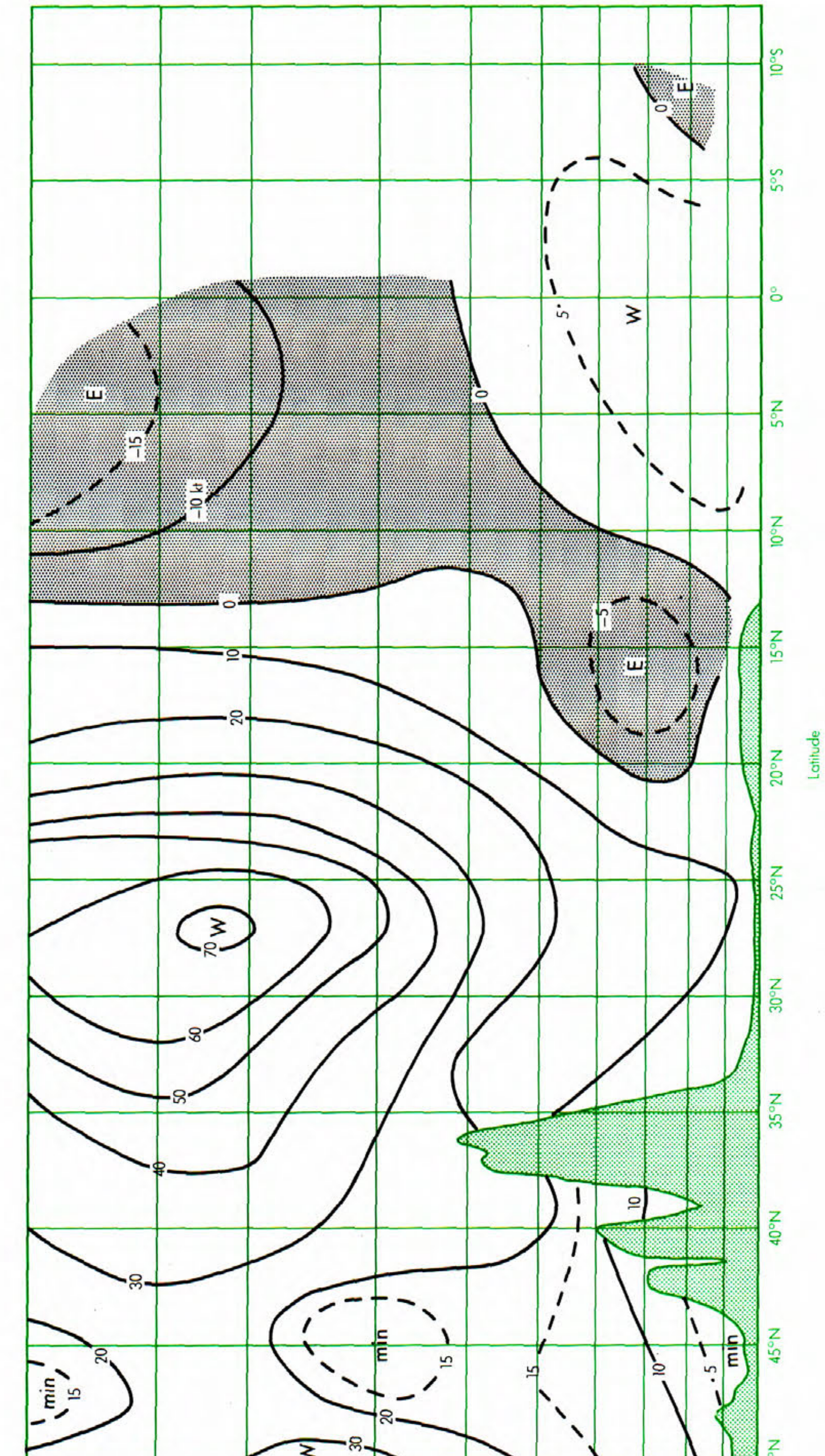

PLATE 32. DECAD MEAN VERTICAL CROSS-SECTION ALONG 75°E, FROM 50°N TO 5°S, FOR *D15* (21-30 MAY), 1958

Black stippling is used to emphasize easterly wind components.

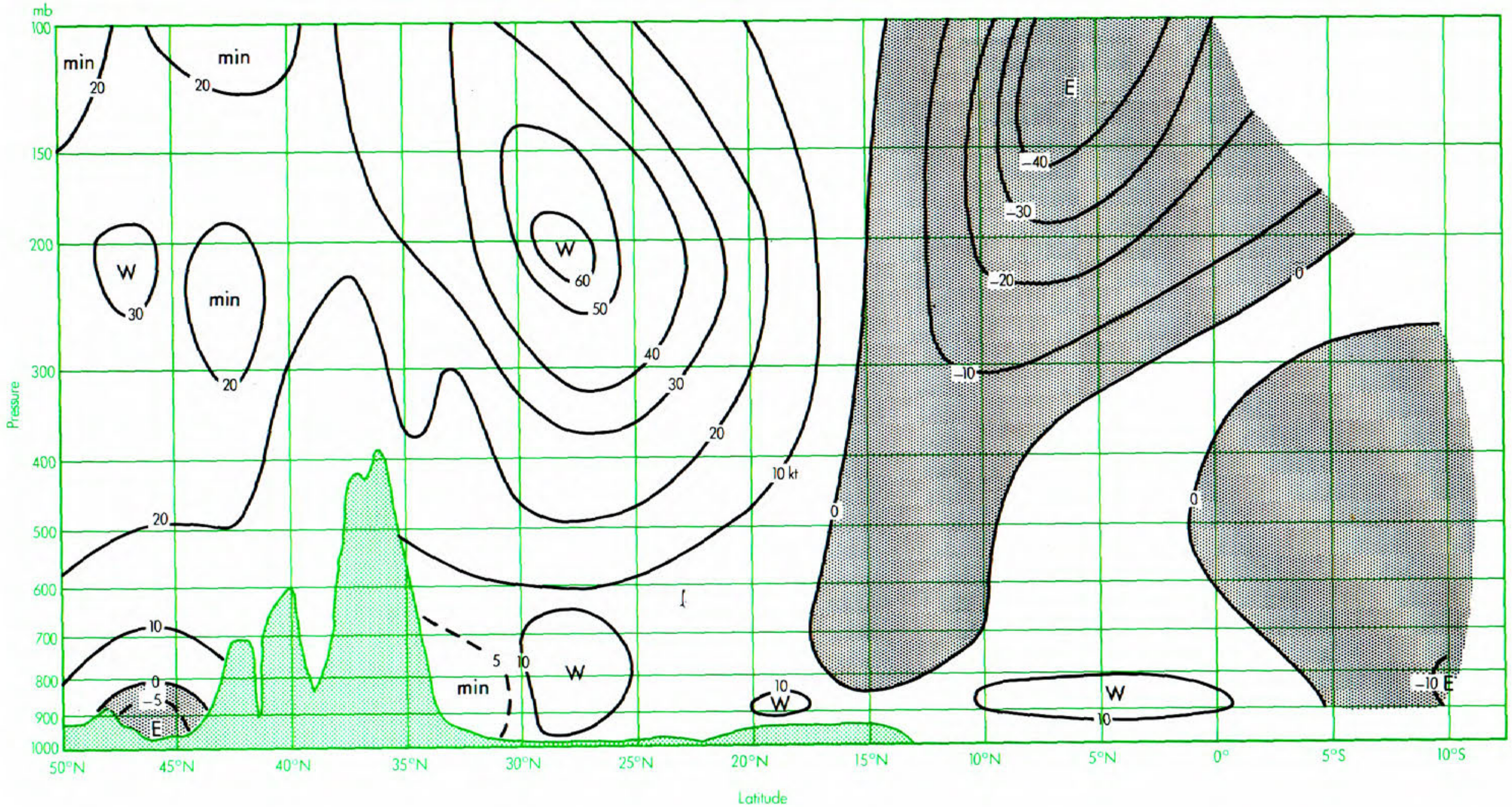

PLATE 33. DECAD MEAN VERTICAL CROSS-SECTION ALONG 75°E, FROM 50°N TO 5°S, FOR *D16* (31 MAY-9 JUNE), 1958
Black stippling is used to emphasize easterly wind components.

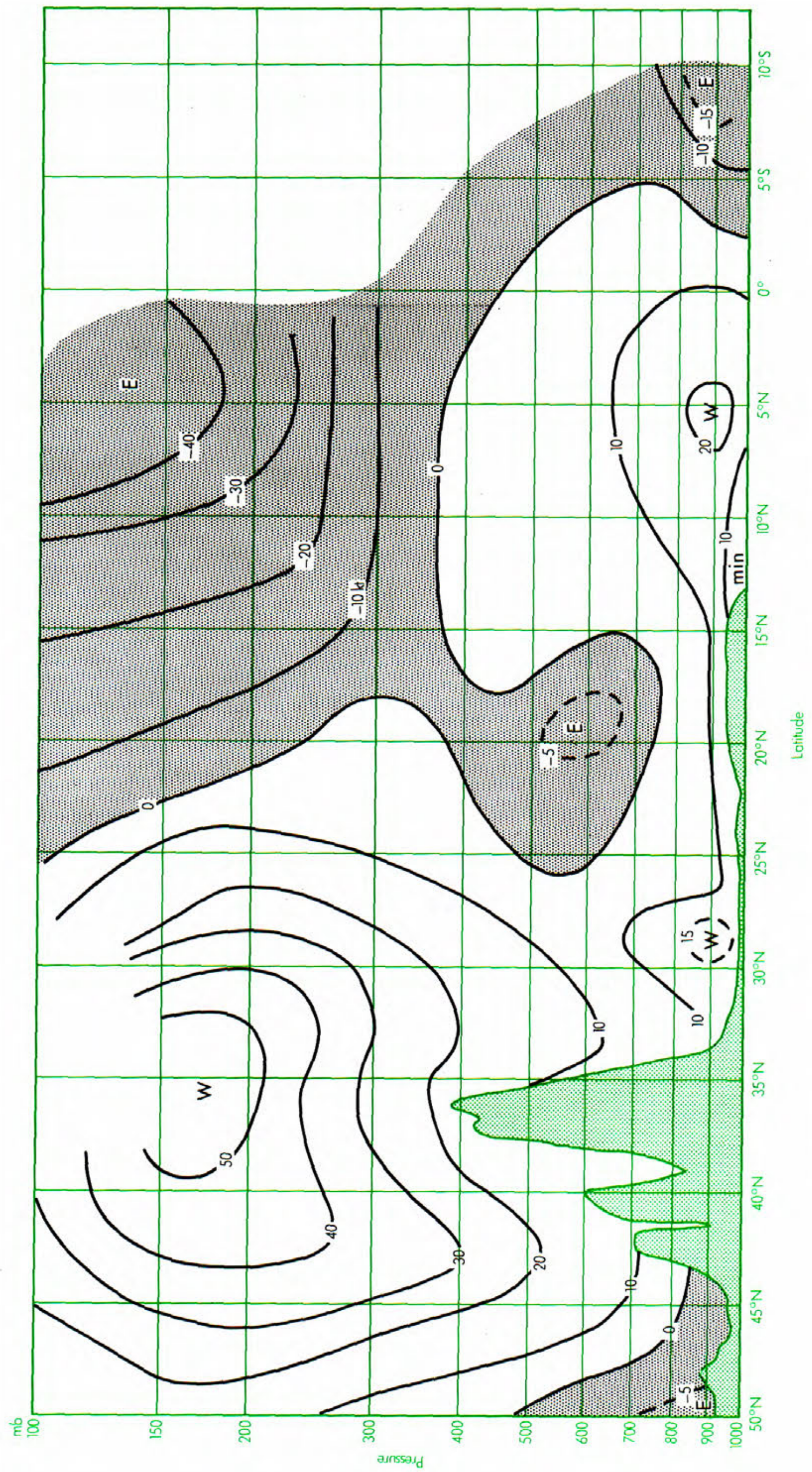

PLATE 34. DECAD MEAN VERTICAL CROSS-SECTION ALONG 75°E, FROM 50°N TO 5°S, FOR *D*17 (10-19 JUNE), 1958
Black stippling is used to emphasize easterly wind components.

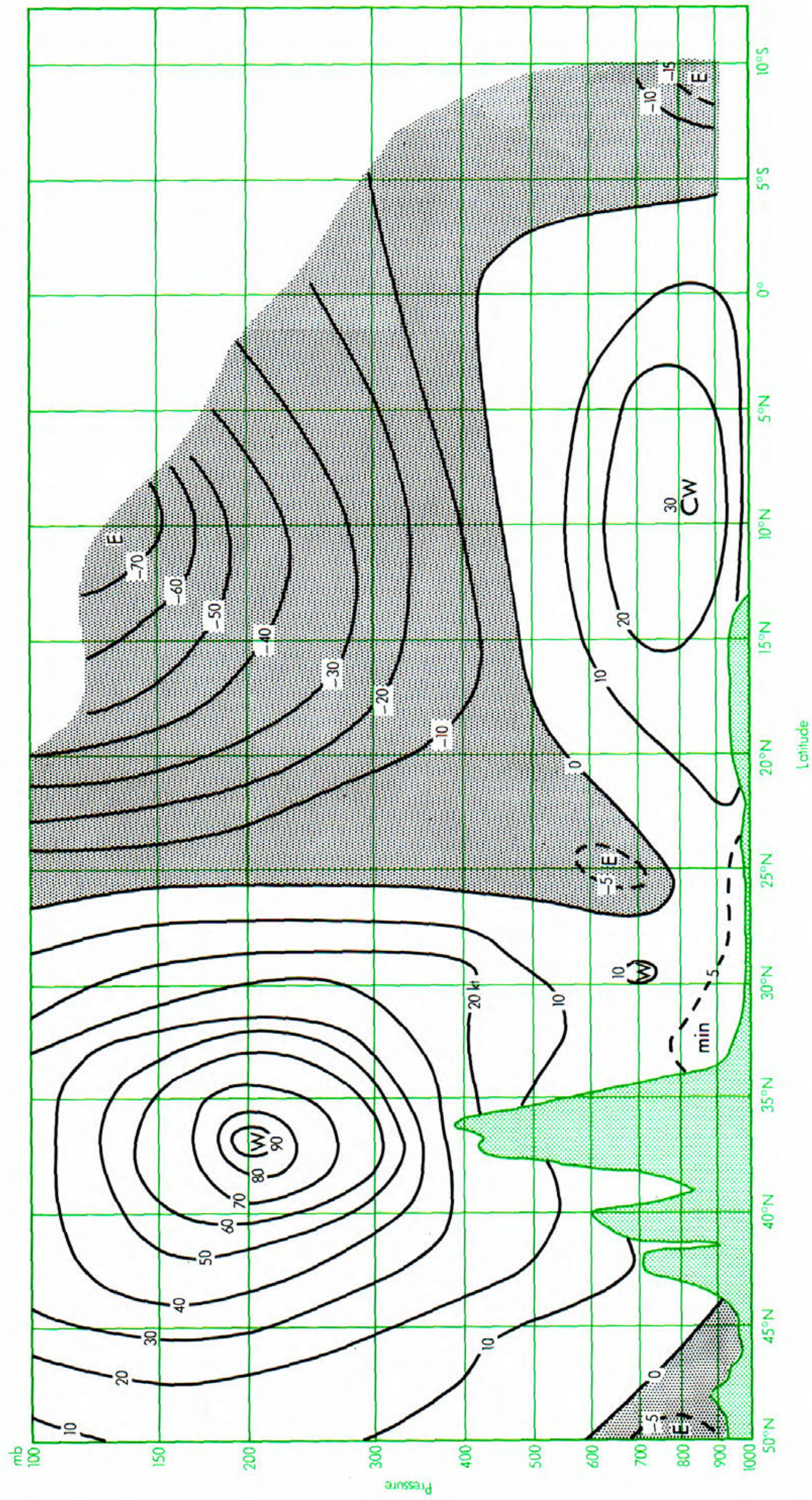

PLATE 35. DECAD MEAN VERTICAL CROSS-SECTION ALONG 75°E, FROM 50°N TO 5°S, FOR *D*18 (20-29 JUNE), 1958
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