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# AVERAGE WATER-VAPOUR CONTENT OF THE AIR

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*Frontispiece*


OBSERVING STATIONS

# AVERAGE WATER-VAPOUR CONTENT OF THE AIR

SUMMARY

Charts are presented of the average water-vapour content of the air above one square centimetre at the earth's surface and the levels 850, 700 and 500 millibars for each of the months January, April, July and October based mainly on data for 1951–55. The area covered by the charts is approximately 70°N.–52°S.

## §1—INTRODUCTION

Water vapour in the atmosphere is usually described by the relative humidity, vapour pressure or some other measure applicable to one level or place. For some purposes, for example, in studies of the absorption of radiation, it is necessary to know the amount of water vapour in various layers of the atmosphere. Observations of humidity in the upper air obtained by radio-sonde are now sufficient to attempt to chart the water-vapour content and this paper presents charts of the amount (mass) of water vapour above one square centimetre at the earth's surface and above each of the levels 850, 700 and 500 millibars over most of the earth except the Antarctic for the months January, April, July and October. No account is taken of water held in suspension by the air in solid or liquid form.

## §2—DATA

The main source of data was the series of CLIMAT TEMP (monthly mean upper air data)[1]* messages. These messages give among other things mean dew-point at the levels 850, 700, 500 and 300 millibars for each month and are broadcast soon after the month to which they refer. The messages are confirmed or corrected in publications of the United States Weather Bureau.[2] The CLIMAT TEMP messages began in 1949 but data for the first two years were considerably fewer than for subsequent years. Accordingly, as far as possible the data used were for the period 1951–55 inclusive. The CLIMAT TEMP data were supplemented by data supplied specially by the United States Weather Bureau for another purpose,[3] for 1951 and 1952, for some of the Pacific Islands. Data for a few stations were also taken from two other publications[4,5] to supplement the CLIMAT TEMP network. Data for stations in the British Isles were available in the form of monthly mean humidity mixing ratios. Surface data were obtained from CLIMAT messages in most cases but some stations which broadcast CLIMAT TEMP messages did not broadcast corresponding CLIMAT messages for the surface and for these stations values had to be interpolated between nearby observations; in a few cases in the Arctic such interpolation was impossible.

CLIMAT TEMP messages were not broadcast for stations in the Union of Soviet Socialist Republics. Radio interceptions of daily upper air observations from this region are published in *Daily series synoptic weather maps*,[6] and Mr. G. A. Tunnell put at our disposal mean dew-points at the surface, 850, 700 and 500 millibars worked from such data for a large number of stations for each mid-season month of the period 1949–52 and for a few stations also for 1946 or 1947. The number of humidity observations for a particular month and station was in many cases small, especially in January, and Mr. Tunnell has attempted to correct his mean values making allowance for the presence of temperature inversions and bias towards high temperatures and using the analogy of observations from

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

similarly situated stations in Canada. These corrected mean values were accepted for the present purpose as the best estimates available. It is emphasized that the period of the observations is not the same as for the remaining observations and that the averages are in some cases based on small numbers of observations.

The frontispiece shows the distribution of stations from which observations of humidity in the upper air were available and utilized for this study. In many cases data were missing for one or more years.

## §3—METHOD OF CONSTRUCTION

The mass of water vapour in the layer of air between pressures $p_1$ and $p_2$ is:

$$\frac{1}{g}\int_{p_1}^{p_2} q\, dp \text{ per square centimetre of horizontal area,}$$

where $q$ is the specific humidity (grammes of water vapour per gramme of air and water vapour) and $g$ is the acceleration of gravity.

$q$ was calculated from the humidity mixing ratio, $r$ (grammes of water vapour per gramme of dry air), which is a convenient parameter as it is tabulated for British stations. The difference between $q$ and $r$ is small and is less than 0·05 for $r$ less than 7 grammes per kilogram, so that the calculation of $q$ from $r$ only involved the application of a small correction for larger values of $r$. Over the British Isles $r$ is less than 7 grammes per kilogram at 850-millibar and higher levels throughout the year and also at the surface in winter and spring.

Most of the data were in the form of average dew-points and these were converted into average humidity mixing ratios. Average humidity mixing ratios so calculated will underestimate the true average humidity mixing ratio but the error is not large (see § 4). Mean humidity mixing ratios for a few American and Japanese stations were calculated from mean relative humidities as published in *Climatological data*[4] and *Aerological data of Japan*[5]; this method was also used for the observations from some Pacific islands. Again there will be a small systematic error because the relation between relative humidity and humidity mixing ratio is not linear.

The integrations of the water-vapour content were made using the simple trapezium rule, for the layers (i) above 500 millibars, (ii) 700–500 millibars, (iii) 850–700 millibars and (iv) surface–850 millibars. Errors involved in this method are discussed in § 4.

Usual methods of measuring humidity by radio-sonde in the upper air do not work at low temperatures, about −40°C. and below. Observations are lacking therefore for levels above 300 millibars and in many cases for lower levels also. However, the saturated water-vapour content of the air at low temperatures in the high atmosphere is very low and, moreover, available evidence indicates that relative humidity is often very low in these layers also. Accordingly when temperature was low and water-vapour content at 300 millibars was not measured it was assumed to be zero.

The average surface pressure was used in the integral for the lowest layer; if there is a significant correlation between humidity mixing ratio and surface pressure this could lead to error but such a relation is unlikely. This method of evaluating the integral of $q$ with respect to $p$ was compared with the more accurate method of taking the distribution of $q$ with pressure as defined by values at 100-millibar intervals of pressure and also at 850 millibars. This was done for 27 different distributions of $q$ with $p$ covering different months at stations in Britain and overseas. It was found that when $q$ falls sharply between the surface (near 1000 millibars) and 850 millibars the "short" method over-estimates the true value of

$$\int_{850}^{surface} q\, dp.$$

An empirical rule for correcting water-vapour content of the layer surface–850 millibars in such cases was devised by plotting the necessary correction against the lapse of specific humidity, surface–850 millibars, when surface pressure was near 1000 millibars. This rule shows the correction (to be subtracted) is equal to $2{\cdot}6\times10^{-2}$ $(q_s-q_{850}-3{\cdot}5)$ grammes where $q_s$, $q_{850}$ are specific humidities (grammes per kilogram) at the surface and 850 millibars respectively.

The water-vapour contents of the layers above the levels 500, 700, 850 millibars and the surface, calculated as above, were then plotted on charts for each of the months January, April, July and October. The units were tenths of a gramme per square centimetre. As seen from the frontispiece there was only one observing station in the South American continent. Accordingly values of surface humidities were used to make rough estimates of the total water-vapour contents. Long-period average humidity mixing ratios for a few stations in South America (see the frontispiece) were compared with similar values for stations in other parts of the world with similar climates for the particular season. For example, values in the Amazon Basin in the most rainy season were compared with values over parts of India in the south-west monsoon. In this way estimates of water-vapour content above 700 millibars were obtained for three high-level stations in the Andes and for twelve low-level stations elsewhere. The charts were then drawn to the observations as far as possible and using normal rainfall maps and analogies with similar regions with good observations as guides over areas without observations. The chart for 500 millibars and above was drawn first, then the 700-millibar and above chart followed by those for 850 millibars and the surface. Account was taken of the major mountain masses; thus the water-vapour content shown over the Himalayas is small on the charts for every level. On the surface charts there are areas of low water-vapour content over all the large mountain regions. It is emphasized, however, that it was only possible to take account of the more important areas of high ground and then only in a rough manner. More detail would be undesirable on world charts and would also be misleading, remembering the crude nature of some of the material from which the charts were prepared. The horizontal gradients of total water-vapour content are large in regions of steeply sloping mountains and the isopleths therefore run together in many places on the charts.

The charts for January are in Figure 1; Figure 1(*a*) shows the water-vapour content above one square centimetre at the earth's surface; Figure 1(*b*) that above 850 millibars; Figure 1(*c*) above 700 millibars and Figure 1(*d*) above 500 millibars. Figures 2, 3 and 4 show corresponding charts for April, July and October respectively.

## §4—ACCURACY OF THE DATA AND CHARTS

Measures of humidity are perhaps the least reliable of those made by radio-sonde and there are probably considerable differences in the typical errors of different types of sonde.[7]

Apart from this heterogeneity in the observations there are the following possible sources of systematic error in the water-vapour contents calculated from various data and used in the construction of the charts (casual errors of measurement of humidity are assumed to be unimportant in the mean):

(i) lag errors of the radio-sonde,
(ii) calculation of mean humidity mixing ratios from mean dew-points,
(iii) calculation of mean specific humidity from mean humidity mixing ratio,
(iv) errors in performing the integration with respect to pressure.

(i) *Lag errors.*—All forms of humidity measuring in routine use on radio-sondes are subject to lag errors. These errors result in the mean in a slight over estimation of humidity in the upper air over Britain in summer[8] and it is likely that this is a general fault as the middle troposphere is often dry even over the tropics. This over-estimation may amount to perhaps two per cent on the average in mid-troposphere,[8] but is probably very much smaller in the layer below the 850-millibar level where most of the water vapour lies.

Errors from this source will be positive (that is, over estimation) and will probably be less than one per cent for the total water-vapour content above the surface.

(ii) *Errors in mean humidity mixing ratios calculated from mean dew-points.*—This is a more serious source of error. Since for low relative humidities there is a much larger range in dew-point than in the corresponding humidity mixing ratio, the relation between the two variables being non-linear, the humidity mixing ratio corresponding to the mean dew-point will be lower than the true mean humidity mixing ratio. The errors will be greatest for those stations with the largest variability in humidity.

Monthly mean humidity mixing ratios for 850, 700 and 500 millibars for four months for each of the years 1951–55 inclusive for Lerwick, Aden and Gibraltar were compared with corresponding values computed from the mean dew-points. Results were as follows. If $r^1$ is the average humidity mixing ratio for one month for five years, calculated from the average dew-point, and $r$ is the true average humidity mixing ratio, then $r^1 = 0{\cdot}96r$ fits most observations at 850 millibars for Aden and Lerwick and for two of the four months for Gibraltar; the fit is especially good for the high water-vapour contents at Aden. For 700 and 500 millibars, $r^1 = 0{\cdot}92r$ fits most months but the higher water contents at Aden and also the values for one or two other months at Lerwick are better described by the former relation. Humidity appears to be more variable at Gibraltar than at Aden or Lerwick.

It would seem, therefore, that there may be a systematic under estimation of mean water-vapour content of four per cent over most of the charts and up to eight per cent in regions of great variability of humidity. This error will not apply to observations over Britain which are true mean humidity mixing ratios. It should be noted however that in drawing the charts the observations from Lerwick, Leuchars and Larkhill/Crawley did not seem consistently higher than neighbouring observations from the weather ships and western Europe but often the reverse.

(iii) *Errors in mean specific humidity calculated from mean humidity mixing ratio.*—Errors from this source are very small. It can be shown that the difference between the value of the specific humidity obtained from the mean humidity mixing ratio and the true value is approximately the mean square of the humidity mixing ratio. (Humidity mixing ratio must then be expressed as grammes per gramme; the mean square is of order $(5 \times 10^{-3})^2$ or less at low levels in the atmosphere, that is, $25 \times 10^{-6}$ or less. Humidity mixing ratios are commonly of order $10 \times 10^{-3}$ grammes per gramme or less at low levels.)

(iv) *Errors in integration with respect to pressure.*—The crude trapezium rule applied to thick layers of 150 millibars or more may lead to error in the calculation of the total water-vapour content. Typical variation of water-vapour content with height is shown in Figure 5 (Larkhill). The curve is usually concave upwards. The "short" method of integrating the water-vapour content will therefore tend to over estimate. The integrals for 27 different mean distributions of water-vapour content with pressure, covering different months at stations in Britain and overseas, were calculated using values of specific humidity at 100-millibar intervals and also at the level of 850 millibars and the results compared with the "short" method of computation actually used in the preparation of the charts. This comparison showed that there was a small error in the "short" method above the 850-millibar level. After correcting the surface–850-millibar integral (see § 3) the over estimate in the total water-vapour content above the earth's surface was of the order of two per cent over Britain and five per cent in the Mediterranean–Middle East region.

The errors from the sources (i), (ii), (iii) and (iv) in the total water-vapour content above the earth's surface are thus of the order:

(i) less than one per cent over estimate,
(ii) four to eight per cent under estimate,
(iii) negligible,
(iv) two to five per cent over estimate.

The net error would appear to be an under estimate of one to three per cent.

Apart from the above systematic errors the errors in drawing up the charts from the observations may be considerable. The observations showed considerable scatter and were difficult to reconcile among themselves especially over Europe and the Union of Soviet Socialist Republics. In many regions there were no observations. The average distribution of water-vapour shown in Figures 1–4 is, it is hoped, correct in broad outline but cannot be accurate in detail.

## §5—DISCUSSION

The charts in Figures 1–4 show few surprising features. In winter the continents have least and the oceans most water vapour above them, the reverse being the case in summer, except over Australia. This is no doubt associated with the similar temperature distribution. Over the oceans the charts for April and October (Figures 2(*a*) and 4(*a*)) are more like those for January in the northern hemisphere than those for July. The low values of water-vapour content over North Africa and the Near East are interesting.

Although there are few island observing stations in the tropics, what observations there are show that the water-vapour content of the air over the tropical oceans is less than over land. Again this is doubtless associated with the higher temperatures over land and the more regular and effective convection there to transport water vapour upwards. The greatest water-vapour contents appear to be over the Ganges Valley in July (6·5 grammes per square centimetre) and the greatest value over the sea is also in July over the western Pacific, south of Japan (5·6 grammes per square centimetre).

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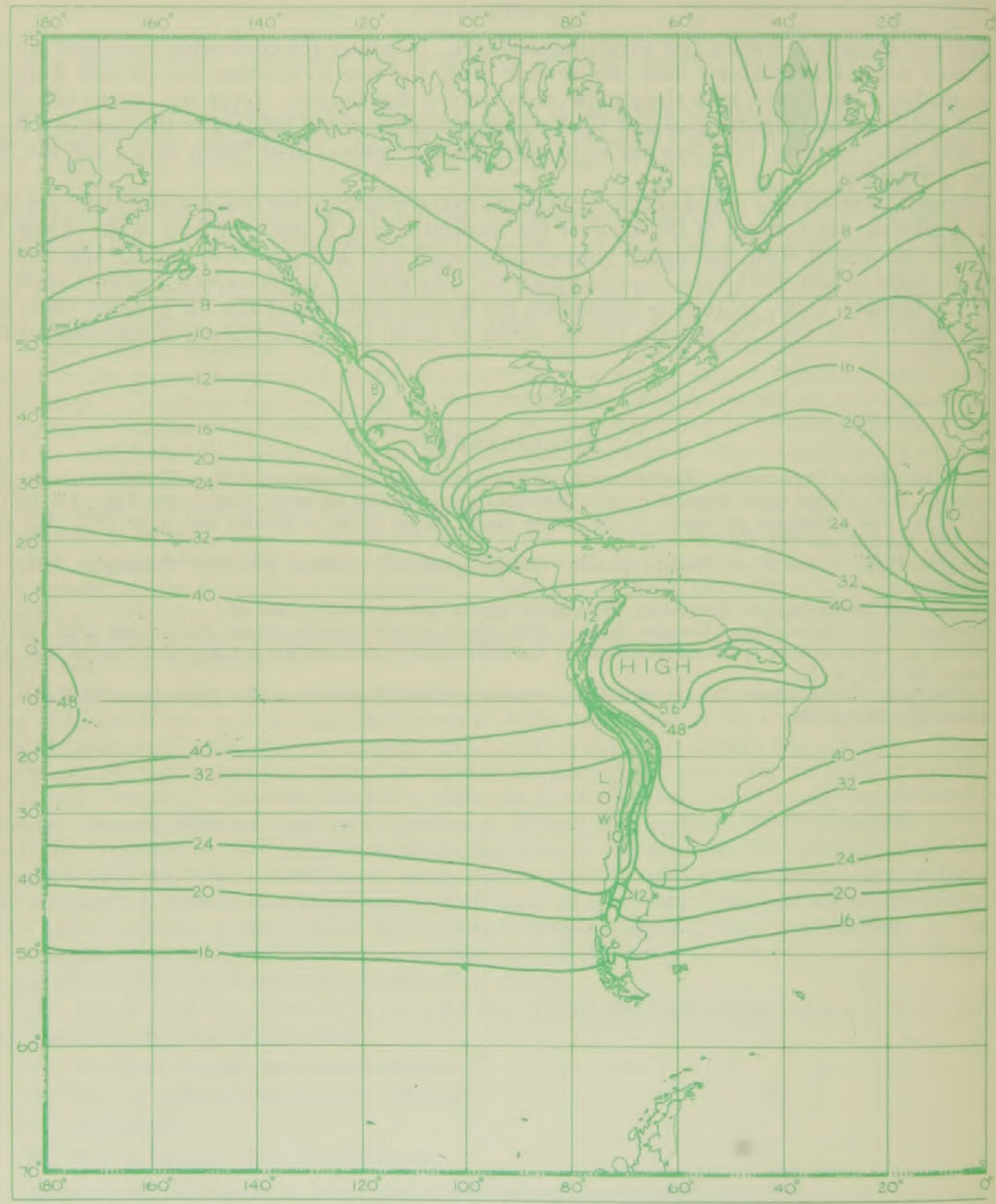


FIG. 1(*a*)—AVERAGE WATER-VAPOUR CONTENT OF THE AIR, IN DECIGRAMS, ABOVE ONE SQUARE CENTIMETRE AT THE EARTH'S SURFACE, JANUARY 1951–55

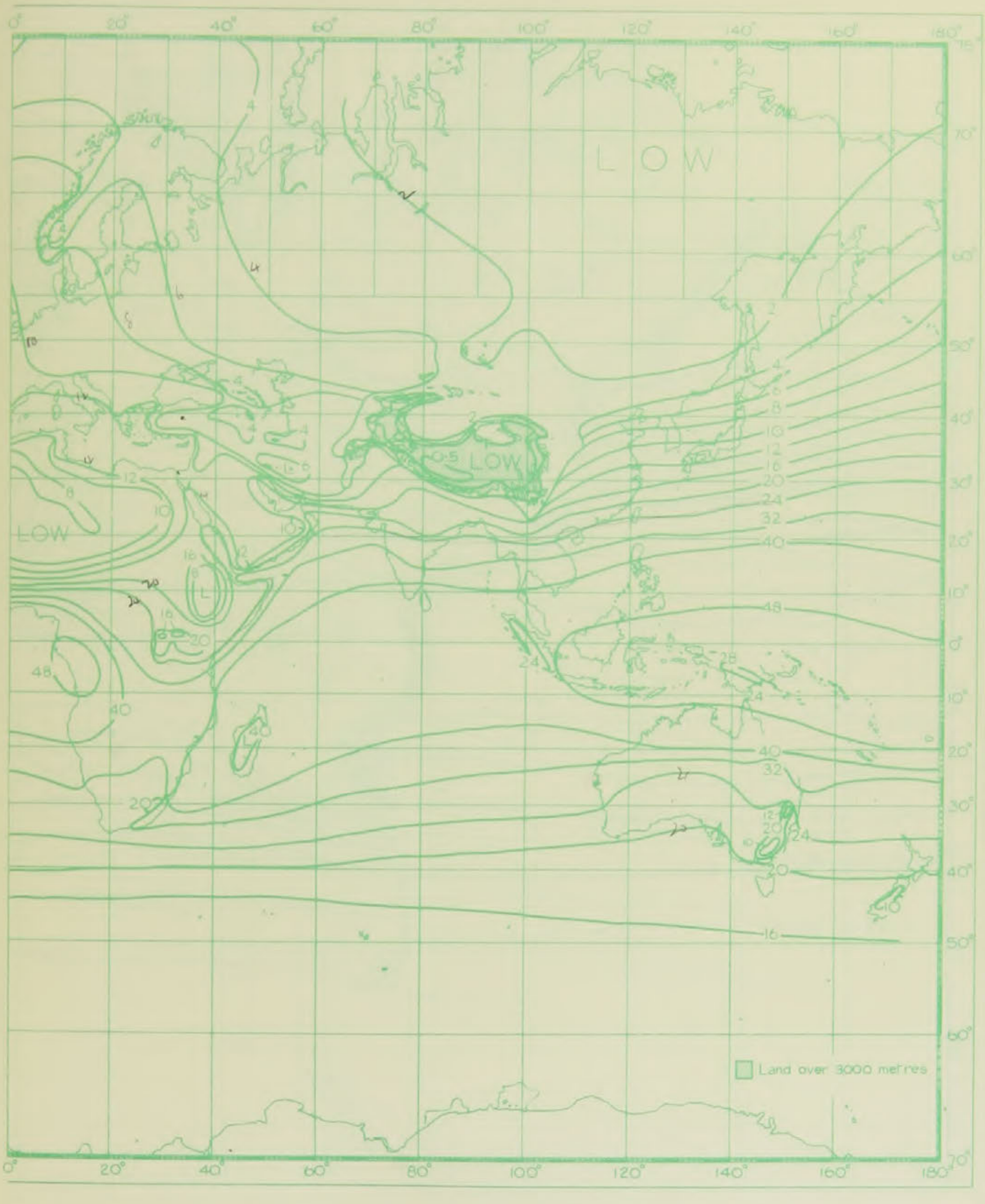


FIG. 1(*a*)—CONTINUED

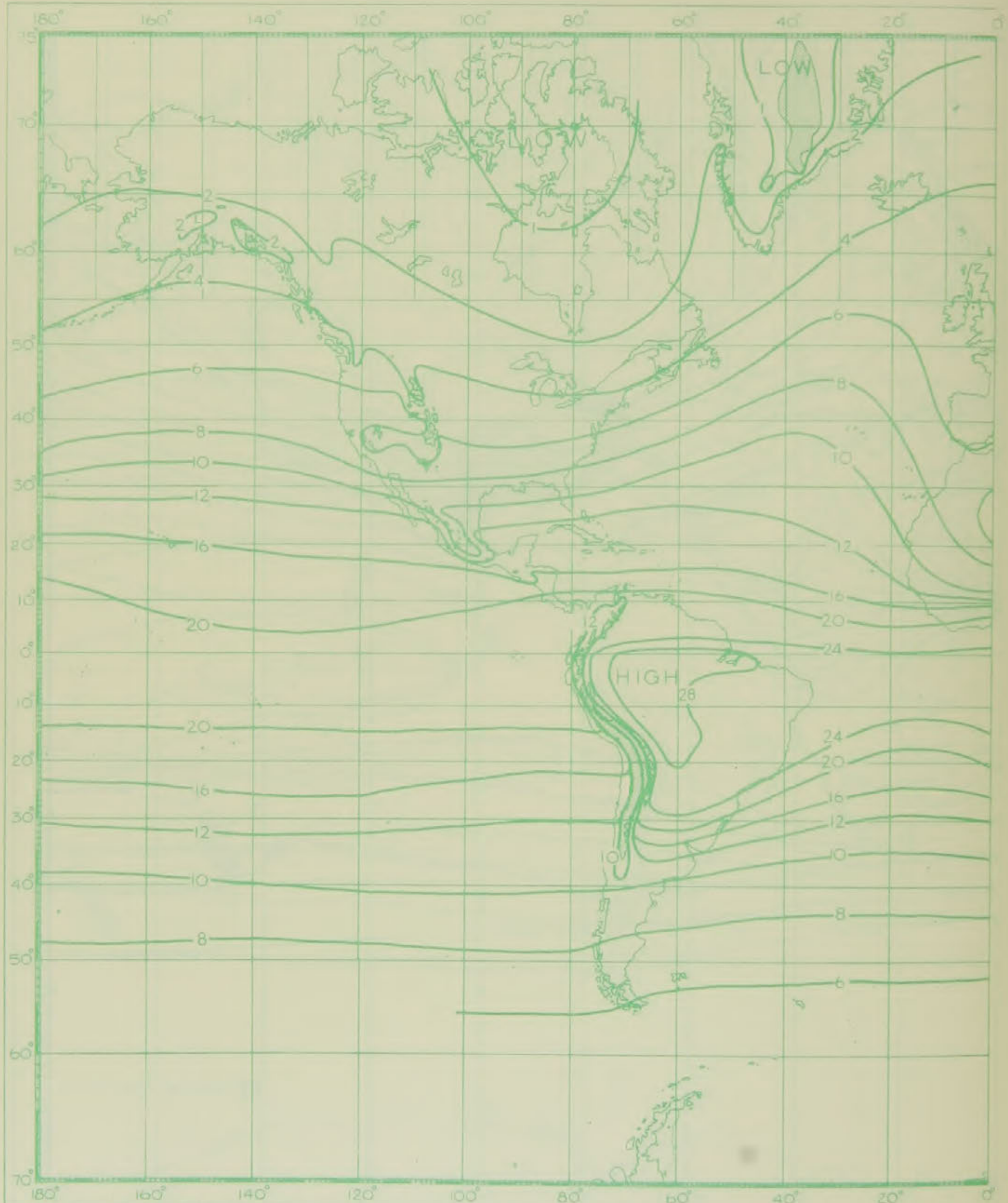


FIG. 1(*b*)—AVERAGE WATER-VAPOUR CONTENT OF THE AIR, IN DECIGRAMS, ABOVE ONE SQUARE CENTIMETRE AT 850 MILLIBARS, JANUARY 1951–55

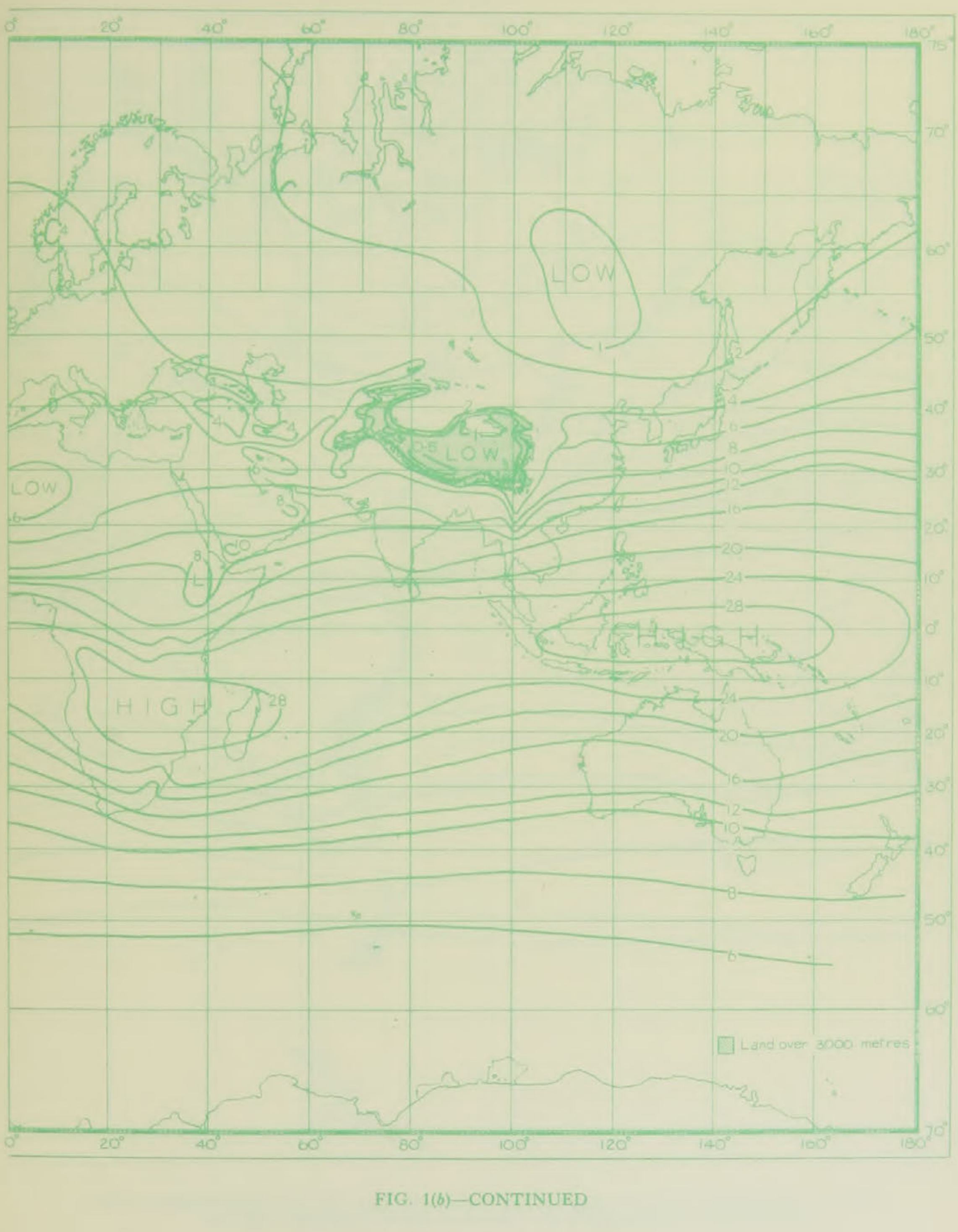


FIG. 1(*b*)—CONTINUED

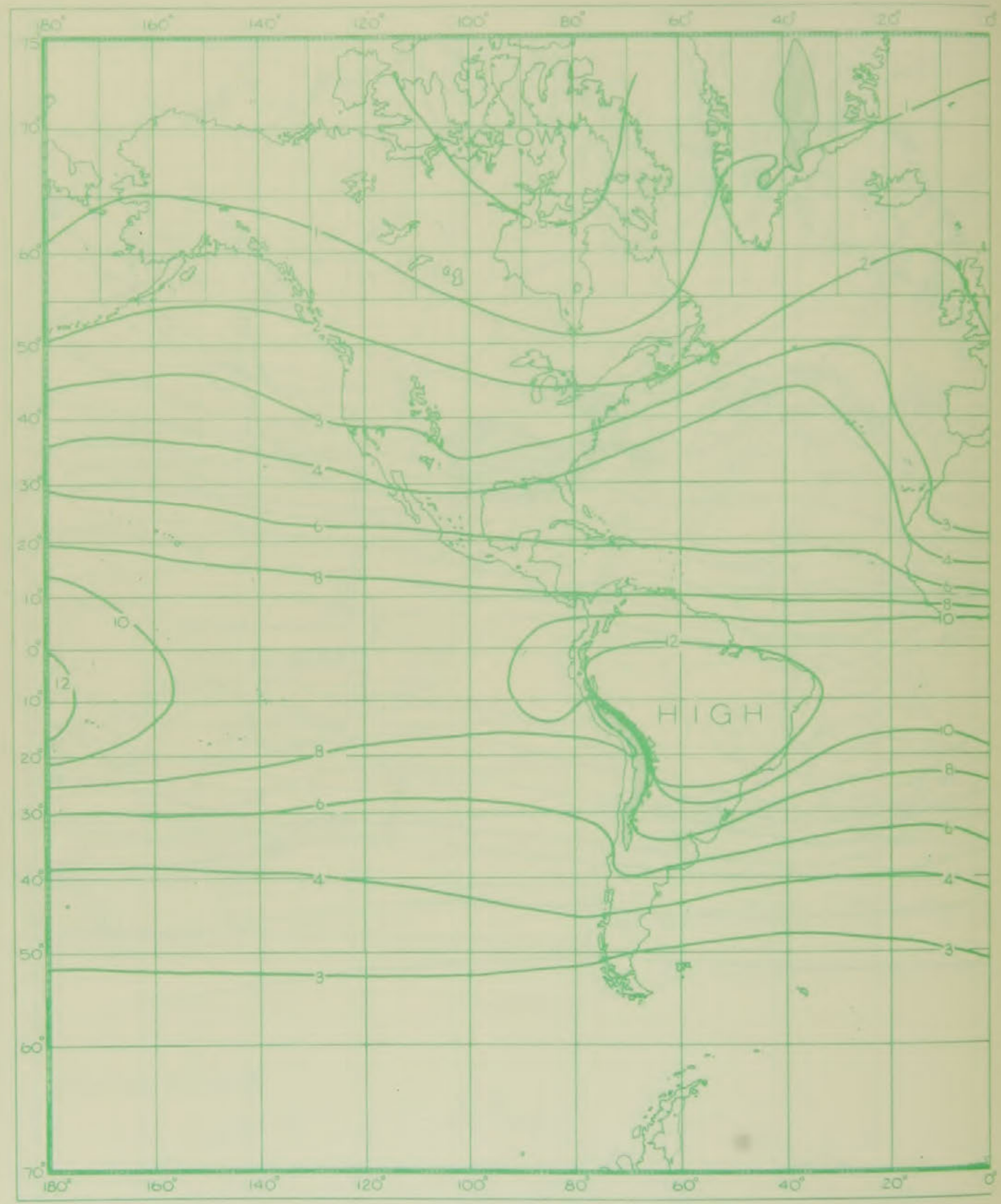


FIG. 1(c)—AVERAGE WATER-VAPOUR CONTENT OF THE AIR, IN DECIGRAMS, ABOVE ONE SQUARE CENTIMETRE AT 700 MILLIBARS, JANUARY 1951–55

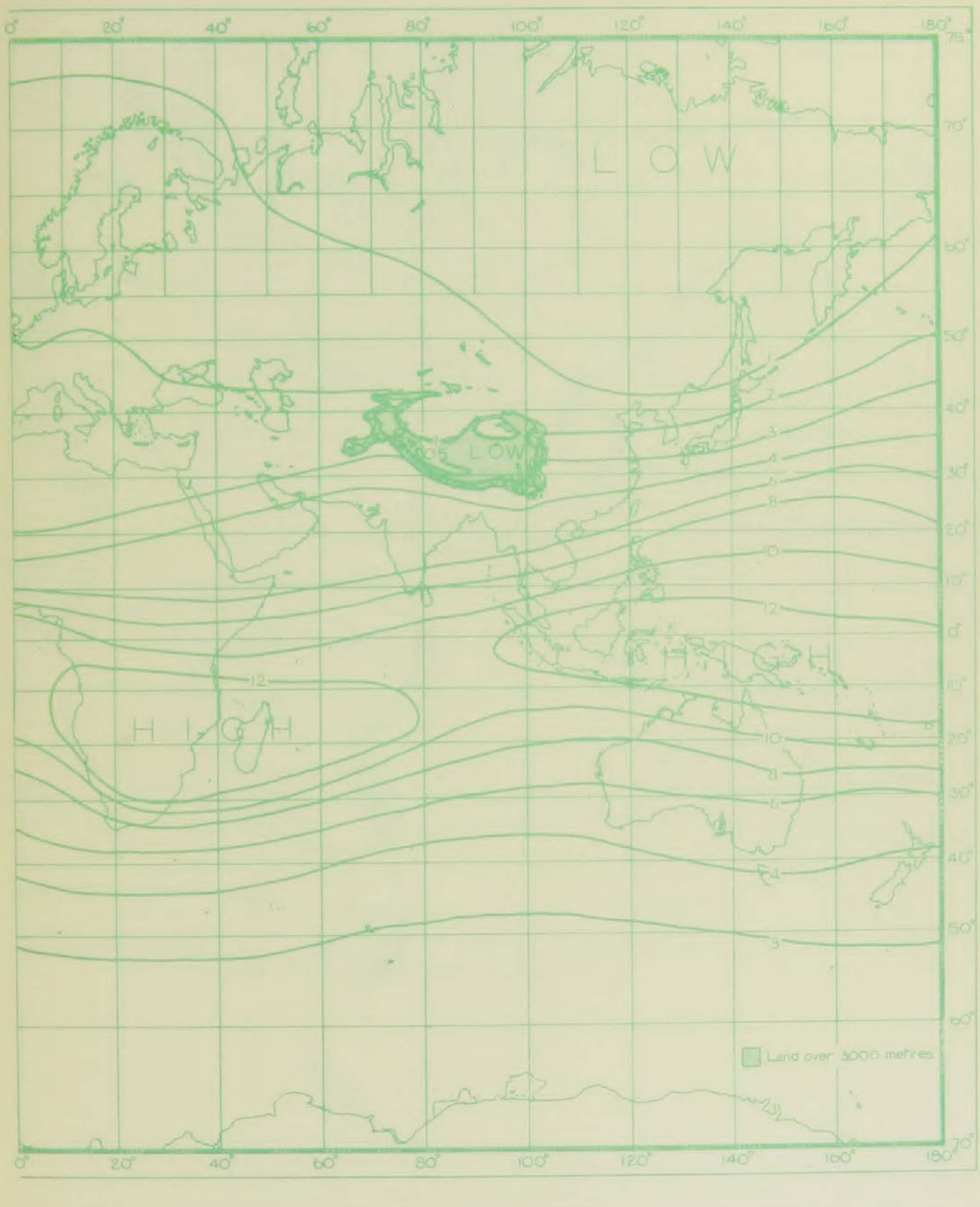


FIG. 1(*c*)—CONTINUED


FIG. 1(*d*)—AVERAGE WATER-VAPOUR CONTENT OF THE AIR, IN DECIGRAMS, ABOVE ONE SQUARE CENTIMETRE AT 500 MILLIBARS, JANUARY 1951–55

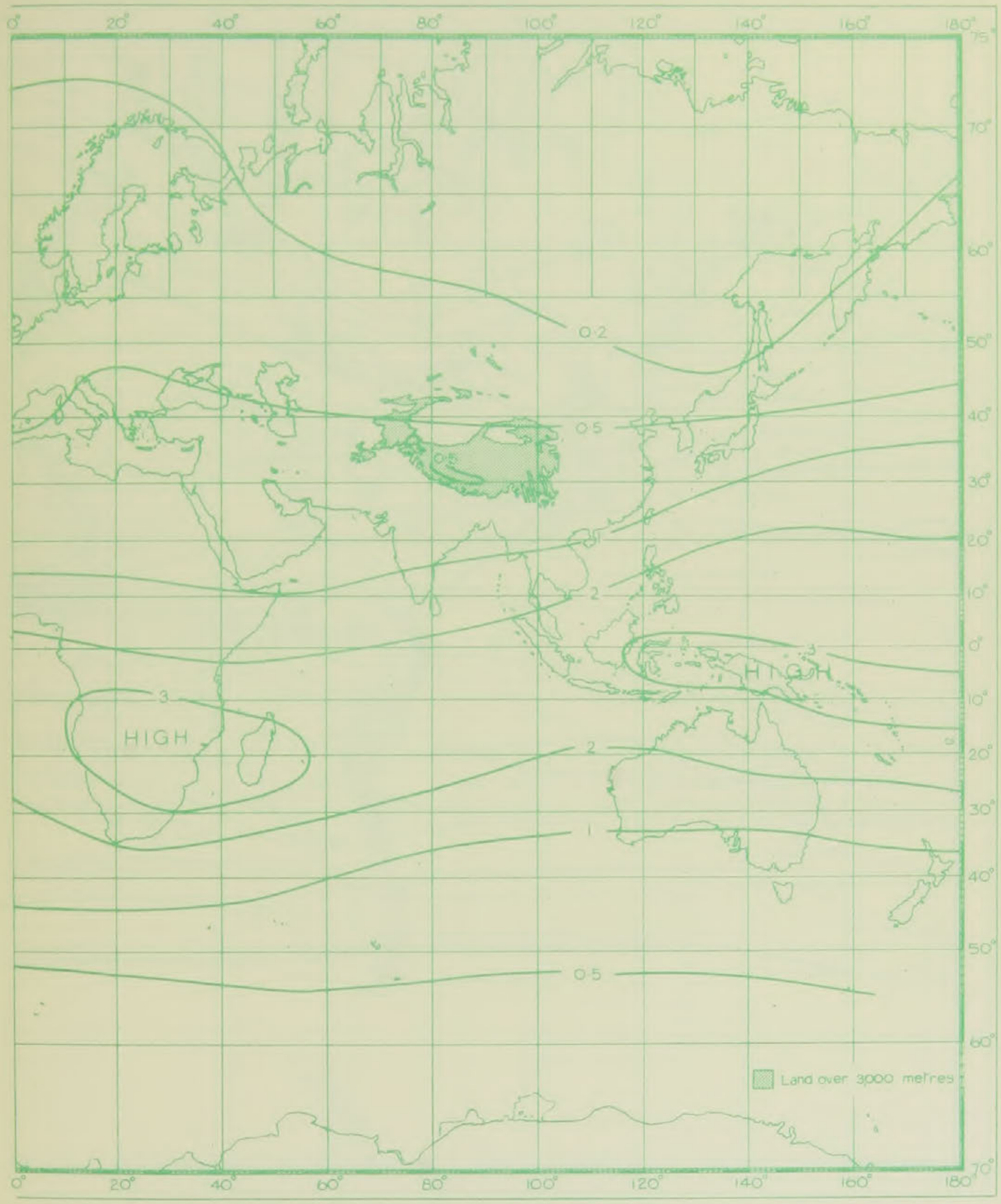


FIG. 1(*d*)—CONTINUED

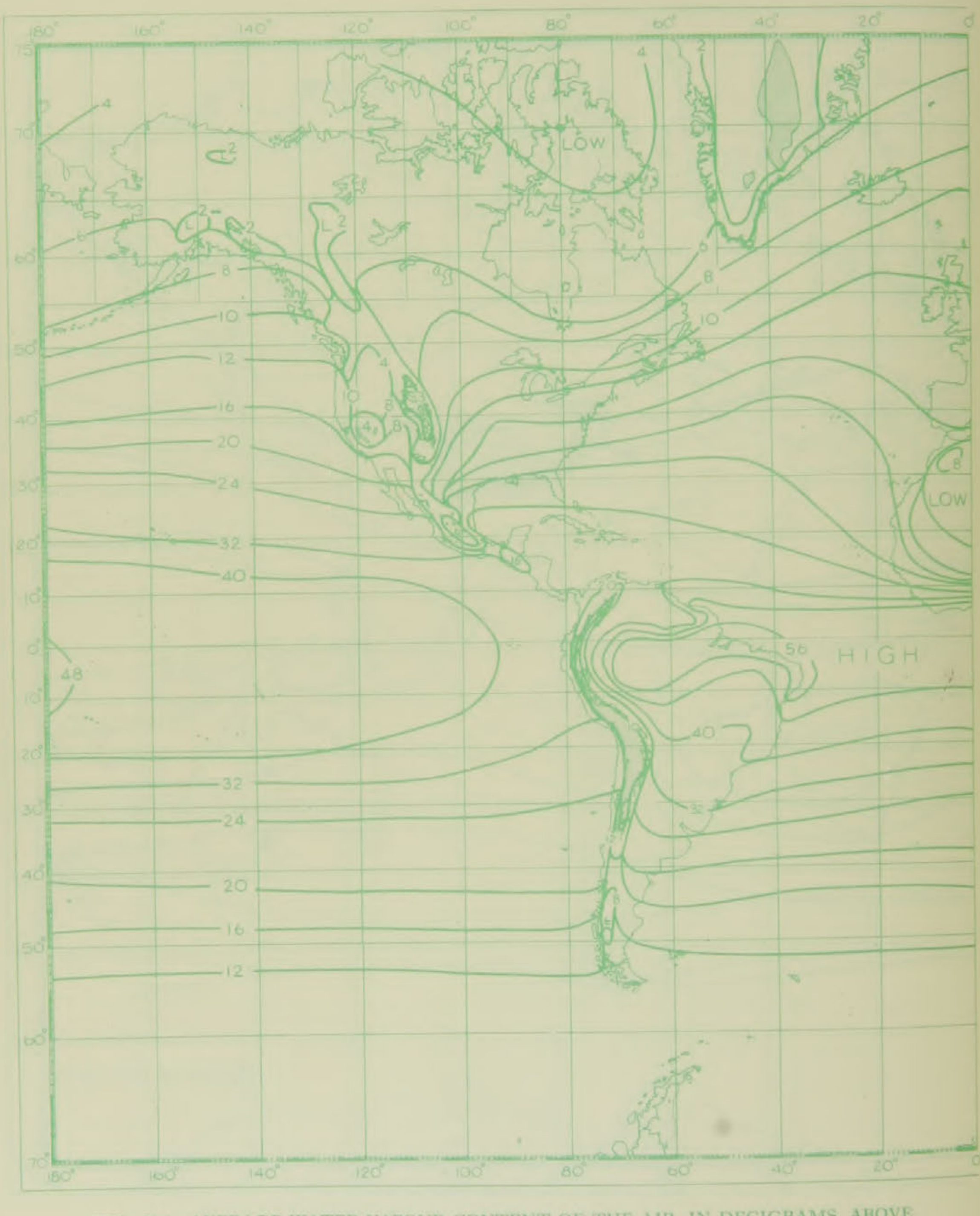


FIG. 2(*a*)—AVERAGE WATER-VAPOUR CONTENT OF THE AIR, IN DECIGRAMS, ABOVE ONE SQUARE CENTIMETRE AT THE EARTH'S SURFACE, APRIL 1951–55

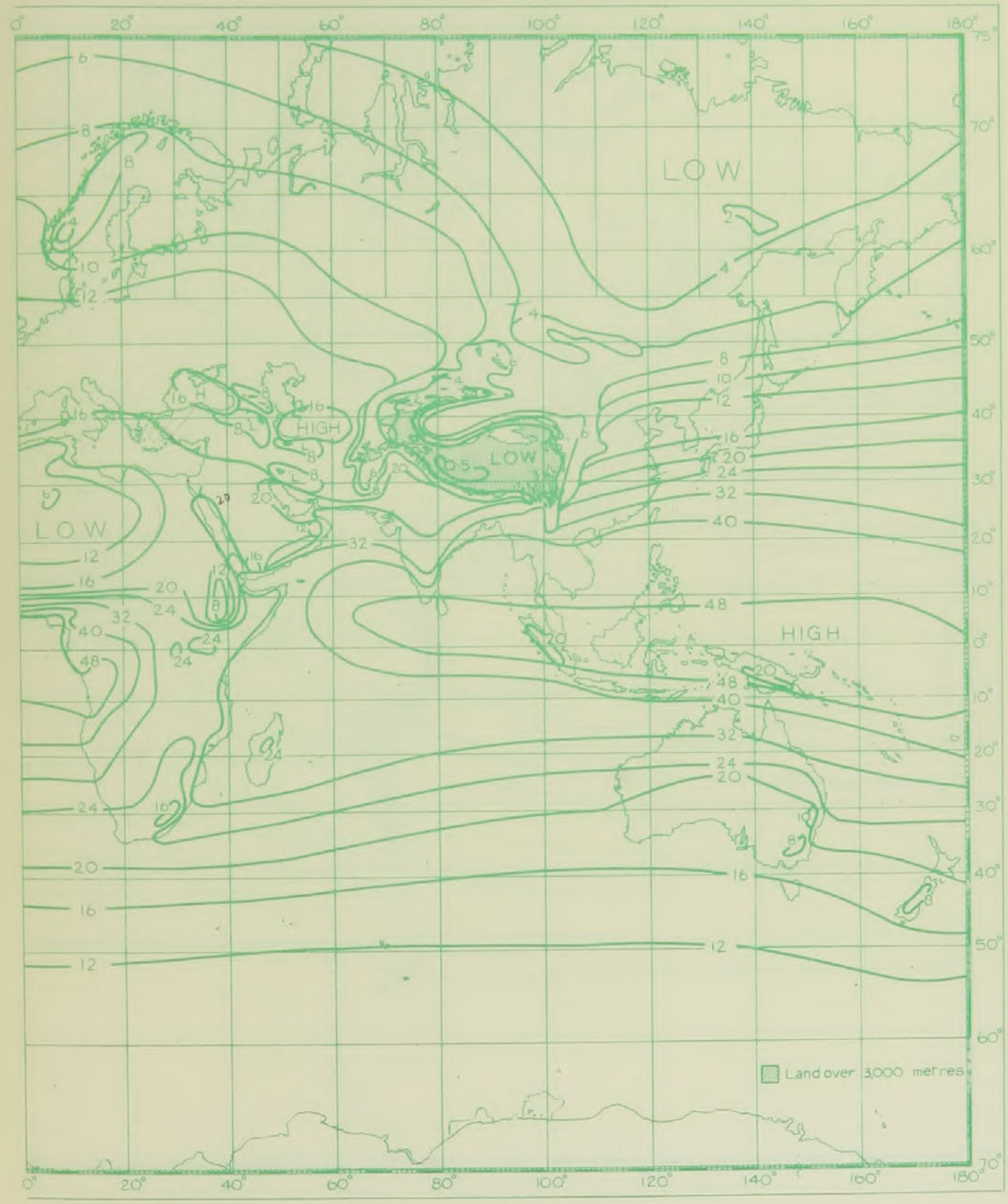


FIG. 2(*a*)—CONTINUED

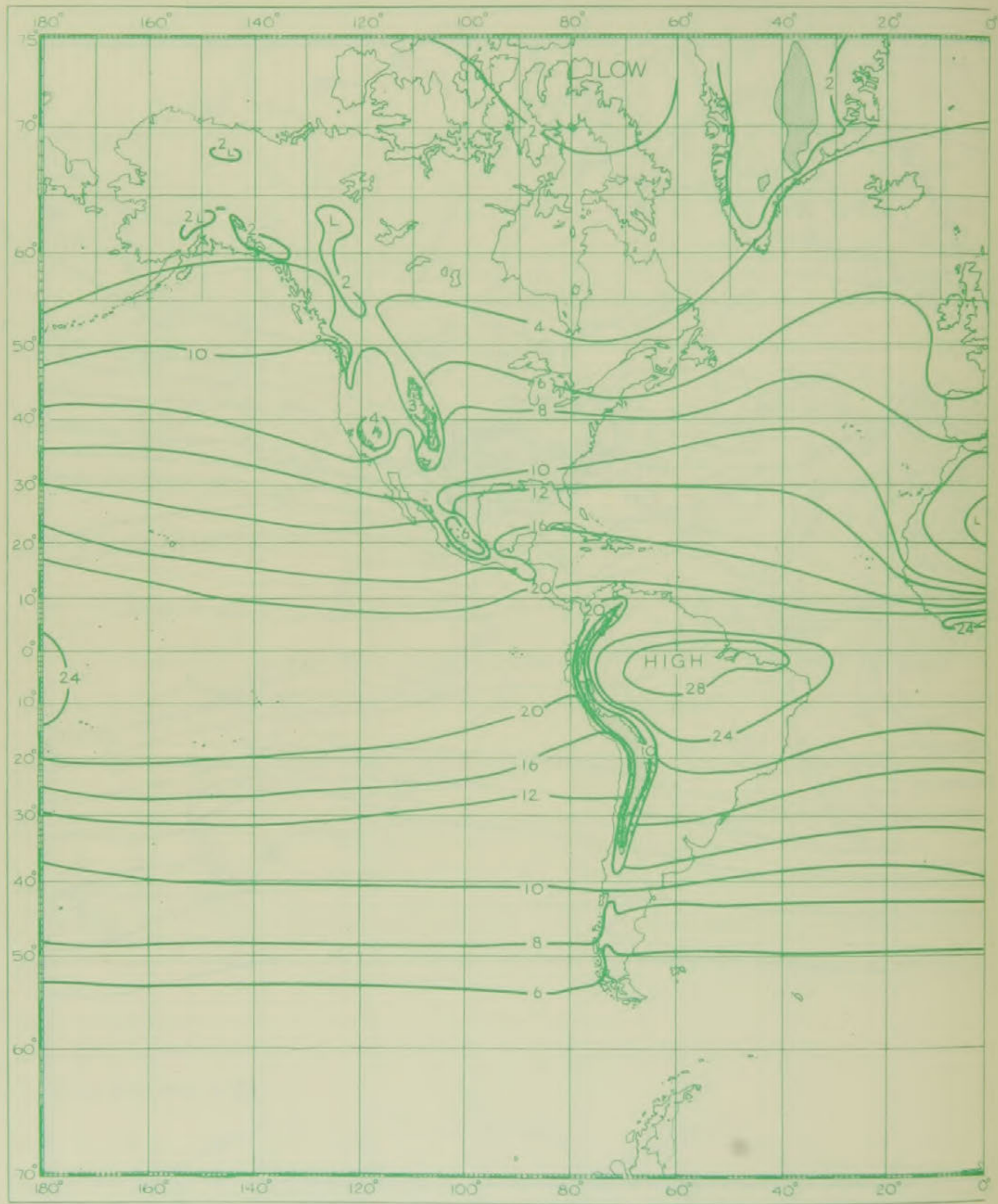


FIG. 2(*b*)—AVERAGE WATER-VAPOUR CONTENT OF THE AIR, IN DECIGRAMS, ABOVE ONE SQUARE CENTIMETRE AT 850 MILLIBARS, APRIL 1951–55

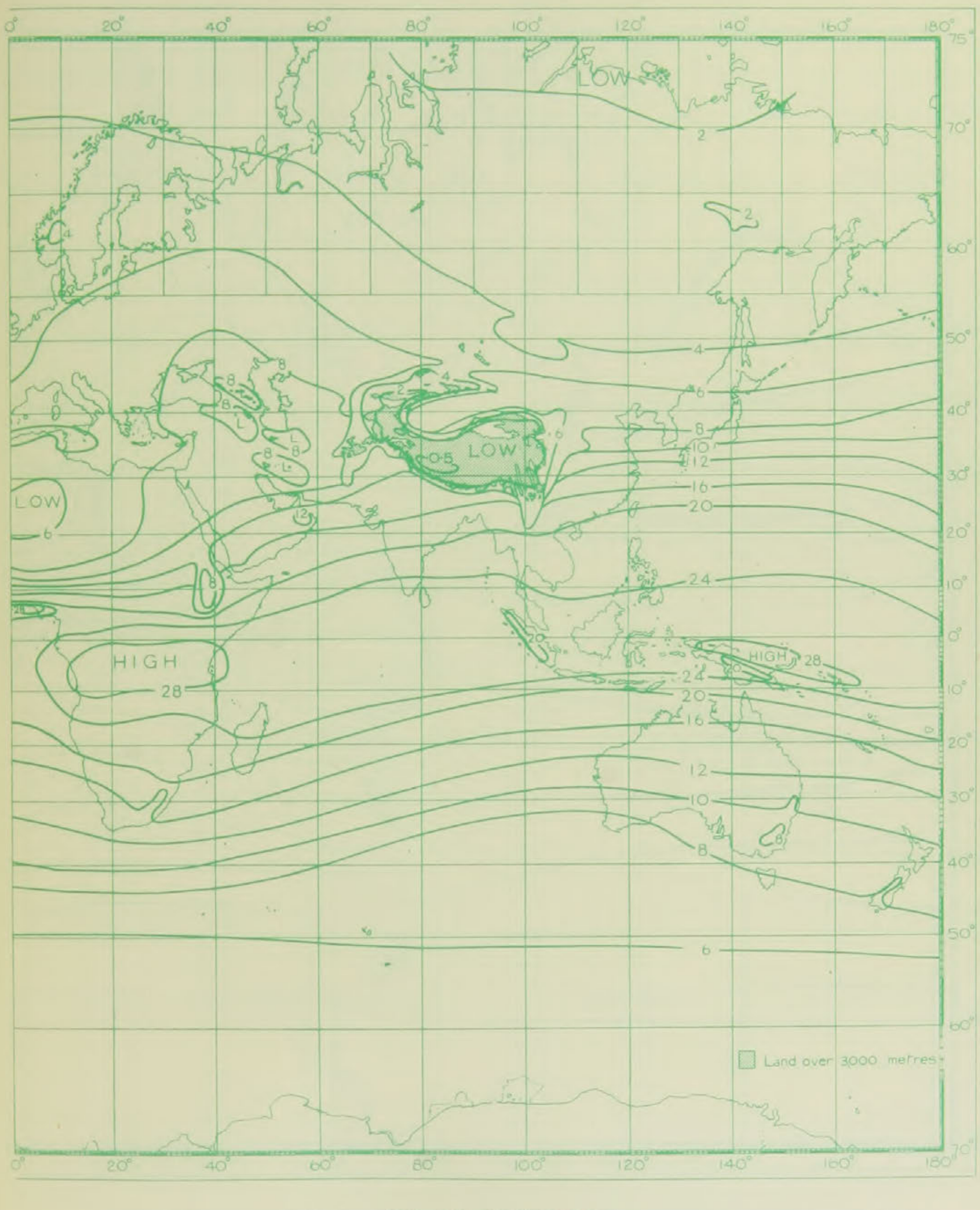


FIG. 2(b)—CONTINUED

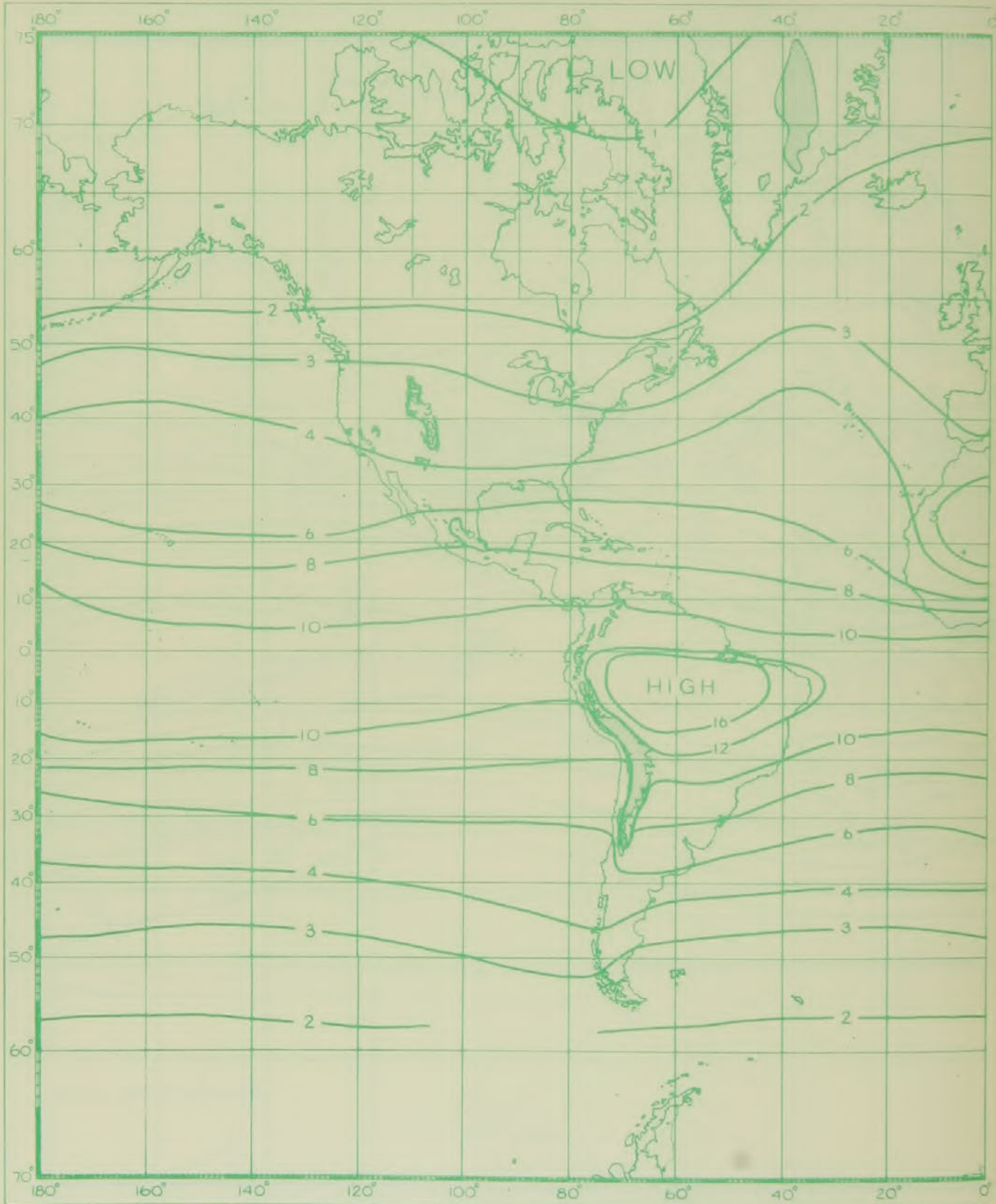


FIG. 2(c)—AVERAGE WATER-VAPOUR CONTENT OF THE AIR, IN DECIGRAMS, ABOVE ONE SQUARE CENTIMETRE AT 700 MILLIBARS, APRIL 1951–55

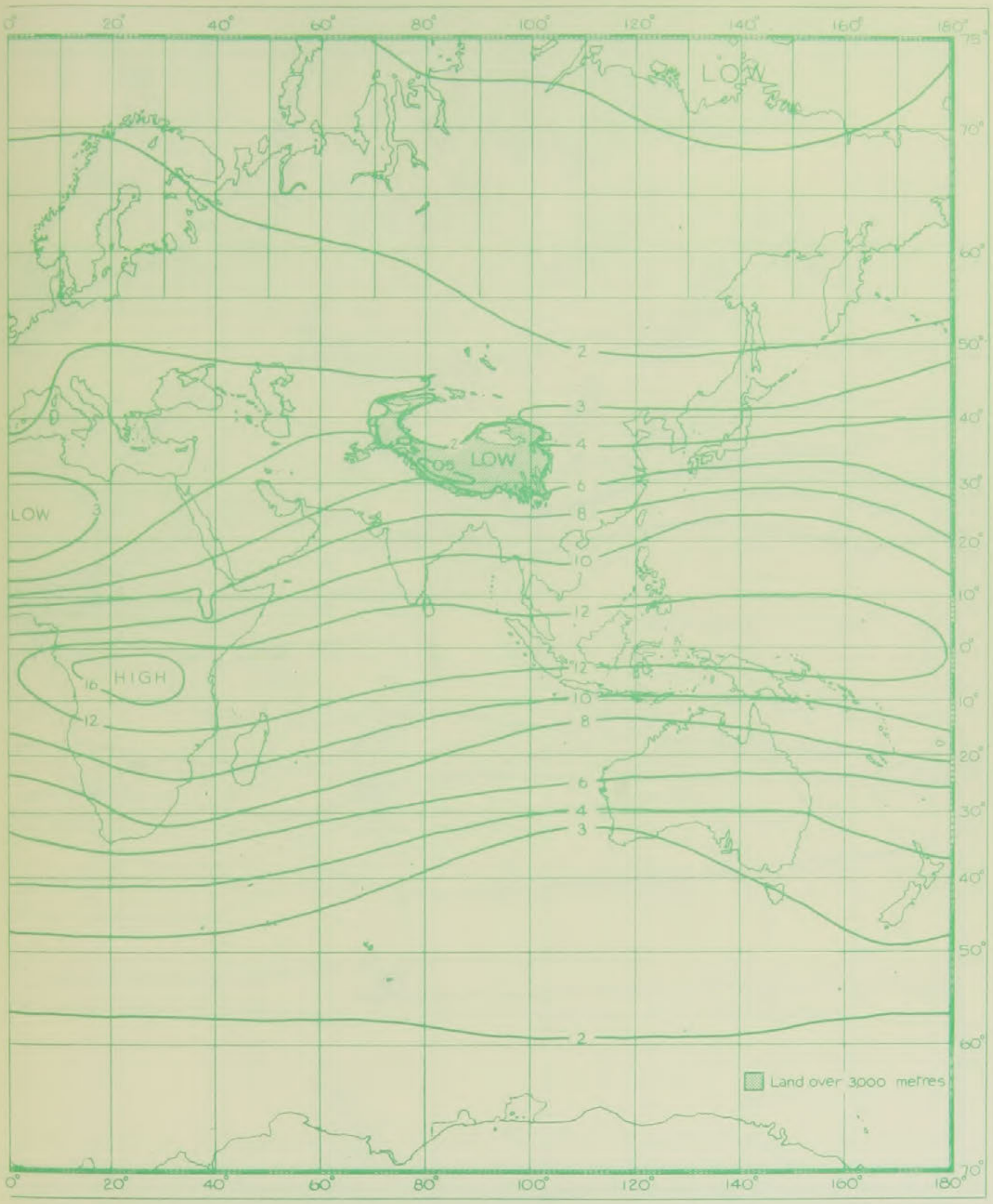


FIG. 2(c)—CONTINUED

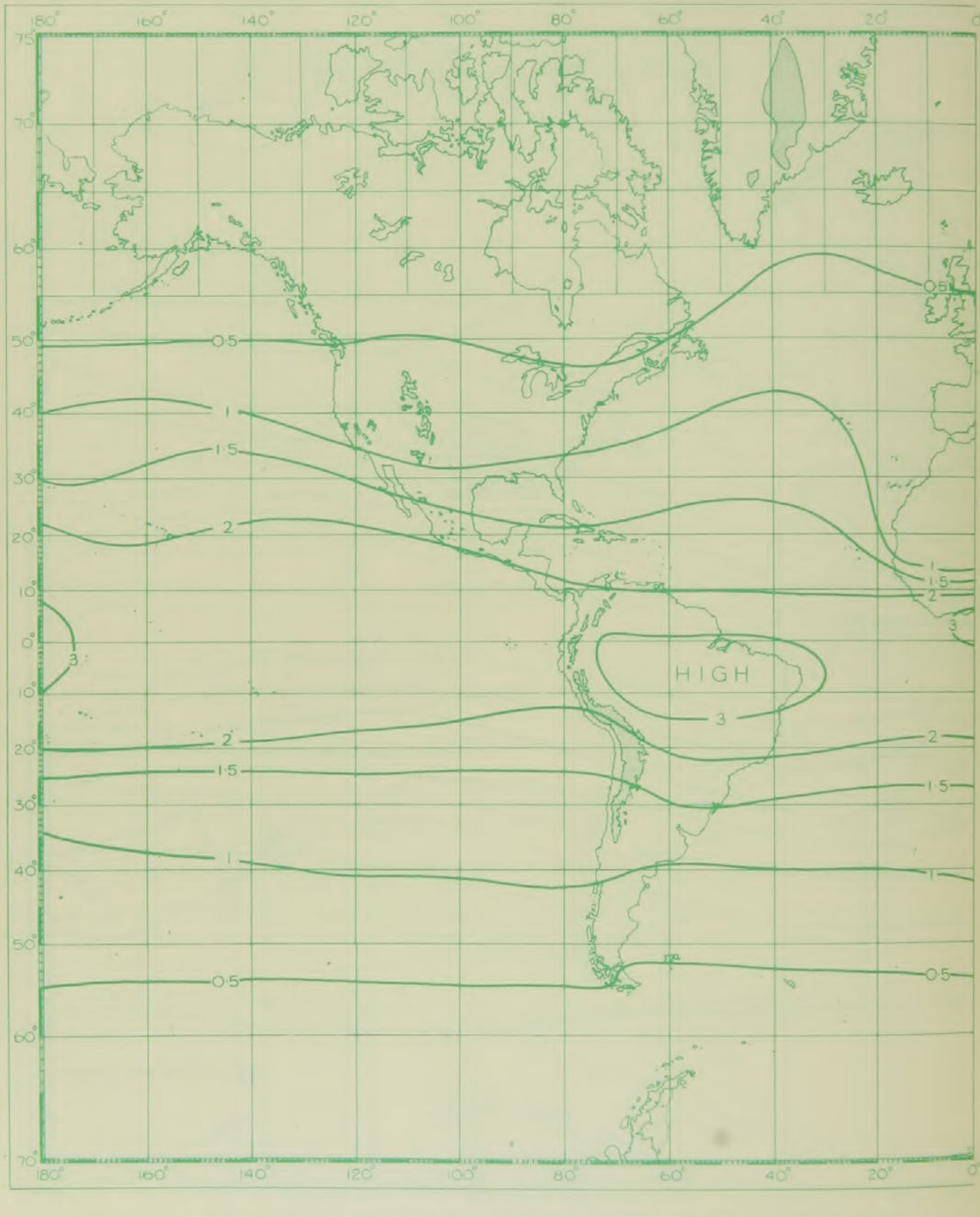


FIG. 2(*d*)—AVERAGE WATER-VAPOUR CONTENT OF THE AIR, IN DECIGRAMS, ABOVE ONE SQUARE CENTIMETRE AT 500 MILLIBARS, APRIL 1951–55

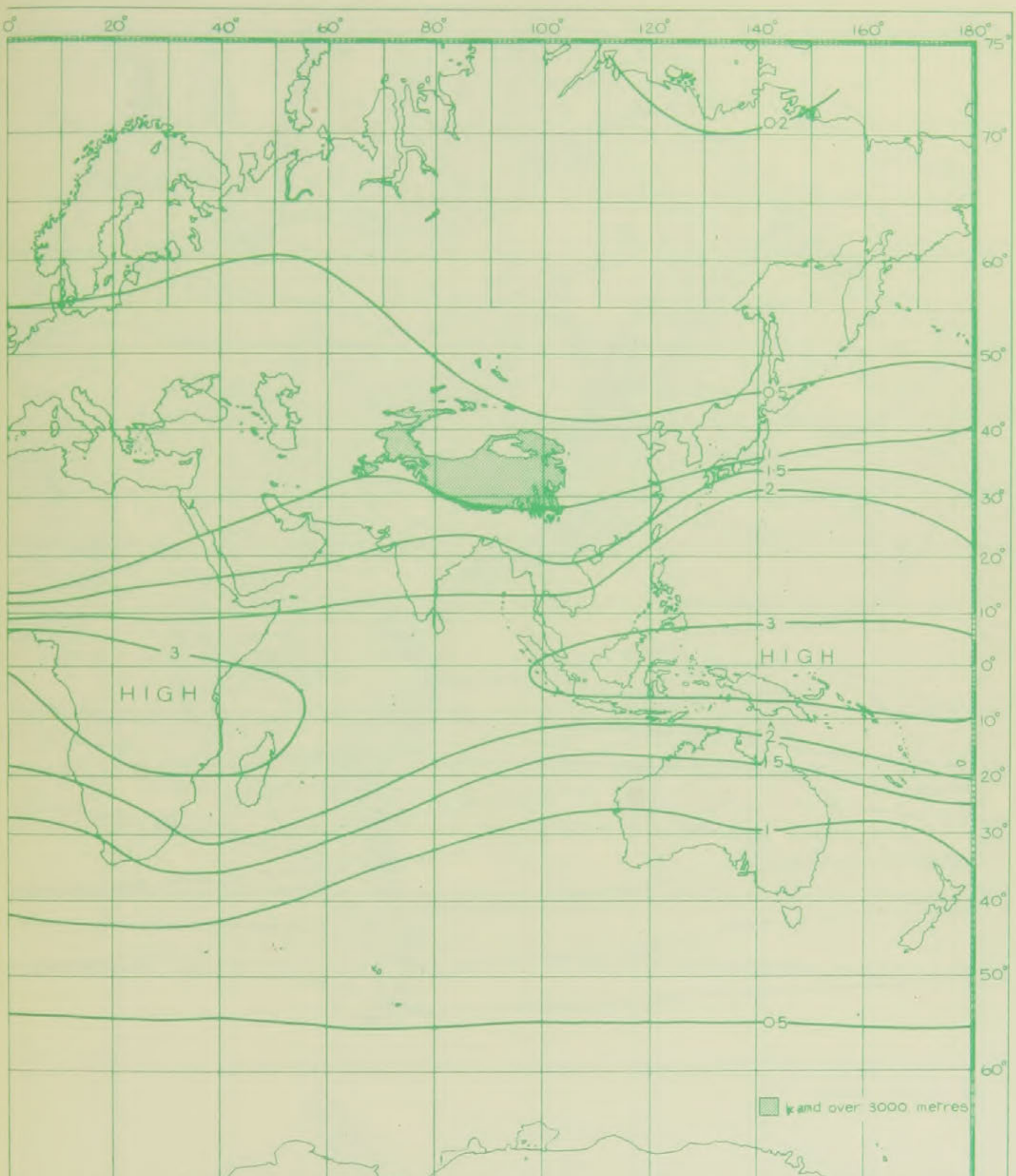


FIG. 2(*d*)—CONTINUED

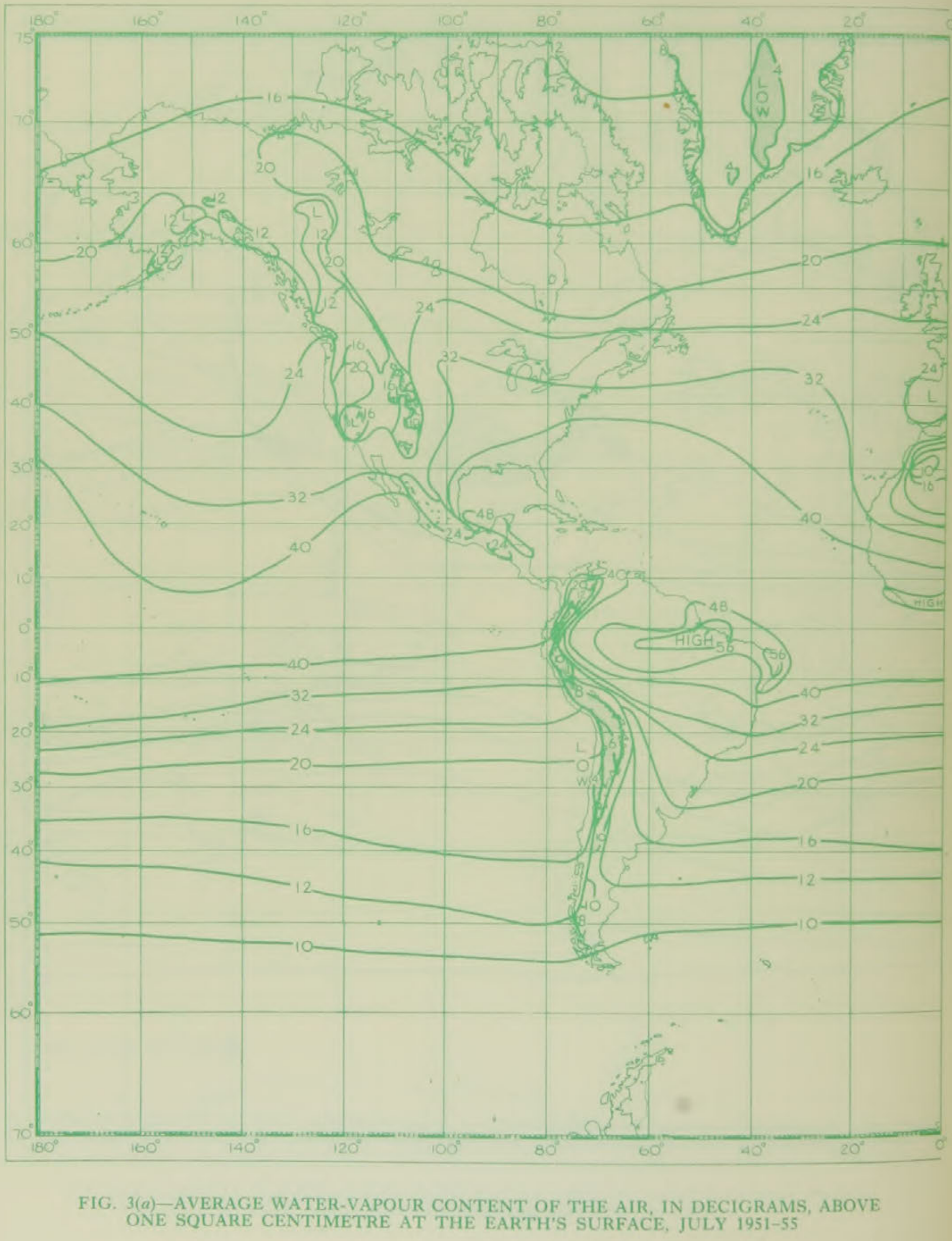


FIG. 3(*a*)—AVERAGE WATER-VAPOUR CONTENT OF THE AIR, IN DECIGRAMS, ABOVE ONE SQUARE CENTIMETRE AT THE EARTH'S SURFACE, JULY 1951–55

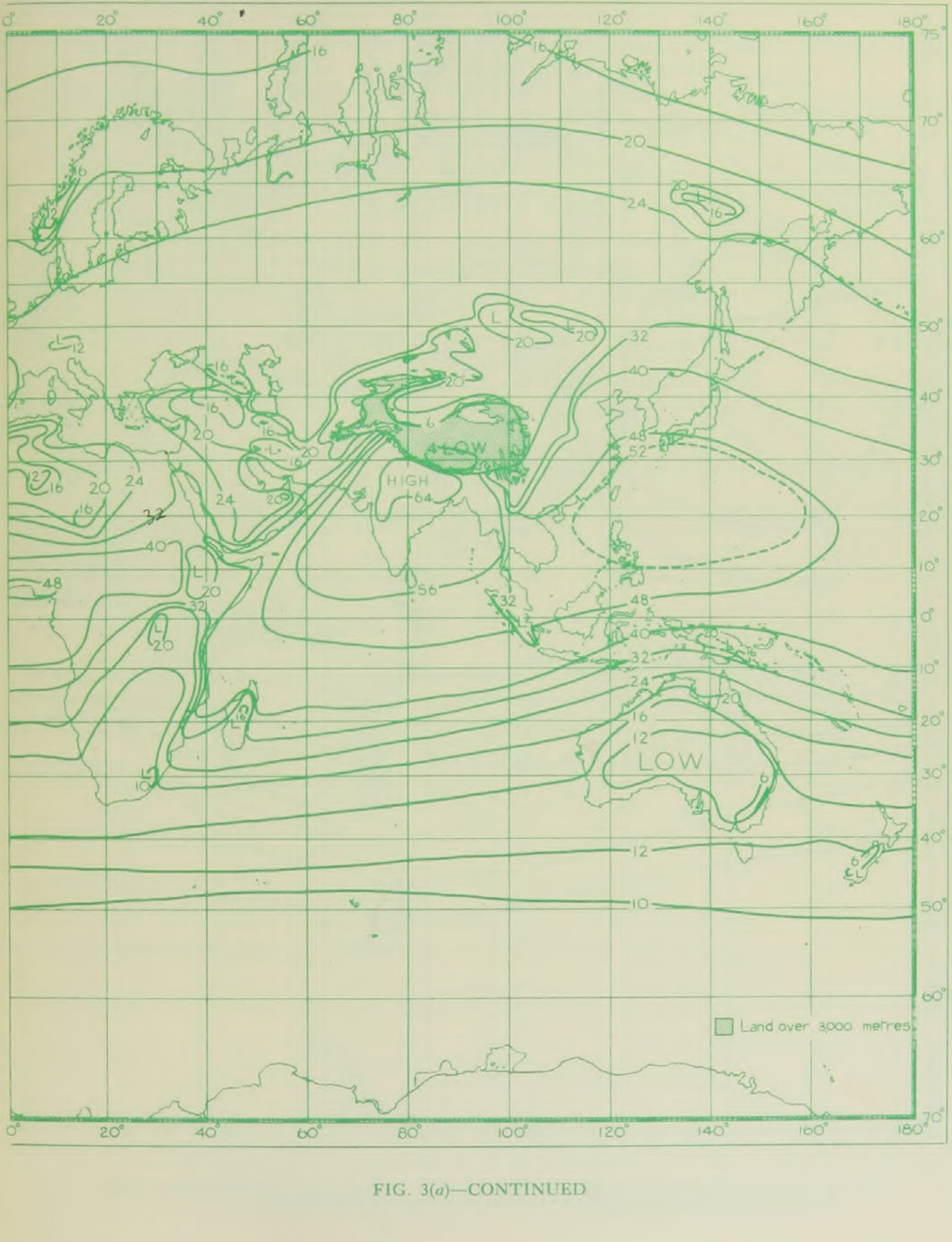


FIG. 3(*a*)—CONTINUED

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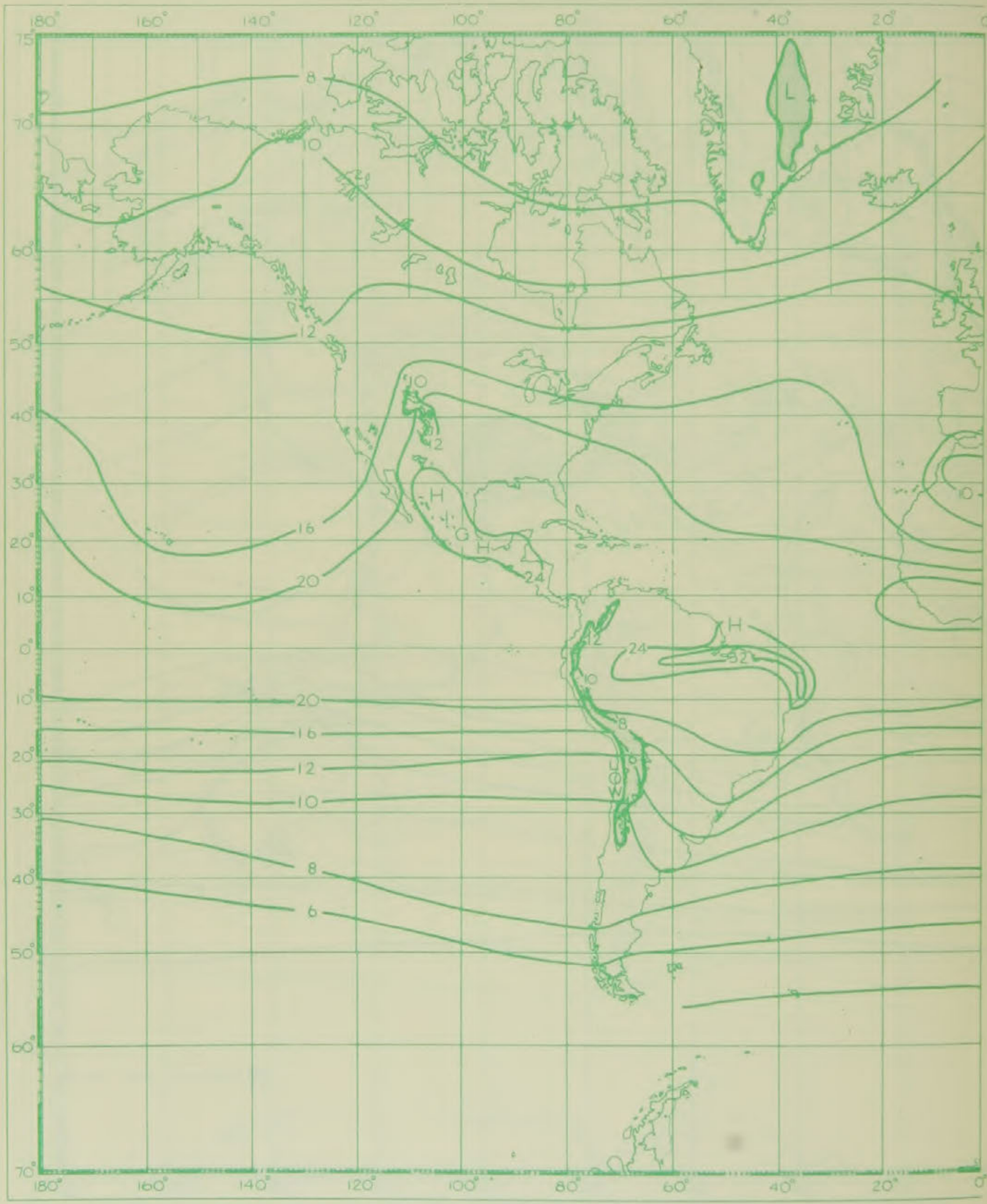


FIG. 3(*b*)—AVERAGE WATER-VAPOUR CONTENT OF THE AIR, IN DECIGRAMS, ABOVE ONE SQUARE CENTIMETRE AT 850 MILLIBARS, JULY 1951–55

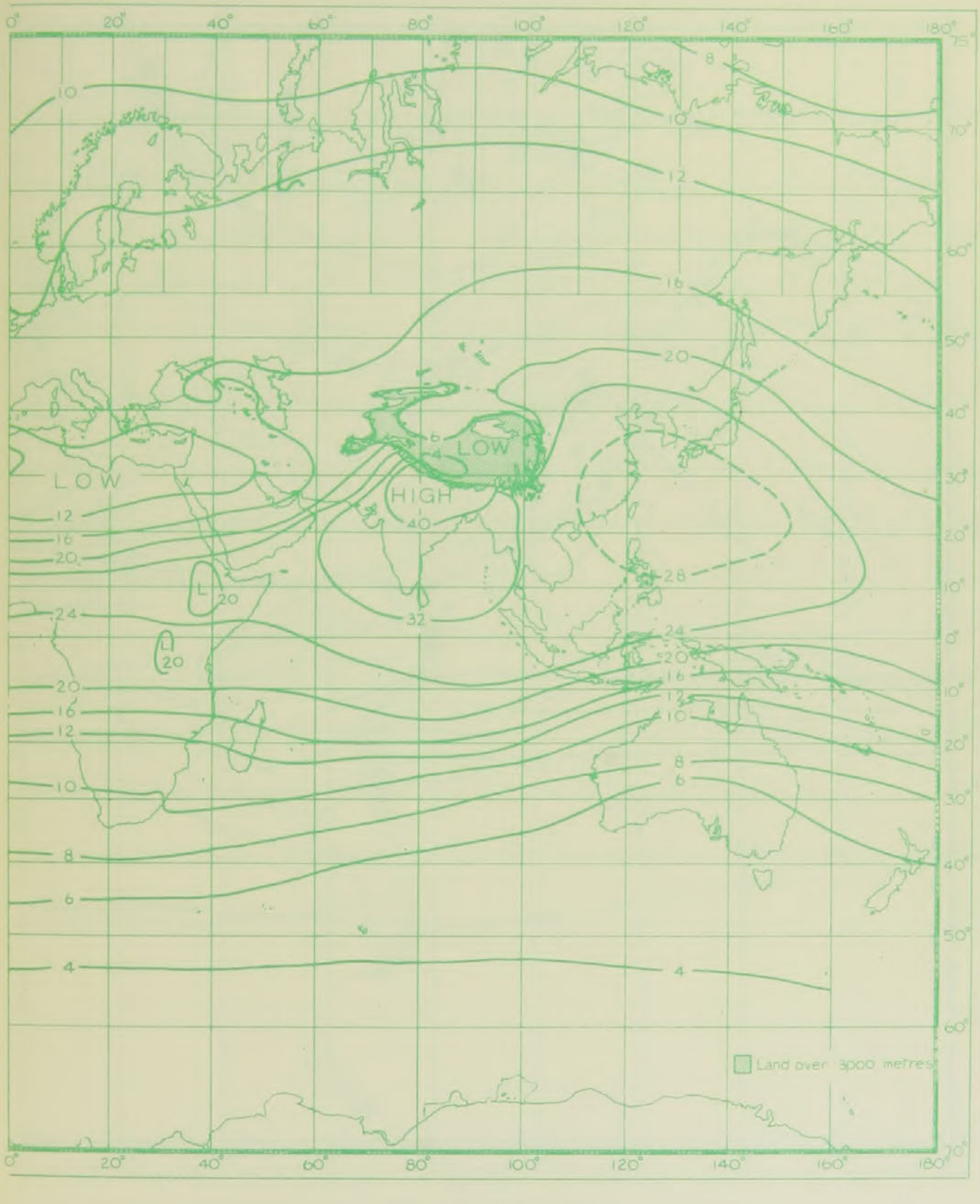


FIG. 3(*b*)—CONTINUED

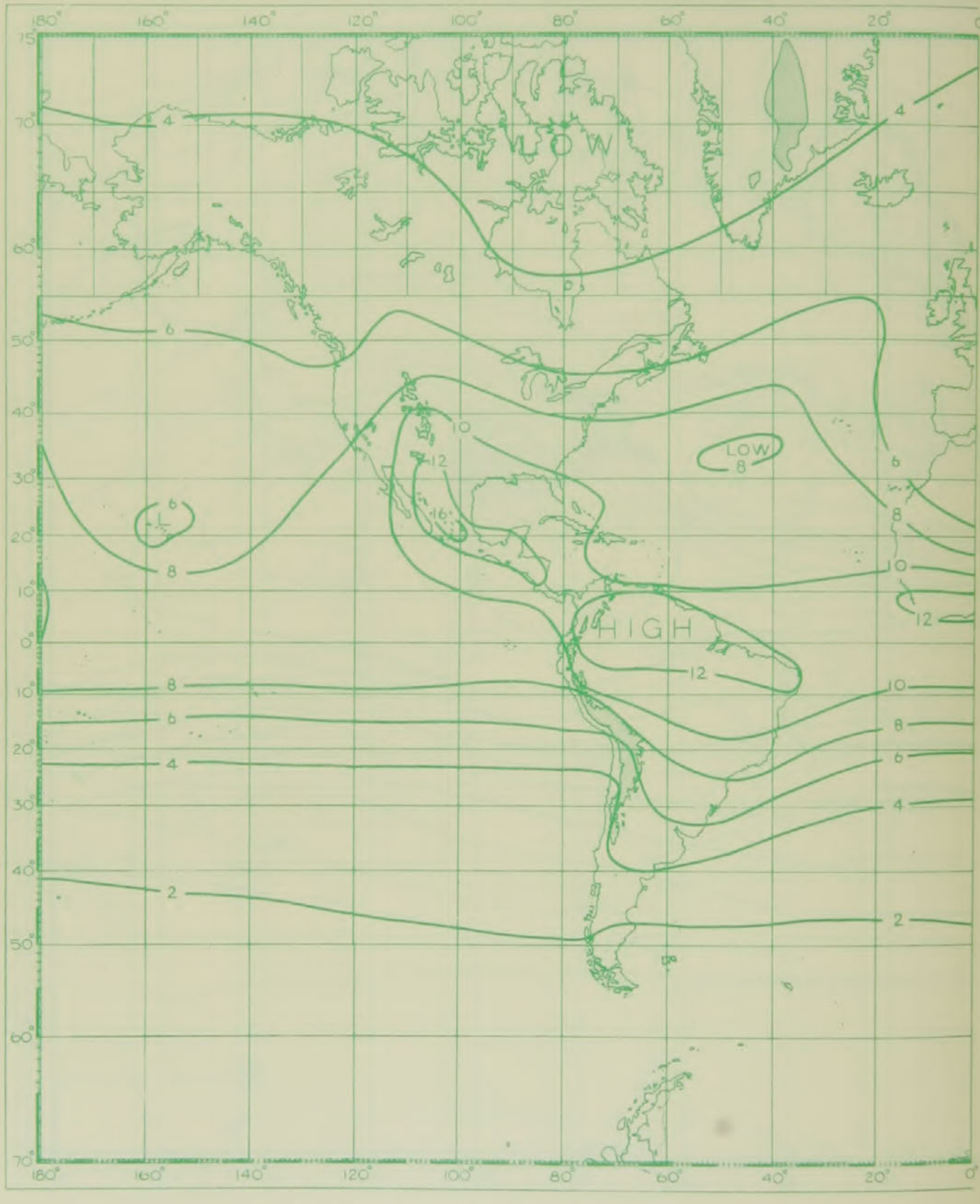


FIG. 3(*c*)—AVERAGE WATER-VAPOUR CONTENT OF THE AIR, IN DECIGRAMS, ABOVE ONE SQUARE CENTIMETRE AT 700 MILLIBARS, JULY 1951–55

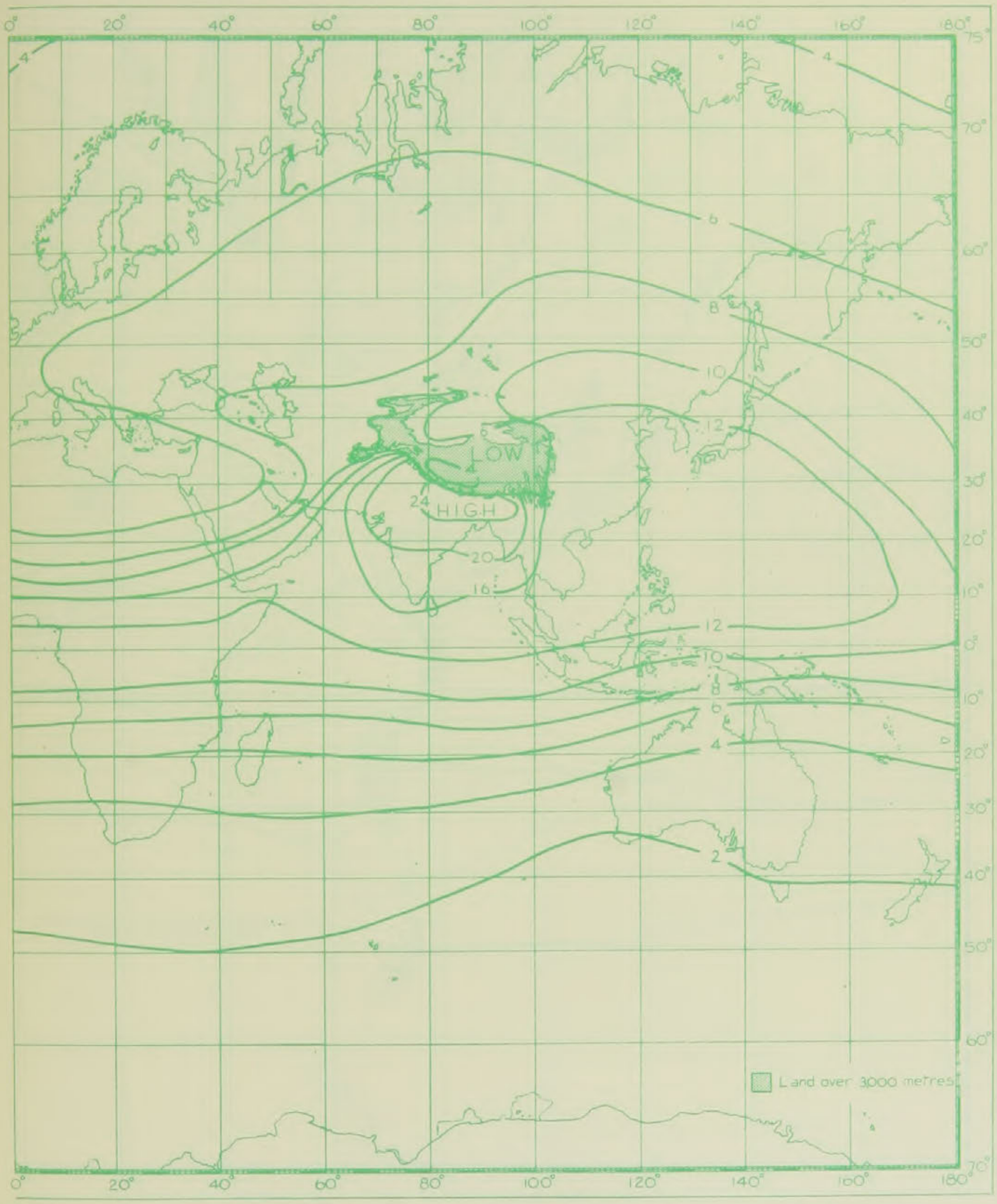


FIG. 3(c)—CONTINUED

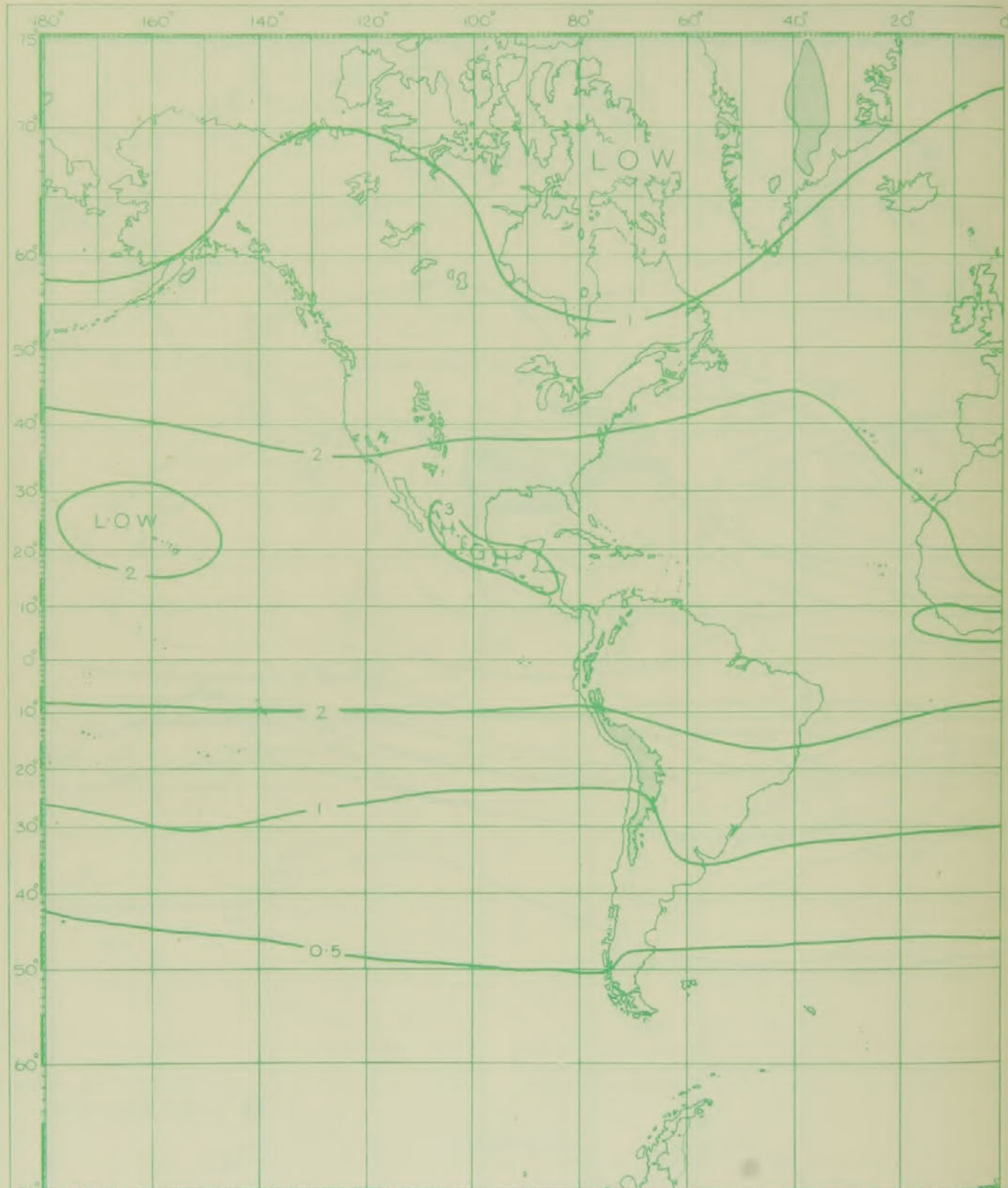


FIG. 3(*d*)—AVERAGE WATER-VAPOUR CONTENT OF THE AIR, IN DECIGRAMS, ABOVE ONE SQUARE CENTIMETRE AT 500 MILLIBARS, JULY 1951–55

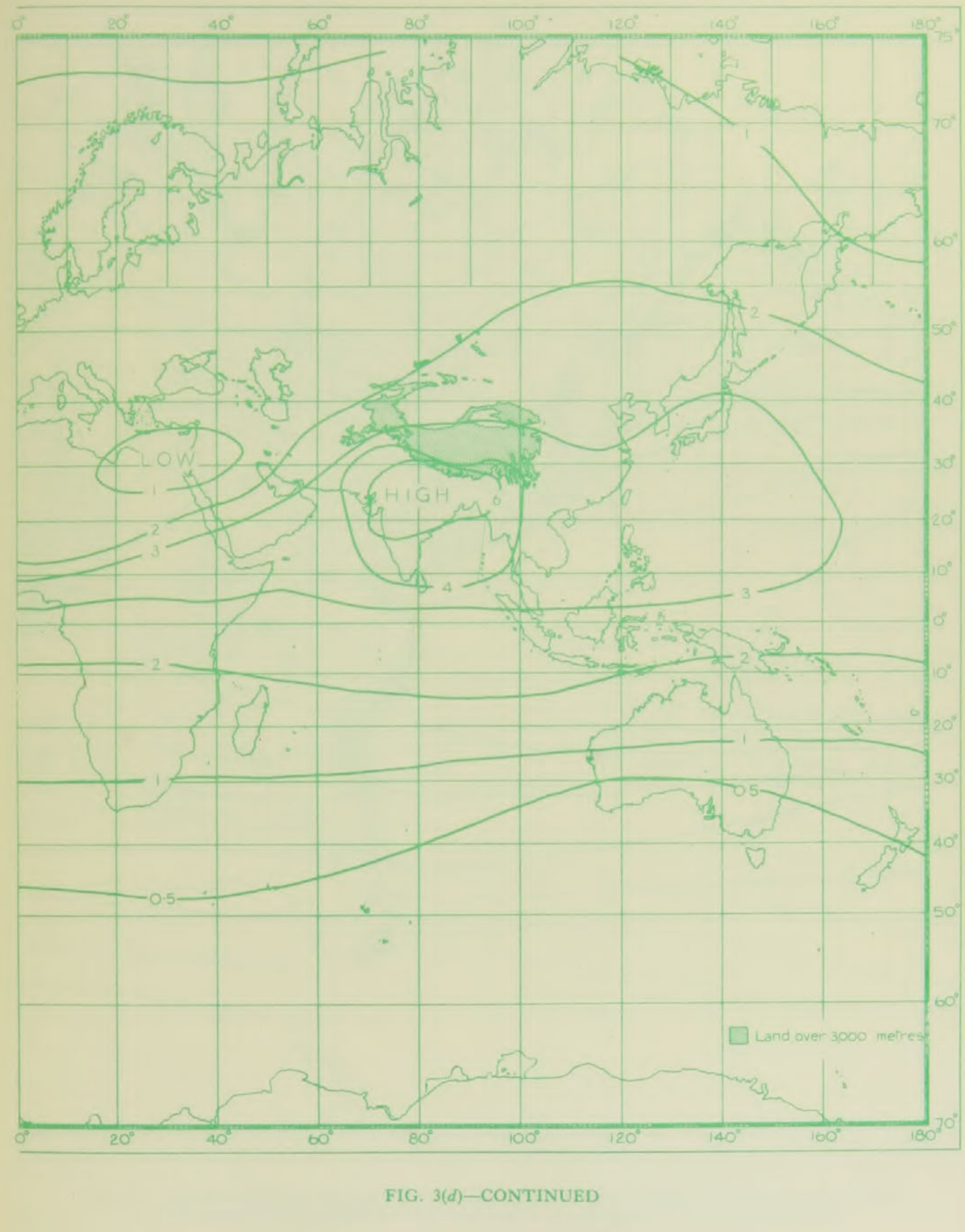


FIG. 3(*d*)—CONTINUED

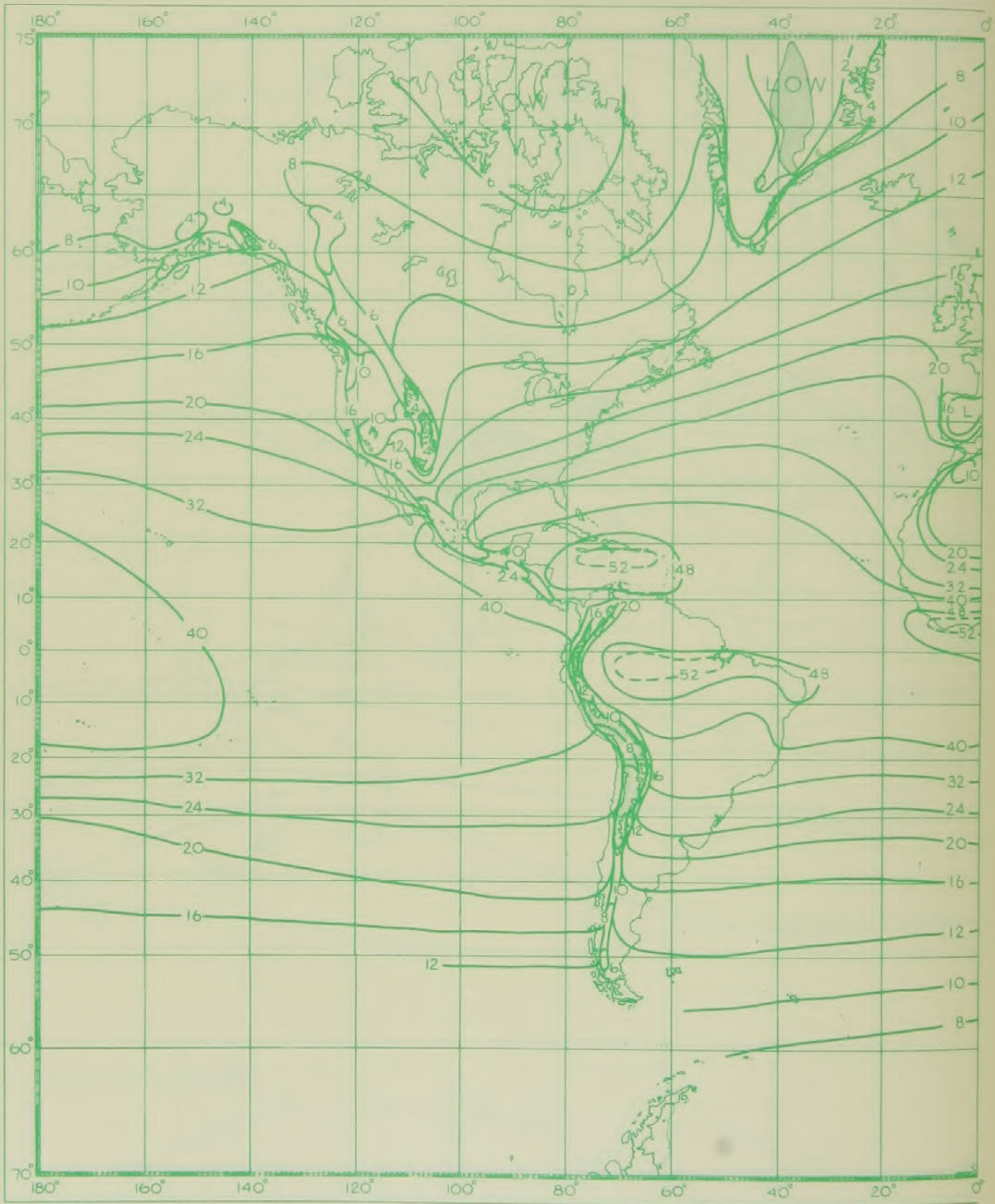

FIG. 4(*a*)—AVERAGE WATER-VAPOUR CONTENT OF THE AIR, IN DECIGRAMS, ABOVE ONE SQUARE CENTIMETRE AT THE EARTH'S SURFACE, OCTOBER 1951–55

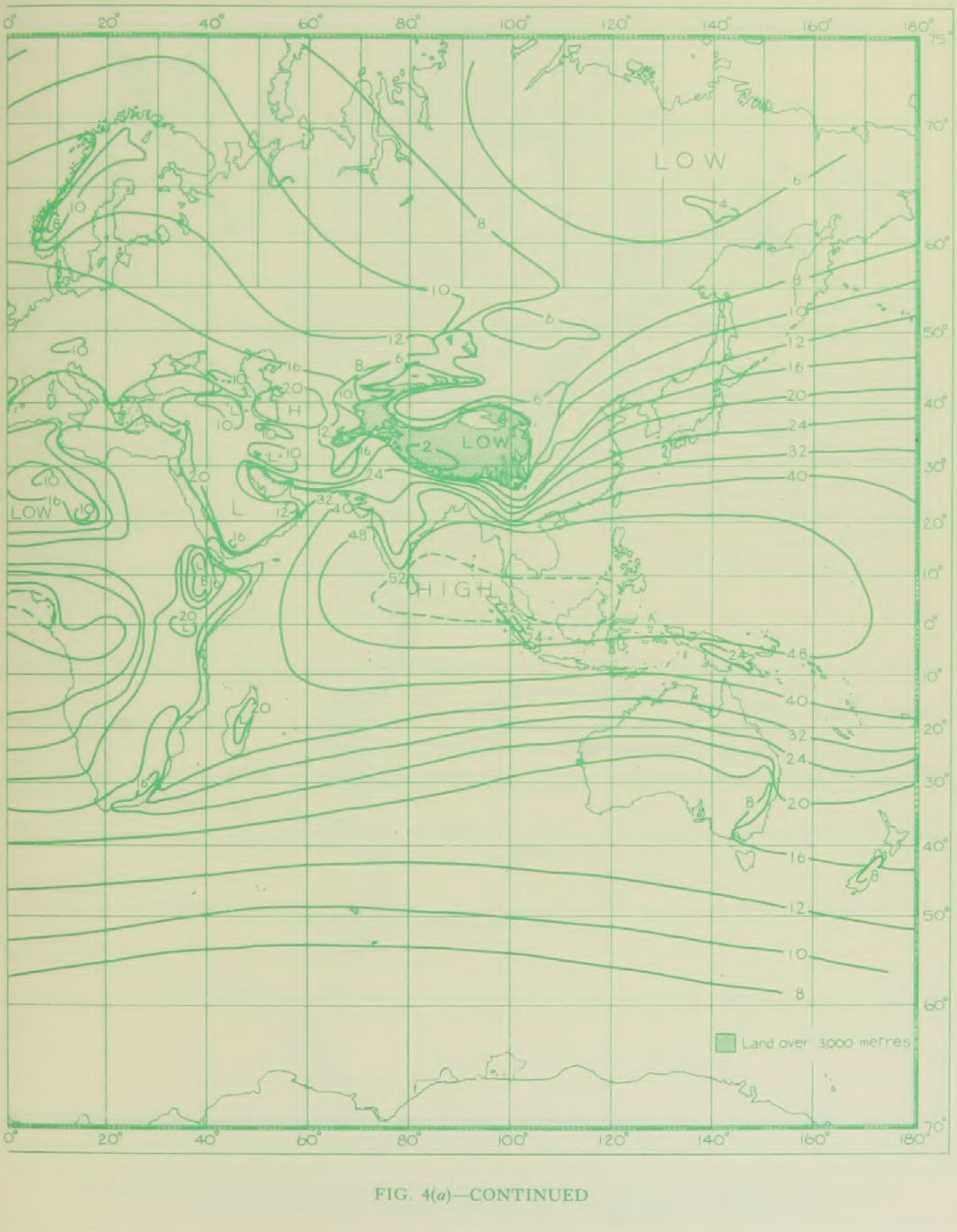


FIG. 4(*a*)—CONTINUED

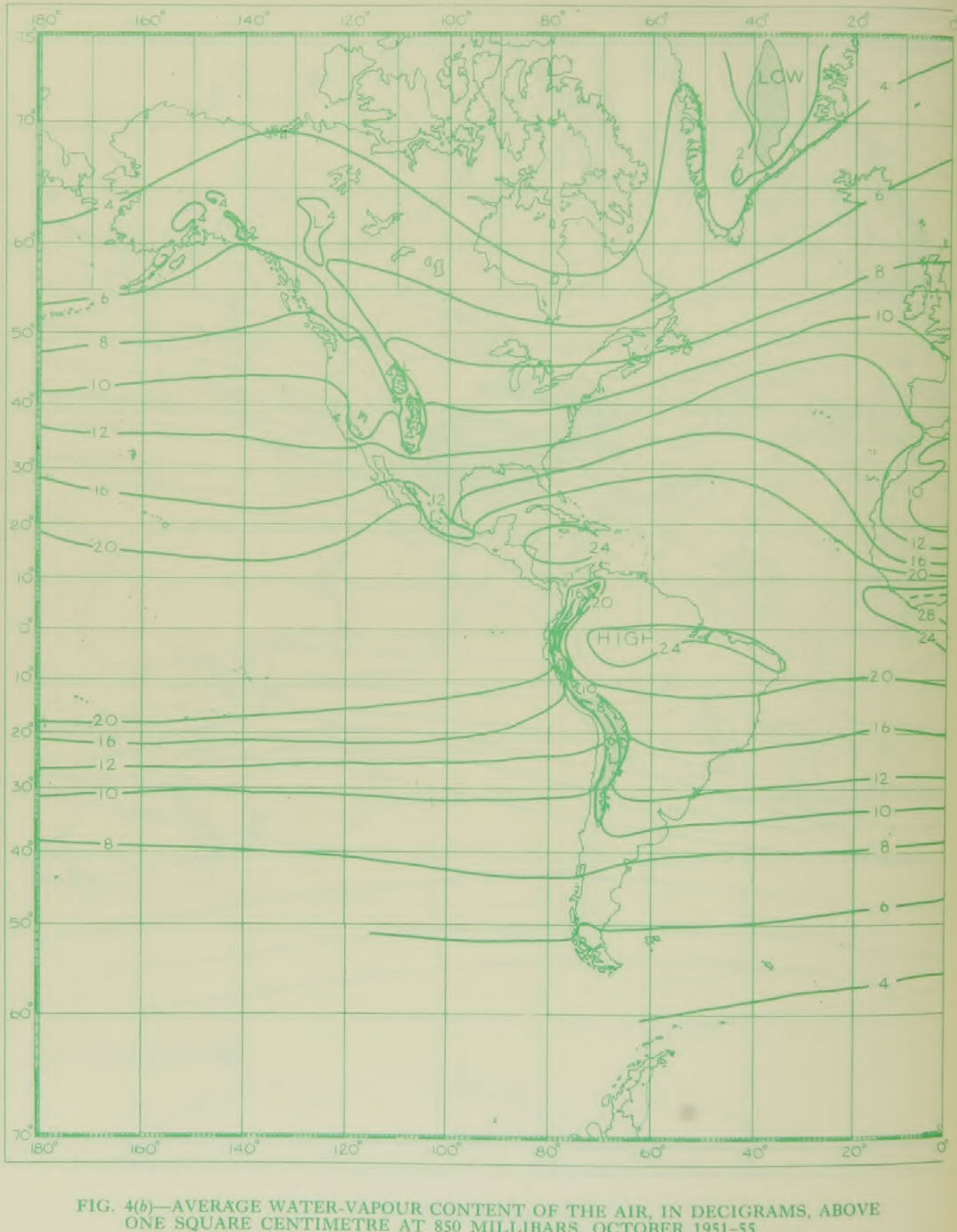


FIG. 4(*b*)—AVERAGE WATER-VAPOUR CONTENT OF THE AIR, IN DECIGRAMS, ABOVE ONE SQUARE CENTIMETRE AT 850 MILLIBARS, OCTOBER 1951–55

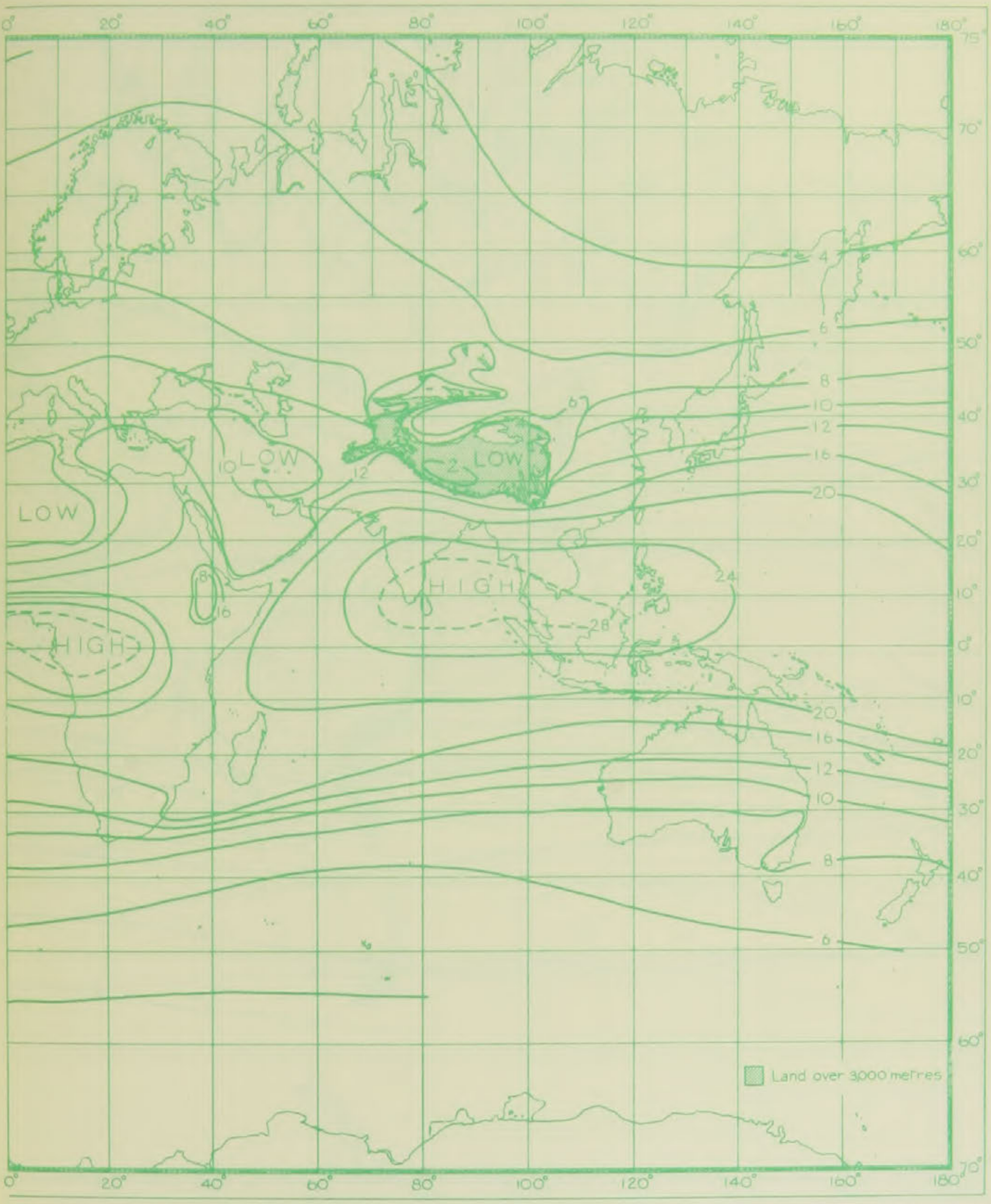


FIG. 4(*b*)—CONTINUED

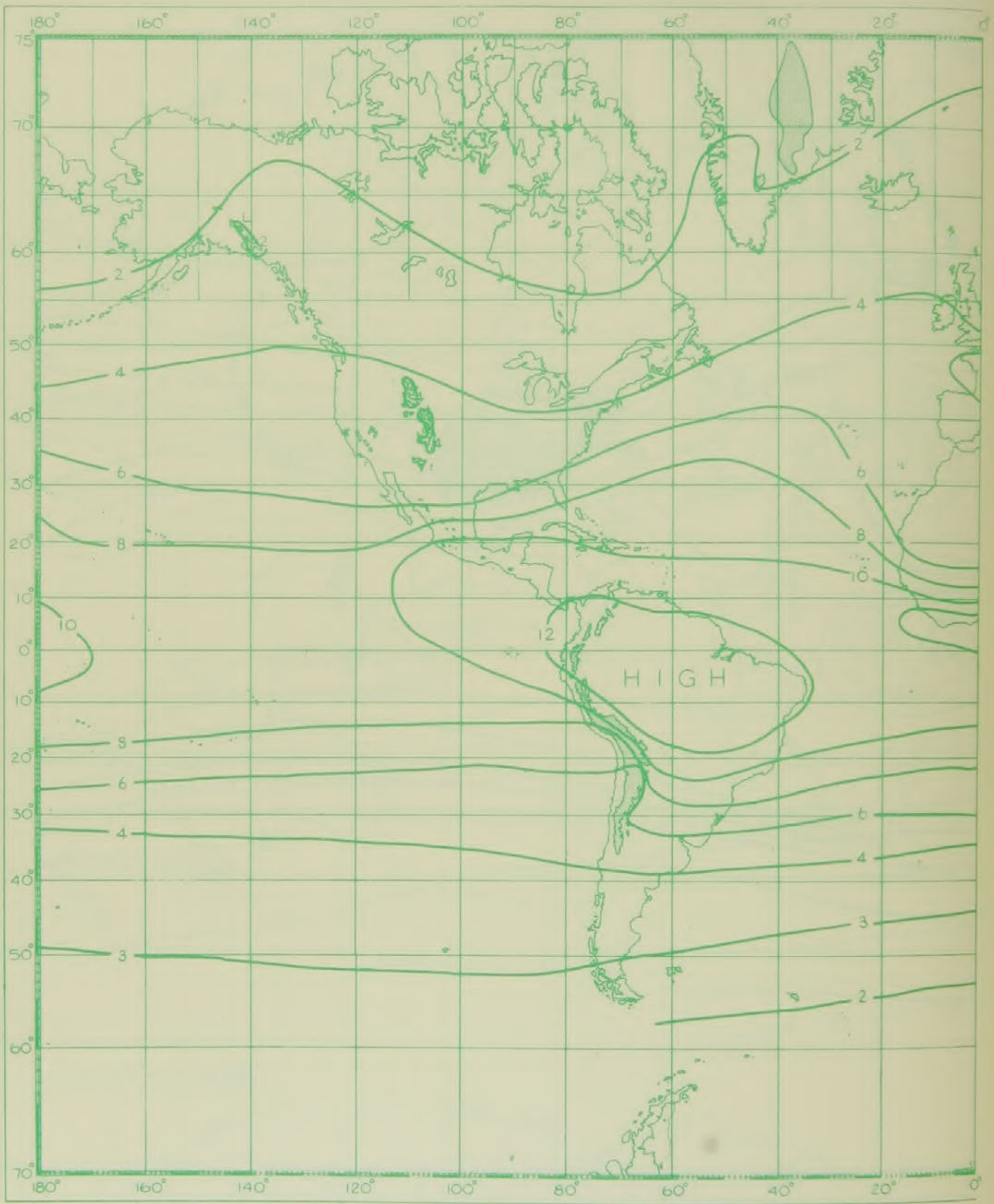


FIG. 4(c)—AVERAGE WATER-VAPOUR CONTENT OF THE AIR, IN DECIGRAMS, ABOVE ONE SQUARE CENTIMETRE AT 700 MILLIBARS, OCTOBER 1951–55

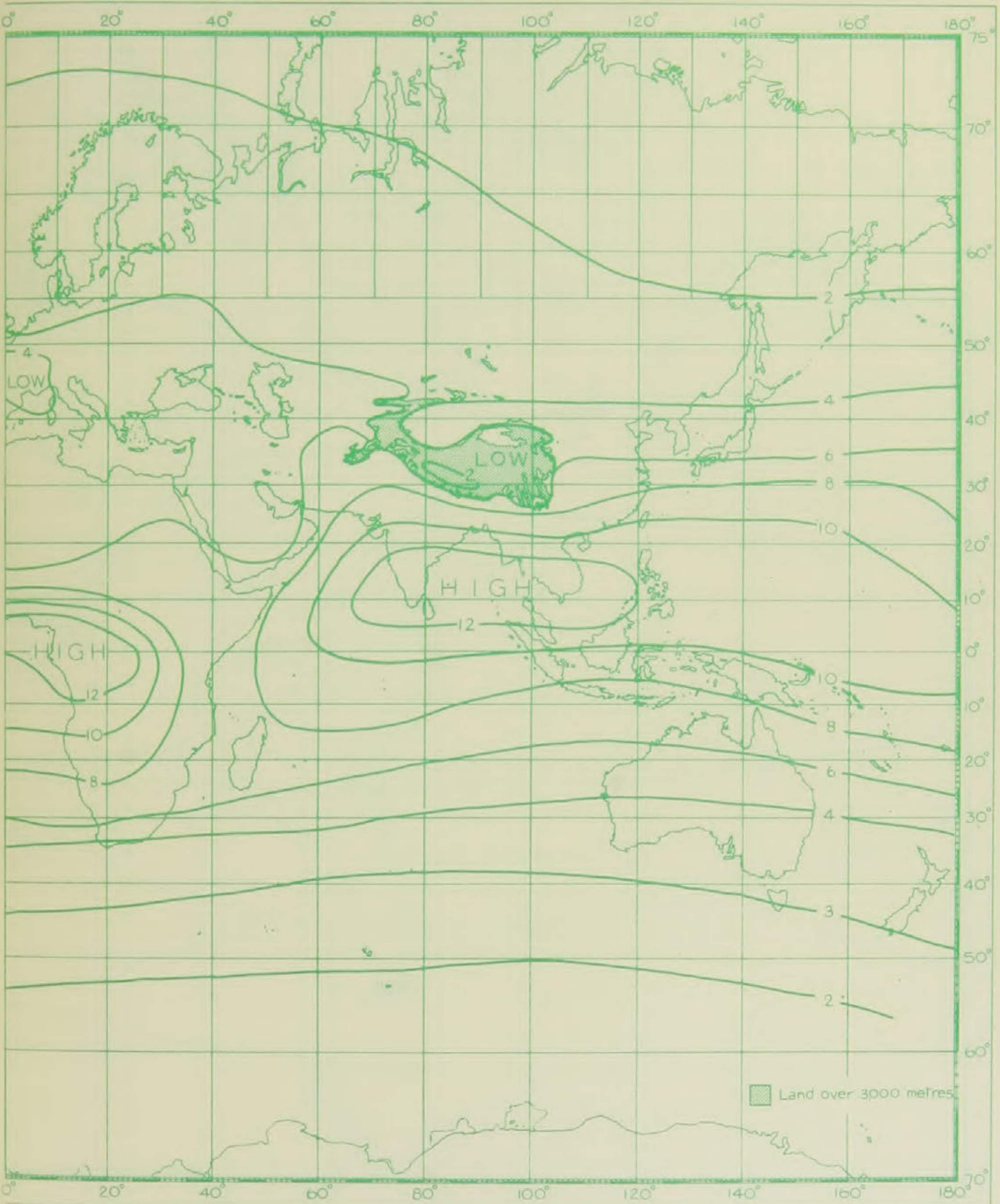


FIG. 4(*c*)—CONTINUED


FIG. 4(*d*)—AVERAGE WATER-VAPOUR CONTENT OF THE AIR, IN DECIGRAMS, ABOVE ONE SQUARE CENTIMETRE AT 500 MILLIBARS, OCTOBER 1951–55

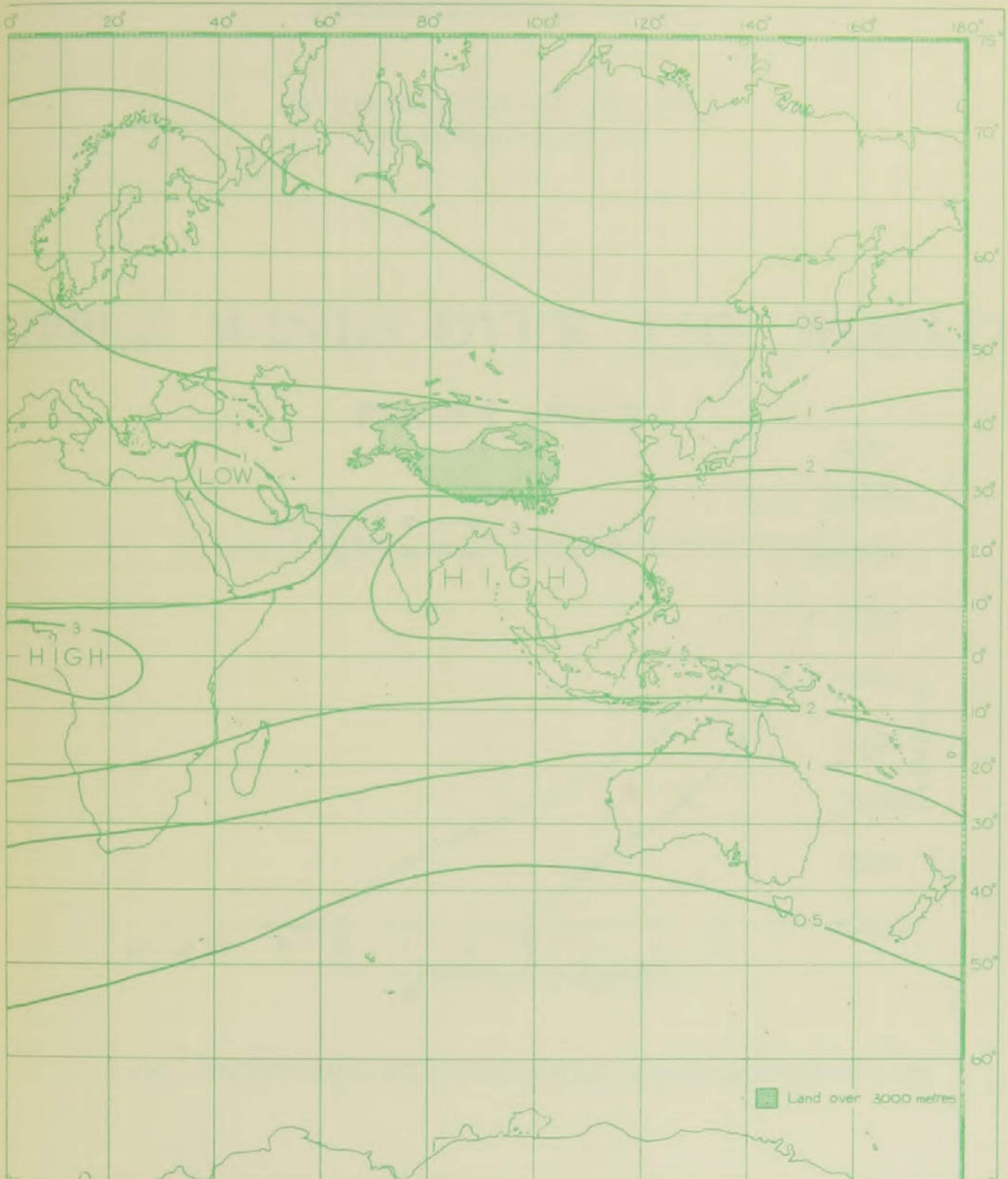


FIG. 4(d)—CONTINUED

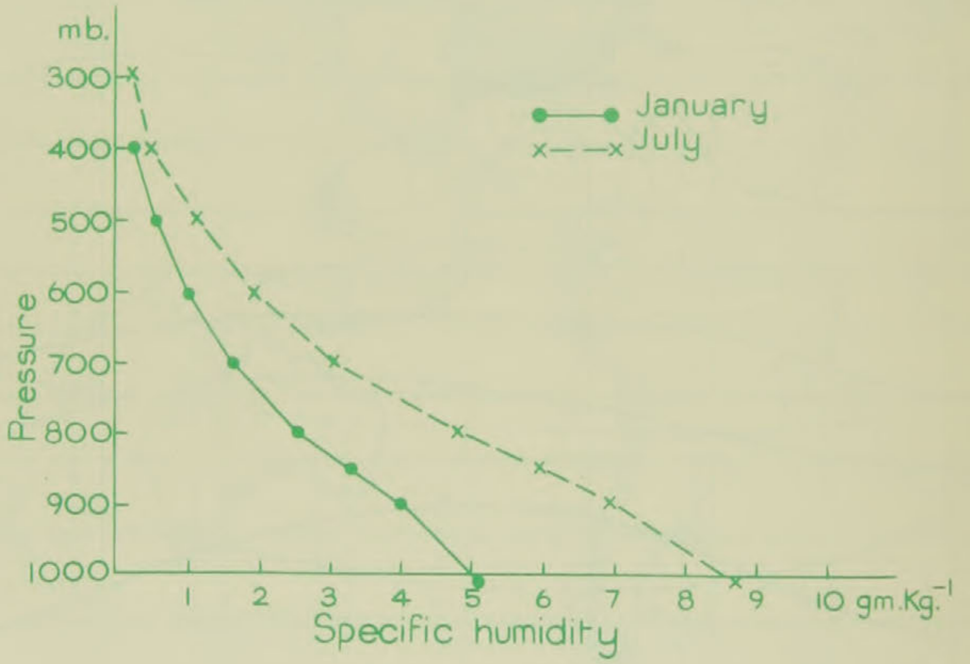


FIG. 5—MEAN WATER-VAPOUR CONTENT OF THE AIR ABOVE LARKHILL, 1946–50

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