SOUTHERN HEMISPHERIC ZONAL CIRCULATION

DURING THE IGY

by

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ABSTRACT

Using IGY data, tabulations of daily observational values of the wind were made at eight levels (850, 700, 500, 400, 300, 200, 100 and 50 mb) for 121 southern hemisphere plus 22 northern hemisphere equatorial stations during the six months period from April through September 1958. The mean value of the zonal component of the wind along with its standard deviation was computed for each station and pressure level. Maps of the mean values and standard deviations were analyzed to evaluate the mean southern hemisphere zonal circulation during winter.

It is found that the southern hemisphere has a much more intense zonal circulation than the northern hemisphere. Meridional profiles of zonal means reveal a double maximum in the upper tropospheric westerlies and a very intense stratospheric circulation surrounding the pole.

Thesis Supervisor: Victor P. Starr
Title: Professor of Meteorology

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To

Anna Belle

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I. INTRODUCTION

Up to now very little has been known about the state of the general circulation over the southern hemisphere. Earlier attempts at describing it were limited to theoretical estimates from surface data combined with analogies of northern hemisphere circulation. The only quantitative estimates made have been confined largely to cross sections of the Australia-New Zealand sector where reliable upper air data have been available for about 12 years. Meanwhile most of the hemisphere has remained in a relatively unexplored state due to lack of upper air observations.

But thanks to the International Geophysical Year and the effort put forth to establish new observation sites, mainly in Antarctica, and to collect data from all possible existing stations, the means are now available from which an almost complete analysis can be made of the southern hemisphere. Quantitative statements about the mean circulation, as represented during the IGY, can therefore be made.

In this report the mean zonal circulation of the southern hemisphere for the winter season (April to September inclusive) is examined by using the actual wind reports, following a procedure suggested by Starr (1954) and carried out by the General Circulation Project at M.I.T. in investigating the northern hemisphere circulation during 1950. The procedure involved tabulation of daily wind values for eight standard pressure levels from 850 to 50 mb for 143 stations. For each station the season mean and standard deviation of the zonal wind was computed. The hemispheric distribution of these quantities are presented on polar stereographic charts. Zonally averaged values were computed by integrating along the latitude circles, from which meridional profiles of the mean zonal circulation were constructed.

II. PREVIOUS INVESTIGATIONS

All previous attempts at describing the zonal circulation of the southern hemisphere have been plagued by the same problem - lack of sufficient representative data. This, mainly, is due to the vast ocean areas and the Antarctic where it has not been feasible to collect upper air data, but can also be attributed to the fact that southern hemisphere inhabitants, especially in South America, have been much slower in establishing upper air sounding stations than have been their northern hemisphere counterparts.

Since the Australia - New Zealand area was the first in the hemisphere to develop a radiosonde network, most of the earlier attempts at representing the southern hemisphere zonal circulation based on radiosonde observations were for the Australian sector. Lowe and Radok (1950) constructed a meridional cross section of the wind profile along eastern Australia (150° E) by using all the radiosonde data available at that time. Even then the area south of 54° was completely void of data except for some reports from Little America (78.5° S). Figure 1 shows their cross section

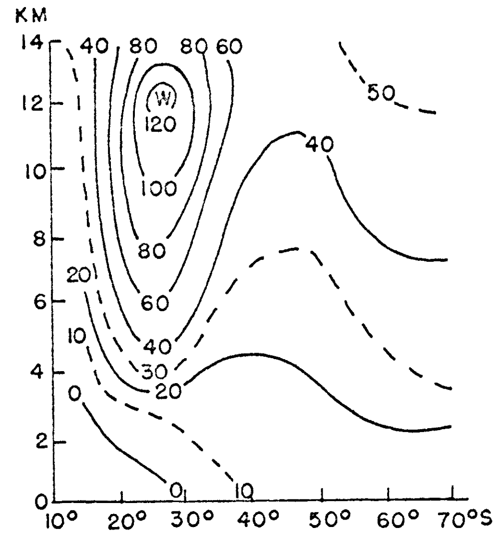

Figure 1. Mean zonal wind in miles per hour for southern hemisphere winter at 150° E. (From Lowe and Radok)

for the winter (June - August) season based on geostrophic approximations.

Their data indicated a maximum of westerlies at 12 km (200 mb) centered at 25° S, with a relative minimum of the westerlies throughout the middle and upper portion of the troposphere centered near 45° S. Another relative maximum was suggested near 65° S. At the time of the Lowe and Radok report the reality of the minimum at 45° was questioned, since it was based primarily on one year of data for Macguarie Island. Later information has confirmed this minimum, while the present report indicates that it may be hemispheric in nature.

In view of the more uniformly oceanic character and lesser continental protrusions into the atmosphere in the southern hemisphere, it was reasoned that a cross section along a certain longitude was likely to be closer to the general average than would be the case for the northern hemisphere. For these reasons and also for lack of any other data, cross sections through the Australia - New Zealand sector, of which Figure 1 is an example, were used as an estimate of the southern hemisphere zonal circulation.

Van Loon (1955) constructed a purely oceanic cross section by using only ocean data from different parts of the South Indian Ocean plus Antarctica data (Little America). Due to the diverse locations of stations used, his cross section cannot be considered as typical of any longitude but rather was designed to give a comparison of the oceanic regions to those cross sections valid for the Australia - New Zealand sector. His work is reproduced as Figure 2. Using the geostrophic approximation, he found the maximum winds to be in excess of 50 m/sec at about 200 mb centered over 38° S, thus being of the same magnitude but differing considerably in the position of the maximum when compared to those of Lowe and Radok. Neither report attempted to

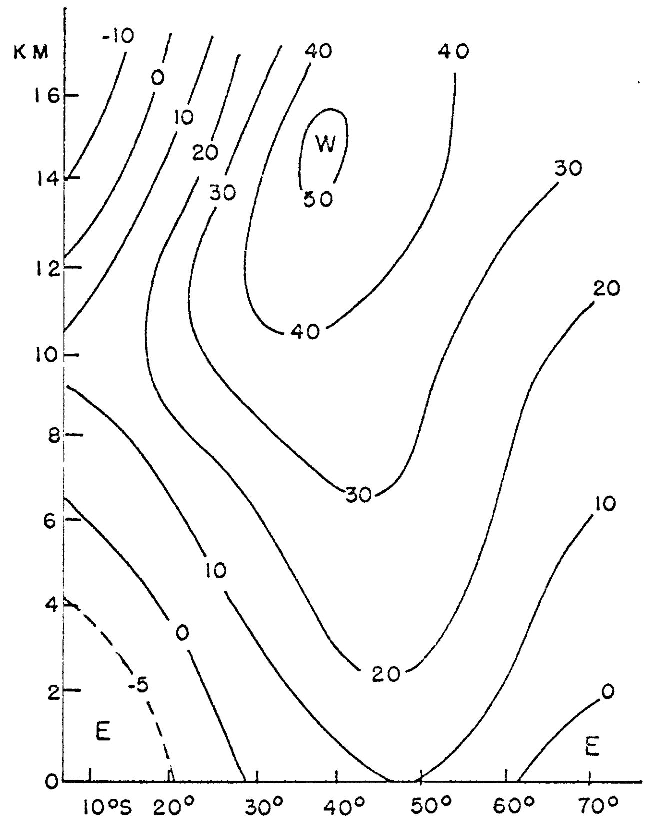

Figure 2. Mean zonal wind in meters per second for an oceanic region in southern hemisphere winter. (From van Loon)

describe the wind pattern equatorward of 10° S or poleward of 70° S.

Brooks (1950) using data available prior to 1950 attempted to construct the upper wind patterns over the world for pressure levels 700, 500, 300, 200 and 130 mb. Upper air soundings were used when available, but over large parts of the world where upper air data were insufficient, extrapolated data from surface observations were used. Even by these standards the data were too sparce to attempt a southern hemisphere analysis south of 50° S and no analysis whatsoever was attempted at or above 200 mb anywhere south of the equator.

The latest effort at achieving comprehensive analyses of the southern hemisphere came as a result of the Brussels meeting of CSAGI in 1955. At that time the Meteorological Service of the Union of South Africa was requested to analyze and publish daily synoptic weather maps for the southern hemisphere for the IGY. They agreed to analyze and publish the surface and 500 mb charts for the area south of 20° S. Upper air data representative of only about one third of the hemisphere were available (see Figure 3) and these were primarily from land stations. Using a method devised by Taljaard and van Loon (1960) whereby the 500 mb heights could be inferred from the local surface circulation pattern plus the 1000 mb height, the 500 mb pattern could be fairly well represented over one half the hemisphere (utilizing also ocean surface data). However, due to the slow receipt of data for the IGY by the Union of South Africa Meteorological Service publication of the daily series will be delayed (at least until the end of 1962).

Taljaard and van Loon (1958) using all the climatological data available for 59 radiosonde stations constructed monthly mean 1000-500 mb thickness charts for the entire southern hemisphere south of 20° with the exception of interior Antarctica. Their radiosonde data varied by station from one to two years of observations for the South American and Antarctic stations to 8 years or more for Australian stations. From their analyzed 1000-500 mb thickness charts the 500 mb geostrophic isotach patterns were constructed.

Since this work represents possibly the first and most comprehensive effort at analyzing the southern hemisphere mean circulation, reference to it will be made, as a comparison, for the middle troposphere.

III. DATA

Three data centers were established to maintain collections of IGY data (1960), WDC-A at Asheville, N. C., WDC-B in Russia, and WDC-C in the Secretariat of World Meteorological Organizations at Geneva. It was the responsibility of WDC-C to collect all essential synoptic observational data in meteorology for the IGY. These data were then reproduced on microcards and made available to participating countries, scientific institutions and research workers.

The basic data in this report were taken from microcards furnished by the WMO. A total of 143 stations (Table 1) were used in making this report of which 22 were in the northern hemisphere equatorial region but close enough to be valuable in completing the analysis near the equator. All the wind reports available between 1 April and 30 September 1958 were tabulated for the eight pressure levels: 850, 700, 500, 400, 300, 200, 100 and 50 mb. This represents the winter season for the southern hemisphere. The 00Z observation was used as the primary ones, but where some stations lacked sufficient 00Z reports and had a more complete

Table I. List of Stations

(Stations are listed according to WMO index numbers. Under Type the letter W indicates Pibals; R indicates Radio Winds.)

Index	Station Name	Latitude	Longitude	Type
43-371	Trivandrum	08 29 N	76 57 E	R
43-369	Minicoy	08 18 N	73 00 E	W
43-466	Colombo	06 54 N	79 52 E	R
48-694	Singapore	01 18 N	103 53 E	R
61-832	Conakry	09 34 N	13 37 W	R
61-931	S. Tome	00 23 N	06 43 E	R
61-967	Diego Garcia	07 14 S	72 26 E	W
61-974	Agalega	10 33 S	56 45 E	W
61-986	St. Brandon	16 25 S	59 33 E	W
61-988	Rodrigues	19 41 S	63 27 E	W
61-993	Pample Mousses	20 26 S	57 40 E	R
61-995	Vacoas	20 18 S	57 30 E	W
63-450	Addis Ababa	09 00 N	38 44 E	W
63-705	Entebbe	00 03 S	32 32 E	R
63-741	Nairobi	01 15 S	36 49 E	R
63-894	Dar-es-Salaam	06 48 S	39 12 E	W
64-005	Coquilhatville	00 03 N	18 17 E	R
64-076	Bunia	01 30 N	30 13 E	W
64-210	Leopoldville	04 19 S	15 18 E	R
64-360	Elisabethville	11 36 S	27 32 E	R
64-501	Port-Gentil	00 42 S	08 45 E	R
64-650	Bangui	04 22 N	18 34 E	R
64-910	Douala	04 01 N	09 42 E	R
65-201	Lagos	06 35 N	03 20 E	R
65-578	Abidjan	05 15 N	03 56 W	R
66-160	Luanda	08 50 S	13 12 E	R
67-009	Diego-Suarez	12 17 S	49 18 E	R
67-085	Tannanarive	18 54 S	47 32 E	R
67-197	Ft. Dauphin	25 02 S	46 48 E	R
67-341	Margues	25 55 S	32 34 E	W
67-198	N'lle Amsterdam	37 50 S	77 34 E	R
67-587	Lilongwe	13 59 S	33 45 E	R
67-663	Broken Hill	14 28 S	28 27 E	R

Index	Station Name	Latitude	Longitude	Type
67-774	Salisbury (Observatory)	17 50 S	31 01 E	R
68-100	Swakopmund	22 41 S	14 31 E	R
68-032	Maun	19 59 S	23 25 E	R
68-262	Pretoria	25 45 S	28 14 E	R
68-406	Alexander Bay	28 37 S	16 29 E	R
68-442	Bloemfontein	29 07 S	26 11 E	W
68-588	Durban	29 50 S	31 02 E	R
68-816	Capetown	33 58 S	18 36 E	R
68-906	Gough Island	40 03 S	09 55 W	W
68-994	Rio Gallegos	46 51 S	37 52 E	R
78-806	Albrook	08 58 N	79 34 W	R
81-405	Cayenne	04 50 N	52 22 W	R
82-400	Fernando Noronha	03 50 S	32 25 W	R
82-798	Monteiro	07 53 S	37 07 W	R
83-781	Sao Paulo	23 33 S	46 38 W	R
84-129	Guayaquil	02 10 S	79 52 W	R
84-377	Iquitos	03 45 S	73 11 W	W
84-390	Talara	04 34 S	81 15 W	W
84-452	Chiciavo	60 47 S	79 50 W	W
84-631	Lima	12 04 S	77 02 W	R
84-691	Pisco	13 45 S	76 14 W	W
85-406	Arica	18 22 S	70 21 W	W
85-442	Antofagasta	23 28 S	70 26 W	R
85-487	Vallenar	28 36 S	70 47 W	W
85-543	Quintero	32 47 S	71 32 W	R
85-579	Los Cerrilos	33 30 S	70 42 W	W
85-801	Puerto Montt	41 27 S	72 50 W	R
87-157	M. A. Resistencia	27 28 S	58 59 W	R
87-344	Meteo Aero Corbuba	31 19 S	64 13 W	R
87-576	Ezeiza	34 50 S	58 32 W	R
87-596	Punta Indio	35 22 S	57 27 W	W
87-715	Neuquen	38 57 S	68 09 W	R
87-748	Base Aerea Command Espora	38 44 S	62 10 W	W
87-774	Maquinchao	41 15 S	68 44 W	W
87-860	Comodoro Rivadavia	45 47 S	67 30 W	R
87-983	Ushuaia	58 48 S	68 19 W	W
88-890	Port Stanley	51 42 S	57 52 W	R
88-952	Argentine Island	65 15 S	64 16 W	R
88-968	Orcadas	60 44 S	44 44 W	R

Index	Station Name	Latitude	Longitude	Type
89-001	Norway Base	70 20 S	02 00 W	R
89-009	Amundsen-Scott Station	90 00 S		R
89-002	Halley Bay	75 31 S	26 36 W	R
89-043	Ellsworth Station	77 43 S	41 07 W	R
89-125	Byrd Station	80 00 S	120 00 W	R
89-162	Little America V	78 14 S	161 55 W	R
89-522	Base Belge	71 00 S	23 00 E	R
89-592	Mirny	66 33 S	93 00 E	R
89-601	Oazis	66 16 S	100 44 E	R
89-606	Boctok	78 S	107 E	R
89-611	Wilkes IGY Station	66 15 S	110 35 E	R
89-664	Williams Facility	77 50 S	166 36 E	R
89-671	Adare Station	72 25 S	170 55 E	R
91-334	Truk	07 23 N	151 51 E	R
91-348	Ponape	06 58 N	158 13 E	R
91-366	Kwajalein	08 43 N	167 44 E	R
91-376	Majuro	07 05 N	171 23 E	R
91-408	Koror	07 20 N	134 29 E	R
91-413	Yap	09 29 N	138 08 E	R
91-680	Nandi	17 45 S	177 27 E	R
91-517	Honiara	09 25 S	159 58 E	R
91-489	Christmas Island	02 00 N	157 23 W	R
91-700	Canton Island	02 49 S	171 43 W	R
91-830	Aituataki	18 52 S	159 46 W	W
91-843	Rarotonga	21 12 S	159 46 W	W
91-938	Tahiti	17 32 S	149 35 W	R
91-958	Rapa	27 30 S	144 31 W	W
93-112	Whenuapai	36 47 S	174 38 E	R
93-291	Gisborne	38 40 S	177 59 E	W
93-401	Ohakea	40 12 S	175 23 E	R
93-434	Wellington	41 17 S	174 46 E	R
93-780	Harewood	43 29 S	172 32 E	R
93-844	Invercargill	46 25 S	168 19 E	R
94-027	Lae	06 43 S	147 00 E	R
94-035	Port Moresby	09 26 S	147 13 E	R
94-120	Darwin	12 26 S	130 52 E	R
94-203	Broome	17 57 S	122 13 E	R
94-234	Daly Waters	16 16 S	133 23 E	W
94-287	Cairns	16 55 S	145 46 E	W

Index	Station Name	Latitude	Longitude	Type
94-294	Townsville	19 15 S	146 46 E	R
94-299	Willis Island	16 18 S	149 59 E	W
94-300	Carnarvon	24 53 S	113 39 E	W
94-312	Port Hedland	20 23 S	118 37 E	R
94-326	Alice Spring	23 48 S	133 53 E	R
94-335	Cloncurry	20 40 S	140 30 E	R
94-374	Rockhampton	23 23 S	150 29 E	W
94-403	Geraldton	28 48 S	114 42 E	W
94 461	Giles	25 02 S	128 18 E	R
94-510	Charleville	26 25 S	146 17 E	R
94-610	Guildford	31 56 S	115 57 E	R
94-637	Kalgoorlie	30 46 S	121 27 E	W
94-693	Mildura	34 12 S	142 10 E	W
94-776	Williamtown	32 49 S	151 50 E	R
94 791	Coffs Harbour	30 18 S	153 08 E	W
94-821	Mt. Gambier	37 49 S	140 46 E	W
94-865	Melbourne	37 52 S	144 46 E	R
94-907	East Sale	38 06 S	147 08 E	W
94-910	Wagga	35 08 S	147 25 E	W
94-926	Canberra	35 18 S	149 12 E	W
94-968	Western Junction	43 33 S	147 13 E	W
94-974	Hobart	42 50 S	147 28 E	R
94-986	Mawson	67 36 S	62 53 E	R
94-995	Lord Howel Island	31 31 S	159 04 E	R
94-996	Norfolk Island	29 03 S	167 56 E	R
95-502	Dumont d'Urville	66 60 S	140 01 E	R
96-413	Kuching	01 29 N	110 20 E	W
96-933	Surabaja	07 13 S	112 43 E	R
97-502	Jefman	00 56 S	131 07 E	W
97-560	Biak	01 10 S	136 00 E	W
97-690	Sentani Hollandia	02 30 S	140 29 E	W
97-980	Merauke	08 28 S	140 23 E	W

set of data at 12Z, then the 12Z observations were substituted. For a station lacking representative observations at both 00Z and 12Z, the 06Z or 18Z observations were used. These reports were normally from pilot balloon observations, since the radio winds were taken only at 00Z and 12Z.

The horizontal wind vector at each station and level was resolved into its meridional and zonal components. In this study only the zonal component u is being considered. From these data the winter mean value of u was estimated by the formula

$$\bar{u} = \frac{1}{N} \sum_{i=1}^{N} u_i \tag{1}$$

where N is the total number of observations for the six month period. If the set of data is complete, then N has the value 183. Throughout this report the bar operator will indicate a time average.

A second quantity, the standard deviation, for each station and pressure level was estimated by the formula

$$s(u) = \sqrt{\frac{\sum_{i=1}^{N} (u_i - \bar{u})^2}{N - 1}} \quad . \tag{2}$$

Where the number of reports are fairly complete the estimated mean and standard deviation can be expected to describe the distribution of the zonal wind as was shown by Buch (1954).

To assess the southern hemisphere zonal circulation the values of $\bar{u}$ and s(u) computed by equations (1) and (2) for each station and pressure level were plotted on polar stereographic maps (scale approximately 1:40 million). The number of observations, N, from which the statistic was estimated was also plotted to serve as a guide in evaluating the data for analysis. Since the purpose of this study is to present the mean zonal flow over the entire hemisphere, the analysis of each chart was extended to cover the total area. In regions like the Pacific Ocean between 90 - 140° W, completely void of data, the analysis can be considered little more than a plausible guess. However, it is believed that a truer value of the zonal mean can be approximated from the "complete" analysis as opposed to having these large areas blank and assuming the good data areas to be representative of the whole latitude circles. This is particularly true when the perimeter data of the void area suggests different values than are found in the mean for the good data areas.

The analysis in the polar region where the zonal wind presents a singularity at the pole was carried out following a procedure suggested by Barnes (1962). Here the mean of the total wind vector was considered as valid in the region surrounding the pole. From this, the analysis could be extended as close to the pole as desired, but not to the pole itself.

To supplement the microcard data in the regions around Antarctica, the monthly mean constant pressure charts (700, 500, 300 and 200 mb) as presented by Alt (1959) were used. From his analyzed monthly mean charts the zonal components of the geostrophic wind were taken for 5 degree latitude increments along 40° W, 170° W and 60° E between 75° and 55° S. Using the six proper monthly maps in this fashion, the winter means were computed and plotted to aid in the isotach analysis for the area surrounding Antarctica. These data substantiated the secondary circumpolar maximum found near 55° S at both the 300 and 200 mb levels. (See Plates 5 and 6.)

IV. REPRESENTATIVENESS OF THE DATA

Mainly because of the large extent of ocean area (approximately 80%), the lack of island observing sites, and no weather ships, vast areas of the southern hemisphere are without upper air observations. The geographical locations of the 143 observation sites are shown in Figure 3. As can be seen, the land areas are fairly well saturated with the exception of interior Brazil, whereas the ocean areas are very sparcely covered. The 96 stations which reported radio winds during the IGY are indicated with an R while the 47 pilot balloon stations are indicated by W. Each observation site has a circle of radius 300 nautical miles surrounding it. If we assume that a station's observations are representative over this area, then throughout the lower troposphere about one third of the hemisphere can be represented accurately. In the upper troposphere and stratosphere where only the radio winds can be considered as accurate, the area of representative data is even less.

The mean values and standard deviations computed for

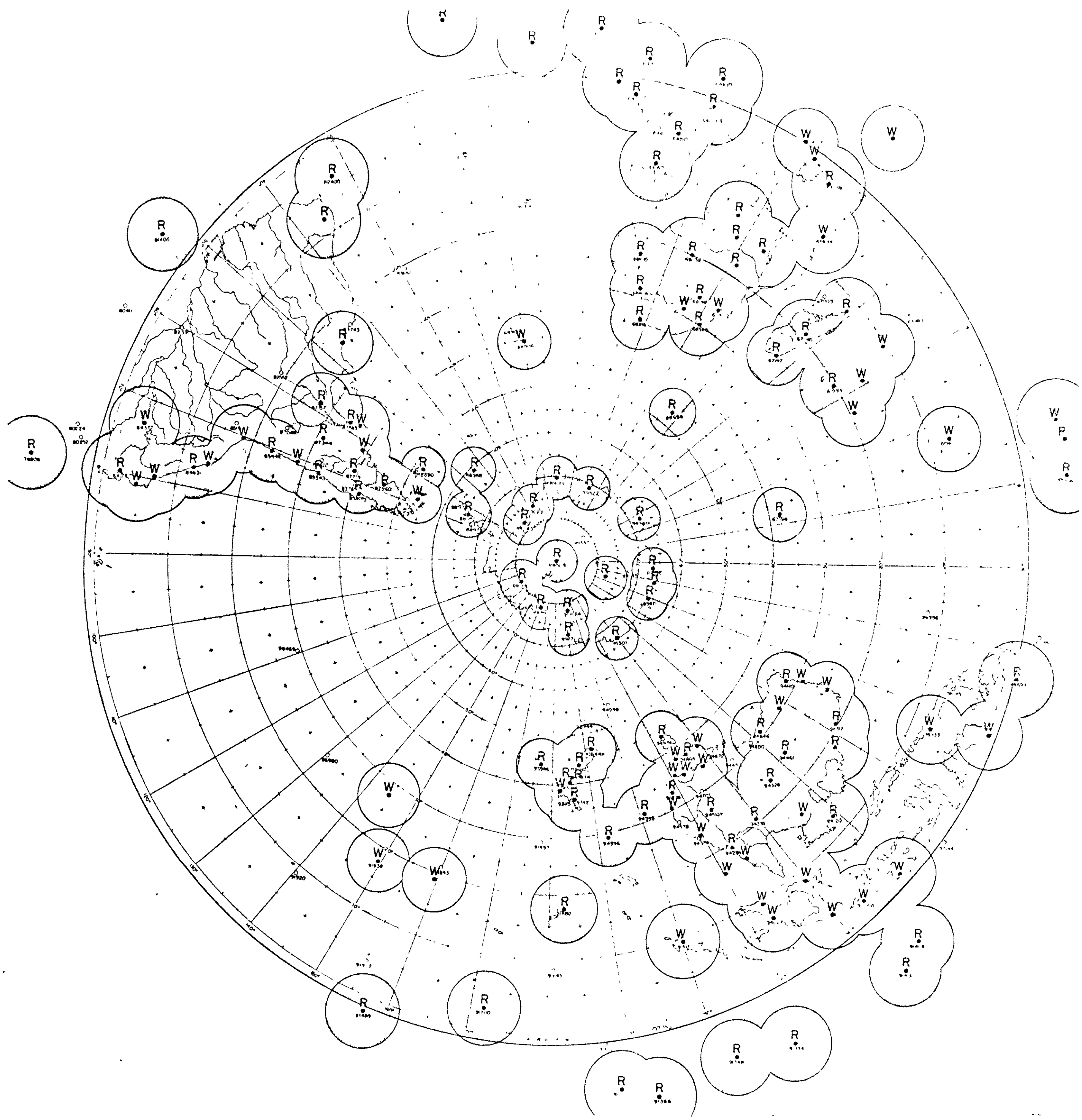

Figure 3. Geographical location of stations used in this report. R indicates radio wind sites; W indicates Pibal stations.

various stations are intended to be representative of the winter season. This requires that the selection of data be a random sample. The fact that the observations were taken at regular time intervals would suggest they are not random, however, we may still consider them random unless the winds just happened to have a period of fluctuation that coincided with the period of observations (one day).

The pilot balloon observations may be considered biased in favor of light winds and fair weather. Unless there are few or no clouds at low levels the balloon has a good chance of being lost near the ground. If the weather is fair and winds are strong then the balloon may have a short run due to drifting out of sight. For these reason pilot balloons cannot be considered representative unless the number of observations were a high percentage of the total possible. This being the case normally for the 850 and occasionally the 700 mb levels.

Because of the shortcomings of the pibal data, the primary data used were the 96 radio winds. Figure 3 reveals that the radio wind stations are even more landlocked than when considered in combination with the pibals. Most of these stations had fairly complete sets of data at least up to 100 mb where 50 stations reported more than one half of the possible 183. At 50 mb the percentage of reports drops off markedly, especially in the Antarctic regions. This has been attributed, in part, to the large percentage of balloon bursts due to the extremely cold stratospheric air where the polar night occasionally goes to -90°C. Nevertheless, due to the less variable wind patterns found in the stratosphere a fewer number of observations should be required for a representative estimate of the circulation.

It has been argued in the past that even radio wind observations should be biased towards lighter winds, especially at the higher levels, due to the balloons being lost in strong wind situations. The data in this report would appear to be complete enough to discount this argument. At 200 mb forty stations still report at least 150 times. One station, Forrest, in southern Australia located very near the maximum winds throughout the middle and upper troposphere reports a complete set of data, 183 observations, at 300 mb and 182 observations at 200 mb. Consequently, in this report no attempt has been made to compensate for any bias in the reported winds at the upper levels.

The analysis at 100 and 50 mb suffers from an almost

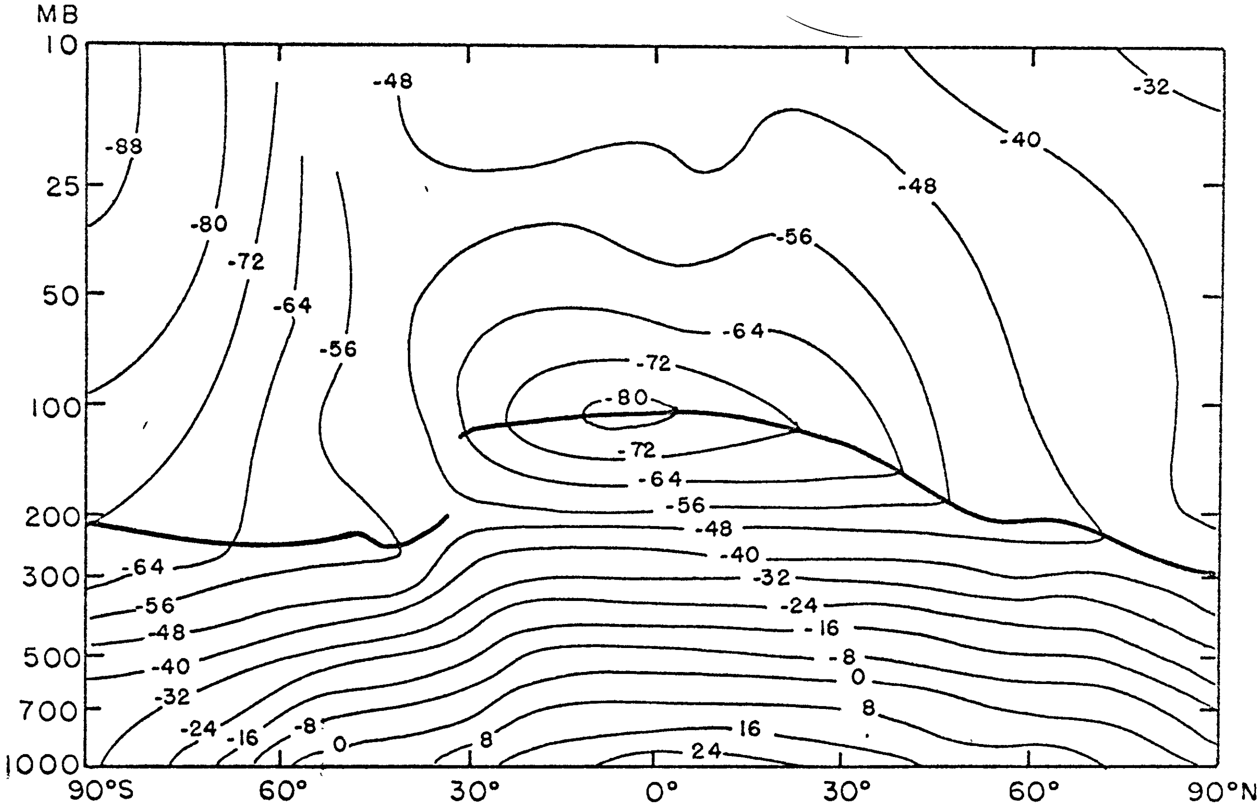

Figure 4. Mean temperatures near 170°E July 1957. Heavy line indicates mean tropopause; isotherms in °C. (From Taylor)

complete lack of representative data between the Antarctic reporting stations and about 50°S. Due to the hesistancy to analyze an extreme maximum in an area of no data, it is felt that the analysis of the stratospheric jet at 100 and 50 mb may be an underestimate of the true picture. Reference to Figure 4 for the mean isotherms during July 1957 (mid-winter) shows a rather strong horizontal temperature gradient throughout the stratosphere south of 45° S, thus suggesting increasing westerlies with height.

V. DISCUSSION OF THE ANALYSIS

In the discussion of the analyzed data (Plates 1 - 8) occasional reference will be made to the report by Buch (1954) in which he performed a similar analysis of northern hemisphere data for the year 1950. To the extent that we can say that each of the reports represents the winter circulation of the respective hemispheres, a comparison of the circulation of the northern and southern hemispheres can be made.

As indicated in Figure 3, the South Pacific Ocean between 90° - 140° W, and between the equator and 60° S, is completely lacking in data. Therefore, the analysis of this region has been entered in a dashed-dot pattern to set it aside from areas where the analysis can be considered more accurate. Due to the much more symmetrical arrangement of land and ocean areas and the absence of any barriers to the zonal flow, with the exception of the Andes affecting the lower troposphere down to about 30° S, the southern hemisphere should be expected to display a correspondingly more symmetrical distribution of zonal wind statistics.

In the lower troposphere (850 and 700 mb) the easterly trades are very much in evidence, extending on the average to about 22° S at 850 mb and 18° S at 700 mb. The center of the easterlies at 850 mb is near 10°S across the Indian Ocean and reaches its absolute maximum value of 10 m/sec over the northern tip of Madagascar. Near Brazil the maximum is found near the equator. Along the western side of South America the Andes Mountains disrupt the easterly flow causing a sharp dip in the isotach pattern.

The southern hemisphere westerlies which have been termed the "roaring forties" show as a continuous belt centered at about 46° S with two centers of maxima separated by the southern tip of South America. The southern hemisphere westerlies appear to be about 5° nearer the pole and about 5 m/sec stronger along their maximum than are the northern hemisphere westerlies. At 700 mb the westerly pattern is similar with the magnitude increased by about 5 m/sec.

The Antarctic is characterized mainly by easterlies along the perimeter, which show a maximum at 850 and then decrease rather rapidly at 700 mb, where they become westerly from 130°W - 30°E.

In the middle troposphere (500 and 400 mb) the tropical easterlies are confined to a narrower belt near the equator extending only to about 12° S and fairly symmetric as compared to the meandering of the easterlies of the lower troposphere. The westerlies now occupy the remainder of the hemisphere with some very minor exceptions over Antarctica.

In the middle of this broad belt of westerlies there now appears a relative minimum centered over the Tasman Sea. This remarkable zone of weak westerlies was discussed by Taljaard (1958) and referred to as the "Tasman Minimum" of geostrophic wind. At 400 mb the minimum has become more extensive, both upstream and downstream, effecting a split in the maximum of the westerlies between 80° W and 70° E.

There appears to be a definite connection between the minimum of the westerlies and the blocking action in the southern hemisphere. An investigation of blocking situations by van Loon (1956) based on five years of historical charts showed three regions favorable to blocking actions. Listed in order of decreasing importance they are (1) Eastern Australia - Western Pacific, (2) the Scotia Sea, and (3) the Marion-Crozet Island area, with nearly one half of the total blocks occurring in the first area. Interestingly, all areas are to the southeast of the continental masses located approximately on 45° S. By contrast northern hemisphere blocks are usually found on the west side of continents. The yearly trend shows a pronounced maximum during the late winter similar to the northern hemisphere pattern. Once the blocking has occurred there is a tendency to spread downstream, especially from the area around New Zealand.

During the winter Australia cools off much more rapidly than the surrounding seas to the north thus further accentuating the westerlies in the middle and upper troposphere over Australia. The strong westerlies thus generated, appear to influence the circulation far downstream.

The same pattern which began at 500 mb continues on to 300 and 200 mb where the minimum now appears to encircle the hemisphere, still superposed over the latitude of blocking action. The most impressive minimum, however, still lies downstream from the Tasman Sea. Along each side of this minimum, the maxima are approximately of equal strength. One centered over 30° S and the other at about 55° S. The strongest tropospheric winds of the hemisphere are centered over Australia where they reach a maximum of about 48 m/sec at 200 mb.

At 100 mb and well into the stratosphere at all latitudes except near the equator, the equatorward maximum has decreased rapidly in magnitude reflecting the reversal of horizontal temperature gradient at those latitudes (see Figure 4), while the poleward maximum continues to increase in response to the colder stratosphere over Antarctica. This pattern is in sharp contrast to the northern hemisphere polar regions where the circulation is very weak and shows no symmetry about the pole.

At the 50 mb level (Plate 8) the low latitude maximum is no longer present but rather is replaced by a band of light westerlies. The high latitude maximum (or polar night jet) has continued to increase and is characterized by nearly concentric isotachs of more than 40 m/sec. A close inspection reveals the isotach pattern not to be strictly symmetrical about the geographical pole, however, Astapenko (1960) has reported that the center of the vortex for the monthly mean 50 mb charts over Antarctica is not at the South Pole but near the Pole of Inaccessibility (82° S and 55° E). This position agrees very well with the isotach pattern, and would suggest that the circulation at this level is not only controlled by the position of the sun but also by surface geographic influences.

Due to the inversion of temperature in the stratosphere, a belt of light easterlies encircling the hemisphere is present at low latitudes centered near 15° S. These easterlies have their northern hemisphere counterparts as shown by Murakami (1962), except that in the northern hemisphere the easterlies are not continuous, being broken over North Africa.

Near the equator can be seen a meteorological "paradox" or what has now become known as the "biennial stratospheric wind oscillation'. In this report is shows as a band of light westerlies near the equator. However, due to the nature of the oscillations and our particular time period (April-September) our data merely reflects the difference between two regimes where the changeover (from westerly to easterly) supposedly occurred near the middle of July 1958. From data presented by Reed (1962) it appears that the equatorial stratospheric winds oscillate with a period of approximately 26 months. Although 26 months appears to be the best figure for the average period for 1954-1960 it is possible that a longer period of data may establish the period as 2 years, therefore making it a subharmonic of the annual period. Studies to date indicate that easterlies and westerlies appear earlier at the higher levels and progress downwards at an average speed of approximately 1 km per month. A time height cross section from Canton Island (3° S) from February 1954 to October 1960 shows the maximum amplitude to be 25 m/sec near 25 mb level. The amplitude diminishes downward with the decrease becoming very rapid near the tropopause, while stratospheric and tropospheric oscillations in the equatorial regions show little or no correlation. Angell (1962) presents data for four equatorial stations (Canton Island 172° W, Singapore 104° E, Nairobi 47° E and Fernando de Naronha 32° W) which show the oscillation at 50 mb at all stations to be in phase, thus indicating that the currents are global in extent.

VI. ZONAL AVERAGES AS A FUNCTION OF LATITUDE AND PRESSURE

Zonally averaged values of $\bar{u}$ and s(u) were evaluated from the analyzed maps by using a system of grid points for every 5° of latitude and 10° of longitude.

The zonal averages of $\bar{u}$ and s(u) were estimated by

$$[\bar{u}] = \frac{1}{36} \sum_{i=1}^{36} \bar{v}_i \; ; \quad [s(u)] = \frac{1}{36} \sum_{i=1}^{36} s(u)_i \; .$$

The bracket operator will refer to the space average of a quantity along a latitude circle. Values of $[\bar{u}]$ and $[s(u)]$ are tabulated in Tables 2 and 3. The mean values for the vertical integral resulted from applying weighting factors of .225, .175, .150, .100, .100, .100, .075 and .075 respectively to the 850, 700, 500, 400, 300, 200, 100 and 50 mb winds.

Meridional cross sections of the zonal averages for $[\bar{u}]$ and $[s(u)]$ are presented in Figures 5 and 6. In order to make a comparison with the northern hemisphere circulation the winter values for 1950 are reproduced from Buch (1954) as Figures 7 and 8.

TABLE 2. $[\bar{u}]$ m/sec

	80°	75°	70°	65°	60°	55°	50°	45°	40°
50 mb	9.34	15.70	24.35	32.90	38.94	37.19	28.75	19.64	12.42
100	7.77	11.92	17.74	24.68	30.67	31.80	26.47	20.81	19.24
200	4.96	8.19	12.79	19.42	25.89	29.65	26.29	22.04	24.32
300	5.00	7.07	11.00	16.54	22.91	26.26	24.11	20.28	20.78
400	4.71	4.95	7.15	11.39	16.24	19.70	20.60	20.66	19.44
500	3.41	3.99	6.49	11.30	16.20	18.33	19.40	19.17	17.21
700	0.29	0.80	2.88	6.08	10.32	13.79	15.86	15.43	13.11
850	−3.62	−4.20	−2.90	0.31	4.10	7.67	10.29	10.79	8.90
Mean	2.50	3.89	7.07	11.88	16.88	19.62	19.24	17.33	15.71

	35°	30°	25°	20°	15°	10°	5°	0°
50 mb	7.79	3.97	1.36	−1.37	−4.17	−2.58	1.41	4.93
100	22.67	25.10	21.78	14.72	8.94	3.39	0.01	−2.78
200	30.75	35.42	31.14	21.42	12.03	4.04	−1.60	−6.61
300	25.17	27.99	25.13	17.67	8.99	1.72	−2.93	−6.31
400	19.51	19.03	16.34	12.10	5.14	−0.96	−5.30	−6.65
500	15.26	13.23	10.83	7.57	2.76	−2.03	−4.89	−6.10
700	9.99	6.80	4.29	1.81	−1.08	−3.09	−4.07	−4.54
850	5.81	2.82	0.19	−2.12	−4.93	−5.09	−4.11	−3.58
Mean	15.17	14.24	11.41	7.10	2.10	−1.45	−2.19	−4.31

TABLE 3. $[s(u)]$ m/sec

	80°	75°	70°	65°	60°	55°	50°	45°	40°
50 mb	5.58	8.08	12.38	15.21	14.79	12.78	10.42	8.97	8.07
100	6.14	7.20	8.45	9.28	9.86	10.31	10.64	10.83	11.00
200	8.62	9.27	10.51	11.84	13.00	14.25	15.40	16.53	17.44
300	11.45	12.10	13.22	14.69	15.89	16.78	17.35	17.64	17.40
400	10.43	11.19	12.47	13.96	15.01	15.76	15.92	15.63	14.82
500	8.84	9.69	10.80	12.10	13.05	13.48	13.57	13.26	12.60
700	6.09	7.21	8.56	10.09	11.18	11.59	11.58	11.11	11.13
850	4.72	5.76	7.09	8.36	9.20	9.57	9.49	9.07	8.33

	35°	30°	25°	20°	15°	10°	5°	0°
50 mb	7.47	6.90	6.37	5.88	5.53	5.97	6.84	7.74
100	11.07	10.94	10.38	9.39	8.34	7.76	7.76	8.21
200	17.95	17.30	15.45	12.96	10.87	9.47	8.63	8.43
300	16.75	15.54	13.63	11.28	8.94	7.23	6.39	5.91
400	13.63	12.14	10.57	8.81	7.06	6.05	5.48	5.12
500	11.41	9.91	8.58	7.13	5.99	5.02	4.48	4.29
700	8.81	7.49	6.52	5.50	4.68	4.17	4.04	4.18
850	7.39	6.35	5.38	4.30	3.58	3.36	3.41	3.69

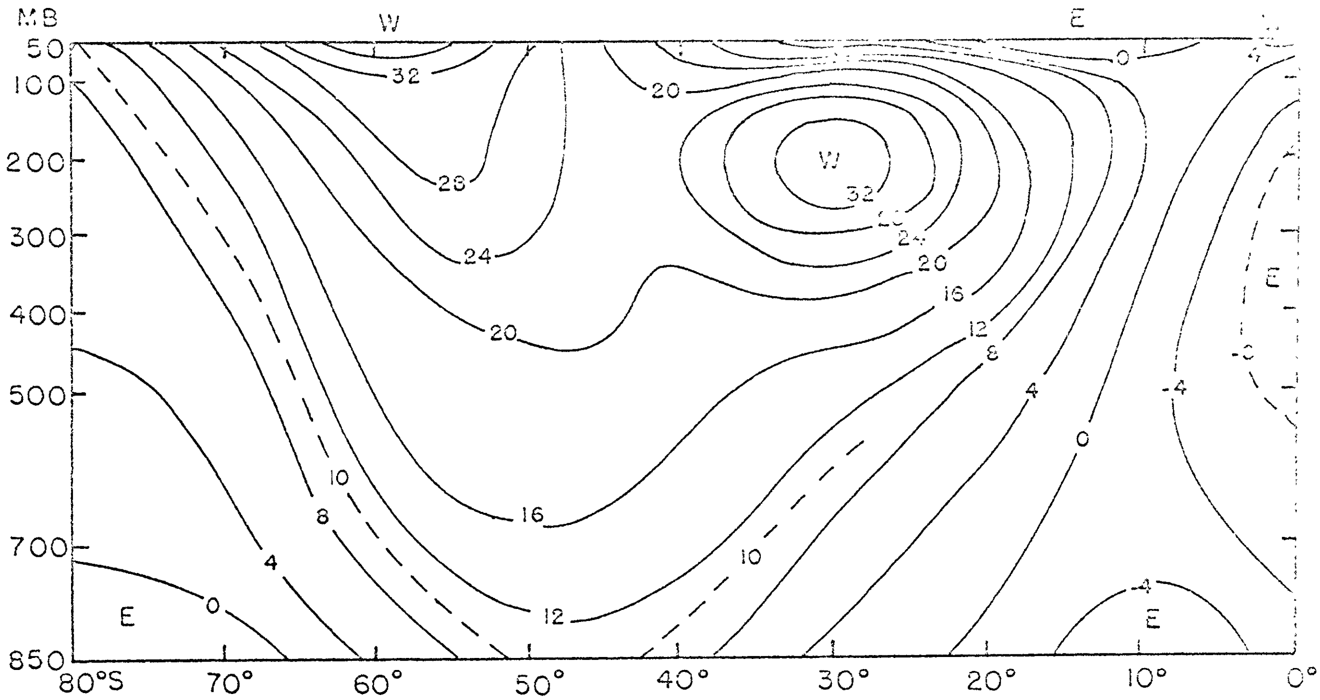

Figure 5. [ū] for a southern hemisphere winter (April - September 1958). Isotachs in meters per second.

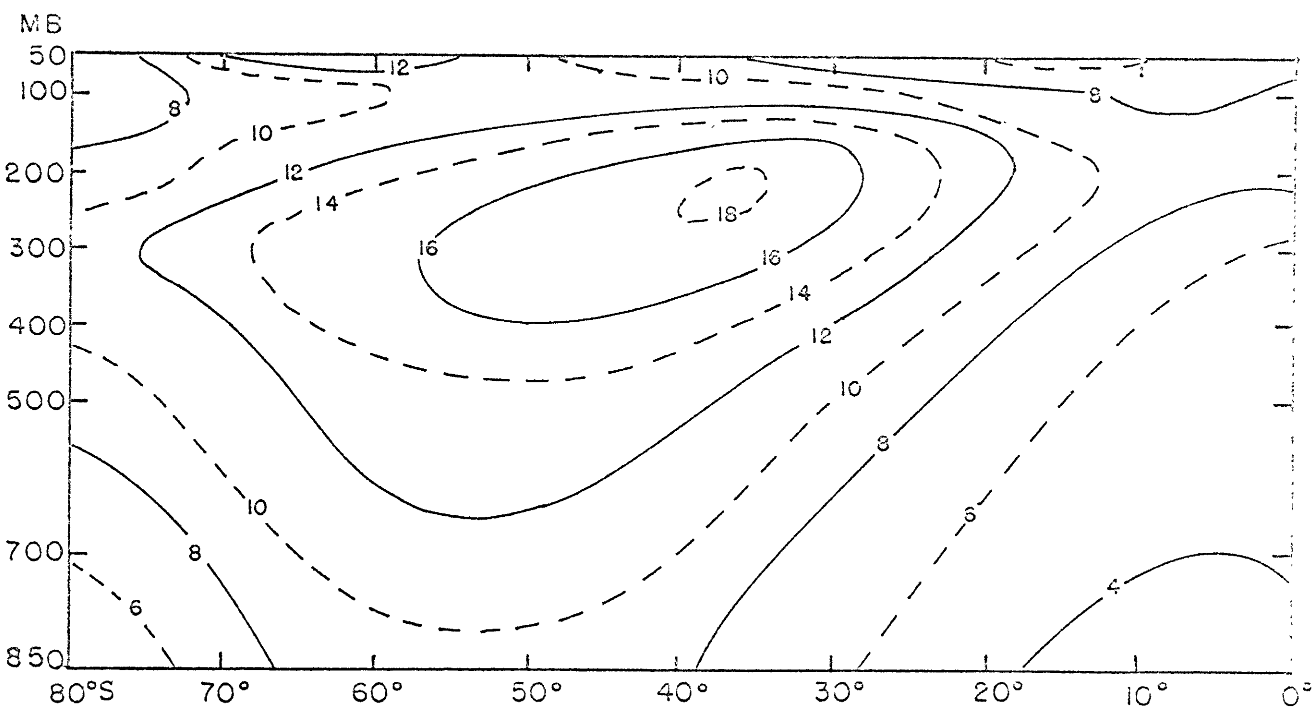

Figure 6. [s(u)] for a southern hemisphere winter (April - September 1958). Isotachs in meters per second.

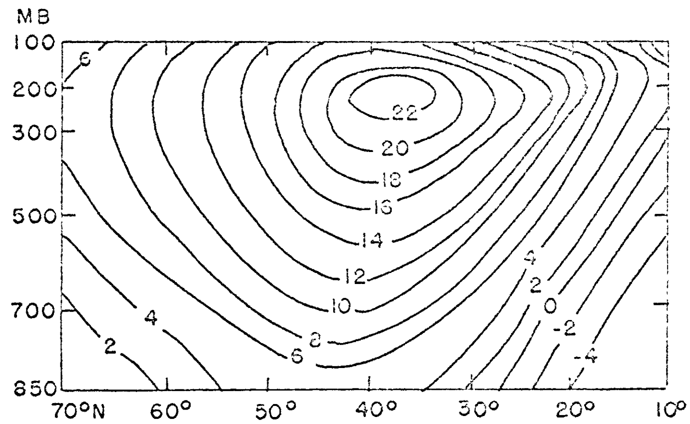

Figure 7. $[\bar{u}]$ for a northern hemisphere winter (1950). (From Buch, 1954)

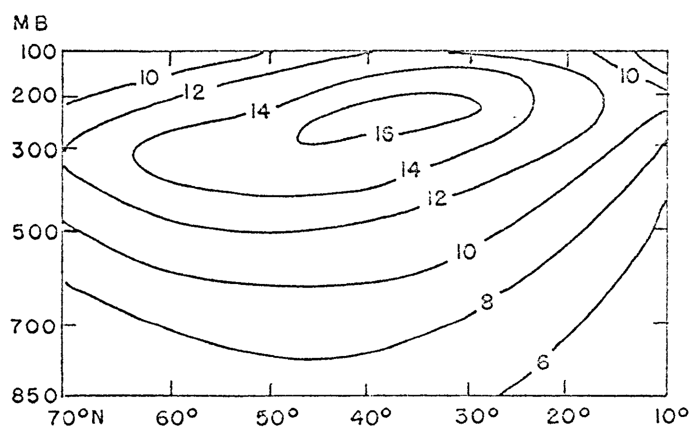

Figure 8. $[s(u)]$ for a northern hemisphere winter (1950). (From Buch, 1954)

First examining the pattern of $[\bar{u}]$, it can be seen that the circulation is completely dominated by the westerlies. Only the weak low level polar easterlies resulting from the anticyclonic circulation over the Antarctic, and the deep equatorial easterlies being the exceptions. The pattern of the low latitude easterlies resembles, very much, the northern hemisphere profile for 1950.

The maximum of the lower tropospheric westerlies is near 47°S or 5° of latitude nearer the pole than is the case for the northern hemisphere. Its magnitude of 11 m/sec is some 5 m/sec greater, or nearly double that of the northern hemisphere.

In the middle and upper troposphere basic differences in the profiles are apparent. While the northern hemisphere shows a single maximum over 37°S at 230 mb, the southern hemisphere has a more complicated pattern. It shows a tropospheric maximum over 30°S at about 200 mb. This is seven degrees of latitude nearer the equator. At greater than 32 m/sec this jet is some 10 m/sec stronger than the mean winter jet of the northern hemisphere. At higher latitudes a secondary maximum is present which continues to increase with height culminating in a very intense stratospheric jet stream centered near 58°S.

The effect of the stratospheric temperature inversion (Figure 4) is very evident between 40° and 15° resulting in the very rapid decrease of the westerlies above 100 mb and even turning them into easterlies between 7 and 22° at 50 mb.

The profiles of standard deviation (Figures 6 and 8) appear, in general, very similar for the two hemispheres. As expected, the trades are the most stable winds. At low levels the middle latitudes are the most variable, depicting the general area of frontal activity.

The pattern of maximum variability follows closely that of maximum winds, with the largest value of the standard deviation appearing just poleward of the tropospheric jet. A weak secondary maximum is associated with the stratospheric jet, otherwise the pattern is one of rapidly increasing stability above the tropopause.

VII. CONCLUSION

The data collected during the IGY and made available through the WMO has made it possible, for the first time, to investigate the zonal circulation of the entire southern hemisphere.

From the analysis of data for the winter season (April through September) it was revealed that the southern hemisphere has a much stronger westerly circulation as compared to the northern hemisphere winter of 1950. A basic difference in the patterns of the two hemispheres is shown by a double maximum in the upper troposphere. The low latitude maximum being approximately 7° of latitude nearer the equator than is the northern hemisphere jet stream.

A poleward maximum, undoubtedly a result of the Antarctic influence, increases upward throughout the stratosphere and becomes (at 50 mb) the strongest circulation of the hemisphere. The Antarctic zonal winds appear to be symmetric about the Pole of Inaccessibility (82°S and 55°E) rather than the geographic pole. The southern hemisphere displays a much more symmetrical circulation pattern reflecting the greater symmetry of land and ocean areas in that hemisphere.

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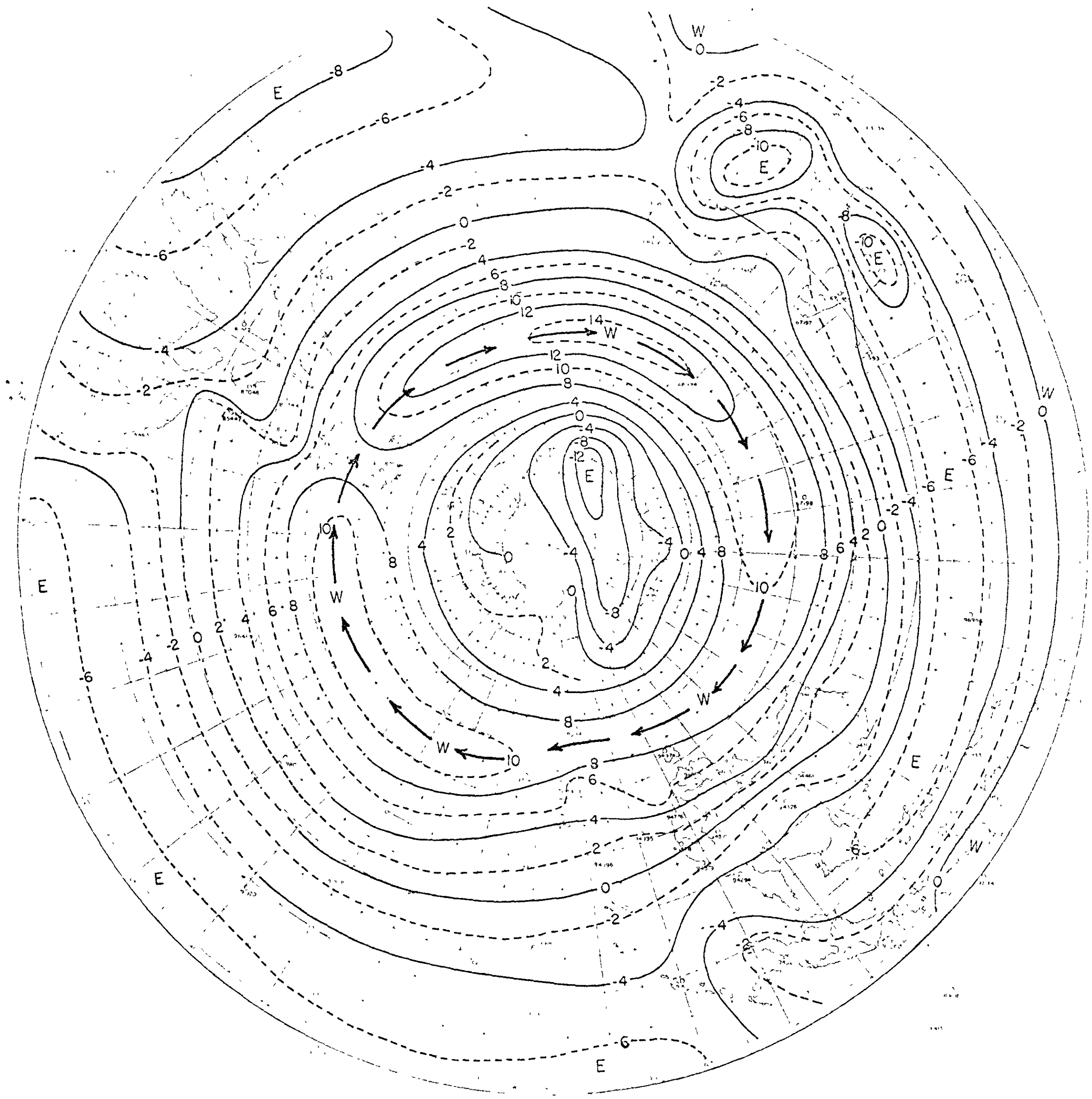

PLATE I. $\bar{U}$ IN M/SEC

700 MB

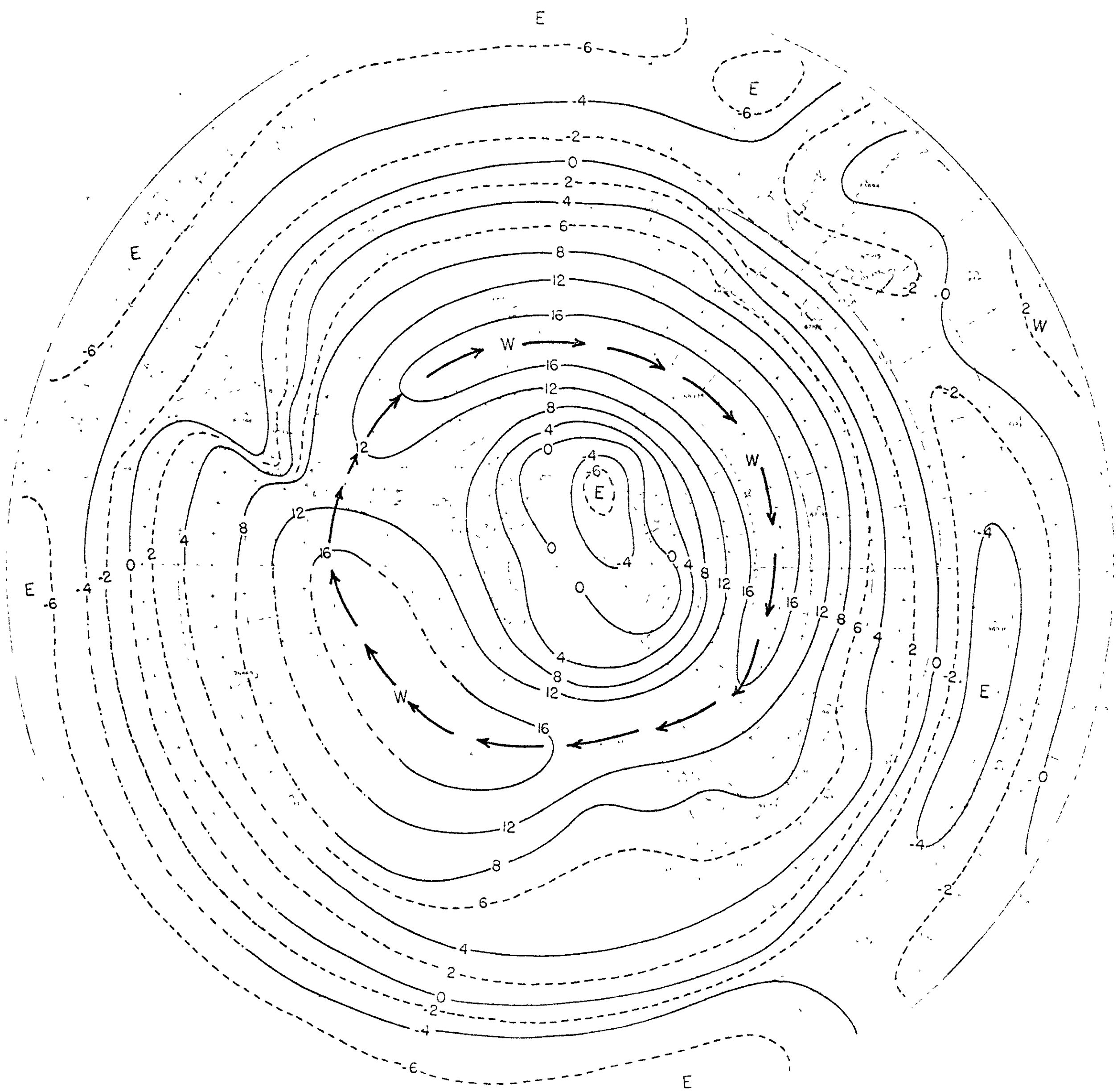

PLATE 2. $\bar{U}$ IN M/SEC

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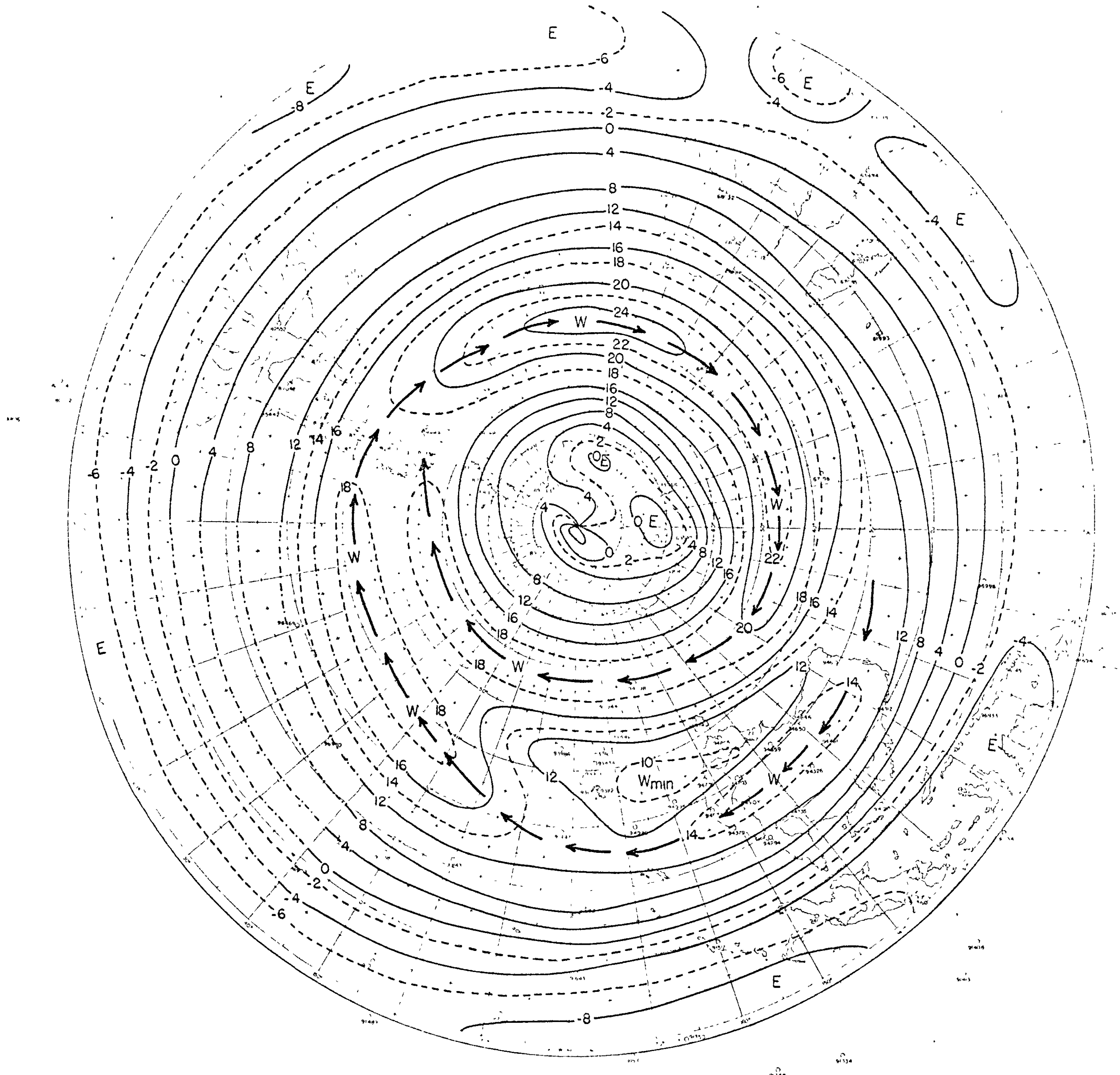

PLATE 3 $\bar{U}$ IN M/SEC

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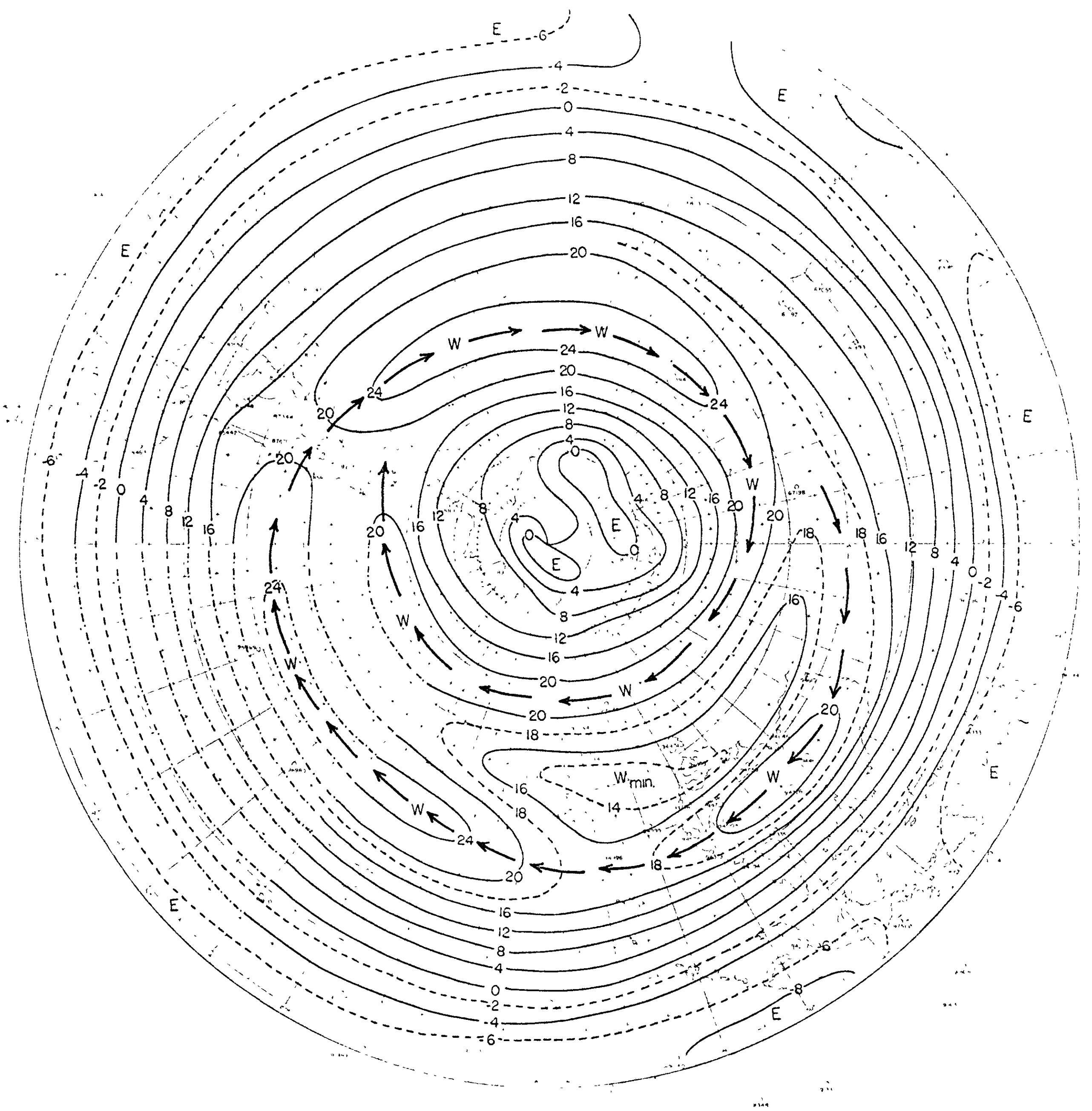
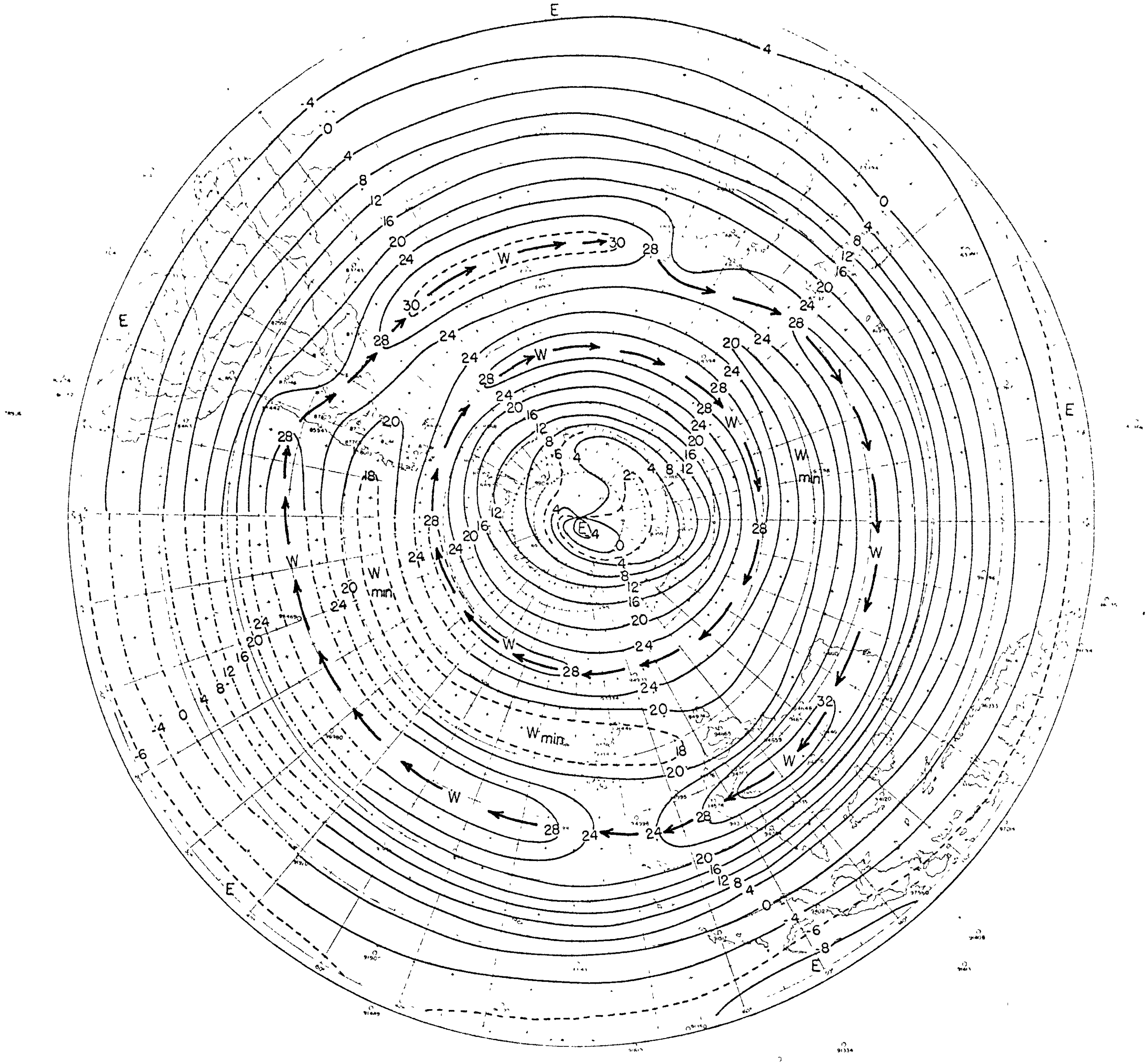


PLATE 4. $\overline{U}$ IN M/SEC

300 MB



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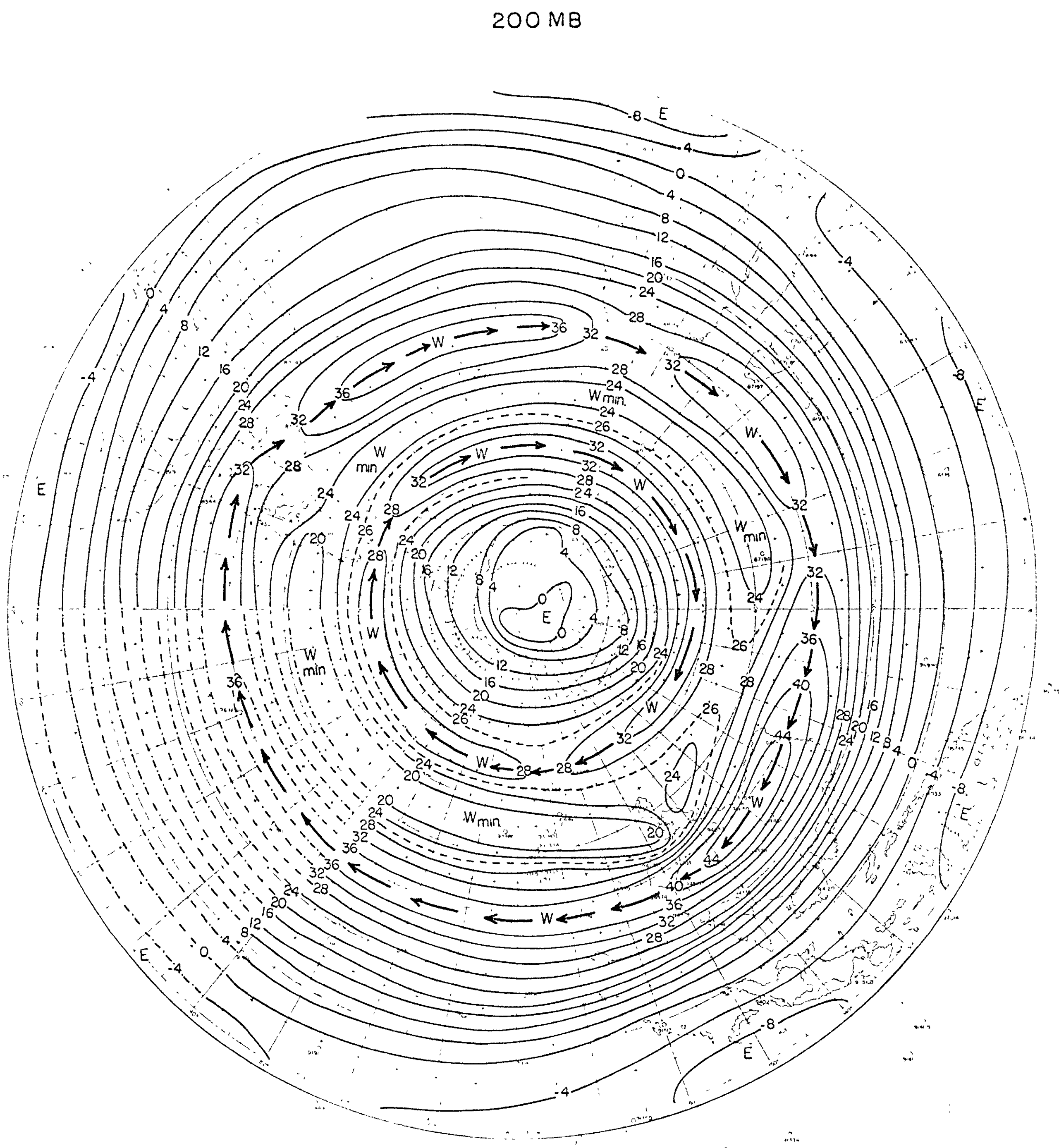

PLATE 6. $\overline{U}$ IN M/SEC

100 MB

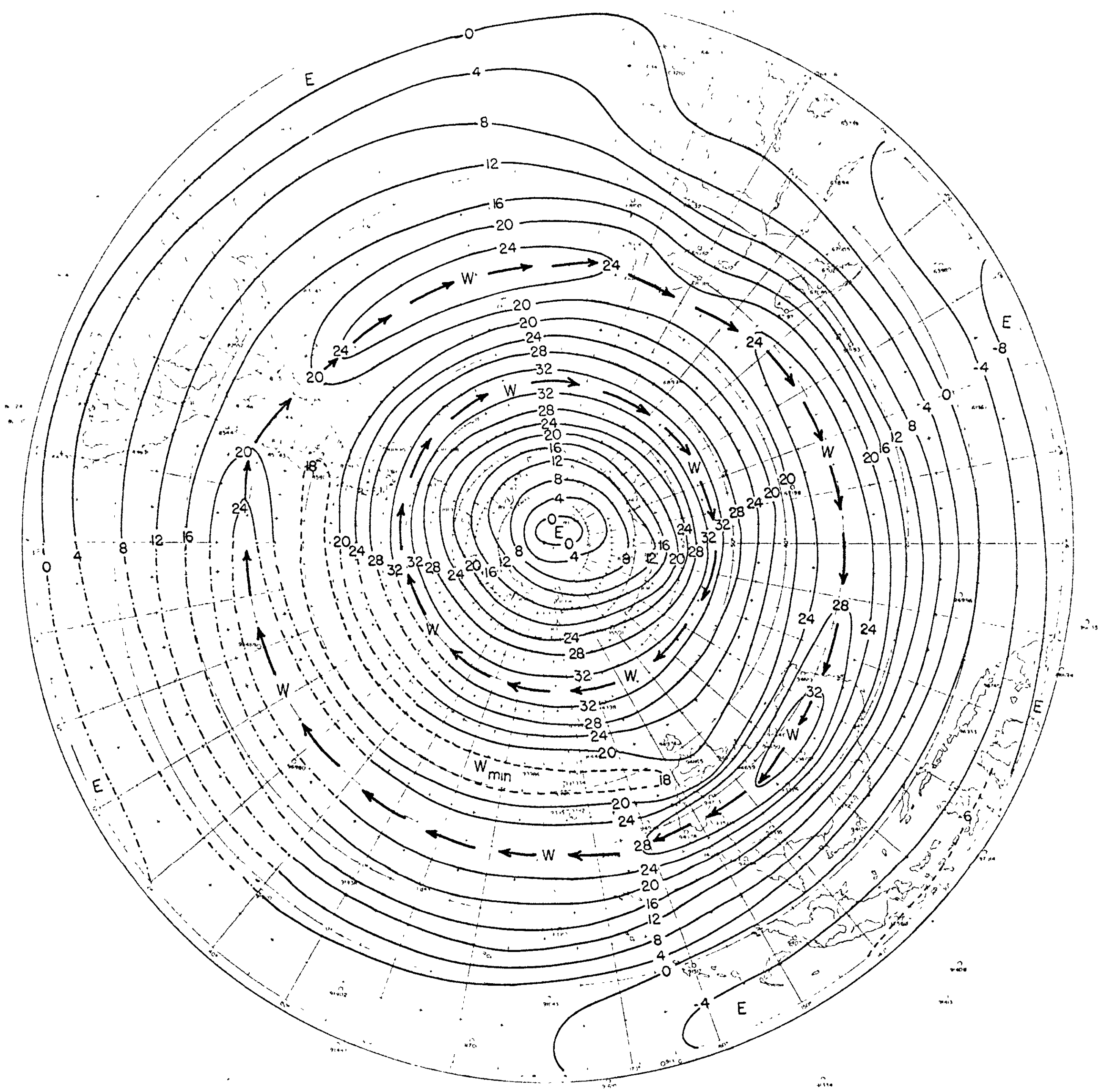

PLATE 7. $\bar{U}$ IN M/SEC

50 MB

PLATE 8. $\overline{U}$ IN M/SEC

850 MB

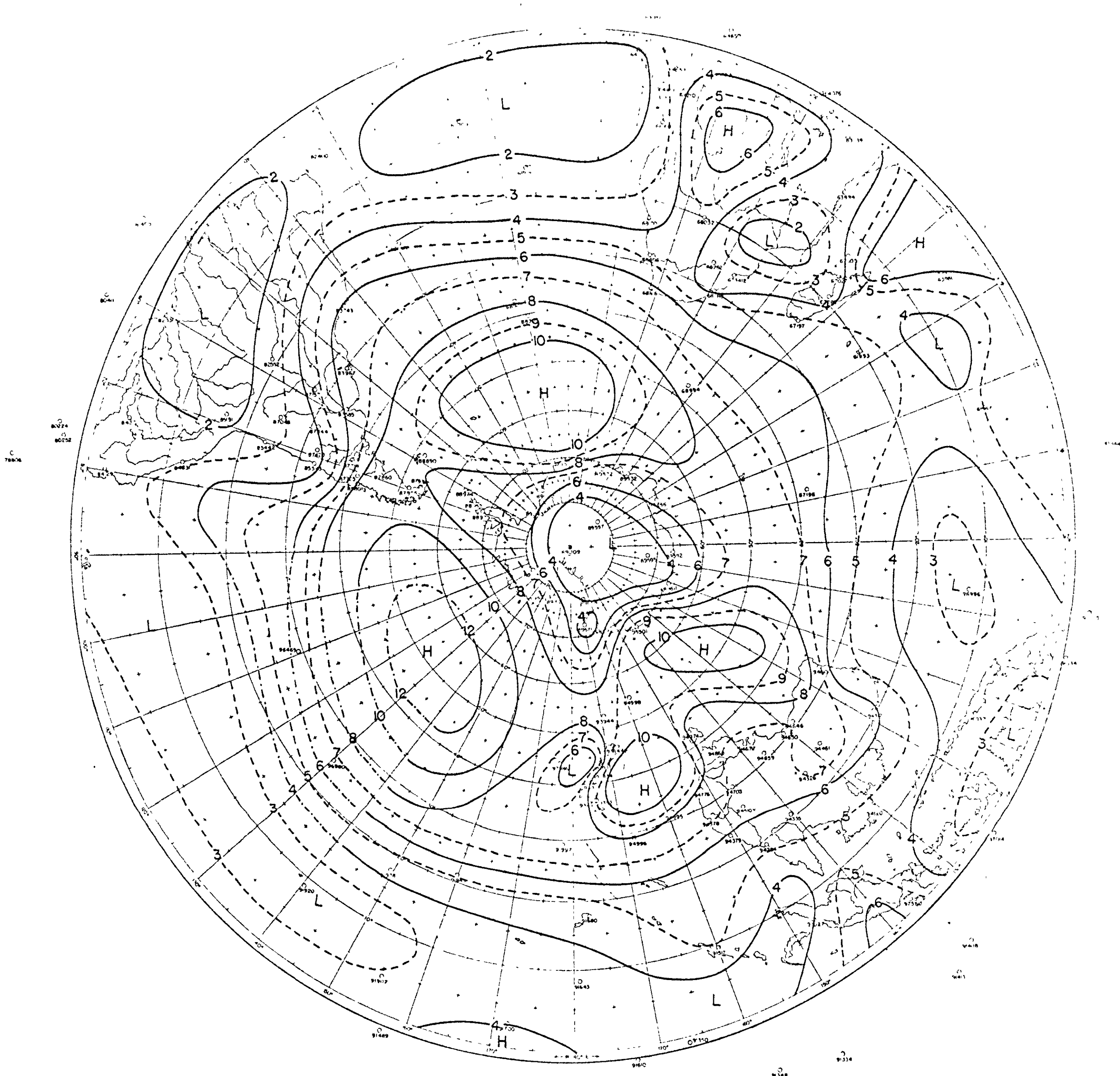

PLATE 9. S (U) IN M/SEC

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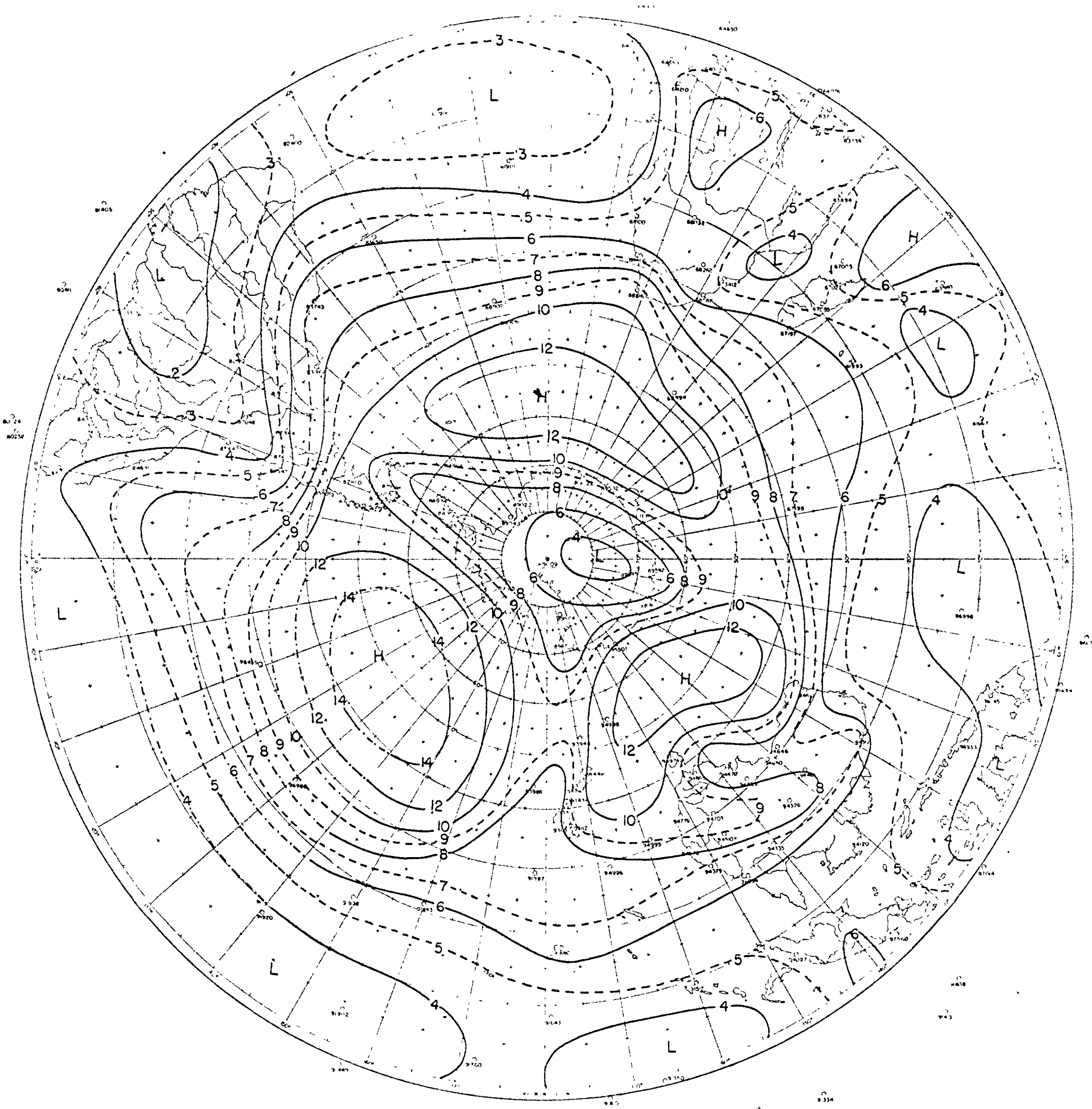

PLATE 10 S (U) IN M/SEC

500 MB

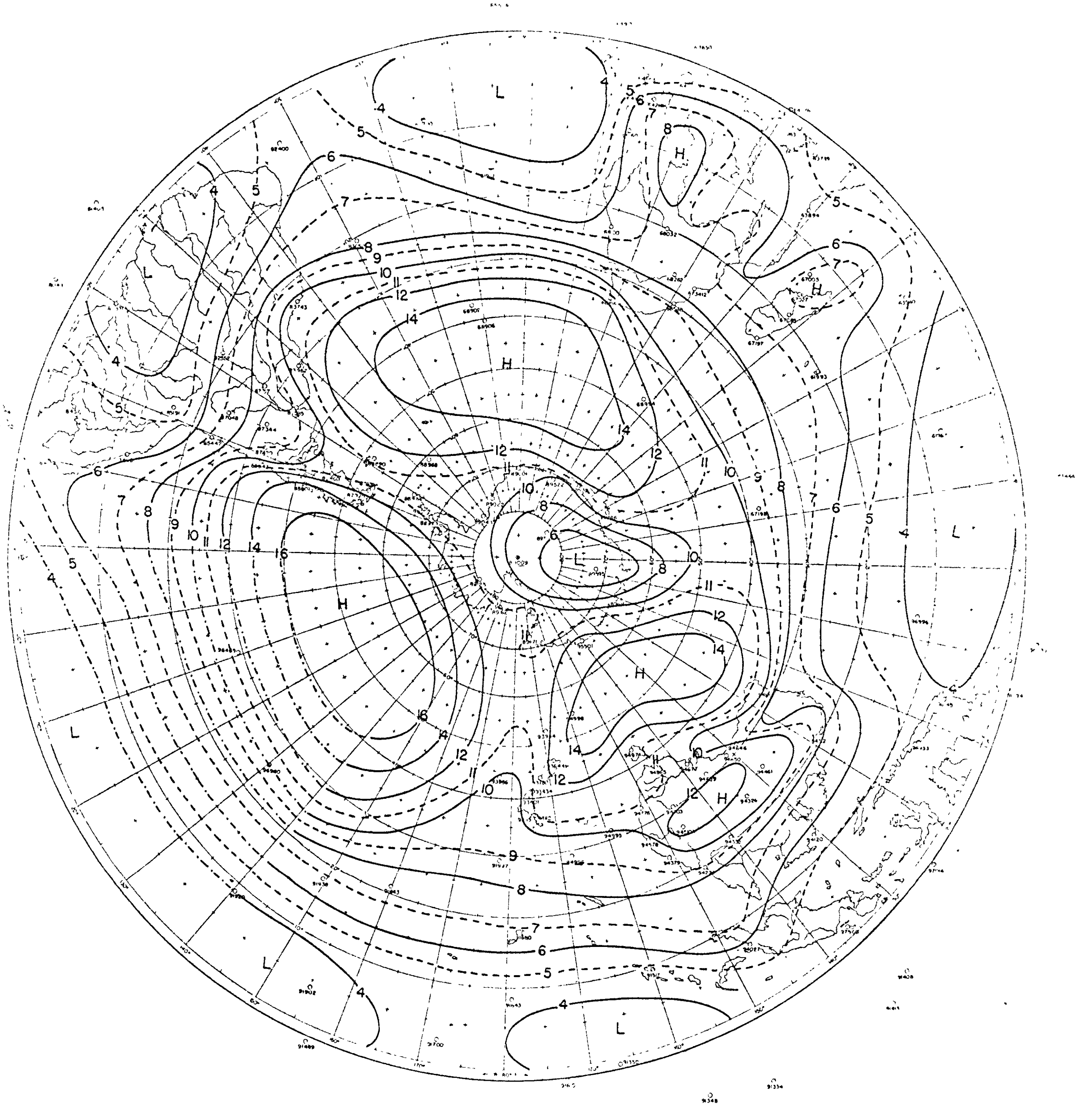

PLATE II. S (U) IN M/SEC

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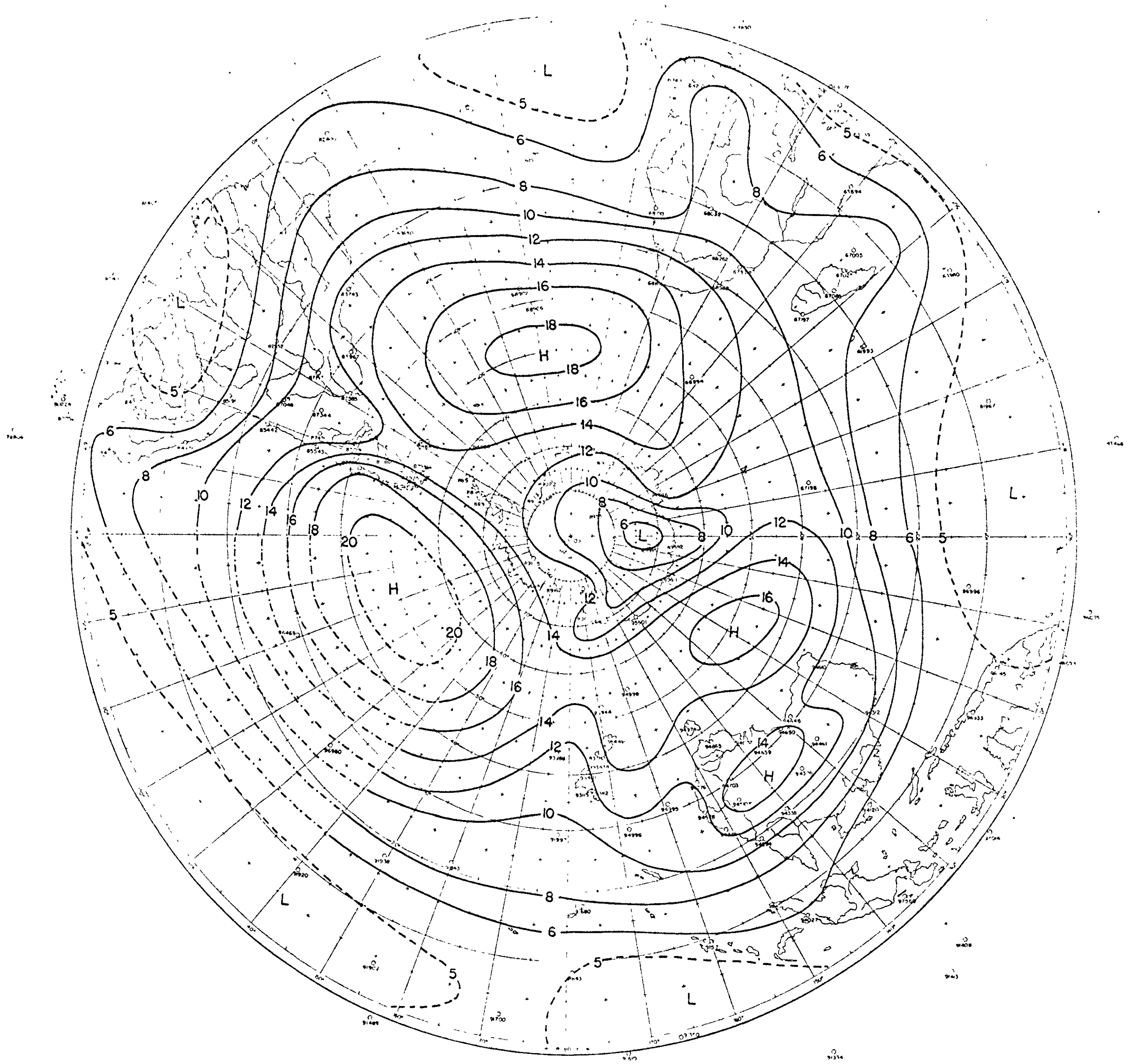

PLATE 12. S (U) IN M/SEC

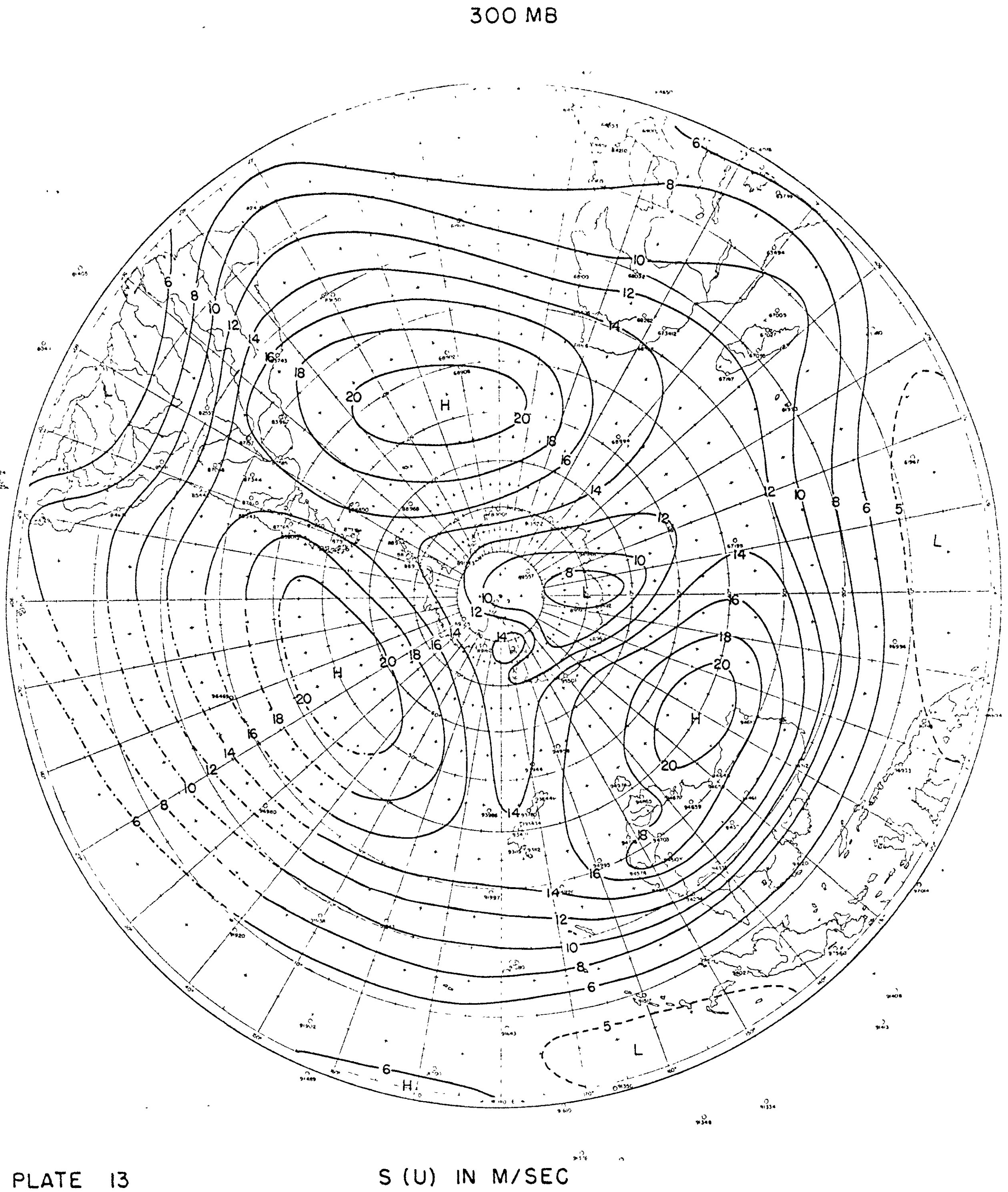

PLATE 13

S (U) IN M/SEC

200 MB

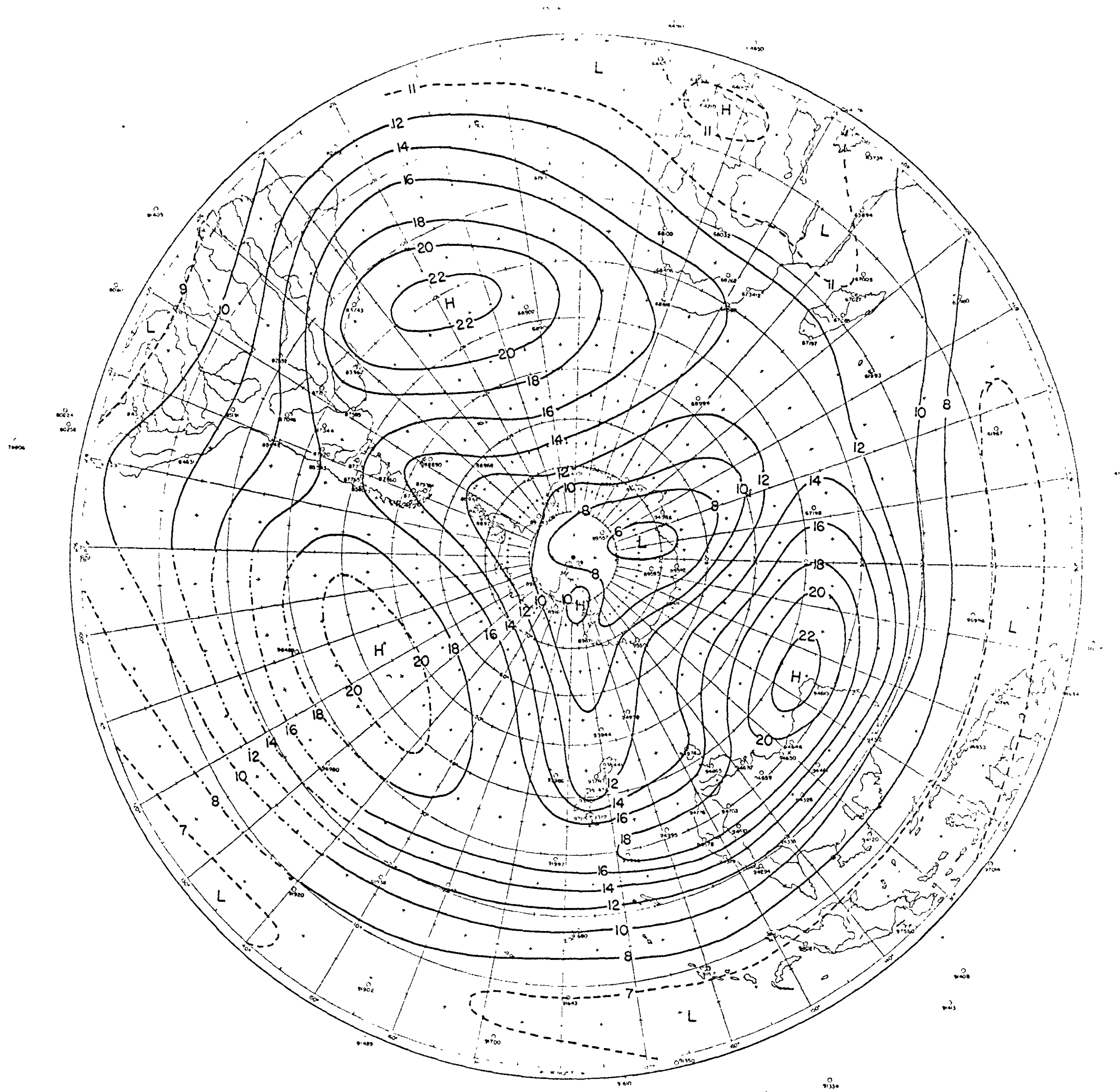

PLATE 14

S (U) IN M/SEC

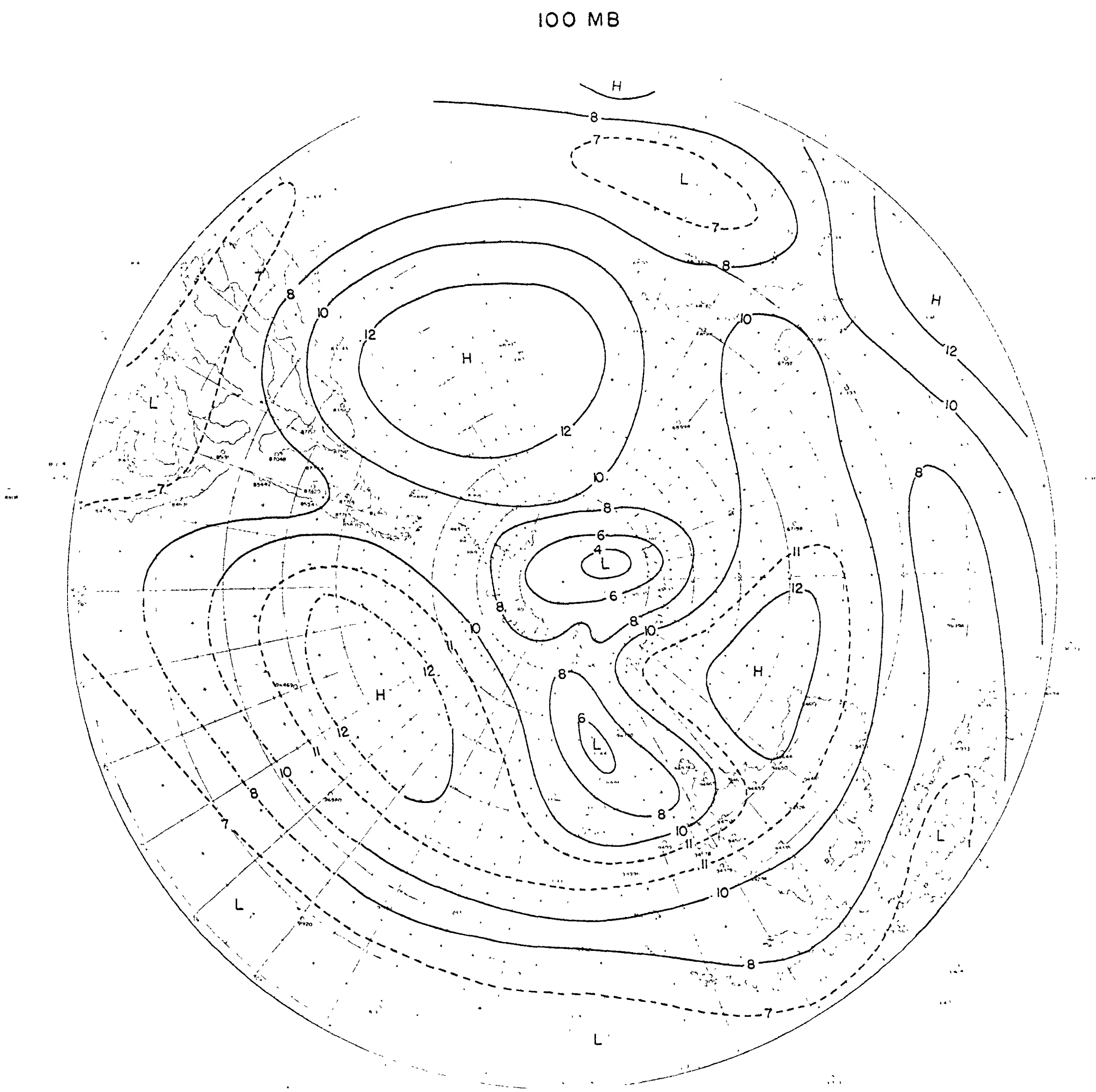

PLATE 15

S (U) IN M/SEC

50 MB

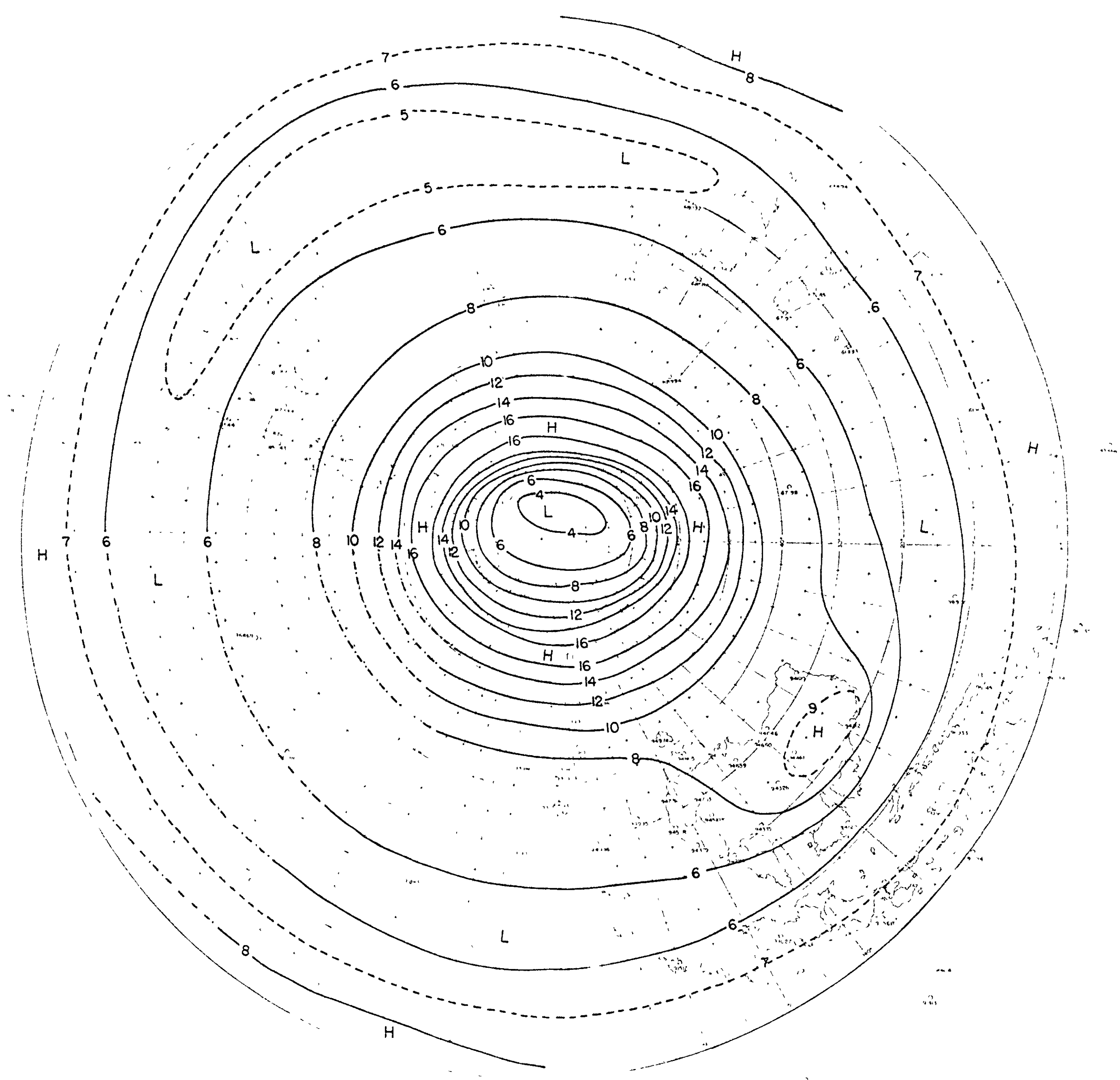

PLATE 16

S (U) IN M/SEC