ASPECTS OF THE CIRCULATION OF THE SOUTHERN HEMISPHERE

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ABSTRACT

An evaluation is made of the synoptic features and characteristic pressure patterns of the Southern Hemisphere as they relate to the seasonal circulations. Examples of both strong and weak polar outbreaks are presented, and their effect on the zonal circulation is discussed. The implications of the strong zonal circulation and its short-term as well as seasonal variations are examined.

1. Introduction

The knowledge of the circulation patterns of the southern hemisphere is incomplete mainly because the distribution of land and ocean is unfavorable for the establishment of an adequate network of stations in middle and high latitudes [1]. Whenever new stations have been set up in these relatively unknown regions, there has always been an immediate response from meteorologists in the form of intensive studies of the data so obtained. These studies have included several attempts to describe synoptic patterns, usually, however, only for limited regions. At present the Hemisphere Weather Maps Unit of the U. S. Weather Bureau has completed a series of daily hemispheric maps for a period of two and one-half years. Many of the synoptic features previously considered singly can now be seen in relation to each other as elements of the large-scale circulation. We shall call attention to the characteristics which have been observed in the course of the analysis, and point out that there appears to be more seasonal variation of the essentially zonal patterns than had been considered formerly.

The topography of the southern hemisphere strongly favors a zonal circulation. Only where South America extends toward relatively high latitudes will the dynamic and thermal influences of this continent disturb the almost uniformly zonal character of the circulation between 40°S and 60°S. The effects of the southeastern part of Australia and New Zealand on the circulation are mostly limited to the immediate vicinity of these regions, and are very quickly damped downstream.

2. The polar highs

One of the effects of the southern-hemisphere topography is to limit the formation of polar highs to the Antarctic continent. The topography of the continent, however, appears to be unfavorable for the formation of extensive polar anticyclones. Only at the coasts, where some relatively low-level plains exist, is it possible for the cold air to accumulate and form peripheral anticyclones. These do not, by far, obtain intensities comparable to those of polar highs in the northern hemisphere, nor do they form so frequently. Due to the strong zonal circulation, it has been thought [2] "that antarctic air rarely, if ever, moves out from the continent in great outbursts accompanying a cold polar anticyclone moving from antarctic to lower latitudes. It seems rather as if this continental air, moving northward to the west of the great traveling depressions, becomes very rapidly transformed over the ocean into maritime polar air." It seems now that an argument can be advanced in favor of both strong and weak polar highs, moving out from the continent. The strong ones are able to penetrate the westerlies, but the weak ones are carried away rapidly in the zonal flow, and soon break down.

During the winter season, strong polar outbreaks, although seldom comparable in intensity to those of the northern hemisphere, occasionally occur and are able to maintain their identity as they move toward lower latitudes. The modifying influence of the ocean is great, and the air soon loses its continental characteristics in the lowest layers, although the cP air does not change completely into the mP air which is usually found over the southern oceans. In the case of a prolonged outflow of cP air, its relative coldness and dryness are sufficiently retained, so that the air mass is readily discernable from the local air masses even when it has reached fairly low latitudes. There appears to be no preferred region from which strong polar outbreaks take place. The opportunity to detect them is limited by the fact that the high-latitude stations are widely scattered in the South Atlantic and the South Indian Ocean.

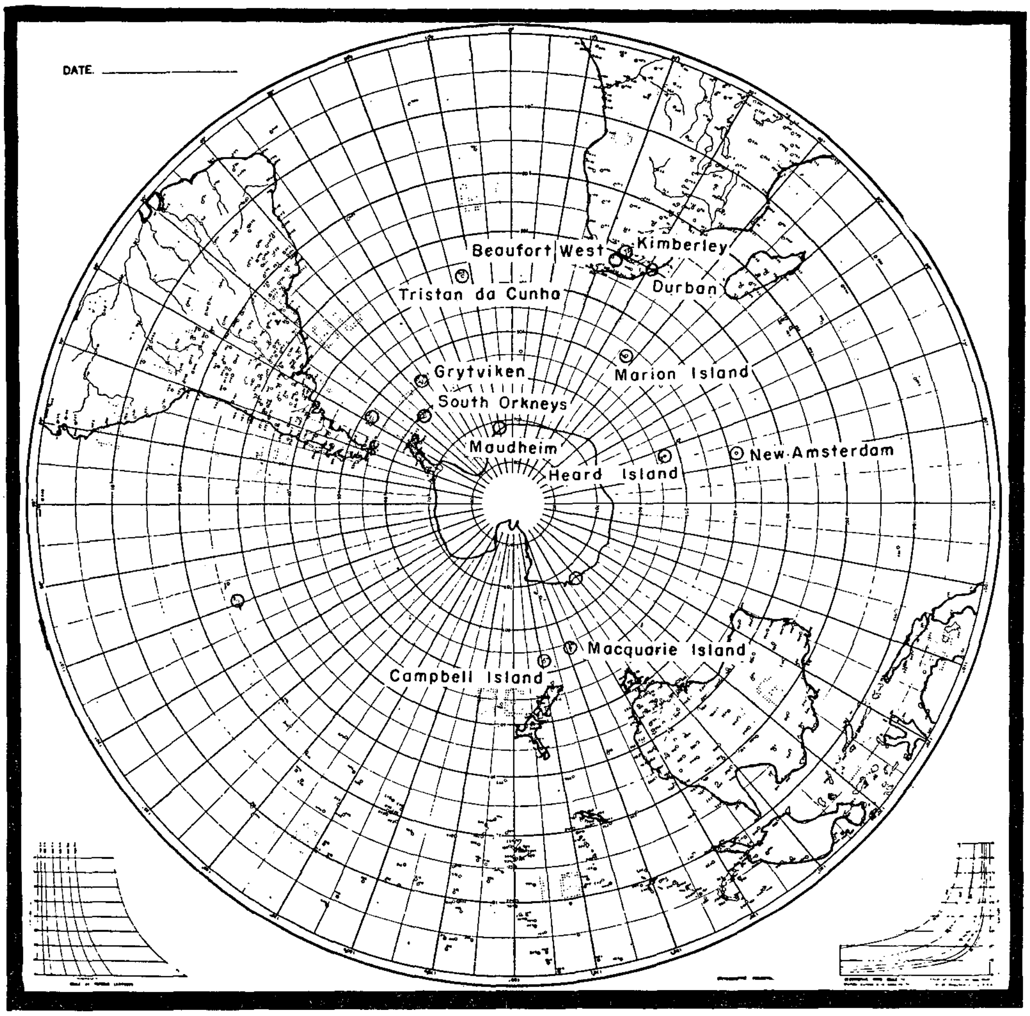

FIG. 1. Outline map of Southern Hemisphere, showing stations referred to in text.

An illustrative case is one in the South Atlantic during the period 18–28 July 1950. Data for this situation are shown in table 1. The cold air seemed to pass northward from the Weddell Sea to the west of Maudheim (71°S, 11°W)[1] in two surges, the first on 19 July and the second on 23 July. Since there is no significant diurnal variation of temperature at this latitude in the winter season, the temperature changes are due almost entirely to advection. Any extended periods of low temperature are likely associated with outflow of air from the continent. The radiosonde observations from Maudheim are missing from 15 July to 25 July, but the sounding of the 25th clearly shows the character of the polar air. The surface inversion is very strong (fig. 2), the temperature rising from −41C at the surface (995 mb) to −27C at 956 mb. The air is dry, as evidenced by clear skies on 25 July, and a dew-point depression of from 5 to 10C above the surface inversion. The sounding of 26 July, also shown in fig. 2, is that of maritime air which reached Maudheim on that day. The lower

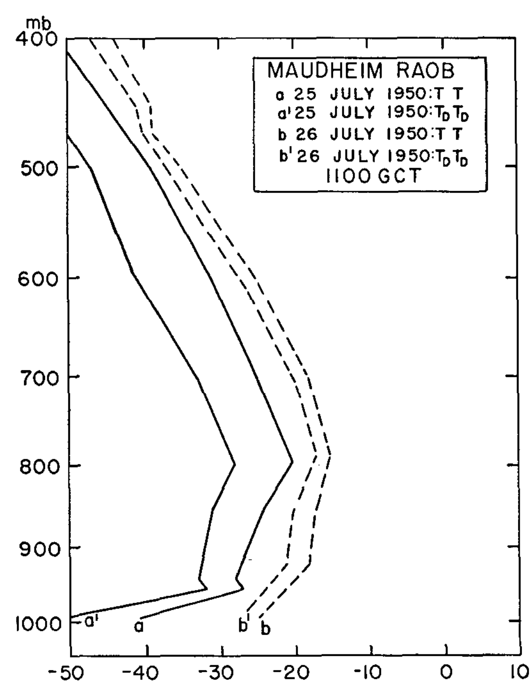

FIG. 2. Maudheim raobs, 25 and 26 July 1950.

[1] The locations of stations referred to in this paper are shown in fig. 1.

Table 1. Surface data (1200 GCT) for selected South Atlantic stations, July 1950.

Station	Date	Press. (mb)	Temp. (deg C)	Dew point (deg C)	Wind dir. (deg)	Wind speed (knots)
Maudheim	18	987.2	−19	−20	060	28
	19	996.0	−26	−27	120	02
	20	986.0	−13	−13	270	07
	21	991.6	−31	−32	170	07
	22	982.4	−24	−25	230	07
	23	994.0	−42	−43	160	07
	24	—	—	—	—	—
	25	999.4	−41	−43	110	08
South Orkney	18	969.6	− 2	− 4	300	18
	19	996.8	−24	—	270	15
	20	1017.7	−24	—	000	00
	21	1022.6	−24	—	160	06
	22	1015.7	−15	—	000	00
	23	1008.0	1	− 2	340	15
Grytviken	19	982.8	0	− 2	290	18
	20	992.9	− 4	− 7	190	12
	21	1012.1	− 6	−10	000	00
	22	1021.1	− 6	−10	270	03
	23	1026.8	− 5	− 7	000	00
Tristan da Cunha	20	1019.5	14	14	320	12
	21	1016.2	14	9	290	15
	22	999.0	14	13	360	10
	23	1015.2	5	4	230	30
	24	1022.3	8	6	260	36
	25	1029.6	11	8	020	09
	26	1028.7	14	11	250	18
	27	1031.1	16	11	340	06
Beaufort West	24	877.2	24	2	290	34
	25	876.2	22	0	320	26
	26	878.5	8	0	250	24
	27	891.5	8	− 2	000	00
	28	889.1	12	− 4	180	07
Kimberley	24	882.7	21	2	320	12
	25	880.9	21	3	320	05
	26	880.0	13	4	250	25
	27	888.8	11	− 4	140	12
	28	887.0	16	3	340	09

levels give evidence of the continental cooling, while all levels reflect the much higher moisture content and the relative warmth of the air.

The high which was associated with the cold air moved first to the north and later to the northeast. The first station to feel the effect of the cP air was South Orkneys (61°S, 46°W) on 19 July. When the first surge of cold air reached Grytviken (54°S, 36°W), a substantial drop in temperature was experienced. In the second surge the higher pressure was to the east, and the station was in the return flow of the cold air with little change in temperature and dew point. The next point of reference is Tristan da Cunha (37°S, 12°W). On 20 July an old polar front had passed to the north of the island, and a weak wave was located approximately 900 mi to the west. The cold air coming from Antarctica served to reinforce the old front and to intensify the wave, which then proceeded to move southeastward across Tristan da Cunha. This last cold air, passing between 22 and 23 July, and the high associated with it can be still further traced to about 30°S over the African continent, as shown in table 1 by data from Beaufort West (32°S, 23°E) and Kimberley (29°S, 25°E). The upper-air data from Durban (30°S, 31°E) in table 2 suggest that the cold air reached the 700-mb level. The synoptic maps of the South Atlantic sector for 22, 23 and 27 July are presented in figs. 3 to 5.

Table 2. Durban raob data (1200 GCT), July 1950.

Date	Press. (mb)	Ht. (m)	Temp. (deg C)	Dew point (deg C)
26	1000	90	21	11
	850	1484	14	− 2
	700	3089	6	−14
27	1000	280	14	4
	850	1622	2	− 2
	700	3166	− 6	−15
28	1000	253	16	7
	850	1609	7	− 5
	700	3181	0	−14
29	1000	232	17	5
	850	1596	8	−19
	700	3174	0	− 7
30	1000	126	18	5
	850	1510	12	−10
	700	3100	2	−25

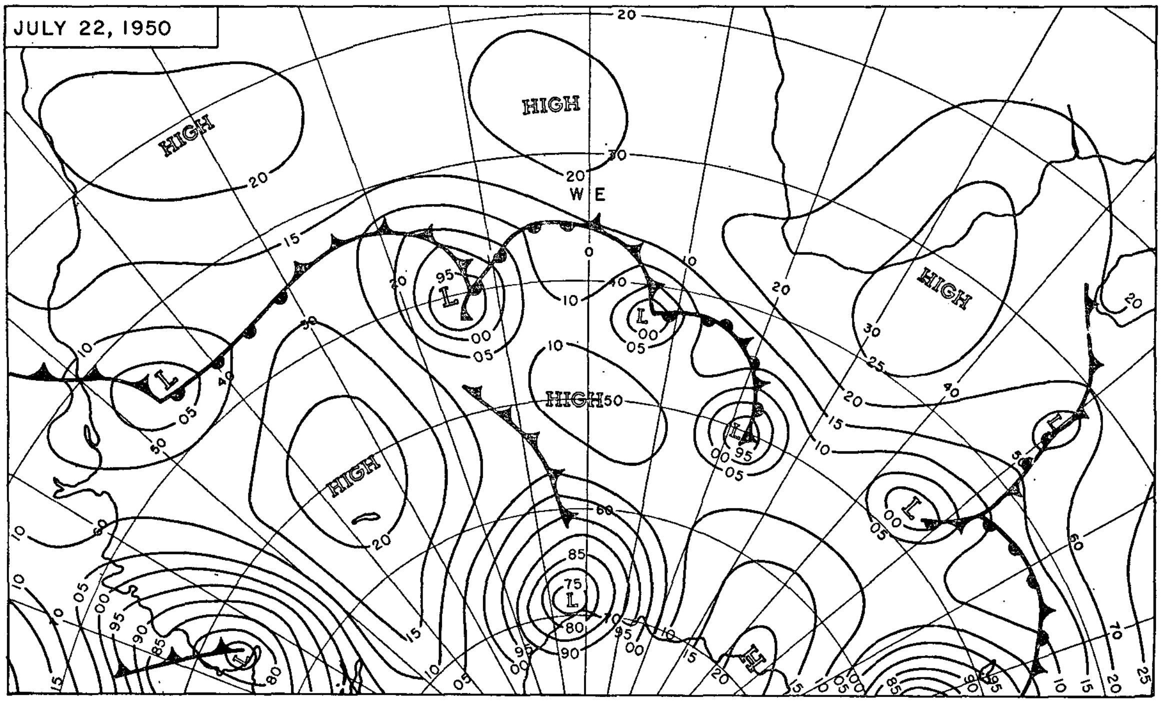

Fig. 3. Surface synoptic map of South Atlantic sector, 22 July 1950.

The South American – South Atlantic quadrant is where we find the zonal character of the circulation most disturbed. During the period of the strong polar outbreak it is interesting to examine the zonal-index values in this region. The indices we shall refer to are (1) the zonal-westerly (ZW) index, which is a measure of the mean west-east wind between the fixed latitudes 35°S and 55°S, and which is based upon the difference of mean pressure between those latitudes, and (2) the maximum zonal-westerly (MZW) index, which is based upon the variable 20-deg latitude zone having the maximum pressure-difference. On 20 July (table 3) the value of the zonal-westerly index, as well as that of the maximum zonal-westerly index, is 6.5 m/sec, which is about normal. But by 22 July the influence of the polar outbreak is felt, and the fixed ZW index

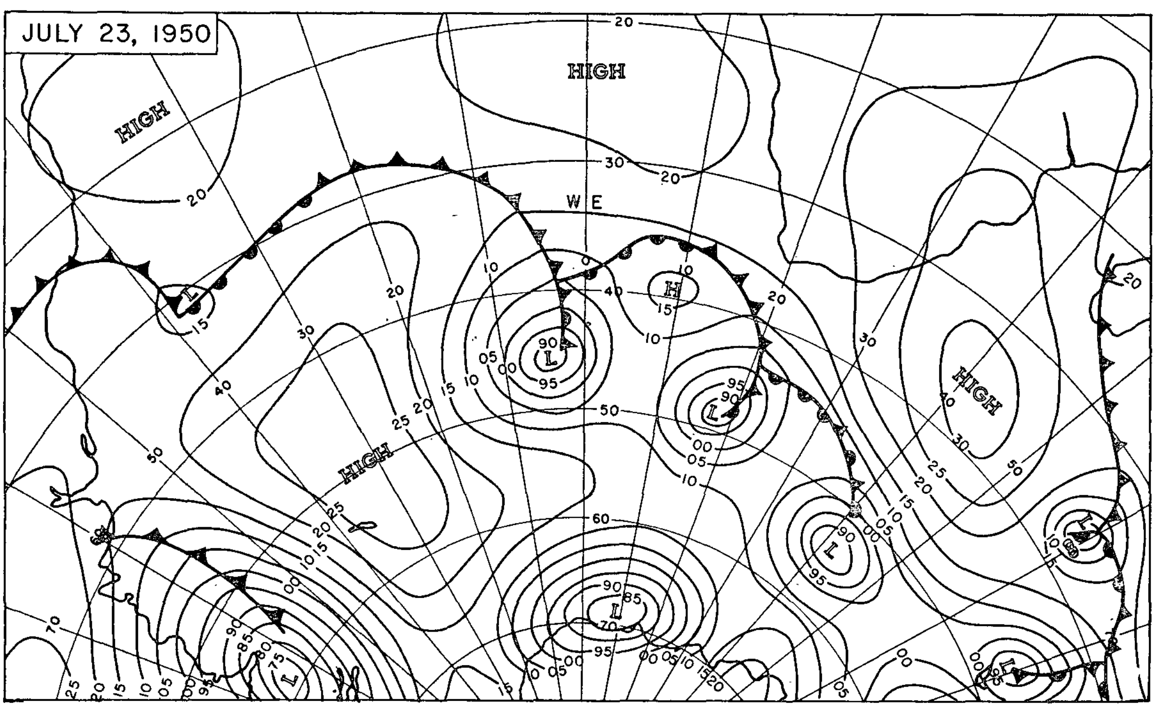

Fig. 4. Surface synoptic map of South Atlantic sector, 23 July 1950.

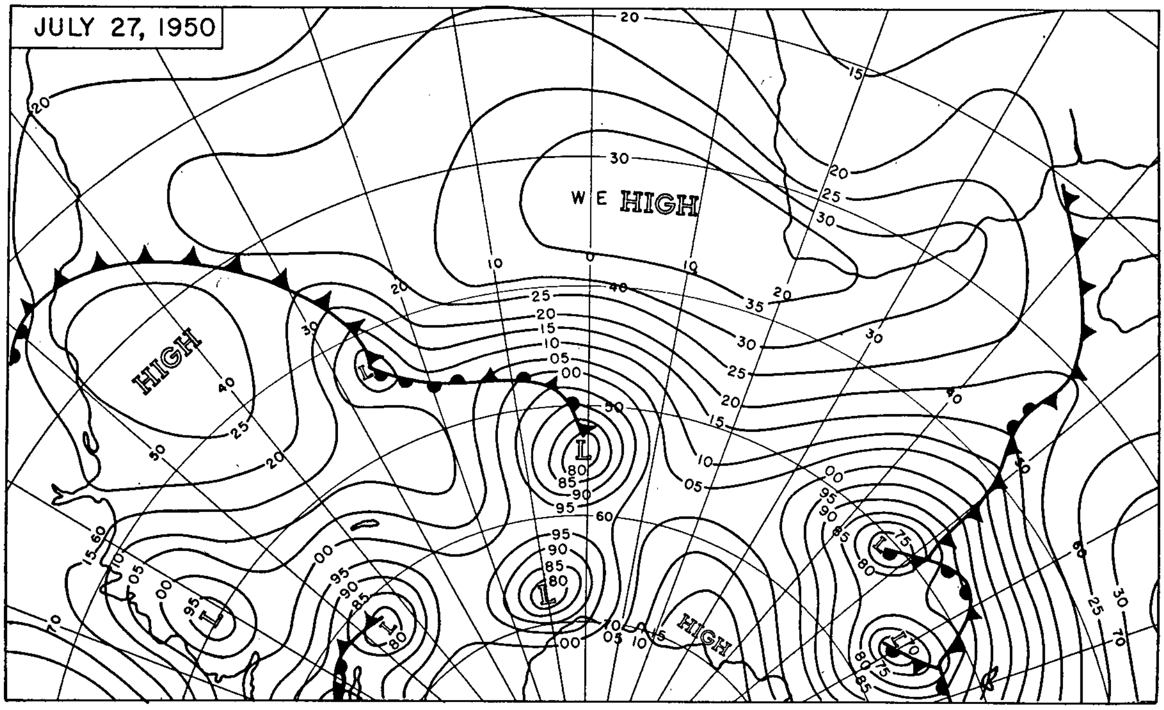

FIG. 5. Surface synoptic map of South Atlantic sector, 27 July 1950.

drops off to only 1.0 m/sec in this sector (40°E to 50°W). At the same time, the belt of westerlies divides into two streams; one of 4.0 m/sec at 50–70°S, and the other of 2.6 m/sec at 25–45°S. The situation thereafter, until 27 July, was one in which the ZW index increased as the polar high moved northward. The second belt of westerlies, between 50–70°S, disappeared by 25 July. The maximum value of the ZW index, 11.5 m/sec, was reached on 27 July, when the polar high was at its northernmost position and had greatly reinforced the subtropical ridge.

Polar highs such as the above, or weaker ones, regenerate or reinforce subtropical highs, the mechanism being very likely analogous to the dynamic anticyclogenesis described by Wexler [3]. At the time the polar high was moving northward, it appeared to have reached a maximum central pressure of 1030 mb. However, when it began to undercut the subtropical ridge which was located along 25°S, during the period 25–27 July, it intensified to at least 1039 mb, and at

TABLE 3. Index values (m/sec) for sector 40°E to 50°W, July 1950.

Date	ZW*	MZW*	Lat. MZW*
20	6.5	6.5	45°
21	5.8	6.2	40°
22	1.0	4.0/2.6	60°/35°
23	1.8	3.1/3.3	60°/35°
24	3.0	3.0/4.2	60°/40°
25	5.5	5.5	45°
26	8.9	8.9	45°
27	11.5	11.5	45°
28	8.1	8.1	45°

* Zonal-westerly and maximum zonal-westerly index, and latitude of mid-point of maximum zonal-westerly index.

the same time became much more extensive (figs. 3 to 5). At the time that the polar high moved to the north of Tristan da Cunha, it was far enough removed from its original source of cold air to preclude a third surge from Anarctica as the cause of the pressure rise in the lower middle latitudes. It is likely, as the African radiosonde observations indicate, that the mass of cold air in the polar high, as it replaced the warmer subtropical air in the lower levels of the ridge, caused much of the rise in pressure. Both this effect of the greater density in the colder air mass, and perhaps also the strengthening of the inversion in the ridge, which is the final result of the combination of the two highs, may be regarded as causing the rather unusual increase in pressure.

Similar strong outbreaks from Antarctica have been noted in other sectors, as evidenced by their effect at Marion Island (47°S, 38°E), New Amsterdam (38°S, 78°E), Macquarie Island (54°S, 159°E), Campbell Island (53°S, 169°E), and Heard Island (52°S, 73°E). Since these islands are widely scattered in the South Atlantic Ocean and South Indian Ocean, it can be concluded that the source of the cold air is not restricted to only one region of Antarctica. It is not possible to state any facts or draw any conclusions as to the occurrence of similar polar highs in the South Pacific Ocean, because of the complete lack of data from that area.

It is not often that the polar highs are able to break through the westerlies; they are almost always limited in extent and are carried away rapidly downstream. Because of the normally high speed of the

Table 4. Surface data for Heard Island, 1950.

Date	Time (GCT)	Press. (mb)	Temp. (deg C)	Dew point (deg C)	Wind dir. (deg)	Wind speed (knots)
Sept. 30	12	989.9	−2	−4	310	18
	15	994.3	−4	−8	270	32
	18	994.1	−4	−6	260	30
	21	996.7	−3	−5	230	26
	24	998.3	−4	−6	220	18
Oct. 1	03	1001.2	−4	−8	220	20
	06	1003.8	−4	−9	220	18
	09	1005.7	−4	−8	220	20
	15	1009.0	−5	−9	220	11
	18	1008.4	−6	−10	240	04
	21	1006.9	−6	−9	270	02
	24	1001.1	−4	−6	040	10

zonal flow, the invasions of modified cP air at any particular station are of short duration. Heard Island, from which radiosonde data are available, is far enough into the westerly flow to serve as a checkpoint in the search for these small polar highs. A clear example is shown in the sea-level data (table 4) and raob curves (fig. 6).

On 30 September a low pressure center, immediately followed by a minor wave, had passed over Heard Island from the northwest, and moved off to the southeast. The cold air behind the low was at first the usual mP air of these latitudes, characterized by a steep lapse rate and high moisture content up to high levels (fig. 6). Following the mP air, there appears on 1 October a sharp thrust of modified cP air. The 0900 GCT raob of this day shows the change of air mass. The ascent is typical of cP air which has traveled some distance over water, and the subsidence inversion, at 840 mb, is clearly an anticyclonic feature. The surface temperature and dew point on the 30th are near the normal of the period. The coldness and dryness of the surface air on the 1st may be considered as evidence of the continental origin, since, despite the obvious warming of the lowest layers due to the trajectory over water, the usual temperature and dew point of the normal mP air of this region have not been obtained.

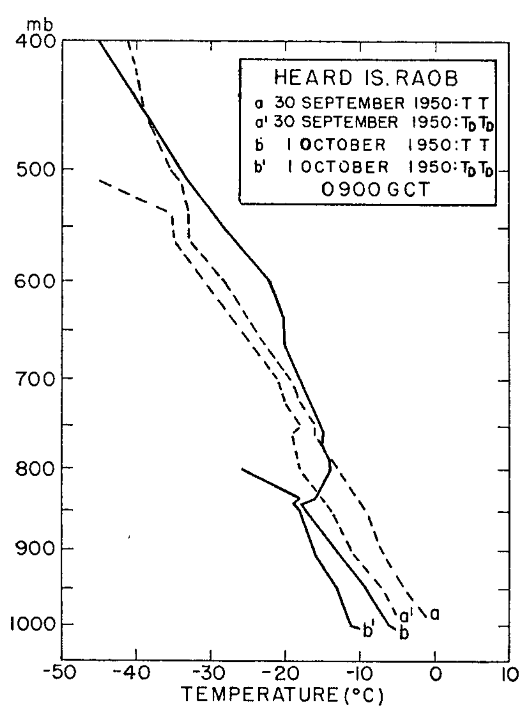

Fig. 6. Heard Island raobs, 30 September 1950 and 1 October 1950.

3. The zonal circulation

The circulation in the southern hemisphere is essentially zonal during all seasons of the year. In the South American quadrant the effect of the continent is such that the zonal pattern becomes confused; this is, therefore, the sector where the greatest exchange between high and low latitudes takes place.

The non-seasonal variations of the circulation, by which is understood the change from high to low index, or *vice versa*, seem to be reflected in the southern hemisphere primarily by changes in the latitude of the west-wind belt rather than in a complete breakdown into a cellular pattern. The change from one circulation pattern to the other may be described as an expansion (high to low index) or a contraction (low to high index). As in the other hemisphere, the index changes are usually not simultaneous all over the hemisphere. Although the fixed zonal index may decrease, synoptic evidence indicates that such a decrease may, to a certain degree, be compensated for by an increase in another belt of latitude. The zonal character is always maintained, while the latitude of the westerlies may fluctuate. During a low-index period the variations from the mean are at times considerable, but rarely do the westerlies at any point become discontinuous. In cases of extremely low index in spring and summer, it seems that warm ridges extend all the way to Antarctica, and great depressions exist in the middle latitudes. The high-index circulation is characterized by a contraction of the storm tracks and a more than usual west-east orientation of the polar front. The pressure and wind variations at a station in the westerly belt are good indications of index changes. During a period of high index the storm tracks are invariably south of Heard Island, which station may be considered as being representative of its latitude. The wind directions during such a period remain roughly within the northwest to southwest quadrants. During a low-index situation, when the storm tracks are over or to the north of Heard Island, even easterly winds are observed.

Another implication of the zonal character of the circulation is the existence of long, unbroken latitudinal fronts, as favored by Gibbs *et al* [4]. This tendency is interrupted over South America and the adjacent oceans, where the influence of the continent tends to establish the fronts in a meridional orientation, and to a smaller degree likewise in the vicinity of Australia and New Zealand. The meridional orientation of the fronts becomes more pronounced in all sectors during low-index periods. The waves formed on the latitudinal fronts will most often have a rapid motion downstream. In the prevailing strong poleward pressure gradient, it is difficult to establish east winds on the poleward side of the waves. It is believed [5] that the waves often start out with an incomplete cyclonic circulation, and it is not until they reach fairly high latitudes that there is a complete circulation established around them. Even then there exists some deformation in the shape of the lows, so that, instead of being mainly circular vortices, the cyclones have their greatest extension latitudinally. They appear on the maps as elliptical systems, with more latitudinal flow than meridional flow.

4. The subtropical ridge

Contrary to the northern-hemisphere subtropical oceanic highs, the intensity of those of the southern hemisphere decreases from winter to summer. Since their positions vary from one ocean to another, it is more satisfactory to discuss them individually. First, however, although the mean maps may give the impression of a permanent or semi-permanent high in each of the southern oceans, the southern hemisphere subtropical highs have a much more migratory character than those of the northern hemisphere. Only in the eastern South Pacific, where the air flow is impeded and diverted by the Andes, is it correct to speak of a more or less permanent high. It should be kept in mind that the following discussion is concerned with mean maps. The highs which are discussed are not the individual migratory systems.

In the South Indian Ocean the subtropical ridge is affected by the strong reversal of circulation over Asia from the warm to the cold season, as well as by the monsoonal changes over South Africa and Australia. Whereas the latitude of the center of the South Atlantic high varies little from winter to summer, the center of the South Indian Ocean high shifts poleward by about ten degrees of latitude in summer and decreases in intensity. On the other hand, there is no appreciable poleward expansion of the high during the summer season, which may imply little variation in the position of the polar trough. Even the pressure gradient on the equatorward side of the trough need change little, since the high decreases in intensity as it undergoes the poleward displacement.

Although Heard Island provides too short a record to give conclusive evidence, the indications are that there is little variation in the distribution of wind direction from season to season [4]. The storm activity has a uniform annual frequency, and the two wind directions of maximum frequency are southwest and west-northwest throughout the year. From this it is concluded that there are frequent trough passages at Heard Island during all seasons of the year.

South of Australia, due to the relatively strong summer monsoonal low over the continent, the ridge weakens considerably more than in the Indian Ocean sector, and shifts southward. This shift need not affect the position of the polar trough nor the strength of the westerlies, since the intensity of the high is much less in summer than in winter due to the continental

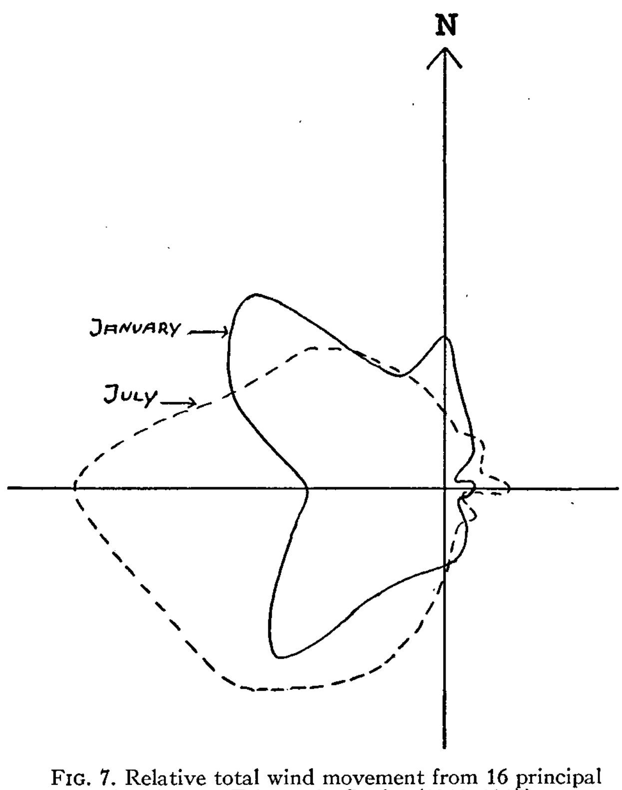

FIG. 7. Relative total wind movement from 16 principal directions at Tristan da Cunha (1943–1947).

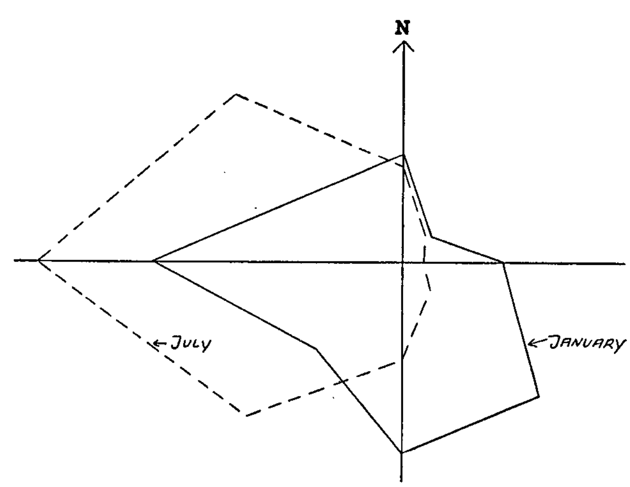

FIG. 8. Percentual direction of low clouds at Laurie Island during January and July (1925–1949).

heating and the more general shift of mass from the summer to the winter hemisphere.

In the South Atlantic Ocean, the subtropical high is of greater intensity during the cold season than during the warm season. At the same time, it reaches its largest equatorward and latitudinal extension. The west-east expansion takes place as a result of the change in circulation over the two neighboring continents from summer to winter. In the warm season, the high shrinks from its northern periphery and also laterally. The center is concurrently displaced eastward toward Africa, and the axis takes on a northwest-southeast orientation as opposed to the west-east orientation of the wintertime anticyclone. The South Atlantic high in summer is a relatively permanent phenomenon and is not made up of a succession of migratory systems to the same degree as is the wintertime anticyclone. The tilt of the horizontal axis of the high reflects the greater meridional circulation in summer. There is no appreciable poleward shift of the high from one season to another. Synoptically the winter pattern signifies that the high-latitude anticyclones move equatorward on the west side of the South Atlantic, and that the mean tracks of the waves forming on the South Atlantic polar front in winter will tend to lie along a latitude circle in the general zonal flow. In the summer there are fewer high latitude anticyclones, and their equatorward path is shifted eastward. At the same time there is a trough on the west side of the ocean, and the mean path of the waves on the polar front in this comparatively low-index pattern is in a general northwest-southeast line. The summertime trough in the western South Atlantic is mostly stationary because of the effect of the continental heating, but the orographic effects and the changing synoptic patterns cause fluctuations in the strength of the trough. In the winter there is no heating effect, and the trough never attains the same permanence and equatorward extension as it does in summer.

The change in circulation is seen in figs. 7 and 8. Fig. 7 shows relative values of total wind movement from sixteen principal directions at Tristan da Cunha, based on the windroses for that place [6]. The July wind movement, which is strongly west and southwest, substantiates the concept of a ridge north of Tristan da Cunha, and the preferred western South Atlantic path taken by the equatorward-moving anticyclones from high latitudes. At the same time, the zonal character of the middle latitude circulation is emphasized. The predominant northwest and southwest flow in January shows the new position of the ridge and the new orientation of the storm tracks. The greater total wind movement in July, as compared to January, is caused by the strengthening of the high in winter, and not necessarily by an intensification or equatorward movement of the polar trough.

Fig. 8 shows the percentual direction of low clouds at Laurie Island in the South Orkneys during January and July. The predominance of the zonal circulation in winter is brought out by the almost complete absence of directions other than westerly in July. The significant increase in southerly and easterly directions in January, alternating with an equivalent amount of westerly directions, reflects the increased meridional component of the circulation in this sector.

In the South Pacific Ocean there are few data, but from what are available on the west coast of South America it is evident that the eastern core of the South Pacific anticyclone is a relatively permanent feature. The center undergoes shifts in latitude such that in summer it is farthest poleward, although the absolute value of the pressure is lowest.

5. The polar pressure trough

In the northern hemisphere the Icelandic low weakens much from winter to summer, while the Aleutian low disappears almost completely. Although the mean maps which have been prepared for the southern hemisphere suffer somewhat in accuracy because of the incomplete network of observing stations, the persistence and extent of the polar pressure trough during all seasons is unquestioned. It is still not established, however, whether the trough remains approximately in the same latitude, or whether it moves poleward or equatorward in one season or another. Also open to discussion is whether the minimum pressure in the trough undergoes seasonal variation. Finally, consideration must be given to the problem of whether one season is more favorable to a meridional flow (low index) than another. These questions are intimately related and contain a solution to some of the problems of the circulation of the southern hemisphere. It is hoped that later studies, based upon more complete coverage of data, will throw light upon these points.

If it is assumed that the circulation over and immediately around Antarctica during the winter causes a steady outflow from the continent, with less inflow aloft [7], this region will have its lowest mean pressure in the late winter and spring, as found by Kidson [8], among others. At the same time, the continental conditions are most widespread because of the normal seasonal extension of the sea ice. The pressure gradient over the continental area itself may be assumed to be generally rather weak, and it is not until the vicinity of the ice rim that the gradient increases. The tracks of the cyclonic systems which reach high latitudes will then be found, in the mean, close to the ice edge in the cold season. In summer and autumn the ice recedes, and at the same time the pressure in the antarctic regions rises to its maximum [8]. The cyclone tracks fail to come closer to the continent, but rather remain in about the same latitudes as during the cold season. This can also be inferred from a consideration of the shift in latitude and variation in intensity of the subtropical ridge. To preclude any misunderstanding, it is emphasized that the above concept has to do only with the high-latitude storm tracks as they may be on seasonal mean maps. The question of whether or not individual low-pressure centers travel far inland or even cross Antarctica deserves a study of its own when sufficient data are available.

Mean pressure maps [9] for the southern hemisphere show that, where continuous observations are to be had, the pressure in the trough is about 5 mb lower in summer than in winter. This feature may be caused by the general shift of mass to the northern hemisphere during the winter season of the latter. Since the subtropical ridge is also weakened at the same time, the zonal winds in the higher middle latitudes do not change significantly from winter to summer.

6. Summary

1. The strong zonal circulation in the southern hemisphere usually prevents antarctic air from reaching middle and low latitudes in pronounced outbursts. Polar highs, which have their origin in or near Antarctica, at times attain sufficient strength to break through the zonal flow to reach and reinforce the subtropical ridge.

2. A high-index pattern in the southern hemisphere is characterized by a broad belt of strong westerlies all around the southern oceans. During such periods fronts are oriented almost latitudinally, and the waves formed on them move rapidly, and often with an incomplete circulation on the poleward side.

3. A change from high to low index takes place as a shift in latitude of the belt of maximum zonal westerlies, and a pronounced trough and ridge pattern is produced, rather than a complete breakdown of the circulation into a cellular structure. The westerly-wind belt always maintains its continuity. The winter circulation tends to be one of high index; in the summer it is comparatively low.

4. There is little variation in the latitude and intensity of the circumpolar trough from season to season.

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