Mid-Season Average Zonal Winds at Sea Level and at 500 mb South of 25 Degrees South, and a Brief Comparison with the Northern Hemisphere

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ABSTRACT

Meridional profiles of sea-level and 500-mb average zonal winds at mid-season in both hemispheres are presented and described. Over much of the southern hemisphere the mean zonal westerly flow changes little during the year, and in each season it is always stronger for the hemisphere as a whole in the southern than in the northern hemisphere. The southern hemisphere circulation and its seasonal changes are shown to be closely related to the surface temperature distribution.

It is pointed out that despite the seemingly symmetrical distribution of heat and cold sources over the southern hemisphere, regional differences in the strength and distribution of the mean zonal wind do exist, particularly during the colder part of the year. Thus, although on the whole there is a strong control arising from the oceanic dominance of the hemisphere, there are, especially in the Australian sector, large disturbances connected with continental influences on heating and cooling.

The strongest zonal westerly mean circulation in the southern hemisphere at the levels dealt with here is found over the Indian Ocean.

1. Introduction

In the southern hemisphere few wind observations are available outside the continents and their near surroundings. Until a few years ago Marion and Amsterdam Islands (approximately at 47S, 38E and 38S, 78E) were the only *isolated* ocean stations in middle and high latitudes where rawinsondes were taken. In 1961 the station on the Kerguelen Islands (approximately at 49S, 70E) began rawinsonde ascents, but even if the distribution of wind over the southern oceans is assumed to be a simple one, three wind-measuring stations in the South Indian Ocean will not suffice to describe the average distribution and seasonal variation over such a vast area.

Since the average pressure patterns at sea level in the southern hemisphere are reasonably well known, and since maps of average geopotential heights can be drawn with some confidence over most of the hemisphere, it is feasible to compute the distribution of zonal wind by means of the geostrophic wind equation and use it as a fair substitute for the zonal component of the actual wind. This has been done by Heastie and Stephenson (1960). Where the work in the present article repeats that of Heastie and Stephenson, it is based on a better coverage over a longer period. Obasi (1963) summarized the observed winds of twelve IGY months and extrapolated from these data to cover the entire hemisphere. The spatial distribution of the average zonal wind at 500 mb in Obasi's work agrees in parts with that shown below. His maps are, however, averages of six months: October to March (summer) and April to September (winter), and therefore much information about seasonal variations has been smoothed away. Even the use of only mid-season months neglects significant changes at other times of the year.

The mean maps of sea level pressure and 500-mb height which have been used for the computation of southern hemisphere zonal winds in this paper are those published by van Loon (1961). The sea level maps are six- to seven-year means based on historical analyses and corrected in higher latitudes to fit the more abundant data of recent years. The 500-mb mean maps were constructed by adding these sea level maps and the monthly average 1000-500-mb thickness maps published by van Loon and Taljaard (1958), taking into account also all available wind and height data. To give an idea of the distribution of the data, which were from periods of different length, the January 500-mb mean map is reproduced in Fig. 1. The thickness maps were built up from maps of sea level mean temperatures by means of average 1000-500-mb lapse rates obtained from nine oceanic stations between 35S and 65S. The maps were adjusted to fit actual thickness values and thermal winds from the 58 radiosonde stations south of 20S. The northern hemisphere pressure and height data were taken from Jacobs (1958).

The average zonal winds were computed from profiles of pressure and geopotential height for overlapping intervals of five degrees of latitude. The resulting zonal

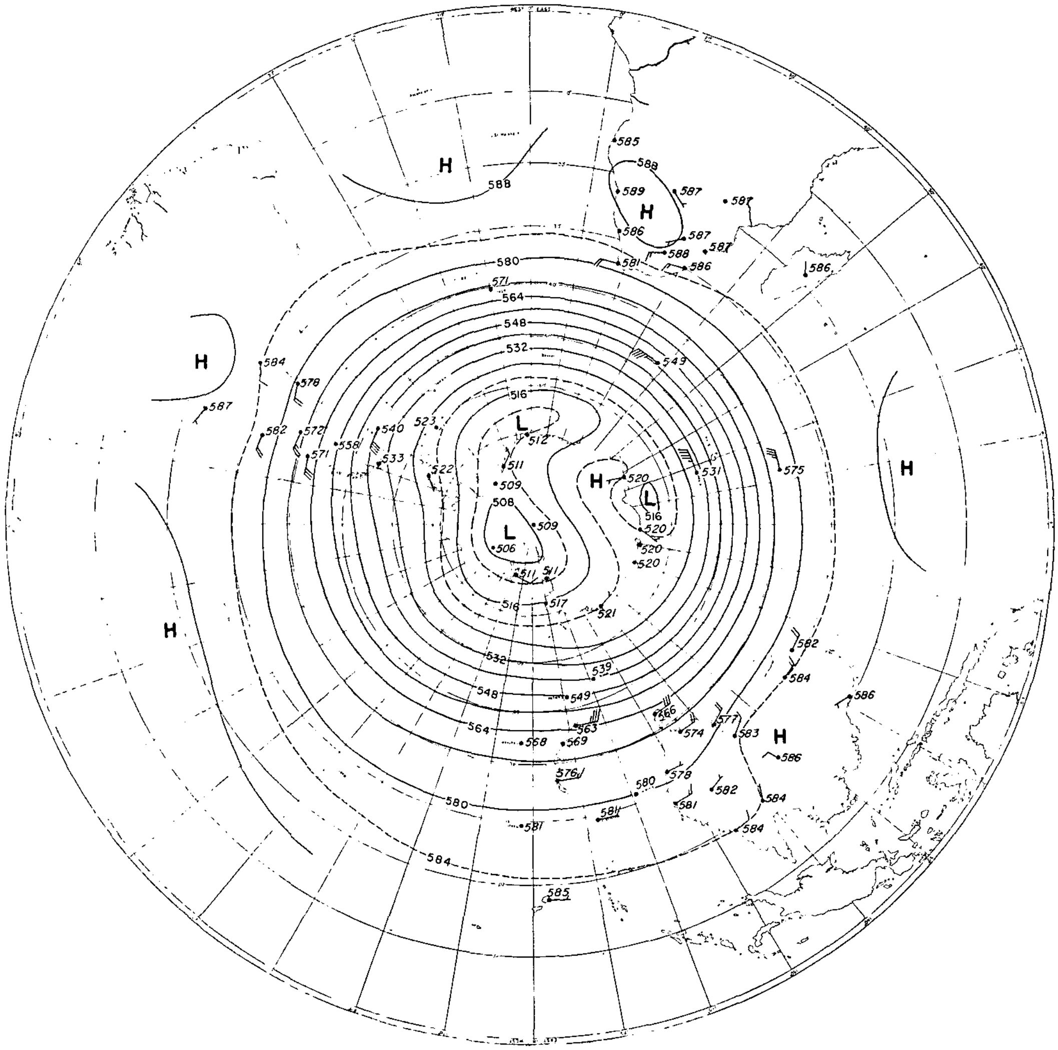

Fig. 1. Mean contours of the 500-mb level in the southern hemisphere in January. The units are geopotential dekameters and the contour spacing 8 gpDm. Reproduced from Van Loon (1961).

wind profiles were nowhere smoothed more than half a meter per second, generally not more than a quarter of a meter per second, and so are likely to be too irregular. Because of the heterogeneous data and the methods used in constructing the maps of sea level pressure and 500-mb height in the southern hemisphere, no accuracy in detail can be claimed for the derived data.

2. Mid-season meridional profiles of average zonal winds at sea level and 500 mb

Sea level. Fig. 2 contains the meridional profiles of the mid-season zonal winds in both hemispheres. It shows that the zonal westerlies in the southern hemisphere change little through the year. They cover a narrower latitude belt in summer but their maximum, 9.2 m sec^{-1} at 51S, is in summer. It is 1.7 m sec^{-1} higher than the winter maximum of 7.5 m sec^{-1} at 50S. This agrees with Priestley's results (1951) in his study, based on actual winds, of the stress between ocean and atmosphere.

The profiles of the southern hemisphere zonal winds have been terminated at 67.5S because it is meaningless to reduce pressure over the high Antarctic plateau to sea level. The border between westerlies and polar easterlies, i.e., the mean position of the Antarctic trough, can be seen on three of the four profiles. In spring it lies farthest poleward, beyond the profile, in summer farthest equatorward. The border between westerlies and subtropical easterlies, i.e., the mean position of the subtropical ridge, moves six degrees of latitude from 34.5S in summer to 28.5S in winter. But the mean maps (van Loon, 1961) reveal that the meridional movement is small over the oceans and that the

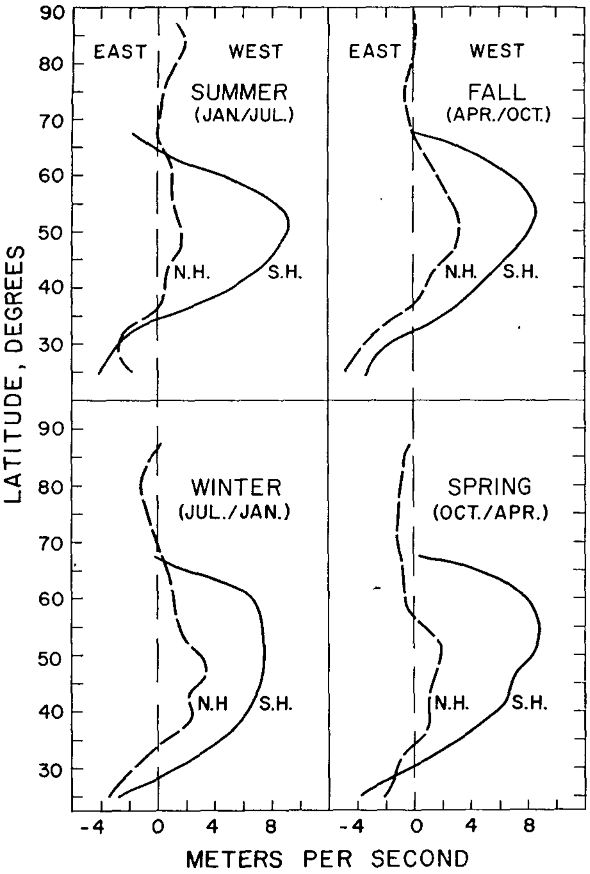

FIG. 2. Profiles of mid-season average zonal wind at sea level. Units are meters per second.

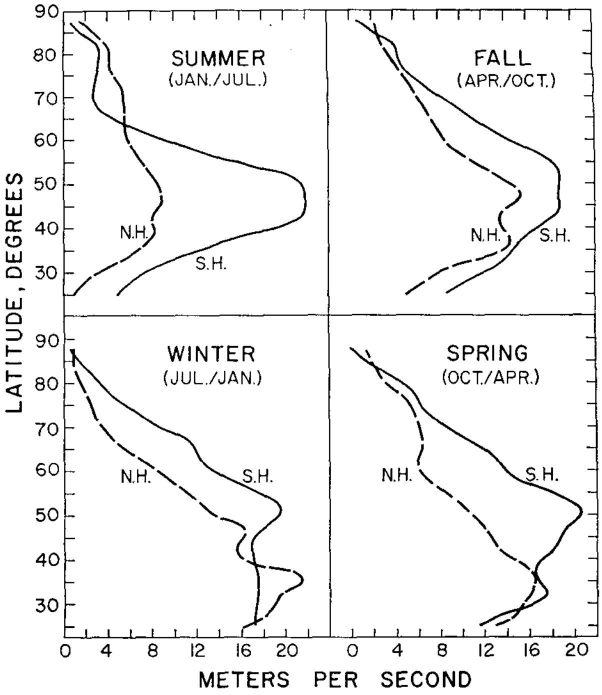

FIG. 3. Profiles of mid-season average zonal wind at 500 mb. Units are meters per second.

change of circulation over the subtropical continents and their surroundings accounts for most of the displacement.

It is worth noting that in the northern hemisphere in April the sea level westerlies cover a smaller area than in any other season. The polar easterlies begin already at 57N, and the sea level pressure profiles show that there is more mass north of the Arctic Circle in April and May than during the rest of the year.

500 mb. At this level the zonal wind profile for the southern summer (Fig. 3) is the most noteworthy one. The maximum strength, ca. 22 m sec^{-1} between 42.5S and 50S, is almost 2.5 times greater than that of the northern summer, *and* greater than that of any of the three other months in either hemisphere. The northern hemisphere winter profile comes close to the same value but only along one parallel of latitude (35N). On the other hand, the strong horizontal shear on both sides of the westerly maximum in the southern summer makes the latitude belt covered by strong westerlies narrower than that of any other season in the hemisphere. In general it can be said that the strongest westerlies in the southern hemisphere vary little (3.0 m sec^{-1}) from one mid-season month to another, and that their average position is nearly constant near 50S, somewhat closer to the pole in *winter* than in summer. In the northern hemisphere the maximum strength has a range of 12.5 m sec^{-1} from a summer low to a winter high, and the position of the maximum changes from 47.5N in summer to 35N in winter.

The northern hemisphere profiles have marked double maxima, ten degrees apart, in January and October. An explanation of the two maxima can be gathered from the maps of monthly mean isotachs (Heastie and Stephenson, 1960). They show that the wind maximum in the trough over eastern Asia lies about ten degrees farther south than that in the trough over the North American east coast. In April when the wind maxima in the two troughs are located in the same belt of latitude (curiously because of an equatorward movement of the American wind maximum) only one peak appears on the profiles in lower latitudes. Spring in the northern hemisphere is further distinguished by a minor maximum in latitudes 65N to 75N, derived from the region from 70W eastwards to 100E. During most of the year the southern hemisphere shows the stronger zonal westerly circulation in high latitudes to about the 85th parallel. This is not so in summer when the northern hemisphere has the stronger westerly circulation poleward of the 65th parallel.

The greater strength of the zonal westerly circulation in the southern than in the northern hemisphere is apparent from the profiles at both sea level and 500 mb.

This does not necessarily mean that there is always less atmospheric exchange across middle latitudes in the southern hemisphere, a conclusion which is often reached from the appearance of the mean map. Pfeiffer (1958) calculated Austausch coefficients for the southern hemisphere using both Wagner's and Lettau's methods. The former considers the exchange across a latitude circle, the latter the exchange at a point. Wagner's method then includes not only the exchange due to irregular turbulent movements considered by Lettau, but also that resulting from semi-permanent large-scale circulations like the trade winds or quasi-stationary systems. Pfeiffer's conclusion was that, considering the two types of Austausch coefficient together, the intensity of the meridional exchange is frequently as strong as in the northern hemisphere.

Perhaps the mean temperature gradient across middle latitudes in the lower half of the troposphere may serve as a measure of the net exchange. Under similar conditions (the same amount of incoming radiation and the same kind of underlying surface) a weaker meridional mean temperature gradient would indicate a more effective meridional exchange. The 1000-500-mb thickness gradients between the 30th and 60th parallels of latitude (from van Loon and Taljaard, 1958, and Jacobs, 1958) are, in winter:

Northern hemisphere......45 dekameters (22.5C)
Southern hemisphere......37 dekameters (18.5C)

and in summer:

Northern hemisphere......23 dekameters (11.5C)
Southern hemisphere......39 dekameters (19.5C).

To compare the two summers is, however, not fair. With nearly continuous daylight in higher latitudes the different thermal properties of the predominant surface in either hemisphere create basically different temperature patterns. The winters are more comparable, not only because there is little or no incoming radiation in higher latitudes, but the surfaces, both to a great extent covered with ice and snow, are more similar (see, for instance, Simpson's maps of the intensity of the net radiation, reproduced opposite page 474 in Godske *et al.* (1957)). The comparatively small difference between the thermal gradients across middle latitudes in both hemispheres *in winter* would suggest that as regards the atmospheric layer below 500 mb, at any rate, there is little difference between the two in the amount of exchange across middle latitudes.

3. The spatial distribution of average zonal wind in the southern hemisphere and it relation to surface temperatures

The most distinctive trait of the January (summer) map of average zonal wind (Fig. 4) is the well defined maximum of zonal westerlies which lies along 45S across the South Atlantic and Indian Oceans. It is located directly above the region between the Antarctic and Subtropical convergences in the ocean, a region which is distinguished by its strong temperature gradient in the ocean surface compared with the temperature gradients to the north and south. Considering the part of the hemisphere where the westerly maximum at 500 mb is strongest, i.e., from about 25W eastwards to 110E, one finds the distribution of temperature gradient in the ocean surface to be approximately as follows:

30S to 40S.....0.6C per degree latitude
40S to 50S.....1.2C per degree latitude
50S to 65S.....0.3C per degree latitude in January.

In winter, pack ice spreads over much of the Antarctic Ocean, and the Antarctic continent has cooled at a rate much higher than the oceans in middle latitudes. This results in increased poleward temperature gradients:

50S to 65S.........1.0C per degree latitude in July,

and, consequently, stronger zonal westerlies in higher latitudes than in summer (Fig. 5). Over Australasia a second maximum of zonal westerly wind forms in winter in latitudes lower than 30S. Between this maximum and the one in higher latitudes, both reaching 20 to 25 m sec^{-1}, lies a minimum with average speeds of about 10 m sec^{-1} between Tasmania and New Zealand. A tentative explanation of this wind distribution over Australasia was given by van Loon (1961), linking it with the comparative coldness of the central and southern parts of Australia in winter.

Before one looks more closely at the seasonal change of the zonal wind and its relation to the surface temperature, it is worth studying the maps of the range (January to July) of surface temperature and 1000-500-mb thickness (Figs. 6 and 7). If the zonal wind at 500 mb is closely related to the surface temperature distribution in those regions where the latter is representative of a deeper layer of the atmosphere, then the seasonal wind changes must correspond to the seasonal changes in surface temperature gradients in those regions.

If temperature were dependent only on latitude and season, one would expect that its seasonal range would be lowest at the equator and increase towards the pole. The southern hemisphere with its vast expanse of ocean, nearly unbroken between 35S and 65S, might be expected to approximate such a pattern of temperature range. Instead both the surface temperature and the 1000-500-mb thickness range maps show a belt of low range coinciding with the zone of strongest cyclonic activity between 40S and 60S. Thus the seasonal range acquires the appearance of being arranged in four alternating rings of high and low range: low in the tropics, high in the subtropics, low in middle latitudes, and high in polar latitudes.

On the surface map all four continents stand out as

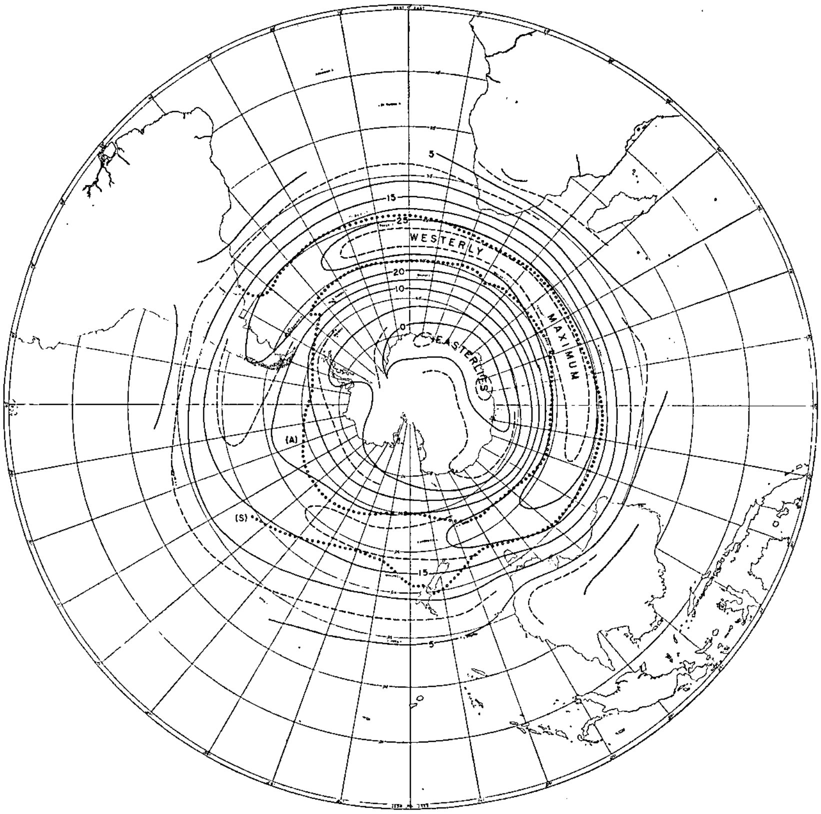

FIG. 4. Distribution of average zonal wind at 500 mb south of 25S in January. Units are meters per second. Open circles denote approximate position of Antarctic (A) and Subtropical (S) convergences in the ocean.

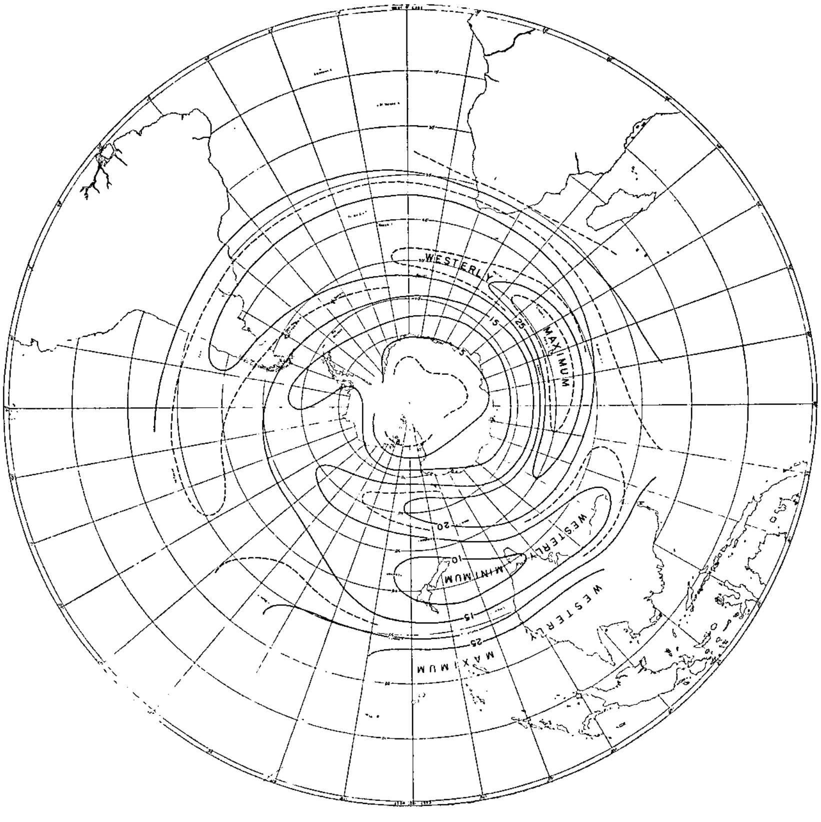

FIG. 5. Distribution of average zonal wind at 500 mb south of 25S in July. Units are meters per second.

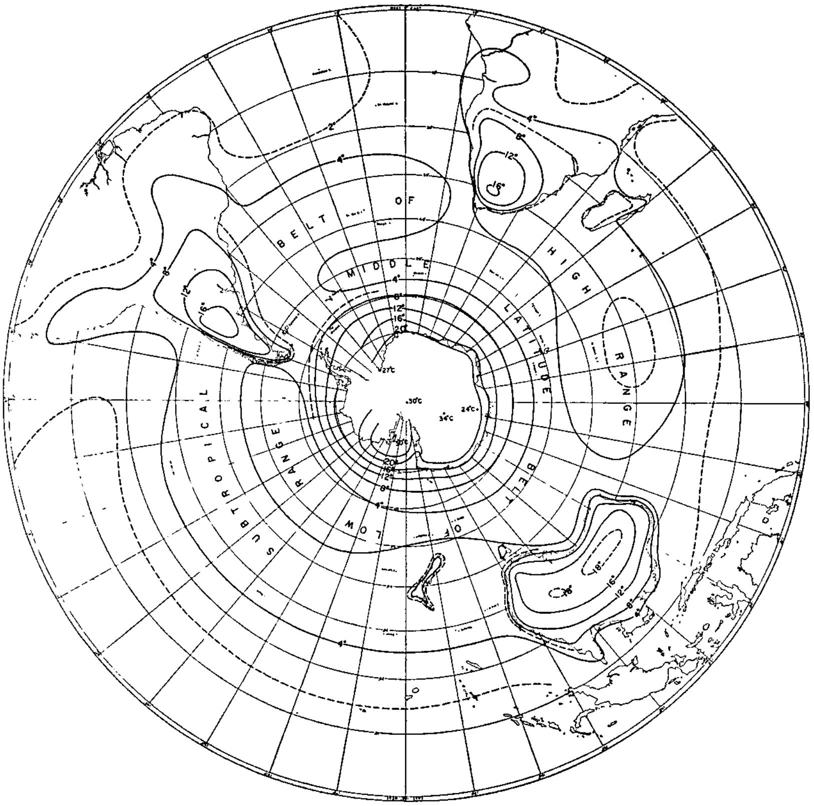

Fig. 6. Seasonal range (January–July) of surface temperature in the southern hemisphere. Units are degrees Celsius.

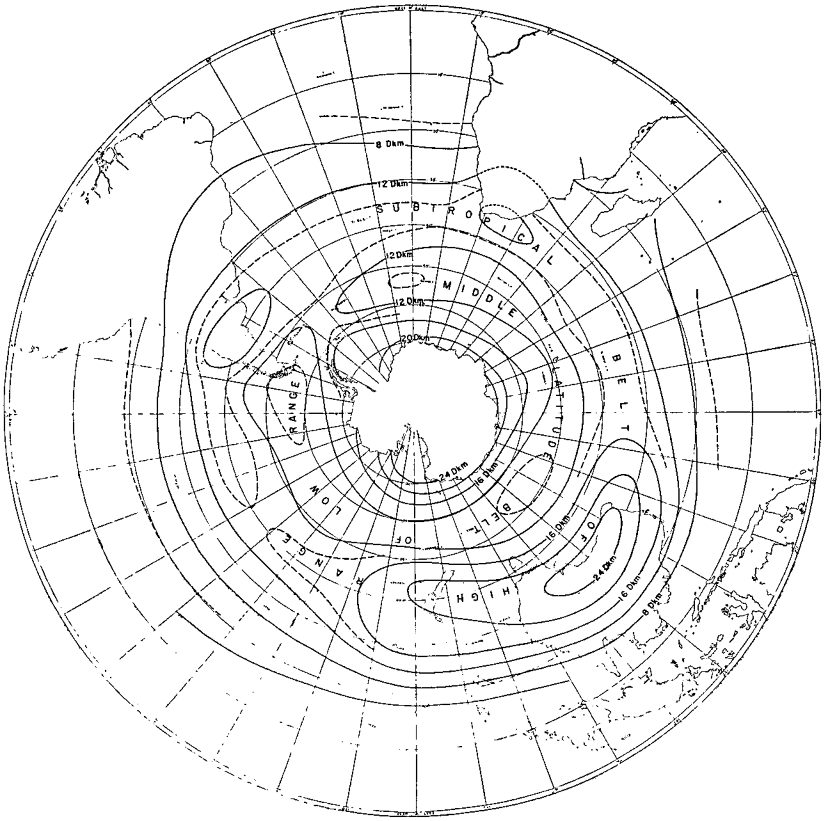

Fig. 7. Seasonal range (January–July) of the 1000-500-mb thickness in the southern hemisphere. Units are geopotential dekameters. Reproduced from Van Loon and Taljaard (1958).

areas of high seasonal range, but on the thickness map the range maxima over South America and Africa are little higher than the general level of the values in the subtropical belt of high range over the surrounding oceans. The high range at the surface of these two continents is therefore not representative of a very thick layer of the atmosphere—in contrast with conditions over Australia.

An annular distribution of temperature range such as shown on the two maps to exist in the southern hemisphere is perhaps the kind of distribution one might expect over a hemisphere with a uniform water surface. The four alternate belts may be explained in the following manner:

1. The belt of low range in the tropics as resulting from low radiation range;
2. The belt of higher range in the subtropics by higher radiation range than in the tropics with the added effect of comparatively little cloudiness because of the predominantly anticyclonic circulation;
3. The low range in middle latitudes is in a region where the circulation throughout the year is predominantly cyclonic and where, therefore, a high degree of cloudiness and frequent meridional exchange of air masses will keep the seasonal range low;
4. The high range in polar latitudes is directly caused by the high radiation range. In addition most of the Antarctic Ocean is open sea in summer but ice covered in winter.

The subtropical range maximum of 1000-500-mb thickness lies poleward of the corresponding maximum of surface temperature range. This is probably ascribable to the fact that the region of prevalent subsidence associated with the subtropical ridge of high pressure moves equatorward towards winter. Because of the corresponding expansion of the westerlies the region where the ridge is situated in summer will frequently be the seat of rising, or neutral, motion and of incursions of cold air. The seasonal range of 1000-500-mb thickness between roughly 30 and 40S is therefore increased beyond what might be expected from the temperature range at the surface.

On the basis of the annular arrangement of the zones of seasonal surface temperature and 1000-500-mb thickness range, the following may be stated: The meridional temperature gradient in the layer between 500 mb and the surface must increase from summer to winter between tropical and subtropical regions, and between middle and polar latitudes. This must contribute toward increased westerly wind at 500 mb over the regions of stronger temperature gradient in winter. Between subtropical and middle latitudes temperature gradients must decrease from summer to winter, so that here the strength of the westerlies at 500 mb will tend to decrease.

The high zonal westerly wind maximum which is found in the southern hemisphere between 42.5S and 50S *in summer* (Fig. 3), and which is stronger than the corresponding maxima of the other seasons in either hemisphere, is therefore not so surprising as it might seem in comparison with the northern hemisphere.

Fig. 7 has been prepared to stress the direct relationship between surface temperature distribution and atmospheric circulation in the southern hemisphere. It shows the changes, July (winter) minus January, in surface temperature, 1000-500-mb thickness, and in zonal wind at sea level and 500 mb. The figure is divided into two parts: One from 70W eastwards to 100E, the other from 110E to 170W, to bring out the contrast between the nearly exclusively oceanic control over the South Atlantic and Indian Oceans, and the continental influence of Australia. Beginning with the curve which shows the change of surface temperature from summer to winter between 70W and 100E, it is seen that the temperature gradient must increase equatorward of 30S in winter, decrease between 30 and 50S, and increase poleward of 50S. The range of 1000-500-mb thickness shows a similar configuration but, as mentioned above, its subtropical maximum lies eight degrees of latitude poleward of the corresponding surface temperature maximum.

Between 110E and 170W the January-July curves of surface temperature and 1000-500-mb thickness range resemble the set of curves described above, but the effect of continentality is reflected partly in the greater amplitude of the range in subtropical latitudes, and partly in the fact that the maximum range, because of the location of Australia, is equatorward of that in the other sector.

With regard to seasonal change of the zonal component of the geostrophic wind at 500 mb, Fig. 6 shows that it increases from summer to winter equatorward of about 40S, decreases between 40S and 51S, and increases poleward of 50S. The strongest part of the increase in lower latitudes coincides with the strengthening of the surface temperature gradient equatorward of 30S. The increase in zonal wind continues, at a diminishing rate, as long as the thickness gradient shows an increase. The decrease in 500-mb zonal wind from summer to winter between 40S and 51S agrees with the slackening of the poleward temperature gradient in middle latitudes, and the increase in higher latitudes corresponds to the increase in poleward temperature gradients.

In the sector between 110E and 170W the parallel between the behavior of temperature gradients and wind is as close as over the oceans to the west. In agreement with the larger amplitude of temperature range. there is a greater amplitude of the range of zonal wind over Australasia.

As the 500-mb maps from which the zonal winds have

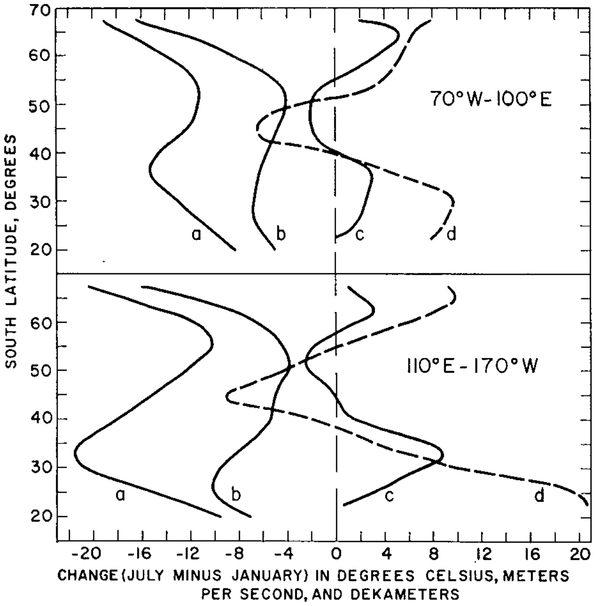

Fig. 8. Change (July minus January) in (a) 1000-500-mb thickness, (b) surface temperature, (c) sea level zonal geostrophic wind, and (d) 500-mb zonal geostrophic wind, in the southern hemisphere. The sector 70W to 100E covers the South Atlantic and Indian Oceans; 110E to 170W covers Australasia. Units are geopotential dekameters, degrees Celsius, and meters per second.

been derived are not likely to be very accurate over most of the South Pacific Ocean, nothing will be said about that part of the hemisphere. It may be mentioned that it is known, from periods when observations made on board whaling ships have made analysis feasible over the South Pacific Ocean, that the sea level circulation in summer is weaker there than over the South Atlantic and Indian Oceans (van Loon, 1960), the Zonal Westerly Index between 35S and 55S being about 40 per cent lower.

Regional differences. As suggested above, the southern hemisphere has distinct regional differences in atmospheric circulation despite the wide extent of its oceans and seemingly symmetrical arrangement of heat and cold sources. To bring out the most important differences, profiles of 500-mb and sea-level zonal winds were prepared for four sectors in January and July: 70W–10E (South Atlantic Ocean); 20E–100E (South Indian Ocean); 110E–170W (Australasia); and 160W–80W (South Pacific Ocean). They are shown in Fig. 9.

The four regional zonal wind profiles at 500 mb in summer are not appreciably different equatorward of 35S. The maxima all lie between 40 and 55S; those of the Indian and Atlantic Oceans are farthest north. They vary in strength from 16 m sec^{-1} in the South Pacific

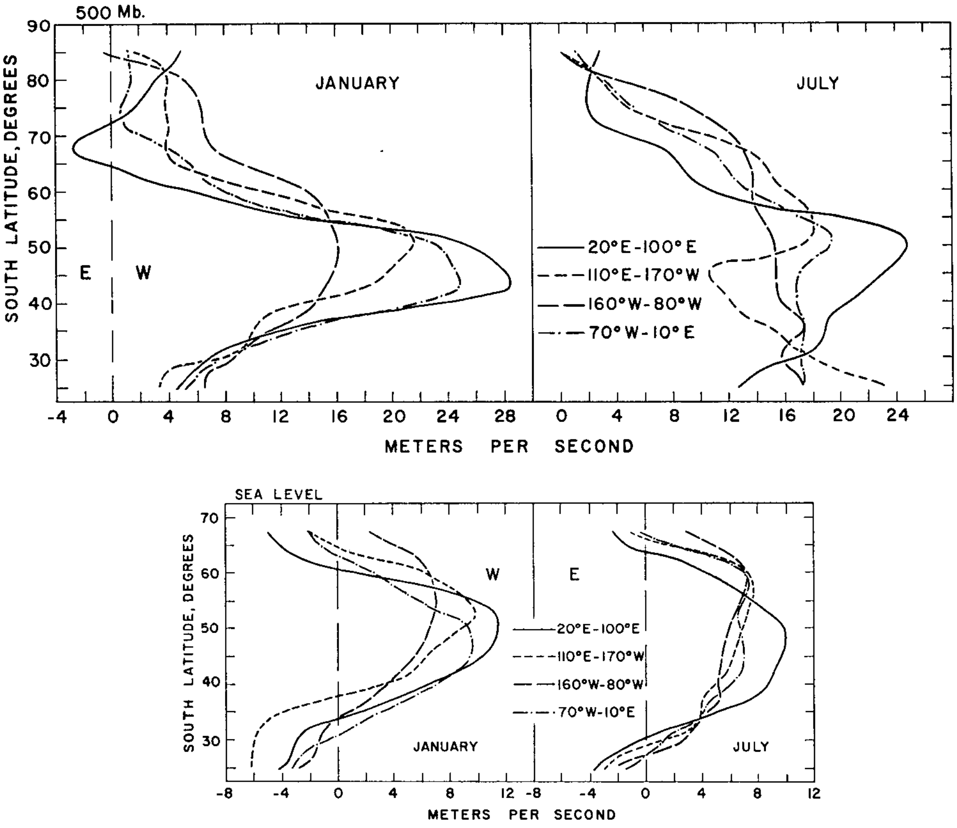

Fig. 9. Profiles of average zonal wind at sea level and 500 mb in the southern hemisphere in sectors of 90 degrees of longitude. Units are meters per second.

Ocean to 28 m $\sec^{-1}$ over the Indian Ocean. The zonal westerly wind decreases polewards at different rates in the four sectors; that in the Indian Ocean has the strongest shear so that westerlies turn to easterlies already at 64S. Although the strength of the zonal wind varies from one sector to another in summer, the meridional distribution is basically similar. In winter this is not so. The profiles for the Indian Ocean and Australia are then nearly opposite in phase. The Indian Ocean westerly maximum of 25 m $\sec^{-1}$ at 50S, confirmed in the recent publication (Barbé *et al.*, 1963) of the rawin observations made at the Kerguelen Islands, is the strongest of all. It is nearly equalled in low latitudes over Australasia. The South Atlantic Ocean has a broad zone of comparatively strong westerlies in middle and lower latitudes culminating in a weak peak at 50S.

At sea level (Fig. 9) the Indian Ocean is still the region with the strongest zonal westerlies, in winter particularly it appears as the most striking profile. It is worth stressing the remarkable difference between the South Indian Ocean and Australasia as regards the strength and latitude of the maximum zonal westerly flow. Since Australasia has the best network of radiosonde stations in the southern hemisphere it is sometimes used to illustrate the atmospheric circulation of the hemisphere. The results in this paper indicate that, especially during the colder part of the year, Australasia is probably representative of little more than itself and a region downstream.

The January sea level wind profiles show that the mean position of the subtropical ridge varies seven degrees of latitude from 38S over Australasia to 31S in the South Atlantic Ocean. In July the difference between the four regions is smaller: three degrees of latitude, from 27S in the South Atlantic to about 30S in the Indian Ocean. The range of the position of the Antarctic trough in summer is eight degrees of latitude between 61S in the Indian Ocean and 69.5S in the Pacific Ocean. In winter the range is six degrees of latitude between 64S in the Indian Ocean and 70S in the South Pacific Ocean.

Tables of the average zonal westerly indices between 35 and 55 degrees of latitude at sea level and 500 mb in both hemispheres are appended.

4. Conclusions

1. The strength and position of the maximum westerlies in the lower half of the troposphere in the southern hemisphere change little through the year, but the area covered by comparatively strong westerlies is considerably increased outside the summer season.

2. The zonal westerly circulation is stronger in the southern than in the northern hemisphere, particularly in summer.

3. The southern hemisphere circulation and its seasonal changes appear to be directly related to the surface temperature distribution.

4. The oceanic dominance of the hemisphere exerts a strong control on the atmospheric circulation, but regional differences do exist. Particularly over Australasia in winter large disturbances are found which may be related to continental influences on heating and cooling.

5. The strongest zonal westerly circulation in the southern hemisphere, both at sea level and 500 mb, is found over the Indian Ocean.

Acknowledgment. The author gratefully acknowledges his debt to Dr. C. W. Newton who suggested changes which have added to the usefulness of the paper.

APPENDIX

TABLE 1. Average zonal westerly indices (35–55 deg latitude) at sea level and 500 mb. In meters per second.

Southern hemisphere	January	April	July	October
Sea level	7.1	6.2	6.8	6.9
500 mb	20.1	18.0	17.9	18.6
Northern hemisphere	July	October	January	April
Sea level	1.1	2.0	2.6	1.4
500 mb	8.4	14.1	15.7	12.6

TABLE 2. Averages of zonal westerly indices (35–55 deg latitude) over sectors of 90 degrees of longitude in the southern hemisphere at sea level and 500 mb. In meters per second.

	20E–100E (Indian Ocean)	110E–170W (Australasia)	160W–80W (Pacific Ocean)	70W–10E (Atlantic Ocean)
Sea level				
January	9.1	5.8	5.1	8.2
July	9.2	5.9	5.7	6.5
500 mb				
January	24.5	18.0	15.2	22.5
July	22.6	13.7	15.6	19.4

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