Tellus (1984), *36A*, 76–86

Interannual variations in the half-yearly cycle of pressure gradients and zonal wind at sea level on the Southern Hemisphere

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(Manuscript received January 27; in final form April 26, 1983)

ABSTRACT

We outline the half-yearly oscillations in sea-level pressure gradients and zonal winds on the Southern Hemisphere by means of daily synoptic maps for several years. The pressure oscillation has amplitude peaks near 50°S and the Antarctic coast, separated by a minimum along 60° S where the phase changes from maxima in the extreme seasons in the south to maxima in the transitional season in the north. The zonal geostrophic wind consequently has a half-yearly wave with equinoctial maxima in the latitudes near 60° S, and one with solstitial maxima north of 50° S.

We describe the interannual variability of the half-yearly oscillations in the pressure gradients and winds, and give examples of the oscillations during FGGE and the IGY.

1. Introduction

The sea-level pressure in middle and high latitudes of the Southern Hemisphere has a marked half-yearly rhythm whose amplitude is appreciably larger than that of the yearly wave. The sparse data available before World War II were used by Reuter (1936) and Wahl (1942) to outline the half-yearly wave in the pressure over middle southern latitudes. Schwerdtfeger and Prohaska (1956) extended the analysis to the entire hemisphere and showed that the phase of the wave reverses between middle and high southern latitudes. Further analyses were made, e.g., by Schwerdtfeger (1962) in which he discusses the possible cause of the wave; and by van Loon (1967, 1972) who deals with the extent of the wave in the pressure, wind, and temperature through the troposphere, its relation to the sub-Antarctic trough in the sea-level pressure, and its association with the heat balance at the surface in the region where it exists. Further references to literature on the half-yearly wave are listed in van Loon (1967).

The mean state of the half-yearly wave is thus well known, but not its interannual variation. The latter is the topic of this report. Since the half-yearly wave dominates the seasonal variation of the wind in the area of the Antarctic Circumpolar Drift it is important to know its spatial distribution and fluctuations from year to year to be able to assess the related fluctuations in the wind-driven component of the current.

Additional information about the interannual variation of the half-yearly wave in the sea-level pressure and pressure gradients may be found in van Loon and Rogers (1981).

2. The half-yearly wave in sea-level pressure

The analyses below are based on daily synoptic maps from the South African Weather Bureau's

[1] The National Center for Atmospheric Research is sponsored by the National Science Foundation.

historical map series (December 1954–December 1958) and on daily operational maps from the Australian Bureau of Meteorology (May 1972–July 1980). The period thus covers 12 years from January to April and August to November, and 13 years for the four other months. South of 60° S, however, only 8–9 years could be used as the grid point values are not available there for the winter months in some of the earlier years.

The half-yearly wave is defined as the second harmonic in a series of 12 monthly means:

$$y = a_2 \sin(2x + A_2)$$

where a_2 is the amplitude (half range), and A_2 the phase angle which determines the value of x at which the extremes of y occur.

The spatial distribution of the mean half-yearly wave can be seen in Figs. 4.7–4.9 of van Loon (1972) and in van Loon and Rogers (1981): the amplitude has a peak between 45° S and 50° S in each of the three oceans, a minimum along 60° S, and another peak over Antarctica. The phase reverses between the two peaks from equinoctial maxima in middle latitudes to solstitial maxima in the Antarctic. The analysis of the half-yearly wave at six stations between 38° S and 52° S and four south of 65° S in Table 1 provides information about amplitude, phase, and the amount of the annual variance which is explained by the wave for some of the longest possible records in the two regions. The stations do not necessarily lie in or near the peaks of the wave, but at these available points the wave accounts for as much as 78% of the variance at middle latitudes and 69% in the Antarctic. The spatial distribution in van Loon (1972) and van Loon and Rogers (1981) indicate that the wave's share of the variance is as high as 80% to 85% in the mid-Indian Ocean and just east of New Zealand, and 70% to 80% on the Antarctic coast. Table 1 demonstrates the uniform phase in either domain, as the extremes of the wave from one place to another fall within a two-week period.

In the first approximation, the opposing half-

Table 1. *The second harmonic (half-yearly wave) in the sea-level pressure at stations in middle and high latitudes on the Southern Hemisphere. n is the number of years available; a_2 the amplitude in mb; phase the dates of the maxima; and percent is the part of the total annual variance explained by the harmonic*

	n	a_2	Phase	Percent
	A. Middle Latitudes			
P. Stanley (52° S, 58° W)	35–37	1.3	25 Mar/Sep	30
Gough I. (40° S, 10° W)	22–24	1.7	10 Mar/Sep	73
Marion I. (47° S, 38° E)	30–31	2.1	15 Mar/Sep	43
New Amsterdam I. (38° S, 78° E)	26–28	2.0	11 Mar/Sep	75
Kerguelen I. (49° S, 70° E)	24–28	2.8	14 Mar/Sep	53
Chatham I. (44° S, 177° W)	49	2.3	11 Mar/Sep	78
	B. Antarctica			
Argentine I. (65° S, 64° W)	25–27	2.6	2 Jan/Jul	69
SANAE (70° S, 2° W)	18–21	2.3	1 Jan/Jul	51
Mawson (68° S, 63° E)	14–17	1.4	11 Dec/Jun	20
d'Urville (67° S, 140° E)	19–22	3.3	28 Dec/Jun	68

yearly waves are associated with the seasonal changes in the position and intensity of the trough of low pressure which encircles the hemisphere between 60° S and 70° S (van Loon, 1972, Fig. 4.10). This trough lies farther north in the mean and is weaker in the extreme than in the transitional months. Van Loon (1967) explained the wave in terms of the differences in the seasonal cooling and heating trends in the oceanic middle and continental high latitudes, combined with the fact that the annual temperature wave in the middle troposphere is nearly equal over the two regions. The different seasonal trends of temperature in middle and high latitudes were tentatively related to the different response of the earth's surface in the two regions to the heat budget.

Because the half-yearly wave explains as much as 80% of the annual variance in the sea-level mean pressure in the two regions where it reaches its peaks, its part in the seasonal change of pressure is easily discernible. This is demonstrated in Fig. 1, which shows the average change of pressure from

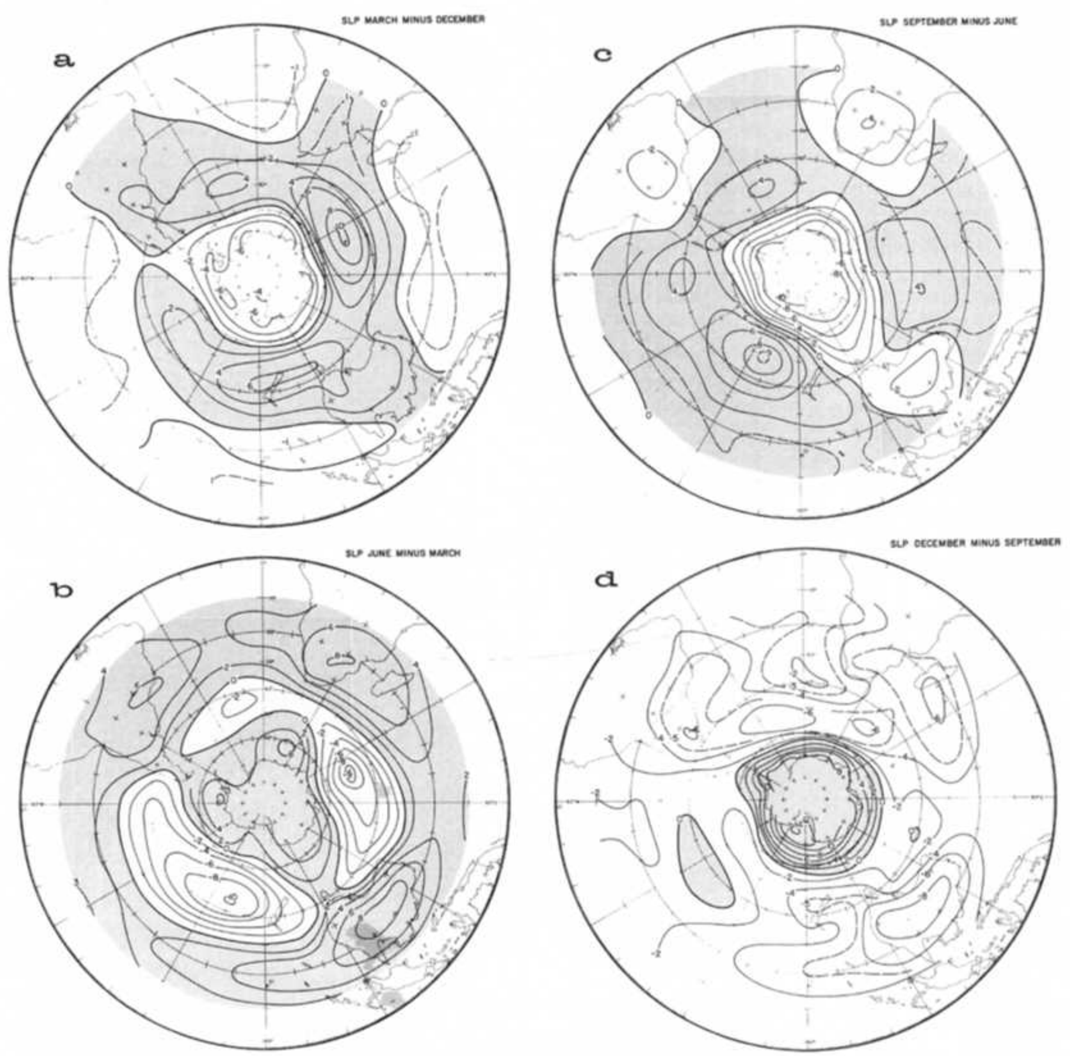

Fig. 1. The difference in sea-level mean pressure (mb). (a) March minus December, (b) June minus March, (c) September minus June, and (d) December minus September.

December to March, March to June, June to September, and September to December, which are the months when the wave has its peaks and troughs. The yearly wave dominates over and near the three continents at lower latitudes (cf. van Loon, 1972, Fig. 4.5), but the prevalance of the half-yearly wave is plain in middle latitudes where the pressure rises from December to March and June to December, and falls from March to June and September to December. The changes over the Antarctic are in the opposite sense so that the effect is an exchange of mass between polar and middle latitudes which reverses twice a year.

The pressure changes in middle latitudes which are associated with the half-yearly wave affect the quasi-stationary waves, particularly over the Indian and South Pacific Oceans and during the colder part of the year. A comparison between Figs. 1b and 1c, for instance, shows that the troughs on either side of Australia on the average amplify from March to June and contract from June to September. Wave 3, the second strongest mean zonal harmonic wave over the Antarctic Ocean (van Loon and Jenne, 1972; Trenberth, 1980), is the wave most affected by this seasonal pressure change. Its mean phase at 1000 mb and 50° S, expressed as the longitude of the first ridge east of Greenwich, is 65° E in March, 38° E in June, and 57° E in September. While it moves towards the west from March to June its amplitude increases by 20 m from 8 m to 28 m, and as it moves east again from June to September the amplitude decreases by 19 m to 9 m in September. This zonal harmonic analysis is based on the long-term means in Taljaard et al. (1969).

The pressure difference between about 50° S and Antarctica acquires a marked half-yearly wave owing to the twice-yearly reversal of sign of the seasonal pressure changes in middle and high latitudes. This is evident in the zonally-averaged pressure differences between 50° S and 70° S which are shown in Fig. 2. In single years of those covered in the illustration the half-yearly wave accounts for from 23% (1958) to 67% (1975) of the total annual variance, and its presence is always immediately visible. The yearly wave, first harmonic, is much smaller and cannot be distinguished in some years.

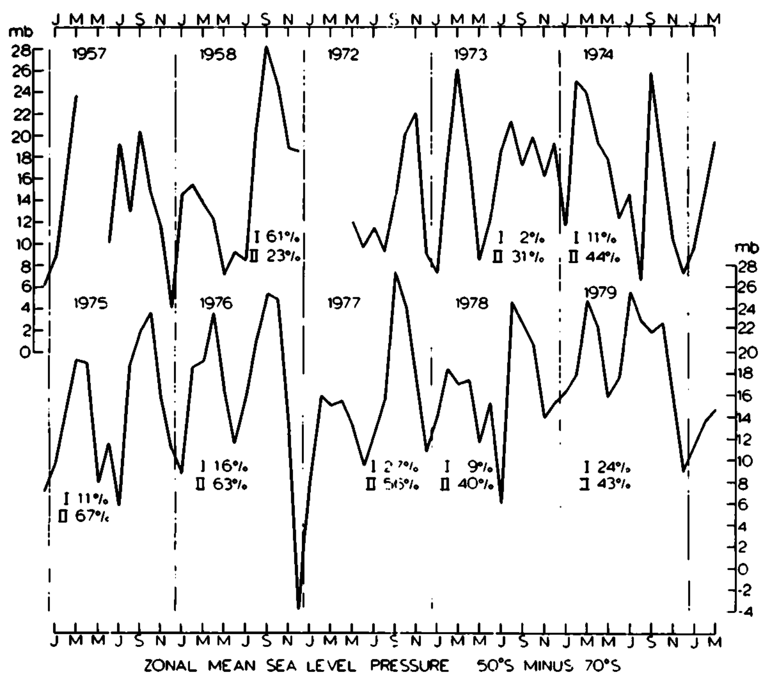

Fig. 2. Time series of the zonally averaged pressure difference, 50° S–70° S, and the amount of the annual variance accounted for by the first and second harmonic in each year.

The two latitudes for which the pressure difference is given in Fig. 2 were chosen because each is near the mean latitude of the peak of the half-yearly wave in its opposing phases. As the lowest pressure in the sub-Antarctic trough in the zonal and annual mean is at 66° S, with extreme monthly positions at 64° S and 69° S (van Loon, 1972, Fig. 4.10), the pressure difference 50° S–70° S spans a small part of the Antarctic easterlies as well as the sub-Antarctic westerlies. Nevertheless, it does give an idea of the large variability of the pressure gradient in these westerlies within a year (for instance, from −4 mb to 26 mb in 1976) and from one year to another. The whole year of the first GARP Global Experiment (FGGE, 1979) had strong latitudinal pressure differences between middle and high latitudes (Trenberth and van Loon, 1981), which is also evident in Fig. 2, and 1979 was in this respect an extreme year. In many single months of the other years shown in the illustration the pressure contrast was as large as or larger than the largest one in FGGE; such occasions were always associated with one of the maxima of the half-yearly wave, whereas the largest value in FGGE was in July—another indication of the abnormality of that year.

The mean zonally averaged pressure difference between 50° S and 70° S for the 12–13 years is shown in Fig. 3. Owing to the persistent occurrence of the half-yearly wave in the same phase, it comes to dominate the long-term zonal average in which it explains 81% of the annual variance. The standard deviations of the zonally averaged monthly pressure difference lie between 3 mb and 7 mb; but the sample is comparatively small and this is not likely to be a stable statistic. The large σ in December is, e.g., strongly influenced by the low value in 1976 when the summer pressures were unusually high over Antarctica and low in middle latitudes (Trenberth, 1979).

As noted, the largest amplitude of the half-yearly wave with maxima in the transitional seasons is reached in 45° S–50° S. Whereas the amplitude decreases north of this peak, the phase is nearly the same as far as 35° S–40° S; and because the mean pressure rises from 50° S to 35° S the pressure difference between 50° S and 35° S thus contains a half-yearly wave opposite in phase to that in the pressure difference between 50° S and Antarctica. An example of this is given in the following: at New Amsterdam Island (38° S, 78° E) and Kerguelen

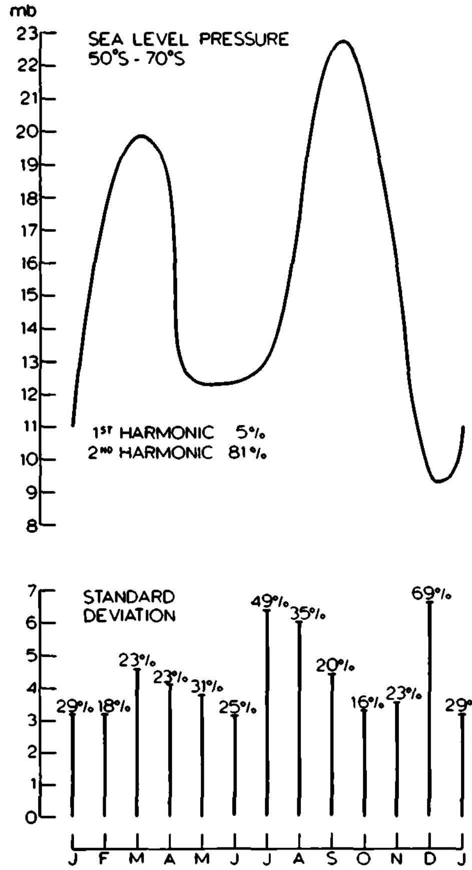

Fig. 3. Top: The zonally averaged sea-level mean pressure difference, 50° S–70° S, and the percentage of the annual variance accounted for by the first and second harmonics. *Bottom:* The standard deviations of the monthly mean, zonally averaged pressure differences, 50° S–70° S, and the standard deviations expressed as a percentage of the mean.

Island (49° S, 70° E) the half-yearly wave's amplitude is 2.0 mb and 2.8 mb, respectively, and the phases are only three days apart, 11 and 14 March and September; at Mawson (68° S, 63° E) the phase is 11 June and December and the amplitude 1.4 mb (Table 1). Whereas the *overall* pressure difference between New Amsterdam Island and Mawson naturally has a half-yearly wave with maxima in the transitional seasons, in the interval between Kerguelen and New Amsterdam Islands the wave in the pressure difference has its maxima in the extreme seasons (Fig. 4). The wave in this

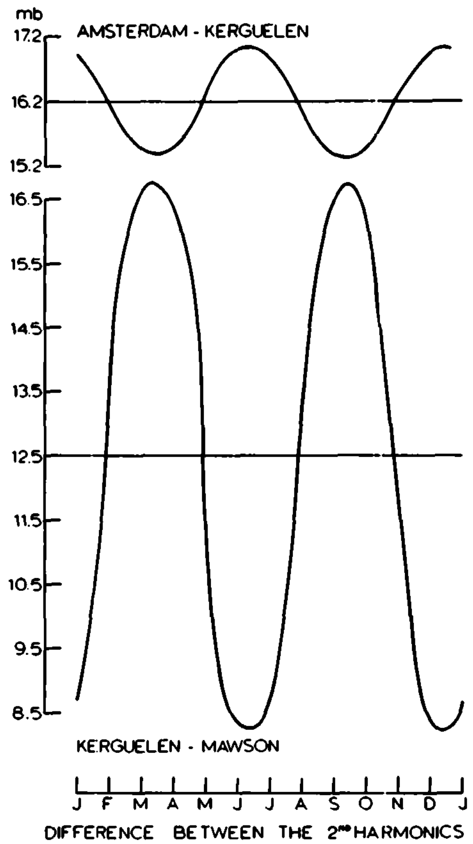

Fig. 4. The second harmonic in the sea-level mean pressure difference between New Amsterdam Island and Kerguelen Island and between Kerguelen Island and Mawson. The position of the stations are in Table 1.

phase is small but its presence means that the wind stress north of Kerguelen contains a half-yearly wave opposite in phase to the one south of the island. The effect of the half-yearly wave in the wind on the ocean surface current north of 50° S was demonstrated by van Loon (1971) for the Indian Ocean where the current derived from ship's drifts contains a marked half-yearly component with maxima in January and July.

The zonally-averaged pressure difference 35° S minus 50° S is shown in Fig. 5 for 17 years. In this instance we added the years 1951–1956 from the South African historical analyses because the data coverage north of 50° S was then as good as in later years. The half-yearly wave north of 50° S is not so immediately visible in individual years as the one south of 50° S and its share of the total annual variance is generally smaller; but because of its stable phase it dominates the long-term mean annual curve in this latitude belt, accounting for 46% of the variance as seen in Fig. 6.

It is of interest to note that not only does the zonal mean pressure difference between 35° S and 50° S vary less within the year than that between 50° S and 70° S (cf. Figs. 2 and 5), but the same holds for the interannual variation of the monthly means given by the standard variations in Figs. 3 and 6.

3. The half-yearly wave in the zonal geostrophic wind at sea level

The mean annual course of the zonal mean geostrophic wind at sea level and the standard deviations of the monthly means are shown in Fig. 7 for the area between 17.5° S and 62.5° S. A half-yearly fluctuation with peaks in March and September/October is directly visible south of 50° S, and another with peaks in the extreme seasons north of 50° S, in agreement with the latitudinal differences of pressure in Figs. 3 and 6. One can get an idea of the amplitude of the half-yearly wave (second harmonic) in the zonally averaged wind in single years from Fig. 8, which contains meridional profiles of the wave in four years with some of the best daily analyses. The largest amplitudes of the harmonic south of 50° S are at 57.5° S–60° S and they account for from 33% to 50% of the total variance in individual years. The amplitude is negligible in the latitudes 45° S–50° S where the phase reverses, and the harmonic there explains less than 2% of the variance. Further north the amplitude rises again, but the peaks of the single years are distributed over a wide range of latitudes and values. Similarly, the harmonic's share of the total variance between 35° S and 45° S varies at its peak from 15% to more than 50%. Clearly, the half-yearly wave of the wind in the sub-Antarctic is more stable from one year to another than is the wave at lower latitudes.

The maps in Fig. 9 illustrate the pattern of the mean half-yearly wave in the zonal wind over the hemisphere south of 10° S. It is clear that the three

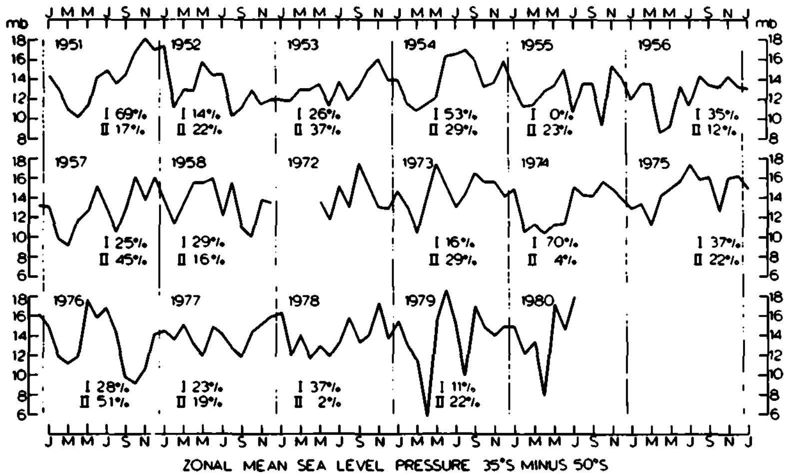

Fig. 5. The same as Fig. 2, but for the pressure difference 35° S–50° S.

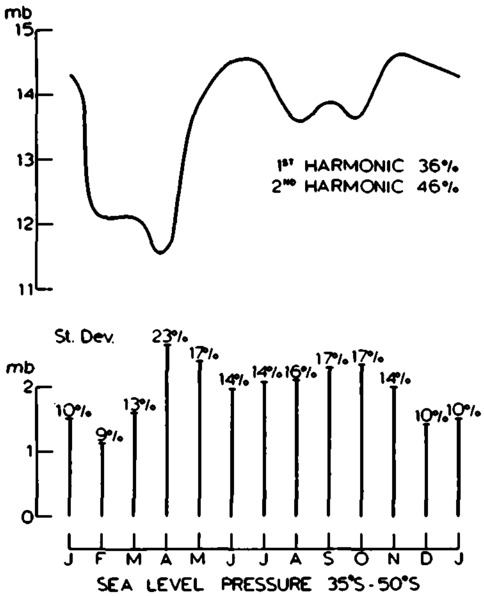

Fig. 6. The same as Fig. 3, but for the pressure difference 35° S–50° S.

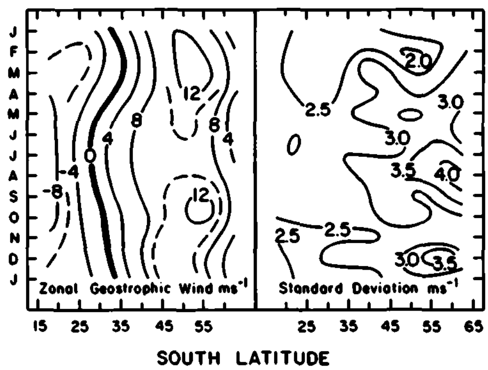

Fig. 7. Time series of the zonally averaged, zonal geostrophic wind (m s^{-1}), and of the standard deviation of the monthly mean zonally averaged, zonal geostrophic wind.

lower-latitude continents, where the annual wave dominates, interfere with the zonal symmetry of the wave in its solstitial phase, especially Australia which south of 25° S is the widest of the three and thus exerts more of a continental influence. The phase shift between the two domains is abrupt between 45° S and 50° S in the Atlantic and Indian Oceans; and in the belt where the phase reverses the amplitude is below 0.5 m s^{-1} and the wave accounts for little of the total variance. The amplitude decreases notably over a short distance south of the peak near 60° S so that the wave plays a comparatively minor role in the seasonal variation of the Antarctic coastal winds.

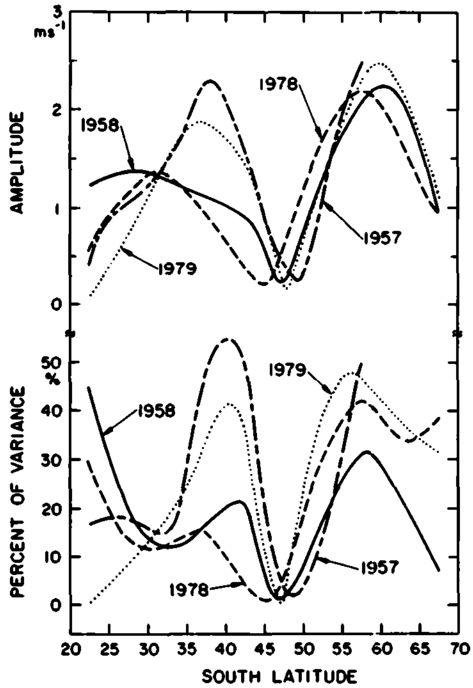

Fig. 8. Top: The second harmonic of the zonally averaged, zonal geostrophic wind in 1957, 1958, 1978, and 1979 (m s^{-1}). *Bottom:* The percent of the total variance accounted for by the above second harmonics.

Africa, and Australia in the latitudes of the subtropical ridge (see Fig. 4.5 in van Loon, 1972).

Finally, we give two examples of the half-yearly wave in the wind of individual years (Fig. 11): 1979, the year of FGGE, and 1957 which was part of the International Geophysical Year (IGY). In each instance, profiles of the phase along meridians through the amplitude peaks are shown on the insets, and the biggest percentages of the annual variance in the given year are shown on the map themselves.

The overall picture is the same in both years: e.g., the amplitude peaks over middle and high latitudes, separated by a minimum where the phase reverses from maxima in the transitional months to maxima in the extreme months; but there are large local differences. Over the Tasman Sea across the North Island into the central Pacific Ocean, for instance, the wave was strong in the IGY, reaching an amplitude above 7 m s^{-1} and accounting for as much as 85% of the variance. In FGGE the Pacific peak of these latitudes was at 120° W, where with a amplitude of 4.7 m s^{-1} it explained only 40% of the variance. A similar displacement happened to the peak at higher latitudes in the Pacific. The reader will find other examples of difference between the two years, but it is well to remember that the differences occur within similar overall patterns.

The standard deviation of the amplitude of the second harmonic is given in Fig. 10. In the region of the subpolar amplitude peak the standard deviation often approaches 50% of the mean; in the mid-latitude peak the standard deviation may even exceed the value of the mean, such as it does near New Zealand.

The standard deviation of the phase, Fig. 10, is small in the sub-Antarctic, only between one and two weeks. This is no more than the mean range of phase along 60° S in Fig. 9b, and the two figures testify to the persistence and strength from one year to another of the half-yearly wave in these latitudes. The interannual variability of phase is bigger in the region of solstitial maxima, where also the amplitude and the percent of the total annual variance explained by the wave tend to be more variable (Fig. 8). The annual wave is stronger here than in subpolar latitudes (cf. Figs. 3 and 6) because of the influence exerted by South America,

4. Conclusion

Associated with the marked half-yearly wave in sea-level pressure over the almost landless region between 35° S and the coast of Antarctica there is a strong half-yearly wave in the zonal geostrophic wind. The phase of the wave in the pressure reverses near 60° S from maxima in the extreme months over the Antarctic to maxima in the transition months in the west wind belt. The peaks of the half-yearly wave in the wind lie in the zone of phase reversal in the pressure where the wave in the wind has its maxima in the transitional months, and in the region north of 50° S where the maxima fall in the extreme months.

In subpolar latitudes the half-yearly wave's interannual variation is smaller than in middle latitudes, the phase is in particular very stable.

Although in the mean the second harmonic, or

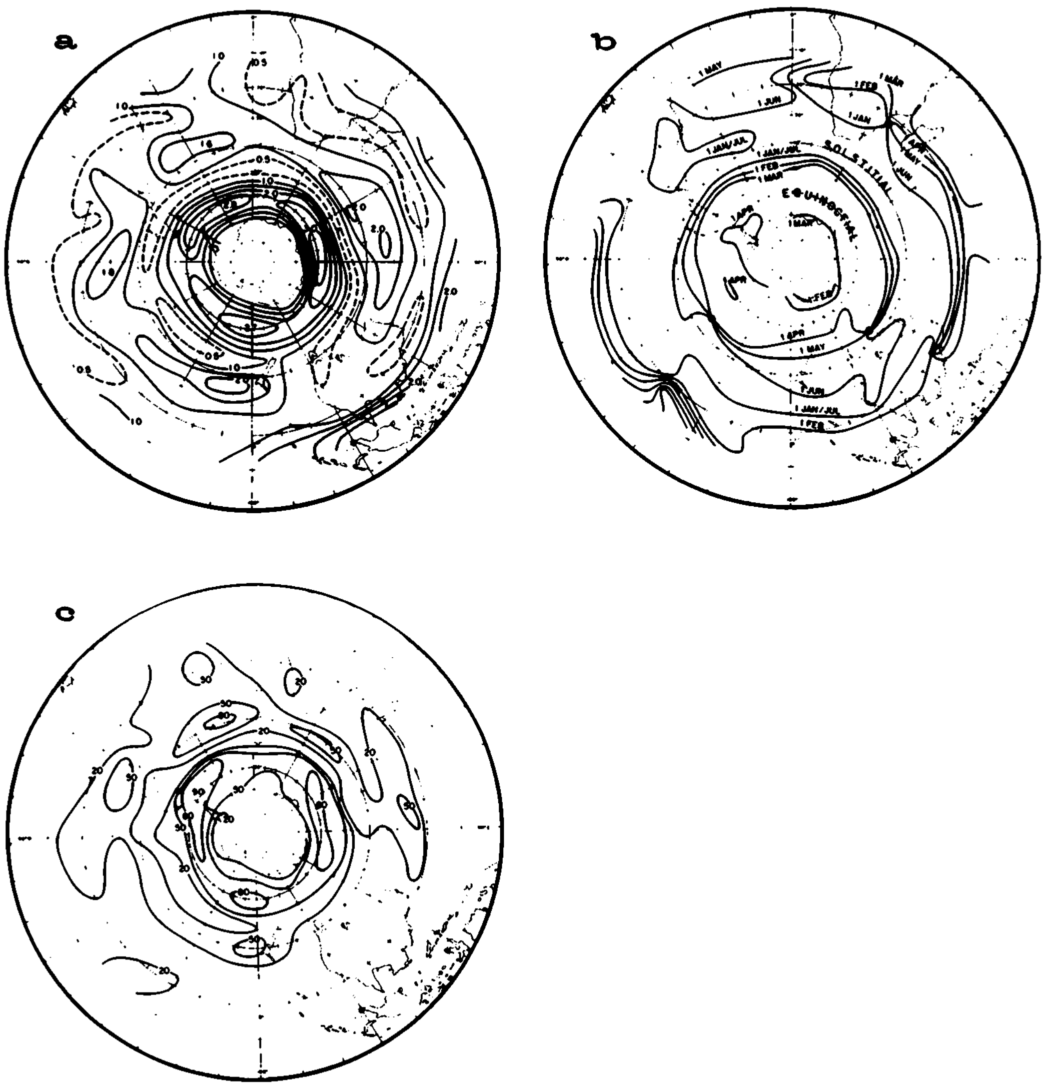

Fig. 9. The second harmonic in the mean zonal geostrophic wind: (a) Amplitude in m s^{-1}. (b) phase (date of first maximum). (c) percentage of the total annual variance.

half-yearly wave, at middle and high latitudes tends to dominate the annual pressure curve, in single years it is frequently surpassed by one or more of the other harmonics. But as the latter have variable phases and the phase of the second harmonic is comparatively stable, it comes to dominate the long-term mean of pressure and wind.

5. Acknowledgement

We wish to thank W. Spangler for handling the data and the computations. This investigation is supported by the Division of Atmospheric Sciences, National Science Foundation, under Grant ATM-8006330.

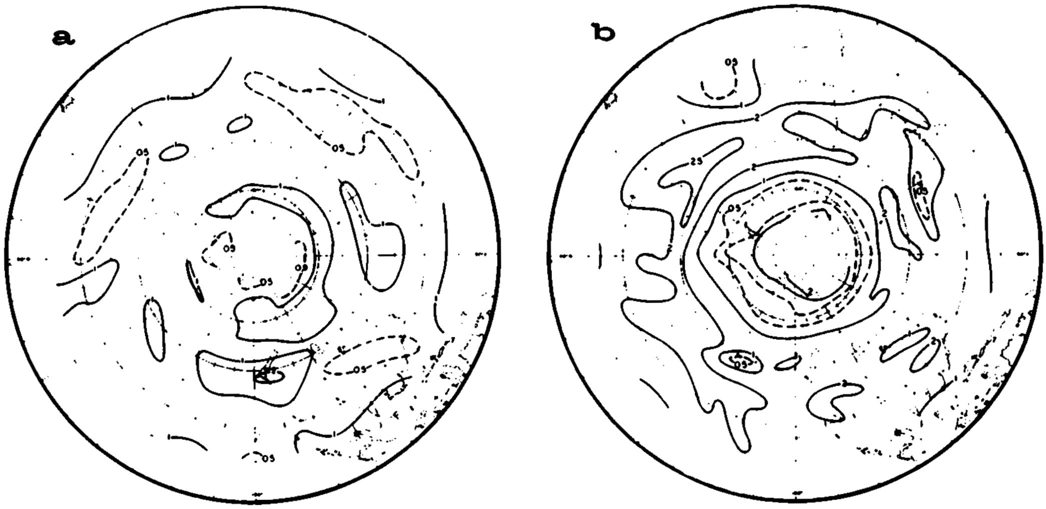

Fig. 10. Standard deviation of (a) the amplitude (m s^{-1}) of the second harmonic in the mean zonal geostrophic wind, (b) of the phase (months).

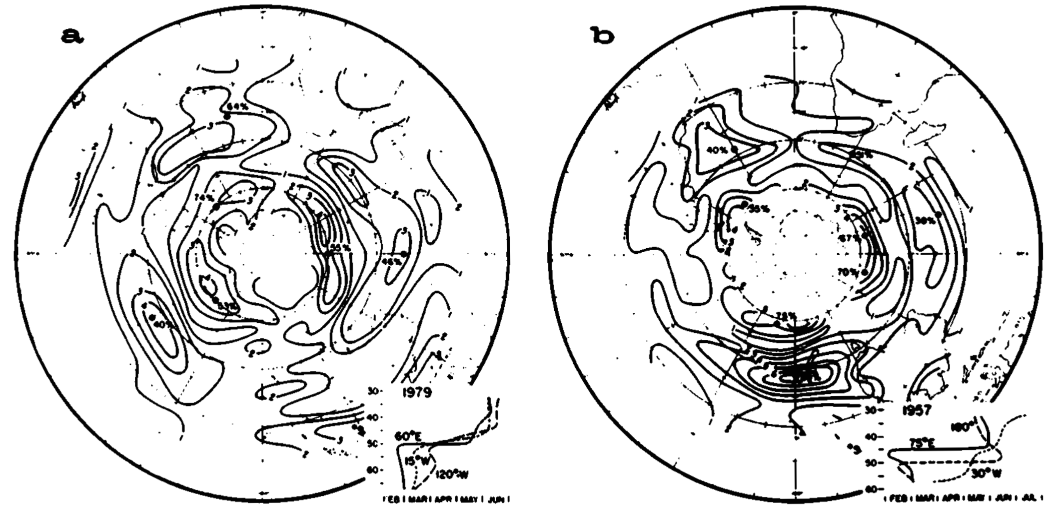

Fig. 11. The amplitude (m s^{-1}) of the second harmonic in the zonal geostrophic wind. The percentages are the largest shares of the annual variance and the insets show profiles of the phase (date of first maximum) along meridians near the peaks of amplitude. (a) 1979, (b) 1957.

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