Variations of Stratospheric Zonal Winds, 20-65 km, 1961-1971[1]

A. D. BELMONT, D. G. DARTT AND G. D. NASTROM

Control Data Corporation, Minneapolis, Minn. 55440

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ABSTRACT

The observed variability patterns of monthly mean zonal winds over an 11-year period, from 80°N–70°S and from 20–65 km, are explained in terms of component patterns of a long-term mean, quasi-biennial, annual and semi-annual periodic variations. Interannual variations are displayed by monthly mean height-time sections for each of eleven years, and Northern Hemisphere–Southern Hemisphere differences are seen from 11-year mean, latitude-month sections for each 10 km. An 11-year mean, height-month section at the equator shows the transition of the easterly regime at low levels to a westerly one at highest levels. Summer easterlies extend from equator to pole, from 30 to 50 km, but winter westerlies extend from equator to about 70° only at 60 km. Also, only at 60 km are there westerlies from pole to pole during the equinoxes. The stronger Southern Hemisphere westerly circulation of the troposphere is found to extend to at least 40 km, and possibly to 60 km. Southern summer easterlies are the same as, or stronger than, those in the Northern Hemisphere. Improved latitudinal rocket network coverage is needed in the Southern Hemisphere. Finer time resolution is essential everywhere to obtain diurnal variations.

1. Introduction

The purpose of this paper is to examine the variability of the mean observed stratospheric zonal wind field as a function of latitude, altitude, month and year, and to describe its features with reference to component time and space sinusoidal variations. Of the many possible ways of presenting the data, only the following are discussed here:

- Latitude-time (month and year) for five levels and eleven years
- Latitude-month for consolidated years, for five levels
- Height-month sections for consolidated years.

These observed patterns of resultant east and west winds are important for trajectory and flux computations, but to model them it is necessary to understand how these result from the time and space variations of their component waves in the stratosphere.

Time-latitude sections of the monthly mean zonal wind pattern at 40 and 50 km were presented for the period 1961–67 by Belmont and Dartt (1971). In this paper these diagrams are extended through 1971, and also prepared for the 20, 30 and 60 km levels. Periodic analysis was performed on grid-point values read off the 11-year time section at each 10° of latitude. The patterns for the long-term mean, quasi-biennial oscillation (QBO), and six harmonics of the annual wave were resolved; however, as they are just smoothed versions of the analysis presented in Belmont *et al.* (1974a), they are not reproduced here.

One of the first attempts to model the mean summer and winter zonal wind fields in the upper stratosphere was that of Kellogg and Schilling (1951); this was followed by improved versions by Murgatroyd (1957), Batten (1961, 1964), Kantor and Cole (1964), CIRA (1965) and Groves (1971). As additional observations in this region became available, the mean patterns portrayed were able to show increasing detail. Although this paper adds only about three more years of data to those available to Groves, the number of observations is now one and a half to four times as great [see Table 2 in Belmont and Dartt (1973)] as at that time.

2. Data

The principal source of data was the meteorological rocket network (MRN) data publications for levels from 40–60 km. At 20 km the data were rawinsonde, and at 30 km a mixture of both rocket and balloon data were used. Details are given in the Appendix. At a number of rocket stations multiple ascents are frequently taken during a single day. These were first averaged to form a single value and then averaged with other daily values to obtain better independent estimates of monthly means. When more than one station was available at a given latitude the station closest to 80°W was selected to minimize longitudinal variability. In the Southern Hemisphere, however, where data are very sparse, Australian station data were used when South American data were not available. Analyses took

[1] Some of the results of this paper were presented at the IAMAP Assembly at Melbourne, Australia, January 1974.

into consideration the standard deviation and number of observations of each mean. Monthly mean data were plotted at the indicated tick marks on the graphs; hence these ticks represent the middle of each month (long ticks are for 15 January in Figs. 1–5). Shading indicates winds from the west in all figures.

It must be realized that shorter period fluctuations exist which may greatly affect the monthly means shown at some altitudes and latitudes where the number of observations is relatively small. No attempt has been made to account for the diurnal tidal variation due to lack of adequate observations. The purpose here is to analyze the behavior of the larger time and space scale phenomena.

3. Results

a. Time sections (Figs. 1–5)

The annual wave is the most prominent of all variations at all levels and at all latitudes other than tropical. In a restricted physical sense, the "seasonal reversal" of the stratosphere refers only to the amplitude and phase of the annual wave corresponding to the annual variation in insolational heating. In a more climatological sense the "seasonal reversal" may refer to the changes in the total observed circulation which is treated in a companion paper in this issue and will not be discussed further here.

The time sections for 20 and 30 km will be discussed first since they are based on a larger data sample and, hence, the patterns observed on them should be the most reliable. The QBO in the tropics and the annual cycle of summer easterlies and winter westerlies at extratropical latitudes are the most prominent features of these two figures (Figs. 1 and 2). Near the equator the long-term mean at 20 km is easterly at about 4 m s^{-1} while at 30 km it is about 12 m s^{-1}. The QBO amplitude is near 12 m s^{-1} near 20 km and 17 m s^{-1} at 30 km. Thus, the combined effect of the mean and QBO at 20 km appears as roughly equal periods of easterlies and westerlies, but at 30 km it generally appears as a long period of easterlies followed by a relatively short westerly regime.

At 20 km during these years, the tropics have two basic patterns of easterly and westerly winds depending on the phase of the QBO: When the QBO is from the east, the summer easterlies from each hemisphere merge with it to form generally a three-lobed triangle of easterlies with the point of the triangle in the Southern Hemisphere. During the westerly QBO phase the triangle of easterlies is pointed northward and surrounds the westerly zone at the equator.

The annual east-west cycle in the Northern Hemisphere is frequently interrupted at high latitudes at 30 km (Fig. 2) by the well-known mid-winter sudden warmings. Although these are smoothed to a large degree by the use of monthly means, a good example is present at the end of 1970 when the westerlies increased to over 40 m s^{-1} near 60°N, followed by a rapid decrease to nearly zero or even easterlies for a brief period. The polar vortex reformed but not to the strength observed in early winter. This same sequence of events can also be seen at 20 km (Fig. 1).

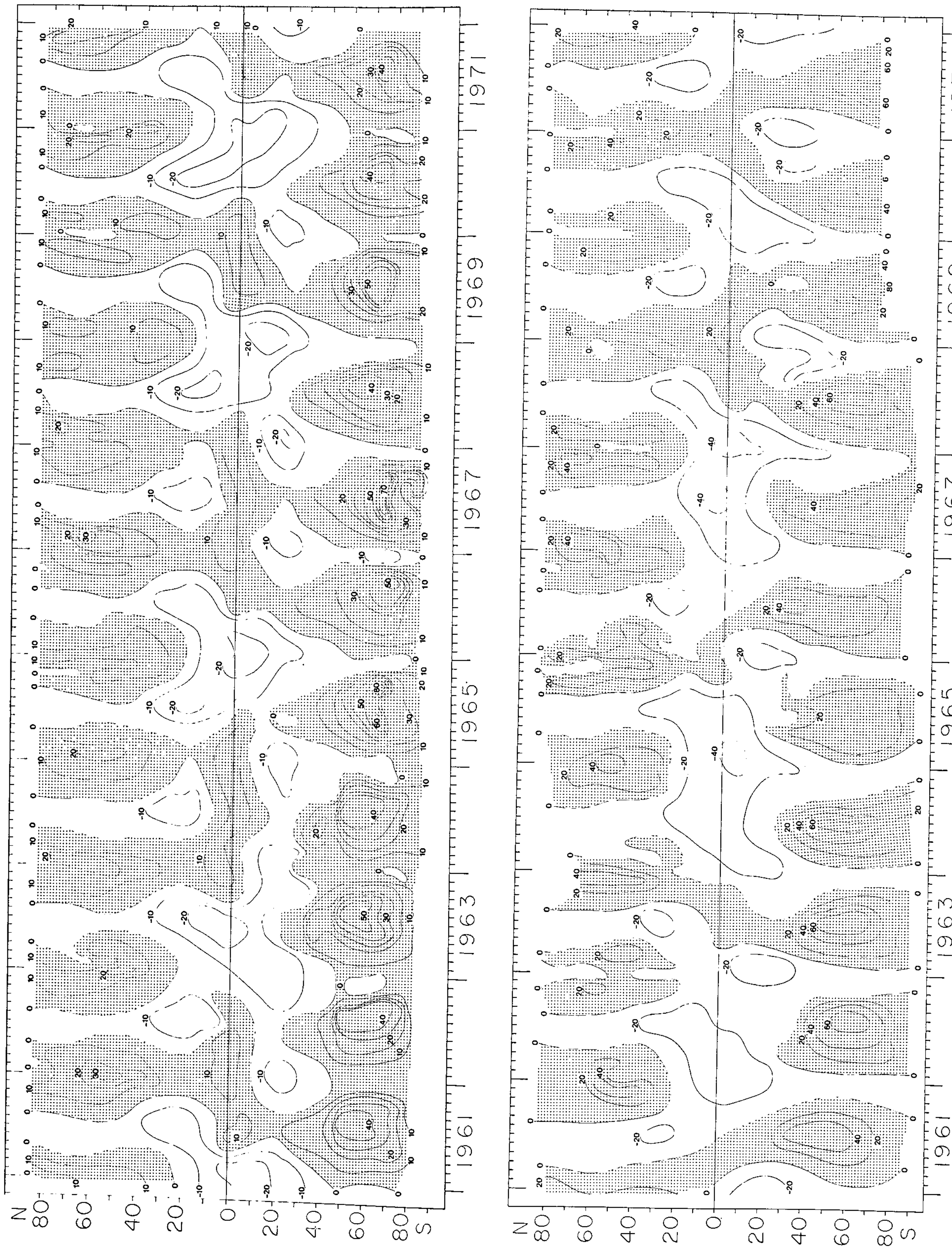
While sudden warmings do not show up as dramatically in the Southern Hemisphere data, a mid-winter decrease of the monthly mean values can often be seen during those periods when dense data coverage was available (see the Appendix): 1968 and 1971 at 30 km and 1967 at 20 km, for example. More striking is the greater intensity of circulation in the Southern Hemisphere at these levels, and the shorter duration of summer easterlies. This will be discussed later.

At 40, 50 and 60 km (Figs. 3, 4, 5) the equatorial flow pattern is dominated by the tropical semi-annual wave. This pattern is particularly clear at 50 km where the long-term mean is nearly zero. It appears as the alternate extension of summer easterlies into the winter hemisphere followed by a bridge of westerlies near the equinox. Meyer (1970) has suggested that this wave is the result of momentum flux divergence from the diurnal tide.

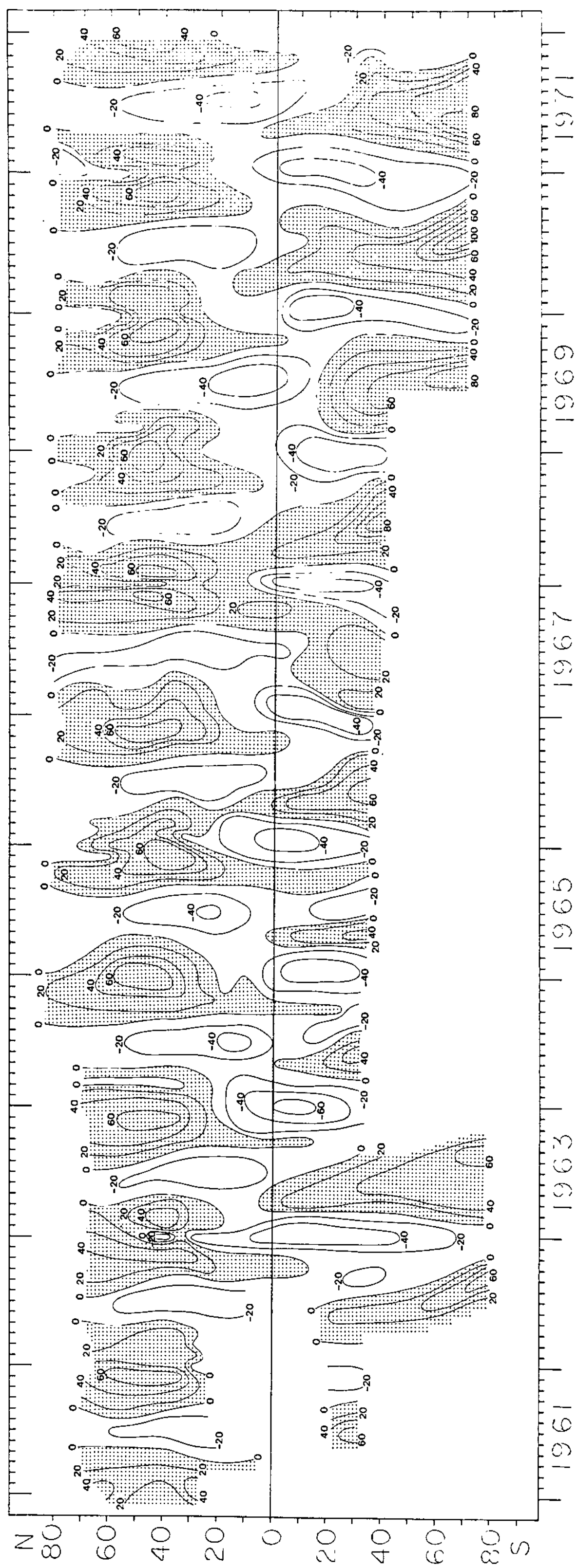
The arctic semi-annual wave is apparent at 60 km (Fig. 5) and can be discerned at lower levels. The occurrence of this wave's minima at the time of summer easterlies and the mid-winter warming easterlies is probably more than coincidence. However, all attempts to model stratospheric warmings have so far had shortcomings [see Trenberth (1973) for a review]. Trenberth has suggested that this may be partly due to insufficient definition of the upper boundary condition. Belmont *et al.* (1974b) have hypothesized that the arctic semi-annual wave arises from physical processes independent of sudden warmings. Thus, in agreement with Trenberth, future attempts to model sudden warmings may be more successful if they take into account other physical processes that are unique to the high-altitude polar regions.

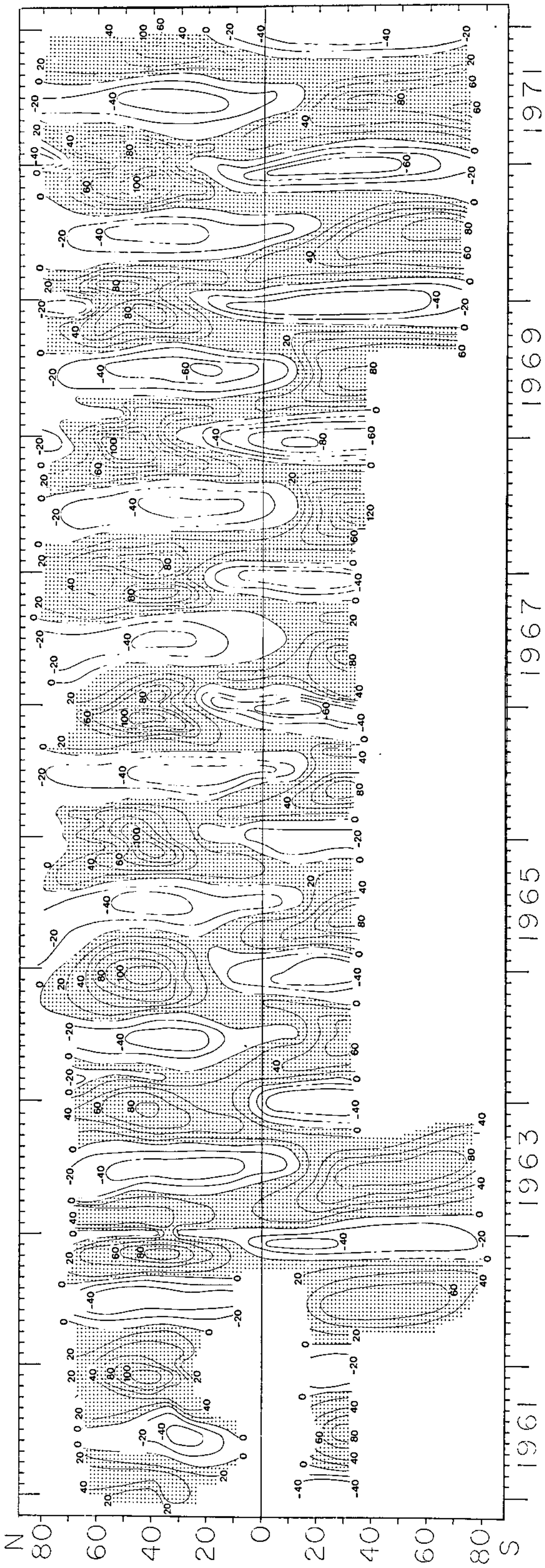
b. Consolidated time sections (Figs. 6–10)

Figs. 1–5 have been averaged over the 11-year period to obtain an "average" variation to enable comparison of the hemispheres. At 20 and 30 km (Figs. 6 and 7) the tropical QBO is completely suppressed through the use of data for consolidated years. A slight annual cycle does appear at the equator which is probably real, due to the annual cycle in earth-sun distance, while the long-term mean is a very strong function of period of record due to the changing QBO phase with respect to a fixed calendar. The use of monthly means in Figs. 1 and 2 has already smoothed the appearance of high-latitude mid-winter warmings considerably, and they are completely lost in Figs. 6 and 7 as the result of consolidation of years. The operational use of long-term mean values (at high and low latitudes) can thus



FIGS. 1 and 2. Monthly mean zonal winds (m s^{-1}) 1961–71 at 20 km (top) at 30 km (bottom). West winds are shaded.





FIGS. 3 and 4. Monthly zonal winds at 40 km (top) and 50 km (bottom).

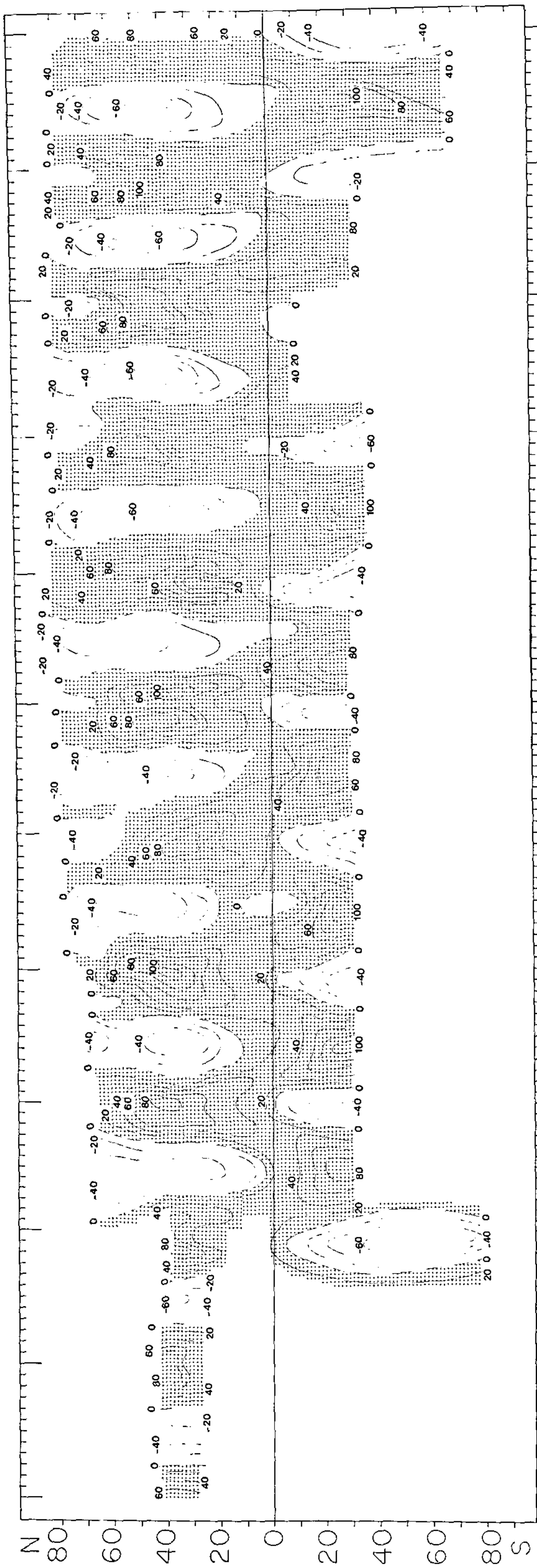


FIG. 5. Monthly mean zonal wind ($m\ s^{-1}$), 60 km.

TABLE 1. Latitude of maximum mean monthly wind (Figs. 6–11).*

Height (km)	Winter westerlies Northern Hemisphere	Winter westerlies Southern Hemisphere	Summer easterlies Northern Hemisphere	Summer easterlies Southern Hemisphere
60	40	(35)	40	45
50	40	(30)	30	30
40	40	(70)	20	15
30	45	60	20	20
20	60	60	20	20

* Parentheses indicate uncertainty because of lack of data at a neighboring latitude.

be misleading because such values have a lower probability of occurrence than both higher and lower values, as the distribution of data may not be Gaussian, or may not have a period which is a harmonic of 12 months.

The relatively stronger westerly circulation in the Southern Hemisphere than in the Northern Hemisphere observed in Figs. 1 and 2 does survive the consolidation process in Figs. 6 and 7. At 40 and 60 km (Figs. 8 and 10) it can be detected but is not present at 50 km (Fig. 9). Note that this difference in intensity seems to be strongest at 20 and 30 km. In harmonic decomposition this is seen as due to a stronger westerly mean and a larger annual component in the Southern Hemisphere at lower levels (Figs. 1 and 4 in Belmont *et al.*, 1974a). From Table 1 we note that, to the extent data are available, the winter maximum winds are at highest latitudes in both hemispheres at 20 km, and tend to remain at higher latitudes in the Southern Hemisphere up to 40 km. The average difference in the magnitude of the maximum wind between Northern Hemisphere and Southern Hemisphere winters, regardless of latitude or month, for each of the 11 years shown in Figs. 1–5 is given in Table 2. This shows that on the average, the Southern Hemisphere winter westerlies were appreciably stronger at each level in winter, except at 50 km where the Northern Hemisphere was apparently stronger (if uncertainty due to lack of data at adjoining latitudes in the Southern Hemisphere can be accepted). This may not necessarily be true for any individual year, however. In summer, both latitude of maximum wind and usually the speed are almost the

TABLE 2. Hemispheric difference (Southern−Northern) of maximum mean monthly zonal winds ($m\ s^{-1}$), regardless of latitude or month.*

Height (km)	Winter	Summer
60	(10)	5
50	−(10)	0
40	(10)	10
30	25	0
20	30	0

* Parentheses indicate uncertainty because of lack of data at a neighboring latitude.

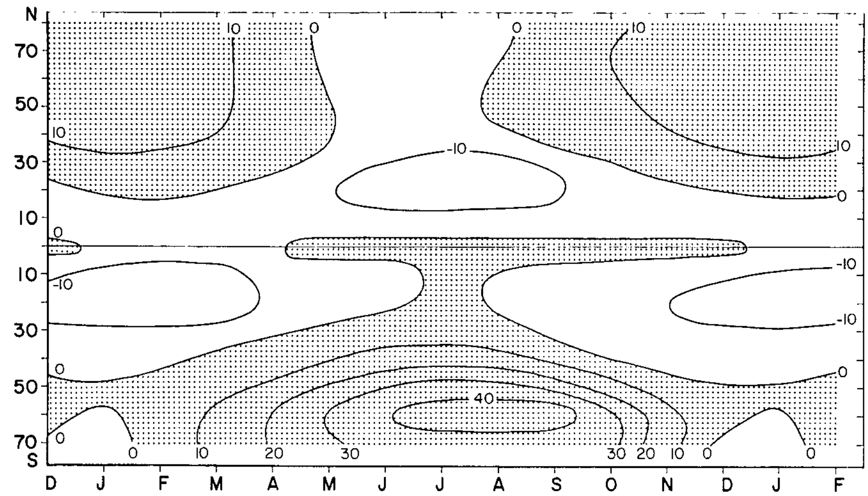


FIG. 6. Monthly mean zonal wind (m s^{-1}), 11-year mean, 20 km.

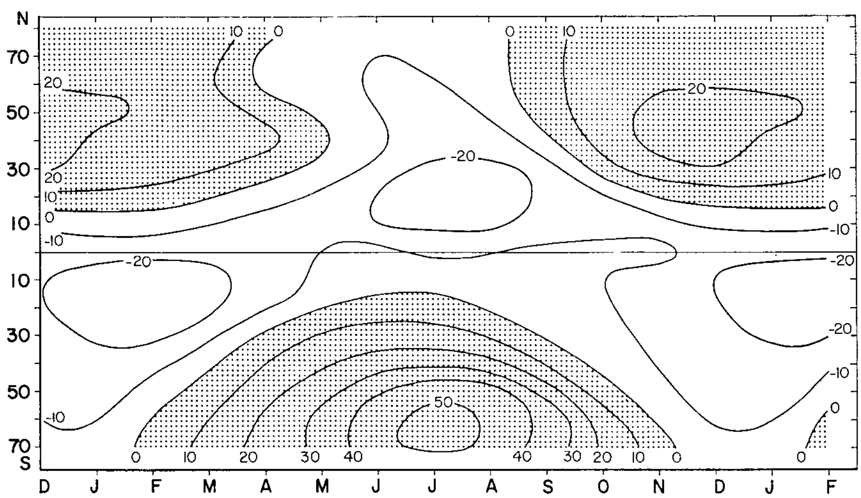


FIG. 7. Monthly mean zonal wind (m s^{-1}), 11-year mean, 30 km.

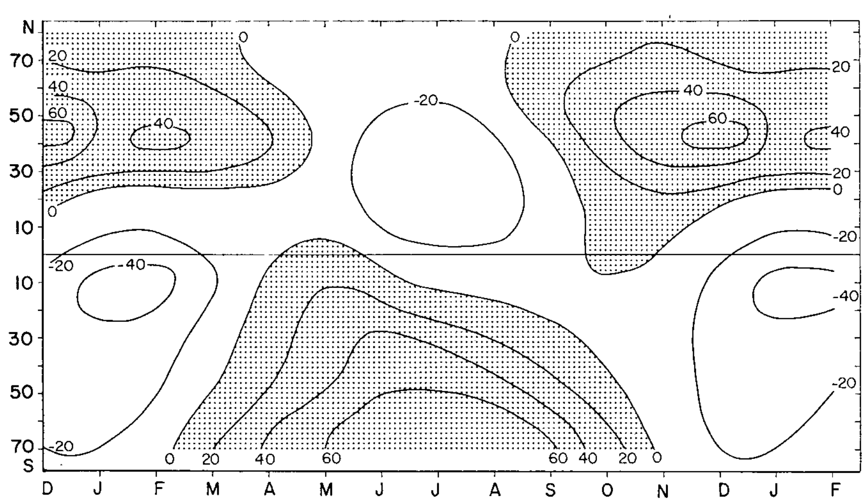


FIG. 8. Monthly mean zonal wind (m s^{-1}), 11-year mean, 40 km.

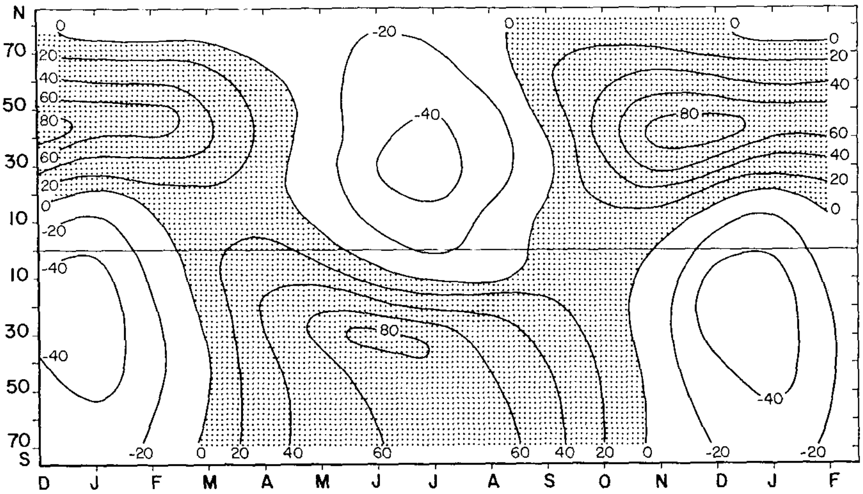


FIG. 9. Monthly mean zonal wind (m s^{-1}), 11-year mean, 50 km.

same in the two hemispheres. The stronger westerlies of the Southern Hemisphere have been a long-recognized feature of the troposphere, but to our knowledge, not previously measured in the stratosphere. As this effect decreases with height in the stratosphere, it is likely that an appreciable fraction of energy of the lower stratospheric circulation propagates upward from the troposphere, although some of the difference may result from *in situ* processes.

There are several reasons why the annual cycle should be stronger in the Southern Hemisphere. First, about 7% more radiation is received during the southern summer than during the northern summer (List, 1963), resulting in more intense insolation in the Southern Hemisphere during a year, affecting both surface and ozone layer heating. Second, the permanent antarctic continental glacier is colder than the Arctic Ocean and Greenland, and the more oceanic Southern Hemisphere is less variable in temperature than the Northern Hemisphere. The resulting zonal circulation is less disturbed in the southern troposphere because of fewer topographic barriers, and hence has a lesser meridional and a stronger zonal component than in the Northern Hemisphere, even for the same thermal gradient in each hemisphere. Still another factor increasing the thermal gradient in the Southern Hemisphere is caused by the greater latitudinal extent of the antarctic cold source which reduces the effective distance to the warm equator, although the Northern Hemisphere winter land masses partially counteract this influence. Further, the ability of warm ocean currents and warm air to penetrate into high arctic latitudes reduces the thermal gradient in the arctic. These effects lead to stronger thermal gradients from pole to equator in the Southern, than in the Northern Hemisphere. The resulting stronger tropospheric west-

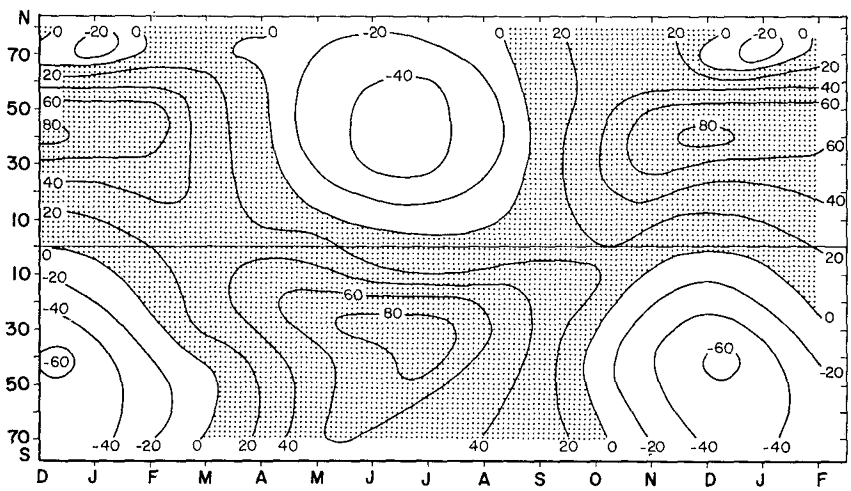


FIG. 10. Monthly mean zonal wind (m s^{-1}), 11-year mean, 60 km.

erly jet extends into the lower stratosphere and persists often even during the summer season in the Southern Hemisphere.

Hence, at 20 km (Fig. 6), Southern Hemisphere summer easterlies do not appear between 50 and 60°S in the mean. At all other altitudes, in both hemispheres, summer easterlies extend from equator to pole. As altitude increases, the easterlies retreat from the equator and shrink in extent, except at high latitudes where they expand. During late arctic winter the wind becomes easterly at 50 km but not at 60 km where westerlies are restored during the spring equinox with an increased amplitude of the semi-annual wave. The westerlies during the fall equinox are caused by the coincidence of the annual and semi-annual waves. Thus, only at 60 km can there be westerlies from pole to pole during the equinoxes.

From this last example it can be seen that explanation of the observed field in terms of component waves is dependent upon the complicated properties of the component waves.

c. Height-month section at the equator (*Fig. 11*)

The equatorial region is most interesting because of the unique overlap there of the QBO and semi-annual wave. Since observations at Gan are too few to reliably show equatorial patterns, we have included a consolidated height-month section based on the 11 year time series (Figs. 1–5). As mentioned, the QBO is lost by consolidation; however, the resultant of the interaction of the mean wind and the semi-annual wave is very apparent. Above 35 km this twice yearly oscillation appears in the form of westerly winds during the equinoxes. At 50 km (where the long-term mean is nearly zero), the winds are of even east and west duration. Note that the easterlies occurring during the Southern Hemisphere summer are stronger, at all levels above 30 km, than those occurring during the Northern Hemisphere summer, and similarly for the equatorial westerlies (see Figs. 3 and 8).

d. Height-month sections at 30°, 50° and *70°* (*Figs. 12–14*)

Height-month sections similar to the above are given in Figs. 12, 13 and 14 for 30°N, 50°N and 70°N, respectively. The annual wave, with summer easterlies and winter westerlies, is the most striking feature of these charts although the semi-annual wave can also be discerned in Figs. 12 and 14. In Fig. 12 it appears at 35–55 km as a midwinter weakening of the westerlies and in Fig. 14 it produces midwinter easterlies above 50 km. There is no indication of a semi-annual wave at 50°N (Fig. 13). Note that the shortest duration of summer easterlies at 20 km is at 50°N, which is probably due to the influence of the mid-latitude tropospheric jet and is discussed further in the following paper on seasonal reversals.

4. Conclusions

1) The annual wave in the Southern Hemisphere stratosphere is greater than that in the Northern to at least 50 km. This is probably due to the eccentricity of the earth's orbit and the consequent difference in radiation received by each hemisphere.

2) The stronger mean winter westerly circulation in the troposphere of the Southern Hemisphere, known for many years, is found here to continue into the stratosphere at 20, 30 and 40 km, and possibly also to 60 km. The summer easterlies are the same as, or stronger than, those in the Northern Hemisphere.

3) The major features of the zonal wind variations on time scales of one month or longer are now well resolved in the Northern Hemisphere. The major observational needs are for improved latitudinal coverage in the southern hemisphere and for finer time resolution, especially with respect to diurnal variations, everywhere.

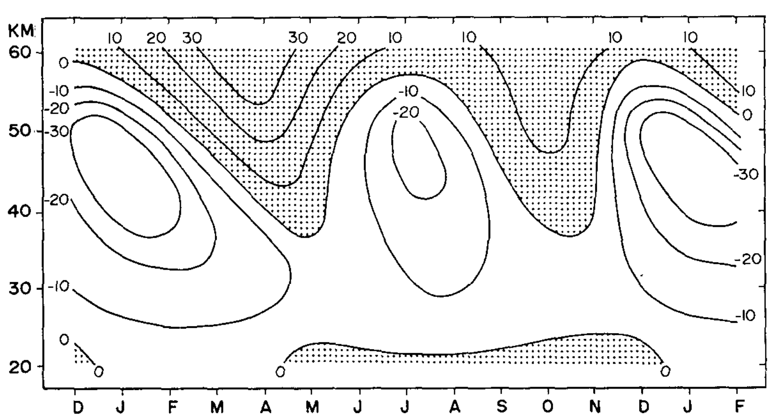


FIG. 11. Equatorial monthly mean zonal winds (m s^{-1}), 11-year mean.

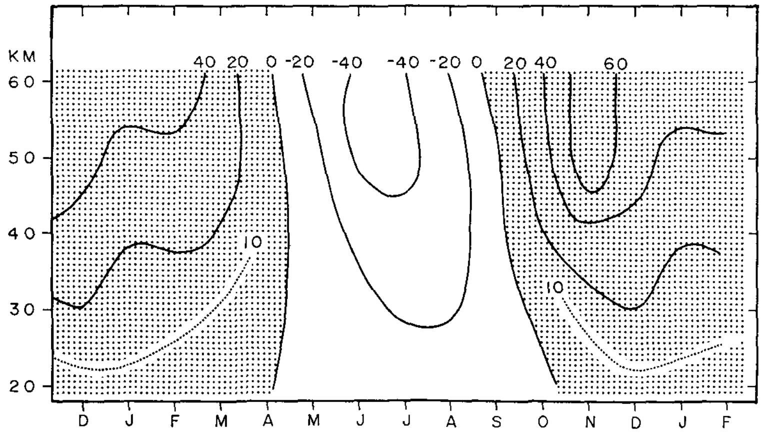


FIG. 12. Monthly mean zonal winds (m s⁻¹) at 30°N, 11-year mean.

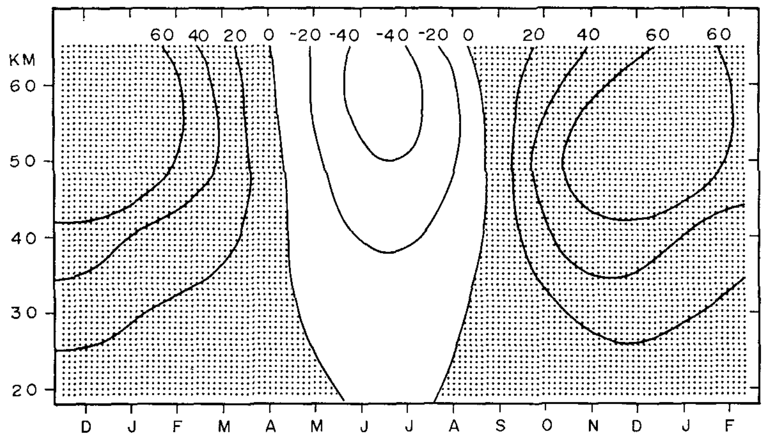


FIG. 13. Monthly mean zonal winds (m s⁻¹) at 50°N, 11-year mean.

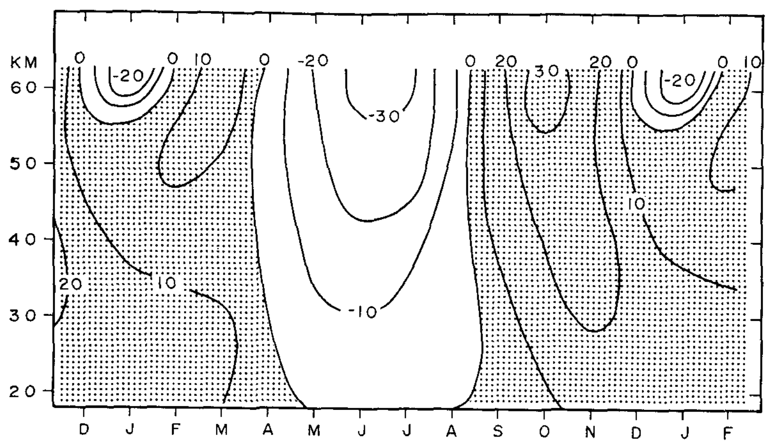


FIG. 14. Monthly mean zonal winds (m s⁻¹) at 70°N, 11-year mean.

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APPENDIX

Data Used

The time sections for 20 and 30 km were prepared mainly from rawinsonde data obtained from routine serial publications of NOAA's National Climatic Center, Asheville, N. C., and from foreign meteorological services. At 20 km station coverage at approximately 5° latitude intervals is complete from Alert (82°N) to Campbell Island (53°S) and from Wilkes and Mirny (66°S) to Byrd (80°S). Macquarie Island (55°S) was available from 1968–71 and Bellinghausen (62°S) from 1969–71. Stations near 80°W were used from 8°N to 82°N and stations near 150°E from 7°S to 55°S. Tropical stations were Bogota and Cayenne (5°N), Singapore (1°N), Gan (0°), Canton Island (2°S), Lae (7°S), Ascension (8°S) and Fanafuti (9°S).

At 30 km, adequate station coverage was available between 76°N and 31°S from 1960–64, and Kerguelen (49°S), Wilkes (66°S), Hallett (72°S) and Byrd (80°S) were used to extend the analysis southward. From 1964–67 adequate coverage was available to 38°S and was supplemented with Invercargill (45°S) and Byrd (80°S). After 1967, coverage extended to 53°S and Byrd (80°S) for 1968 and Molodezhnaya (68°S) for 1969–71 were also used. The magnitude of the winds at Amundson-Scott (90°S) was included at both 20 and 30 km but generally aided the interpretation and analysis little.

High-level balloon winds (Laby and Unthank, 1972) were intermittently available at 40 km at Laverton (38°S) for 1965–71, at Longreach (23°S) for 1967–71, and at Coff's Harbor (30°S) for 1969–71. Otherwise, the time sections for 40, 50 and 60 km were based on rocket observations. The bulk of the data is from those stations listed in Table 1 of Belmont *et al.* 1974 (a, b), although all available data from 43 stations were used. The number of observations by station and altitude for 18 stations north of 8°S is given in Belmont and Dartt (1973).

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