**NASA TECHNICAL NOTE**

**NASA TN D-6522**
c. 1

NASA TN D-6522

# THE GENESIS OF SUDDEN STRATOSPHERIC WARMINGS AND THE QUASI-BIENNIAL CYCLES

*by J. W. Smith*

*George C. Marshall Space Flight Center*
*Marshall Space Flight Center, Ala. 35812*

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1971

| | | |
|---|---|---|
| 1. Report No.<br>NASA TN D-6522 | 2. Government Accession No. | 3. Recipient's Catalog No. |
| 4. Title and Subtitle<br>The Genesis of Sudden Stratospheric Warmings and the Quasi-Biennial Cycles | | 5. Report Date<br>October 1971 |
| | | 6. Performing Organization Code |
| 7. Author(s)<br>J. W. Smith | | 8. Performing Organization Report No.<br>M176 |
| 9. Performing Organization Name and Address<br>George C. Marshall Space Flight Center<br>Marshall Space Flight Center, Alabama 35812 | | 10. Work Unit No.<br>160-44-58-02-62 |
| | | 11. Contract or Grant No. |
| 12. Sponsoring Agency Name and Address<br>National Aeronautics and Space Administration<br>Washington, D. C. 20546 | | 13. Type of Report and Period Covered<br>TECHNICAL NOTE |
| | | 14. Sponsoring Agency Code |
| 15. Supplementary Notes | | |

16. Abstract

A mechanism believed to be responsible for sudden stratospheric warmings, as well as biennial cycles in temperature, wind, ozone, pressure, and perhaps precipitation and the January thaw, is discussed. These biennial cycles are caused by hemispheric exchanges of air in the stratosphere. The hemispheric exchanges are caused by unequal heating of the hemispheres because of the ellipticity of the earth's orbit. The resulting annual atmospheric surges are minimized or omitted during the 11-year sunspot minima, resulting in long-term mean cycles of about 26. 4 months.

## ACKNOWLEDGMENTS

This paper would not have been written without the help and encouragement of Mr. William W. Vaughan of the Marshall Space Flight Center.

| | | | |
|---|---|---|---|
| 17. Key Words (Suggested by Author(s)) | | 18. Distribution Statement | |
| 19. Security Classif. (of this report)<br>Unclassified | 20. Security Classif. (of this page)<br>Unclassified | 21. No. of Pages<br>27 | 22. Price*<br>$3.00 |

*For sale by the National Technical Information Service, Springfield, Virginia 22151

# TABLE OF CONTENTS

# LIST OF ILLUSTRATIONS

# THE GENESIS OF SUDDEN STRATOSPHERIC WARMINGS AND THE QUASI-BIENNIAL CYCLES

## INTRODUCTION

Clayton [1] was the first to report that pulses of 2 years or slightly more could be found in meteorological data. Since then many investigators have found periods in surface temperature, pressure, and precipitation ranging from 2 to 2. 5 years in length [2]. Berlage [3] discussed a 2- to 3-year southern oscillation of worldwide significance. Reed and Rogers [4] reported a 26-month cycle of global extent in the equatorial stratosphere. Funk and Garnham [5] suggested a 24-month ozone cycle based on Australian observations; Scherhag [6] reported an explosive warming of the stratosphere over Berlin. Labitzke [7] found that such warmings occur over Europe every 2 years; while in alternate years, similar warmings occur over the United States and Canada. Therefore, sudden stratospheric warmings appear to be still another of the biennial cycles. Labitzke also found the troposphere to be affected by the stratospheric warmings.

Many authors have discussed these events. A few have attempted to explain the cause, and none has succeeded. Stanley [8] suggested that a 26-month period in solar ultraviolet could cause a 26-month cycle in stratospheric winds, but he rejected a subharmonic response or a resonant mode as a possible cause. Unfortunately for his theory, a definite 26-month cycle in solar emission cannot be shown to exist, nor has any specific mechanism been proposed that could translate such an ultraviolet cycle into a stratospheric wind reversal. Other authors searched in vain for a force occuring at intervals of approximately 13 months to explain equatorial, stratospheric wind reversals and the related wind changes of opposite phase observed in higher latitudes as reported by Reed [9]. Since, in the opinion of the author, a major force at 13-month intervals cannot reasonably exist in the earth-sun system, the search has been in vain. Forces of such magnitude may be logically expected only at annual or semiannual intervals. If forces great enough to cause worldwide atmospheric changes did exist at other intervals, like the 26-month interval in the winds, they would surely have been recognized long ago. Nevertheless, some elusive cause does bring about worldwide atmospheric changes at intervals averaging approximately 13 months in length.

## THE QUASI-BIENNIAL OSCILLATION THEORY

With the above conditions in mind, a theory was formulated, based on the physics of the earth-sun relationship. The stratosphere is heated chiefly by ultraviolet radiation from the sun, and heating is believed to be strongest in the ozone layer near 50 km[10]. The greatest heating occurs in January when the earth and sun are closest. Smith [11] has shown a greater range of tropopause temperatures at high latitudes in the Southern Hemisphere than in the Northern Hemisphere. While it was not published, the International Geophysical Year-International Geophysical Cooperation (IGY-IGC) data showed greater temperature differences at 25 km than at the tropopause and still greater temperature differences at 30 km. Data are extremely scarce near 50 km. However, the few rocketsonde observations available tend to confirm the theoretical view that the temperature range is much greater there than at lower levels and greater in the Southern than in the Northern Hemisphere. The resulting expansion of the southern stratosphere initiates an exchange of air with the Northern Hemisphere. Such air exchanges cannot be simple straight-line north-south exchanges because of the rotation of the earth. However, rotating high- and low-pressure cells are known to exist in the stratosphere which can facilitate such exchanges. The details of such hemispheric air exchanges are still very imperfectly known, but they appear to be strong and brief.

In any event, air does move northward across the Equator and eventually reaches its northern extremity somewhere north of the equatorial belt. The extent and speed of such air movements will vary with the intensity of stratospheric heating and the resulting temperature and pressure differences. In some cases, sudden stratospheric heating extends as far north as the Arctic [12-13]. When the thrust of air from the Southern Hemisphere nears its northern extremity, some of the air turns downward and some, aided by cyclonic circulation, turns upward to start the return journey to the Equator. Quiroz [13] finds that both subsidence and upward motion, the latter preferentially in high latitudes, appear to be of importance with the stratospheric warming. The downward thrust of adiabatically heated air plus advection of warmer air from southerly latitudes cause the sudden stratospheric heatings first described by Scherhag [6]. It seems likely that adiabatic heating following major warmings may also be responsible for the less widely studied January thaw, a short period of unseasonably warm weather, frequently, though not regularly, observed about 3 weeks after perigee when the coldest weather of the year might reasonably be expected. Little evidence is available to prove this, although Labitzke found the troposphere to be affected during stratospheric warmings. However, timing and the absence of any other known cause make the supposition attractive. While the southern stratosphere receives stronger radiant heating than the northern stratosphere, to cause stronger air exchanges, it must be recognized that air from the northern stratosphere also moves southward across the Equator in the northern summer. Also, some compensating air exchange probably takes place at the time of the southerly breakthrough, although it may occur at some far distant point and may not be equal in volume. Observations are more limited in the southern stratosphere, but a southern oscillation of 2 to 3 years has been discussed by Berlage [3].

Funk and Garnham [5] found that ozone fluctuations occured at 38° S earlier than at 27° S. This is consistent with the type of circulation proposed to explain sudden stratospheric warmings in the Northern Hemisphere and suggests that such sudden stratospheric warmings will occur in the Southern Hemisphere, although they will probably be weaker than similar heatings in the Northern Hemisphere. Landsberg et al. [14] found a persistent periodicity, somewhat in excess of 2 years in duration, in the surface temperatures at widely separated stations along two meridians, from Norway to South Africa and from Canada to Cape Horn. They also found the 2.1-year pulse to be present in the polar regions and a preference for the maximum biennial pulse to occur in winter, especially January, February, and March. They had no doubt that the pulse, slightly in excess of 2 years in period, was a worldwide phenomenon that had been fairly persistent during the past century. Landsberg et al. [15] also found the 11-year sunspot cycle to be suggested in temperature data but not in precipitation data.

The outbreak of wind from the southern stratosphere is the main power phase of the 26-month cycle. Winds approaching the Equator will be given an easterly direction by the rotation of the earth, and winds leaving the Equator will be given a westerly direction. The easterly wind belt in the equatorial stratosphere has become widely known as the Krakatoa easterlies, and the lower belt of westerlies is sometimes called the Berson westerlies. This circulation is similar to the Hadley cell in the troposphere, but it is not bound to a fixed level. It rises in altitude over at least a part of the equatorial belt in one year and descends the following year. When the easterlies are at the higher levels of their altitude range, they are above most rawinsonde observations; the balloons terminate in the westerlies. The resulting reversal of wind direction in the 20-to 30-mb (~24-to 27 km) region has attracted much attention, although the winds here are not nearly as strong as the winds at higher levels. The rise and fall in altitude of the easterly and westerly wind currents set up a 24-month cycle centered near the 25 mb (~25 km) level. This is usually a 24-month cycle as can be readily seen from the Canton Island wind cross section presented as Reed's Figure 1 [9]. Using advanced techniques, Reed found a 26-month cycle in the Canton Island winds. To use a less sophisticated technique, if vertical lines were drawn through the center of his west-wind areas, one would find that the west-wind centers occurred in July in 1953, 1955, 1957, 1959, 1961, and 1963. Thus at Canton Island a virtually perfect 24-month cycle can be shown to occur in this particular 11-year period that has been used to demonstrate a 26-month cycle. It is, perhaps, a case of finding what one is looking for.

The 24-month cycle becomes a 26-month cycle, in the long-term means, because of the action of the 11-year sunspot cycle. In the years when sunspot occurrence is at its lowest, the radiant heating of the southern stratosphere is insufficient to inititate the usual strong hemispheric exchange of stratospheric winds, although a weak exchange may occur. In such years, if this theory is correct, sudden stratospheric warmings and other biennial cycles will either fail to occur or will be weaker than usual. A prediction of this was made by the author before data for the sunspot minimum of 1964-1965 became available.* The events of 1964-1965 provide adequate verification for the prediction. Figure 1 shows that the 25 mb (~25 km) level winds did not reverse over Ascension Island during the sunspot minimum of 1964-65. If the irregular 11-year sunspot cycle averaged exactly 11 years, it would give rise to a mean cycle of 26. 4 months. That is, only 5 cycles would occur in 11 years, which is 132 months, since no wind reversal occurs at the sunspot minimum: 132 months/5 = 26. 4 months.

Stanley and Reed found the mean cycle to be about 26 months. Since the sunspot cycle varies from about 7 to 15 years, it is easy to see how variable atmospheric cycles of about 2 to 2. 5 years could occur. A mean atmospheric cycle of 25. 7 months would occur in a 15-year sunspot cycle, while a mean cycle of 28. 5 months would occur in a 7-year sunspot cycle. The length of these cycles could be further exaggerated by short-term variations in sunspot activity within the cycles. For oscillations other than sudden stratospheric warmings and the wind reversals of the equatorial stratosphere, the quasi-biennial oscillations are so weak that they are barely detectable. The unbalanced hemispheric surges of air, greatest when the sun is in the Southern Hemisphere, can obviously cause weak biennial pressure changes that have been discussed by Clayton and Landsberg. The winds that spread outward from the sudden stratospheric warmings, occurring alternately over Europe and North America, will result in wind flows in different directions, causing the biennial temperature and ozone oscillations. Such biennial oscillations may give rise to precipitation oscillations also, but it is still not certain whether biennial precipitation oscillations actually occur. It has been noted that oscillations in temperature and pressure vary in intensity and period from one station to another and that such oscillations do not coincide with the 11-year sunspot cycle at any station. This has been generally accepted as proof that these oscillations are not connected with the 11-year sunspot cycle. Such conclusions are not valid. It should be obvious that, when outbreaks of air from the Southern Hemisphere, which vary greatly in intensity, occur over different areas of Europe one year and over North America the next, the resulting oscillations will spread and ultimately mingle at various times in various ways so that the oscillation patterns will be highly confused and irregular. Such irregularities should be considered as proving rather than disproving the mechanism outlined herein.

---

* Oral prediction to Mr. W. Vaughan and written but unpublished to Mr. Reed.

As can be seen in Figure 1 and as noted by Staley, Reed, and others, stratospheric easterlies are about 50 percent stronger than stratospheric westerlies. At least two causative factors appear to be involved. The greatest stratospheric heating occurs in the southern stratosphere when the earth and sun are closest. Hence, winds that are driven northward across the Equator by the radiant heating of the southern summer should be stronger than winds driven southward by the less powerful heating of the northern stratosphere when the earth and sun are farther apart. The literature does not report these north-south wind exchanges; mainly zonal flow has been reported in the stratosphere. The reason for this is twofold: The north-south wind exchanges are brief and occur chiefly at high altitudes above the reach of standard observational procedures. In the case of Hadley-cell-type circulation near 25 mb (~25 km) at other times of the year, part of the air returns as Berson westerlies; but it appears that a larger portion returns as mesospheric westerlies, and the Berson westerlies are often weak and sometimes missing. Why outbreaks of southerly winds, which cause sudden stratospheric warmings and other atmospheric cycles, shift from easterly to westerly longitudes in alternate years as shown by Labitzke is unknown at this time. However, the location of the sudden stratospheric warmings is understandable.

A brief inspection of the 10 mb (~31 km) level charts published by the Free University of Berlin is sufficient to show that the principle high- and low-pressure centers of the stratosphere are oriented across the principal land masses of the Northern Hemisphere. Such a regular land-marine pressure distribution can be no accident. If the stratosphere were heated only by direct solar radiation, isobars and isotherms would be concentric around the poles. The stratosphere must be heated, in part, by long-wave radiation from the earth to cause such a land-water pressure distribution. Furthermore, long-wave radiation from the African land-mass must create favorable conditions for stratospheric air movements from Africa to eastern Europe during the peak heating of the southern stratosphere in some years, while similar radiation heating creates favorable conditions for air movements from South America to eastern North America in alternate years. Since no other land masses are favorably situated to produce such stratospheric exchanges, it seems likely that sudden stratospheric warmings of the Northern Hemisphere cannot originate elsewhere.
A further study of these factors may lead to a better understanding of exactly why the easterly and westerly wind belts rise and fall in the equatorial stratosphere and why southerly outbreaks come from Africa and South America in alternate years.

# DISCUSSION OF FIGURES

A long-term force has been discussed that is capable of producing stratospheric wind changes over periods that average 26.4 months in length. It meets conditions proposed by several independent investigators. That this solution is also a key to a solution of several other unexplained meteorological cycles makes this theory worthy of serious consideration. Yet, a completely satisfactory proof does not exist because of insufficient observations at high altitudes. The available information is incomplete and is more in the nature of signs that point the way. Valuable evidence in support of this theory comes from the time cross section of rocketsonde wind observations over Ascension Island at 7.5° S latitude. The highest rocketsonde observations were used to produce Figure 1 and were plotted for at least every fifth day when available. They are supplemented by radiosonde observations in the lower levels. While a longer record would be desirable, this is sufficient to show that the Krakatoa easterlies and Berson westerlies form two almost continuous wind belts, which rise and fall in alternate years, rather than being a single reversing wind belt as some authors have believed. Average monthly sunspot numbers, from the Zurich observations, have been plotted in Figure 2 for comparative purposes.

It will be observed that the peak easterlies occur in southern summer, and the strongest easterlies occurred in 1967 and 1968 when the sunspot activity was greatest. At the time of peak easterlies in January and December 1968, both the Berson westerlies and mesospheric westerlies virtually disappeared. This is very significant. Any wind that flows toward the Equator must be deflected by the rotation of the earth to become easterly and must necessarily displace an equal quantity of air that must flow away from the Equator as a westerly wind. The almost total absence of westerly winds during the peak of the southern summer easterlies suggests that the easterlies have not turned back toward the south, as expected in a Hadley-cell-type circulation, but have probably continued across the Equator. Such hemispheric exchanges have not been observed in the troposphere, but apparently they do occur in the stratosphere. It will also be observed that the peak westerlies occur in northern summer, which suggests that they have been forced across the Equator by the summer expansion of the northern stratosphere. No other explanation of these strong westerly winds at this location at this time of year seems reasonable.

A comparison of Figures 1 and 2 shows that the strength of the Krakatoa easterlies fluctuates with the level of sunspot activity. In the winter of 1965-1966 when sunspot activity was very low, the peak easterly wind component was 32.0 m/s occurring at about a 45-km altitude. However, in the winters of 1966-1967 and in 1968, when sunspot activity had increased sharply, the easterly components sometimes exceeded 46.0 m/s. Wind data for 1962 and 1963 were so scarce that they are not shown here, but similar east-west cycles are indicated. Some west winds were observed at 25 km in 1963, but during the sunspot minimum in 1964-1965 and in early 1966 winds at the 25-km level were uniformly easterly. Westerly winds did not return to the 25 mb (~25 km) level until sunspot activity increased in 1966. Observed irregularities in temperature and pressure, sudden warmings of the stratosphere, and stratospheric wind reversals in earlier years may well be associated with irregularities of the sunspot cycle. Ozone cycles would also be a logical result of hemispheric air exchanges associated with irregularities of the sunspot cycle since ozone would be carried long distances by the winds.

## SUPPORTING DATA FROM OTHER STUDIES

A review of the literature shows that Craig and Lateef [16] reported a very large area of uniformly downward motion in connection with the stratospheric warming of 1957. Scherhag [17] found both summer and winter warmings to be preceded by high solar activity and high stratospheric winds. An east-west ridge line at 30 km moving northward across the Caribbean in 1960 was reported by Riehl and Higgs [18]. They believed that it came from South America. Finger and Teweles [19] reported warm air moving northward and a rotating ridge line crossing the Caribbean and Mexico in 1963, before the midwinter warming of 1963. They found indications that maximum intensities occurred near 45 km. They also reported that major warming events of this type tend to start in the latter half of January. Labitzke suggested a connection between stratospheric warmings and the 26-month cycle in equatorial and stratospheric winds. Johnson and Gelman called the stratospheric warming of 1963 a major warming. Quiroz reported a major warming in 1966 and found both subsidence and upwelling in connection with it. Johnson [20] reported a major warming in 1967-1968 with the first warming signs in the 45- to 50-km region. The first sign at the 10 mb (~31 km) level was a warm ridge over the Azores that later moved northward over Berlin at the rate of 15 deg of latitude per day. However, only minor stratospheric warmings occurred in 1964 and 1965 [21]. It has already been seen from Figure 1 that the 25 mb (~25 km) level winds over Ascension Island were continuously easterly through 1964, 1965, and early 1966. Since this was the period of minimum sunspot activity shown by Figure 2, it seems logical from this theory that the minor stratospheric warmings of 1964, 1965, and early 1966 should occur at the same time the 25 mb (~25 km) level winds failed to reverse. A number of authors [13, 20] find that sudden stratospheric warmings are associated with unusually strong winds and point to sources of energy near the 45- to 50-km level or above. Figure 1 shows that the peak easterly winds over Ascension Island occur in southern summer from 45 to 60 km. The fact that the peak easterlies occur at the same altitude as the energy sources for sudden warmings, found by other authors, is very significant. Johnson points to both southerly winds and a downward propagation of the warming in connection with the stratospheric warming of 1967-1968.

Much can be learned from a study by Friend et al. [22] of the movement of radioactive debris put into the stratosphere by atomic bomb tests at high altitudes. Large-scale air movements across the Equator have been shown which distributed radioactive debris throughout the stratosphere of both hemispheres. Radioactive debris, from bomb tests in the Northern Hemisphere, has on some occasions been found in even higher concentrations in the southern than in the northern stratosphere. Meridional air movements in the stratosphere are often slow, but on some occasions, have been quite rapid. The fastest meridional exchanges in the Northern Hemisphere generally take place in northern winter and spring, although some rapid movements from the northern to the southern stratosphere have been observed in northern summer. Debris may move from arctic to tropical latitudes in less than 1 month. Radioactive debris movements indicate that radioactivity from the high tropical stratosphere enters the lower stratosphere, preferentially, in the polar regions. It appears that, regardless of the latitude and altitude of injection, most debris, which has stabilized above the tropopause layer, must pass through the polar stratosphere before it will fall out into the troposphere. One of the earlier atomic tracer studies, presently unavailable for reference, stated that atomic debris once moved from the Northern Hemisphere to the Antarctic in a period of 2 weeks. These observations from the high-altitude sampling program are entirely consistent with the biennial cycle theory that has been presented here.

It can be seen from the temperature graphs published by Landsberg et al. [14] that the amplitude of the temperature pulse is greatest at high latitudes and lower at low latitudes. This would be the logical result if winds spreading out from sudden stratospheric warmings were the cause of quasi-biennial cycles in temperature. It is also noteworthy that Landsberg's et al. [15] study of the Woodstock temperature data suggested the effects of the 11-year sunspot cycle. The 11-year sunspot cycle did not appear in the precipitation data of the same study.

# ITEMS IN PROOF OF HEMISPHERIC AIR EXCHANGES

Items in proof of hemispheric air exchanges are as follows:

1. The easterlies peak over Ascension Island in southern summer in the 45- to 60-km region where maximum radiant heating of the ozone layer would be expected.

2. The studies of sudden stratospheric heating, referenced herein, report that the energy comes from 45- to 50-km altitude or higher.

3. East-west ridge lines, at the 10 mb (~31 km) level, have been observed moving northward out of the Caribbean before sudden stratospheric warmings, and a similar ridge line moved northward over Europe before a sudden stratospheric warming there.

4. Evidence of both upward and downward motion during sudden stratospheric warmings has been reported.

5. When the strongest easterlies occur, westerly winds disappear from the equatorial stratosphere and mesosphere over Ascension Island. The only logical explanation is a south-to-north equatorial crossing. Otherwise, a return westerly current would be inevitable.

6. The westerlies peak over Ascension Island in northern summer. This could be a result of winds from the Northern Hemisphere crossing the Equator.

7. The occurrence of ozone fluctuations at 38° S before their occurrence at 27° S confirms a circulation in the Southern Hemisphere similar to the one that causes sudden warmings in the Northern Hemisphere.

8. Observations of radioactive debris following the high-altitude bomb tests showed that the radioactive particles spread throughout the entire stratosphere. Movement was often slow, but sometimes rapid meridional exchanges occurred. Once a sudden outburst of radioactive particles moved from north of the Equator to Antarctica in 2 weeks. Only a very strong hemisphere air exchange could accomplish this.

9. Stratospheric wind reversals failed to occur at the 25 mb (~ 25 km) level during the sunspot minimum in 1964, 1965, and the first half of 1966.

10. Major stratospheric warmings were absent during the sunspot minimum in 1964, 1965, and the first half of 1966.

11. Sudden stratospheric warmings occur north of the only major land masses adjacent to the Equator in the Southern Hemisphere.

12. The mean length of the 26-month cycle is the same as the period derived from the mechanism discussed herein, and a force capable of producing observed irregularities in the quasi-biennial cycles has been discussed.

13. The time of the quasi-biennial oscillation from station to station varied.

14. The temperature oscillation decreased at lower latitudes.

15. Any feasible mechanism, based on sound physical principles, which can reconcile apparently illogical atmospheric cycles of 26-months with a 12-month solar orbit, is almost certain to be the only possible solution.

## CONCLUSIONS

Since the major thrust of air from the southern stratosphere should and does occur near midwinter, when the greatest atmospheric heating would be expected, an annually occurring force produces quasi-biennial cycles of various types in the atmosphere. Irregularities in the induced biennial pulses and the weakness of the pulse at sunspot minima result in variable atmospheric cycles with a long-term mean length of 26. 4 months. No one of these factors could be considered as conclusive proof that hemisphere exchanges of air occur, which cause sudden stratospheric warmings and other biennial cycles. However, the combination of events occurring in this particular way at the time, place, and altitude required by a logical application of sound physical principles constitutes a chain of evidence that is difficult to refute.

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812, May 3, 1971
160-44-58-02-62

# REFERENCES

1. Clayton, H. H.: A Lately Discovered Meteorological Cycle. Am. Meteorol. J., vol. 1, No. 130, 1885, p. 528.

2. Landsberg, H. E.: Biennial Pulses in the Atmosphere. Beiträge zur Physik der Atmosphäre, vol. 35, 1962, pp. 184-194.

3. Berlage, H. P.: The Southern Oscillation, a 2-3 Year Fundamental Oscillation of World-Wide Significance. Scientific Proceedings International Association of Meteorology, London, I. U. G. G. 10th General Assembly, Rome 1954, 1956, pp. 336-345.

4. Reed, Richard J.; and Rogers, Dale G.: The Circulation of the Tropical Stratosphere in the Years 1954-1960. J. Atmos. Sci., vol. 19, 1962, pp. 127-135.

5. Funk, J. P.; and Garnham, G. L.: Australian Ozone Observations and a Suggested 24 Month Cycle. Tellus, vol. 14, 1962. pp. 378-382.

6. Scherhag, R.: Die Explosionsartigen Stratosphären-Erwärmungen des Spätwinters 1951-52. Ber. Deut. Wetterd (U. S. Zone), No. 38, 1952, pp. 51-63.

7. Labitzke, Karin: On the Mutual Relation Between Stratosphere and Troposphere During Periods of Stratospheric Warmings in Winter. J. Appl. Meteorol., vol. 4, 1965, pp. 91-99.

8. Staley, D. O.: A Partial Theory of the 26-Month Oscillation of the Zonal Wind in the Equatorial Stratosphere. J. Atmos. Sci., vol. 20, 1963, pp. 506-515.

9. Reed, Richard J.: The Present Status of the 26-Month Oscillation. Bull. Am. Meteorol. Soc., vol. 46, 1965, pp. 374-387.

10. Reed, Richard J.: The Quasi-Biennial Oscillation of the Atmosphere Between 30 and 50 km Over Ascension Island. J. Atmos. Sci., vol. 22, 1965, pp. 331-333.

11. Smith, J. W.: The Vertical Temperature Distribution and the Layer of Minimum Temperature. J. Appl. Meteorol., vol. 2, 1963, pp. 655-667.

# REFERENCES (Continued)

12. Johnson, Keith W.; and Gelman, M. E.: Temperature and Height Variability in the Middle and Upper Stratosphere During 1964-1966 as Determined from Constant Pressure Charts. Monthly Weather Review, vol. 96, 1968, pp. 371-382.

13. Quiroz, Roderick S.: The Warming of the Upper Stratosphere in Feb. 1966 and the Associated Structure of the Mesosphere. Monthly Weather Review, vol. 97, 1969, pp. 541-552.

14. Landsberg, H. E.; Mitchell, J. M. Jr.; Crutcher, H. L.; and Quinlan, F. T.: Surface Signs of the Biennial Atmospheric Pulse. Monthly Weather Review, vol. 91, 1963, pp. 549-556.

15. Landsberg, H. E.; Mitchell, J. M., Jr.; Crutcher, H. L.; Power Spectrum Analysis of Climatological Data for Woodstock College, Maryland. Monthly Weather Review, vol. 87, 1959, pp. 283-298.

16. Craig, Richard A.; and Lateef, M. A.: Vertical Motion During the 1957 Stratospheric Warming. J. Geophys. Res., vol. 67, 1962, pp. 1839-1854.

17. Scherhag, R.: Stratospheric Temperature Changes and the Associated Changes in Pressure Distribution. J. Meteorol., vol. 17, 1960, pp. 575-582.

18. Riehl, H.; and Higgs, R.: Unrest in the Upper Stratosphere over the Caribbean Sea During Jan. 1960. J. Meteorol., vol. 17, 1960, pp. 555-561.

19. Finger, F. G.; and Teweles, S.: The Mid-Winter 1963 Stratospheric Warming and Circulation Change. J. Appl. Meteorol., vol. 3, 1964, pp. 1-15.

20. Johnson, Keith W.: A Preliminary Study of the Stratospheric Warming of Dec. 1967-Jan. 1968. Monthly Weather Review, vol. 97, 1969, pp. 553-564.

# REFERENCES (Concluded)

21. Environmental Sciences Survey Administration, Stratospheric Synoptic Density Maps for 1964-1965 and for the Warming Event of Dec. 1967. NASA TM X-1903, Hillcrest Heights, Md., Nov. 1969.

22. Friend, J. P.; Feely, H. W.; Krey, P. W.; Spar, J.; and Walton, A.: The High Altitude Sampling Program. Defense Atomic Support Agency, DASA 1300, vol. 3, Washington, D. C., 1961. (copies obtainable from Isotopes Inc., 123 Woodland Ave., Westwood, N. J.).

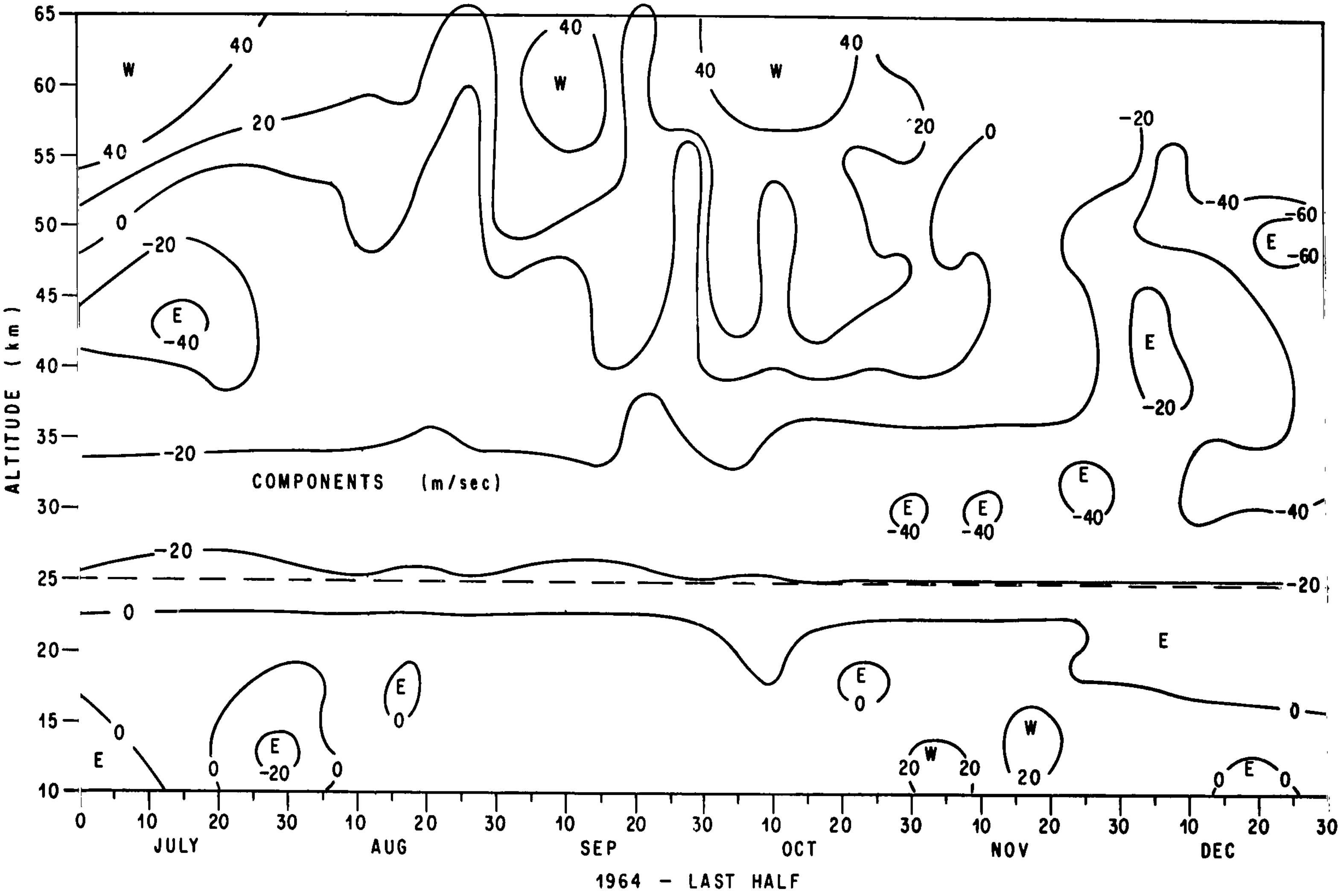

Figure 1a. Ascension Island east-west wind components.

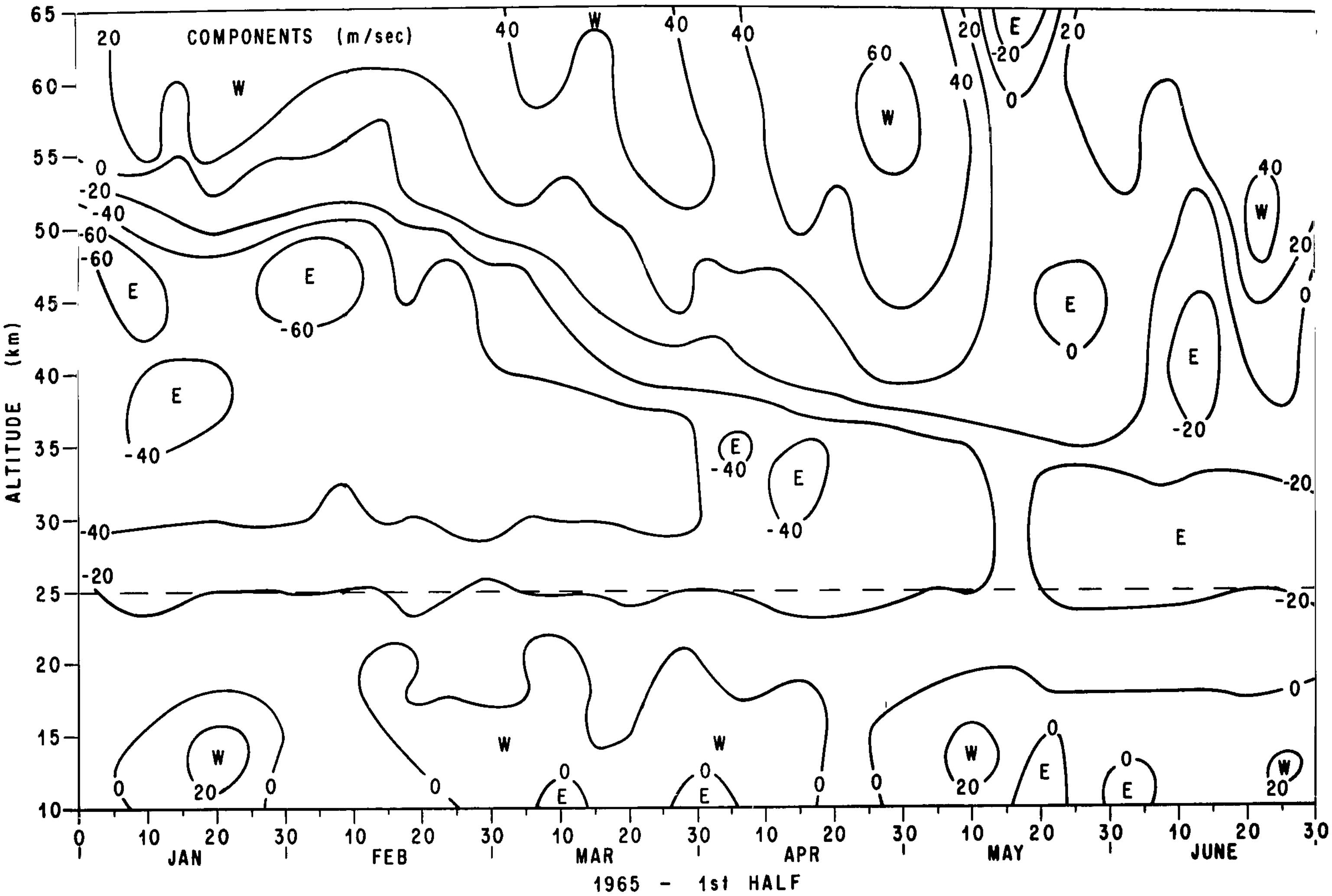

Figure 1b. Ascension Island east-west wind components.

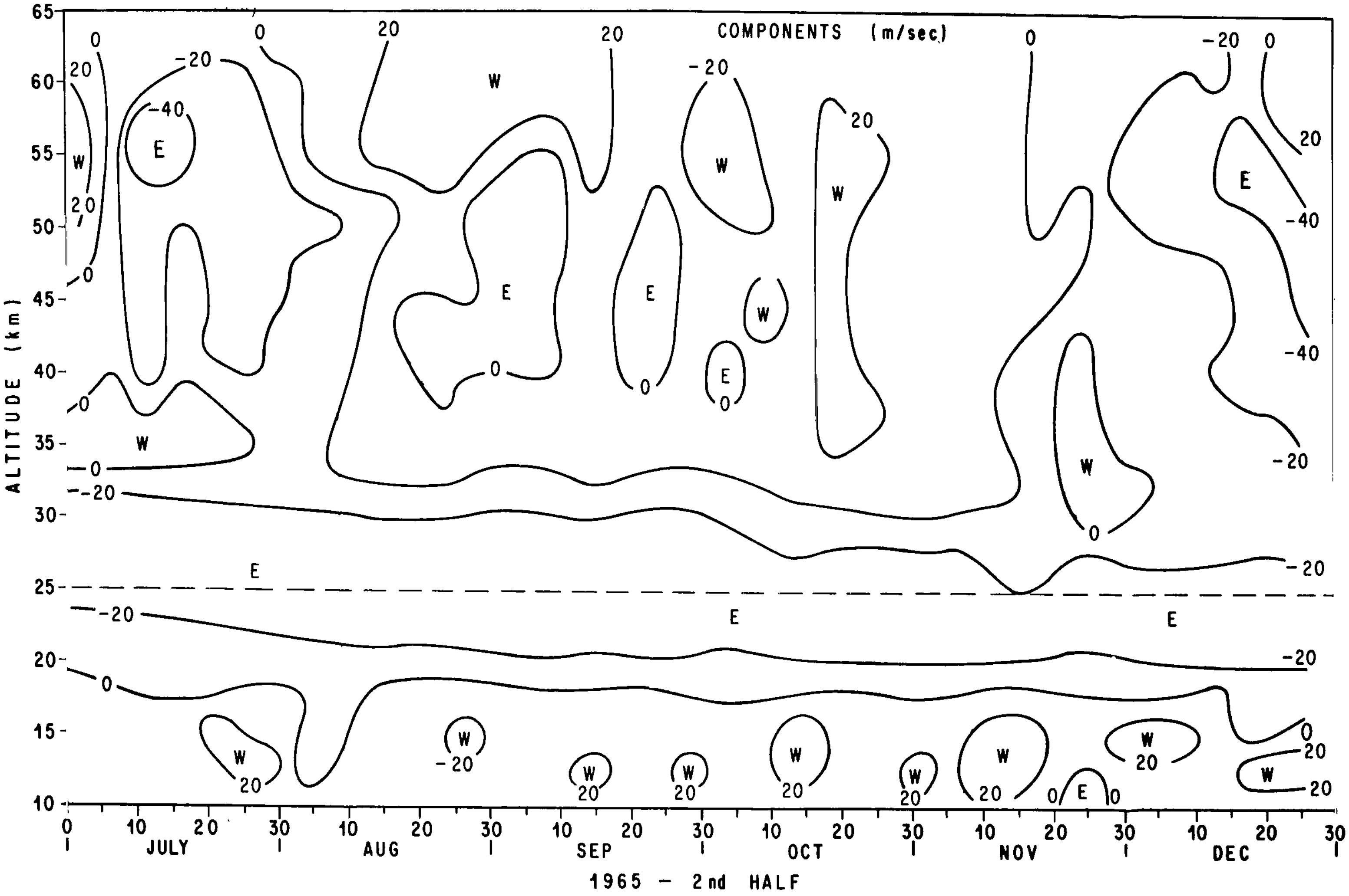

Figure 1c. Ascension Island east-west wind components.

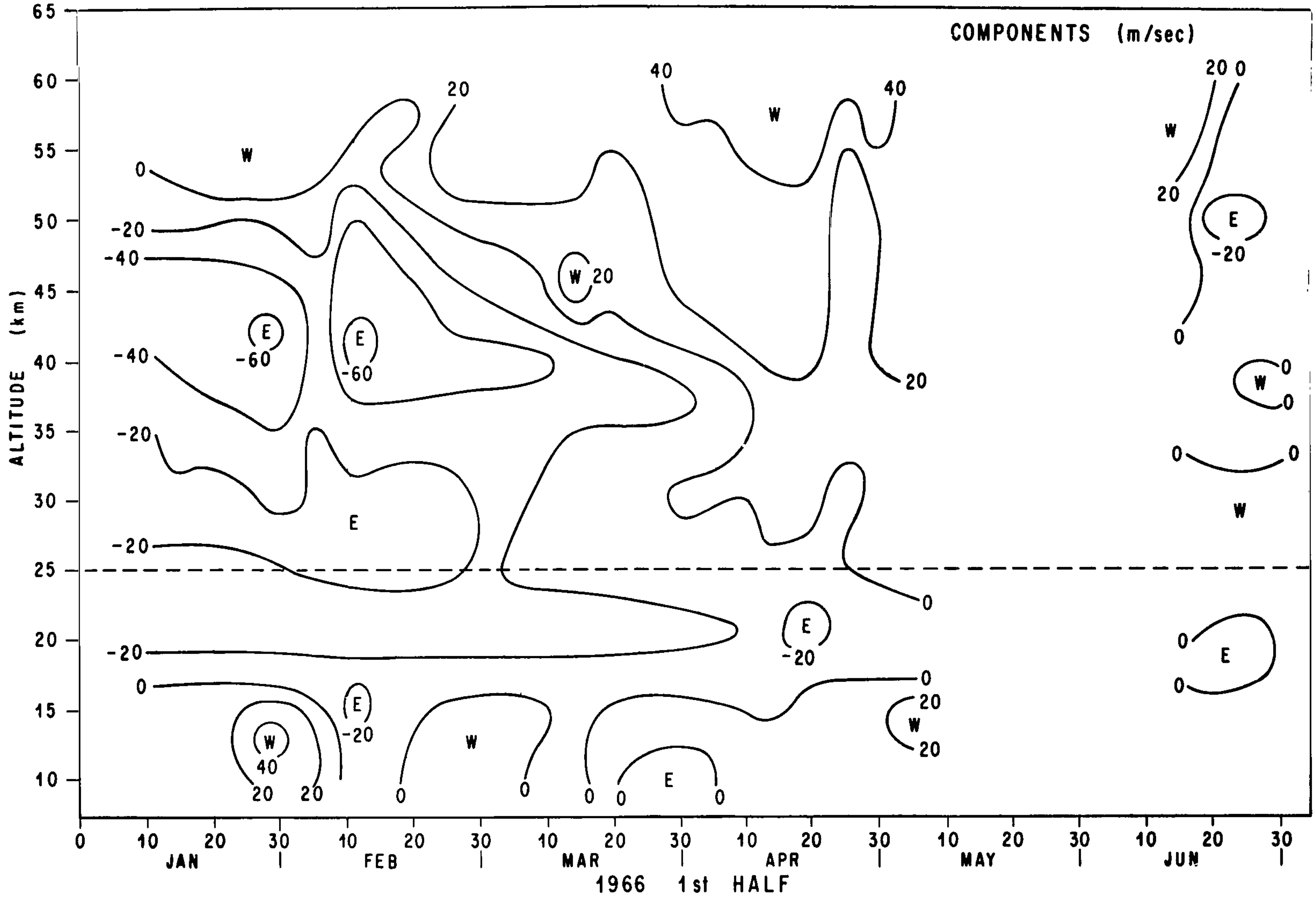

Figure 1d. Ascension Island east-west wind components.

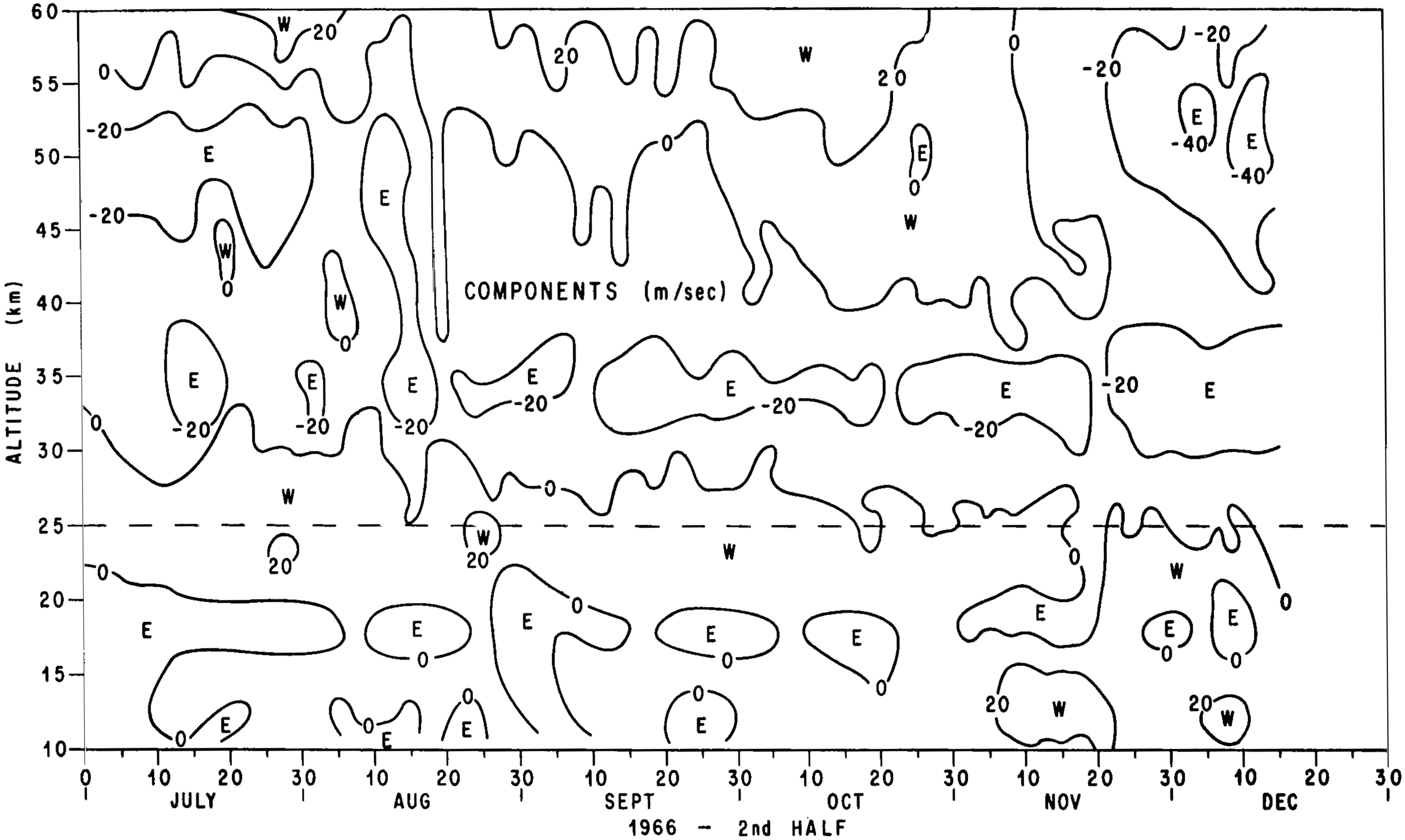

Figure 1e. Ascension Island east-west wind components.

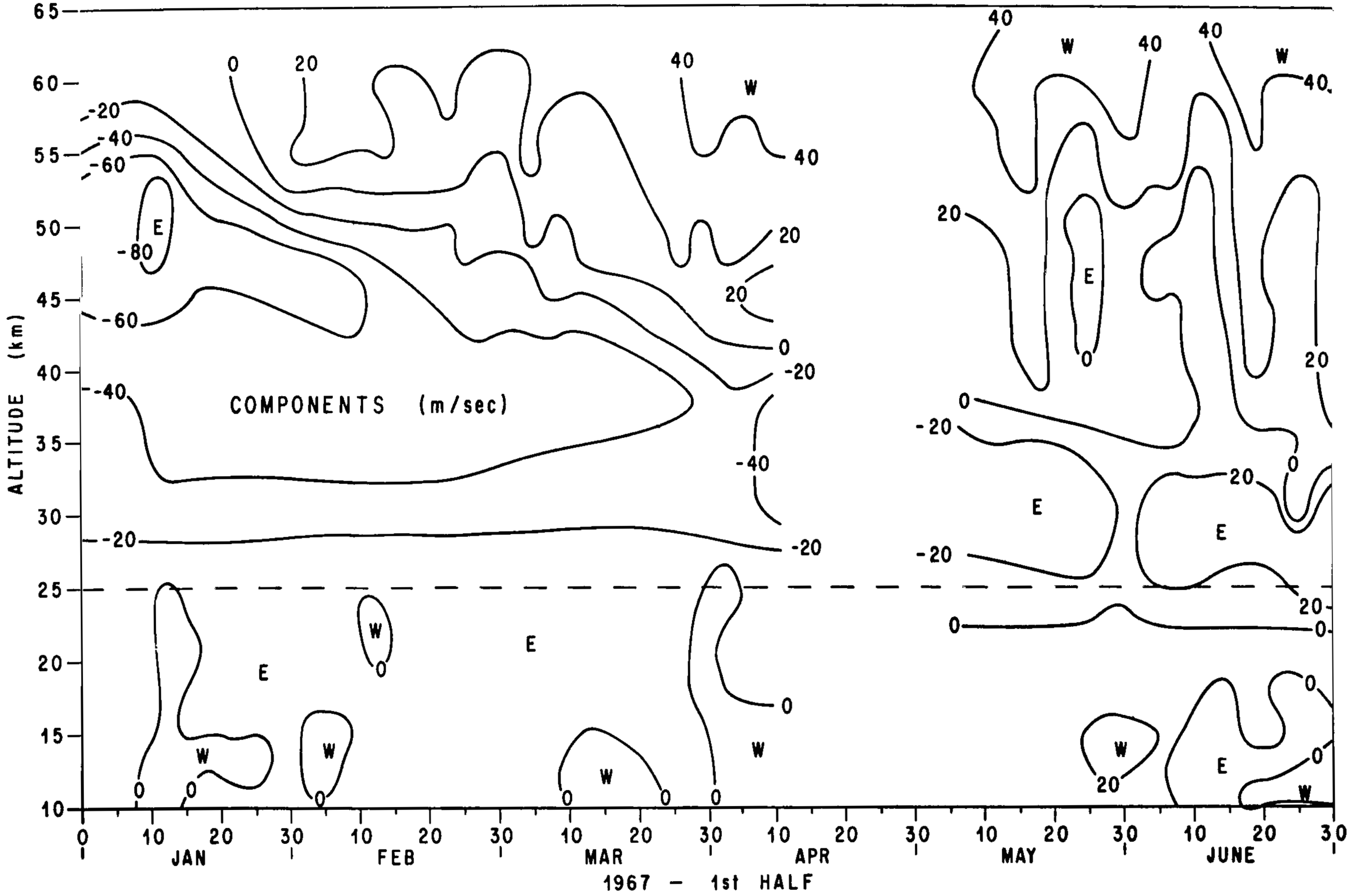

Figure 11. Ascension Island east-west wind components.

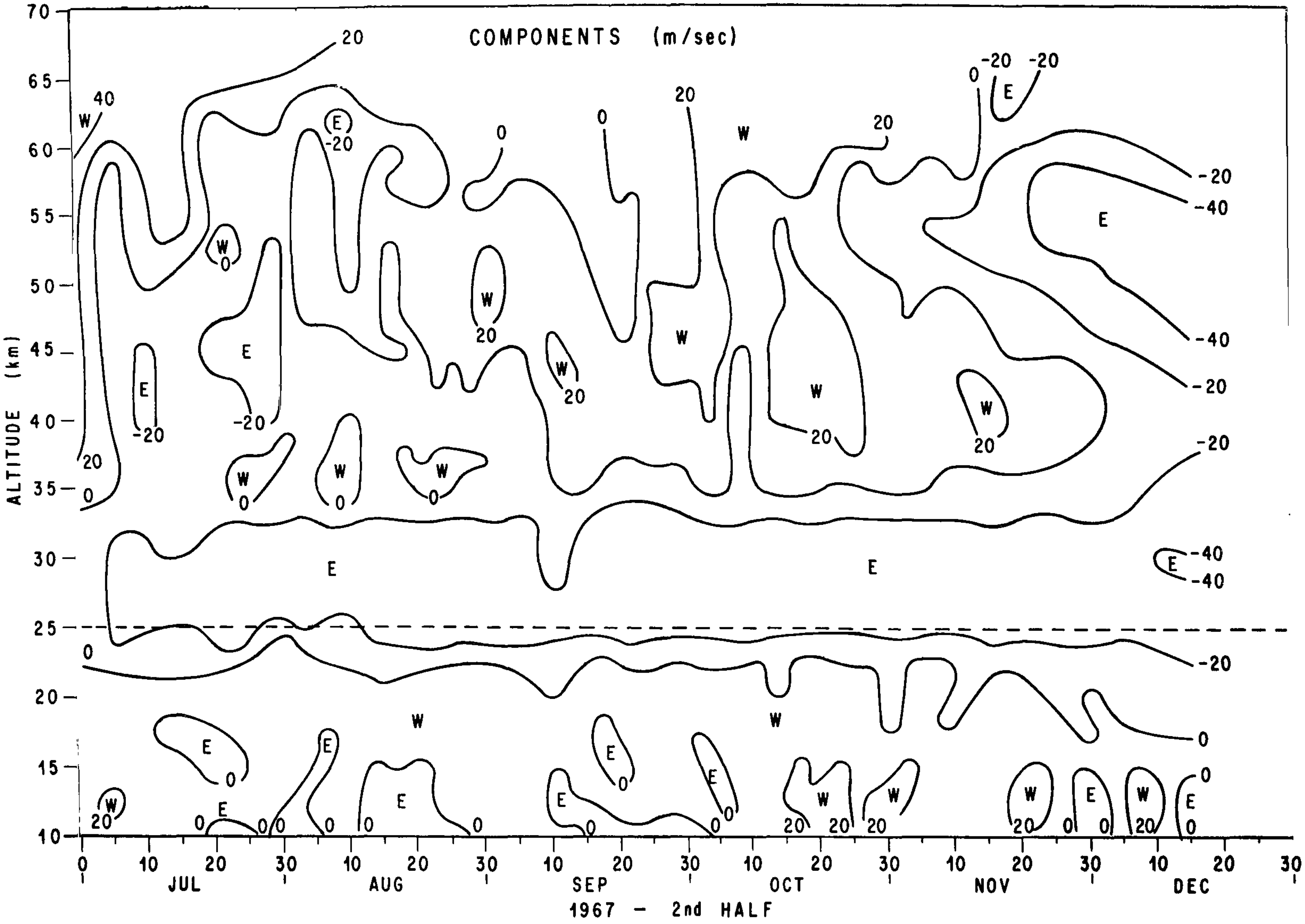

Figure 1g. Ascension Island east-west wind components.

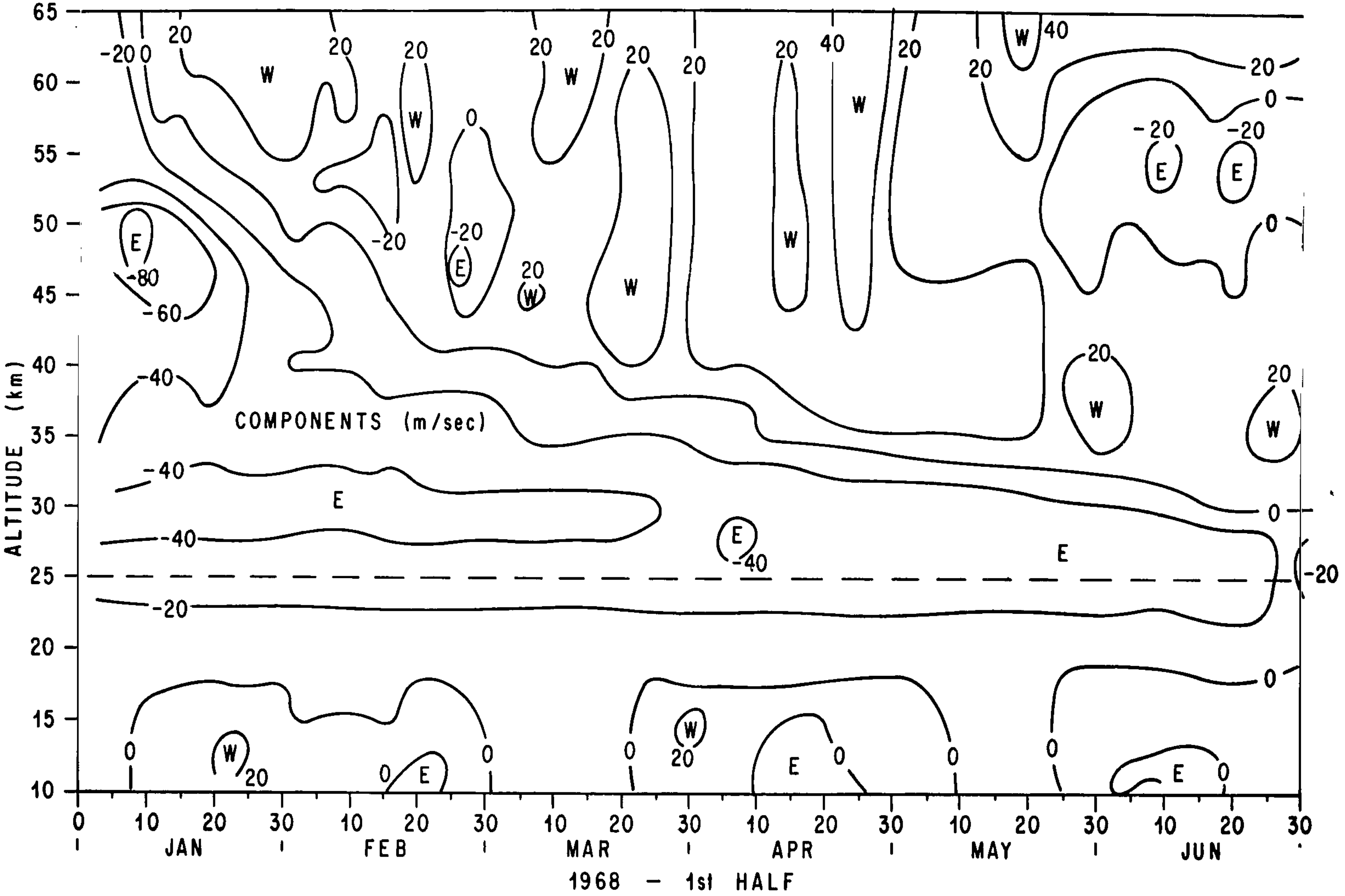

Figure 1h. Ascension Island east-west wind components.

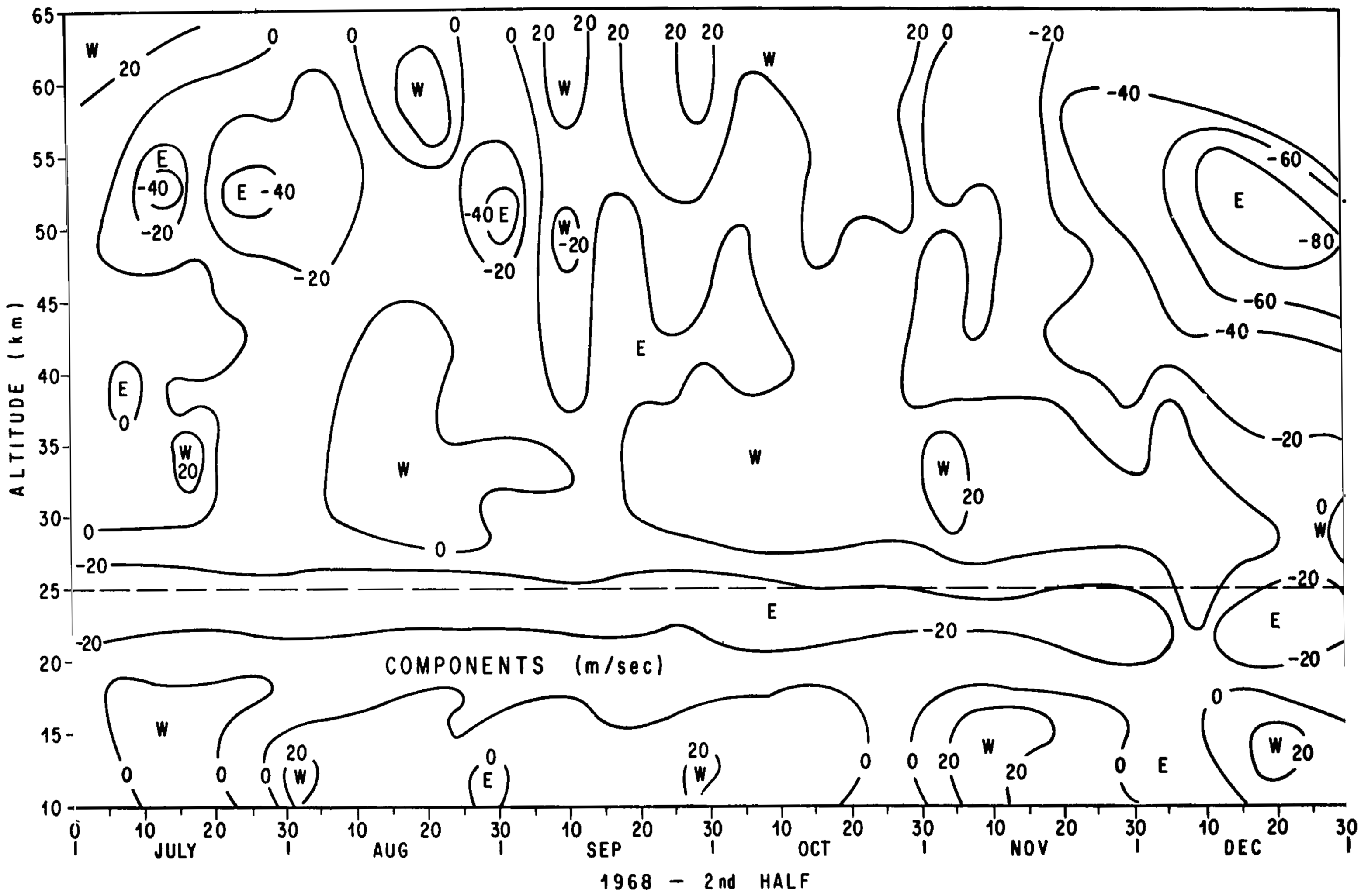

Figure 1i. Ascension Island east-wind components.

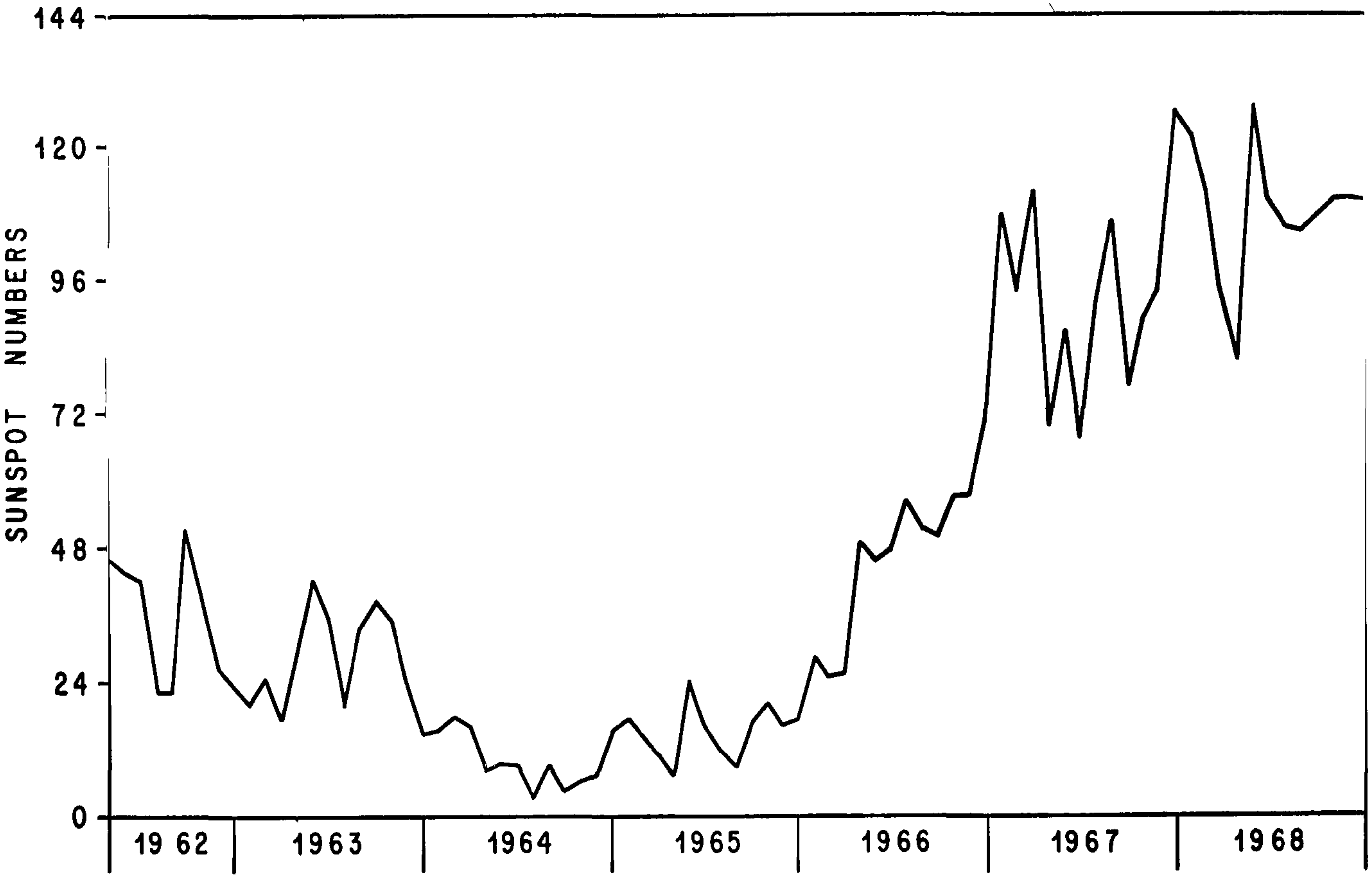

Figure 2. Monthly average Zurich sunspot numbers, 1962-1968.

NASA-Langley, 1971 — 20 M176

> *"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."*
>
> —NATIONAL AERONAUTICS AND SPACE ACT OF 1958

# NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

*Details on the availability of these publications may be obtained from:*

**SCIENTIFIC AND TECHNICAL INFORMATION OFFICE**

**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**
**Washington, D.C. 20546**