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# SOUTHERN HEMISPHERE STRATOSPHERIC CIRCULATION AS INDICATED BY SHIPBOARD METEOROLOGICAL ROCKET OBSERVATIONS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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## SUMMARY

Meteorological data from the NASA Mobile Launch Expedition aboard USNS Croatan are utilized to investigate the early autumn stratospheric circulation of the Southern Hemisphere. Time-height and cross section analyses indicate the vertical and areal extent of the developing wintertime polar vortex. A comparison is made between this cyclone and that of the Northern Hemisphere at a similar stage of development. Additional sets of analyses illustrate segments of the circulation patterns in both hemispheres along the 78th meridian at the time period of the Croatan observations.

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## INTRODUCTION

During March and April 1965, the National Aeronautics and Space Administration conducted an expedition (NASA Mobile Launch Expedition No. 1) in which scientific rocket experiments were conducted from shipboard primarily near the west coast of South America. A total of 77 rockets of various sizes were launched from the converted escort carrier USNS Croatan, as part of the International Years of the Quiet Sun (IQSY) sounding rocket program. Of interest in this paper are wind data from twenty-four, and temperature data from fourteen, meteorological rocket observations made in connection with various experiments carried out by NASA Langley Research Center, Sandia Corporation and China Lake Naval Ordnance Test Station. The analysis of this data was undertaken as part of the Experimental Inter-American Meteorological Rocket Network (EXAMETNET) program which is a cooperative effort among Argentina, Brazil, and the United States (National Aeronautics and Space Administration) to conduct and facilitate studies of the atmospheric structure and behavior in both the Northern and Southern Hemispheres.

All of the observations taken by the expedition within the Southern Hemisphere are representative of the early autumn season, when large-scale circulation changes take place in the middle and upper stratosphere (30 to 60 km). Hare (ref. 1), Belmont (ref. 2), and others have described the gradual formation of the wintertime polar cyclone, but primarily in terms of Northern Hemisphere conditions. An attempt will be made to present information concerning the vertical and lateral extent of the Southern Hemisphere winter vortex during a stage in its development. In addition, comparisons will be made between this system and its counterpart in the Northern Hemisphere.

## DATA ACQUISITION AND PROCESSING

The route of the Croatan along the South American west coast as well as the date of each meteorological rocket launch is shown in figure 1. Information concerning types of equipment employed and altitude ranges of usable data are given in table 1. The Southern Hemisphere sounding program began in the Tropics and continued southward between the 70th and 80th meridians to approximately 60°S, where the ship began its return northward.

As indicated in table 1, all temperatures were measured by the Arcasonde 1A instrument. The initial temperature reduction, in accordance with routine meteorological rocket procedures used at Wallops Station, did not include any corrections or adjustments. Studies by, Barr (ref. 3), Wagner, (ref. 4) and Drews (ref. 5) have shown that appreciable corrections are needed for bead thermistor measurements above 40 km. Drews has suggested correction values for the Arcasonde 1A. These corrections are a function of altitude, and are based on a nominal parachute trajectory and average meteorological conditions. Although the significance of the correction may vary for individual cases, adjustments to the reported data should yield an overall improvement in accuracy. Therefore all rocketsonde temperatures used in this study have been lowered by amounts suggested by Drews, which vary from 0°C at 40 km to 12°C at 60 km.

Wind information was obtained by radar tracking of 15-foot parachutes or chaff (see table 1). Two MPS-19 radar systems were available for this purpose. A major problem associated with shipboard tracking is the difficulty in separating true target motion from that induced by the complex motions of the ship. This separation should be accomplished by direct input to the radar from the ship's gyrostabilizing equipment. The Croatan was not equipped in such a manner; however, radar coordinates were adjusted on the plot board with the aid of a deck mounted gyrosystem. The derived wind components were then smoothed by computing means for 2-km layers. The latter procedure is identical to that utilized for reduction of rocket winds observed at the NASA Wallops Station.

The rocket wind profiles include a number of small-scale perturbations, some of which undoubtedly represent components of the ship's motions. While the perturbations may in part be real, analysis of such features is not the purpose of this paper -- nor is it feasible in view of the limitations of the data. To eliminate these features and yet preserve the overall character of the soundings, all individual u (eastward)- and v (northward)-component profiles were further smoothed by means of the simple procedure known as "hanning" (ref. 6):

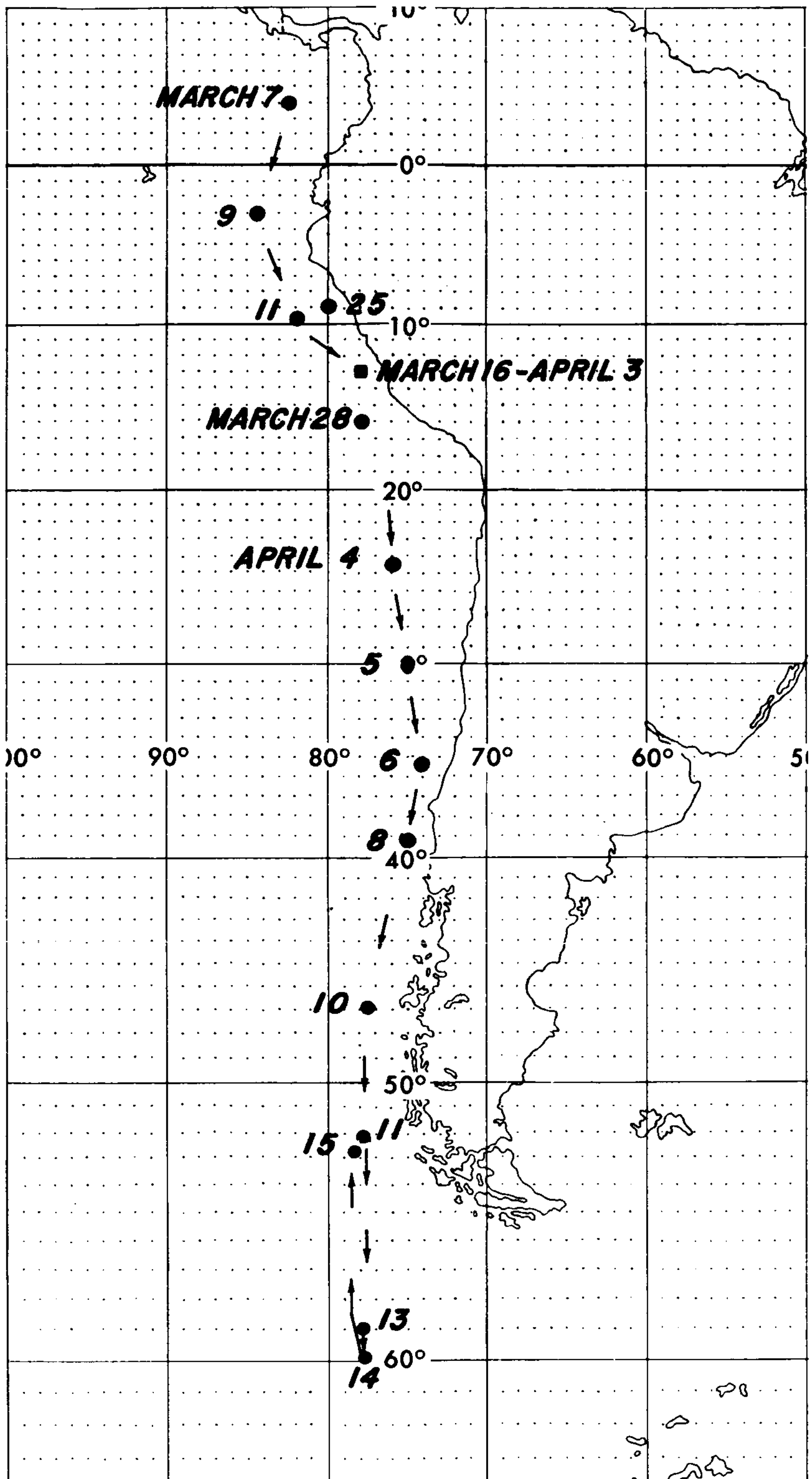


Figure 1. Route of USNS Croatan in March and April 1965, with dates of meteorological rocket launchings.

TABLE 1. Technical Data for Meteorological Rockets Launched from USNS Croatan

| DATE | POSITION | ROCKET | SENSORS WIND | SENSORS TEMP (a, b) | TRACKS(KM) WIND | TRACKS(KM) TEMP | SUPPORT RAWINSONDE (b) |
|---|---|---|---|---|---|---|---|
| March | | | | | | | |
| 7 | 03°55'N 82°46'W | ARCAS | Chute | - | 54-18 | - | + |
| 9 | 03°04'S 84°23'W | ARCAS | Chute | - | 50-18 | - | + |
| 11 | 09°32'S 82°10'W | HASP | Chaff | - | 60-30 | - | - |
| 16 | 12°55'S 78°00'W | ARCAS | Chute | + | 64-24 | 63-24 | + |
| 17 | 12°38'S 78°03'W | HASP | Chaff | - | 58-22 | - | + |
| 18 | 12°49'S 77°58'W | ARCAS | Chute | + | 50-20 | 57-19 | + |
| 19 | 13°06'S 78°00'W | HASP | Chaff | - | 60-24 | - | + |
| 21 | 12°57'S 78°03'W | ARCAS | Chute | + | 42-20 | 35-22 | + |
| 22 | 12°28'S 77°54'W | HASP | Chaff | - | 60-20 | - | - |
| 24 | 11°34'S 78°23'W | ARCAS | Chute | + | 56-20 | 56-17 | + |
| 25 | 09°02'S 79°56'W | HASP | Chaff | - | 66-20 | - | - |
| 27 | 14°10'S 77°59'W | ARCAS | Chute | + | 38-20 | 55-18 | + |
| 28 | 16°01'S 78°00'W | HASP | Chaff | - | 56-20 | - | - |
| April | | | | | | | |
| 2 | 12°19'S 78°11'W | ARCAS | Chute | + | 60-20 | 59-18 | + |
| 3 | 14°34'S 77°47'W | ARCAS | Chute | + | 62-20 | 52-22 | + |
| 4 | 24°36'S 76°01'W | ARCAS | Chute | - | 42-20 | - | - |
| 5 | 29°52'S 75°09'W | ARCAS | Chute | - | 44-20 | - | - |
| 5 | 30°52'S 75°00'W | ARCAS | Chute | + | msg | 53-20 | + |
| 6 | 35°12'S 74°16'W | ARCAS | Chute | - | 50-20 | - | + |
| 8 | 39°07'S 75°11'W | HASP | Chaff | - | 56-20 | - | - |
| 10 | 47°02'S 77°45'W | ARCAS | Chute | + | 52-20 | 45-18 | + |
| 11 | 48°35'S 77°42'W | ARCAS | Chute | + | msg | 47-18 | + |
| 11 | 52°11'S 77°49'W | ARCAS | Chute | + | 44-20 | 47-18 | + |
| 13 | 59°52'S 77°58'W | ARCAS | Chute | + | 64-20 | 57-18 | - |
| 14 | 59°46'S 77°50'W | ARCAS | Chute | + | 56-20 | 48-18 | + |
| 15 | 52°28'S 78°09'W | ARCAS | Chute | + | 46-20 | 48-18 | + |

(a) Arcasonde 1A

(b) + if yes; - if no (Note; 5 ARCAS-CHUTE payloads consisted of ozonesondes)

$$\bar{u}_i = 0.25u_{i-1} + 0.5u_i + 0.25u_{i+1}$$

$$\bar{v}_i = 0.25v_{i-1} + 0.5v_i + 0.25v_{i+1}$$

where the index i denotes successive levels, at intervals of 2 km in this case, and the overbar indicates a mean or smoothed value. The u and v profiles for two soundings, both before and after "hanning," are shown in figure 2. It is evident that the smoothing procedure preserves the general nature of each profile, and eliminates nearly all of the "small-scale noise." While the locations of extremes are preserved, there is some loss in amplitude.

## TIME-SECTION ANALYSIS

During a significant portion of the cruise, specifically in late March and early April, thirteen meteorological rockets were launched from the Croatan in the vicinity of 13°S, 78°W. This relatively stationary position, near the geomagnetic equator, was maintained while experiments involving larger rockets were being conducted. The time-height section shown in figure 3 was constructed from the meteorological rocket data and the associated supporting rawinsonde information. Such a procedure was deemed valid, in that small departures from fixed position should have negligible effect on the representation of broad-scale patterns.

Prevailing easterly winds below 40 km exhibit a high degree of day to day persistence, while at higher levels, westerly winds dominate and propagate downward with time. The demarcation line between easterlies and westerlies, obtained from the u-component profiles, is found near 49 km at the beginning of the period and gradually descends to about 43 km within a three-week interval. Rocketsonde and rawinsonde temperature data are also shown in the time section, and in general are in good agreement within layers of overlap. The cold tropical tropopause can be located near 16 km, at the lower boundary of the deep layer of easterlies. The horizontal thermal gradient dictated by the generally increasing easterly components from the tropopause to approximately 34 km would place colder air toward the Equator. Above 34 km the thermal gradient is reversed, with warmer air toward the Equator. Although the stratopause cannot be precisely delineated, a few observations indicate more than one temperature maximum. The suggestion of a multi-layered stratopause structure has also been noted from relatively low latitude observations in the Northern Hemisphere.

Rocketsonde observations taken in March and April 1965 at Ascension Island (7°55'S 14°25'W) were utilized to construct the time-height section shown in figure 4. The wind pattern is similar to that indicated by the Croatan

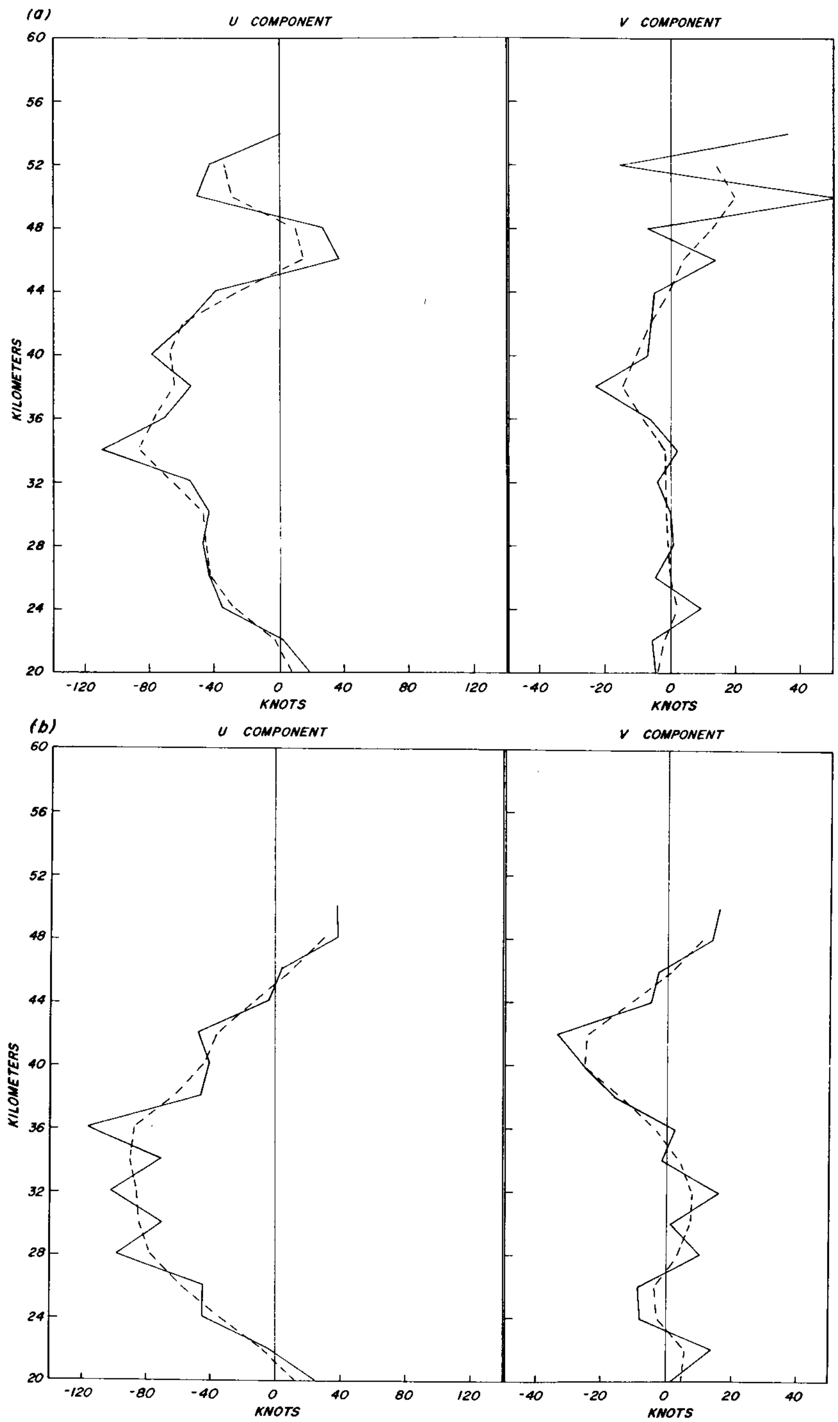


Figure 2. Profiles of observed (solid lines) and smoothed (dashed lines) eastward (u) and northward (v) wind components: (a) 7 March 1965 at 4°06'N 82°42'W; (b) 9 March at 3°04'S 84°23'W.

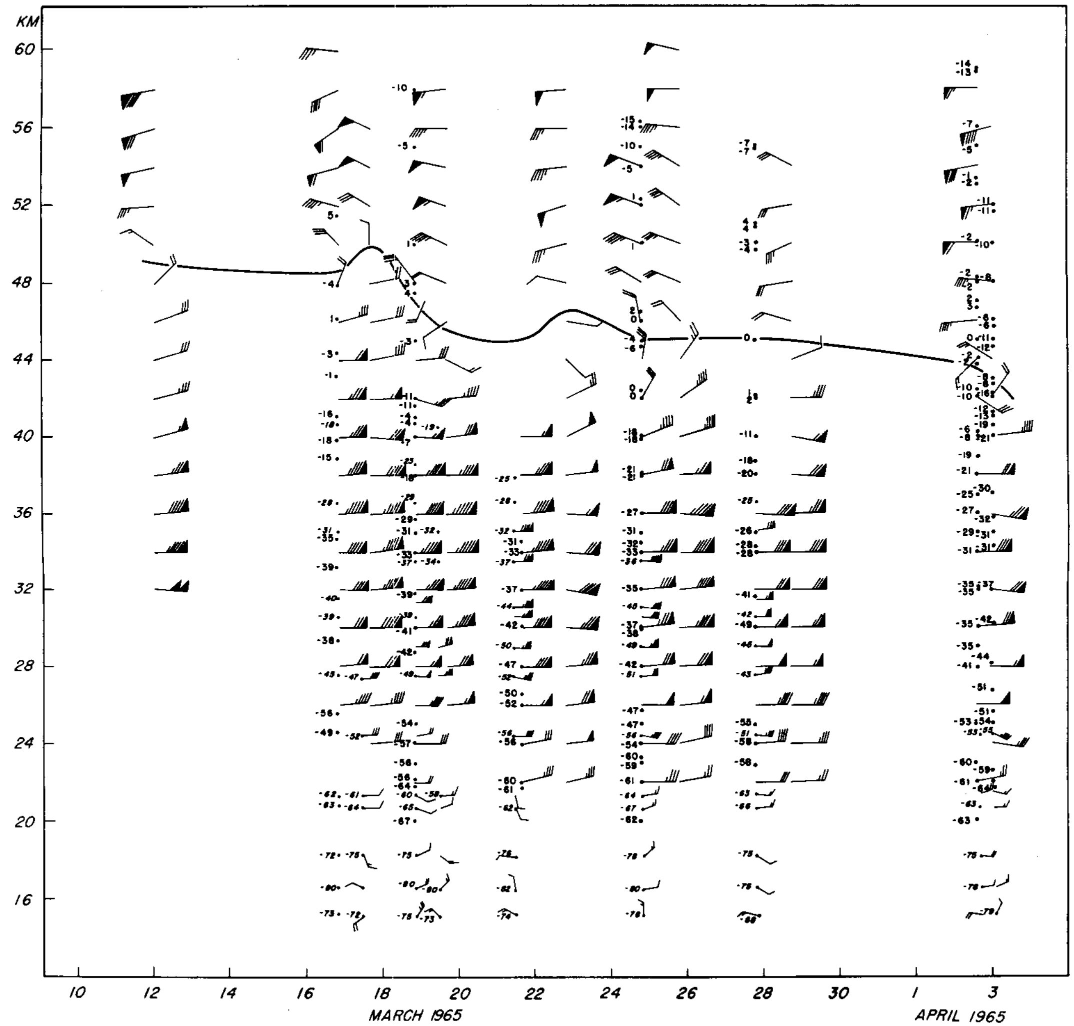


Figure 3 Time-height section of wind and temperature for the nominal location 13°S 78°W. Rocketsonde winds (knots) are denoted by large symbols, and temperatures (deg C) by upright numerals; support rawinsonde data, by small wind symbols and slanted numerals.

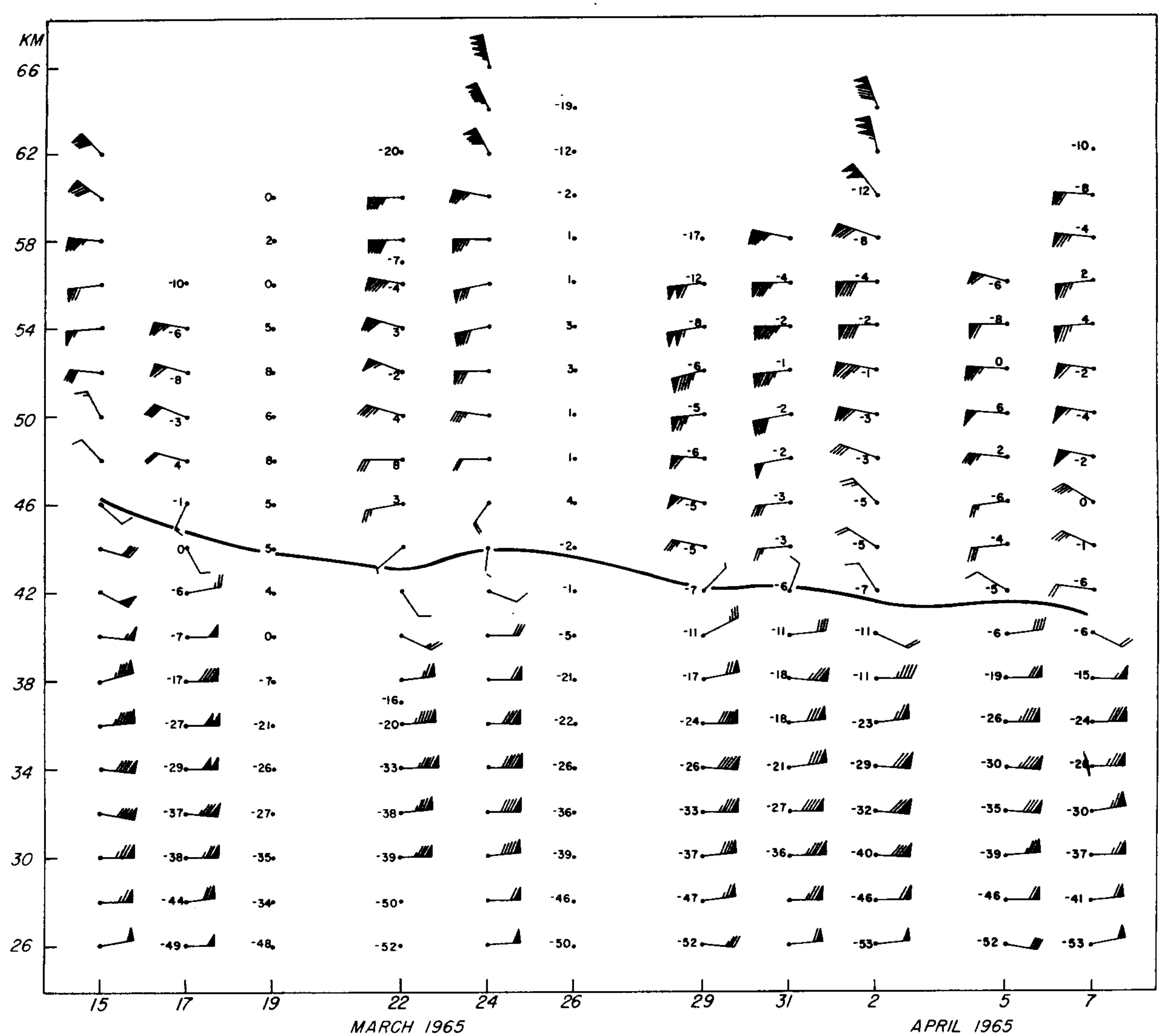


Figure 4. Time-height section of rocketsonde winds (knots) and temperatures (deg C) for Ascension Island, 7°55'S 14°25'W (Note; wind data are doubtful above 58 km).

soundings, especially in the 5- to 6-km descent of westernlies within the three-week period, although throughout this time interval the demarcation zone appeared to be slightly lower at Ascension. Meridional temperature gradients implied by the vertical wind shears are also analogous to those deduced from the observations in the Croatan time-section, particularly with regard to the reversal located near 35 km. The increasingly strong northerly components above 58 km in several observations suggest a very large zonal temperature gradient. The reality of these winds is questionable, however, since rockets are usually launched in a southward direction at Ascension Island.

The transitions from easterly to westerly noted on the low-latitude time sections may not necessarily be representative of early autumn conditions of all years. Reed (ref. 7), in utilizing two years of Ascension Island rawinsonde and rocketsonde data, has shown that the zonal component varies markedly with time and height. Predominant periods of oscillation appear to be 24-26 months near 29 km, 12 months between 32 and 40 km and 6 months above 40 km. All of these periodicities may interact, affecting the wind variations at the stratospheric levels of concern in a complex manner.

## CROSS-SECTION ANALYSIS

For a period of fourteen days, between 2 and 15 April 1965, the Croatan cruised generally southward from 13°S to 60°S, and then began a return toward the north (see figure 1). During this portion of the expedition 13 meteorological rockets were launched (table 1). Although movement in both space and time were involved, only the largest-scale circulation features are to be discussed and the time lapse of two weeks may reasonably be neglected. Thus the data are exhibited in the form of a two-dimensional cross section (figure 5), in which both rocketsonde and support rawinsonde observations are utilized. The orientation is generally north-south along the west coast of South America between the 73rd and 78th meridians. It should be noted that two of the low-latitude observations were also utilized in the time-section discussed previously.

In obtaining the temperature analysis, some smoothing of reported values, especially for higher levels, was necessary. The analysis illustrates the cold core associated with the low-latitude tropopause, and a relatively isothermal lower stratosphere over more poleward regions. The tropopause has been delineated near 17 km in lower latitudes, and slopes downward to about 9 km at 60°S. In the 25- to 45-km layer horizontal temperature gradients are relatively weak over low and middle latitudes. Poleward of 40°S, however, there is a significant decrease in temperature consistent with the pronounced vertical increase in the magnitude of the

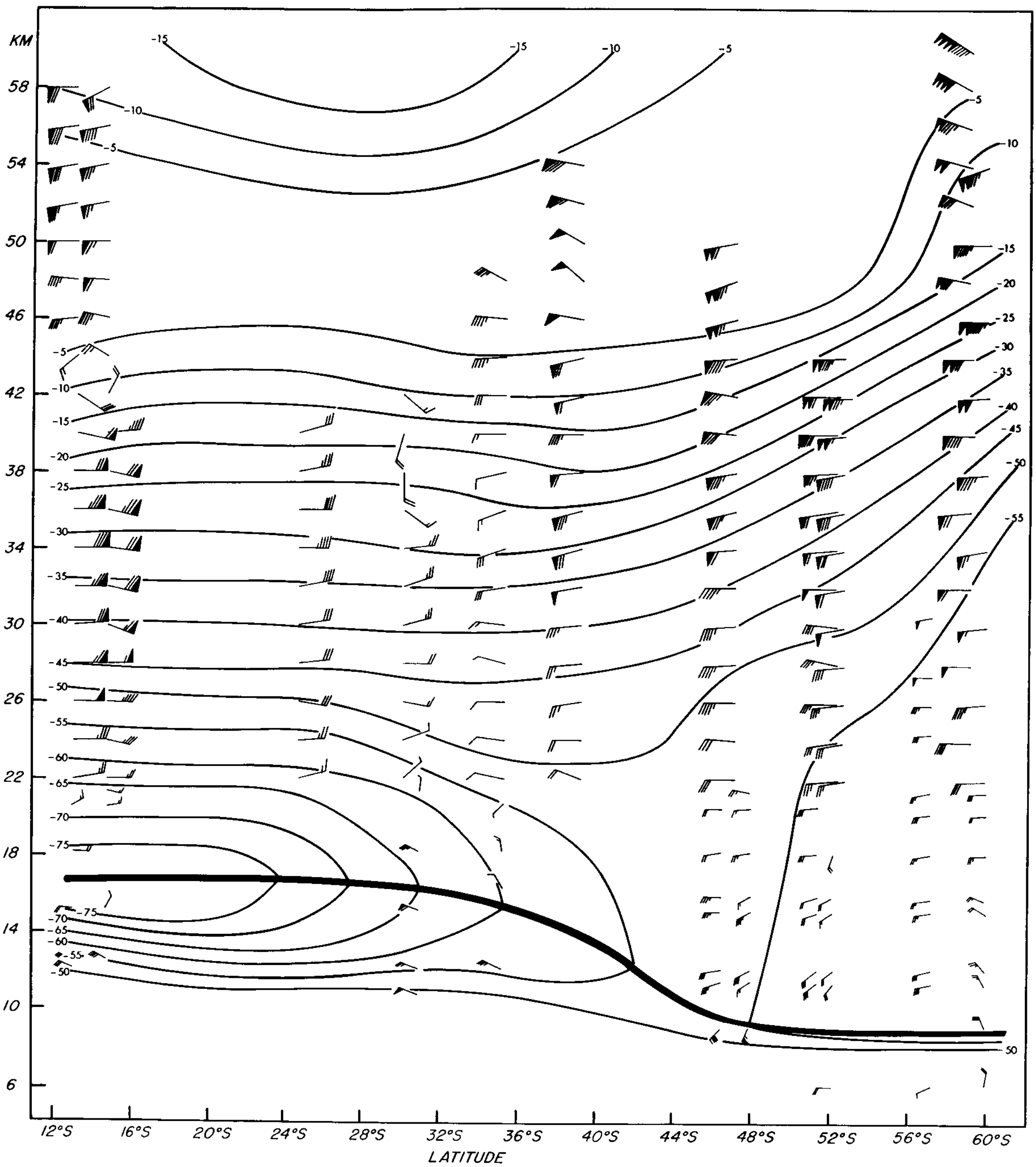


Figure 5. Space-time cross-section of wind and temperature from 12°S to 60°S along 78°W. Rocketsonde and support rawinsonde winds as in figure 3; isotherms at 5°C intervals.

westerly components in this layer. Although no exact definition of the stratopause is possible, it appears to be located between 45 and 50 km at the lower latitudes, and to slope upward toward the Pole.

Two distinct wind regimes are indicated by the observations. The demarcation between the deep layer of westerlies and the zone of low-latitude easterlies is located between 30°S and 35°S in the layer from 20 to 40 km. An equatorward increase in vertical extent of the easterlies is evident.

During late April and early May 1959, the U.S.S.R. Third Antarctic Expedition aboard the ship Ob gathered information up to about 44 km between 65°S and 27°S near 110°W (ref. 8). A section analogous to figure 5 reveals a comparable temperature pattern. The Ob wind data also show a similar field of westerlies over the entire latitude range sounded, but the reported observations did not extend northward far enough to delineate the low-latitude stratospheric easterlies.

## COMPARISON OF NORTHERN AND SOUTHERN HEMISPHERE CIRCULATION

Stratospheric mean charts of the Antarctic region drawn by Viebrock (ref. 9) and Northern Hemisphere maps constructed by Free University of Berlin (ref. 10) and ESSA, Weather Bureau (ref. 11) indicate that the autumnal circulation change, at least in the middle stratosphere (20-30 km), is quite regular from year to year in both hemispheres. The initial weakening of the anticyclonic circulation is first evident in the sub-polar region and at the lower boundary of the layer, and progresses rapidly upward. High-level observations, primarily from the North American Meteorological Rocket Network (ref. 12), were sufficient in number during the IQSY period to facilitate broad-scale quasi-synoptic analysis for levels as high as 0.4 mb (approximately 55 km). These analyses constructed by ESSA, Weather Bureau (ref. 13) have been described by Finger, Woolf and Anderson(ref. 14). These charts suggest that the initial weakening of the summertime circulation progresses upward and affects the middle and upper stratosphere within a relatively short period of time.

A set of the high-level analyses, based on data for the week centered on 7 October 1964, is shown in figure 6. Rocketsonde and rawinsonde data employed for these charts represent the same early autumn period in the Northern Hemisphere as do the Croatan data for the Southern Hemisphere. The most prominent feature of the circulation at all three levels is the polar cyclone, which began to form in late August and subsequently intensified and expanded. Persistence of the summertime anticyclonic flow at low latitudes resulted in the appearance of a ridge line oriented along the southern periphery of the cyclone. Another aspect obvious from the analyses

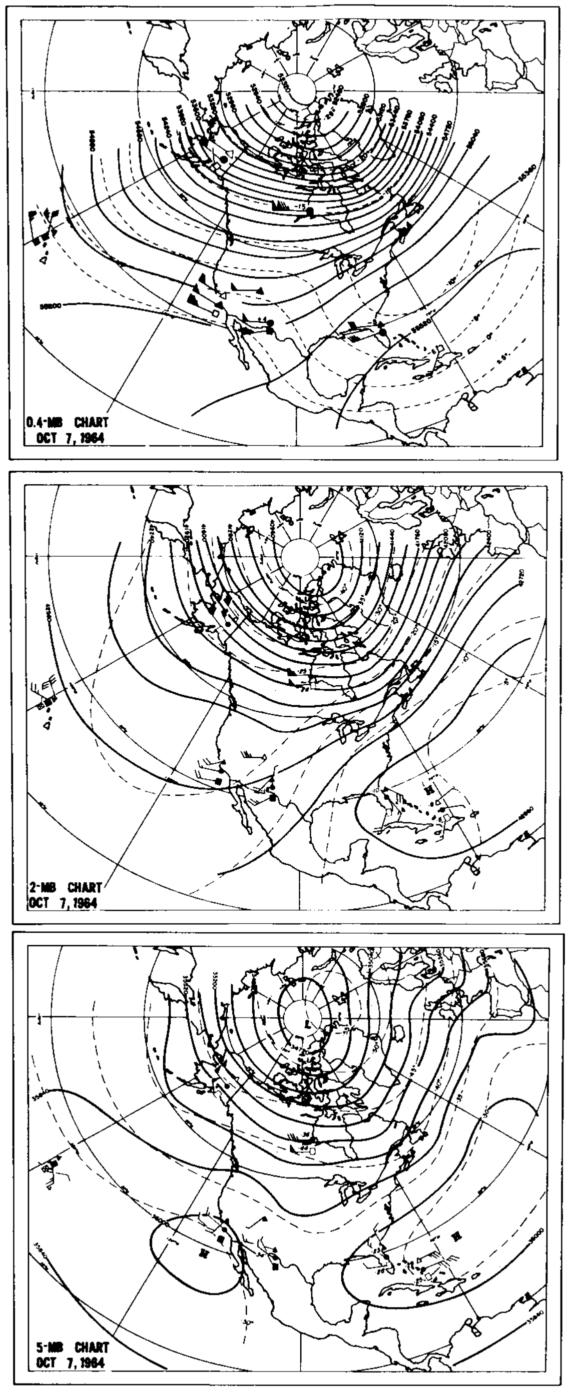


Figure 6. (a) 5-mb, (b) 2-mb, (c) 0.4-mb charts for 7 October 1964. Contours (solid lines) at 160-m intervals; isotherms (dashed lines) at 5°C intervals. Observed rocketsonde winds (knots) and temperatures (deg C), are for map day ( ● ), one day previous ( ▲ ), one day subsequent ( ■ ), two days previous ( Δ ), two days subsequent ( □ ), and three days subsequent ( ⊠ ). (from ESSA, ref. 13).

is the increase with height of the area covered by the cyclone. This areal expansion can be seen in terms of the above-mentioned ridge line, which is located near 25-30°N at 5 mb (approximately 36 km) and is displaced to somewhat lower latitudes in the Pacific sector at 2 mb (about 42 km). At 0.4 mb (55 km) the available data indicate that the ridge line, if it exists, is located beyond the southern boundary of the map.

The Croatan data may be presented in an alternate form to facilitate a more lucid comparison with North American conditions than can be accomplished with the cross section described earlier. An attempt has been made to depict portions of the contour and isotherm fields along the section line at the 5-, 2- and 0.4 mb levels (figures 7d, e, f respectively). Contour values for each level were estimated by hydrostatic build-up, utilizing geopotential thicknesses computed from rocketsonde temperature data. The reported heights of the support rawinsonde observations formed the base level for this procedure. Gradients in the height field have been adjusted by the winds (assumed to be in geostrophic balance), which were selected from the smoothed rocketsonde wind profiles at the computed constant-pressure heights.

The Southern Hemisphere representations indicate that the polar vortex is already well developed two or three weeks after the autumnal equinox. A ridge line can be delineated at approximately 30°S at both the 5- and 2-mb levels, in agreement with the more complete North American analyses for the comparable season (figure 6). There appears to be correspondence between the two hemispheres even at the 0.4-mb level, as there is no indication of a ridge, at least to 10°S. Although the Southern Hemisphere analyses are very restricted in area and represent a single isolated time period, the height values and contour gradients suggest that the stratospheric polar cyclone is more intense there than in the Northern Hemisphere for the analogous season. This feature has been noted previously by Wexler, (ref. 15) and Rubin and Weyant, (ref. 16).

Portions of concurrent analyses from the IQSY series of North American charts, shown in conjunction with the Croatan data, facilitate a view of the upper stratospheric circulation along most of the 78th meridian in early April. Sections of the 7 April 1965 5-, 2- and 0.4-mb charts centered along the 78th meridian are shown in figures 7a, b and c, and may be compared with the Croatan analyses in the lower parts of the figure. At this time the Northern Hemisphere vortex, undergoing the vernal breakdown, was still centered in the Arctic region. Most striking is the symmetrical appearance of the subtropical ridges at 5 and 2 mb. Although the 0.4-mb patterns are dissimilar in intensity, the presence of westerly winds at all latitudes shown is noteworthy. Webb (ref. 17) has speculated that at the 50-km level, the

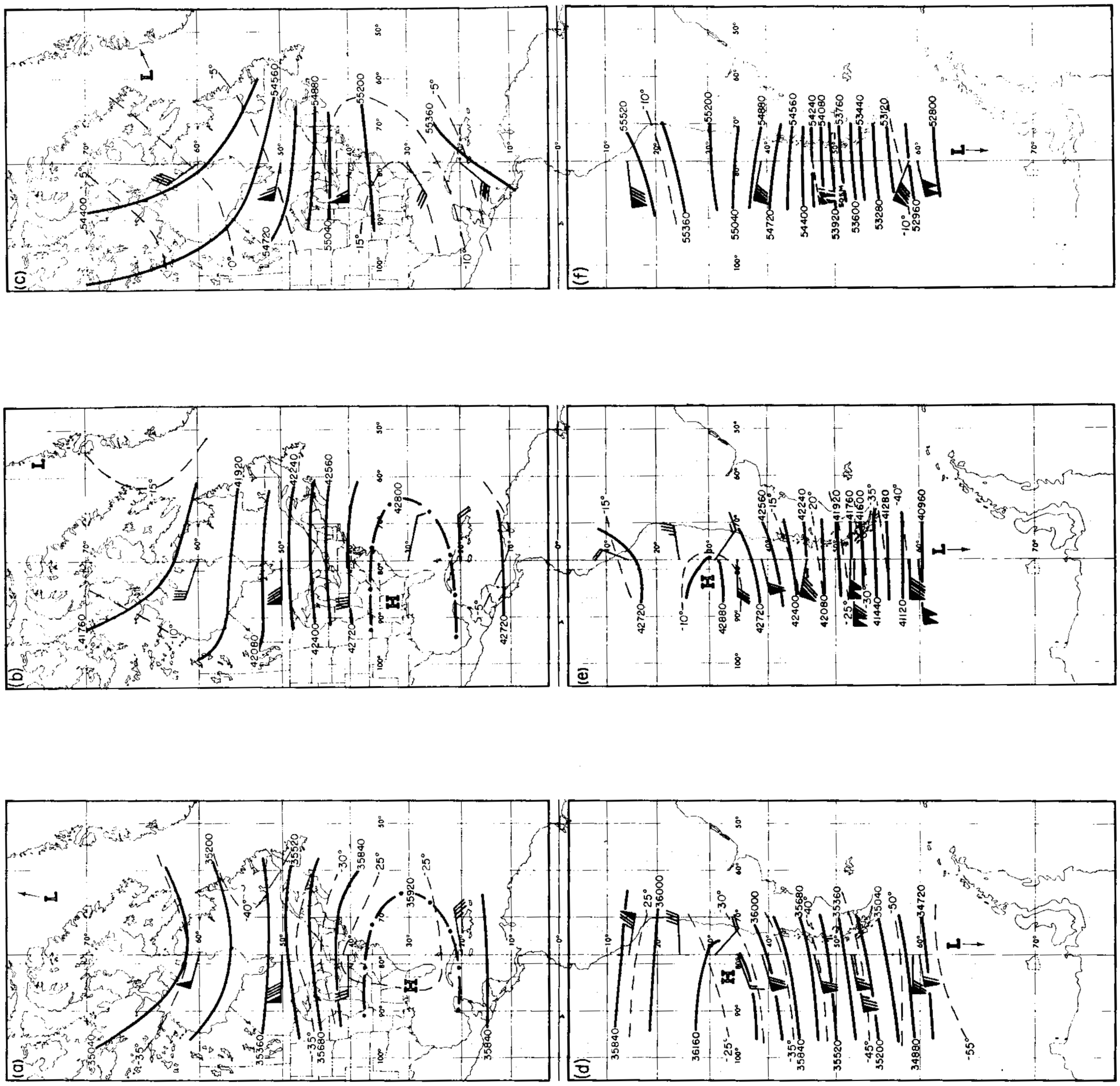

Figure 7. (a) 5-mb, (b) 2-mb, (c) 0.4-mb analyses (Northern Hemisphere) centered on 78°W for 7 April 1965, with interpolated geostrophic winds (after ESSA ref. 13); (d) 5-mb, (e) 2-mb, (f) 0.4-mb analyses (Southern Hemisphere) centered on 78°W and 9 April 1965, based on Croatan data. Rocketsonde winds in knots: contours and isotherms as in figure 6.

entire globe is dominated by westerlies during a short period while the Northern Hemisphere wintertime circulation is decaying and that of the Southern Hemisphere is developing. It should be emphasized that the Northern Hemisphere vernal changeover is complex in nature and quite variable in time, and therefore the degree of symmetry between hemispheres may vary from year to year.

A further, small-scale comparison between hemispheres may be made with the aid of the two Croatan wind observations taken immediately north (figure 2a) and south (figure 2b) of the Equator in early March. At that time easterly components were present within the 22- to 46-km layers at both locations. This information, coupled with the other presentations, tend to verify the inter-hemisphere extent of the mid-stratosphere easterly regime. It is interesting that the observations indicate northerly flow across the Equator at about 40 km. Unfortunately, the soundings did not attain sufficient height to substantiate the inference that the high-altitude westerlies are continuous across the Equator.

## CONCLUDING REMARKS

The meteorological observations taken from the Croatan were sufficient to permit the construction of various types of analyses. Although the observations were limited in number and restricted in time, some inferences may be drawn from the analyses:

1. The middle-and upper-stratospheric circulations of both hemispheres behave in a similar manner during the early autumn season. In the case of the Northern Hemisphere several series of synoptic analyses indicate that high-latitude autumnal cyclogenesis progresses rapidly upward from 20 km or below to at least 55 km. Furthermore, once the polar cyclone is established, intensification and expansion proceed most rapidly at the higher levels. Recent information for the high latitudes of the Southern Hemisphere, although restricted in vertical extent, confirms the upward progression of cyclogeneses to at least the 20-mb level. The Croatan rocketsonde data, although restricted in latitudinal extent, tend to substantiate the accelerated intensification of the Southern Hemisphere polar cyclone at the higher levels.

2. The analysis accomplished with the Croatan data supports the proposition that the Southern Hemisphere polar cyclone is more intense than that of the Northern Hemisphere.

3. A degree of symmetry exists between the flow patterns of the two hemispheres during portions of the equinoctial periods. Results for the specific case investigated indicate a predominantly westerly flow above about 45 km. Below that level to near the tropopause a band of easterlies was situated nearly symmetrically about the Equator. The greatest latitudinal extent of these easterlies occurred in the layer from about 26 to 36 km. More data will be required to ascertain whether the indicated inter-hemisphere symmetry exists during all phases of the quasi-biennial wind oscillation and also during the various modes of Northern Hemisphere vernal circulation change.

It is quite obvious that a world-wide view of the entire stratosphere cannot be obtained with the present number and distribution of meteorological rocket stations. However, this situation is gradually improving. For example, the Experimental Inter-American Meteorological Rocket Network (EXAMETNET) includes recently activated stations at Chamical, Argentina (30°S 67°W) and Natal, Brazil (6°S 35°W). Regular soundings at these and other stations will soon permit construction of more complete synoptic representations of high-level circulation throughout the year.

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