Southern Hemisphere Stratospheric Circulation as Indicated by Shipboard Meteorological Rocket Observations

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(Manuscript received 28 December 1966)

ABSTRACT

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.

1. 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 24, and temperature data from 14, meteorological rocket observations made in connection with various experiments carried out by NASA Langley Research Center, Sandia Corporation, and the China Lake Naval Ordnance Test Station.

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 (1960), Belmont (1962), 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.

2. 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 Fig. 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 60S, 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. However, a number of studies [for example, Barr (1961), Wagner (1964), Drews (1966)] 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 increase from 0C at 40 km to 12C at 60 km.

Wind information was obtained by radar tracking of 15-ft 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

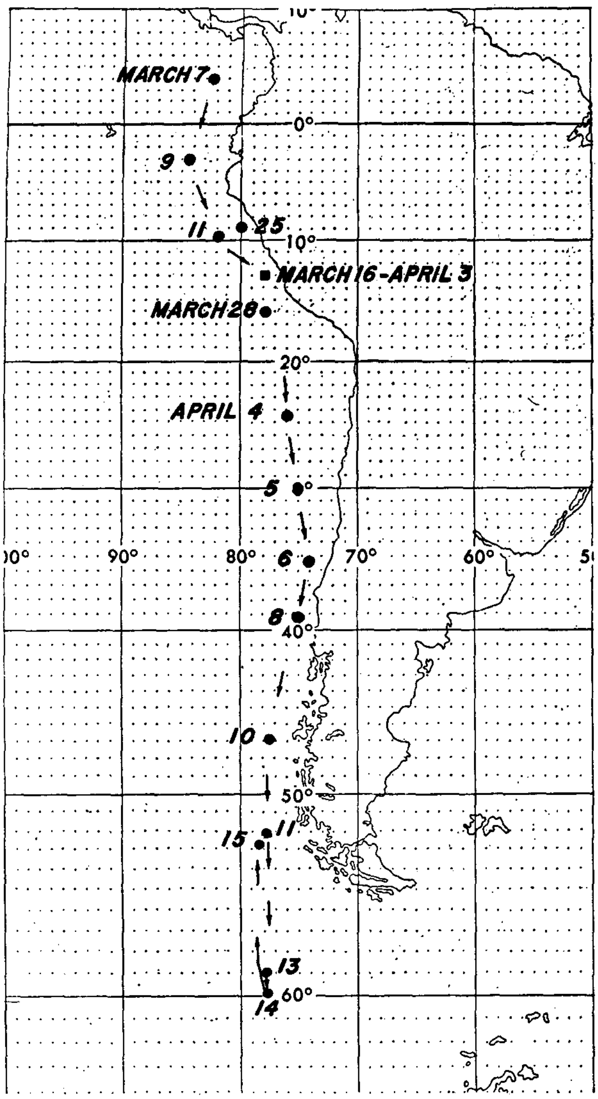

FIG. 1. Route of USNS *Croatan* in March and April 1965, with dates of meteorological rocket launchings.

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" (Blackman and Tukey, 1958), i.e.,

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

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

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 Fig. 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.

3. 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 13S, 78W. This relatively stationary position, near the geomagnetic equator, was maintained while experiments involving larger rockets were being conducted. The time-height section shown in Fig. 3 was constructed from the meteorological rocket data and the

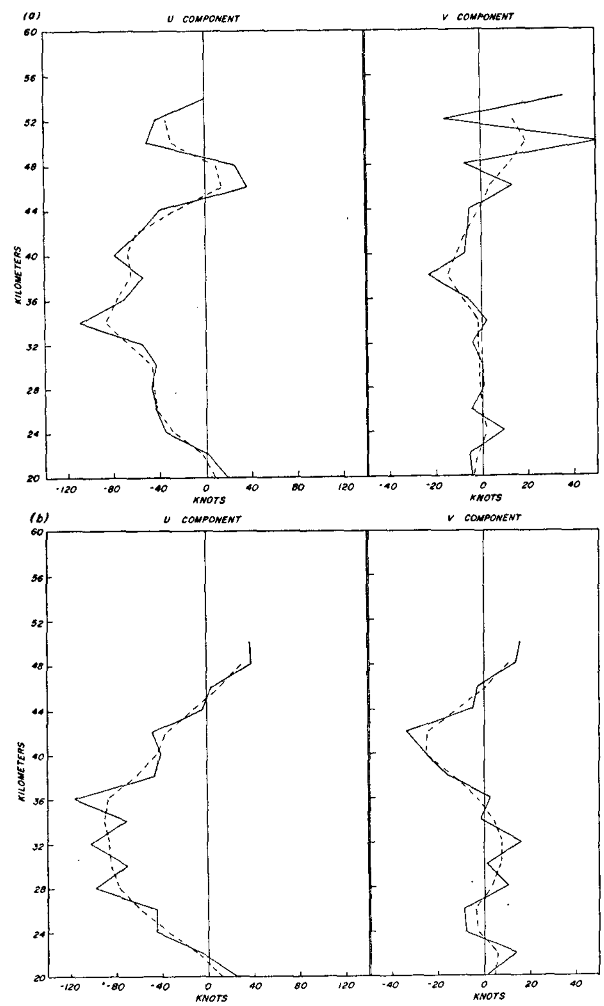

FIG. 2. Profiles of observed (solid lines) and smoothed (dashed lines) eastward u and northward v wind components: (a) 7 March 1965 at 3°55′N, 82°42′W; (b) 9 March at 3°04′S, 84°23′W.

associated supporting rawinsonde information. Such a procedure was deemed valid, in that small departures from fixed position should have a 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 Fig. 4. The wind pattern is similar to that indicated by the *Croatan* soundings, especially in the 5- to 6-km descent of westerlies 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, and winds measured shortly after ejection of the payload may be contaminated by its ballistic motion if the sensor (parachute) is not yet fully wind-sensitive.

The transitions from easterly to westerly noted on the low-latitude time sections may not necessarily be representative of early autumn conditions for all years. Reed (1965), 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

Table 1. Technical data for meteorological rockets launched from USNS *Croatan*.

Date	Position	Rocket	Sensors: Wind	Sensors: Temperature*	Tracks (km): Wind	Tracks (km): Temperature	Support rawinsonde**
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	+

* Arcasonde 1A temperature sensors with 5 ARCAS-CHUTE payloads consisting of ozonesondes. Plus values indicate temperature records made.
** Plus values indicate support rawinsondes taken.

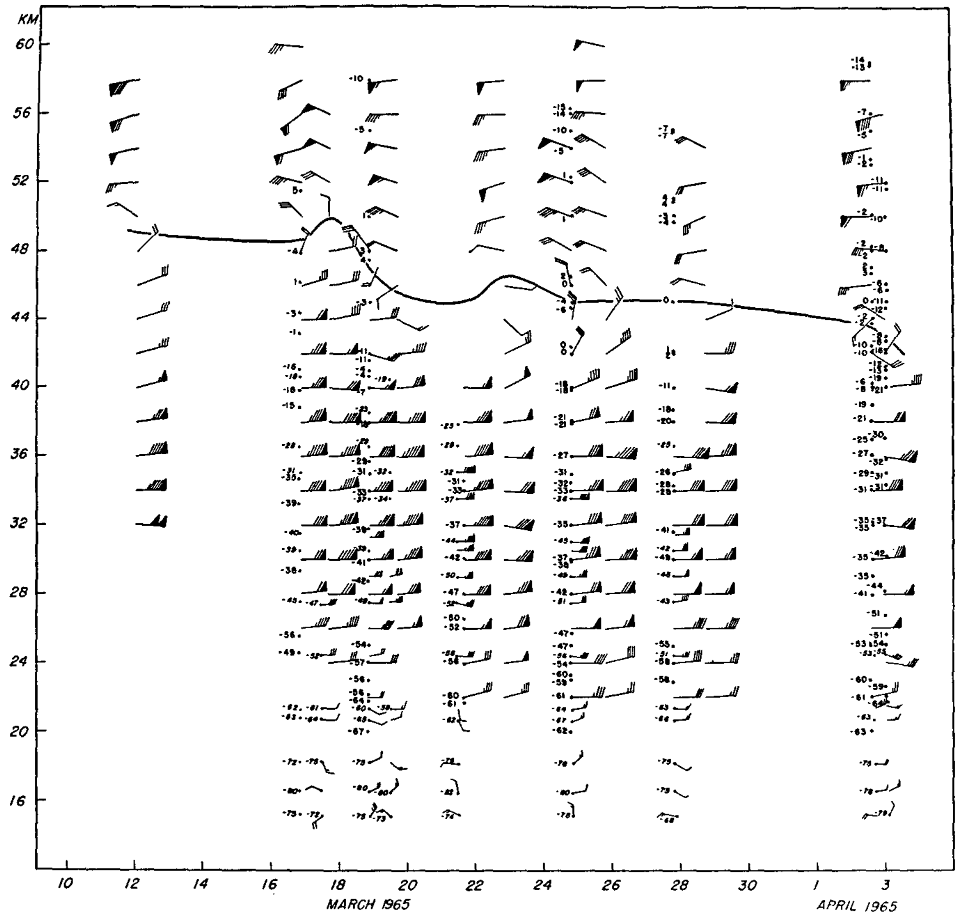

FIG. 3. Time-height section of wind and temperature for the nominal location 13S, 78W. Rocketsonde winds (kt) are denoted by large symbols, temperature (°C) by upright numerals, and support rawinsonde data by small wind symbols and slanted numerals.

periodicities may interact, affecting the wind variations at the stratospheric levels of concern in a complex manner.

4. Cross-section analysis

For a period of fourteen days, between 2 and 15 April 1965, the *Croatan* cruised generally southward from 13S to 60S, and then began a return toward the north (see Fig. 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 (Fig. 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 60S. In the 25–45 km layer horizontal temperature gradients are relatively weak over low and middle latitudes. Poleward of 40S, however, there is a significant decrease in temperature consistent with the pronounced vertical increase in the magnitude of the 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 and 35S 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 65S and 27S near 110W (Borovikov *et al.*, 1963). A section analogous to Fig. 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.

5. Comparison of Northern and Southern Hemisphere circulation

Available information (Viebrock, 1966; Free University of Berlin, 1958–1966; ESSA, 1966a) indicates 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 in first evident in the subpolar region and at the lower boundary of the layer, and progresses rapidly upward. High-level observations, primarily from the North American Meteorological Rocket Network (MRNC, 1965–1966), 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 (Finger *et al.*, 1966; ESSA, 1966b). These analyses 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 Fig. 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 evident from the analyses 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 25–30N 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

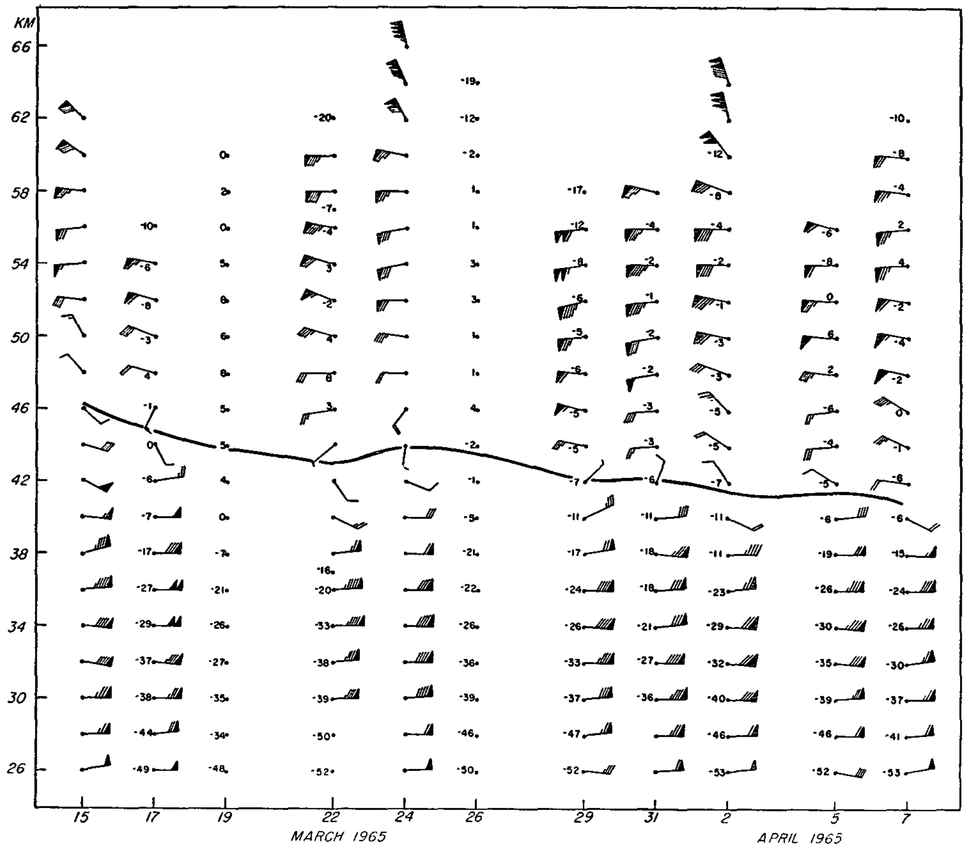

Fig. 4. Time-height section of rocketsonde winds (kt) and temperatures (°C) for Ascension Island 7°55′S, 14°25′W (wind data doubtful above 58 km).

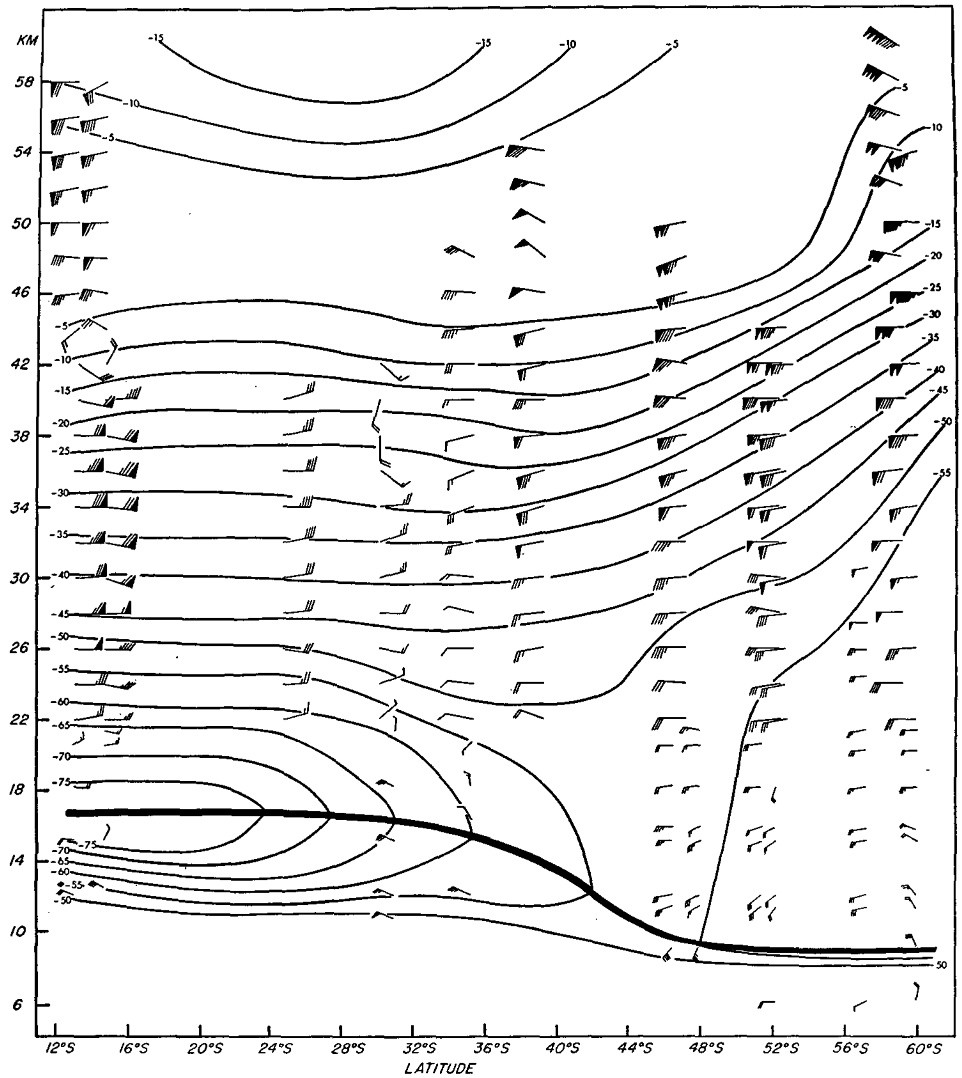

FIG. 5. Space-time cross section of wind and temperature from 12S to 60S along 78W. Rocketsonde and support rawinsonde winds as in Fig. 3; isotherms at 5C intervals.

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 (Figs. 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 30S at both the 5- and 2-mb levels, in agreement with the more complete North American analyses for the comparable season (Fig. 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 10S. 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 (Wexler, 1959; Rubin and Weyant, 1965).

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 (1964) has speculated that at the 50-km level, the 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 (Fig. 2a) and south (Fig. 2b) of the equator in early March. At that time easterly components were present within the 22–46 km layers at both locations. This information, coupled with the other presentations, tends to verify the interhemisphere 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.

6. 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 cyclogenesis 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

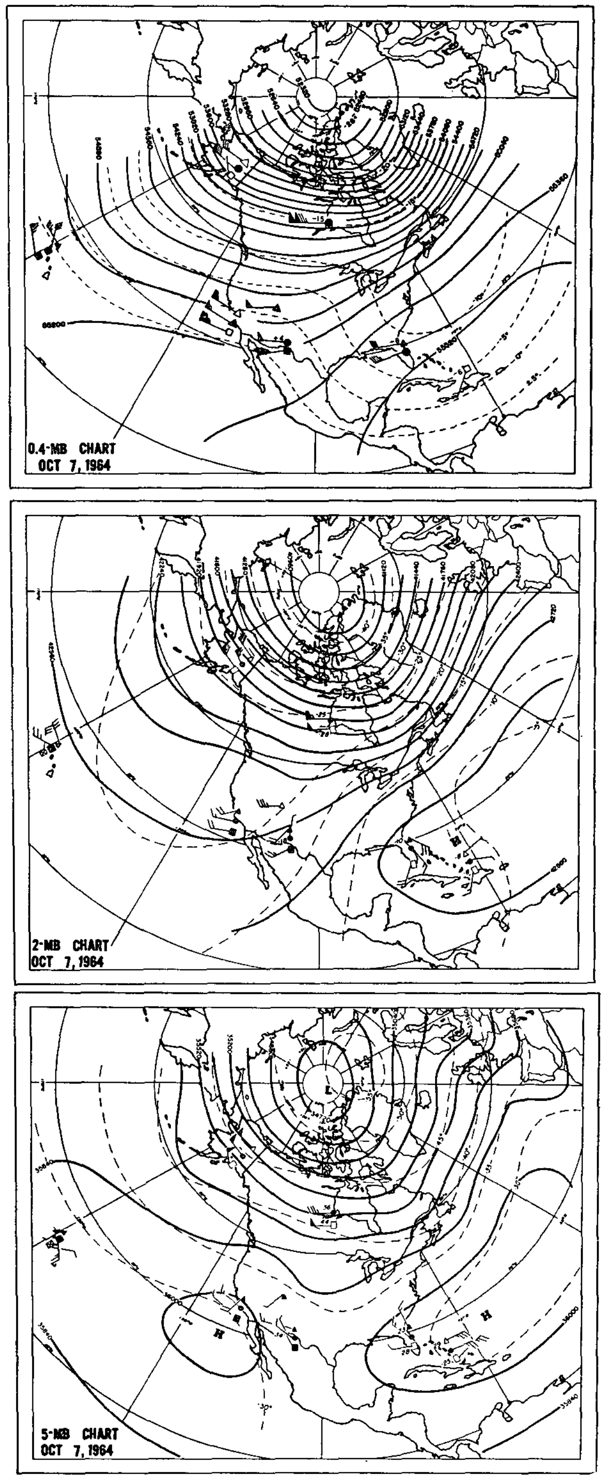

FIG. 6. 0.4-mb, 2-mb, and 5-mb charts for 7 October 1964. Contours (solid lines) at 160-m intervals; isotherms (dashed lines) at 5C intervals. Observed rocketsonde winds (kt) and temperatures (°C) are for map day (●), one day previous (▲), one day subsequent (■), two days previous (△), two days subsequent (□), and three days subsequent (⊠) [from ESSA (1966b)].

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 interhemisphere 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, (30S, 67W) and Natal, Brazil (6S, 35W). Regular soundings at these and other stations will soon permit construction of more complete synoptic representations of high-level circulation throughout the year.

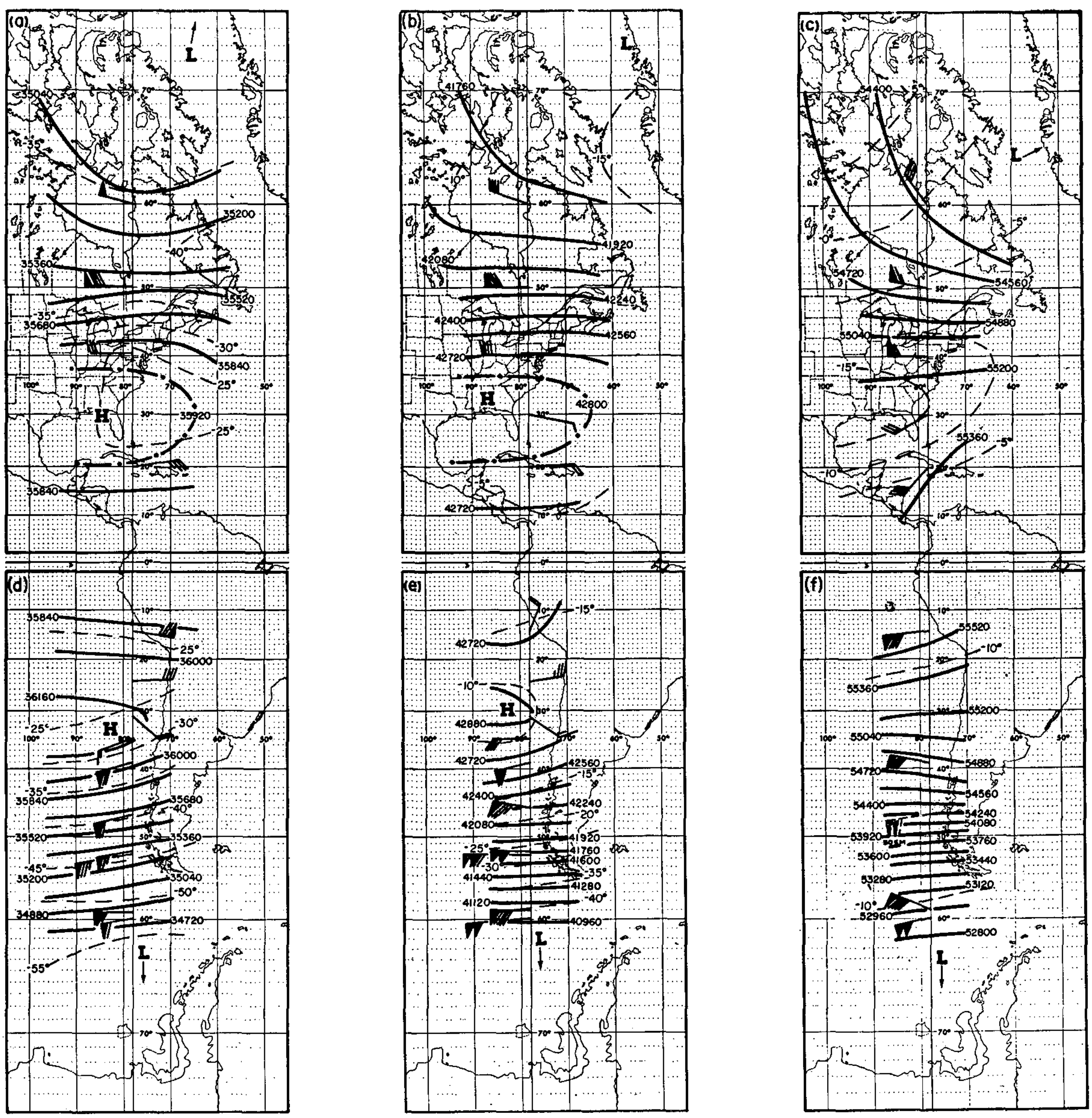

FIG. 7. (a) 5-mb, (b) 2-mb, (c) 0.4-mb analyses (Northern Hemisphere) centered on 78W for 7 April 1965, with interpolated geostrophic winds [after ESSA (1966b)]; (d) 5-mb, (e) 2-mb, (f) 0.4-mb analyses (Southern Hemisphere) centered on 78W for 9 April 1965 based on *Croatan* data. Rocketsonde winds in knots; contours and isotherms as in Fig. 6.

Acknowledgments. The research reported in this article was sponsored primarily by the Office of Space Science and Applications, National Aeronautics and Space Administration. We wish to acknowledge Mr. Harold Tolefson, NASA Langley Research Center, for supplying the *Croatan* data. Other segments of the research are supported by the U. S. Materiel Command, the Naval Air Systems Command, and the National Science Foundation. The authors are grateful for the assistance of Messrs. Calvin Anderson, Melvyn Gelman and Leo Hortch in the analysis phase of the work.

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