Air Motions in the Tropical Stratosphere Deduced from Satellite Tracking of Horizontally Floating Balloons

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ABSTRACT

Between June and November of 1970, 26 GHOST-type constant-level balloons were released from Ascension Island (8S) for flight at 30 and 50 mb. The balloons were positioned by the Interrogation, Recording and Location System (IRLS) aboard the Nimbus D satellite. Eight of the flights at 50 mb and three of the flights at 30 mb were tracked for more than one month, and one 50-mb flight was tracked continuously for more than five months while making seven circumnavigations of the earth. During the period June 1970 to March 1971, the 50-mb flights drifted northward at a mean speed of ~0.1 m sec^{-1}. The northward drift was a maximum in the Northern Hemisphere winter, suggesting a weak upward extension of the Hadley cell to at least 50 mb (the 30-mb data were insufficient for such an analysis). Superimposed on this drift were oscillations in meridional velocity having an approximate two-month period, with these oscillations also being most pronounced in the Northern Hemisphere winter. Small (1–3 m sec^{-1}) short-period fluctuations in meridional velocity were evident directly above the equator at 50 mb. These waves appear to move ***westward*** at speeds of 30–40 m sec^{-1} and to have a wavelength of about 90° longitude. They were responsible for transporting small amounts of westerly momentum into the winter hemisphere. Kelvin waves were also delineated by flights near the equator. These waves appear to move ***eastward*** at speeds of 30–40 m sec^{-1} and to have a wavelength of 360° longitude. Some comparisons are made between these IRLS data and those obtained from GHOST balloon flights at the same heights in early 1969.

1. Introduction

Between June and November 1970, 26 GHOST-type constant-volume balloons were launched from Ascension Island (8S) for flight at 30 and 50 mb (or at heights of ~20 and 24 km). These balloons were positioned at ~12-hr intervals by the Nimbus D satellite using the Interrogation, Recording and Location System (IRLS). Pertinent statistics concerning the flights are provided in Table 1. Note that the flight numbers are not ordered according to date of release. Ambient air temperatures were obtained on occasion, but they were of dubious quality and will not be reported on in this paper. The details of the IRLS system have been discussed by Cote (1970), and it suffices here to state that balloon positioning was accomplished by ranging at least twice on the balloon during a given pass of the satellite. Since two positions, one on either side of the satellite subtrack, result from the intersections of two or more range loci with the surface of the earth, there may be doubt as to which is the true balloon position, particularly if the position estimates are not available at frequent intervals. This ambiguity may possibly have contaminated the results presented herein in the sense that one naturally accepts the "reasonable" or climatological solution in comparison with the unusual solution. Thus, actually existing small-scale cyclonic or anticyclonic circulations may have been glossed over in the analysis. It would be most desirable to avoid such position ambiguity in the future.

These constant-level balloons also carried the "sun-seeker" instrument developed by the National Center for Atmospheric Research (NCAR), which permits the estimation of balloon latitude and longitude from the sun's elevation angle at given local times (Lally *et al.*, 1966). These alternate positions were only recently made available to the writer, and they will not be considered in this paper, although on occasion they could probably have helped resolve the above-mentioned ambiguity in IRLS balloon positioning.

2. Procedures

In general, balloon positions were obtained at ~12-hr intervals. Occasionally, however, positions were not obtained for 1 or 2 days. Because of these data gaps, it was deemed necessary to use as a data base only once-a-day positions. In order to ensure that each 12-hr position was considered equally, a 1-2-1 smoothing of the 12-hr positions was applied to each 24-hr position to be used. Accordingly, our data is slightly smoothed latitude and longitude positions at approximately 24-hr intervals (to be precise, usually at ~25-hr intervals), together with the approximately 24-hr average zonal and meridional velocities derived therefrom.

The constant-level balloons provide velocity informa-

Table 1. IRLS flights in the tropical stratosphere during 1970–71.

Flight number	Launch date	Float surface (mb)	IRLS tracking duration (days)	Cause of termination
26	5/27	30	3	BIP* failure
23	6/1	50	29	Balloon failure
24	6/8	30	0	Balloon failure at launch
7	6/11	30	105	Balloon failure
11	6/22	50	134	Balloon failure
3	6/23	30	70	BIP failure
2	6/24	50	123	Balloon failure
12	6/29	50	63	BIP failure
20	6/30	30	47	Balloon failure
21	7/1	50	0	BIP failure at launch
6	7/3	50	23	Balloon failure
10	7/6	50	120	Balloon failure
5	7/8	50	129	Balloon failure
17	10/20	50	7	BIP failure
15	10/21	50	19	Balloon failure
8	10/22	50	155	Balloon failure
28	10/23	30	2	Balloon failure
16	10/24	50	54	BIP failure
4	10/29	50	0	BIP failure at launch
29	10/30	50	96	Cut down
30	10/31	50	2	BIP failure
14	11/1	50	0	Balloon failure at launch
1	11/2	50	13	BIP failure
13	11/9	30	5	Balloon failure
9	11/20	30	11	BIP failure
25	11/12	30	24	BIP failure

* BIP: Balloon instrument package.

tion as a function of time, latitude and longitude. It would, of course, be most desirable to indicate the velocity variability in a three-dimensional diagram, with time, latitude and longitude as the coordinate axes. However, the writer has been unable to come up with a satisfactory method of doing so, and in this paper the velocity variability is related to only two of the above parameters at a time.

3. Balloon trajectories

Fig. 1 presents the trajectories of the six longest 50-mb flights. In order clearly to delineate the meridional motions, the latitude scale is exaggerated 10 times relative to the longitude scale. The balloons are moving from east to west, or from right to left in the figure, and the longitude scale is repeated along the abscissa for successive circumnavigations of the earth. The dots indicate daily positions, and isochrones connect the positions of flight pairs at the same time.

The top diagram of Fig. 1 shows the trajectories of two 50-mb flights which moved close to the equator after being launched two days apart in July 1970. Slightly asymmetric wave-like oscillations are noted along both trajectories, especially when the balloons are very close to the equator. The unfortunate data gap in early October resulted from an antenna failure at Fairbanks, Alaska.

The middle diagram of Fig. 1 presents the trajectories of two 50-mb balloons, launched two days apart in June, which remained close to their launch latitude of 8S. Regular wave-like oscillations are not evident on these flights a short distance from the equator. Flight 2 became nearly stationary as it approached 20S near the end of August, illustrating the latitudinal extent of the easterlies at this time.

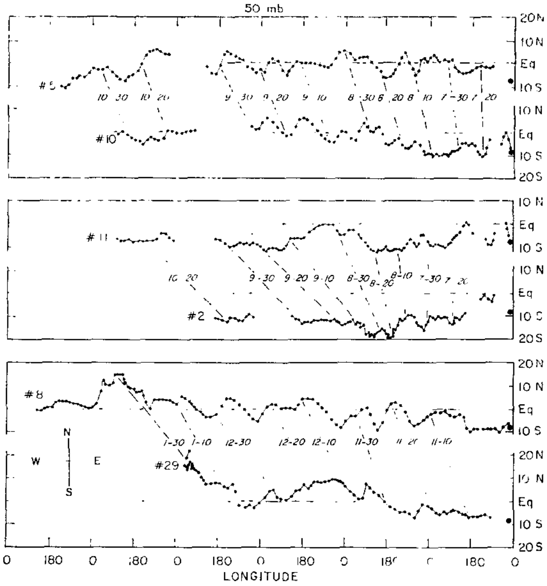

Fig. 1. Trajectories of the six longest 50-mb constant-level balloon (IRLS) flights in the easterlies in 1970–71. Balloon positions are indicated by dots at approximately 1-day intervals, with isochrones (dashed lines) connecting positions for the same month and day. Flight numbers are indicated at left. Note that the longitude scale is repeated along the abscissa for successive circumnavigations of the earth and that the latitude scale is exaggerated 10 times relative to the longitude scale.

The bottom diagram of Fig. 1 shows the trajectories of two 50-mb flights, launched one week apart in October, which also moved close to the equator. Flight 8 exhibits more uniform wave-like oscillations than does flight 29. Toward the end of January, flight 29 moved north of 20N over East Africa and was purposely cut down after entering the temperature latitude wester-

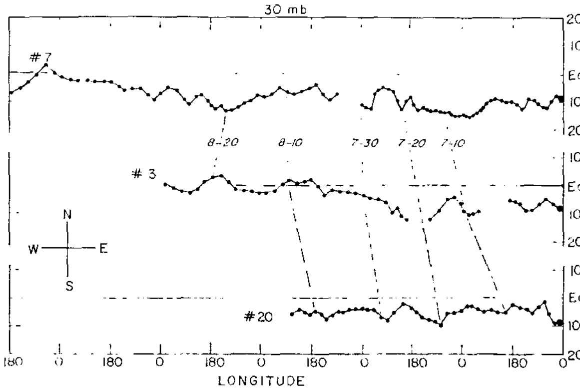

Fig. 2. Trajectories of the three longest 30-mb constant-level balloon flights in the easterlies in 1970. Otherwise, see legend for Fig. 1.

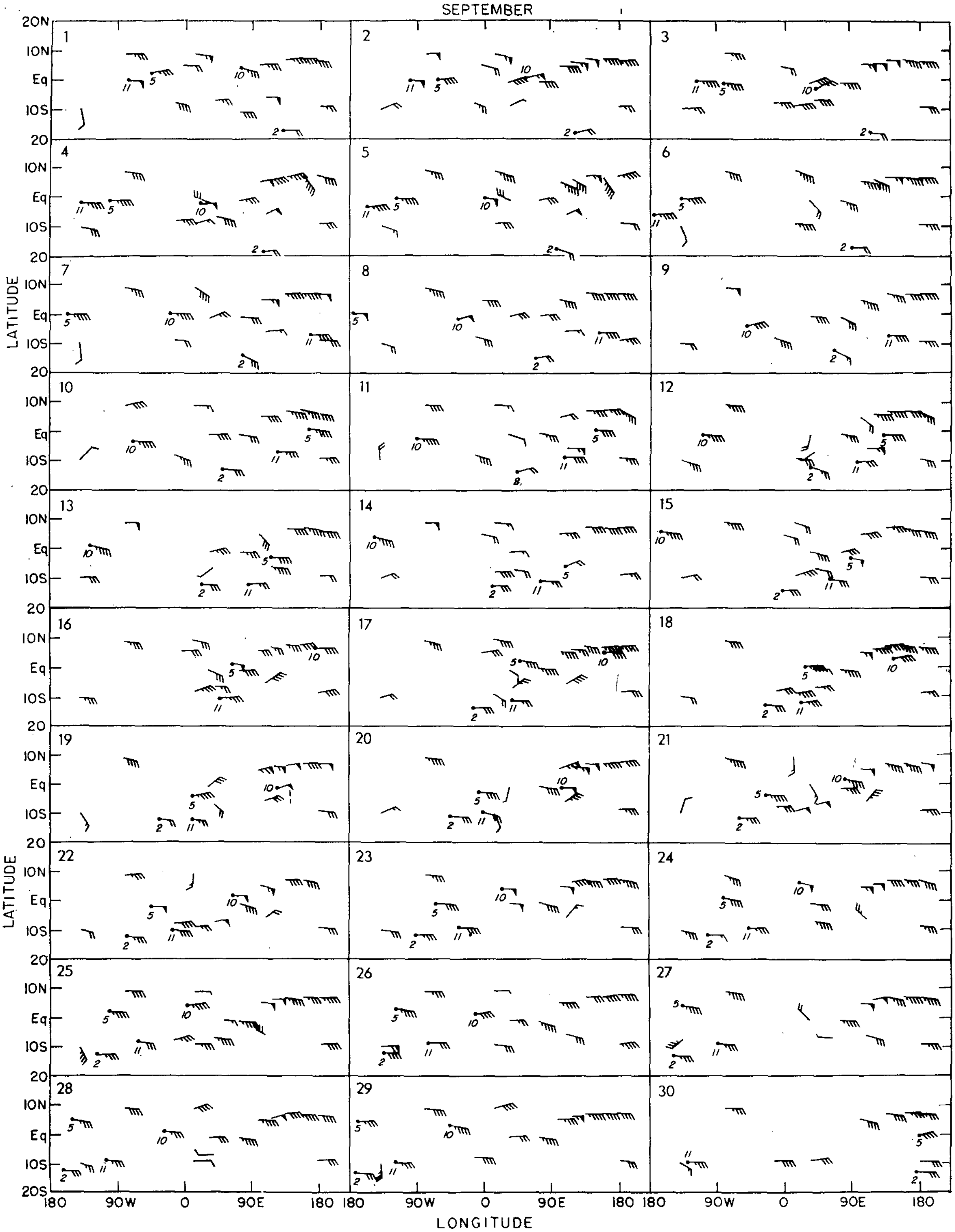

FIG. 3. Comparison of 24-hr average constant-level balloon winds at 50 mb with conventional 50-mb winds obtained from rawinsondes between 1 and 30 September 1970 (dates at upper left in boxes). The constant-level balloon winds are distinguished by dots at the front of the barbs and by the flight numbers beneath. One full barb equals 10 kt, a half barb 5 kt, and a solid triangle 50 kt. Northern Hemisphere barbs have been used in all cases.

lies. At the same time, but farther to the east, flight 8 approached the westerlies, but subsequently moved rapidly south and remained just north of the equator for the remainder of the tracking period.

Fig. 2 shows the trajectories of the three longest 30-mb flights. Regular wave-like oscillations are not at all obvious on these flights, occurring a few degrees south of the equator.

To show the reader how these constant-level balloon (CLB) data collate with conventional wind data, Fig. 3 presents 50-mb winds obtained from both sources during September 1970. The rawinsonde data plotted are those obtained for purposes of real-time tropical analysis at the National Meteorological Center, Suitland, Md. In a few cases, the rawinsonde wind directions seem to be in error by 180° but, in general, the 24-hr average CLB winds are in good agreement with the rawinsonde winds. It would appear from Fig. 3 that, due to the absence of large-amplitude waves, a 24-hr average wind obtained from a CLB in the tropical stratosphere is not nearly so likely to be in serious error as a similar averaged wind in the temperate troposphere.

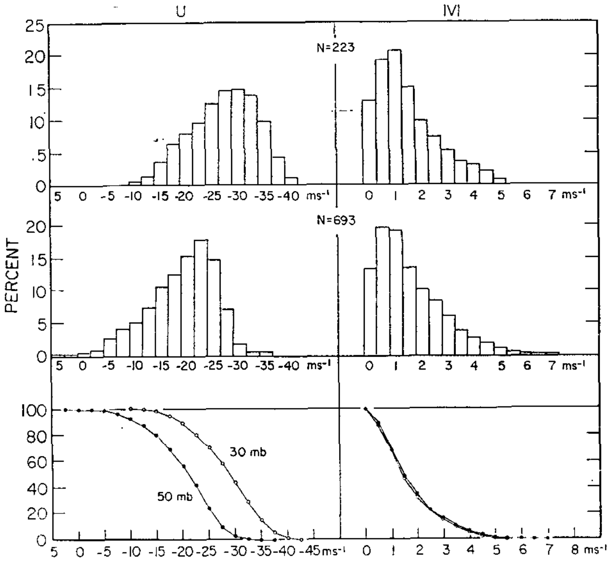

Fig. 4. Histograms and cumulative frequency curves showing the distribution of 24-hr average zonal velocity and absolute magnitude of the meridional velocity at 30 mb (top) and 50 mb (middle) derived from all IRLS flights. The total number N of velocities obtained at each surface is also shown.

4. Velocity statistics

Fig. 4 presents histograms and cumulative frequency curves for the 24-hr average zonal velocity and the absolute magnitude of the 24-hr average meridional velocity at 30 and 50 mb. The easterlies at 30 mb were nearly 10 m sec^{-1} stronger than the easterlies at 50 mb, partly as a result of the phase of the quasi-biennial oscillation. However, the absolute magnitude of the meridional velocity was almost identical at the two levels. Note that the 24-hr average meridional velocity exceeds 3 m sec^{-1} only about 10% of the time, so that the meridional velocities in the low equatorial stratosphere are very small; indeed, they are so small that they could hardly be discerned above the "noise" inherent in rawinsonde-derived winds at these heights. Thus, a meridional velocity of 3 m sec^{-1} and a zonal velocity of 30 m sec^{-1} yields a wind direction deviation from pure zonal flow of only 6°, and since rawinsonde winds are usually coded to the nearest 10°, the difficulty in detecting such meridional motions from conventional data is obvious. It is likely that the wave-like oscillations delineated by the constant-level balloons in Fig. 1 represent atmospheric structures never before observed and studied.

Fig. 5 shows the variation of CLB-derived zonal wind with date and latitude, as well as traces depicting the variation with date and latitude separately. At 50 mb, the maximum easterlies occurred near the end of November, whereas at 30 mb they occurred near the end of September. This is the correct phase relationship for the quasi-biennial oscillation, and analysis of rawinsonde data confirms that we are seeing here the maximum easterlies associated with this oscillation. At 50 mb, the maximum easterlies appear to occur directly above the equator; at 30 mb the CLB data are insufficient to be certain. The anticyclonic shear vorticity associated with the mean decrease in east winds with distance from the equator in Fig. 5 is only one-third the vorticity of the earth about the local vertical at these latitudes, so that inertial instability is not approached on the average.

Fig. 6 shows the absolute magnitude of the CLB-derived meridional velocity as a function of date and longitude. Near the equator, the meridional velocity is relatively large at intervals slightly greater than one month, suggesting periodic fluctuations in the amplitudes of the wave-like oscillations in the equatorial stratosphere. Overall, the absolute meridional velocity appears to decrease in magnitude from June to October or November, resulting in a minimum in meridional velocity, and hence a minimum in wave motion, when the easterlies are maximum (compare with Fig. 5). At least at 50 mb, the meridional velocity appears to be a maximum directly above the equator.

Based on all the flights at 30 and 50 mb, Fig. 7 shows the variation with date of the mean meridional velocity taking into account the sign of the meridional velocity. Some caution is required when estimating mean meridional velocities from a few CLB flights circumnavigating the earth. To take an extreme example, if the balloons were always spaced at the wavelength of waves moving with the wind, the derived mean meridional velocity would be meaningless. This eventuality, or anything approaching it, is very unlikely, however, and because a trajectory represents an integration of

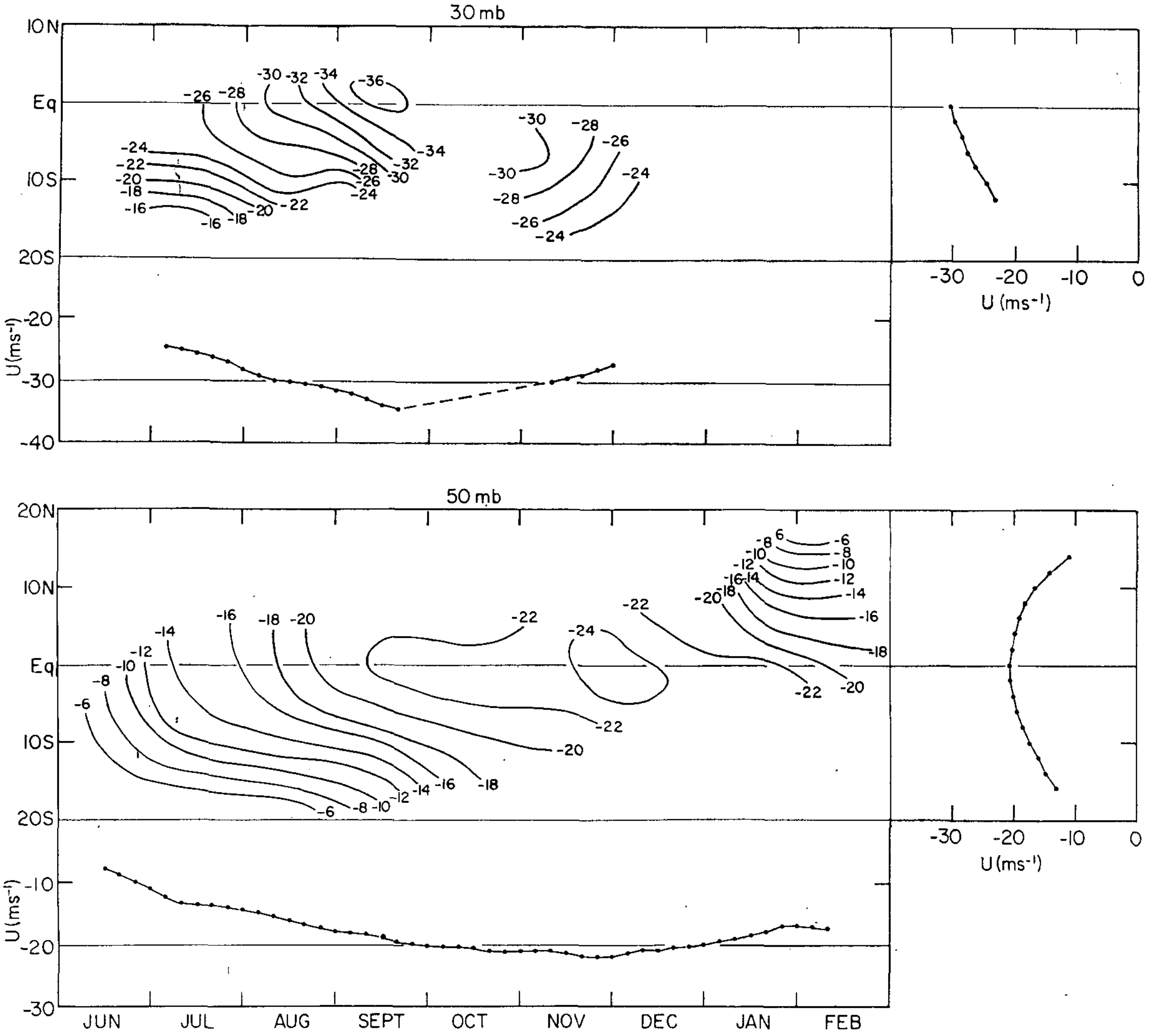

FIG. 5. IRLS-derived variation of zonal velocity (m sec^{-1}) with date and latitude at 30 and 50 mb. The average variation of zonal velocity with date is indicated at the bottom, the average variation with latitude at the right. Negative velocities signify east winds.

the velocity at every point along the trajectory it is probable that these few flights give a better estimate of the mean meridional flow than do long data records from scattered rawinsonde stations.

The solid line in Fig. 7 is based on 9-day running means of the CLB-derived meridional velocity, the dotted line on 81-day running means. The dotted line shows that from July through February there was a mean northward drift of about 0.1 m sec^{-1} at 50 mb, with the drift a maximum (0.2 m sec^{-1}) in December. The maximum northward drift in the Northern Hemisphere winter suggests that the Hadley cell may extend, in weakened form, to the 50-mb level, since it has been shown by Newell *et al.* (1969) and Oort and Rasmusson (1970) that the Hadley cell of the winter hemisphere tends to straddle the equator, producing flow toward the winter pole in the upper troposphere above the equator. An extension of the Hadley cell into the lower stratosphere has also been deduced recently by Telegadas (1971) based on the transport of nuclear debris.

Superimposed on this northward drift are meridional velocity fluctuations with a period of about two months. These two-month periodicities almost disappear during the Northern Hemisphere summer and appear to build to a maximum during the Northern Hemisphere winter. Such alternations in meridional velocity imply the existence of an interhemisphere seiche phenomenon which may be associated with the satellite-derived stratospheric temperature changes observed by Fritz and Soules (1970). The dashed traces in Fig. 7 represent results obtained from seven GHOST balloon flights launched from Ascension Island by NCAR in 1969. These flights were positioned by the "sunseeker"

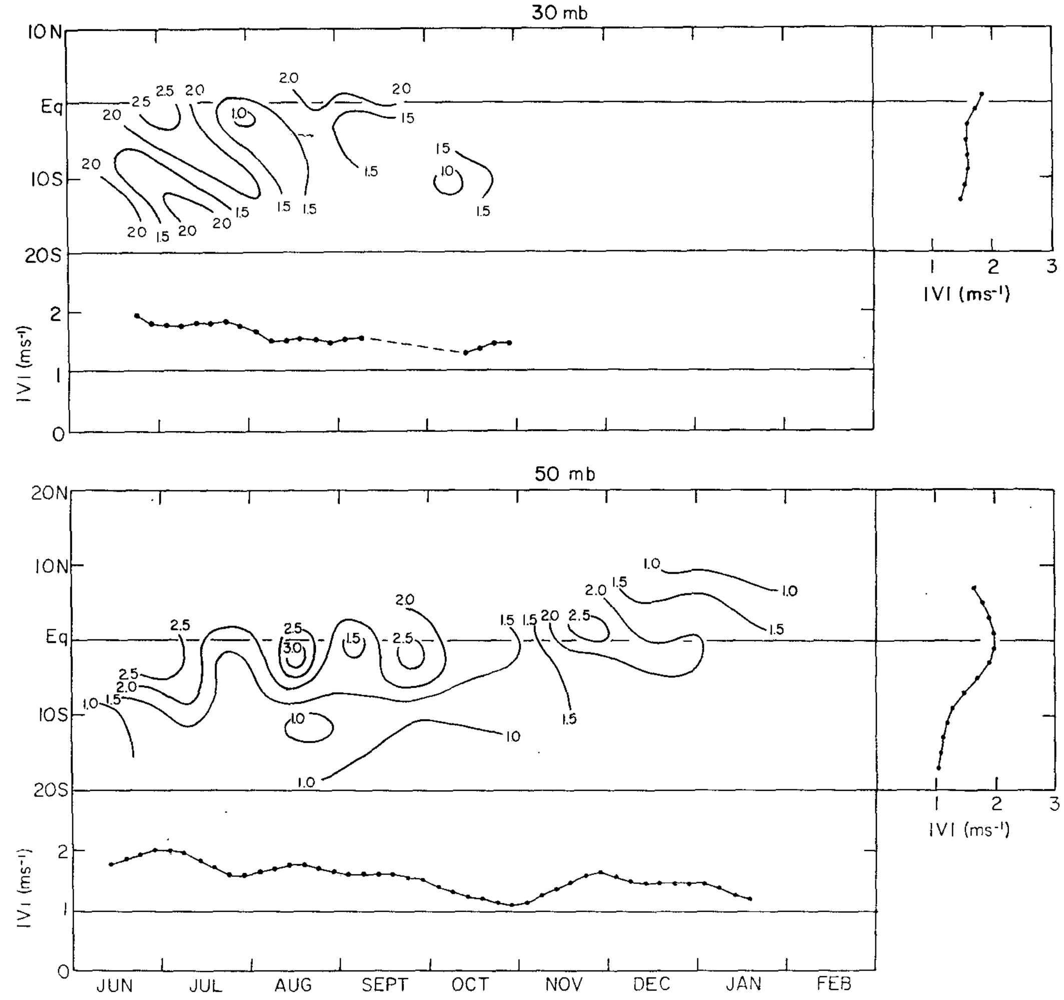

Fig. 6. Same as Fig. 5 except for the absolute magnitude of the meridional velocity.

rather than by satellite, and while the positioning is not as accurate as satellite positioning, it is presumably sufficient for gross estimates of the meridional velocity. The variation in meridional velocity derived from the four 1969 flights at 50 mb is similar to that obtained in 1971, but with a 10-day phase lag. Thus, there is the suggestion that the nearly two-month periodicity in meridional velocity is of frequent occurrence.

The top diagram of Fig. 7 shows the results obtained at 30 mb. The flight durations at this surface were too short to provide a clear picture of the temporal variation of meridional velocity, although there also appears to be a mean northward drift during the Northern Hemisphere Summer of 1970. The maximum northward or southward velocity does not occur at the same time at 30 and 50 mb during the Northern Hemisphere summer, but appears to do so during the Northern Hemisphere winter based on the GHOST flights.

The question arises as to whether the mean northward drift from July through February at 50 mb reflects mainly an annual or quasi-biennial variation, or merely indicates that a northward drift always occurs at this surface. With the given duration of the CLB flights, it is impossible to be sure. If we are seeing an annual variation in mean meridional velocity, it is an asymmetric one, since the northward flow appears to exist for at least eight months. Note that the 50-mb east wind maximum associated with the quasi-biennial oscillation occurred in November 1968, and, as we have seen, occurred again in November 1970. Thus, the balloon flights between January and April of 1969 are in the same phase relationship to the quasi-biennial oscillation as the flights between January and April of 1971, and this unfortunate coincidence prevents us from easily delineating any influence of the quasi-biennial oscillation on CLB-derived parameters.

Fig. 8 shows the longitudinal variation of the meridional (solid line) and zonal (dashed line) velocity at 50 mb obtained by averaging the nearly 10 months of CLB-derived velocities at this surface. The data obtained at 30 mb were believed insufficient for repre-

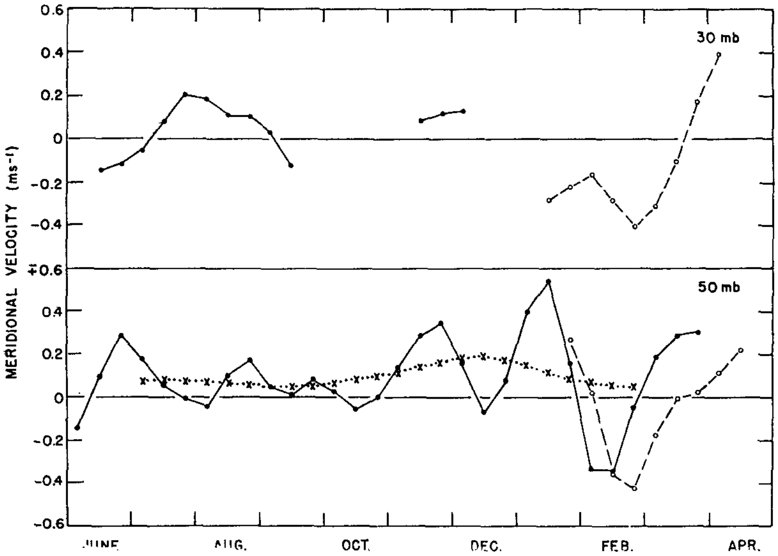

FIG. 7. Mean time variation of 9-day running-average meridional velocity (m sec^{-1}) at 30 (top) and 50 mb (bottom) as determined from all IRLS flights (solid lines) and from GHOST balloon flights in 1969 (dashed lines). The dotted line represents an 81-day running-average meridional velocity based on the IRLS data. A positive meridional velocity signifies flow toward the north.

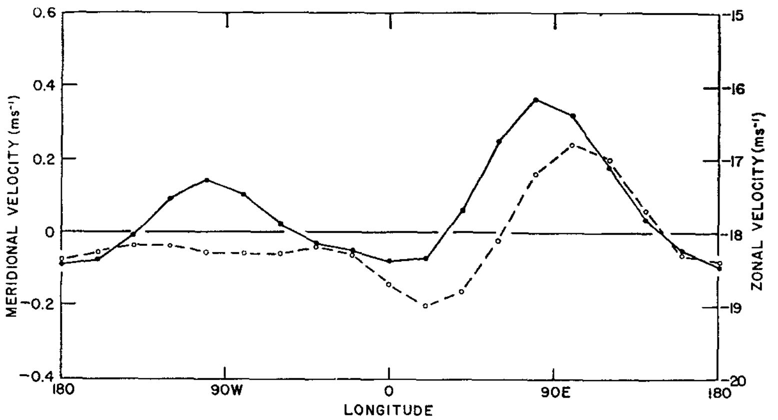

FIG. 8. Mean variation with longitude of the meridional (solid line) and zonal (dashed line) velocity determined from all 50-mb IRLS flights between June 1970 and March 1971. A positive meridional velocity signifies flow toward the north.

sentative results and are not presented here. At 50 mb there is a standing two-wave pattern in meridional velocity with the maximum northward flow of 0.4 m sec^{-1} at the longitude of India and a secondary northward maximum of 0.2 m sec^{-1} off the west coast of South America. It is interesting that the maximum northward flow at 50 mb occurs at the longitude where the surface monsoonal effect is a maximum. The strength of the east wind is a minimum south of India and a maximum over West Africa. There is a correlation between east wind minima and northward flow of 0.68, so that in the mean these standing waves transported westerly momentum into the Northern Hemisphere during this period.

5. Fluctuations in zonal wind

The delineation of zonal wind fluctuations by constant-level balloons is complicated in the equatorial stratosphere by the considerable variation of zonal wind with latitude (Fig. 5). Thus, a CLB undergoing periodic variations in latitude will exhibit periodic variations in zonal wind which may mask any of the real fluctuations noted at a fixed point. In order to minimize this wind-shear problem, we shall examine CLB trajectories only near the equator where the wind shear is small. We therefore consider the zonal winds along 50 mb from flights 5 and 10 in September and flights 8 and 29 in December (Fig. 1), and the zonal winds along 30 mb from flights 3 and 29 in July–August (Fig. 2).

The left-hand diagram of Fig. 9 shows the correlation coefficient of the 50-mb zonal wind as a function of lag time (autocorrelation coefficient) determined from the two September and the two December flights. In the figure these correlations are denoted by the letter L for Lagrangian. In both months the Lagrangian autocorrelation goes to zero at a time lag of 2¾ days, implying a Lagrangian zonal wind periodicity of about 11 days since the autocorrelation should first fall to zero at a time lag nearly equal to one-fourth the period of fluctuation. In comparison, the mean Eulerian (E) or fixed point periodicity in zonal wind in September is about 16 days based on the average of the Caroline Island rawinsonde stations of Koror (7N, 134E), Ponape (7N, 158E) and Majuro (7N, 171E), the only equatorial stations where 50-mb winds were consistently reported on a daily basis. This 16-day periodicity is in good agreement with the nearly 15-day zonal wind periodicity found in the equatorial stratosphere by Wallace and Kousky (1968), and hypothesized by them to reflect the movement of Kelvin waves (waves with no associated fluctuations in meridional velocity) past the fixed rawinsonde stations.

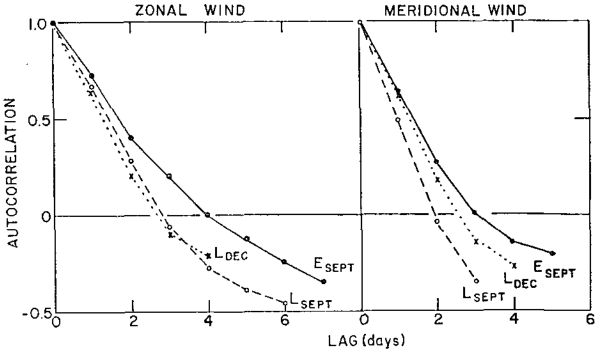

Fig. 9. Lagrangian (L) autocorrelation coefficients of 50-mb zonal and meridional winds based on near-equator flights 5 and 10 in September and flights 8 and 29 in December 1970. The Eulerian (E) autocorrelation of the zonal and meridional winds was determined in September from the tropical stations of Koror, Ponape and Majuro.

Let us see what the pairs of CLB flights simultaneously aloft in September, December, and July–August can tell us about the wavelength and propagation speed of such zonal wind fluctuations. September flights 5 and 10 are particularly useful for this purpose because during the entire month flight 5 led (was to the west of) flight 10 by between 110° and 120° longitude, with an average separation distance of 114° longitude (Fig. 3). The solid line in the upper left diagram of Fig. 10 shows that the time-lagged correlation between the zonal winds along these two flights is a maximum (0.30) at a positive lag of 2¾ days, where the positive lag signifies that a zonal wind fluctuation was noted first by flight 5 and then by flight 10. This raises various possibilities depending on the wavenumber and propagation speed of the zonal wind fluctuations which, *a priori*, we do not know. Assuming a zonal wind fluctuation pattern invariant in wavenumber and speed of propagation during the month, and considering only wavenumbers 1–6 as possibilities, it is seen from Fig. 10 that wavenumbers 2 and 5 are improbable because the zero-lag correlation would then be strongly negative (recall the 114° longitude balloon separation), which it is not, while wavenumbers 3 and 6 are improbable because the zero-lag correlation would then be nearly maximum positive, which it is not.

Wavenumber 1 is a possibility (in which case the small positive correlation at zero phase lag must be considered due to simultaneous increases and decreases in zonal wind right around the hemisphere, which varia-

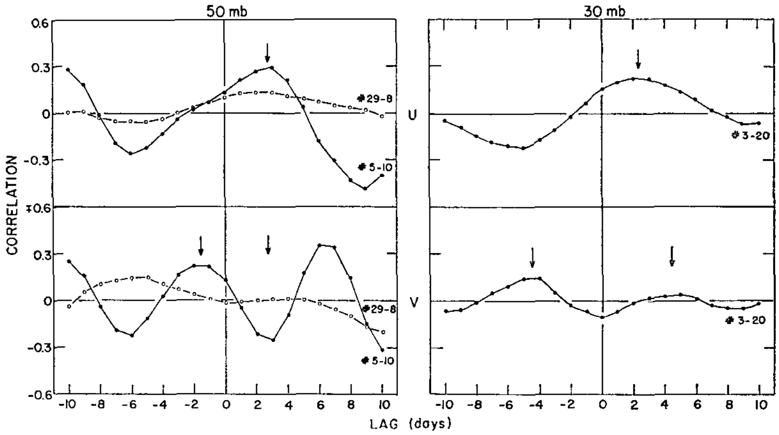

Fig. 10. Correlation coefficients between zonal (top) and meridional winds (bottom) at given temporal lags for pairs of IRLS flights aloft at the same time. The correlations are determined for near-equator 50-mb flights 5 and 10 in September and 8 and 29 in December, and 30-mb flights 3 and 20 in July–August. A correlation maximum at a positive lag signifies that the wave oscillation was noted first at the westernmost of the two flights. The arrows denote correlation maxima and minima.

tion would be independent of the fluctuation under discussion), and, since the zonal wind fluctuation occurred first at the westernmost balloon, the fluctuation and balloons must be approaching each other at the rate of 114° longitude in $2\frac{3}{4}$ days, i.e. at 53 m sec^{-1}. Since the mean east wind during this period was 23 m sec^{-1}, there is the implication of a zonal wind fluctuation moving *eastward* at a speed of 30 m sec^{-1}. Wavenumber 1 moving at such a speed would result in a Eulerian periodicity of 16 days (the same as that observed) and a Lagrangian periodicity of 9 days, in reasonable agreement with the observed value of 11 days (Fig. 9).

Wavenumber 4 is also a possibility (in which case the small positive correlation at zero phase lag again must be considered due to simultaneous increases and decreases in zonal velocity right around the hemisphere), and, since the zonal wind fluctuation occurred first at the westernmost balloon, the fluctuation must be moving *westward* more slowly than the balloons. Inasmuch as in this case the balloons must move westward through the fluctuation at a rate of 24° longitude in $2\frac{3}{4}$ days (11 m sec^{-1}), a westward fluctuation speed of 12 m sec^{-1} (23 m sec^{-1} minus 11 m sec^{-1}) is obtained. Wavenumber 4 moving westward at such a speed would result in an Eulerian periodicity of 10 days (in rather poor agreement with the observed value of 16 days) and a Lagrangian periodicity of 10 days, in good agreement with the observed value of 11 days. Because of the poor agreement between computed and observed Eulerian periodicity in this case, wavenumber 1 moving eastward at a speed of ~30 m sec^{-1} appears more likely to be the correct solution; this will be confirmed in a moment.

First of all, however, it is of interest to note in passing that if one has complete faith in the derived Lagrangian (T_{L}) and Eulerian (T_{E}) periods of fluctuation, then the above two alternatives for fluctuation velocity can be obtained directly from the well-known expression relating the two periods of fluctuation, i.e.,

$$\pm T_{\mathrm{E}}/T_{\mathrm{L}}=(U-C)/C, \tag{1}$$

where U is zonal wind speed and C the wave or fluctuation speed. The plus or minus signs depend upon whether the wave moves eastward (T_{E} positive) or westward (T_{E} negative) relative to the earth and whether the balloons move eastward (T_{L} positive) or westward (T_{L} negative) relative to the wave. Obviously, there are always two alternative values for the wave speed with, in our case, the large eastward speed resulting from T_{E} positive (equal to 16 days) and T_{L} negative (equal to −11 days) and the slow westward speed from the assumption of T_{E} negative and T_{L} negative.

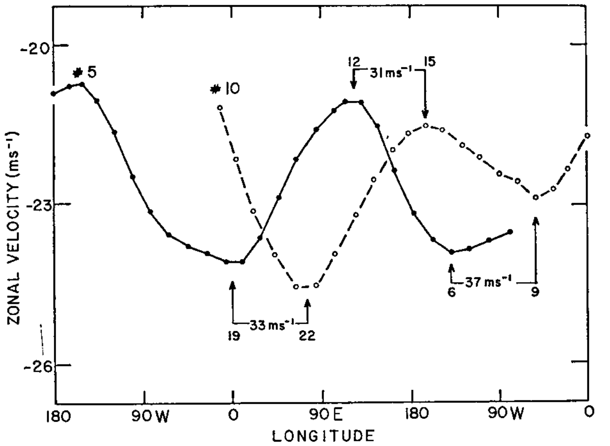

FIG. 11. Seven-day running-average zonal winds along 50-mb flights 5 and 10 in September 1970. The numbers at the base of the vertical arrows show the dates of east wind maxima or minima along the two flights. The values shown between the pairs of arrows are the inferred propagation speeds of the zonal wind maxima and minima.

In order to confirm that during the month of September 1970 there was a zonal wind fluctuation moving eastward at a speed of ~30 m sec^{-1}, we have recourse to the detailed zonal wind data along 50 mb from flights 5 and 10 during this month as well as to the 50-mb zonal winds obtained at the Caroline Island stations. Fig. 11 shows the smoothed zonal winds along flights 5 and 10 as a function of longitude and time. The smoothing involved the evaluation of 7-day running means, and was necessary to minimize zonal wind fluctuations occurring in response to latitude changes even along these near-equator flights. There appears to be little doubt that the east wind minimum which flight 5 passes through on September 12 at 120E is the same minimum which flight 10 passes through on September 15 at 170W, yielding an eastward fluctuation speed of 31 m sec^{-1}; furthermore, the east wind maximum which flight 5 passes through on September 19 at the Greenwich meridian is the same maximum which flight 10 passes through on September 22 at 80E, yielding an eastward fluctuation speed of about 33 m sec^{-1}. The indicated Lagrangian wavelength is slightly more than 180° longitude and the indicated zonal wind amplitude is about 2 m sec^{-1}. Because of the smoothing applied, the true amplitude of the zonal wind fluctuation would be at least 4 m sec^{-1}.

The left-hand diagram of Fig. 12 shows, for all possible pairings of the three Caroline Island stations (longitudinal separations of 13°, 24° and 37° longitude), the correlations between zonal winds forward and backward lagged at daily intervals up to 10 days in September. A correlation maximum at a positive lag signifies that a west or east wind maximum occurred first at the westernmost station and, hence, that the fluctuation is moving eastward. Despite the short period of record, the pairs of Caroline Island stations also provide convincing evidence that there exists a zonal wind fluctuation moving eastward at a speed slightly exceeding 30 m sec^{-1}, in agreement with the solution

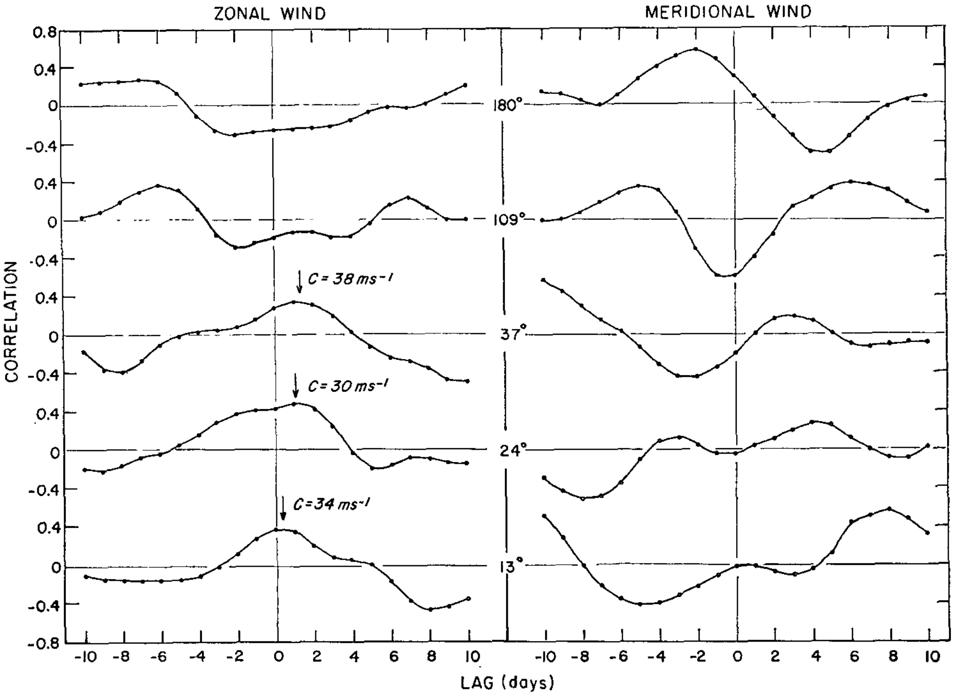

Fig. 12. Correlation coefficients, in September 1970, between rawinsonde-derived 50-mb zonal winds (left) and 50-mb meridional winds (right) at given temporal lags for tropical rawinsonde stations with the indicated longitudinal separation in degrees (center). A correlation maximum (vertical arrow) at a positive lag signifies an eastward wave velocity. Wave velocities derived from some correlation maxima are also indicated.

arrived at from the constant level balloons. Note that a phase speed of 30 m sec^{-1} is near the middle of the phase speed range of 12 to 58 m sec^{-1} specified by Kousky and Wallace (1971) for Kelvin waves, but is outside the range −12 to 15 m sec^{-1} specified by Lindzen (1971).

The rawinsonde stations at Balboa (9N, 80W) and Penang (5N, 100E) serve to provide an estimate of the Eulerian wavelength, although the data at Penang are of marginal quality. It is seen from Fig. 12 that at zero phase lag the zonal winds at Balboa and Penang (180° longitude apart) are out of phase as are the winds at Balboa and Majuro (109° longitude apart). Thus, the wavelength of the zonal wind fluctuation is unlikely to be 180°, 120°, 90° or 60° longitude. Wavenumber 5 (72° longitude wavelength) is an unlikely alternative because the two Caroline Island stations 37° longitude apart have a positive correlation at zero phase lag. Thus, the Eulerian data suggest an Eulerian wavelength of 360° longitude. We have just seen that the balloon (Lagrangian) data suggest a wavelength near 180° longitude. This is compatible because, with a wind fluctuation moving eastward at a speed slightly greater than the balloons move westward, the balloons would intersect the fluctuation twice in nearly the same time interval that the fluctuation passes a point on the ground once, with a corresponding 2:1 ratio in the wavelengths. This is seen analytically from the expression [similar to Eq. (1)] relating Eulerian (L_E) and Lagrangian (L_L) wavelengths:

$$L_E/L_L=(U-C)/U\approx 2.3. \tag{2}$$

Is there evidence for the existence of an eastward moving zonal wind fluctuation in other months and at other levels? The dashed line in the upper left-hand diagram of Fig. 10 shows that the correlation coefficient as a function of phase lag between 50-mb flights 8 and 29 in December is similar to that found for flights 5 and 10 in September, but much reduced in the value of the maximum correlation (0.13) at a phase lag of $2\frac{3}{4}$ days. This smaller correlation would be expected because the longitudinal separation of these two flights varied all the way from 180° to 90° longitude, with flight 29 leading (to the west of) flight 8 by an average of 134° longitude. This increase in the separation distance over the 114° longitude value found for flights 5 and 10 leads to an inferred eastward speed of ~40 m sec^{-1} for the zonal wind fluctuation in December. At 30 mb, flight 3 leads flight 20 by an average of 100° longitude in July–August. Thus, the correlation maximum (0.22) at a phase lag of $2\frac{1}{4}$ days (upper right diagram of Fig. 10) implies an eastward propagation speed of 29 m sec^{-1}, in good agreement with the September results at 50 mb.

The phase shift with height of the zonal wind fluctuations may be estimated for the period 30 July–15 September 1970, when 30- and 50-mb flights were aloft simultaneously. This has been done by constructing time-longitude diagrams and determining the longitude lag at which the correlation between 30- and 50-mb winds is a maximum. It was thus determined that, on a given date, the maximum east wind at 30 mb tended to occur about 60° of longitude to the east of the maximum east wind at 50 mb, yielding an eastward wave tilt with height with a slope of nearly 1:2000. An eastward wave tilt with height is in agreement with the Kelvin-wave model of Wallace and Kousky (their Fig. 7), but a slope of only 1:2000 seems too small.

6. Fluctuations in meridional wind

We have seen in Fig. 1 the evidence for small periodic fluctuations in meridional wind at 50 mb near the equator. The purpose of this section is to determine the wavenumber and propagation speed of these waves. The procedure will be the one used in the case of the zonal wind fluctuations, with an examination of the same flights for the same periods of time.

The lower left diagram of Fig. 10 shows that in the case of 50-mb flights 5 and 10 in September, the maximum correlation (0.21) between the meridional velocities along the two flights occurs at a negative phase lag of $1\frac{1}{2}$ days and the minimum correlation (−0.28) at a positive phase lag of $2\frac{1}{2}$ days. As in the case of the zonal wind fluctuation, wavenumbers 2 and 5 are improbable solutions because the zero-lag correlation would then be strongly negative, which it is not, and wavenumbers 3 and 6 are improbable because the zero-lag correlation would then be nearly maximum positive, which it is not.

Wavenumber 1 is a possible solution, in which case the small positive correlation at zero phase lag must be due to the same sense of meridional velocity right around the earth, which we know occurs because of the mean northward drift of the balloons. Since the meridional wind fluctuation occurred first at the easternmost balloon (positive correlation at a negative phase lag), the wave would be moving westward faster than the balloons are moving westward, overtaking the balloons at a rate of 114° longitude in $1\frac{1}{2}$ days based on the correlation maximum, and 66° longitude in $2\frac{1}{2}$ days based on the correlation minimum. The average of these two rates yields a westward wave speed of 87 m sec^{-1}, nearly four times the zonal wind speed. Such a wave speed would lead to an Eulerian periodicity in meridional wind of 5 days, in poor agreement with the 12 days observed, and a Lagrangian periodicity of 7 days, in good agreement with the 8 days observed (right-hand diagram of Fig. 9).

Wavenumber 4 is also a possible solution, in which case one would derive a westward wave speed of 38 m sec^{-1}, similar to the westward wave speed of about 30 m sec^{-1} inferred by the writer from the GHOST balloon flights in early 1969. Such a wave speed is also similar to the 30 m sec^{-1} westward speed of the tem

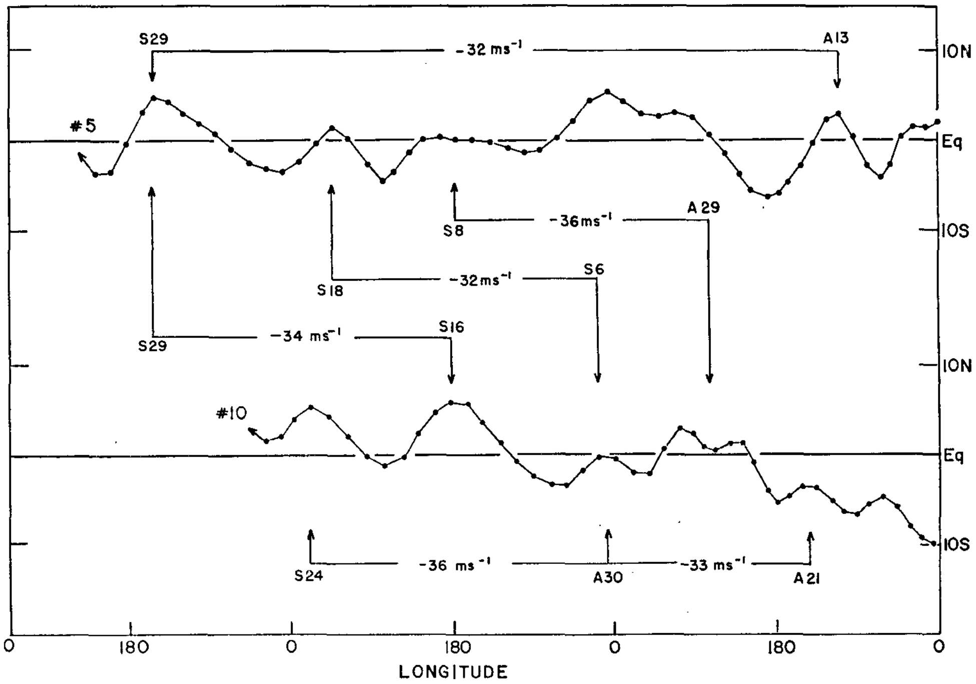

FIG. 13. Trajectory segments of 50-mb flights 5 and 10 showing the dates and longitudes of the wave crests delineated by the two flights, the presumed identification of the same wave, and the wave speed derived therefrom. Dates are indicated at the base of the arrows for both August (A) and September (S). Note that the latitude scale is exaggerated 10 times relative to the longitude scale.

perature (radiance) wave found by Fritz (1970) in the equatorial stratosphere in early May 1969. A 38 m sec^{-1} wave speed leads to an Eulerian periodicity of 3 days in meridional wind, in poor agreement with the 12 days observed, and a Lagrangian periodicity of 8 days, in exact agreement with that observed. Since in neither this case nor in that of wavenumber 1 do the calculated Eulerian periodicities in meridional wind come even close to that observed, there is at this stage no obvious choice between the two solutions, although, *a priori*, a wave moving westward as fast as 90 m sec^{-1} seems rather unlikely.

The right-hand diagram of Fig. 12 shows that, unlike the case for the zonal wind fluctuations, the rawinsonde data are of little help in determining wavenumber or wave speed of the meridional wind fluctuations. The Caroline Island station-pairs exhibit no correlation at zero phase lag, indicating that the waves delineated by the constant-level balloons are in the noise level of the rawinsonde data, as surmised earlier. This would also explain the poor comparison between calculated and observed Eulerian periodicities in meridional wind noted above.

As a consequence, in order to confirm the wavenumber and wave speed of the fluctuations in meridional wind, our only recourse is a detailed examination of the CLB data. Fig. 13 shows again, in slightly smoothed form, the wave-like oscillations along the 50-mb flights of 5 and 10 in August and September. The dates at which wave crests are delineated by the balloons are given by the numbers at the base of the vertically pointing arrows. These individual waves do not fit well with the concept of wavenumber 1 moving rapidly westward. For example, wavenumber 1 passing flight 10 on 16 September at 180° and flight 5 on 18 September at 40E would indicate a westward wave speed of 91 m sec^{-1}, whereas such a wave passing flight 10 on 24 September at 20E and flight 5 on 29 September at 160W would indicate a westward wave speed of 47 m sec^{-1}; there is thus a certain lack of consistency.

With the assumption of a wavenumber 4 regime, however, there is good consistency. The connected arrows in Fig. 13 indicate the waves which are presumed to be the same, together with the wave speed which would be derived with this assumption. That is, the wave which passes flight 10 on 6 September at 20W is believed to be the same wave which passes flight 5 on 18 September at 40E, yielding a westward wave speed of 32 m sec^{-1}, and the wave which passes flight 10 on 16 September at 180° is believed to be the same wave which passes flight 5 on 29 September at 160W, yielding a westward wave speed of 34 m sec^{-1}. The similarity in wave shape in both cases also tends to confirm that this is the correct pairing. Furthermore, substitution into Eq. (2) of the observed Lagrangian wavelength of $\sim$180° longitude, together with the observed zonal velocity of -23 m sec^{-1} and the deduced wave velocity of about -35 m sec^{-1}, leads to an Eulerian wavelength very close to 90°. Thus, in September, most evidence points to the existence of a wavenumber 4 regime moving westward at speeds of 30–40 m sec^{-1}.

The correlation as a function of phase lag between the meridional velocities along 50-mb flights 8 and 29 in December is not at all conclusive (dashed line at bottom left in Fig. 10), the correlation maximum at a negative lag of $5\frac{1}{4}$ days suggesting a westward wave speed of only 29 m sec^{-1} with the assumption of wavenumber 4. One of the reasons for the rather indeterminant correlation is that the wave-shaped oscillations are much more pronounced along flight 8 than along flight 29 (Fig. 1).

At 30 mb the weak correlations as a function of phase lag (lower right diagram of Fig. 10) indicate a westward wave speed of 40 m sec^{-1} with the assumption of wavenumber 4, in reasonable agreement with the 50-mb results.

7. Momentum flux statistics

The zonal-meridional velocity covariance has been evaluated at monthly intervals from the CLB data and plotted as a function of latitude, permitting an estimate of the meridional eddy flux of westerly momentum as a function of latitude and date. Fig. 14

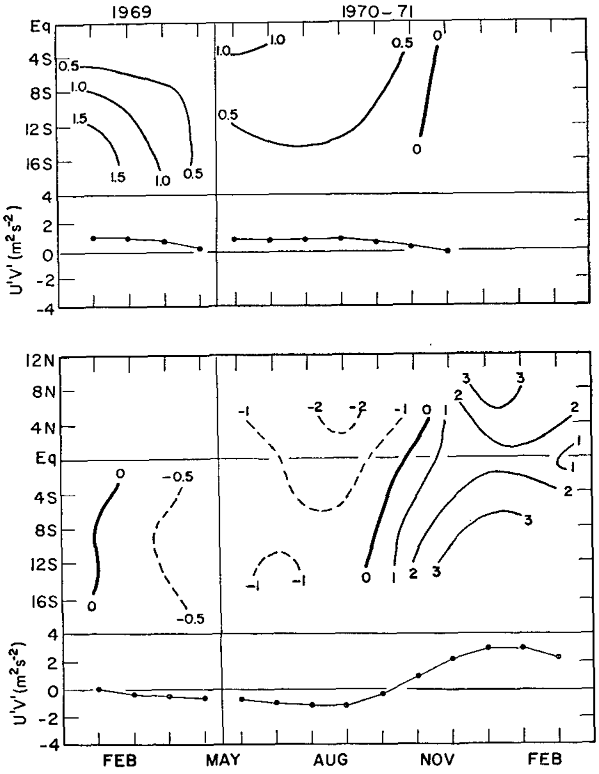

Fig. 14. Variation of the mean monthly zonal-meridional velocity covariance (m^2 sec^{-2}) with date and latitude at 30 mb (top) and 50 mb (bottom). Data from the 1970–71 IRLS flights are indicated at the right, from the 1969 GHOST balloon flights at left. A positive covariance signifies a northward eddy flux of westerly momentum. The average variation of the covariance with date is shown at the bottom.

shows that, at 50 mb in the tropics, there is an obvious tendency for a northward eddy flux of westerly momentum during the Northern Hemisphere winter, and a southward eddy flux during the Northern Hemisphere summer. There is also evidence at 50 mb for a variation with latitude of the zero momentum flux line near the time of the equinox, implying a convergence of the westerly momentum flux above the equator during this time. Since the quasi-biennial east wind maximum occurred in November, there is no obvious association of the convergence of the meridional eddy momentum flux with the quasi-biennial variation in zonal wind. Even at 50 mb, these eddy momentum fluxes are small, only about 3% of the values found at jet stream levels in temperate latitudes. The 30-mb eddy flux values are even smaller than at 50 mb, and there is some evidence that the flux at 30 mb is out of phase with that at 50 mb. At the left in Fig. 14, we present the results obtained from the GHOST flights in 1969. At 50 mb the results are in reasonable agreement with the IRLS results in suggesting a southward eddy momentum flux in the Northern Hemisphere summer. In 1969, the northward eddy flux at 30 mb is greater than at 50 mb and extends later into the year. Referring back to Fig. 1, the asymmetric shape of the waves delineated by 50 mb flights 5 and 10 in September would be appropriate to the southward eddy flux of westerly momentum indicated as occurring at this time.

8. Conclusion

The constant-level balloon (CLB) flights have successfully delineated wave-like oscillations in the equatorial stratosphere which, because of their small amplitude, apparently cannot be detected from conventional rawinsonde data. Such flights near the equator also have the capability of delineating Kelvin waves and providing information on their speed and amplitude. The CLB represents a superior tool to estimate mean meridional velocities, and the indicated mean northward drift at 50 mb as well as the 2-month periodicity in meridional velocity with the largest amplitude in the Northern Hemisphere winter are worthy of further investigation. Finally, these balloons furnish estimates of the meridional eddy momentum flux around the hemisphere which could hardly be obtained from rawinsonde data.

In recent years, largely through the work of Lindzen and Holton (1968), the hypothesis has been advanced that the interaction of vertically propagating gravity waves and the semiannual zonal wind oscillation induces a quasi-biennial oscillation through the process of critical level absorption (Bretherton, 1969). This raises the interesting possibility of placing anemometers on constant-level balloons in order to measure the vertical air flow past the balloon and thereby obtain a direct measure of the gravity wave effect and its variation in space and time. It is suggested that this might be one of the profitable uses of constant-level balloons in the future.

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