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Results of Equatorial Wave Campaign of IMAP in May-June 1984

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A scientific campaign to delineate the characteristics of equatorial waves in the middle atmospheric wind field has been conducted in May-June 1984 from three equatorial stations, viz. Trivandrum (8.6°N, 77°E), SHAR (13.7°N, 80.2°E) and Balasore (21.5°N, 86.9°E), as part of the Indian Middle Atmosphere Programme (IMAP). The zonal and meridional wind data obtained in the campaign have been analyzed to characterize the fluctuating components in them. An interesting observation is the upward phase propagation of long period (12-20 days) zonal oscillation in the lower stratosphere. The present campaign revealed some features of the equatorial wave disturbances which are peculiar to the Indian zone. All the results of this study are presented and their implication and significance are discussed in the light of the current observational knowledge and theoretical background regarding the equatorial waves.

1 Introduction

In the late sixties and early seventies, a satisfactory theory has been advanced involving wave mean flow interaction[1,2] to account for the quasi-biennial oscillation (QBO) in which most of the variance in the zonal wind is contained at equatorial latitudes (± 20°) in the altitude region 18-30 km. This theory is based on the vertical momentum fluxes carried by the eastward propagating Kelvin (westerly momentum) and westward propagating mixed Rossy-gravity (MRG) waves (easterly momentum) to explain the downward propagation of alternating westerly and easterly wind regimes of the QBO. At still higher altitudes (30-60 km) the zonal wind variance at equatorial latitudes is mainly in the semi-annual oscillation (SAO). The explanation for the SAO[3] also involves vertical momentum flux carried by waves.

Kelvin waves exhibit only zonal amplitudes whereas the MRG waves exhibit both zonal and meridional amplitudes and the periods are in the range of 10-15 days for the former and 4-5 days for the later. The first evidence for the existence of these waves in the equatorial lower atmosphere came from the works of Yanai and Maruyama[4] and Wallace and Kousky[5]. These and other observations (e.g. Angell *et al.*[6]; Maruyama[7]) provided evidence for many of the characteristics of these waves according to the theory. Hirota[8] found eastward propagating mode with a period of about 10 days and a vertical wavelength of 15-20 km in the upper stratosphere in relation to the SAO. This observed period is somewhat less than the typical 15 days period for the Kelvin waves associated with QBO at lower altitudes. Salby *et al.*[9] and Devarajan *et al.*[10] identified a shorter period and shorter wavelength in the zonal wind in the upper stratosphere which is attributed to Kelvin wave with wave number 2.

Most of the evidence for these equatorial waves came from the data (rawinsonde and rocket) corresponding to stations located in the Pacific zone. It is quite likely and probable that characteristics of equatorial waves are different in different longitude zones as is the case with SAO and QBO[11]. Particularly, observations pertaining to the Indian zone are lacking in this regard. In view of the large scale monsoon circulation over the Indian zone, when the stratospheric winds reverse from westerlies to easterlies, it will be of great interest to study the equatorial wave characteristics over the Indian zone. Moreover, as the origin of the lower stratospheric equatorial waves (Kelvin and MRG) is believed to be in the troposphere, a study in this region assumes particular significance as also in the higher altitude region in regard to SAO.

With these in view, a comprehensive experimental programme has been planned as part of the Indian Middle Atmosphere Programme (IMAP) and carried out during the period May-June 1984 involving balloon and rocket experiments to delineate the characteristics of the equatorial waves over the Indian zone.

In this paper, we present the results of this experimental programme.

2 Characteristics of Equatorial Kelvin and MRG Waves

In this section, we briefly present the chief characteristics of the equatorial Kelvin and MRG waves and their role in the overall middle atmosphere dynamics. We certainly do not intend to present a comprehensive review of the topic which is beyond the scope of the present paper but only highlight the major features of these equatorial waves.

The major features of the observed characteristics of the equatorial Kelvin and MRG waves are summarized in Table 1[3,12].

As given in Table 1, both Kelvin and MRG waves are characterized by an in-phase relation between u' and w'. As the upward flux of zonal momentum is given by $\rho\, u'w'/2$ (ρ is the density) these waves carry an upward flux of relative westerly momentum. However, for MRG waves, an additional factor comes into picture because of its meridional amplitude which is associated with a mean meridional circulation driven by the wave. This is because of the quadrature phase relation between v' and w'. At any level, air parcels experience their maximum equatorward motion after 1/4 wavelength of their upward motion. Thus, the air parcels describe ellipses in the meridional plane within the waves. The rising motion takes place away from the equator than the sinking motion. Thus the rising parcels carry less westerly momentum (due to earth's rotation) than the sinking parcels resulting in net upward easterly momentum flux. This predominates over the momentum flux due to the zonal component alone and hence the MRG waves transport a net upward easterly momentum[13]. The net upward flux carried by Kelvin (westerly flux) and MRG (easterly flux) is calculated to be $\sim 6\times10^{-3}$ m^2 s^{-2} and $\sim 3\times10^{-3}$ m^2 s^{-2} (Refs 7 and 12).

The vertical flux of wave energy is directly proportional to $(C-U)$ where C is the wave speed relative to the ground and U is zonal wind speed. It can be easily seen that the Kelvin waves propagate without attenuation in easterly wind regimes while MRG waves propagate in westerly wind regimes. The wave energy cannot propagate according to this, through the 'critical level' at which $U=C$. At such a level, there is an abrupt transfer of momentum from the waves to the mean flow. However, observations show that the Kelvin waves are absorbed by the mean zonal flow even without crossing the critical level. There are two other mechanisms by which the energy of waves can be absorbed. In the presence of strong vertical shears in the mean flow the waves break down into smaller scale

Table 1—Major Features of the Observed Characteristics of the Equatorial Kelvin and MRG Waves*

Characteristics (typical)	MRG waves	Kelvin waves
Period (ground based)	4-5 days	10-20 days
Zonal wave number	4	1-2
Horizontal wavelength	10,000 km	30,000 km
Vertical wavelength	4-8 km	6-10 km
Phase speed (zonal) relative to ground	− 23 m/s (easterly) (mean wind 7 m/s)	+ 25 m/s (westerly) (mean wind − 25 m/s)
Amplitudes:		
Zonal wind (u')	2-3 m/s	8 m/s
Meridional wind (v')	2-3 m/s	0
Temperature (T')	1°C	2-3°C
Geopotential height (Z')	30 m	4 m
Vertical velocity (w')	0.15 cm/s	0.15 cm/s
Symmetry about the equator		
Zonal wind	Odd	Even
Meridional wind	Even	—
Geopotential height	Odd	Even
Phase relations		
p' (pressure) and u'	Out of phase	In phase
p' and T'	Quadrature phase (T' leading)	Quadrature phase (T' leading)
p' and v'	Quadrature phase (p' leading)	—
u' and w'	In phase	In phase

*These are the characteristics representative of the lower stratosphere. In the upper stratosphere, Hirota[8] isolated an eastward propagating mode with a period of about 10 days and a vertical wavelength of 15 to 20 km.

Kelvin-Helmholtz waves and turbulence (Richardson's number is proportional to $|C-U|^3$) and thus will be dissipated. Another process is radiative damping (Newtonian cooling). Above 25 km the characteristic time scale for radiative relaxation is comparable to the Doppler shifted period of Kelvin wave. For the Kelvin wave, these two mechanisms are operative for absorption by the mean flow whereas for MRG, the first mechanism is relatively less important because generally the easterly shears are weak (less than the westerly shears).

3 Data and Method of Analysis

The Indian summer monsoon sets in over the Kerala coast (southern end of the west coast of Indian peninsula), generally, between 20 May and 10 June, the most probable date of occurrence being June 1. The stratospheric zonal winds which are westerly during the preceding winter reverse their direction and become easterly a few days prior to the onset of monsoon. The easterly propagating Kelvin waves are expected to be absorbed in the westerly wind regime and hence, an easterly wind regime would be conducive for the detection of these waves. However, the easterly wind regime would not be favourable for the detection of the westerly propagating MRG waves. The experimental programme was planned to commence around monsoon onset time, so that the conditions are conducive for Kelvin wave detection. But, under these conditions MRG waves would be strongly absorbed. Another programme is planned in a winter season when the mean winds are more favourable for MRG wave detection.

The programme consisted of rocket borne chaff releases for wind measurements in the altitude region 20-50 km and rawinsondes (balloon) in the lower region. The rockets were launched from three stations near simultaneously (in no case, the time difference exceeded 2 hr between launches at the three stations on the same day), namely, Trivandrum (8.6°N, 77°E), SHAR (13.7°N, 80.2°E) and Balasore (21.5°N, 86.9°E), to study the latitudinal variation of the equatorial wave activity. The launchings were on alternate days between 1800 and 1900 hrs IST starting from 23 May 1984 and extending up to 12 June 1984. In all, there were 11 launchings from each station giving a duration of 20 days which is adequate to cover the expected period of the Kelvin waves. In addition to the rocket chaff release, balloon rawinsonde experiments have also been conducted a few hours prior to the rocket launchings to obtain the low level winds (tropospheric winds) from all the three stations. Table 2 gives the details of launch campaign and data acquired.

The rocket chaff was tracked by S-band radars at Trivandrum and Balasore, and by one S-band and two C-band radars at SHAR. The chaff track data of range (r), elevation (θ) and azimuth (ϕ) have been reduced to the zonal and meridional wind components using a reduction programme which gives an altitude resolution of 3 km.

It is necessary to estimate the errors in the wind values (zonal and meridional) in order to make any mea-

Table 2—IMAP Equatorial Wave Campaign—RH-200 Rocket Launch Details

Date (1984)	Trivandrum		SHAR		Balasore	
	Time hrs IST	Altitude km	Time hrs IST	Altitude km	Time hrs IST	Altitude km
23 May	1818	No data	1815	63.9	1820	56.6
	1924	61.0				
25 May	1800	68.0	1800	42.1	1905	69.4
			1906	66.6		
27 May	1804	64.3	1800	No data	1815	64.8
			1900	64.4		
29 May	1807	65.9	1800	72.0	1816	68.3
31 May	1800	68.7	1800	67.8	1800	59.0
2 June	1927	68.4	1800	54.7	1810	61.7
4 June	1800	71.5	1810	72.8	1909	No data
					1950	66.8
6 June	1820	70.0	1800	61.1	No launch	—
8 June	1800	57.9	1831	72.1	1803	64.0
10 June	1831	60.1	1810	72.1	1815	61.9
12 June	1800	59.3	1800	72.0	1800	No data
					1920	66.0

Note: (i) The times in the table are the launch times in hrs IST.
(ii) The altitudes in the table are the altitudes of chaff acquisition by the radar.

ningful interpretation of the wind characteristics. For this, the chaff track data obtained by the three radars in SHAR are made use of[14]. Out of the three radars, two (R_1 and R_2) operate in the C-Band and one (R_3) in the S-Band. The zonal and meridional components of the wind are obtained using the reduction programme mentioned above. The mean wind component at intervals of 1 km is obtained using the values from the three radars for each of the eleven flights. Then the deviations of the R_1, R_2 and R_3 wind values from the mean are obtained for all the flights. From these, the standard error is estimated as a function of altitude for both zonal and meridional components of the wind and is shown in Fig. 1. Below 48 km the error in zonal component is less than 1.7 m/s and that in meridional component it is less than 1 m/s. The error is around 2 m/s between 48 and 50 km in zonal component, and in meridional component it reaches 3 m/s at 50 km. The analysis described in the following is carried out using data only up to 50 km. We also assume that the errors derived are applicable to the Trivandrum and Balasore data. For SHAR, the wind profiles from radar-3 (S-band) were used for the subsequent analyses.

For altitudes below about 20 km, balloon data have been used. Balloons were launched on the same day at each station. The balloon wind data have again been converted to zonal and meridional components at 1 km intervals. The error in the wind components from balloonsonde is < 2 m/s.

4 Mean Wind

The mean zonal and meridional wind profiles of the 11 flights have been obtained for the three stations and are shown in Figs 2 and 3, respectively. Considering first the zonal component, westerlies prevail at lower levels (< 8 km) and strong easterlies prevail at higher levels (> 8 km). Strong easterly jets are seen in the upper troposphere with the jet at Trivandrum being the stronger and narrower compared to the other two stations. The altitude of the jet maximum increases from Trivandrum to Balasore (with increasing latitude). This is similar to the behaviour of tropopause altitude itself. In the lower stratosphere (20-35 km), there is a broad easterly maximum with the one at Trivandrum being stronger. At the higher levels of stratosphere the zonal winds do not show any significant shears (vertical) particularly at SHAR and Balasore. At these levels, the zonal component at Balasore is greater than at the two lower latitude stations. It is seen that below 33 km the zonal wind component (easterly) decreases with latitude and above 33 km it increases with latitude.

Examining the mean meridional wind (Fig. 3) we find that it is mainly northerly in the altitude range un-

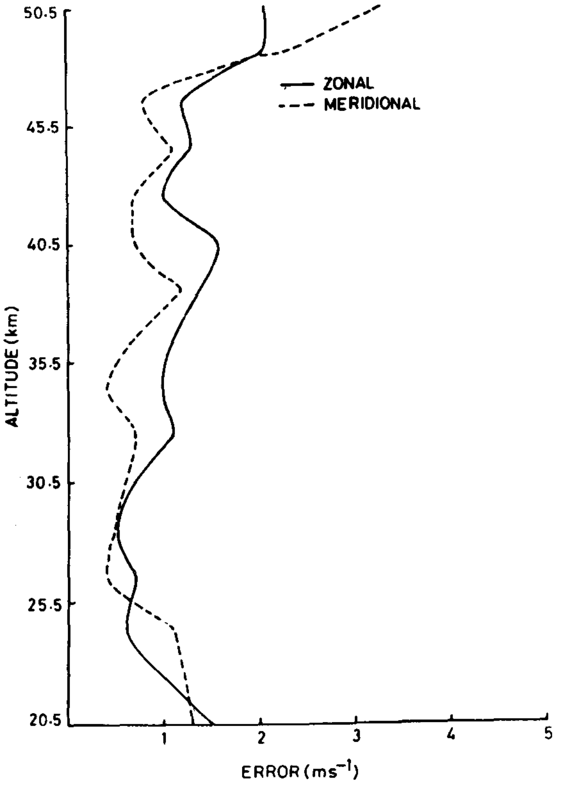

Fig. 1—Errors in zonal and meridional wind components obtained from rocket experiments

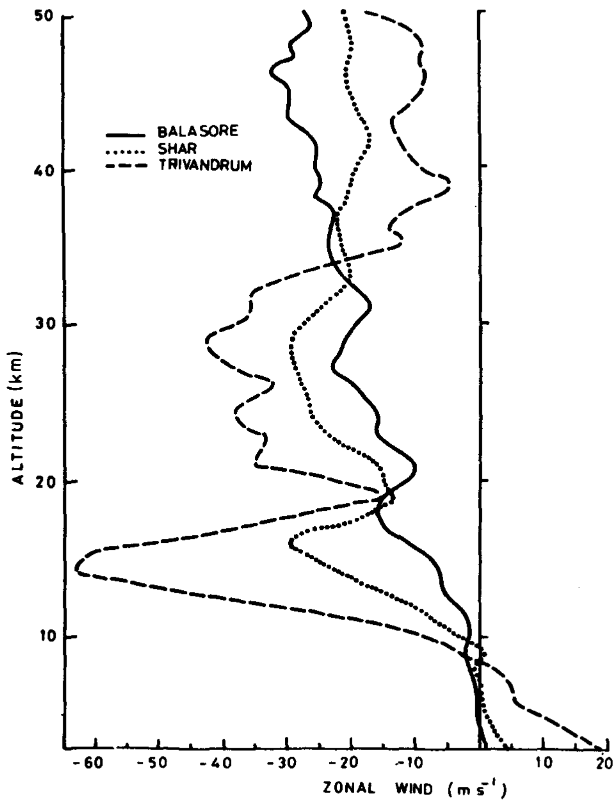

Fig. 2—Mean zonal wind component as a function of altitude

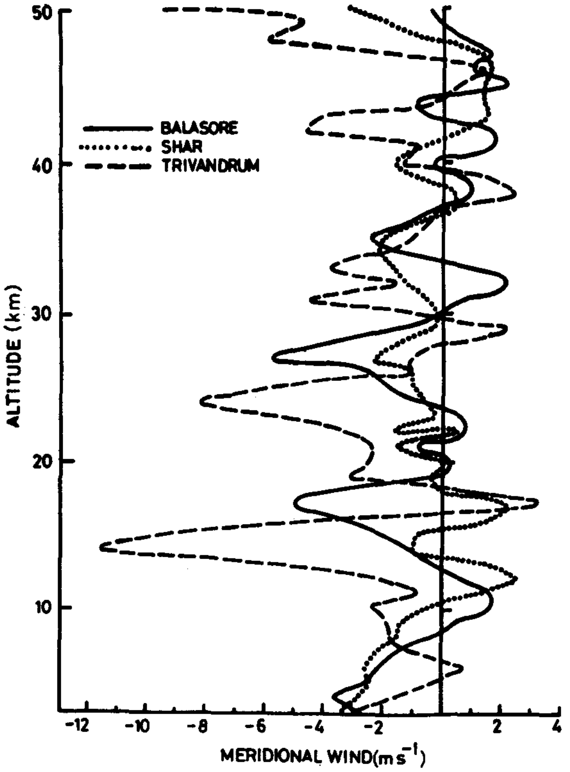

Fig. 3—Mean meridional wind component as a function of altitude

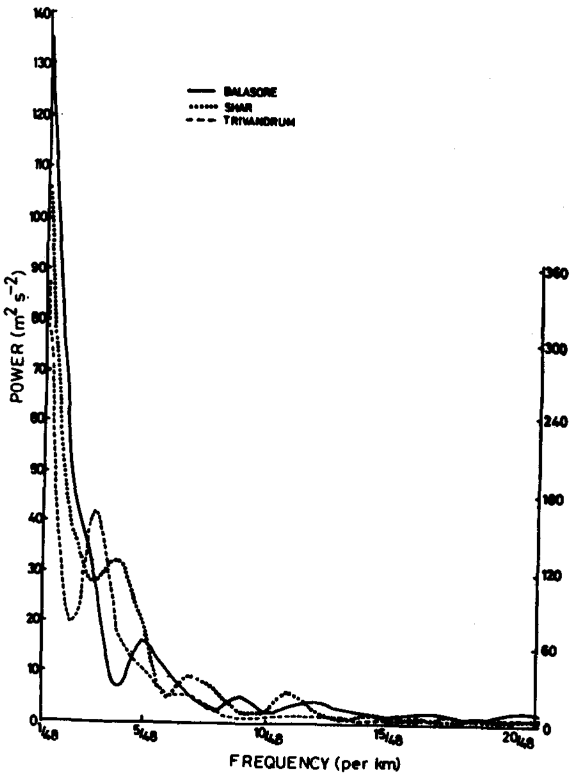

Fig. 4—Power spectra of mean zonal wind component [Error in the power estimates is 1 (m s^{-1})^2.]

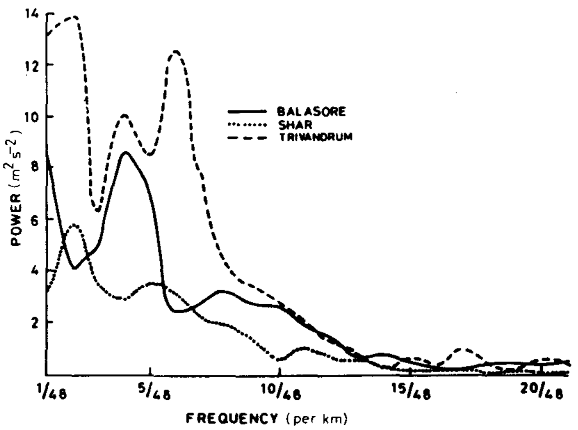

Fig. 5—Power spectra of mean meridional wind component [Error in the power estimates is 0.8 (m s^{-1})^2.]

der consideration but for a few southerly excursions. The meridional wind at Trivandrum is stronger, in general, compared to the other two stations. A strong northerly excursion is seen at about the same altitude as the upper tropospheric easterly jet at Trivandrum. In fact, this excursion repeats at higher altitudes, with the maximum at about 24, 32 and 42 km. Interestingly, Balasore also shows similar pattern, with the corresponding peaks displaced to higher altitudes by about 3-4 km. But at SHAR, this behaviour is not clearly seen and, in general, the meridional wind is weaker compared to the southern (Trivandrum) and the northern (Balasore) stations. The meridional wind shows, in general, much smaller scale variations in altitude compared to the zonal wind.

In order to delineate the altitude structure of the mean wind in a quantitative way, the mean wind profiles are subjected to power spectrum analysis. For this purpose, only data in the altitude range 3-50 km are considered giving a total of 48 points (corresponding to intervals of 1 km). The power spectra thus obtained are shown in Figs 4 and 5 for zonal and meridional wind, respectively. In Fig. 4, the right-hand side ordinate scale is for Trivandrum data and the left-hand side scale is for SHAR and Balasore.

Prominent peaks in the mean zonal wind spectra occur at 16, 12 and 10 km at Trivandrum, SHAR and Balasore, respectively signifying a decreasing vertical scale size with latitude. The SHAR spectrum exhibits two minor peaks at 7 and 4 km and Balasore spectrum at about 5 km. But no such secondary peak is seen in the Trivandrum spectrum. The mean meridional wind spectrum at Trivandrum shows prominent peaks at 16 and 8 km. The 16-km peak is seen at Balasore also but not at SHAR. SHAR shows a peak at 10 km and a stronger one at 24 km.

The mean profile spectrum discussed above represents the vertical structure present over the period of averaging of the wind profiles. Thus this mean structure is indicative of the characteristics of wind fluctuations of greater period than at least the data period under consideration (> 20 days). As our interest in the present work is mainly on periods < 20 days, we obtained residue profiles for each of the 11 flights by subtracting the mean profile from them. These residue profiles are then subjected to power spectrum analysis and the resulting 11 power spectra are averaged and shown in Figs 6 (the ordinate scales being as in Fig. 4) and 7 for zonal and meridional wind, respectively. These spectra thus indicate the vertical structures related to periods 20 days and weighted over the entire altitude range under consideration (3-50 km).

Trivandrum and Balasore zonal wind (Fig. 6) shows a prominent peak at 10 km whereas a peak is indicated at SHAR at 8 km. They show also much larger vertical structures (20 km) as revealed by the peaks in the low frequency end of the spectrum. Considering the meridional wind spectra, we observed peaks at 80 km for Trivandrum and SHAR whereas Balasore shows broad peak centered around 5 km. All the three stations show also much larger (20-30 km) and stronger structures.

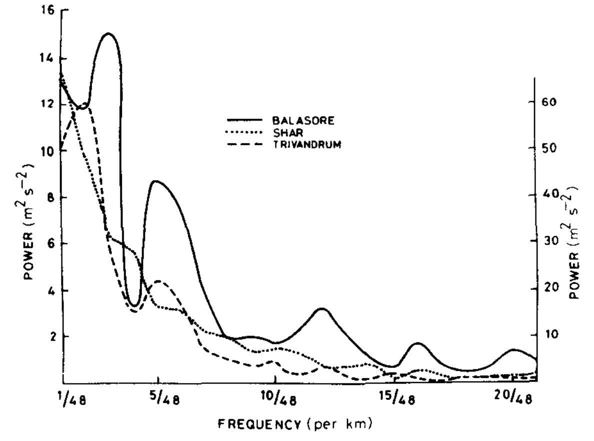

Fig. 6—Power spectra of residue zonal wind component [Error in the power estimates is 1 (m s^{-1})^2.]

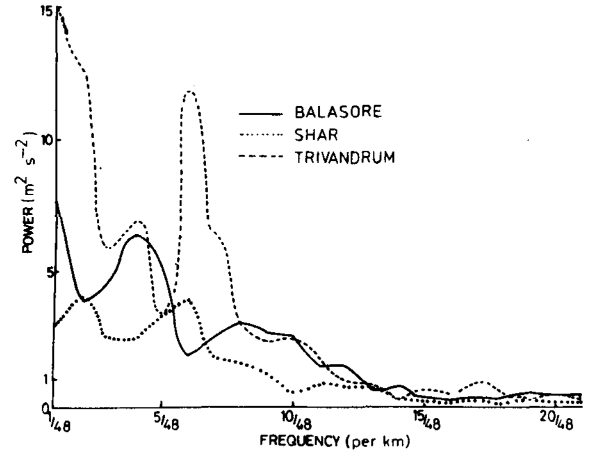

Fig. 7—Power spectra of residue meridional wind component [Error in the power estimates is 0.8 (m s^{-1})^2.]

5 Temporal Variations

As mentioned above the campaign covered a duration of 20 days (23 May 1984 to 12 June 1984) with the objective of extracting the characteristics of waves with periods < 20 days, if any, in the zonal and meridional wind at the three stations. So, the wind data have to be analyzed in the time (or frequency) domain to delineate the wave characteristics.

The zonal and meridional wind data are plotted against time (data) at 2 km intervals (not shown) in the altitude range 4-50 km for the three stations. It may be noted that there are gaps in Trivandrum data at some altitudes. Visual examination of these plots shows significant temporal fluctuations in zonal wind in the upper troposphere and middle and upper stratospheres. The fluctuations are more like episodic type than continuous variations. Meridional wind also indicates a similar pattern. A closer examination of the plots reveals oscillatory type of fluctuations only at a few altitudes; for example, in the upper troposphere between 12 and 16 km. The prominent features of these oscillations do not appear to show any temporal progression in altitude and they also show significant changes in their shape. As stated earlier, at many of the altitudes the fluctuations are like episodic type with changing structure. As these fluctuations are over a mean flow which has strong vertical shears, the fluctuations may not retain their characteristics with altitude due to their interaction with the mean flow. It may be pointed out here, that the fluctuations in zonal and meridional components are well above the errors in them as indicated in Fig. 1.

In order to quantify the strength of fluctuations, we have obtained the variance (S) of the zonal and meridional wind in the altitude range under consideration at intervals of 1 km. This quantity S is plotted as a function of altitude for all the three stations and is shown in Figs. 8 and 9 for zonal and meridional wind, respectively. As mentioned above, S represents the strength of the fluctuating signal. Prominent peaks of S in the altitude range under consideration indicate the presence of fluctuating component with no propagation in the vertical direction. If there is vertical propagation, then S would show no altitude dependence in the altitude range of propagation. This, of course, assumes that the fluctuations do not suffer any significant attenuation in the altitude range.

From Fig. 8, we see that S at Trivandrum and Balasore shows prominent peaks whereas the peaks at SHAR are, in general, weaker. These occur centred around 14, 24, 29 and 40 km at Trivandrum and SHAR, and around 17, 28 and 45 km at Balasore. The peak at 24 km is followed by a secondary peak at 29 km at Trivandrum and at Balasore, the peak at 28 km is followed by a secondary one at 32 km. The peaks in

S are interspersed with deep troughs. The peak in *S* at 14 km at Trivandrum occurs at the maximum of the easterly jet (as seen from the mean zonal wind profile in Fig. 2). This means that the maximum value of the jet fluctuates considerably. Similar peaks in *S* at the jet maximum are seen at Balasore and SHAR also. Two other peaks occurring in the lower stratosphere (24-30 km) correspond to the broad maximum in the zonal wind in the same region. The higher peak near the stratopause occurs in a region of no wind variation with altitude. It is interesting to note that *S* at Balasore is greater than that at the lower latitude stations of Trivandrum and SHAR in the upper stratosphere where the mean wind is also greater at Balasore. Further, *S* of meridional wind at Trivandrum also shows peaks at about the same altitudes as the zonal wind except for the one at higher altitude. These correspond to the maximum in the mean meridional wind. The quantity *S* (meridional wind) at SHAR and Balasore shows many peaks with altitude similar to the mean meridional wind.

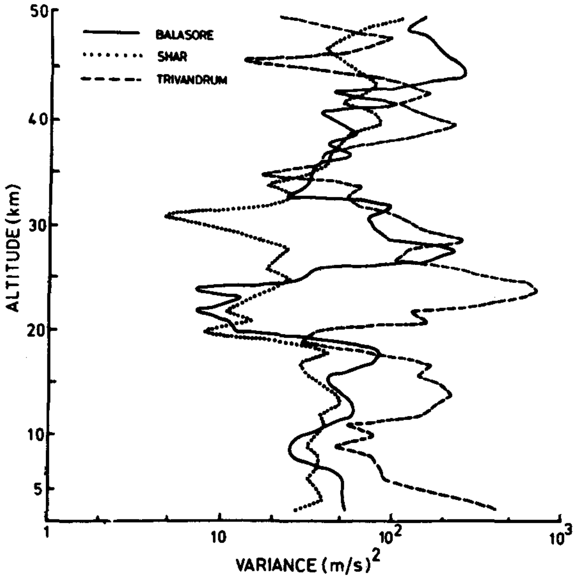

Fig. 8—Variance of zonal wind component as a function of altitude

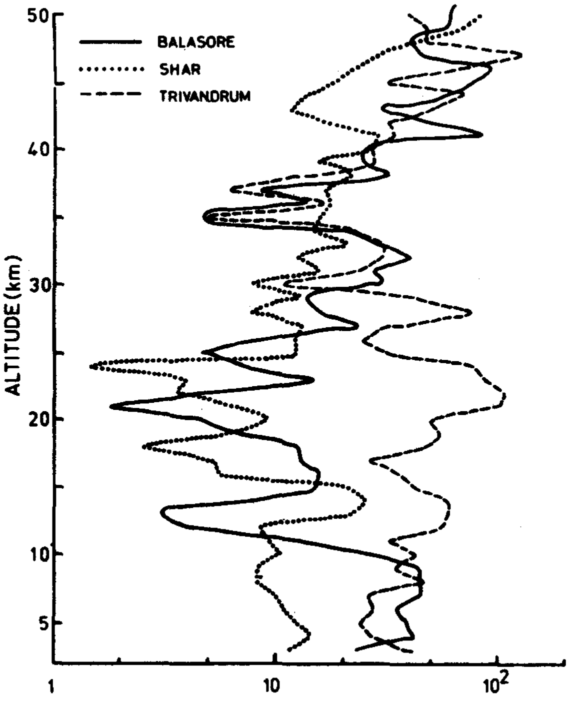

Fig. 9—Variance of meridional wind component as a function of altitude

Thus, it appears that there are mainly three regions of strong fluctuations in zonal component at all the three stations. Meridional component at Trivandrum shows similar behaviour whereas at SHAR and Balasore it shows more number of peaks.

In order to extract the periods of fluctuations from the available length of the data we followed the procedure given below. The data are subjected to harmonic analysis for the data segments equal to 20, 18, 16, 14, 12 days, always starting from the data on 23 May 1985. This analysis is carried out for all the data at 1 km intervals. From an examination of the amplitude and phases of different periods keeping in view the consistency of the values, it would be possible to delineate the temporal characteristics of the fluctuations. This method has been resorted to mainly because the data length is short covering one cycle (at the longer periods) of the possible periods of fluctuations which range from 20 days down to 4-6 days.

The amplitudes are plotted against the corresponding periods and the plots at 4 km intervals are shown in Figs. 10 and 11 for zonal component and Figs. 12 and 13 for meridional component. The error in the amplitudes of the harmonic components works out to be $E/0.7\sqrt{N}$ ($E/1.9$ to $E/2.5$ for harmonic analysis from 12 days to 20 days periods) where *E* is the error in the wind value (Fig. 1) and *N* is the number of points in the harmonic analysis. It can be seen that the amplitudes of the harmonic components are, in general, above the errors in them.

The following are the main features of the zonal wind periodicity amplitudes (Note that in the altitude range 18-31 km the data at Trivandrum are not continuous).

(i) In the troposphere, the amplitudes at Trivandrum are greater compared to the two higher latitude stations (SHAR and Balasore).

(ii) In the troposphere, a peak centred around 12 days emerges as a prominent one apart from one around 8 days at 14 and 16 km. At lower altitudes the peaks are much broader. Also, quite prominent amplitudes are seen at the shorter periods (5-8 days). These features are revealed more prominently in

Trivandrum data than in the data for the other two stations.

(iii) In the lower stratosphere (18 to 30 km) no prominent peaks are seen. However, in the upper stratosphere (30-50 km) two broad peaks, one in the longer period region (10-20 days) and the other in the shorter period region (5.5-8 days) appear to emerge. It is also to be noted that the atmosphere does not, in general, exhibit any monochromatic periods and so it is natural to expect a wide band of periodicities.

(iv) In the stratosphere, the amplitudes at Trivandrum are, in general, greater compared to the other stations except in the range 44-50 km where Balasore amplitudes appear to be strong.

The following features are discernible from the amplitudes of meridional wind components (Figs 12 and 13).

(i) In the troposphere, Trivandrum shows prominent peaks around 12-14 days and 8 days as in the case of zonal wind. The other two stations do not show any prominent peaks with altitude in a consistent manner.

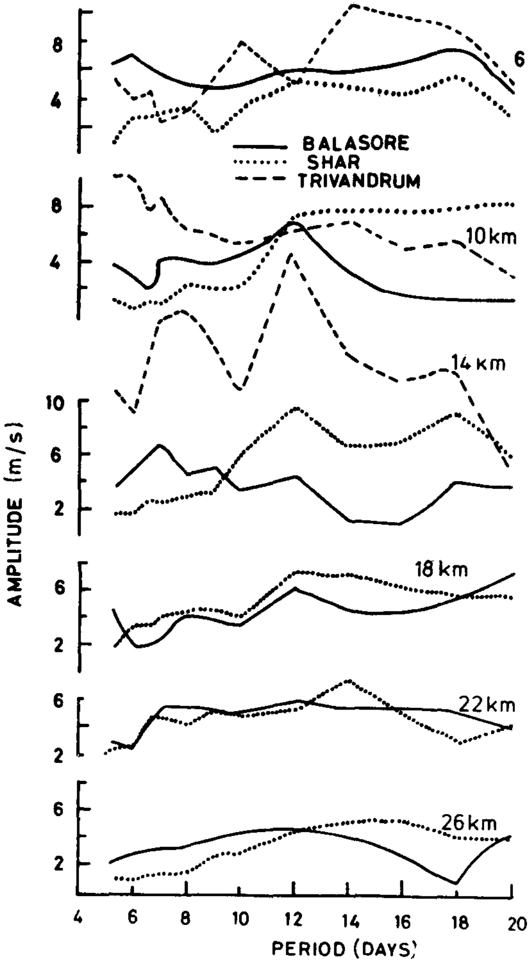

Fig. 10—Plots of amplitude of periodic components in zonal wind versus period in days at 6, 10, 14, 18 and 22 km

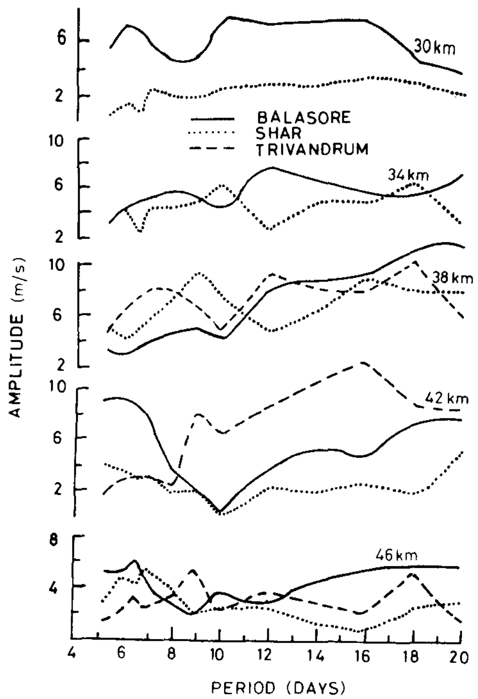

Fig. 11—Plots of amplitude of periodic components in zonal wind versus period in days at 26, 30, 34, 38, 42 and 46 km

(ii) In the stratosphere, Balasore appears to show broad peak around 14-16 days whereas such a feature is apparent at the other two stations only at greater altitudes.

The above described features of the periodic components clearly reveal that there is no preferred single period in the wind fluctuations at all the three stations except perhaps in the troposphere (~ 16 km) at Trivandrum. In general, the components exhibit wide band nature in period (or frequency). This is also revealed by the raw data plots where the wind fluctuations are episodic rather than continuous type with definitely identifiable periods. It is more realistic to consider bands of periods (or frequencies) than a single period or frequency. Thus, in order to examine the phases of the periodic components, we adopted the following method. The periodicities are broadly divided into long and short bands with the former covering the range 12-20 days and the latter 6-10 days. Then the phases of the individual component in the long period band and short period band are averaged at each km interval. For this, first, the phase angles are converted to fractions of cycles for each of the periods in the two bands and then these are averaged. The average phase is expressed as a fraction of the cycle corresponding to the mean frequency for the particular band. For example, the long period band has its mean frequency at 0.0645 c/day (period 15.5 days) and short period band at 0.130 c/day (period 7.7 days).

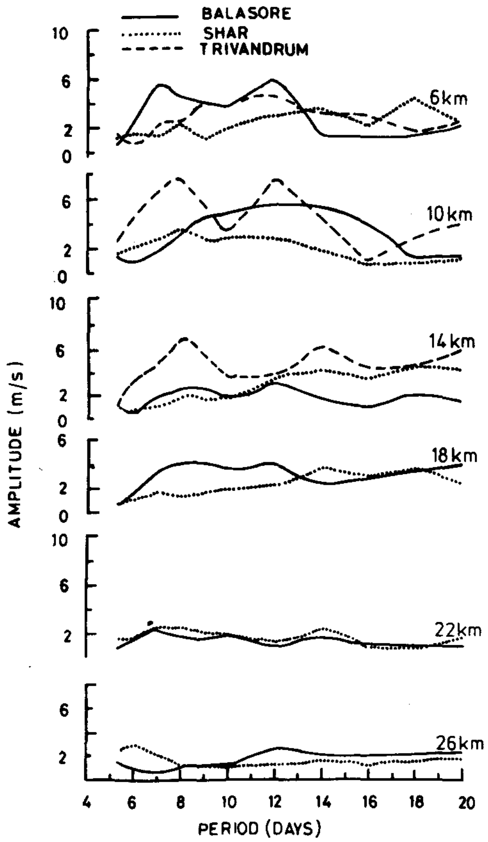

Fig. 12—Plots of amplitude of periodic components in meridional wind versus period in days at 6, 10, 14, 18 and 22 km

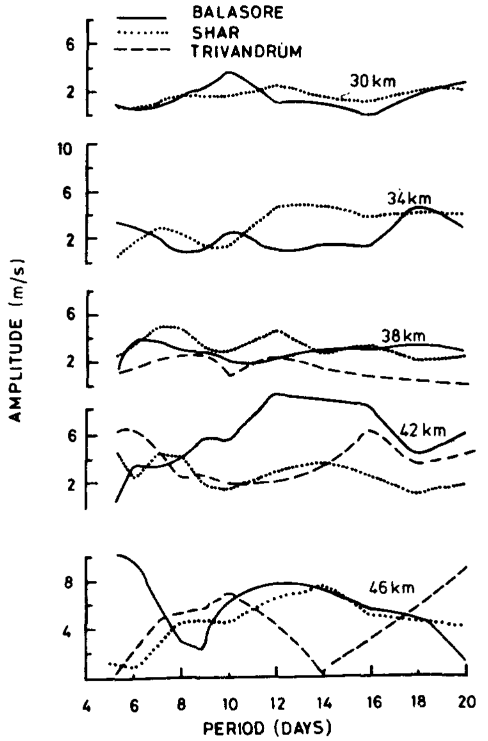

Fig. 13—Plots of amplitude of periodic components in meridional wind versus period in days at 26, 30, 34, 38, 42 and 46 km

There is a justification for adopting this procedure of obtaining the average phase in fractions of cycles in two bands of periods. This is based on the fact that there is no significant dispersion in the phases of the components in the two bands (Thus averaging the phases would not affect the phase characteristics and helps in smoothing out any spurious variations.). In Figs 14 and 15, we show the phases of the 20 and 12 day period components, respectively, for all the three stations to illustrate this aspect. There is a remarkable agreement between the phases at the three stations both for the 20-day and 12-day components which is a strong evidence for the reality of their existence. It can be clearly seen that the behaviour of the phases of the 20-day and 12-day components is very much similar to a remarkable degree. The phases remain

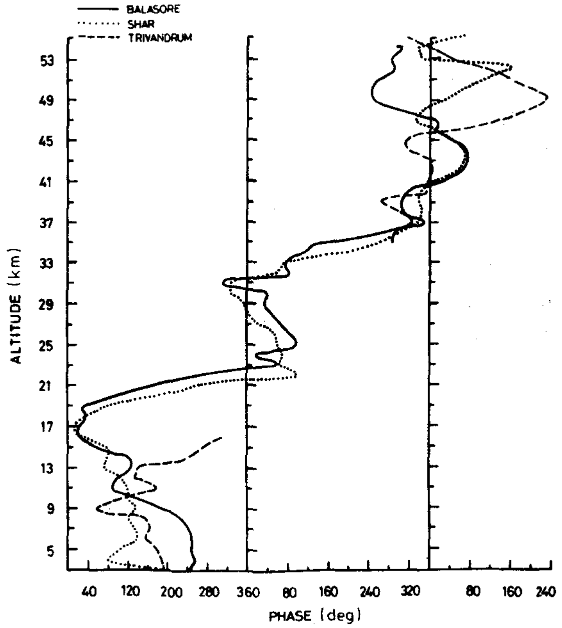

Fig. 14—Phase in degrees of the 20-day periodic component in zonal wind as a function of altitude

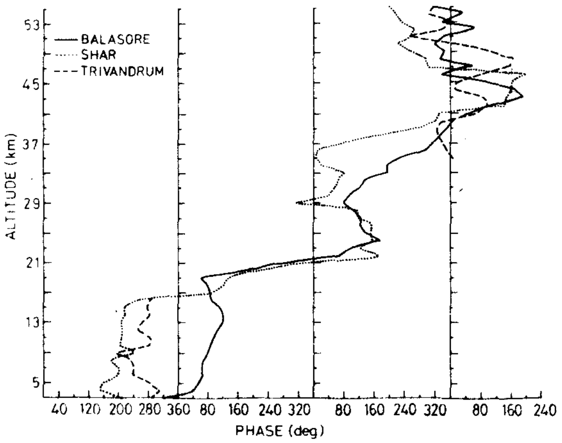

Fig. 15—Phase in degrees of 12-day periodic component in zonal wind as a function of altitude

more or less steady in the troposphere followed by increasing phase. In the middle stratosphere, the phase is again steady. In the upper stratosphere phase increase is revealed generally. The phases of the 6-day component obtained from the data length of 18 days (as 3rd harmonic) and 12 days (as 2nd harmonics) are found to agree very well.

From the above mentioned aspects, it can be seen that averaging the phases in two bands would not affect the phase characteristics and helps in smoothing out any spurious variations.

The average phases obtained as described above are plotted against altitude and are shown in Fig. 16 for zonal winds and in Fig. 17 for meridional winds. The following features are discernible from these figures.

Zonal Wind—Long Period Band (*Fig.* 16)

(i) In the troposphere, the phase is almost steady at all the three stations indicating that there is no significant vertical propagation of the disturbances.

(ii) In the region 17-21 km for SHAR and 16-21 km at Balasore, there is a phase progression indicating an upward propagation. Conversion of these phase differences to vertical wavelength, gives a value of about 6 km for the vertical wavelength. It may be noted that the vertical wavelength of Kelvin waves is in the range 6-10 km (Ref. 3) in the lower stratosphere.

(iii) In the altitude range 22-32 km the phase remains fairly steady for Balasore and SHAR except for a phase excursion between 28 and 32 km at SHAR (which is a region of strong gradient in the mean wind).

(iv) Between 32 and 36 km there is again phase progression shown both at SHAR and Balasore. The vertical wavelength (λ_z) is obtained as ~ 8 km.

There are two more similar phase progressions seen at SHAR—one between 37 and 41 km giving a λ_z of ~ 10 km and the other between 42 and 48 km giving a λ_z of ~ 10 km. Trivandrum data show a phase progression (downward propagation) between 38 and 43 km giving a λ_z of ~ 6 km.

Zonal Wind—Short Period Band (*Fig.* 16)

(i) In the troposphere, SHAR and Trivandrum show similar phase progression. Two phase excursions are revealed between 6 and 17 km each excursion completing only part of the phase cycle. It may be noted that the mean wind changes over from westerly to easterly (Fig. 2) at about the same altitude as the region from where phase propagation is downwards and upwards (7 km for Trivandrum and 9 km for SHAR). The higher altitude of 15 km from where again the phase propagation is downwards and upwards is same as the altitude of easterly jet maximum. The mean vertical wavelength comes out as ~ 7 km. At Balasore, the phase is fairly steady.

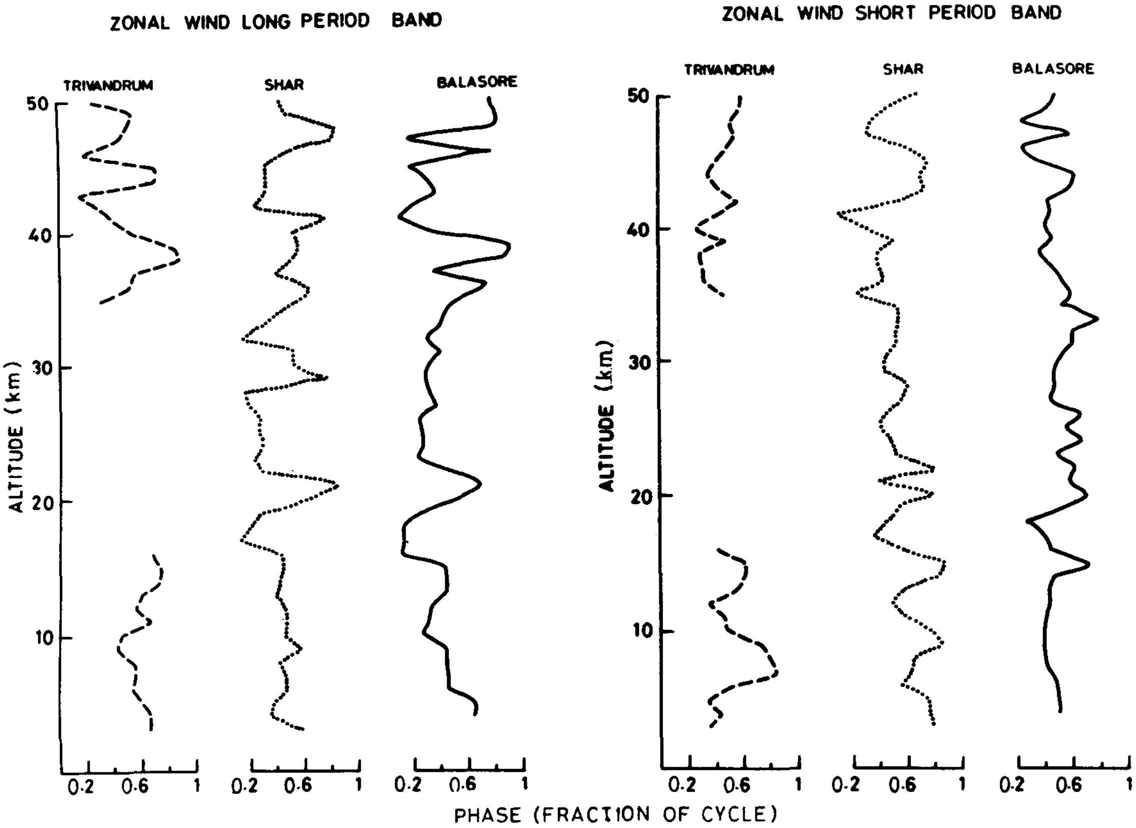

Fig. 16—Phase in fraction of cycle of long and short period band components in zonal wind as a function of altitude

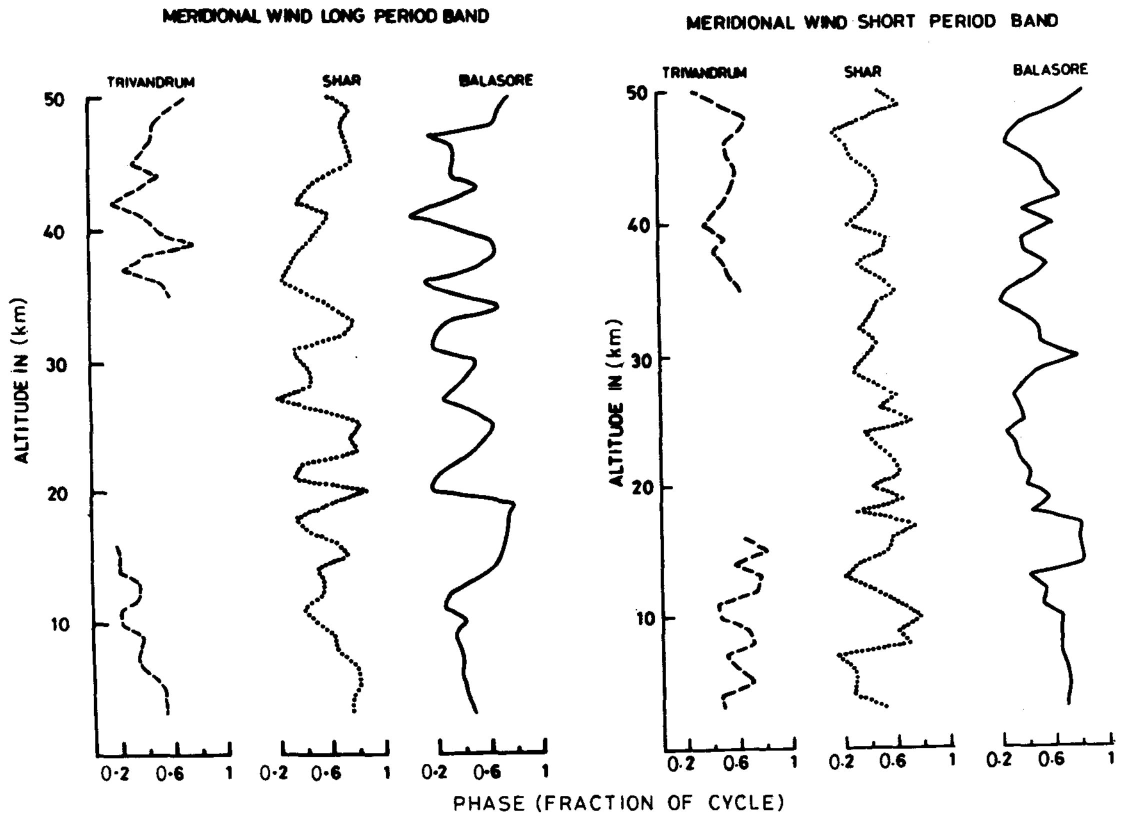

Fig. 17—Phase in fraction of cycle of long and short period band components in meridional wind as a function of altitude

(ii) At greater altitudes (in the stratosphere) there are no consistent phase changes. The fluctuations resemble noise fluctuation.

Meridional Wind—Long Period Band (*Fig.* 17)

(i) In the troposphere, both at Trivandrum and SHAR, phase decreases with altitude between 4 and 10 km, whereas at Balasore it remains more or less steady in this range of altitude. But in the upper troposphere, between 11 and 18 km there is a steady phase progression at Balasore giving a λ_z of about 10-12 km. This is in contrast to the behaviour of zonal wind—long period band.

(ii) In the stratosphere a very interesting feature is seen at SHAR and Balasore. Four excursions of phase are revealed in the altitude range 21-41 km. Each phase excursion covers approximately half a cycle. The vertical wavelength works out to be approximately 6 km. At Trivandrum, no consistent phase change is seen in the limited altitude range in the stratosphere for which the analysis could be done.

Meridional Wind—Short Period Band (*Fig.* 17)

(i) In the troposphere at SHAR one and half excursions of phase are seen between 7 and 17 km with a λ_z of 7 km. Trivandrum data show phase fluctuations in the same altitude range but with twice the number of excursions. At Balasore, the phase is steady, except for phase jumps between 13 and 18 km.

(ii) At greater altitudes, i.e. in the stratosphere, phase fluctuations are seen but no consistent picture emerges except in the region between 28 and 34 km at Balasore. In this range, there is a phase excursion at Balasore with a λ_z of about 6 km.

6 Discussion

In the troposphere, the wind variance (both zonal and meridional) is found to be maximum around 13 km with that at Trivandrum to be greater than that at the other two stations. We find from analysis of the phases of the zonal and meridional periodic components that at Trivandrum and SHAR, long period oscillations (~ 15.5 days) show no significant vertical phase propagation while the short period ones (7.7 days) show with a vertical wavelength λ_z of ~ 7 km. The fact that these are revealed by independent sets of data at different stations adds further credence to the reality of their existence. As the peak in variance represents mainly a non-propagating disturbance, the observed peak at about 13 km can be attributed mainly to the long period component. At Balasore, in the troposphere phase propagation is seen only for long period band of the meridional component. Other than these, the fluctuations of the three stations do not show any consistent phase change attributable to its progression.

Wallace and Chang[15] from an analysis of lower (~ 500 mbar level) tropospheric wind at low latitude stations in the Pacific region found that the low frequency oscillations with periods > 10 days and westward propagation account for most of the variance in the zonal wind component. It was also reported that their characteristics vary considerably from one year to another and from one season to another. Yanai and Murakami[16] from an analysis of data at stations in the Pacific region situated north and south of the equator, separated odd and even mode waves in the zonal and meridional components and obtained their horizontal and vertical propagation characteristics. They reported that all the major waves in the period range between 16.67 days and 4.17 days show sharp peaking of the spectral density in the 12 to 14 km levels. The odd-mode eastward propagating wave with 16.67-day period observed in the zonal component only, but not in the meridional component, showed phase propagation upwards and downwards with respect to the 12 to 14 km region. Yanai and Murakami[16] also found even-mode westward propagating waves of period 16.67 days in both zonal and meridional components with no vertical phase propagation in the upper troposphere. An eastward propagating wave of period 12.5 days in both zonal and meridional components was identified with no significant vertical phase propagation in the altitude region 10-15 km. The even mode shorter period waves with periods of 6.25 and 4.55 days in both zonal and meridional components show upward and downward propagation with respect to the altitude region around 10 km.

The present investigation reveals a long period component with no significant phase propagation and a shorter period component with vertical phase propagation. The strength of the components in the meridional wind is less than that in the zonal wind. With the limited amount of data available, it is not possible to extract propagation characteristics of the disturbances especially in the source region (e.g. tropospheric region). An important difference in the characteristics of troposphere in the Indian zone compared to the Pacific zone is the presence of strong easterly jet in the upper troposphere during the monsoon[17]. In the Pacific and Atlantic zones no such jet stream exists and instead, the high tropospheric circulation consists of a train of vortices[18]. The tropospheric disturbances have their origin and energy source in the large quantities of latent heat and fluctuations in the rain fall and cloud patterns[3]. So, one can expect a modified behaviour of the disturbances in the Indian zone as compared to other zones (e.g. the Pacific). To be able to delineate the characteristics of the disturbances with respect to their propagation features, wind data spanning a longer duration than available in the current campaign would be advantageous.

A further comment on the observed features of the tropospheric wind field is called for in view of its association with monsoon dynamics. One of the most facinating features of the southwest monsoon system in southeast Asia is the strong upper tropospheric easterly jet. This has been studied in great detail observationally and theoretically (including modelling) by many authors[17,19,20]. This tropical easterly jet extends longitudinally from the International date line to the Greenwich meridian and maximizes around 5-10°N in latitude. Krishna Murti and Bhalme[21] delineated a quasi-biweekly oscillation in the monsoon parameters including the tropical easterly jet. The tropical easterly jet exhibits high variability even on a day-to-day basis. In our present investigation which considered data in the beginning phase of the southwest monsoon, the strong easterly jet is seen at the lower latitude station of Trivandrum and it showed weakening at the two higher latitude stations. Also, a quasi-periodicity of ~ 12 days has been observed.

The equatorial stratospheric waves (MRG and Kelvin waves) have their origin (source) in the tropospheric disturbances[3]. Modelling studies[22] suggest that the stratospheric Kelvin wave activity does not result from a similar spectral distribution of disturbances in the troposphere. It appears that the natural band-pass selectivity of the atmosphere combined with a red noise forcing spectrum in time and/or space can account for the stratospheric Kelvin wave spectrum. The model also shows that the long period oscillations in the upper troposphere have no vertical propagation into the stratosphere. The present investigation reveals a broad band long period activity in the upper tropospheric wind at Trivandrum and SHAR with no vertical propagation. It may be noted that at Trivandrum, a preference for periods centred around 12 days and 8 days is revealed in the upper tropospheric zonal wind. The long period wave activity is greater at the region of the easterly jet maximum. It is quite likely that the long period activity is associated with the easterly jet which is stronger at Trivandrum.

We have also observed short period wave activity in the upper troposphere, changing phase with altitude. Both increases and decreases of phase with altitude are seen. This is characteristic of source region with a narrow vertical extent.

In the lower stratosphere (just above the tropopause), first, considering the zonal wind, we have observed an upward phase propagation of the long period activity, in the altitude region 16 to 21 km both at

SHAR and Balasore (Unfortunately, Trivandrum data were discontinuous in the lower stratosphere.). It can be noticed that this altitude region is in the topside of the easterly jet (The long period wave activity represents a spread of periods over 12 to 20 days.). In the long period component of the meridional wind no similar feature is found. This may qualify the long period activity in this region to be attributed to Kelvin wave. However, Kelvin wave phase propagation is expected to be downwards whereas the observed phase propagation is upwards.

Earlier investigators (e.g. Wallace and Kousky[5]) have reported downward phase propagating long period waves in the zonal wind. In almost all of these earlier works, large amounts of data spreading over a few months have been used in the analysis with the result that these results mainly represent the general behaviour of these wave disturbances. In contrast, in the present investigation data covering about one period of the disturbances are only used. It is quite likely that in the earlier investigations, the behaviour of individual cycles of the wave is not reflected as they represent mainly their general behaviour. It may also be noted that strong easterly jet is present in the troposphere during the current observational period and that the upward phase propagation is observed in a region of strong wind shear (17-22 km). These factors may be influencing the propagation of the disturbances. It should be interesting to see the propagation characteristics of these disturbances in the winter season when the strong easterly jet gives way to a weak westerly jet with smaller wind shears.

In the region from 23 to 35 km a strong maximum is seen in the zonal wind variance while no change in phase with altitude is seen. This is also the region where a broad easterly peak is seen in the zonal mean wind. Above this region (in the upper stratosphere) phase variations are seen both in the long period and short period bands. The long period band indicated a vertical wavelength around 7 km with phase increase (upward propagation) and followed by decrease (downward propagation). On the other hand, the short period band indicates phase fluctuations resembling noise fluctuations.

The observation that no phase variation in the long period band is seen in the region 23-35 km indicates two possibilities; namely, that this region could be a source region for the disturbances or that the energy of the disturbances leaking from lower levels is vertically trapped in this region. The fluctuating power of the zonal wind component (variance) multiplied by the atmospheric density gives an estimate of the energy of the disturbances. A comparison of this quantity thus estimated for the region 25-35 km and 10 to 18 km shows that this quantity is comparable at the two altitude regions. This indicates that the leakage of disturbance energy from lower levels is not adequate to explain the observed disturbances in the region 23-35 km.

It may be noted that the region 23-35 km is where the number density of ozone reaches its maximum. Evidence is presented recently that ozone mixing ratio and temperature at ~2mbar level show fluctuations with quasi-periods in the range 3-5 weeks[23], with a fluctuation amplitude of about 8-10%. Using the heating rate of ozone at this altitude (~30 km) and the fluctuation amplitude of ozone, the fluctuating power density is estimated to be $\sim 7.5 \times 10^{-5}$ W/m^3. The power density of the zonal wind fluctuations observed at this altitude is $\sim 10^{-7}$ W/m^3 which is much less than the fluctuating component of power density (of heating) of ozone. Thus, the fluctuating component of ozone can be the generating agency of the observed wind fluctuations in the region 25-35 km as it has large enough power density compared to that of wind fluctuations. This aspect needs theoretical investigation to see whether indeed ozone fluctuations (or any other agency) can be the source for the zonal wind fluctuations.

The waves propagating downwards from suggested source region in 25-35 km would interfere with the upward propagating waves of tropospheric origin (which, according to theory, and earlier observations based on longer data periods, show downward phase propagation) and could disturb/alter their phase propagation characteristics. This may even lead to an upward phase propagation in the region below 25 km as is observed in the present investigation.

Kelvin wave activity is believed to be responsible for the westerly phase of the semi-annual oscillations in the upper stratosphere and above. Kelvin wave activity has been found in this region[8,12], but the characteristics of these are somewhat different from the Kelvin wave activity in the lower stratosphere which is responsible for the westerly phase of the QBO. There is also the problem of Kelvin wave propagations from lower stratosphere where they are strongly absorbed producing westerly phase of QBO to upper stratosphere with considerable strength to account for the SAO. These considerations point towards a source for upper stratosphere Kelvin wave activity which is different from that for the lower stratosphere Kelvin wave activity (tropospheric origin). The present observations lend strong support to this view with the source region for the upper stratospheric Kelvin wave activity in the altitude region 25-35 km.

The meridional wind long period component shows prominent phase fluctuations in the stratosphere giving a vertical wavelength of about 6 km in the stratosphere.

In the present investigation, it is found that, in general, phase propagation is seen only in regions of low wind variance and in regions of strong wind variance, the phase is more or less steady. Another interesting observation which has theoretical implications is that wind variance (both zonal and meridional) is less at SHAR, than at Balasore, a higher latitude station. This could be due to the mixing up of contributions from different types and modes of waves in the total variance.

The results of the present investigation have revealed certain departures from the earlier observations on equatorial waves and also opened up some interesting possibilities regarding the source region of the equatorial waves. The effect of the latitudinal gradients in the mean wind on the generation and propagation of the equatorial waves coupled with that arising due to longitudinal differences (e.g. due to influence of monsoon) needs detailed investigations theoretically and observationally. The changes in the characteristics of the disturbances due to reflection (partial), refraction and absorption as they propagate through the prevailing mean wind with strong wind shears need to be examined theoretically to understand the observed features.

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