Proc. Indian Acad. Sci. (Earth Planet. Sci.), Vol. 99, No. 3, September 1990, pp. 413–423.
© Printed in India.

Vertical structure and characteristics of 23–60 day (zonal) oscillations over the tropical latitudes during the winter months of 1986 – Results of equatorial wave campaign—II

R RAGHAVARAO[1], R SUHASINI[2], R SRIDHARAN[2a],
B V KRISHNAMURTHY[3] and O P NAGPAL[4]

[1] Present address: Code 614, Planetary Atmospheres Br., Goddard Space Flight Centre (GSFC), NASA, Greenbelt, MD 20771, USA
[2] Physical Research Laboratory, Navarangpura, Ahmedabad 380 009, India
[2a] For correspondence: Physical Research Laboratory, Navarangpura, Ahmedabad 380 009, India
[3] Space Physics Laboratory, Vikram Sarabhai Space Centre, Trivandrum 695 022, India
[4] Delhi University, Delhi 110 001, India

MS received 9 January 1990; reivsed 23 July 1990

Abstract. The equatorial wave campaign-II which formed a part of the Indian Middle Atmosphere Programme (IMAP), was conducted from SHAR (13·7°N, 80·2°E) from 15 January to 28 February 1986. Winds were measured from ground to 60 km by means of high altitude balloon and a meteorological rocket (RH-200), once everyday, for 45 days. The frequencies of the oscillations in the deviations of the east-west component of the winds from its mean at each height with one kilometer interval were obtained by the maximum entropy (ME) method and phases/amplitudes of these frequencies were determined by the least squares technique on the wind variation time series. The ME method has the inherent advantage of providing periodicities up to 1·5 times the data length.

The height structure of the long period waves of > 23 day periodicities that have larger amplitudes nearly by a factor of 2 as compared to the medium (9 to 22 day) or shorter period (4 to 8 day) ones, reveal two height regions of enhanced amplitudes, one in the troposphere and another in the upper stratosphere/lower mesosphere, that too, mostly in the regions of positive (westerly increasing or easterly decreasing with height) wind shears. The waves are seen to be inhibited in the negative wind shear regions. From the abrupt changes in the altitude variation of phase, the possible source region has been identified. The vertical wavelengths have been estimated to be 34 km and 19 km in the troposphere and lower stratosphere respectively and 8 km in the upper stratosphere and lower mesosphere. Around 56 km the wave amplitude is reduced to 1/4 of its value below, while the vertical shear strength in the mean wind doubled up. The tropospheric waves are suggested to be Rossby waves of extratropical origin penetrating to tropical latitudes. The stratospheric/mesospheric waves however appear to emanate from a source around the stratopause.

Keywords. Equatorial waves; vertical structure; 23–60 day period; zonal-oscillations; Indian Middle Atmosphere Programme; source regions.

1. Introduction

Atmospheric circulation in low latitudes is marked by the presence of several wave modes. In general Kelvin waves or Mixed Rossby waves (MRG) are the dominant wave modes. Recently Webster (1983) has shown that in the presence of westerlies, Rossby waves of extratropical origin could penetrate to lower latitudes. The Rossby gravity waves and the MRG waves propagate in the westward direction while the Kelvin waves propagate eastward. It was Madden and Julian (1971, 1972) who first reported the long period (40–50 days) oscillations in the troposphere followed by several other workers (Sikka and Gadgil 1980; Yasunari 1981; Gao and Standford 1987; Chen 1987 and the references therein). The oscillations in the temperature and wind fields were identified to be Kelvin waves. Observations in the stratosphere and mesosphere are scanty and the complete altitude profile starting from lower atmosphere extending to the mesosphere are not available.

In the present paper we report the detailed results of an equatorial wave campaign conducted in the winter months of 1986 from Sriharikota (SHAR 13·7°N, 80·2°E), a near equatorial station in India. Forty five RH-200 meteorological rockets and as many high altitude balloons were launched for the measurement of winds from 15 January to 28 February 1986. The uniqueness of these measurements is that a 'snap-shot' picture of the atmospheric wave activity form ground to 60 km is obtained.

2. Experimental details and presentation of data

One pair of high altitude balloon and a RH-200 rocket with chaff payload were launched in sequence, everyday, between 1700 and 1730 hours local time and were tracked by three radars (two C-band and one S-band). This combined set of measurements from the balloon and the chaff-release by the rocket yielded the wind profile from 1 to 60 km altitude each day. The method of raw data analysis to derive the winds and as well as the estimation of errors, is described by Krishnamurthy *et al* (1986). The wind profiles obtained from the three radars were in agreement upto 1 m/s all through the altitude of measurement and these are averaged at the respective height to obtain the mean profile that is taken as representative for that day.

Figure 1 depicts the 5-day running average of the zonal component ($\bar{U}$) of the measured winds at 2 km height intervals for the campaign period. Westerly wind is taken as positive on the Y-axis and the day number starting from 15 January represents the X-axis. It is clear from figure 1, that strong oscillations are observed in two height regions, i.e. 2–16 km in the troposphere and 30 to 60 km in the upper stratosphere/lower mesosphere with clear indication of downward phase propagation.

In order to identify the wave periods and their respective phases at different heights, we adopted a two-step procedure. In the first step the deviation of the zonal component $\bar{U}_h(t)$ with respect to the 45 day mean ($\bar{U}_h$) i.e. ($\bar{U}_h(t) - \bar{U}_h$) at each altitude h is considered as a time series in days (t) and is analysed by the maximum entropy (ME) method for the frequency component $f_{ih} \ldots f_{kh}(\text{day}^{-1})$ at any height h. The specific advantages of this method over the conventional methods (Blackmann and Tukey 1958) lies especially in analysing short length of data and these are discussed later. The data length being 45 days, the highest periodicity of waves that can be looked for by the ME method can be around 3/2 times the data length which is 67·5 days (Ulrych 1972). The lowest period is the Nyquist limit i.e. 2 days due to the data sampling rate of one measurement on each day.

The second step in the data analysis is to obtain the amplitudes P_i (m/s) and phases Q_i (measured in days) of those frequencies $f_i(\text{day}^{-1})$ at each height h. For this a

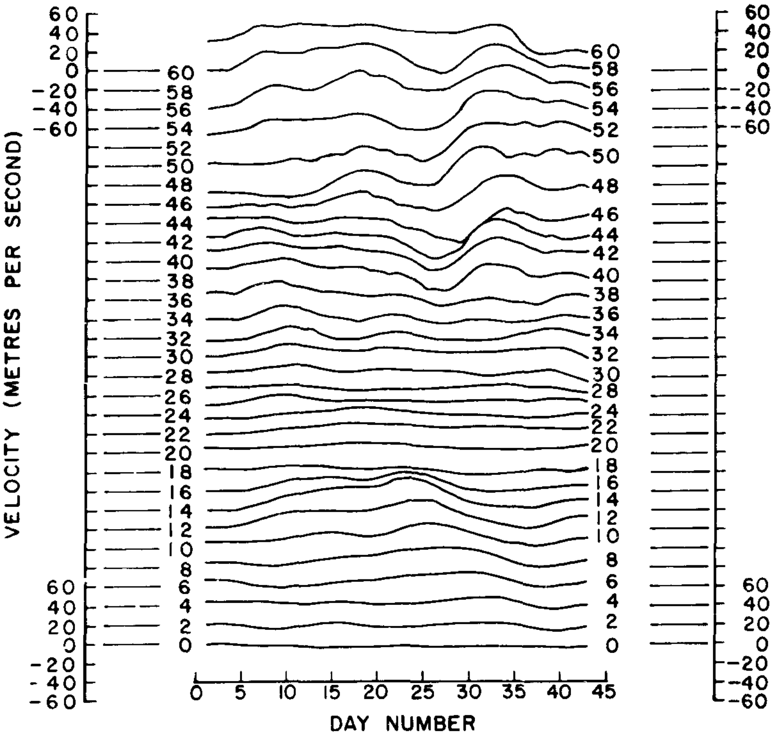

Figure 1. Five-day running average of the zonal component ($\bar{U}$) of the measured winds at every 2 km interval for the campaign period (Jan. 15 to Feb. 28). On the Y-axis westerly wind is treated as positive. On the X-axis Jan. 15 is denoted as the starting point.

regression model of the type

$$\bar{U}_h(t) = \bar{U}_h + (a_i \cdot \cos 2\pi f_i t + b_i \sin 2\pi f_i t) \pm e(t)$$

$$i = 1, 2 \ldots k$$

is adopted. $e(t)$ is the error component which is less than 10% of $\bar{U}_h(t)$ except in a narrow height region around 9 km where it is 40%. The parameters a_i and b_i for $i = 1, 2 \ldots k$ are estimated using the least squares technique. The amplitudes (P_i) and phases (Q_i) of different wave frequencies (or periods) are obtained as:

$$P_i = (a_i^2 + b_i^2),$$

$$Q_i = \arctan(-b_i/a_i).$$

Thus the zonal wind component $\bar{U}_h(t)$ at each height is represented by the mean wind $\bar{U}_h$ and the waves of different periodicities. The results of this analysis for the wave period of 23 days and above are plotted in figure 2. These are grouped together as they are the longest period (lowest frequency) waves at any particular altitude. The dots represent the wave amplitudes in m/s and the number just besides the dot represents the period of the wave approximated to the nearest integer value. The

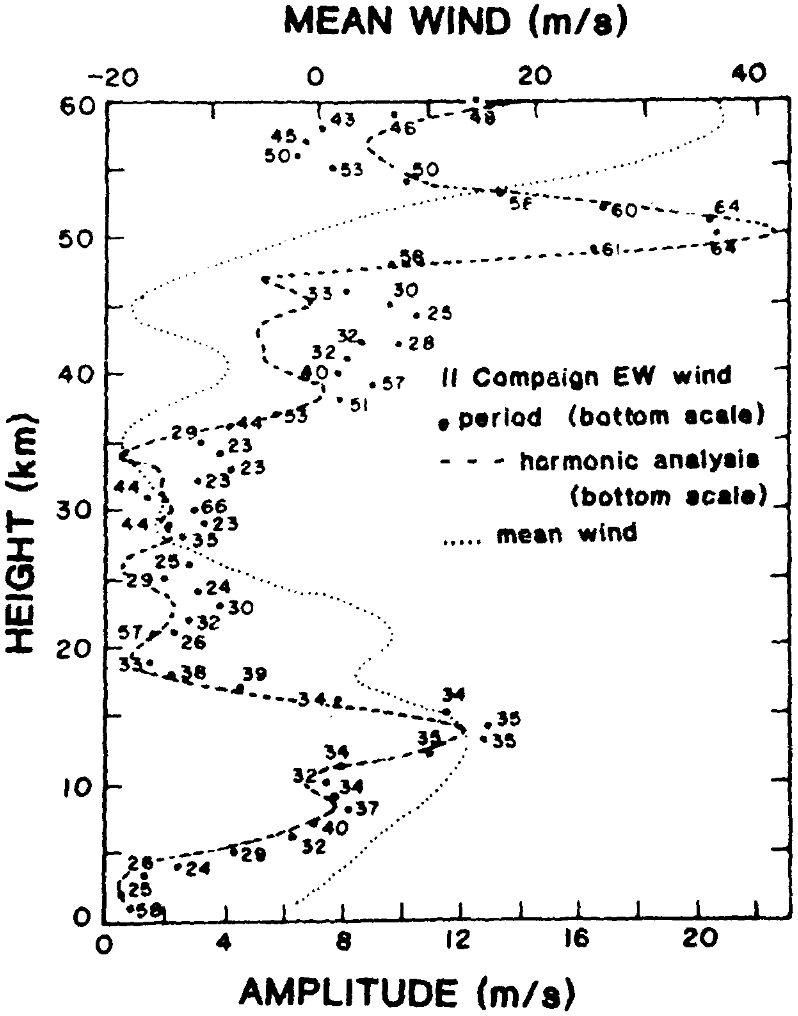

Figure 2. Variation of the amplitude of the long-period (> 23 days) waves with altitude. The dots and the adjoining numbers represent the amplitude and the corresponding period as obtained by the ME method. The thin dotted curve (....) represents the mean zonal wind for which the scale is provided at the top of the panel. The dashed curve (----) represents the amplitude obtained from the harmonic analysis for a fundamental frequency of 45-days.

dashed line represents the results obtained from harmonic analysis of the same data sample corresponding to a period of 45 days. The dotted (thin) curve represents the mean zonal wind $\bar{U}_h$ for which the scale is given on the X-axis at the top of the diagram. The westerly component of the mean zonal wind is shown as positive and easterly as negative. The mean wind is westerly from 2·5 to 23 km altitude and turns to easterly higher above. It remains so up to 51 km with a sharp switchover to westerlies at 52 km. $\bar{U}_h$ shows a westerly maximum of 13 m/s in the upper troposphere, an easterly maximum of 19 m/s at 35 km and again a westerly maximum of 38 m/s at 58 km.

3. Wave characteristics

The waves in the troposphere reveal that they grow from near zero value at 2·4 km to a maximum amplitude of about 13 m/s at 14 km. A secondary maximum of 8 m/s around 8 km is also noticeable. It decreases to 2 m/s at the tropopause ($\sim$ 17 km). The wave amplitudes are quite small in the altitude region of 18 to 35 km with a recognizable maximum of 4 m/s at 23 km. Above 35 km the amplitude increases with height to a maximum of 20·5 m/s at 50 km. There is a sharp fall in amplitude to 6 m/s at 56 km followed by a steep increase to 12·6 m/s at 60 km.

The composite picture of both mean wind and wave amplitude, as depicted in figure 2 indicates that the amplitude of the wave tends to be associated with the regions of positive (westerly increasing or easterly decreasing with altitude) wind shears. Steep increases are seen around 5 km, 35 km and 50 km. The only exception to this being the decrease of wave amplitude to 6 m s^{-1} at 55 km from its amplitude of 20·5 m s^{-1} at 50 km, while the positive shear strength of the mean wind, as noticed from the mean wind amplitude, had increased from 3·6 m/s/km to 7·85 m/s/km in the same height region. This appears to be a region where the waves impart momentum to the mean wind.

The height structure of the phase variation of the waves observed in the present campaign is depicted in figure 3. Similar to the wave amplitude diagram dots represent the phase angles in terms of number of days; reckoned from the start of the campaign for the wave amplitude maximum to occur at the corresponding altitudes, while the number above the dot represents the periods. The thin dotted line is the mean wind profile as in figure 2. A systematic decrease of phase with height is seen up to 20 km with a small maximum located at 4 km. Sudden spurts in phase are recorded thrice between 20 and 30 km. At lower altitudes i.e. at 2,3 and 4 km, the phase corresponding to the periods determined by the ME method, is shifted by one cycle i.e., by 2π radians mainly on the basis of the trend in the phase variations with altitude higher above. This is done as one cannot distinguish between θ and $\theta + 2\pi$. Different slopes of phase variations could be seen in atleast four height regions namely (i) 1–20 km, (ii) 21–30, (iii) 34–40 km and (iv) 55–60 km respectively. From these slopes the vertical wavelength λ_z of the waves of mean period in these height regions are estimated to be 34 km, 19 km in the troposphere and lower stratosphere respectively and 8 km in the upper stratosphere and lower mesosphere.

4. Discussion

To bring out the hidden periodicities in any given sample power spectral analysis methods are needed. The two methods that are often used, are, the periodogram method (Jones 1965) and the autocorrelation method (Blackman and Tukey 1958). These methods make rather unrealistic assumptions about the extension of the data outside the given data interval. Periodogram assumes a periodic extension of the data, whereas autocorrelation method assumes zero extension. Both these methods use window functions which are independent of the data to have a smooth spectrum. Maximum entropy (ME) method (Burg 1967, 1970) makes no such assumptions about the data extension and does not have a fixed window function. In fact, it may be taken that the window function adapts itself into the spectrum of the noise under

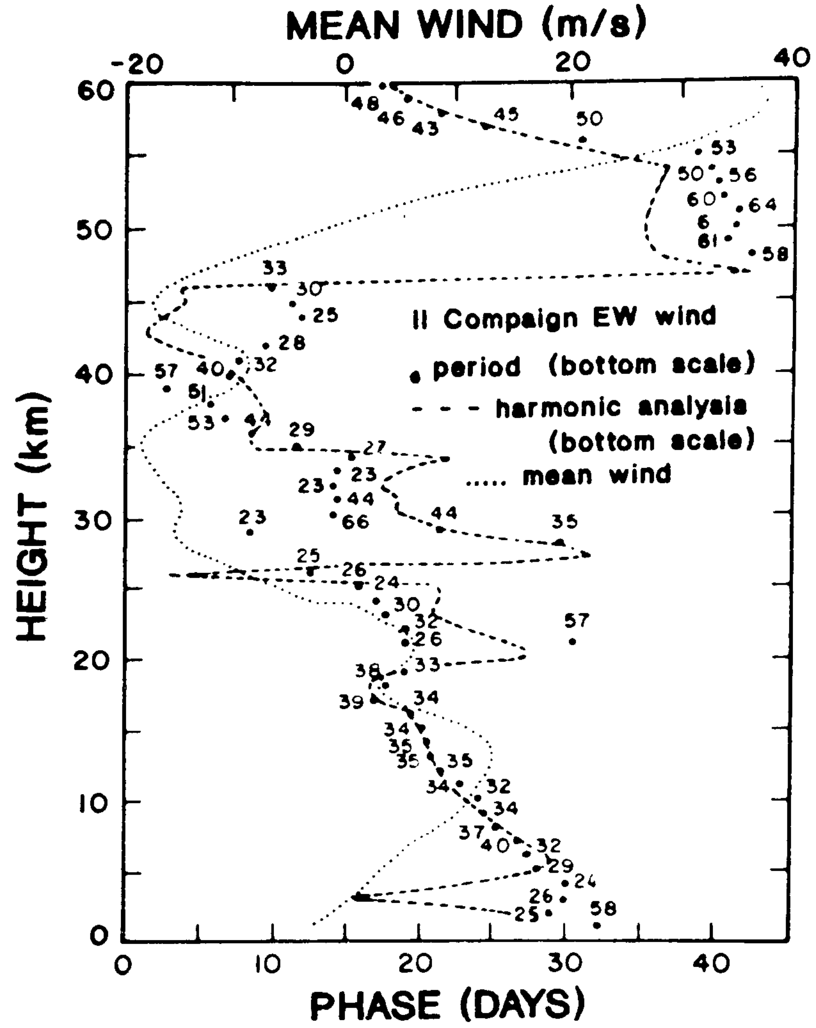

Figure 3. Altitude variation of the phase of the measured long period waves. The notations are as in figure 2. The thin dotted line represents the measured wind.

study (Lacoss 1971). In addition ME method spectra have higher resolution than the Blackman-Tukey method and achieves this resolution for a smaller number of weights (lags). Further, whenever the period is longer than the length of the data, the conventional methods show the spectral power maximum at zero frequency whereas the ME method tries to locate the spectral power maximum in the low frequency end even with a data length of only 0·58 times the period (Ulrych 1972). These considerations made the choice, of the ME method for the analysis of the present data set, more suitable. This method is described and compared extensively with other conventional methods in literature (Smylie *et al* 1973; Ulrych and Bishop 1975; Radoski *et al* 1975, 1976; Fougere 1977). As a crosscheck the present data set was subjected to analysis by Blackman-Tukey method with a slightly higher lag number than is usually allowed. The frequency components obtained in this case are almost the same as those obtained by the ME method but with a much lesser resolution. Figures 4 and 5 depict a comparison of these results by the two methods at two different altitude ranges. It should be noted that in our present analysis no unstable results were obtained inspite of the usage of a large number of lags sometimes extending to even 2/3rd of the period. Further, the dashed lines in figures 2 and 3 are the results

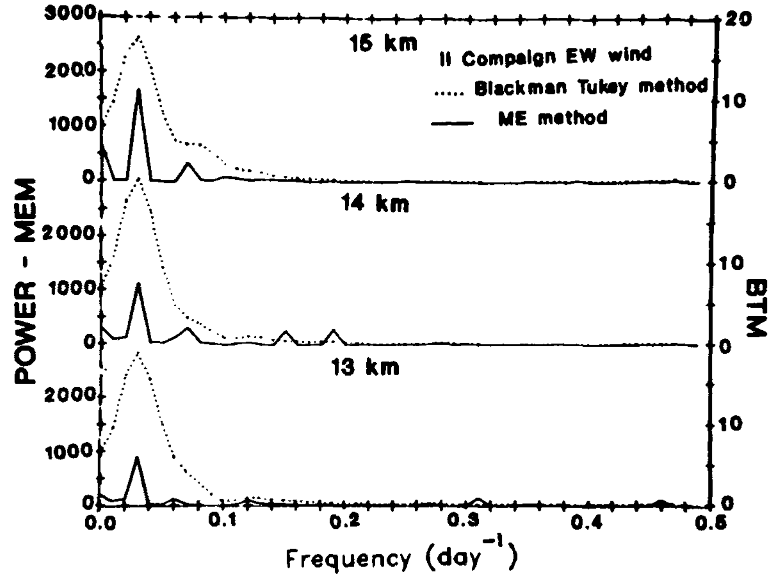

Figure 4. Frequency components obtained by two independent methods: namely the Blackman-Tukey method and the ME method, for the altitude region of 13 to 15 km.

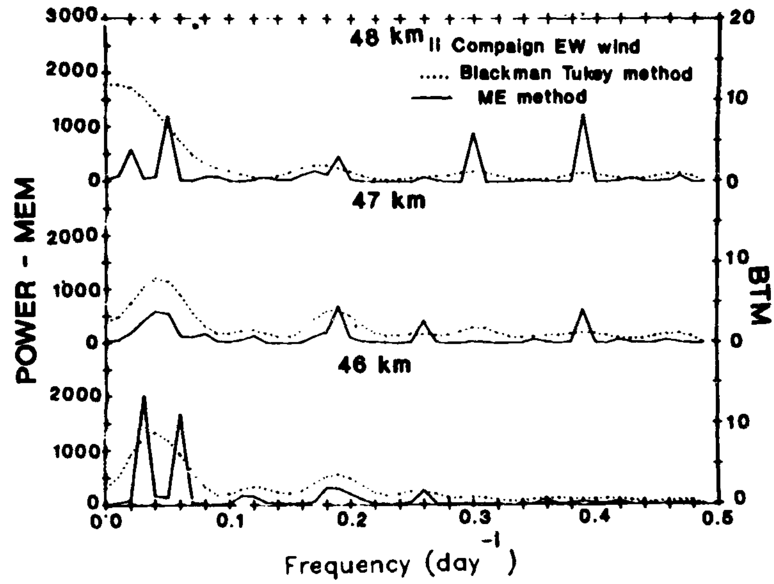

Figure 5. Same as in figure 4 for the altitude region of 46 to 48 km.

obtained from subjecting the data to harmonic analysis for the 45-day period which is the fundamental period for our observations. The excellent agreement on the overall features of the amplitudes and phases of the wave components between the ME method and the harmonic analysis and, the higher resolving capacity of the ME method are amply demonstrated through these comparison.

Coming back to the main results presented in this paper, they concern only with waves of longer periodicities i.e. > 23 days. In general, from our observations, these waves were noticed to have twice as large the amplitudes of the 9–22 day (say medium) periodicities. Wave periods less than 9 days (short periods) had still smaller amplitudes. Detailed discussions on the shorter period (< 23 days) waves will be presented in a separate communication. The observed characteristics of the long-period wave modes in the troposphere indicate that these may be different from the Kelvin or MRG waves. MRG waves are known to be 4–5 day periods only, with shorter vertical wavelength (4–8) km). Though Kelvin waves are known to have such large periodicities they still have vertical wavelengths of 6–10 km only (Wallace 1971; Hirota 1979). However, recent investigations by Zhang and Webster (1989) have revealed that the fundamental effect of the basic state is only to Doppler-shift the wave frequencies and alter the meridional structure in terms of equatorial trapping, thus making it possible for these wave modes to exist even in the presence of a westerly mean flow, which incidentally is the case during the course of the measurements. Further the long vertical wavelengths of 34 km in the troposphere could be generated through the barotropic mode that causes the interaction between the tropics and the extra-tropics in westerlies.

Another possibility is that these may be due to Rossby waves originating in the extratropical regions and penetrating deep into the tropics or vice versa. This suggestion is favoured by the presence of westerlies in the entire troposphere in the vicinity of the latitude of measuremens. Recent studies by Webster and Holton (1982) and Webster and Chang (1988) show that Rossby waves can indeed propagate from mid-latitudes deep into tropical latitudes as long as the mean zonal wind is westerly in the troposphere. The nature of the meanwinds in the latitude region of 8°N to

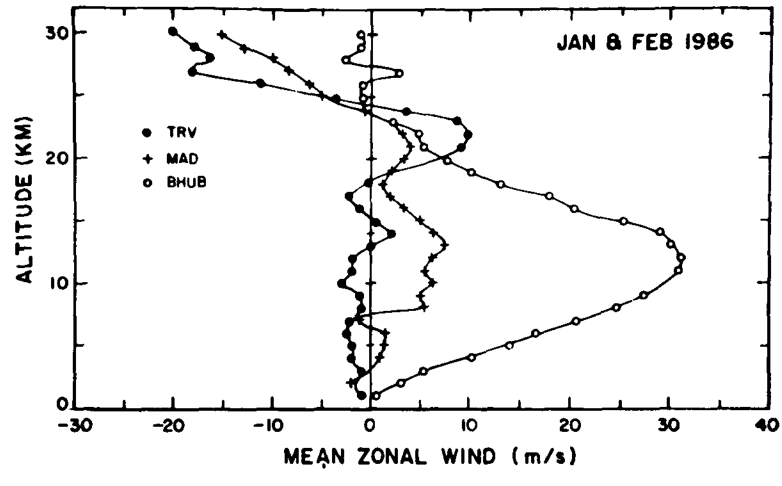

Figure 6. Nature of the mean winds in the latitude belt of 8°N to 21°N for the campaign duration, as obtained from high altitude balloon launchings.

21°N was looked into and figure 6 depicts the same obtained by high altitude balloon measurements for the entire period of observations from three locations: Bhubaneshwar (20·3°N, 85·9°E), (Madras (13·1°N, 80·3°E) and Trivandrum (8·5°N, 77·5°E). The presence of westerlies in the troposphere at SHAR (13·7°N) makes it conducive for the penetration of Rossby waves. Hence the suggestion.

As regards the large amplitude of the wave activity at the upper stratosphere, the classification is still open. It is well known that only the shorter period waves originating in the troposphere might escape into the stratosphere (Holton 1975) and therefore the presence of such large amplitude long-period waves is possible only when a localized source region exists. This aspect is discussed in the following.

5. Source region

The upward propagation of energy is indicated by the linear decrease of phase with altitude from ground consistent with the known behaviour of the planetary waves. From the variation of phase with altitude, a possibility for another source region to be present below 30 km exists. The wave amplitude increases above 35 km from its near zero value in the region of 25–30 km (figure 2), while the phase (figure 3) decreases up to 40 km from a nearly constant phase in 30–35 km height region. In the altitude region of 40–46 km both phase and amplitude vary in consonance. At 46 km something interesting happens. While both phase and amplitude registered a sudden increase, the amplitude continues to increase to a maximum around 50 km while the phase remains steady up to 55 km and decreases beyond. From these considerations the source for the mesospheric waves appears to be at about 46 km. As this is the height region where the reversal of the temperature with altitude occurs, the phase variations and their possible affiliation to the temperature reversal needs to be investigated by numerical simulation of the propagation characteristics. Further, it should be noted that the altitudewise distribution of various periodicities shows a clear-cut feature. Below 30 km the wave components are dominated by periods less than 40 days while above 30 km the longer periods (> 40 day) are dominant. The exact cause for such behaviour along with the difference in the dominant periods by a day or two within one or two kilometers all along the altitudes is also puzzling. These aspects need further investigation.

6. Conclusion

The results of the rocket campaign on the characteristics of various wave modes in the tropical latitudes during the winter months of 1986 reveal two height regions of enhanced wave activity, one in the troposphere and another in the lower mesosphere. From the observed behaviour, the tropospheric waves are suggested to be Rossby waves of extratropical origin penetrating to tropical latitudes. This suggestion has the limitation that the available data length is only 45 days, that too from a single station and it is difficult to firmly conclude that extra-tropical interactions do occur on the long period variations reported in the paper. The higher altitude waves seem to originate in the stratosphere with a possible source region located at 46 km. In the altitude region of 50–60 km the wave appears to impart momentum to the mean wind.

Acknowledgements

Our thanks are due to the equatorial wave campaign teams at Vikram Sarabhai Space Centre, Trivandrum and SHAR Centre, Sriharikota and the IMAP team, Bangalore for the successful operations. We thank the Chairman, Indian Space Research Organisation for sanctioning the rockets and the Director General, India Meteorological Department for the balloons. The constant encouragement received from Professors A P Mitra, R R Daniel and P D Bhavsar is duly acknowledged. The computational assistance provided by Miss Ranna Patel is highly appreciated. This work is supported by the Department of Space, Goverment of India.

References

Blackman R B and Tukey J W 1958 *Measurement of power spectra from the point of view of communications engineering* (New York: Dover)

Burg J P 1967 Maximum entropy spectral analysis; *Paper presented in the 37th meeting Soc. Explor. Geophys.*, New Orleans

Burg J P 1970 New concepts in power spectra estimation; *Paper presented in 40th meeting Soc. Explor. Geophys.*, New Orleans

Chen T C 1987 30–50 Day Oscillation of 200-mb Temperature and 850-mb height during the 1979 Northern Summer; *Mon. Weather Rev.* **115** 1569–1605

Fougere P S 1977 A solution to the problem of spontaneous line splitting in maximum entropy power spectrum analysis; *J. Geophys. Res.* **82** 1051–1054

Gao X H and Stanford J L 1987 Low frequency oscillations of the large-scale stratospheric temperature field; *J. Atmos. Sci.* **44** 1991–2000

Hirota I 1979 Kelvin waves in the equatorial middle atmosphere observed by the Nimbus 5 SCR; *J. Atmos. Sci.* **36** 217–222

Holton J R 1975 The Dynamic Meteorology of the Stratosphere and Mesosphere; *Meteor. Monogr.* **37** (Amer. Meteor. Soc.)

Jones R H 1965 A reappraisal of the periodogram in spectral analysis; *Technometrics* **7** 531–542

Krishnamurthy B V, Indukumar S, Raghava Reddi C, Raghavarao R and Rama G V 1986 Results of equatorial wave campaign of IMAP in May-June 1984; *Indian Radio Space Phys.* **15** 125–138

Lacoss R T 1971 Data adaptive spectral analysis methods; *Geophysics* **36** 661–675

Madden R A and Julian P R 1971 Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific; *J. Atmos. Sci.* **28** 702–708

Madden R A and Julian P R 1972 Description of global-scale circulation cells in the tropics with a 40–50 day period; *J. Atmos. Sci.* **29** 1109–1123

Radoski H R, Fougere P S and Zawalick E J 1975 A comparison of power spectral estimate and application of the maximum entropy method; *J. Geophys. Res.* **80** 619–625

Radoski H R, Zawalick E J and Fougere P S 1976 The superiority of maximum entropy power spectrum techniques applied to geomagnetic micro pulsations; *Phys. Earth Planet. Int.* **12** 208

Sikka D R and Gadgil S 1980 On the maximum cloud zone and the ITCZ over Indian longitudes during South west monsoon; *Mon. Weather Rev.* **108** 1840–1853

Smylie D E, Clarke G K S, Ulrych T J 1973 Analysis of irregularities in the earth's rotation; *Meth. Comput. Phys.* **13** 391–430

Ulrych T J 1972 Maximum entropy power spectrum of truncated sinusoids; *J. Geophys. Res.* **77** 1396–1400

Ulrych T J and Bishop 1975 Maximum entropy spectral analysis and auto regressive decomposition; *Rev. Geophys. Space. Phys.* **13** 183–200

Wallace J M 1971 Spectral studies of tropospheric wave disturbances in the tropical western Pacific; *Rev. Geophys. Space. Phys.* **9** 557–612

Webester P J 1983 Large-scale structure of the tropical atmospheres; *Large scale dynamical process in the* atmospheres (ed) B J Hoskins and R P Pearce (London: Academic Press) pp. 235–275

Webester P J and Chang H R 1988 Equatorial energy accumulation and emanation regions: Impacts of a zonally varying basic state; *J. Atmos. Sci.* **45** 803–829

Webester P J and Holton J R 1982 Cross equatorial response to mid latitude forcing in a zonally varying basic state; *J. Atmos. Sci.* **39** 722–733

Yasunari T 1981 Structure of an Indian summer monsoon system with around 40 day period; *J. Meteor. Soc. Jpn.* **59** 336–354

Zhang C and Webester P J 1989 Effects of zonal flows on equatorially trapped waves; *J. Atmos. Sci.* **46** 3632–3652