Indian Journal of Radio & Space Physics
Vol. 27, December 1998, pp. 247-259

Investigation of gravity waves in the atmospheric boundary layer using sodar and microbarograph

K Krishna Reddy*, T R Vijaya Kumar, S Vijaya Bhaskara Rao, P Kishore† and D Narayana Rao
Department of Physics, Sri Venkateswara University, Tirupati 517 502

Received 10 December 1997; revised 3 September 1998; accepted 10 October 1998

Presence of irregularities and irregular motions in the atmospheric boundary layer (ABL) have been detected and studied by a variety of techniques, including sodars and microbarographs. The infrasonic pressure variations have been recorded at Tirupati using a microbarograph. Wave motions associated with temperature inversions in ABL are studied using an acoustic sounder and a microbarograph. Two-year investigation of waves and wave perturbations in low-level inversions in the atmosphere over Tirupati valley region are reported. A detailed study on wave motions in terms of diurnal variation, seasonal variation, occurrence percentage and amplitude of the wave motion associated with different structures in ABL is made. Simultaneous study of the nature of waves in the atmosphere is made using echosonde and microbarograph data. Gravity waves are mostly observed in this region during winter and premonsoon seasons due to temperature inversions and thunderstorms. In order to characterize the wave nature and to study the effect of their motions occurring mostly at nighttime stable conditions, cross-correlation and power spectral density technique have been applied.

1 Introduction

Various processes in the troposphere tend to generate gravity waves with periods between a few minutes and a few hours. Gravity waves play an essential role in dynamic processes of the troposphere and upper atmosphere[1]. Several studies of the behaviour of gravity waves in the boundary layer were carried out[2-4]. From these studies it was concluded that more measurements are necessary in various geographical locations so as to establish a climatology of gravity waves under various meteorological events such as fronts, low-level and tropospheric jet streams, local wind shear, temperature inversions and storms. In the atmospheric boundary layer (ABL), oscillatory motions are often observed in association with stable stratified layers[5]. The study of gravity waves is important for understanding the dynamics of many micro- and mesoscale processes in the planetary boundary layer (PBL). Gravity waves interact with many processes such as turbulence, diffusion, local flows and inversions[6]. Evidence of atmospheric gravity waves propagating in PBL is also common in sodar records[7-9]. Keliher[10] utilized microbarograph to detect many atmospheric phenomena which can shed light on the wave motion mechanism in the lower atmosphere. Hauf *et al.*[11] utilized a ground-based network for atmospheric pressure fluctuations. They reported gravity waves, frontal passages, positive and negative solitary waves and turbulent wind situations that can be identified from the pressure signals.

Gravity waves usually propagate horizontally without transmitting their energy to great heights. Theoretically it can be shown that they require more than a low-level inversion[12]. Gravity waves in ABL were observed by McAllister *et al.*[13] in the nocturnal radiation inversion using a monostatic sodar. Hall *et al.*[14] observed gravity wave structures in the nocturnal inversion and noted that strong wind shear at the top of the inversion may have induced dynamic instability in the inversion layer, resulting in oscillation in the stable cold air below. Hooke *et al.*[15] noticed that these undulations are a major dynamical feature of the stable ABL, which at nighttime may contain waves of a broad range of temporal and presumably spatial scales, from periods of a few minutes to oscillations of the entire boundary layer on periods of several hours (IST). Monostatic acoustic sounders have several limitations in offering definite interpretation to the observed waves and

---

*Presently at Communications Research Laboratory, Tokyo, Japan.

†Presently at Kyoto University, Kyoto, Japan

instabilities, especially, with regard to the velocity and direction of propagation. The facsimile records alone give little quantitative information other than the wave period and a somewhat indirect measure of wave amplitude. They yield no information on wavelength, phase velocity, the wave-associated momentum and energy transports, all of which must be known if the role of the waves in the boundary layer dynamics is to be properly understood. To obtain some of this missing information with echosounder equipment, a microbarograph is used to study the nature of gravity waves. Gossard *et al.*[16] investigated gravity waves with concurrent wind data and microbarograph data, and concluded that these waves have periods of the order of 10 min, wavelength of a few kilometres, and amplitudes of about 100 m. Emmanuel *et al.*[17] observed waves in the lower atmosphere with an acoustic sounder. The generation of gravity waves by shear instability and the association of such waves with clear-air turbulence in elevated layers using sodar and surface microbarograph arrays were monitored by Frisch *et al.*[18] Greene and Hooke[19] also observed that gravity waves are generated by shear instability in the temperate-latitude troposphere. Direct evidence of turbulence caused by gravity wave motions in the lower atmosphere was provided by Lilly[20]. Nevertheless, study of atmospheric dynamic structure with the help of a single sodar located in the Tirupati valley revealed interesting features of ABL phenomena.

In this paper an attempt has been made to characterize the wave perturbations observed over Tirupati. A better insight into the boundary layer dynamics is achieved by supplementing the acoustic data with microbarograph data collected at the same time. Gravity waves observed during various meteorological events such as temperature inversions and storms are also discussed.

2 Atmospheric gravity waves

The atmosphere moves ceaselessly on scales ranging from the dimension of the earth down to mean free path of individual air molecules. Acoustic sodar can observe processes like jet streams, frontal zones and atmospheric gravity waves, and small-scale processes like Kelvin-Helmholtz instability and turbulence preferably at scales equal to half the sodar wavelength. All these processes interact nonlinearly, e.g. winds can enhance gravity waves and gravity waves can accelerate winds (wave-mean flow interaction) or gravity waves at a given wavelength and period can enhance gravity waves at other wavelengths and periods (wave-wave interaction). It is difficult to discuss the whole variety of atmospheric motions with single instrument; therefore, we will confine the studies to some basic aspects of mesoscale and small-scale gravity waves and instability mechanisms.

Remote sensing devices using microwaves or acoustic waves have often been used to provide documentation for special case studies of waves and turbulence within the nocturnal inversion layer[21]. It has been observed that most of the time the wave motions are regular and periodic with periods of the order of a few minutes. The most common waves in ABL are gravity waves. These waves may have periods ranging from a few minutes to several hours[22]. Gravity waves, in general, are generated by shear instabilities in the boundary layer flow, with the boundary layer becoming unstable at the height of the observed waves[23,24]. Besides shear instability, convective cells penetrating into a stable layer, storm systems and fronts may also generate gravity waves with scales ranging from a kilometre to a few tens of kilometres.

2.1 Nature of infrasonic pressure variations

Atmospheric waves are characterized by variations in the wind speed, atmospheric density and atmospheric pressure. Therefore, besides the direct visual evidence for atmospheric waves that is afforded—for example, by mountain wave clouds, it is possible to determine the existence of the waves by measuring small changes in atmospheric pressure produced during the passage of a wave. This is done by using a microbarograph that is capable of measuring pressure changes of the order of a few microbars[25]. Microbarograph records show random variations due to infrasonic pressure fluctuations. The origin of these microbaroms (pressure variations of a few microbars) has been explained as originating from interfering ocean waves in the marine storm areas. Microbaroms originating over the ocean can be received at distant ground-based stations after one or more upper-level reflections[26]. If an adequate and continuous microbarom source is present, short-interval variations in signal strength can be related to variations in temperature or wind or both at the reflection level[19]. Gedzelman[27] in his study for one year of gravity waves shows that there is a distinct minimum activity at periods about 1 and 3 min in the pressure spectra obtained through microbarograph. This enables us to distinguish between higher and lower frequency oscillations (caused due to turbulence). The oscillations with periods greater than 3 min are taken as gravity waves in the present study.

Microbarograph can detect and measure small amplitude pressure fluctuations occurring with periods of a few seconds to several tens of minutes and has been used for years to detect the acoustic signals from explosions, severe weather, aurora and other natural sources. However, on certain nights infrasonic variations are present in spite of a strong inversion and no-wind conditions. These variations must, therefore, be an indicator of the dynamic state of the upper atmosphere (beyond the probing range of the acoustic sounder). The microbarograph provides data on the wave amplitude, wave period, horizontal phase speed and direction of propagation and horizontal wavelength.

3 Experiment

To study various features of the atmosphere, a monostatic acoustic sounder (sodar) is developed at Sri Venkateswara University, Tirupati, India, and is operated at a frequency of 2.2 kHz. The system transmits a 50-ms burst of sound every 6 seconds (inter-pulse period) using a 1.9-m parabolic dish. The backscattered signal is recorded by the same antenna and using a facsimile recorder. Sodar system characteristics are given elsewhere[29]. Sodar monitors the dynamics of the thermal structure of ABL from the ground up to an altitude of about 1km. Simultaneously, the infrasonic pressure variations are recorded at Tirupati (50 m from the sodar site) using a microbarograph operating in the 0.001-2.0 Hz range. The equipment (microbarograph) is essentially a linear capacity-type microphone and the range of pressure variations noted is ± 1 mbar. With this objective, the two techniques are deployed to study the characteristics of wave motions in the boundary layer over Tirupati in southern India.

4 Site description and data base

Tirupati (lat. 13° 40′ N, long. 79° 27′ E) is located at the foothills of the Tirupati range of Cuddapah formations in the eastern coastal plains at an elevation of 170 m above msl. It is bounded by ridges to the north and to the south, and thus is in a valley. The data recorded from January 1988 to December 1989 have been used for the present study. The nature of wave motions over Tirupati is studied for both diurnal and seasonal behaviour. The seasons are classified as winter (December-February), premonsoon (March-May), monsoon (June -September) and post-monsoon (October and November). In order to carry out these studies, surface meteorological data (temperature, relative humidity and wind velocity) collected at Agronomy Department, Sri Venkateswara Agricultural College, Tirupati (situated at a distance of about 700 m from the sodar site) for the aforesaid period are used. The nearby radiosonde stations are at Chennai, Bangalore and Hyderabad and their radial distances are 100 km, 300 km and 650 km, respectively, from Tirupati. Hence, the distributions of Brunt-Vaisala frequency and Richardson number are not possible to calculate, which are fundamental parameters to detect the nature of the gravity waves. However, Chennai radiosonde data from January 1988 to December 1989 have been used to study the low level temperature inversions with respect to the general gravity wave characteristics. Because of this limitation we have not focused much on the quantitative analysis of gravity wave activity in PBL over Tirupati region.

5 Statistical characterization of gravity waves observed over Tirupati

The occurrence of wave motion is observed as a sinusoidal-like periodicity associated with an elevated/multiple-elevated layer, ground-based inversion or lifting inversion. Absence of such sinusoidal periodicity indicates the absence of such wave motions. Analysis of sodar echograms over a period of two years (January 1988 to December 1989) shows that the wave motions with characteristic oscillations mostly occurred in ABL at Tirupati under the conditions of nocturnal radiative inversion. These wave-like structures are mostly superimposed on stable nocturnal radiative inversions, mostly occurring between midnight and dawn. Diurnal variation in the occurrence of wave motions is shown in Fig. 1(a). It is observed that the occurrence percentage of wave motions starts increasing from 0000 hrs IST, attains a maximum value of the order of 12 % at around 0400 hrs IST, and then decreases rapidly. From 1200 hrs IST to 1600 hrs IST the occurrence of wave motions is almost negligible. During the evening hours (1800-0000 hrs IST), the occurrence of wave motions is of the order of 2-8 %. The occurrence percentage of wave motions with respect to the wave period (min) for different structures observed from sodar is shown in Fig. 1(b). It is observed that 17 % of elevated and multiple elevated layers (EL/MEL) are responsible for the wave motions with periods up to 10 min. The seasonal distribution of the occurrence percentage of wave motions is presented in Fig. 1(c). The occurrence percentage of wave motions is maximum in winter, followed by premonsoon, monsoon and postmonsoon seasons. Figure 1(d) shows the diurnal variation of the magnitude of infrasonic pressure variations observed over Tirupati. This shows the random variations of infrasonic pressure with daytime showing higher amplitude than nighttime. From Fig. 1(d) it can be observed that during nighttime pressure, fluctuations remains suppressed as the prevailing inversions suppress the vertical mixing. After sunrise, the convection builds up below the capping inversion, causing the infrasonic pressure variations to grow, which ultimately attain maximum in their magnitude in the afternoon. Sodar is monitoring the structure of the lower atmosphere both during day and nighttime during

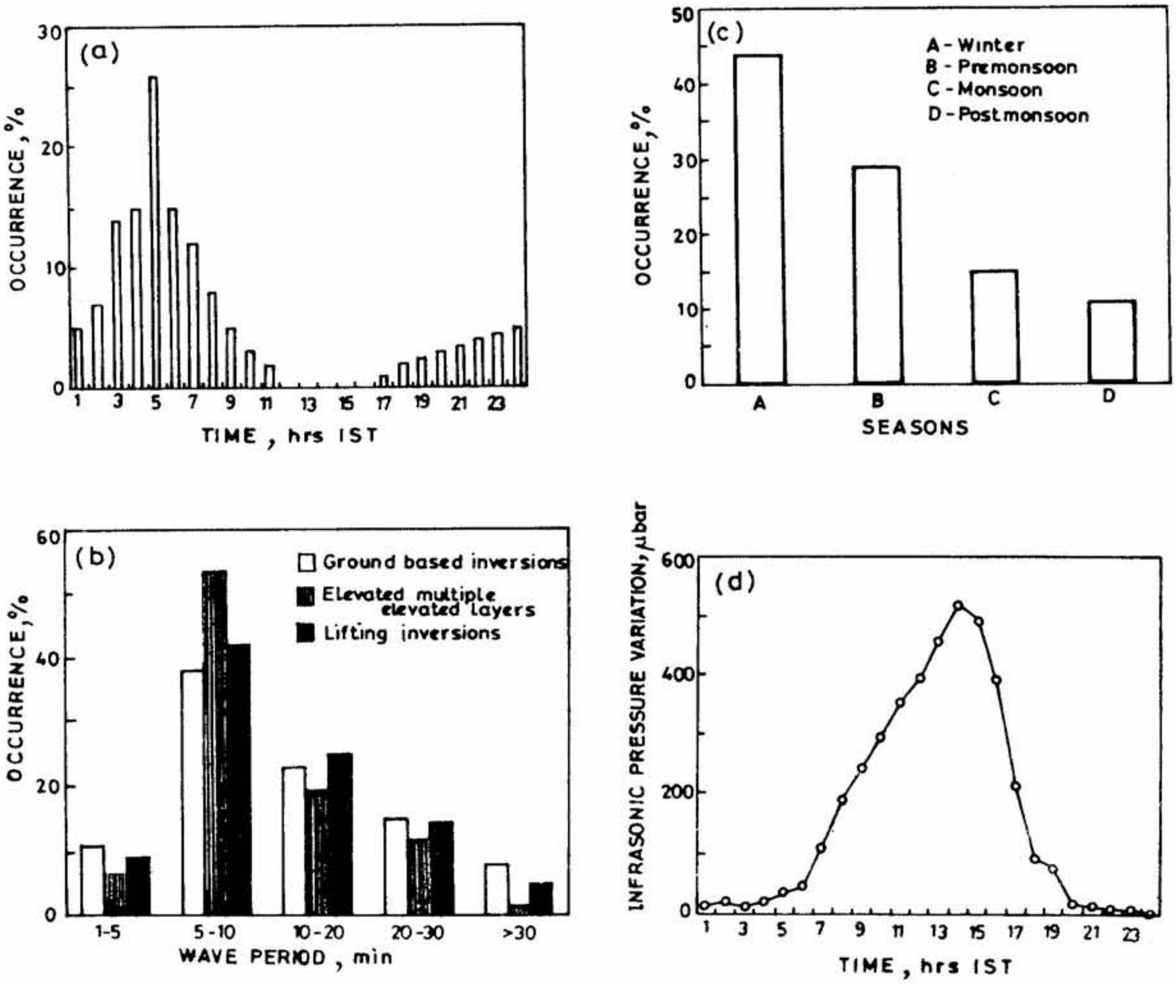

Fig. 1—(a) Histograms showing the (a) diurnal variation of occurrence percentage of wave motions (b) occurrence percentage of sodar structures for different wave periods (min) of wave motions, (c) seasonal variation of occurrence percentage of wave motions and (d) curve showing the diurnal variation of the magnitude of infrasonic pressure variations

the observational period. The nighttime atmospheric structures have shown high degree of variabilities as (i) the presence of ground based-inversion of variable thickness, (ii) the appearance of highly variable elevated/multiple elevated layers, (iii) the wave motions within and above the inversion and (iv) the turbulence structure. All these contribute towards the maximum variability in the nighttime atmosphere. Waves and wave perturbations have been noticed many times on the sodar echograms under stable atmospheric conditions.

Stilke[28] have experimentally shown that the pressure and wind variations together with gravity waves in low-altitude temperature inversion layers can be sensed at ground level. We utilized sodar, microbarograph and radiosonde data (obtained from the nearest radiosonde station, Chennai, at 0000 hrs GMT and 1200 hrs GMT) to investigate the monthly variation of wave motions over this region. As Tirupati is away from sea-breeze influence, an evaluation of two years of measurements was made with a microbarograph and we found pressure waves 8.7% of the time. Figure 2 shows the monthly variation of the occurrence of wave motions from microbarograph, sodar and low-altitude temperature inversions for a period of two years. As depicted in Fig. 2 the wave motions observed from sodar echograms, pressure fluctuations (waves) obtained from microbarograph and temperature inversions seen from radiosonde show similar trend during the observational period.

An acoustic echo sounder and microbarograph are deployed to study the oscillatory behaviour of wave motions in the stable boundary layer. Simultaneous observation of wave periods (from sodar echograms) and pressure fluctuations (from microbarograph data) is illustrated in Fig. 3 which shows a linear relationship between wave period and pressure fluctuations. A good/high correlation between wave period and pressure fluctuations is observed.

Figure 4 shows the occurrence percentage of sodar structures associated with wave motions in different height ranges and infrasonic pressure fluctuations. From Fig.4 it is evident that elevated and multiple-elevated layers, lifting inversions and ground-based inversions in the height range 100 - 250 m are dominant in their occurrence. The wave

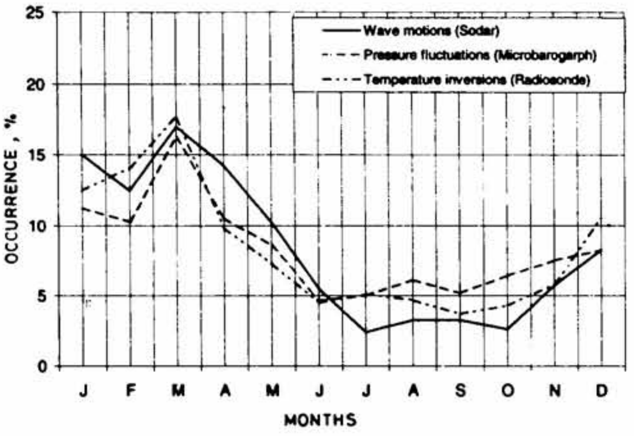

Fig. 2—Curves showing the comparison of monthly occurrence of wave motions (sodar), pressure waves (microbarograph) and of temperature inversions (radiosonde) from January 1988 to December 1989

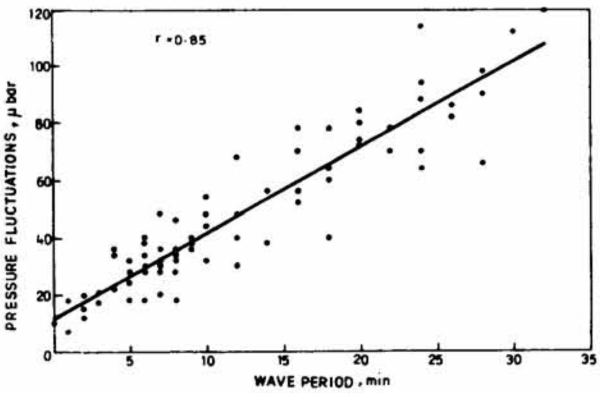

Fig. 3—Plots of wave periods versus pressure fluctuations

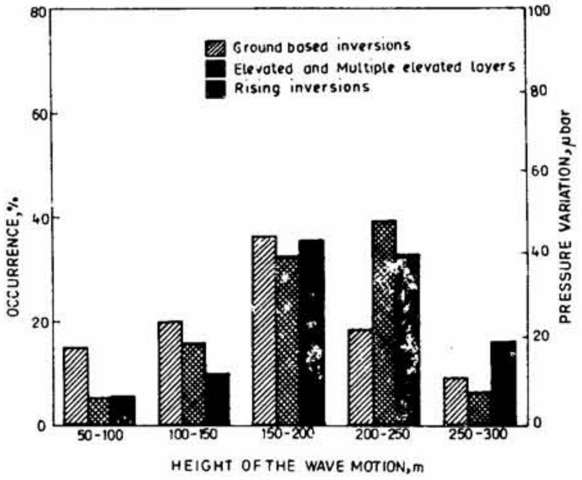

Fig. 4—Histograms showing the occurrence percentage of sodar structures for different heights of the wave motion and infrasonic pressure fluctuations

motions in this height range have pressure fluctuations in the range of 45-125 μbar. The occurrence of gravity waves in the 50-100 m and 250-300 m height ranges is less as compared to that in the height range of 100-250 m during the two years of observational period.

6 Simultaneous study of gravity waves using sodar and microbarograph

Stable layers are commonly perturbed by buoyancy (gravity) waves generated by many natural sources including convection cells, travelling disturbances such as weather fronts, flow perturbations due to topographic features, and the jet stream and its fluctuations. These perturbations are always associated with ground based or elevated inversions. Some typical records of wave motions (gravity waves) observed from sodar and microbarograph are shown in Fig. 5. Gravity waves are often caused by a travelling boundary between two types of air of different density. If the velocity of travel is of proper magnitude relative to the height and intensity of the inversion and the slope of the boundary, such a travelling disturbance can cause an internal wave train to be generated in its wake. This type of tropospheric wave train is short, lasting less than 2 h. The microbarograph records observed on 6 Sep. 1988 are found to be very regular and essentially sinusoidal in character. It is a fair weather phenomenon, rarely associated with storm fronts. An example of sodar recording is also shown in the upper panel of Fig. 5(a).

Figure 5(b) shows wave motions observed on sodar and microbarograph on 13 Jan. 1988. Sodar echogram shows usual laminated structure characteristic of the stable atmospheric boundary layer, and wave-associated undulations in the strata of strong echo returns from 0100 hrs IST onwards. Of particular interest here is a change in the character of the record beginning at about 0130 hrs IST. This change manifests itself in the appearance of the wave motions, and this can be observed in the microbarograph record.

Under strongly stratified conditions, sodar records commonly reveal a multiple-layer fine structure as seen in Fig. 5(c). Layers such as these are often very regularly spaced vertically, and Gossard *et al.*[29] also showed that these thin zones of strong acoustic returns are also common zones of sharp gradients in temperature and/or humidity.

6.1 Analytical studies of wave patterns

Visual examination of sodar echograms and microbarograph records shows that both the systems can detect the wave motions under various atmospheric processes in ABL. To investigate whether sodar and microbarograph system have been detected/affected the same wave phenomena, the lagged cross-correlation function has been utilized under the following assumptions:

(i) The differences in the system characteristics/parameters are ignored. The time series data of the sodar and microbarograph are only focused.

(ii) The wave motions observed from sodar and microbarograph will be fairly similar and will be associated with a time shift existing between two time series of the data.

(iii) The wave propagation is quite dispersive and the wave parameters are changing very rapidly.

With the above assumptions, we applied lagged cross-correlation on the 3-h time series of sodar and microbarograph data and the results are shown in Fig. 6. Figure 6 reveals that both the sodar and microbarograph are able to detect gravity-wave motions present in elevated/multiple elevated inversions, lifting inversions and ground-based inversions even during intervals when the boundary layer itself is convectively unstable. Apparently, the maximum cross-correlation coefficient will be occurring at a specific time lag which represents the time shift between sodar and microbarograph time series. By definition, if the lag is positive, the sodar data leads microbarograph, and vice versa. As indicated in the Fig. 6, the time delays between sodar and microbarograph data on 11 Feb.1988, 18 Feb. 1988 and 27 Nov.1989 are –2 min, 2 min and 1 min, respectively.

In order to characterize these wave motions, a detailed analytical study is made. For the purpose of analytical study of gravity waves, the data observed on 11 Feb.1988, 18 Feb. 1988 and 27 Nov. 1989 are chosen (as shown in Fig. 7). Calibrated shades/scale of the sodar echograms are utilized to study the wave activity over Tirupati. For the power spectral analysis, 64-min data with 1-min sampling time and 64 data points are

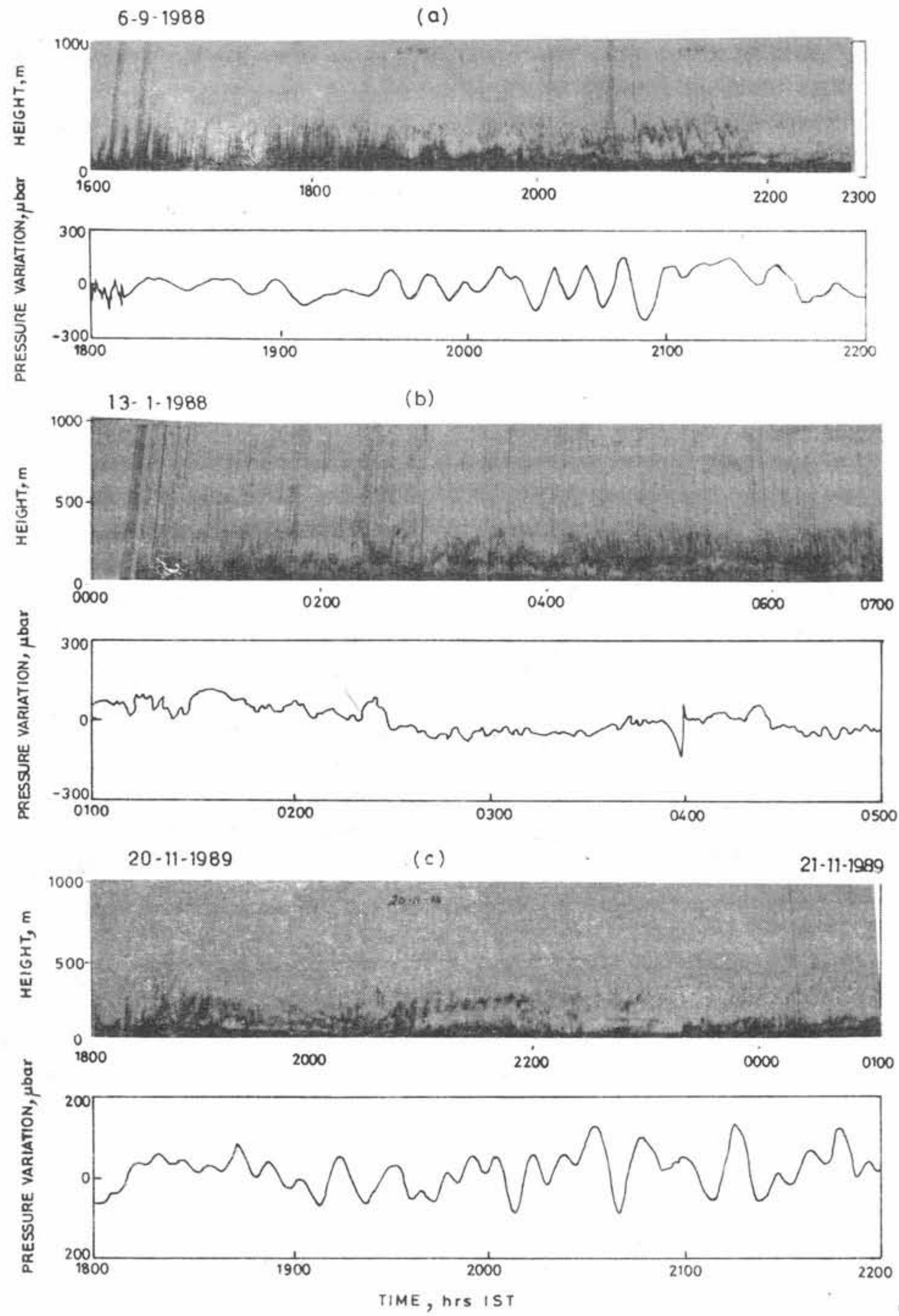

Fig. 5—Records of gravity waves using sodar and microbarograph during different meteorological conditions such as local wind variations, storms and temperature inversions on (a) 6 Sep. 1988, (b) 13 Jan. 1988 and (c) 20-21 Nov.1989

utilized. Fourier analysis is performed for assessing the nature as well as the dominant frequencies of the wave form observed on 11 Feb. 1988, 18 Feb. 1988 and 27 Nov. 1989 and this result is shown in Fig.8 as power spectral density plot. However, the surface meteorological conditions prevailing around the wave perturbation time are tabulated in Table 1 and the overall results of these analyses are given. The details of the result of the Fourier analysis and background meteorological phenomena are discussed briefly.

Rain was recorded in the midnight before the start of wave perturbations occurring around 0300 hrs IST on 18 Feb. 1988. From the spectral analysis the dominant frequency of 0.00098 Hz with an overall periodicity of the order of 17 min is observed during 0445-0549 hrs IST. The surface meteorological data obtained from S V Agricultural College, Tirupati, about 700 m from the sodar site have indicated pressure and velocity enhancement by 2 mbar and 5 km/h, respectively. Figure 7(a) shows wave motions observed on sodar and microbarograph on 17-18 Feb. 1988. Height range of the propagating waves is within 100-750 m. This type of phenomena is generally associated with tropospheric storms and synoptic scale features[29]. On 18 Feb. 1988, Rao *et al.*[30] observed thermal inversion with oscillatory behaviour. Krishna Reddy[31] showed that the oscillations of long duration are usually generated by storms and frontal disturbances and the presence of stable layer in the lower atmosphere. This situation constitutes an accurate description of the atmospheric state when a frontal surface lies overhead. Therefore, increased gravity wave activity is often a sign of either approaching warm fronts or passing cold fronts.

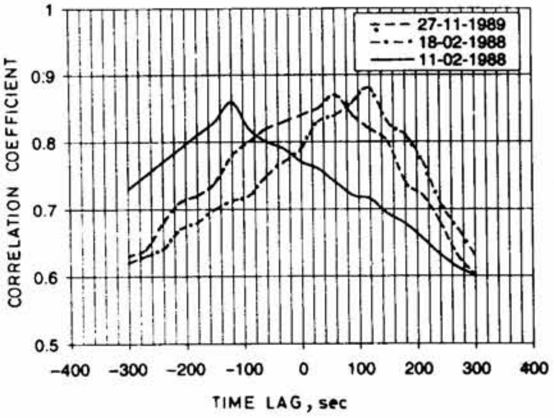

Fig. 6—Cross-correlation of sodar and microbarograph time series data on different dates

There was a neutral condition of atmosphere to the formation of wave perturbations during 0506-0610 hrs IST on 11 Feb. 1988. Wave motions, at that time, are superposed on a very shallow inversion layer. Corresponding meteorological data show increase of pressure by 1mbar and sharp-fluctuations of wind velocity from 4 to 10 km/h were observed. The wave motions are almost sinusoidal in nature having distinct peaks with peak-to-peak amplitude variation of about 50 m. The wave motion has a single dominant frequency of 0.0016 Hz with a period of about 10 min only.

Similarly, prior to the wave perturbation on 27 Nov. 1989, a severe thunderstorm with a wind

Table 1—Results of analytical studies of gravity waves using sodar echograms and surface meteorological data

		Date and Time (in hrs IST)		
Type of data	Meteorological parameters	18 Feb.1988 0445-0549	11 Feb. 1988 0506-0610	27 Nov.1989 1600-1704
Sodar data & weather condition	---------	Multiple elevated layers Rain on night Cloudy	Lifting inversion Clear sky Mild wind	Ground-based inversion Thunderstorm Strong wind
Surface data	Surface wind velocity	9 km/h	4 km/h	17 km/h
	Velocity fluctuations	Sharp, 3 - 7 km/h	Almost nil	Sharp 3-13 km/h
	Pressure fluctuations	+ 1.2 mbar	+ 0.6 mbar	+ 0.9 mbar
	Surface temperature changes	−1.5 °C	−1.0 °C	+ 1.5 °C
	Relative humidity changes at surface	− 5%	+ 6%	− 4%
Computed values	Dominant frequency (/ies)	9.8×10^{-4} Hz	1.6×10^{-3} Hz	4.8×10^{-4} Hz 1.6×10^{-3} Hz
	Periodicity	About 17 min	About 10 min	About 10-35 min

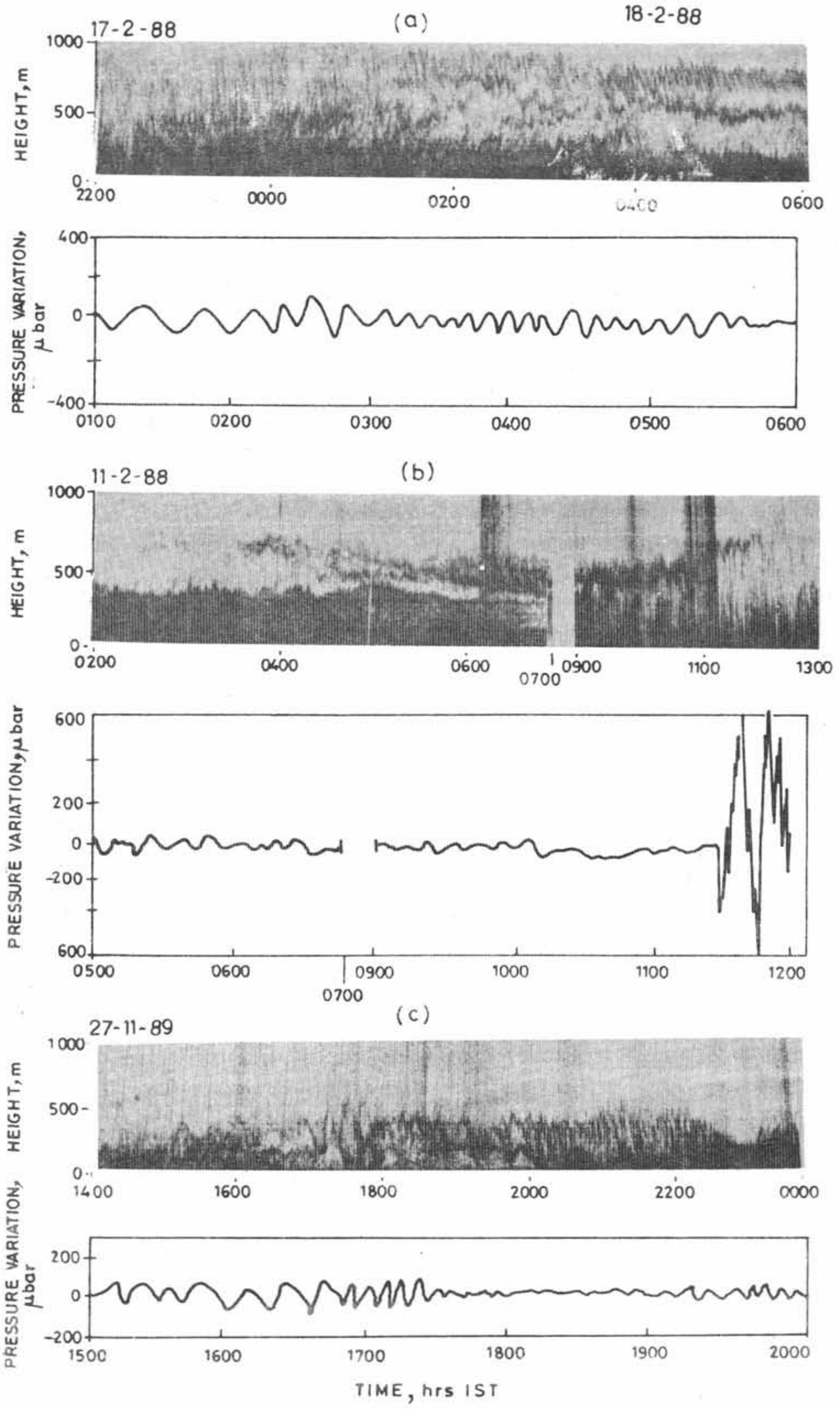

Fig. 7—Simultaneous study of wave motions (a) associated with elevated layers, (b) ground-based inversions and (c) various types of waves using sodar and microbarograph data

speed of 40 km/h was recorded around afternoon. On 27 Nov. 1989 two dominant frequencies of 0.0016 Hz and 0.00048 Hz (Fig. 8) with periodicity of 10 min to about 38 min is observed during 1600-1704 hrs IST from the spectral analysis. Gravity waves from thunderstorms have been detected at the ground level by a number of researchers[32,33] using microbarograph. The exact mechanism of generation of acoustic and gravity waves by thunderstorms is far from clear. However, we have used the surface wind, pressure and temperature data during the wave activity. The possible mechanism is the instability associated with strong wind shear. Also, forced waves may exist due to intense convection and liberation of latent heat[12].

Atmospheric gravity waves are frequently observed on microbarograph recordings. The spectrum of periods measured by microbarograph ranges from 10^{-1} to 10^{5} s. The high frequency, generally, non-periodic noise is due to turbulence, whereas the low frequency portion of the pressure spectrum is characterized principally by the semi-diurnal and diurnal tides. Within the narrow band of periods (between 5 and 10 min), uniform sinusoidal oscillations in the pressure variation appear[34] frequently. These are the results of tropospheric gravity waves. Convection and the influence of nearby weather system produce rather more irregular fluctuations with periodicity of 15 min to 1 h. The vertical fluctuations in the temperature can also form waveguides within the atmospheric wave system and can become ducted and propagate its energy over very large distances. For the spectral analysis, 64 min data with one-minute sampling time and 64 data points are utilized. The spectrum of waves on microbarograph records observed on 18 Feb. 1988 (0445-0549 hrs IST), 11 Feb. 1988 (0506-0610 hrs IST) and 27 Nov. 1989 (1600-1704 hrs IST) were sorted into its frequency components and the results are displayed in Fig. 9. In the analysis, waves with periods less than 3 min or longer than 2 h are filtered out for the spectral plot. From Fig. 9, the band of tropospheric gravity waves is clearly observed.

7 Summary of results

Study of wave motions in ABL is made using an echosonde and microbarograph, which are capable of detecting many atmospheric phenomena. The observational results can be summarized as follows:

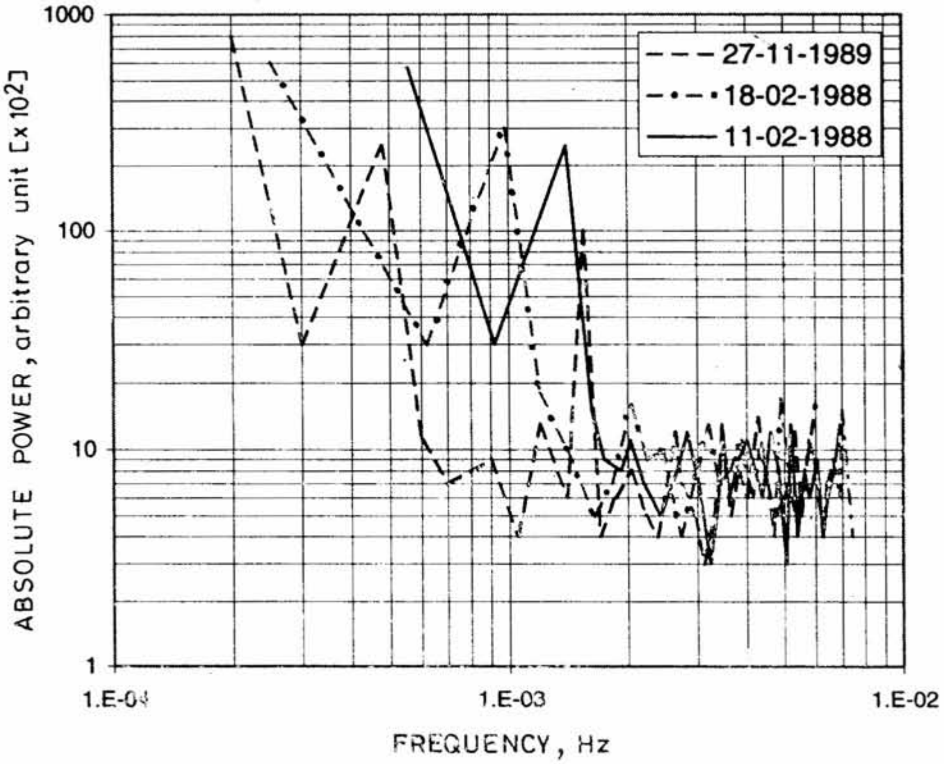

Fig. 9—Spectral plot of wave perturbations on different dates

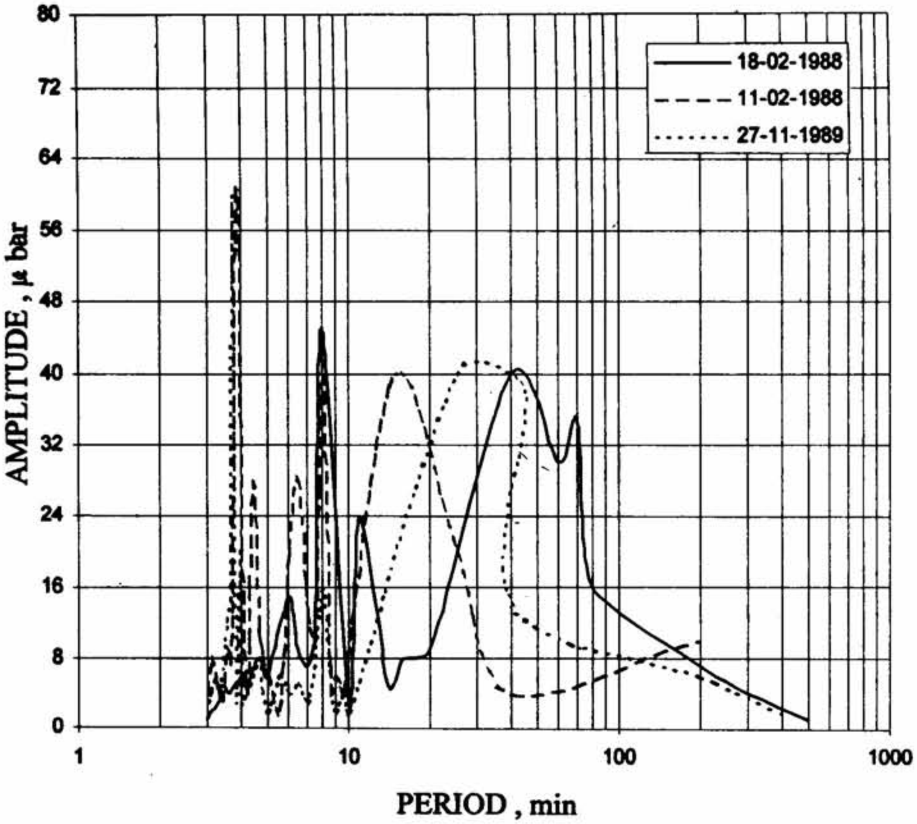

Fig. 9—Frequency spectrum estimation from the microbarograph data on different dates

(i) Statistical analysis shows that wave motions are usually associated with ground-based inversions, elevated layers/multiple elevated inversions or lifting inversions in ABL. The wave motions are mostly observed during nighttime with maximum occurrence during the early morning hours (IST). The morning lifting inversions and evening cold fronts may also contribute, to some extent, to the observed wave motions. A detailed study of wave motions in terms of diurnal variation, occurrence percentage, wave periods in ABL are made using an echosonde. It is observed that most of the time the wave motions are regular and periodic with periods of the order of a few minutes.

(ii) The studies outlined above provide insight into the climatological behaviour of the waves. Diurnal and seasonal variation of wave activity occurrence is maximum during winter months when the winds aloft are the strongest and the static stability of the lower troposphere is the highest on an average. The occurrence of wave activity is maximum between midnight to dawn and minimum during mid-afternoon because of the diurnal variation of stratification.

(iii) Analysis of microbarograph records shows random variations of infrasonic pressure with daytime records having higher amplitudes than those observed during nighttime. Daytime amplitudes continue increasing after sunrise, presumably, due to convective heating.

(iv) A comparison between microbarograph records and sodar echograms shows the occurrence of wave motions with characteristic oscillations mostly occurred in the boundary layer at Tirupati under the conditions of nocturnal radiative (ground-based) inversion, lifting inversion, elevated/multiple elevated layers and thunderstorms.

(v) To investigate if sodar and microbarograph systems have been detected/affected the same wave phenomena, the lagged cross-correlation function has been utilized with some assumptions. The study shows that sodar and microbarograph are able to detect gravity wave motions present in elevated/multiple elevated inversions, lifting inversions and ground-based inversions even during intervals when the boundary layer itself is convectively unstable.

(vi) Spectral analysis of sodar echograms shows the low level gravity waves with a periodicity of 10-35 min.

(vii) The frequency spectral analysis of microbarograph also indicates the existence of tropospheric gravity waves in this region.

8 Conclusions

Atmospheric gravity waves are frequently observed on sodar echograms and microbarograph recordings during the observational period. The waves investigated in this paper have typical periods from 10 to 35 min. Although it seems to be a characteristic of gravity waves that no one mechanism affords a complete explanation for their behaviour, many of the waves seem to be generated by low level inversions/thermal inversions and thunderstorms.

Most of the energy in meso- or smaller scales is due to internal gravity waves in the free atmosphere and it has been recognized that they play a significant role in the dynamics of such scales. Although climatological knowledge of gravity waves is limited, there is still enough evidence to suggest that for substantial periods of time they prevail in the atmosphere. As they generate significant Reynolds stresses, they may be considered as important for the overall evolution of ABL, especially, at night. Largely due to the lack of VHF/UHF radar (during the observational period) and upper air data in the vicinity, only the synoptic implications of such findings were stressed. It is encouraging to see that the sodar facsimile records and the microbarograph data appear to give a reasonably consistent picture of the low level gravity wave activity in ABL.

Acknowledgements

The authors are highly thankful to Dr H N Dutta and Dr R Venkatachari (retired) of the National Physical Laboratory, New Delhi, India, for their keen interest in this work and also for providing the microbarograph for the studies. They wish to thank the Director of the India Meteorological Department Observatory, Madras, for providing radiosonde data. The financial support extended by the Council of Scientific and Industrial Research (CSIR), Govt. of India, to two of the authors (KKR and P K) in the form of research fellowships is gratefully acknowledged. Thanks are due to the authorities of Sri Venkateswara University, Tirupati, for providing necessary facilities to carry out the research work.

References

1 Bull G A, *Z Meteorol (Germany)*, 35 (1985) 73.
2 De Bass A F & Driedonks A G M, *Bound-Layer Meteorol (Netherlands)*, 31 (1985) 303.
3 Finnigan J J, *J Atmos Sci (USA)*, 45 (1988) 486.
4 Coulter R L, *Bound-Layer Meteorol (Netherlands)*, 52 (1990) 75.
5 Eymard L & Weill A, *Bound-Layer Meteorol (Netherlands)*, 17 (1979) 231.
6 Bull G & Neisser J, *Appl Phys B Photophys and Laser Chem (Germany)*, B57 (1993) 3.
7 Beran D W, Hooke W H, & Clifford S F, *Bound-Layer Meteorol (Netherlands)*, 4 (1973) 133.
8 Ottersten H, Hardy K R, & Little C G, *Bound-Layer Meteorol (Netherlands)*, 4 (1973) 47.
9 Einaudi F & Finnigan J J, *J Atmos Sci (USA)*, 50 (1993) 1841.
10 Keliher T E, *J Geophys Res (USA)*, 80 (1975) 2967.
11 Hauf T, Finke U, Neisser J, Bull G & Stangenberg J G, *J Atmos & Ocean Tech (USA)*, 13 (1996) 1001.
12 Lindzen R S & Tung K K, *J Atmos Sci (USA)*, 31 (1974) 800.
13 McAllister L G, Pollard J R, Mahoney A R & Shaw P J R, *Proc IEEE (USA)*, 57 (1969) 579.
14 Hall F F (Jr), Wescott J W & Simmons W R, *Acoustic echo sounding of the atmospheric thermal and wind structure*, in *Proceeding of 7th International Symposium on Remote Sensing of Environment*, Univ. of Mich.USA, 1715-1732, 1971.
15 Hooke W H, Hall F F & Gossard E E, *Bound-Layer Meteorol (Netherlands)*, 6 (1973) 371.
16 Gossard E E, Richter J H & Atlas D, *J Geophys Res (USA)*, 75 (1970) 3523.
17 Emmanuel C B, Bean B R, McAllister L G & Pollard J R, *J Atmos Sci (USA)*, 29 (1972) 886.
18 Frisch A S, Chadwick R B, Moninger W R & Young J M, *Bound-Layer Meteorol (Netherlands)*, 10 (1976) 55.
19 Greene G E & Hooke W H, *J Geophys Res (USA)*, 84 (1979) 6362.
20 Lilly D K, *J Atmos Sci (USA)*, 40 (1983) 749.
21 Van Zandt T E, *Radio Sci (USA)*, 55 (1985) 1323.
22 Hooke W H, Young J M & Bearn D W, *Bound-Layer Meteorol (Netherlands)*, 2 (1972) 371.
23 Gedzelman S D & Rilling R A, *Mon Weather Rev (USA)*, 106 (1978) 196.
24 Stull R B, *J Atmos Sci (USA)*, 33 (1976) 1279.
25 Beer T, *Atmospheric Waves* (Adam Hilger Ltd., Bristol, England, U K), p. 300, 1974.
26 Venkatachari R & Bhartendu, *Indian J Radio & Space Phys*, 8 (1979) 273.

27 Gedzelman S D, *Mon Weather Rev (USA)*, 111 (1983) 1293.

28 Stilke G, *Bound-Layer Meteorol (Netherlands)*, 4 (1973) 493.

29 Gossard E E, Gaynor J E, Zamora R J & Neff W D, *J Atmos Sci (USA)*, 42 (1985) 2156.

30 Narayana Rao D, Krishna Reddy K, Ravi K S, Rao S V B, Murthy M J K, Dutta H N, Sarkar S K & Reddy B M, *IEE Proc H: Microw Antennas & Propag (UK)*, 138 (1991) 313.

31 Krishna Reddy K, *Remote sensing of the troposphere and studies on microwave propagation characteristics over Southern India*, Ph D Thesis, S V University, Tirupati, India, 1991.

32 Uccellini L W, *Mon Weather Rev (USA)*, 103 (1975) 497.

33 Balachandran N K, *Mon Weather Rev (USA)*, 108 (1980) 804.

34 Narayana Rao D , Krishna Reddy K, Vijaya Kumar T R, Bhaskara Rao S V & Dutta H N, *Indian J Radio & Space Phys*, 23 (1994) 259.