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Statistical characterization of thermal inversions observed over Tirupati using sodar and microbarograph

K Krishna Reddy, T R Vijaya Kumar & D Narayana Rao
Department of Physics, Sri Venkateswara University, Tirupati 517 502

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A monostatic acoustic sounder (sodar) has been developed for the study of dynamical behaviour of the atmospheric boundary layer (ABL) phenomena over Tirupati. The infrasonic pressure variations have been recorded near sodar site using a microbarograph. A systematic study is made on ABL phenomena (over inland region) using sodar and microbarograph. Ground-based inversions and elevated layers have been observed to be predominantly the nighttime phenomena. Statistical analysis of ground-based inversions, elevated inversions, wave motions and rising inversions is made along with the variations in their heights of occurrences. Simultaneous observations of ABL using sodar and microbarograph are made. Some of the case studies are presented.

1 Introduction

Acoustic sounding has emerged as the most effective technique to monitor the dynamics of thermal structures in the lowest 1 km of the atmospheric boundary layer[1] (ABL). It plays a significant role in the fields of communications, air pollution, aviation, etc. Sodar observations of ABL reveal a variety of echo patterns on the facsimile records which are representative of the time of the day and location where the study is made and environmental conditions[2,3]. Several types of temperature inversions such as ground-based inversions, elevated layers, wave motions and rising inversions are observed[4,5] in ABL. McAllister[6] was the first to describe the ground-based wind shear layer, noting its frequent similarity to a herringbone structure. The shear instabilities within such layers were examined by Emmanuel *et al.*[7].

In India, the monostatic acoustic sounding system is being used by several research groups for the study of ABL phenomena. Table 1 shows the locations of monostatic acoustic sounders (sodar) operating at different places in India for ABL studies. The studies on infrasonic pressure fluctuations were mainly confined to the study of pressure fluctuations originated due to man-made or natural events like atomic explosions, tornadoes and cyclones[8]. Also these fluctuations can be utilized for characterizing the ABL phenomena. The sodar and microbarographs have been used over the years to study the ABL phenomena[9-11]. Beran *et al.*[12] have utilized acoustic echo-sounding technique and microbarograph for the study of gravity-waves, turbulence and stability. Finnigan[13] carried out a stability analysis and made a detailed study of the turbulence budgets for stable event in ABL. For the present study, the sodar and microbarograph techniques form a comprehensive system to study the characteristic features of the thermal inversions over Tirupati.

2 Site description and data base

Tirupati (lat. 13°40'N, long. 79°27'E) is located on the foot-hills of the Tirupati range of Cudda-

Table 1—Monostatic acoustic sounders operated at different locations in India

Place and location	Nature of the study
National Physical Laboratory, New Delhi	Nocturnal thermal boundary layer structures, air-pollution and radiopropagation
Central Pollution Control Board, New Delhi	Air pollution studies
Andhra University, Waltair	Coastal boundary layer studies
Punjabi University, Patiala	Atmopheric boundary layer studies
Indian Statistical Institute, Calcutta	Coastal boundary layer and radio propagation studies
Sri Venkateswara University, Tirupati	Studies on atmospheric boundary layer studies, radiopropagation and environmental impact assesment (EIA)
Guwahati University, Guwahati	Studies on ABL and radiopropagation

pah formations in the eastern coastal plains at an elevation of 170 m above mean sea level. It is bounded by ridges to the north and to the south, and thus is in a valley. The data recorded with the monostatic sodar at Tirupati during the period January-December 1988 forms the data base for the present study to monitor the ABL phenomena. The data have been studied for both diurnal and seasonal behaviour. The seasons are classified as premonsoon (March, April and May), monsoon (June, July, August and September), postmonsoon (October, November) and winter (December, January and February). The infrasonic pressure variations are recorded near the sodar site using a microbarograph operating in 0.001-2.0 Hz range. Sodar and microbarograph systems' descriptons are given elsewhere[14].

3 Thermal inversions

In acoustic sounding technique, recognition of a pattern or identification of the signature of the atmospheric phenomena is important[15,16]. Various types of atmospheric structures are observed on sodar echograms, which give complete information about the height, depth and period of existence of convection/inversions[17] in ABL.

From sodar observations it has been found that several types of temperature inversions exist in the lower atmosphere[18]. The most frequent ones are the ground-based inversions, caused by the radiative cooling of the earth's surface at night. The thickness of the ground-based inversions usually ranges from several tens of metres to within a few hundred metres from the surface at night. Elevated layer and multiple elevated layers may also occur and sometimes cause inversions based above the ground. The earth is heated up at sunrise, resulting in convection near the ground which pushes up the ground-based inversions formed at night. The phenomenon starts an hour or so after the sunrise and continues for 3-4 hr before the rising inversions get completely mixed up with the atmosphere at certain altitude.

Figure 1 shows various types of atmospheric structures observed on sodar echograms recorded at Tirupati. The sodar echograms give the time-height record of the atmospheric structure in real time.

A ground-based inversion can be identified on the facsimile record as a continuous patch extending from the ground up to certain altitude. During nighttime ground-based inversion is observed to be formed due to radiative cooling of the earth's surface and usually extends up to a height of 100-200 m (Ref. 19). Figure 1(a) shows the development of ground-based inversion on a clear night under very ligth wind conditions. It shows the growth of inversion with time. Normally the formation of ground-based inversions is a nighttime phenomenon. The ground-based inversion once formed due to radiative cooling of the earth's surface in the evening hours, persists throughout the night and gets eroded by the incoming sodar radiation.

Elevated and multiple elevated layers form the next class of inversions[20,21]. The formation of elevated and multiple elevated layers is mostly associated with certain atmospheric conditions and/or local topographical features, such as, subsidence and advection associated with the passage of cold front in uniform and complex terrain[22], cold-air out-flows from local thunder storms[23] and drai-

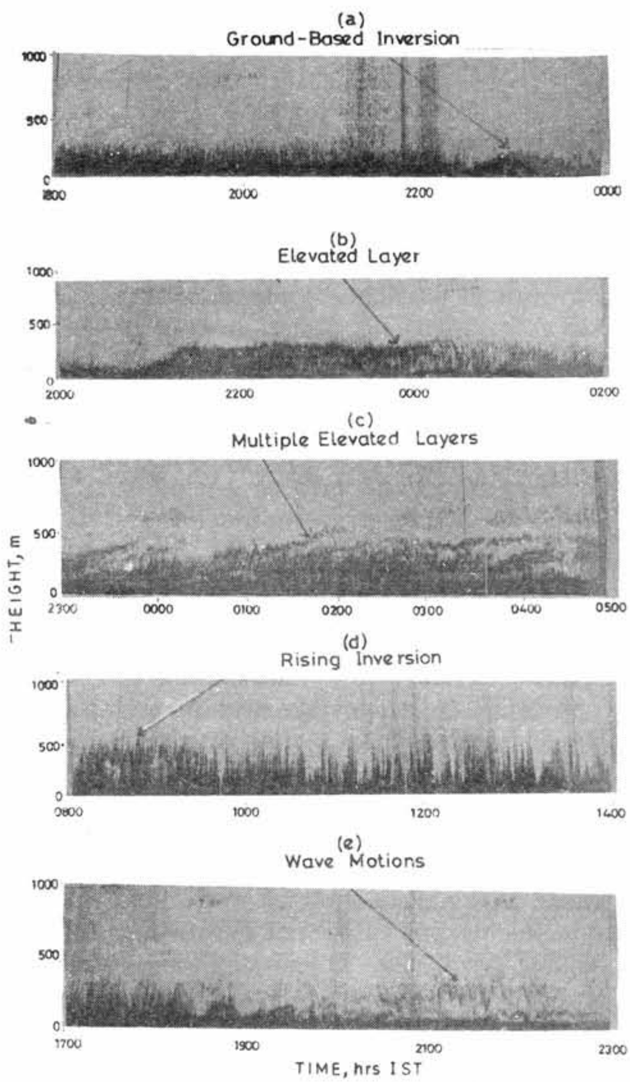

Fig. 1—Different types of sodar structures (a) ground-based inversion, (b) elevated layer, (c) multiple elevated layer, (d) rising inversion and (e) wave motions observed over Tirupati.

nage winds in the vicinity of mountain ranges[24]. An elevated layer is essentially a suspended layer of some thickness in the atmosphere as shown in Fig. 1 [(b) and (c)]. The formation of elevated layers is observed to be predominantly a nighttime phenomenon. They usually occur with a ground-based inversion. The elevated layers, once formed, persist for several hours. The dissipation of inversions usually takes place in the form of rising inversion [Fig. 1(d)]. The nighttime stable layer does not dissipate soon after the sunrise. After the sunrise, most of the heat energy is utilized in heating up the ground which, in turn, warms the stable layer and pushes it upwards. The thickness of the inversion goes on decreasing with time and finally dissipates at certain height depending upon the strength of the inversion which does not allow any suspended layer to persist for a long time and, therefore, elevated layers are normally seen to be associated with the stability and static conditions observed at night[20,21] near the surface.

With stable stratification, the atmosphere can support wave motions of both simple and complex nature with sufficiently large wave periods of the order of a few minutes and amplitudes around 100 m as shown in Fig. 1(e). The wave motions are usually associated with ground-based inversions, elevated layers and rising inversions. Sometimes just wave motions are also observed on the sodar echograms. The common types of wave motions observed in the boundary layer are the gravity waves generated by the shear instabilities in the boundary layer flow with the boundary layer becoming dynamically unstable at the height of the observed waves[25,26]. Besides shear instability, convective cells penetrating into stable layer, storm systems and fronts may also generate grav-

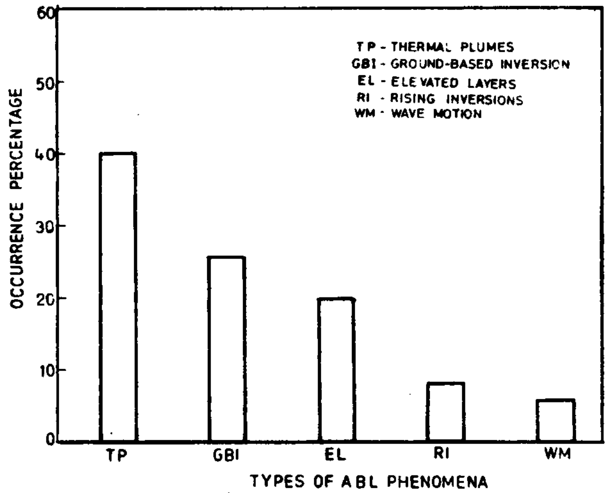

Fig. 2—Occurrence percentage of various sodar structures observed over Tirupati (Jan.-Dec. 1988)

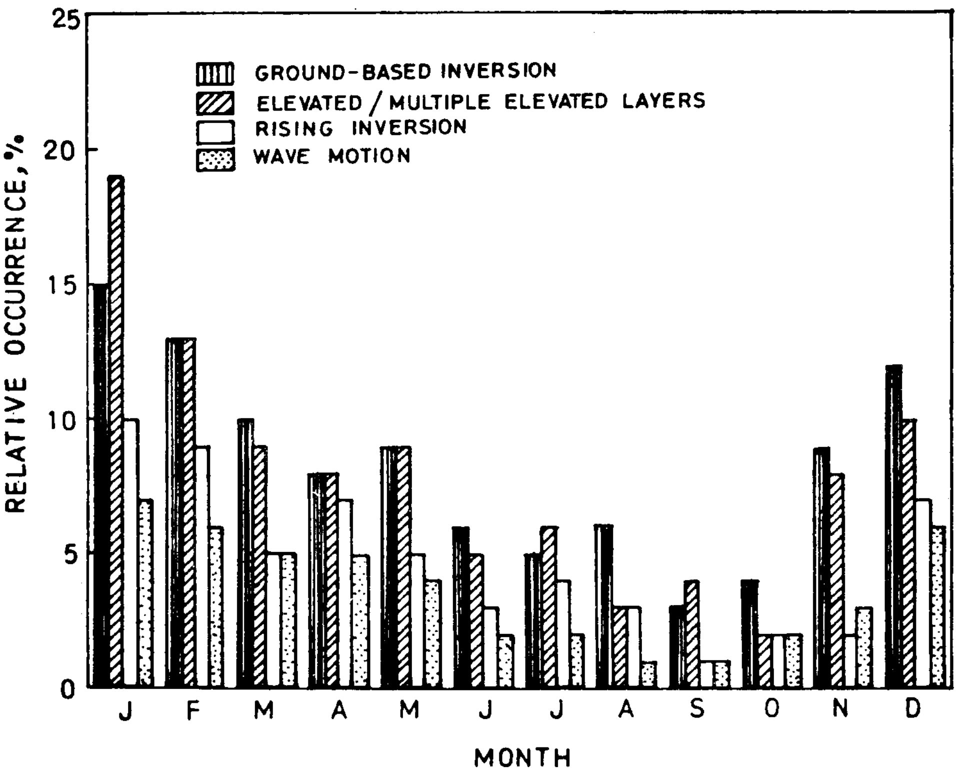

Fig. 3—Relative occurrence of various nocturnal thermal inversions (Jan.-Dec. 1988)

ity waves with scales of a kilometre to a few tens of kilometres.

The occurrence percentage of various types of structures observed from January to December 1988 is shown in Fig. 2, where a large variation in the occurrence of these patterns (structures) is clearly seen. Thermal plumes (TP) are the dominant phenomena with an occurrence of ~40%. This is followed by ground-based inversions (GBI), elevated/multiple layers (EL), rising inversions (RI) and wave motions (WM). The wave motions are the least frequently observed phenomena with 5% occurrence.

Over the Indian subcontinent, the study of inversions has been taken up using radiosonde and tower measurements. However, statistical information of the inversions round-the-clock, using high resolution techniques are very limited. Figure 3 shows the relative occurrence probabilities of the nocturnal structures observed over Tirupati. From Fig. 3 it is observed that the ground-based inversions, elevated layers, wave motions and rising inversions are maximum in winter followed by premonsoon and minimum in monsoon and postmonsoon months.

Cumulative distributions of ground-based inver-

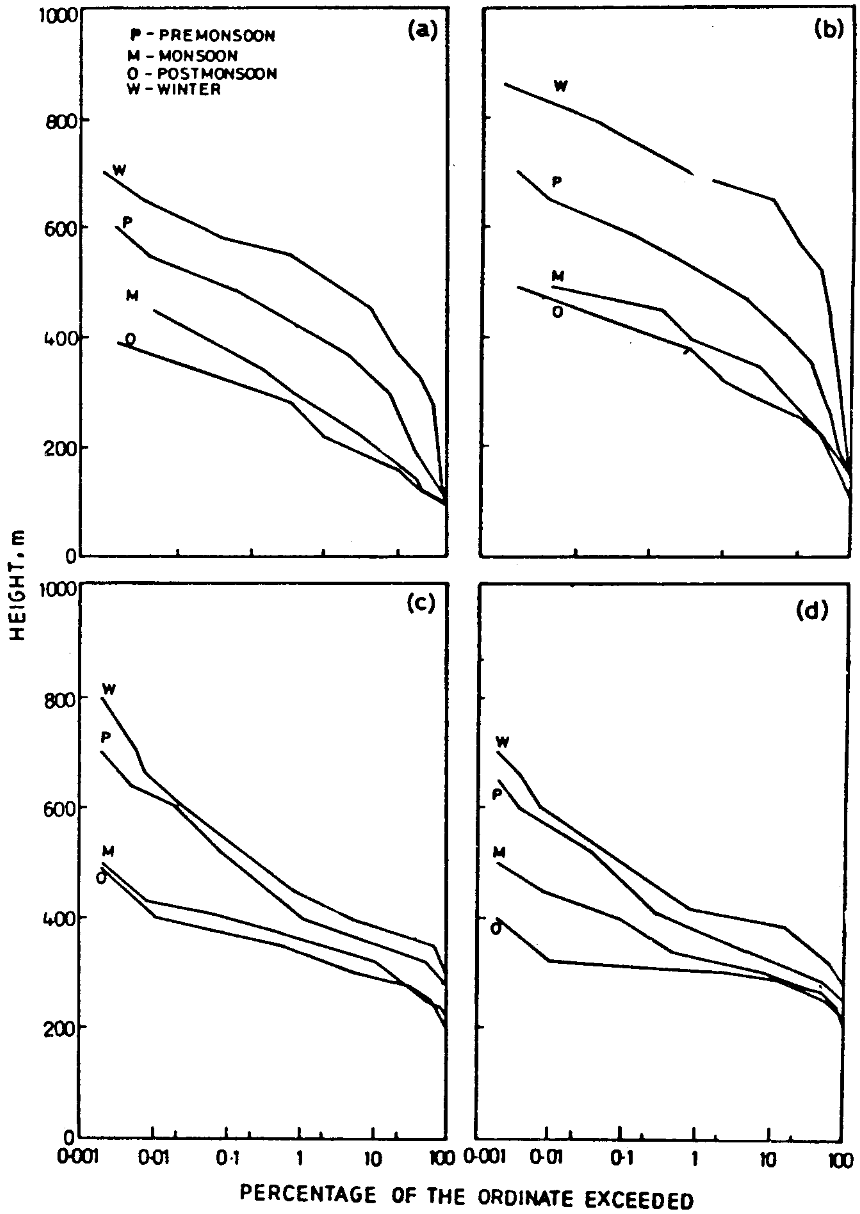

Fig. 4—Cumulative distribution of height of (a) ground-based inversions, (b) elevated layers, (c) wave motions and (d) rising inversions (Jan.-Dec. 1988)

sions, elevated layers, wave motions and rising inversions observed for different seasons are shown in Fig. 4. It is evident from Fig. 4 that during all probability levels, the height of the thermal inversions is maximum in winter and premonsoon seasons and minimum in monsoon and postmonsoon seasons. Madras radiosonde data, and the data from a nearby stations show that the inversions are maximum during winter and premonsoon and minimum during the monsoon and postmonsoon seasons[27].

4 Diurnal behaviour of different atmospheric structures and infrasonic pressure fluctuations

An acoustic echo-sounder and a microbarograph are deployed to study the down-flow structures in ABL. Diurnal variation of the occurrence percentage of different structures and infrasonic pressure variations are shown in Fig. 5. From Fig. 5, it is seen that ground-based inversions, elevated layers and wave motions are mostly the nighttime phenomena. It is observed that the thermal plumes are observed mostly during daytime. The diurnal variation of the magnitude of infrasonic pressure variations shows higher values in the daytime compared to the nighttime values. From Fig. 5 it is also observed that at nighttime, pressure fluctuations remain 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 a maximum in their magnitude around midday. Thereafter, in the afternoon, with the decreasing convective activity the pressure fluctuations become lesser. Moreover, the nighttime recordings exhibit rather slow and smooth changes in infrasonic pressure.

Figure 6 shows the occurrence percentage of sodar structures with different height ranges and infrasonic pressure fluctuations. From Fig. 6 it is evident that ground-based inversions in the height range 100-200 m are dominant in their occurrence and have pressure fluctuations up to 150 μ bar. Elevated/multiple elevated layers occurrence is maximum in the 300-400 m height range, and pressure fluctuations up to 125 μ bar is observed. The elevated layers, rising inversions and wave motions are dominant at the height of 500 m and above with pressure variations up to 70 μ bar. From Fig. 6 it is also observed that the maximum occurrence percentage of thermal inversions is associated with smaller pressure fluctuations.

5 Simultaneous study of ABL phenomena using sodar and microbarograph

Simultaneous observations made by sodar and microbarograph revealed the ABL characteristics. The study has also demonstrated the compatibility of the two techniques in offering a better insight into the dynamics of ABL. Some of the case studies are presented here.

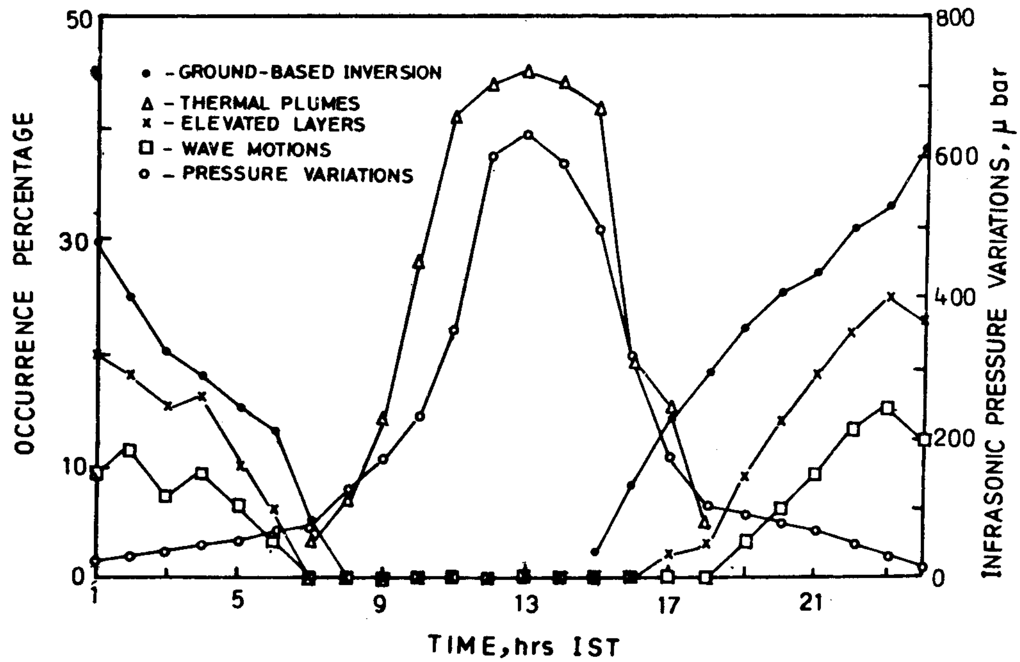

Fig. 5—Diurnal variation of occurrence percentage of different sodar structures and infrasonic pressure fluctuations (Jan.-Dec. 1988)

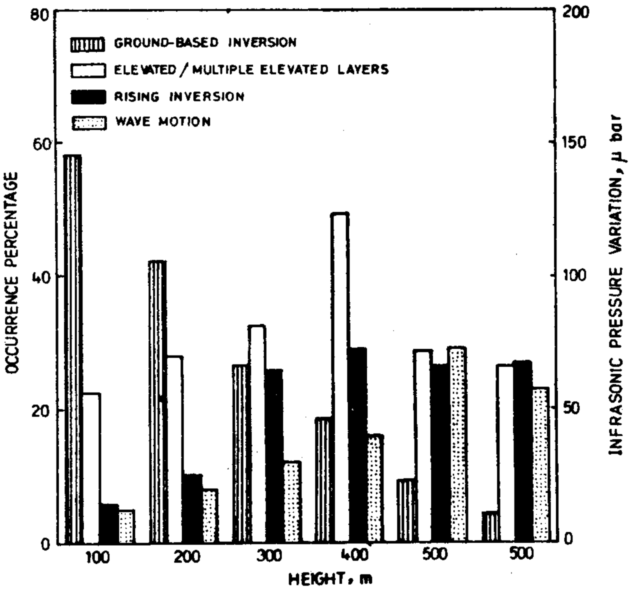

Fig. 6—Occurrence percentage of sodar structures for different heights and infrasonic pressure fluctuations (Jan.-Dec. 1988)

Under both ground-based inversions and elevated layers the infrasonic pressure fluctuations are normally steady, but if the wind is prevailing, the fluctuations associated with wind can cause the infrasonic pressure variations. However, at certain nights the infrasonic pressure variations are observed even in the absence of a strong inversion and no wind conditions. These variations must, therefore, be an indicator of the dynamic state of the atmosphere at higher levels, beyond the probing range of sodar. Both the sodar and the microbarograph can detect the presence of gravity waves in the stable atmosphere. However, if the phase cancellations of the gravity waves are there, then the microbarograph record may not respond to such events.

Figure 7(a) shows simultaneous sodar and microbarograph observations on 1 Feb. 1988. The sodar structure shows ground-based inversion formed due to the radiative cooling of the earth's surface. The corresponding microbarograph recording shows rather a steady and slow variation in infrasonic pressure level with the amplitude variations around $\pm 80\ \mu$ bar.

Figure 7(b) shows wave motions observed on sodar and microbarograph charts on 13 Jan. 1988. The sodar echogram shows wave motions with an amplitude of ~ 75 m and wave period ~ 25 min. They finally dissipate into the ground-based inversion structure. The microbarograph recording shows pressure variations of the order of $\pm 100\ \mu$ bar from 1830 to 2030 hrs IST.

Figure 7(c) shows rising inversion observed on 14 Oct. 1988 and the simultaneous microbarograph recordings. A sudden growth or dissipation of a rising layer acting as a lid on the development of thermal plumes makes a typical signature on the microbarograph with a depression in pressure caused by the fast erosion of rising layer and thereby removing the lid on the plumes below the rising layer. However, when the growth is gradual and inversion breaks slowly, this type of typical signature may not appear. Thus, for detecting the dynamics of the rising layer, sodar is a better technique than the microbarograph.

6 Discussion

Sodar is now being accepted in the country as a potential technique which can be used to study atmospheric phenomena[28]. In southern India, ABL studies over a valley are scanty and for this purpose a systematic study of thermal inversions over Tirupati is made. The localized inversions are common in a valley, as cold air mass gets collected near the ground. The salient feature of the temperature inversions is that the inversions inhibit vertical mixing which leads to the development of large atmospheric inhomogeneities including the accumulation of pollutants below and within the inversions[29]. Consequently, radio communication is affected in a number of ways[30] including the range and elevation errors in radar tracking[31]. The meteorological conditions are considered to be important in the design of stacks of major industries, refineries and thermal and nuclear power plants[32].

As already illustrated, the microbarograph is capable of detecting many atmospheric phenomena, which can throw light into the dynamics of the lower atmosphere. Nevertheless, it is encouraging to see that the sodar facsimile records and the microbarograph data appear to give a reasonably consistent picture of the boundary layer dynamics. As tower/kytoon facility is not available in the vicinity of the sodar site, quantitative study of ABL phenomena could not be made.

7 Conclusions

The study of diurnal and seasonal behaviour of ground-based inversions, elevated layers, wave motions and rising inversions reveals that the ground-based inversions are formed due to strong radiative cooling of the earth's surface during nights, after the incoming solar energy is shut off after sunset. Most of the elevated/multiple elevated layers are observed due to the accumulation of cold air mass which slides down the slopes of the

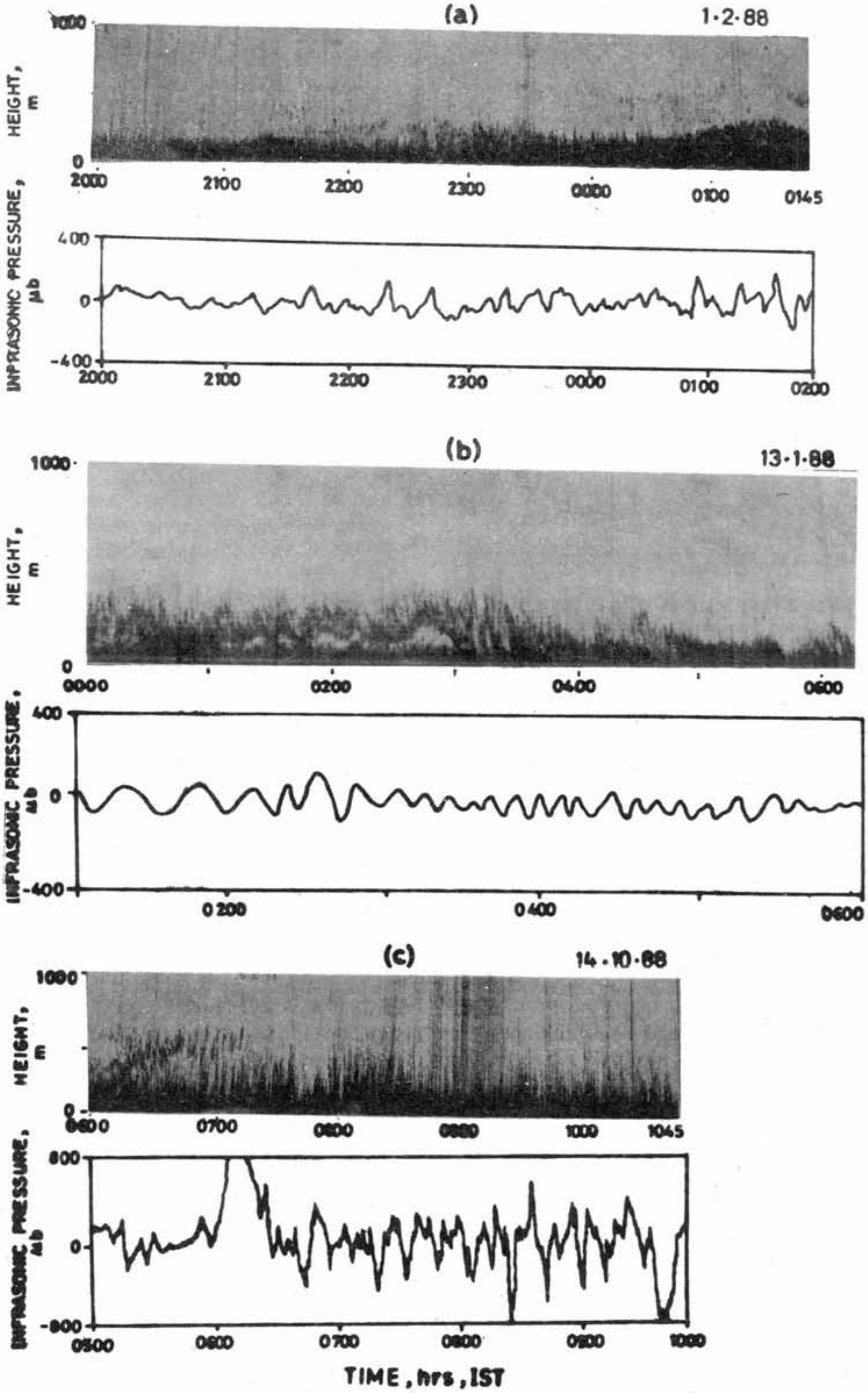

Fig. 7—Simultaneous observations of (a) ground-based inversions, (b) wave motions and (c) rising inversions

hill situated at a close proximity from the sodar. However, the occurrence of wave motions and rising inversions is quite low as compared to the ground-based inversions and elevated layers. From the simultaneous study of sodar and microbarograph data, it is evident that these two techniques offer a better insight into the dynamics of the boundary layer. We are, therefore, optimistic about the usefulness of acoustic echo-sounder/microbarograph data for future studies of ABL.

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