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~~A study of~~ thermal plumes over Tirupati using sodar and microbarograph

D N~~arayana~~ Rao, K K~~rishna~~ Reddy, T R Vijaya Kumar, S V B~~haskara~~ Rao
Department of Physics, Sri Venkateswara University, Tirupati 517 502
~~and~~
H N Dutta
National ~~Physical~~ Laboratory, New Delhi 110 012
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An acoustic sounder, operating at a frequency of 2.2 kHz and a probing range of 1 km, has been designed and developed for the study of atmospheric boundary layer. A detailed study of diurnal variations of height, onset and dissipation timings of thermal plumes has been made and it shows that the thermal plumes are the characteristic features of daytime atmospheric conditions and do not show much seasonal variation in their occurrence. Diurnal variation~~s~~ of infrasonic pressure fluctuations have also been studied in detail using a microbarograph. Simultaneous observations made by sodar and microbarograph are able to detect the thermal plumes in the boundary layer. In addition, sodar and microbarograph data seem to correlate well to study the thermal plume activity in the atmospheric boundary layer. (12 ref)

(ABL)

1 Introduction

Acoustic sounding has emerged as the most effective technique to monitor the dynamics of thermal inversions in the lowest 1 km of the atmospheric boundary layer (ABL)[1]. It is this region which also contributes predominantly to the infrasonic pressure variations recorded through a microbarograph system. Although the infrasonic pressure fluctuation studies were mainly confined to the study of pressure fluctuations originated due to man-made or natural events like atomic explosions, tornadoes and cyclones[2], this technique coupled with the acoustic sounding technique forms a comprehensive system to study the thermal plumes in the ABL most effectively.

2 Experimental details and data collection

To study the characteristic features of thermal plumes at Tirupati, sodar and microbarograph have been employed. A monostatic acoustic sounder has been designed and developed at the Department of Physics, S V University, Tirupati, for the study of ABL round the clock.

Echosonde (sodar), which can probe up to an altitude of 1 km from the ground, was operated at a frequency of 2.2 kHz. The recording was done using a facsimile recorder which displays the intensity of the backscattered signals arriving at different time intervals and gives a three-dimensional view of the received signals, where the two axes represent the height range and time, while the third axis represents intensity of the shade produced on the paper. An electrosensitive paper of dynamic range 22 dB and 1V as the threshold for writing was used for recording. The system characteristics of sodar and specifications of the facsimile recorder are given in Table 1. The infrasonic pressure variations were recorded near sodar site using a microbarograph operating in 0.001-2.0 Hz range. The data from January 1988 to December 1989 have been used for the present study. The seasons are classified as pre-monsoon (March to May), monsoon (June to September), post-monsoon (October and November), and winter (December to February).

3 Characteristics of thermal plumes

Transfer of heat, moisture and momentum from the surface to the overlying boundary layer is accomplished to a large extent by discrete convective elements called thermals or plumes. They are buoyant parcels or plumes 50 to 1000 m in diameter that develop above a surface which is considerably warmer than the overlying air. Thermals transport heat, momentum, moisture and turbulence from near the surface up into the overlying mixed layer. Thermal can be defined[3] as an isolated volume of buoyant fluid which, as it rises, loses its connection with the surface. In the upper part of the boundary layer, thermals may lose their buoyancy, but still have sufficient momentum to distort the capping inversions at the top of the mixed layer, entrain overlying warmer air and then fall back into the mixed layer. Although other convective elements exist such as longitudinal rolls

Table 1—(a) System characteristics of sodar

Carrier frequency	2.2 kHz adjustable from 500 to 4000 Hz
Pulse width	50 ms adjustable from 10 to 100 ms
Duration of each cycle	6 s adjustable in three steps as 2,4 and 6 s
Range of operation	1020 m adjustable in three steps as 340, 680 and 1020 m
Max. transmitted power	60 W electrical 12 W acoustic
Transmitting antenna	1.9 m parabolic dish with transducer at its focus
Receiver blanking period	60 ms adjustable from 50 to 200 ms
Receiver bandwidth	30 Hz
Display	Electrosensitive paper facsimile recording
System operating duration	Around the clock

(b) specifications of facsimile recorder

Input impedence	220 Ω
Helix speed	30, 15 and 10 Rev/min
Probing range	340, 680 and 1020 m
Triggers	(i) Photooptical (ii) Magnetic reed-relay
Paper width	27.5 cm
Paper speed	6, 12 and 18 in/h
Paper sensitivity	1 V
Paper dynamic range	22 dB

dust devils and small scale turbulent eddies, thermals are the dominant mode of turbulent mixing in highly convective situations[4]. Thermal plumes, which are characteristic of daytime structures present, are thermally non-uniform air parcels rising upward from the ground. This phenomenon starts after the sunrise and is associated with solar heating of the ground. The thermal plumes are best formed on calm, clear and sunny days, and are the most repeatable atmospheric features observed during daytime[5-7].

3.1 Diurnal variation of height of thermal plumes

The height up to which themal plumes rise gives an idea of the height of the boundary layer or the mixing depth during daytime. Diurnal variation of the average height of thermal plumes is shown in Fig. 1. It shows that thermal plumes start forming after 2-3 h of sunrise and their occurrence frequency starts increasing from 0900 hrs IST, attaining maximum value by the afternoon around 1400 hrs IST and then starts decreasing as the day further advances. After the sunset, the plume activity subsides because of the radiative cooling of the earth. After the sunrise most of the solar energy is utilized in heating the earth's surface, thereby pushing the nighttime inversions upwards in the form of rising inversion. This process continues for 2-3 h depending on the strength of the available falling solar radiation. From the figure it is also observed that the heights reached by thermal plumes during pre-monsoon, monsoon, winter and post-monsoon are around 330,390, 400 and 440 m respectively. During all the seasons the maximum height of thermal plumes is observed at around 1400 hrs IST.

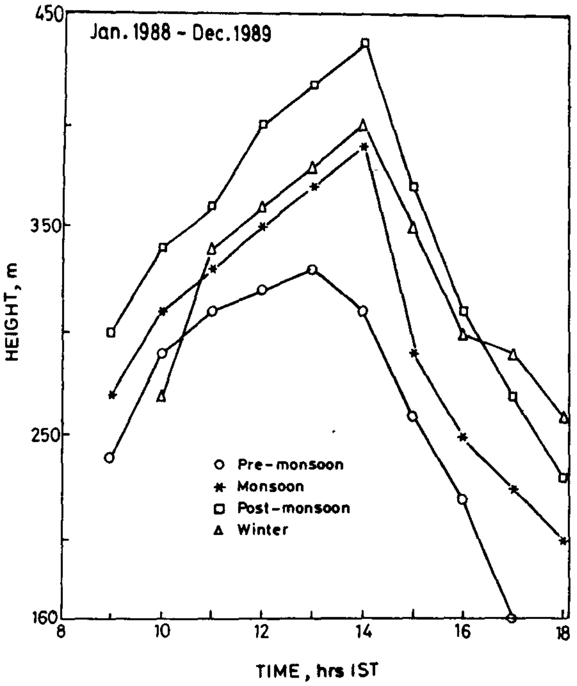

Fig. 1—Diurnal variation of height of thermal plumes observed during all the seasons.

3.2 Onset and dissipation of thermal plumes

The nighttime stable layer does not get dissipated immediately after sunrise; rather the entire volume of positive lapse rate moves upwards in the form of rising inversion, resulting in the formation of plumes. The thickness of the inversion goes on decreasing with time and finally it dissipates at certain altitude depending upon the nighttime temperature gradient of the ground-based inversions and daytime heating conditions. After the dissipation of inversion, the atmosphere is in fully convective state and this marks the onset of plume structures on the surface. The seasonal behaviour of the onset of thermal plumes is shown in Fig. 2(a). It is seen that in pre-monsoon season the maximum occurrence percentage of onset time is around 0900 hrs IST, whereas it is around 1000 hrs IST in monsoon and post-monsoon and around 1100 hrs IST in winter. From the observations of the onset timings of the thermal plumes in different seasons, it can be concluded that the onset timings of the thermal plumes are well related to the timings of sunrise and intensity of solar flux in various seasons.

The plume activity disappears soon after the sunset and is replaced by radiative inversion. In the afternoon hours as the solar heating of the earth's surface starts decreasing, the atmospheric convection is affected. The environmental temperature gradient decreases, thus marking the end of convection, and by evening, plume structures are not observed on the facsimile recorder. The evening transition from convection to inversion activity is an important phenomenon. Generally the plumes disappear completely, leaving a clear demarcation between the daytime convective conditions and the onset of nighttime structures (stable conditions). Most of the time it has been observed that the daytime convective structure does not dissipate completely but rather turns out slowly from convective to less convective and to a mixed structure, which takes the shape of a typical nighttime structure. The time of dissipation of thermal plume activity for different seasons is shown in Fig. 2(b). It is observed that plume activity subsides earlier in winter (between 1630 and 1700 hrs IST), followed by post-monsoon (1730-1800 hrs IST), monsoon (1800-1830 hrs IST) and pre-monsoon (1830-1900 hrs IST) seasons.

3.3 Plume dimensions and velocities

The plume periods can be estimated from the facsimile paper chart speed and the length of the paper covered by the base of plume structure. The plume periods pertaining to clear plumes are calculated and their distribution in different intervals ranging from 1 to 16 min is shown in Fig. 3. The maximum occurrence of plume periods is observed in the range of 2 to 6 min. The plume periods give an indication of the diameters of the plumes and give an idea of the horizontal extent of the plume base on the ground as well as at other altitudes[8]. The horizontal extent of the plumes, S, is given by

$$S = tv \qquad \dots (1)$$

where t is the plume period and v is the surface wind velocity. The distribution of the horizontal extent of the plumes at the surface is shown in Fig. 4. This horizontal extent of the plumes can be used to calculate the area of the plumes A on the ground by

$$A = tv^2/4 \qquad \dots (2)$$

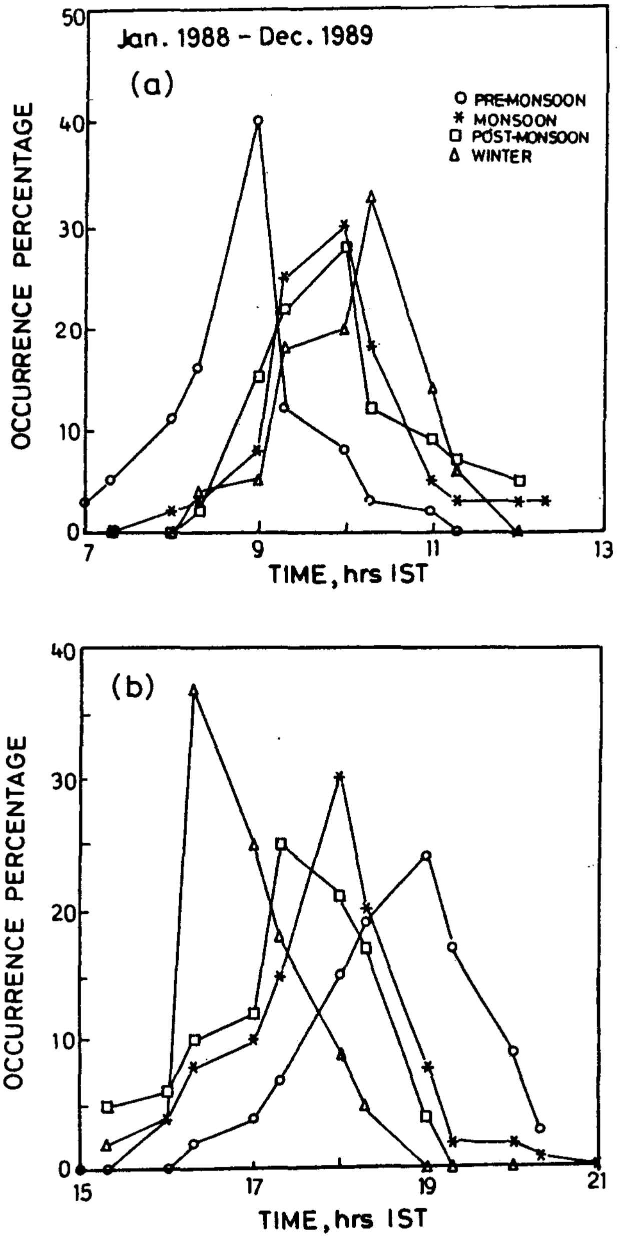

Fig. 2(a)—Onset timings of thermal plumes during all the seasons.

(b)—Dissipation timings of thermal plumes during all the seasons.

It is observed that the plumes have horizontal extent as short as 90 m and as large as 2 km corresponding to an area of 0.0065 sq km to 3.4 sq km on the ground.

The time taken by the convection to reach any height gives an average upward velocity of plumes W and is given by

$$W = 2H/t \qquad \dots (3)$$

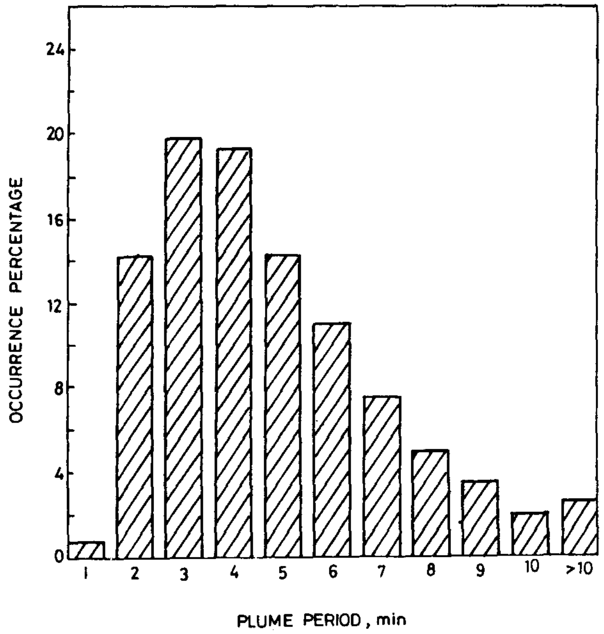

Fig. 3—Distribution of plume periods.

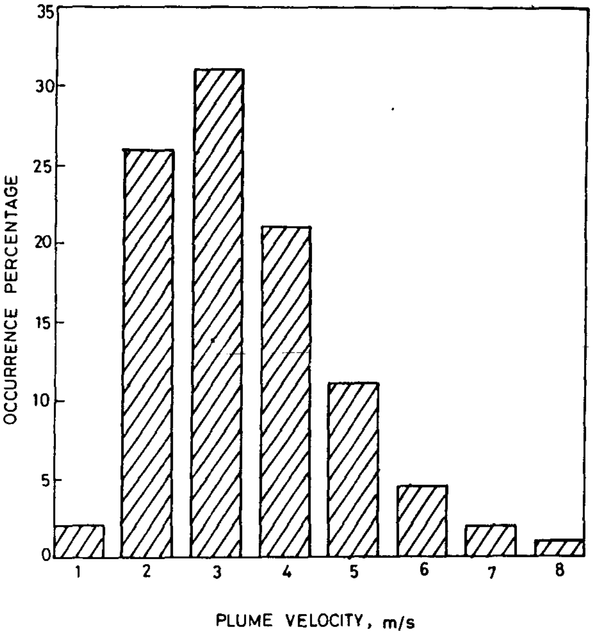

Fig. 5—Distribution of velocities of thermal plumes.

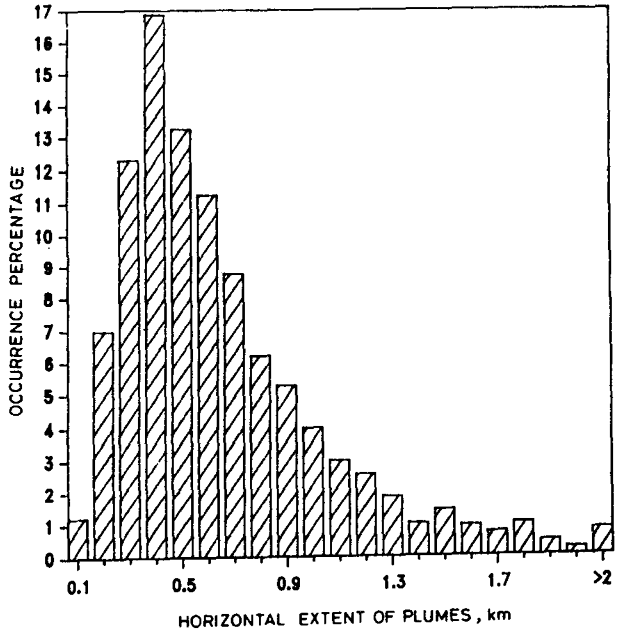

Fig. 4—Distribution of horizontal extent of thermal plumes.

where H is the plume height.

The occurrence of plume velocities in different ranges are shown in Fig. 5. It is observed that nearly 90 per cent of the plumes are having velocities ranging between 1 and 5 m/s, and the percentage of the plumes having velocities above 5 m/s and below 1 m/s is very small.

4 Characteristic of infrasonic pressure variations

The normal microbarograph records show random variations of infrasonic pressure fluctuations. The origin of these microbaroms (pressure variations of few microbars) has been explained as generating from effects of 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[9]. 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[10].

The diurnal variation of the magnitude of infrasonic pressure variations observed over Tirupati is shown in Fig. 6. The figure shows random variations of infrasonic pressure, with daytime showing higher amplitudes than nighttime. Further, it can be observed that in the 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 maximum in their magnitudes in the afternoon.

5 Simultaneous study of thermal plumes using sodar and microbarograph

An acoustic echo sounder and microbarograph are

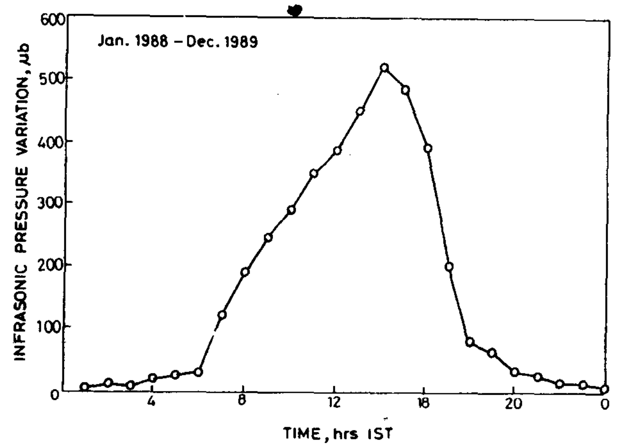

Fig. 6—Diurnal variation of the magnitude of infrasonic pressure variations.

deployed to study the thermal plumes in the convective boundary layer[11]. These instruments which detect and measure small-amplitude pressure fluctuations occurring with periods of a few seconds to several tens of minutes have been used for years to detect the acoustic signals from explosions, severe weather, aurora, and other natural sources. The microbarograph provides data on the amplitude, period, horizontal phase speed and direction of propagation, and the horizontal wavelength of pressure fluctuations. Figure 7 shows the average diurnal variations of the height of thermal plumes and pressure fluctuations on clear, sunny and calm days. It is clearly seen that both the parameters have a similar diurnal variation. However, it is important to note that towards evening the convection ceases on acoustic sounder, indicating a homogeneous atmosphere; the microbarograph fluctuations of the order of 50 μb are still seen. Similarly, in the morning, convection is first detected by the microbarograph. Another important parameters of the plumes and the infrasonic pressure fluctuations are the period of thermal plumes and the period of depressions in pressure caused by these plumes.

Case studies

Simultaneous observations of infrasonic pressure variations and sodar stuctures on 17 Feb. 1988 are shown in Fig. 8(a). From the figure it can be oberved that the convection was built up below the capping inversion, causing the infrasonic pressure variations to grow which ultimately attained maximum in their magnitudes in the afternoon.

Simultaneous observations made on 28 Oct. 1988 are shown in Fig. 8(b). Under the convection, acoustic sounder depicts thermal plumes while microbarograph depicts infrasonic pressure variations caused by the thermal plumes. An upward going thermal plume caused the pressure to fall on the ground while the impinging air mass caused the pressure to go high. Thus pressure variations both in the positive and negative directions are seen to be associated with the thermal plumes. Their magnitude on this clear sunny day was observed to be ± 1 mb. From the figure it can be seen that the sodar sructure reveals that at low levels there was a great deal of convective plume activity of the type observed and discussed by McAllister *et al.*[12] This plume activity manifested itself on the microbarograph record as pressure fluctuations of rather high amplitudes.

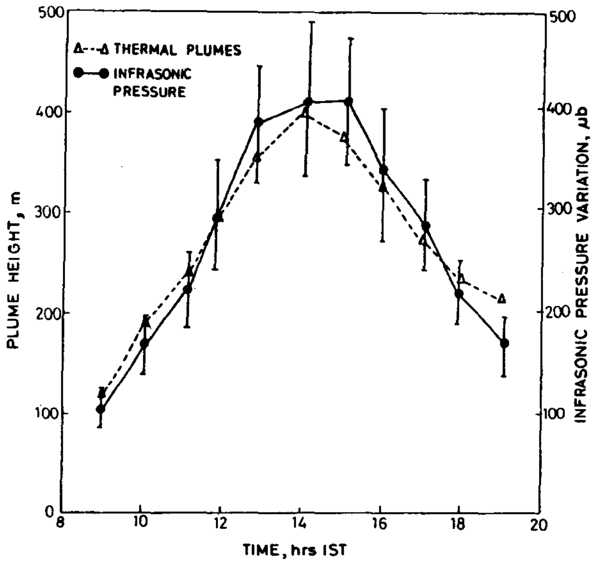

Fig. 7—Diurnal variations of the height of thermal plumes and magnitude of infrasonic pressure variations.

Figure 8(c) illustrates simultaneous pressure amplitudes and sodar observations taken on 6 July 1989. From 1100 to 1630 hrs IST the amplitudes of the pressure fluctuations were high and were of the order of ± 700 μb. From the sodar echograms it is observed that for the above period thermal plumes attained an average height of 400 m. In microbarograph from 1700 to 1800 hrs IST the fluctuations were abruptly decreased to ± 50 μb. Similarly in the sodar structures, the thermal plumes were dissipated and ground-based inversion was formed.

6 Discussion

Thermal plumes are the characteristic feature of daytime atmospheric conditions and allow good vertical mixing of the atmosphere. Most of the monostatic sounder facsimile records show convective plumes extending to only 600 m or so, yet it is well known that convection and vertical transport of heat must still be going at higher levels.

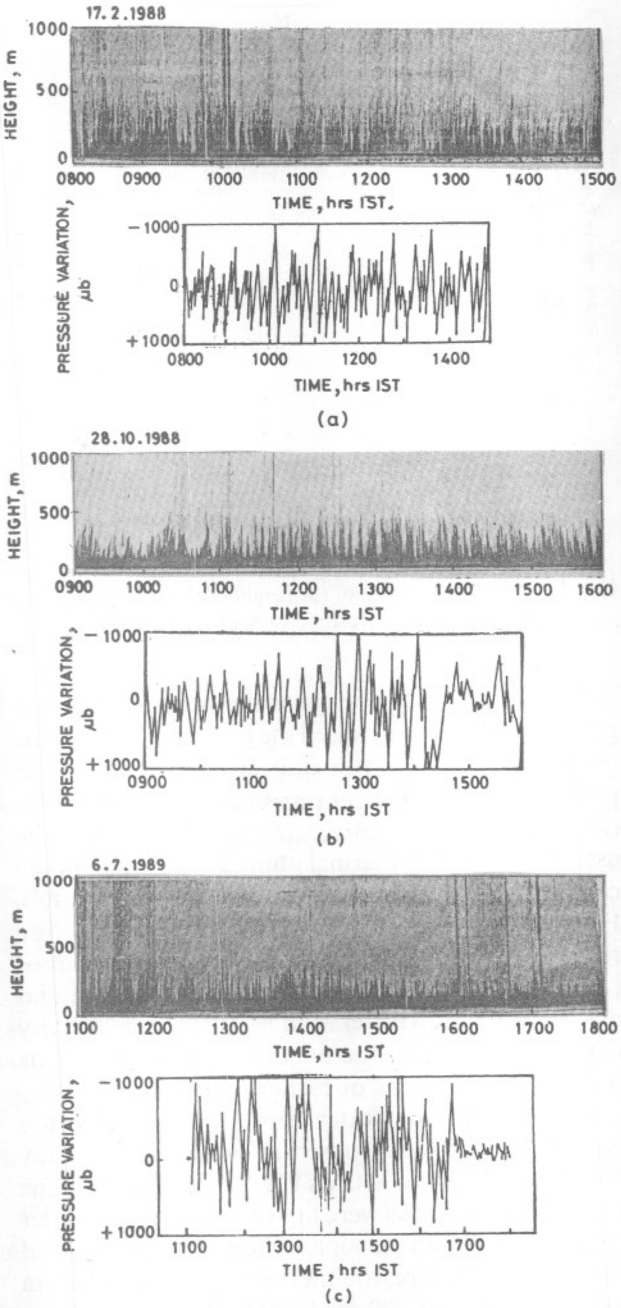

Fig. 8—Typical daytime records of the thermal plumes and the infrasonic pressure variations observed on 17 Feb. 1988, 28 Oct. 1988 and 6 July 1989.

The microbarograph is capable of detecting many atmospheric phenomena which can throw light on the thermal plumes in the lower atmosphere. Analysis of microbarograph records shows random variations of infrasonic pressure, with daytime records having higher amplitude than that of nighttime. Daytime amplitude goes on increasing after sunrise presumably due to convective heating.

Tirupati (lat. 13° 40′ N, long. 79° 27′ E) is situated at the foot of Tirupati range of Cuddapah formations in the eastern coastal plains at an elevation of 170 m above mean sea level. It is situated between two ridges on northeren and southern sides.

7 Conclusions

Detailed investigations were carried out to study the characteristics of thermal plumes in ABL. Thermal plumes do not show much seasonal variation in their occurrence. Height of thermal plumes is an important parameter as it indicates the depth of the mixing boundary layer. Onset and dissipation timings of the plume activity give the duration of the effective day (convective conditions of the atmosphere). The plumes provide a natural force to dilute the air pollution near the ground. Analysis of microbarograph records shows random variations of infrasonic pressure, with daytime records having higher amplitudes than that of nighttime. Simultaneous study clearly demonstrates the compatability of the two techniques in offering a better insight into the dynamics of thermal plumes in ABL.

Acknowledgements

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