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Acoustic Sounding of Coastal Boundary Layer

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The acoustic sounder data obtained during the period June 1980-May 1981 have been analyzed with special reference to sea breeze. Simultaneous measurements of sea breeze using pilot balloon ascents and acoustic sounder were made on eight days in May 1981. A reasonably good agreement has been obtained between the acoustic sounder estimation of the depth of the sea breeze and the height of the onshore flow as deduced from hourly balloon ascents. The height variations of the elevated layer on the sounder record were also reflected in the flow patterns. The development of the elevated layer associated with the sea breeze circulation was delayed due to the limited vertical extent of sea breeze in the first few hours after the onset. The alternation of land and sea breeze more than once during a day in the observational period was partly due to the oscillatory behaviour of a trough of low pressure inland. The monthly charts prepared for the 12 months showed a definite seasonal variation in the diurnal behaviour of the coastal boundary layer at Visakhapatnam.

1 Introduction

Acoustic sounders have been used for a wide variety of research and applied atmospheric measurements[1,2]. Relatively very little amount of data has been collected on the coastal environment using acoustic sounders. Coastal boundary layer is influenced not only by the conditions at the ground surface but also by the surface discontinuity at the land-water interface. Coastal stations differ from those of inland in several ways. Coastal zones enjoy more moderate climate with less intense radiation inversions at night and less convective activity during daytime. The most significant phenomenon is the occurrence of sea breeze.

Sea breeze is a mesoscale circulation driven by pressure gradient forces arising from the differential heating of the lower troposphere over adjacent land and sea surfaces. If the prevailing gradient winds are light, a shallow layer of cool, dense marine air will move inland undercutting the warm air. Several observational studies of sea breeze have been made in the past. Primarily, all the studies were based on conventional meteorological data obtained either from surface autographic records, special ascents of pilot balloons or from light aircraft measurements of temperature and related parameters. The vertical extent of sea breeze was primarily determined from flow patterns obtained from some pilot balloon ascents conducted during a day or part of a day. Experiments of this type cannot be continued for longer periods, say for a season or a year for obvious reasons. The development of acoustic sounding technique has provided a unique opportunity to continuously monitor the sea breeze and its effect on the thermal structure of the lower atmosphere.

Basically, there are two regions in the sea breeze circulation that produce acoustic backscattering. The first one, adjacent to the surface (land), in which the temperature gradient is superadiabatic, and above it the second one, which is stable or slightly stable. After the onset of sea breeze, surface heating rapidly re-establishes a shallow superadiabatic layer at the base of the inflowing marine air. Turbulent transport and free convection transfer heat upwards resulting in the growth of a thermally modified turbulent internal boundary layer[3]. The layer is thermally non-homogeneous and produce acoustic backscattering. Above it, this layer is followed by a 'no echo' region, which may probably indicate a turbulence free zone. The other region that produces acoustic backscattering is the boundary between the inflowing cool marine air and the prevailing gradient wind over-riding the sea breeze. This region is a turbulence producing shear zone where small scale inhomogeneities are predominant[4]. The acoustic sounder records showed marked variability in the structure of sea breeze at Visakhapatnam both during summer[5] and southwest monsoon[6]. To confirm the variability in the structure of the sea breeze as detected by acoustic sounder, balloon ascents were conducted. The month of May was selected for such a study as it is the hottest month of the year at Visakhapatnam and sea breeze occurs almost everyday.

An attempt has also been made to get an insight into the behaviour of the boundary layer using the data for 12 months. Only a few studies on the climatology of the boundary layer using acoustic sounder have been made in the past. This type of studies require classification schemes to bring some order out of the diversity of sounder record patterns. Among the various classifications schemes that have been reported so far, the pictorial scheme developed by Fukushima *et al.*[7] is simple in its form to understand and to process large sets of continuous sounder data. Although these charts do not provide any quantitative information about the heights of the layers, etc., they do provide information on the general behaviour of the boundary layer. The results presented here are based on the 12-monthly charts prepared for the period June 1980-May 1981.

2 Site Location, Experimental Technique and Data Analysis

The observational site is roughly 1 km away from the coastline and nearly 40 m above mean sea level. The sea coast at Visakhapatnam is oriented nearly in the southwest-northeast direction with Bay of Bengal to the east.

The acoustic sounder used in the present study is a pulsed one which sends out an intense burst of sound beamed vertically into the atmosphere where it encounters atmospheric inhomogeneities and suffers partial reflection. The energy scattered back to the antenna is only due to temperature inhomogeneities at a scale equal to half the wavelength of the transmitted signal[8]. The received signal, after proper amplification, is fed to a sweep recorder of facsimile type, displaying height range versus time pictures. This system has been operated with 100 ms tone burst of 1600 Hz repeating every 18 s with a peak power of 100 W and probing range of 1 km.

Every wednesday and sunday, pilot balloon ascents were conducted on round-the-clock basis at 1-hr interval from 0600 to 0600 hrs LT of the following day at the same area where the sounder antenna system is placed. No criterion was followed for selecting the days. Single theodolite method was followed for the estimation of winds. The winds at various heights were deduced from the trajectories of the balloons. The balloons were inflated to give 30 g free-lift which corresponds to an average ascent rate of 9 km/hr. A still lower ascent rate is better to get a more detailed picture of the sea breeze current with enhanced resolution. Pibal ascents are carried out in collaboration with the Cyclone Warning Centre, India Meteorological Department, Visakhapatnam.

The facsimile charts obtained by the acoustic sounder during the period 1 June 1980-31 May 1981 are subjected to qualitative analysis in order to get an idea about the diurnal cycle variability of boundary layer at Visakhapatnam. Rough sketches of the sounder echo trace for all the days of 12 months are prepared. Each row corresponds to the 24-hr records of the bottom 1-km atmosphere. A semi-quantitative analysis is also carried out on the occurrence of the three principal sounder echoes, namely, convection, sea breeze and inversions. The occurrence of each type of echo at each hour of the day is estimated for all the seasons. The percentage of each hour thus obtained for a season is plotted against the hour of the day.

3 Results and Discussion

3.1 24 May 1981

The sea breeze on this day showed great variability in respect of both its height variation and its duration. Shown in Fig.1 is the acoustic sounder record obtained from 0415 hrs on 24 May to 0735 hrs on 25 May 1981. In the morning hours of 24 May, 6-7 octa cloud cover was observed and the surface winds were also light.

Shortly after 1000 hrs, the character of the sounder record changed significantly with the onset of sea breeze. Thermal plume activity was disturbed and diffusive type of echo structure was observed. Although not displaying the layering characteristic of a stable region, the sounder record indicated that the thermal plume activity had been replaced by a weakly restricted regime of thermal turbulence. These conditions prevailed up to around 1300 hrs.

A close look at the vertical time sections of both wind direction and speed given in Fig.2 shows the beginning and the subsequent development of sea breeze with the backing and strengthening of wind in the morning hours. Prior to the onset of sea breeze, the winds were offshore throughout the vertical column of the atmosphere considered. The surface (land) level winds in the morning hours were light and they speeded up only after 0800 hrs when the clouds began to clear off. Sea breeze arrived from southwesterly direction shortly after 1000 hrs with a sharp increase in the wind speed at the onset and a steady increase in the following hour. The diffusive type of echoes which appeared on the sounder record during 1000-1300 hrs may be due to the very low depth of the sea breeze as inferred from the vertical time sections of wind. The maximum intensity of the sea breeze before 1300 hrs was found below 100 m. Offshore winds prevailed throughout the day above 800 m level with varying

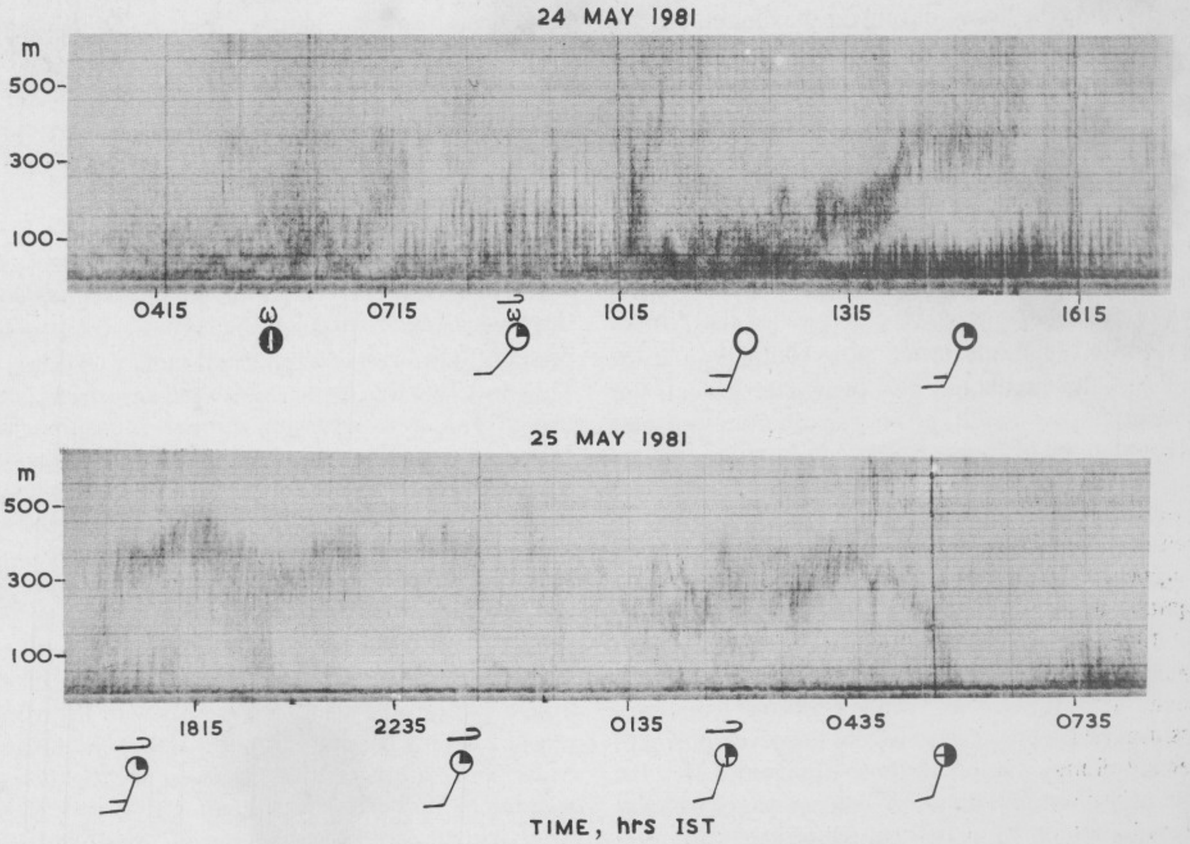

Fig. 1 — Acoustic sounder record obtained from 0415 hrs on 24 May 1981 to 0735 hrs on 25 May 1981

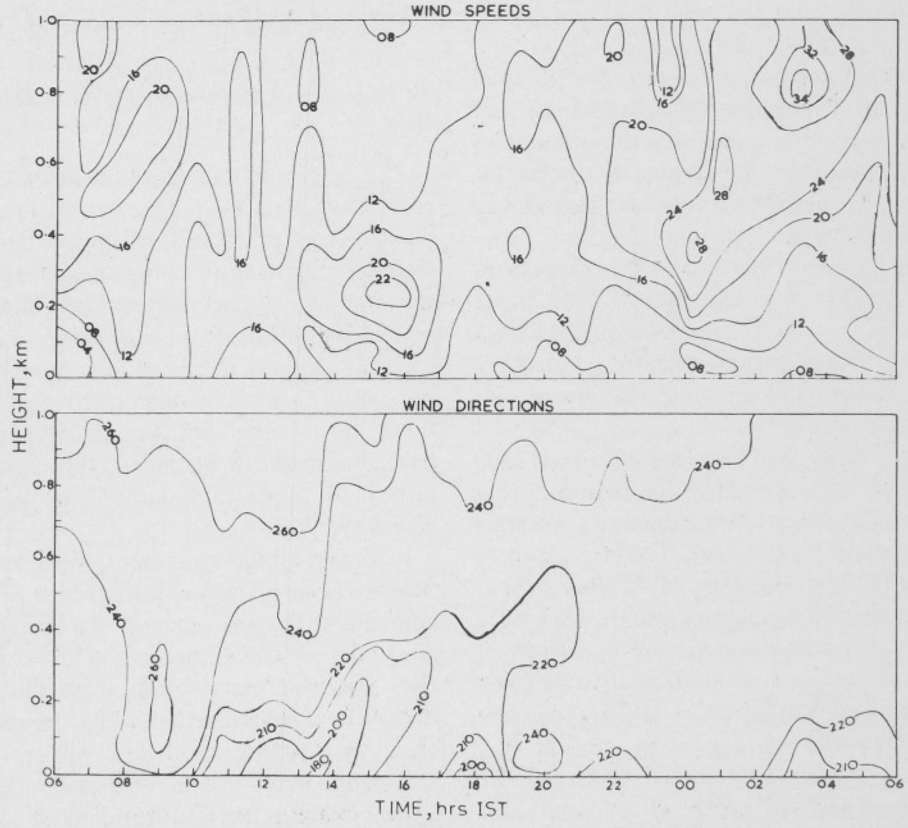

Fig. 2 — Wind directions and speeds on 24/25 May 1981

speeds, being the lowest during the maximum intensity of sea breeze circulation.

Just after 1300 hrs, a layer began to rise separating from the low level scattering region. At around 1355 hrs, this layer suddenly rose to a height of 300 m and persisted there till 1530 hrs and then disappeared. It appeared again only after 1650 hrs at the same height where it disappeared before, and underwent a nearly sinusoidal oscillation. The vertical time sections of wind direction and speed (Fig.2) revealed that the sea breeze after 1300 hrs turned more southerly and the height of the circulation also increased. In fact, this increase in the depth of the circulation was also mirrored in the hygrogram obtained from the antenna site. The relative humidity increased by 8% within a period of 20 min after 1300 hrs[9]. During a period of about an hour from 1530 hrs, when the elevated layer disappeared, thermal plume activity, though weak, began to appear again on the sounder record. During this time, the winds in the lower levels veered and turned parallel to the coast with a slight decrease in speed. This turning of winds causing temporary cessation of sea breeze gave way to the development of thermal plumes, similar to those observed before the onset of sea breeze. This plume activity was replaced at around 1700 hrs by a uniform scattering region that extended to a height of 200 m. The reduced thermal plumes was associated with the backing of low level winds after 1700 hrs and the revival of sea breeze current.

There was no surface-based scattering after 1820 hrs. This may be due to the absence of solar heating of the ground which eventually reduces the amount of heat to be transferred from the ground to the marine air. This reduces the thermal turbulence at ground to cause an acoustic echo[10].

The scattering between 1900 and 2020 hrs was from the base to a height of nearly 300 m. The exact mechanism for this scattering is not known, but a look at the wind data indicates that offshore winds were blowing in the lowest 150 m while sea breeze was persisting at higher levels[11].

Acoustic echo returns were very feeble between 2300 and 0200 hrs. This corresponds to the period during which sea breeze was absent. Sea breeze revived after 0200 hrs and persisted till 0600 hrs. The last ascent of the balloon was made at 0620 hrs of 25 May 1981.

A peculiar but interesting character of the sea breeze on this day was its intermittent nature in respect of both its appearance and its continuation up to the early hours of the next day. Similar cases of this type were studied earlier by other workers with conventional meteorological instruments. Ramdas[9] observed the alternation of land and sea breeze at Karachi more than once during a day and he attributed it to a moving low pressure area across Sind and Rajputana. Dayakishan and Pradhan[12] reported an unusual sea breeze over Bombay which lasted for about 19 hr mainly due to an anticyclone over Sind and adjoining areas of Gujarat.

The onset (weakening and strengthening) of sea breeze on 24/25 May is examined with reference to the weather charts. At 0530 hrs on 24 May, a feeble low pressure area lay off Visakhapatnam. Subsequently this moved inland, weakened and lay as a trough of low pressure to the west of Visakhapatnam by 0830 hrs. By 1130 hrs, there was further westward movement of the trough with its axis passing through Jagadalpur and Masulipatnam. The sea breeze set in shortly after 1000 hrs when the trough was far west of Visakhapatnam. Prior to 1700 hrs, the trough of low pressure showed eastward shift as could be inferred from its position at 1730 hrs, when it passed through Koraput and Gannavaram. There was no sea breeze between 1530 and 1700 hrs, probably due to the proximity of the trough to Visakhapatnam. The oscillation of the trough continued even after 1730 hrs with the trough axis at 2330 hrs passing through Kanker and Ongole. At 2330 hrs, another trough was seen passing through Jagadalpur and Visakhapatnam, but it was feeble. After the subsequent weakening of this trough, sea breeze again set in at 0200 hrs. It may be mentioned that the axis of the trough at 0530 hrs on 25 May passed through Ramagundam and Ongole.

3.2 Some General Characteristics of the Sea Breeze Observed on 8 Days

The height of the elevated layer on the sounder record directly provided the depth of the onshore flow. Comparison of 62 sets of Pibal derived data with sounder records shows a high degree of approximation to a one-to-one correlation. The correlation is much higher for lower levels. For other sets of data, the sounder derived depth of sea breeze is ambiguous because the layer structure on the record is feeble or, at times, not visible. The measurement of the time of onset and cessation by the two techniques is essentially same in all the cases. No difference worth mentioning is observed.

In almost all the eight cases, the development of the elevated layer on the sounder record was not followed immediately by the onset of sea breeze. This may be due to the very low depth of sea breeze for a few hours after the onset as inferred from the flow patterns. It may be concluded that when the depth of the sea breeze is very low, say below 100 or 150 m, thermal turbulence necessary for the generation of acoustic echoes extends to the full depth of sea breeze. The continuation of the elevated layer on the sounder record to late night hours or to the early hours of the following day indicates the continuation of sea breeze till that time. This is in agreement with the vertical time sections of wind.

The sea breeze at Visakhapatnam initially begins to blow from a southwesterly direction and as the day progresses, it turns more southerly with an increase in speed. The sea breeze attains full strength in the afternoon and often shows maxima during 1200-1400 hrs. The location of the maximum intensity of the circulation is difficult because it showed some variation with the height of the circulation itself. When the depth of sea breeze is higher, the maximum intensity of the circulation is also pushed up.

3.3 Climatology of the Coastal Boundary Layer

The year at Visakhapatnam is divided into four seasons[13], viz. dry season (January-March), hot season (April and May), southwest monsoon (June-September), and northeast monsoon (October-December).

A striking difference among the 12 monthly charts is in respect of the daytime convective activity. During the northeast monsoon, boundary layer behaviour over Visakhapatnam is largely controlled by the classical cycle of solar heating and radiative cooling of the surface (land). From around midnight to a few hours after dawn, a surface-based echo layer,

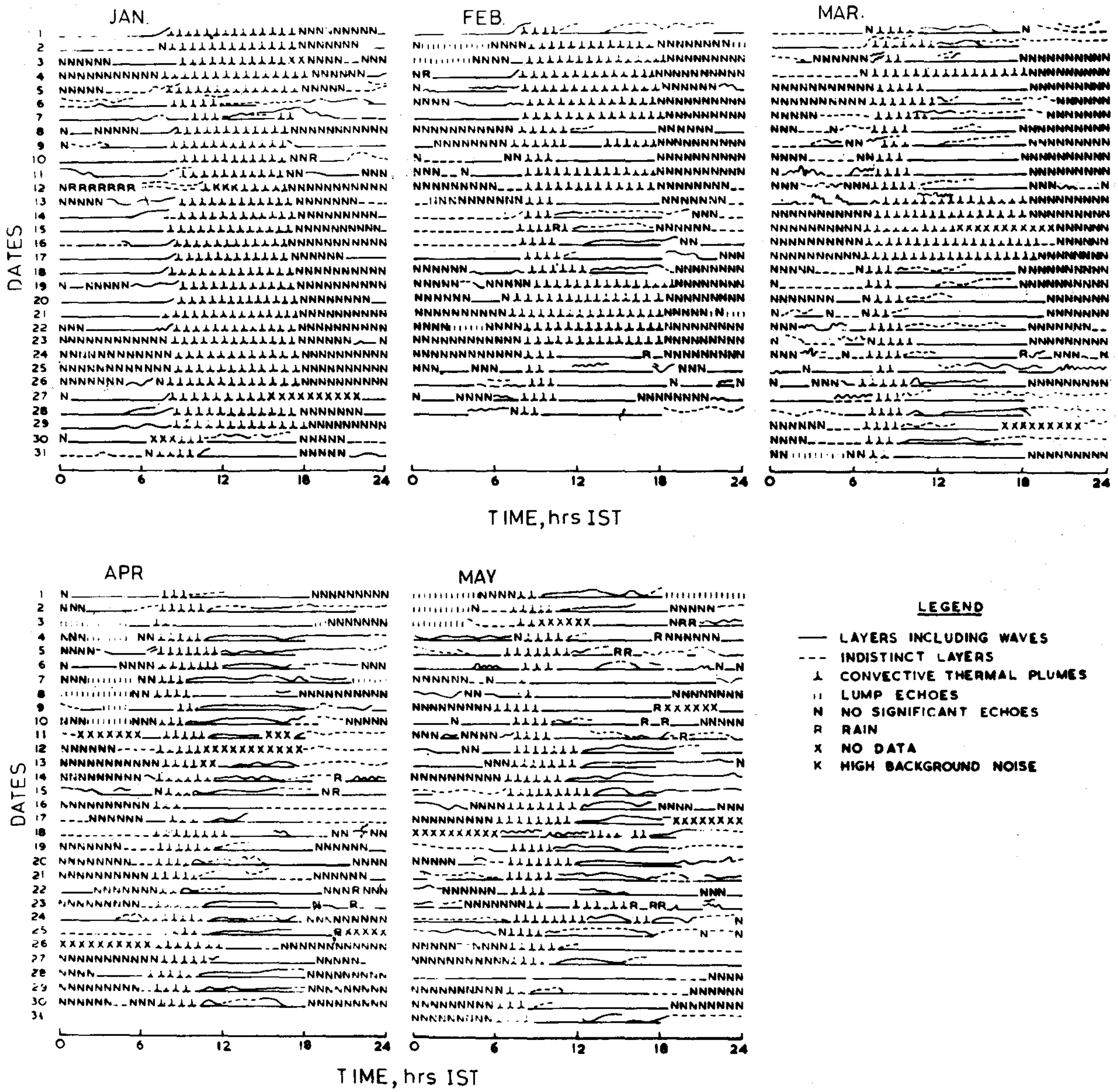

Fig. 3 — Sketches of the daily sounder echo trace during Jan.-May 1981 (dry and hot seasons)

frequently in the height range of 100-500 m, is observed. This marks the stable layer formed by heat transfer to the radiatively cooled ground[14]. As the ground is heated by the incoming solar radiation in the morning hours, the air closest to the ground becomes unstable and convective cells begin to form. The convective activity continues in the afternoon until about 1600 to 1700 hrs, when solar surface heating weakens. Later, when radiative cooling of the surface re-establishes a ground-based stable layer, sounder record shows the formation of a ground-based layer echo. Thus the boundary layer behaviour in northeast monsoon is mostly controlled by the classical cycle of solar heating and cooling of the surface.

The diurnal cycle of the boundary layer during the remaining seasons of the year is found to be different. This is illustrated in Fig.3. The sketches of sounder echo trace correspond to dry and hot seasons (January-May). Layered structures (either ground-based or elevated, or both) are observed during the daytime in contrast to the northeast monsoon. The frequency of occurrence of the layered structures in the daytime during these two seasons seems to be increasing as the seasons progress. In the month of January, daytime layered structures made their appearance on 4 days. But in February, they were for 14 days. In March, they were detected on 25 days. By April, the occurrence of layered structures during daytime was almost a daily phenomenon. This daily occurrence of layered structures continued in the month of May also. All these layered structures are associated with sea breeze. Thus, the diurnal cycle of the boundary layer during the dry and hot seasons is mostly controlled by land and sea breeze.

During the period June-September (southwest monsoon), the weather at Visakhapatnam is characterized by thunderstorms, prolonged rains and increased cloud amount. Because of these factors, there is no recognizable order in the diurnal cycle during this season. But sea breeze does occur on days of fair weather and moderate wind conditions[6].

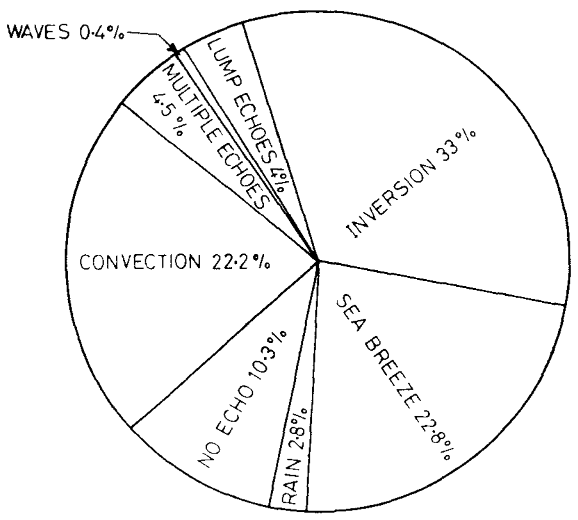

Fig. 4 Occurrence percentage of classified sounder echoes

The average percentage time of occurrence of the classified sounder echoes for the total observational period is shown in Fig.4. Inversions occurred over 33% of time, while sea breeze and convection appeared over 22.8% and 22.2%, respectively. 'No echo' is observed over 10.3% of the total period. Absence of echo on sounder record means that either there is no turbulence or temperature gradient is nearly dry adiabatic. Echo-free regions are generally observed during the evening transition period falling between the time of decay of convective activity and the time of onset of radiation inversions[1].

Shown in Fig.5 is the diurnal variation of the three principal structures observed on the sounder record during the four seasons of the year. During daytime, convective activity is dominant during the two monsoons and dry season, while sea breeze is more

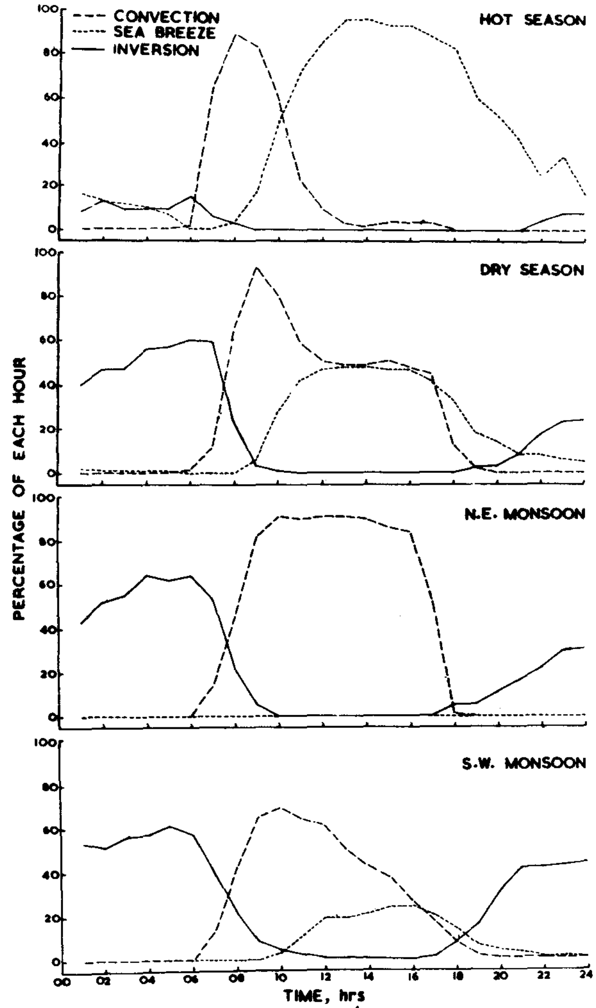

Fig. 5 – Percentage distribution by hour of the day of the three principal sounder echoes for the four seasons

active in the hot season. Sea breeze activity is feeble in southwest monsoon and moderate in the dry season, while no sea breeze activity is observed during the northeast monsoon. The wind roses for 0730, 1230 and 1730 hrs revealed that during northeast monsoon, the wind is predominantly from northeast quadrant irrespective of time[15]. Another important point to be noted here is that the increase in sea breeze activity decreases the convection during daytime. This can be clearly seen during the hot season. The sudden in-rush of the onshore flow suppresses the convection even on hot summer days. Inversions, both ground-based and/or elevated, are rarely found in daytime. Inversions develop after sunset and become dominant throughout the night. The percentage occurrence of inversions is almost same in both the monsoons and dry season, and is very low in the hot season. This is due to the enormous increase in the sea breeze activity in the hot season which reduces the radiative cooling of the ground because of the higher moisture levels in the atmosphere.

A mention may be made here that on some of the days in all the seasons, vertical line echoes, frequently called 'lump echoes' appeared on the sounder record for quite a good amount of time. One such typical sounder record is shown in Fig.6. One interesting feature of these echoes is that they begin to appear from evening and continue till late in the night or throughout the night. The mechanism responsible for this type of echoes is not understood but they generally occur after a heavy rain or on a thunderstorm or on a cloudy night. This is also supported by the fact that this type of echoes is observed for a maximum number of hours in southwest monsoon (Table 1) when the general weather pattern is more cloudy. Singal and Gera[16] have also reported such type of echo structures at Delhi and attributed them to the presence of excessive moisture in the air. By operating a monostatic acoustic sounder in the western suburb of Beijing (China), Mingyu *et al.*[17] detected such type of echo structures at night, when the wind was light and

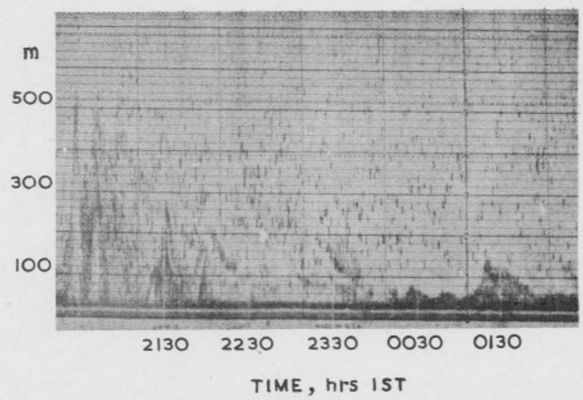

Fig. 6 – Acoustic sounder record showing lump echoes

Table 1—Observed Duration of Lump Echoes in Different Seasons of the Year

Season	Duration hrs
Dry	18
Hot	44
SW monsoon	187
NE monsoon	29

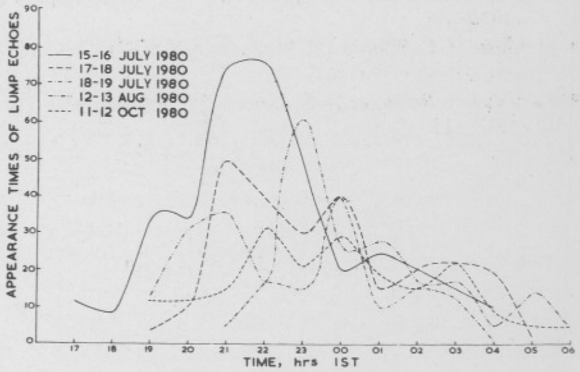

Fig. 7— Variation of appearance of lump echoes with time

the atmosphere was stably stratified with large relative humidity. They found that the lump echoes usually appear in late spring, summer or early autumn, but rarely in autumn and winter. They further stated that the lump echoes occur more often in cloudy, shower and thunderstorm weather conditions and they continue for a long time. But the mechanism that produces these lump echoes is still not known.

The variation in the frequency of lump-echo appearance in half an hour with time on five days at Visakhapatnam is shown in Fig.7. It is found that the lump echoes generally appear at night. Lump echoes are rarely found before 1700 hrs and after 0600 hrs. The frequency of occurrence of these lump echoes is higher between 2000 and 0100 hrs. Other data also show this trend.

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