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# Climatological studies of tropical sea breeze at Tarapur

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**सार** — पश्चिमी घाट परिसर पर समुद्री तट के निकट, तारापुर नामक स्थान पर वायुमंडलीय परिसीमा स्तर के एक साथ प्रेक्षित सोडार और बुर्ज आंकड़ों का विश्लेषण किया गया है। इसमें पाया गया है कि जनवरी से मई और अक्तूबर से दिसम्बर के महीनों के दौरान प्रबल समुद्री हवायें चलती हैं। ये लगभग दोपहर के समय प्रारम्भ होती हैं जबकि आंतरिक परिसीमा स्तर का विकास 500 मी. तक होता है। इनके प्रारम्भ होने के समय और सोडार की क्षमता और आंतरिक परिसीमा स्तर की ऊंचाई का पता लगाने की सोडार की क्षमता को एक मामले के अध्ययन द्वारा दर्शाया गया है। प्रेक्षित समुद्री समीर परिसंचरण पर कोरिऑलिस बल और विद्यमान अनुप्रवण पवन के प्रभावों का भी परीक्षण किया गया है।

**ABSTRACT.** An analysis of the simultaneously observed sodar and tower data of the atmospheric boundary layer at Tarapur, a site near the sea coast on the Western Ghat range, has been made. It has been found that a strong sea breeze blows during the months of January to May and October to December during the year. The onset times are around noon hours while the development of the internal boundary layer is up to 500 m. The capability of the sodar to detect the onset time and the height of the internal boundary layer is shown through a case study. The effects of the coriolis force and prevailing gradient wind on the observed sea breeze circulation have also been examined.

## 1. Introduction

Sea breeze is a phenomenon occurring in a coastal region associated with the manifestation of onshore local winds which set in from the sea onto land in the late forenoon or early afternoon. The phenomenon is marked by drop in surface temperature, rise in humidity level and increase in wind speed and azimuth rotation. During the course of the day due to azimuth rotation, the wind becomes parallel to the sea coast.

Studies of the thermal boundary layer near the sea coast with the help of acoustic sounding Aggarwal *et al.* (1980), Asimakopoulos *et al.* (1983), Bacci *et al.* (1984), Raghukumar *et al.* (1986), Singal *et al.* (1986) Best *et al.* (1986) have shown that sodar is one of the techniques to detect the occurrence of sea breeze phenomenon and monitor the depth and intensity of turbulence of the internal boundary layer. We have studied this phenomenon at Tarapur (19°50′ N, 72°41′ E), a place near Bombay on the west coast of India through the use of sodar and tower data. The terrain of the place is flat. Arabian Sea lies to its west (Fig. 1) and Western Ghat range starts about 13 km east of the site.

## 2. Experimental procedure

Data from the acoustic sounding system (Singal & Gera 1982) and the 120 m instrumented tower (BARC 1974) for the year 1982 have been used for the present studies. The monostatic sodar system set up near the site of the instrumented tower ( Fig. 2), probed the thermal structure of the lower atmosphere to a height range of 700 m while wind and temperature were measured at levels of 6 m, 15 m, 30 m, 60 m and 120 m of the instrumented tower. The accuracy of measurement of temperature was ± 0.1°C, of wind speed it was ±0.2 m/s and of wind direction it was 4.5°. Surface data of temperature, wind speed, wind direction and relative humidity were also measured. Besides, radiosonde data of Bombay were were available.

Since the actual wind at the surface and in the lower level of the atmosphere at a coastal site is composed of the gradient and local winds, and the gradient winds hinder the development of the sea breeze, therefore, the gradient wind which is technically considered to be the same as the geostrophic wind, has been assumed to be the prevailing wind occurring just before the onset of sea breeze. Similarly, any surface onshore wind with a component normal to the coastline stronger than the equivalent component of the 'free stress wind' is considered to constitute sea breeze. Further, we know that coriolis force is responsible for the orientation or rotation of the winds with the time of the day, therefore, sea breeze is considered to last for the period during which winds rotate by 90°, *i.e.*, they become parallel to the sea shore. The mean rotation per hour of these winds has been estimated from the hodogram of winds for the period between the onset and dissipation time of sea breeze.

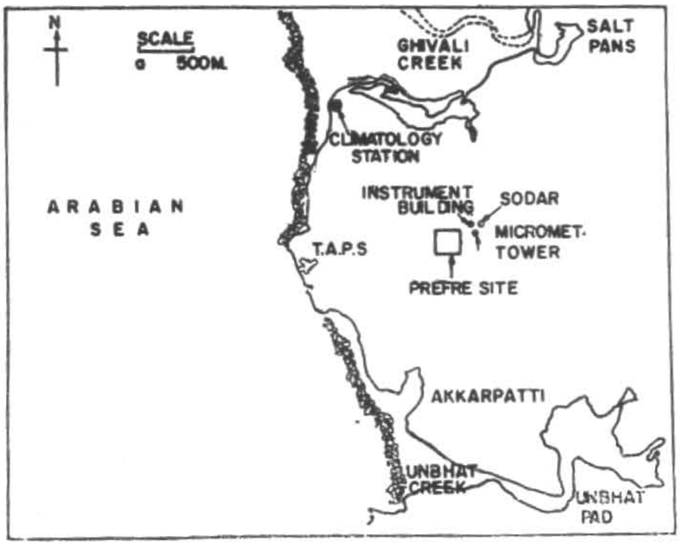


Fig. 1. The site of location of sodar and instrumented tower on the sea coast at Tarapur (19° 50′N, 72° 41′E)

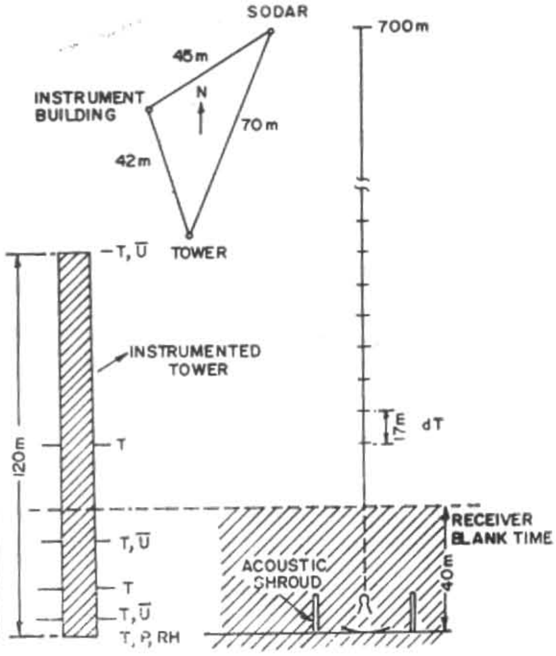


Fig. 2. Location, range, resolution and measurable parameters from the met. tower and monostatic sodar

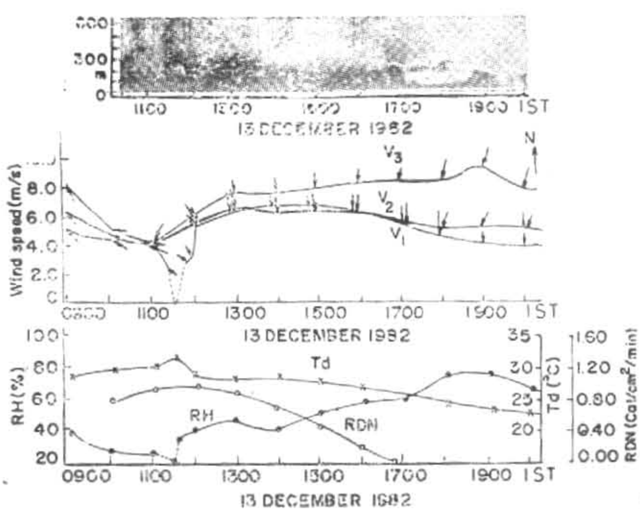


Fig. 3. Sodar echograms and plots of wind velocity data at heights of 6 m ($V_1$), 30 m ($V_2$) and 120 m ($V_3$) and surface data of temperature ($T$), relative humidity (RH) and solar radiation (RDA) on 13 December 1982. It may be noted that the structure at the top of the sodar echograms is due to noise

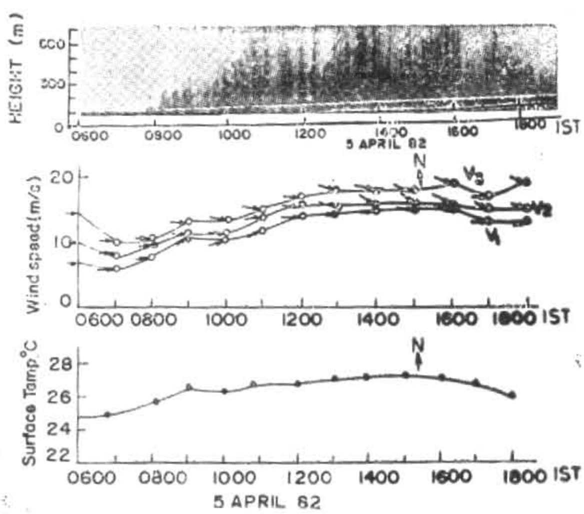


Fig. 4. Clear distinct thermal plumes on a day of onshore winds. Corresponding surface temperature and wind velocity data at height of 6 m ($V_1$), 30 m ($V_2$) and 120 m ($V_3$) have also been plotted. It may be noted that the structure at the top of the sodar echograms is due to noise

### 3. Characteristics, onset time and duration of sea breeze

Sea breeze can be detected on the sodar echograms either through the formation of gapping layer contiguous to the day time slightly diffused thermal plume structure soon after the erosion of the morning rising inversion layer or through the diffused nature of the thermal plume structure alone following the distinct thermal plumes on a clear sunny day. These characteristic changes in the thermal plume structure on the sodar echograms give a measure of the onset time of the sea breeze as also of the progress of the internal boundary layer during the period of sea breeze. The acquisition of this information can be discussed through the citation of a case study of the data on 13 December 1982.

13 December 1982 was a clear sunny day. Sodar echograms (Fig. 3) recorded on this day showed that at 1030 IST thermal plumes were still capped by the overriding morning eroding inversion layer at a mean height of 300 m. By 1100 IST the eroding layer started fading out with the formation of clear distinct thermal plumes under it. By 1140 IST thermal plumes attained a height of more than 400 m but at 1150 IST this height got lost slightly, followed by a diffused structure. The height of this diffused thermal plume structure fluctuated between 250 and 350 m, however, at 1650 IST it got sufficiently reduced separating out a faint elevated layer located at a mean height of 200 m. This elevated layer faded out by 1900 IST when a clear ground based structure was formed up to a height of 175 m.

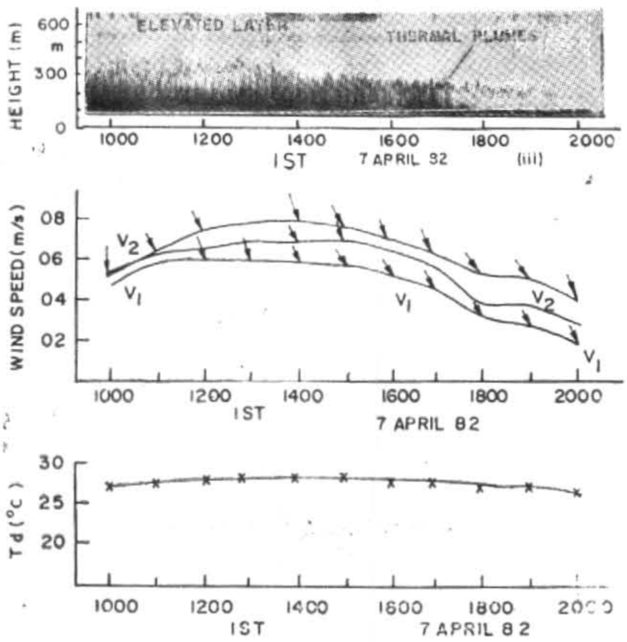


Fig. 5. Elevated layer above clear distinct thermal plumes. Corresponding surface temperature and wind velocity data at heights of 6 m ($V_1$), 30 m ($V_2$) and 120 m ($V_3$) have also been plotted. It may be noted that the structure at the top of the sodar echograms is due to noise

The wind vector plots of the same day at the three levels 6 m, 30 m and 120 m of the instrumented tower (Fig. 3) showed that winds at 1100 IST had more or less the same magnitude but were from southeast at the lower levels and northeast at the 120 m level. At 1125 IST winds at the 6 m level started changing their direction and by 1140 IST they were blowing from the northwest (sea breeze). The magnitude of the wind speed was 2.5 m/s at 1120 IST and became 3.0 m/s by 1140 IST but had passed through a transition phase touching zero at 1128 IST. During this time interval, at the 120 m level also the winds changed their direction from northeast to northwest but the transition period was 1132-1140 IST. The magnitude of the wind speed was 2.6 m/s at 1120 IST which changed to 3.2 m/s by 1155 IST touching zero many a times during that time period with the first zero level occurring at 1130 IST. The magnitude of the wind speed kept on increasing at all the three levels from this time onward achieving a maximum value by 1300 IST. Up to 1600 IST the wind direction at all the levels remained northwest, favourable for sea breeze. From 1700 IST onwards the direction of the winds started changing and by 2000 IST, winds were blowing from northnortheast at all the levels, a direction favourable for land breeze.

A look on the surface parameters of temperature and relative humidity showed (Fig. 3) that they had values of 29.0° C and 29% respectively at 1000 IST. With the increase in solar radiation, surface temperature attained a value of 30.8° C by 1100 IST. At 1135 IST when the temperature had gone to 31.7° C, reverse trend started, *i.e.*, the temperature started dropping inspite of the increase in the solar radiation. By 1200 IST, the temperature had dropped to 29° C. With the increase in temperature, the relative humidity had been correspondingly decreasing reaching the lowest value of 22% by 1128 IST when it started increasing quickly attaining a value of 42% by 1200 IST.

An analysis of the changes in the meteorological parameters clearly indicates that the insurgence of the sea breeze was felt at ground level at 1125 IST and by 1140 IST (*i.e.*, after 15 minutes) the effect could be felt up to 120 m. The sodar echograms have given a further additional information that sea breeze could set in throughout the internal boundary layer by 1150 IST offering the opportunity to measure and monitor the depth of the internal boundary layer throughout the period of sea breeze.

The echograms further give information that sea breeze lasted up to 1900 IST while as per the surface parameters the sea breeze should have receded by 1700 IST. The tower data, of course, correlates with the sodar echograms to a large extent in as much as that the wind vector shows signs of change during this time interval with the direction of wind vector becoming northeast at all levels by 1900 IST.

The observed mean wind rotation on that day was only 3.0° per hour which showed that coriolis force was not effective enough to rotate the winds significantly. In other words, local forces must have been responsible to oppose the effects of the coriolis force. The gradient wind was 2.5 m/s on that day which seems to be significant and may be responsible for the non-development of the elevated layer contiguous with the diffused thermal plumes in the early stages as also for the insignificant rotation of the winds during the sea breeze.

The above is a very good example of a case study wherein the sea breeze had a visible impact on the sodar echogram structure. However, many a time it has been seen that tower data indicates continuous flow of sea breeze, while sodar echograms do not show any signs of flow of the sea breeze (Fig. 4). To analyse such conditions the study of the temperature rise rate has been made. It has been observed that the temperature rise rate is less than 1.0° C per hour on all days when sea breeze did not induce turbulent structural changes on the sodar echograms while it was higher than 1.0° C per hour on days of observed structural changes due to sea breeze. This analysis indicates that on days when solar heating is not strong to develop a good temperature contrast between sea and land surfaces, the flow of winds from sea represents prevailing winds and not the development of sea breeze.

Again, many a time elevated layers without the contiguous diffused thermal plumes have been seen (Fig. 5). These elevated layers change height with time and may also be extended to the night time. Observations of such elevated layers were also reported earlier (Aggarwal *et al.* 1980) wherein their presence was found correlated with the low level inversion layers observed on the radiosonde data of Bombay for the same days. In consonance with this observation it is being considered that these elevated layers represent advected inversion structures which might have been formed due to subsidence above the sea surface.

#### 4. Climatology of sea breeze

Based on the above studies of sodar and tower data and typical characteristic sodar structures indicating sea breeze circulation, the climatology of sea breeze has

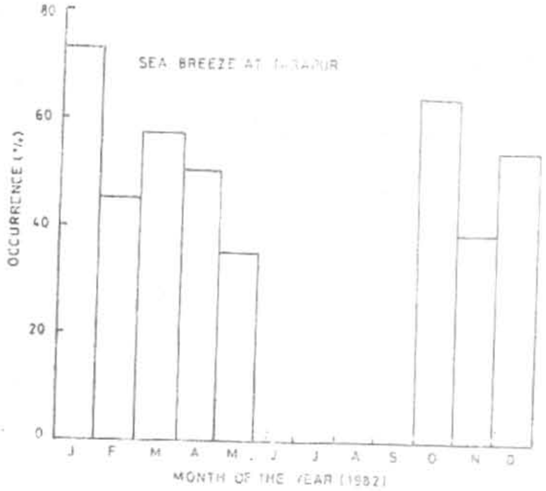


Fig. 6. Plot of monthly distribution of sea breeze occurrence

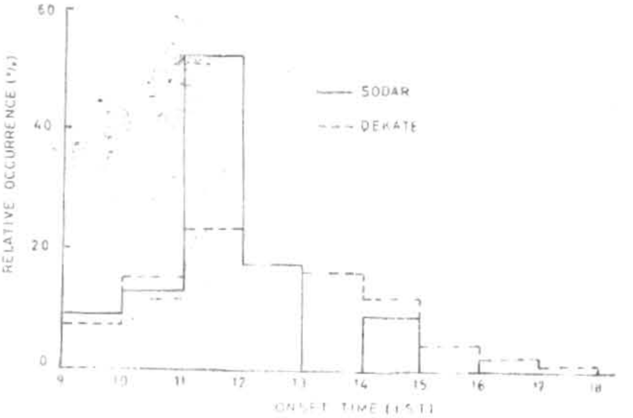


Fig. 7. Studies of relative occurrence probability of onset time of sea breeze on the basis of present studies and those reported by Dekate

been studied for the year 1982. It has been seen (Fig. 6) that the phenomeon of sea breeze occurs more or less on all sunny days during the months of January to May and October to December. For the rainy period June to September, however, our data had not been enough to scan the occurrence of sea breeze phenomenon. Dekate (1968) has also analysed probability of occurrence of sea breeze phenomena at Bombay based on data for the years 1961 to 1964 from conventional *in situ* tools like radiosonde, anemometer, thermograph and hydrograph. According to him, the probability of occurrence of sea breeze during the non-monsoon months is more or less daily except in May when he has observed sea breeze only for ten days, results more or less similar to those reported above.

The height of the internal boundary layer has also been studied from the sodar structures. It has been found to lie in the range 150 m to 450 m during the year. It has been further found that the formation of the sea breeze is mostly before noon (Fig. 7), a result which also corroborates with the observations made by Dekate (1968). The duration of the sea breeze is up to nine hours or a little more with 50% occurrence probability up to six hours.

**5. Concluding remarks**

It has been seen that acoustic sounding can be successfully used to study onset and duration of the sea breeze as also the depth of the internal boundary layer. It has also been seen that wind vector information alone does not always suffice to interpret intelligently complete information for sea breeze circulation. Further, solar radiation should be strong enough to develop a good contrast in temperature between land and sea surfaces for development of sea breeze circulation and at the same time gradient wind should be light.

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