On the spectral behaviour of atmospheric boundary-layer parameters at Thumba, India

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SUMMARY

The features of the spectra of meteorological fields of wind velocity and temperature observed at Thumba, a site on the western coast of India, are discussed. Data utilized for the study are mostly from an instrumented tower, sodar and long-period temperature data available for the site. The influence of local circulations like the sea breeze is manifested also in the general spectral characteristics of horizontal wind, as with the spectral gap in the mesoscale region between the synoptic-scale region and the turbulent-scale region of the spectra. The width of the spectral gap observed between the wave-active region and the microscale region in the wind velocity spectra is seen to be dependent on the stability of the medium, and the gap is found to shift to the high-frequency side with increasing stability. The composite spectrum of temperature also reveals a prominent gap at about an hour. It is seen that with the advection of a sea breeze over the land, a shallow thermal internal boundary layer is formed and regions above one tenth of this depth obey mixed-layer similarity.

1. INTRODUCTION

The study of atmospheric fluctuation and its spectral characteristics has interested investigators primarily because of its efficacy to provide insight into the wide range of scales over which atmospheric motions occur (Kolesnikova and Monin 1965; Hwang 1970; Oort and Taylor 1969; Mori 1980; Ishida 1990).

It has, therefore, indirect implications for describing and explaining meteorological field fluctuations, and for weather forecast and control, thus spanning a large area in the subject of atmospheric physics.

It is now understood that the kinetic energy of the atmosphere is not spread uniformly over all the wavelengths but has certain preferred scales with gaps in between (Smedman-Hogstrom and Hogstrom 1975; Fiedler and Panofsky 1970; Courtney and Troen 1992). Studies on the effect of local circulations like the sea breeze on spectral characteristics, particularly the spectral gaps, are very few for equatorial coastal stations. For Thumba, an equatorial coastal station on the west coast of India, the observed characteristics and the structure of the thermal internal boundary layer (TIBL) are now well documented using data from a Doppler sodar, tower-based instruments, radiosonde and pilot-balloon ascents (KunhiKrishnan 1990). The purpose of this paper is to bring out a comprehensive survey of the features of spectra of the atmospheric boundary-layer (ABL) variables like wind and temperature at Thumba.

The experimental site is located about 0.5 km inland from the Arabian sea (Fig. 1) over a terrain which is fairly flat, sandy and with sparse vegetation.

2. EXPERIMENTAL DATA AND METHOD OF ANALYSIS

The basic data used for the study are from the following:

(a) Sensors mounted on a 25 m tower having facilities for measurements of vector wind components \( u, v \) and \( w \) using Gill propeller anemometers and temperature using platinum resistance thermometers (Panicker et al. 1986) at three levels (5, 11 and 25 m). The digital data are recorded on computer compatible tapes at a sampling rate of 10 Hz.

(b) A Doppler sodar (Peter George et al. 1986) which provides digital data once in every five seconds with a height resolution of 11 m for vertical wind and strength of temperature turbulence.

For the composite spectrum of temperature perturbations, data of longer duration from slow-response sensors available for the site have been taken.

For the microscale spectra, the chosen data length is 1 hour and the sampling rate is 5 Hz. After visual examination of the raw data, if a trend is indicated, a first-degree polynomial fit is applied to the data for trend removal. The 18 000 data points, corresponding to 1 hour, have

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been subjected to a mixed radix fast Fourier transform (Singleton 1972) and the spectrum is then smoothed by averaging the spectral information over frequency bands of increasing width (Kaimal 1988). The frequency range is then from $2.78 \times 10^{-4}$ Hz to $2.5$ Hz.

To study the spectral range (mesoscale) between synoptic scale and turbulence spectrum, a data length of about 3 hours has been taken with a sampling rate of one per second and covering a frequency range of $9.26 \times 10^{-5}$ Hz to $0.05$ Hz. The detrending, spectral analysis and smoothing of the spectra is done in much the same way as for the turbulence spectra, but with 10800 data points.

For the composite spectrum of temperature, 1-minute averaged data for 8 hours covering a frequency interval of $3.47 \times 10^{-5}$ Hz to $8.3 \times 10^{-3}$ Hz, 1-hour averaged data for 6 months for a frequency interval of $6.4 \times 10^{-6}$ Hz to $1.39 \times 10^{-4}$ Hz, and monthly mean values of temperature for 20 years covering the frequency range of $2.0 \times 10^{-9}$ Hz to $3.86 \times 10^{-7}$ Hz have been used.

### 3. Features of the Atmospheric Boundary Layer at Thumba

During the morning hours, one generally observes a rise in the temperature inversion at Thumba followed by the appearance of thermal plumes which reach greater heights till the sea breeze sets in (Sen Gupta et al. 1986). The sea breeze usually sets in between 0800 and 1200 IST (IST = GMT + 5½ hours) and ceases between 1600 and 2200 IST. The advection of the cool sea breeze over the air above the heated sea coast results in the formation of a shallow TIBL at Thumba (Sen Gupta et al. 1990). The thermal-plume activity gets weakened progressively with the formation of a well developed TIBL (Kunhirikrishnan et al. 1990; Nair et al. 1989). During the evening hours one observes weak signals in the sodar, and the facsimile appears almost featureless associated with the near-neutral stability condition of the atmosphere. Ground-based inversion and wave structures are often observed during night-time. Thermally stratified structures are also usual for night-time records.
4. SPECTRAL STUDIES

Since spectral analysis of meteorological variables is essentially a statistical method of describing fluctuations, it enables us to study the various aspects of the boundary-layer structure, like the predominant scales of motion, the nature of energy containing eddies, the nature of cascading in the inertial sub-range, the intermittent outbreak of turbulence induced by terrain and mesoscale processes, modifications by plume and wave activity and the estimation of the size of eddies that carry maximum energy. In the first subsection the spectrum of the $u$ component of horizontal wind in the surface layer is discussed, in general, during stable and unstable conditions. This is followed by subsections on the effect of sea-breeze circulations on the power spectral density and the stable spectrum of wind. The composite spectrum of temperature forms the concluding subsection.

(a) Wind spectra

The general nature of frequency-weighted unstable spectrum and stable spectrum of horizontal wind is depicted in Fig. 2(a) and Fig. 2(b) respectively, corresponding to a height of 5 m. The characteristics of the unstable spectrum are a $+1$ slope in the energy-containing region and $-2/3$ slope in the inertial sub-range region. For the stable spectrum one observes a $-2$ slope in the buoyancy sub-range region (Lumley 1964; Weinstock 1981) and a $-2/3$ slope in the inertial sub-

![Graph showing wind spectra](image)

Figure 2. Frequency-weighted spectra of horizontal wind at 5 m for (a) unstable and (b) stable conditions as observed at Thumba.
range region (Kaimal et al. 1972, 1982; Busch and Panofsky 1968). The peaks in Fig. 2(b) correspond to waves of the respective periodicity in the atmosphere. The power spectral density for the unstable spectrum is in general high due to the increased turbulence activity for the convective atmosphere boundary layer.

(b) Influence of the sea breeze on the spectral characteristics

Sea-breeze circulation is observed to have a profound influence on the wind spectrum. It is well known that with the onset of the sea breeze, and the subsequent formation of the TIBL, the depth of the ABL is in general lowered, consequently inhibiting large-scale motions. Hence the computed spectral densities of wind fluctuations before the onset of the sea breeze show marked deviations from that observed after the onset of the sea breeze, both for vertical wind and horizontal wind spectra. Figure 3 shows the frequency-weighted spectrum of the longitudinal component of wind before and after the onset of the sea breeze over Thumba. The shift in the spectral peak after the onset of the sea breeze is attributed, as mentioned previously, to the formation of the TIBL which brings down the height of the boundary layer. The increase of spectral power in the high-frequency range is due to an increase in the wind shear consequent to a sudden change in roughness as the wind moves from a smooth sea to a rough coastal terrain. On the low-frequency side, on the other hand, there is a decrease in power, because the buoyant production, which is the major source of energy in the region, is relatively less. Hojstrup (1981) presents a model for surface-layer spectra consisting of a buoyancy-produced part in the low-frequency region of the spectra, and a shear-produced part in the high-frequency region, with sufficiently little interaction between the two regions such that they can be modelled separately.

Kaimal et al. (1982) have established a relation

$$\lambda_m = \frac{\bar{U}}{f_m} = 1.5 z_i$$

for the spectra of the $u$ and $v$ components of the wind. Here $\lambda_m$ is the scale size of the eddies that carry maximum energy, $\bar{U}$ is the mean horizontal wind, $f_m$ is the peak frequency of the frequency-weighted spectrum and $z_i$ is the depth of the ABL. Using relation (1), the depths of the ABL before and after the onset of the sea breeze have been estimated for 8 December 1989, 29 August 1990, 19 September 1990, 20 September 1990 and 20 February 1991 and are detailed in Table 1. From the table it is evident that the ratio between the depth of the TIBL to that of the convective boundary layer (CBL) is in the range 1:9 to 1:4 and for an early onset (e.g. 20 September 1990).

![Figure 3](image-url)  
**Figure 3.** Frequency-weighted spectra of the longitudinal component of wind before and after the onset of a sea breeze at Thumba.
### TABLE 1. Depths of the Boundary Layer Estimated from $u$ Spectra

<table>
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<tr>
<th>Date</th>
<th>Time (IST)</th>
<th>$\bar{u}$ (m s$^{-1}$)</th>
<th>$f_0$ (Hz)</th>
<th>$\lambda_m$ (m)</th>
<th>$Z_z$ (m)</th>
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<tr>
<td>Before onset of sea breeze</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 December 1989</td>
<td>0903-1003</td>
<td>1.54</td>
<td>0.0017</td>
<td>906</td>
<td>604</td>
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<tr>
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<td>0.0028</td>
<td>1484</td>
<td>990</td>
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<tr>
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<td>945</td>
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<tr>
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<td>428</td>
</tr>
<tr>
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<td>4.13</td>
<td>0.0020</td>
<td>2110</td>
<td>1412</td>
</tr>
<tr>
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<td></td>
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<td></td>
</tr>
<tr>
<td>8 December 1989</td>
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<td>2.56</td>
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<td>163</td>
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<tr>
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<td>4.83</td>
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<tr>
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<td>3.34</td>
<td>0.0138</td>
<td>242</td>
<td>161</td>
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The depth of the TIBL, is relatively less. In one of our recent communications (Kunhikrishnan et al. 1992) we have shown that the depth of the TIBL derived from $u$ spectra matches well with that from a slow-rise-balloon temperature profile and from sodar. Moreover, experiments conducted with a recently procured tethersonde also show discontinuities in the ABL variables between 100 and 200 m once the TIBL is formed. Figure 4 shows the effect of the sea-breeze circulation on vertical wind spectrum. In Fig. 4(b), the peak of the $w$ spectra for all the heights is seen to shift progressively with height, implying that the peaks scale with the height of observation, which is characteristic of surface-layer vertical wind spectra. This is valid for the height range $10z_0 \leq z \leq 0.1z_0$. After the onset of the sea breeze (Fig. 4(b)), one observes that the peaks of the $w$ spectra for 11 and 25 m coincide, implying that the spectral peaks scale with $z$ rather than with $z_0$, which according to Kaimal (1988) is characteristic of a mixed-layer $w$ spectra in the height range $z = 0.2z_0$ to 1.0$z_0$. The conclusion that emerges is that, after the formation of the TIBL, the height regions of 11 and 25 m which were well within the surface layer before the onset of the sea breeze have now become part of the mixed-layer region, thereby implying that the depth of the ABL has been reduced considerably. An alternative explanation for the 25 m spectrum in Fig. 4(b) could be that the layer above 11 m is no longer so unstable (owing to advection of marine air) as to obey free-convection scaling.

The spectra shown in Fig. 5 are from the $u$ component of wind for a data length of 3 hours with a view to observing the effect of mesoscale fluctuations. Three spectra corresponding to the times (a) before onset of the sea breeze (0820-1120 IST), (b) after onset of the sea breeze (1120-1220 IST) and (c) after onset of the land breeze (1920-2220 IST) are taken for the study. The wind-speed range for the above times are respectively 5-6 m s$^{-1}$, 7-8 m s$^{-1}$ and 3-4 m s$^{-1}$. Apart from the shifting of the peak with the onset of the sea breeze as discussed in the earlier section, one observes that the spectral gap which was seen at about $8 \times 10^{-4}$ Hz before the onset has widened, and the power corresponding to mesoscale fluctuations has dropped abruptly (b). This again is a consequence of the development of the TIBL and inhibition of long-period fluctuations. Whereas for (c), i.e. after onset of the land breeze, we observe that the energy corresponding to mesoscale fluctuations has built up again and that the spectral gap has narrowed and shifted to about 1.25 $\times 10^{-3}$ Hz. Also, the depth of the boundary layer computed using relation (1) (for wind-speed range 3-4 m s$^{-1}$) is of the order of a few tens of metres, which is consistent with sodar observations.

#### (c) Stable spectra

For classifying the stably stratified conditions, for the wind spectra, the gradient Richardson number ($Ri$) has been chosen since it can provide a simple criterion for the existence or nonexistence of turbulence in a stably stratified environment (Ayra 1972; Blanc 1983). Also $Ri$ can take indefinitely large values compared with the flux Richardson number ($Ri_f$) and stability parameter ($z/L$) which do not exceed the critical values (Kondo et al. 1978).

The night-time stable spectra of horizontal components of wind for various increasing values of $Ri$ are shown in Fig. 6. The solid line is a least-square fit to the spectral points using a fifth-degree polynomial. In Fig. 6(a), where $Ri = 0.001$, the spectral characteristic of a $-2/3$ slope in the inertial sub-range is still seen. A gap is seen in the low-frequency region at 0.0007 Hz between
Figure 4. Frequency-weighted spectra of the vertical wind (a) before and (b) after the onset of a sea breeze.

the wave-active region and turbulent region. The wave activity is relatively weak and the peak of the turbulent region is at about 0.004 Hz. For $Ri = 0.83$ (Fig. 6(b)) the prominence of the wave-active region is reasonable. The turbulent peak is still present and the spectral gap and the peak are shifted to 0.002 Hz and 0.02 Hz respectively. The presence of a buoyancy sub-range is indicated with a slope of '-2' in the low-frequency region, and similarly an inertial sub-range is implied in the high-frequency region with a slope of '-2/3'. In Fig. 6(c) ($Ri = 1.55$) we notice the prominent wave-active region. A slope of '-2' again bespeaks the presence of a buoyancy sub-range, but the peak in the turbulent region is not seen. However, the presence of a '-2/3' slope indicates the inertial sub-range where energy produced as a result of the breaking down of waves by Kelvin-Helmholtz instability is dissipated directly. The spectral gap has shifted to 0.1 Hz. $Ri = 2.95$ (Fig. 6(d)) is suggestive of an extremely stable environment wherein turbulence is effectively suppressed.
Figure 5. Three-hour spectra of the $u$ component of the wind showing mesoscale and microscale features.

at the low-frequency side. The spectrum thus indicates higher-amplitude fluctuations at higher frequencies than the less stable case (Fig. 6(c)). The inference from the above study regarding the spectral gap between the turbulent and the wave-active region is that the width of the spectral gap is dependent on the stability of the medium, and that the gap shifts towards the high frequency with increase in stability.

(d) Temperature spectra

Figure 7 shows the composite spectrum of temperature for Thumba. It is obtained by patching up overlapping spectra based on four sets of data, viz. data of 1-hour duration with a 200 ms sampling time, 1-minute averaged data for 8 hours, 1-hour averaged data for about 6 months, and monthly mean values for 20 years. The salient features in the spectra are: a synoptic annual peak and a semi-annual peak, a 13-day peak, a peak at about 1 day, and turbulent peaks at about 6 minutes and 3 minutes corresponding to natural oscillations of the atmosphere and thermal plumes respectively. The distinct spectral gap at about 1 hour demarcates the wave-active region from the turbulent region. A peak corresponding to 4 days has been reported for mid-latitude stations (Kolesnikova and Monin 1965; Oort and Taylor 1969). This is not seen for Thumba, probably because of the dominant nature of the local circulations peculiar to it as a coastal station.

5. Conclusions

The present investigation on the spectral studies conducted with data for Thumba, a near equatorial sea-shore station, on wind and temperature gives valuable information on the influence of a local circulation like the sea breeze. The land–sea baroclinicity leads to the formation of the TBL, resulting in the lowering of the depth of the ABL and enhancing turbulent kinetic energy; this has implications for sea coast fumigation. The following conclusions are based on the results which emerged from the above study. However, since the results are based on observations from a site about 500 m inland, away from the sea shore, no general conclusions are implied.

(1) The characteristics of the unstable wind spectrum are a +1 slope in the energy-containing region and a spectral fall of $-2/3$ in the inertial sub-range, whereas the stable spectrum gives a $-2$ slope in the buoyancy sub-range and $-2/3$ in the inertial sub-range.

(2) With the onset of the sea breeze and subsequent formation of the TBL, the depth of the ABL is in general lowered, consequently inhibiting large-scale motions. There is a shift in the spectral
peak and an increase in the spectral power in the $u$ spectra after the formation of the TIBL. The ratio between the depth of the TIBL to that of the CBL is in the range $1:9$ to $1:4$. The depth of the TIBL is relatively less for an early onset of a sea breeze. The height regions which were well within the surface layer before onset of the sea breeze become part of the mixed layer after the formation of the TIBL, as seen from the $w$ spectra.

(3) The spectral gap seen at about $8 \times 10^{-4}$ Hz, before the onset of the sea breeze, widens after the onset of the sea breeze; this can be attributed to inhibition of large-scale fluctuations by the lowering of the TIBL depth. The width of the observed spectral gap is atmospheric stability dependent and shifts towards the high-frequency region with increase in stability.
(4) The salient features in the temperature spectra are: a turbulent peak at 3 minutes associated with thermal-plume activity, semi-diurnal and diurnal peaks associated with the daily cycle, and an annual peak associated with seasonal changes. The spectral gap at about the 1-hour period demarcates the wave-active region from the turbulent region.

ACKNOWLEDGEMENT

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Figure 7. Composite spectrum of temperature for Thumba.

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<table>
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<th>Author(s)</th>
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<tr>
<td>Kunhikrishnan, P. K.</td>
<td>1990</td>
<td>‘Studies of atmospheric boundary layer.’ Ph.D. Thesis (University of Kerala). Space Physics Laboratory, Vikram Sarabhai Space Centre, Trivandrum-695 022, India</td>
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