A short review on wind profiler observations of lower and middle atmospheric processes over Gadanki

T Narayana Rao & D Narayana Rao
National Atmospheric Research Laboratory, Gadanki 517 112, India
Received 17 August 2007; accepted 30 August 2007

National Atmospheric Research Laboratory (NARL), a unique site having Mesosphere Stratosphere Troposphere (MST) Radar, Lower Atmospheric Wind Profiler (LAWP), Lidars, disdrometer, Optical Rain Gauge, Automatic Weather Station, vertical profiling with GPS soundings, and a dual frequency GPS receiver, has been operating all these instruments to support the scientific research dealing with dynamics of the lower, middle and upper atmosphere, coupling between these regions and precipitating systems. Several interesting results have been obtained making use of the experimental facilities at NARL. It is, indeed, a difficult task to review all of them in a short paper. In this communication, an attempt has been made; however, to review the exciting scientific outcome resulted from Indian MST radar LAWP measurements, confining ourselves to dynamical and microphysical aspects of atmospheric processes in the troposphere and lower stratosphere. A variety of atmospheric phenomena occurring over a wide range of temporal and spatial scales are discussed, starting from microscale turbulence within the radar resolution volume to mesoscale processes, like convection and associated processes, and to synoptic and planetary scale waves with proper referencing, wherever required.

Keywords: Wind profilers, Middle atmospheric dynamics, Radar meteorology, Clear air turbulence, Gravity waves
PACS No.: 92.60.Dj; 92.60.Ek

1 Introduction
The development of completely indigenous and the state-of-art Indian Mesosphere, Stratosphere, Troposphere (MST) radar, an offshoot of Indian Middle Atmospheric Program (IMAP), is a major break through in coherent backscatter radar technology in India. The radar is being operated regularly since 1991 (1993 in MST mode), for better understanding of the structure and dynamics of the middle atmosphere (troposphere, lower stratosphere and mesosphere). The MST radar can detect echoes caused by ~ 3 m irregularities in the radio refractive index due to the variations in, primarily, humidity and temperature. It also gets strong backscatter from electron density variations in the earth’s ionosphere (including the D region) and can be used to study the ionospheric irregularities. However, they are not discussed in this paper; because of the large antenna array of the MST radar, it is not possible to probe the lower region of the atmosphere below 1.5 km with this radar. To obtain the missing information below 1.5 km, a small radar (but at a different frequency), known as Lower Atmospheric Wind Profiler (LAWP), was installed at Gadanki in August 1997 under Indo-Japanese collaboration program.

The subject of radar remote sensing is too vast to be discussed in depth and therefore only a flavor of recent advances in atmospheric sciences and present research activities making use of clear air Doppler radars at Gadanki are included. The organization of this paper is as follows: Details of the Indian MST radar and LAWP are given in section 2. Section 3 reviews the research work, pertaining to troposphere and lower stratosphere, carried out using Indian MST radar and LAWP. The paper is summarized in section 4.

2 Description of Indian MST radar and LAWP
The Indian MST radar and LAWP are located at NARL, Gadanki (13.5°N, 79.2°E) in the south-eastern part of India. The Indian MST Radar is a highly sensitive, pulse coded, VHF phased array system operating at 53 MHz with an average power aperture of $7 \times 10^{10}$ Wm$^2$. The phased array consists of two orthogonal sets, one for each polarization of $32 \times 32$ three-element Yagi antennas occupying an area of $130 \times 130$ m. The array is illuminated in either of linear (EW, NS) polarizations using 32 transmitters of different power levels, each feeding a linear sub array of 32 antennas. The power distribution across the array follows an approximation to modified Taylor weighting in both principal planes to suppress the side lobes to desired level. The large antenna array facilitates to radiate narrow beams with large
directional gain. For instance, the Indian MST radar generates a radiation pattern with a main beam of 2.8°, gain of 36 dB; and a side lobe level of −20 dB. The main beam can, in principle, be positioned at any look angle within ±20° in EW and NS planes. An inter-antenna spacing of 0.71λ is used in both planes to allow the beam scanning up to an angle of about 24° from Zenith. It is possible to transmit both coded and uncoded pulses with a pulse repetition frequency (PRF) in the range of 62.5 Hz to 8 kHz, keeping the duty cycles not exceeding the limit. The uncoded pulses can be varied in pulse width from 1 to 32 µs in multiples of 2. The coded pulses are either 16 or 32-baud bi-phase complementary pair with a baud length of 1 µs, providing a range resolution of 150 m. The Indian MST radar is a versatile system and the parameters can be modified as required for different experiments. The larger antenna array and the T/R switch limit the lowest probing height to 1.5 km. A complete description of the system, signal processing and parameter retrievals can be found in Rao et al.1

The operating frequency of the LAWP is 1357.5 MHz. The phased antenna array consists of 24 × 24 elements occupying an area of 3.8 × 3.8 m². It transmits a peak power of 1 kW. To suppress the side-lobe levels, feeding power to each antenna is distributed as the maximum power to the central and decreasing toward the corners. The pulse width can be set as 0.33, 1 and 2 µs, corresponding to a range resolution of 50, 150 and 300 m, respectively. The pulse repetition period can be set from 20 to 999 µs and can be operated with a maximum duty ratio of 5%. The number of coherent and incoherent integrations can be in the range of 1-256. The number of fast Fourier transform (FFT) points can be from 64 to 2048 (limited to 2ⁿ). The beam spread is ~4°.

To obtain the wind speed and direction, LAWP measures data in three beam directions, namely, zenith, north and east in one observation cycle. The zenith angle of the off-vertical beams is 15° and is achieved by introducing a phase shift of 68° between the array in zenith-north plane and by extending each feeder cable as corresponding length to 68° phase delay in zenith-east plane. The LAWP is operated in two modes, low and high mode, alternatively, to extend the height coverage. In the low mode, radar samples are taken up to 4.8 km with a range resolution of 150 m, while in the high mode the data are collected up to ~10 km with a range resolution of 150 m. However, the typical height coverage in the clear air is 3-4 km and is ~10 km during precipitation. Details of the LAWP can be found in Rao et al.2 and Reddy et al.3 The selected parameters of the Indian MST radar and LAWP are shown in Table 1.

3 Scientific results and discussion

Several interesting studies in the neutral and ionospheric region have been carried out with the Indian MST radar since its inception. In addition to numerous papers published in journals of international repute, two special issues of Indian J Radio & Space Physics4,5 were brought out exclusively showcasing the scientific outcome based on NARL experimental facilities, in general, and the Indian MST radar, in particular. Since it is impossible to discuss all the results in a single article, a review of different atmospheric processes (pertaining to the troposphere and stratosphere) is provided in this paper by giving proper references, wherever required.

3.1 Horizontal and vertical winds

Wind profilers provide cost effective means of obtaining long-term measurements of 3-D wind in the MST region with excellent temporal and range

<table>
<thead>
<tr>
<th>Specification</th>
<th>MST radar</th>
<th>LAWP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>53 MHz</td>
<td>1357.5 MHz</td>
</tr>
<tr>
<td>Antenna aperture</td>
<td>130 × 130 m</td>
<td>3.8 × 3.8 m²</td>
</tr>
<tr>
<td>Beam width</td>
<td>3°</td>
<td>4°</td>
</tr>
<tr>
<td>Beam directions</td>
<td>82</td>
<td>3</td>
</tr>
<tr>
<td>Peak power</td>
<td>2.5 MW</td>
<td>1 kW</td>
</tr>
<tr>
<td>Maximum duty ratio</td>
<td>2.5%</td>
<td>5%</td>
</tr>
<tr>
<td>Pulse width</td>
<td>1-32 µs</td>
<td>0.33, 1 and 2 µs</td>
</tr>
<tr>
<td>Pulse repetition frequency</td>
<td>62.5 Hz-8 kHz</td>
<td>1-50 kHz</td>
</tr>
<tr>
<td>Maximum range resolution</td>
<td>150 m</td>
<td>50 m</td>
</tr>
<tr>
<td>Maximum FFT points</td>
<td>1024</td>
<td>64-2048</td>
</tr>
<tr>
<td>Radar controller</td>
<td>PC-AT (with programmable ESF*)</td>
<td>PC-AT (with programmable ESF*)</td>
</tr>
</tbody>
</table>

*Experiment Specification File
resolutions. However, the measurements need to be quality checked before using the data for scientific research. The quality of the Indian MST radar data have been verified several times by comparing MST radar derived winds with concurrent winds measured by radiosondes / rawinsondes at SHAR and Chennai. The wind profiles show very good agreement with an average discrepancy of 2-2.5 ms\(^{-1}\). Maximum discrepancies were found in the upper troposphere, where quality of the data is uncertain in the regions of low signal-to-noise ratio. Application of quality control techniques, such as consensus and continuity algorithms, to the Indian MST radar wind data shows improved agreement with the balloon wind data\(^a\).

Using the Indian MST radar winds several large scale meteorological phenomena are studied extensively in recent years. The interaction between low- and mid-latitudes is studied by Annes et al.\(^7\). They found anomalous features in wind patterns for few days during winter and attributed them to the north-south movement of anticyclones during the passage of western disturbances over north-west India. Such anomalous circulations on a slightly larger scale are noticed by Annes et al.\(^8\) and Rao et al.\(^9\). An anomalous northerly wind is observed in the lower troposphere over Gadanki during summer monsoon months instead of expected southerlies. The observed reverse Hadley circulation and the downward vertical velocity values at Gadanki conclude that the downward limb of the Hadley cell exists north of the equator during summer.\(^8\) Rao et al.\(^9\) observed significant differences in all three wind components during El Nino year from that of climatological mean profiles. The observed wind differences are attributed to the weakening of Hadley circulation. Mrudula et al.\(^10\) tried to characterize the wind field during the passage of a cyclonic storm. Horizontal wind components in the upper troposphere and lower stratosphere showed an abrupt increase during the passage of the storm, whereas the wind changed its direction and became very weak in lower levels (4-8 km). After the passage of the cyclonic storm upper and lower tropospheric wind speed reduced considerably, whereas the mid-tropospheric wind speed increased.

The measurement of vertical air motion, though very small in magnitude in fair weather conditions, is extremely important, as it is linked to several atmospheric processes. The radar, perhaps, is the only remote sensing instrument that provides the vertical air motion with a great accuracy. Long-term mean vertical air motions in the troposphere and lower stratosphere (between 4 and 20 km) are found to be in the range of 3-20 cm\(^{-1}\), with larger magnitudes in monsoon and post-monsoon seasons. A reversal in vertical wind direction is observed at two heights; one coincides with the change in zonal wind direction and the other with the jet stream. The vertical wind reversal is attributed to the horizontal wind convergence and also to instabilities associated with the jet streams.\(^11\) Comparison of MST radar derived vertical winds with those estimated indirect methods, like kinematic and adiabatic, reveals that the kinematic method agrees with the MST values in direction, but differs in magnitude. On the other hand, the vertical velocities computed with the adiabatic method are found to be small.\(^12\)

### 3.2 Wave dynamics

Continuous wind measuring capability of wind profilers makes it an ideal remote sensing instrument for studying waves over a wide range of time scales, in general and short period waves, like gravity waves, tides, etc., in particular. A large number of studies focused in identifying gravity waves with different periodicities generated by a variety of mechanisms, discussed above. Dutta et al.\(^13\) fitted exponential curves of the form \(e^{\frac{z}{H}}\) (where, \(z\) is the height in km and \(H\), scale height) to the variance profiles (indicator for gravity wave activity), estimated for 2-6 h periodicities, to study the wave activity. They have shown that the estimated value of \(H\) is found to be less than the theoretical value of neutral atmosphere in the troposphere, indicating that the sources of gravity waves are present in the troposphere.

Reddy et al.\(^14\) observed that the gravity wave activity is prominent in summer and monsoon seasons, particularly in the upper troposphere and lower stratosphere. The diurnal cycle observations made on 13 days have been used to study the slope of wave number spectra in three height regions (Dutta et al.\(^15\)). They found that the steepest slopes are observed in the tropopause region for both horizontal and vertical winds. The average slopes are found to be \(\sim 2.5\) for horizontal winds and \(\sim 2.2\) for vertical winds, which are smaller than the theoretically predicted value (\(\sim 3\)). They found that the mesoscale spectra can be influenced by mechanisms like 2D turbulence and background winds.

It is well known that the short period gravity waves contain most of the energy and are very important in transporting momentum and energy from their source regions to other regions. Several techniques are
available in the literature for estimating the fluxes of momentum. A comparison of these techniques using MST radar observations reveals that symmetric beam method shows excellent matching with other methods, when the average of vertical winds derived from E-W and N-S beams is used in the formula for both zonal and meridional fluxes. However, all these methods assume the horizontal homogeneity in the volume between the beam positions to estimate the horizontal wind and also momentum fluxes. During convection, such assumptions may not be valid in the presence of highly variable, and intense up- and down-drafts.

On the other hand, the power spectral method for momentum flux estimation, which assumes that the phase passing occurs equally at the two symmetrical beam pairs instead of assuming homogeneous field of disturbances, may work better in such situations. This method is used by Nayar and Sreelatha to estimate the momentum flux during convection. They found that the zonal momentum flux value at 16 km height during convection is 10 times higher than those obtained during the quiet period. They also found that the vertical momentum flux magnitude is not evenly distributed in all wave periods, rather peaked at certain wave periods in the range of 10-100 min. Note that the effect of geophysical noise on the precision of momentum flux estimations is very significant. The momentum flux estimates have to be averaged for longer periods to obtain meaningful values. Dutta et al.18 made a study to find out how the uncertainty involved in the measurement of momentum flux of short period (< 2 h) wind fluctuations vary with the time of integration. Error analysis has been carried out by varying the length of integration time and the results are plotted in Fig. 1. They have shown that an optimal time averaging of about 15-16 h minimizes the error at a value nearly equal to the irreducible error observed by an ideal anemometer, measuring $u$, $v$ and $w$ at a point.

It is now widely accepted that the convection is an important source of generation for gravity waves. Convection triggers gravity waves primarily through three processes: (1) mechanical oscillator effect, (2) obstacle effect and (3) thermal forcing. Several studies have attempted to characterize convectively generated gravity waves and relate the observed wave activity to the wave generation processes discussed above. Dhaka et al.19 have observed signatures of gravity waves in the vertical velocity data collected during the passage of two convective storms. The dominant vertical wave length and wave periods obtained from the observations are 2-5 km and 10-20 min in the lower stratosphere and ~ 10 min in the troposphere. They suggested that the generation of observed gravity waves is the manifestation of the mechanical oscillatory character of the updrafts.

Several studies have shown weakening of the tropopause during convection, perhaps, may be due to the turbulent mixing induced by penetrative convection (Jain et al.20, Dhaka et al.21 and Kumar22). Interestingly, they have seen gravity wave activity in the lower stratosphere, when the tropopause layer was weakened, which implies that this leakage might have allowed the waves to propagate into the stratosphere. Recent studies with the MST radar on gravity waves triggered by convection revealed interesting features. The phase profiles of convectively generated gravity waves obtained from two case studies show [Fig. 2(a)] a constant phase in the middle troposphere and downward and upward phase propagation, below and above, respectively, indicating the possibility of source in that region22. Wavelet analysis of vertical air motions observed during convection in the height region 10-14 km has shown two distinct oscillations with time periods 28 and 12 min [Fig. 2(b)]. The resultant oscillation, with periodicities 21 and 8.4 min, due to the interaction of these two modes is observed in the lower stratosphere23.

Though the sources of tides are well known24, their characteristics vary considerably from polar latitudes to mid-latitudes and to tropics. The diurnal (24-hr) measurements of Indian MST radar have been used to understand the tidal oscillations in a better way. Significant progress has been made in characterizing the tides (both migrating and non-migrating modes) and their seasonal variability at Gadanki. A study on
Fig. 2 — (a) Phase profiles of dominant wave periods in vertical velocity measurements made on 21 June 2000 and 22 June 2000 (after Kumar); (b) wavelet spectrum of tropospheric peak vertical velocities in the height region 10-14 km and (c) wavelet spectrum of lower stratospheric vertical velocities in the height region 18-20 km (after Kumar).

tidal oscillations in horizontal winds during autumnal equinox season shows that the amplitude of these oscillations is of the order of 1-2 m/s with vertical wavelengths of 3 and 6 km in the lower and upper troposphere, respectively. A comparison of these amplitudes, vertical wavelengths and phase propagation with results from theoretical tidal models suggests that these oscillations are manifestations of non-migrating tidal components (Sasi et al. 25).

On occasions, non-migrating tides of large amplitudes (~ 10 m/s) are observed over Gadanki, which are thought to be associated with the latent heat released by deep convective clouds. Interestingly, not much variation is seen in amplitudes of both zonal and meridional components with season; however, significant seasonal variation is seen in phase profiles. A comparison of the simulated amplitudes and phases with the observed ones shows that agreement between the two is quite good for the equinox seasons, especially the vertical structure of the phases of the meridional wind components. Though the simulation was done by taking all heat sources, the seasonal variation of heat sources was not considered in simulation. Part of the discrepancy between the simulated and observations could be attributed to that factor.

Equatorial waves play a key role not only at their source altitudes but also at higher altitudes through their wave mean flow interaction and thereby producing QBO. An important parameter used for the simulation of the QBO is the prescription of meridionally averaged vertical flux of horizontal momentum $\mathbf{u}\mathbf{w}$ of the Kelvin and RG waves at the lower boundary (at a height of 17 km) of the model. An attempt has been made to estimate the momentum flux of these waves using Indian MST radar measurements. The maximum observed amplitudes are seen in the upper troposphere (10-15 km altitude), and are ~ 2.2, ~ 1.6, and ~ 1 m/s$^{-1}$ for the 12-, 5.3-, and 3.4-day oscillations, respectively. The vertical wavelengths estimated from the vertical phase profiles are ~ 10, ~ 10, and ~ 6 km for the 12-, 5.3-, and 3.4-day period oscillations, respectively. The momentum fluxes due to slow Kelvin waves (12-day period), fast Kelvin (5.33-day period) and Rossby-Gravity (RG) (3.43-day period) waves are estimated as $16 \times 10^{-3}$, $8 \times 10^{-3}$, and $5.5 \times 10^{-3}$ m$^2$s$^{-1}$, respectively.

In a subsequent study, Sasi and Deepa have shown that momentum flux values are larger during equinox seasons than solstices, with values near the tropopause level being $16 \times 10^{-3}$, $7.4 \times 10^{-3}$, $27 \times 10^{-3}$, and $5.5 \times 10^{-3}$ m$^2$s$^{-1}$ for Kelvin waves and $5.5 \times 10^{-3}$, $3.5 \times 10^{-3}$, $6.7 \times 10^{-3}$ and $2.1 \times 10^{-3}$ m$^2$s$^{-1}$ for RG waves during autumnal equinox, winter, vernal equinox and summer seasons, respectively. They argued that the proximity of ITCZ to the radar location during equinoxial months is responsible for the enhancement of wave activity and zonal momentum flux values during equinox.
3.3 Turbulence and its variability

Since clear-air wind profilers obtain backscatter mainly from irregularities in radio refractive index induced by turbulence, they can be effectively utilized to quantify turbulence. Three parameters are generally used to quantify the turbulence: (1) $C_n^2$, the refractivity turbulence structure constant, for intensity of refractivity turbulence, (2) $\varepsilon$, eddy dissipation rate, for turbulence in the velocity field and (3) $K$, eddy diffusion coefficient.

The refractivity turbulence structure constant, $C_n^2$, is estimated using the backscattered power (signal-to-noise ration, SNR) of radar and also from radiosonde measurements. Reasonable agreement is found between the estimates obtained with these methods\textsuperscript{31,32}. The variation of $C_n^2$ at various scales has been studied by several investigators. A detailed study using 36 diurnal cycles of data collected with the Indian MST radar shows significant variations in $C_n^2$ in the range of 4-7 dB in the lower and middle troposphere (< 12 km) in all seasons\textsuperscript{33}. Monthly mean $C_n^2$ profiles show broad maxima in June-October period and minima in February-March and November. Monthly mean $C_n^2$ values are found to vary by as much as 12-15 dB through the course of the annual cycle below 12 km, while the variation above 12 km is in the range of 5-8 dB. A secondary peak is observed in $C_n^2$ profile at about 16 km in the monsoon and is attributed to shear induced turbulence due to the prevailing tropical easterly jet stream\textsuperscript{33,34}. Significant inter-annual variability is also observed with lower values of seasonal mean $C_n^2$ in 1998 than in other years.

Turbulence in the atmosphere can be generated by static or/and dynamic instability. For the static instability the atmospheric temperature lapse rate should be greater than the adiabatic lapse rate, whereas for the dynamic instability the vertical gradient of horizontal wind speed should be strong enough to disturb the static stability (due to stratification by gravity). These strong wind shears often generate Kelvin–Helmholtz Instabilities (KHI), which are extensively studied by several investigators with the help of radars. Using Indian MST radar observations, Singh et al.\textsuperscript{35} identified the presence of a KHI at shear maximum just above the meteorological tropopause. They characterized the observed KH wave as having a periodicity of 12 min and a horizontal wavelength of 7.2 km. A detailed investigation of the Doppler width structure reveals that the KH billows undergo breakdown in between the shear layer, causing peaked structure in the Doppler width profile.

To estimate the eddy dissipation rate and eddy diffusion coefficient from radar measurements any of the following three methods are generally used (Rao et al.\textsuperscript{33} and references therein). The first method, called as power method, utilizes the calibrated radar backscattered power (or SNR) and temperature and humidity measurements, basically from radio soundings. The second and third methods, called as spectral width methods, utilize the spectral width of the radar spectra. Among two spectral width methods, one requires temperature measurements for quantifying turbulence, while the other method does not depend on temperature measurements, at least for the estimation of $\varepsilon$. However, in both methods, a correction for non-turbulent contributions (beam, shear and transience broadening) has to be made to obtain spectral width due to turbulence alone. The advantages and limitations of these methods are discussed in detail in Rao et al.\textsuperscript{33} The monthly variation of log $\varepsilon$ and log $K$ profiles (Fig. 3) shows a broad peak in May-October up to ~ 11 km with a variation of ~ 8 dB in a year. Above 11 km, the variation is slightly less (6 dB) and also the peak is confined to monsoon months. The year-to-year variation of these parameters is found to be small in winter. Interestingly, both $C_n^2$ and $\varepsilon$ (also $K$) profiles show similar inter-annual variation with smaller values in 1998 than in other years.

The traditional method of estimating TKE from spectral width requires the application of correction factors to the measured spectral widths. However, during relatively strong winds, estimate of correction factor sometimes becomes larger than the measured spectral width, which implies relatively large uncertainty either in correction factors or in the observed spectral widths. To overcome this problem, two methods are suggested: (1) variance method, and (2) dual beam width method. The advantage of the variance method, suggested by Satheesan and Krishnamurthy\textsuperscript{36}, is that all the required data for estimation of $\varepsilon$ are available from the MST radar itself. In other words, both the variance and temperature information is obtained from the temporal spectrum of vertical wind. They estimated $\varepsilon$ and $K$ using Indian MST radar observations in winter season and noticed a prominent peak in the upper troposphere. From Richardson number considerations the enhanced turbulence observed in the upper troposphere is attributed mainly to wind shear.
Fig. 3 — Monthly variation of $\log \varepsilon$ and $\log K$ (top); inter-annual variation of $\log K$ in (a) monsoon, (b) post-monsoon, (c) winter, and (d) summer (after Rao et al.\textsuperscript{33})
In a subsequent study, Satheesan and Krishnamurthy\textsuperscript{37} compared the profiles of $\varepsilon$ retrieved by velocity variance method with power and spectral width methods. It is found that value of $\varepsilon$ by the variance method differs from that by the other two methods significantly in the upper troposphere, where the background horizontal wind is high. The observed difference is attributed to the presence of anisotropic turbulence. The second method, a dual beam width method, has been implemented at Gadanki to estimate the TKE\textsuperscript{38}. Figure 4 shows monthly medians of corrected spectral widths during April (left panel) and May (right panel) for all beams using dual beam width technique (top panel) and traditional method (bottom panel). It is evident from the figure that during light wind conditions, the spectral width from the modified dual-beam width method and the traditional method are the same. During strong wind conditions (over about 15 m s$^{-1}$) the modified dual-beam width method continues to give realistic estimates in the beam parallel to the wind, while for the other plane, and for both planes with the traditional method, the corrections are larger than the observed spectral width.

### 3.4 Aspect sensitivity, stable layers and the tropopause

The main mechanisms that give rise to atmospheric radar echoes at VHF are isotropic, anisotropic backscattering, Fresnel reflection/scattering and Rayleigh scattering. Anisotropic turbulence and Fresnel reflection/scattering make the radar echo aspect sensitive (i.e., the received power falls off as a function of zenith angle), which in turn influences the beam pointing angle and beam width and thereby the determination of horizontal wind components and turbulence parameters.

A series of experiments have been conducted with MST radar to better understand the properties of scatterers and also to detect the stable regions in the atmosphere\textsuperscript{31,39-43}. Results of these experiments have shown that aspect sensitivity is more prominent between the altitude range of 15-21 km. Results also show the presence of scatterers with different horizontal correlation lengths. Aspect sensitivity

---

![Fig. 4 — Median TKE with dual beam width method (upper) and traditional method (lower) over all observations taken at 10° zenith angle during April (left) and May (right) [Bars extending ±2σ are entered at representative heights along the E and N curves (after Nastrom et al.\textsuperscript{38})] ](image-url)
measurements for different beam combinations show significant differences for two orthogonal planes, i.e., E-W and N-S, indicating the azimuthal anisotropy of the scatterers. The effect of aspect sensitivity on beam pointing angle and wind measurements is estimated. For beams with small zenith angle (i.e., ≤ 4°), the underestimation of winds can be as much as 30%, whereas for larger zenith angles (≥ 8°), the same would be ≤ 5%. The generation mechanisms of aspect sensitivity based on simultaneous MST radar and GPS-sonde observations appear to be due to high $N^2$, low wind shear and high $R_i$. This indicates that the aspect sensitivity is caused by the thermal structures of the atmosphere, particularly in the upper troposphere and lower stratosphere (Ghosh et al.). Significant power differences are observed between symmetric beams, which they attribute to the tilting of the scatterers by KH billows. For many purposes, the radar backscatter arising from beams tilted ≥ 10 is often assumed to be due to isotropic turbulence. However, such assumptions may not be always valid.

Jain et al. have shown that the contribution of enhanced $N^2$ to radar reflectivity can be very significant even for beams tilted ≥ 10, particularly near the tropopause and in the lower stratosphere. At the height where $N^2$ contribution to oblique echo power is significant, the radar backscatterers appear to be relatively more anisotropic with the horizontal correlation length (ζ) of 16-20 m. This result has significant implication in interpreting the radar reflectivity observations.

Atmospheric stable layers are observed, utilizing the aspect sensitive nature of MST radar echoes, at various heights in the troposphere and lower stratosphere (Jain et al.). The authors have observed multilayer structures near the tropopause and in the lower stratosphere. These structures seem to persist for more than an hour, indicating their large horizontal extent. The tropopause is also identified, in a similar way, from radar measurements. The day-to-day variability of the tropopause has been studied by Rao et al. and they found three dominant modes of tropopause oscillation (50-70 d, 30-50 d, and 10-20 d).

The MST radar, in its routine mode of operation, does not provide temperature information. In a seminal work, Revathy et al. described a technique to retrieve temperature profile from MST radar measurements. This method mainly depends upon identification of Brunt-Vaisala (BV) frequency in the spectra of vertical wind velocity oscillations. After obtaining BV frequency, deduction of temperature information is straight forward. However, this method requires temperature information at a reference altitude and for which two ways have been proposed by Revathy et al. Figure 5 shows a comparison of temperature profiles retrieved with the methods proposed by Revathy et al. and those obtained with radiosonde. It is clearly evident from the figure that the comparison is quite good. However the technique has a few limitations. The method is applicable only under convectively stable conditions. Further, when the background wind speed is high (≥ 40 m/s), identification of $N$ from the vertical wind temporal spectra may become difficult due to Doppler shifting of the lower frequency gravity waves. The errors arise mainly due to the errors in the estimation of $N$ and in the boundary value of temperature. The standard deviations of the temperature are estimated to be

![Figure 5](image-url)
typically 0.7, 1.2, and 1.6 K at altitudes 6.75, 14.25 and 20.25 km, respectively, for an altitude resolution of 150 m.

The temperature information deduced by the above method has been effectively utilized to study the variation of temperature and the tropopause at different scales and also to retrieve other meteorological parameters. Revathy and Nayar observed significant diurnal variation in tropospheric temperature with afternoon peak, which shifted right with height. Krishnamurthy et al. noticed that the tropopause altitude and temperature are modulated by wave disturbances with periodicities in the range 15.7-3.6 d in winter 1999. In a subsequent study, modulation of tropical tropopause temperature, zonal and meridional velocities near the tropopause, by wave disturbances in the winter season of 2000 and 2002, and in the summer season of 2001 has been studied to discern the seasonal variability in tropopause modulations (Satheesan and Krishnamurthy). They reported that in the summer season, the modulation in the tropopause temperature in the periodicity range 18-7 d is manifestation of equatorial Kelvin waves. In the winter season, there is no clear evidence of manifestation of equatorial Kelvin or RG waves in the tropopause parameters. However, it is quite likely that extra-tropical wave activity influences the tropical tropopause.

It has been recognized recently that the tropical tropopause is not a sharp boundary, but a transition layer, so called Tropical Tropopause Layer (TTL), between the troposphere and stratosphere. Accordingly, several studies focused their attention on identifying the boundaries of the TTL in a number of ways, based on their research requirements. The most accepted definition of the TTL is that it is the region between the cold point tropopause and the convective outflow level. The vertical wind data obtained with the MST radar have been used to retrieve the horizontal divergence profile, which, in turn, is used to identify the convective outflow level. The level of convective outflow has been compared with the lapse rate tropopause height, cold point tropopause height and the level of minimum potential temperature gradient on a day-to-day basis to better understand the tropical tropopause characteristics.

One of the important meteorological parameters required for better understanding of the weather is humidity. Like temperature, humidity profile has to be retrieved from MST radar measurements indirectly. Mohan et al. extended the temperature profiling technique from MST radar measurements, proposed by Revathy et al., to extract humidity measurements. The technique depends on exact estimation of potential refractive index gradient (M) from volume reflectivity (η), ε and BV frequency. By neglecting humidity gradient term, it is possible to deduce the humidity profile by integrating the equation from a known reference humidity value. Mohan et al. found a fairly good agreement between retrieved profiles from MST radar measurements and radiosonde humidity profiles, in fair weather.

3.5 Boundary layer studies

Though the Indian MST radar can probe as low as 1.5 km, LAWP is an ideal instrument to study boundary layer processes and their interaction with free troposphere. Making use of continuous atmospheric boundary layer data obtained with LAWP, diurnal evolution of boundary layer has been studied in different seasons. The evolution of Convective Boundary Layer (CBL) height, determined from refractive index structure constant profiles, in different seasons shows distinct features, which can be used to monitor the onset of convective instability. The vertical mixing of the atmospheric pollutants is strongly influenced by the height of the Atmospheric Boundary Layer (ABL), which acts as an interface between the more polluted regions near the earth’s surface and the relatively cleaner free atmosphere above. Temporal variations of ABL height and ventilation coefficient (VC), a parameter that depends on the ABL height and mean wind within the mixed layer, are studied using LAWP measurements. The monthly variation of VC, ABL height and wind speed reveals that the average ABL height over Gadanki is high in April (~ 2.3 km) and low in January (~ 1.4 km). The monthly variation of VC indicates highest value in July and lowest in January. A detailed analysis shows that VC is strongly influenced by wind speed during monsoon seasons, whereas both ABL height and wind speed determine the value of VC during the other seasons over Gadanki.

A few studies focused on the effect of meteorological parameters, like temperature, humidity and wind, on backscattering at UHF. For instance, Das et al. have shown that the trapped humidity layers, just above the boundary layer and the KHI are very important for UHF radar backscattering. Further, characteristics of the low level jet, like the occurrence frequency, amplitude, etc., have also been studied.
The LAWP measurements are utilized to study diurnal and seasonal variability of TKE dissipation rate ($\varepsilon$) in the CBL. The eddy dissipation rate has shown significant variability in the CBL varying from $10^{-1}$ to $10^{-5}$ m$^2$s$^{-3}$. In all the seasons, $\varepsilon$ has shown pronounced diurnal variability with larger values in the noon-evening period and smaller values in the morning period. Among seasons, $\varepsilon$ values are larger in monsoon and summer seasons and also these larger values are extended to higher altitudes in these seasons.

Krishnan et al. have studied the evolution of intra-seasonal oscillations (ISO) using continuous measurements of LAWP (Fig. 6). It is clearly evident from the figure that 30-60 day oscillations are prominent during SW-monsoon period, whereas 10-25 day oscillations are prevalent in pre-monsoon. The prominent 10-25 day period present during March to the beginning of June is gradually replaced by 30-60 day periodicity by June and peaked during July to September (left panel). The Figure also demonstrates that NCEP data captures the time evolution of the oscillations reasonably well, even though it is averaged over the 2.5$^\circ$ latitude-longitude grid containing the location. The right panel of Fig. 6 shows the height-time evolution of ISO in a drought year, 2002. One can observe that the time evolution of the oscillation from 10-25 day during pre-monsoon to 30-60 day during SW-monsoon during the year 2001 is systematic. Whereas, in 2002: (1) the evolution of 10-25 day periodicity is not clear and 30-60 days oscillations are present even during pre-monsoon season in contrast to the presence of 10-25 day period during the preceding years and (2) the evolution of the periodicities from June, to September shows an irregular pattern of oscillation in the range 20-50 days. This study suggests that the evolving periodogram of zonal wind during normal monsoon years shows a systematic evolution of periodicities, whereas it shows different pattern during drought year.

3.6 Tropical convection and precipitation

The unique capability of VHF radars is to detect echoes simultaneously, from both the radio refractive index irregularities through Bragg scattering and precipitation particles through Rayleigh scattering during moderate to heavy precipitation. In such a scenario, the traditional single peak picking algorithms, generally used to retrieve moments from wind profiler spectra, may either treat both these echoes as single echo or picks up the wrong echo. In both the cases, the error will be significant. To circumvent this problem, special processing techniques are required. The simplest way of separating the clear-air and precipitation echoes is by assuming that the minimum power spectral density point (valley point) represents the boundary between the two peaks. Characteristics of the radar

Fig. 6 — Time series of LAWP observed zonal wind at 1.5 km (solid), 1.8 km (dashed) and NCEP reanalysis zonal wind at 850 hPa (gray curve) (top panel) [Time-height evolution of ISO in zonal wind (below top panel); (bottom two panels): same as top panels but for a drought year, 2002 (after Krishnan et al.).]
backscattered echoes from precipitating environment have been studied extensively. It has been found that the clear air echo power weakens in the presence of strong updrafts in convection\textsuperscript{59} and also near the radar bright band in stratiform rain\textsuperscript{58}. The suppression of clear-air echo power is attributed to the effect of entrainment of dry and cold ambient air into the warm and moist cloud. The turbulent mixing of the ambient with in-cloud air weakens the gradients of temperature and humidity and thereby the backscattered power of clear air echoes (Fig. 7).

Several campaigns have been carried out to study the convective systems over Gadanki. On the basis of the database available for both the south-west and north-east monsoons, the convective systems are classified as single-cell and multi-cell. The observations show that most of the convective systems at this latitude are multi-cell systems\textsuperscript{60}. The vertical extent of these cloud systems is very large, quite often penetrating the tropopause, and therefore transport the mass and atmospheric constituents effectively from the boundary layer to higher heights, often into the stratosphere. Few studies have attempted to quantify the mass flux during these events\textsuperscript{20, 22} across the tropopause. Enhanced mass flux is observed during penetrative convective events; however, one should note that the estimated values are of first order. Mandal \textit{et al.}\textsuperscript{61} observed enhanced ozone concentration in the troposphere during such events.

Classification of tropical precipitating systems is essential, because the cloud dynamical processes are distinctly different in different systems. Realizing the importance of classifying tropical precipitating systems, Rao \textit{et al.}\textsuperscript{2, 58} partitioned mesoscale convective systems observed with MST radar and LAWP over Gadanki into convection, stratiform and transition regions (Fig. 8). They studied the characteristics of radar echoes, from turbulence as well as from precipitation, in these regions. Simultaneous observations of disdrometer have been used to derive \textit{Z-R} relations for different precipitating systems as well as for different monsoon seasons. These relations have several practical applications in the field of radar meteorology, particularly in estimating rainfall with ground based and space borne radars. Characteristics of the radar bright band, a signature of stratiform rain, have been studied with the MST radar and LAWP observations. The mean thickness of the radar bright band is found to be 900 m, which seems to be higher than those reported at

![Fig. 7 — Height-time section of VHF radar (a) signal-to-noise ratio (dB) and (b) vertical velocity (m/s). The arrow mark indicated the WER in convection. (c) Vertical profiles of echo power from refractivity fluctuations and precipitation (after Rao \textit{et al.}\textsuperscript{58}, Kumar \textit{et al.}\textsuperscript{59})]
mid- and high latitudes. It is also found that the thickness of the radar bright band increases with peak reflectivity in the radar bright band. This is mainly because large particles will give high reflectivity and fall rapidly but take more time and fall more distance while melting, thus increasing the thickness of the bright band.

The data collected with the Indian MST radar and LAWP in south-west monsoon-2000 have been used to study the variation of drop size distribution with height and also with the type of precipitating system. The drop size distribution (DSD) parameters obtained in case studies reveal systematic variations of DSD from case to case and also from one rain regime to another within the same precipitating system. The retrieved DSD profiles are divided into separate rain regimes (stratiform and convection), based on reflectivity, to examine salient microphysical characteristics and vertical variability of DSD in different precipitation regimes. The vertical variation of gamma parameter distribution in the stratiform rain regime is minimal, indicating that the microphysical processes (growth and decay), which alter the rain DSD, may be in equilibrium.

On the other hand, the distribution in convective rain regime appears to be more complex with the mean profile of shape parameter varying significantly with height. The observed vertical variability of gamma parameters and median volume diameter in the convective rain regime is attributed to two major microphysical processes, evaporation and break-up. The gamma parameters obtained from the radar and disdrometer measurements are used to derive the $\mu$-$\Lambda$ relation over Gadanki (Fig. 9). The $\mu$-$\Lambda$ relation simplifies the retrieval of gamma parameters from radar remote measurements by reducing the three-parameter gamma function to a two-parameter function. The $\mu$-$\Lambda$ relation obtained at Gadanki differs from that derived at Florida and Oklahoma indicating climatic differences in the relation. For the first time, an attempt has been made to study the variation of this relation with height, and the analysis clearly reveals a significant variation in the coefficients of the relation with height. The vertical variability of the relation has been ascribed to the microphysical processes occurring in the height region concerned in the present study. These results suggest that for accurate retrieval of DSD from polarimetric measurements and also for studies on the
microphysics of rain systems, the vertical variability of the relation needs to be accounted for, in particular in an environment where the DSD variations are considerable.

3.7 Advances in signal and data processing techniques

The operational algorithm of Indian MST radar for routine soundings follows traditional peak picking algorithm, i.e., considering the echo with strongest peak in each range gate as the signal. Though it is a simple approach to follow with good performance, but severely hampers the height coverage. Several studies highlighted the problems in simple traditional approach and developed alternative algorithms to improve the signal extraction, and thereby, the radar height coverage. Hooper suggested the removal of ground clutter and dc bias in time domain rather than the usual practice of removing it in frequency spectra. He estimated the effect of dc removal on signal could be up to 30 dB, for cases when the Doppler shift is close to zero. Instead of using single taper techniques, which are generally plagued by a trade-off between the variance of the estimate and the bias caused by spectral leakage, Anandan et al. used multi-taper spectral analysis to improve the SNR and detectability of the MST radar signal. They have used sinusoidal taper and compared their results with those obtained with other single tapering analyses: Hanning and rectangular. They found that in all beams the sinusoidal taper gives the smallest number of range corruption, followed by Hanning and rectangular tapers.

Further, an adaptive spectral moment estimation technique has been developed, in which the algorithm picks the signal based on SNR, wind shear within a sliding Doppler window. The height coverage of the radar improved significantly, even in low SNR cases, with the adaptive signal tracking method. The wind profiles obtained with the adaptive technique have been compared with those obtained with GPS soundings. A very good agreement is found between these measurements, giving confidence on the adaptive technique. In an independent study, Varadarajan et al. used wavelet and harmonic decomposition techniques to clean the spectra before estimating profiler moments. They have shown improvement in SNR as well as in height coverage with their algorithms.

4 Summary

As indicated earlier, it is extremely difficult to review 15 years of scientific excellence in a short paper. However, an attempt has been made to include most of the significant results obtained on lower atmospheric processes making use of Indian MST radar and LAWP. In addition to radars, NARL is equipped with Nd-YAG lidar, sodium lidar, boundary layer lidar, Doppler sodar, and several surface meteorological measuring instruments, like
Acknowledgements

The authors acknowledge and appreciate the efforts of technical and supporting staff of NARL for successfully operating the radar for more than 15 years and also for generating high quality data, which is the basis for all exciting scientific outcome reported in this paper. The authors also acknowledge the scientists, engineers and other research faculty for allowing them to use their published material for this paper.

References


