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A comparison study of zonal drift velocities measurements as seen by MF spaced antenna and HF Doppler radar in the Indian dip equatorial mesospheric and lower thermospheric (80–100 km) region

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[1] The simultaneous measurements of zonal drift velocities, observed in the heights of 84–98 km in the Indian geomagnetic dip equatorial region by an medium frequency (MF, 1.98 MHz) spaced antenna and a high-frequency (HF, 18 MHz) Doppler radars, are compared on selected few days in the solar maximum years of 1998, 1999, and 2000. The agreement between the two radar measurements is found to be good below about 88 km, where the neutral turbulence induced ionospheric irregularities are more predominant. Above 90 km, however, the agreement becomes poor and at the highest height of 98 km it becomes the least. At this height, more often the HF Doppler radar shows a westward drift of about 200 m/s whereas the MF spaced antenna radar values lie within ±10 m/s and sometimes attain maximum values of ±50 m/s. Detailed discussions are made on the possible sources of underestimation of the drift velocities measured by the MF radar and the nature of scattering irregularities that are produced because of large neutral turbulences and plasma instabilities. It is suggested that these neutral and plasma turbulences (particularly type II plasma irregularities) contribute in a different manner to different radar frequencies and techniques and hence very different drift velocities in the heights of 90–100 km particularly in the geomagnetic dip equatorial region. Discussions are also made on (1) the real atmospheric and ionospheric physical process prevailing in the 90–100 km region and (2) the technical aspects of the radars that limits them to measure only particular types of motion in this region.

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1. Introduction

[2] Radars operating in spaced antenna and Doppler modes at medium, high, and very high frequencies (MF, HF, VHF) are being widely used to study the lower, middle, and upper atmospheric wind dynamics [*Stubbs*, 1973; *Woodman and Guillen*, 1974; *Vincent*, 1984; *Hocking*, 1983a, 1989, 1997]. In general, all the commonly existing radar techniques are based primarily on the Doppler shift of the received radar signals but the ways in which the data are processed are different with different techniques [*Briggs*, 1980, e.g.]. The measurement of winds by the spaced antenna technique began with the work of *Mitra* [1949]. By measuring the time delays of the received signals, he calculated the mean apparent horizontal drift speed of the winds. Taking into account the random nature of the radio scatterers in both space and time frames, the modified pattern analysis, namely, the full correlation analysis (FCA) [*Briggs*, 1984, for a review on this topic], has yielded valuable wind information of the middle atmosphere and particularly more of the mesosphere and lower thermosphere region [*Vincent and Lesicar*, 1991; *Rajaram and Gurubaran*, 1998, e.g.].

[3] Comparison studies show that there is a notable discrepancy between the Doppler and spaced antenna mode measurements of horizontal drift motions in the 90–100 km region [*Cervera and Reid*, 1995]. In this region, the radar scattering processes are influenced by both neutral turbulence and the instabilities driven by plasma turbulence [*Reddy et al.*, 1987]. Additional problems arise with radars located in geomagnetic dip equatorial regions where the echoes from ionospheric plasma irregularities associated with equatorial electrojet (EEJ) can easily overshadow the normal neutral turbulent echoes [*Gurubaran and Rajaram*, 2000; *Ramkumar et al.*, 2002; *Gurubaran et al.*, 2007; *Dhanya et al.*, 2008].

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The primary instabilities associated with EEJ are the two-stream and gradient drift instabilities, which are believed to generate the type I and type II irregularities, respectively [*Fejer and Kelley*, 1980].

[4] In this paper, we present our studies on zonal drift motions, measured simultaneously by the MF spaced antenna partial reflection radar (1.98 MHz) and the HF Doppler radar (18 MHz) in the heights of 84–98 km for a few days. Both are located in the Indian geomagnetic dip equatorial region with a separation radial distance of ~125 km. Also, the ground-based measurement of nearby geomagnetic field variations was carried out at and off the EEJ stations to estimate the strength of the EEJ current on the corresponding days. The measurements have been compared using the two different techniques, and a discussion on the basis of real atmospheric and/or ionospheric phenomena as well as the technical aspects of the radars is presented.

2. Description of Experimental Techniques

[5] The MF spaced antenna radar, operating at Tirunelveli (8.7°N, 77.8°E geographic, 0.4°N magnetic dip), since mid-1992, gives valuable information on the mesospheric and lower thermospheric (MLT, 60–98 km) neutral winds and their dynamics [*Rajaram and Gurubaran*, 1998]. The radar system details are the same as given by *Vincent and Lesicar* [1991]. Using a wide beam (~40° half power half width) and a transmitter pulse width of 30 μs (4.5 km height resolution) for the vertically pointed radar, it effectively receives the signal returns from the first Fresnel zone of the stratified as well as corrugated scattering medium (anisotropic as well as aspect sensitive). The horizontal dimension of first Fresnel zone is of the order of $(z\lambda/2)^{1/2}$ (Fresnel radius), where λ(= 150 m) is the wavelength of the radar transmitting signal and z is the distance of the target from the surface of the Earth. For example, at 85 km it is about 2.5 km. Since the reflected signals are attributed to Fresnel or partial reflections, the effective vertical scale of the gradient in the radio refractive index is less than a quarter of the radar wavelength.

[6] The HF (18 MHz) Doppler radar, operating at Trivandrum (8.5°N, 77°E geographic; 0.5°N magnetic dip), gives valuable information on the electrodynamic properties of the EEJ. This radar is located at about 0.2° south of and 0.8° west (geographical) of the Tirunelveli MF radar. The HF radar is a coherent, pulsed, monostatic Doppler radar capable of operating at three frequencies of 18, 9, and 2.5 MHz. The system design is, however, optimized for 18 MHz, corresponding to the irregularity scale size of 8.3 m. And the system employs the Doppler beam swinging technique to measure the vertical and horizontal velocities. Vertical motion of the irregularities is studied using the zenith beam and the E–W motions using oblique (tilted ±30° from zenith in the east-west plane) and zenith beams. It has to be noted here that the aspect sensitivity of the scatterers can actually make the effective zenith angle less than 30° and it will have its implications on the measured horizontal velocities. For example, assuming that the effective zenith angle is 25° instead of the theoretical value of 30°, the underestimation of the determined horizontal drift speed is by about 15 and 4 m/s, respectively, for a real horizontal drift speed of 100 and 25 m/s when the vertical velocity is zero. A single 12 × 6 antenna array (12 in geomagnetic E–W and 6 in geomagnetic N–S direction) is employed. A center-fed dipole of full wavelength (18 MHz; 16.6 m) is used as an antenna element. An electronically phased and uniformly fed horizontal dipole array is used. The array has a half-power beam width of 7.3° for the oblique beam in the E–W plane at 18 MHz. The corresponding two-way beam width is 5.1°. For electrojet studies, where the altitude of interest is around 100 km, the pulse width option of 20 μs is used to get reasonable good altitude resolution. The pulse repetition frequency is 120 Hz, and the transmitter peak power is 50 KW.

[7] The line-of-sight phase velocities of the irregularities are determined by measuring the Doppler shift of the received radar echoes. Assuming that the mean flows are primarily horizontal (in the east-west direction) and the vertical velocity is the same in both the beam directions, the zonal velocity can be obtained by using the parallelogram law of addition of velocities. For the present study, we have taken the daytime data from a selected few days in the years 1998, 1999, and 2000. The experiments conducted in the years 1998 and 1999 used only the west beam and are used to investigate the local time dependence of oblique beam spectral parameters as a function of height. In the following subsequent sections, the nature of the drifts obtained by both radars is discussed.

3. Results and Discussion

[8] Figure 1 shows the altitude profiles (84–98) of zonal drift velocities measured simultaneously by both the MF and HF radars for the days 17, 19, 20, and 21 August 1998; 1, 2, and 6 February 1999; 20 and 23 June 2000; and 7 July 2000. Positive values of drift speeds represent westward velocities. The 2-min samples are averaged, separately for each of the days in the time interval of 1000–1300 local time (LT). The error bar indicates the standard error of mean at 95% confidence level. It may be observed that on 17 August 1998 (Figure 1a), the MF radar shows drift values in the range of 25–80 m/s eastward in the heights of 84–98 km, respectively, whereas the HF radar shows correspondingly 25–200 m/s westward. And on 19 August 1998 (Figure 1b), the drifts measured by MF radar are from about 25 m/s westward at 84 km to about 40 m/s eastward at 98 km whereas the values by HF radar are in the range of 65–200 m/s westward above 88 km. For 20 August (Figure 1c), the values by the MF radar are in the range of 15–30 m/s westward in the entire 84–98 km range whereas the HF radar shows 40–140 m/s westward in this height region. On 21 August (Figure 1d), the MF radar shows small drift values in the range of ±5 m/s whereas the HF radar shows large westward drift speeds (40–200 m/s).

[9] For 1 February 1999 (Figure 1e), the MF radar shows a constant amplitude of about 10 m/s westward at all heights except at 84 and 88 km, where the amplitude is about 25 m/s each westward. The HF radar also shows the same amplitude of about 10 m/s westward from 86 to 92 km, but above this height the values changed drastically to about 200 m/s westward at 98 km height. On 2 February 1999 (Figure 1f), with a small change at 92 km, the HF radar values repeated

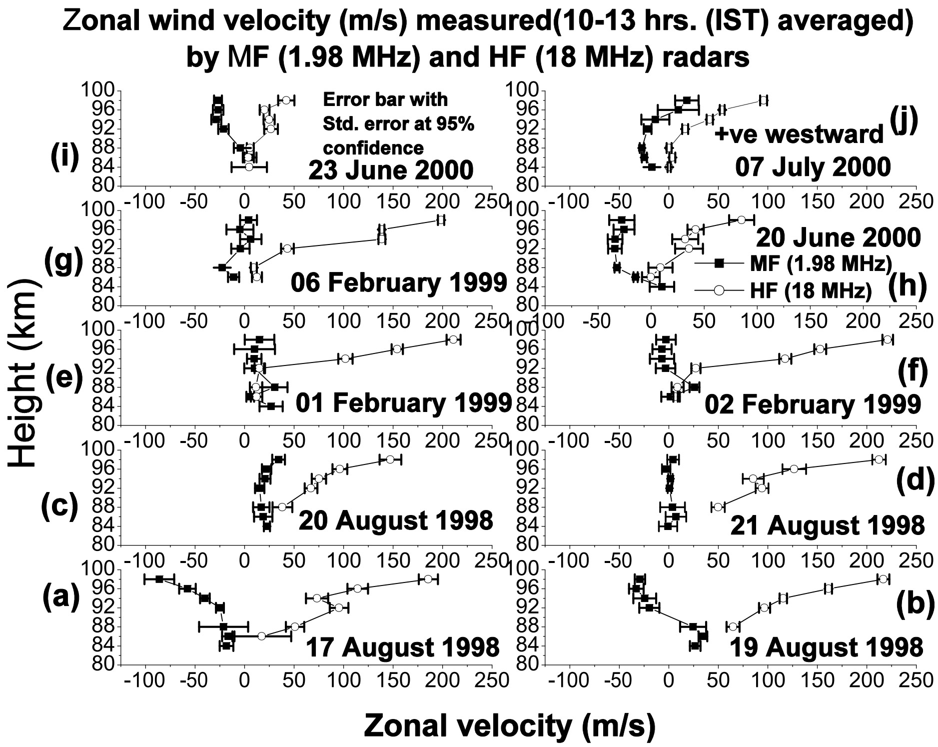

Figure 1. Noontime (10–13 h Indian standard time (IST)) 4 h averaged height profiles (84–98 km; *y* axes) of zonal drift velocities (m/s, *x* axes) measured by MF (2.5 MHz) radar at Tirunelveli and high-frequency radar (18 MHz) at Trivandrum on (a) 17, (b) 19, (c) 20, and (d) 21 August 1998; (e) 1, (f) 2, and (g) 6 February 1999; (h) 20 and (i) 23 June 2000, and (j) 7 July 2000. Positive velocities correspond to westward velocities, and the error bars are standard errors at the 95% confidence level.

the same as on 1 February 1999 while the MF radar values remained within about 10 m/s eastward at all heights except at 88 km, where the value is 25 m/s westward. For 6 February 1999 (Figure 1g), the MF radar values remained within about 10 m/s eastward at all heights except at 88 km where the value is about 25 m/s eastward, whereas the HF radar values vary from about 20 to 200 m/s westward from 86 to 98 km. On 20 June 2000 (Figure 1h), the MF radar shows drift values of about 10 m/s westward and eastward, respectively, at 84 and 86 km and almost a constant value of about 30 m/s eastward at all other heights up to 98. However, the HF radar shows westward drift values of a few to ~80 m/s from 86 to 98 km. The same drift velocities as shown on 20 June 2000 are obtained for 23 June 2000 (Figure 1i) except that the HF radar shows maximum drift value of about 40 m/s westward at 98 km instead of 80 m/s as on 20 June 2000. On 7 July 2000 (Figure 1j), while the HF radar shows values in the range of 0–100 m/s westward from 84 to 98 km, the MF radar shows from about 20 m/s eastward in the lower heights to about 20 m/s westward at higher heights. It is noted that almost all the observation periods are geomagnetically quiet days during noon times and hence there are no influences on the measured drift velocities by both the radars from anomalous solar activities.

[10] It is obvious from the above observations that in general there is some agreement between the two radar techniques below 88 km where the neutral turbulence induced ionospheric irregularities are the most dominant. Here in this region, because of the strong collisional coupling between the neutral air and charged plasma particles, the drifts observed by both radars are attributed to the neutral wind speeds. Above 90 km, almost always, the difference between the values measured by both the radars increases and reaches a maximum at 98 km where the bottom tail of the EEJ begins.

[11] In sections 4–7, various aspects such as the real atmospheric and ionospheric physical processes prevailing in the 90–100 km region as well as the technical aspects of the radars, height discrepancies within the large beam width, total reflection problem for MF radar in the dip equatorial region, and the day-to-day variations of the EEJ electrodynamics influences above about 90 km are discussed to explain the disagreements in measurements between these two radars. In particular, the discussions in sections 7 and 8 deserve more attention as they stress the need for real-time measurement of electron density in the heights above about 80 km in the geomagnetic dip equatorial stations to determine the time variation of total reflection heights corresponding to radar transmitting frequency of 1.98 MHz. This is because in the dip equatorial stations the competing physical processes of time variation of total reflection height and the downward penetration of EEJ electric fields and the associated plasma irregularities make the observation of drift velocities by MF radar more complex. For example, the zonal drift velocities measured by MF radar on 20 and 21 August 1998 (Figures 1c and 1d) and 1, 2, and 6 February 1999

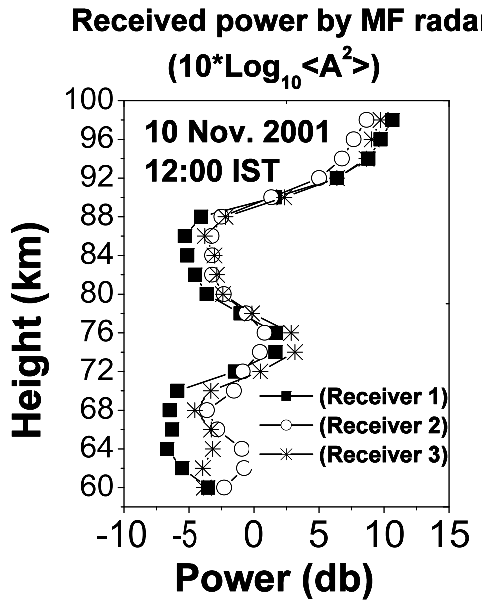

Figure 2. Height profiles (60–98 km; *y* axis) of received power (*db*, *x* axis) obtained by the MF radar at Tirunelveli with three receiver antennae separated by about 180 m at 12 h IST on 10 November 2001.

(Figures 1e, 1f, and 1g, respectively) remain constant at almost all heights with small values between +10 and −10 m/s when the HF radar shows the largest velocity of the order of 200 m/s at the highest height of 98 km. And also the difference in velocity measured by both the radars is significant on some days even at the lowest height of 84 km. For example, the data obtained in August 1998 and July 2000 belong to this category. Although many aspects are discussed to explain the large difference between the measurements by MF and HF radar with spaced antenna and Doppler techniques, respectively, it is yet difficult to pinpoint the exact processes causing this discrepancy. The major drawback is the absence of data on electron density.

4. Aspects Based on Atmospheric and Ionospheric Physical Processes

[12] First, it is intended to show distinctly that at above 90 km the EEJ-related plasma processes are important during noontime periods. For example, Figure 2 shows height profiles (60–98 km) of 2 min averaged (256 data points, 0.4 s each) echoes received by the MF radar for the three spaced receivers. The profiles are taken at 12:00 noon on 10 November 2001 by converting the digitized output, varies from 0 to 255, of the analog to digital converter from the receivers into the −5 to +5 V range without taking into account of the receivers gain factor. However, the receivers gain is constant with height at any time of observation. It may be noted that above a strong partially reflecting layer (approximately +3 db) at about 76 km and following the "valley" (approximately −3 db) at 80–88 km, the received signal strength started to increase drastically and reached the maximum value (approximately +10 db) at 98 km. So, there are two distinct regions, which are contributing to the received echoes, one is below about 88 km and the other one is above that height. Similar types of height variation of echoes are reported for the HF radar also by *Tiwari et al.* [2003] over Trivandrum, India. Since the MF radar is located near geomagnetic dip equatorial region, the latter height region is located in the bottom tail of the EEJ region and the signals belonging to this region are often primarily associated with the unstable plasma waves like type II irregularities because of gradient drift plasma instability [*Fejer and Kelley*, 1980]. In situ rocket measurements of the electron density fluctuations have shown the indication of plasma irregularities in this height region [*Prakash et al.*, 1980; *Lehmacher et al.*, 1997]. It is assumed that the neutral turbulence induced echoes are also embedded in the 90–98 km signal but overshadowed sometimes either by the type II unstable plasma wave echoes [*Gurubaran and Rajaram*, 2000; *Ramkumar et al.*, 2002; *Gurubaran et al.*, 2007; *Dhanya et al.*, 2008] or by the overlapping of the strong signals from the EEJ region because of finite broad pulse width of the radar beam [*Hocking*, 1997]. While comparing the drift measurements by narrow-beam high-frequency radar with larger-beam low-frequency radar, it is to be noted that there are different scale sizes of plasma irregularities generated and they move with different speeds in different directions in the EEJ region [*Sudan et al.*, 1973; *Fejer and Kelley*, 1980; *Diwakar et al.*, 2003]. The smaller-scale irregularities move with larger speeds and lesser the influence of neutral winds on these irregularities. As a result, the smaller wavelength radar (HF radar) with narrow beam (~5°) sees more probably the larger line of sight speed associated with smaller-scale plasma irregularities, while the larger wavelength radar (MF radar) with wide beam (90°) sees the smaller speed associated with larger-scale irregularities influenced often by the neutral winds. Because the larger-scale irregularities with sizes of the order of hundred meters (MF radar half wavelengths) but not the smaller scales (few meters corresponding to high-frequency radars) fall under the category of Kolmogorov's "inertial subrange" in the MLT region. As the neutral turbulence, with Kolmogorov's "inertial subrange" scale sizes, induced plasma irregularities are also under the influence of EEJ electric field while moving along the neutral winds, it is still an issue that is why only sometimes and what physical conditions in the atmosphere that really determine the ability of the MF radars to measure neutral winds in the height region above 90 km in the EEJ region [*Gurubaran and Rajaram*, 2000; *Ramkumar et al.*, 2002; *Gurubaran et al.*, 2007; *Dhanya et al.*, 2008].

[13] Here in this height region of 90–100 km, the plasma irregularities are under the competing influences of the EEJ electric field and neutral wind motions [*Reddy et al.*, 1987; *Gurevich et al.*, 1997; *Schlegel and Gurevich*, 1997]. It is shown earlier that often the zonal drifts measured at 98 km by the MF radar are directly related to the electron drift velocities [*Gurubaran and Rajaram*, 2000; *Ramkumar et al.*, 2002; *Gurubaran et al.*, 2007; *Dhanya et al.*, 2008]. It is to be noted here that both the Kolmogorov's "−5/3" power spectrum dominated neutral turbulence and the primary type II ionospheric plasma irregularities induced by gradient drift instability are having the scale sizes of the order of some 30–100 m in this height region [*Sudan et al.*, 1973; *Hocking*, 1983b]. This order of scale sizes will easily match the Bragg's backscatter cross section while probing the atmosphere with the MF radar. For example, 1.98 MHz corresponds to the wavelength of 150 m, and the scale size of the scattering medium that satisfies the Bragg's backscatter condition is 75 m. This is

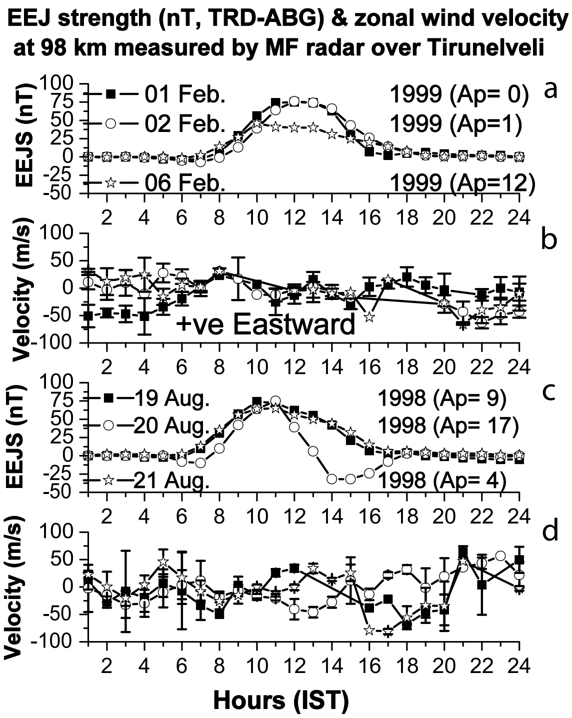

Figure 3. Diurnal variation of hourly averaged equatorial electrojet (EEJ) strength (nT; TRD-ABG) and the corresponding variation of zonal drift velocity (m/s) at 98 km measured by the MF radar over Tirunelveli on (a and b) 1, 2, and 6 February 1999 and (c, d) 19, 20 and 21 August 1998. The error bars in the drift velocities are standard error at the 95% confidence level.

well inside the inertial subrange scale sizes of the neutral atmosphere turbulence as well as the primary unstable type II plasma waves. In the case of unstable plasma waves, the phase velocity of the irregularities, according to linear theory of instabilities, is directly proportional to the electron drift velocities [*Sudan et al.*, 1973]. So, the drifts observed in this region can be attributed to either the mean electron drift velocities or neutral wind motions or a combination of both.

[14] To ascertain whether or not the zonal drifts measured by the MF spaced antenna radar are due to the electron drift velocities, Figure 3 shows the zonal drifts at 98 km for the days corresponding to the years 1998 (Figure 3d) and 1999 (Figure 3b) as in Figures 1b–1d and Figures 1e–1g, respectively, and the simultaneously measured geomagnetic field variations due to the EEJ current (plotted above the respective velocity panels (Figures 3d and 3b)). The EEJ strength is obtained by taking the difference of the geomagnetic field variations measured at the EEJ station, Trivandrum (8.5°N, 77°E geographic; 0.5°N magnetic dip) and the other at the off-EEJ station Alibag (18.6°N, 72.9°E, geographic; 25.5° N magnetic dip), India [*Kane*, 1973]. On all the days mentioned, the correlation between the drifts and the field variations is poor, though we expected a good correlation as reported by *Gurubaran and Rajaram* [2000] and *Ramkumar et al.* [2002]. So the drifts cannot be associated with pure electron drifts as they are contaminated largely by the neutral winds.

[15] On the other hand, the HF Doppler radar drifts seem to be moderately contaminated by the electron drift velocities as their magnitudes always increase with height from 90 km and reach the maximum value at 98 km. The earlier EEJ electric field measurements in this region showed such an increase in the strength as we approach the center of the EEJ region, which is thought to be at about 103 km with a scale height of about 7 km [e.g., *Reddy et al.*, 1987]. A small-scale strong neutral eddy type motion may also lead to such enhancements in the drift velocities measured by the narrow pencil beam of the Doppler radar when directed at the edge of eddies [*Royrvik*, 1984]. But the spaced antenna will not be able to see such narrow regions because of the large beam widths (half power half width is about 40°). There is one more possibility of measuring the mean horizontal drift motion of the larger horizontal scale size irregularities by the MF radar.

[16] To give more quantitative assessment of this region, we calculated the power spectrum of the MF radar received echoes by using the fast Fourier transform technique [*Press et al.*, 1992]. In Figure 4, such a picture is shown, taken at the same time as in Figure 2, for the heights of 60, 70, 76, and 82–98 km. It is to be noted that in the neutral turbulence dominated region of below 88 km, the spectrum with narrow strong spike at zero Doppler shifted frequency is believed to be due to specular reflections from the stably stratified layers of the atmosphere [*Lesicar et al.*, 1994]. Above 90 km, the spectrum appears broad in nature with several distinct spikes at both the positive and negative Doppler-shifted

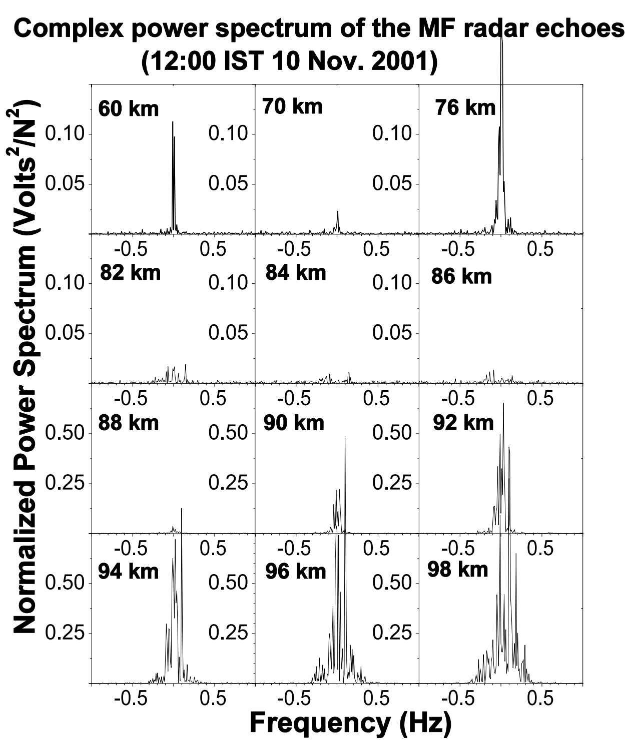

Figure 4. Normalized complex power spectrum of the received echoes by the MF radar at 12 h. IST on 10 November 2001 in the height regions of 60, 70, 76, and 82–98 km with 2 km as height separation. The x axis denotes the Doppler shifted frequency (in Hz).

frequencies within ±0.5 Hz. The broad nature of the spectrum may be attributed to the beam broadening effect, but a smooth Gaussian shape is expected in the power spectrum as the component of the mean horizontal motion varies smoothly with respect to angle from the horizontal. The discrete spikes imposed on the Gaussian shape are due to the random motion of the discrete specular targets embedded in the radar probing volume [*Hocking*, 1983b, 1989, 1997].

[17] The "broadness" of the spectrum also indicates that the scattering region is either more isotropic in nature or the reflecting layer is corrugated rather than being a specularly reflecting anisotropic layer [*Lesicar and Hocking*, 1993]. They also showed that the "aspect sensitivity" of the scatterers decreases significantly at above 90 km, which indicates that they are more isotropic in nature at higher heights. In this case, the oblique part of the wide beam of the MF radar will also contribute significant information on the scatterers and the process, which is generally called the "volume scattering" [*Lesicar et al.*, 1994]. Using a wide beam spaced antenna, the "volume scattering" will surely lead to the averaged behavior of the differing scattering motions, which in turn will give the underestimated drifts [*Holdsworth*, 1995; *Holdsworth et al.*, 2001; *Hocking and Rottger*, 2001, and references therein].

[18] To further explain about the large drift velocities associated with the HF radar data in the 90–100 km region, a short discussion on unstable plasma waves is also included. There are two types of type II irregularities, which move primarily in horizontal and vertical directions, in the EEJ region. They are called primary and secondary type II irregularities, respectively. Since the primary type II irregularities are nearly nondispersive in nature for wavelengths of the order of 10–100 m, both the HF (ν = 18 MHz; $\lambda/2$ = 8.3 m) and MF (ν = 1.98 MHz; $\lambda/2$ = 75 m) radars will measure the same zonal electron drift speeds in the EEJ region [*Sudan et al.*, 1973]. This is because of the linear relationship between the phase velocity of the type II irregularity and the electron drift velocity. The secondary type II irregularities are due to the horizontal polarization electric fields—induced by the primary type II irregularities, which are due to the vertical gradients in the electron density and the parallel vertical polarization EEJ electric field and the associated vertical $\mathbf{E} \times \mathbf{B}$ drift motion of the electrons in the EEJ region. These irregularities will move in general with speeds as large as the horizontal drift speed of the primary type II irregularities [*Sudan et al.*, 1973]. In this case, the narrow pencil beam of the HF Doppler radar, directed at 30° from the zenith, will see the vectorially added components of the horizontal and vertical and any other obliquely propagating unstable plasma waves. Furthermore when the EEJ strength is strong enough, the HF radar measurement may also be contaminated by type I irregularity echoes. This irregularity is due to two-stream instability, which arises when the drift speed of the electrons with respect to ions exceeds the ion-acoustic speed of about 360 m/s [*Fejer and Kelley*, 1980]. Because the scale size of the type I irregularities is of the order of few meters, they will easily satisfy the Bragg's condition of backscatter at HF wavelengths. Hence the drift velocities measured by HF radars in the EEJ region will generally be greater than the MF spaced antenna radar. The following section discusses the technical aspects that underestimate drifts measured by MF spaced antenna radar.

5. Potential Problems Regarding the MF Spaced Antenna and HF Doppler Radar Techniques

[19] Using the FCA technique, the MF radar is able to calculate the neutral wind and other antenna/scattering irregularity parameters [*Briggs*, 1984; *Lesicar and Hocking*, 1993]. The elliptical diffraction pattern falling on the ground possess some characteristic scales such as major to minor axis ratio, pattern scale size, axial direction with respect to geographic north, pattern decay time, and so on. There are four principal potential problems with MF spaced antenna technique in measuring the MLT region neutral winds. These may underestimate the actual drift speeds above 90 km [*Cervera and Reid*, 1995].

[20] 1. Possible undersampling of the diffraction pattern because of small pattern scales and relatively large pattern velocities:

[21] It may happen that when the stratified anisotropic turbulent layers (specular scatterers) causing specular echoes are modulated by large amplitude gravity waves, the scale of diffraction pattern falling on the ground will be considerably smaller than the actual gravity wave scale. Gravity waves can curve the electron density isopleths and produce focusing and defocusing of the incident radio waves, and therefore faster fading of the radio signal falling on the ground. In this condition, when many gravity waves with different scales are present, they will lead to fast fading of the signals falling on the antenna. Fading of the received echoes because of many scales of propagating gravity waves is sometimes referred to as "interference fading," which is not a real fading but looks like fast fading and hence it cannot be utilized to determine the drift velocities. [*Hines and Raghava Rao*, 1968; *Brownlie et al.*, 1973; *Hocking*, 1983a].

[22] 2. "The triangle size effect" (TSE) happens when the average spatial separation of the receiver antennae is less than the actual horizontal scale sizes of the irregularity patterns [*Briggs*, 1968; *Golley and Rossiter*, 1970; *Chandra*, 1978; *Meek*, 1980, 1990].

[23] However, these reports mostly concentrated on the TSE arising because of random noise, which has significant impact on the autocorrelation and cross-correlation functions when the receivers are closely spaced. Detailed works on the others sources of TSE arising because of multiple motions in the diffraction pattern, received signal saturation and digitization errors, different characteristics of different receivers, etc., are yet to be reported (as per the knowledge of the present authors) to fully quantize the TSE that causes the underestimation of drift velocities.

[24] 3. The saturation of receivers will lead to the clipping of the signal that will in turn produce changes in calculating the FCA parameters.

[25] If the receivers are saturated for a significant amount of time, then determining the pattern of time variation of received signals and hence the correlation functions between different spaced antennae is not possible without significant errors. And this will lead to erroneous results of drift velocities. And the receiver saturation effect is essentially identical to the effects of digitization of the received analog signals and

contributes to the "TSE" [*Holdsworth*, 1995; *Holdsworth and Reid*, 1995].

[26] 4. The averaging effect of the large beam widths of spaced antenna MF radar can also lead to underestimation of the drift measurements using correlation techniques.

[27] The wind speed measured by the spaced antenna radar is the average of the wind speeds over a large area of the sky [*Hocking*, 1989, 1997]. It is to be noted that the wide beam spaced antenna drift (SAD) technique ultimately relies (SAD assumption) on differential line-of-sight velocities associated with horizontal winds within the wide beam to calculate the horizontal wind [*Briggs*, 1980; *Royrvik*, 1984]. The interference of echoes associated with changing line-of-sight components of the horizontal wind, which is a function of changing look angle within the finite beam width of the antenna, causes the diffraction pattern falling on the ground. Apart from changing line of sight velocities of horizontal wind, if there are different vertical velocities associated with traveling gravity waves, turbulent eddies etc., in different parts of the wide beam, then the resulting motion of the ground diffraction pattern will not represent the true horizontal wind speed but will be contaminated by differential vertical velocities within the wide beam [*Royrvik*, 1983, 1984). This may lead to the underestimation of the measured horizontal wind speeds. For example, the half power half width of 40° will span about 84 km radius in the horizontal direction at 100 km. So, the area of the sky being probed at 100 km is about 22,156 km^2 area. For a pulse width of 30 μs (4.5 km height resolution), the volume of the scattering region is estimated as about 99,701 km^3. Hence the wind speed measured at 100 km is actually the average of the wind speeds observed in this whole sampled area. Within this region, the scatterers in different parts of the volume may move with different speeds. Particularly, the small-scale eddies will have high speeds in the highly turbulent region. In this case, we call the scattering process as a "volume scattering." Below about 88 km, we call the process by an "anisotropic specular reflection," where the aspect sensitivity of the scatterers is almost zero zenith. That is, most of the signals come from the vertical backscattering [*Lesicar et al.*, 1994].

6. Height Discrepancies Within the Large Beam Width

[28] As the aspect sensitivity, as much as about 15° from the zenith [*Lesicar et al.*, 1994], of the scattered echoes decreases significantly at above 90 km, the fixed range gate for the vertical beam may also receive the echoes from the lower heights through the oblique part of the vertical beams. For example, if we assume that the given aspect sensitivities are 10°, 15°, 20°, and 40°, then at above 90 km the height discrepancies of the oblique parts of the wide antenna beam from the zenith are about 2, 3, 6, and 30 km, respectively. This means that, for a vertically pointed wide beam, while the echoes from a particular height in the zero zenith angle are being received by the fixed range gate of the receiver, it is also receiving echoes simultaneously from lower heights through the oblique parts of the wide beam. The difference in height between the signals simultaneously received from the zero zenith angle and the oblique part (the lowest elevation angle) depends on the aspect sensitivity of the anisotropic scatterers. Since 2 and 3 km differences are within the range resolution of the radar pulse length (4.5 km), aspect sensitivities of 10° and 15° will not cause significant contamination from lower heights, because they are almost within the normal layer, but this is not true for 20°. In case of 40° aspect sensitivity, corresponding to half power half width of the radar beam, the height discrepancy of 30 km may introduce only noise signals from the lower heights below 70 km, where the signals are very weak in strength when compared with the higher height signals. And also it is to be noted that when the range markers on a receiver system are calibrated, they are set to the peak of the echoes and not to the instant of arrival of the pulse. When the pulses are received from the height range of 90–98 km, normally the signals from the leading edge of the pulse will be stronger as the E region of the ionosphere approaches and the receiver system will detect those stronger signals instead of the signals from the middle or lower end of the pulse and hence there are height discrepancies [*Hocking*, 1997]. This problem is severe in the geomagnetic dip equatorial region because of the EEJ located at ~105 km with its tail extending down to about 90 km *Fejer and Kelley* [1980].

7. Total Reflection Problem for MF Radar in the Dip Equatorial Region

[29] During noon hours of solar maximum periods, it is possible that the total reflection of incident medium frequency (1.98 MHz) radio waves (from the MF radar) may take place at heights below the EEJ irregularity dominated region. At these times, the drifts recorded for the heights above about 92 km by the fixed range gates of the receivers might not have been influenced by the electric field associated with EEJ. Under these circumstances, it may be expected that the radar might be detecting the severely group retarded (total reflection) signals for these higher heights. Because of severe group retardation, the echoes that are totally reflected below about 92 km take such a time delay that the fixed range gates of the receivers would record them as though they are from above this height. But during solar minimum periods when the production of the electron density is reduced, since the total reflection level is inside the region where the creation of EEJ irregularities is predominant, the incident 1.98 MHz radio wave may easily pass through even above about 100 km. This is because of the diffusive or sporadic nature of the plasma irregularities. In this condition, the drifts recorded for all the heights up to 98 km may represent the irregularity drifts associated with actual heights without any appreciable group retardation. However, it is possible that the drifts recorded for the heights above about 90 km might have been influenced by electric fields associated with EEJ. The most severe influence would be at the highest height of 98 km. It is worth to recall here that the total reflection at high/medium frequencies inside the sporadic E region irregularities may be masked or blurred by the effects produced by these irregularities [*Reddy and Mukunda Rao*, 1968; *Reddy*, 1968]. It is known that during day times, on most ionograms in the dip equatorial regions, the intensities of echoes from lower E region may look like blurred or sporadic in nature, extending over a wide range of medium/high frequencies from about 1 to 10 MHz.

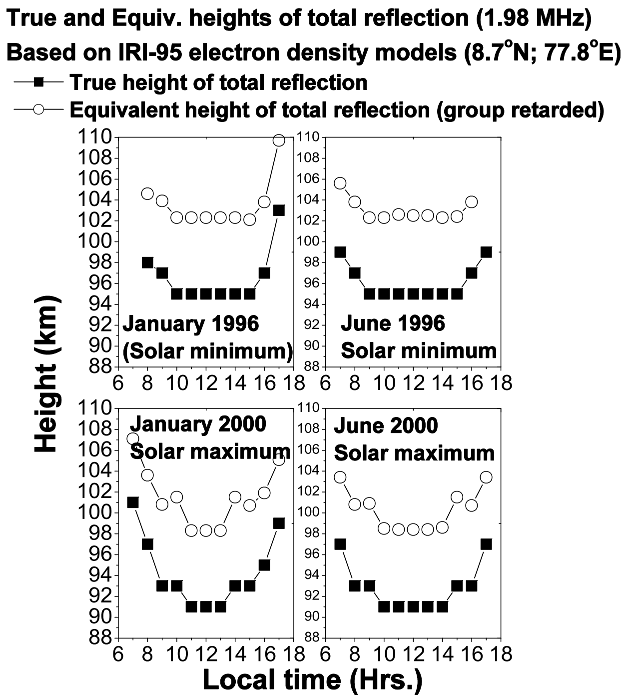

Figure 5. Local time variation of true and equivalent heights of total reflection for the 1.98 MHz signal at Tirunelveli in January and June during the solar minimum and maximum years of 1996 and 2000, respectively. The IRI-95 model is used to determine the electron densities for the calculation of total reflection heights.

[30] Figure 5 shows the local time (6–18 h LT) variation of both the true and equivalent heights (group retarded) of total reflection corresponding to the plasma frequency of 1.98 MHz (IRI-95 model of electron density is used) during

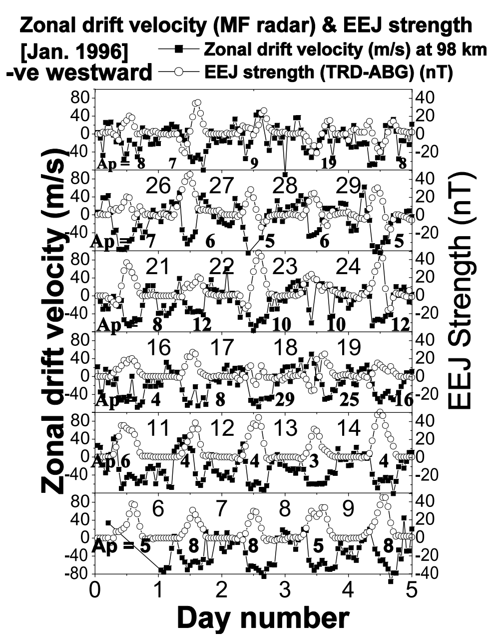

Figure 6. Local time variation of the EEJ strength and zonal drifts at 98 km for the entire month of January 1996 (solar minimum year).

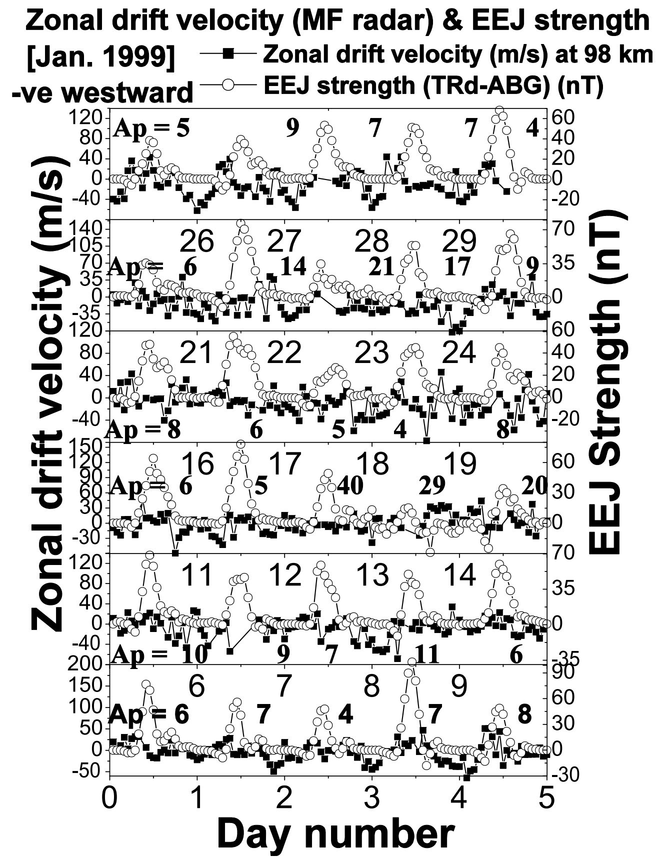

Figure 7. As for Figure 6 but for the solar maximum year 1999.

winter and summer months of January (Figure 5, left) and June (Figure 5, right), respectively, for the solar minimum (1996) (Figure 5, top) and maximum (2000) (Figure 5, bottom) years. It is observed that during noon hours the true heights of total reflection are at about 95 and 91 km, respectively, for the solar minimum and maximum years of 1996 and 2000. The difference between the winter (January) and summer (June) months is that in summer the total reflection layers exist at the same height for 2 h more in the noon times. The respective equivalent heights found are at about 103 and 99 km for the solar minimum and maximum years. It may be noted that the difference between the true and equivalent heights of total reflection is about 8 km.

8. Day-to-Day Variations of the EEJ Electrodynamics Influences Above About 90 km

[31] Making use of the direct relation between the strengths of EEJ currents and **H** component (northward) of the geomagnetic field in dip equatorial regions, this section illustrates how the MF radar measurements are affected by the EEJ electric fields above about 90 km. One of the convenient ways of inferring such electric field influences on the parameters measured by radar is to compare the local time variations of zonal drifts with H-field variations due to EEJ currents. Figure 6 shows the hourly averaged EEJ strength and zonal drifts at 98 km for the entire month of January 1996. Since the MF radar at Tirunelveli has been

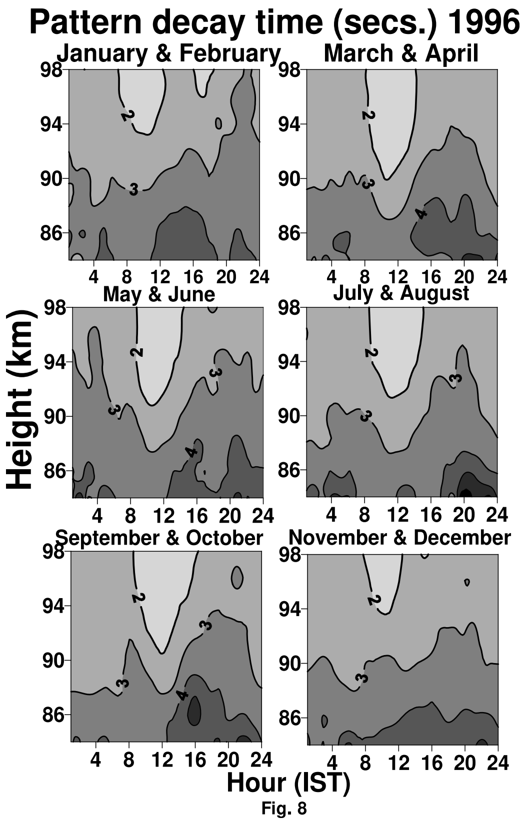

Figure 8. Contour plots of diurnal variation of two-monthly averaged pattern decay time (in seconds) of the scattering irregularities as observed by MF radar in the solar minimum year 1996.

monitoring the atmospheric motions only up to 98 km, the present study took this height as a reference height (because of the proximity to the center of EEJ currents located at about 105 km) for comparing the zonal drifts with the EEJ strength. As the strength of the electric field increases and the collisional coupling between the charged and neutral particles decreases with height above 90 km, the EEJ electric field is expected to be very effective in influencing the irregularity drifts in zonal direction at this highest height of 98 km. Figure 7 illustrates the same as in Figure 6 but for the year 1999.

[32] It may be noted that during the solar minimum year of 1996 (Figure 6), often the zonal drift velocity at 98 km is in westward direction during day times. And the positive enhancement in the EEJ strength during day times corresponds to the enhancements in the westward drift speed of electrons, causing the normal eastward flow of currents in the lower E region ionosphere. The corresponding similar variations but in opposite directions of the zonal drift speed and EEJ strength indicate that the zonal drift velocities resemble mean electron drift velocities [*Gurubaran and Rajaram*, 2000; *Ramkumar et al.*, 2002; *Gurubaran et al.*, 2007; *Dhanya et al.*, 2008].

[33] It may be suggested that during the solar maximum year, the incident 1.98 MHz radio waves are totally reflected from below about 92 km during noon hours. At these heights, it is known that the EEJ electric fields are weak and only have negligible influence on the ionospheric irregularities. Furthermore, at these heights below about 92 km, the strong collisional coupling between the ionized plasma and neutral air particles would make the ionospheric irregularities to move with neutral winds.

[34] Since the incident radio waves are totally reflected at heights below the EEJ plasma irregularity region, the drift information recorded with the fixed range gate of the receivers for the heights above about 92 km might not be belonging to these real heights. Often, only the severely group-retarded signals that are totally reflected might have been recorded even for the highest height of 98 km. Under these circumstances, the drifts recorded for 98 km may not show the electric field contamination as the drifts actually belong to regions below about 92 km.

[35] Furthermore, it may be noted from Figure 8 (contour plots) that in 1996, the pattern decay time (measure of life time of scattering irregularities in the horizontal wind frame of reference) shows well-defined pattern “U-shaped” during noon hours (during the time when the EEJ strength and the associated electric field reaches maximum) above about 90 km in any season of the year. And in the solar maximum year 1999 (Figure 9), there is no well-defined “U-shaped” structure above about 92 km in the contour plots of pattern decay time during noon hours for any season of the year, illustrating that the echoes received for the higher heights

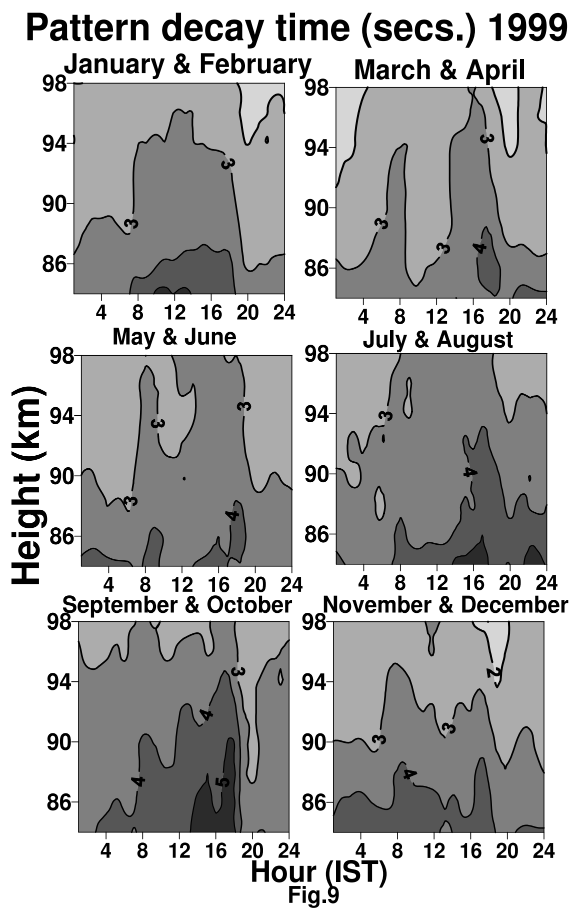

Figure 9. As for Figure 8 but for the solar maximum year 1999.

are not the real height echoes but the group-retarded echoes coming actually from the lower heights below about 91 km. All these physical processes make more complex the comparisons between drift measurements by the spaced antenna and Doppler radar techniques with different frequencies of 1.98 and 18 MHz, respectively, particularly in the geomagnetic dip equatorial stations.

9. Summary and Conclusions

[36] The present paper illustrates and discusses on the nature of simultaneous measurements of zonal drift motions observed by a MF (1.98 MHz) spaced antenna and a high-frequency (HF, 18 MHz) Doppler radar in the height range of 84–98 km. Both the radars are located in the Indian geomagnetic dip equatorial stations of Tirunelveli and Trivandrum with a spatial separation of about 100 km (radial distance) in the east-west direction and about 50 km in the north-south direction. The averaged (10–13 h, Indian standard time (IST)) zonal drift velocities for a selected few days in the solar maximum years of 1998 (August), 1999 (February), and 2000 show that the agreement, in general, is good below 88 km but above that height the deviation starts and reaches its maximum at the highest height of 98 km. The possible reasons argued for the discrepancies arising between these two radars are based on (1) the real atmospheric and ionospheric physical processes prevailing in the 90–100 km region and (2) the technical aspects of the radar. It seems that the former case is significantly more accountable in explaining the differences observed. This is because the overall technical aspects of the radar will contribute only a 10%–15% discrepancy [*Holdsworth and Reid*, 1995]. But the observed differences between the two radar measurements show that often they are easily exceed 100% at higher heights above 90 km. When the zonal wind velocities measured by MF radar varies within ±10 m/s in the height range of 90–100 km, the HF radar shows continuously increasing speed with the maximum value of about 200 m/s at the highest height of 98 km almost always. Also, since the 90–100 km region is situated in the bottom tail of the EEJ region, the unstable plasma waves, particularly because of type II irregularities in the equatorial sporadic E, contribution is quite significant in the case of the HF Doppler radar. As a result, it is tempting to conclude that radars with different operating frequencies and employing different techniques of Doppler and spaced antenna methods will give an entirely different type of drift motions in the heights of 90–100 km in the equatorial EEJ region [e.g., *Tabbagh et al.*, 1977].

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