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Study of ionospheric electron content (IEC) depletions and their association with VHF scintillations

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Significant depletions in IEC data observed in the Indian sector from the Faraday rotation of VHF signals of the ETS-II and SIRIO satellites for high (1978-81) and low (1983-84) solar activity periods at a low latitude station, Waltair (17.7°N, 83.3°E), are studied. Their diurnal, seasonal and solar cycle variations in the occurrence characteristics are presented. The diurnal variations in the occurrence of depletions show a maximum around pre-midnight hours of 2100 hrs LT. With the available data, excluding the months of satellite eclipses, the month-to-month variation in the occurrence of depletions shows maximum in February during low solar activity period and in August during high solar activity period. The amplitudes of depletions vary from 1 to 9 IEC units (1 IEC unit = 10^{16} el./m^2) and the duration of most depletions vary from 5 to 15 min during the high and low solar activity periods. Further, the amplitudes of depletions vary linearly with their durations indicating that bubbles with long durations have large depletions. All these depletion events are invariably accompanied by amplitude scintillations.

1 Introduction

The occurrence of strong amplitude scintillations closely associated with a significant drop in the ionospheric electron content (IEC), termed as electron content depletion, has been reported by many workers at the equatorial and low latitude stations. These depleted density bubbles originating at the bottom side of the equatorial ionosphere rise into the region above the peak of F2-layer resulting in steep electron density gradients at the edges of the depleted region and help in generating small-scale irregularities causing intense scintillations in the amplitude of the received satellite signal[1-5].

Plume-like structures in electron density distribution were first detected by Woodman and Lahoz[6] in the coherent backscatter radar measurements at Jicamarca, Peru. Basu *et al.*[7] showed that the plume-like structures give rise to intense scintillations at VHF and UHF. Tsunoda and Towle[8] and Tsunoda *et al.*[9] from the measurements at Kwazalein Atoll, Marshall Islands, using ALTAIR radar, clearly indicated that the backscatter plumes observed with VHF radar are longitudinally coincident with IEC depletions.

VHF scintillation of satellite radio waves caused by nighttime F-layer irregularities is a frequently observed phenomenon[10-12] in the equatorial region and is closely related to plasma "bubbles" and "plumes" appearing after sunset. The formation and dynamics of these ionospheric bubbles have been studied by several workers[9,13-17]. Coordinated measurements with other techniques[10], such as *in situ* radar backscatter and airglow, have shown that these patches are the regions of depleted ionization in the F-region of the ionosphere. The depletions may occur over a considerable height range and sometimes have amplitudes as large as orders of magnitude of the ambient ionization level[18].

Simultaneous measurements of amplitude scintillations and Faraday rotation (FR) of a linearly polarized transionospheric signal can be used for investigation of equatorial IEC depletions[4,19]. In the recent past several workers[20-24] have reported the diurnal, seasonal and solar cycle behaviour of IEC depletions and their association with amplitude scintillations during sunspot number maximum years. These results show that IEC depletions associated with amplitude scintillations occur not only at an equatorial station but also at stations located near the equatorial anomaly crest regions or even beyond.

The use of FR technique, as discussed by Klobuchar *et al.*[19] and Das Gupta *et al.*[22], to measure depletions in IEC is however limited to certain locations within the equatorial belt. At a station

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situated close to the magnetic equator (like Huancayo or Legon), the detection of plasma bubbles is very difficult due to the near-transverse propagation condition of the ray path and the low value of *M*-factor[25]. On the other hand, at locations near the crest of the equatorial anomaly[21,26,27], the FR records often exhibit fast and intense polarization fluctuations during the periods of strong amplitude scintillations. During such times, even the concept of FR becomes invalid due to the depolarization[28] of the received signal caused by scattering from small scale power law type density irregularities. Because of the above two conditions, the detection of bubbles in FR records is more probable at stations located off the magnetic equator, but well within the anomaly crest regions, such as Natal in Brazil (5.85°S, 35.23°W) and Arequipa in Peru (16.4°S, 71.5°W). The present observing station, Waltair (Geog. lat. 17.7°N, Geog. long. 83.3°E) is situated at an intermediate location between the equator and the anomaly crest region of the Indian longitudinal zone and is thus suitably located to detect a large number of depletions (bubbles) in the FR records.

The paper reports the results obtained in the Indian subcontinent on IEC depletions and their association with amplitude scintillations for both high and low solar activity periods at a low latitude station, Waltair. The diurnal, seasonal and solar cycle variations in the occurrence of depletions at Waltair and a comparison of these results with those obtained at similar locations from other parts of the world are presented and discussed in this paper.

2 Data

The data of Faraday rotation and scintillations obtained using the VHF radio beacon signals at 136 MHz from ETS-II (130°E) and SIRIO (65°E) geostationary satellites for the periods 1978-81 and 1983-84 respectively have been used in the present study. The two periods of observation correspond to high and moderately low solar activity periods with the sunspot numbers (R_z) varying from 76 to 188 and 25 to 85 respectively. It should, however, be mentioned that no data could be recorded during the months of March and September due to satellite eclipses.

A typical record of FR showing significant depletions and their association with amplitude scintillations is presented in Fig. 1. This record shows three discrete patches of scintillations accompanied by significant depletions in the FR. The onset of the first patch of scintillations is at 2317 hrs LT and scintillation terminates abruptly at 2356 hrs LT. The simultaneous FR record shows a gradual decrease from 2100 hrs LT followed by a sudden drop starting at 2322 hrs LT (i.e. 5 min after the onset of scintillation) and continued to decrease to its minimum value up to 2332 hrs LT. The

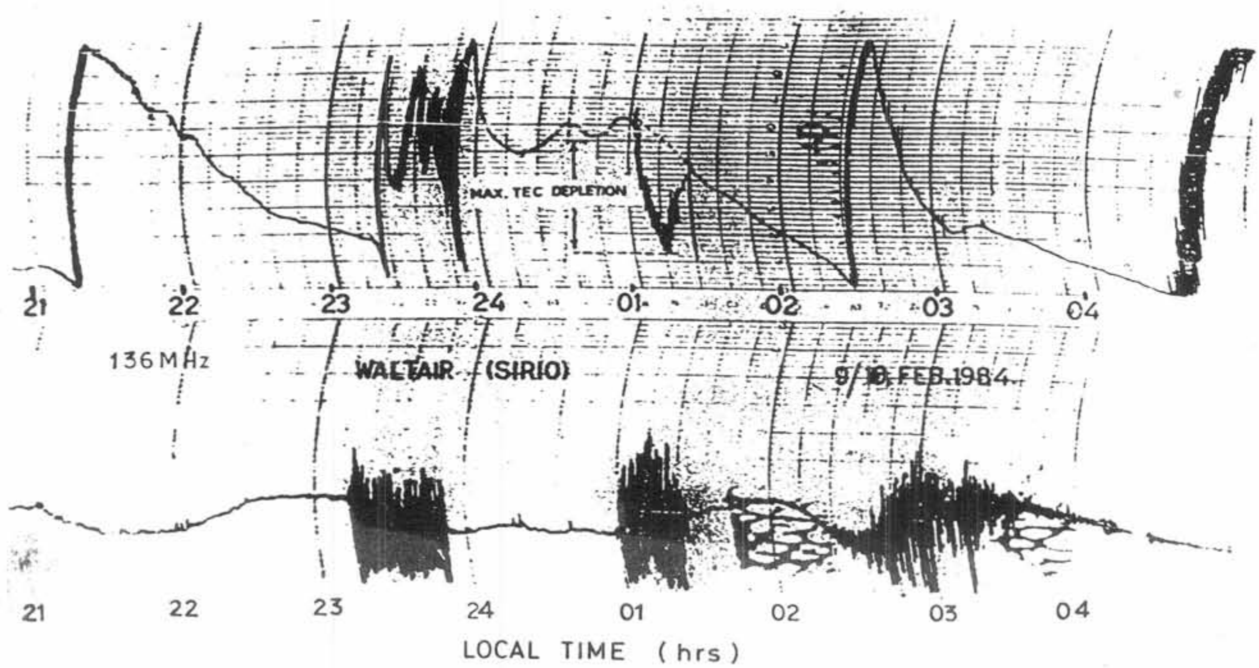

Fig. 1 – Typical record showing IEC depletions associated with amplitude scintillations at Waltair.

decrease in the FR angle of 120° observed in this record corresponds to a IEC depletion of 6.4 IEC units which is a significant decrease in IEC units and consequently in IEC. The duration of the depletion is found to be 16 min. The second patch of scintillation starts in 0102 hrs LT and gradually decreases by 0132 hrs LT. In the corresponding FR, the depletion started around 0106 hrs LT and reached its maximum by 0116 hrs LT. This depletion event is found to have a total duration of 22 min and a magnitude of 90° FR which corresponds to 4.7 IEC units. The third patch of scintillation starts from 0228 hrs LT and reaches its peak value by 0304 hrs LT followed by a gradual decrease in the fading rate and finally disappears around 0346 hrs LT. The corresponding FR record shows a small dip around 0310 hrs LT. No significant depletion is associated with this patch of scintillation. From a comparison of the characteristics of these three patches of scintillations it is noticed that the first two patches are abrupt and are followed by significant depletions in IEC, whereas the third patch has a slow start and a gradual increase of scintillation amplitude followed by a slow decay in amplitude and fade rate and it is not associated with a comparable depletion.

3 Analysis

The onset of each event of IEC depletion is identified as a sudden drop in the FR angle record and is used for scaling. For each occurrence of IEC depletion, a non-depleted (Normal) FR variation trend (which is shown as a dotted line in Fig. 1) is drawn based on the background variation. The amount of depletion is measured from this assumed non-depleted level. The IEC depletion, ΔN_T, is thus determined from the FR records as $N_T'-N_T$, where N_T represents the actually observed IEC and N_T' represents the assumed IEC when no IEC depletion occurs. The duration of the depletion is obtained from these records by measuring the time difference between the starting and ending times of the depleted region. The local time of occurrence of depletion corresponding to the time at which the maximum IEC depletion takes place is also obtained from the records. In the present analysis only those cases of IEC depletion have been considered which were not contaminated by any other quasi-random fluctuations or IEC enhancements (during moderate and high solar activity periods). In the data of IEC corresponding to 1978-81 and 1983-84, a total of 500 and 293 cases respectively of clear and isolated events of depletion associated with amplitude scintillations have been identified, carefully scaled and used in the present investigation.

4 Results and discussion

4.1 General features

The data of simultaneous occurrence of depletions and scintillations pertaining to two typical months, namely, October 1983 ($R_z = 56$) and March 1979 ($R_z = 138$) corresponding to low and high solar activity periods respectively are presented in Fig. 2. It is seen that the scintillation activity starts from around 1900 hrs LT during both low and high solar activity periods and disappears mostly by midnight during the year of low sunspot number but continues up to post-midnight hours during the year of high sunspot number. Further, it is seen that the depletions in IEC are mostly associated with scintillations in the premidnight hours during both the solar activity periods. The duration of scintillations is found to vary from a minimum of 15 min to a maximum of 90 min during both the solar activity periods, while the duration of the depletions varies from 10 to 30 min. It is interesting to note that the occurrence of scintillations is in general greater than that of IEC depletions. This is due to the fact that all scintillation occurrences are not associated with IEC depletion. Several workers[5,22,29] have report-

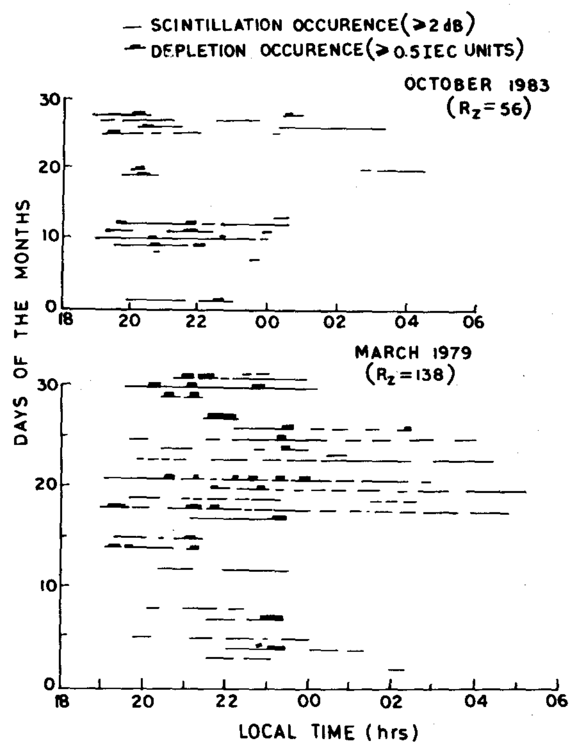

Fig. 2 — Occurrence of IEC depletions and scintillations for two typical months during low and high solar activity periods.

ed the occurrence of equatorial amplitude scintillation patches of several hours' durations without detectable IEC depletions. It has been reported that these amplitude scintillations without IEC depletions are associated with frequency spread-F signatures on ionograms[22] and with bottomside sinusoidal (BSS) irregularities observed by *in situ* measurements[22,29].

4.2 Temporal variation in the occurrence of depletions

The diurnal and seasonal variations in the occurrence of depletions and their dependence on solar activity are also of interest to this study.

The percentage occurrence of depletions as a function of local time for three different seasons, separately for the high and low solar activity periods, is presented in Fig. 3. It is seen that all the depletion events occur during the nighttime hours from 1900 to 0400 hrs LT only. The hour-to-hour variation in the occurrence of depletions during the high solar activity period distinctly shows two peaks, one before midnight and the other after midnight, similar to the nature of occurrence of equatorial scintillations[30]. The pre-midnight peak occurs around 2100 hrs LT while the post-midnight peak occurs between 0000 and 0200 hrs LT. In the equinoctial and winter months of low sunspot number years, only the pre-midnight peak is prominent and it occurs around 2030 hrs LT.

The month-to-month variation in the occurrence of depletions for both the solar activity periods is presented in Fig. 4. With the available data, excluding the months of satellite eclipses, the occurrence of depletions during the high solar activity period is found to be maximum during August followed by February. During the low solar activity period, the occurrence of depletions is maximum during the winter and equinoctial months of February, October and November, followed by September, January, March, April, and December. During the summer months of May, June, July, and August, the occurrence is lowest. Thus the month-to-month variation in the occurrence of depletions shows a maximum in August during high solar activity period while it shows a maximum in February followed by October and November during low solar activity period. It is also seen from this figure that there is a prominent secondary maximum in the occurrence of depletions during February of high solar activity period.

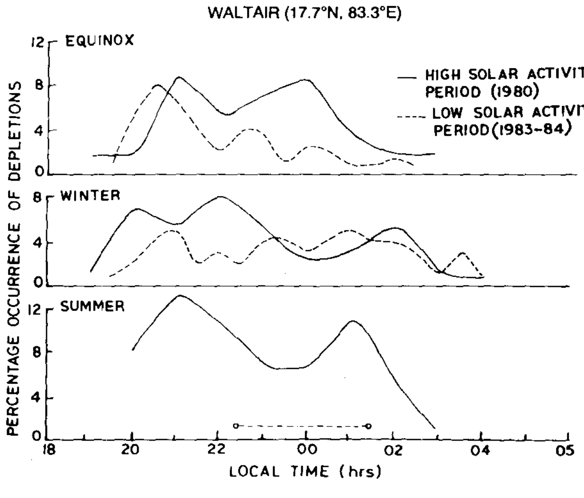

Fig. 3 – Nocturnal variation of IEC depletions during three different seasons.

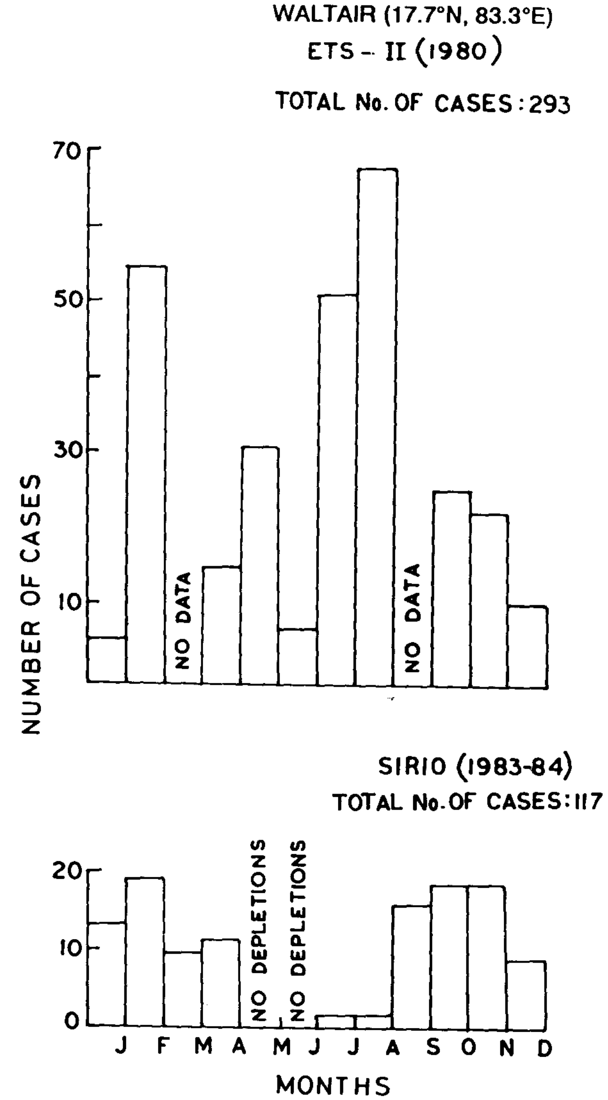

Fig. 4 – Month-to-month variation in the occurrence of IEC depletions during high (1980) and low (1983-84) solar activity periods.

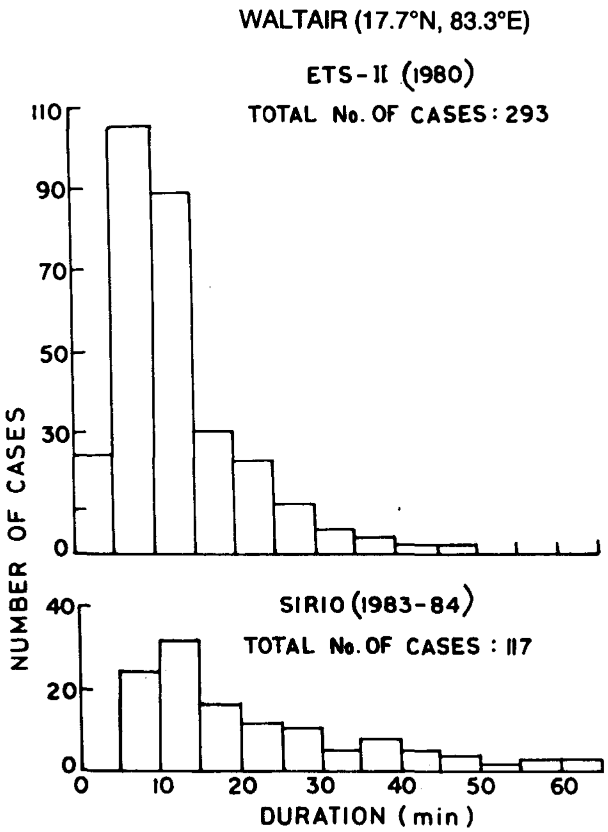

Fig. 5 – Distribution of IEC depletions with duration during high (1980) and low (1983-84) solar activity periods.

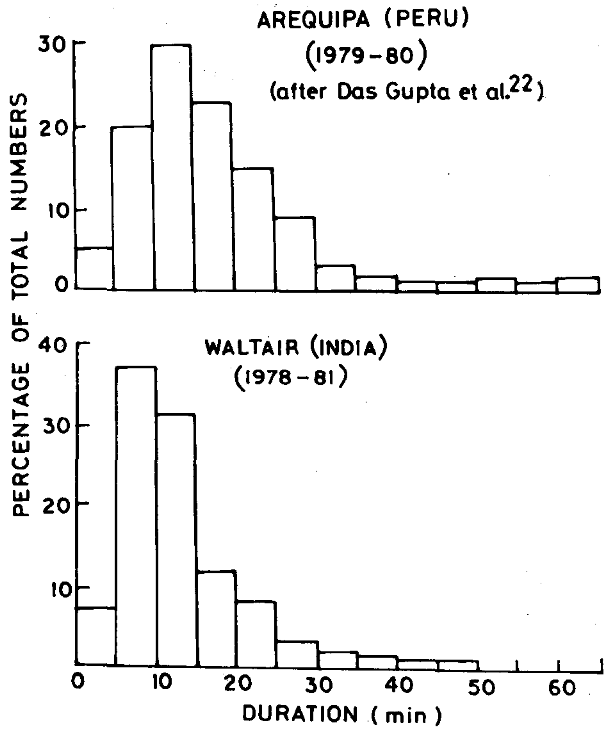

Fig. 6 – Distribution of duration of IEC depletions at Arequipa and Waltair during high solar activity periods.

Das Gupta *et al.*[22] from a study on the occurrence of depletions during the high solar activity period from a similar southern-hemisphere station Arequipa, Peru, reported maximum occurrence during equinoctial months and minimum during May-July months. Huang[23] from a study on the occurrence of depletions during the high solar activity period (1977-80) at Lunping in Taiwan (25°N, 121°E) reported that the seasonal maximum of IEC depletions varies with sunspot number.

4.3 Duration of depletion

The duration of depletion is measured as the difference in local time between the onset of deviation from the normal trend and its recovery to the expected level of diurnal variation in IEC. This duration in the present data is found to vary from a minimum of 5 min to a maximum of about 60 min. With a view to studying the nature of variation in the duration of depletions, histograms showing the distribution of IEC depletions with their durations for both the solar activity periods are presented in Fig. 5. It is seen from the figure that the most probable duration ranges from 5 to 15 min in both the solar activity periods and there is no seasonal dependence in the duration of depletions. From similar measurements from the data of Natal, Brazil, for the high solar activity period, Yeh *et al.*[5] reported that the average duration of the bubble is in the range 8-10 min. Das Gupta *et al.*[22] from the data of Arequipa, Peru, for the high solar activity period reported that the most probable duration of depletion varies in the range 10-15 min (Fig. 6). Thus the duration of 5 to 15 min in the present case falls in the range of results reported by Yeh *et al.*[5] and Das Gupta *et al.*[22]. Haung[23] from the data of anomaly crest region Lunping, Taiwan, for the high solar activity period reported that the most probable duration ranges from 10 to 33 min, which is on the higher side of the values observed at this low latitude station, Waltair.

4.4 Depletion amplitude

Another parameter of interest is the amplitude or depth of depletion in IEC. In Fig. 7 is presented the distribution of amplitudes of depletion for both the solar activity periods. The amplitude of depletion varies from 1 to 9 IEC units during both the solar activity periods, with the most probable amplitudes being 1 to 4 IEC units during the high solar activity period and 1 to 2 IEC units during the low solar activity period. These results are also in agreement with the depletion amplitudes

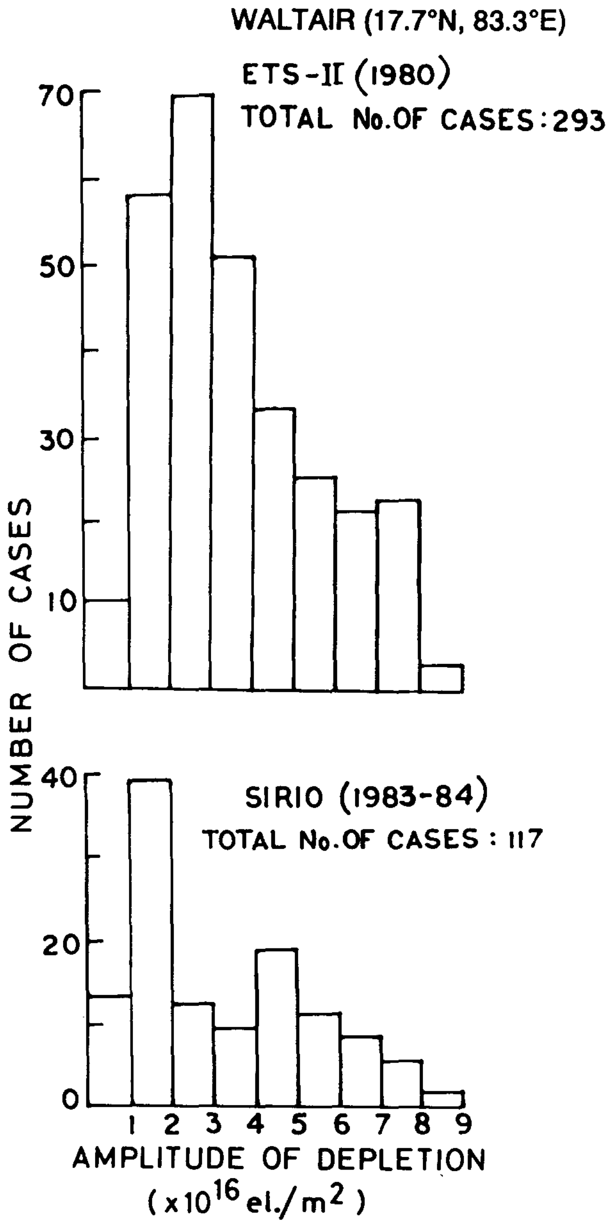

Fig. 7 – Distribution of IEC depletions with amplitude of depletion during high and low solar activity periods.

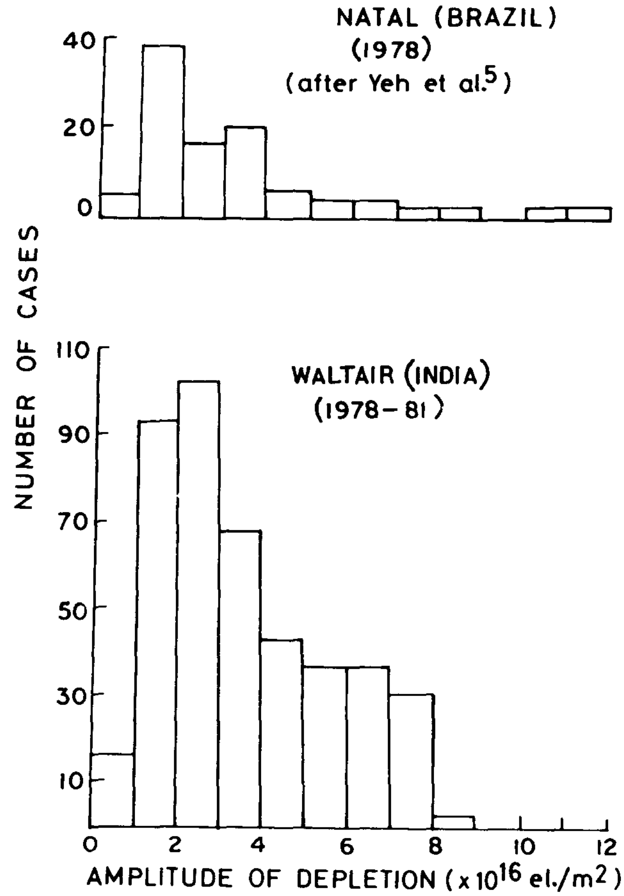

Fig. 8 – Distribution of amplitudes of depletion in IEC at Natal and Waltair during high solar activity periods.

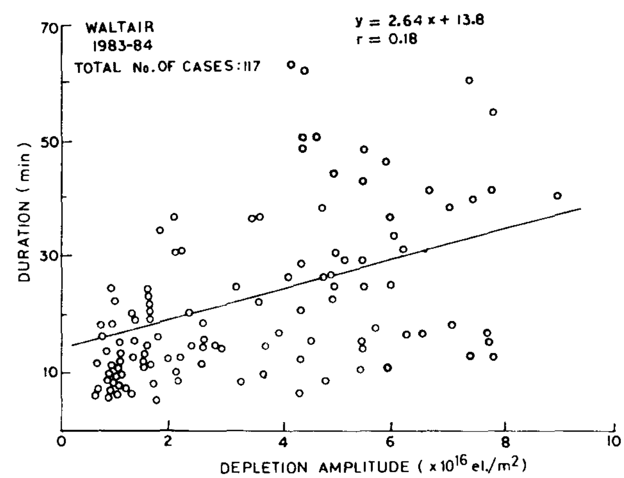

Fig. 9 – Scatter plot showing the duration of depletions as a function of its amplitude.

of 1 to 4 IEC units (Fig. 8) reported by Yeh *et al.*[5], 1 to 5 IEC units by Das Gupta *et al.*[22] and 0.8 to 3.6 IEC units by Huang[23].

A scatter plot of the amplitude of IEC depletions and the corresponding durations observed during the low solar activity period of 1983-84 is presented in Fig. 9. Although there is a considerable scatter of points, it is interesting to note that there is a definite linear trend of variation with the depletions of long durations having larger amplitudes, i.e. the longer the duration the larger is the size of the bubble and thus the amplitude of depletion in IEC is greater. Although Das Gupta *et al.*[22] and Huang[23] from a similar study reported that there is no definite relation between the amplitude of a depletion and its duration, Yeh *et al.*[5] reported that there is a definite relation between the two parameters with longer duration bubbles having a tendency to associate themselves with large depletions.

5 Summary

The results obtained with the available data of depletions and scintillations show the following features:

(i) The occurrence of scintillations is high and the depletions are moderate during high solar activity period (1978-81).

(ii) The occurrence of both depletions and scintillations is low during the low solar activity period (1983-84).

(iii) The occurrence of depletions is found to be maximum in August followed by February during high solar activity period.

(iv) The occurrence of depletions is found to be maximum in February followed by October and November during low solar activity period.

The present study of the characteristic variations of the ionospheric electron content depletions associated with amplitude scintillations reveals that the occurrence of depletions associated with scintillations at equatorial and low latitude stations during low solar conditions is more pronounced in the pre-midnight hours of the equinoctial months. It is interesting to note that the occurrence of scintillations and the presence of depletions are found to be associated with one another during the evening hours of certain seasons. Further, it is also seen that the occurrence of the scintillations show a definite seasonal trend in both the hemispheres of the Asian and American longitudinal zones. But it is seen from the present results (from Waltair) and also from the results of a few other locations (like Lunping) that no definite seasonal trend similar to that of scintillations is observed in the occurrence of depletions. These differences may be attributed to the limitations in the detection of the bubbles by the Faraday rotation technique at different locations of the observing stations with respect to the magnetic equator.

It is also observed that the occurrence of electron content depletions associated with amplitude scintillations is remarkably high during high solar activity period. Further, it is interesting to note that there is a significant relation between the amplitude of IEC depletion and its duration.

From the present study it is noticed that scintillations are not always associated with the occurrence of depletions in IEC. The depletions are observed when the irregularities are intense and occur over a large spatial extent in the vertical direction. During the developmental phase in the post-sunset and pre-midnight hours, the equatorial irregularities in the form of bubbles are very strong and occupy several hundred kilometres of the topside ionosphere. Irregularities with scale sizes extending over hundreds of km to cm coexist in this phase. During this local time interval, scintillation at VHF and UHF is saturated with a very fast fading rate and depletions are observed in Faraday rotation records.

In the post-midnight hours, the overall strength of the irregularities diminishes, the smaller scale irregularities decaying faster. In this time interval, saturated or weak scintillation at VHF with a slow fading rate is still recordable but the IEC depletion amplitude is too small to be detected. The observed characteristics of the depletions and scintillations may be related to the enhancement of the eastward electric field in the ionosphere near the magnetic equator during the post-sunset hours.

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