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Phase variability of $Sq(H)$ on normal quiet days in the equatorial electrojet region

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Summary. From a study of 'abnormal quiet days' (AQDs) at equatorial latitudes it was found earlier (Sastri) that the occurrence of an abnormal $Sq(H)$ phase confined to the equatorial electrojet belt is closely associated with the incidence of complete or partial counter-electrojet (CEJ) conditions (marked daytime depressions in the H field in the electrojet region) for about 5 hr around the normal time interval of the diurnal maximum of the H field. In this paper, we investigate the causative mechanism of the $Sq(H)$ phase variability on 'normal quiet days' (NQDs), defined as days on which the diurnal maximum of the H field occurs in the time interval 0930–1230 LT, in the equatorial electrojet belt using published geomagnetic data of stations in the Indian equatorial region. It is found that much of the phase variability of $Sq(H)$ on NQDs may be caused by the influence of southward (negative) perturbation fields in the H component, similar in nature to those associated with AQDs but of a much smaller amplitude, close to the usual time of the diurnal maximum of the H field. The perturbation fields are noticed to be essentially of the ionospheric dynamo region origin. Possible mechanisms that might give rise to the observed perturbation fields are discussed.

1 Introduction

One well-known characteristic feature of $Sq(H)$, the solar quiet day variation of the horizontal component of the Earth's magnetic field is the marked day-to-day variability of its amplitude (range) and time of diurnal extremum (phase), which manifests itself even on 'International Quiet Days' (IQDs). Brown & Williams (1969) made a detailed study of the occurrence of the anomalous $Sq(H)$ phase at mid-latitude locations using the concept of 'Abnormal Quiet Days' (AQDs) (defined as IQDs on which the extremum in the H field falls outside the time range 0830–1330 LT). Studies similar to that of Brown & Williams (1969) using data of equatorial stations showed the morphology of AQDs at these latitudes to be distinctly different from that at mid-latitudes (Last, Emilia & Outhred 1976; Sastri & Murthy, 1978). The difference in the characteristics of the phase variability of $Sq(H)$ (e.g. local time variation, spatial extent) between equatorial and mid-latitude locations suggested the origin of AQDs to be different in the two latitude regions.

Butcher & Brown (1981a) demonstrated the occurrence of the abnormal $Sq(H)$ phase at mid-latitude stations on the poleward side of the Sq focus to be essentially due to: (a) a reduction in the amplitude of $Sq(H)$ in the normal time interval (0830–1330 LT) of the diurnal minimum due to the superposition of a northward field; and (b) superposition of a small (average amplitude 6 nT) southward (negative 'bay'-like) perturbation field lasting for about 4 hr outside the interval 0830–1330 LT. The two perturbation fields acting in union cause a shift of the diurnal minimum in the H field to an anomalous local time. The northward and southward perturbation fields are assessed to be of a large geographical extent and are closely related to parameters of the interplanetary magnetic field (IMF), whose features suggest an extraterrestrial or magnetospheric origin of AQDs at mid-latitude locations. Sastri (1981a), on the other hand, showed that the occurrence of AQDs at equatorial latitudes is primarily due to a suppression of the quiet day Sq and electrojet field around the normal time of its diurnal maximum by a southward field of limited spatial extent. AQDs confined to the electrojet belt are found further to occur in close association with depressions in the H field characteristic of complete or partial counter-electrojet (CEJ) conditions (see Mayaud 1977 for a review of the magnetic aspects of CEJ) around the normal time interval of the diurnal maximum of the H field (Sastri 1981b). The sense of shift of the $Sq(H)$ phase depends on the time of incidence of CEJ conditions relative to the normal time of the diurnal maximum of the H field. If CEJ conditions set in just prior to the normal time, the resultant diurnal maximum is delayed (PM AQD), and if they set in just after the normal time, the resultant maximum is advanced (AM AQD). The cause of CEJ conditions is now being widely sought in terms of changes in the local ionospheric dynamo (90–130 km) region (e.g. Mayaud 1977; Reddy 1977; Bhargava *et al.* 1980). It follows, therefore, that although perturbations in the normal H field variation are indeed basically responsible for the occurrence of AQDs both at equatorial and mid-latitude locations, the times of incidence and source regions of the same are quite different for the two latitude regions.

Very recently Butcher & Brown (1981b) showed that the day-to-day variability of the $Sq(H)$ phase on 'normal quiet days' (NQDs) at mid-latitude stations on the poleward side of the Sq focus could result from the incidence of 'bay'-like southward perturbation fields of the type associated with AQDs, but at times close to the normal time interval of the diurnal minimum. It would appear that the bay-like southward perturbation fields also affect the phase of $Sq(H)$ at mid-latitude stations on the equatorward side of the focus as well as the phase at stations on the poleward side. Small-scale depressions in the H field of extraterrestrial or magnetospheric origin thus seem more or less to govern the phase variability of $Sq(H)$ at mid-latitudes. In view of these considerations, it is conceivable that a similar situation also prevails in the equatorial electrojet region in that the phase variability of $Sq(H)$ on NQDs at these latitudes might be due to changes in the equatorial electrojet current of the type associated with AQDs (depression in the H field), but of much smaller amplitude so as to cause a slight shift of the $Sq(H)$ phase from the usual time on individual days. In this paper we examine this possibility and present evidence in support of it.

2 Data and analysis

Published hourly values of the magnetic H component of Trivandrum (geographical coordinates 8°29′N, 76°57′E, dip 0.6°S), Kodaikanal (geographical coordinates 10°14′N, 77°28′E, dip 3.0°N), Annamalainagar (geographical coordinates 11°22′N, 79°41′N, dip 5.4°N) and Alibag (geographical coordinates 18°38′N, 72°52′E, dip 24.5°N) and the Z component of Annamalainagar pertaining to epochs of low (1963–1965) and high sunspot activity (1957–59) have been used for this study. Out of these four stations in the Indian equatorial region. Trivandrum is right on the dip equator, Kodaikanal well within and

Annamalainagar around the northern fringe of the electrojet belt and Alibag well outside the influence of the electrojet. From the five IQDs of each month over the periods mentioned, NQDs at Trivandrum, defined as days with a diurnal maximum of the H field in the time interval 0930–1230 LT (Sastri & Murthy 1978) have been selected for analysis. NQDs that occurred immediately prior (within two days) to International Disturbed Days (IDDs) have been omitted in view of the possible presence of residual disturbance effects. The time interval 0930–1230 LT for the diurnal maximum of the H field on NQDs is divided into three blocks of 1 hr duration, i.e. 0930–1030, 1030–1130 and 1130–1230 LT and NQDs have been separated into groups corresponding to these three time blocks. The diurnal evolution of the H field at Trivandrum on each of the days in the three groups of NQDs during years of both low and high sunspot activity is obtained by first correcting the hourly values for non-cyclic variation and then subtracting the mean 'night-time base' from the hourly data. The diurnal variation of the Z field at Annamalainagar is evaluated in the same manner. The signature of the equatorial electrojet (EEJ) current is well known to be largest in the H field near the axis of the electrojet belt and in the Z field near the fringes (about 2.5° dip latitude) of the electrojet belt. If small amplitude perturbations in electrojet strength are indeed responsible for the variability of the $Sq(H)$ phase in the interval 0930–1230 LT on individual NQDs as conceived, then there should be systematic and significant differences in the mean diurnal variation of the H field at Trivandrum and the Z field at Annamalainagar between NQDs corresponding to the three time blocks.

3 Results and discussions

During the low sunspot activity years 1963–65, out of the 147 NQDs at Trivandrum, 41 days (28 per cent) had diurnal maximum of the H field in the interval 0930–1030 LT, 78 day (53 per cent) in the interval 1030–1130 LT and 28 day (19 per cent) in the interval 1130–1230 LT. During years of high sunspot activity (1957–59) the corresponding figures for the three time blocks are 18 day (18 per cent), 57 day (55 per cent) and 28 day (27 per cent). A clearcut change in the distribution of the time of diurnal maximum of the H field on NQDs with the level of sunspot activity is apparent, the implications of which will be discussed at a later stage in this paper.

Fig. 1 depicts the average patterns of diurnal variation of the H field at Trivandrum (H_T) and the Z field at Annamalainagar (Z_{ANR}) on NQDs at Trivandrum corresponding to the three time blocks of the $Sq(H)$ phase during years of low sunspot activity. The patterns pertaining to years of high sunspot activity are presented in Fig. 2 in the same format as Fig. 1. It is evident from Figs 1 and 2 that the diurnal developments of H_T and Z_{ANR} are markedly different on NQDs with the diurnal maximum of the H field in the intervals 0930–1030 and 1120–1230 LT from that on NQDs with the diurnal maximum in the interval 1030–1130 LT (the most usual time span of diurnal maximum of the H field on IQDs in the equatorial electrojet region, Sastri & Murthy 1978). On NQDs with a diurnal maximum of the H field in the interval 1130–1230 LT (i.e. later than usual) the H field undergoes a significant reduction in the forenoon period from 0800 to 1100 LT and on NQDs with a diurnal maximum in the interval 0930–1030 LT (i.e. earlier than usual) the depressions manifest in the time span 1000–1500 LT. The changes in the diurnal evolution of Z_{ANR} on these two groups of NQDs correspond to those in H_T (the depressions in H_T are associated with enhancements in Z_{ANR}, i.e. less negative values). The diurnal range of H_T is comparatively lower on NQDs with a diurnal maximum in the intervals 0930–1030 and 1130–1230 LT than on NQDs with a diurnal maximum in the interval 1030–1130 LT as may be seen from Figs 1 and 2. These statistical trends strongly suggest that much of the day-to-day variability of the $Sq(H)$ phase in the immediate vicinity of the dip equator on

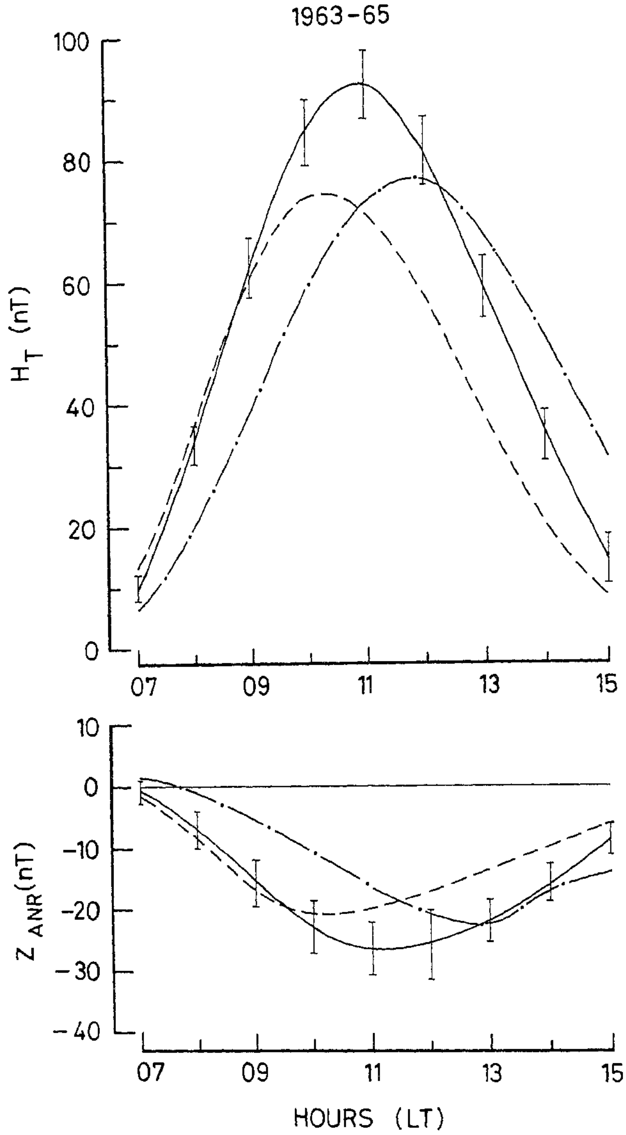

Figure 1. Mean diurnal variations of the H field at Trivandrum (H_T) and the Z field at Annamalainagar (Z_{ANR}) on NQDs at Trivandrum with diurnal maximum of the H field in the intervals 0930–1030 (– – –), 1030–1130 (——) and 1130–1230 LT (– · –). The variations shown correspond to years of low sunspot activity 1963–65. The vertical bars indicate 99 per cent confidence intervals of the mean values.

NQDs may be caused by small amplitude reductions in the normal Sq and electrojet field lasting for several hours, close to the usual time of its diurnal swing. The average amplitude of the reductions in the H field varies with local time and is a maximum around 1200 LT on NQDs with an early diurnal maximum and around 1000 LT on NQDs with a late diurnal maximum. There is no significant change in the maximum amplitude of the perturbation fields between low and high sunspot activity years. These features may be seen in Fig. 3 which is a reconstructed version of the data presented in Figs 1 and 2.

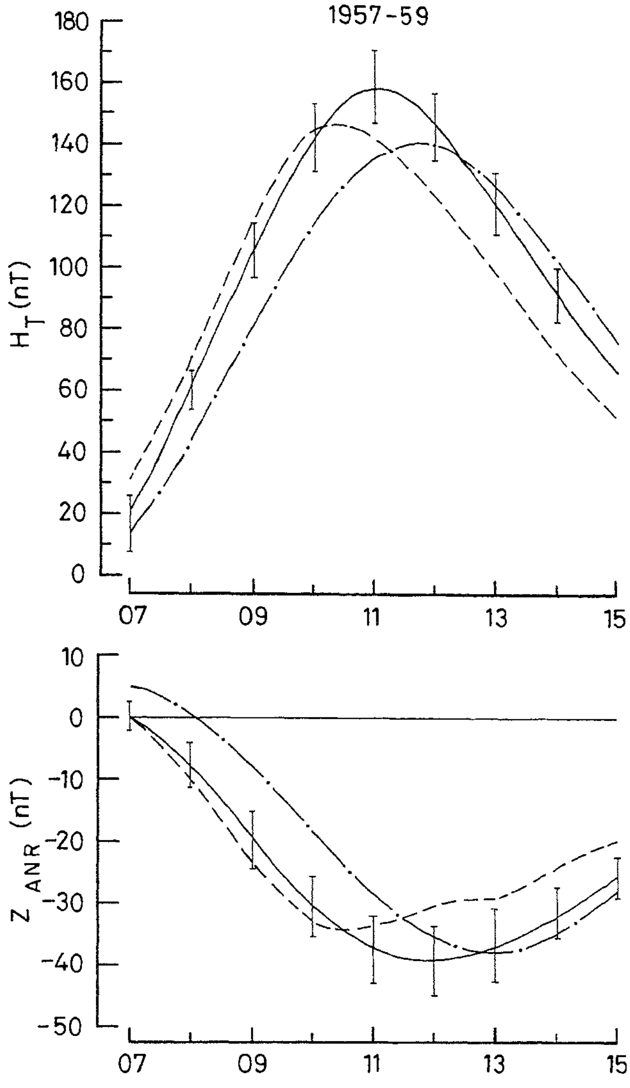

Figure 2. Same as in Fig. 1 but for years of high sunspot activity 1957–59.

Since the geomagnetic field variation monitored at ground level in the electrojet belt is influenced by both overhead currents in the ionospheric dynamo region and by distant currents associates with magnetospheric sources through ionosphere–magnetosphere interaction processes (see, e.g. Reddy, Somayajulu & Devasia 1979), a further analysis of the data is carried out to ascertain the source region of the small-scale depressions in the H field responsible for the phase variability on NQDs. For this purpose the H component data of Alibag is analysed following the procedure detailed earlier and the mean diurnal variation of the difference field between Trivandrum and Alibag ($H_T - H_A$) is obtained for the three groups of NQDs during years of low and high sunspot activity. The difference field $H_T - H_A$ is widely considered to represent the field due to currents of ionospheric origin (e.g. Rush & Richmond 1973; Rastogi 1975; Bhargava *et al.* 1980). In Fig. 3 is shown the mean diurnal

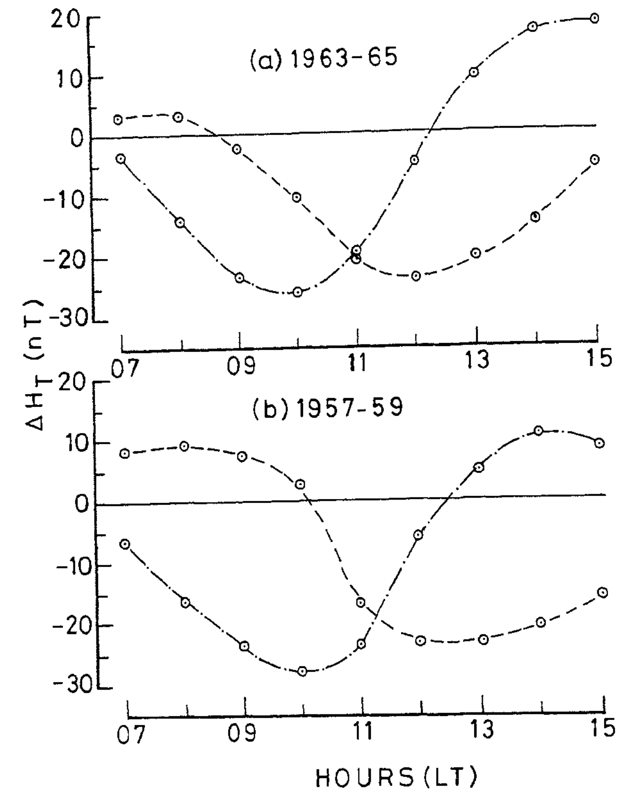

Figure 3. Local time variation of the difference in the H field at Trivandrum (ΔH_T) on NQDs with diurnal maximum in the intervals 0930–1030 (– – –) and 1130–1230 LT (– · –) from that on NQDs with diurnal maximum in the interval 1030–1130 LT during: (a) 1963–65, and (b) 1957–59.

variation of $H_T - H_A$ corresponding to the three groups of NQDs during years of low and high sunspot activity. It is quite evident from Fig. 3 that the nature of the diurnal variation of $H_T - H_A$ is essentially the same as that of H_T for all three groups of NQDs, and the forenoon and early afternoon depressions noticed in H_T persist in $H_T - H_A$. This feature indicates that the small-scale perturbation fields on NQDs are primarily of the ionospheric dynamo origin.

The statistical analysis attempted here thus shows that a modulation of the normal diurnal development of the Sq and electrojet field by small-scale southward (negative) perturbation fields for several hours around the usual time of the diurnal maximum may be responsible for the phase variability of $Sq(H)$ on NQDs in the equatorial electrojet region. The observed modulation of the Sq and electrojet field does not appear to be of lunar tidal origin as the occurrence of NQDs having early or late diurnal maxima of H at Trivandrum is found not to bear a systematic and favourable relationship with the lunar phase. The southward perturbation fields on NQDs observed here are similar, as regards their influence on the $Sq(H)$ phase to those found earlier on AQDs in the electrojet region (Sastri 1981b). The perturbation fields on AQDs and NQDs, however, differ from one another in one respect. That is that while on AQDs the perturbation fields are actual decreases in the H field, the reductions in the H field on NQDs (with early or late diurnal maxima) are relative to the H field variation on NQDs with a diurnal maximum of H in the most common time interval

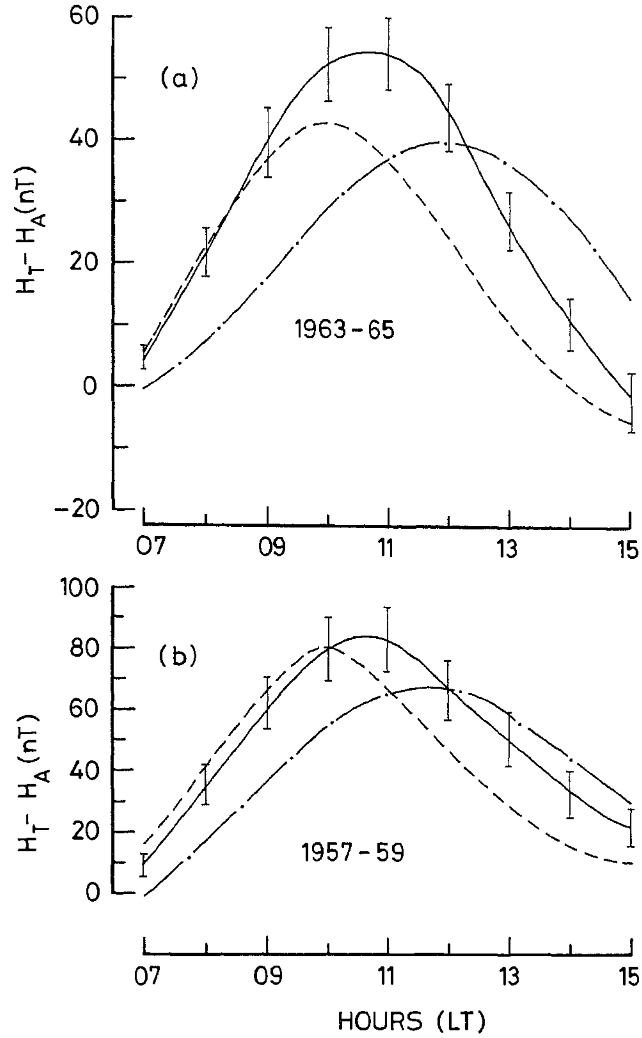

Figure 4. Same as in Fig. 1 but depicting the variations of the difference field between Trivandrum and Alibag ($H_T - H_A$) during: (a) 1963–65, and (b) 1957–59.

and hence are of a much smaller amplitude to cause only a slight shift of the diurnal maximum from the usual time. It has been suggested that the occurrence of reductions in the H field that result in AQDs may be due to vertical (rather than horizontal) wind variability in the electrojet region (Sastri 1981b). Recent theoretical studies (e.g. Richmond 1973; Fambitakoye *et al.* 1976; Reddy & Devasia 1978, 1981; Raghava Rao & Ananda Rao 1980) have shown that the latitudinal structure of the effect of shearing horizontal winds is different from that of vertical winds in the equatorial region. It is therefore felt necessary to attempt a study of the variation of the amplitude of the depressions in the H field across the width of the electrojet belt and beyond to assess the role and nature of local winds involved in the observed perturbations in EEJ on NQDs. With this in view, the H component data of Kodaikanal and Annamalainagar have also been analysed in the same manner as those of Trivandrum and Alibag for the various categories of NQDs. In Figs 5 and 6 are shown the

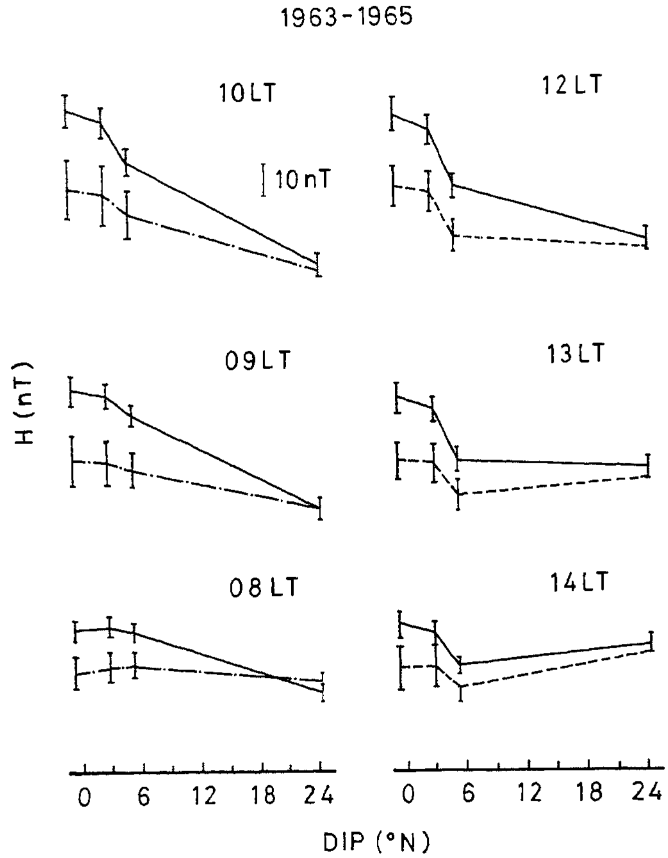

Figure 5. Mean latitudinal profiles at selected times of the *H* field in the Indian equatorial region on NQDs at Trivandrum with diurnal maximum of the *H* field in the intervals 0930–1030 (– – –), 1030–1130 (——) and 1130–1230 LT (–·–) during years (1963–65) of low sunspot activity. The vertical bars represent 99 per cent confidence intervals of the mean values.

mean latitudinal profiles of the *H* field in the Indian equatorial region corresponding to the three groups of NQDs during years of low and high sunspot activity respectively. The profiles are depicted for appropriate local times and pairs of groups of NQDs keeping in view the results presented earlier. It is evident from Figs. 5 and 6 that the forenoon and early afternoon depressions of the *H* field associated with NQDs with diurnal maximum in the intervals 1130–1230 and 0930–1030 LT respectively are confined to the electrojet region. The differences in the *H* field between the various groups of NQDs are not significant at the higher latitudes (Alibag) away from the electrojet. The average amplitude of the depressions of the *H* field is a maximum at the dip equator and decreases with increase in latitude in the electrojet belt. A consideration of this consistent behaviour in the light of results of the theoretical studies mentioned earlier suggests a prominent role of time-varying vertical winds in the phase variability of *Sq*(*H*) in the electrojet region on NQDs (see Raghava Rao & Ananda Rao 1980 and Sastri 1981b for conceptual details of the nature of changes in EEJ and hence in *Sq*(*H*) phase that may be brought about by time-varying vertical winds). It is found that the station Alibag, which lies away from the influence of the electroject, does not show the same phase variability systematically as Trivandrum on the Trivandrum NQDs.

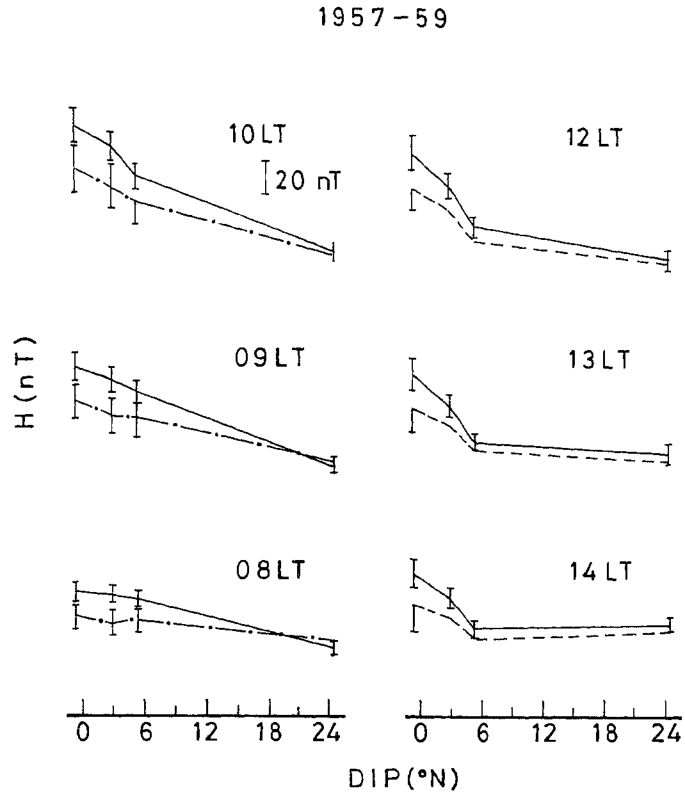

Figure 6. Same as in Fig. 5 but for years of high sunspot activity.

This lends support to the inference of wind variability as a plausible cause of phase variability. Alternatively, the observed depressions of the *H* field may also be produced by changes in the characteristics (height and electron density) of the ionization distribution profile in the local dynamo region. An upward movement of the electron density profile in association with a decrease in electron density will cause a reduction in the height integrated conductivity of the dynamo region, and the reduction will be more in Hall conductivity than in Pedersen conductivity. Such changes in the electron density profiles of the *E*-region have been reported earlier by Stenning (1977) during CEJ conditions at different local times. Since the EEJ is effectively dependent on Cowling conductivity (which is dependent on Hall and Pedersen conductivities) and since an abnormally high dynamo region conductivity exists only in the electrojet belt, a reduction in the height integrated conductivity of the region will lead to a corresponding reduction in the electrojet current and the effect will be confined to the electrojet region.

The results of this study provide a qualitative understanding of the origin of the sunspot cycle variation of the *Sq*(*H*) phase at electrojet locations which is known to occur, on an annual basis, about 1 hr earlier at sunspot minimum than at sunspot maximum (Rastogi & Iyer 1976). As mentioned earlier, although the percentage occurrence of NQDs at Trivandrum with diurnal maximum of the *H* field in the usual time interval 1030–1130 LT is more or less the same during low and high sunspot activity years, the percentage occurrence of days with diurnal maximum in the interval 0930–1030 LT is more than that of days with diurnal maximum in the interval 1130–1230 LT at low sunspot activity and the opposite is the situation at high sunspot activity. Further, it is known from earlier studies that the occurrence of AQDs at Trivandrum bears an anti-phase relationship with sunspot activity and that 59 per cent of AQDs are of AM AQD type (Last *et al.* 1976). These features when viewed together and in the light of the recent studies of Sastri (1981a, b) indicate that the sunspot cycle variation of the $Sq(H)$ phase at electrojet locations may be intimately linked with systematic changes in the times of incidence of perturbations (small- and large-scale) in electrojet strength with sunspot activity.

4 Conclusions

It has been shown that small-scale reductions in EEJ strength lasting for several hours superposed on the normal diurnal development of the electrojet current close to the usual time of its diurnal maximum may be responsible for much of the $Sq(H)$ phase variability in the equatorial electrojet regions on NQDs. The perturbation fields are basically of the ionospheric dynamo region origin and may represent changes in the electrojet current associated with day-to-day variability in the local vertical wind structures and/or in the electron density profiles of the *E*-region. Localized changes in the ionospheric dynamo thus seem to control both the abnormal and normal phase variability of $Sq(H)$ in the electrojet regions. A comparison of the salient findings of the current study with those of Butcher & Brown (1981b) mentioned earlier suggests that, although southward perturbation fields superposed on the H field variation close to the usual time of its diurnal swing seem to account for much of the $Sq(H)$ phase variability on NQDs both at mid-latitude and equatorial electrojet locations, the characteristics and source regions of the perturbation fields are distinctly different for the two latitude zones.

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