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16. Summary/Notes *Phase recordings at Atibaia, Brazil, (23°, 46°W) of 13.6 KHz VLF signal transmitted from Golfo Nuevo, Argentina (43°S, 65°W), a trajectory confined almost completely within the South Atlantic Anomaly region, show significant perturbations, indicative of the lowering of the VLF reflection level, immediately following the onset of magnetic disturbances. Simultaneous measurements of the E_s-layer parameters, f_tE_s and f_bE_s, over Cachoeira Paulista (22°S, 45°W) also show enhancements, with some delay with respect to the magnetic disturbance onset, as was found in our earlier work (Batista and Abdu, 1977). These results show magnetic storm associated ionization enhancements taking place in a height region from approximately 110 km down to 70 km, which we interpret as having been produced by precipitation of high energy charged particles in the South Atlantic Geomagnetic Anomaly. The results also suggest some degree of day to day variability in the abundance of metallic species, and/or in the dynamics of the E region over this region.*

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MAGNETIC STORM ASSOCIATED ENHANCED PARTICLE PRECIPITATION IN THE SOUTH ATLANTIC ANOMALY: EVIDENCE FROM VLF PHASE MEASUREMENTS

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ABSTRACT

Phase recordings at Atibaia, Brazil, (23°S, 46°W) of 13.6 KHz VLF signal transmitted from Golfo Nuevo, Argentina (43°S, 65°W), a trajectory confined almost completely within the South Atlantic Anomaly region, show significant perturbations, indicative of the lowering of the VLF reflection level, following the onset of magnetic disturbances. Simultaneous measurements of the E_S-layer parameters, $f_t\ E_S$ and $f_b\ E_S$, over Cachoeira Paulista (22°S, 45°W) also show enhancements, with some delay with respect to the magnetic disturbance onset, as was found in our earlier work (Batista and Abdu, 1977). These results show magnetic storm associated ionization enhancements taking place in a height region from approximately 110 km down to 70 km, which we interpret as having been produced by precipitation of high energy charged particles in the South Atlantic Magnetic Anomaly. The results also suggest some degree of day to day variability in the abundance of metallic species, and/or in the dynamics of the E-region over this region.

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INTRODUCTION

The South Atlantic Magnetic Anomaly region, characterized by a global minimum in the Earth's total magnetic field intensity, provides a permanent sink for the inner belt quasi-trapped particles that, during their longitudinal drift, dip down to low levels in the atmosphere over the Anomaly region. Numerous satellite measurements of the particle concentration and their spectra have been carried out in the past (Ginzberg et al., 1962; Imhof and Smith, 1965; Vernov et al., 1967; Seward et al.,1973).Further characteristics of the South Atlantic Anomaly, the predicted and observed zones of particle precipitation and the dependence of particle precipitation on magnetic activity can be obtained from the papers by Paulikas (1975), Torr et al., (1975), Gledhill (1976) and Voss and Smith (1980).

In a recent paper, Batista and Abdu (1977) analysed sporadic E-layer behaviour during magnetically disturbed periods over Cachoeira Paulista, located very near the Center of the South Atlantic (also known as Brazilian) Geomagnetic Anomaly. It was observed that significant enhancements in the E_S layer parameters, f_tE_S and f_bE_S, took place for short durations (1 - 3 hours), within 1 to 3 days, following the onset of a magnetic disturbance of moderate intensity. During some events, the enhancements in the night E-region ambient electron densities were comparable to regular daytime maximum values produced by solar radiation. Further, the E_S traces were accompanied by range spreading echoes resembling the a-type E_S usually observed over auroral latitudes under disturbed conditions. These effects were interpreted as caused by precipitation of inner belt particles in the South Atlantic Anomaly during magnetically disturbed periods. Several cases of E_S layer enhancements recorded since then have corroborated the results of Batista and Abdu (1977). An earlier study by Abdu and Batista (1977) on the basis of monthly average E_S-layer characteristics had indicated presence of charged particle precipitation as a regular source of nighttime E-region ionization over Cachoeira Paulista (see also Abdu et al., 1979). Specific cases of E_S-layer enhancements, therefore, indicated corresponding enhancements in the charged particle precipitation rate under conditions of magnetic disturbances. In the present paper we have undertaken to analyse data of VLF phase recordings in order to examine to what degree the particle precipitation detected at the E-region heights might extend to lower altitudes. (For further works on the subject, see Abdu et al., 1973, 1979; Gledhill, 1976.) Numerous works regarding disturbances on middle and high latitude VLF propagation paths during particle precipitation events are available in the literature (see for example Potemra and Rosenberg, 1973; Westerlund and Reder, 1973; Larson et al., 1977).

The data used in the present study are the phase recordings of the 13.6 KHz signals transmitted from Golfo Nuevo, Argentina (43^{o}S, 65^{o}W) and received at Atibaia, São Paulo, a low latitude propagation path, located within the magnetic Anomaly region, (Atibaia being located near the central region of the Anomaly). The VLF phase recordings were made with respect to a cesium frequency standard. Propagation effects during geophysical disturbances on VLF trajectories using data collected in the Anomaly region have been studied earlier by Mendes and Ananthakrishnan (1972), Ananthakrishnan and Hackradt (1972), Abdu et al. (1973) and Gough (1975). However, all these studies made use of propagation path very long compared to the Anomaly extension, and in such cases precise identification of propagation disturbances that could be attributed to the influence of the Anomaly is usually difficult, especially from observations carried out at a single site in the Anomaly region. This difficulty is nearly overcome in the present analysis since the VLF trajectory of Golfo Nuevo - Atibaia lies almost entirely within the Anomaly region.

VLF WAVE DATA

Figure 1 presents a plot of the day to day variations in VLF phase received at Atibaia for a period starting from April 29 till May 14, 1978, during which there were a few magnetic disturbances, as can be seen from the 3 hourly planetary magnetic index, Kp, also plotted in the same figure (SSC is marked with arrows). The quiet diurnal phase variation used as reference was prepared taking the average of a few quiet days (5 to 7 days) immediately preceding the period under consideration. These "quiet day" curves undergo certain variabilities during different parts (equinox, summer and winter months) of the year as can be verified by comparing the reference curves used in Figures 1 and 3. Such changes should be taking place due to seasonal variations in the mesospheric minor constituent concentrations and temperature. The standard deviation (σ) of the "quiet time" phase variation is generally larger during night hours than during days hours. For the different cases presented in this work the σ varied from 2.1 to 2.4 μs for night and from 1.0 to 1.5 μs for day. The vertical bars on the reference curves in Figure 1 and 3 correspond to 2σ.

A magnetic storm with a sudden commencement had its onset in the morning of April 30 followed by moderate increase in K_p lasting till about midnight. A second SSC occurred in the morning of May 1 which was followed by disturbances in K_p lasting for several days. The VLF phase showed only minor advances, namely, lowering of the reflecting layer, for a few hours during the night following the first SSC. However, on the night of May 1 - 2 there was a pronounced decrease in the VLF phase during which the maximum phase advance registered exceeded 10 μs. This is comparable to the maximum phase advances observed during magnetic disturbances, on midlatitude VLF propagation paths that have been interpreted as caused by energetic electron precipitation (Potemra and Rosenberg, 1973; Larsen et al., 1977). Since the day and night VLF reflection heights are usually considered to lie in the vicinity of 70 km and 90 km respectively (see the above references, also Wait and Spies, 1964; Rasmussen et al., 1980) and the phase advance, $\Delta\phi$, is nearly directly proportional to the reflection height change, Δh, (Wait, 1959), the maximum lowering of the reflection height on the night of May 1 - 2 will be ~10 km. The VLF phase advance was present on subsequent nights and continued even after the magnetic disturbance had become weak in the afternoon of May 4. Enhancement in K_p occurred again on May 8 and the VLF response to this seems to be somewhat weak except for a short lived, but significant, lowering of the reflection height occurring during istics, but to different degrees, are observed also in the early morning hours (00-04 LT) on May 6 and around 19 LT on May 12.

Ionograms showing E_S trace characteristics during some of the enhancements are presented in Figure 2 and they show range spreading echoes resembling the a-type E_S (the type of E_S usually observed over auroral latitude during particle precipitation events), as presented also in our earlier work (Batista and Abdu, 1977). The range spreading E_S traces are regularly observed over Cachoeira Paulista following magnetic disturbances of moderate intensity. We may observe in Figure 2 that the degree of range spreading is more pronounced in the nighttime ionograms of 0100 LT on May 2 and 0300 LT on May 6, 1978. Ionospheric absorption of weak scattered echoes is probably responsible for the less pronounced range spreading echoes in the day time ionogram on May 7. These characteristics have been pointed in our earlier paper also (Batista and Abdu, 1977).

Occurrence of the range spreading E_S traces in our ionograms similar to those that accompany E_S events over auroral region would suggest energetic particle precipitation as the cause of these traces. However, unlike in the auroral latitude the neutral wind shears could be largly responsible for producing the blanketing type E_S layers over low latitudes in which case the blanketing frequency of the E_S trace is usually considered to be equal to the peak plasma frequency of the E_S layer (Reddy and Mukunda Rao, 1968). Thus, the irregularities giving rise to the range spreading echoes seem to be distributed mostly in the bottom of the E_S layer, since, in the alternative hypothesis of the irregularities being located above the E_S layer, the echo range is expected to increase as the frequency gets obove the penetration frequencies in the oblique direction, a feature usually observed for equatorial type E_S (E_S-q) but very rarely observed over Cachoeira Paulista. On the other hand, from the close resemblance between the E_S traces such as the one at 0100 on May 2 with the auroral type E_S, we may be tempted to believe that perhaps the blanketing frequency is itself significantly modified by the intense scattering of the incident ratio waves by irregularities that are distributed in a height range starting from ~100 km upwards, the upper limit in the present example being ~200 km. It might be interesting to point out here that eventhough these E_S layer enhancements occur following magnetic disturbances, the local magnetograms (those of Vassouras, Rio de Janeiro) did not indicate any significant magnetic field variations in step with the variations of the E_S parameters, a fact that is evident also in Figure 3 of Batista and Abdu (1977). This last point may not, however, rule out the possibility that irregularities associated with some cases of the E_S enhancements might as well be produced by a plasma instability mechanism in the presence of enhanced E region conductivity arising from the particle precipitation events. Direct measurement of the electron density profiles during the E_S layer enhancements would be useful to further identify the nature of the range spreading E_S traces.

The time delay observed in the E_S enhancements with respect to the onset of the magnetic disturbances, seen in the present results which is in agreement also with our earlier work (Batista and Abdu, 1977), does not seem to be clearly evident in the VLF response characteristics. In Figure 3 different degrees of delays can be observed in the three cases, presented as further examples of the VLF phase response to magnetic disturbances. These varying delays in the VLF response, however, could be an apparent effect arising in large part from the day to night change in the height of the VLF reflecting layers, combined with the height dependent sensitivity to magnetic storm disturbances. Following the onset of the magnetic disturbances near 00 LT on October 3, 1977 and the subsequent SSC near the midday, the first significant VLF effect seems to have taken place from 00-04 LT on the morning of October 4. No significant effect was produced during daytime when in fact K_p was relatively high, which could be attributed to the fact that the ionization enhancement did not apparently extend to the daytime reflection level, as the phase values on the following days (October 4 and 5) also suggest. On the other hand, the magnetic disturbance on June 29, 1978 seems to have produced some effect on the daytime VLF phase following the SSC. A pronounced increase in K_p from 18-21 LT on the same day was followed by a prompt (within 1 hour) VLF response. The phase disturbances continued on the following day with smaller intensity and the disturbance in K_p had become relatively weaker. A temporary recovery and even a positive deviation in phase can be observed in the early morning of July 1. The third case presented here corresponds to a period with relatively higher degree of magnetic disturbances, and VLF phase advances were present during night as well as during day. The day time effects seem to be significant compared to the standard deviation in ϕ of ~1 μS for this case. A careful examination will show a few cases of prompt VLF phase response to specific and rapid rises in K_p values. Thus, no well-defined delay, beyond one or two hours, between magnetic disturbance index and VLF phase response is suggested from this figure (it may be pointed out that none of the daytime VLF effects presented in this figure is produced by Solar x-ray events).

A superposed epoch analysis of $\Delta\phi$ (= $\phi_{quiet} - \phi_{dist}$), corresponding to nine events selected arbitrarily, is presented in Figure 4. In part (a) of the figure the superposition is done at fixed local times, so that local time dependent effects are added in phase. The zero time was taken as 18 LT at the beginning of the night that showed the first major VLF response following a magnetic disturbance. The results presented in Figure 4 represent the mean $\Delta\phi$ variations of all the events considered in the analysis. The first curve (top one) represents four events only as during these events 15 minutes resolution was used in the data scaling, whereas in the case of the second curve that involves nine events, hourly values were used, and many of the five extra events correspond to relatively weaker magnetic disturbances. The lower two curves represent the superposition of the K_p and D_{st} values. The precedence, by approximately one day of the magnetic disturbance relative to the VLF phase perturbations, seen in the figure, seems to be an apparent effect produced, as noted before, by height dependent response; the daytime response following the SSC's that occur during the day being significantly smaller than nighttime response. We may further note in the figure that nighttime disturbance dominates the VLF phase response and the amplitudes of the disturbances seem to be more pronounced in the premidnight hours. The $\Delta\phi$ amplitude reached upto ~8 μs on the first night which is quite significant indeed compared to the σ whose maximum value was 2.4 μs. However, the maximum $\Delta\phi$ is only ~5 μs in the second example that included many weak events scaled with less time resolution. The genuineness of the VLF response is borne out also by the pronounced day to night difference in the observed $\Delta\phi$ response. Recovery of the VLF phase disturbances seems to be indicated on the 4th night. However, a renewed increase on the 5th night seems to be caused by a minor increase in the magnetic activity prior to this. A short lived recovery to levels above the quiet time values seems to be taking place every day from 07 to 09 LT. The reason for this behaviour is not clear to us.

In part (b) of the figure we have carried out the superposition taking zero time as the time of the SSC. In this case, the VLF response is spread out, obvioully, due to the local time dependence of the effect as observed before. However, the response is seen to take place soon after the onset of the magnetic disturbances, as we have observed earlier in the case of events that had storm onset in the night hours. A superposed epoch analysis of magnetic storm associated E_S layer occurrences has been presented by Batista and Abdu (1977).

DISCUSSION

The results presented here clearly demonstrate evidence of magnetic storm associated VLF phase perturbations. The magnitudes of these perturbations are quite significant, the highest values presented here being comparable to those observed on midlatitude propagation path during energetic electron precipitation events associated with magnetic disturbances (eg. Larsen et al., 1977; Potemra and Rosenberg, 1973). On the other hand, magnetic storm associated sporadic E-layer enhancement is a well-established phenomenon as our previous study has shown (Batista and Abdu, 1977) over this general region of the VLF observations. Simultaneous occurrences of the VLF phase perturbations and E_S layer enhancements as seen in the present work, therefore, defines a certain height range in which the storm associated ionization enhancements should be taking place. This height range may be considered to lie between approximately 70 km (the day time VLF reflection height), during more disturbed period, and 100-110 km, the heights of the E_s layers, Our results are not sensitive to changes outside this region. However, association of these ionization enhancements with magnetic disturbances suggests energetic particles as their source.

For possible explanation of these effects we may first look into magnetic storm associated sources that are believed to be operative over the latitude regions pertinent to these observations. Theoretical as well as experimental studies (Dessler et al., 1961; Mezera and Blake, 1973; Scholar et al., 1975; Tinley, 1976; Lyons and Richmond, 1978) have suggested energetic neutral particles resulting from charge exchange chemistry of outer radiation belt as a source of ionization over low latitude. The flux of these particles maximises during the storm main phase. Their precipitation effects have been estimated to be most significant above 170 km near the equator and between 120 and 180 km over latitudes 20^0 to 30^0, with the altitude of peak energy absorption decreasing from 230 km over the equator to 130 km and 125 at latitudes 20^0 and 30^0 respectively. It seems unlikely, however, that the ionization enhancements, detected from VLF and E_s layer observations, could be produced by the ring current particle precipitation for the following reasons: (1) the height region of ionization enhancement observed by us is well below that estimated for the ionization of energetic neutral particles, (2) the ring current particle precipitation effect is more intense during the main phase of a storm whereas significant VLF perturbations continue well into the recovery phase and E_s layer enhancements are observed more often during the late recovery period than during the main phase of the storm and (3) ionization enhancements of the type reported in this work has not been reported for low latitude station over other longitudes. Our examination of the limited ionogram data (evailable to us) over Ahmedabad, a low latitude station in India, did not show any E_s layer enhancement following the magnetic disturbance that occurred in the second week of January 1978 when significant enhancement in the a-type E_s layer took place over Cachoeira Paulista. (More such comparisons possibly with data from other low latitude stations as well may also be useful, but it is beyond the scope of the present work).

The possibility of these effects being interpreted by magnetic storm induced changes in the upper atmosphere dynamics seems also very unlikely, since such disturbances are known to originate over auroral latitudes and the times of their propagation to low latitudes can not explain either the prompt VLF response to magnetic storm or the delayed E_S enhancements often observed upto 3 days (Batista and Abdu, 1977) after the storm onset.

We may, therefore, conclude that the magnetic storm associated lower ionosphere enhancements presented here must be arising from sources peculiar to the South Atlantic Magnetic Anomaly region within which the entire VLF trajectory was confined. Evidence for the presence of particle ionization in this region was suggested also, in our earlier work, on E_S layer enhancements following magnetic disturbances, and one of the characteristics of the E_S layer that suggested particle ionization as its source was the occurrence of range spreading echoes resembling that of the a-type E_S-layer usually observed over auroral latitudes under disturbed conditions. The association among magnetic activity, particle precipitation and a-type E_S over auroral latitude is well known (see for example, Reddy et al., 1969). The independent evidence that the VLF results provide in the present work would therefore, suggest that the occurrence of range spreading E_S traces in the ionograms over Cachoeira Paulista may possibly be considered as a reliable indicator of the presence of charged particle precipitation in the South Atlantic Magnetic Anomaly.

The VLF results presented here, in particular, the Figure 4(a) on the superposed epoch analysis, might appear to suggest that the magnetic storm associated particle precipitation occurs mainly during night with little effect during daytime. However, this does not seem to be the case. Our results merely suggests that, in an average case, ϕ disturbance gets more pronounced at the higher nighttime VLF reflection level, near 90 km, than at the lower daytime reflection level, near 70 km. In fact, significant daytime phase disturbances do take place when the magnetic disturbance is sufficiently strong as the third example in Figure 3 illustrates. Perhaps, stronger magnetic disturbances are necessary to cause energetic electron precipitation of harder energy spectra. We may point out further that a larger height change near 90 km than near 70 km does not necessarily imply a correspondingly stronger precipitating flux at the higher level as the following consideration would show. If, as an example, we consider exponential electron density distribution at the VLF reflection heights, then a height change, Δh, (which is proportional to the observed phase advance, $\Delta\phi$), could be written as $\Delta h = (\Delta N/N)\ H$, where N is the electron density and H is the scale height of its distribution. Examination of published measurements of daytime and nighttime lower ionosphere electron density profiles (see for example, Sagalyn and Smiddy, 1963; Prakash et al., 1974; Geller et al., 1975) shows that the ambient electron density near 90 km at night could be at times even less than the daytime values near 70 km due to the absense of direct solar UV radiation at night. Thus, a given increase in electron density, ΔN, at the two height regions could produce larger Δh for nighttime cases, which can only be offset by differences in the scale heights of the electron density distributions at the two heights. However, for the same ΔN the required ion production rate would be significantly higher at lower heights due to the well-known decrease with height in the effective recombination coefficient (or cluster ion concentrations) at these heights (see for example, Reid, 1970). Therefore, under certain circumstances even minor daytime phase perturbations might be as important as larger scale nighttime fluctuations from the view point of an ion production source. These considerations would lead us to conclude that during at least some of the events presented in this analysis particle precipitation might have occurred in the entire region of 90 to 70 km to explain the VLF results.

We have seen that the VLF phase disturbances take place almost immediately after the onset of the magnetic disturbances, especially when the later occurs at night. This contrasts with the well-known "storm after effect" of the mid latitude D-region during which several days of delay are observed between the particle precipitation effect in the D-region and the magnetic storms (Belrose and Thomas, 1968; Lauter and Taubenheim, 1970; Beynon and Williams, 1974; Spjeldvik and Thorne, 1975). The VLF phase disturbances in the examples presented here continued well after the magnetic disturbances subsided, a characteristic that was observed also in the case of the magnetic storm associated E_s enhancements (Batista and Abdu, 1977). In contrast to the VLF disturbances, the onset of the E_s enhancements, however, were, in most cases, considerably delayed (from < 1 to 3 days) with respect to the magnetic disturbance onset. Such delays show that the presence of particle ionization, though necessary, is not a sufficient condition for the occurrence of these E_s layers. Simultaneous presence of the additional prerequisites would be (a) sufficient concentration of metal atoms (M) to be available for conversion to metal ions, (M^+), the constituent ions of most of the sporadic E layers, through charge transfer reaction of the type $M + X^+ \rightarrow M^+ + X$, where X^+ is the ambient molecular ions, O_2^+ and NO^+, produced by the precipitating particles (Narcisi, 1968, see also the discussion by Batista and Abdu 1977), (b) wind shears of sufficient magnitude in case the E_s layers are of blanketing type and (c) conditions that produce irregularities or patchy ionizations, that give rise to range spreading echoes of the a-type E_s; perhaps, an E x B instability mechanism working at the bottomside gradient of an E_s layer, or that of a patchy layer, in the presence of appropriate electric fields (Reid, 1968). The possibility that the spatial structures and irregularities might be inherent in the precipitating electron energy and flux distribution can not also be ruled out. Thus, it is clear that while the appearence of the E_s layers, of the type and under the circumstances presented here, could be taken as positive evidence for the presence of charged particle precipitation, their non occurrence is not a sufficient evidence for the absence of particle induced ionization. From the above argument it follows that day to day variabilities in the occurrence or in the intensity of any one of the above factors could cause delay in the onset of the magnetic storm associated E_s enhancements even if particle produced ionization was present immediately following the magnetic disturbances which indeed seems to be the case as the VLF results indicate.

We may point out further that enhancements of blanketing type E_s layers constituted of molecular ions must be very rare since wind velocities of abnormally large magnitude are needed to produce layering of these ions due to their relatively faster recombination rate compared to that of the metallic ions (see Abdu and Batista 1977). If molecular ion E_s layers do get enhanced due to magnetic disturbance associated particle precipitation then they should also be observed immediately following the disturbance onset concurrent with the VLF effects. Since our observations show that the E_s layer enhancements occur with variable time delay with respect to the magnetic disturbance onset we may conclude that these enhancements could be in the metallic ion E_s layers (since winds of moderate intensity could produce them) so that the variable delays could be caused by possible variabilities in the magnitudes of the parameters that are the essential prerequisites for the E_s formation (namely, a, b and c) mentioned above. For example results of regular Laser Radar measurements of mesospheric sodium, over São José dos Campos, have shown significant day to day variability in the sodium abundance (Simonich et al., 1979), which might suggest a similar variability in other metallic species as well. Information on possible day to day variability of the E-region winds is completely lacking for this region. It would be of great interest to know also about possible magnetic storm influence on these parameters.

CONCLUSIONS

VLF propagation in a trajectory situated almost completely in the South Atlantic Magnetic Anomaly region undergoes significant perturbations in association with magnetic disturbances. These disturbances are characterized by advancements in the phase of the received signal indicative of lowering of the VLF reflecting layer. The phase perturbations are seen more pronounced when the VLF reflection takes place at higher levels (~90 km) at night than when it is from the lower daytime reflection height. Qualitative considerations on the ambient electron densities at the day and night reflection levels and the lower ionosphere recombination process would suggest that the sources of enhanced ion production, which we attribute to precipitation of high energy particles, could be important in the height region of 90 km extending downward during strong events up to 70 km. Considerations on the enhanced E_s occurrences would extend the upper height limit to at least 110 km, the height of some of the observed E_s layers. The enhanced precipitation seems to be occurring immediately following the onset of the magnetic disturbance and continues, in general, well after the recovery of the magnetic disturbances as represented by K_p. The characteristics of sporadic E-layer enhancements, in the example presented here and in a previous study, are similar to that of the VLF effects, except, that the onset of the E_s enhancements were generally delayed by ~ 1 to 3 days with respect to the onset of the magnetic disturbance. Such delay might, perhaps, be caused by day to day variabilities in the metallic species, and/or in the dynamics, of the E-region.

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FIGURE CAPTIONS

Fig. 1 - Day to day variations (solid curve) in VLF phase, ϕ, of 13.6 KHz transmission from Golfo Nuevo, Argentina and received at Atibaia, Brazil, plotted for a period starting from April 29 to May 14, 1978 together with a quiet day reference curve (broken curve). Also plotted in this figure are f_tE_S (broken curve) and f_bE_S (solid curve) over Cachoeira Paulista and the three hourly planetary magnetic index K_p (as histograms). The right hand scale is used for K_p, while on the left hand scale the upper portion in each frame refers to the VLF phase and the lower portion for the frequencies, f_bE_S and f_tE_S.

Fig. 2 - Examples of ionograms showing the E_S traces during some of the enhancements associated with magnetic disturbances (see text for details).

Fig. 3 - Examples of VLF phase response to magnetic disturbances (K_p) plotted for three cases to show variable apparent delay between the onset of the magnetic disturbance and the VLF phase changes. Note that the first example represents hourly reduced phase values whereas the time resolution is 15 minutes in the other examples. Presence of small peaks of post sunset and presunrise enhancements in ϕ during June and July, and their absence in October, in the reference curves as well as in the disturbance curves, are genuine features.

Fig. 4 - A superposed epoch analysis of 9 events of magnetic disturbances and associated VLF phase variations. In part (a) of the figure the superposition is carried out so as to add up local time dependent effect taking 18 LT immediately prior to the first major VLF response during an event as zero reference time. In part (b) of the figure the superposition is done taking the zero time as the time of SSC. (For further details see the text).

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83 Phase recordings at Atibaia, Brazil 23 degree S, 46 degree W), of 13.6 -kHz signal transmitted from Golfo Nuevo, Argentina (43 degree S, 65 degree W), a trajectory confined almost completely within the South Atlantic anomaly region, show significant perturbations, indicative of the lowering of the VLF reflection level, following the onset of magnetic disturbances. Simultaneous measurements of the Es layer parameters ftEs and fbEs over Cachoeira Paulista (22 degree S, 45 degree W) also show enhancements, with some delay with respect to the magnetic disturbance onset, as was found in our earlier work (Batista and Abdu, 1977). These results show magnetic storm associated ionization enhancements taking place in a height region from approximately 110 km down to 70 km, which we interpret as having been produced by precipitation of high-energy charged particles in the South Atlantic magnetic anomaly. The results also suggest some degree of day to day variability in e abundance of metallic species and/or in the dynamics of the E region over this region.
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MAGNETIC STORM ASSOCIATED ENHANCED PARTICLE PRECIPITATION IN THE SOUTH ATLANTIC ANOMALY: EVIDENCE FROM VLF PHASE MEASUREMENTS

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Abstract. Phase recordings at Atibaia, Brazil 23°S, 46°W), of 13.6 -kHz signal transmitted rom Golfo Nuevo, Argentina (43°S, 65°W), a rajectory confined almost completely within the outh Atlantic anomaly region, show significant erturbations, indicative of the lowering of the LF reflection level, following the onset of agnetic disturbances. Simultaneous measurements f the E_s layer parameters f_tE_s and f_bE_s over achoeira Paulista (22°S, 45°W) also show nhancements, with some delay with respect to the agnetic disturbance onset, as was found in our arlier work (Batista and Abdu, 1977). These esults show magnetic storm associated ionization nhancements taking place in a height region from pproximately 110 km down to 70 km, which we nterpret as having been produced by precipitation f high-energy charged particles in the South tlantic magnetic anomaly. The results also uggest some degree of day to day variability in he abundance of metallic species and/or in the ynamics of the E region over this region.

Introduction

The South Atlantic magnetic anomaly region, haracterized by a global minimum in the earth's otal magnetic field intensity, provides a ermanent sink for the inner belt quasi-trapped articles that, during their longitudinal drift, ip down to low levels in the atmosphere over the nomaly region. Numerous satellite measurements f the particle concentration and their spectra ave been carried out in the past [Ginzberg et l., 1962; Imhof and Smith, 1965; Vernov et al., 967; Seward et al., 1973]. Further haracteristics of the South Atlantic anomaly, he predicted and observed zones of particle recipitation and the dependence of particle recipitation on magnetic activity, can be btained from the papers by Paulikas [1975], orr et al. [1975], Gledhill [1976], and Voss and mith [1980].

In a recent paper, Batista and Abdu [1977] nalyzed sporadic E layer behavior during agnetically disturbed periods over Cachoeira aulista, located very near the center of the outh Atlantic (also known as Brazilian) eomagnetic anomaly. It was observed that ignificant enhancements in the E_s layer arameters, f_tE_s and f_bE_s took place for short urations (1-3 hours) within 1-3 days, following he onset of a magnetic disturbance of moderate ntensity. During some events the enhancements in he night E region ambient eletron densities were comparable to regular daytime maximum values produced by solar radiation. Further, the E_s traces were accompanied by range spreading echoes resembling the a-type E_s usually observed over auroral latitudes under disturbed conditions. These effects were interpreted as being caused by precipitation of inner belt particle in the South Atlantic anomaly during magnetically disturbed periods. Several cases of E_s layer enhancements recorded since then have corroborated the results of Batista and Abdu [1977]. An earlier study by Abdu and Batista [1977] on the basis of monthly average E_s layer characteristics had indicated the presence of charged particle precipitation as a regular source of nighttime E region ionization over Cachoeira Paulista (see also Abdu et al. [1979]). Specific cases of E_s layer enhancements therefore indicated corresponding enhancements in the charged particle precipitation rate under conditions of magnetic disturbances. In the present paper we have undertaken to analyze data of VLF phase recordings in order to examine to what degree the particle precipitation detected at the E region heights might extend to lower altitudes. (For further works on the subject, see Abdu et al. [1973, 1979] and Gledhill [1976]). Numerous works regarding disturbances on middle- and high-latitude VLF propagation paths during particle precipitation events are available in the literature (see for example Potemra and Rosenberg [1973], Westerlund and Reder [1973] and Larson et al. [1977]).

The data used in the present study are the phase recordings of the 13.6 -kHz signals transmitted from Golfo Nuevo, Argentina (43°S, 65°W), and received at Atibaia, São Paulo, a low-latitude propagation path located within the magnetic anomaly region (Atibaia being located near the central region of the anomaly). The VLF phase recordings were made with respect to a cesium frequency standard. Propagation effects during geophysical disturbances on VLF trajectories using data collected in the anomaly region have been studied earlier by Mendes and Ananthakrishnan [1972], Ananthakrishnan and Hackradt [1972], Abdu et al. [1973], and Gough [1975]. However, all these studies made use of propagation paths very long compared to the anomaly extension, and in such cases, precise identification of propagation disturbances that could be attributed to the influence of the anomaly is usually difficult, especially from observations carried out at a single site in the anomaly region. This difficulty is nearly overcome in the present analysis, since the VLF trajectory of Golfo Nuevo-Atibaia lies almost entirely within the anomaly region.

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VLF Wave Data

Fig 1 presents a plot of the day to day variations in VLF phase received at Atibaia for the period from April 29 to May 14, 1978, during which there were a few magnetic disturbances, as can be seen from the 3 hourly planetary magnetic index kp, also plotted in the same figure (ssc is marked with arrows). The quiet diurnal phase variation used as reference was prepared by taking the average of a few quiet days (5-7 days) immediately preceding the period under consideration. These 'quiet day' curves undergo certain variabilities during different parts (equinox, summer and winter months) of the year as can be verified by comparing the reference curves used in Figure 1 and 3. Such changes should be taking place due to seasonal variations

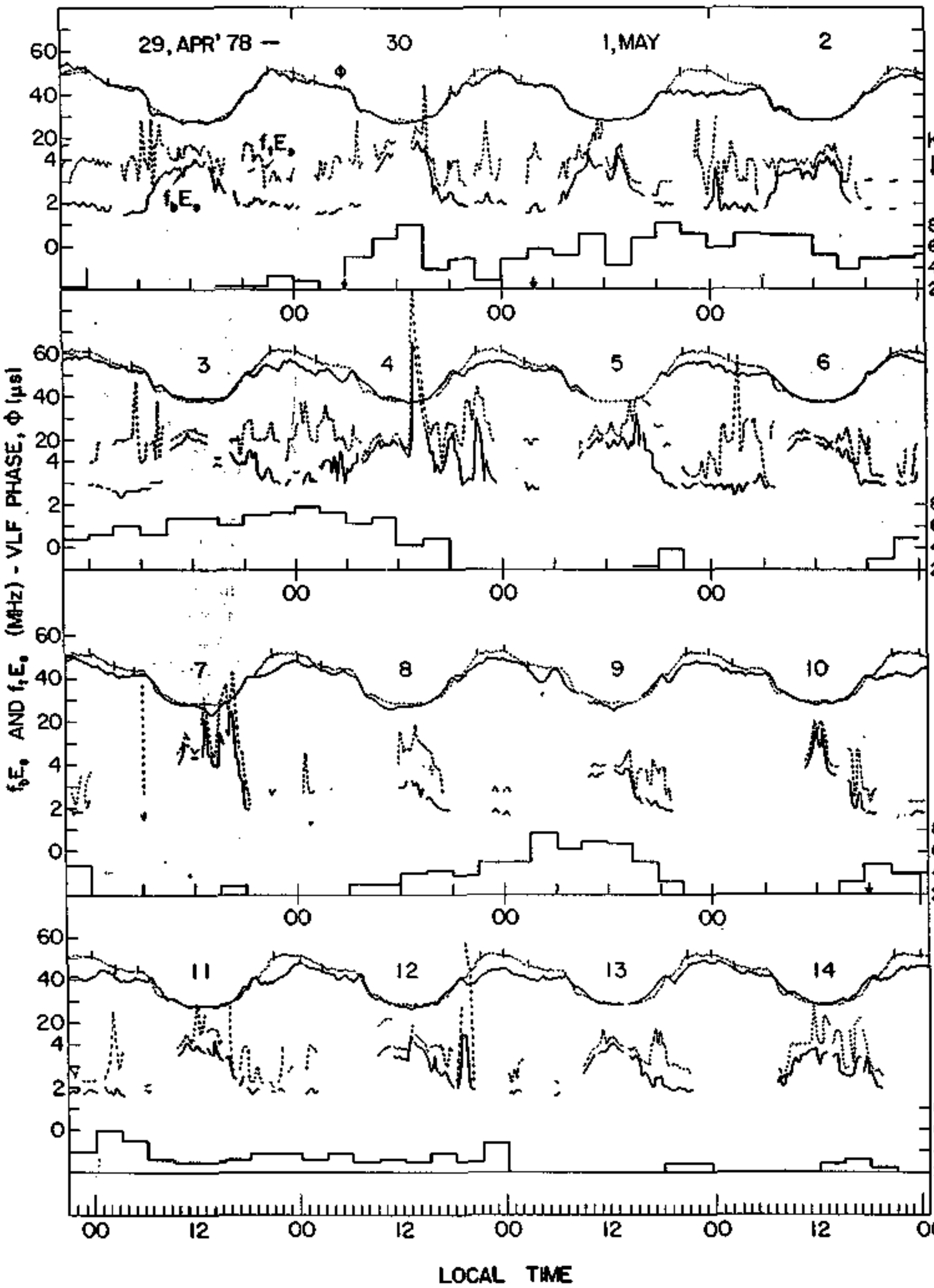

Fig. 1. Day to day variations (solid curve) in VLF phase ϕ of 13.6 -kHz omega transmission from Golfo Nuevo, Argentina, and received at Atibaia, Brazil, plotted for a period from April 29 to May 14, 1978, together with a quiet day reference curve (dashed curve). Also plotted in this figure are f_tE_s (dashed curve) and f_bE_s (solid curve) over Cachoeira Paulistá and the 3 hourly planetary magnetic index Kp (as histograms). The right-hand scale is used for Kp, while on the left-hand scale the upper portion in each frame refers to the VLF phase and the lower portion to the frequencies, f_bE_s and f_tE_s.

the mesospheric minor constituent ncentrations and temperature. The standard viation σ of the 'quiet time' phase variation is nerally larger during night hours than during y hours. For the different cases presented in is work the σ varied from 2.1 to 2.4 μs for ght and from 1.0 to 1.5 μs for day. The rtical bars on the reference curves in Figure 1 d 3 correspond to 2σ.

A magnetic storm with a sudden commencement d its onset in the morning of April 30, llowed by moderate increase in Kp lasting until out midnight. A second ssc occurred in the rning of May 1 which was followed by sturbances in Kp lasting for several days. The F phase showed only minor advances, namely, wering of the reflecting layer, for a few hours ring the night following the first ssc. However, the night of May 1-2 there was a pronounced crease in the VLF phase during which the ximum phase advance registered exceeded 10 μs. is is comparable to the maximum phase advances served during magnetic disturbances, on mid-titude VLF propagation paths that have been terpreted as being caused by energetic ectron precipitation [Potemra and Rosenberg, 73; Larsen et al., 1977]. Since the day and ght VLF reflection heights are usually nsidered to lie in the vicinity of 70 km and km, respectively (see the above referencees d also Wait and Spies [1964] and Rasmussen et . [1980]), and the phase advance Δϕ is nearly rectly proportional to the reflection height ange Δh [Wait, 1959], the maximum lowering of e reflection height on the night of May 1-2 will ~10 km. The VLF phase advance was present on bsequent nights and continued even after the gnetic disturbances had become weak in the ternoon of May 4. Enhancement in Kp occurred ain on May 8, and the VLF response to this ems to be somewhat weak except for a short-ived, but significant, lowering of the eflection height occurring during 0300-0600 LT May 9 simultaneously with an increase in Kp up 8-. In the evening of May 10 an ssc occurred, d VLF response was promptly observed as a ignificant lowering of the reflection height sting throughout the night. The phase isturbance continued on subsequent nights until y 13. Renewed increase in the phase disturbance the night of May 14 could perhaps be related to e small increase in kp registered in the ternoon of the same day.

As important aspect to be noted in these esults is that the VLF phase response is observed ily during the nighttime hours, even though agnetic disturbances were present without eference for day or night. Thus the effect seems be confined, in the examples cited above, to he ionospheric region near the nighttime VLF eflection level (the phase anomaly seen around 400 LT on May 7 and around 1200 LT on May 9 were roduced by solar X ray flares). We will come ack to this point later.

Also plotted in Figure 1 are f_bE_s, the lanketing frequency of the E_s layer, and f_tE_s, he top frequency reflected by the E_s, over achoeira Paulista (22°S, 45°W) (situated very ear Atibaia) obtained simultaneously with the LF observations. Enhancements in f_bE_s and f_tE_s or short durations are observed in association with the magnetic disturbances, in agreement with our earlier results [Batista and Abdu, 1977]. In particular, significant Es enhancements occurred near 2200 LT on April 30, 0000 LT on May 2, almost the entire night of May 3-4, 1800-2400 LT on May 4, during the postmidnight period of May 5-6, and near 1900 LT on May 12, almost simultaneously with the VLF phase perturbations (daytime enhancements are not usually considered unless they are extraordinarily large, as happened in the case of the Es enhancement in the afternoon of May 4). In some of these examples, enhancements are observed only in f_tE_s. Quasi-periodic variations in f_tE_s, roughly in step with oscillations in VLF phase, may in particular, be noted on the night of May 3-4. Considering the horizontal ionosphere separation between the VLF reflection region and that sampled by the ionosonde, the oscillations in the two parameters seem to be very significant. Similar characteristics, but to different degrees, are observed also in the early morning hours (0000-0400 LT) on May 6 and around 1900 LT on May 12.

Ionograms showing E_s trace characteristics during some of the enhancements are presented in Fig 2, and they show range spreading echoes resembling the a-type E_s (the type of E_s usually observed over auroral latitude during particle precipitation events), as presented also in our earlier work [Batista and Abdu, 1977]. The range spreading E_s traces are regularly observed over Cachoeira Paulista following magnetic disturbances of moderate intensity. We may observe in Figure 2 that the degree of range spreading is more pronounced in the nighttime ionograms of 0100 LT on May 2 and 0300 LT on May 6, 1978. Ionospheric absorption of weak scattered echoes is probably responsible for the less pronounced range spreading echoes in the daytime ionogram on May 7. These characteristics have been pointed out in our earlier paper also [Batista and Abdu, 1977].

Occurrence of the range spreading E_s traces in our ionograms similar to those that accompnay E_s events over auroral region would suggest energetic particle precipitation as the cause of these traces. However, unlike the case in the auroral latitude, the neutral wind shears could be largly responsible for producing the blanketing-type E_s layers over lower latitudes, in which case the blanketing frequency of the E_s traces is usually considered to be equal to the peak plasma frequency of the E_s layer [Reddy and Mukunda Rao, 1968]. Thus the irregularities giving rise to the range spreading echoes seem to be distributed mostly in the bottom of the E_s layer, since in the alternative hypothesis of the irregularities being located above the E_s layer, the echo range is expected to increase as the frequency gets above the penetration frequencies in the oblique direction, a feature usually observed for equatorial type $E_s(E_{sq})$ but very rarely observed over Cachoeira Paulista. On the other hand, from the close resemblance between the E_s traces, such as the one at 0100 on May 2 with the auroral type E_s, we may be tempted to believe that perhaps the blanketing frequency is itself significantly modified by the intense scattering of the incident ratio waves by irregularities that are distributed in a height range starting from ~ 100 km upward, the upper limit in the present example being

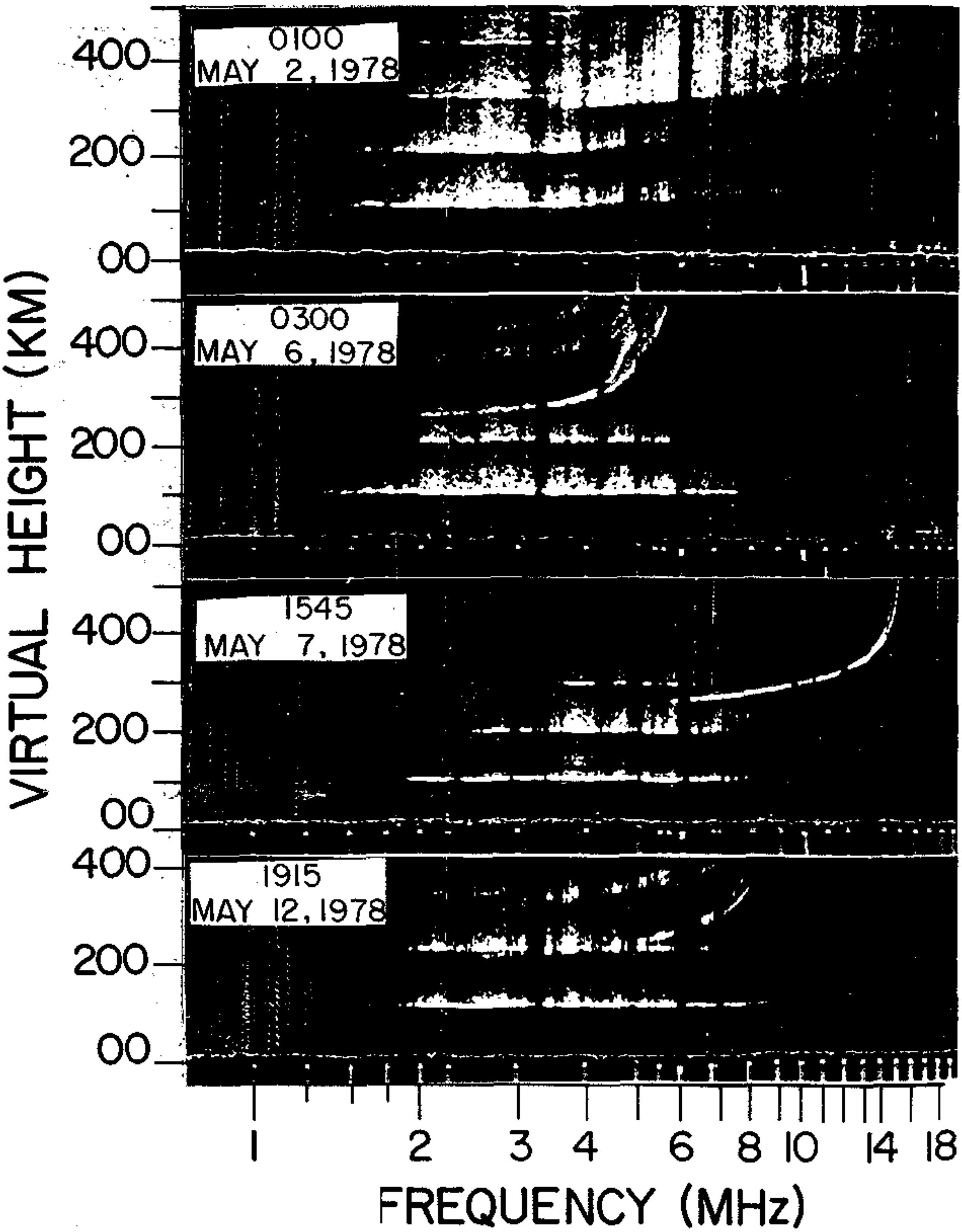

Fig. 2. Examples of ionograms showing the E_s traces during some of the enhancements associated with magnetic disturbances (see text for details).

~ 200 km. It might be interesting to point out here that even though these E_s layer enhancements occur following magnetic disturbances, the local magnetograms (those of Vassouras, Rio de Janeiro) did not indicate any significant magnetic field variations in step with the variations of the Es parameters, a fact that is evident also in Figure 3 of Batista and Abdu [1977]. This last point may not, however, rule out the possibility that irregularities associated with some cases of the E_s enhancements might also be produced by a plasma instability mechanism in the presence of enhanced E region conductivity arising from the particle precipitation events. Direct measurement of the electron density profiles during the E_s layer enhancements would be useful to further identify the nature of the range spreading E_s traces.

The time delay observed in the E_s enhancements with respect to the onset of the magnetic disturbances, seen in the present results, which is in agreement also with our earlier work [Batista and Abdu, 1977], does not seem to be clearly evident in the VLF response characteristics. In Fig 3, different degrees of delays can be observed in the three cases, presented as further examples of the VLF phase response to magnetic disturbances. These varying delays in the VLF response, however, could be an apparent effect arising in large part from the day to night change in the height of the VLF reflecting layers, combined with the height dependent sensitivity to magnetic storm disturbances. Following the onset of the magnetic disturbances near 0000 LT on October 3, 1977, and the subsequent ssc near midday, the first significant VLF effect seems to have taken place from 0000 to 0400 LT on the morning of October 4. No significant effect was produced during daytime when in fact kp was relatively high, which could be attributed to the fact that the ionization enhancement did not apparently extend to the daytime reflection level, as the phase values on the following days (October 4 and 5) also suggest. On the other hand, the magnetic disturbance on June 29, 1978, seems to have produced some effect on the daytime VLF phase following the ssc. A pronounced increase in Kp from 1800 to 2100 LT on the same day was followed by a prompt (within 1 hour) VLF response. The phase disturbances continued on the following day with smaller intensity, and the disturbance in Kp had become relatively weaker. A temporary recovery and even a positive deviation in phase can be observed in the early morning of July 1. The third case presented here corresponds to a period with a relatively higher degree of magnetic disturbances, and VLF phase advances were present during night as well as during day. The daytime effects seem to be significant compared to the standard deviation in ϕ of ~1 μs for this case. A careful examination will show a few cases of prompt VLF phase response to specific and rapid rises in Kp values. Thus no well defined delay, beyond 1 or 2 hours, between magnetic disturbance index and VLF phase response is suggested from this figure (it may be pointed out that none of the daytime VLF effects presented in this figure are produced by solar X ray events).

A superposed epoch analysis of $\Delta\phi$ ($=\phi_{quiet}-\phi_{dist}$), corresponding to nine events selected

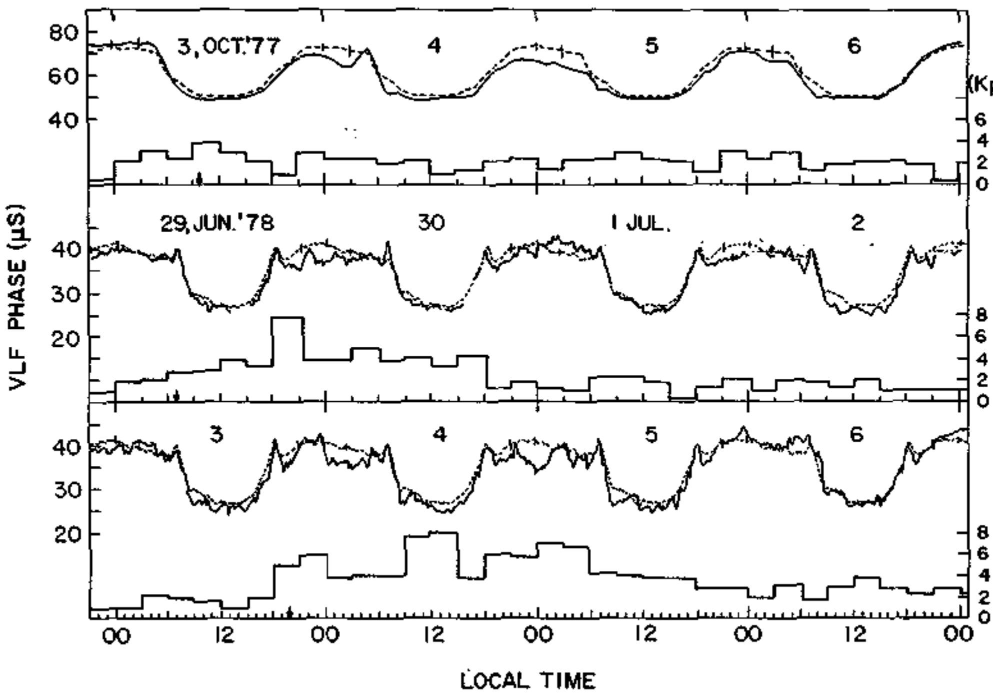

Fig. 3. Examples of VLF phase response to magnetic disturbances Kp plotted for three cases to show variable apparent delay between the onset of the magnetic disturbance and the VLF phase changes. Note that the first example represents hourly reduced phase value, whereas the time resolution is 15 min in the other examples. The presence of small peaks of postsunset and presunrise enhancements in ϕ during June and July, and their absence in October, in the reference curves as well as in the disturbance curves, are genuine features.

arbitrarily, is presented in Fig 4. In the top panel of the figure the superposition is done at fixed local times, so that local time dependent effects are added in phase. The zero time was taken as 1800 LT at the beginning of the night that showed the first major VLF response following a magnetic disturbance. The results presented in Figure 4 represent the mean Δϕ variations of all the events considered in the analysis. The first (top) curve represents four events only, as during these events, 15- min resolution was used in the data scaling, whereas in the case of the second curve that involves nine events, hourly values were used, and many of the five extra events correspond to relatively weaker magnetic disturbances. The lower two curves represent the superposition of the kp and Dst values. The precedence, by approximately 1 day, of the magnetic disturbance relative to the VLF phase perturbations, seen in the figure, seems to be an apparent effect produced, as noted before, by height dependent response, the daytime response following the ssc's that occur during the day being significantly smaller than nighttime response. We may further note in the figure that nighttime disturbance seem to be more pronounced in the premidnight hours. The Δϕ amplitude reached ~8 μs on the first night, which is quite significant indeed compared to the σ whose maximum value was 2.4 μs. However, the maximum Δϕ is only ~5 μs in the second example that inclued many weak events scaled with less time resolution. The genuineness of the VLF response is borne out also by the pronounced day to night difference in the observed Δϕ response. Recovery of the VLF phase disturbances seems to be indicated on the fourth night. However, a renewed increase on the fifth night seems to be caused by a minor increase in the magnetic activity prior to this. A short-lived recovery to levels above the quiet time values seems to be taking place every day from 0700 to 0900 LT. The reason for this behavior is not clear to us.

In the bottom panel of Figure 4, we have carried out the superposition taking zero time as the time of the ssc. In this case, the VLF response is spread out, obviously, due to the local time dependence of the effect as observed before. However, the response is seen to take place soon after the onset of the magnetic disturbances, as we have observed earlier in the case of events that had storm onset in the night

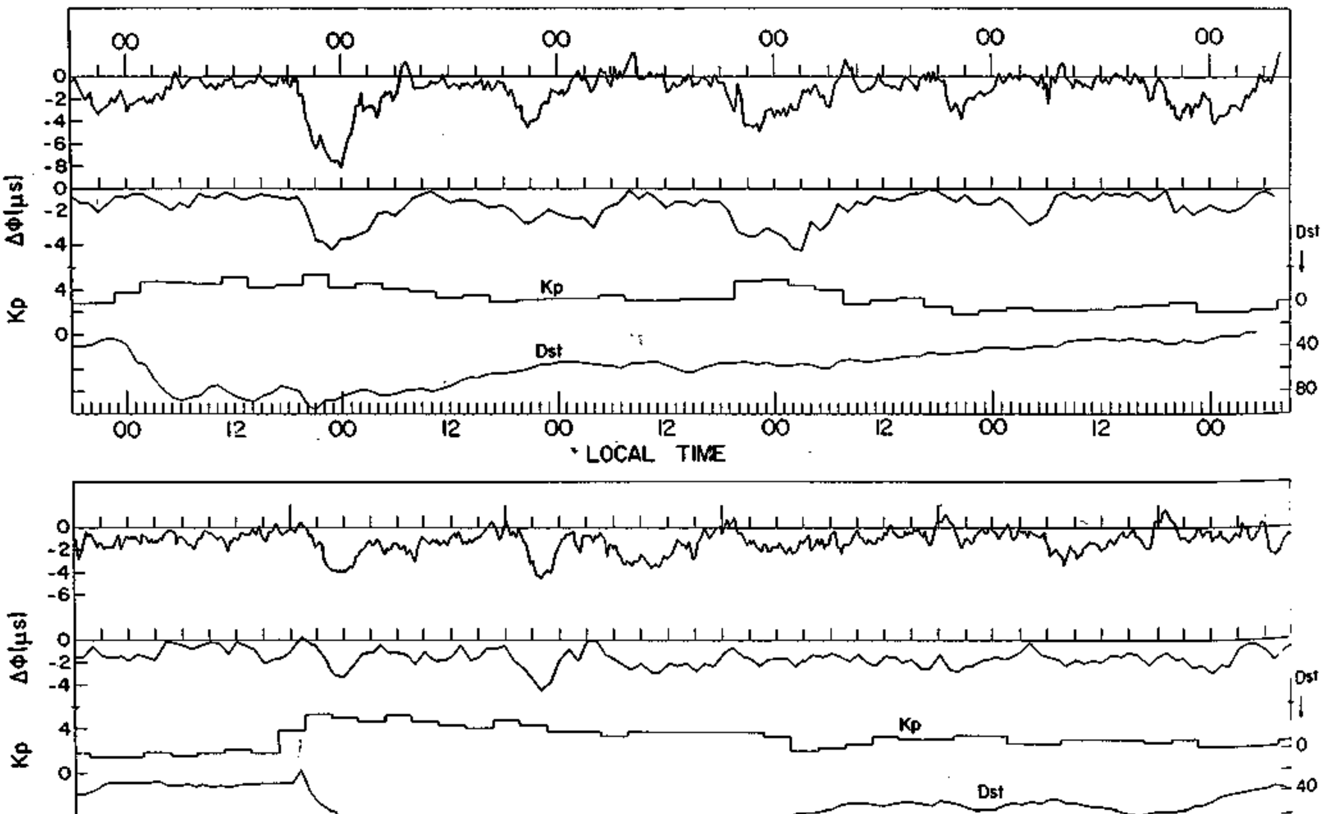

Fig. 4. A superposed epoch analysis of nine events of magnetic disturbances and associated VLF phase variations. In the top panel the superposition is carried out so as to add up local time dependent effects taking 1800 LT immediately prior to the first major VLF response during an event as zero reference time. In the bottom panel the superposition is done by taking the zero time as the time of ssc. (For further details see the text.)

hours. A superposed epoch analysis of magnetic storm associated E_s layer occurrences has been presented by Batista and Abdu [1977].

Discussion

The results presented here clearly demonstrate evidence of magnetic storm associated VLF phase perturbations. The magnitudes of these perturbations are quite significant, the highest values presented here being comparable to those observed on a mid-latitude propagation path during energetic electron precipitation events associated with magnetic disturbances [e.g., Larsen et al., 1977; Potemra and Rosenberg, 1973]. On the other hand, magnetic storm associated sporadic E layer enhancement is a well-established phenomenon, as our previous study has shown [Batista and Abdu, 1977], over this general region of the VLF observations. Simultaneous occurrence of the VLF phase perturbations and E_s layer enhancements as seen in the present work therefore define a certain height range in which the storm associated ionization enhancements should be taking place. This height range may be considered to lie between approximately 70 km (the daytime VLF reflection height), during more disturbed periods, and 100-110 km, the heights of the E_s layers. Our results are not sensitive to changes outside this region. However, association of these ionization enhancements with magnetic disturbances suggests energetic particles as their source.

For possible explanation of these effects we may first look into magnetic storm associated sources that are believed to be operative over the latitude regions pertinent to these observations. Theoretical as well as experimental studies [Dessler et al., 1961; Mizera and Blake, 1973; Scholar et al., 1975; Tinsley, 1976; Lyons and Richmond, 1978] have suggested energetic neutral particles resulting from charge exchange chemistry of the outer radiation belt as a source of ionization over low latitude. The flux of these particles maximizes during the storm main phase. Their precipitation effects have been estimated to be most significant above 170 km near the equator and between 120 and 180 km over latitudes 20^o-30^o, with the altitude of peak energy absorption decreasing from 230 km over the equator to 130 and 125 km at latitudes 20^o and 30^o, respectively. It seems unlikely, however, that the ionization enhancements, detected from VLF and E_s layer observations, could be produced by the ring current particle precipitation for the following reasons: (1) the height region of ionization enhancement observed by us is well below that estimated for the ionization of energetic neutral particles, (2) the ring current particle precipitation effect is more intense during the main phase of a storm, whereas significant VLF perturbations continue well into the recovery phase and Es layer enhancements are observed more often during the late recovery period than during the main phase of the storm, and (3) ionization enhancements of the type reported in this work have not been reported for low-latitude stations at other longitudes. Our examination of the limited ionogram data (available to us) over Ahmedabad, a low-latitude station in India, did not show any E_s layer enhancement following the magnetic disturbance that occurred in the second week of January 1978, when significant enhancement in the a-type E_s layer took place over Cachoeira Paulista. (More such comparisons, possibly with data from other low-latitude stations as well, may also be useful, but it is beyond the scope of the present work).

The possibility of these effects being interpreted as magnetic storm induced changes in the upper atmosphere dynamics seems also very unlikely, since such disturbances are known to originate over auroral latitudes and the times of their propagation to low latitudes cannot explain either the prompt VLF response to magnetic storm or the delayed E_s enhancements often observed up to 3 days [Batista and Abdu, 1977] after the storm onset.

We may therefore conclude that the magnetic storm associated lower ionosphere enhancements presented here must be arising from sources peculiar to the South Atlantic magnetic anomaly region, within which the entire VLF trajectory was confined. Evidence for the presence of particle ionization in this region was suggested also, in our earlier work, on E_s layer enhancements following magnetic disturbances, and one of the characteristics of the E_s layer that suggested particle ionization as its source was the occurrence of range spreading echoes resembling those of the a-type E_s layer usually observed over auroral latitudes under disturbed conditions. The association among magnetic activity, particle precipitation, and a-type E_s over auroral latitude is well known (see, for example, Reddy et al. [1969]. The independent evidence that the VLF results provide in the present work would therefore suggest that the occurrence of range spreading E_s traces in the ionograms over Cachoeira Paulista may possibly be considered as a reliable indicator of the presence of charged particle precipitation in the South Atlantic magnetic anomaly.

The VLF results presented here, in particular the superposed epoch analysis in the top panel of Figure 4, might appear to suggest that the magnetic storm associated particle precipitation occurs mainly during night with little effect during daytime. However, this does not seem to be the case. Our results merely suggest that in an average case, ϕ disturbance gets more pronounced at the higher night-time VLF reflection level, near 90 km, than at the lower daytime reflection level, near 70 km. In fact, significant daytime phase disturbance do take place when the magnetic disturbance is sufficiently strong, as the third example in Figure 3 illustrates. Perhaps stronger magnetic disturbances are necessary to cause energetic electron precipitation of harder energy spectra. We may point out further that a larger height change near 90 km than near 70 km does not necessarily imply a correspondingly stronger precipitating flux at the higher level, as the following consideration would show. If, as an example, we consider exponential electron density distribution at the VLF reflection heights, then a height change Δh (which is proportional to the observed phase advance $\Delta\phi$) could be written as $\Delta h = (\Delta N/N)\ H$, where N is the electron density and H is the scale height of its distribution. Examination of published measurements of daytime and nighttime lower ionosphere electron density profiles (see for example, Sagalyn and Smiddy [1963],Prakash et al. [1974], and Geller et al. [1975]) shows that the ambient electron density near 90 km at night could be at times even less than the daytime values near 70 km due to the absense of direct solar UV radiation at night. Thus a given increase in electron density, ΔN, at the two height regions could produce larger Δh for nighttime cases, which can only be offset by differences in the scale heights of the electron density distributions at the two heights. However, for the same ΔN the required ion production rate would be significantly higher at lower heights due to the well-known decrease with height in the effective recombination coefficient (or cluster ion concentrations) at these heights (see, for example, Reid [1970]. Therefore under certain circumstances, even minor daytime phase perturbations might be as important as larger-scale nighttime fluctuations from the viewpoint of an ion production source. These considerations would lead us to conclude that during at least some of the events presented in this analysis, particle precipitation might have occurred in the entire region of 90-70 km to explain the VLF results.

We have seen that the VLF phase disturbances take place almost immediately after the onset of the magnetic disturbances, especially when the later occurs at night. This contrasts with the well-known storm after effect of the mid-latitude D region, during which several days of delay are observed between the particle precipitation effect in the D region and the magnetic storms [Belrose and Thomas, 1968; Lauter and Taubenheim, 1970; Beynon and Willians, 1974; Spjeldvik and Thorne, 1975]. The VLF phase disturbances in the examples presented here continued well after the magnetic disturbances subsided, a characteristic that was observed also in the case of the magnetic storm associated E_s enhancements [Batista and Abdu, 1977]. In contrast to the VLF disturbances, the onset of the E_s enhancements, however, were, in most cases, considerably delayed (from <1 to 3 days) with respect to the magnetic disturbance onset. Such delays show that the presence of particle ionization, though necessary, is not a sufficient condition for the occurrence of these E_s layers. Simultaneous presence of the additional prerequisites would be (1) sufficient concentration of metal atoms (M) to be available for conversion to metal ions (M^+), the constituent ions of most of the sporadic E layers, through charge transfer reaction of the type $M + X^+ \rightarrow M^+ + X$, where X^+ is the ambient molecular ions, O_2^+ and NO^+, produced by the precipitating particles [Narcisi, 1968]; see also the discussion by Batista and Abdu [1977], (2) wind shears of sufficient magnitude in case the E_s layers are of the blanketing type, and (3) conditions that produce irregularities or patchy ionizations, that give rise to range spreading echoes of the a-type E_s perhaps an $E \times B$ instability mechanism working at the bottomside gradient of an E_s layer, or that of a patchy layer, in the presence of appropriate electric fields [Reid, 1968]. The possibility that the spatial structures and irregularities might be be inherent in the precipitating electron energy and flux distribution cannot also be ruled out. Thus it is clear that while the appearence of the E_s layers, of the type and under the circumstances presented here, could be taken as positive evidence for the presence of charged particle precipitation, their nonoccurrence is not sufficient evidence for the absence of particle-induced ionization. From the above argument it follows that day to day variabilities in the occurrence or in the intensity of any one of the above factors could cause delay in the onset of the magnetic storm associated E_s enhancements even if particle-produced ionization was present immediately following the magnetic disturbances, which indeed seems to be the case, as the VLF results indicate.

We may point out further that enhancements of blanketing-type E_s layers constituted of molecular ions must be very rare, since wind velocities of abnormally large magnitude are needed to produce layering of these ions due to their relatively faster recombination rate compared to that of the metallic ions [see Abdu and Batista, 1977]. If molecular ion E_s layers do get enhanced due to magnetic disturbance associated particle precipitation, then they should also be observed immediately following the disturbance onset concurrent with the VLF effects. Since our observations show that the E_s layer enhancements occur with variable time delay with respect to the magnetic disturbance onset, we may conclude that these enhancements could be in the metallic ion E_s layers (since winds of moderate intensity could produce them), so that the variable delays could be caused by possible variabilities in the magnitudes of the parameters that are the essential prerequisites for the E_s formation (namely, prerequisites 1-3) mentioned above. For example, results of regular laser radar measurements of mesospheric sodium, over São José dos Campos, have shown significant day to day variability in the sodium abundance [Simonich et al., 1979], which might suggest a similar variability in other metallic species as well. Information on possible day to day variability of the E region winds is completely lacking for this region. It would be of great interest to know also about possible magnetic storm influence on these parameters.

Conclusions

VLF propagation in a trajectory situated almost completely in the South Atlantic magnetic anomaly region undergoes significant perturbations in association with magnetic disturbances. These disturbances are characterized by advancements in the phase of the received signal indicative of lowering of the VLF reflecting layer. The phase perturbations are seen to be more pronounced when the VLF reflection takes place at higher levels (~90 km) at night than when it is from the lower daytime reflection height. Qualitative considerations on the ambient electron densities at the day and night reflection levels and the lower ionosphere recombination process would suggest that the sources of enhanced ion production, which we attribute to precipitation of high-energy particles, could be important in the height region of 90 km extending downward during strong events up to 70 km. Considerations of the enhanced E_s occurrences would extend the upper height limit to at least 110 km, the height of some of the observed E_s layers. The enhanced precipitation seems to be occurring immediately following the onset of the magnetic disturbances and continues, in general, well after the recovery of the magnetic disturbances as represented by Kp. The characteristics of sporadic E layer enhancements, in the example presented here and in a previous study, are similar to those of the VLF effects, except that the onset of the E_s enhancements were generally delayed by ~1-3 days with respect to the onset of the magnetic disturbance. Such delay might, perhaps, be caused by day to day variabilities in the metallic species, and/or in the dynamics, of the E region.

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