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IONOSPHERIC RESPONSE TO MAGNETIC STORMS IN THE SOUTH ATLANTIC ANOMALY REGION

Kalvala Ramanuja Rao

The ionospheric response to magnetic storms is studied during the ascending branch of solar cycle in the South Atlantic Geomagnetic Anomaly Region (SAGAR). It is seen that a positive phase sets in after about 12 hours after the Storm sudden commencement (SSC) and persists for about 72 hours thereafter. The effective neutral winds are strongly equatorwards during the main and early recovery phase and appear to be due to particle precipitation into the region.

Key words: Winds in ionosphere; South Atlantic anomaly region; Magnetic storms.

RESPOSTA DA IONOSFERA ÀS PERTURBAÇÕES MAGNÉTICAS NA REGIÃO DA ANOMALIA GEOMAGNÉTICA DO ATLÂNTICO SUL – *A resposta da ionosfera para perturbações magnéticas na região da Anomalia Geomagnética do Atlântico Sul é estudada durante o período ascendente do ciclo solar. Uma fase positiva é estabelecida 12 horas após um Início Súbito de Tempestades (SSC) e persiste por cerca de 72 horas depois. Os ventos neutrais meridionais são fortemente direcionados ao equador durante as fases principal e de recuperação e parecem ser uma conseqüência da precipitação das partículas carregadas na região.*

Palavras-chave: *Ventos na ionosfera; Região da Anomalia do Atlântico Sul.*

Universidade Regional de Blumenau,
Caixa Postal 1507
Blumenau, SC, Brasil.

INTRODUCTION

The response of ionospheric F layer to geomagnetic storms has been studied for decades. The ionosonde data at various sites have been used, first to study the regional effects, and then the combined data have been used to elicit global response. Based on these data, theoretical models have been constructed, which were fed back to study local effects again. Even with all these efforts, the F region response to geomagnetic storms is still not fully understood. The present paper is yet another attempt to study the F region response to geomagnetic storms in the geomagnetic anomaly region using ionosonde data in view of the thermospheric models.

It is well known that an initial positive phase of geomagnetic activity lasting for about 6 hours after a Storm Sudden Commencement (SSC), in general, gives way to a negative phase with a return to undisturbed electron concentration level during a recovery period covering 2 to 3 days. (Miller et al., 1979). Frank & Ackerson (1971) have shown that geomagnetic storms are accompanied by increased precipitation of energetic particles into the auroral atmosphere. Lauter & Knuth (1967) came to similar conclusions at middle and low latitudes and Abdu et al. (1981) for the geomagnetic anomaly region. The relation between prolonged geomagnetic disturbances and enhanced global heating effects within the neutral thermosphere were studied by Blamont & Luton (1972). The theoretical models of Rishbeth et al. (1978) and Fejer et al. (1979) have emphasized the role of **E X B** drifts, neutral winds and plasma flux in the F region in response to SSCs and the coupling of thermosphere-ionosphere system. Fuller-Rowell & Rees (1981) have shown the important consequences of high latitude energy and momentum input over global wind and temperature distribution following a moderately strong geomagnetic storm. Mayr & Volland (1972; 1973) developed models of the evolution of thermospheric meridional neutral winds, temperature and neutral composition due to thermospheric heating induced by precipitation of high energy particles at high latitudes.

In the present paper, the response of ionospheric F region to a magnetic storm is studied during the main and recovery phases in the South Atlantic Geomagnetic Anomaly Region (SAGAR) along with the dynamics of the predominant neutral atmosphere at the time. An attempt is made to understand the phenomenon as due to the precipitation of particles in the region.

OBSERVATIONS

In the present paper, the geomagnetic storm of July 25, 1981, during the ascending branch of solar cycle is studied utilizing the ionospheric data available from the ionosonde situated at Blumenau, Brazil, almost at the center of SAGAR (The geographic coordinates are -26.3° latitude and -48.9° longitude, dipole latitude -16.31°). The h_{max} values, calculated using Dudeney's formula (Dudeney,1983), and foF2 values are used in the study. No true heights were calculated. The first sudden commencement occurred at 05:14 UT and a second SSC was registered at 13:22 UT on the same day (though this was registered at only a few observatories). The sum of Kp index reached 53 with an Ap value of 134 on that day. The storm ended near 1.800 UT on 26th, but the storm effects were seen on 27th also. Only on July 29 the indices became normal, though the Dst did not become equal to that of normal day by that time. Before the start of the SSCs, July 22 and 23 presented also high geomagnetic indices (with SKp index 28^+ and 34^-, respectively) as a consequence of an earlier magnetic storm on 23rd at 06:46 UT.

In Fig. 1 the foF2 values are plotted along with the hourly medians of the five quiet days and the Dst values (divided by 10). Till about 14:00 LT on 24th the foF2 accompanied the medium quiet day values, thereafter showing an increase in the maximum electron density till about 02:00 LT on 25th. This increase is probably due to the earlier storm on 23rd. On 23rd, the SSC commenced at 06:45 UT and was observed at many places. The intensity was slightly less compared to the SSC on 25th, but the effects of this storm also could be seen in the figure, more clearly before the onset of the SSC on 25th. Immediately after the SSC on 25th, a negative phase is seen for about an hour. Though , as Spurling & Jones (1976) observed at mid-latitudes, the positive and negative mechanisms are in competition for the first few hours after the storm commencement, a positive phase sets in finally at about 20:00 LT on 25th, which lasts till about 05:00 LT on 28th. One interesting thing is the occurrence of oscillations in foF2 when the density is maximum. The oscillations are more intense on the first maximum after SSC, diminishing on subsequent maxima. The difference between the average quiet value and the disturbed value reaches maximum about 24 hours after the SSC. The positive response of foF2 lasts for more than 72 hours after the storm commencement.

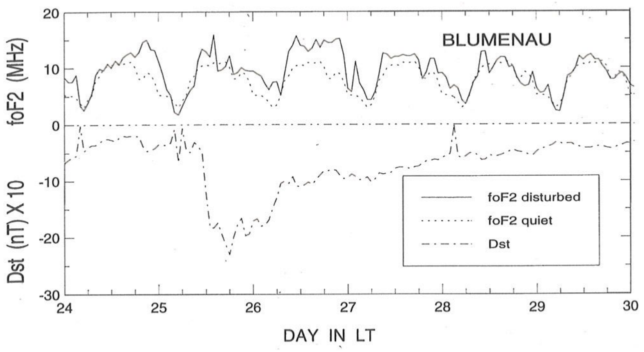

Figure 1 - Disturbed and quiet time foF2 values at Blumenau with Dst values (Local Time LT = UT-3 hrs)

Figura 1 - *Valores de foF2 para períodos perturbados e quietos e de Dst, para a região de Blumenau (Hora local LT = UT-3hrs)*

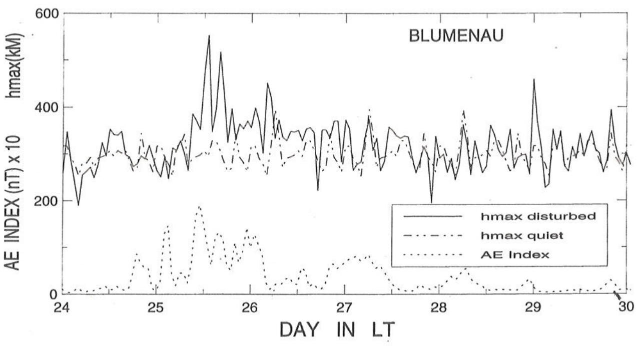

Figure 2 - Disturbed and quiet time h_{max} values at Blumenau with AE Index. (Local Time LT= UT- 3 hrs.)

Figura 2 - *Valores de h_{max} para períodos perturbados e quietos, e o índice AE, para a região de Blumenau (Hora local LT= UT- 3 hrs.)*

Fig. 2 shows the h_{max} values calculated by Dudeney's formula during the storm time and average quiet time, along with AE index (divided by 10). The correspondence between the variations in AE index and h_{max} is evident in the figure. When the AE index is maximum on 25th and early part of 26th, the h_{max} value is well above the average quiet day value. Though the h_{max} curve accompanies the AE curve on other days as well, the value is no more above the quiet day value from later part of July 26 till 22 hours LT on July 28. At this hour, a small increase in AE appears to have provoked a surge in h_{max} value.

MERIDIONAL WINDS DURING THE STORM

Rishbeth et al. (1978) showed the variation of h_{max} resulting from changes in the meridional wind to be approximately linear for small winds under steady state condition. In general, the dominant poleward wind in the daytime and equatorward wind at night have the effect of lowering the daytime F2 layer and raising the nighttime F2 layer beyond the normal diurnal variation from production, recombination and diffusion. Miller et al. (1986) and Forbes et al. (1988) used the h_{max} values to calculate the neutral wind component along the magnetic lines of force. An effective average meridional wind component, calculated using the method given by Forbes et al.(1988), for the two most quiet days of July, 1981 (Fig. 3, the negative direction gives the equatorward winds) shows the winds predominantly poleward during day and night with strong equatorial winds only at early morning hours. Fig. 4, however, shows the winds predominantly equatorward for daytime as well as nighttime during a disturbed period. The strong equatorward winds start well before the first SSC on 25th (02:14 LT), but appear to correlate well with the high AE index which started earlier on 24th. The start of auroral activity earlier than the SSC is a well known phenomenon (Mayaud,1980) and the energy input during the magnetic storm appears to accompany this activity. The strong equatorward winds are seen during the first part of recovery phase and particularly when the AE index is high.

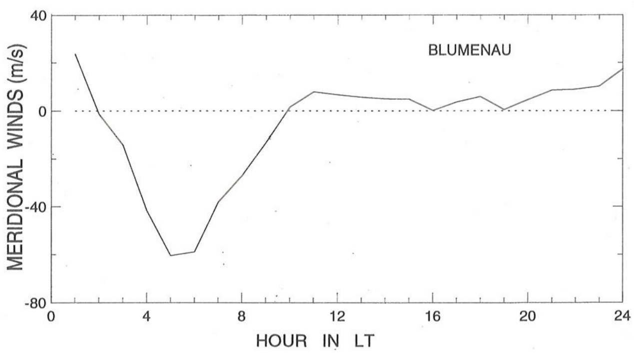

Figure 3 - Average effective meridional winds at Blumenau for two quiet days, 10 and 15, July, 1981. (Local Time LT = UT-3 hrs.)

Figura 3 - *Média dos ventos meridionais efetivos em Blumenau, para dois dias quietos, 10 e 15 de julho, 1981 (Hora local LT = UT-3hrs.)*

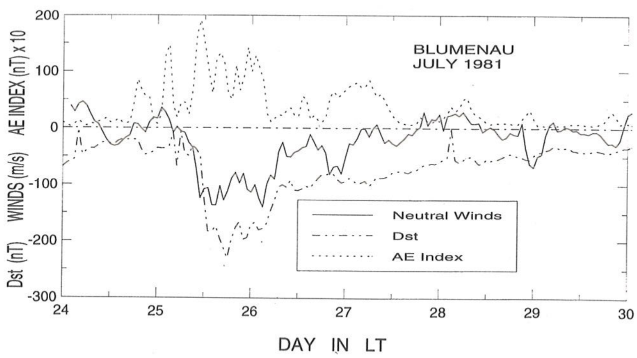

Figure 4 - Effective meridional winds at Blumenau for July 24 to July 29, 1981, along with Dst and AE Index. (Local Time LT = UT - 3 hrs.)

Figura 4 - *Ventos meridionais efetivos em Blumenau para 24 a 29 de julho, 1981, em conjunto com Dst e índice AE (Hora local LT = UT-3hrs.)*

Fig. 5 shows the winds calculated during other disturbed periods at the same station, and Fig. 6 shows the winds calculated for the disturbed period under study (July 25, 1981), for Cachoeira Paulista (latitude -22.70°, longitude -45.2°), another Brazilian station at the verge of SAGAR. For this station, the hpF2 values observed from the ionograms were used instead of calculated h_{max} values, as the parameters to utilize in the Dudeney's formula were not available.

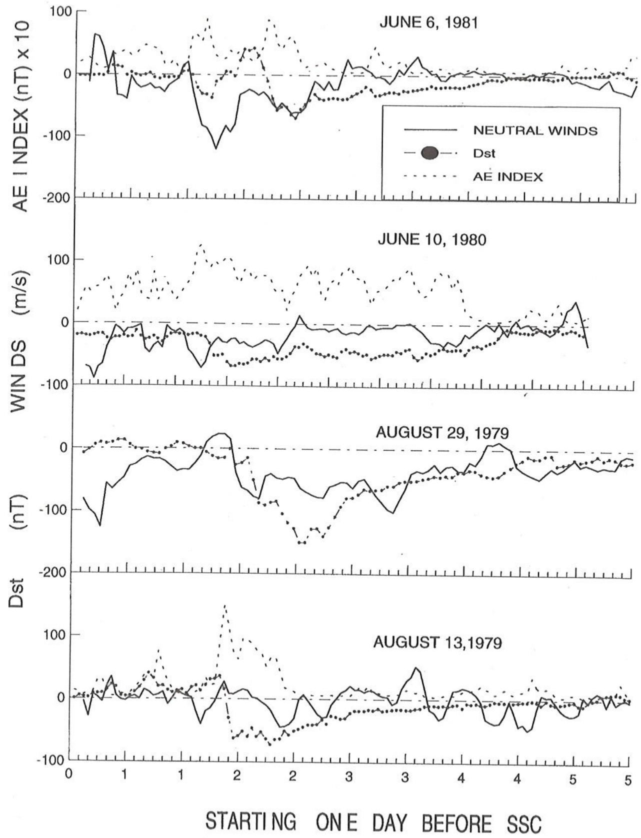

Figure 5 - Effective meridional winds at Blumenau along with Dst and AE Index.

Figura 5 - *Ventos meridionais efetivos em Blumenau, em conjunto com Dst e índice AE.*

DISCUSSION AND CONCLUSIONS

The rapid increase in Dst indicates a rapid injection and energization of particles into trapped orbits in the magnetosphere. During magnetic storms a very large amount of energy contained in the ring current due to these trapped particles is deposited in the thermosphere at middle, low and equatorial latitudes. After the start of a magnetic storm, Dst recovers more slowly, indicating that the ring current dies away less rapidly than the polar disturbance. As shown above the strong equatorward winds are confined to the main and early recovery phase. This may indicate that the injection of energetic particles and the consequent perturbation is occurring mainly during this phase. It is also clearly seen, from Fig. 4 (and also from Fig. 5), that the strong equatorward winds are also confined to the period of high AE variation, indicating that the energy input varies simultaneously with the Joule heating at higher latitudes, as AE is an index of this high latitude phenomenon. As it is assumed that a minimum time delay exists to transport heat from high latitude Joule heating source to low latitudes, about 2.5 hours to the equator, the simultaneous variation with the AE index indicates a local energy input. Tinsley et al. (1988) made optical measurements of particle precipitation and temperature during a magnetic storm using 391.4 nm emission at Cachoeira Paulista, Brazil, and 630.4 nm Fabry-Perot observations from Peru and came to a similar conclusion that the prompt thermospheric temperature enhancement observed is consistent with the concept of local energy deposition and cannot be identified as due to the transport of heat from mid-latitude ring current source or the high latitude joule heating source.

Since the early experiments by Russian satellites, the South Atlantic Geomagnetic Anomaly Region (SAGAR) has been recognized as a major sink for trapped electrons of the radiation belts (Paulikas, 1975). Batista & Abdu (1977) and Abdu et al. (1981) have shown that the electron precipitation into D and E regions is a dominant process during the night after a geomagnetic storm (See Pinto Jr. & Gonzalez (1989), for a review of electron precipitation into SAGAR.) Several mechanisms for the precipitation of electrons into the lower layers of the region have been proposed including wave-particle interactions (Gonzalez,1989, and Pinto Jr. & Gonzalez, 1989, and references therein). Particles of different energies deposit most of their energy at different levels in the ionosphere. The electron energies most relevant for F region heights are in the range of 2 keV, whereas the energies in the range of 2 to 40 keV are relevant for the E region. Electrons with energies greater than 40 keV lose their energy in the D region.

Though the flux of electrons of higher energies have been measured in many satellite experiments, not many attempts have been made to measure electron fluxes below 40 keV. This is because the high-energy background radiation makes it difficult to measure the fluxes and spectra of low energy particles with any degree of certainty. Gledhill et al. (1967) showed a very significant correlation between the flux of electrons with energies greater than 40 keV and the critical frequency of the F_2 layer, f_oF_2. Since electrons with such high energies have little direct effect on the atmosphere at F region heights, depositing their energy around the 85 km level in the D region, the correlation found by them might imply that the energetic electrons were accompanied by fluxes of lower energy particles which were responsible for ionizing the F- region. Lieu et al. (1988), using the electron spectrometer on board Spacelab 1 in its 240-km altitude and 57^0 inclination circular orbit, have obtained a flux of about 2×10^4 electrons $cm^{-2} s^{-1} Sr^{-1}$ for the 1 - 12.5 keV electron energy range near the equator and outside the anomaly region. Lieu et. al. (1988) further show that the spectrum obeys an $E^{-3.5}$ power law between 0.1 and 1 keV. Gledhill & Hoffman (1981), however, using low energy ion detector on the satellite Atmospheric Explorer, AE-C, found electrons in the range of 0.2- to 26- keV in the SAGAR, the spectrum being in the form

$$J = 1.66 \times 10^4 E^{-0.96} cm^{-2} s^{-1} sr^{-1} keV^{-1}$$

Thus, it is seen that, though the experimental difficulties precludes the observation of low energy cletrons at ionospheric heights, the lower energy end spectrum is well evidenced by other experiments and these low energy electrons precipitate to F region heights during disturbed conditions. These increased precipitated electrons, along

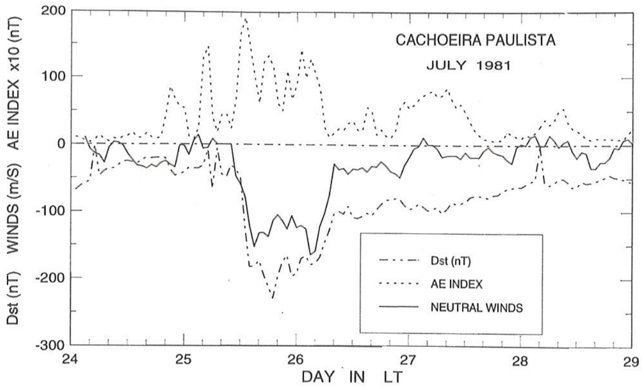

Figure 6 - Effective meridional winds at Cachoeira Paulista for July 24 to July 28, 1981, along with Dst and AE Index. (Local Time LT = UT - 3 hrs.)

Figura 6 - *Ventos meridionais efetivos em Cachoeira Paulista, para 24 a 28 de julho, 1981, em conjunto com valores de Dst e índice AE (Hora local LT = UT-3hrs.)*

with the increased ionization induced by other precipitating high energy particles, in turn, will enhance the overall electron density of the F region to produce the positive effect seen here.

As mentioned above and as can be seen from Fig. 1, the positive response of ionosphere (increased electron density compared to average quiet time value) starts around 22:00 LT on 25th July, about 12 hours after SSC, and lasts for more than three days, indicating a delayed precipitation of these low energy electrons into higher regions.

Figs. 4 and 6 show that the effective winds calculated are of the same order at Blumenau and Cachoeira Paulista. Both stations are within the geomagnetic anomaly region and may be governed by the same dynamical effects. The difference which may exist (the winds at Blumenau appear to be slightly stronger during main and recovery phase of the storm) may be either due to (i) different parameters used in the calculation or (ii) the difference in dip angle. The winds were obtained using the calculated values of h_{max} at Blumenau and the observed values of hpF2 at Cachoeira Paulista. Batista et al. (1991) have shown that the F layer peak heights calculated by these two methods, in general, are in good agreement during nighttime, though during daytime the hpF2 is always higher than the real peak height, whereas h_{max} is sometimes above and sometimes below the real height. This is because during nighttime, very few underlying ionization is present in and below E region and both the formulas for hpF2 and hmF2 represent well the F2 layer peak height. On the other hand, during the daytime, when ionization is present in the D and E regions, the Dudeney formula (Dudeney, 1983) takes into account a correction for the retardation by the underlying ionization, lowering the deduced hmF2 during daytime and letting them unchanged during nighttime and the formula for hpF2 does not take this effect into account. The average daily winds for the period under study, July 24 to July 29, 1981, show that (figure not shown here) the winds at Blumenau are slightly lower during daytime, and slightly higher during night, compared to those at Cachoeira Paulista. Neglecting the influence due to this effect, the differences encountered, if any, may be due to the difference in the dip angle of the two stations.

In conclusion, it can be seen that the strong equatorward wind during geomagnetic storms is a common phenomenon, for at least winter months (as the study has been carried out only during July and August, the winter months in the Southern Hemisphere) in the anomaly region, and might be induced by the local energy input in the form of particle precipitation into the region.

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RESPOSTA DA IONOSFERA ÀS PERTURBAÇÕES MAGNÉTICA NA REGIÃO DA ANOMALIA GEOMAGNÉTICA DO ATLÂNTICO SUL

No presente trabalho, a resposta da região F às perturbações magnéticas durante suas fases principais e de recuperação, na região da Anomalia Geomagnética do Atlântico Sul, foi estudada juntamente com as condições dinâmicas existentes na época. Em partícular, as perturbações magnéticas de 25 de julho de 1981 foram estudadas utilizando os parâmetros ionosféricos disponíveis da ionossonda de Blumenau, Brasil (latitude geográfica -26,3°, longitude -48,9° e latitude dipolar -16,31°). Os valores de h_{max}, calculados usando a fórmula de Dudeney e os valores de f_oF_2, foram utilizados. O primeiro início súbito (SSC) da perturbação magnética ocorreu às 05:14 UT e um segundo às 13:22 UT do mesmo dia. As perturbações cessaram às 18:00 UT do dia 26 de julho, mas os efeitos prosseguiram até o dia 27. A Fig. 1. mostra os valores de f_oF_2 para períodos perturbados e calmos, junto com os valores Dst. Imediatamente após a SSC, é observada uma fase negativa por cerca de uma hora. Ainda que os mecanismos que geram as fases positiva e negativa continuem atuando por algumas horas após o SSC, finalmente às 17:00 UT de 25 de julho, a fase positiva domina e se manifesta até às 02:00 UT de 28 de julho, agindo assim por mais de 70 horas após o SSC. A Fig. 2 mostra a correspondência entre o índice de AE e h_{max}. Rishbeth et al. (1978) mostraram que a variação de h_{max} inferida da variação do vento meridional é linear para pequenas intensidades dos ventos em condições estáveis. Miller et al. (1986) e Forbes et al. (1988) usaram os valores de h_{max} para calcular a componente do vento neutro ao longo das linhas de força magnética. O método, dado por Forbes et al. (1988) é utilizado neste trabalho para calcular os ventos meridionais durante dois dias calmos (Fig. 3) e 5 dias perturbados (Fig. 4). Os ventos têm a direção predominante para o pólo durante todo o dia e noite, e em direção ao equador somente no início da manhã, para os dias calmos. Nos dias perturbados, a direção predominante é para o equador durante todo o dia e noite. O aumento rápido no valor absoluto do índice Dst indica a injeção rápida e a energização das partículas presas nas órbitas Van

Allen. Durante as perturbações magnéticas, uma grande quantidade de energia, contida na corrente de anel, devido a partículas presas, é depositada na termosfera em latitudes médias, baixas e equatoriais. Depois do início da perturbação, Dst recupera-se mais lentamente indicando que a corrente de anel diminui mais devagar do que a perturbação polar. O fato que os fortes ventos em direção ao equador são confinados nas fases principal e de recuperação indica que a injeção das partículas energéticas e a conseqüente perturbação ocorrem principalmente durante estas fases. A Fig. 4 indica que esses ventos fortes em direção ao equador são confinados, também, durante períodos de altos valores de AE, o que indica uma origem local para a energia fornecida. A região da Anomalia Geomagnética do Atlântico Sul é reconhecida como um sumidouro de partículas presas nos cinturões de radiação. Vários mecanismos foram propostos para explicar a precipitação dos elétrons para as camadas mais baixas da região (Pinto Jr. & Gonzalez, 1989). A energia dos elétrons, relevante para a altitude da região F, está na faixa de 2 keV, enquanto que a energia na faixa de 2 a 40 keV é relevante para a região E. Elétrons com energia maior que 40 keV perdem sua energia na região D. A pouca precisão na medida do fluxo de elétrons com energia abaixo de 40 keV deve-se à alta energia de fundo da radiação. Porém, existem algumas observações esporádicas de fluxo de partículas de baixa energia (Gledhill et al., 1967; Gledhill & Hofman, 1981; Lieu et al., 1981). Estes elétrons com baixa energia precipitam-se para a região F durante as perturbações magnéticas. Estes elétrons, junto com outros produzidos localmente pelas partículas de alta energia, contribuem para aumentar a densidade da região F e produzem um efeito positivo. O efeito positivo, que começa 12 horas após a SSC e dura mais de três dias, indica um efeito retardado da precipitação das partículas de baixa energia nas altas regiões da ionosfera. A Fig. 6 mostra que os ventos efetivos calculados são de mesma ordem tanto em Blumenau quanto em Cachoeira Paulista. Ambas as estações, estando localizadas na mesma região da Anomalia, podem ser governadas pelos mesmos mecanismos dinâmicos. As diferenças, se existem, são talvez devidas aos diferentes parâmetros usados nos cálculos, ou por causa da inclinação magnética.

NOTAS SOBRE O AUTOR
NOTES ABOUT THE AUTHOR

Kalvala Ramanuja Rao

The author, Kalvala Ramanuja Rao, was born in India on the 13th of March, 1931. Graduated in physics from Osmania University and obtained Master's degree with honours in Nuclear Physics in 1961 from the same University. Joined the Physical Research Laboratory, Ahmedabad, India, for a research career in 1962 and obtained a Ph. D. degree in Aeronomy (Space Geophysics) in 1967 from Gujarat University, Ahmedabad, India. Joined the Instituto Nacional de Pesquisas Espaciais (INPE), São José dos Campos, SP, Brazil, in October 1969 and worked in Solar Terrestrial relations, Aeronomy, X-ray and Gammaray astronomy till 1984. Joined the Universidade Regional de Blumenau (FURB), Blumenau, SC, Brazil in 1986, in the group of Radioscience. Presently, he is the coordinator of the group since 1989. The research interests include Solar Terrestrial Relations, Ionosphere and Aeronomy, and Astrophysics.