A Conductivity Model for the Brazilian Equatorial E-Region

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Abstract

In this paper we present field-line-integrated local ionospheric conductivity model for the Brazilian equatorial region. It was developed aiming to calculate the E-region electric fields that drive the 3-meter plasma irregularity of the equatorial electrojet. This model was based on the neutral atmosphere and electron densities, on the ion composition, and on E-region critical frequency *fo*E measured by digisonde. Due to the large magnetic declination angle in the Brazilian sector we approximate the geomagnetic field model with a dipole which is not located at the centre of the Earth. We have also considered the eccentric dipole having an inclination of 20° with respect to the Earth rotation axis. The local conductivities resulting from our model are compared to the local conductivities obtained from the conductivity model of the Kyoto University.

Introduction

In the equatorial E region, the partial or total inhibition of the vertical Hall current driven by the primary east-west (dynamo) electric field produces a strong vertical Hall polarization electric field that in turn enhances the equatorial electrojet (EEJ) current (Forbes, 1981). This strong E-region electric field drives plasma instabilities at these heights (Fejer and Kelley, 1980), which propagate westward during day and eastward during night. The presence and characteristics of these instabilities can be monitored using coherent back-scatter radars (Bowles and Cohen, 1960; Bowles et al., 1960).

Since 1998, the 50 MHz coherent back-scatter radar system (also known by the acronym RESCO) is operational at São Luís (2.3° S, 44.2° W, dip: ~ -0.5°), Brazil. Coherent radars operating at 50 MHz (λ = 6 m) are sensitive to 3-meter plasma irregularities. Radar observation of the EEJ plasma instabilities are routinely carried out at São Luís. Through this constant monitoring we are able to determine Doppler shifts from the irregularities echoes power spectrum, among other EEJ information. Afterwards, electric fields, which drive the irregularities propagation, can be deduced from these Doppler so long we have an ionospheric conductivity model.

Hence, we have developed a geomagnetic field-line-integrated ionospheric conductivity model for the Brazilian equatorial region over the radar site, which is presented and discussed here. For validating our results we have deduced the vertical conductivity profile for the Pedersen and Hall conductivities and compared the local Hall-to-Pedersen conductivity ratio obtained from our model with that given by the Kyoto's Model. The resulting profiles had shown agreements in the height of peak and magnitude. In the following sections we present our model description, and the results and discussions regarding the comparisons with the model from the Kyoto University.

Neutral Atmosphere and Electron Density Models

We have developed a local ionospheric conductivity model for the Brazilian E-region based on the neutral atmosphere and electron densities, on the ion composition, and on E-region critical frequency *fo*E measured by digisonde. Using a magnetic field line model we have, than, obtained integrated conductivities for all height of radar soundings at the RESCO radar site. The model gives the field-line integrated ionospheric conductivities as a function of local time and season.

As a magnetic filed line model we have approximate the geomagnetic field model with a dipole which is not located at the centre of the Earth. We have also considered the eccentric dipole having an inclination of 20° with respect to the Earth rotation axis. This model was chosen because the magnetic equatorial region possesses certain peculiarities in the geomagnetic field configuration that are distinctly different from other longitude sectors. A notable peculiarity is the large magnetic declination angle (being ~ 21° W) at the RESCO radar site. Figure 1 present a sketch of the magnetic filed lines (between 89 and 125 km) on the magnetic meridian corresponding to the magnetic longitude of São Luís. The RESCO radar, the magnetic and the geographic equators are also located in this figure.

The neutral atmosphere is considered constituted by the gases: molecular nitrogen (N_2), molecular oxygen (O_2), atomic oxygen (O) and argon (Ar). The height distributions of these neutral gases densities are given by Banks and Kockarts (1973). The ionized atmosphere is assumed to be constituted basically by the ions: nitric oxide (NO^+), molecular oxygen (O_2^+) and atomic oxygen (O^+). The vertical electron density profiles and the relative ion composition were obtained from the International Reference Ionosphere Model - IRI Model (Bilitza, 2001). But, the electron density values were increased by a factor based on *fo*E measured by digisonde around the dip equator.

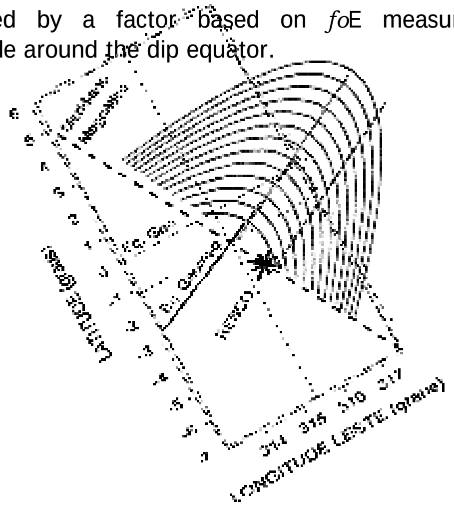

Fig. 1. Sketch of the magnetic filed lines (between 89 and 125 km) on the magnetic meridian corresponding to the magnetic longitude of São Luís.

Abdu et al. (2004) have compared the *fo*E values predicted by IRI with those measured over three locations that constituted a conjugated points station pair: Campo Grande in south (20.45º S, 54.65º W, dip: -22.5º) and Boa Vista in north (02.8º N, 60.66º W, dip: 22.5º), and an equatorial station, Cachimbo (09.47º S, 54.83º W, dip: -3.9º). They have stated that the daytime equatorial E-layer (*fo*E) is reasonably well represented by the IRI. But they have pointed out the IRI model underestimates the E-region peak density in the Brazilian sector (se, for example figure 4 in Abdu et al, 2004). Thereafter, we have adjusted the absolute electron density given by IRI to the mean electron density obtained from *fo*E at these three stations. All E-region peak density values obtained from simulations at the dip equator were set to the peak density calculated from the mean *fo*E measured at the corresponding local time. The rest of the electron density vertical profile was adjusted proportionally to its previous value considering an α-Chapman layer decay. For latitudes outside dip equator, the vertical profiles simulated were corrected by a factor give by the ratio between the peak density obtained from *fo*E and that given by IRI.

Figure 2 shows of vertical density distributions of the ionospheric constituents, the electron content and the neutral atmospheric constituents for the equatorial E-region in the Brazilian sector. These profiles, taken as examples, refer to the southern hemisphere summer at local midday. The black line is the electron density. The dashed colored lines refers to individuals ionospheric constituents indicated in the graph with the same line color. And the dot-dashed colored lines refers to individuals atmospheric constituents also indicated in the graph with the same line color.

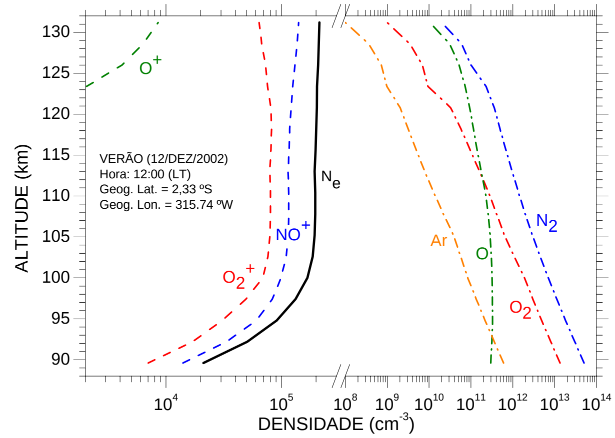

Fig. 2. Vertical density distributions of the ionospheric constituents (dashed lines), the electron content (black line) and the neutral atmospheric constituents (dot-dashed lines).

Results and Discussions

Using the neutral atmosphere model and the ionospheric model as described above we were able to calculate the collision rates for all latitudes and heights along the magnetic meridian at the radar site longitude. The ions-neutral collision rates were calculated as per equation (Kelley, 1989):

$$\nu_i = \left(2{,}6 \times 10^{-9}\right) \cdot \left(N_n + N_i\right) \cdot A^{-1/2} \ , \qquad (1)$$

where N_n is the neutral atmosphere density, N_i is the ion density and A (= A_n + A_i) is the weighted molecular mass (neutral and ionized). But, at the E-region heights, the neutral density is around 3 to 7 time the magnitude of the ion density. Then, the term (N_n + N_i) was approximated to N_n. In the same way, the weighted molecular mass A was approximated to the neutral mass A_n. Finally, the equation (1) became:

$$\nu_i = \left(2{,}6 \times 10^{-9}\right) \cdot N_n \cdot A_n^{-1/2} \ . \qquad (2)$$

The electron-neutral collision rates were calculated as per equation (Kelley, 1989):

$$\nu_e = \left(5{,}4 \times 10^{-9}\right) \cdot N_n \cdot T_e^{1/2} \ , \qquad (3)$$

where T_e is the electron temperature. In the height range the model runs, the electron temperature can be approximated to the neutral atmosphere temperature (T_n) without no prejudice to the precision of the model.

Figure 3 shows examples of the vertical profiles of the collision rates calculated by the model using equations (2) and (3). The red line is vertical profile for the ion-neutral collision rate and the blue line gives vertical profile for the electron-neutral. They were calculated for the RESCO radar site coordinates, covering the range height from 90 to 130 km, for the equinox period, at 12 h (local time).

Ion (Ω_i) and electron (Ω_e) cyclotron frequencies were calculate, respectively, as per equations:

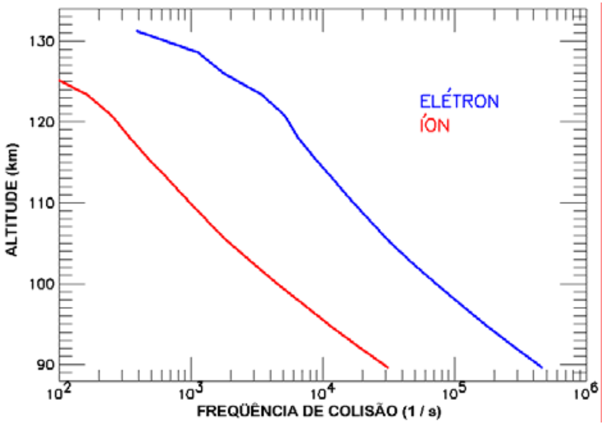

Fig. 3. Vertical profile of the ion-neutral collision rate (red line) and vertical profile of the electron-neutral (blue line) calculated for the RESCO radar site location, covering the range height from 90 to 130 km, during equinox, at 12 h (local time).

$$\Omega_i = (q_e \cdot B_0) / m_i \quad \text{and} \quad \Omega_e = (q_e \cdot B_0) / m_e \qquad (4)$$

where B_0 is the geomagnetic field intensity (from the IGRF model), m_i and m_e are, respectively, the mean ion mass and the electron mass, and q_e is the elementary charge.

In order to evaluate our model, the Hall (σ_H) and Pedersen (σ_P) locals conductivities obtained from our model where compared to the same conductivities obtained from the ionospheric conductivity model of the Kyoto University, Japan, available on line. However, these quantities were not compared directly. Our model were developed aiming to calculate the equatorial E-region electric fields using the information from the RESCO coherent radar data, i. e., the phase velocity of 3-meter plasma irregularities. The east-west (dynamo) electric field (E_p) relates to the phase velocity of 3-meter plasma irregularities as per equation:

$$V_\phi \cong (\sigma_H / \sigma_P)[(E_p / B_0)(1+\psi)^2] \ , \qquad (5)$$

where $\psi = \nu_i \nu_e / \Omega_i \Omega_e$ and the other terms have been defined before. Therefore, we have used the Hall-to-Pedersen local conductivity ratio for comparison between the models. Figure 4 presents vertical profiles of the Hall-to-Pedersen local conductivity obtained from both our model and the model of the University de of Kyoto. The conductivities used in these profiles where calculated for the RESCO radar site location, at the local midday, during equinox for high solar activity (SSN > 100) as indicated in the top right corner of the graph.

Despite the ionospheric conductivity model of the University of Kyoto be efficient, it has several limitation. It gives the monthly averaged local conductivities instead of daily values. The grid of calculation used by the Kyoto's model is considerably larger than ours. Besides, it is based on the 1990 version of IRI model as electron density model, while our conductivity model is based on the version 1995-2000 of the same electron density

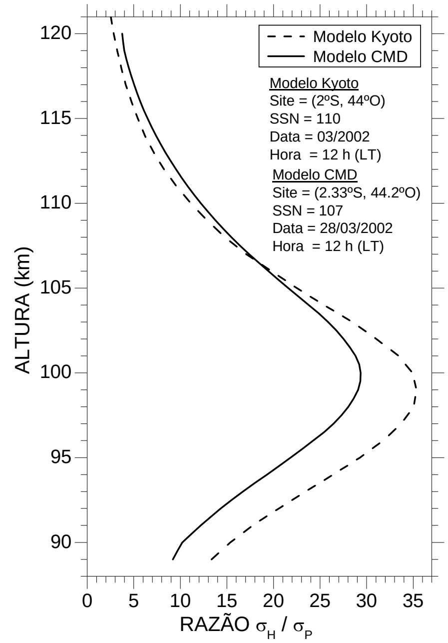

Fig. 4. Vertical profiles of the local Hall-to-Pedersen conductivity ratio obtained from our model (continuous line) and obtained from the model of the University de of Kyoto (dashed line).

model. In addition, as commented before, the IRI model underestimates the E-region electron densities in the Brazilian sector. Thus, the result observed in the figure 4 should be discussed taken these differences in to consideration.

An examination of the profiles in the figure 4 reveals that the peak height of Hall-to-Pedersen local conductivity ratio calculated from our model is located at about 100 km. At this height we have found the ration between the conductivities is around 29. This is in very good agreement with the previous results presented by Sugiura and Cain (1966) for 80º W in the equatorial region. They found the peak height laying on ~100 km with the conductivity ratio being ~29, (see, for example, figure 1 in Sugiura and Cain, 1966). The results obtained from Kyoto's model, however, did not coincide neither in the height of the peak nor in the ratio value. The peak height of the Hall-to-Pedersen local conductivity ratio obtained from the Kyoto's model laid on about 99 km and the ration at this height was found to be around 35. We attribute the difference in the values of ratio at the peak heights obtained from the two models to the equation used to calculate the collision frequencies as well as to the neutral model chosen.

Richmond (1973) and later Forbes and Lindzen (1976) presented models for the EEJ where the vertical current in the magnetic equator was not totally inhibited. In order to include the effect of such current, the model given by Richmond (1973) used integration of the EEJ electric current equation along the magnetic field lines. He stated that since the vertical polarization electric field (E_z) that

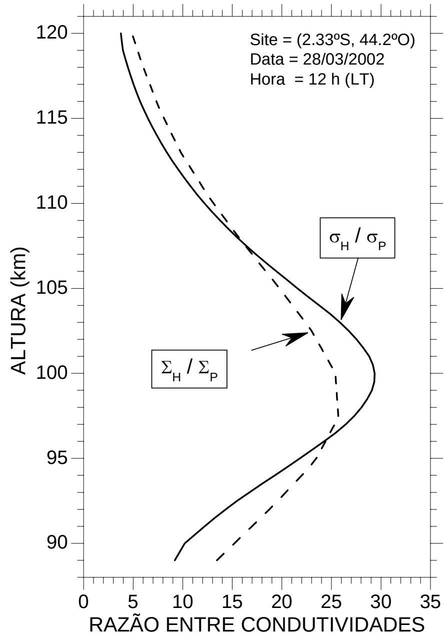

Fig. 5. Vertical profiles of the local Hall-to-Pedersen conductivity ratio calculated using local conductivities (continuous line) and magnetic field lines integrated conductivities (dashed line).

drives the EEJ current is mapped along the magnetic field lines, its value should also depend on the conductivity integrated along the magnetic field line.

For this reason we have chosen the approach used by Richmond (1973) regarding the filed line integration. Thus, our model was designed to calculate the Hall (σ_H) and Pedersen (σ_P) conductivities at each point of the geomagnetic field lines along the magnetic meridian at the radar site with height resolution of 1 km, and than integrate them along the geomagnetic field line. Hence, the ratio (σ_H / σ_P) could was replaced by (Σ_H / Σ_P) in the calculations of the electric fields, now given by:

$$E_z = \frac{\int_{-\theta}^{+\theta} \sigma_H \quad \mathbf{r} \cdot d\boldsymbol{\theta}}{\int_{-\theta}^{+\theta} \sigma_P \quad \mathbf{r} \cdot d\boldsymbol{\theta}} \cdot E_P \Rightarrow E_z = \frac{\Sigma_H}{\Sigma_P} \cdot E_P \ . \tag{6}$$

Here **r** is the position vector of the magnetic field line element considering dipole geometry, θ is the magnetic latitude, $d\boldsymbol{\theta}$ is the differential magnetic latitude element vector and the quantities Σ_H and Σ_P are, respectively, the Hall and Pedersen field-line integrated conductivities. Figure 5 shows the vertical profiles of Hall-to-Pedersen conductivity ratio calculated using local conductivities and magnetic field-lines integrated conductivities. Hall-to-Pedersen Integrated conductivity ratio was calculated as per equation 6. These profiles where calculated for the RESCO radar site location, at the local midday, during equinox for high solar activity (SSN > 100).

The effect of replacing the term (σ_H / σ_P) by (Σ_H / Σ_P) can be clearly observed in this figure. The peak height has descent by about 2 km and the magnitude has decrease from 29 to around 26. The first implication of this replacing is having the maximum of the polarization electric field at a lower altitude. Secondly, the intensity of the polarization electric field should be around 10% lower than that expected if we have not considered field-line integrated quantities. However, it should produce a horizontal EEJ current with the same intensity than that observed with no field line integration. A third implication that could influence in the polarization electric field and then the EEJ current would be the presence of a sporadic E-layer outside the radar sight. The presence of such layer could change the shape of the profile by increasing the Pedersen conductivity in the upper heights through increasing the ion-neutral collision frequency (as see in equation 1). These effects of considering the integrated conductivity in the determination of the polarization electric field intensity should be checked through comparisons between electric fields obtained from the RESCO coherent radar and in situ measurements with rockets indeed.

Conclusions

We have developed a magnetic field line integrated conductivity model for the Brazilian equatorial E-Region. It is consistent with previous results published for another equatorial sector when comparing the local conductivities. Comparison the vertical profiles of Hall-to-Pedersen conductivity ratio obtained from local conductivities and that from integrated conductivities have shown the height of the peak decent by about 2 km and its amplitude reduced around 10%. The implication of these changes in the conductivity ratio lays on the polarization electric fields which drives the EEJ horizontal current. Considering integrated conductivities we expect this electric field to be 10% weaker than that consider local conductivities, with the same affectivity on the EEJ current. Also, we expect its maximum intensity to be observed 2 km lower.

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