

Longitudinal dependence of the daily geomagnetic variation during quiet time

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[1] The daily variation of the geomagnetic field during quiet time at equinox features a longitudinal dependence, which is observed in the dip-latitude/longitude frame. Two explanations are considered: (1) the longitudinal changes of the geomagnetic latitude at constant dip-latitude and (2) the longitudinal variations of the main field, which modulates the ionospheric dynamo e.m.f. and determines and constrains the field-aligned currents (FAC) that flow between ionospheric hemispheres to maintain the current continuity. The Prairie View ionospheric dynamo model simulates this inter-hemispheric coupling within the International Geomagnetic Reference Field (IGRF) by using magnetic coordinates, and is used for this investigation. Two distinct types of magnetic variation observed at midlatitudes in African and American sectors are explained by the differences in geomagnetic latitude. IGRF longitudinal effects are also in evidence. They account for one singular feature (a large positive excursion of the declination around 4 LT at Plateau). At African midlatitudes, they improve the horizontal component amplitude and the morning decrease of the declination, which are better reproduced with IGRF than with a dipolar main field. FAC, which generate a variation of the geomagnetic field of up to 40% of the horizontal current contribution around midday, are essential to simulate these three cases. *INDEX*

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1. Introduction

[2] The daily variation of the geomagnetic field during times of magnetic quiescence originates with currents in the ionosphere. Thermotidal forces cause ions to move through Earth's magnetic field and thus generate ionospheric currents. Models of this ionospheric dynamo have been developed for decades and have been successful in reproducing its main features [see reviews by *Wagner et al.*, 1980; *Richmond*, 1989, 1995].

[3] The geomagnetic field variation has a spatial dependence primarily on latitude and is affected by other factors including time of the year and level of solar activity. Its longitudinal dependence has also been reported by *Matsushita and Maeda* [1965]. The authors performed a spherical harmonic analysis on the field variation and gave the average pattern at different dip latitudes in three longitudinal sectors: America, Asia/Australia, and Europe/Africa. While the differences between the three sectors mainly consist of slight phase and magnitude differences, contrasting behaviors are present in the South hemisphere. They are particularly noticeable in the horizontal component of the field variation during equinox and have never been

explained or simulated. An example is shown in Figure 1, where magnetic variations are plotted for two dip latitudes at three longitudes. This figure is drawn from the Sq1 model of *Campbell et al.* [1989], which is built from a spherical harmonic analysis similar to that of *Matsushita and Maeda* [1965]. The equinox longitudinal difference between the American sector and the two other sectors is obvious: the H components in the Asian and African sectors have very similar behavior characterized by a positive peak around noon, while in the American sector this peak is negative and accompanied by a positive secondary peak in the morning.

[4] In this paper, we question if this longitudinal variability stems from the Universal Time (UT) variation of the global dynamo system or simply from the difference between geographic and dip latitudes. The UT dependence of the dynamo system, which has been first discovered in the worldwide ionospheric equivalent current Sq [*van Sabben*, 1964; *Malin and Gupta*, 1977; *Wagner et al.*, 1980], produces a longitudinal variation of ionospheric ion drifts that has been observed in situ by satellite [*Maynard et al.*, 1995; *Fejer et al.*, 1995], and should be also present in the magnetic field perturbation. In the other hand, locations at the same dip latitude but different longitudes are found at quite different geographic latitudes, and then are differently affected by the dynamo.

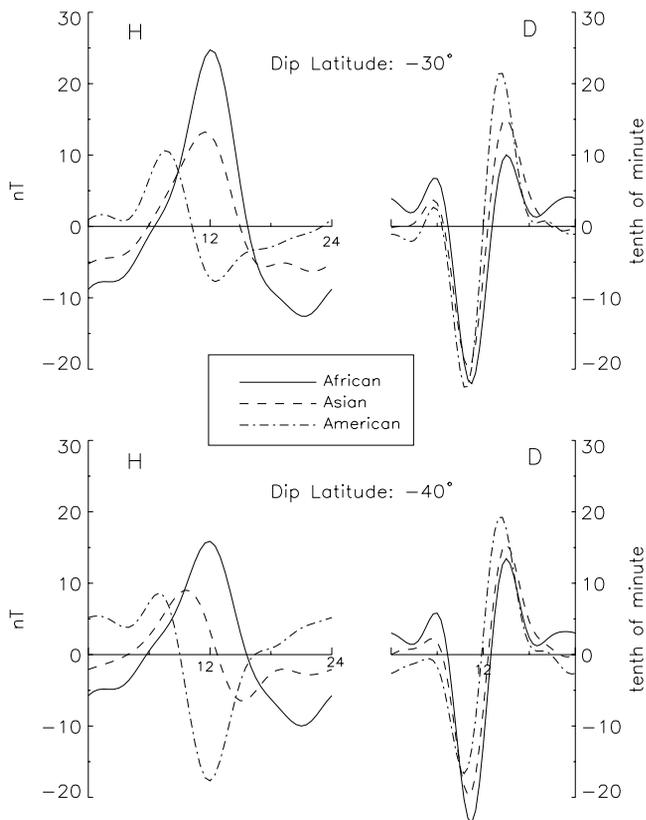


Figure 1. Horizontal component (left column) and declination (right column), at -30° (top) and -40° (bottom) dip latitudes, in three sectors at equinox from the Sq1 model of *Campbell et al.* [1989]. Longitudes used for American, African, and Asian sectors are -90° , $+15^\circ$ and $+120^\circ$, respectively.

[5] The UT variability of the dynamo system originates in the longitudinal variations of the main geomagnetic field, which alongside the distributions of ionospheric conductivity and of neutral wind conditions the dynamo. To reduce discrepancies between observations and their predictions, ionospheric dynamo models have usually been improved by refining conductivity and neutral wind distributions. This includes taking the feedback of ions dynamics on neutral dynamics into account [e.g., *Richmond et al.*, 1976], incorporating experimental-data-based distributions [*Haerendel et al.*, 1992; *Eccles*, 1998] or sophisticated self-consistent plasma distributions [*Crain et al.*, 1993]. Meanwhile, the geomagnetic field was generally approximated by a spin-aligned dipole that prevents from reproducing UT/longitudinal variations. Few modelers have used a tilted dipole field and noted the induced UT variability [*Schildge et al.*, 1973; *Takeda*, 1982; *Richmond and Roble*, 1987]. However, they did not reproduce any UT variation of the Sq system or any longitudinal variation of ionospheric electrodynamics and related geomagnetic variation.

[6] Inclusion of a realistic field model into a dynamo model has two primary effects. First, it modulates conductivities through their dependence on gyrofrequencies, as well as the dynamo electric field $\mathbf{u} \times \mathbf{B}$, where \mathbf{u} is the

neutral wind. Effects of the modulations produced by the International Geomagnetic Reference Field (IGRF) have been investigated and have been shown to account for some of the UT variations in the Sq system [*Stening*, 1971].

[7] The second effect, on which this paper focuses, is due to the coupling between both hemispheres, which allows currents to flow along the highly conducting magnetic field lines to maintain the current continuity in the ionosphere. Modeling this coupling is necessary to reproduce observations [*Wagner et al.*, 1980, and references therein], and its consequences are strongly dependent on the magnetic field configuration. The difficulty to incorporate the interhemispheric coupling within a realistic geomagnetic field lies in the necessity to use a coordinate system aligned with the magnetic field. Two models have overcome this difficulty: the TIE-GCM of *Richmond et al.* [1992], and the Prairie View dynamo model (PVDM) of *Le Sager and Huang* [2002] (referred to hereafter as paper 1). PVDM shows that the interhemispheric coupling along realistic field lines allows the reproduction of a local time shift between the centers of the two vortices that form the current pattern in the ionosphere. Moreover, the simulated time shift and the one observed on Sq pattern present a similar UT-dependence.

[8] The relatively modest goal here is to use PVDM, briefly described in the next section, to reproduce some longitudinal variations of the daily magnetic variation and to explore the role of IGRF in this reproduction. We also examine the contribution of field-aligned currents to the daily magnetic variation.

2. Model Description

[9] The ionosphere is represented by a thin E-layer, where electric field and current are related through the generalized Ohm's law:

$$\mathbf{J} = \Sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B}) \quad (1)$$

where Σ is the conductance tensor, \mathbf{J} is the horizontal current density, and \mathbf{E} is the electric field. Fairly realistic conductances are used following *Farley et al.* [1986], and the fundamental diurnal (1, -2) tidal mode, which has been shown to be the main contributor to the dynamo [e.g., *Richmond et al.*, 1976], models the neutral wind according to equations 25 and 26 of paper 1.

[10] Current continuity is maintained by field-aligned currents, \mathbf{j}_\parallel , flowing between both hemispheres:

$$\nabla \cdot \mathbf{J} = \mathbf{j}_\parallel \cos \chi \quad (2)$$

where χ is the angle between the magnetic field and the normal to the ionosphere. The coupling between ionospheric hemispheres occurs along field lines and is expressed as:

$$\left(\frac{j_\parallel}{B}\right)_S = \left(\frac{j_\parallel}{B}\right)_N \quad (3)$$

where subscripts N and S stand for north and south hemisphere footprints. To model this coupling in a realistic

geomagnetic field, magnetic coordinates are used. They are based on Euler potential and have been built for IGRF 1995 [AGA Division V, 1996], following the method developed in our group and applied with success to Uranus [Gao et al., 1998] and Neptune [Ho et al., 1997] magnetic fields.

[11] Equations (1) and (2) are expressed at both footprint of each field lines and then combined with (3) to provide, under assumption of equipotential field lines, a differential equation for the potential Φ , which is expressed in magnetic coordinates α and β as:

$$P_1 \frac{\partial^2 \Phi}{\partial \alpha^2} + P_2 \frac{\partial^2 \Phi}{\partial \beta^2} + P_3 \frac{\partial \Phi}{\partial \alpha} + P_4 \frac{\partial \Phi}{\partial \beta} + P_5 \frac{\partial^2 \Phi}{\partial \alpha \partial \beta} = P_6 \quad (4)$$

The P_i ($i=1, \dots, 6$) coefficients are given in paper 1. Equation (4) is numerically solved on a 101×60 grid representing one magnetic hemisphere. The boundaries are the magnetic pole and the dip magnetic equator, near which smaller grids are used to compute sharply changing coefficients. The electric potential is then mapped onto the other hemisphere, and electric fields, ionospheric and field-aligned currents are computed on the 201×60 grid. The chain of computations ends with the integration of Biot-Savart law,

$$\Delta \mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int_V \frac{\mathbf{j}(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV \quad (5)$$

to get the magnetic field induced at \mathbf{r} by ionospheric and field-aligned currents $\mathbf{j}(\mathbf{r}')$. This last step is time consuming and many numerical techniques have been used to accelerate it. The further from the planet the field-aligned current element is, the longer the interval length along the field line is. This interval length ranges from $1.10^{-6} R_E$ for $r' < 2 R_E$ to $0.1 R_E$ for $r' > 15 R_E$. We do not take into account the contribution of current element located further than 30 Earth radii. Noting that the expansion up to order 10 of IGRF magnetic moments is also significantly time consuming, we also limit the expansion when we go away from the planet. IGRF is reduced to a tilted dipole at $20 R_E$.

[12] The details of the model are given in paper 1, where it has been shown that PVDM is successful in reproducing the main features of the dynamo system and some of its UT variations. The main limits consist of unrealistic nighttime and high-latitudes, and are a result of having neglected the polar cap potential drop, electron precipitation in the auroral region, and the F-layer. The model fails also in the vicinity of the magnetic equator, where the shell approximation is not valid. Finally, note that currents induced in the Earth are not taken into account in computing the ground magnetic perturbation. The following results are then mainly qualitative.

3. Results

[13] All results are for equinox conditions. Simulations have been performed for 24 evenly spaced UT and the results have been pieced together to provide local variation at specific locations. Magnetic perturbations induced by all

currents, included those in the unrealistic high-latitude and the nighttime regions, are taken into account. However, nighttime currents being generally a lot smaller than daytime currents, they do not significantly affect the results.

3.1. Contribution of Field-Aligned Currents

[14] Field-aligned currents (FAC) arise from asymmetry between the dynamo actions in both hemispheres. In paper 1, we found that IGRF asymmetry is as efficient as conductivity and neutral wind asymmetries in driving FAC, with an order of magnitude of 10^{-8} A/m^2 at midlatitudes. In Figure 2, absolute values of the total field perturbation produced by FAC and ionospheric horizontal currents are compared. Mollweide projections centered on the noon meridian are used to emphasize the relevant daytime midlatitude results. The shell approximation of the model assumes a constant dip angle along each field line within the E region. This is not valid in the vicinity of the magnetic equator, and the structures around the equator in Figure 2 are consequently not reliable. The percentages are also irrelevant toward the terminators, where they refer to small values. The three evenly spaced UT illustrate the variability of the FAC contribution pattern. The 8 and 0 UT patterns are representative of all other UT patterns, while the 16 UT result is a particular case featuring low FAC-produced perturbation. It is worth noting that the FAC-produced perturbation is typically between 0 and 40% of the perturbation produced by ionospheric currents during midday, in accordance with the 25% average estimate of *Richmond and Roble* [1987]. In the following section, the FAC importance in computing magnetic perturbation is also addressed, but through each magnetic element separately.

3.2. Local Comparisons

[15] With our simple model, observed magnetic variations are fairly reproduced but not in details. Better reproductions for few American midlatitude locations have been published by *Richmond and Roble* [1987], probably because they use more realistic neutral wind and conductivities than we do, and because they take into account the currents induced in the Earth. They use a tilted dipole for the geomagnetic field, which is a good approximation for the American sector, but do not attempt to reproduce measurements in other sectors. Our approach is complementary and investigates the longitudinal variations generated by using IGRF.

[16] To compare our results with observations analyzed by *Matsushita and Maeda* [1965], we should interpolate our results on a dip-latitude/longitude grid and then average them by longitudinal sector. To avoid additional processing on simulation results, we choose to directly compare them with observations at selected geomagnetic stations. Besides, individual day data are used instead of an average of many equinox quiet days. This choice is dictated by our qualitative approach: we try to reproduce some common trends of the magnetic perturbation, but not exactly all the details, which depend on many factors like the solar activity. Thus, individual days data may be used if the observed variations are common and if the comparisons are qualitative and focus on the regular trends.

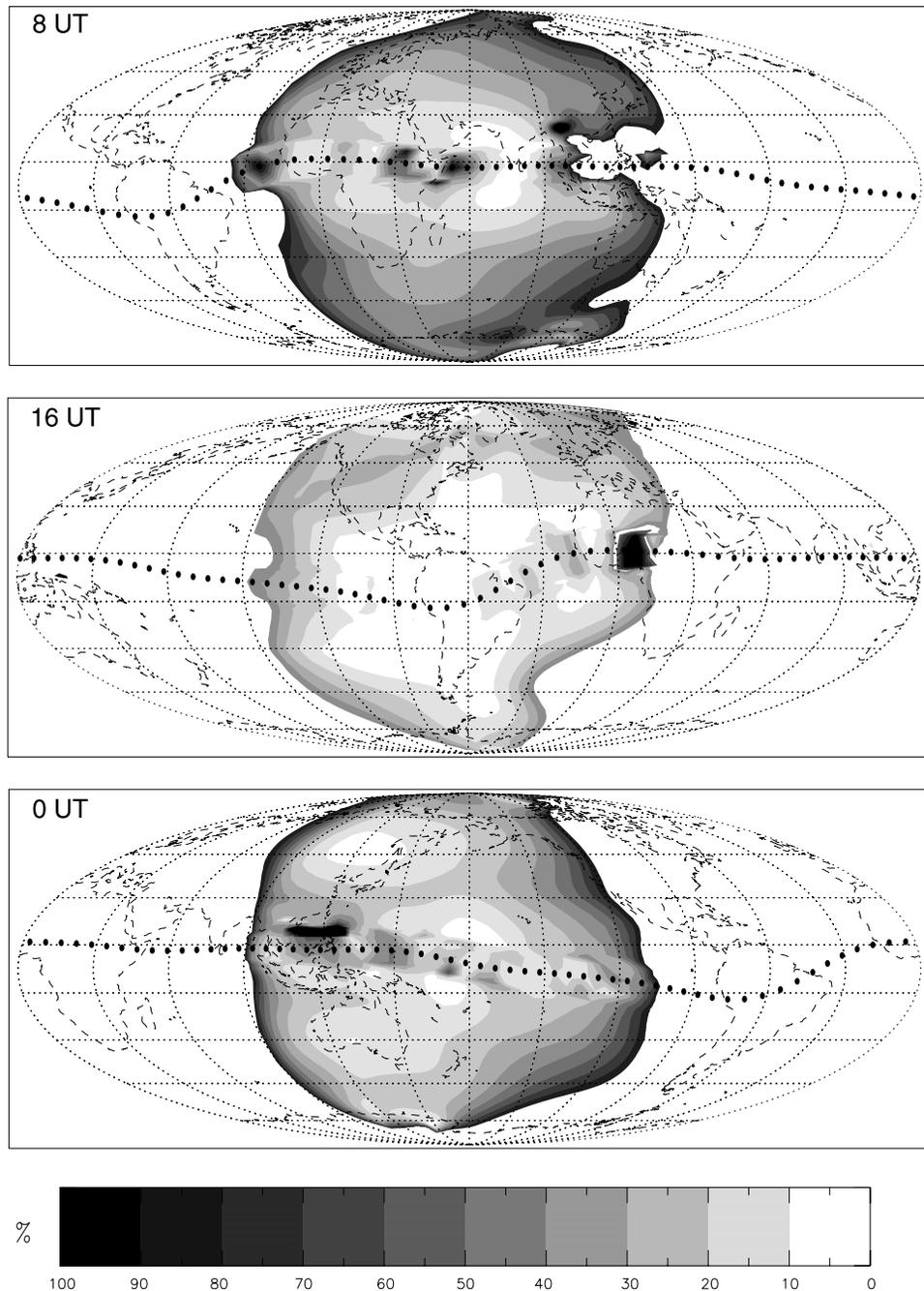


Figure 2. Magnitude of the perturbation induced by field-aligned currents in percentage of the magnitude of the perturbation induced by ionospheric currents, for 3 UT. Each projection is centered on noon.

[17] Table 1 provides the coordinates of each selected observatory, while Figure 3 shows their location along contours of dip latitude. The dip latitude θ , defined as

$$\tan(\varphi) = 2\tan(\theta) \quad (6)$$

where φ is the dip angle, is considered as a much better latitudinal parameter than the geomagnetic or geographic latitudes to organize geomagnetic data. Dip latitude contours in Figure 3 show the significant departures of the geomagnetic field from dipolar configuration in the

Table 1. Observatory Coordinates

Observatory	Geographic Latitude	East Geographic Longitude	Dip Latitude
Plateau	-79.25	40.50	-51.6
Gnangara	-31.78	115.95	-49.6
Canberra	-35.32	149.36	-49.0
Luanda	-8.92	13.17	-28.4
Tsumeb	-19.22	17.70	-41.5
South Georgia	-54.28	323.52	-34.3
Argentine Island	-65.25	295.74	-38.4

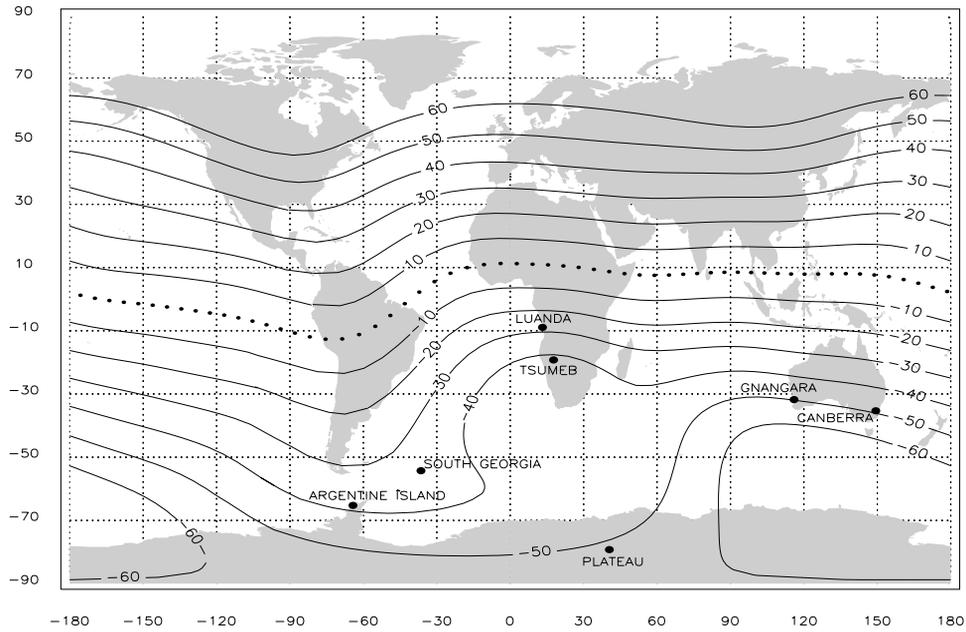


Figure 3. Dip latitude contours for IGRF 1995 and localization of the geomagnetic stations selected for this report.

African and South American sectors. The following comparisons will determine if the longitudinal variations observed on magnetic perturbation, as shown in Figure 1, are mainly related to these departures or to the difference in geographic latitude of stations at similar dip latitude but different longitudes. In the latter case, dipole results should reproduce observed differences. Otherwise, if IGRF is needed, then the non-dipolar effects (FAC, i.e. differences between dynamo processes at conjugated footprints, and modulation of e.m.f.) produce non-negligible longitude variations.

[18] Quiet days, in such a way that the geomagnetic index, A_p , was less than or equal to 7, have been selected for all observations. The declination D , positive eastward, and the horizontal component H , positive northward, have only been considered, because the vertical component Z does not feature a strong longitudinal dependence. For the same reason, the North hemisphere results are not reported.

For each of the following comparisons, the dip latitude, the observation day and the A_p index are indicated above the related figures. Results for IGRF and the dipolar (DP) main field are compared with observations. In the case of IGRF we examine the perturbation created by horizontal currents only by neglecting the FAC contribution. Such a comparison can be misleading. Indeed, if the perturbation induced by FAC is not taken into account, FAC effects are still present because they appear implicitly into the computation of the shell current distribution. In other words, the inter-hemispheric coupling is still in effect.

3.3. Around -50° Dip Latitude

[19] Three stations are considered: Plateau in the African sector, and Gnangara and Canberra in the Australian sector. The declination measured at these stations is shown in Figure 4. Gnangara and Canberra data are characterized by a morning minimum and an afternoon maximum, while

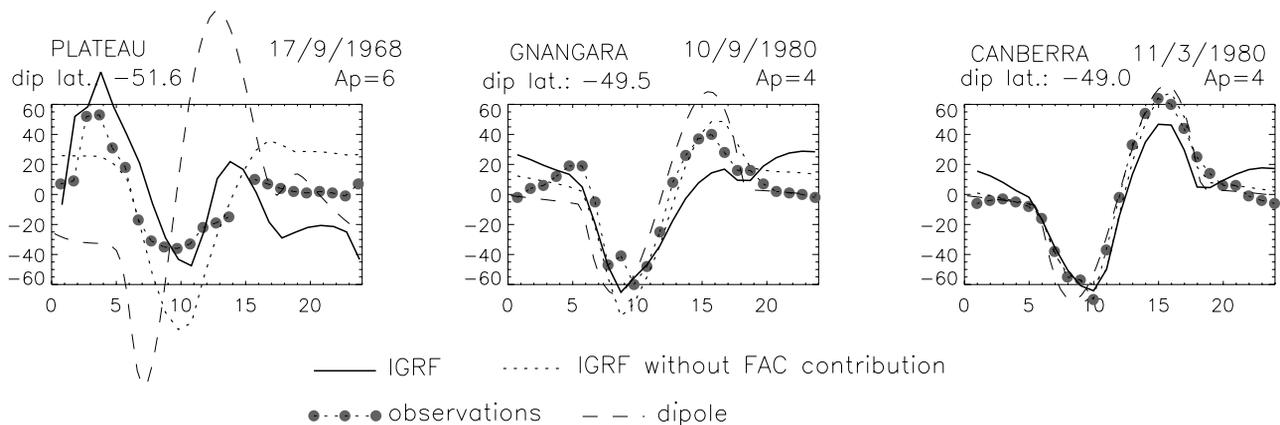


Figure 4. Declination of the magnetic variation in tenth of minute, observed (grey circles) and simulated around -50° dip latitude. Abscises are in Local Time.

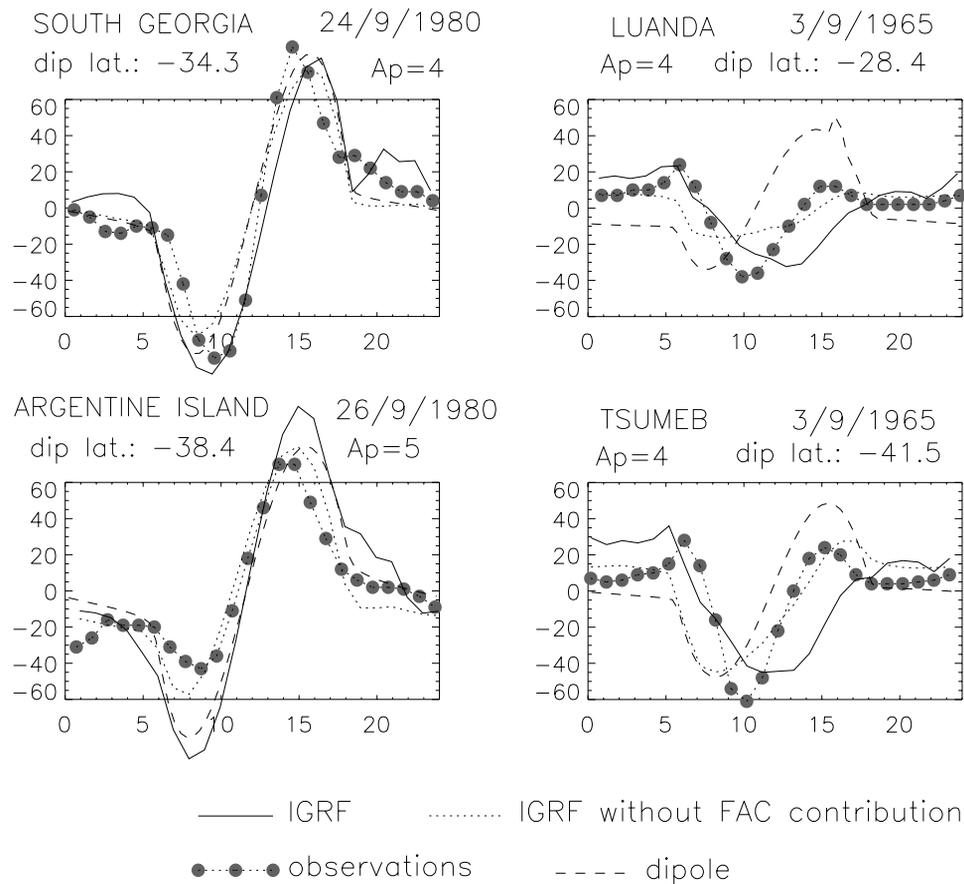


Figure 5. Declination, as Figure 4, but at 4 midlatitude stations. Two stations in the American sector (left column) and two in the African sector (right column).

the main feature at Plateau is an enhancement at 4 LT, probably related to the unique magnetic topology around the station, as seen in Figure 3. The simulated results with IGRF and DP reproduce a morning minimum at both Gwangara and Canberra, but only in case of IGRF a maximum at 4 LT is featured at Plateau. Given that similar variations are produced at the three stations in DP case, non-dipolar magnetic moments are then responsible of Plateau's morning feature, despite the failure of IGRF results to reproduce a clear afternoon peak at Gwangara. Furthermore, Plateau's morning feature can be reproduced only if the FAC-induced perturbation is taken into account. This follows the fact that the E region conductivity drastically drops at night, and horizontal currents are small. An exceptionally large FAC is then responsible of the positive excursion at 4 LT at Plateau. One may wonder why FAC are present at night. Although small, the night conductivity plays an important role, because there are always field lines with one footprint in daytime and the other one in nighttime. This is the crucial point. Daytime and nighttime dynamo are not isolated from each other, and to maintain the current continuity, there will always be some current flowing between day and night. Nighttime currents (both horizontal and parallel) are usually a lot smaller than daytime currents. However, the FAC density can exceptionally reach daytime level, like around Plateau at about 4 LT.

[20] Figure 4 also shows discrepancies after sunset between observations and model results when FAC are

taken into account. These discrepancies may stem from neglecting the F region or assuming infinite conductivity along field lines. They may also be related to neutral wind and conductivities uncertainty, but a definitive answer requires an improved model.

3.4. D and H Components at Midlatitudes

[21] We now consider four other stations: South Georgia and Argentine Island in the American Sector, and Luanda and Tsumeb in the African sector. At these midlatitude locations, the two components D (Figure 5) and H (Figure 6) present the most striking differences between two sectors. The horizontal H component features a negative variation in the American zone and a positive variation in the African zone. As for the declination D, a negative variation in the morning is followed by a positive one in the afternoon in the American sector that contrasts with the daytime negative variation in Africa. Note that the four selected stations are representative of the whole dip latitude range between about -25° and -40° in each sector. Moreover, these midlatitude American/African differences are still present in observations averaged over 120° -width sectors [Matsushita and Maeda, 1965]. This suggests that station differences reflect a systematic change over a large geographical area.

[22] However, the $[-40^\circ; -25^\circ]$ dip latitude range corresponds with two distinct geographic-latitude ranges (cf. Figure 3): $[-70^\circ; -40^\circ]$ in South America and $[-20^\circ; -10^\circ]$ in Africa. The observed trends are then likely to be

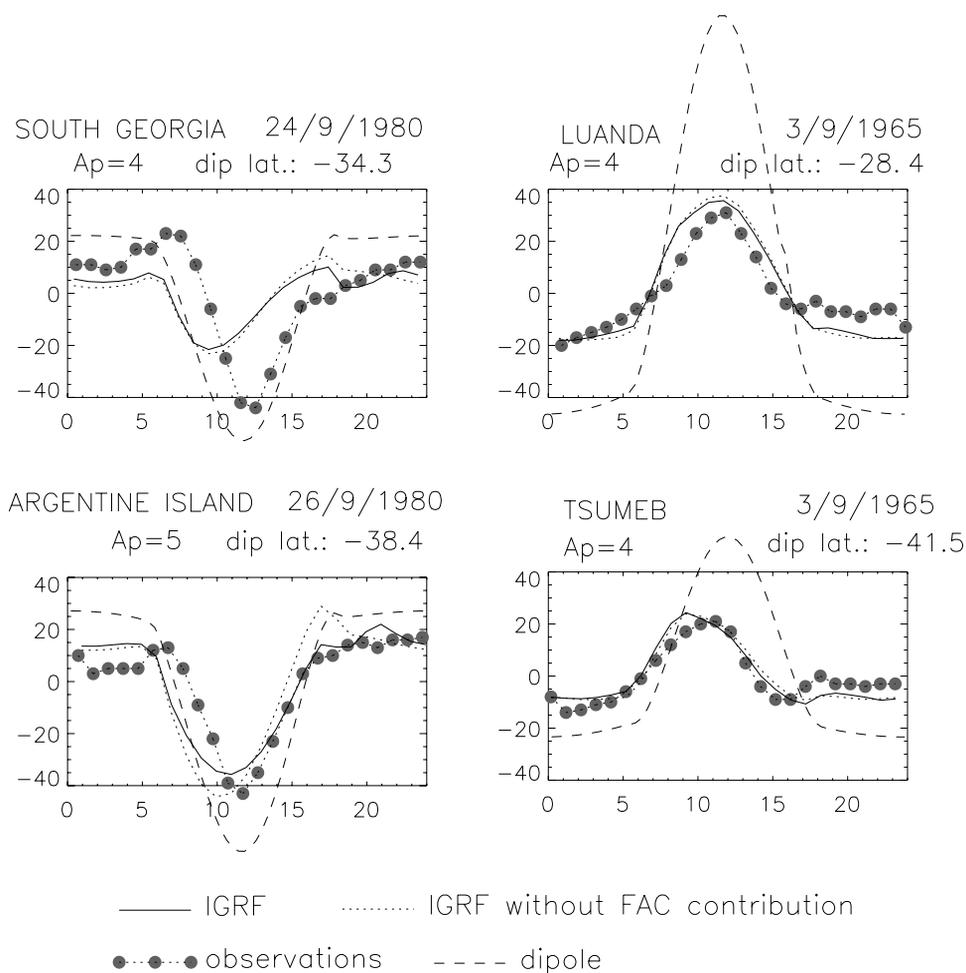


Figure 6. Same as Figure 5 but for the horizontal component H, in nT.

determined by the latitudinal distance to the magnetic equator and not to the longitudinal changes in the main field. Figure 6 provides a typical example: keeping in mind that the current in the Sq south vortex flows clockwise, the positive H variation in Africa corresponds with stations above the Sq focus, while the negative excursion at South Georgia and Argentine Island are typical of stations below the Sq focus. Using IGRF instead of DP only improves the perturbation magnitude in African stations. This confirms that the differences between the two sectors at mid-dip-latitudes are due to the difference in geographic latitude, and that IGRF effects are secondary and do not determine the type of variation.

[23] As for the D component (Figure 5), DP simulations show a similar variation, i.e. a morning minimum and an afternoon maximum, in both sectors, with an amplitude difference. This variation is also the one observed in America but not exactly in Africa, where the local time of the morning minimum happens later and the afternoon positive excursion is not usually as important as the morning negative excursion. To reproduce the latter case, let us consider IGRF simulations. They do not significantly modify DP results in the American sector, where they are still very similar to observed data. In the African sector, a noticeable improvement appears with IGRF around morning, but discrepancies remain along the all afternoon. In con-

clusion, the differences in geomagnetic latitudes explain the main difference observed on the H component, while using IGRF provides better amplitudes for H in Africa and closer-to-observation morning features for D in Africa.

[24] Finally, it is interesting to examine the contribution of FAC-induced perturbation within IGRF. In Figure 6, it is seen that this contribution brings no significant difference for the H component. The declination (Figure 5) is more sensitive to the FAC perturbation, particularly in Africa, where its morning decrease is better reproduced with this contribution. Thus, like at Plateau, when IGRF is needed to explain observations, the perturbation due to FAC cannot be neglected.

4. Conclusion

[25] A longitudinal dependence in the equinoctial daily geomagnetic variation has been observed in the dip-latitude/longitude framework. In this framework, two possible causes of longitudinal changes compete: longitudinal changes in the main geomagnetic field, and longitudinal changes in geomagnetic latitude. The latter indicates the distance to the dip equator and varies along lines of constant dip-latitude. As for the geomagnetic field, its asymmetry produces a longitudinal dependence in the dynamo system through the interrelated following characteristics: inter-

hemispheric coupling (FAC), modulation of dynamo e.m.f. and conductivities, and asymmetric feedback on neutral dynamics.

[26] We used the Prairie View ionospheric dynamo model to simulate the daily geomagnetic variation, under a dipolar main field and IGRF. Conductivities modulation and asymmetric feedback on neutral wind are neglected, but FAC can flow along the magnetic field lines. The dipolar simulations are used to isolate longitudinal variations that come from longitudinal changes in geomagnetic latitude.

[27] Comparing observations with simulation results, we showed that two distinct types of variation observed at mid-dip-latitudes on the H component are explained by the difference in geomagnetic latitude. One type corresponds with observatories above the ionospheric current focus, the other one with observatories below it. The longitudinal effects due to IGRF asymmetry have also been determined. They allow the reproduction of one large positive excursion of the declination around 4 LT at -50° dip latitude in the African sector. They also improve the magnitude of the H component and the morning decrease of the D component, both at African midlatitudes. Moreover, these effects are visible only if FAC-generated perturbations are taken into account.

[28] These results confirm the importance of IGRF effects and of the inter-hemispheric coupling for ionospheric electrodynamics, although their noticeable consequences are very localized.

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References

- Campbell, W. H., E. R. Schiffmacher, and H. W. Kroehl, Global quiet day field variation model WDCA/SQ1, *Eos Trans. AGU*, 70, 66–74, 1989.
- Crain, D. J., R. A. Heelis, G. J. Bailey, and A. D. Richmond, Low-latitude plasma drifts from a simulation of the global atmospheric dynamo, *J. Geophys. Res.*, 98, 6039–6046, 1993.
- Eccles, J. V., Modeling investigation of the evening prereversal enhancement of the zonal electric field in the equatorial ionosphere, *J. Geophys. Res.*, 103, 26,709–26,719, 1998.
- Farley, D. T., E. Bonelli, B. G. Fejer, and M. F. Larsen, The prereversal enhancement of the zonal electric field in the equatorial ionosphere, *J. Geophys. Res.*, 91, 13,723–13,728, 1986.
- Fejer, B. G., E. R. de Paula, R. A. Heelis, and W. B. Hanson, Global equatorial ionospheric vertical plasma drifts measured by the AE-E satellite, *J. Geophys. Res.*, 100, 5769–5776, 1995.
- Haerendel, G., J. V. Eccles, and S. Çakir, Theory for modeling the equatorial evening ionosphere and the origin of the shear in the horizontal plasma flow, *J. Geophys. Res.*, 97, 1209–1223, 1992.
- Gao, S., C. W. Ho, T.-S. Huang, and C. J. Alexander, Uranus' magnetic field and particle drifts in its inner magnetosphere, *J. Geophys. Res.*, 103, 20,257–20,265, 1998.
- Ho, C. W., T. S. Huang, and S. Gao, Contributions of the high-degree multipoles of Neptune's magnetic field: An Euler potentials approach, *J. Geophys. Res.*, 102, 24,393–24,401, 1997.
- IAGA Division V, Working Group 8, Revision of International Geomagnetic Reference Field released, *Eos Trans. AGU*, 77(17), Spring Meet. Suppl., S153, 1996.
- Le Sager, P., and T. S. Huang, Ionospheric currents and field-aligned currents generated by dynamo action in an asymmetric Earth magnetic field, *J. Geophys. Res.*, 107(A2), 1025, doi:10.1029/2001JA000211, 2002.
- Malin, S. R.C., and J. C. Gupta, The Sq current system during the International Geophysical Year, *Geophys. J. R. Astron. Soc.*, 49, 515–529, 1977.
- Matsushita, S., and H. Maeda, On the geomagnetic solar quiet daily variation field during the IGY, *J. Geophys. Res.*, 70, 2535–2558, 1965.
- Maynard, N. C., T. L. Aggson, F. A. Herrero, M. C. Liebrecht, and J. L. Saba, Average equatorial zonal and vertical ion drifts determined from San Marco D electric field measurements, *J. Geophys. Res.*, 100, 17,465–17,479, 1995.
- Richmond, A. D., Modeling the ionosphere wind dynamo: A review, *Pure Appl. Geophys.*, 47, 413–435, 1989.
- Richmond, A. D., The ionospheric wind dynamo: effects of its coupling with different atmospheric regions, in *The Upper Mesosphere and Lower Thermosphere: A Review of Experiment and Theory*, *Geophys. Monogr. Ser.*, vol. 87, edited by R. M. Johnson and T. L. Killeen, pp. 49–65, AGU, Washington, D.C., 1995.
- Richmond, A. D., and R. G. Roble, Electrodynamic effects of thermospheric winds from NCAR TGCM, *J. Geophys. Res.*, 92, 12,365–12,376, 1987.
- Richmond, A. D., S. Matsushita, and J. D. Tarpley, On the production mechanism of electric currents and fields in the ionosphere, *J. Geophys. Res.*, 81, 547–555, 1976.
- Richmond, A. D., E. C. Ridley, and R. G. Roble, A thermosphere/ionosphere general circulation model with coupled electrodynamics, *Geophys. Res. Lett.*, 19, 601–604, 1992.
- Schildge, J. P., S. V. Venkateswaran, and A. D. Richmond, The ionospheric dynamo and equatorial magnetic variations, *J. Atmos. Terr. Phys.*, 35, 1045–1061, 1973.
- Stening, R. J., Longitude and seasonal variations of the Sq current system, *Radio Sci.*, 6, 133–137, 1971.
- Takeda, M., Three dimensional ionospheric currents and field aligned currents generated by asymmetrical dynamo action in the ionosphere, *J. Atmos. Terr. Phys.*, 44, 187–193, 1982.
- van Sabben, D., North-South asymmetry of Sq, *J. Atmos. Terr. Phys.*, 26, 1187–1195, 1964.
- Wagner, C.-U., D. Möhlmann, K. Schafer, V. M. Mishin, and M. I. Matveev, Large scale electric fields and currents and related geomagnetic variations in the quiet plasmasphere, *Space Sci. Rev.*, 26, 391–446, 1980.

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