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TRANSEQUATORIAL FIELD-ALIGNED CURRENTS AT LOW LATITUDES AND THEIR POSSIBLE CONNECTION WITH THE EQUATORIAL ELECTROJET

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The seasonal dependence of the geomagnetic Sq-field reveals the existence of three principal transequatorial field-aligned currents in the magnetosphere, i.e., a winter-to-summer current at middle latitudes connecting the regions of the northern and southern Sq current foci, and a pair of low-latitude currents (summer-to-winter in the morning and winter-to-summer in the early afternoon). The latter two currents at low latitudes seem to extend down to the lower ionosphere to interact or coexist with the equatorial electrojet. The three-dimensional current closure of the equatorial electrojet must be discussed taking into account these transequatorial field-aligned currents in the magnetosphere and various experimental results obtained with rockets and satellites.

CORRENTES TRANSEQUATORIAIS PARALELAS AO CAMPO EM BAIXAS LATITUDES E SUAS POSSÍVEIS RELAÇÕES COM O ELETROJATO EQUATORIAL *A variação sazonal do campo geomagnético Sq indica a existência de três correntes transequatoriais principais ao longo de B na magnetosfera, isto é, uma corrente de inversão-verão em latitudes médias ligando as regiões dos focos Sq norte e sul, e um par de correntes de baixas latitudes (verão-inverno pela manhã e inverno-verão no começo de tarde). Estas correntes de baixas latitudes parecem estender-se até a baixa ionosfera, interagindo e participando do eletrojato equatorial. O circuito tridimensional do eletrojato equatorial deve ser discutido levando em conta estas correntes transequatoriais ao longo do campo na magnetosfera, e esta discussão deve considerar os vários resultados experimentais obtidos com foguetes e satélites.*

INTRODUCTION

For the success of the IEEY (International Equatorial Electrojet Year) project, it is necessary to compare simultaneous observational results at a number of low-latitude stations, and it is desirable that the observed data be analyzed by the people belonging to each observatory (or its parent organization), so as to show up the specific characteristics proper to each observatory as their own scientific contributions to the IEEY project.

The equatorial electrojet is a concentrated eastward current along the magnetic dip equator during the daytime at the bottom of the ionosphere, but its global current circuit in the ionosphere-magnetosphere is still to be studied in the future. The present paper points out a possible interaction of the equatorial electrojet (flowing in the lower ionosphere) with low-latitude (also low-altitude) field-aligned currents (in the upper ionosphere and magnetosphere). The discussion in this paper is based on the analysis of the ground magnetograms and the experimental contribution from MAGSAT.

EQUIVALENT CURRENT-SYSTEM FOR Sq IN SUMMER AND WINTER

The geomagnetic daily variation on quiet days (Sq-field) and its seasonal dependence has been extensively studied with a reasonable hypothesis that the Sq-field must be mostly attributable to horizontal currents in the lower ionosphere at the E layer level, so-called the dynamo region at a height of 100-120 km above the ground. There is a theorem that the ground magnetic effect of any three-dimensional space current can be represented uniquely by an "equivalent overhead current-system" on a spherical shell at a certain height above the ground concentric with the earth.

With this equivalent current representation, Price and Stone (1964) discussed the line of demarcation between the northern and sourthern Sq current systems with the world data in 1958, and they stated as follows: "There is unmistakable evidence that, during the J months (May, June, July and August, i.e., the northern summer months), the northern system penetrates deeply into the southern hemisphere in the morning hours, crossing and recrossing both the geographic and magnetic dip equators. There is also evidence that the southern system penetrates into the northern hemisphere, though less deeply, in the afternoon. Further, there is evidence of corresponding but smaller penetrations during the E (for Equinoctial, i.e. March, April, September and October) and D months (November, December, January and February, i.e., the southern summer months). This disproves the assumption sometimes made that the dip equator is always the boundary line between the northern and southern systems".

FIELD-ALIGNED CURRENTS AT MIDDLE AND LOW LATITUDES

Actual currents in the earth's space environment must be three-dimensional, consisting of horizontal currents flowing in the ionosphere (collision-dominant gas for charged particles) and field-aligned currents in the magnetosphere (rather collisionless medium). Although there is no unique conversion from a two-dimensional equivalent current-system to an actual three-dimensional one, it is quite natural to think of some transequatorial field-aligned currents that will easily flow even under a small difference in the electric potential values in the ionosphere at conjugate-pair points of the northern and southern hemispheres (note here that the electric conductivity in N-S direction at 250 km altitude is approximately 10^3-times that at 100 km level).

Experimental evidence for field-aligned current sheets has been known since the middle 1960's from a steep spatial gradient of the E-W component of the geomagnetic field measured by various satellites above the northern and southern auroral zones. In comparison with field-aligned currents at high latitudes, the current density at middle and low latitudes is too low (much less than 1 $\mu A/m^2$) to be detected by satellite instruments, but this does not mean at all the absence of field-aligned currents there. We can infer the existence of field-aligned currents at middle and low latitudes from an analysis of the ground magnetic data, in particular from the seasonal dependence of the diurnal variation in the magnetic declination.

Fig. 1 is a schematic illustration for three principal field-aligned currents flowing in the magnetosphere (Fukushima, 1991), which is deduced from the seasonal dependence of the diurnal geomagnetic Sq-variation. These field-aligned currents flow so long as an electric potential difference exists between the conjugate-pair points of the northern and southern hemispheres. An intuitive explanation for the dynamo action in the ionosphere is given by Fukushima (1979), and it is outlined in the Appendix.

MID-LATITUDE FIELD-ALIGNED CURRENT

At the Sq current vortex centre, the electric potential in the dynamo region shows a minimum value, both in the summer and winter hemispheres (see Appendix). A field-aligned current will then flow out from the winter hemisphere into the summer one, because the potential value is more negative in the summer. Such a field-aligned current from/to the Sq current foci was advocated by van Sabben (1966, 1969, 1970), Maeda (1974), and others.

Fig. 2 shows a schematic diagram for the ground magnetic effect of a field-aligned current connected to the return current spreading all over the ionosphere. The resulting ground magnetic effect is given with its equivalent current (by broken lines), and the diverging return current in the ionosphere from point N is replaced simply by an upward line-current, referring to Fukushima (1971, 1976). In general, the ground magnetic effect from a field-aligned current is cancelled, up to a considerable extent (depending on the magnetic dip angle also), by the effect from its return current flowing in the ionosphere. Mazaudier (1985) showed experimental evidence for this fact. In the case of Fig. 2 the ground effect is appreciable only near both feet of the field-aligned current.

Fukushima (1991) showed the transequatorial field-aligned currents from the seasonal dependence of the Sq-variations at middle latitudes. Since all middle-latitude field-aligned currents flow without any interaction with the equatorial electrojet, they will not be discussed any more in this paper. However, it will be worth mentioning that the potential difference between the two hemispheres might produce hot electrons detectable only near the Sq current focus in the winter, as reported by Oyama and Hirao (1979).

LOW-LATITUDE FIELD-ALIGNED CURRENTS IN THE MORNING AND AFTERNOON

A very interesting feature of the daily Sq variation at an IGY temporary observatory at Koror 7°20'N, 134°30'E was reported by Gettemy (1962). The station was just on the magnetic equator; the monthly mean *Z*-value was 0 nT in July 1957 and -84 nT in December 1958. Fig. 3 shows the daily variation at Koror on quiet days for the three components of the geomagnetic field, where we notice that ΔD daily variations are reversed in the summer and winter seasons. The seasonal dependence of ΔD was reported also by Onwumechilli and Alexander (1959), Glover (1963), Hutton (1967) and others.

Although the ground magnetic effect of field-aligned current is considerably reduced at middle latitudes by the return current flowing in the ionosphere, as explained with Fig. 2, the effect is noticeable in the equatorial region for low-latitude field-aligned current because of a small dip angle there.

POSSIBLE INFLUENCE OF INDUCED CURRENT IN THE SEA UNDER THE ELECTROJET

The geomagnetic field variations observed on the earth's surface comes primarily from electric currents in the surrounding space, and partly also from currents induced within the earth due to the time variation of external magnetic field. The effect of induced currents appears most clearly in the vertical

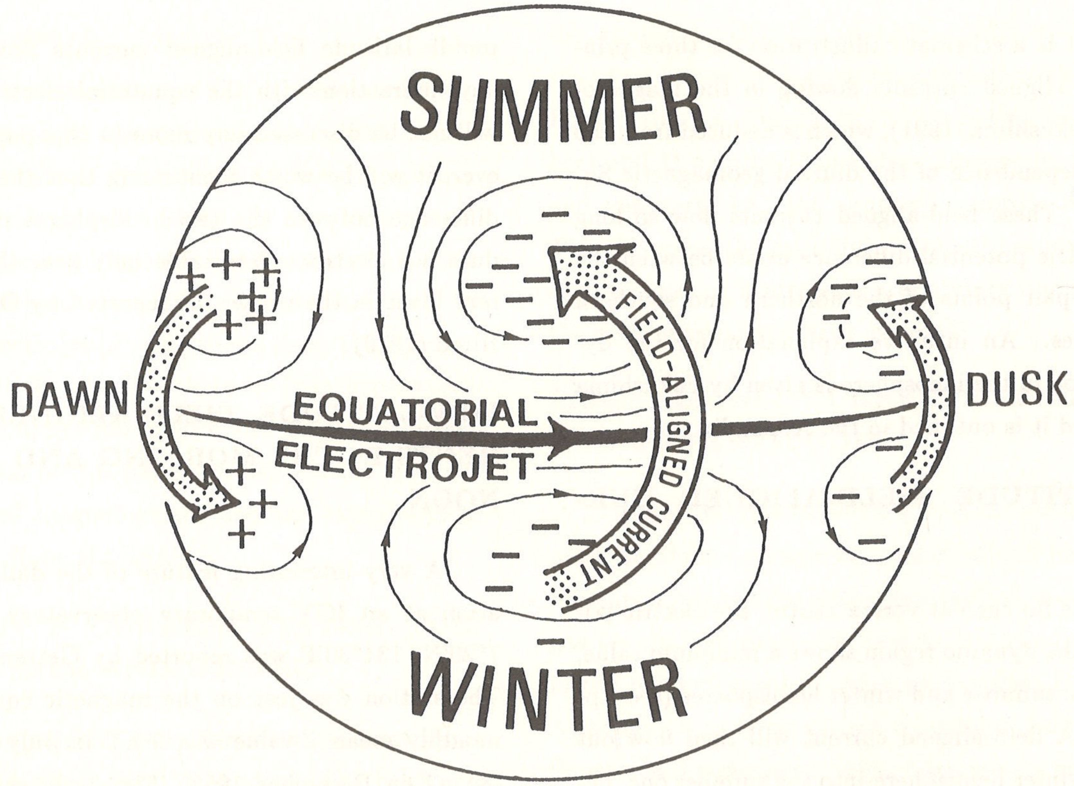

Figure 1. A schematic model of interhemispheric field-aligned currents in the magnetosphere at middle and low latitudes.

Modelo esquemático de correntes inter-hemisféricas ao longo de B na magnetosfera em latitudes médias e baixas.

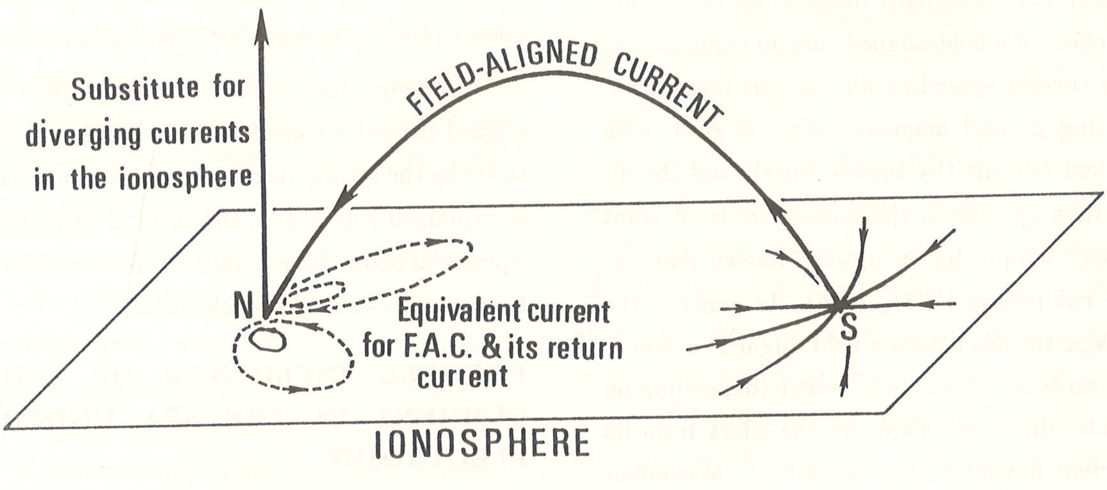

Figure 2. Equivalent current in the ionosphere (by dotted lines) for the ground magnetic effect of a field-aligned line-current connected to diverging and converging horizontal return currents in the ionosphere. At point N, the diverging current is replaced by an upward line-current based on their equivalence in the ground magnetic effect.

Corrente equivalente na ionosfera (linhas pontilhadas) para o efeito magnético de superfície de uma corrente linear ao longo de B ligada a correntes horizontais de retorno divergentes e convergentes, na ionosfera. No ponto N, a corrente divergente é reposta por uma linha de corrente para cima, baseada na sua equivalência no efeito magnético de superfície.

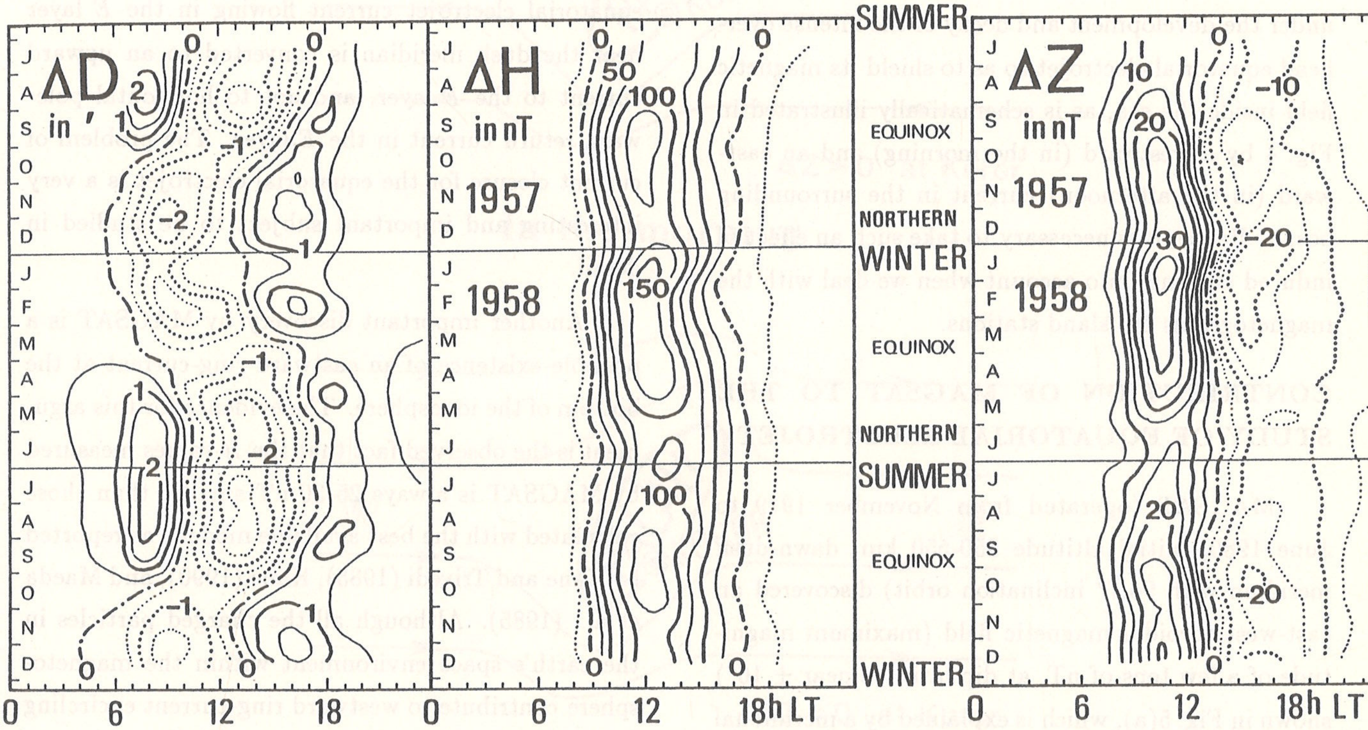

Figure 3. Magnetic daily variation (deviations from daily-mean values) for the three components of the geomagnetic field on quiet days on Koror island (situated on the magnetic equator in the West Pacific) during the IGY (based on Gettemy's 1962 paper).

Variação magnética diária (desvios das médias diárias) para as três componentes do campo geomagnético em dias calmos, na ilha de Koror (situada no equador magnético no Pacífico ocidental), durante o IGY (com base no artigo de Gettemy, 1962).

component of the geomagnetic field, if the electric conductivity of the earth's surface medium shows a remarkable nonuniformity around the observing station. The electric conductivity of the sea water is much higher than the ground soil, so that the magnetogram traces on isolated islands depend strongly on the topographic condition around the observing station.

In the Sq variation at Koror shown in Fig. 3, ΔZ is positive in the forenoon and negative in the afternoon, regardless of the season throughout the year. This systematic daily variation in ΔZ is attributable to the effect of induced currents at the sea surface, under the development and decay of the intense overhead equatorial electrojet so as to shield its magnetic field inside the sea, as is schematically illustrated in Fig. 4 by a westward (in the morning) and an eastward (in the afternoon) current in the surrounding ocean. Hence, it is necessary to take such an effect of induced currents into account when we deal with the magnetograms on island stations.

CONTRIBUTION OF MAGSAT TO THE STUDY OF EQUATORIAL ELECTROJET

MAGSAT (operated from November 1979 to June 1980, initial altitude 350-550 km, dawn-dusk meridian with 96.7° inclination orbit) discovered an east-west toroidal magnetic field (maximum magnitude of a few tens of nT, at dip latitude near ± 10°) shown in Fig. 5(a), which is explained by a meridional current circulation modelled in Fig. 5(b). This experimental evidence reported by Maeda et al. (1982, 1985) is to be compared with the earlier theoretical predictions for the existence of such a meridional current circulation by Untiedt (1967), and Sugiura and Poros (1969). On the other hand, this discovery by MAGSAT triggered the study of the interaction of the ionospheric E and F regions, discussed for example by Duhau and Louro (1983), Louro and Duhau (1988), and Takeda and Maeda (1983).

Looking at Fig. 5(b), we see that the meridional current circulation (with an upward vertical current at the dip equator) requires a pair of equatorward currents on both sides of the equator at the bottom of the ionosphere. On the other hand, the gradual decay with local time in the eastward electrojet intensity in the dusk region requires some poleward currents from the electrojet. It is interesting to point out that these two currents in the lower ionosphere (one towards the equator, and the other in the opposite direction from the equator) are nearly of the same density, at least in the order of magnitude estimation. If these two currents have the same density, we may state that the equatorial electrojet current flowing in the E layer near the dusk meridian is converted to an upward current to the F layer, and not to horizontal poleward return current in the E layer. The problem of current closure for the equatorial electrojet is a very interesting and important subject to be studied in detail.

Another important discovery by MAGSAT is a possible existence of an eastward ring-current at the bottom of the ionosphere. The evidence for this argument is the observed fact that the H-values measured by MAGSAT is always 25-30 nT smaller than those calculated with the best available models, as reported by Kane and Trivedi (1985), Kane (1990), and Maeda et al. (1985). Although all the charged particles in the earth's space environment within the magnetosphere contribute to westward ring-current encircling the earth, there must be an eastward current at the bottom of the ionosphere, where the spatial gradient of the total kinetic energy density of charged particles is upward, due to the gyrating and drifting motions of charged particles in the geomagnetic field.

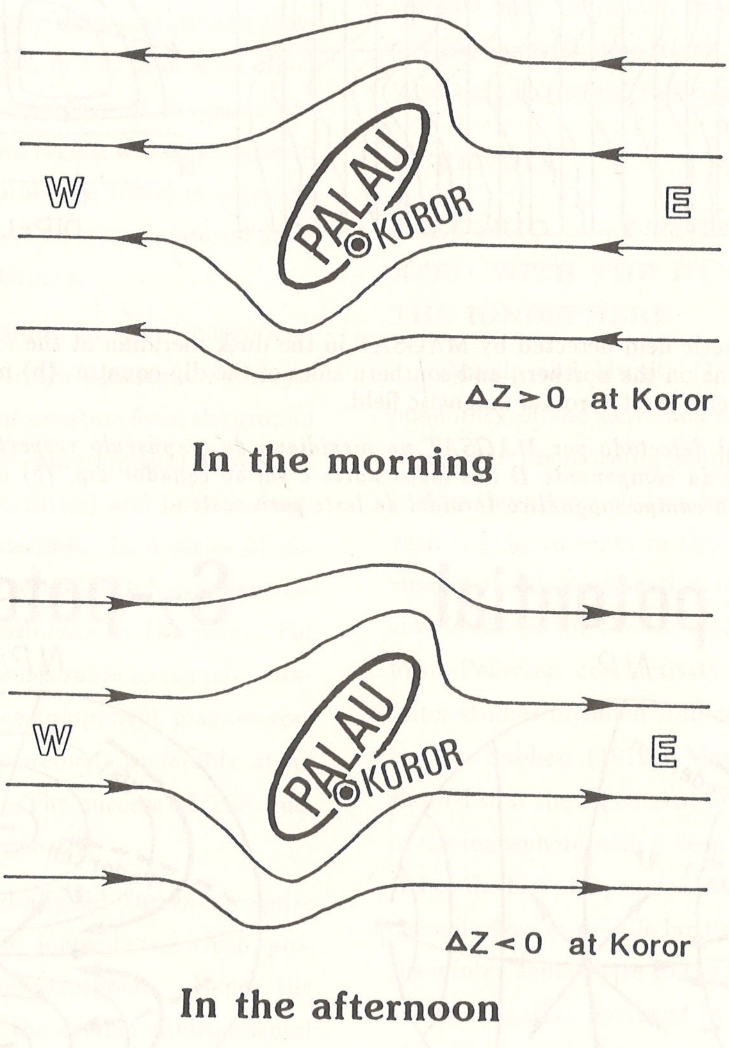

Figure 4. A schematic illustration of electric current flow in the ocean around Palau islands (Koror is on one of these islands) induced by the developing and decaying eastward overhead electrojet in the morning and the afternoon.

Ilustração esquemática do fluxo de corrente elétrica no oceano perto das ilhas Palau (Koror fica numa destas ilhas), induzidas pelo eletrojato de oeste para leste pela manhã e à tarde.

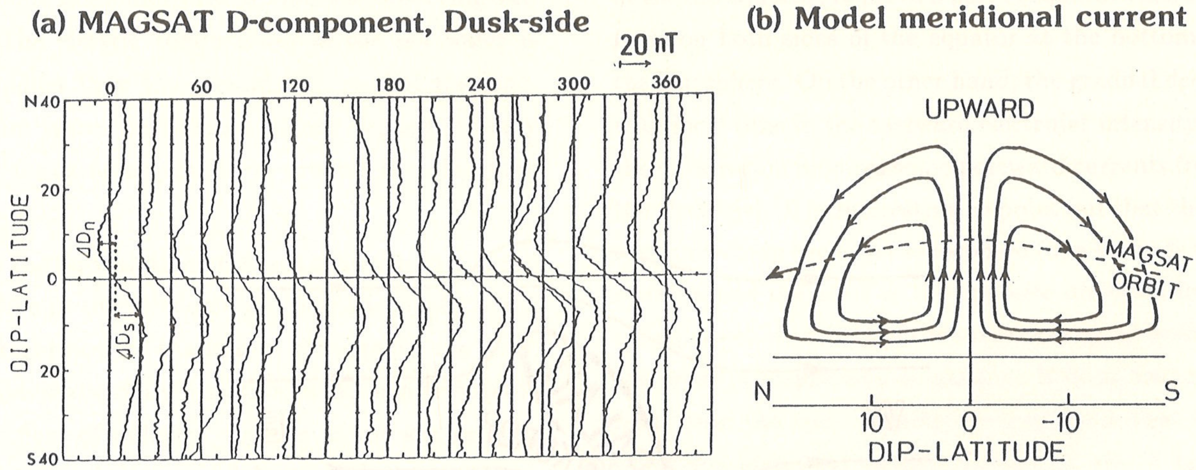

Figure 5. Toroidal magnetic field detected by MAGSAT in the dusk meridian at the ionospheric F-layer level: (a) D-component deviations on the northern and southern sides of the dip equator, (b) meridional current circulation responsible for the east-west toroidal magnetic field.

Campo magnético toroidal detectado por MAGSAT no meridiano do crepúsculo vespertino a níveis da camada ionosférica F: (a) desvios da componente D nos lados norte e sul do equador dip, (b) circulação meridional de correntes responsáveis pelo campo magnético toroidal de leste para oeste.

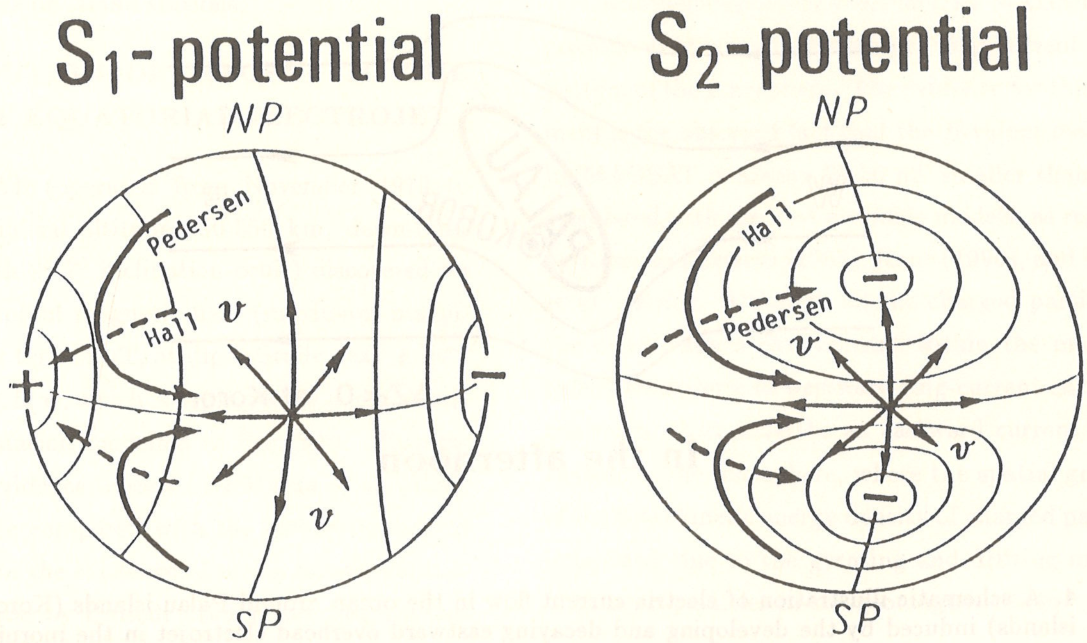

Figure 6. Two kinds of the electrostatic potentials (S_1 and S_2) associated with the dynamo action in the ionosphere with Pedersen and Hall conductivities. Field-aligned currents will flow if a potential difference arises between conjugate-pair points from an asymmetric dynamo in the northern and southern hemispheres.

Dois tipos de potenciais eletrostáticos (S_2 e S_2) associados com a ação do dínamo da ionosfera com condutividades Pedersen e Hall. As correntes alinhadas fluirão se existir uma diferença de potencial entre pontos conjugados de um dínamo assimétrico nos hemisférios Norte e Sul.

CONCLUDING REMARKS

This paper shows some examples of the contribution to the study of the equatorial electrojet from the analysis of magnetic observational data on the ground. The author hopes that each magnetic observatory contributing to the IEEY project will report on the seasonal dependence of the Sq daily variations, preferably following the way of demonstration by Gettemy (1962), which is shown in Fig. 3 in a modified way. The reports from a number of magnetic observatories in the equatorial region will contribute to studying some unsolved problems listed in a review paper by Barreto (1992), and on transequatorial field-aligned currents at low latitudes.

The current circulation in the ionosphere-magnetosphere connected to the equatorial electrojet must be studied with the information from the ground data analysis (including all other kinds of aeronomic studies with the ground facilities) and in-situ observations by rockets and satellites. In a series of papers, Onwumechili (1993) wrote useful summary reports for the rocket experiments in the past. For satellite measurement, it is desirable to launch a low-latitude satellite with three-component magnetometers to carry out the measurement preferably at all local times during its life. The success of TSS mission by NASA is greatly expected.

Interhemispheric field-aligned currents require the return currents in the ionosphere, which produce Joule heating in the ionosphere. Hence the electromagnetic energy in the earth's environmental space will be lost more easily in the solstitial seasons through the Joule loss by the ionospheric currents connected to field-aligned currents in the magnetosphere, because field-aligned currents are more intense than in the equinoctial seasons. Although we need a quantitative study of this problem in the future, it will solve the problem why the overall world energy for the geomagnetic Sq-field is greater in the equinoctial seasons and smaller in the solstitial seasons.

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APPENDIX

ELECTRIC POTENTIAL ASSOCIATED WITH THE DYNAMO ACTION IN THE IONOSPHERE

Maeda and Murata (1965) first pointed out a possibility of the existence of a pair of field-aligned currents in the morning (summer-to-winter direction) and in the afternoon (winter-to-summer) associated with the Sq currents in the June solstice, after discussing the dynamo action in the ionosphere with a simple model for the ionospheric conductivity (uniform Pedersen conductivity and no Hall current). Later studies included Hall conductivities, e.g. those by van Sabben (1970), Maeda (1974) and others, showed that the Sq current is mainly the Hall current in the ionosphere with a deep negative electric potential at the foci of Sq current vortices, and field-aligned currents flow at middle latitudes on the dayside from the winter hemisphere to the summer one, because of a more negative potential in the summer. With the aid of an intuitive illustration by Fukushima (1979), it is outlined below why we have the three principal field-aligned currents illustrated in Fig. 1, as a result of the dynamo action in the ionosphere for producing the Sq current in the sunlit hemisphere.

Fig. 6 shows a schematic pattern of the resulting static potential values in the dynamo region, under an air motion divergent from the subsolar point. The nonuniformity of the static potential values in the ionosphere originates from the anisotropy of the ionospheric gas with both Pedersen and Hall conductivities. S_1 denotes the electric potential arising from the Pedersen current under the electric field of ($\mathbf{v}\times\mathbf{B} - \nabla S_1$), so as to produce a closed current circuit in each hemisphere. On the other hand, S_2 denotes the electric potential responsible for the Hall current, which flows under the electric field of $-\nabla S_2$ so as to intensify the closed Pedersen current. It is seen in these illustrations, as shown by broken lines, that the Hall current under the electric field of ($\mathbf{v}\times\mathbf{B} - \nabla S_1$) and the Pedersen current under the electric field of $-\nabla S_2$ cancel out each other.

If the dynamo action and resulting currents are asymmetric with respect to the equator, field-aligned currents will immediately flow in the magnetosphere between conjugate-pair stations with different electric potential values in the northern and southern hemispheres. It will be reasonable to think that the total intensity of interhemispheric field-aligned currents is strong in the solstitial seasons, and the current direction is opposite in the summer and winter.

REFERENCES

BARRETO, L.M. (1992) The Equatorial Electrojet: A Brief Review. Geofísica Internacional, 31, 115-120.

DUHAU, S. and LOURO, A.A. (1983) The Current Flow between the Equatorial E and F Region. J. Geophys. Res., 88, 9205-9211.

FUKUSHIMA, N. (1971) Electric Current Systems for Polar Magnetic Storms and Their Magnetic Effect Below and Above the Ionosphere. Radio Sci., 6, 269-275.

FUKUSHIMA, N. (1976) Generalized Theorem for No Ground Magnetic Effect of Vertical Currents Connected with Pedersen Currents in the Uniform-Conductivity Ionosphere. Rept. Ionos. Space Res. Japan, 30, 35-40.

FUKUSHIMA, N. (1979) Electric Potential Difference between Conjugate Points in Middle Latitudes Caused by Asymmetric Dynamo in the Ionosphere. J. Geomag. Geoelectr., 31, 401-409.

FUKUSHIMA, N. (1991) Field-Aligned Currents in the Magnetosphere. Geofísica Internacional, 30, 241-248.

GETTEMY, J.W. (1962) Magnetic Daily Variation at Koror. J. Geophys. Res., 67, 1885-1888.

GLOVER, F.N. (1963) Recent Magnetic Observations in the Philippines. J. Geophys. Res., 68, 2385-2394.

HUTTON, V.R.S. (1967) Sq Currents in the American Equatorial Zone during the IGY-I. Seasonal Effects. J. Atmos. Terr. Phys., 29, 1411-1428.

KANE, R.P. (1990) Altitude Dependence of H Changes at MAGSAT Altitudes (325-550 km). Planet. Space Sci., 38, 883-888.

KANE, R.P. and TRIVEDI, N.B. (1985) Storm Time Changes of Geomagnetic Field at MAGSAT Altitudes (325-550 km) and Their Comparison with Changes at Ground Locations. J. Geophys. Res., 90, 2451-2464.

LOURO, A.A. and DUHAU, S. (1988) Meridional Electric Currents in the Equatorial F-region. J. Atmos. Terr. Phys., 50, 977-981.

MAEDA, H. (1974) Field-Aligned Current Induced by Asymmetric Dynamo Action in the Ionosphere. J. Atmos. Terr. Phys., 36, 1395-1401.

MAEDA, H., IYEMORI, T., ARAKI, T. and KAMEI, T. (1982) New Evidence of a Meridional Current System in the Equatorial Ionosphere. Geophys. Res. Lett., 9, 337-340.

MAEDA, H., KAMEI, T., IYEMORI, T. and ARAKI, T. (1985) Geomagnetic Perturbations at Low Latitudes Observed by MAGSAT. J. Geophys. Res., 90, 2481-2486.

MAEDA, K. and MURATA, H. (1965) Ionospheric Dynamo Theory with Consideration for Magnetospheric Current along the Geomagnetic Lines of Force. Rept. Ionos. Space Res. Japan, 19, 272-285.

MAZAUDIER, C. (1985) Strange Current over Saint-Santin. J. Geophys. Res., 90, 9727-9735.

ONWUMECHILI, C.A. (1993) A Study of Rocket Measurements of Ionospheric Currents - I. General Setting and Night-time Ionospheric Currents, II. Ionospheric Currents Outside the Dip Equatorial Zone, III. Ionospheric Currents at the Magnetic Dip Equator. IV. Ionospheric Currents in the Transition Zone and the Overview of the Study, V. Modelling Rocket Profiles of Low-Latitude Ionospheric Currents. Geophys. J. Int., 108, 633-640, 641-646, 647-659, 660-672, 673-682.

ONWUMECHILI, C.A. and ALEXANDER, N.S. (1959) Variations in the Geomagnetic Field at Ibadan, Nigeria - I. Solar Variations. J. Atmos. Terr. Phys., 16, 106-114.

OYAMA, K.-I. and HIRAO, K. (1979) Distortions of the Energy Distribution of Ionospheric Thermal Electrons near the Focus of Sq Current Vortex. Planet. Space Sci., 27, 183-192.

PRICE, A.T. and STONE, D.J. (1964) The Quiet-Day Magnetic Variations during the IGY. Annals of the IGY, 35, 63-269.

SUGIURA, M. and POROS, D.J. (1969) An Improved Model Equatorial Electrojet with a Meridional Current System. J. Geophys. Res., 74, 4025-4034.

TAKEDA, M. and MAEDA, H. (1983) *F*-region Dynamo in the Evening - Interpretation of Equatorial ΔD Anomaly Found by MAGSAT. J. Atmos. Terr. Phys., 45, 401-408.

UNTIEDT, J. (1967) A Model of the Equatorial Electrojet Involving Meridional Currents. J. Geophys. Res., 72, 5799-5810.

VAN SABBEN, D. (1966) Magnetospheric Currents Associated with the N-S Asymmetry of Sq. J. Atmos. Terr. Phys., 28, 965-981.

VAN SABBEN, D. (1969) The Computation of Magnetospheric Currents, Caused by Dynamo Action in the Ionosphere. J. Atmos. Terr. Phys., 31, 469-474.

VAN SABBEN, D. (1970) Solstitial Sq-Currents through the Magnetosphere. J. Atmos. Terr. Phys., 32, 1331-1336.

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