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Field-aligned currents in the magnetosphere

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RESUMEN

Las corrientes alineadas con el campo en la magnetosfera fluyen en todas partes, no sólo a altas latitudes sino también a medianas y bajas. Sin embargo, su detección con satélites sólo ha sido posible en la región por encima de las zonas aurorales. La existencia de estas corrientes a medianas y bajas latitudes se puede inferir de un análisis de los magnetogramas en tierra, en particular, a partir de la diferencia estacional en la variación diurna del campo geomagnético. A latitudes medias, la componente dominante de las corrientes alineadas son las corrientes transecuatoriales de verano a invierno que combinan las regiones de focos de corrientes *Sq* en los hemisferios norte y sur. A bajas latitudes cerca del ecuador, la dirección de las corrientes alineadas con el campo es de verano a invierno en las horas anteriores al mediodía y de invierno a verano en las de la tarde.

PALABRAS CLAVE: magnetosfera, corrientes alineadas con el campo (medianas y bajas latitudes), variaciones del campo geomagnético; dependencia estacional de la variación diurna, vórtice de corrientes *Sq*, electrochorro ecuatorial.

ABSTRACT

Field-aligned currents flow everywhere in the magnetosphere, not only at high latitudes but also at middle and low latitudes, but their experimental detection by satellites has been possible only in the region over the auroral zones. The existence of field-aligned currents at middle and low latitudes can be inferred from an analysis of the ground magnetograms, in particular from the seasonal difference in the daily variation of the geomagnetic field. At middle latitudes the dominant component of the field-aligned currents is the winter-to-summer transequatorial currents combining the regions of *Sq* current foci in the northern and southern hemispheres. At low latitudes near the equator, the field-aligned current direction is summer-to-winter in the forenoon and winter-to-summer at dusk hours.

KEY WORDS: field-aligned currents (at middle and low latitudes), geomagnetic field variation, daily variation and seasonal dependence, *Sq* current vortex, equatorial electrojet.

INTRODUCTION

Every day the ground magnetic field shows regular or irregular variations, which are attributable to electric currents flowing in the Earth's environmental space in and above the ionosphere. From spherical harmonic analysis of simultaneous geomagnetic records at various places of the world, it is possible to obtain the "equivalent overhead current-system" at a certain height above the ground, which gives rise to the same magnetic field as that actually observed at the Earth's surface.

Any three-dimensional current-system in the Earth's space environment (consisting of horizontal currents in the ionosphere and field-aligned currents flowing in the magnetosphere) can be uniquely replaced by a two-dimensional equivalent horizontal overhead current-system at a certain height above the Earth's surface, insofar as its magnetic effect on the ground is concerned. On the other hand, there is no unique conversion from a two-dimensional horizontal current-system to a three-dimensional one extending from the ionosphere to the magnetosphere. In order to know the actual three-dimensional current structure in the entire space above the Earth, it is necessary in principle to know the magnetic field perceived at all points above the ionosphere.

The development of scientific satellites with three-axis magnetometers made it possible to detect field-aligned currents at high latitudes, first by the satellite 1963-38C (Zmuda *et al.*, 1966) from a steep spatial gradient of the persistent E-W component of the geomagnetic field detected above the northern and southern auroral zones. Later studies with TRIAD, MAGSAT, HILAT, and some other satellites enabled us to reveal various important characteristics of the field-aligned currents at high latitudes, including their persistence, and the systematic dependence of their direction (incoming or outgoing) on local time, latitude, as well as solar-wind condition.

Although field-aligned currents in the magnetosphere have been detected only above the auroral zones at high latitudes, it is natural to think of the presence of field-aligned currents above the ionosphere also at middle and low latitudes, because they tend to flow whenever any small electric potential difference appears in the ionosphere between conjugate-pair stations in the northern and southern hemispheres, though the current density is not strong enough to be detected by satellite instruments. The present paper shows a possibility of deducing such field-aligned currents at middle and low latitudes from their integrated ground magnetic field through an appropriate analysis of the magnetograms at a number of magnetic observatories.

A number of useful reports have been published on the results of observation and analysis for the geomagnetic daily variation on quiet days (designated *Sq*-field), such as an extensive summary of IGY results by Price and Stone (1964). Before the experimental detection of field-aligned currents, the discussion on the electric currents responsible for *Sq* was based simply on an implicit assumption that *Sq* would be entirely attributable to the current flowing in the lower ionosphere at the level of the *E* layer, the so-called dynamo region of height roughly 100-120 km above the Earth. Hence, it has been often stated that the electric current in the summer hemisphere in the forenoon invades the winter hemisphere across the magnetic equator, despite some doubt from the physics point of view on the electric current flow in the ionosphere across the magnetic equator. In this paper it is assumed that (1) no current flows in the dynamo layer across the magnetic equator, and (2) an apparent invasion of the summer hemisphere "equivalent overhead current" across the magnetic equator must be attributable to some transequatorial field-aligned currents flowing in the magnetosphere.

It is also emphasized in this paper how important it is to study carefully the geomagnetic field variation recorded at each observatory all over the world. The dispatch of the magnetogram copies to the World Data Centres is by no means the final purpose of the ground magnetic observation, but it is the real beginning of our effect to squeeze a scientific contribution from each observatory. All scientists affiliated to the magnetic observatories or belonging to their parent institutions are urged to clarify the specific characteristics of the geomagnetic field variations proper to their own observatories.

GENERAL REMARKS ON THE GROUND MAGNETIC EFFECT OF FIELD-ALIGNED CURRENTS

When the ground magnetic effect of field-aligned currents is calculated with the aid of Biot-Savart's law, we must deal always with a closed current circuit in the space above the Earth. At high latitudes, the magnetic field by an incoming line-current over the auroral zone (a clockwise field seen from above the Earth) is nearly cancelled out by a current spreading over the ionosphere from the point of current inflow from the magnetosphere. The cancellation is perfect if the current from the magnetosphere is vertical, and the ionosphere has a uniform Pedersen conductivity and no Hall conductivity. Hence, the ground magnetic field of field-aligned currents in the magnetosphere connected to horizontal currents in the ionosphere depends on (1) an oblique incidence of field-aligned currents into the ionosphere, (2) non-uniformity of the ionospheric Pedersen conductivity, and (3) the existence of Hall conductivity in the ionosphere (Fukushima, 1969, 1971, 1976).

The field-aligned currents at middle latitudes have been discussed by van Sabben (1966, 1969, 1970), Yanagihara (1971), Maeda (1974), Mishin (1976), Fukushima (1979), Wagner *et al.* (1983) and others. The total amount of field-aligned currents between the northern and southern hemispheres on the sunlit side has been estimated to be of the order of 10^5 A. If this current is assumed to flow only in a 20° x 20° area near the *Sq* current foci, the current density at the ionospheric level is much less than 1 $\mu A/m^2$, so that it is difficult to detect such a weak current in space.

SEASONAL DEPENDENCE OF THE *Sq* GEOMAGNETIC FIELD VARIATION

The *Sq* geomagnetic variation is generally greatest in summer and weak in winter. The total intensity of the *Sq* current over the entire Earth shows the greatest value in the equinoctial season (e.g., Matsushita and Maeda, 1965). This indicates that the summer-equinox difference of the *Sq* magnitude is small in comparison with the equinox-winter difference.

Price and Stone (1964) discussed the line of demarcation between the northern and summer current systems, by means of the world data obtained in 1958, 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."

This conclusion was written when we did not think of field-aligned currents flowing in the magnetosphere, and there was an implicit agreement in those days that the "equivalent overhead current" would be reasonably represented by the real horizontal current flowing in the ionosphere. Later studies, such as the work by van Sabben (1964) on the north-south asymmetry of the geomagnetic *Sq* field, and the analysis of the *Sq* current vortex by Yanagihara (1971), supported a possible existence of field-aligned currents flowing in the magnetosphere at middle latitudes.

In this paper, the following new viewpoint is introduced in the interpretation for electric current flow in the Earth's space environment for the geomagnetic *Sq* field: (1) the dip equator is the natural boundary for the northern and southern current systems *in the ionosphere,* because of a high electric conductivity along the dip equator, (2) the seasonal variation of the *Sq* field (in particular for magnetic declination or *Y*-component) will be attributable to some field-aligned currents in the magnetosphere flowing in summer-to-winter or winter-to-summer direction. Although it is in principle impossible to derive a three-dimensional current system in the Earth's space environment without knowing the magnetic field above the ionosphere, it is still possible to infer to some extent the existence of such interhemispheric field-aligned currents flowing in the magnetosphere.

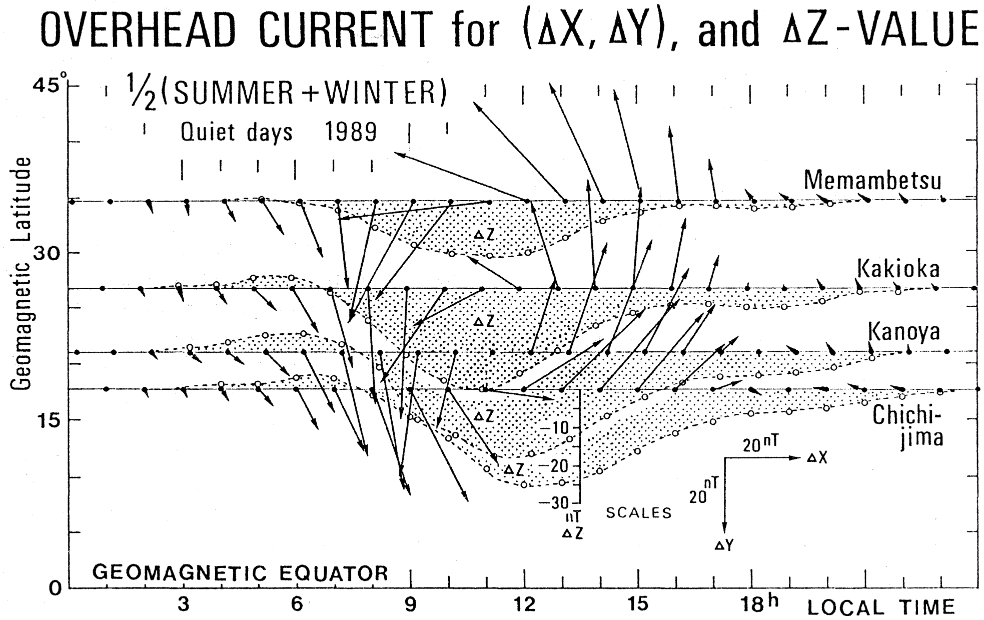

Fig. 1. *Sq* current pattern for 1/2(Summer+Winter) on quiet days in 1989 derived from the observed data of 4 stations in Japan.

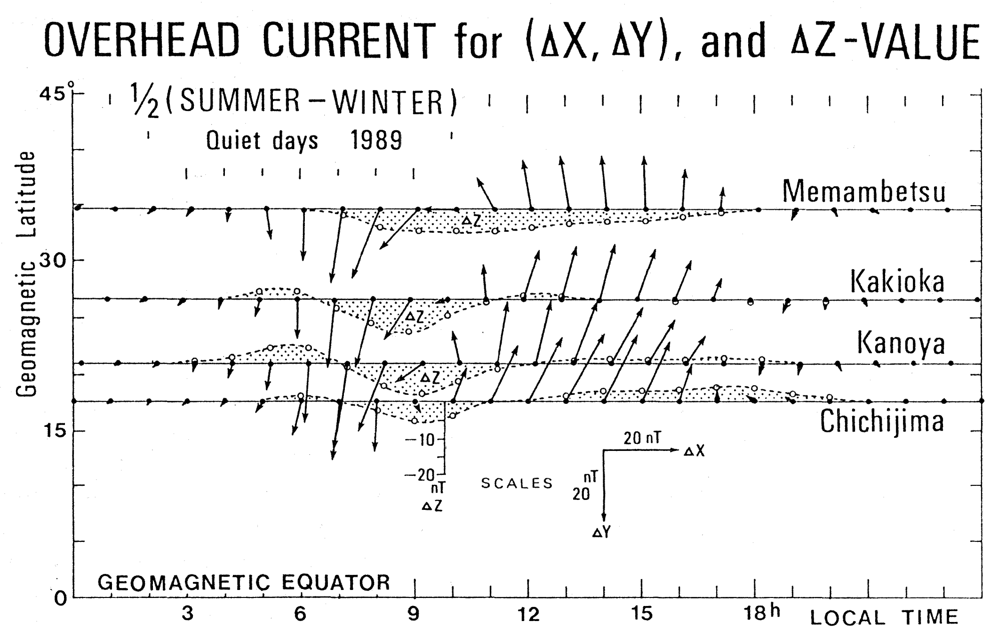

Fig. 2. *Sq* current pattern for 1/2(Summer-Winter) on quiet days in 1989 derived from the observed data at 4 stations in Japan.

FIELD-ALIGNED CURRENTS AT MIDDLE LATITUDES

Using the hourly values at 4 magnetic observatories (Memambetsu, geomagnetic latitude 34.6°; Kakioka, 26.8°; Kanoya, 21.1°; Chichijima, 17.8°) in 1989, the mean daily variations of ΔX, ΔY and ΔZ for 5 quiet days in the summer (May, June, July and August) and winter (January, February, November and December) seasons were calculated, and the results are shown for 1/2 (Summer + Winter) and 1/2 (Summer - Winter) respectively in Figs. 1 and 2, where ΔX and ΔY are given to indicate the overhead current arrows for the *Sq* field, and ΔZ vertically in the diagram. If the *Sq* patterns were exactly the same for both the summer and winter seasons, with their difference only in the magnitude, the pattern for 1/2 (Summer + Winter) should be the same as that for 1/2 (Summer - Winter) except for scale. The dissimilarity of current patterns in Figs. 1 and 2 reveals the difference in the *Sq* current pattern in summer and that in winter.

At the June solstice, the geomagnetic *Sq* current system in the northern hemisphere is the superposition of Figs. 1 and 2, whereas the current pattern in the southern hemisphere is the mirror image of Fig. 1 minus Fig. 2 with respect to the geomagnetic equator. The summer-winter difference of the geomagnetic *Sq* variation exists not only in its magnitude but also in its local-time dependence, i.e., the *Sq* current vortex centre in the summer hemisphere is located at a slightly earlier local time than in the winter hemisphere.

The *Sq* current in the southern hemisphere flows clockwise, seen from above the Earth, producing downward (i.e. positive) ΔZ value. This means that the electric potential near the *Sq* vortex centre in the southern hemisphere is also negative as in the northern hemisphere. If the *Sq* current pattern and intensity are symmetric with respect to the equator, there would be no electric potential difference between the northern and southern hemispheres to produce interhemispheric field-aligned currents. Field-aligned currents will flow through the magnetosphere, in order to cancel or at least reduce the potential difference between the northern and southern conjugate places, when such a potential difference happens to take place.

If transequatorial field-aligned currents flow towards the northern hemisphere, their oblique incidence into the ionosphere produces a ground magnetic effect that can be expressed by an equivalent overhead current system with a pair of circular current loops (a clockwise current loop with a positive ΔZ on the eastern side, and a counter-clockwise current loop with a negative ΔZ on the western side of the region of incident field-aligned currents in the northern hemisphere.

Looking at Fig. 2, we notice a distinct negative ΔZ area centering at 9 h local time over Kakioka, Kanoya and Chichijima associated with a counter-clockwise overhead current-arrows. This might be considered a ground signature of the middle-latitude field-aligned currents flowing at 11-12 h local time, although we can only see a faint signature of clockwise current loop on the afternoon side of the sunlit hemisphere.

The author hopes that the data of geomagnetic field variation at a number of stations in middle and low latitudes will contribute significantly to the study of electrodynamics in the Earth's environmental space. The analysis of the seasonal variation of the *Sq* field will be useful to infer the interhemispheric field-aligned currents at middle and low latitudes. A comparison of *Sq* records at a conjugate pair of stations is also desirable.

DOES THE EQUATORIAL ELECTROJET CROSS THE MAGNETIC EQUATOR?

It has been a point of some discussion whether or not the equatorial electrojet (hereafter abbreviated to EEJ) flows everywhere and any time along the magnetic equator. The electric conductivity in the ionosphere is greatly enhanced in a narrow belt along the magnetic equator; it tends to σ_0 in N-S direction, to $\sigma_3 = (\sigma_1^2 + \sigma_2^2)/\sigma_1$, i. e., Cowling conductivity in E-W direction. It is to be studied in detail how great is the effect of the presence of a narrow high-conductive belt in the equatorial ionosphere on the global electric current circuit in the ionosphere and magnetosphere around the Earth. However, it is assumed in this paper that no current flows across the magnetic equator in the ionosphere or the dynamo layer. As a consequence of this simple assumption, the invasion of the equivalent overhead current from one hemisphere to the other is attributed in the present paper entirely to transequatorial field-aligned currents flowing in the magnetosphere, even in the space not so far from the bottom of the magnetosphere with the L value only slightly greater than 1.

GEOMAGNETIC DAILY VARIATION OBSERVED AT KOROR DURING IGY

It is worth paying attention to a paper by Gettemy (1962), which showed a very interesting feature of the daily *Sq* variation at an IGY temporary observatory at Koror (7°20'N, 134°30'E). The station was just on the magnetic equator; the monthly mean Z-value was 0 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. It is noteworthy in Fig. 3 that (1) ΔD daily variations are reversed in the summer and winter seasons, and (2) ΔZ is always positive in the morning and negative in the afternoon throughout the year. The former observational fact is discussed in the next Section in connection with transequatorial field-aligned currents in the magnetosphere, whereas the latter fact is briefly considered here in reference to the induced current in the sea around the observatory.

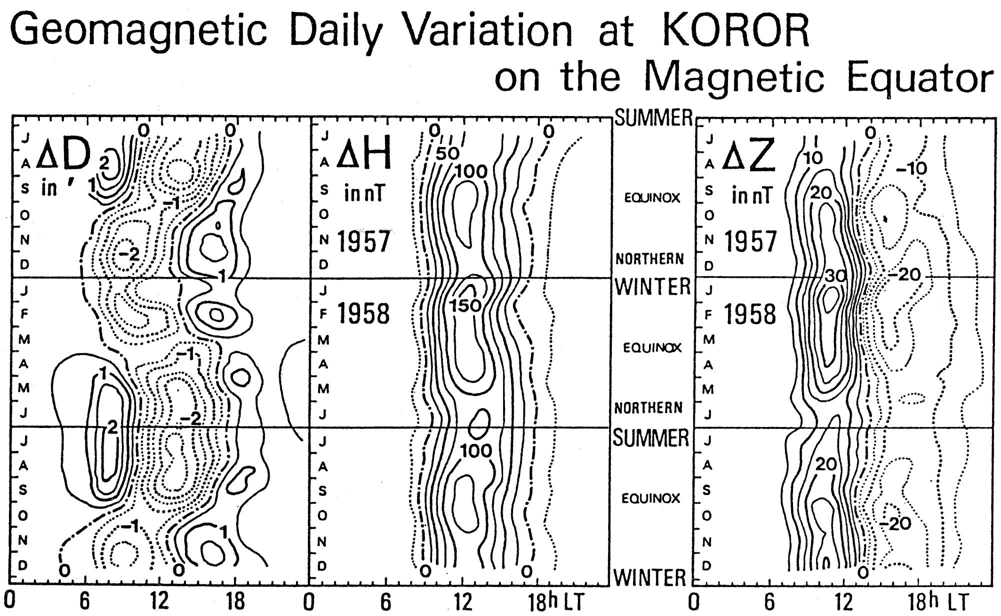

Fig. 3. Magnetic daily variation (deviations from daily-mean values) for the three components of the geomagnetic field at Koror on quiet days during the IGY (Gettemy, 1962).

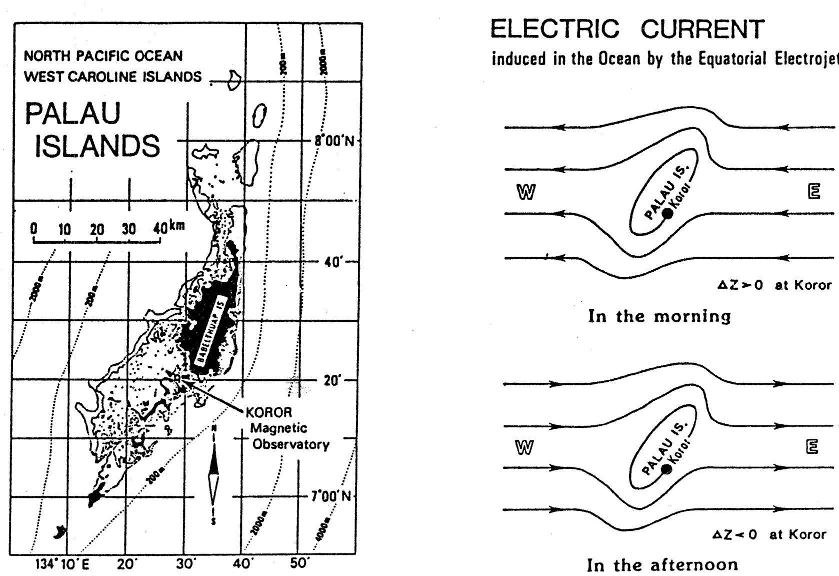

Fig. 4. Geographic chart around Koror (white area is reef; black area is land), and schematic electric current in the surrounding ocean induced by the developing and decaying eastward electrojet in the morning and the afternoon.

The ground magnetic variation generally depends on geographic and geologic conditions of the observing station and its neighbourhood, because the magnetic field variation recorded on the ground contains the contributions from both external currents above the observatory and currents induced within the Earth by the time variation of the magnetic field originated from the external currents. The electric conductivity is much greater in the sea water than in the Earth's crust, so that the geomagnetic field variation observed on an island is greatly affected by electric currents induced in the sea around the island. Fig. 4 shows a chart in the vicinity of Koror Magnetic Observatory, and a schematic illustration of the flow of induced currents in the surrounding ocean, westward in the morning and eastward in the afternoon in the sea so as to shield the magnetic effect from the overhead eastward electrojet, the intensity of which increases in the morning and decreases with time in the afternoon. The daily variation of ΔZ at Koror seems to be attributable mainly to the reversal of the induction current direction associated with the growth and decay of the overhead EEJ.

In the coming years for EEJ observations, it is desirable to intensify the network of EEJ observation, possibly by setting up a number of temporary stations on islands of the Pacific or Atlantic Ocean near the equator. It is desirable to check whether or not the above interpretation for the Koror ΔZ data holds for other island stations in the equatorial region, because we need to eliminate in advance the effect from electric currents induced within the Earth, before the observed data is utilized for discussing the external current pattern in the space above the Earth.

FIELD ALIGNED CURRENTS FOR N-S ASYMMETRY OF THE EQUATORIAL *Sq* FIELD

In the equatorial region the equivalent overhead current for the geomagnetic *Sq* field often crosses over the geomagnetic equator, as already mentioned in Section 4, as in papers by Onwumechilli and Alexander (1959), Knapp and Gettemy (1963), Glover (1963), van Sabben (1964), Hutton (1967a,b), and many others. If we may attribute the cross-equatorial equivalent current of the *Sq*-field to interhemispheric field-aligned currents in the magnetosphere at low latitudes, the seasonal reversal of the daily variation of ΔD in the equatorial region is attributable to a pair of field-aligned currents in the sunlit hemisphere near the dawn and dusk meridians, as schematically illustrated in Fig. 5. This picture shows also the winter-to-summer field-aligned current between the *Sq* current foci in the two hemispheres on the sunlite side, the existence of which is seen in Fig. 2 for the summer-winter asymmetry of the *Sq* field at middle latitudes. The total intensity of these interhemispheric field-aligned currents in the magnetosphere has been estimated to be a few tens of kA.

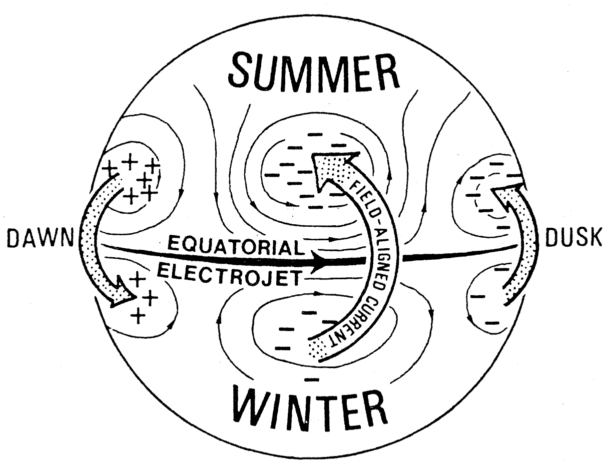

Fig. 5. A model of interhemispheric field-aligned currents in the magnetosphere at middle and low latitudes.

The pair of field-aligned currents near the dawn and dusk meridians was surmised by Schlapp *et al.* (1988) after their comparison of the *Sq* variation observed at two middle latitude stations in the northern and southern hemispheres. Maeda and Murata (1965) first pointed out the 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 solstitial season. They discussed the dynamo action in the ionosphere to produce the *Sq* current and the ionospheric conductivity was assumed to be the Pedersen conductivity alone. Later studies of this kind of problem, in which the ionosphere has both the Pedersen and Hall conductivities, e.g. those by van Sabben (1970) or Fukushima (1979), showed that the *Sq* current is mainly the Hall current in the ionosphere with a large negative electric potential at the foci of *Sq* current vortex, and field-aligned currents flow at middle latitudes on the dayside from the winter hemisphere to the summer hemisphere, because of a deeper negative potential in the summer season.

CONCLUSION AND SOME REMARKS

This paper introduces a new picture of the possible electric current system for the geomagnetic *Sq* field and the equatorial electrojet, assuming that the electrojet always flows along the magnetic equator and the summer-winter asymmetry would be entirely attributable to interhemispheric field-aligned currents in the low-latitude magnetosphere. The new picture must be checked with future data in the coming years for EEJ observation. It is also necessary to check the fundamental assumption in this paper, i.e. the absence of electric current across the magnetic equator. The magnetograms stored at all (or at least some) magnetic observatories in Latin America, where the discrepancy between the geographic and geomagnetic equators is greatest in the world ought to be utilized to infer the pattern of field-aligned currents in low latitudes. Such a study will be a great contribution to space physics, for studying the electrodynamics in the Earth's environmental space.

The role of field-aligned currents in the magnetosphere for the energetics of the Earth's environmental space is to be studied in detail in the future. It seems very probable that interhemispheric field-aligned currents in the magnetosphere will eventuallly contribute to some extent to the dissipation of electromagnetic energy stored in the magnetosphere through the Joule heating associated with electric currents in the ionosphere. It would not be unnatural to think that the total amount of interhemispheric field-aligned currents in the magnetosphere will be much greater in the solstitial seasons than in the equinoctial seasons, because the electric potentials in the ionosphere will be considerably different between the summer and winter hemispheres in the solstitial seasons, whereas the potential values will be nearly the same in the equinoctial seasons. This will cause a greater loss of energy in the magnetosphere in the solstitial seasons in comparison with the equinoctial seasons. It has been an open question why the geomagnetic variation in the equinoctial seasons shows a greater amplitude in comparison with the average of two solstitial seasons. There would be a possibility to explain it through an effect of field-aligned currents in the magnetosphere, but a quantitative check for this idea is desirable.

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