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SEASONAL VARIABILITY OF SOLAR QUIET AT MIDDLE LATITUDES

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Abstract

A comprehensive study of solar quiet daily, Sq, geomagnetic field variations at middle latitudes has been carried out using an extensive data set of the three geomagnetic elements H, D and Z for all the years of solar cycle #22 (1986-1996). Only quiet condition was examined. Sq has consistent seasonal variations of in H, D and Z. The observed Sq seasonal variation is maximum in June solstice, followed by Equinox, and least in December solstice. Interrelationships exist among the seasonal Sq in the three elements H, D and Z. The variabilities of semi-diurnal tides, Sq focus, and ionospheric electron content are shown to be the mechanisms jointly responsible for the Sq seasonal variations.

Résumé

RABIU, B. A.: *Variabilité saisonnière de soleil calme (Sc) aux latitudes centrales.* Une étude approfondie du soleil calme quotidien, Sc, variations de champ géomagnétique aux latitudes du milieu s'est déroulée utilisant une série des données extensives de trois éléments géomagnétiques H, D et Z pour tous les années de cycle solaire #22 (1986-1996). Seule la condition calme était étudiée. Sc a des variations saisonnières logiques de Sc en H, D et Z. La variation saisonnière de Sc observé est au maximum en solstice de juin, suivi par équinoxe et minimum en solstice de Decembre. Corrélation existe parmi le Sc saisonnier dans les trois éléments H, D et Z. Les variabilités des courants de demi-diurne, convergence de Sc, et le contenu d'électron ionosphérique étaient prouvés d'être les mécanismes conjointement responsables pour les variations saisonnières de Sc.

Introduction

Graham first observed the Sq variation in 1722. Much later Canton in 1759 discovered the seasonal variability of Sq field. Okeke, Onwumechili & Rabiu (1998), in a recent paper, gave a comprehensive review of earlier works on variabilities of geomagnetic field variations. Several aspects of the variability of the seasonal variations of Sq are evident in findings by Campbell (1987), Rabiu (1992), Onwumechili, Oko & Ezema (1996) and Oko, Onwumechili & Ezema (1996). Also the variability of the current intensity and total forward current of the EEJ equatorial electrojet and worldwide Sq current layers, as well as the variability of their landmark distances and structural parameters have been studied by Onwumechili & Ogbuehi (1962), Suzuki (1978, 1979), Onwumechili & Agu (1981), Takeda (1984, 1985), Onwumechili (1992 a, b, c) and Oko, Onwumechili & Ezema (1996).

Yacob & Rao (1966) suggested that the month-to-month variability of Sq (H) might be related to the latitudinal variability in the position of the Sq focus, and that both changes are caused by month-to-month variations in the atmospheric tidal forces or wind systems in the Sq layer. Butcher & Brown (1981) ascribed the variability of Sq to irregularities in the winds at E-region altitudes and to solar-activity-related changes in the ionospheric conductivity and wind systems. Mann & Schlapp (1988) also observed that the variability of Sq is due mainly to variability in dynamo winds, which may be cuased by *in situ* heatings (Greener & Schlapp, 1979) or the varibility of the upward, propagating semidiurnal tidal modes driven from below (Briggs, 1984), or both. More emphatically, Mann & Schlapp (1988) asserted that a movement in the latitude of the Sq focus is equivalent to a change in the range of Sq (H) at a station near the latitutde of the focus.

Using correlation studies of Sq ranges for the dense network of European observatories for the IGY (1958), the IQSY (1965-66) and 1969, Greener & Schlapp (1979) gave an evidence that Sq variability arises mainly from variations in dynamo winds and electric fields rather than conductivity. Greener & Schlapp (1979) argued that, if Tarpley's (1970) explanation that the of diurnal evanescent (1,-1) mode gives rise to the Sq variability, then the driving force responsible for the mode variability is most likely to be located at dynamo region heights. They suggested that the likely source of the E-region contribution to the (1,-1) mode is absorption of ultraviolet radiation by molecular oxygen, and that a cause of day-to-day variability could be a spatial variation in the concentration of molecular oxygen at a given height, resulting in the product of patchy heating by the ultraviolet radiation and, consequently, some irregularity in the resulting thermotidal wind patterns.

Butcher (1982) ascribed the variability of the focus latitude to the addition of a superposed northward magnetic field which tends to shift the apparent focus latitude poleward in the northern hemisphere. The additional northward field which produces an apparent poleward motion of the focus must be caused by some redistribution of the Sq (H) ionospheric currents (Butcher & Brown, 1980). Butcher (1982) found that the focus latitute move equatorward in D-solstice and poleward in J-solstice in the northern hemisphere. At the Australian region (southern hemisphere), Campbell & Shiffmacher (1987) discovered that the total Sq current magnitude indicated at the focus in summer (J-solstice) was greater than the winter (D-solstice) value by a factor of 2.9. They also observed that the latitude of the Sq focus shifts within a range of 2.5°, most poleward in February and most equatorward in August. The amplitudes of Sq were largest in summer and smaller in winter.

The bulk of the work done on Sq focused on low latitude while only few have been made for middle latitudes. Therefore, the essence of this paper is to study the seasonal variability of Sq at middle latitudes using a set of observational data from a network of middle latitude geomagnetic observatories. With proper techniques of analysis, the study investigates the seasonal variation of Sq with particular emphasis on the nature of the seasonal Sq and the physical mechanisms responsible for it.

TABLE 1
Geographical location of the stations used in the analysis

Stations	*Geographical coordinates*		*Geomagnetic coordinates*	
	Latitude	*Longitude*	*Latitude*	*Longitude*
Castello Tesino	46.2° N	11.7° E	46.5° N	93.5° E
Furstendeldbruck	48.1° N	11.3° E	48.8° N	93.3° E
Wingst	53.7° N	9.1° E	54.5° N	94.1° E
Average	49.3 ± 3.2° N	10 ± 1.1° E		

Data analysis

The data

The geomagnetic data set consists of published hourly values of H, D, Z, recorded at a network of three northern hemisphere mid-latitude geomagnetic observatories; Castello Tesino, Furtenfeldbruck and Wingst - for all the eleven years of solar cycle #22 (1989 - 1996). Table 1 gives the locations of the stations used in the anaylsis.

The international quiet days (IQD's) which are by definition the sets of five quietest days per month based on the disturbance Kp index were selected and the hourly values of H, D, Z, analysed for Sq. The IQD's were selected so as to ensure that only quiet conditions are examined.

Mean hourly values of Sq

The concept of local time is used throughout the analysis. The average longitude of the geomagnetic stations involved in the research is 10.7 ± 1.1 °E (Table 1), which implies that the local time (LT) at the stations is 1 h ahead of the universal time (UT). So when it is 24 h UT at Wingst, for instance, the local time is 01 h. LT of the next day.

The Sq variation base line is taken as the average of the fields in the 2 h flankings local midnight (01 h LT and 24 h LT). The base line values for the elements are:

$$H_o = (H_1 + H_{24})/2 \qquad \text{........1}$$

$$D_o = (D_1 + D_{24})/2 \qquad \text{........2}$$

$$Z_o = (Z_1 + Z_{24})/2 \qquad \text{........3}$$

where H_1, D_1, Z_1, represent the values of the magnetic elements H, D, Z, respectively, at 01 h LT. H_{24}, D_{24}, Z_{24}, represent the values of the magnetic elements H, D, Z, respectively, at 24 h LT.

The hourly values of Sq (W), where W can be either of H, D, Z, were analyzed by first subtracting the hourly values of W at *t* h LT in each element from the base line value, to get the variation amplitude ΔW.

$$\Delta W = W_1 - W_o \qquad \text{.........4}$$

where, W_t is the hourly value of the geomagnetic element W at *t* h LT and W_o is the base line value on a particular day.

The variation amplitude is then corrected for non-cyclic variation to remove disturbance effects due to local sources following Vestine (1967).

Chapman & Bartels (1940) allowed Sq to be derived from the five IQDs per month. Therefore, the mean hourly values of Sq is obtained by averaging the hourly values of these variation amplitudes which have been corrected for non-cyclic variation.

Seasonal values of Sq

Following Lloyd's seasons, the months of the year are classified into three seasons: December solstice or D-season (January, February, November, December), Equinox (March, April, September, October), and June solstice or J-season (May, June, July August). The seasonal means were evaluated by finding the average of the monthly means under a particularl season. For example, for D-seasonal means the monthly means of Sq in January, February, November and December were summed up and the average taken. The seasonal means of Sq in H, D, and Z, were evaluated every year, as illustrated in Fig. 1, 2, and 3, respectively.

Correlation studies

Correlation analysis were carried out between the seasonal mean values of Sq in the three elements H, D, and Z using the EXCEL software. The result is displayed on Table 2.

Discussion

Seasonal variation of Sq

The seasonal variations of Sq in three geomagnetic elements H, D, Z (Fig. 1, 2 and 3) are consistent and very clear. In all the three elements, the Sq variation are highest in June solstice and lowest in December solstice, an evidence of consistency. This seasonal variation of Sq is in accord with the low latitude Sq variation of Mitra (1947).

The observed variability is quite consistent with some proposed theories from literature. For example, Tarpley (1970), Greener & Schlapp (1979), Forbes (1981), Okeke & Rabiu (1999) suggested that the seasonal variability of Sq can be explained

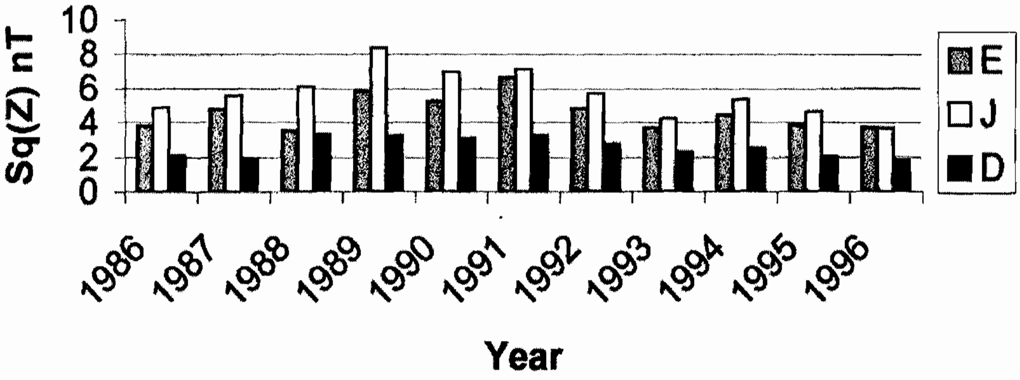

Fig. 1. Seasonal variation of Sq(H)

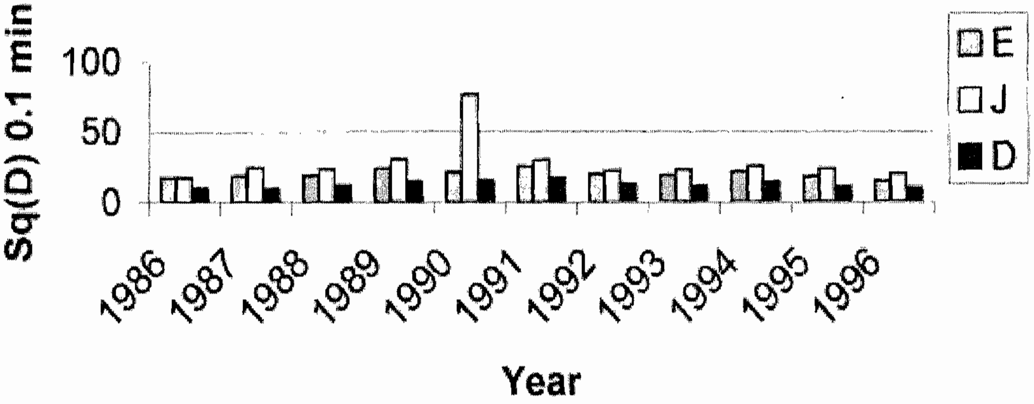

Fig. 2. Seasonal variation of Sq(D)

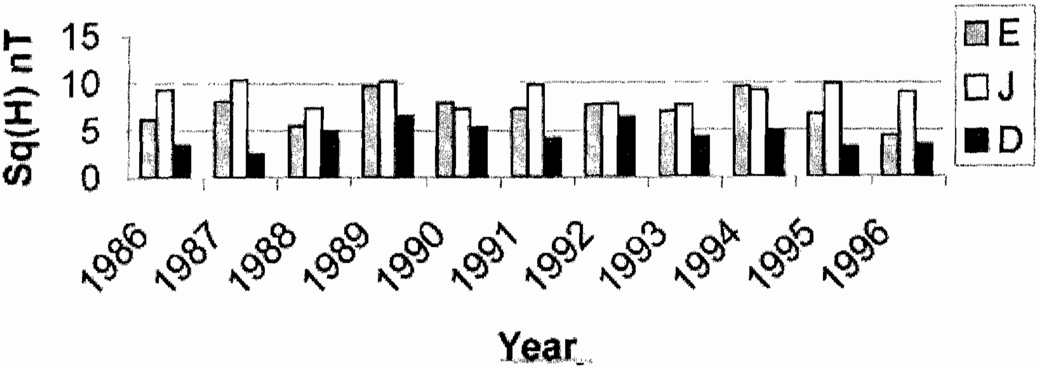

Fig. 3. Seasonal variation of Sq(Z)

TABLE 2

Correlation coefficients among the seasonal Sq

	HE++	*HJ*	*HD*	*DE*	*DJ*	*DD*	*ZE*	*ZJ*	*ZD*
HE[++]	*								
HJ	0.291**	*							
HD	0.491	-0.403	*						
DE	0.708	0.172	0.560	*					
DJ	0.659	0.235	0.468	0.916	*				
DD	0.522	-0.081	0.629	0.919	0.821	*			
ZE	0.562	0.336	0.367	0.891	0.831	0.807	*		
ZJ	0.598	0.127	0.619	0.844	0.836	0.744	0.800	*	
ZD	0.318	-0.328	0.753	0.754	0.683	0.814	0.578	0.824	*

[++] The first letter represents the geomagnetic element while the second letter stands for the season. For example, HE implies the Sq variation in H at the Equinox (E- season)

in terms of seasonal variability of semidiurnal tides. Studies by Bernard (1981), Haper (1981), Fesen, Dickinson & Roble (1986), among others, have revealed a measurement of significant seasonal variation in the semidiurnal tides using radar. The semidiurnal tide, which maximizes in the E-dynamo region, has been shown to also be strongest in June solstice, weak in Equinox and weaker in December solstice (Brekke, Nozawa & Sparr, 1994).

The seasonal variability of Sq field confirms the seasonal redistribution of the Sq current systems (Butcher & Brown, 1980; Onwumechili, Oko & Ezema, 1996). It has been suggested that seasonal movement in the position of the focus of Sq current could also account for seasonal variation of Sq (Hasegawa, 1960; Yacob & Rao, 1966; Forbes, 1981; Mann & Schlapp, 1988). Butcher (1982) found that the focus latitude moves equatorward in D-solstice. Campbell & Schiffmacher (1987) found that the Sq current magnitude indicated at focus in June solstice was greater than the D-solstice value by a factor of 2.9. This June solstical maximum is in accord with the result obtained in the study.

Possible physical mechanisms responsible for variability of Sq foci include ionospheric wind variations (Hasegawa, 1960), atmospheric tidal forces or wind systems in the Sq layer (Yacob & Rao, 1966); variability in the dynamo winds caused by *in-situ* heatings (Mann & Schlapp, 1988; Greener & Schlapp, 1979); variability of the upward propagating semidiurnal modes driven from below (Briggs, 1984); addition of a superposed northward magnetic field (Butcher & Schlapp, 1992); seasonal changes in molecular viscosity heat conduction of ion drag in the ionoshpere (Van Velthoven, 1990); seasonal variability of EEJ (Osborne, 1966; Rajaram, 1983); distant current systems such as currents in the magnetosphere and in the tail of the magnetosphere (Matveyenkov, 1983).

Seasonal variation of ionospheric electron content (IEC) can also account for the observed Sq field variation. The IEC have been observed to have seasonal variation with a similar pronounced maximum in June solstice (Van Velthoven, 1990). The variability of IEC has been explained to be caused by erratic equatorward neutral winds (Kane, 1975), equatorial electroject (Balan & Iyer, 1983; Aravidan & Iyer, 1990), and solar activity (Hargreaves, 1979).

Comparison of seasonal Sq in H, D, and Z

The seasonal Sq variation (Fig. 1, 2 and 3) has maximum in June solstice and minimum in D-solstice in the three elements. This common pattern indicates a remarkable co-response to factors and mechanisms responsible for Sq variation as well as some degree of inter-relationships among the elements.

In D- and E- seasons (Table 2), the seasonal Sq variation in each element is strongly and positively correlated with others, while in the season of maximum Sq, that is J-solstice, Sq in H is poorly correlatd with any of the pair of Sq in D and Z; in J-season, r(H,D) = 0.235, r(H,Z) = 0.127; in D-season, r(H,Z) = 0.753, r(H,D) = 0.629; in E-season r(H,Z) = 0.562, r(H,D) = 0.708. In all the seasons, Sq in D and Z are strongly correlated with each other; in J-season, r(D,Z) = 0.836, in D-season, r(D,Z) = 0.814 and in E-season, r(D,Z) = 0.891. Thus, the pair of Sq in D and Z have stronger correlation than does either of them with Sq in H at any season of the year.

Therefore, Fig. 1, 2 and 3, as well as Table 2, clearly reveal that inter-relationships with varying degree exist among the seasonal Sq in the three elements H, D, and Z.

Conclusion

An extensive study of the geomagnetic Sq field variation has been carried out at middle latitudes using the data from three geomagnetic observatories: Castello Tesino (46.2° N, 11.7° E), Furstenfeldbruck (48.1° N, 11.3° E) and Wingst (53.7°N, 9.1°E). The data, which consists of hourly values of magnetic elements H, D, and Z for all the eleven years of solar cycle #22, was analyzed for seasonal Sq variations on quiet conditions.

The main conclusions are:

1) The seasonal variation of Sq in the three elements is quite consistent and is in accord with the classical order in the low latitude: Maximum in June solstice, followed by Equinox and least in December solstice.

2) The seasonal variation of Sq in H, D, Z is demonstrated to be explicable in terms of variability of semidiurnal tides, seasonal variability of Sq focus and variability of ionospheric electron content.

3) The seasonal variation of Sq implies the seasonal redistribution of ionospheric currents responsible for Sq.

4) H, D, and Z have a remarkable co-response to factors and mechanisms responsible for Sq seasonal variation.

5) Inter-relationship with varying degree exist among the seasonal Sq in the three elements H, D, and Z.

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References

ARAVINDAN, P. & IYER, K. N. (1990) Day-to-day variability in ionospheric electron content at low latitudes. *Planet Space Sci.* **38**, 743-750.

BALAN, N. & IYER K. N. (1983) Equatorial anomally in ionospheric electron content and its relation to dynamo currents. *J. Geophys. Res.* **88**, 10259-10292.

BERNARD, B. (1981) Variability of the semi-diurnal tide in the mesosphere. *J. atmos. Terr. Phys.* **43**, 663-67.

BREKKE, A., NOZAWA, S. & SPARR, T. (1994) Studies of the E-region neutral wind in the quiet auroral ionosphere. *J. Geophys. Res.* **99**, 8801-8824.

BRIGGS, B. H. (1984) The variability of ionospheric dynamo currents. *J. atmos. Terr. Phys.* **46**, 419-429.

BUTCHER, E. C. (1982) On the latitude of the Sq (H) focus in years of sunspot minimum. *Geophys. J. R. astro. Soc.* **69**, 113-120.

BUTCHER, E. C. & BROWN, G. M. (1980) Abnormal quiet days and the effects of the interplanetary magnetic field on the apparent position of the Sq focus, *Geophys. J. R. astro. Soc.* **69**, 783-789.

Butcher, E. C. & Brown, G. M. (1981) The variability of Sq (H) on normal quiet days. *Geophys. J. R. astro. Soc.* **641**, 527-537.

Butcher, E. C. & Schlapp, D. M. (1992) The annual variation of the night-time values of the geomagnetic field. *Geophys. J. Int.* **111**, 151-158.

Campbell, W. H. (1987) Some effects of quiet geomagnetic fields changes upon values used for main field modeling. *Phys. Earth Planet. Inter.* **48**, 193-199.

Campbell, W. H. & Schiffmacher, E. R. (1987) Quiet ionospheric currents and earth conductivity profile computed from quite-time geomagnetic field changes in the region of Australia. *Aust. J. Phys.* **40**, 73-87.

Champan, S. & Bartels, J. (1940) *Geomagnetism.* Oxford: Oxford University Press.

Fesen, C. G., Dickinson, R. E. & Roble, R. G. (1986) Simulation of the thermospheric tides at equinox with the National Center for Atmospheric Research Thermospheric circulation model. *J. Geophys. Res.* **90**, 4471-4489.

Forbes, J. M. (1981) The equatorial electrojet. *Rev. Geoph. Space Phys.* **19**, 469-504.

Greener, J. G. & Schlapp, D. M. (1979) A study of day-to-day variability of Sq over Europe. *J. atmos. Terr. Phys.* **41**, 217-223.

Hargreaves, J. K. (1979) The *Upper Atmosphere and Solar Terrestrial Relations. An Introduction to Aerospace Environment.* New York: Van Nostrand Reinhold Campany.

Harper, R. M. (1981) Some results on mean tidal structure and day-to-day variability over Arecibo. *J. atmos. Terr. Phys.* **43**, 255-262.

Hasegawa, M. (1960) On the position of the focus of the geomagnetic Sq current system. *J. Geophys. Res.* **65**, 1437-1447.

Kane, R. P. (1975) Day-to-day variability of ionospheric electron content at Mid-latitudes. *J. Geophys. Res.* **80**, 3091-3103.

Mann, R. J. & Schlapp, D. M. (1988) The equatorial electrojet and the day-to-day variability of Sq. *J. Atmos. Terr. Phys.* **50**, 57-62.

Matveyenkov, I. T. (1983) Possible effects of distant field sources on Sq variations. *Geomagnetic and Aeronomy* **23**, 276-277.

Mitra, S. K. (1947) *The Upper Atmoshpere.* Calcutta: The Royal Asiatic Society of Bengal.

Okeke, E. N., Onwumechili, C. A. & Rabiu, A. B. (1998) Day-to-day variability of geomagnetic hourly amplitudes at low latitude. *Geophys. J. Int.* **134**, 484-500.

Okeke, F. N. & Rabiu, A. B. (1990) Some aspects of the Earth's mid latitude geomagnetic field variations. *Irish Astr. J.* **26** (1), 29-32.

Oko, S. O., Onwumechili, C. A. & Ezema, P. O. (1996) Geomagnetic quiet day ionospheric currents - II. Equatorial electrojet current. *J. atmos. Terr. Phys.* **58**, 555-564.

Onwumechili, C. A. (1992a) A study of rocket measurement of ionospheric currents - I. General setting and night-time ionospheric current. *Geophys. J. Int.* **108**, 633-640.

Onwumechili, C. A. (1992b) A study of rocket measurements of ionospheric currents - II. Ionospheric currents outside the dip equatorial zone. *Geophys. J. Int.* **108**, 641-646.

Onwumechili, C. A. (1992c) Study of the return current of the equatorial electrojet. *J. Geomang. Geoelectr.* **44**, 1-42.

Onwumechili, C. A. & Agu, C. E. (1981) The relationship between the current and the width of the equatorial electrojet. *J. atmos. Terr. Phys.* **43**, 573-578.

Onwumechili, C. A. & Ogbuehi, P. O. (1962) Fluctuation in the geomagnetic horizontal field. *J. atmos. Terr. Phys.* **24**, 173-190.

Onwumechili, C. A., Oko, S. O. & Ezema, P. O. (1996) Geomagnetically quiet day ionospheric currents I. Worldwide Part of Sq. currents. *J. atmos. Terr. Phys.* **58**, 541-553.

Osborne, D. G. (1966) Correlations between quiet day magnetic ranges. *J. atmos. Terr. Phys.* **28**, 45-51.

Rabiu, A. B. (1992) *Day-to-day variability in the geomagnetic variations at the low latitude observatory of Muntinlupa in the Muntillupa in the Phillippines,* (MSc. Thesis.) University of Nigeria, Nsukka, Nigeria.

Rajaram, M. (1983) Determination of the latitude of Sq focus and its relation to the electrojet variations. *J. atmos. Terr. Phys.* **45**, 573-578.

Suzuki, A. (1978) Geomagnetic Sq field at successive universal times. *J. atmos. Terr. Phys.* **40**, 449-463.

Suzuki, A. (1979) U. T. and day-to-day variations in equivalent current systems for world geomagnetic variations. *J. Geomag. Geoelectr.* **31**, 21-46.

Takeda, M. (1984) Day-to-day of variation in equivalent Sq current systems during March 11-26, 1976.

J. Geomag. Geoelectr. **36**, 215-228.

Takeda, M. (1985) U. T. variation of internal Sq currents and the oceanic effects during 1980 March 1 - 18. *Geophys. J.R. astro. Soc.* **80**, 649-659.

Tarpley, J. C. (1970) The ionospheric wind dynamo II, solar tides. *Planet Space Sci.* **18**, 1091-1103.

Van Velthoven, P. F. T. (1990) *Medium scale irregularities in the ionospheric electron content*, (PhD. Thesis.) Eindhoven University of Technology, Netherlands.

Vestine, E. H. (1967) Main geomagnetic field. In *Physics of Geomagnetic Phenomena* (ed. S. Matsushita and W. H. Campbell) Vol. 1, pp. 181-234. New York: Academic Press.

Yacob, A. R. & Rao, D. R. (1966) Solar cycle and annual variations of Sq (H) at Alibag. *J. atmos. Terr. Phys.* **28**, 351-388.

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