Zonal and meridional ionospheric currents in the Central Asian sector

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The daily and seasonal variations of all the three components $H$, $Y$, and $Z$ of the geomagnetic field have been described on the basis of the data from a unique network of observatories within a narrow longitude belt extending from the magnetic equator to 60° dip latitude. The daily variations of the eastward field ($Y$) show remarkable changes between the summer and winter months. The amplitude of the daily variation is reduced to an insignificantly small value during the local winter months. The horizontal field ($H$) also does not show clear variation at observatories north of the latitude of the $Sq$ focus during local winter months. These features lead to the absence of vortex-type $Sq$ current system during local winter months. The latitudinal variations of the diurnal and semi-diurnal components are discussed in detail. Seasonal variations in solar and lunar tides have been discussed and attributed to rather independent sources in the zonal and meridional currents. The tidal modes of ionospheric winds in the Central Asian sector need to be probed for explaining the drastic changes of the observed effects with season.

1 Introduction

Both India and former USSR have long tradition of geomagnetic studies. With the passage of time, both the countries extended the network of geomagnetic observatories in their region. Under the project 'Geomagnetic Meridians', with the cooperation of IZMIRAN, Moscow and Indian Institute of Geomagnetism, Bombay, number of new observatories were established since 1975 along the 145°E geomagnetic meridian, using Bobrov Quartz Magnetometers, which have proved to be very sensitive, stable and free from temperature effects. Figure 1 shows the locations of these geomagnetic observatories. A unique network of observatories from equator to the pole within a narrow belt of longitudes is clearly seen. During December solstices, the usual $Sq$ loop current system seems to vanish with significant reduction of electrojet currents. Former studies of global $Sq$ current system have missed these results probably due to combining the data from different longitudes. Using the simultaneous $D$, $H$ and $Z$ data from network of these observatories Rastogi has shown that the counter electrojet events are consequent to the modifications of the current system over the whole latitudes in Asian region and are not due to a phenomenon confined to equatorial latitudes only. A semi-diurnal current superposed on the normal $Sq$ current system was shown to be the cause of equatorial counter electrojet currents.

A detailed study of the geomagnetic field variations of available data from Central Asian longitudes has been undertaken here to understand the current system in low sunspot period (1976-1977) in this zone under different seasons of the year. The list of stations and their geomagnetic parameters used in the present analysis are given in Table 1. The declination data have been converted into eastward field ($Y$) for the present analysis.

2 Results and analysis

The monthly mean daily variations of $H$ and $Y$ fields at different stations for each month were averaged for three Lloyd seasons, namely, the D-months consisting of November, December, January and February, the E-months consisting of March, April, September and October and J-months consisting of May, June, July and August. The seasonally averaged daily variations of $H$ and $Y$ at each of the stations are shown in Fig. 2. It is seen that the daily variation of $\Delta H$ shows a strong enhancement around noon hours at low latitudes at all seasons. The amplitude of $\Delta H$ is strongest during E-months and least during D-months. During the E-months, the magnitude of the daily variation of $\Delta H$ decreases towards higher latitudes and changes sign at Tashkent and stations further north, a minimum of $\Delta H$ is seen slightly before noon. This is exactly what is expected of the classical $Sq$ current system in the ionosphere. The variations are more or less simi-
During J-months, the amplitude of the daily variation decreases with latitude and becomes negligibly small at Tashkent and at higher latitude stations. No significant decrease of the $H$ field around midday hours can be seen at stations north of Sabhawala.

Referring to the curves of daily variations of $Y$ field, the annual pattern discussed earlier by Patil et al. with a forenoon maximum and an afternoon minimum is seen only during the J- and E-months. The amplitude of the daily variations of the $Y$ field at all the stations is larger during J-months than during E-months. During D-months, the daily variation of $Y$ field is considerably small at all the stations and is practically opposite to that in other seasons with an additional dip around early morning.

The hourly departures of $\Delta H$ and $\Delta Y$ (with respect to nightbase) are combined for all stations to demonstrate the daily rotation of the current vector. These vector diagrams for D-months (winter) and J-months (summer) are separately shown in Fig. 3. The primary eastward current at equatorial stations changes to north-south current with increasing latitude. The axis of the loop slowly shifts from E-W direction at the equator to N-S direction at high latitudes. Thus the importance of zonal current at low latitudes and of meridional current at high latitudes are apparent.

During D-months, a predominantly zonal current is seen at equatorial stations. But at tropical and middle latitudes, there is no significant elliptical structure, suggesting highly reduced meridional currents.

Table 1—Coordinates and the geomagnetic parameters of the observatories in the Indo-Russian longitude sector, whose data have been used for the year 1976

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Code</th>
<th>Geogr. long. $^\circ E$</th>
<th>Geogr. lat. $^\circ N$</th>
<th>Dip. long. $^\circ E$</th>
<th>Dip. lat. $^\circ N$</th>
<th>Dipole long. $^\circ E$</th>
<th>Dipole lat. $^\circ N$</th>
<th>$D$ nT</th>
<th>$H$ nT</th>
<th>$Z$ nT</th>
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<tr>
<td>Novosibirsk</td>
<td>NVS</td>
<td>82.9</td>
<td>55.0</td>
<td>58.5</td>
<td>44.7</td>
<td>158.8</td>
<td>+8$^\circ$32.3</td>
<td>17302</td>
<td>56457</td>
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<td>Karaganda</td>
<td>KGD</td>
<td>73.1</td>
<td>49.8</td>
<td>52.5</td>
<td>40.3</td>
<td>149.8</td>
<td>+8$^\circ$12.7</td>
<td>20269</td>
<td>52338</td>
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<tr>
<td>Alma Ata</td>
<td>AAA</td>
<td>76.9</td>
<td>43.3</td>
<td>43.0</td>
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<td>151.9</td>
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<td>Tashkent</td>
<td>TKT</td>
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<td>41.3</td>
<td>41.0</td>
<td>32.3</td>
<td>145.2</td>
<td>+4$^\circ$36.8</td>
<td>25869</td>
<td>45300</td>
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<td>Gulmarg (1978)</td>
<td>GUL</td>
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<td>34.1</td>
<td>31.4</td>
<td>24.8</td>
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<td>SAB</td>
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<td>30.4</td>
<td>26.9</td>
<td>20.8</td>
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<td>+0$^\circ$22.1</td>
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<td>Jaipur</td>
<td>JAI</td>
<td>75.8</td>
<td>26.9</td>
<td>22.4</td>
<td>17.3</td>
<td>147.4</td>
<td>-0$^\circ$48.8</td>
<td>35941</td>
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<td>Ujjain</td>
<td>UIJ</td>
<td>75.8</td>
<td>23.2</td>
<td>18.1</td>
<td>13.5</td>
<td>147.0</td>
<td>-0$^\circ$32.9</td>
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<td>Alibag</td>
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<td>9.5</td>
<td>143.6</td>
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<td>10.7</td>
<td>7.6</td>
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<td>Annamalainagar</td>
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<td>2.8</td>
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<tr>
<td>Kodakkanal</td>
<td>KOD</td>
<td>77.5</td>
<td>10.2</td>
<td>1.6</td>
<td>0.6</td>
<td>147.1</td>
<td>-2$^\circ$24.4</td>
<td>39318</td>
<td>2208</td>
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<tr>
<td>Trivandrum</td>
<td>TRD</td>
<td>77.0</td>
<td>8.5</td>
<td>-0.3</td>
<td>-1.2</td>
<td>146.4</td>
<td>-2$^\circ$46.4</td>
<td>39929</td>
<td>473</td>
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Fig. 2—Solar daily variations of horizontal and eastward components of geomagnetic field at each of the observatories averaged for the three seasons during 1976-1977
To understand the role of diurnal and semi-diurnal modes of geomagnetic field variations on the current system, the daily variations of $H$ and $Y$ at each stations for different seasons were subjected to Fourier analysis and the amplitudes and times of maximum phase are shown in Fig. 4. Referring to $H$ field, amplitudes of $C_1$ and $C_2$ show, in general, decreasing value with increasing latitude. Seasonally, at low latitudes the largest amplitudes of $C_1$ and $C_2$ are observed in E-months and least during D-months. At high latitudes the largest values of $C_1$ and $C_2$ occur during J-months and least during D-months, suggesting that the amplitudes are controlled by the solar zenith angle. Thus, ionospheric currents at stations north of the $S_q$ focus are solar controlled in their seasonal behaviour but, at low latitudes, an additional source of current develops during the equinoctial months. The ratio $C_1/C_2$ shows a minimum around the latitudes of the $S_q$ focus during E- and J-months. The time of maximum ($T_2$) of semi-diurnal variation in $H$ is around 12 hrs LT at low latitudes for all the seasons. The value of $T_2$ increases uniformly with latitudes and becomes about 16 hrs LT at 60° dip latitude. There is no seasonal difference in the latitudinal variation of the phase of the semi-diurnal oscillation. The times of maximum excursion of the diurnal component $T_1$ at stations south of $S_q$ focus are around 12 hrs LT during any of the seasons. The values of $T_1$ changes to 24 hrs LT at stations north of $S_q$ focus during E- and J-months, but no such reversal of phase with latitude is seen during D-months. Thus, the absence of phase reversal of the diurnal oscillation with latitude is associated with the absence of $S_q$ current system during D-months.

Referring to the $Y$ field, amplitudes $C_1$ and $C_2$ are largest in J-months and least during D-months and thus follow the elevation of the sun with season. The semi-diurnal amplitude $C_1$ for E- and J-months increase smoothly with latitude. The diurnal amplitude $C_1$ of $Y$ field shows a minimum around the latitude of $S_q$ focus in D-months only. The time of maximum of the semi-diurnal oscillation increases from 07 hrs LT at the equator to 09 hrs LT at higher latitudes. There is no significant change with season. The time of diurnal component during E- and J-months changes from 03 hrs LT at equator to 05 hrs LT at high latitudes. During D-months, the phase of the diurnal oscillation ($T_1$) is very different from that during other seasons. It occurs around 19 hrs LT at the equator and changes with latitude to about 23 hrs LT at 60° dip latitude. Here again it is found that the features of the diurnal component of the $Y$ field are associated with existence of the $S_q$ current during E- and J-months and with its near-absence during D-months.

In Fig. 5 are shown the contour plots of $\Delta H$.
Fig. 4—Latitudinal variations of the amplitudes (C1 and C2) and times of maximum excursions of the daily variation of \( H \) and \( Y \) averaged for D-, E- and J-months.

**HORIZONTAL FIELD**

**EASTWARD FIELD**

Fig. 5—Contour plots of \( \Delta H \) and \( \Delta Y \) in latitude versus local time coordinates, averaged for different seasons E-, J- and D-months of the year 1976-77.
and $\Delta Y$ for different seasons of the period 1976-1977.

Referring to $\Delta H$ plots, during E-months, one finds a very strong electrojet around 10 hrs LT over the equator but a negative value of $S_q$ at latitudes greater than 40° around the same time. The zero isoline ($\Delta H=0$) changes latitude with time in a very clear fashion. The value of $\Delta H$ becomes 0 at the dip equator at around 06 hrs LT, at 30° at around 10 hrs LT, near the time of maximum equatorial electrojet and the latitude reaches 50° at around 16 hrs LT for $\Delta H$ becoming 0. Moreover, similar features of $\Delta H$ contours are seen in J-months with slightly reduced magnitudes. During D-months, the $\Delta H$ contours at low latitudes are symmetrical around 10 hrs LT axis and no reversal of $\Delta H$ is seen at higher latitudes.

Regarding the contours of $\Delta Y$, one can clearly see positive values in the morning and negative values in the afternoon hours during summer and equinoxes. During the winter months, the contours of $\Delta Y$ show negative values at all latitudes.

The current vectors at different stations for different local solar hours can be represented in another form as shown in Fig. 6 for E-, J- and D-months. The arrows indicate the direction and magnitude of the current vector at a particular hour and station. During E- and J-months the $S_q$ loop current is very clearly evident with its focus at latitudes between Sabhawala and Tashkent and centred at about 11 hrs LT. During D-months the eastward current at equatorial latitudes during the midday is very clear. Weak westward currents at

![Fig. 6—Current vectors at each of the hours at different stations during D-, E- and J-months of the period 1976-77 (Y-axis represents the geographic latitude of the stations.)](image-url)
other stations in Indian latitudes are also clear but no loop can be identified suggesting the disintegration of the $S_q$ loop current during D-months along Indo-Russian longitudes.

3 Seasonal effects on solar daily range of $H$ and $Y$

In Fig. 7 are shown the month-to-month variations of the solar daily ranges of $H$ and $Y$ components of the geomagnetic field for different stations during 1976-1977. The eastward field ($Y$) shows remarkably similar seasonal variations at all the stations. The daily range of $Y$ is highly negative during March-October but reverts to positive value during local winter (December) months. This suggests that besides the general equatorward current, in most of the months there is meridional current towards the equator during the midday hours of winter months.

The solar daily range of horizontal field ($H$) shows remarkable equinoctial maxima at equatorial stations Trivandrum, Kodaikanal and Annamalainagar. At low latitude stations outside the electrojet region but south of the $S_q$ focus, namely, HYB, ABG, UJJ, JAI and SAB, the horizontal fields do not show any significant seasonal variation during the period under study. At stations north of the $S_q$ focus, a clear summer minimum of the range of $H$ is seen. Thus, it is obvious that there are three regions of $S_q$ current system as regards to the seasonal variation.

In Fig. 8 are shown the lunar current vectors during the new moon days of D- and J-months during the period 1976-1977. During J-months, two vortices of the current system with foci at about 15° dip latitudes are distinctly seen. In any particular local hour the meridional current vectors are seen to be along the same directions for any latitude.

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Fig. 8—Lunar current systems during the new moon days averaged for J- and D-months of 1976-77
During D-months, a semi-diurnal variation of the zonal current vectors is evident but, there is no reversal of the direction of zonal current across any latitude, i.e. there is no vortex system seen in northern hemisphere. These results show that both the solar and lunar (new moon days) current systems are drastically different during the two solstices in the Central Asian longitude sector.

Rastogi and Verma⁴ have shown that, analogous to the failure of the single vortex ($S_q$) current system in the Asian sector during the local winter (December) months, the lunar twin vortex ($L_2$) current system also fails to develop during the local winter months in the Asian sector.

4 Discussion

The first spherical harmonic analysis of geomagnetic daily variation by Chapman⁵ using horizontal field ($H$), vertical field ($Z$) and declination ($D$) data from 21 observatories had yielded the classical pattern of ionospheric current system with the clockwise current loops at northern hemisphere with vortices at around 11 hrs LT and 35° geographic latitude. The basic assumption in this and other analyses has been that the potential of the $S_q$ field depends only on latitude and local time, i.e. the daily variations of the different geomagnetic field components at two stations at similar latitudes are identical. Matsushita and Maeda⁶ analysed the $H$ and $Z$ data for the different seasons of the IGY. They divided the data into three longitude zones. The $S_q$ current system for any season and longitude sector was basically similar to the classical pattern derived earlier by Chapman⁵. Parkinson⁷, using the north component ($X$), derived the ionospheric current pattern for 00, 06, 12, 18 hrs UT of these different seasons for the IGY period. Again, well known pattern of current system was obtained. Further analysis of IGY data from 21 observatories had yielded the classical pattern of ionospheric current system.

Analysing the ionospheric electron content data along the Indian and East Asian longitudes Walker et al.⁸ noticed that, on some days, quite different diurnal variation of magnetic field components were recorded at similar latitude stations in East Asia and India separated by a longitude difference of 40° only. This indicated a longitudinal variation of the localised pattern of the dynamics of the ionospheric region, causing the geomagnetic field variations at ground. Suzuki⁹ obtained equivalent ionospheric current system at fixed universal times on individual days and showed distorted pattern varying considerably from day to day and thus indicating a day-to-day variability of winds in the dynamo region. Examining the geomagnetic $H$ and $D$ data at geomagnetic observatories along 125°E longitude, Walker and Kannangara¹¹ found that during December 1976, the observed daily variations of $H$ and $D$ did not conform to the standard pattern which were present during the individual days of summer and equinoxes of 1976. During the winter solstices no $S_q$ current vortex was evident in the northern hemisphere.

Rastogi¹² observed an abnormally large number of days when ionospheric electron content ($N_e$) anomaly did not develop in Indian subcontinent and traced these events to the absence of the equatorial enhancement of the daily range of $H$ field. He showed that ionospheric current system over India during December 1975 presents a very complex pattern from day to day. Rastogi¹³ treated this abnormal feature to be the disintegration of the ionospheric loop current system during local winter months. Similar disappearance of vortex current system during winter months of 1976-1977 were observed by Campbell et al.¹³

Assuming that the observed daily variations of geomagnetic fields are due to the winds in the dynamo region caused by upward propagation of tidal modes from lower atmosphere, various tidal modes of wind have been suggested to explain the observed variations¹⁴,¹⁵. Schieldge et al.¹⁶ simulated the electrojet variations at different longitudes around the world with coupled numerical models of the atmospheric dynamo and found that in addition to (1, 2) tidal effects, additional semi-diurnal modes (2, 2), (2, 3) and (2, 4) are needed. Forbes and Lindzen¹⁷ have explained the global magnetic field variations using tidal wind modes (1, 2), (1, 1), (2, 2) and (2, 4).

Van Saben¹⁸ has suggested that the asymmetry in the diurnal magnetic field variations between the northern and southern hemispheres, even during equinoxes, leads to field aligned currents across the equator. During June, the field aligned currents were suggested to flow from north to south in the morning and back in the afternoon hours¹⁸. Such currents were suggested to be consequent to the difference of electric potential at conjugated points or due to the asymmetry of wind system in the two hemispheres.

Significant daily variations of $\Delta Y$ at low latitudes suggests the presence of field aligned currents around midday hours during E- and J-months. Maeda¹⁹ had suggested field aligned currents flowing, mainly in the daytime, from winter to summer hemispheres. Stening²⁰ showed that
(1, 2) mode wind system generates a band of intense low latitude currents which contribute substantially to the eastward daily variation of $\Delta Y$. Fukushima\textsuperscript{21} has suggested the existence of field aligned currents at low latitudes near the equator in the direction of summer to winter in the forenoon and winter to summer at dusk-afternoon and dusk hours.

Rastogi\textsuperscript{22} had discussed the cases when $\Delta H$ at Trivandrum showed a suppression simultaneously with the increase of $\Delta Z$ at Annamalainagar but minimum value of $\Delta H$ (TRD) was significantly above zero (sometimes about 100 nT). The ionospheric drifts at Trivandrum showed reversal of eastward direction and the $E_{\text{eq}}$ layer had disappeared, suggesting the imposition of westward field at the height of the $E_{\text{eq}}$ layer. The positive $\Delta H$ at TRD indicated the integrated eastward current. It was suggested that the ionospheric currents over the magnetic equator consists of normal eastward current at a level of 107 km associated with global Sq current. There is another current at 100 km level which may be non-Sq generating mechanism. Reversal of east-west electric field with altitude over the magnetic equator has been observed by VHF backscatter radar at Thumba\textsuperscript{23} during counter electrojet events.

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