Dynamo currents, winds, and electric fields

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After a brief presentation of $S_q$ and $L$ electric current systems deduced from geomagnetic data, electric conductivities and wind models in the dynamo region are discussed. It is then shown that the solar negative-mode thermal diurnal tide and the lunar semidiurnal gravitational tide having a phase shift with altitudes produce the best fit $S_q$ and $L$ current systems, respectively. Distributions of electrostatic fields are computed, and electromagnetic drift speeds in the ionospheric $F$ region are also examined. These calculated values agree well with observed results.

1. DEDUCED DYNAMO CURRENT SYSTEMS

Methods of deduction of dynamo currents and the remaining problems, particularly the $S_q$ and $L$ current systems and the equatorial electrojet, were reviewed by Matsushita [1967a, b] and Omwumehilli [1967]. Since the electric conductivity in the dynamo region (90–150 km altitude) is very low at night on geomagnetically quiet days, the dynamo currents on quiet nights may be almost zero. On the basis of this idea, Matsushita [1968] obtained computer-plotted $S_q$ and luni-solar current systems for three seasons and the yearly average from his previously obtained current systems [Matsushita, 1967b] by shifting the base line. Figure 1 shows $S_q$ current systems deduced in this way.

To obtain better luni-solar current systems than those deduced by using a relatively simple adjustment parameter [Matsushita, 1968, Figure 11], more realistic parameters are estimated from global $(f,E)^{\alpha}$ distributions in equinoctial and solstitial months during moderate sunspot periods. Figure 2 presents distributions of the parameter with respect to the dip latitude and the local time for the equinoctial and the June solstitial months; a reversal of the hemisphere for the June solstitial months is assumed to be the distribution for the December solstitial months. Multiplying the $L$ current systems of a mean luni [Matsushita, 1967b] by these parameters produces the $L$ current systems for a new moon or the luni-solar current systems exhibited in Figure 3. The total current intensities are compared in Table 1. The deduced $S_q$ and $L$ current systems clearly show the electrojet over the magnetic equatorial zone. These equatorial electrojets in the dynamo region were further confirmed by recent rocket observations ($S_q$ by Davis et al. [1967], Maynard [1967], and Sastry [1968]; $L$ by Maynard [1967]). In section 4, $S_q$ and $L$ current systems with the electrojet, computed from estimated electric conductivities and wind models, are compared with these deduced current systems.

2. ELECTRIC CONDUCTIVITY MODEL

By assuming that the physical quantities of the ionosphere are the same everywhere along the dip equator except for the differences arising from the asymmetry of the earth’s permanent magnetic field, the cross-sectional profiles of the effective conductivity (hence the electrojet), were determined by Sugiuira and Cain [1966] for different longitudes, particularly 80øE for India and 280øE for Peru. Price [1968, 1969] examined the applicability of the layer conductivities in the two-dimensional treatment of the dynamo theory of $S_q$. Calculations with a simple three-dimensional model suggest that the currents arising from wind-induced electromotive forces are nearly horizontal throughout the dynamo layer, so that the two-dimensional equations involving the layer conductivities can be used. However, the assumption that the horizontal current density is non-divergent and that consequently a current function can be found has been shown to be quite untrue.

For the purpose of obtaining total electric field distributions calculated from the deduced current sys-
tem and of computing current systems with wind models, a simple but reasonable model of the electric conductivity is needed. From the COSPAR-1965 atmosphere model, collision frequencies were computed by using the equations derived by Nicolet [1953] for the electron-ion collision frequency and by Dalgarno [1961] for the electron-neutral and the ion-neutral collision frequencies. Obtained height-integrated anisotropic electric conductivity distributions for two seasons during the IGY are shown in Figure 4. The conductivity distribution for December solstitial months can be approximated by the reversal of the hemisphere in the distribution for June solstitial months. The height-integrated conductivities for moderate sunspot periods are assumed to be 1/1.3 of the values for the IGY indicated in Figure 4. These conductivities and the \( L \) current system exhibited in Figure 3 give the total electric field (dynamo and electrostatic fields) for the \( L \); the \( S_q \) current system in Figure 1 and the conductivity in Figure 4 present the total electric field for the \( S_q \). These total field distributions for the \( S_q \) and \( L \) were illustrated by Matsushita and Reddy [1968]: the total electric field in low latitudes is a few mvolt/m for the \( S_q \) and a few tenths of mvolt/m for the \( L \). The very small values of the field over the equator indicate that the estimated conductivity is probably too large for the equator.

Fig. 1. Computer-plotted external \( S_q \) current systems for December solstitial, equinoctial, and June solstitial seasons and the yearly average during the IGY (1958) when the current intensity at the midnight is zero. The current intensity between two consecutive lines is \( 25 \times 10^3 \) amp, and the numbers near the cross marks indicate the total current intensities of vortices in units of \( 10^3 \) amp [Matsushita, 1968].
To compute current systems, a slightly modified conductivity model for equinoctial months during moderate sunspot periods was obtained by Tarpley [1969]. The maximum value of $\sigma_1$ (Pedersen conductivity) in middle latitudes at noon is $3.1 \times 10^{-15}$ emu at 127 km altitude and that of $\sigma_2$ (Hall conductivity) is $4.5 \times 10^{-16}$ emu at 117 km. The tensor components of the height-integrated conductivity at noon are shown in Table 2. For the daily variation of the conductivity

$$\Sigma = \sum_{\text{noon}} \cos^{1/2} t$$

is adopted, and the conductivity during the period 1830 through 0530 LT is assumed to be constant and equal to 1/30 of the noon value. For details of temporal, latitudinal, and height distributions of the conductivity, refer to Tarpley [1969]. Computed results of the current systems using this conductivity model are presented in section 4.

3. WIND MODEL

We have recently gained a large amount of knowledge about the movements of ionospheric irregularities and upper atmospheric winds by various observational techniques and extensive theoretical estimations [e.g., Hines, 1966; Woodrum and Justus, 1968; Kent and Wright, 1968]. Data from a new meteor-wind observation system in France for 80–110 km altitudes (M. A. Spizzichino, private communication) have been processed by power spectral analysis to assess prevailing and tidal components and to analyze the residual nontidal contributions. The major component is semidiurnal, with a vertical wavelength greater than 50 km and an amplitude of 10–70 m/sec. A downward phase velocity of 5–10 km/hr is largely due to the semidiurnal component. Similar results for 90–130 km altitudes at night have also been obtained by observations of chemiluminous trails released by rockets and gun-launched projectiles [e.g., Wright et al., 1967; Bedinger et al., 1968].

A statistical analysis of seventy midlatitude vapor trails between 90 and 150 km altitude made by Rosenberg [1968] showed not only a consistent zonal flow to the east below 100 km, but also mean values of total velocity of 50 to 70 m/sec and mean shears of 0.02 to 0.004 m/s/m, varying with height. One full rotation occurs between 90 and 110 km and another occurs between 105 and 150 km. The height-integrated current intensity caused by the dynamo action of this type of rotated wind will be very small.

Those areas of wind measurements in which adequate data are not yet available include vertical winds, daytime winds above 110 km, and horizontally spaced winds to permit convergence estimates. Thus it is still difficult from observations to know a detailed global picture of the wind system responsible for dynamo currents. Also estimations of the wind patterns from dynamo currents and given conductiv-

| TABLE 1. Total current intensities of $L$ current systems ($\times 10^3$ amp) |
|-----------------|---|---|---|---|---|---|---|---|
| Season, Luni-solar | $D$ | $E$ | $J$ | Average |
| Hemisphere: | $N$ | $S$ | $N$ | $S$ | $N$ | $S$ | $N$ | $S$ |
| Mean lunation | 3.77 | -5.54 | 5.09 | -5.09 | 4.59 | -2.68 | 4.16 | -4.11 |
| Luni-solar (before 1200) | 6.15 | -10.74 | 10.24 | -10.24 | 9.54 | -4.03 | 8.34 | -8.19 |
| (after 1200) | -9.00 | 10.82 | -11.77 | 11.77 | -8.90 | 6.89 | -9.47 | 9.51 |
ity models are an interesting practice, but they are not always very meaningful because of the phase shift [e.g., Maeda and Fujiwara, 1967]. One possible way to attack the problem of explaining dynamo currents is (1) to assume a reasonable wind model based on currently available knowledge of the upper atmospheric winds, (2) to calculate current systems from the wind model and a reasonable conductivity distribution, and (3) to compare the obtained current systems with the ones estimated from geomagnetic variations. If the calculated current systems are similar to the estimated ones, the assumed wind model may give a hint as to the actual wind pattern.

On the basis of this idea, Maeda and Murata [1968] and Maeda [1968] assumed meridional and zonal wind systems and obtained current systems for each of the wind systems. Also, to explain the $S_r$ and solar flare current systems, Greenfield and Venkateswaran [1968] assumed various periodic and non-periodic wind models and computed current systems for each model. One common difficulty with these results was that the computed current focus appeared at places greatly different from the estimated one.

To have theoretical wind models, tidal theories need to be examined. The latitudinal structure of a tidal mode can be determined by the solution of Laplace's tidal equation, which has the Hough function $\Theta_{m,s}$ and its associated eigenvalue, namely, the equivalent depth $h_{m,s}$ for the tidal mode $(m, s)$, where $m$ denotes the longitudinal wave number ($m = 1$ for diurnal and $m = 2$ for semidiurnal tides) and $|s| - m$ is the number of modes in the Hough func-
Fig. 4. Distributions of height-integrated anisotropic electric conductivities $\Sigma_{xx}$, $\Sigma_{yy}$, and $\Sigma_{xy}$ with respect to the dip latitude and the local time for the IGY period. The unit is emu. The bottom two diagrams present $\Sigma_{xy}$ distributions enlarged for low latitudes.
TABLE 2. Height-integrated conductivities in different latitudes at noon

<table>
<thead>
<tr>
<th>Latitude, deg</th>
<th>(\Sigma_{zz}, \text{emu} )</th>
<th>(\Sigma_{zy}, \text{emu} )</th>
<th>(\Sigma_{zy}, \text{emu} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>(1.07 \times 10^{-4})</td>
<td>0</td>
<td>(2.50 \times 10^{-7})</td>
</tr>
<tr>
<td>1</td>
<td>(1.03 \times 10^{-4})</td>
<td>(5.88 \times 10^{-7})</td>
<td>(5.28 \times 10^{-8})</td>
</tr>
<tr>
<td>2</td>
<td>(2.83 \times 10^{-4})</td>
<td>(3.31 \times 10^{-7})</td>
<td>(2.58 \times 10^{-8})</td>
</tr>
<tr>
<td>3</td>
<td>(1.28 \times 10^{-4})</td>
<td>(2.25 \times 10^{-7})</td>
<td>(1.95 \times 10^{-8})</td>
</tr>
<tr>
<td>6</td>
<td>(3.24 \times 10^{-7})</td>
<td>(1.12 \times 10^{-7})</td>
<td>(1.51 \times 10^{-8})</td>
</tr>
<tr>
<td>9</td>
<td>(1.45 \times 10^{-7})</td>
<td>(7.30 \times 10^{-8})</td>
<td>(1.38 \times 10^{-8})</td>
</tr>
<tr>
<td>12</td>
<td>(8.28 \times 10^{-7})</td>
<td>(5.34 \times 10^{-8})</td>
<td>(1.30 \times 10^{-8})</td>
</tr>
<tr>
<td>15</td>
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<td>(4.15 \times 10^{-8})</td>
<td>(1.22 \times 10^{-8})</td>
</tr>
<tr>
<td>21</td>
<td>(2.89 \times 10^{-7})</td>
<td>(2.79 \times 10^{-8})</td>
<td>(1.08 \times 10^{-8})</td>
</tr>
<tr>
<td>30</td>
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<td>(1.78 \times 10^{-8})</td>
<td>(8.90 \times 10^{-9})</td>
</tr>
<tr>
<td>45</td>
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<td>(1.03 \times 10^{-8})</td>
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</tr>
<tr>
<td>60</td>
<td>(5.41 \times 10^{-8})</td>
<td>(6.91 \times 10^{-9})</td>
<td>(4.99 \times 10^{-9})</td>
</tr>
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<td>75</td>
<td>(4.27 \times 10^{-8})</td>
<td>(5.38 \times 10^{-9})</td>
<td>(4.19 \times 10^{-9})</td>
</tr>
<tr>
<td>90</td>
<td>(4.05 \times 10^{-8})</td>
<td>(5.12 \times 10^{-9})</td>
<td>(4.05 \times 10^{-9})</td>
</tr>
</tbody>
</table>

It must be noted that the solar (1, \(-1\)) mode is excited by a hypothetical E-region heat source, which is assumed constant with altitude and confined to a layer one scale height in thickness [Kato, 1966b].

Detailed theoretical work on the lunar atmospheric tide was conducted by Sawada [1954, 1956]. The lunar (2, 2) mode has the form

\[
u = \frac{130}{0.25 - \cos^2 \theta} \sin (\lambda + \gamma) \text{ m/sec}
\]
\[
u = \frac{130}{0.25 - \cos^2 \theta} \left(2 \cos \theta \frac{\partial}{\partial \theta} + \csc \theta \right) \Theta_{1,-1}(\theta)
\]

where \(\gamma = 250^\circ\) and \(\Theta_{1,-1}(\theta) = 0.7767P_1^1(\theta) + 0.5822P_3^1(\theta) + 0.0752P_5^1(\theta) + \cdots\). Here \(P_n^m(\theta)\) are Schmidt functions. The wind distributions of these two models, particularly the latter one shown in Figure 6, present a surprising similarity to the diurnal wind distribution deduced from the dynamo theory of \(S_q\) for the rotating earth model by Kato [1956].

A modified model for the solar (1, \(-1\)) mode suggested by Tarpley [1969] has the form

\[
u = \frac{100 \Phi_{u}(-1)}{0.25 - \cos^2 \theta} \sin (\lambda + \gamma) \text{ m/sec}
\]
\[
u = \frac{100 \Phi_{v}(-1)}{0.25 - \cos^2 \theta} \left(2 \cos \theta \frac{\partial}{\partial \theta} + \csc \theta \right) \Theta_{1,-1}(\theta)
\]

where \(\gamma = 250^\circ\) and \(\Theta_{1,-1}(\theta) = 0.7767P_1^1(\theta) + 0.5822P_3^1(\theta) + 0.0752P_5^1(\theta) + \cdots\). Here \(P_n^m(\theta)\) are Schmidt functions. The wind distributions of these two models, particularly the latter one shown in Figure 6, present a surprising similarity to the diurnal wind distribution deduced from the dynamo theory of \(S_q\) for the rotating earth model by Kato [1956].

Detailed theoretical work on the lunar atmospheric tide was conducted by Sawada [1954, 1956]. The lunar (2, 2) mode has the form

\[
u = \frac{130}{0.25 - \cos^2 \theta} \sin (\lambda + \gamma + 90^\circ) \text{ m/sec}
\]
where \( \tau \) is the lunar time taken to be zero at the lower transit, \( \nu \) is the elongation of the moon or the age of the moon in hours, \( \lambda = \tau + \nu \), and \( k \) is the vertical wave number. Here \( \Theta_{2,2}(\theta) = 3.4641P_2^2(\theta) - 1.2987P_4^2(\theta) + 0.1736P_6^2(\theta) - \cdots \), and \( z \) is the vertical height above the lower boundary of the dynamo region, namely, 90 km in our model. In Sawada’s wind fields for the altitude 90 km the phase constant \( \gamma \) lies in the range 210°–225°,

Fig. 6. Distribution of the wind vector by the negative-mode thermal diurnal tide represented by equation 2, which produces the best fit \( S_0 \) current system. The lengths equal to 5° latitude correspond to 50-m/sec wind speed.

\[
\mu = \frac{A(z)}{0.93 - \cos^2 \theta} \left( \frac{\partial}{\partial \theta} + \frac{2 \cot \theta}{0.96} \right) \Theta_{2,2}(\theta) \\
\nu = \frac{A(z)}{0.93 - \cos^2 \theta} \left( \frac{\cos \theta \partial}{0.96 \partial \theta} + 2 \cosec \theta \right) \Theta_{2,2}(\theta) \\
\sin(2\lambda - 2\nu + kz + \gamma)
\]

(3)

Fig. 7. Computer-plotted \( S_0 \)-type current system (top) and electrostatic field distribution (bottom) calculated from the thermal tidal wind model shown by equation 1. The current intensity between two consecutive lines is 10^4 amp, and the circular current flow in the northern hemisphere is counterclockwise. The vector of the static field is plotted in 10° steps of latitude and longitude.

Fig. 8. Computer-plotted \( S_0 \)-type current system calculated from the thermal tidal wind model shown by equation 2. The total current intensity is 121,850 amp and the position of the focus is at 36° latitude at 11.4 hour LT.

Fig. 9. Average \( S_0 \)-type electrostatic field distribution expanded in low latitudes and plotted for each 10° step of longitude and each 3° step of latitude (also at 1° and 2° latitude) for the wind model shown by equation 2.
and the amplitude at latitude 30° lies in the range 2–8 m/sec, depending on the temperature profile of the lower atmosphere. Taking into consideration Sawada's theory, Tarpley [1969] adopted $A(z) = 7.5$ m/sec, $k = 4.25°$/km, and $\gamma = 228°$. This model of the lunar tide produces the best fit L current system, as shown in the next section.

4. OBTAINED DYNAMO CURRENTS AND ELECTROSTATIC FIELDS

The electric conductivity model mentioned in section 2 and the wind model represented by equations 1 and 2 in section 3 produce the current systems and electrostatic field distributions shown in Figure 7 and Figures 8 and 9, respectively. The general current pattern, the total current intensity, and the location of the current focus of both current systems present very reasonable results, comparing them with the deduced $S_q$ current system shown in Figure 1 and bearing in mind that the current system in Figure 1 is for the active sunspot period (hence, large current intensity), whereas the current systems in Figures 7 and 8 are for the equinox during the moderate sunspot period. The phase constant $\gamma$ in equation 2 can vary by $\pm 45°$ about the value of 250° without greatly changing the current pattern.

It is clear in Figure 9 that the N-S component of the electrostatic field is very small in low latitudes, whereas the E-W field has a magnitude of near 1 mvolt/m and is directed eastward during daylight hours and westward at night. The change of direction occurs around the sunrise and sunset times.

The vertical electromagnetic drift speeds at 400 km altitude due to the coupling of the earth's main northward magnetic field and the computed E-W electrostatic field were calculated by Tarpley [1969]. The upward speed at noon is about 30 m/sec in the equatorial region and about 20 m/sec in middle latitudes, whereas the downward speed around midnight is about 30 m/sec in the equatorial region and about 15 m/sec in middle latitudes. In general, the results agree well with the observations of drift motions and estimations of the static field made by radio waves at Jicamarca, Peru [Balsley, 1969], and by barium release experiments at Thumba, India (R. Lüst, private communication).

Fig. 10. Computer-plotted L-type current systems (top) and electrostatic field distributions (bottom) calculated from the semidiurnal lunar (2, 2) tidal wind model. The moon is over the 0- or 12-hour meridian in the left-hand diagrams, and over the 3- or 15-hour meridian in the right-hand diagrams. The current intensity between two consecutive lines is $10^3$ amp, and the solid and dotted circular lines indicate counterclockwise and clockwise currents, respectively. The vector of the static field is plotted for each 10° step of latitude and longitude.
The current systems and the electrostatic field distributions for two lunar phases calculated from the conductivity and lunar tidal wind models discussed in the preceding sections are presented in Figure 10. The current system at the top left of Figure 10 is very similar to the yearly average L current pattern in Figure 3. The electrostatic field distributions for the two lunar phases expanded in low latitudes are shown in Figure 11. From these plots we see that the static field in the equatorial region is 0.2 mV/m or less.

In the same way as the solar variation, the vertical electromagnetic drift speeds for L at 400 km altitude can be computed. The maximum speed is about 5 m/sec in the equatorial region and a few meters per second in middle latitudes. Previously estimated electric fields and drift speeds due to $L$ [Matsushita, 1967a, b] agree fairly well with these results.

This report provides only essential points and main results of dynamo currents, winds, and electric fields. For details of computations and discussions of the ionospheric wind dynamo, refer to Tarpley [1969] and his future full papers.

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REFERENCES


