Solar Tidal Wind Structures and the E-Region Dynamo

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Recent theoretical models predict complicated tidal structures in the lower thermosphere which deviate from the classical Hough mode structures commonly used in E-region dynamo calculations. The present paper investigates the electrodynamic effects of such a theoretical wind field, and examines its consistency with measured magnetic effects on the ground. The model of tidal structure is constructed by synthesizing diurnal and semidiurnal contributions excited in-situ and propagating upwards from the mesosphere and below. The individual tidal structures, which are inseparable in their latitude and height dependence, are each determined by solving the linearized tidal equations for a spherical, rotating, viscous atmosphere with anisotropic ion drag. The amplitudes and phases of the individual tidal components are calibrated with incoherent scatter and satellite measurements. The dynamo computations are generally in good agreement in amplitude and phase with the diurnal and semidiurnal harmonics of the observed ground variations at minimum and maximum levels of solar activity. There are, however, real discrepancies on the order of 20% in amplitude and 1 to 2 hr in phase which require explanation. In interpreting our theoretical simulations, we attempt to point out the structural features of the E-region tidal winds and conductivities which are most critical to establishing such a consistency between theory and experiment, and to evaluate the status of dynamo theory with particular regard to the structure and variability of the solar tidal winds.

1. Introduction

The phenomenon referred to as the ionospheric Sq (solar quiet) wind dynamo, wherein E-region electric currents and polarization electric fields are generated by the electromotive force induced by solar tidal winds, has been actively investigated in recent years using numerical models (Forbes and Lindzen, 1976a, 1976b; Richmond et al., 1976; Tarpley, 1970). Although these models are moderately successful in reproducing the abundant body of existing ground magnetic data, the assumed winds are based on limited observational data and simplifying assumptions. For instance, the wind structures are approximated by a superposition of the first

symmetric trapped diurnal (1, -2) mode; the first symmetric propagating semidiurnal (2, 2) mode; and the second symmetric propagating semidiurnal (2, 4) mode. Amplitudes and phase are usually calibrated with observed values from midlatitude incoherent scatter stations.

Numerical models of thermospheric tides have also been recently developed which simulate observed features of the thermosphere fairly well (Hong and Lindzen, 1976; Forbes and Garrett, 1976, 1978; Mayr and Harris, 1977; Straus et al., 1975). Although the extensions into the thermosphere of semidiurnal modes excited below the thermosphere do not deviate significantly from the Hough mode shapes below 130 km (Hong and Lindzen, 1976; Lindzen et al., 1977), tidal winds above 130 km are responsible for over half the magnetic variation measured at the ground. In addition, Garrett and Forbes (1978) find that lower thermospheric semidiurnal tides excited in-situ are not negligible in importance, thus affecting calibration of the upward propagating modes. Diurnal tidal structures (Forbes and Garrett, 1976, 1978) are also considerably more complicated than those adopted in previous dynamo calculations. The amplitudes and phases as well as horizontal structures, vary with height and level of solar activity.

The purpose of this paper is to examine the consistency of new theoretical tidal calculations with ground magnetic data, to point out the structural features of the E-region tidal winds which are most critical in establishing such a consistency, and to evaluate the status of dynamo theory with particular regard to the structure and variability of the solar tidal winds.

2. Diurnal and Semidiurnal Wind Structures

Garrett and Forbes (1978) have computed and synthesized the various semidiurnal and diurnal tidal components into a three-dimensional model of the thermospheric wind and temperature structure at equinox. Calibration of the model was performed as follows. Since the diurnal thermospheric tide is generated almost exclusively by in-situ heating, the amplitude of the EUV solar flux was adjusted at sunspot minimum and sunspot maximum to reproduce temperature and wind oscillations determined from incoherent scatter and satellite measurements. (See Forbes and Garrett (1976, 1978) for additional discussion.) Combined with these choices of EUV heating rates, Fourier decomposition of the shape of the EUV heat source in turn fixed the in-situ semidiurnal excitation. Coupling between the diurnal tidal wind and the diurnally-varying ion drag force provided an additional in-situ momentum source for the semidiurnal tide. Finally, by subtracting the in-situ component of the semidiurnal wind and temperature fields from observed values at the St. Santin, Millstone Hill, and Arecibo incoherent scatter facilities, calibration of the upward-propagating semidiurnal tidal structures was achieved by fitting the residual semidiurnal variation in a least-squares sense with the thermospheric extensions (Lindzen et al., 1977) of the (2, 2), (2, 4), (2, 3), and (2, 5) tidal modes.

The semidiurnal component of the Garrett and Forbes model was designed to
simultaneously fit temperature and wind data from both the E- and F-regions. Thus, the quality of fit with respect to E-region data was compromised. In particular, the E-region temperature amplitudes were underestimated, and the northerly velocities overestimated, by nearly a factor of two in some instances. Thus, any dynamo calculation using this model would not provide true measure of the electrodynamical consequences of the observed E-region winds. In this paper, the semidiurnal E-region wind structures are calibrated with incoherent scatter data from Millstone Hill and Arecibo below 160 km only. Reconciliation of the whole theoretical dynamical system with wind and temperature measurements covering both E- and F-regions, must await further theoretical and observational research.

In Garrett and Forbes (1978) it was demonstrated that the semidiurnal tide excited in-situ by EUV absorption amounts to roughly 30 to 50% of the observed values between 120 and 160 km at Millstone Hill, St. Santin, and Arecibo. (See Fontanari and Alcayde, 1974; Amayenc, 1974; Salah, 1974; Harper, 1977; Salah and Wand, 1974). Thus, in constructing wind models for dynamo calculations, one must take into consideration the in-situ contribution, as well as the modes propagating from below 100 km.

The total semidiurnal wind structures determined by the present calibration procedure are shown in Fig. 1 for sunspot minimum and maximum under equinoct conditions at 20° and 40° north latitude. Differences in the vertical amplitude structures between Arecibo (18°N) and Millstone Hill (42°N) are well reproduced by the model, although the wind magnitudes at Arecibo underestimate the observed values by about 40%. Note that there is a transition in the phase variation with height—from a vertical wavelength of about 30–50 km below 120 km to 120–140 km above 130 km.

Diurnal tidal structures of northerly velocity at 20° and 40° for sunspot mini-

Fig. 1. Amplitude (left) and phase (right) of semidiurnal component of northerly velocity for SSMIN at 20°N (—) and 40°N (—), and SSMAX at 20°N (•••) and 40°N (•••).
mum and maximum conditions are presented in Fig. 2, demonstrating the latitudinal and solar cycle variations of the diurnal tide as predicted by theory. These calculations are the equinox complement of the summer/winter curves presented in Forbes and Garrett (1978).

3. Conductivity Distributions and Harmonic Coupling

Ionospheric conductivities utilized in the computations to follow were calculated in the manner outlined in Forbes and Lindzen (1976a), except that the Ching and Chiu (1973) model (as modified by Ching, 1975) was used to specify the E-region electron densities. The local time dependence of the conductivities is modelled by applying a day-night shape factor of the form

$$C = C_0 + C_1 \cos \lambda + C_2 \cos 2\lambda$$

(1)

to the noon time values, where $\lambda$ is positive eastward reckoned from local noon. The Forbes and Lindzen (1976a) study assumed constant values for $C_0$, $C_1$, $C_2$, and higher-order terms. A more detailed analysis, however, has revealed that these coefficients vary with height, latitude, and solar activity. Contours of the zero-order term, $C_0$, are plotted in Fig. 3 for maximum and minimum levels of solar activity.

Most investigations of the $Sq$ current system, whether reconstructed from ground magnetic data or theoretically-computed, have concentrated on the latitude-local time distribution of the stream function for the height-integrated currents. The Forbes and Lindzen (1976a) study, however, dealt with the individual harmonics of the ground magnetic data, since this approach provided a much more quantitative and sensitive measure of the coupling which occurs between the harmonic components of the wind, electric field, and conductivity distributions. As discussed in Forbes (1975) and Forbes and Lindzen (1976a), the observed height-integrated
current ratios of $J_1:J_2:J_3 \approx 1.0:1.0:0.5$ at midlatitudes, and of $J_1:J_2:J_3 \approx 1.0:0.5:0.25$ at the equator thus place rigid constraints on the relative amplitudes of diurnal, semidiurnal, and terdiurnal electric fields (and winds) which can exist in the $E$-region.

4. Dynamo Computations

In this section, dynamo computations using the Forbes and Lindzen (1976a)
numerical model are presented. For present purposes, it is adequate to compare theoretical and observed values of the midlatitude (30°–60° geomagnetic) eastward magnetic component. At midlatitudes, this magnetic component is a well-documented, steady feature of the $S_q$ current system, and provides a good measure of the total current flowing in what is called the "$S_q$ current vortex". Computations are performed for sunspot minimum (SSMIN) and sunspot maximum (SSMAX) conditions. SSMAX refers to a mean Zurich sunspot number of $R=10$ and globally-averaged exospheric temperature of $T_e=800$ K, and SSMAX to $R=180$ and $T_e=1400$ K. These conditions are representative of the IQSY and IGY periods, respectively.

A harmonic dial for the diurnal and semidiurnal eastward magnetic components at SSMIN and SSMAX is presented in Fig. 4. Data points represent midlatitude averages determined from the IQSY and IGY magnetic data given by GUPTA and CHAPMAN (1970). One general conclusion which emerged from these calculations

![Figure 4: Harmonic Dial for Diurnal and Semidiurnal Eastward Magnetic Components](image)

![Figure 5: Observed (-----) and Computed (——) Local Time Variations of the Midlatitude Eastward Magnetic Component at SSMIN and SSMAX](image)
is that the semidiurnal wind field was noted to be much less efficient (than the diurnal wind field) in generating a diurnal electric current, whereas the semidiurnal current generated by the diurnal wind was of the same order as that generated by the semidiurnal wind. As illustrated in Fig. 4, the magnitude of the diurnal electric current is close to the observed value during SSMIN, but overestimates the observed value by 20% during SSMAX; furthermore, the computed diurnal phase leads the observed value by 3 hr during SSMAX, and lags behind by almost 1 hr during SSMIN. Computations for the semidiurnal component indicate a 20% underestimate of the observed amplitude during SSMAX, and a 30% overestimate at SSMIN. The computed semidiurnal phases are within 1 hr of the observed values during both SSMIN and SSMAX.

Observed and computed local time variations of the midlatitude eastward magnetic component at SSMIN and SSMAX, obtained by synthesizing diurnal, semidiurnal, and terdiurnal harmonics, are illustrated in Fig. 5. Note that while the agreement is quite good for both SSMIN and SSMAX conditions, it is difficult to quantitatively designate errors to the individual harmonic components.

5. Summary and Evaluation of Results

The major results to emerge from the present examination of solar tidal winds and the E-region dynamo are summarized in the following.

In constructing wind models for dynamo calculations, inconsistencies can arise by simply fitting (2, 4) and (2, 2) vertical wind structures to midlatitude incoherent scatter measurements. For example:

a) Data from a single station do not provide information on the possible existence of the (2, 3) and (2, 5) antisymmetric components. At least a two-station calibration is needed to separate symmetric and antisymmetric components.

b) Vertical structures of the (2, 2), (2, 3), (2, 4), and (2, 5) model extensions vary considerably between Arecibo (18°N) and Millstone Hill (42°N) or St. Santin (45°N). A three-dimensional spherical viscous calculation is required to determine the appropriate structures.

c) The in-situ exited semidiurnal tide is not negligible in comparison to observed values, thus affecting calibration of the upward propagating modes.

d) Upward extensions of theoretical E-region temperatures and winds which are consistent with E-region observations can be inconsistent with F-region measurements. Ideally, the complete E- and F-region dynamical system should be internally-consistent.

Computations of the eastward magnetic variation on the ground using the calibrated tidal wind model indicate differences from observed values of order 5–20% in amplitude and 1–3 hr in phase for the diurnal component, and 10–30% in amplitude and of order 1 hr in phase for the semidiurnal component. There are several factors which contribute to these discrepancies between theory and experiment. First, concerning the diurnal tide, diagnostic studies by the present authors indicate
that computations of phase structures of tidal winds in the dynamo region can differ by up to 2 hr, depending on the assumed background (zonally-averaged) thermal structures, and thermal conductivity and molecular viscosity parameterizations assumed in the model. Hence, it is likely that part of the 3-hr discrepancy in the computed diurnal dynamo current during SSMAX is linked to errors in specifying certain properties of the background atmosphere which are only approximately known.

There are additional factors which could contribute to uncertainties in the computed semidiurnal component, particularly with regard to the overestimate of the electrodynamic consequences of the semidiurnal winds during SSMIN:

1) The dynamo-generating efficiency of a given wind field decreases with decreasing vertical wavelength, since cancellation effects occur in the height integration of the electromotive driving force in the thin-shell formulation (TARPLEY, 1970; FORBES and LINDZEN, 1976a). Errors in estimating the semidiurnal vertical wavelength in the present formulation could therefore account for discrepancies in the computed magnetic variation depicted in Fig. 4.

2) As discussed in Section 3, the height, latitude, and solar-cycle variability of the harmonic coefficients of the conductivity distribution, which affect the relative efficiency of diurnal and semidiurnal winds in driving dynamo currents, are dependent on the assumed ionospheric model. In fact, preliminary calculations for the present study, where the constant harmonic coefficients of FORBES and LINDZEN (1976a) were assumed, led to a considerable overestimate of the electrodynamic consequences of semidiurnal tides.

3) Finally, since the electromotive force driving the dynamo is proportional to the vertical component of the earth's magnetic field, horizontal tidal structures weighted too greatly towards high (low) latitudes would tend to overestimate (underestimate) the current-generating efficiency of the wind field.

6. Concluding Remarks

The present authors prefer and recommend the approach of comparing theoretical and observed values of the individual harmonic components of the height-integrated current densities, rather than a current stream function which is a synthesisization of 4 Fourier components. (The stream function approach can still be used to perform the raw theoretical calculations, and the harmonic decomposition performed a posterior). The midlatitude eastward and equatorial southward magnetic components are ideal for such studies, since these represent steady, coherent features of the diurnal, semidiurnal, and terdiurnal harmonics of the Sq ground magnetic variation. Furthermore, the midlatitude eastward component does not vary significantly between 30° and 60° geomagnetic latitude.

The present theoretical model suffers from several assumptions and approximations inherent to the thin-shell formulation (see FORBES and LINDZEN, 1976a), and it may be questioned whether further refinements in modelling ionospheric conduc-
activities and winds will exceed the level of sophistication imposed by these limitations. While it is generally accepted that dynamo action due to E-region tides is the major mechanism for generating electric fields and currents in the E-region, it is becoming increasingly evident that F-region and magnetospheric coupling mechanisms can play an important role in understanding and connecting magnetic fluctuations on the ground and polarization fields observed in the ionosphere and magnetosphere. It appears that theoretical dynamo studies in the immediate future would be more fruitfully directed towards an understanding of the physics of the asymmetric dynamo, of mutual coupling between the E-region, F-region, and magnetosphere, and nighttime conductivities and electric fields, as suggested in several other papers presented at this symposium.

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REFERENCES


