DIRECTIONAL CURRENTS IN NOCTURNAL
E-REGION LAYERS

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Abstract—In the mid-latitude E-region, the wind-shear mechanism produces thin ionized layers at levels where the vertical ion velocity is zero. We show that such layers conduct electric current only towards the magnetic equator, and not in the zonal direction. We surmise that this property may influence the electric field distribution in the nocturnal ionosphere, and possibly also the coupling between ion drifts and neutral air winds in the F-region. Detailed case studies of nocturnal layers located near the peak of ion Pedersen conductivity (around 130 km) are needed to test this idea.

1. INTRODUCTION

The wind-shear theory of sporadic E has been quite successful in describing the formation and behaviour of certain thin layers in the ionospheric E-region. The theory predicts that, under the influence of the geomagnetic field, plasma will be concentrated at or near levels where the zonal wind pattern produces "convergent nulls" in the vertical ion velocity. Within the complex tidal structure of thermospheric winds, the nulls move progressively downwards, imposing their vertical motion on the layers of plasma by the so-called "corkscrew effect". The wind-shear theory, and related topics such as the metallic ion composition of Es-layers and the corkscrew mechanism, have been extensively discussed in the literature (Whitehead, 1961; Axford, 1961; Axford and Cunnold, 1966; Whitehead, 1970, etc.). Experimental data on the relationship between winds and plasma layers have been obtained by rocket-borne techniques (e.g. Fujitaka *et al.*, 1971; Rees *et al.*, 1976) and ground-based radars. The most detailed and systematic case studies have been made with the Arecibo incoherent scatter radar (e.g. Rowe, 1974; Harper *et al.*, 1975; Shen *et al.*, 1976; Miller and Smith, 1978; Trost, 1979; Mathews and Bekeny, 1979). Many of the observed plasma layers are quite long-lived and stable, and should be termed "intermediate layers" or "night E" rather than sporadic E. Our discussion applies to any noctur-nal layer, sporadic or otherwise, produced by the wind-shear mechanism. The observations of Harper *et al.* (1975) and the theoretical calculations of Macleod *et al.* (1975) and Mathews and Bekeny (1979) all illustrate the way in which the layers follow the "convergent nulls" of vertical ion velocity.

In Section 2 we develop the appropriate equations for ion and electron motions and electric currents. We then show in Section 3 that levels of zero vertical ion velocity are also levels of zero zonal electric current. Electric currents at these levels are therefore meridional, in fact equatorward. *If* the concentrations at these levels represent an appreciable fraction of the total E-region plasma content, as may be the case at night (Section 4) the total E-region current will have a meridional bias. This bias might be reflected in the degree to which F-region polarization fields are short-circuited in the night E-region, and hence in the coupling of neutral air and plasma motions in the F-region (Section 5).

2. EQUATIONS FOR THE CURRENT FLOWING IN A THIN LAYER

To demonstrate the directional nature of the current in a thin layer at a level where the vertical ion velocity is zero, we start with the familiar equations of motion for ions and electrons in the ionosphere, in the presence of an electrostatic

polarization field $\mathbf{E}$, normal to the geomagnetic flux density $\mathbf{B}$, and a neutral air wind $\mathbf{U}$. We neglect gravity and pressure gradients which, though they influence the detailed structure of the layers, are not important to the present discussion. We assume for simplicity that there is a single ion species with concentration N, mass m_i, charge $+e$, collision frequency ν_i with neutral particles and gyrofrequency $\omega_i = Be/m_i$. The assumption of a single ion species ought to be dispensed with in future work, since a mixture of metallic and gaseous ions may exist in the layers under discussion. The height h_i at which $\nu_i = \omega_i$ is around 130 km.

Following Rishbeth and Garriott (1969) (pp. 132–135) we write the force equation for ions in terms of a tensor mobility $[\mathbf{k}]$ of which the components are the "direct", "Pedersen" and "Hall" ion mobilities (velocity/force ratios) k_0, k_1, k_2. If $\mu = \omega_i/\nu_i = Be/m_i\nu_i$ then

$$k_0 = \frac{1}{m_i\nu_i}, \qquad k_1 = \frac{1}{Be}\frac{\mu}{1+\mu^2},$$

$$k_2 = \frac{1}{Be}\frac{\mu^2}{1+\mu^2}. \qquad (1)$$

We use two different right-handed sets of directions, the geometric set x, magnetic east; y, magnetic north; z (or h), vertically up and the field perpendicular/parallel set x, magnetic east; n, equatorward and downward at angle $(\frac{1}{2}\pi - I)$; $\parallel$, field parallel, i.e. northward and downward at angle I; the dip angle I being positive (negative) in the northern (southern) hemisphere. The latter set is useful for the electrostatic field $\mathbf{E}$ which is essentially field-perpendicular, the former set for wind $\mathbf{U}$ and current $\mathbf{j}$ which are essentially horizontal. The ion drift velocity given by

$$\mathbf{V}_i = [\mathbf{k}] \cdot (e\mathbf{E} + m_i\nu_i\mathbf{U}) \qquad (2)$$

has components

$$V_{ix} = k_1(eE_x + m_i\nu_iU_x) + k_2(eE_n + m_i\nu_iU_n) \qquad (3)$$

$$V_{in} = -k_2(eE_x + m_i\nu_iU_x) + k_1(eE_n + m_i\nu_iU_n) \qquad (4)$$

$$V_{i\parallel} = k_0(eE_\parallel + m_i\nu_iU_\parallel). \qquad (5)$$

For the electrons the gyrofrequency so greatly exceeds the collision frequency at all E- and F-region heights that only the "Hall" equations need to be considered.

$$V_{ex} = E_n/B; \qquad V_{en} = -E_x/B. \qquad (6)$$

Owing to their excellent field-aligned mobility, electrons can move freely along the magnetic field to neutralize any field-aligned component $E_\parallel$. Furthermore, the bounded nature of the ionosphere inhibits any substantial vertical current j_z, the electric field being so adjusted that $j_z \doteq 0$. This assertion holds well enough even allowing for field-aligned currents caused by asymmetries in the global dynamo system [e.g. Rishbeth and Garriott (1969), p. 238]. There may be additional localized field-aligned currents at the periphery of the layers discussed in this paper; but within the layers we may take

$$j_z \equiv -j_\parallel \sin I - j_n \cos I = 0 \qquad (7)$$

and the northward horizontal current is then given by

$$j_y \equiv j_\parallel \cos I - j_n \sin I = -j_n/\sin I. \qquad (8)$$

It follows that the electric current density

$$\mathbf{j} = Ne(\mathbf{V}_i - \mathbf{V}_e), \qquad (9)$$

has components

$$j_x = \frac{Ne/B}{1+\mu^2}[\mu E_x - E_n + BU_x - \mu BU_y \sin I] \qquad (10)$$

$$-j_y = \frac{Ne/B}{1+\mu^2}[E_x + \mu E_n - \mu BU_x$$
$$\qquad\qquad - BU_y \sin I]\,\mathrm{cosec}\,I. \qquad (11)$$

3. THE DIRECTIONAL EFFECT

To proceed further we make use of the finding (which is both observational and theoretical) that the thin layers occur at or near levels where the vertical ion velocity is zero. This condition may be written as

$$V_{iz} \equiv -V_{i\parallel} \sin I - V_{in} \cos I = 0. \qquad (12)$$

From (1, 4 and 5) we can obtain an expression for V_{iz} in terms of $\mu = \omega_i/\nu_i$ and components of $\mathbf{U}$ and $\mathbf{E}$. Since $\mathbf{E}$ is essentially field-perpendicular we retain its components in the $(x, n, \parallel)$ set of directions; but we convert the wind components to the (x, y, z) set. We find that

$$V_{iz} = \frac{\mu/B}{1+\mu^2}[\mu E_x - E_n + BU_x - \mu BU_y \sin I]\cos I$$
$$\qquad - \frac{eE_\parallel}{m_i\nu_i}\sin I + \frac{1+\mu^2\sin^2 I}{1+\mu^2}U_z. \qquad (13)$$

The square bracket in equation (13) is the same as in (10). If now we assume $E_\parallel = 0$ (as previously mentioned) and furthermore assume that the vertical wind U_z is small compared with the horizontal components U_x, U_y (as seems reasonable) we neglect the last two terms in equation (13) so that

$$j_x = NeV_{iz}/\mu \cos I. \qquad (14)$$

This shows that if a layer forms at the level where $V_{iz} = 0$, as observed, it will carry no east–west or x-component of current. The current in the layer is therefore purely meridional. The conditions under which this happens depends on the relative magnitudes of the terms in the square bracket of equation (10) or (13). The electric field components E_x, E_h may be assumed height-independent, but the wind components U_x, U_y are part of a tidal system in which the wind vector rotates with height. Provided the electric field is not too large in relation to the wind, there will be levels at which the square bracket vanishes and hence
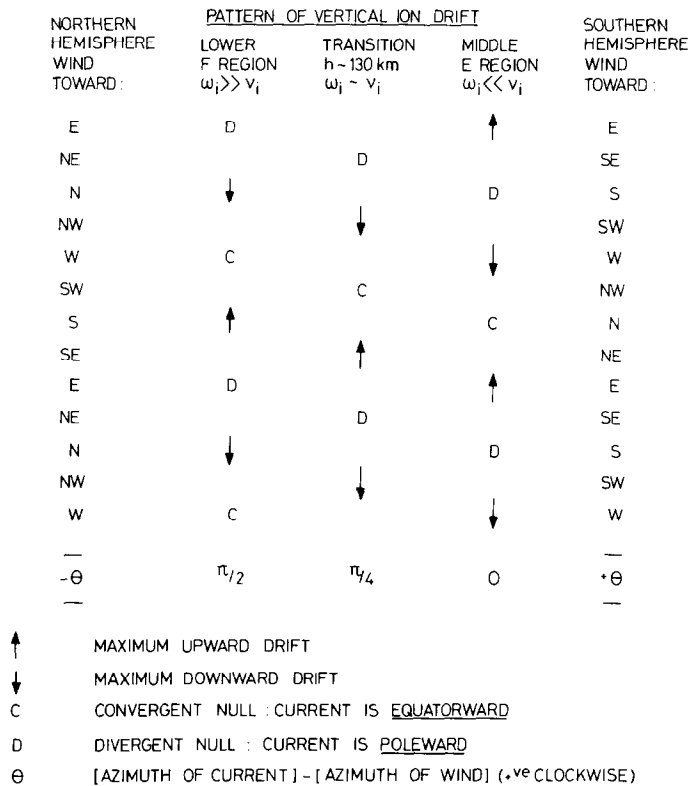
$V_{iz} = 0$. For the moment, take $E_x = E_n = 0$ in which case V_{iz} is simply given by

$$V_{iz} = \frac{\mu \cos I}{1 + \mu^2} [U_x - \mu U_y \sin I] \qquad (15)$$

with j_x proportional to V_{iz}, as in (14), while the northward current from (11) is now

$$j_y = \frac{Ne}{1 + \mu^2} [\mu U_x \operatorname{cosec} I + U_y]. \qquad (16)$$

At Arecibo Harper (1977) found that the wind vector in the E- and lower F-regions rotates clockwise with increasing height. Though the E-region wind measurements were confined to daytime, the dominant semidiurnal wind system is believed responsible for producing the night-time layers. In such a rotating wind system the sign of V_{iz} oscillates with height in the manner shown in Figure 1, for the three regimes $\mu \gg 1$, $\mu \sim 1$ and $\mu \ll 1$. In reality these regimes are not distinct but

NORTHERN HEMISPHERE WIND TOWARD:	PATTERN OF VERTICAL ION DRIFT			SOUTHERN HEMISPHERE WIND TOWARD:
	LOWER F REGION $\omega_i \gg v_i$	TRANSITION h ~ 130 km $\omega_i \sim v_i$	MIDDLE E REGION $\omega_i \ll v_i$	
E	D		↑	E
NE		D		SE
N	↓		D	S
NW		↓		SW
W	C		↓	W
SW		C		NW
S	↑		C	N
SE		↑		NE
E	D		↑	E
NE		D		SE
N	↓		D	S
NW		↓		SW
W	C		↓	W
$-\theta$	$\pi/2$	$\pi/4$	0	$\cdot\theta$

↑   MAXIMUM UPWARD DRIFT
↓   MAXIMUM DOWNWARD DRIFT
C   CONVERGENT NULL : CURRENT IS EQUATORWARD
D   DIVERGENT NULL : CURRENT IS POLEWARD
θ   [AZIMUTH OF CURRENT] − [AZIMUTH OF WIND] (+ve CLOCKWISE)

EACH COLUMN REPRESENTS 1½ VERTICAL WAVELENGTHS OF THE WIND PATTERN

FIG. 1. WIND DIRECTIONS AND VERTICAL ION DRIFTS.
The direction of ion drift and the angle θ are deduced from equations (14–16).

merge into one another, since the range of heights embraced by the figure (namely $1\frac{1}{2}$ vertical wavelengths of the wind pattern) occupies a substantial height range in the real atmosphere, perhaps as much as 80 km. The angle between the wind and current depends on μ, as shown, but in all cases *the current at a convergent null (C) is equatorward*, i.e. $j_x = 0$, $j_y < 0$. The same applies to the southern hemisphere on the assumption that the wind vector rotates in the opposite sense, as shown by the right hand column in Figure 1; in this case $j_x = 0$, $j_y > 0$ at any convergent null.

The assumption of no electric field is not justified, and can be removed by rewriting equations (15) and (16) in terms of "effective" wind components

$$U'_x = U_x + (E_y/B \sin I), \qquad U'_y = U_y - (E_x/B \sin I) \tag{17}$$

and proceeding as before. Since the condition for $V_{iz} = 0$ is now in terms of U'_x and U'_y, the inclusion of the electric field alters the levels of the convergent nulls, but the electric current at those nulls is still equatorward. There are several complications to be considered in future work. The electric field, being height-independent, makes no contribution to the vertical convergence dV_{iz}/dh on which the detailed structure of the layer depends. It may, however, increase or diminish the current flowing at the nulls. If the electric field is too large in relation to the wind velocity, nulls may not exist at all. Without actual detailed experimental data, it does not seem worth enlarging on the possibilities here.

4. ESTIMATE OF CONDUCTIVITY

The directional properties of the layer currents can only be of significance if the conductivity within the layers is an appreciable fraction of the total night-time conductivity. Without attempting detailed calculations, we can assume that a typical night-time layer has a thickness $\Delta h = 1$ km and mean ion density $N = 5 \times 10^{10}$ m^{-3}. This typical

layer, if centered at the level $h_i \simeq 130$ km, at which $\mu = 1$ and where the Pedersen and Hall conductivities (σ_1, σ_2) are both equal to $\frac{1}{2} Ne/B$, has integrated layer conductivity given by

$$\Sigma_1, \Sigma_2 = \sigma_1 \Delta h, \sigma_2 \Delta h$$
$$= (\tfrac{1}{2} Ne/B)\Delta h \cong 10^{-4}\Omega^{-1} \text{ m}^{-1} \cdot 10^3 \text{ m} = 0.1\,\Omega^{-1} \tag{18}$$

where we take $B = 40\,\mu$T for Arecibo. As the layer departs from the height h_i, either upward or downward, its Pedersen conductivity Σ_1 falls off, at first slowly but ultimately exponentially with scale height $\pm H$, according to the ordinary theory of ionospheric conductivity. The integrated Hall conductivity Σ_2 increases below h_i to a peak value twice that of equation (18), i.e. $0.2\,\Omega^{-1}$, and falls off rapidly with height above h_i. These values may be compared with the E- and F-region conductivities computed by Harper and Walker (1977) from Arecibo data for 16 nights at various seasons in 1974–1976, the minimum, average and maximum values being respectively as follows (Table 1):

TABLE 1. NIGHT-TIME CONDUCTIVITIES AT ARECIBO

Conductivity (Ω^{-1})	Minimum	Average	Maximum
F-region Pedersen ($h > 185$ km)	0.016	0.1–0.2	0.88
E-region Pedersen (95–185 km)	0.03	0.08–0.15	0.25
E-region Hall	0.14	0.3–0.5	0.91

For average conditions, the contribution made by a single thin layer, namely $0.1\,\Omega^{-1}$ as in equation (18), is marginal. However, there are sometimes several layers, sometimes thicker than 1 km, and a value of $0.5\,\Omega^{-1}$ is quite possible. With so much variability from night to night, we can only conclude that the directional effect of the layer currents may be significant on some individual nights, particularly if a well-developed layer exists around 130 km where its Pedersen conductivity will be greatest. We may remark that, should significant layers form in daytime by the same process (even with larger ion densities) their contribution to overall E-region conductivities of order $10\Omega^{-1}$ is not likely to be significant.

From equations (10) and (11) we may deduce the conductivities that relate each current component to a component of electric field or neutral-air wind. To put each quantity in terms of eastward (x) and northward (y) components, we write $E_y = E_n \sin I$ (thereby taking $E_\parallel = 0$) where $s = \sin I$ for brevity.

The Pedersen-like conductivities are:

$$\left.\begin{array}{r} j_x/E_x \\ j_y s^2/E_y \\ -j_x/BU_y s \\ j_y s/BU_x \end{array}\right\} = \frac{\mu Ne/B}{1+\mu^2} \qquad (19)$$

The Hall-like conductivities are:

$$\left.\begin{array}{r} j_x s/E_y \\ -j_y s/E_x \\ j_x/BU_x \\ j_y/BU_y \end{array}\right\} = \frac{Ne/B}{1+\mu^2} \qquad (20)$$

5. EFFECT ON F-REGION MOTIONS

The nocturnal E-region layers may influence F-region motion if their conductivity is sufficient to discharge F-region polarization fields to any extent. It is the Pedersen current that is important in this respect, the Hall currents being largely non-divergent and therefore relatively ineffective in discharging polarization fields. Consider first F-region drifts due to the polarization fields. The distribution of polarization charges and field is determined by the global pattern of tidal winds and magnetospheric sources, in accordance with the need to satisfy current continuity (div $j = 0$) everywhere in the ionosphere to a very high degree of approximation. The resulting field at Arecibo, say, is not likely to depend on local factors to any great extent. The existence of E-region layers with directional properties may have some influence on the global field distribution, but hardly an important one if the layers are localized and small, say a hundred kilometres or so in size. Since the tidal and magnetospheric sources are capable of driving substantial currents through the daytime ionosphere, with conductivities two orders of magnitude greater than those of the nocturnal layers [as estimated in equation (18)] it seems unlikely that the extra loading represented by nocturnal layers will have much effect. The most that could be expected is that meridionally-conducting layers, if sufficiently widespread, might slightly reduce the meridional polarization field as compared to the zonal field.

With thermospheric winds the situation is rather different. The F-region dynamo driven by such winds (Rishbeth, 1971a) is fairly easily short-circuited by the E-layer. The effect of this short-circuiting is to decouple zonal winds and ion drifts. In the equatorial zone the F-region dynamo acts strongly because of the geometry and, with open-circuit conditions in the sub-equatorial E-region, zonal F-region winds and ion drifts are strongly

coupled (Rishbeth, 1971b). This effect decreases away from the equator, with decreasing curvature of the field lines, but is still strong at Arecibo (dip 50°) according to the observations of Behnke and Hagfors (1974). Our analysis suggests that a nocturnal thin layer would help to decouple eastward winds and drifts, but have no effect on motions in other directions. The effect would depend on the horizontal extent of the thin layer. Studies of individual cases, some with and some without well-formed layers at around 130 km, are clearly needed. The meridional wind structure at night over Arecibo is complex and interesting (Herrero and Meriwether, 1980; Burnside et al., 1981), and it appears that the F-region winds are dominated by meridional pressure gradients. The ion drifts, however, are probably dominated by zonal tidal fields and there is no obvious reason why these should be closely coupled to the winds.

6. CONCLUSION

We have drawn attention to the directional current-carrying properties of E-region layers formed at levels of zero vertical ion drift; we have shown that the current carried by such layers is purely equatorward and is essentially Pedersen current or Hall current, according as the layer is above or below about 130 km; and we have suggested that individual case studies of F-region winds and drifts are needed to establish whether these E-region layers influence F-region dynamics by their electrical properties.

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