Planet. Space Sci., Vol. 36, No. 1, pp. 1–10, 1988
Printed in Great Britain.

0032–0633/88 $3.00+0.00
Pergamon Journals Ltd.

THE MID-LATITUDE THERMOSPHERE*

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(*Received* 30 *March* 1987)

Abstract—The *F*-region ionosphere at middle latitudes moves up and down in an irregular manner on a time scale of hours. This behavior is a manifestation of complex coupling between photochemical, fluid dynamical, and electrodynamical processes in the thermosphere. This closely coupled system is explored using a computationally simple theoretical model of the *F*-region .

Observations of ionospheric properties, including the ion drift velocity vector and the neutral wind speed, have been made at the Arecibo Observatory in Puerto Rico. The theoretical model is used to interpret these observations in terms of electric currents and pressure gradients. Measured gradients in ionospheric properties imply local current divergence in the sense that the eastward gradient of the eastward current is significantly different from zero. It appears that current continuity is maintained by the exchange of charge between hemispheres, so that a gradient in the current in one hemisphere is matched by an opposite gradient at the conjugate point. The consequence of this global current pattern is that the conjugate ionospheres behave differently at night, with one *F*-region moving down when the other one moves up, and with one *F*-region tilting upward to the East when the other tilts downward to the East.

INTRODUCTION

I was a graduate student at Columbia University when Alex Dalgarno gave a seminar at the Goddard Institute for Space Studies in New York. He described recent theoretical work (Dalgarno *et al.*, 1963) on electron temperatures in the ionosphere. The talk was a revelation to me. Until then I had had no idea that parts of the natural world could be analyzed and understood in terms of atomic collision processes. The approach to space physics captivated me, and he became, unofficially, my dissertation advisor.

Dalgarno's reputation led to his involvement in the interpretation of data collected by the *Explorer* 17 Satellite (Brace *et al.*, 1965) and in the development of plans for the *Atmosphere Explorer* Program. These collaborations were so fruitful that he became a Co-Investigator for the Langmuir Probe Experiment and a theoretical member of the scientific team for the *Atmosphere Explorer* Program. This was the first time that theorists had been included from the outset as full members of the investigator team of a NASA satellite mission. Alex Dalgarno served with distinction for a number of years as Chairman of the *Atmosphere Explorer* Program's Aeronomy Team.

The *Atmosphere Explorer* Program was a prolific source of research and new results on the thermosphere, principally the middle and low-latitude thermosphere because of the orbits of the satellites. The instrument complement made possible the simultaneous measurement of ion and neutral densities and temperatures, airglow surface brightnesses, and energy sources. The measurements lent themselves particularly to quantitative exploration of atomic collision processes and the photochemistry of the thermosphere. By the time the project ended, many of the rate coefficients and collision cross-sections of most importance to thermospheric physics, particularly those involving metastable species, had been more precisely determined from *Atmosphere Explorer* data than from laboratory measurement.

The success of the *Atmosphere Explorer* Program in its investigations of the microphysics of the thermosphere has caused renewed interest, in recent years, in the large scale, dynamical behavior of this region of the atmosphere. The *Dynamics Explorer* Satellite Program was one manifestation of this interest. The development of the European incoherent scatter radar in Scandinavia and the American incoherent scatter radar chain extending from Greenland to Peru are other manifestations. This paper is concerned with aspects of the dynamical behavior of the mid-latitude thermosphere.

IRREGULAR BEHAVIOR

The mid-latitude thermosphere exhibits irregular behavior on a time scale of hours. This behavior is most readily seen in ground-based measurements of

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* Dedicated to ALEX DALGARNO in his sixtieth year in honour of his many important contributions to aeronomy.

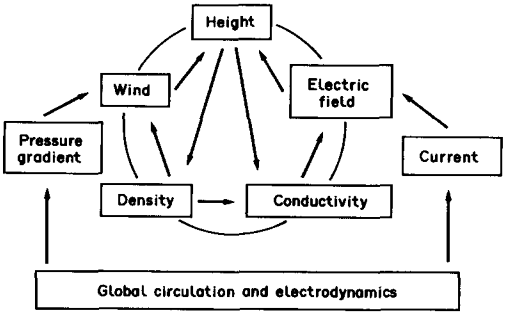

FIG. 1. THE THERMOSPHERIC SYSTEM INVOLVES A CLOSE COUPLING OF CHEMICAL, FLUID DYNAMICAL, AND ELECTRODYNAMICAL PROCESSES.

These coupled interactions are illustrated schematically here.

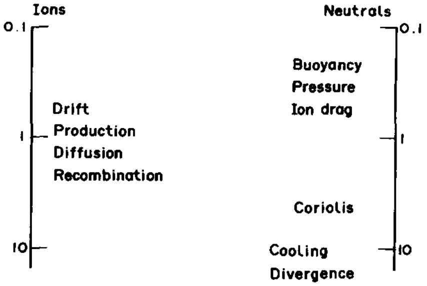

FIG. 2. CHARACTERISTIC TIMES, EXPRESSED IN HOURS, ASSOCIATED WITH THE DIFFERENT PROCESSES THAT AFFECT THE DENSITIES AND MOTIONS OF THE ION AND NEUTRAL CONSTITUENTS OF THE THERMOSPHERE.

the height of the maximum in *F*-region electron density as a function of time. Particularly graphic illustrations of the temporal behavior of electron density profiles over the Arecibo Observatory in Puerto Rico have been presented by Shen *et al.* (1976).

These irregular fluctuations of thermospheric properties are in some ways reminiscent of weather, but any analogy would be misleading. The physical conditions that yield irregular behavior in the thermosphere are entirely different from those that cause unpredictable changes in the weather. For one thing, the thermosphere is stably stratified—gas temperature increases with height. The thermosphere is therefore not susceptible to the growth of unstable, planetary waves such as those that dominate the weather in the mid-latitude troposphere. Moreover, the low densities and large mean-free paths of the thermosphere yield a large dynamic viscosity for the fluid. Nonlinear, advective processes have little influence on the general circulation of the thermosphere—turbulence is generally absent. Most importantly perhaps, the thermosphere lacks significant concentrations of a condensable substance and therefore is not subject to the irregular perturbation of its properties caused by clouds and their interaction with radiation and by the release of latent heat.

It is clear, therefore, that the irregular behavior of the mid-latitude thermosphere is not analogous to tropospheric weather. Surprisingly, there is no complete explanation of thermospheric variability. Elements of the overall system are known, but they are hard to combine into a plausible theory that can survive observational testing.

Theoretical and computational difficulties arise because of the degree to which diverse properties of the thermosphere are coupled to one another locally while dependent, also, on global fields of wind, current, and electric potential. This coupling is illustrated, schematically, by Fig. 1, which shows how thermospheric properties affect one another. The height of the ionospheric *F*-region affects the electron density through the rate of ion–neutral reactions and the electrical conductivity through the ion–neutral collision frequency. The conductivity also depends on the electron density. The electron density controls the wind through ion drag while the elecrical conductivity affects the electric field. The wind and the electric field, however, control the height of the ionospheric *F*-region, so the coupled cycle of interdependence is closed. But global influences also are important. They control the horizontal gradient in pressure and the electric current density, which in turn influence the wind and the electric field.

The coupling of these processes is close in the sense that no one of the illustrated interactions is markedly less important than any of the others. Figure 2 illustrates the characteristic times associated with these interactions on a logarithmic scale in hours, with the ions on the left of the figure and the neutrals on the right. Ionospheric densities are controlled by four processes all with characteristic times close to 1 h. These are vertical drift of ionization caused by a wind or electric field, production of ionization by photochemical processes, diffusion of the ions vertically through the background neutral gas, and recombination of ions and electrons through reactions with neutral molecules. The motions of the neutral gas, on the other hand, are influenced principally by three processes with time scales somewhat less than an hour. Buoyancy describes the tendency of a parcel of air to return to its initial level after any perturbation in altitude. Its effect is to constrain thermospheric winds largely to the horizontal. Pressure describes the time scale for the neutral wind to change in response to the horizontal pressure gradients that exist in the thermosphere. This acceleration is generally balanced by frictional ion drag between ions and neutrals. Processes affecting the neutral motions on longer time scales include the

Coriolis force, cooling of the thermosphere by thermal conduction and emission of infrared radiation, and the evolution of the pressure distribution resulting from divergent flow.

There exist theoretical and computational models of parts of the complex web of interactions illustrated in Fig. 1, but none that tie the whole system together. The computational complexity of a comprehensive model would be great because it would need to follow ion and neutral densities, motions and temperatures as functions of altitude and of time over the whole globe and would in addition need to keep track of electric fields and currents. This complexity, however, is hardly likely to exceed the complexity of the class of general circulation models that is now routinely applied to studies of tropospheric dynamics. Why, then, has a comprehensive theoretical model of global thermospheric electrodynamics not been developed? Probably because of a grievous lack of data on which to base such a model and against which to test it. Only incoherent scatter radar observatories, operating cooperatively, can provide the kind of synoptic data needed to explore thermospheric electrodynamic interactions on a time scale of hours. There are very few such observatories, so a global theoretical model, if made, could be verified at only a few locations. With due regard for the inadequacy of the weather analogy, the problem would be like verifying a general circulation model of the troposphere against data from a handful of weather stations.

In order to permit theoretical study of thermospheric electrodynamics without undue computational complexity, my colleagues and I have proposed a simple model of the *F*-region ionosphere that reproduces many aspects of ionospheric behavior reasonably well, although not exactly (Rishbeth *et al.*, 1978).

A SIMPLE MODEL

The simple theory takes advantage of the observation that the profile of electron density with height does not change very much with time. A large number of such profiles can be compared in the plots of Shen *et al.* (1976). If it is assumed that the shape of the height profile is invariant, the partial differential equations in three space coordinates and time that describe the thermospheric properties can be reduced to coupled ordinary differential equations for the time evolution of the properties at the height of the ionospheric *F*-region. There are four of these coupled ordinary differential equations (Rishbeth *et al.*, 1978):

$$\mathrm{d}N/\mathrm{d}t = -c\beta N \exp(-kZ) - \phi/aH \qquad (1)$$

$$\mathrm{d}Z/\mathrm{d}t = (D \sin^2 I/2H^2)\{\exp(-kZ) - \exp(Z)\} + \cos I \exp(Z) J_x/(NH) \qquad (2)$$

$$\mathrm{d}U_y/\mathrm{d}t = F_y - fU_x + vK \sin I \exp(Z) \times \{DN \cos I/2H + J_x\} \qquad (3)$$

$$\mathrm{d}U_x/\mathrm{d}t = F_x + fU_y - vK \sin I \exp(Z) J_y \qquad (4)$$

where N is the peak electron density, Z the reduced height of the layer (the departure in neutral scale heights, H, from an equilibrium height), and U_x and U_y the components of the neutral wind in the *F*-region. The coordinate system is x positive eastwards, and y positive northwards. The parameters are: $k = 1.75$, $C = 1.6$, $v = 0.9$, $H = 50\,\mathrm{km}$, $I = 50°$, $\beta = 9 \times 10^{-5}\,\mathrm{s}^{-1}$, $D = 3 \times 10^6\,\mathrm{m}^2\,\mathrm{s}^{-1}$, $\phi/aH = 10^6\,\mathrm{m}^{-3}\,\mathrm{s}^{-1}$, $f = 0.45 \times 10^{-4}\,\mathrm{s}^{-1}$, and $K = 7.5 \times 10^{-16}\,\mathrm{m}^3\,\mathrm{s}^{-1}$ (Rishbeth *et al.*, 1978).

Also, the relative eastward current

$$J_x = N \exp(-Z)\{E_x/B - U_y \sin I\} \qquad (5)$$

and relative northward current

$$J_y = N \exp(-Z)\{E_\perp/B + U_x\}/\sin I. \qquad (6)$$

F_x and F_y are the components of the pressure gradient acceleration, adjusted to yield calculated winds close to measured winds. The measured ion drift speeds are E_x/B perpendicular to the magnetic field and northward and $E_\perp/B$ in the eastward direction.

In what follows I shall use this simple theoretical description of the ionosphere to interpret data from the Arecibo Observatory that illustrate aspects of the electrodynamic behavior of the mid-latitude thermosphere. The Arecibo Observatory is located at 18° North and 67° West, at a geomagnetic latitude of 31°N. The geomagnetic field dips at 50° to the North. Although electrodynamic processes in the thermosphere operate both day and night, I shall concentrate on the nocturnal situation because the ground-based optical data that provide a direct measure of the neutral wind in the thermosphere are available only at night. Moreover, the suppression of the electrical conductivity of the ionospheric *E*-region at night over Arecibo simplifies the interactions by restricting the ionospheric dynamo to the *F*-region.

The essential behavior of the simple ionospheric model is illustrated by Fig. 3. The bottom panel of the figure shows how the equilibrium height of the electron density peak responds to an imposed vertical drift of ionization caused by either wind or electric field. Imposed vertical drift of some $80\,\mathrm{m\,s}^{-1}$ moves the *F*-layer maximum up or down by about one neutral atmosphere scale height (50 km). At high altitudes the ion–neutral collision frequency is small and

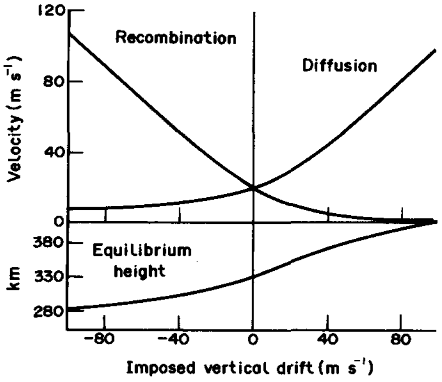

Fig. 3. Equilibrium behavior of the ionospheric model. The bottom panel shows how the equilibrium height of the *F*-region varies with imposed vertical ion drift. The top panel shows how the imposed vertical drift is balanced by diffusion if the layer is displaced upward and by chemical recombination if the layer is displaced downward.

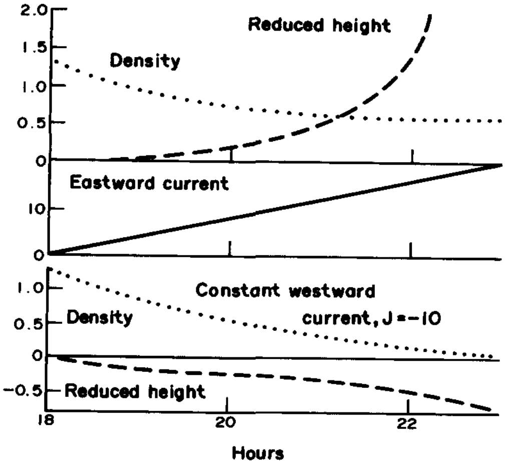

Fig. 4. The top panel shows how a steadily increasing eastward current causes the height of the ionosphere to increase without limit when the Lorentz Force on the current exceeds the weight of the ionospheric plasma.
The bottom panel shows that even a small westward current, if it flows for several hours, drives the *F*-region downward, causing accelerated recombination and a large reduction in ionospheric density.

the diffusion velocity is large, as illustrated in the top panel of the figure. The layer settles at a height that will just balance an upward imposed vertical drift by a downward diffusion velocity. At low altitudes, however, diffusion is negligible because the diffusion velocity is inversely proportional to the ion–neutral collision frequency. The height of the layer, when it is displaced downwards, depends on a balance between recombination and imposed vertical drift. The recombination velocity plotted in the top panel of Fig. 3 shows how fast the ions must move downwards through the peak of the layer in order to replace ionization recombining on the bottom of the layer. The recombination rate is proportional to the density of neutral molecules, so increases rapidly with decreasing altitude. Downward displacement of the layer causes it to settle at a level at which the recombination velocity is almost equal to the downward imposed vertical drift.

Imposed vertical drift can always be thought of, in the appropriate frame of reference, as a consequence of the Lorentz Force acting on a zonal electric current in the ionospheric plasma. In the Northern Hemisphere, an eastward current causes an upward component of the Lorentz Force. This upward force is counteracted by the downward gravitational force corresponding to the weight of the plasma and by frictional drag between the vertically moving ions and the background neutral gas. It is clear that an eastward current that is sufficiently large will yield a vertical component of the Lorentz Force that exceeds the weight of the ionospheric plasma, causing this plasma, no longer gravitationally bound, to accelerate off into space. The top two panels of Fig. 4 illustrate how the simple ionospheric model reproduces this behavior. In the computations illustrated here the eastward current has been increased linearly with time as shown in the middle panel. The reduced height of the *F*-region increases slowly at first and then more rapidly until it goes to infinity shortly after 22 h. The density at the *F*-region maximum decreases with time at first more rapidly when the layer is at low altitudes and then negligibly slowly when the layer is at high altitudes. Such behavior of the ionosphere is, of course, never observed, and the reason is not hard to find. As pointed out by Perkins (1973), the electric current does not remain constant as the layer height increases. The electrical conductivity decreases with decreasing ion–neutral collision frequency, and current is diverted away from the region of the ionosphere that is moving upward.

A phenomenon that has not, to my knowledge, been discussed before is illustrated in the bottom panel of Fig. 4. The nocturnal ionosphere cannot sustain a westward current for very long because such a current drives the layer to low altitudes where it recombines quickly. The figure shows that a constant westward current of a magnitude less than that of the westward current that caused ionospheric escape leads, in just a few hours, to very low electron densities. Such low electron densities are not normally observed in the mid-latitude thermosphere. Evidently, zonal electric currents in the nocturnal thermosphere must be generally eastward. What property of the system causes this rectification of the zonal current? It is probably a consequence of the generally equatorward flow of the neutral wind at night. The coldest and lowest pressure regions of the thermosphere tend to be at low-latitudes in the middle of the night, at the greatest possible distance from daytime and auroral heat sources. Thermospheric winds tend to blow toward these cold, low pressure regions. For an equatorward wind, the induced electric field is eastward, and the resulting electric current is eastward also.

If this argument is correct it implies that electric currents in the nocturnal mid-latitude thermosphere are generated mainly by the ionospheric dynamo and not by charge separation in the magnetosphere. It has been suggested that the electrodynamics of the mid-latitude thermosphere are extensively influenced by magnetospheric processes, and in particular, that electric fields of magnetospheric origin penetrate throughout the mid-latitude thermosphere to cause ionospheric perturbations. The argument that electric fields are generally a consequence of the ionospheric dynamo suggests that the penetration of magnetospheric electric fields, if it occurs at all, is unusual.

Vertical drift of ionization can be imposed by a meridional neutral wind as well as by a zonal electric field. As already noted, in the reference frame of a southward wind (in the Northern Hemisphere) there is an eastward induced electric field. This field causes an **E** × **B** drift which, when added to the wind velocity, yields resultant ion motion parallel to the magnetic field and equal to the wind component along the field. However, this motion results only if there is no inhibition of the eastward current generated by the eastward induced field. It is helpful to consider the simple representation of the electrical circuit shown on the left of Fig. 5. Imagine the ionospheric dynamo in the local ionosphere generating an electromotive force and causing current to flow. The magnitude of this current depends both on the resistance of the local ionosphere and on the resistance of all of the rest of the electrical circuit, wherever it is located. This latter resistance is here called the external resistance, *R*. If the external resistance is negligibly small compared with the resistance of the local ionosphere there is no significant inhibition of current, and the ions drift along the magnetic field line with the parallel component of the wind velocity. Increasing external resistance, however, leads to reduced current flow, a consequence of a developing polarization electrostatic field that opposes the induced field in the reference frame moving with the wind. The **E** × **B** drift is reduced and so is the vertical component of the imposed ion velocity. In the limit of infinite external resistance, no current flows, the electrostatic field just balances the induced field in the reference frame moving with the neutral wind, the magnetic field has no effect on the motion of the ions, and the ions move horizontally with speed equal to the wind speed, *U*, as shown on the right of Fig. 5. It is therefore necessary to consider the global flow of electric current in order to understand how meridional winds may affect the height of the ionospheric *F*-region.

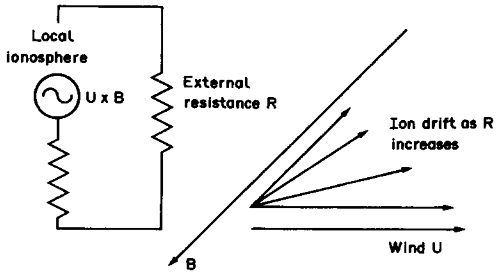

FIG. 5. THE RESPONSE OF THE IONOSPHERE TO A MERIDIONAL WIND DEPENDS ON THE RESISTANCE OF THE ENTIRE ELECTRICAL CURRENT CIRCUIT AS IT COMPARES WITH THE ELECTRICAL RESISTIVITY OF THE LOCAL IONOSPHERE.

If the external resistance is zero the ions move parallel to the geomagnetic field at the speed of the parallel component of the wind. If the external resistance is large, the ions move horizontally at the wind speed.

With this background I turn now to the interpretation of a particular night of data from the Arecibo Observatory.

OVERHEAD PROPERTIES OF THE IONOSPHERE

Figure 6 shows how the theory is fitted to observations for a particular night, in this case the night of 17–18 August 1982. The points in the upper panel of the figure show measured northward horizontal ion drift and neutral wind. The solid line in the upper panel is the theoretical fit to the neutral wind achieved by using the measured ion drift in equation (5) and adjusting the pressure gradient term in equation (3), F_y, without restriction to achieve the desired fit. The deduced values of the pressure gradient acceleration are shown in the bottom panel of Fig. 6. This figure illustrates the phenomenon already noted, that the nocturnal neutral wind is generally southward at Arecibo and that the pressure gradient acceleration is also generally southward. I concentrate, in this paper, on the meridional ion and neutral motions because these are the ones that influence the *F*-layer height and thus the electron density. The theory could, of

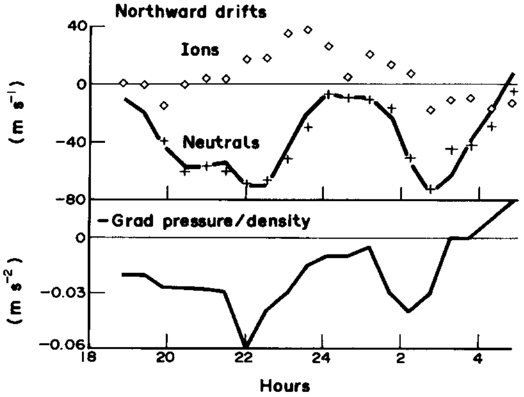

FIG. 6. THE PRESSURE GRADIENT TERM ILLUSTRATED IN THE BOTTOM PANEL HAS BEEN ADJUSTED TO YIELD A THEORETICAL NEUTRAL WIND (SOLID LINE), PLOTTED IN THE TOP PANEL, THAT CLOSELY REPRODUCES THE MEASURED WIND (POINTS). The measured ion drift speed is also shown by points.

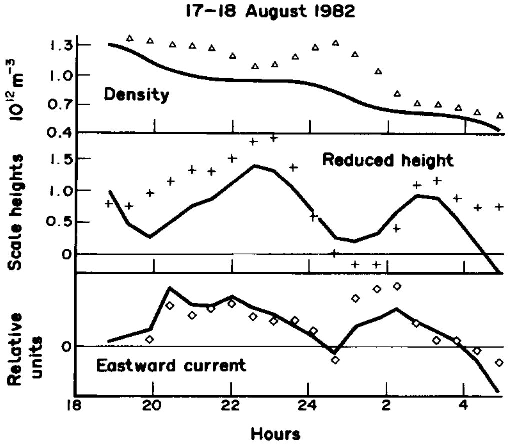

FIG. 7. COMPARISON OF THE THEORETICAL RESULTS, PLOTTED AS SOLID LINES, WITH THE OBSERVATIONS, PLOTTED AS POINTS, USING THE PRESSURE GRADIENT TERM ILLUSTRATED IN FIG. 6, WITHOUT FURTHER TUNING OF THE THEORY.

course, be fitted to zonal drift velocities also.

There are no other tuning parameters in the theory that significantly affect the results. Figure 7 compares the theoretical prediction of peak density and reduced height with the measured values depicted by points. This theory, with velocities adjusted to fit the measurements precisely, fails to reproduce the full amplitude of the excursions in reduced height, but it is behaving in a manner not very different from the real ionosphere. The theoretical density declines more rapidly than the observed density, which is almost certainly a result of theoretical heights that are smaller than observed heights. The observed eastward current depicted by points in the bottom panel of Fig. 7 is not directly observed. It is deduced from the measured height and peak density of the ionosphere and the measured difference between ion and neutral drift velocities. The agreement between calculated and observed current is not precise, but these results also suggest that the theoretical system is behaving much like the real ionosphere. The bottom panel shows that the electric current is generally eastward as already noted.

Some tinkering with the theory might yield a closer fit to observations, but the theoretical system is probably a sufficiently close representation of the ionosphere to permit further exploration without further tinkering.

HORIZONTAL GRADIENTS IN IONOSPHERIC PROPERTIES

By making measurements with the radar beam pointed in different directions, the incoherent scatter radar at Arecibo can measure horizontal gradients in F-region properties (Burnside *et al.*, 1985). The simple ionospheric theory of Rishbeth *et al.* (1978) can be readily extended to predict horizontal gradients simply by differentiating with respect to the horizontal coordinate system the equations presented above. Eastward gradients are denoted a and northward gradients are denoted b. In performing this differentiation I ignore advective terms and terms in the products of derivatives. These terms are generally small. I also ignore horizontal gradients in the geomagnetic field and in neutral atmospheric densities. The ordinary differential equations that describe the time evolution of the horizontal gradients are:

$$\mathrm{d}a_N/\mathrm{d}t = -c\beta \exp(-kZ)\{a_N - kNa_z\} \qquad (7)$$

$$\mathrm{d}b_N/\mathrm{d}t = -c\beta \exp(-kZ)\{b_N - kNb_z\} \qquad (8)$$

$$\mathrm{d}a_z/\mathrm{d}t = -(D \sin^2 I/2H^2)\{k \exp(-kZ) + \exp(Z)\}a_z + (\cos I \exp(Z)J_x/NH)\{a_{J_x}/J_x a_z - a_N/N\} \qquad (9)$$

$$\mathrm{d}b_z/\mathrm{d}t = -(D \sin^2 I/2H^2)\{k \exp(-kZ) + \exp(Z)\}b_z + (\cos I \exp(Z)J_x/NH)\{b_{J_x}/J_x + b_z - b_N/N\}. \qquad (10)$$

There are similar expressions for the gradients in neutral wind components, but they are not needed in this study.

I use these equations, now, to interpret the measured gradients in peak electron density and reduced height, as shown in Fig. 8. For purposes of this discussion I shall concentrate on the eastward gradients, although the theory can be used also to interpret measured northward gradients. The theoretical fit is achieved by adjusting the eastward gradient in the eastward current,

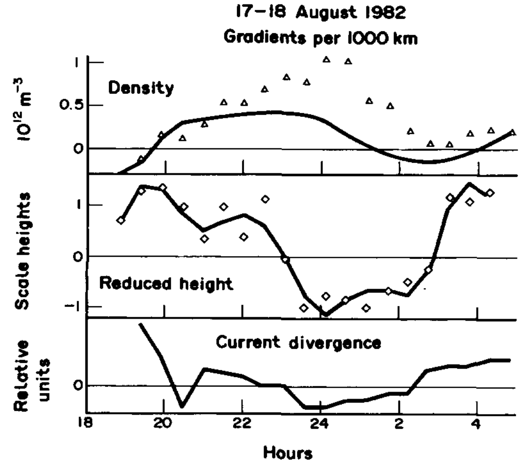

FIG. 8. COMPARISON OF THEORETICAL GRADIENTS IN DENSITY AND REDUCED HEIGHT (SOLID LINES) WITH MEASURED VALUES (POINTS).

The eastward gradient in the eastward current, labeled current divergence in the bottom panel of the figure, has been adjusted to provide the illustrated fit between calculated and measured gradients in reduced height.

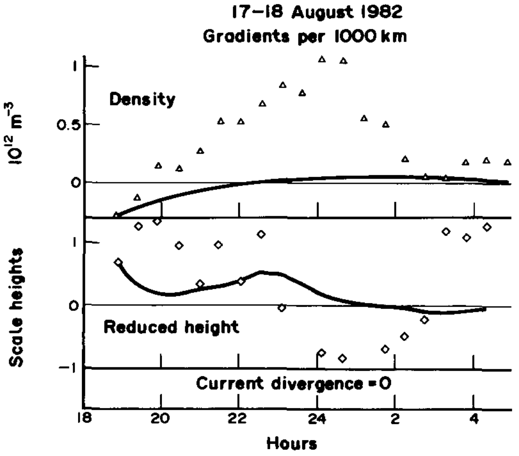

FIG. 9. THE QUALITY OF THE FIT BETWEEN THEORY AND OBSERVATION IS VERY MUCH WORSE IF THERE IS NO GRADIENT IN ELECTRICAL CURRENT.

The results illustrated here, where the theory is given by solid lines and the observations by points, should be compared with the comparison in Fig. 8.

labeled current divergence, in the bottom panel of Fig. 8, in order to achieve the fit to the eastward gradient in reduced height shown in the middle panel. Here, as elsewhere, the points are data and the solid lines are the results of the theory. The top panel compares the calculated and observed eastward gradient in peak density. No further tuning is involved in going from reduced height to density gradients [see equations (7) and (8)]. This comparison therefore provides some indication of how well the theoretical system mimics ionospheric behavior. While the theory fails to reproduce precisely the full amplitude of the electron density gradient, a failure probably related to its failure to reproduce the full amplitude of the excursions in layer height, the theoretical system is certainly behaving much like the ionosphere.

The comparison of Fig. 8 therefore suggests that the measured eastward gradients in *F*-layer properties imply a non-zero eastward gradient in the eastward current. This implication is potentially important because most theoretical treatments of ionospheric electrodynamics on the time scale of interest here have assumed that gradients in electric current are negligible. How robust is the finding of non-zero current gradient?

Figure 9 shows what happens to the calculated gradients if the eastward gradient in the eastward current is set equal to zero. In this case the theoretical system fails completely to mimic ionospheric behavior. Theoretical gradients die out slowly and exhibit none of the marked changes apparent in the measured gradients. I conclude that the eastward gradients in ionospheric properties measured at the Arecibo Observatory are strong evidence for an eastward gradient in the eastward electric current. On the night under study here, the eastward current was larger to the East of the observatory, and therefore divergent, through most of the night; there were a few hours of convergent current around and shortly after midnight.

CURRENT CONTINUITY

Charge must be conserved in the ionosphere and so the total current system must be continuous. What convergent current component is providing the charge to sustain the generally divergent eastward current over Arecibo?

Studies of the height profile of electrical conductivity by Burnside (1984) have shown that the height-integrated *F*-region electrical conductivity was much greater than that of the *E*-region at the time of these measurements. Since *E*-region winds and electric fields are generally no larger than those in the *F*-region, the *E*-region electrical currents must be negligibly small compared with those in the *F*-region. Therefore, current continuity is not being preserved by *E*-region currents. On the other hand, it appears that on the night under study the North–South current at Arecibo was essentially equal to zero throughout the whole night. While it is certainly possible for the local current to be zero while its gradient is not zero it is hardly likely that a current circulation pattern could remain locked

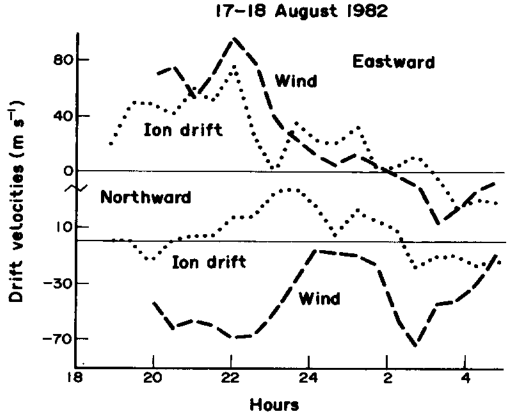

FIG. 10. MEASURED COMPONENTS OF THE ION DRIFT AND NEUTRAL WIND.

The eastward components of wind and drift are equal, within measurement precision, indicating negligible meridional electrical current. The northward components, in contrast, are markedly different, indicating the presence of significant zonal electrical current.

over Arecibo in such a way as to maintain this situation all through the night.

The evidence for zero northward current is shown in Fig. 10. Remember that eastward current produces relative motion of the northward components of ion and neutral drift velocities. In the bottom panel of Fig. 10 we see that the measured northward ion drift and wind are distinctly different because of the non-zero eastward current that has been under study. The top panel shows that the eastward components of neutral wind and ion drift are equal to one another within measurement uncertainties. Non-zero northward current would cause the eastward velocities to differ. It is not altogether surprising that the meridional current should be zero. In the simplest of all worlds the current field would be symmetrical about the equator and the meridional current would be zero at the equator. Arecibo is not very far from the equator.

By elimination, I conclude that the divergence of the eastward current over Arecibo is balanced by convergence at the conjugate point, presumably also in the eastward current. The situation is illustrated schematically in Fig. 11, which shows a map of the middle and low latitude thermosphere with two field lines connecting conjugate point ionospheres. Current can flow readily between the conjugate point ionospheres because the parallel electrical conductivity is large; the field lines are very nearly equipotential.

Figure 7 shows that there are quite marked temporal variations in the eastward current in the local ionosphere. If we think in terms of a plan view of the entire nocturnal ionosphere it is, at first, hard to understand

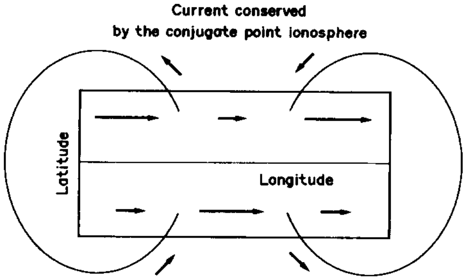

FIG. 11. SCHEMATIC MAP OF THE LOW-LATITUDE NOCTURNAL THERMOSPHERE SHOWING HOW EASTWARD GRADIENTS IN THE EASTWARD CURRENT IN ONE HEMISPHERE ARE TAKEN UP BY OPPOSITE GRADIENTS IN THE OTHER HEMISPHERE, WITH FIELD-ALIGNED CURRENTS TRANSFERRING CHARGE BETWEEN HEMISPHERES IN ORDER TO MAINTAIN A TOTAL CURRENT FREE OF DIVERGENCE.

how such temporal variations in zonal current are possible when meridional and *E*-region currents are generally negligible. Current continuity would seem to require that these temporal changes affect all longitudes of the nocturnal ionosphere together, without regard for local time variations, particularly in peak electron density. The puzzle, of course, disappears if we consider the zonal current in the two hemispheres combined. Presumably the combined zonal current does indeed vary slowly through the night with either longitude or local time, but the locus of current flow switches between hemispheres, dependent on local conditions, so that temporal variations in zonal current at one location are indeed possible, as illustrated in Fig. 11.

A consequence of this understanding of the global current pattern is that changes in *F*-layer height at the conjugate point will be opposite to those in the local ionosphere as eastward current is switched between hemispheres. Figure 12 uses the simple theory to illustrate this behavior, although the assumptions concerning the conjugate point in this calculation are entirely arbitrary. The short dashed lines in Fig. 12 reproduce the theoretical results for the local ionosphere already presented in Fig. 7. The dashed dot line in the bottom panel of Fig. 12 shows the assumed slowly varying sum of the eastward currents in the two hemispheres. The long dashed line in the bottom panel is the assumed eastward current in the conjugate point ionosphere derived by subtraction. This current is then used to calculate the height and the density in the conjugate point ionosphere, assuming initial conditions equal to those in the local ionosphere. With these assumptions, the two ionospheres move vertically in opposite directions as the figure shows.

A further prediction of this view of the global current system is that eastward gradients in the two hemispheres will tend to be opposite because divergent

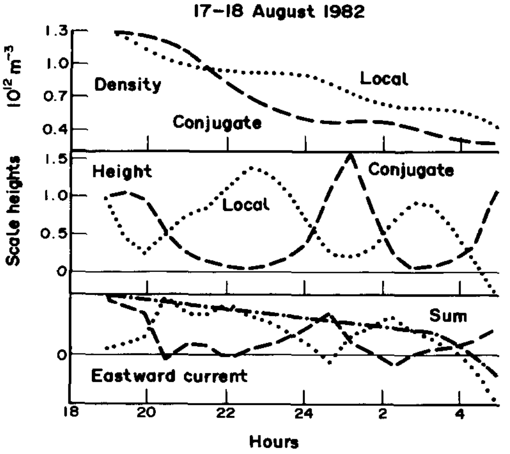

FIG. 12. THEORETICAL RESULTS SHOWING HOW VARIATIONS IN THE CONJUGATE IONOSPHERES ARE OPPOSITE TO ONE ANOTHER IF EASTWARD CURRENT IS CONSERVED BY THE EXCHANGE OF CHARGE BETWEEN HEMISPHERES.

The eastward currents are shown in the bottom panel. Their sum is assumed to vary slowly with time, although, in each hemisphere, there are quite rapid fluctuations in eastward current.

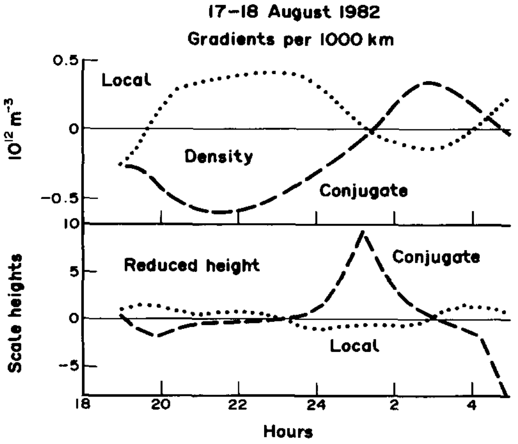

FIG. 13. CONSERVATION OF TOTAL CURRENT REQUIRES THAT AN EASTWARD GRADIENT IN THE EASTWARD CURRENT IN ONE HEMISPHERE BE MATCHED BY AN OPPOSITE GRADIENT IN THE OTHER HEMISPHERE.

The result is that gradients in ionospheric density and reduced height are opposite in the two hemispheres, if all other things are equal, as illustrated by these theoretical results.

current flow in one hemisphere must be balanced by convergent flow in the other. Figure 13 uses the simple theory to illustrate this behavior, where the local gradients are the theoretical values previously presented in Fig. 8 and those for the conjugate point are based on the overhead ionospheric properties of Fig. 12 and the current gradient presented in Fig. 8. The large gradient in reduced height at the conjugate point that occurs just after 1:00 a.m. is a consequence of the instability discussed earlier in which the eastward current imposed on the ionosphere is large enough to drive the ionosphere off into space. The eastward current at the conjugate point is constrained, in the theory, only by the requirement that the sum of the two currents should vary slowly with time. Small adjustments could remove this instability. Figures 12 and 13 are intended to illustrate the negatively correlated behavior in the two hemispheres, not to make detailed predictions of the properties of the conjugate point ionosphere.

CONCLUSION

This analysis of measured eastward gradients in the properties of the nocturnal *F*-region at Arecibo suggests that the properties of the conjugate point ionosphere should be anticorrelated, with the conjugate point ionosphere moving up when the local ionosphere moves down, and the conjugate ionosphere tilting downward to the East when the local ionosphere tilts upward to the East. In principle, these predictions could be checked with fairly simple instrumentation, either an ionosonde or an airglow photometer operated at or close to the conjugate point. Would such a test confirm these predictions of the theory? I suspect that the theory described in this paper would be found to work some of the time but not all of the time. The mid-latitude thermosphere has modes to its electrodynamic behavior that we have not yet begun to explore.

For example, the data analyzed here were obtained near solar maximum. Previous work by Harper and Walker (1977) using data near solar minimum show *E*-region electrical conductivities that are comparable in magnitude to those of the *F*-region. Under these conditions, *F*-region currents could close in the local or conjugate *E*-regions, and the *E*-region dynamo could influence *F*-region behavior. Notwithstanding the argument of symmetry about the equator, there are occasions, at Arecibo, when the meridional current is significant and may play a role in maintaining current continuity. There is also, very probably, useful information to be gained from interpretation of measured northward gradients in ionospheric properties, and in optically measured gradients in the horizontal neutral wind components.

The close coupling of hydrodynamic, electrodynamic and chemical processes in the mid-latitude thermosphere make this medium probably unique among cosmic plasmas. Progress in understanding its complex and dynamical behavior can be expected to result from the interpretation of the increasingly precise synoptic data on a wide range of interrelated properties that are now becoming available.

Acknowledgements—I am grateful to Roger Burnside for making the measurements interpreted in this paper and to Daniel Melendez-Alvira for his help in obtaining these data and in developing the theoretical analysis. This work was presented at the workshop on the 2nd Arecibo Upgrading Project held in Ithaca, New York, in October of 1986. This research was supported in part by the National Science Foundation under grant #ATM8403051. The Arecibo Observatory is operated by Cornell University under contract with the National Science Foundation.

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