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THE PENNSYLVANIA STATE UNIVERSITY

IONOSPHERIC RESEARCH

Scientific Report 443

IONOSPHERIC E-REGION ELECTRON DENSITY AND NEUTRAL ATMOSPHERE VARIATIONS

by

Terrence L. Stick

August, 1976

IONOSPHERE RESEARCH LABORATORY

University Park, Pennsylvania

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Electron density deviations from a basic variation with the solar zenith angle are investigated. A model study has been conducted in which the effects of changes in neutral and relative densities of atomic and molecular oxygen on calculated electron densities have been compared with incoherent scatter measurements in the height range 100-117 km at Arecibo, Puerto Rico. The feasibility of determining tides in the neutral atmosphere from electron density profiles was studied. It was determined that variations in phase between the density and temperature variation and

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Submitted and approved by:

J. S. Nisbet, Director
Ionosphere Research Laboratory

Ionosphere Research Laboratory

The Pennsylvania State University

University Park, Pennsylvania 16802

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ABSTRACT

Electron density deviations from a basic variation with the solar zenith angle are investigated. A model study has been conducted in which the effects of changes in neutral and relative densities of atomic and molecular oxygen on calculated electron densities have been compared with incoherent scatter measurements in the height range 100-117 km at Arecibo, Puerto Rico. The feasibility of determining tides in the neutral atmosphere from electron density profiles was studied. It was determined that variations in phase between the density and temperature variation and the comparable magnitudes of their components makes it appear improbable that the useful information on tidal modes can be obtained in this way.

CHAPTER I

GENERAL STATEMENT OF THE PROBLEM

1.1 E-Region Morphology

Appleton (1953) discussed the differences in time between
the maximum of ionization and the maximum of production in terms
of the "sluggishness" of the E-region. Researchers (Mitra, 1958;
Appleton and Lyon, 1961; and Palluconi, 1963) attempted to
determine the recombination rate, α, of the E-region by observing
asymmetries about noon in foE using the charge continuity equation.
The lag or sometimes lead value τ was employed. While many
attempts were made to calculate recombination rates in this way it
became apparent with modern laboratory measurements (Biondi,
1964) that the time constants were too small to account for the
effect and that the explanation of the phase differences must be else-
where.

Monro, Nisbet and Stick (1976) in the first part of the present
study demonstrated that local noon asymmetries in the E-region
electron density were caused by tides in temperature, density, and
winds as measured by incoherent scatter. They demonstrated that
the effect of the semidiurnal tide on the atomic and molecular oxygen
densities may also be an important factor in explaining E-region
asymmetries.

These studies can only be done at a very few locations none
of which are in the southern hemisphere. The global tidal variations
are extremely important in determining the mode structure and

wider geographical coverage is necessary before the tidal morphology can be resolved. The tidal variations in the lower thermosphere have been shown to be very variable (Wand and Perkins, 1970; Salah and Wand, 1974; and Fellous et al., 1975) and thus a long series of observations is desirable. It, therefore seemed important to reexamine the studies that had been made of E-region changes to determine to what extent the data can now be used to study the tides. A complete analysis of the electron density at fixed heights is necessary to determine morphology of the tidal system. Some indication may, however, be determined from the one parameter that has been extensively studied, τ, the difference in time between the minimum solar zenith angle and the maximum electron density. Palluconi (1963) has shown that τ varies with latitude such that it is generally negative for equatorial stations becoming positive at 20° and reaching a peak at 40°. The value of τ is generally symmetric about the equator during equinox with a shift in the minimum from the equator toward the winter pole during solstice. The general seasonal response for high latitude stations is a maximum value of τ in the summer with a minimum in the winter and generally a negative value throughout the year for equatorial stations. Since the number of southern hemisphere stations is minimal it is not possible to conclude with great certainty the tidal effects simultaneously in both hemispheres from previous studies. Data is available in the World Data Center for several years that could, however, be analyzed.

1.2 Solar Fluxes

The solar wavelengths of importance in photoionizing the
E-region have been reviewed by Rishbeth and Garriott (1969) and
Banks and Kockarts (1973). X-rays from 8 to 140 $\overset{o}{A}$ are important
in ionizing the three major constituents, molecular nitrogen and
atomic and molecular oxygen in the lower E-region, particularly in
times of enhanced solar activity. The EUV flux from 140 to 786 $\overset{o}{A}$
is important in ionizing molecular nitrogen and atomic oxygen in the
upper E-region. Wavelengths from 786 $\overset{o}{A}$ to 1027 $\overset{o}{A}$ are important
with molecular nitrogen being ionized up to 796 $\overset{o}{A}$, atomic oxygen
up to 911 $\overset{o}{A}$ and molecular oxygen up to 1027 $\overset{o}{A}$ including Lyman β.
Nitric oxide is a very minor constituent in the upper atmosphere
however as was shown by Nicolet and Aitkin (1959) it is of importance
in the D-region and lower E-region because of its ability to be
photoionized up to 1340 $\overset{o}{A}$ which includes H Lyman α.

Donnelly and Pope (1973) compiled the results of different
solar flux measurements and normalized them to a 10.7 cm flux of
150×10^{-22} Wm^{-2} Hz^{-1} at 1 AU. Their solar flux model includes
wavelengths of 1 to 3000 $\overset{o}{A}$. As shown by Hall and Hinteregger (1970)
care must be used when applying a flux model for a different 10.7 cm
flux value then for the measurement conditions. Table 1 shows the
solar flux values of Hinteregger et al., (1965) for low solar activity,
Φ_{HHS}, and of Donnelly and Pope (1973) for medium solar activity,
Φ_{DP}.

Variations in EUV spectral lines over one solar rotation
period of 27 days have been reported by Hall and Hinteregger (1970)

Table 1: Absorption Cross Sections, Photoionization Yields and Assumed Photon Fluxes

No.	Wavelength λ Å	Absorption Cross Sections $\sigma/10^{-18}$ cm^2			Photoionization Yields			Photon Fluxes $\Phi/10^9$ Ph-cm^{-2}-sec^{-1}		
		O	O$_2$	N$_2$	O	O$_2$	N$_2$	Φ_{HHS}	Φ_{DP}	λ_{DP}
1	15-10	.135	.27	.15	16.7	16.7	18.9	.0005	.0092	16-10
2	22.8-15	.35	.7	.36	12.4	12.4	13.8	.003	.015	23.3-16
3	31-22.8	.045	.09	1.0	10.1	10.1	12.8	.005	.015	31-23.3
4	41-31	.1	.2	.07	8.4	8.4	9.4	.02	.036	40-31
5	50-41	.17	.34	.14	6.7	6.7	7.6	.03	.040	50-40
6	60-50	.27	.54	.22	6.7	6.7	7.6	.068	.084	60-50
7	70-60	.35	.7	.32	4.8	4.8	5.4	.08	.099	70-60
8	80-70	.45	.9	.42	4.8	4.8	5.4	.08	.094	80-70
9	90-80	.5	1.0	.4	4.2	4.2	4.8	.1	.13	90-80
10	103-90	.9	1.8	.7	3.7	3.7	4.2	.13	.106	100-90
11	139-103	1.1	2.2	.9	2.9	2.9	3.3	.304	.153	140-100
12	165-138	2.1	4.2	1.4	2.3	2.3	2.6	.6	.32	170-140
13	180-165	2.9	5.7	1.9	2.0	2.0	2.3	.5	1.47	180-170
14	190-180	3.9	6.8	2.2	1.9	1.9	2.1	2.2	1.15	190-180
15	205-190	4.0	8.0	2.4	1.8	1.8	2.0	1.5	1.4	210-190
16	220-205	4.7	9.4	2.8	1.6	1.6	1.6	.55	.31	220-210
17	240-220	5.6	11.2	3.1	1.2	1.2	1.2	.85	1.34	240-220
18	260-240	6.7	13.4	3.6	1.2	1.2	1.2	1.3	1.23	260-240
19	256.3-257	7.2	14.4	3.8	1.2	1.2	1.2	.40	.59	256.3
20	280-260	8.0	16.0	4.2	1.0	1.0	1.0	1.4	1.08	280-260
21	810-796	3.3	40.0	6.7	1.0	2.4	0.0	.2	.25	810-796
22	840-810	3.2	26.0	3.3	1.0	.38	0.0	.78	1.00	840-810
23	832-835	3.2	13.5	11.1	1.0	.32	0.0	.52	.53	834.2
24	860-840	3.1	11.7	5.0	1.0	.31	0.0	1.5	1.09	860-840
25	890-860	2.9	8.9	5.0	1.0	.63	0.0	2.7	2.78	890-860
26	911-890	2.7	9.3	4.3	1.0	.75	0.0	3.33	3.23	911-890
27	920-911	0.0	7.4	3.8	0.0	.65	0.0	1.25	2.30	920-911

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Table 1: Absorption Cross Sections, Photoionization Yields and Assumed Photon Fluxes (continued)

No.	Wavelength λ Å	Absorption Cross Sections $\sigma/10^{-18}$ cm^2			Photoionization Yields			Photon Fluxes $\Phi/10^9$ Ph-cm^{-2}-sec^{-1}		
		O	O_2	N_2	O	O_2	N_2	Φ_{HHS}	Φ_{DP}	λ_{DP}
28	950-920	2.7	7.0	3.4	0.0	.65	0.0	.49	.69	950-920
29	937.8	0.0	5.2	5.3	0.0	.78	0.0	.22	.22	937.8
30	949.7	0.0	5.9	4.2	0.0	.89	0.0	.39	.35	949.7
31	972.5	0.0	40.0	250.	0.0	.53	0.0	.8	.82	972.5
32	977.0	0.0	4.0	2.6	0.0	.62	0.0	4.4	4.5	977
33	991.5	0.0	1.9	.3	0.0	.69	0.0	.6	.61	991.5
34	1025.7	0.0	1.6	0.0	0.0	.58	0.0	3.5	3.5	1025.7
35	1215.7	0.0	.01	0.0	0.0	0.0	0.0	300.	310.	1215.7

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compared with the 10.7 cm flux which ranged from 100-200 x 10^{-22} $Wm^{-2} Hz^{-1}$. The ratio of the fluxes 284 $\overset{o}{A}$ to 304 $\overset{o}{A}$ was shown to increase by 200 per cent as the 10.7 cm flux increased from 100 to 200 x $10^{-22} Wm^{-2} Hz^{-1}$. The combined fluxes of 1025 A^o, 977 $\overset{o}{A}$, 584 $\overset{o}{A}$ and 304 $\overset{o}{A}$ increased by 70 per cent as the 10.7 cm flux increased from 60 to 160 x $10^{-22} Wm^{-2} Hz^{-1}$.

A discrepancy has been shown to exist between the results of ion densities calculated using current neutral atmospheric models and photochemistry with the fluxes of Hinteregger (1970) and observations of ionosphere parameters. Swartz and Nisbet (1973) comparing profiles of energy input and loss with similar profiles of ion production and loss concluded that the EUV fluxes needed to be multiplied by a factor of two. Mitra et al., (1974) found the fluxes of soft x-rays to be incompatible with the observations of electron density and the ratio of $\left[NO^+\right] / \left[O^+\right]$ in the altitude range of 90 to 130 km. It was shown that an increase by a factor of three for the soft x-rays is needed to reconcile calculations and observations. Heroux et al., (1974) modeled the region of 110 to 300 km and found an electron density that was generally low by 30 per cent compared with an electron density profile derived from an ionogram. They concluded that the error was probably in the density measurements. Nisbet (1975) showed that a general doubling of the flux would increase the electron densities to match the experimental values. Heroux et al., (1975) replied that while a doubling of the flux would help at the lower altitudes the increase at the upper altitudes would be too great. Donahue et al., (1973) and Monro, Nisbet and Stick (1976) have

shown that the atomic oxygen is very variable and can differ greatly
from models such as CIRA 1972. It is difficult to obtain absolute
values for solar fluxes corresponding to given solar conditions. The
discrepancies appear to be greater under high solar conditions than
for low activity (Miller and Nisbet, 1974). All of these factors
contribute to making such comparisons difficult.

Ionization cross sections were reviewed by Ohshio et al.,
(1966). The absorption cross section along with the photoionization
yield for the major E-region neutrals, N_2, O_2 and O corresponding
to different regions of the EUV and x-ray spectrum are listed in
Table 1. Swider (1969) described the production of secondaries by
x-rays as a function of the total production, the density of the
constituents and the wavelength intervals. The total ion-electron
pair production rate q was shown to be distributed among the
different ions according to the ratio 0.62 : 0.17 : 0.14 : 0.07 : 1.00
for $q(N_2^+)$: $q(O_2^+)$: $q(N^+)$: $q(O^+)$: q_{total}.

1.3 E-Region Tides

Absorption of solar energy by ozone in the strato-mesosphere
causes waves to propagate into the thermosphere. Chapman and
Lindzen (1970) modeled the atmosphere and derived variations in
temperature, wind and density in terms of altitude, latitude and
local time. Richmond (1971) included dissipative effects which
resulted in a dampening of the diurnal (1, 1) mode above 105 km
while the semidiurnal modes were free to propagate through the
region. Bernard and Spizzichino (1971) using incoherent scatter
techniques were able to show that the semidiurnal tide dominated

both wind and temperature oscillations above 100 km. At altitudes below 100 km the diurnal tide, the semidiurnal tide and gravity waves have comparable amounts of energy. Salah (1974) observed a dominant semidiurnal tide in the lower thermosphere in both temperature and meridional winds corresponding to the (2, 4) model. Lindzen and Hong (1974) developed a program which showed a great amount of mode coupling between the main semidiurnal mode (2, 2) and higher modes which results in higher modes of the semidiurnal tide dominating above 100 km and a reduction in the amplitude of the (2, 2) mode.

Salah et al., (1975) discussed results from three incoherent scatter stations for the lower E-region. A good agreement in both magnitude and phase of the average semidiurnal tides was found for Millstone Hill and St. Santin. The tide was identified as a (2, 4) mode. The oscillations at Arecibo were dominated by the semidiurnal tide however great variability in phase was observed. The implications of simultaneous experiments at the three stations are that the E-region is controlled by local effects.

Seasonal variations of the tides were observed by Salah and Wand (1974) for Millstone Hill and St. Santin revealing a smaller amplitude in the semidiurnal tide during the winter than during the summer or equinox due to a larger phase variability in the winter.

Salah (1974) using incoherent scatter data showed the neutral density variations to be semidiurnal and in phase with the temperature at the lower E-region altitudes. The variations for the neutral density were of the order of a factor of two while temperature varied by 11 per cent.

Mayr and Volland (1972) used a neutral atmospheric model to
predict that the atomic oxygen density would vary diurnally with a
maximum shifted toward early morning by the zonal wind and toward
later afternoon by vertical diffusion in the daytime. The net result
is a maximum at 1030 local solar time. Alcayde et al., (1972)
using measurements of satellite drag and incoherent scatter show
atomic oxygen variations at 120 km, extrapolated down from higher
altitudes, to have a dominant diurnal mode with a superimposed
semidiurnal mode. There are maximums at 900 and 1500 hours with
a minimum at 1200. The ratio of maximum to minimum is
approximately 1.5. Danilov (1972) using rocket mass spectrometer
data derived a model of atomic oxygen starting at 130 km for low,
moderate and high solar activity. For all three solar conditions
the model shows a diurnal variation in atomic oxygen with a maximum
at 1300 hours. During moderate activity a ratio of two is reported
for maximum to minimum density at 130 km. Offerman (1974)
using rocket measurements finds a maximum in molecular
nitrogen to occur at 1400 hours at 150 km. Molecular oxygen was
found to have a diurnal variation with a maximum at 900 to 1000 hours
with a 20 per cent variation.

1.4 Ion Chemistry

The major neutral constituents photoionized in the E-region
are N_2, O_2 and O. Nitric oxide ionized by H Lyman α is also of
importance. The photochemistry of the E-region has been reviewed
by Biondi (1969), Bortner et al., (1972) and Ferguson (1974). The
rates used in this work have been determined from a review of current

literature.   They are presented in Table 2.

1.5 Sporadic E and Tides

Whitehead (1961) explained sporadic-E formation as being due to vertical wind shears in the horizontal neutral winds. Whitehead (1967) elaborated on his original explanation by demonstrating that the existence of a second ion with a smaller recombination rate, such as a metallic ion, could explain the general shape of the sporadic-E layer. The theory showed that the vertical wind shear of the zonal wind was more important than that of the meridional in the lower E-region for forming a sporadic-E layer.

Wright et al., (1967) observed neutral winds from visible trails of gun launched vehicles in conjunction with radio soundings of the sporadic-E layer. Their results show that sporadic-E occurs where the vertical ion movements converge. The wind profile was observed to descend at the rate of two vertical wavelengths in 24 hours.

MacDougall (1974) used the theory of wind shear to determine characteristics of the neutral zonal winds in the lower E-region from ionogram measurements of the sporadic-E layer altitude and it's descent with time. He assumed that the sporadic-E layer formed where the neutral wind above had a westward direction and the wind below an eastward direction for layers existing below 115 km. Above about 120 km the vertical shear in the north-south neutral wind determined the convergence of ionization. The ionogram data on the sporadic-E layer height evolution revealed three general patterns;

12) $\quad N_2^+ + NO \rightarrow NO^+ + N_2$ $\qquad$ 3.3×10^{-10} $\qquad$ Fehsenfeld et al., (1970)

13) $\quad N_2^+ + e \rightarrow N + N(^2D)$ $\qquad$ $1.8 \times 10^{-7} \left(\dfrac{300}{T}\right)^{.39}$ $\qquad$ Mehr and Biondi (1969)

14) $\quad N^+ + O_2 \rightarrow NO^+ + O$ $\qquad$ 3×10^{-10} $\qquad$ Lindinger et al., (1974)

15) $\quad N^+ + O_2 \rightarrow O_2^+ + N(^2D)$ $\qquad$ 3×10^{-10} $\qquad$ Lindinger et al., (1974)

16) $\quad N^+ + O \rightarrow O^+ + N$ $\qquad$ 1×10^{-12} $\qquad$ Bortner et al., (1972)

17) $\quad N^+ + NO \rightarrow NO^+ + N$ $\qquad$ 8×10^{-10} $\qquad$ Goldan et al., (1966)

18) $\quad N^+ + e \rightarrow N + h\nu$ $\qquad$ $2.4 \times 10^{-10}\ T^{-.7}$ $\qquad$ Biondi (1969)

Table 2: Chemical Reaction Rates

	Reaction	Rate	Reference
1)	$O^+ + N_2 \rightarrow NO^+ + N$	$6 \times 10^{-13} \, \dfrac{600}{T}$	Lindinger et al., (1974)
2)	$O^+ + O_2 \rightarrow O_2^+ + O$	$2 \times 10^{-11} \left(\dfrac{300}{T}\right)^{1/2}$	Lindinger et al., (1974)
3)	$O^+ + NO \rightarrow NO^+ + O$	$< 1.3 \times 10^{-13}$	McFarland et al., (1974b)
4)	$O^+ + e \rightarrow O + h\nu$	$2.4 \times 10^{-10} \, T_e^{-.7}$	Biondi (1969)
5)	$O_2^+ + NO \rightarrow NO^+ + O_2$	4.4×10^{-10}	Lindinger et al., (1975)
6)	$O_2^+ + N_2 \rightarrow NO^+ + NO$	$< 1 \times 10^{-15}$	Ferguson (1974)
7)	$O_2^+ + e \rightarrow O + O(^1D)$	$1.95 \times 10^{-7} \left(\dfrac{300}{T_e}\right)^{.7}$	Mehr and Biondi (1969)
8)	$NO^+ + e \rightarrow N + O$	$4.6 \times 10^{-7} \left(\dfrac{300}{T}\right)$	Biondi (1969)
9)	$N_2^+ + O \rightarrow NO^+ + N(^2D)$	$1.4 \times 10^{-10} \left(\dfrac{300}{T}\right)^{.44}$	McFarland et al., (1974a)
10)	$N_2^+ + O_2 \rightarrow O_2^+ + N_2$	$5 \times 10^{-11} \left(\dfrac{300}{T}\right)^{.8}$	McFarland et al., (1973)
11)	$N_2^+ + O_2 \rightarrow NO^+ + NO$	$\leq 3.0 \times 10^{-14}$	Warneck (1967)

a semidiurnal, a diurnal, and a steady wind component. The semi-diurnal wind component predominated in the middle latitudes while being sparse in the equatorial zone and at high latitudes. The results indicated a mixture of several semidiurnal modes. The semidiurnal components were found to be in good agreement with that of Bernard and Spizzichino (1971). The diurnal component was found mainly for equatorial stations and weak in the middle latitudes. The steady wind component was observed to be generally eastward in a band of $\pm 10^{\circ}$ of the equator and generally westward in the region of $10^{\circ} - 30^{\circ}$ from the equator.

Harper et al., (1975) found the sporadic-E layer to move in accord with the convergence node in the vertical ion motion. Above 124 km the derived wind in the north-south direction had a node near the sporadic-E layer with a poleward wind above and an equatorial wind below.

Nighttime E-region ionization sources have been reported by Young et al., (1971), Fujitaka et al., (1971), Johnson (1972) and Strobel (1974) to be primarily H Lyman β, interplanetary emission of He I 504 $\overset{\circ}{A}$ and He II 304 $\overset{\circ}{A}$, starlight from 1026 to 910 $\overset{\circ}{A}$ and a minor contribution from H Lyman α. Fujitaka et al., (1971) observed peak electron density layers in conjunction with rocket measurements of vertical ion velocity. The layers of peak density were found to occur where the ions converged. The points of convergence were found to descend throughout the night. Geller et al., (1975) using nighttime rocket measurements of electron density in the continuity equation were able to reconstruct the vertical ion drifts. The drift

velocity was a function of the shape of the enhanced ionization layer. The ion drift so determined indicated a tidal wind of the (2, 4) mode.

1.6 Specific Statements of the Problem

1. To investigate the effects of variations in neutral density, vertical ion velocity and temperature on the E-region electron density profiles and to determine the importance of each in making midlatitude electron density models.

2. To study effects of tides in the E-region on the electron densities and to examine the feasibility of determining tidal information from electron density profiles.

3. To compare measured solar fluxes and electron ion densities with that of a model and to examine causes of any discrepancies found.

CHAPTER II

E-REGION MODEL

2.1 Neutral Model Atmosphere

The E-region is considered to be that part of the ionosphere immediately above the turbopause and therefore its' major neutral constituents may be assumed to follow a molecular diffusion profile. As such the altitude profiles of the major constituents O, O_2 and N_2 are determined by the individual scale heights

$$H_i = \frac{kT}{m_i g} \tag{2.1}$$

where

    k   is Boltzmann's constant

    T   is the neutral temperature

    g   is the acceleration due to gravity

    m_i is the molecular weight of the ith constituent

having the height relation for element n_i

$$n_i(z) = n_{i_o} T_o/T(z) \exp\left[-\int_{z_o}^{z} \frac{dz}{H_i(z)}\right] \tag{2.2}$$

where n_{i_o} and T_o are the number density and temperature respectively of constituent i at altitude z_o and $T(z)$ is the temperature at altitude z. For the initial model it was assumed that the relative densities of O, O_2 and N_2 at each height was as given in CIRA (1972). The density

of the minor constituent nitric oxide was taken to be the model values
reported by Meira (1971). These were in some cases modified as
will be described later. The total amount of any one constituent
above the considered altitude can be approximated by

$$\int_{z_o}^{\infty} n_i \, dz = n_{i_o} H_{i_o} \tag{2.3}$$

Values of ion collision frequency and ion temperature were
obtained by analyzing the incoherent scatter data from Arecibo,
Puerto Rico for the six altitudes 100, 104, 107, 110, 114 and 117 km.
The total neutral density was derived from the ion collision frequency
by the relationship of Banks (1966). Because the accuracy of the
temperature measurements is greater than the accuracy of the
collision frequency measurements at the upper and lower ends of
the altitude range of interest, an averaging procedure based on
diffusion equilibrium was used. Diffusion equilibrium can be
assumed since the vertical accelerations induced by the vertical
motions, including the tides, are much smaller than that due to
gravity. It is thus much better to use all the collision frequencies
measured to derive a best estimate of the collision frequency of each
measurement and the corresponding temperature. This average
collision frequency can then be used to derive the neutral densities
at the six altitudes using scale heights calculated from the
temperature measurements. In this work the collision frequencies
were normalized to 110 km according to the formula

$$v_{j110} = v_j \, T_j/T_{110} \, \exp\left[-\frac{mg}{2k} \sum_j^{110} (z_n - z_m) \left(\frac{1}{T_m} + \frac{1}{T_n}\right)\right]$$

$$(2.4)$$

where v_{j110} is the collision frequency at 110 km based on the jth altitude and v_j is the measured collision frequency at the jth altitude. The average $\overline{v}_{110}$ can then be calaculated as

$$\overline{v}_{110} = \frac{\sum_j v_{j110} \left(\frac{v_j}{\sigma_j}\right)^2}{\sum_j \left(\frac{v_j}{\sigma_j}\right)^2}$$

$$(2.5)$$

where σ_j is the error in collision frequency at the jth height.

The measured ion temperatures were assumed to be equal to the neutral temperatures as shown by Nisbet (1967) for E-region altitudes. As the accuracy of the temperature measurements was considerably better than that of the ion collision frequencies, the reduced temperature measurements were adopted for each height.

2.2 Solar Effects and Photoionization

The equation for calculating the production of ionization by solar photons can be derived using the well known equation (2.6), see for example Rishbeth and Garriott (1969),

$$Q(\chi, z) = \sum_i \Phi_{i\infty} \exp\left[-\sec\chi \sum_j \sigma_{ij} H_j(z)\right] \sum_j \gamma_{ij} \sigma_{ij} n_j(z)$$

$$(2.6)$$

where the subscripts i and j refer to the wavelength group and the individual constituents respectively and

$\Phi_{i\infty}$ is the photon flux outside the earth's atmosphere at one astronomical unit.

χ is the solar zenith angle.

σ_{ij} is the total absorption cross section for constituent j and wavelength i.

$H_j(z)$ is the scale height of the jth constituent.

γ_{ij} is the photoionization yield for constituent j and wavelength group i.

$n_j(z)$ is the density of the jth constituent.

Values for σ_{ij} and γ_{ij} were taken from Ohshio (1966) and are listed in Table 1. The individual neutral densities and scale heights were computed as explained in section 2.1. The photon flux for each wavelength group was taken to be the Hinteregger et al., (1965) value repeated on Table 1. The angle χ was calculated as a function of time of day, latitude and solar declination.

$$\chi = Arccosine \left[\sin (g) \sin (\delta) + \cos (g) \sin (\delta) \cos \left(\frac{2\pi (HL - 12)}{24} \right) \right]$$

(2.7)

where

g   is the geographical latitude.

HL   is the local solar time in decimal hours.

δ is the solar declination angle.

In this study it has been assumed that

$$\delta = -.40915 \cos \left[\frac{2\pi (D + 8)}{365.25} \right] \quad \text{radians} \qquad (2.8)$$

where D is the day number.

The effect of secondaries being formed by x-rays was modeled according to the method described by Swider (1969). First the total production was determined as stated above accounting for increased production through the ionization yield. By energetic photoelectrons the ion production becomes

$$q(O^+) = \frac{1.15 \left[.29\, n\, (O_2) + .5\, n\, (O) \right] / n\, (N_2)}{1 + 1.5 \left[n(O_2) + .5\, (O) \right] / n\, (N_2)} \cdot q_{TOTAL}$$

$$(2.9)$$

$$q(O_2^+) = \frac{1.5 \left[.71\, n\, (O_2) \right] / n\, (N_2)}{1 + 1.5 \left[n\, (O_2) + .5\, n\, (O) \right] / n\, (N_2)} \cdot q_{TOTAL}$$

$$(2.10)$$

$$q(N_2^+) = .81 \left[q_{TOTAL} - (q(O^+) + q\, (O_2^+)) \right] \qquad (2.11)$$

$$q(N^+) = .19 \left[q_{TOTAL} - (q(O^+) + q\, (O_2^+)) \right] \qquad (2.12)$$

Equations (2.9) through (2.12) have the effect of distributing the total ion-electron pair production rate q among the various ions as

$0.62 : 0.17 : 0.14 : 0.07 : 1.00$ for $q(N_2^+) : q(O_2^+) : q(N^+) : q(O^+) : q$
as reported by Swider (1969) for the E-region.

2.3 Chemistry

The ion neutral reactions of importance in the E-region used
in this work were reviewed by Biondi (1969), Bortner et al., (1972)
and Ferguson (1974). Data was available for the ion temperature
which was included into the electron density model. Those rates
which varied as a function of temperature did so according to an
inverse law $(T)^{-a}$ where a is a measured quantity.

A reaction scheme including the more important reactions
(Ferguson, 1974) is shown in Figure 1. The steady state of the ion
densities is solved using the continuity equation

$$\frac{d[n_j]}{dt} = Q(n_j) - l(n_j) + p(n_j) - \text{div}(n_j v_j) \qquad (2.13)$$

where

$\quad Q(n_j) \qquad$ is the photoionization of species n_j.

$\quad l(n_j) \qquad$ is the loss due to ion-neutral charge transfer.

$\quad p(n_j) \qquad$ is the gain due to ion-neutral charge transfer.

$\quad \text{div}(n_j v_j) \quad$ is the divergence of the flux $n_j v_j$.

The equation is solved for the five ions O^+, O_2^+, N_2^+ and NO^+. While
N_2^+ is a major ion produced because of its large concentration, it
is not an abundant ion in this region because of its fast reactions
with O_2 and O. Because of their low ionization potentials most
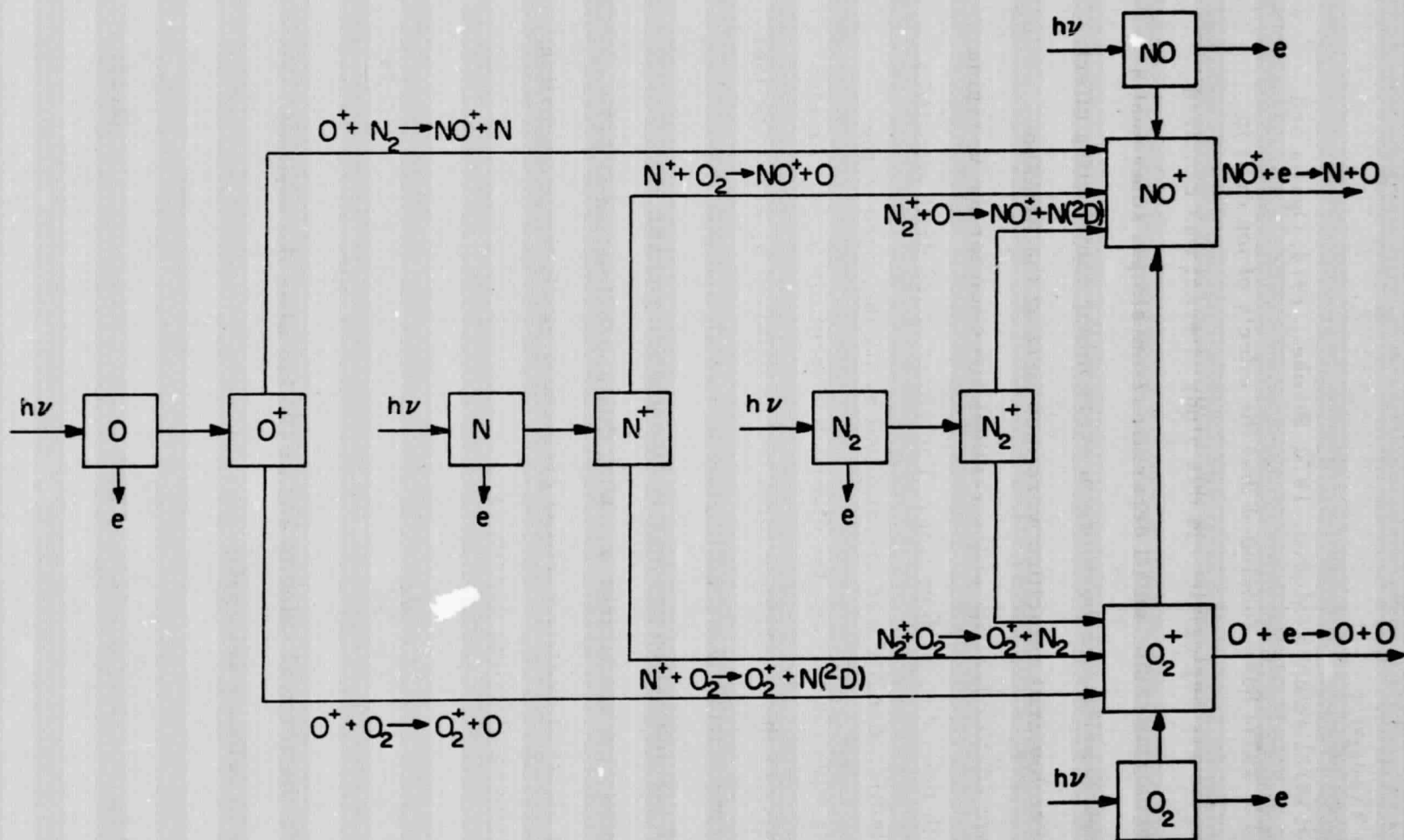ionization takes the form of NO^+ or O_2^+.

Figure 1   Chemical Reaction Diagram

2.4 Ion Transport

Several authors (Monro, 1970; Strobel, 1974; Ogawa and Shimazaki, 1975) have concluded that the effects of ion drift in the E-region are neglegible. In this study interest was centered around exploring rather small departures from simple solar zenith angle dependencies and therefore in every minor contributing effect.

The ion drift velocities were measured at the Arecibo incoherent scatter facility in the vertical direction for the E-region along with the electron densities. The effect of ion drift velocities on the electron density was investigated by its inclusion in the continuity equation through the divergence term div $(n_i v)$. An idea of the effect of the divergence term can be obtained by assuming that the departures from photoequilibrium are small and that the dominant recombination process is dissociative and can be represented by a coefficient α. With this approximation at 117 km when the electron density vertical gradient is small the perturbation from a photoequilibrium density is

$$\Delta n_e \approx - \frac{1}{2\alpha} \frac{dv}{dz} \tag{2.14}$$

where v is the vertical velocity and at 100 km when the vertical gradients in velocity are small

$$\Delta n_e \approx - \frac{v}{2\alpha} \frac{1}{n_e} \frac{dn_e}{dz} \tag{2.15}$$

CHAPTER III

DISCUSSION OF THE ANALYSIS

3.1 Causes of Electron Density Variations

Electron densities measured by incoherent scatter sounding were compared with calculations derived from the model described in section 2.1. The incoherent scatter measurements provided the following information:

1. electron density,

2. collision frequency in the region of 100 to 117 km. This can be used to extract the total density.

3. temperature,

4. vertical amplitude of the ion drift.

An examination of model and experimental electron density profiles in the E-region shows very clearly two regions, a higher region where the electron density gradient with altitude is very small and a lower region of large vertical electron density gradient. Varying the total solar flux has the effect of multiplying the electron density profile by a constant factor at all altitudes. Varying the total density has the effect of varying the height of the profile without changing its shape. A multiplication factor for both the density and solar flux was chosen for each set of data corresponding to measurements of one day.

This study investigated the effect of variations in density, pressure, temperature, vertical ion drift velocity and atomic and molecular oxygen density on the electron density calculated from

Some idea of the vertical velocities in this height range can be obtained from Harper et al., (1975) who found at Arecibo divergences of vertical velocities at 117 km of the order of 6×10^{-3} sec^{-1} and vertical velocities of less than 5 m sec^{-1} at 100 km.

Using these formulae with the values estimated above from Harper et al., (1975) wind measurements give values of $\Delta n_e / n_e$ of the order of 0.1 at 117 km and less than 0.01 at 100 km. The effect at 100 km is not large but at 117 km is not negligible compared to the morning to afternoon differences.

the model described in Chapter II. The investigation was separated between the two regions as described previously with the division occurring at about 110 km.

The sensitivity of the electron density to changes in the neutral density, pressure, temperature, ion drift, and relative atomic and molecular oxygen were investigated in the lower region. Sensitivity factors for density, pressure and temperature were determined by allowing the model to be varied by one of the three parameters and the resulting electron density compared with model results when no parameters varied. The calculations were done for three days, August 12, 1974, September 17, 1974 and September 18, 1974 and the results are shown in Tables 3, 4, and 5. From the relative changes in the electron density due to the three parameters it is evident that no one parameter consistently dominates in the lower E-region. As discussed in section 2.4 the relative change in electron density at 100 km due to vertical ion drifts is on the order of .01. In Figure 2 the contours of electron density as a function of atomic and molecular oxygen are shown for 100 km. The electron density is seen to be almost independent of atomic oxygen. The maximum sensitivity of electron density to molecular oxygen variations is .05.

The same analysis was performed on the upper region. Again not one of the three parameters, density, pressure and temperature, consistently dominated over the other two. As shown in section 2.4 the vertical wind velocity accounts for a relative change in electron density of .10 which is of the same order of magnitude as that due to

Table 3: Relative Electron Density Variations for August 12, 1974

$$\frac{\Delta n_e}{n_e} = A \sin\left(\frac{2\pi}{12}(t - t_c)\right)$$

Altitude	A			t_c		
	Pressure	Temperature	Density	Pressure	Temperature	Density
117	.021	.086	.087	10.4	10.0	12.2
114	.017	.079	.102	12.2	11.6	11.8
110	.020	.066	.053	12.4	12.8	12.4
107	.022	.046	.019	12.4	15.2	13.0
104	.051	.087	.037	12.6	15.6	13.2
100	.096	.196	.200	12.6	15.8	13.6

Table 4: Relative Electron Density Variations for September 17, 1974

$$\frac{\Delta n_e}{n_e} = A \sin \left(\frac{2\pi}{12}(t - t_c)\right)$$

| | | A | | | t_c | |
Altitude	Pressure	Temperature	Density	Pressure	Temperature	Density
117	.056	.077	.066	14.0	12.0	4.0
114	.050	.078	.050	14.2	12.5	6.0
110	.033	.089	.040	6.6	14.0	6.4
107	.027	.041	.034	6.6	17.2	11.2
104	.069	.006	.098	6.6	18.6	11.4
100	.032	.170	.195	11.5	18.0	11.5

Table 5: Relative Electron Density Variations for September 18, 1974

$$\frac{\Delta n_e}{n_e} = A \sin \left(\frac{2\pi}{12} (t - t_c) \right)$$

Altitude	Pressure	A Temperature	Density	Pressure	t_c Temperature	Density
117	.000	.114	.025		12.4	17.6
114	.006	.116	.033	18.8	13.0	17.8
110	.012	.089	.055	18.6	13.4	19.8
107	.028	.049	.019	19.6	16.6	20.6
104	.092	.044	.033	19.6	18.8	18.8
100	.191	.146	.205	19.6	19.6	19.8

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density, pressure and temperature variations. The contours of
electron density as a function of atomic and molecular oxygen are
shown in Figures 2 and 3 revealing a dependence of electron density
on both constituents. The maximum gradient or sensitivity is .05 for
atomic oxygen and .02 for molecular oxygen.

3.2 Feasibility of Determining Neutral Parameters from Electron Density Variations

The three days, August 12, 1974, September 17, 1974 and
September 18, 1974 were used to investigate the feasibility of
determining variations in the neutral atmosphere from deviations
in electron density from a basic secant X variation in electron density.
If one of the parameters totally dominated the others in causing
electron density variations it would be possible to work back from the
electron density to obtain that parameter's variation. From Tables
3, 4, and 5 it is seen that the relative changes in the electron density
corresponding to changes in the temperature, density and pressure
are comparable implying that the electron density variations do not
reflect a variation in just one parameter.

If there existed a relationship among the atmospheric param-
eters it would be possible to determine their variations. For the
three days examined there existed a prevalent semi-diurnal tide.
At 100 km the phase difference between the temperature and the
density were 2, 7 and 0 hours for August 12, 1974, September 17,
1974 and September 18, 1974 respectively. There existed no constant
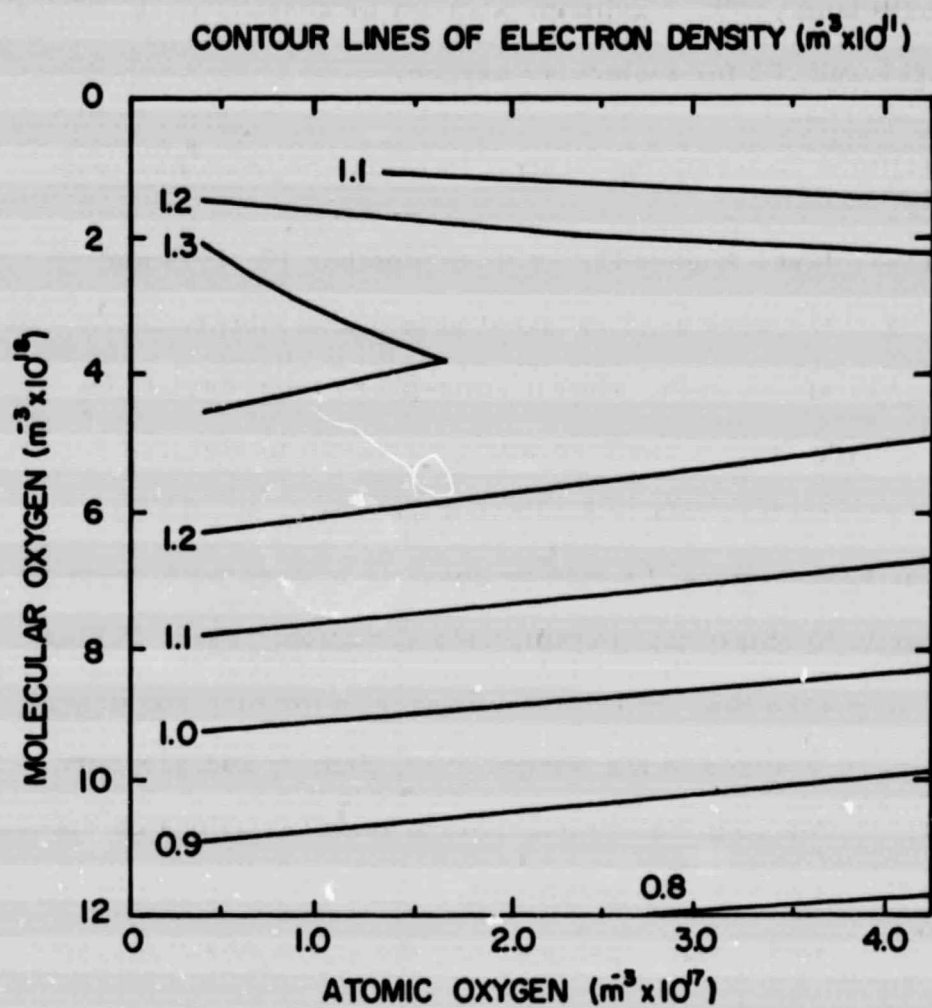phase relationship at any one height.

Figure 2 Electron Density as a Function of Atomic and
Molecular Oxygen Densities at Noon for an
Altitude of 100 km

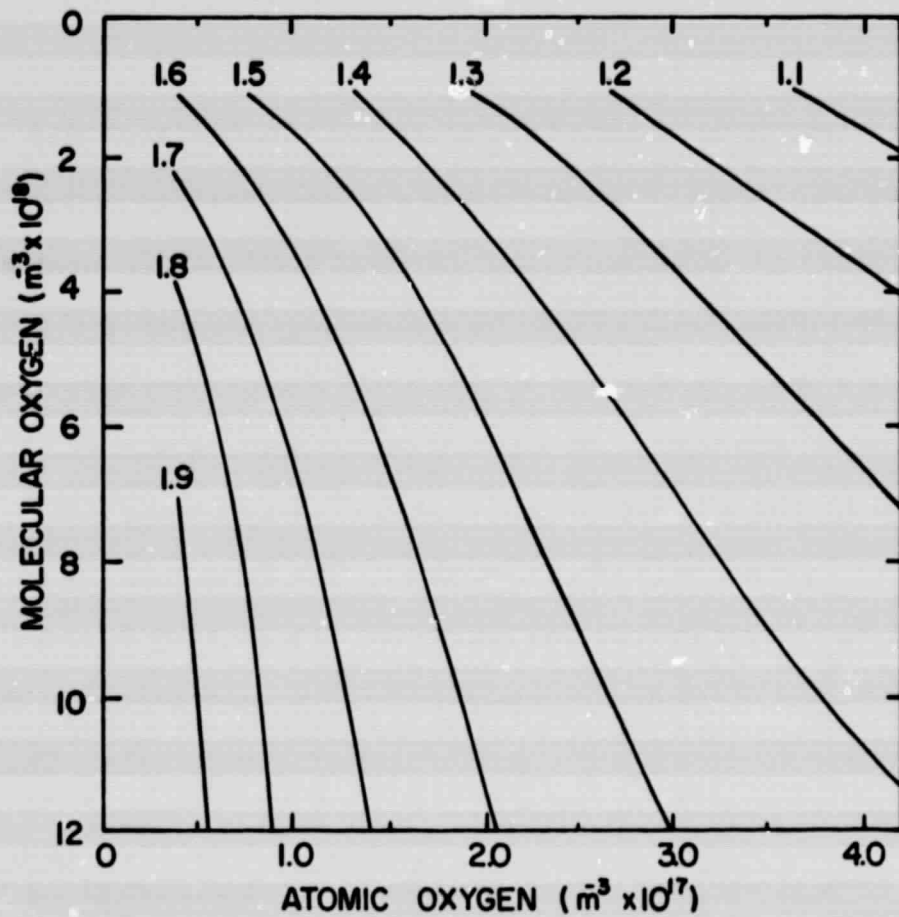**CONTOUR LINES OF ELECTRON DENSITY $(\bar{m}^3 \times 10^{11})$**

Figure 3 Electron Density as a Function of Atomic and
Molecular Oxygen Densities at Noon for an
Altitude of 117 km

It would be very valuable if the amplitude and phase of the tidal motions could be determined from electron density measurements alone since they are available simultaneously at a large number of stations over a long period of time and for a large variety of conditions. It is the conclusion of this study that it is not possible to do this.

3.3 Comparison of the Modeled and Measured Electron Densities

The basic shape of the measured electron densities in the E-region varies as the secant of χ, the solar zenith angle, however there are deviations which can not be explained by a changing solar zenith angle alone. An objective of this study was to investigate the effect of neutral atmospheric variations on the electron density. As stated in section 1.2 care must be taken in using a solar flux model for times other than when measured. The solar flux for one day for all wavelength groups was multiplied by a constant in order to obtain the level of ion density measured in the upper section of the E-region where the gradient in electron density is about zero. The density at all altitudes was multiplied by a constant in order to obtain the level of ion density measured in the upper section of the E-region where the gradient in electron density is about zero. The density at all altitudes was multiplied by a constant in order to have the proper altitude of the division between the upper and lower regions.

The effects of measured temperature, density and vertical ion motion were included in the model of electron density. The inclusion of these variations did not consistently eliminate the

discrepancies between the modeled and measured electron densities.
An attempt was made at reconciling the differences by varying the
relative amounts of atomic and molecular oxygen. To obtain a
good agreement a 45 per cent variation in molecular oxygen was
required for atomic oxygen. Variations of these magnitudes are
unexceptably large when compared with theoretical variations (Mayr
and Volland, 1972) or measured variations (Alacayde et al., 1972;
Danilov, 1972 and Offerman, 1974). The difficulty in using atomic
and molecular oxygen to reconcile discrepancies between measured
and modeled electron densities was discussed by Monro, Nisbet
and Stick (1974).

The basic problem in an analysis of this type is the number
of independent variables. In the present problem the major
uncertainties were in the relative densities of atomic and molecular
oxygen to the molecular nitrogen density and the spectrum of the
EUV solar flux. It would seem that further studies of this kind to be
profitable should be done in conjunction with a series of observations
such as those described by Torr et al., (1976) in which satellite
observations of these important parameters are made simultaneously
with the incoherent scatter measurements.

3.4 Specific Conclusions

E-region density dependence on neutral atmospheric param-
eters was determined for the upper and lower altitude ranges. The
results show that variations in temperature, density and pressure
cause variations in the electron density of comparable amounts.

While the electron density in the lower region is sensitive to variations in the relative molecular oxygen density it is sensitive to variations in both atomic and molecular oxygen density in the upper region. The effect of ion drift while small in the lower region is not negligible in the upper region.

The effects of tides in atmospheric parameters or the electron densities were studied with the objective of determining the feasibility of relating measured electron density variations back to one or more neutral atmospheric parameter variations. Since the major contributing parameters have comparable effects and there exists no fixed relationships between them, it can be concluded that tidal variations in the atmospheric parameters can not be determined from electron density variations alone.

The modeled electron densities including the effect of temperature, density and vertical ion drift measurements were compared with measured values of electron density. While some variations were reproduced there existed differences between them. The basic problem in determining the cause of discrepancies is the number of independent variables. It is concluded that simultaneous measurements of important parameters are necessary to sort out the causes of these discrepancies.

REFERENCES

Alcayde, D., P. Bauer, C. Jaeck and J. L. Falin, Latitudinal diurnal variation of some atmospheric parameters determined be a simultaneous analysis of incoherent-scatter and satellite-drag data, J. Geophys. Res., 77(13), 2368-2376, 1972.

Appleton, E. V., A note on the "sluggishness" of the ionosphere, J. Atmos. Terres. Phys., 3(5), 282-284, 1953.

Appleton, E. V. and A. J. Lyon, Studies of the E-layer of the ionosphere - II. Electromagnetic perturbations and other anomalies, J. Atmos. Terres. Phys., 21, 73-99, 1961.

Banks, P. M., Collision frequencies and energy transfer, Planet. Sp. Sci., 14, 1085-1122, 1966.

Banks, P. M. and G. Kockarts, Aeronomy, Academic Press, New York, 1973.

Bernard, R. and A. Spizzichino, Semi-diurnal and temperature oscillations in the E-region observed by the Nancay incoherent scatter experiment, J. Atmos. Terres. Phys., 33, 1345-1352, 1971.

Biondi, M. A., Electron-ion and ion-ion recombination, Annales de Geophysique, 20, 34-46, 1964.

Biondi, M., Atmospheric electron-ion and ion-ion recombination processes, The Canadian Journal of Chemistry, 47(10), 1711-1719, 1969.

Bortner, M. H., R. H. Kumler and T. Bauer, DNA Reaction Rate Handbook, 24, 2nd Edition, Bortner and Bauer Eds., 1972.

Chapman, S. and R. S. Lindzen, Atmospheric Tides, Gordon and Breach Science Publishers, Inc., New York, 1970.

CIRA, COSPAR International Reference Atmosphere, Akademie-Verlag, Berlin, 1972.

Danilov, A. D., Diurnal variations of atmospheric neutral composition at altitudes of 130-200 km, Space Res., 12, 891-898, 1972.

Donahue, T. M., B. Guenther and R. J. Thomas, Distribution of atomic oxygen in the upper atmosphere deduced from OGO-6 airglow observations, J. Geophys. Res., 78(28), 6662-6689, 1973.

36

Donnelly, R. F. and J. H. Pope, The 1-3000 Å solar flux for a
moderate level of solar activity for use in modeling the
ionosphere and upper atmosphere, NOAA Technical Report ERL
276-SEL 25, 1973.

Fehsenfeld, F. C., D. B. Dunkin and E. E. Ferguson, Rate
constants for the reaction of CO_2^+ with O, O_2 and NO; N_2^+ with O
and NO; and O_2^+ with NO. Planet. Sp. Sci., 18(8), 1267-1269,
1970.

Fellous, J. L., R. Bernard, M. Glass, M. Massebeuf and A.
Spizzichino, A study of the variations of atmospheric tides in
the meteor zone, J. Atmos. Terres. Phys., 37, 1511-1524,
1975.

Ferguson, E. E., Laboratory measurements of ionospheric ion-
molecule reaction rates, Reviews of Geophysics and Space
Physics, 12(4), 703-713, 1974.

Fujitaka, K., T. Ogawa and T. Tohmatsu, A numerical computation
of the ionization redistribution effect of the wind in the nighttime
ionosphere, J. Atmos. Terres. Phys., 33, 687-700, 1971.

Geller, M. A., L. G. Smith and H. D. Voss, Analysis of nighttime
E-region winds and ionization production, Radio Science,
10(3), 335-345, 1975.

Goldan, P. D., A. L. Schmeltekopf, F. C. Fehsenfeld, H. I. Schiff
and E. E. Ferguson, Thermal energy ion-neutral reaction rates
II. Some reactions of ionospheric interest, J. Chem. Phys.,
44(11), 4095-4103, 1966.

Hall, L. A. and H. E. Hinteregger, Solar radiation in the extreme
ultraviolet and its variation with solar rotation, J. Geophys.
Res., 75(34), 6959-6965, 1970.

Harper, R. M., R. H. Wand and J. D. Whitehead, Comparison of
Arecibo E-region data and sporadic-E theory: A measurement
of the diffusion coefficient, Radio Science, 10(3), 357-361,
1975.

Heroux, L., M. Cohen and J. E. Higgins, Electron densities
between 110 and 300 km derived from solar EUV fluxes of
August 23, 1972, J. Geophys. Res., 79(34), 5237-5244, 1974.

Heroux, L., M. Cohen and J. E. Higgins, Reply, J. Geophys. Res.,
80(34), 4771, 1975.

Hinteregger, H. E., The extreme ultraviolet solar spectrum and its
variation during a solar cycle, Annales de Geophysique, 26(2),
547-554, 1970.

Hinteregger, H. E., L. A. Hall and G. Schmidtke, Solar XUV radiation and neutral particle distribution in July 1963 thermosphere, Space Research V, North-Holland, Amsterdam, 1175, 1965.

Johnson, C. Y., Positive ion mass spectrometer observations in the E-region, Radio Science, 7, 99-101, 1972.

Lindinger, W., D. L. Albritton, F. C. Fehsenfeld and E. E. Ferguson, Laboratory measurements of the ionospheric O_2^+ ($X^2 \pi_g$) and O_2^+ ($a^4 \pi_u$) reactions with NO, J. Geophys. Res., 80(25), 3725-3726, 1975.

Lindinger, W., F. C. Fehsenfeld, A. L. Schmeltekopf and E. E. Ferguson, Temperature dependence of some ionospheric ion-neutral reactions from 300° - $900^\circ K$, J. Geophys. Res., 79(31), 4753-4756, 1974.

Lindzen, R. S. and S. Hong, Effects of mean winds and horizontal temperature gradients on solar and lunar semidiurnal tides in the atmosphere, J. Atmos. Sci., 31, 1421-1446, 1974.

MacDougall, J. W., 110 km neutral zonal wind patterns, Planet. Sp. Sci., 22, 545-558, 1974.

Mayr, H. G. and H. Volland, Theoretical model for the latitude dependence of the thermospheric annual and semiannual variations, J. Geophys. Res., 77(34), 6774-6790, 1972.

McFarland, M., D. L. Albritton, F. C. Fehsenfeld, E. E. Ferguson and A. L. Schmeltekopf, Flow-drift techniques for ion mobility and ion-molecule reaction rate constant measurements. II Positive ion reactions of N^+, O^+, N_2^+ with O_2 and O^+ with N_2 from thermal to ~2 ev, J. Chem. Phys., 59(12), 6620-6628, 1973.

McFarland, M., D. L. Albritton, F. C. Fehsenfeld, E. E. Ferguson and A. L. Schmeltekopf, Energy dependence and branching ratio of the N_2^+ + O reaction, J. Geophys. Res., 79(19), 2925-2926, 1974.

McFarland, M., D. L. Albritton, F. C. Fehsenfeld, A. L. Schmeltekopf and E. E. Ferguson, Energy dependence of the rate constant for the reaction O^+ + NO $\rightarrow$ NO^+ + O, J. Geophys. Res., 79(3), 2005, 1974.

Mehr, F. J. and M. A. Biondi, Electron temperature dependence of recombination of O_2^+ and N_2^+ ions with electrons, Physical Review, 181(1), 264-271, 1969.

Meira, L. G., Jr., Rocket measurements of upper atmospheric nitric oxide and their consequences to the lower ionosphere, J. Geophys. Res., 76(1), 202-212, 1971.

Miller, M. J. and J. S. Nisbet, Compatibility of EUV flux measurements and solar cycle variations in the F-region, Paper SA 50, AGU Fall Annual Meeting, San Francisco, 1974.

Mitra, A. P., Time and height variations of the daytime dissipative processes in the ionosphere, PSU-IRL-SCI-99, The Pennsylvania State University, 1958.

Mitra, A. P., J. N. Rowe and R. W. Kreplin, The inadequacies of solar x-ray flux in 1-100 A^o band for production of ionization in the lower E-region, Radio Science Division, National Physical Laboratory Scientific Report 88, New Delhi, India, 1974.

Monro, P. E., The diurnal variation of the concentration of NO^+, O_2^+, NO and N in the ionospheric E-region, J. Atmos. Terres. Phys., 32, 373-382, 1970.

Monro, P. E., J. S. Nisbet and T. L. Stick, Effects of tidal oscillations in the neutral atmosphere on electron densities in the E-region, J. Atmos. Terres. Phys., 389, 523-528, 1976.

Nicolet, M. and A. C. Aikin, The formation of the D-region of the ionosphere, PSU-IRL-SCI-125, The Pennsylvania State University, 1959.

Nisbet, J. S., Neutral atmospheric temperatures from incoherent scatter observations, J. Atmos. Sci., 24(5), 586-593, 1967.

Nisbet, J. S., Comment on 'Electron densities between 110 and 300 km derived from solar EUV fluxes of August 23, 1972' by L. Heroux, M. Cohen and J. E. Higgins, J. Geophys. Res., 80(34), 4770, 1975.

Offerman, D., Composition variations in the lower thermosphere, J. Geophys. Res., 79(28), 4281-4293, 1974.

Ogawa, T. and T. Shimazaki, Diurnal variations of odd nitrogen and ionic densities in the mesosphere and lower thermosphere: Simultaneous solution of photochemical-diffusive equations, J. Geophys. Res., 80(28), 3945-3960, 1975.

Ohshio, M., R. Maeda and H. Sakagami, Height distribution of local photoionization efficiency, Journal of the Radio Res. Laboratories, 13(70), 245-269, 1966.

Palluconi, F. D., The determination of the worldwide effective recombination coefficient of the E-region, PSU-IRL-SCI-198, The Pennsylvania State University, 1963.

Richmond, A. D., Tidal winds at ionospheric heights, Radio Science, 6(2), 175-189, 1971.

Rishbeth, H. and O. Garriott, Introduction to Ionospheric Physics, Adademic Press, New York, 1969.

Salah, J. E., Daily oscillations of the midlatitude thermosphere studied by incoherent scatter at Millstone Hille, J. Atmos. Terres. Phys., 36, 1891-1909, 1974.

Salah, J. E. and R. H. Wand, Tides in the temperature of the lower thermosphere at midlatitudes, J. Geophys. Res., 79(28), 4295-4304, 1974.

Salah, J. E., R. H. Wand and J. V. Evans, Tidal effects in the E-region from incoherent scatter radar observations, Radio Science, 10(3), 347-355, 1975.

Strobel, D. F., Physics and chemistry of the E-region: A review, Radio Science, 9(2), 159-165, 1974.

Swartz, W. E. and J. S. Nisbet, Incompatibility of solar EUV fluxes and incoherent scatter measurements at Arecibo, J. Geophys. Res., 78(25), 5640-5657, 1973.

Swider, W. Jr., Ionization rates due to the attenuation of 1-100 $\overset{o}{A}$ nonflare solar x-rays in the terrestrial atmosphere, Reviews of Geophysics, 7(3), 573-594, 1969.

Torr, D. G., M. R. Torr, J. C. G. Walker, L. H. Brace, H. C. Brinton, W. B. Hanson, J. H. Hoffman, A. O. Nier and M. Oppenheimer, Recombination of NO^+ in the ionosphere, Geophys. Res. Letters, 3(4), 209-212, 1976.

Wand, R. H. and F. W. Perkins, Temperature and composition of the ionosphere: Diurnal variations and waves, J. Atmos. Terres. Phys., 32, 1921-1943, 1970.

Warneck, P., Laboratory rate coefficients for positive ion-neutral reactions in the ionosphere, J. Geophys. Res., 72(5), 1651-1653, 1967.

Whitehead, J. D., The formation of the sporadic-E layer in the temperate zones, J. Atmos. Terres. Phys., 20, 49-58, 1961.

Whitehead, J. D., Survey of sporadic E processes, Space Research VII, North-Holland Publishing Co., 1967.

Wright, J. W., C. H. Murphy and G. V. Bull, Sporadic E and the wind structure of the E-region, J. Geophys. Res., 72(5), 1443-1460, 1967.

Young, J. M., C. S. Weller, C. Y. Johnson and J. C. Holmes, Rocket observations of the far UV nightglow at Lyman α and shorter wavelengths, J. Geophys. Res., 76(16), 3710-3722, 1971.