CHAPTER I

Diurnal variation of F2-ionization

INTRODUCTION

1.1 General: Although the hypothesis of a conducting layer in the upper atmosphere was made in 1902 by Kennelly and Heaviside following the success of Marconi in establishing radio contact across the Atlantic in 1901, its existence could experimentally be proved about 25 years later by APPLETON and BARNETT (1925) and BREIT and TUBE (1925). They could show that not one but three conducting layers viz. E, F1 and F2 with ionization maxima at different heights really existed. The D-layer came to be known later from the observation of the S.I.D. phenomenon in 1931 by MÖGEL. It was Prof. S. Chapman who first gave his classical theory on the production of ionization in the upper atmosphere and formation of an ionized layer, and this theory based on ideal conditions formed the basis for improvement to accommodate other processes which may account for the
observed characteristics of the different layers of the ionosphere. Assuming a recombination process of electrons and ions, CHAPMAN (1931) showed that the height distribution of electron density would follow the relation

$$N = N_0 \exp \left\{ \frac{1}{2} \left( 1 - z - \sec \chi \exp (-z) \right) \right\} \quad (1.1)$$

where $z$ is called the reduced height defined by $(h-h_m)/H$, i.e. height measured from the height of peak ionization in units of scale-height $H = KT/\overline{m}g$, $K$ is Boltzmann constant, $T$ temperature, $\overline{m}$ mean molecular mass and $g$ acceleration due to the earth's gravity in appropriate units. The simple rate of time variation of the electron density $N$ was assumed as

$$\frac{dN}{dt} = q_0 \cos \chi - \alpha N^2 \quad (1.2)$$

in which $\chi$ is the sun's zenith angle, $q_0$ rate of production of ionization when the sun is at zenith and $\alpha$ is the recombination coefficient assumed independent of height.

Under the equilibrium condition (which in reality does not exist) when the rate of variation is very small at a particular instant, the electron density

$$N = \sqrt{\frac{q_0}{\alpha}} \left( \cos \chi \right)^\frac{1}{2} \quad (1.3)$$

Thus the electron density in a Chapman recombination-layer
should vary as square-root of $\cos X$ with the time of the day or with season at a fixed hour. It is found that the diurnal and seasonal variations of the maximum electron density (i.e. density at the height of peak ionization) of the E and F1 layers very nearly obey the above law of eq. (1.3), though there is some discrepancy which might be due to the changes in the effective recombination process, non-constancy of temperature at different heights and perhaps some effect of electromagnetic drift. However, for practical purposes, the behaviours of the E and F1 layers are treated as more or less regular and they are not much affected by the magnetic disturbances except at high latitudes.

In contrast to what is said above, the F2-layer presents many problems. The process of formation of the F2-layer with a peak electron density at 250-300 km was not understood properly until about 1950. There are large variations in the electron density of the F2-layer during the course of a day and a year. From time to time, ideas of a separate ionizing source for the low and midlatitude F2-layer have been advanced, but they are generally not accepted. The theoreticians gave a value of recombination coefficient too small ($\sim 10^{-12} \text{cm}^3\text{sec}^{-1}$). This rate is also too small to explain the nighttime variation of foF2.
It now seems reasonable that the peak rate of production of electron-ion pairs occurs at the Fl-layer peak. The loss of electrons does not take place in a single-step reaction, but in a two-step process, one of atom-interchange or charge exchange

\[
\begin{align*}
0^+ + N_2 & \xrightarrow{\gamma_1} NO^+ + N \\
0^+ + O_2 & \xrightarrow{\gamma_2} O_2^+ + O
\end{align*}
\]

and the other of dissociative recombination

\[
\begin{align*}
NO^+ + e & \rightarrow N + O \\
O_2^+ + e & \rightarrow O + O
\end{align*}
\]

The reaction rate \(\gamma_1 = 5 \times 10^{-12} \text{ cm}^6 \text{s}^{-1}\) and \(\gamma_2 = 1.6 \times 10^{-11} \text{ cm}^6 \text{s}^{-1}\).

Which of these two reactions is more prominent in a particular height range will depend on the distribution of the molecular oxygen and nitrogen and the atomic oxygen. It so happens that at the Fl ledge, reaction II is quicker than reaction I, while above that level since \(O_2\) and \(N_2\) decrease more rapidly than \(O^+\), the reaction I goes on decreasing upward and so the electron loss-rate decreases faster than its production rate as a result of which electron concentration increases continuously with height above the Fl.
ledge. But, as the surrounding atmosphere becomes rarer at greater height, the electrons and ions diffuse downward and halt at some level further increase of $N_e$ in the distribution-profile. Another maximum of ionization is then formed where a balance between the diffusion and the loss rate is reached.

It is interesting to point out here that the $F_1$ ledge is practically absent at middle and high latitudes in winter but it is seen there distinctly in summer and during magnetic storms. These features could be understood with regard to the reactions (RATCLIFFE, 1956). For instance, reaction I is more effective than reaction II in whole of the F-region during winter months. A stratification called $F_{1\frac{1}{2}}$ can also be explained if there are different domains for a particular kind of loss process (KOTADIA, 1963).

At one time, it was thought that gas concentration was too high in the F-region for the diffusion of electrons and ions to be important (FERRARO 1945). Thanks to the advent of rockets and satellites which helped in the measurement of in-situ concentration of different gas constituents, solar radiation fluxes and temperatures of charged and neutral particles. The advent of electronic computers gave a further boost in working out theories and solving complicated "continuity" and "force"
It is now believed that the peak rate of production of electrons and ions occurs by ionizing EUV radiation of wavelengths 200-910 Å at the level of F1 ledge, i.e. 180-200 km. Below this level, the F1 layer behaves as a simple Chapman-recombination layer, whereas above that level, the loss of ionization in the F2-layer is by attachment governed in some way by the process of ion-atom interchange. Availability of information on condition at higher up levels from rockets and satellites roused further interest among theoreticians to work out a time-varying diffusion model of the daytime F2-layer (MARTYN 1955; YONEZAWA 1956, RISHBETH & BARRON 1960). Nighttime variation was treated by DUNCAN (1956) and DUNGEY (1956) and they showed that a peak of F2-ionization would form at a level where diffusion and loss rates are comparable and this peak could be displaced by vertical drift of ions and electrons. The ionization above the F2-peak is in diffusion equilibrium with a scale-height twice that of the region below the peak, i.e. below the F2-layer peak the ionization is approximately in photochemical equilibrium and above it, the shape of the layer corresponds approximately to diffusion equilibrium (RISHBETH et al 1963). A good theoretical and observational account of our knowledge of the F2-layer until 1966 was given by RAWER and SUCHY (1967)
in an exclusive textual and encyclopaedic article.

The continuity equation including the diffusion term is conveniently put as

\[ \frac{dN}{dt} = q - \beta N + D \text{div}(N \omega_p) \]

\[ = q - \beta N + \frac{D_0 e^2}{H^2} \left[ \frac{d^2N}{dz^2} + \frac{3}{z} \frac{dN}{dz} + \frac{N}{z^2} \right] \]  

\hspace{1cm} (14)

in which \( \omega_p \) is vertical drift velocity of plasma diffusion, horizontal motion is neglected and neutral air is assumed to be stationary, \[ D = \frac{2kT}{m_i} = D_0 e^z \] is diffusion coefficient increasing exponentially upwards. Attachment coefficient \[ \beta = \gamma_1 n \left[ N_2 \right] + \gamma_2 n \left[ O_2 \right] \] where \( \gamma \) is reaction rate, \( H_i \) is scale height for positive ions. Negative ions in the F-reion are negligible. The peak of the daytime F2 will be formed at a level where \[ \beta_m \sim D_m / H_i^2 \] and the maximum electron density \( N_m \sim q_m / \beta_m \) (RISHBETH and BARRON 1960).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
 & Day & Night \\
\hline
\( T \) \( ^{\circ} \)K & 900-1700 & 750-1250 \\
\hline
\( q \) \( \text{cm}^{-3} \text{s}^{-1} \) & 50-750 & - \\
\hline
\( \beta \) \( 10^{14} \text{s}^{-1} \) & 0.4 -7 & 0.2-2 summer \\
\hline
\( D \) \( 10^{9} \text{cm}^{2} \text{s}^{-1} \) & 20-70 & 0.06-0.9 winter \\
\hline
\end{tabular}
\caption{Possible numerical values at 300 km}
\end{table}
Studies of the ionosphere at high latitudes were undertaken during the II International Polar Year 1932-33. But the importance of ionosphere-studies on a big scale was realised during the second world war since many a time the radio communication was either interrupted or blacked out and sometimes large rapid and slow fading of signals was occurring (RAWER 1947, 1950). The network of sounding stations expanded and it was only in the IGY-IGC years (1957-1959) that ionospheric and other geophysical observations were organised on a large scale over the globe as a coordinated massive effort. By then, rocket panel of the NRL (USA) had already collected some valuable data on upper air and solar radiations (FRIEDMAN 1960, JOHNSON et al 1958). Ground-based ionosondes had already given basic material for the bottomside of the various ionospheric layers, but this was not sufficient for working out a theoretical model which would explain the regular and irregular variations of the ionization at different heights. Only rocket-borne and spacecraft-borne experiments coupled with incoherent scatter radar and computer techniques helped much progress in the understanding of the physics and chemistry of the ionosphere. International observation programmes were extended to IQSY (1964-65), IASY (1968-69) and even today.
1.2 Equatorial F2-layer

The critical frequency foF2 shows a midday bite-out with a forenoon maximum at 0900 hr and afternoon maximum at about 1600-1700 hr and this bite-out is pronounced at the magnetic equator rather than at the geographic equator. Associated with the bite-out, there is an enhancement in foF2 at places away from the equator towards north and south. One explanation was the thermal expansion of the layer which would depress $N_m$ most when the layer is hottest (GARRIOTT and RISHBETH 1963) in a way $N_m \propto T^{-\frac{3}{2}}$. In the F2-layer, ion-electron diffusion occurs along geomagnetic field lines, so in eq. (1.4), $D$ is to be multiplied by $\sin^2 I$ where $I$ is the magnetic dip angle. Over the equator, $I$ is zero so there cannot be vertical diffusion of ionization. Other terms of transport of ionization such as electromagnetic drift etc. are therefore required to be put in the continuity equation to explain the level of peak electron density and diurnal variation of foF2 at the equator and nearby latitudes.

The midday equatorial trough of foF2 and the follow-up enhancement of foF2 away from the equator was first reported by MAEDA et al. (1942) and later studied in detail as equatorial anomaly by APPLETON (1946). MITRA (1946) explained this trough anomaly as due to diffusion of
electrons from the equator to higher latitudes along field-lines. But simple diffusion gives only a small depth of the trough. MARTYN (1955) suggested the electromagnetic (EM) vertical upward drift of ions and electrons and then their diffusion along field lines. The combined effect of these two processes would give the observed extent of the equatorial trough and the peaks away in north (N) and south (S). The ions will drag air along with which may impede the EM drift. How the electromagnetic drift of F2-ionization could occur by the E-layer dynamo electric field and the earth's magnetic field was worked out theoretically by MAEDA (1952), BAKER and MARTYN (1952), MARTYN (1953), and HIRONO and MAEDA (1955). This could explain the diurnal variation of foF2 at the equator, but not the latitudinal variation.

The detailed theoretical calculations taking into account production, loss, diffusion, neutral wind and EM drift were worked out by MOFFETT and HANSON (1965) and BRAMLEY and PEART (1965) to verify Martyn's suggestion and it was shown that a vertical upward drift of 10 m/s would satisfactorily explain the equatorial F2 anomaly. An asymmetry of 15% between the Appleton peaks in N and S may be caused by neutral wind. The development of the equatorial bite-out and anomaly peaks in foF2 and their extents depend much on the changes in the electric field in
the E-region, the effect being aggravated by increase in the eastward electric field (DUNFORD 1967, KOTADIA and PATEL 1970). According to BRAMLEY and YOUNG (1968) a downward drift velocity of 5-10 m/s may destroy the equatorial anomaly. There is intimate connection between the horizontal drift in the dynamo E-region and the vertical drift velocity in the F2-layer, westward electron drift being accompanied by upward vertical drift of F2-ionization (BALSLEY and WOODMAN 1969; RASTOGI 1974). The E-W electric field is related to the horizontal electron drift velocity (SUGIURA and CAIN 1966) as,

\[ \sigma_p = 30 \text{ at the height of maximum current flow} \]

\[ E_y = -8.8 \times 10^{-7} V_e \text{ volts/m} \]

\[ \sigma_p \] is Pedersen conductivity and \[ \sigma_h \] is Hall conductivity.

MAEDA (1963) worked out a vertical drift \[ E \cos l/B \sim 15 \text{ m/s} \] for an E-W electric field of 0.2 mV/m from the dynamo theory.

It is an observed fact that the morning maximum of foF2 is smaller than the evening maximum in low sunspot period while it is just the reverse in high sunspot years (RAO 1963). Further, there is some seasonal shift in the equatorial trough anomaly. The anomaly peaks are separated out most while the trough deepens at about 1500 hr; after
that, the peaks come close and the trough becomes shallow, eventually to result in a single peak at the equator. The process starts again at 0900 hr and repeats as stated above. These observed facts of the equatorial F2-layer led one to think of a meridional wind, poleward during daytime and equatorward during nighttime over and above the diffusion and EM vertical drifts (KING and KOHL 1965). In fact, MARTYN & PULLEY (1936) had thought early in 1936 of a possibility of neutral wind to explain some features of the F2-layer. The scientists picked up the idea of neutral wind with great interest and this paved a breakthrough for some of the F2-problems hitherto unexplained, not only at the equator but at other latitudes too. The horizontal neutral winds do not produce substantial vertical drift of ionization at low latitudes. Ideally, the vertical drift due to diffusion and neutral wind is nil at magnetic equator, the neutral wind itself is zero at geographic poles and equator. The neutral wind arises from the pressure gradient set up by the heating and cooling of the atmosphere over day and night, the direction of wind being from hotter to the cooler regions, i.e. from heated dayside round the equator and across the poles towards the cooler nightside (KOHL and KING 1967) as shown in fig.1.1. This pattern provided daytime poleward and nighttime equatorward neutral
Fig. 1.1 The northern hemisphere atmospheric wind system at 300 km calculated for a constant peak electron concentration of $3 \times 10^5$ electrons/cc (after Kohl and King, 1967).

wind. A maximum of vertical ionospheric drift of 75 m/s is expected according to this model at a place of dip angle $45^\circ$, neglecting viscosity, Coriolis force and ion-drag.

1.3 Model computations of $N_mF_2$

(a) Diurnal variation of $N_mF_2$ at magnetic equator

The continuity equation may now be written in a general form as

$$\frac{dN}{dt} = \text{Production rate } (q) - \text{loss rate } (L) - \text{div } (Nv) \quad (1.5)$$
where \( v \) is composed of diffusion velocity \( v = v_d \sin I \), EM vertical drift velocity \( v_c \), and neutral wind-induced vertical drift \( U \sin I \cos I \), \( U \) being the horizontal N-S meridional neutral wind and \( v_d \) diffusion velocity along field line. HANSON and MOFFETT (1966) solved the continuity equation and the equation of motion taking into account \( q, L, \) and transport terms relating to diffusion, EM drift and neutral wind-induced vertical drift and concluded that the EM vertical drift is a major factor affecting the diurnal variation of \( NmF2 \) and the \( F2 \)-anomaly at the equator. WU (1972) solved numerically the continuity equation and estimated the value of the EM vertical drift which was found consistent with that measured at the equatorial station Jicamarca by incoherent scatter radar (WOODMAN 1970). Fig.1.2 shows the computed curves of diurnal variation of \( NmF2 \) at Huancayo for D and J solsticial months, once considering the effect of EM drift and then considering the effects of both EM drift and meridional neutral wind (ANDERSON and MATSUSHITA 1974) based on assumed models of the atmosphere, electromagnetic fields, diffusion constants, ionizing flux, neutral wind, ionization cross-section, temperature, loss coefficient etc. Results may vary with different models assumed.
Fig. 1.2 Assumed meridional wind speed (positive equatorward) and vertical EM drift velocity (positive upward) in m/s. The middle portion gives the calculated values of $N_mF_2$ with (---) and without (----) the neutral wind. Dots are observed values of $N_mF_2$. Diurnal variations at Huancayo in (a) D-solstices and (b) J-solstices (after Anderson and Matsushita 1974).

It shows that most of the features of the observed diurnal variation of $N_mF_2$ can be explained by EM drift and a little improvement on this is found when the effect of neutral wind is included. The sharp fall in $N_mF_2$ between 1800 and 2000 hr in D-solstices is associated with a large upward EM drift. Seasonal and solar-cycle shift in the
forenoon and afternoon maxima may result from the phase shift in the vertical drift of electrons and ions due to slight effect of the neutral wind whereas the size of the equatorial trough and the anomalous peaks of $\text{NmF}_2$ on either side of the equator are formed as a result of the combined effects of ambipolar (electro-ion) diffusion and vertical drift. Hedin & Mayr (1973) showed from OGO-6 satellite data that equatorial minima and low-latitude maxima in the distribution of molecular nitrogen and atomic oxygen are also found corresponding to the equatorial trough and low-latitude peaks in $\text{NmF}_2$. The diurnal curves of fig.1.2a,b show that the daytime $\text{NmF}_2$ values computed with neutral wind effect are smaller than those obtained without it.

(b) Computed diurnal variation of $\text{NmF}_2$ at low latitudes

Fig.1.3a,b gives diurnal variations of $\text{NmF}_2$ for D and J solstices at a low-latitude station, viz. Tucuman (27°S, 56°W; $I = 22°$S) which is within the range of fully developed Appleton anomaly peaks. It is again seen that the curves calculated by including the effect of neutral wind give a better fit with the observed values than those calculated with drift alone. (Anderson and Matsushita 1974). One difference in J-solstices is that the observed values at Tucuman are higher than calculated. Perhaps the
assumed models for atmosphere and neutral wind are responsible for this. Equatorward neutral wind raises the ionization to a height of low loss-rate during nighttime.

(c) Computed diurnal variation at midlatitudes

A large number of papers have been published on the effect of neutral winds in the F2-layer since the time when attention was first drawn on this subject by KING.
and KOHL (1965). Some have already been referred to in the previous sections. Fig. 1 gives an example of the computed and observed diurnal variation of foF2 at a midlatitude station, viz. Port Stanley (ECCLES et al 1971). It is seen that the essential features of the diurnal variation of foF2 are satisfied by the vertical drift of electrons caused by the meridional neutral wind. The nighttime high values of electron density are explained as due to movement of the layer to a height-region where the loss-rate is much

![Diurnal variation of foF2 at Port Stanley for summer sunspot minimum conditions. Calculated variation of foF2 by including the effects of neutral wind (-----) and without wind (----). Open circles are observed values of foF2 on the days shown (after Eccles et al 1971).](image)
slower. Such upward movement is caused by the equatorward wind (RISHBETH 1967; KOHL & KING 1967; HANSON & PATTERSON 1964; ECCLES et al 1971; BEHNKE & KOHL 1974). The evening bulge of $\mathrm{foF}_2$ in summer is explained by some as due to sudden downward drift (ECCLES & BURGE 1973; VASSEUR 1970) and by some as due to rapid cooling of electrons (EVANS 1965; TITHERIDGE 1973). However, some have attributed the nighttime midlatitude $\mathrm{F}_2$-ionization to precipitation of electrons from the exosphere or production of fresh ions (JAIN et al 1973; GEISLER & BOWHILL 1965).

The effect of vertical drift of electrons due to neutral wind depends on the direction of the local magnetic field and since the magnetic field is asymmetrically distributed over the globe, there are bound to be longitudinal differences in the diurnal variation of $\mathrm{foF}_2$ and $\mathrm{hmF}_2$ which are controlled by the neutral wind. That such differences are related to the direction of the magnetic field was explained by CHALLINOR et al (1971) and ECCLES et al (1971). U.T. control of nighttime maximum in $\mathrm{F}_2$-ionization at temperate and high latitudes was shown to be associated with the change in phase of the neutral wind-induced vertical drift dependent on the magnetic declination (KOHL et al 1969; EYFRIG 1963; HEISLER 1966). Day-to-day, seasonal and sunspot-cycle changes in the times of maxima and extent of bite-outs may be caused by the changes in the phase and magnitude of
the neutral wind. Development of equatorial anomaly later in the American Zone than in the Asian Zone (LOCKWOOD and NELMS 1964) may also result from the longitudinal differences in the study of the magnetic field.

---

<table>
<thead>
<tr>
<th>Rs.</th>
<th>P.</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>06</td>
</tr>
</tbody>
</table>

Signature of Postmaster/ Supervisor checking correctness of entries

Warehousing charge for days from the first addressee
Redirection charge

Signature of Postmaster/ Sub-Postmaster/Supervisor checking correctness of entries

Signature of the Clerk entering the charges.

N.B. 1. —If the addressee is aggrieved at the amount of the customs duty demanded he should request the local delivery Post office in writing to return the parcel for reassessment stating specifically the grounds for reassessment. Simultaneously he should inform the customs authorities direct about his grounds for reassessment with copies of documents, if any, in support of his claim.

No claim for (1) free entry or (2) refund is considered unless the wrapper of the parcel bearing the address, the customs declaration form and this label is sent to the Collector of Customs and no claim for reassessment of customs duty is considered unless the parcel is returned to the Post Office unopened.

N.B. 2. —The Postal fee represents the cost of the service performed by the Post Office in handling the parcel at the office of exchange.

(a) Rarotonga 21° 28′ S 159° 38′ W 39.0° S
(b) Apia 13° 8′ S 171° 8′ W 30.0° S

Gage until 1972, the study of the mean

<table>
<thead>
<tr>
<th>Magnetic Mean</th>
<th>Mean Declination</th>
<th>H-field</th>
</tr>
</thead>
<tbody>
<tr>
<td>5° N</td>
<td>1° N 7° 36′ W</td>
<td>27653 Y</td>
</tr>
<tr>
<td>3° S</td>
<td>8° 51′ E</td>
<td>22604 Y</td>
</tr>
<tr>
<td>6° N</td>
<td>11° 35′ E</td>
<td>28061 Y</td>
</tr>
</tbody>
</table>

Redirection charge
In the table the ionospheric station is shown against (a) and the place of magnetic observatory nearest to the ionospheric station is shown against (b). The mean diurnal variations described here are for normal and disturbed conditions during a medium-low solar activity period. The monthly mean diurnal variations of foF2, horizontal component H and declination D of the earth's magnetic field are expressed as deviations of their hourly values from the 24-hr mean value. This method serves a double purpose of giving an idea of the range of daily variation and also the duration for which the hourly values are higher and lower than the mean reference level, preserving at the same time the shape of the diurnal curve. The mean reference level values of foF2, H and D are shown on the sides of the figure for northern (N) and southern (S) stations. The work has since been published (PARIKH & KOTADIA 1973; PARIKH & KOTADIA 1974).

1.4 Normal diurnal variation of foF2, H and D in the 60°W sector near dip angle 50°

The magnetically near-conjugate ionospheric stations selected are Puerto Rico (I=52.5°) in north and Port Stanley (I=46.3°) in south for which the diurnal variations of foF2 are shown in Fig.1.5 for winter and summer of 1961. The winter month is December and the summer month is June in the
northern hemisphere and it is the other way round in the southern hemisphere. The mean Zurich sunspot number $R_z$ in June was 77 and in December it was 40, the annual mean being 54.

![Graph](image)

**Fig. 1.5** Monthly mean diurnal variation of $f_{oF2}$, $H$ and $D$ at conjugate places in the 60°W sector near 50° dip during winter and summer. Daily mean values are given at the sides for northern (N) and southern (S) stations.

Since the geographic latitude $\varphi$ of P.Rico is 18.5°, it is a low-latitude station, but Port Stanley which has $\varphi = 51.7°$ is a midlatitude station. It is curious to
find that there is some bite-out effect in foF2 at P.Rico in winter (December) while there is a large bite-out effect at P.Stanley in summer (also December). The forenoon and afternoon maxima are much farther apart at P.Stanley. Corresponding to these, the range of diurnal variation of the H-field is large and the rate of decrease after its maximum is rapid as compared to that in June. The diurnal variation of D in either season is similar in the two hemispheres, with some indication of a lead of about an hour in the south. The northern station has west declination while the southern station has east declination. The mean magnetic field in the north is about 5000 gammas larger than in the south, and mean foF2 is also larger in the north. Considering the same season, instead of same months, the variations of foF2 and H are very much different at the dip conjugates. Whereas there is not much diurnal change in foF2 against large change in H at P.Stanley in summer, there is a large variation in foF2 against small variation in H at P.Rico. In both the cases the afternoon maximum of foF2 occurs much later in summer than in winter, but the bite-out in foF2 is not seen at P.Rico in summer (June) as also it is absent at P.Stanley in winter (also June) corresponding to small variations in H in this month. The nighttime ionization is maintained high in summer at P.Stanley but not at P.Rico. It therefore turns out that the diurnal
variation of \( f_0F_2 \) at P.Rico is influenced primarily by the EM drift whereas that at P.Stanley seems to be under the effect of both EM drift and neutral wind.

The time of presunrise minimum at a place essentially depends on the length of night in different seasons, it being shorter in summer and longer in winter at higher latitudes than at lower latitudes.

1.5 Diurnal variation of \( f_0F_2, H \) and \( D \) in 165°W sector near dip angle 40°

In the last section north-south asymmetry was noted in the variation of \( f_0F_2 \) at conjugate places near dip angle 50°. A typical case given here is that of two conjugate places which have same geographic and magnetic latitudes, and also same geographic longitude. The places are Hawaii in north and Rarotonga in south in the Pacific zone near dip angle 40°. Fig. 1.6 gives the diurnal variations of \( f_0F_2 \) at Hawaii and Rarotonga compared with those of H-field and D at nearby magnetic observatories for summer and winter of 1963. Apia is somewhat away towards equator, but the magnetic declination at Apia and Honolulu is nearly the same and in the same East direction. One difference between this pair and the pair along 60°W longitude is that the mean H-field at 60°W is larger in the north by about 5000 gammas, than in the south, while along 165°W,
the southern station has mean H-field about 6700 gammas larger than at the northern station. Another difference is that regarding the declination. It is West in north and East in south for P.Rico - P.Stanley pair, while it is East both in north as well as south for Hawaii - Rarotonga pair. $R_z$ in June 1963 was 36 and in December 1963 it was 15, the annual mean being 28 as compared to 54 in 1961 for which Fig.1.5 was drawn. The study was done with whatever data were available
with us. The large difference in the H-field at Apia and Honolulu may be due to the fact that Apia is nearer to the equator.

It is noticed from Fig. 1.6 that the diurnal variations of foF2 in winter or summer at Hawaii and Rarotonga are very much different. Whereas the diurnal variation of foF2 at Hawaii is more or less similar to that at P.Rico (at nearly same north geographic latitude), it is not so for Rarotonga and P.Stanley. The daytime bite-out at Rarotonga in summer is not to be seen; instead, it has clear midday maximum compared to the much delayed maximum at its northern conjugate. The variations in the H-field and declination in the two longitude sectors considered here differ significantly; particularly to note is the nearly opposite variation of D at Apia and Honolulu in summer. There is one common feature, and that is the fall in foF2 when the rate of fall in the H-field is rapid. Midday values of foF2 at Rarotonga (winter) and Hawaii (summer) are quite depressed, both of them being in the same month, i.e. June. Moreover, the nighttime values are not maintained high at any of these two places. It is difficult to find any correlation between declination and foF2. The above observations point to a less influence of neutral wind at these low-latitude (\( \varphi = 21^\circ \)) stations than observed at the midlatitude southern station P.Stanley.
1.6 Mean Disturbance Diurnal (DS) Variation of foF2, H and D

Having seen the variation of foF2 at the low conjugate pairs under normal conditions and their comparison with the magnetic field variations, the next step is to extend this study for disturbed conditions and see how far the ionospheric and geomagnetic characteristics are related to each other on magnetically disturbed days. The current systems which produce magnetic disturbances may also change the wind systems in the thermosphere, and the composition of the atmosphere (BLAMONT and LUTION 1972, MAYR and VOLLAND 1974) and such changes may not be effective in a similar way at different places.

1.7 DS variations of foF2, H and D near dip 50° in 60°W sector

The DS variation of foF2 is expressed in terms of the ratio of disturbed-day foF2 to the monthly median foF2 at corresponding hours. For H and D, first the average disturbed-day hourly deviations from monthly mean values are found for five international disturbed days in a month and these deviations are then shown as departures from the 24-hr mean disturbed-day deviation. This 24-hr mean deviation may be considered as a reference level equivalent to a flattened
storm-time Dst component. The values of the mean disturbed reference level for H and D are given at the sides in Fig. 1.7. It is seen that the DS variations of the H-field in the north at San Juan and in the south at Trelew are similar in a particular month in spite of the fact that the local seasons are different. Such similarity was also observed in the normal diurnal variation of the H-field in the same month. However, under disturbed conditions the DS variation of foF2

Fig. 1.7 Disturbance diurnal variation of foF2, H and D at conjugate places in winter and summer near 50° dip in the 60°W sector.
at P.Stanley does not appear to be similar to that at P.Rico in the same month or even in the same season. It is interesting to note that distinct increases in foF2 in winter and decreases in summer for most of the time are seen at P.Rico while decreases as well as increases of foF2 are found at P.Stanley in either season. Also, in winter there does not seem to be much correspondence between the DS variations of foF2 and the H-field both as regards phase and magnitude. As against this, in summer they tend to be in the same phase in the north and in opposite phase in the south. There is no difference between the phases of the normal and disturbed diurnal variation of the H-field in winter. The variation of D does not throw much light on that of foF2 during the two seasons. The H-field varies by about 20 V in June and 40 V in December. The variation in D at Trelew in summer is larger than at San Juan in winter (i.e. in the same month, viz. December). Again, the DS variation of foF2 in winter is somewhat erratic and complex as compared to that in summer. Thus the seasonal and hemispherical differences in the disturbed day variations of foF2 cannot be linked up with those of geomagnetic elements in a simple manner, which means that the EM drift alone cannot explain the disturbed-day changes in foF2 near 50° dip. One interesting point regarding foF2 at P.Stanley is that it shows a bulge in the evening during disturbed period in winter as well as summer, which is not so at P.Rico. It is likely
that the neutral wind blowing equatorward during disturbance may effectively contribute to the disturbance variations of foF2 as observed at the conjugate stations.

1.8 DS variation of foF2, H and D near 40° dip in 165°W sector

Fig. 1.8 shows the average DS variations of foF2, H and D for the five international disturbed days in a winter and a summer month of the year 1963 at places near 40° dip in the 165°W sector. It is seen that the DS variations of foF2 at Hawaii and Rarotonga seem to be similar during the same solsticial
month, i.e. increase of foF2 in northern winter month (December) and decrease in northern summer month (June), a feature somewhat different from what is found at P.Rico and P.Stanley. But, the depressions of foF2 at Rarotonga are less marked than at Hawaii in June. As regards the DS variations of the H-field, they are more or less similar at the two conjugate places in a particular month. It appears, therefore, that the changes in the magnetic field have some influence on the F2-ionization on disturbed days by way of EM drift besides other factors, whereas at midlatitudes, it is probably the changes in the atmosphere and the neutral wind system due to disturbance that markedly influence the F2-ionization. One may note a spiky increase of H at Apia around noon in winter. This might have been only a localized phenomenon at a further lower latitude than Rarotonga and hence not reflected in the variation of foF2 at Rarotonga.

About declination, the total variation is hardly 1.5', but the phases of the DS variations of H and D are almost reversed from what they are under normal conditions.

1.9 Annual mean DS variation of foF2, H and D

Mean DS variations of foF2, H and D for 60 international disturbed days at P.Rico-San Juan/P.Stanley-Trelew pair for the year 1961 are shown in the right column of Fig. 1.9. The same at Hawaii-Honolulu/Rarotonga-Apia pair for 1963 are shown in the left column of the figure.
Fig. 1.9 Annual mean DS variation of foF2, H and D at conjugate places in 40°- 55° dip zone in 60°W and 165°W sectors.

Here the plots of foF2 and H for respective stations are drawn on the same axes while that of D is drawn under them separately. It may be seen that even in the average variation for the whole year when the seasonal influence is minimised, the phase of the DS variations of foF2 and H tend to be in opposite directions, particularly in the southern hemisphere. However, the trend in the variation of foF2 is not so regular as that of the H-field. Further, there is a difference even
among the two northern stations, e.g., while the DS variation of $f_0F_2$ at Hawaii ($I=39^\circ$) appears to follow that of the H-field, it is not so at P.Rico ($I=52.5^\circ$). The maximum of the DS (H) occurs at all the four places around 0500 hr, but its minimum occurs at around 1300 hr in the 40° dip region while it occurs at around 1700 hr in 50° dip region. One can see negligible effect of magnetic disturbance on the F2-ionization at P.Rico on the whole, although the amplitude of the DS (H) variation there is the largest (16r) amongst the four stations.

The DS variation of declination is more or less similar at all these places and the amplitude does not exceed 1.5°, that at Trelew being the largest. The above complex and uncorrelative observations indicate that the changes in the F2-ionization on disturbed days are not caused by the changes in the magnetic field alone.

1.10 CONCLUSIONS AND DISCUSSION

A From the study of monthly mean (normal) diurnal variations of $f_0F_2$, H and D at typical low and middle latitude magnetically dip-conjugate pairs in the American and Pacific zones separated by about 100° longitude, it is concluded that, (1) In the 60°W sector near 50° dip, the daytime bite-out in $f_0F_2$ is observed in winter at Puerto Rico, but in summer
at Port Stanley, i.e. same solsticial month, but these
two bite-outs are of different character. The daily range
of variation in the H-field is also large in this month.
Further, P.Stanley is at higher geographic latitude
(φ = 51.7°S) than that of P.Rico (φ = 18.5°N); the latter
is geographically a low-latitude station, and the former
a midlatitude station. Moreover, the dip of P.Stanley
(46.3°S) is close to 45°. If we look to the model of
neutral wind given in Fig.1.1 and Fig.1.10 it is clear
that the meridional N-S neutral wind is maximum at
φ = 45° and poleward diurnal maximum of wind (~ 120 m/s)
occurs at around 1800 hr in J-solstice, but it is about
80 m/s at φ = 20°. In D-solstice, the poleward wind
has a maximum of about 100 m/s at 45°S and of about
60 m/s at φ = 20° around 1700 hr.

Moreover, maximum neutral wind-associated vertical
drift (downward during day and upward during night) of
electrons is expected at 45° dip according to \( U \cos I \sin I \).
Thus the situation of P.Stanley is such that the effect
of neutral wind on F2-ionization should be very much
marked at P.Stanley as compared to that at P.Rico, in
addition to the small vertical EM drift \( E \cos I/B \)
(upward during day) at these places. Theoretically
computed diurnal variations of foF2 taking into
Fig.1.10 Contour plots of the assumed meridional neutral wind velocity (m/s) as a function of geographic latitude and local time during (a) D-solstices and (b) J-solstices; positive values show equatorward wind (after Anderson & Matsushita 1974).

consideration all drift terms are shown for Lindau ($\phi = 51.6^\circ$N, $I = 67^\circ$N) and P.Stanley (ECCLES et al 1971) in Fig.1.11. The curve for low sunspot period agrees with that studied by the author as shown in Fig.1.5. It is also found that the phase of the neutral wind advances towards lower sunspot activity which results in a pronounced evening maximum after the bite-out as compared to the morning maximum. At P.Rico, the morning maximum of $f_0F_2$ in summer is almost suppressed. A picture showing how these two maxima are controlled by the phase of the neutral wind is shown in Fig.1.12 after ECCLES et al (1971).
Fig. 1.11 Calculated diurnal variation of $f_{\circ F2}$ for Lindau and Port Stanley during sunspot maximum and minimum summer including the effect of neutral wind (after Eccles et al, 1971).

Fig. 1.12 Calculated diurnal variation of $f_{\circ F2}$ for summer sunspot minimum at Lindau showing the effect of change in the phase of neutral wind. The figures 0, 1, 2, 3 indicate hour of occurrence of pressure maximum earlier than that given by Jacchia and Slowey Model, 1968 (after Eccles et al, 1971).
(2) The variation shows low values around noon and high values at night of $f_0F_2$ in summer at P. Stanley. The upward vertical drift of ionization induced by equatorward neutral wind at night maintains low rate of loss. The nature of diurnal variation of $f_0F_2$ is also influenced by the magnetic declination of the place.

(3) The variation of $f_0F_2$ at Rarotonga and Hawaii do not show clear bite-out effects, nor high nighttime ionization. The neutral wind effect seems to be small as compared to that at P. Stanley. Seasonal differences in $f_0F_2$ seem to be more related with the variations in the magnetic field and declination rather than with the neutral wind. BULLEN (1969) attributed the seasonal hemispherical asymmetry in F2-layer at Hawaii and Rarotonga to differences in magnetic field. However, DESHPANDE (1973) showed that neutral wind and its phase may explain the seasonal differences in the diurnal variations of $f_0F_2$ and $h_mF_2$ at the above two places in the Pacific zone. The large antiphase diurnal variation of declination in summer at Honolulu and Apia is also one of the reasons for the observed difference in the variation of $f_0F_2$ as the declination does play part in the vertical drift of ionization due to neutral wind. The variations of $f_0F_2$ at the two low-latitude stations would have perhaps been similar if they had magnetic
declinations in the opposite directions besides their conjugacy in respect of geographic and magnetic latitudes.

B Following are the conclusions and discussion for the DS variations of foF2:

(4) The disturbed-day variations of foF2 at P.Rico in north show pronounced increase in winter and decrease in summer, while at P.Stanley in south they show increases as well as decreases in either season. These do not correlate well with the variations of the H-field. It may be pointed out that owing to heating of the thermosphere in the auroral zone, the N-S neutral wind becomes equatorward during disturbances which produces upward drift of ionization, whereas the EM upward drift is reduced by westward induced electric field during the main phase and the recovery phase. The result will depend on the relative effectiveness of these two competing drift forces. Obviously, the results at P.Stanley with increased foF2 on the whole and pronounced afternoon maximum suggest that the neutral wind is more effective in producing changes in the F2-layer at P.Stanley. Also the differences in the DS variation of foF2 at the conjugate places near 50° dip do not agree with those of the H-field. The changes in the atmospheric composition by the disturbed wind circulation also play an important
role in modifying the production and loss rates of ionization. All these factors make the F2-behaviour complex.

(5) Similarity in the DS variations of $f_0F_2$ and the H-field is found at Hawaii and Rarotonga near 40° dip in 165°W sector, i.e. increase of $f_0F_2$ in December and decrease in June. Seasonal factor seems to be irrelevant. However, decrease of $f_0F_2$ at Rarotonga is not so marked as at Hawaii. On the average, during disturbed days $f_0F_2$ is above normal at Rarotonga during all the hours, whereas at Hawaii, it is depressed in the evening hours and practically normal around midday hours. There seems to be a sizable effect of EM drift at the northern station Hawaii as compared to that at Rarotonga. For DS variations of $f_0F_2$ at different latitudes derived from a statistical study of a large number of SC storms, reference is made to work of JANI and KOTADIA (1971).

To conclude, it may be stated that our study reported in section 1.4 onwards was primarily intended to expose similarities and dissimilarities at magnetically conjugate places along practically the same meridian. The material presented here provides a sufficient evidence that the neutral wind effects are a function of the geographic latitude and the vertical drift of F2-ionization produced by this wind is
controlled by the direction of the magnetic field, i.e. Inclination or Dip and the Declination.

Various theoretical diurnal variations of foF2 and hmF2 have been calculated by assuming different models of atmospheric composition, neutral winds, diffusion and electric fields (ABUR-ROBB 1969; STUBBE and CHANDRA 1970; KING et al 1968). The agreement among these will differ depending upon the assumed models neglecting some supposedly minor parameters for simplifying the solutions of the continuity and force equations. On the whole, now the general impression for the F2-behaviour is that the neutral winds have pronounced influence on it at midlatitudes and the EM drift is so near the equator and low latitudes. The perturbations seen in the F2-layer during magnetic disturbances are a result of a reshuffling in the neutral wind circulation, air composition and electric fields and possibly plasma influx from the magnetosphere, all these contributions manifested in a complex manner.

This chapter provides a good amount of introductory material for the topics discussed in Ch.II, III and IV.
REFERENCES

<table>
<thead>
<tr>
<th>Author/Authors</th>
<th>Year</th>
<th>Journal/Book Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authors</td>
<td>Year</td>
<td>Journal and Volume/Number/Pages</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>MAEDA H.</td>
<td>1963</td>
<td>Proc. Int. Conf. Ionosphere,</td>
</tr>
<tr>
<td>SHINKAWA H.</td>
<td></td>
<td>Tokyo (Japan), No. 2.</td>
</tr>
<tr>
<td>MARTYN D.F.</td>
<td>1955</td>
<td>'Physics of the Ionosphere'</td>
</tr>
</tbody>
</table>