Chapter 4

Servo model and its applicability to low latitudes

4.1 Introduction

The location of peak electron density well above the peak of ion production was an enigma to the ionospheric physicists in the late 1940's and 1950's. Whereas the lower regions ($E$ and $F_1$) conform closely to the Chapman's theory of layer formation, the ionization distribution in the $F_2$ region differs considerably from the expected morphology. It was recognized by then that the behaviour of the $F_2$ layer is complex and inexplicable in terms of solar ionizing radiation and chemical recombination alone. It was Mitra [1946] who first realized the importance of motions of plasma along the magnetic field lines at heights where the plasma-neutral collision frequencies are small, and hence the geomagnetic control of ions and electrons in the $F_2$ region of the ionosphere. Martyn [1956] showed that, under the forces of gravity and of its own partial pressure gradient, diffusion of ionization along the magnetic field lines in the vertical direction would considerably affect the shape and height of the $F_2$ region. Further, he demonstrated that the ionospheric layer with any initial height distribution of electron density, would approach the Chapman form. He was the
first to realise that the morphology of the $F_2$ layer might be explained with the inclusion of electrodynamic drifts of ionospheric plasma. Duncan [1956] extended the conclusions reached by Martyn and showed that a uniform vertical drift would alter the equilibrium height of the $F_2$ layer.

With the plasma diffusion in the upper atmosphere becoming important, Shimazaki [1957] derived expressions for the contribution of diffusion to overall motion of $F_2$ layer plasma. Yonezawa [1958] solved the relevant equations for a particular model atmosphere to arrive at appropriate analytic functions which revealed the formation of the $F_2$ peak by the action of diffusion. Following this, Rishbeth and Barron [1960] in an important work, arrived at general relationships between the parameters, namely, the diffusion and recombination rates, which determine the position and magnitude of the $F_2$ peak for equilibrium conditions. They showed that above the peak electron density, i.e., $N_m F_2$, diffusive equilibrium gets established in a time of order $1/d(z)$,

$$d(z) = D(z)/H^2,$$

where $D(z)$ being the diffusion coefficient at the level $z$ and $H$ the scale height of the ionizable gas. At the peak, the time taken for equilibrium is slower, being of the order $1/d_m$ ($=1/\beta_m$).

Briggs and Rishbeth [1961] obtained an analogue solution to the continuity equation for $F$ region electron density by considering an equivalent electrical network with a series of condensers and resistors. The charge on a condenser represented the electron density at a certain height, and the value of a resistor which provided a path for the leakage of this charge, represented the loss and diffusion coefficients. The continuity equation was first transformed into a type similar to that for the voltage on each condenser. Operation of the electric circuit with the inclusion of a potentiometer representing the diurnally varying ionizing solar radiation, yielded useful outputs which were analogous to the actual ionospheric behaviour. The advantage of analogue method was that any desired height variation of temperature, loss coefficient, etc.,
could be incorporated with ease. It further demonstrated the validity of the concepts about the $F$ region which were originally developed for more restricted models. In spite of the drifts due to electromagnetic forces and the diurnal temperature variation of the atmosphere not being taken into account, this analogue method showed how the $F$ region would behave if controlled by the three basic processes of production, loss and diffusion [Rishbeth, 1963]. By developing a time-varying model, Rishbeth [1964] examined the processes governing the behaviour of the $F$ layer. However, because of the complexity of the problem, it had been difficult to develop a basic theory to account for the major features of the $F$ layer.

One of the intriguing features of the $F$ layer is the large variabilities it exhibits in its vertical motion. It was recognized by Martyn [1956] that the processes responsible for the vertical motion of the $F_2$ layer are the drifts imposed by electrodynamic forces and the winds associated with the ionospheric electric current systems which are manifested as the daily magnetic variations at the ground. The effects of atmospheric heating, and the temperature dependence of reaction rate and the diffusion coefficients, on the equilibrium height distribution of electron density were estimated by Garriott and Rishbeth [1963]. The interest in the wind systems set up by the diurnal heating and cooling of the thermosphere had begun when they were shown to have significant speeds of the order of 100 m/s to be effective at $F$ region heights [King and Kohl, 1965; Geisler, 1966]. These winds were invoked to explain the large vertical displacements the $F_2$ layer showed at midlatitudes, as they are capable of driving the plasma along the geomagnetic lines of force thereby altering the plasma density distribution. Rishbeth [1967] developed an approximate method to compute the theoretical diurnal variation of the peak electron density in the midlatitude ionosphere. Observing that external forces such as winds perturb the equilibrium distribution, the $F_2$ layer was envisaged as behaving like a servo mechanism. The effect of winds on both ‘day equilibrium layer’ and ‘night stationary layer’ was investigated by him. It
became clear from his studies that the day-to-night changes of the height of the peak electron density, \( h_m F_2 \), at midlatitudes, are caused largely by the action of winds on the \( F_2 \) layer.

The servo model of Rishbeth et al. [1978] provides a means of investigating the basic interactive nature of the thermosphere-ionosphere system. With reasonable assumptions, it offers possibilities of examining the behaviour of the \( F_2 \) peak, given the information on thermospheric parameters and the \( F_2 \) layer peak height. The limitations of the servo model as pointed out by Rishbeth et al. [1978], are its limited accuracy and the fact that it treats the \( F_2 \) layer as a unit, and therefore can give no information about height variations within the layer. In spite of this limitation, the servo model is being adopted by various workers to understand and determine the nature and magnitude of the driving forces on the midlatitude \( F \) region and the variabilities associated with them [Yagi and Dyson, 1985; Miller et al., 1986; Buonsanto et al., 1989; Forbes and Roble, 1990].

It is to be noted that the behaviour of the thermosphere-ionosphere system as a servo system at a particular location on the globe needs a large magnetic dip angle in order to aid the diffusion of ionization along the magnetic field lines in the vertical direction. In a region where the magnetic dip is \( I \), the vertical velocity is reduced (from a value for the case \( I = 90^\circ \)) by \( \sin^2 I \). It was the fact that the vertical diffusion gets inhibited over the magnetic equator that allowed earlier workers such as Martyn [1956] to confirm the importance of diffusion at midlatitudes. Martyn [1956] showed that the absence of vertical diffusion at the equator is responsible for the observed large variations in the \( F \) region height, and the same diffusion would prevent the \( F_2 \) region from being elevated above about 400 km in moderate to high latitudes and even this height should seldom be attained. With the absence of vertical diffusion at the magnetic equator, electrodynamical processes control the \( F \) region and its
variabilities.

At low latitudes, where the dip angle is non-zero, it is not known whether the $F$ layer behaves as expected by the servo model. Therefore it became necessary to investigate the basic processes of low latitude thermosphere-ionosphere system, which close the cycle of interactions illustrated in Chapter 1. The behaviour of the low latitude region is complicated by large scale processes such as equatorial ionization anomaly [Moffett, 1969], neutral density anomaly [Hedin and Mayr, 1973], equatorial temperature and wind anomaly [Raghavarao et al., 1991], equatorial spread $F$ [Fejer and Kelley, 1980] and midnight temperature maximum [Spencer et al., 1979], whose role in the energetics and dynamics of the upper atmosphere is largely unknown.

The present investigation was initiated in order to understand the basic interaction mechanisms which play a significant role in the wake of the presence of such large scale processes. In doing so, coordinated measurements of thermospheric parameters, namely, neutral temperature and meridional winds, and ionospheric parameters, namely, the $F$ layer peak height, deduced from the existing ground-based ionosonde, during nighttime, are made use of, along with the servo model concept proposed by Rishbeth as a tool. Rishbeth [1986] in his paper on the $F_2$ layer continuity equation has discussed the possible ways of altering the loss coefficient $\beta$ and also the contributions of various other parameters to the transport term. As suggested by him, it becomes easier and rewarding to interpret the $F_2$ layer processes by means of a term-by-term examination of the continuity equation. In the following section, the significance of the transport parameter in the overall behaviour of the $F_2$ layer is discussed by means of the continuity equation. This is followed by a brief description of the principles underlying the servo model leading to the discussion on 'night stationary layer'. The results providing the first experimental evidence for the validity of servo model at low latitudes is presented next. The effects of neutral temperatures on
the $F$ layer height are determined quantitatively. A new method is being adopted to estimate the $F$ layer peak height i.e., $h_m F_2$, with the available data on winds and temperatures. The estimated heights are compared with observed heights deduced from ground-based ionograms and the factors, namely, electric fields, which contribute to the deviations between the observed and the estimated heights are determined.

4.2 The $F_2$ layer continuity equation

The effects of transport processes on the electron density $N$ at any height become evident through the continuity equation for the $F_2$ layer which is given by

$$\frac{\partial N}{\partial t} = q - L(N) - \text{div}(N \nu)$$

(4.1)

where $q$ is the rate of production of plasma, $L$ the rate of loss which takes the linear form $\beta N$ in the $F_2$ layer and $\nu$ the drift velocity of the electrons whose divergence represents the transport of ionization.

The importance of each of the terms in (4.1) is well documented in the literature [Rishbeth and Garriott, 1969; Rishbeth, 1986]. Below the peak of electron density and during the day, photochemical equilibrium prevails, with $q \sim \beta N$. Above the peak, where the production of ionization becomes unimportant, the transport term dominates and governs the dynamics of the $F_2$ layer. During most of the day, the $F_2$ peak is in a state of quasi-equilibrium in which the production, loss and transport terms are comparable in magnitude and are much larger than $\partial N/\partial t$. This state is established within a time of the order of $1/\beta$ ($\sim 1.5$ h by day). During nighttime, when the average life time of the plasma becomes larger (thrice during solar maximum period) than that during daytime, the layer could be perturbed easily and therefore the term $\partial N/\partial t$ becomes significant. This typically happens during sunrise and sunset times and during when plasma irregularities are generated over short time
The important contributions to the transport term are as follows.

(i) The plasma diffusion velocity, in the absence of thermal diffusion, is given by

$$-v_D = D(h) \left[ \frac{1}{N} \frac{\partial N}{\partial h} + \frac{1}{T} \frac{\partial T}{\partial h} + \frac{\mu}{H} \right] \sin^2 I$$  \hspace{1cm} (4.2)

[Shimazaki, 1957; Rishbeth and Barron, 1960]

$D(h)$ denotes the ambipolar diffusion coefficient at a height $h$, $T$ the temperature, $H$ the scale height of the ionizable gas and $\mu$ the ratio of mean molecular weights of the plasma and the ionized gas which takes the value $1/2$, if the two are chemically the same.

The diffusion velocity can also be derived with a simple physical reasoning as was done by Martyn [1956]. If a particle of mass $m$, making an average of $\nu$ collisions per second with the surrounding gas, is influenced by a force $F$, it will drift through the gas with the velocity $v = F/m\nu$. The vertical gravitational force on an ion pair is $-mg$. In the presence of a pressure gradient, the vertical force per unit volume on the ionization is $-\partial(p_i + p_e)/\partial h$, where $p_i = p_e = NKT$, $K$ being the Boltzmann's constant. Thus this force is $-2KT\partial N/N\partial h$ per ion pair.

The transport velocity due to gravity and pressure gradient is therefore

$$v_D = \frac{m_i g_i}{m_i \nu_i} - \frac{2KT}{N m_i \nu_i} \frac{\partial N}{\partial h}$$

$$= -\frac{g}{\nu_i} \left[ 1 + \frac{2H}{N} \frac{\partial N}{\partial h} \right]$$

For ionization transport along the magnetic field lines with a dip angle $I$, this becomes

$$v_D = -\frac{g}{\nu_i} \left[ 1 + \frac{2H}{N} \frac{\partial N}{\partial h} \right] \sin^2 I$$ \hspace{1cm} (4.3)
(4.2) and (4.3) are equivalent if $D$ takes the form $2gH/\nu$, and the gradient of temperature with height is neglected.

At the peak, the diffusion velocity becomes

$$v_{Dm} = \frac{D_m}{2H} \sin^2 I$$  \hspace{1cm} (4.4)

(ii) A neutral wind $U$ is capable of moving the plasma along the magnetic field lines, at a speed equal to its component in that direction. The resulting drift velocity is given by

$$v_w = (U \cdot B) B/B^2 = U \sin I \cos I$$  \hspace{1cm} (4.5)

At latitudes away from the equator, an equatorward wind can push the plasma upward and a poleward wind can bring it down. By moving the layer vertically, the wind thus alters the balance between the production and loss, increasing $N_mF_2$ if it is equatorward and decreasing $N_mF_2$ if it is poleward.

(iii) The electromagnetic forces in the presence of an electric field $E$ and the magnetic field $B$ produce an $E \times B$ drift, given by the well known formula

$$v_E = \frac{E \times B}{B^2}$$  \hspace{1cm} (4.6)

This can be derived by considering the equation of motion of a charged particle under the influence of electric and magnetic fields [Chen, 1974]:

$$m \frac{dv}{dt} = q[E + v \times B]$$

$m \frac{dv}{dt}$ represents the circular motion of frequency $\omega_c = qB/m$. Omitting this term, the above equation becomes

$$E + v \times B = 0$$
Taking the cross product with $B$, 

$$
E \times B = B \times (v \times B) = vB^2 - B(v \cdot B)
$$

The transverse components (perpendicular to $B$) of this equation are $v_\perp = \frac{E \times B}{B^2}$. $v_\perp$ is the electromagnetic drift of the charged particle and is independent of its charge and mass. Thus ions and electrons in the $F$ region of the ionosphere drift together in the presence of electric and magnetic fields, producing no net current. The collisions of neutrals with ions, namely, the ion-drag, reduce the drift term by a small magnitude.

(iv) The effects of thermal expansion and contraction of the atmosphere on the electron density profile in the $F_2$ layer were first discussed by Garriott and Rishbeth [1963]. It was shown by them that, if the electron density profile is expressed in terms of reduced height $z$, rather than the real height $h$, the temperature dependence of the diffusion and the recombination coefficients can be accounted for. The reduced height $z$ then corresponds to a fixed pressure level. Changes in temperature lead to changes in the height of the pressure levels. The plasma takes part in the thermal expansion and contraction. The continuity equation can be solved in terms of fixed pressure levels thereby properly accounting for the temperature dependence of the coefficients $D$ and $\beta$ [Rishbeth, 1986].

Returning to the continuity equation, an expansion of the transport term leads to

$$
\frac{\partial N}{\partial t} = q - \beta N - N \text{ div } v - v \cdot \text{ grad } N
$$

(4.7)

In the $F$ region, the divergence of velocity is often small. The last term ($v \partial N/\partial h$) on the right hand side represents the effect of moving a density gradient across the point of observation. For upward drifts, this term leads to an increase
of $N$ on the topside ($\partial N/\partial h$ is negative) and a decrease on the bottomside ($\partial N/\partial h$ is positive) and vice versa. The result of the action of an imposed vertical drift is thus the motion of the whole $F$ layer with velocity $v_z$. Since $q$ and $\beta$ vary with height, the density distribution in the translated layer at and below the peak, then adjusts itself within a time of the order of $1/\beta$ to the altered values. Above the peak, the redistribution of ionization occurs at the rate of diffusion. For small displacements, the peak electron density (given by $q_m/\beta_m$) remains unaltered. To have a significant effect, a drift has to move the plasma through a vertical distance (say one scale height) within its lifetime, which in turn, requires the drift velocity $v_z \sim \beta H$.

Fig. 4.1 shows the equilibrium behaviour of the $F$ region following the ionospheric model for Arecibo ($I = 50^\circ$) developed by Walker and his colleagues [Walker, 1988]. When the $F$ layer is displaced upward by forcings such as winds and electric fields, the downward diffusion increases and opposes further upward motion of the layer. For downward drifts, increased recombination rate opposes further lowering of the layer-maximum. Under equilibrium conditions, the imposed vertical drift is balanced by diffusion if the layer is displaced upward and by recombination if the layer is displaced downward. This is illustrated by the top panel. The bottom panel shows how the equilibrium height of the $F_2$ peak responds to the imposed vertical drift.

In what follows, the servo equation for the behaviour of the $F_2$ peak in the absence of applied drifts, is derived from the first principles using the continuity equation.
Fig. 4.1. Response of the F region to changes in imposed vertical drift. The top panel illustrates the roles played by chemical recombination and plasma diffusion in altering the equilibrium height of the $F_2$ peak. The equilibrium height is depicted in the bottom panel. (after Walker, 1988)
4.3 The night stationary layer (Rishbeth's servo model)

The $F_2$ layer behaves like a servo system obeying the following laws [Rishbeth, 1967; Rishbeth et al, 1978]:

(a) In the absence of applied vertical drift, the $F_2$ peak lies at a balance height determined by diffusion and loss.

(b) Vertical drift due to changes in neutral temperature, meridional winds or electric fields, displaces the equilibrium position of the peak to a new level, which is time-varying if the drift is time-varying.

(c) At any instant, the actual height of the peak approaches its equilibrium value at a rate determined by diffusion and loss.

(d) The rate of change of peak electron density is determined by local values of the production rate and loss coefficient.

Expressing the electron density profile in terms of the reduced height $z$, the continuity equation (4.1) is rewritten as

$$\frac{\partial N}{\partial t} = q - \beta N - \frac{1}{H} \frac{\partial}{\partial z} (N v_z)$$

(4.8)

where $H$ is the scale height of the ionizable gas related to $z$ by

$$z = \int_{h_0}^{h} \frac{dh}{H(h)}$$

where $h_0$ is the balance height in the absence of applied drifts. The suffix 'm' is used to represent the quantities at the level of the peak electron density $N_m F_2$. $v_z$ in (4.8) represents the vertical plasma velocity. In the continuity equation, the contribution to the transport term is assumed to arise largely in the vertical direction.
Integrating (4.8) from $z = z_m$ to $z = \infty$,

$$\frac{\partial}{\partial t} \int_{z_m}^{\infty} N dz = H \int_{z_m}^{\infty} (q - \beta N) dz - \Phi_\infty + N v_z |_{z_m}$$

The relative vertical velocity of the plasma and the peak is $(v_{z_m} - H dz_m/dt)$. The above equation then becomes

$$\frac{\partial}{\partial t} \int_{z_m}^{\infty} N dz = H \int_{z_m}^{\infty} (q - \beta N) dz - \Phi_\infty + N_m \left( v_{z_m} - H \frac{dz_m}{dt} \right)$$  \hspace{1cm} (4.9)

$\Phi_\infty$ corresponds to the plasma flux flowing outward along the magnetic field lines at the top of the ionosphere. This outward flux is insignificant over low and equatorial latitudes. However, redistribution of $F$ region plasma due to processes like the equatorial ionization anomaly and transport due to transequatorial winds would contribute significantly to $\Phi_\infty$.

The following assumptions are made in order to arrive at an expression for the rate of change of layer height, $dz_m/dt$, i.e., the servo equation:

(i) The topside of the $F$ layer maintains a constant shape. If $a$ is the layer shape factor, then the integrated ion content is $a H N_m$. The equilibrium distribution of the $F_2$ region takes a Chapman form for which $a = 2.82$. Indeed it was shown by Duncan [1956] that a Chapman layer irrespective of its height, maintains a constant shape.

(ii) The $F_2$ peak is well above the peak of ion production so that $q \propto e^{-z}$.

(iii) The dominant ion is $O^+$ and decays by reacting with neutral $N_2$, for which $\beta \propto e^{-kz}$ where $k (=1.75)$ is the ratio of the scale heights of the molecular gas participating in the charge exchange reaction, i.e., $N_2$ and the ionizable gas, i.e., $O$.

The validity of these assumptions, when it comes to the expected behaviour of the $F$ layer in accordance with the 'servo' concept, is discussed later.
(4.9) then becomes
\[ aH \frac{dN_m}{dt} = q_m H - a' \beta_m N_m H - \Phi_\infty + N_m (v_{zm} - H \frac{dz_m}{dt}) \] (4.10)

For \( k = 1.75 \), the constant \( a' \) which comes from the height integral of \( \beta_m N \) can be approximated by \( 1/k = 0.57 \).

If \( W \) is the vertical drift applied to the layer by a wind or electric field, and \( v_{D_m} \) the drift due to the diffusion (expressions (4.3) and 4.4)), then the vertical plasma velocity is given by
\[ v_{zm} = W - \frac{g}{v_m} \sin^2 I = W - \frac{D_m}{2H} \sin^2 I \] (4.11)

Substituting in (4.10) and dividing by \( N_m H \),
\[ \frac{dz_m}{dt} = \frac{q_m - \Phi_\infty/H}{N_m} - \frac{a}{N_m} \frac{dN_m}{dt} - \frac{\beta_m}{k} - \frac{D_m \sin^2 I}{2H^2} + \frac{W}{H} \] (4.12)

Now the total derivative of \( N_m \) with time is
\[ \frac{dN_m}{dt} = \left( \frac{\partial N_m}{\partial t} + \frac{\partial N_m}{\partial z} \right) \bigg|_{zm} \]
\[ = q_m - \beta_m N_m - \frac{v_z}{H} \frac{\partial N_m}{\partial z} - \frac{N_m v_z}{H} \frac{\partial N_m}{\partial z} \] (4.13)

The term corresponding to \( \partial N_m/\partial z \) vanishes at the peak.

Including the flux \( \Phi_\infty \) uniformly distributed over the 'equivalent thickness' \( aH \), of the layer and combining the effects of diffusion and the transport processes at the peak by introducing a constant \( c \), (4.13) becomes
\[ \frac{dN_m}{dt} = q_m - c\beta_m N_m - \frac{\Phi_\infty}{aH} \] (4.14)

The constant \( c \) has been estimated to be 1.6 by Rishbeth [1967] from idealized solutions of the full diffusion equation. He has ignored the effect of vertical drifts on \( c \).
Combining this expression with (4.12),

\[
\frac{dz_m}{dt} = (1 - a) \frac{q_m}{N_m} + \frac{kac - 1}{k} \beta_m - \frac{D_m \sin^2 I}{2H^2} + \frac{W}{H} \tag{4.15}
\]

During nighttime, \( q_m = 0 \), and in the absence of the applied vertical drift \( W \), and for equilibrium conditions \( \frac{dz_m}{dt} = 0 \), (4.15) reduces to

\[
\beta_s = \frac{kD_s \sin^2 I}{2H^2 (kac - 1)} \tag{4.16}
\]

and if \( z_m \) is measured from this level, the servo equation is

\[
\frac{dz_m}{dt} = \frac{D_m \sin^2 I}{2H^2} \left[ e^{-kz_m} - e^{z_m} \right] + \frac{W}{H} \tag{4.17}
\]

wherein the exponential variation of \( \beta \) and \( D \) with height are made use of.

Further, the whole ionospheric layer, during nighttime, decays with an effective loss coefficient \( \beta_e \) at the \( F_2 \) peak given by

\[
N_e = N_{e_0} e^{-\beta_e t}
\]

With \( q_m = 0 \), it decays continually unless maintained by a downward flux of ionization. However, if the height of the \( F \) layer is altered due to external forces, it would have a significant influence on the rate of decay. Fig. 4.2a shows typical variations of peak electron density after sunset, in the pre-midnight hours on 23 and 24 October, 1986, at a low latitude station, Ahmedabad. Fig. 4.2b shows the plot of \( \log_e (N_{max}) \) with time for the two days. The slope of the curves yields \( \beta \), the recombination coefficient, which turns out to be \( \sim 2.0 \times 10^{-4} \) s\(^{-1} \) during the pre-midnight hours. On 23 October, the layer was pushed upward to higher heights after 2100 h (probably due to increase in neutral temperature as can be seen in Section 4.5) and the decay turned out to be very slow. On the next day, i.e., 24 October, the effect which caused the upward motion of the \( F \) layer occurred at a later time after 2230 h, after \( N_{max} \).
Figs. 4.2a,b. Temporal variation of the peak electron density, $N_{\text{max}}$, and $\log_e(N_{\text{max}})$ over Ahmedabad for the two nights of October 1986. The top panel depicts the decay of peak electron density with time. A measure of $\beta$ ($\sim 2 \times 10^{-4} \text{s}^{-1}$) is obtained from the slope of the best fit line shown in the bottom panel.
attained low values ($\sim 1.6 \times 10^5$ cm$^{-3}$). From these examples, it becomes clear that at a low latitude station, in the absence of any sources of ionization, i.e., during nighttime, the external forces can move the layer to very large heights thereby decreasing $\beta$ and help to sustain the layer without further decay. Indeed it was shown by Hanson and Patterson [1964] that if the $F_2$ peak height is raised by vertical drift, the net effect is to decrease the rate of decay of the layer. They suggested that this appeared to be an attractive alternative for the maintenance of the midlatitude $F$ region at night rather than the protonosphere providing a supply of ionization.

The $F_2$ peak would be formed at a level where equation (4.16) holds. Local changes in neutral temperature cause changes in the neutral composition, which in turn would alter the height where the peak ionization density of the $F_2$ layer occurs. The contribution from the neutral temperature in inducing changes in the height of the $F_2$ peak can be estimated by studying the response of the latter to the changes in the former. Since $\beta$ and $D$ vary with height, the expression (4.16) can be used for determining the layer height directly. The other method would be to use an iteration technique to find the height where the balance occurs. An initial height, say, 200 km is assumed to begin with, and the servo expression is worked out for this height to determine the deviation between the terms corresponding to $\beta$ and $D$. The height is incremented in steps of 1 km and this procedure is repeated till the deviation is minimized and the solution converges towards the height where the balance occurs. We have used both the methods to determine the balance height and examined the effects of changes in neutral temperature on the peak level. The following values are adopted to solve (4.16) for $h_s$, the ‘night stationary height’ of the $F_2$ peak.

\[
\beta = 10^{-18} [N_2] \quad (s^{-1})
\]

\[
[N_2] = 3.22 \times 10^{15} \exp\left[-\frac{k(h_s - 200)}{H}\right] \quad (m^{-3})
\]
[O] = 4.07 × 10^{15} \exp\left[-\frac{(h_s - 200)}{H}\right] \quad \text{(m}^{-3}\text{)}

D = \frac{2gH}{\nu} \quad \text{(m}^2\text{ s}^{-1}\text{)}

\nu = 7.3 \times \left(\frac{T}{1000}\right)^{1/2} \quad \text{(s}^{-1}\text{)}

[Rishbeth et al., 1978; Banks and Kockarts, 1000 K Thermopause model, 1973; Dalgarno, 1964].

A useful approximation for the scale height $H$ in $F$ region is $H_M \approx 0.93T/M$ [Rishbeth and Edwards, 1989], where $M$ is the mean molecular mass, and $H_M$ is expressed in kilometres.

Substituting these values in (4.16), and solving for $h_s$,

$$h_s = 200 \times 10^3 + 21.23 \; T_n \left[1.5 \ln T_n - \ln \sin^2 I - 4.85\right] \quad \text{(m)} \quad (4.18)$$

Fig. 4.3 shows the dependence of the $F$ layer displacement $\Delta h_s$ with dip angle when the exospheric temperature varies from 700 K to 800 K (for solar minimum conditions). From this figure, it is evident that at very low latitudes, the vertical displacements are expected to be significant for 100 K change in $T_n$. To examine the 'servo' nature of the thermosphere-ionosphere system at low and equatorial latitudes, a theoretical simulation was done and the results are presented below.

Figs. 4.4a to 4.4d show the effect of temperature on the equilibrium height of the $F$ layer at four different latitudes (dip angles of 68°, 33°, 11° and 5° respectively). Each set of curves depicts the balance of diffusion and recombination terms (equation 4.16) with temperature being varied from 600 K to 1400 K. These sets of curves are generated with the MSIS-86 model yielding densities of $N_2$, $O_2$ and $O$, which are then
Fig. 4.3. Response of the $F$ region to changes in thermospheric temperature at various dip angles. The $\sin^2 I$ dependence of the layer displacement, $\Delta h$, is brought out here.
Figs. 4.4a,b. Sets of diffusion and recombination curves for various thermospheric temperatures depicted for dip angles of 68° (top panel) and 33° (bottom panel). The balance height of the $F_2$ peak occurs at a level where plasma diffusion and chemical recombination are of equal importance. Each set of curves correspond to the balance terms of the servo expression (4.16).
Figs. 4.4c,d. Same as Figs. 4.4a,b but for dip angles, 11° (top panel) and 5° (bottom panel).
made use of in the computation of $\beta_m$ and $D_m$ as given below.

$$\beta_m = 10^{-17}O_2 + 4 \times 10^{-19}[N_2] \quad (s^{-1}) \quad (4.19)$$

$$D_m = \frac{R(T_i + T_e)}{16[O]K_1 + 28K_2[N_2]} \quad (m^2s^{-1}) \quad (4.20)$$

where $K_1 = 0.93 \left(T_n/1000\right)^{0.37} \times 10^{-16} \text{m}^3\text{s}^{-1}$ and $K_2 = 3.9 \times 10^{-16} \text{m}^3\text{s}^{-1}$ [Rishbeth and Edwards, 1989]. $R$ is the gas constant and $T_i$ and $T_e$ are the ion and electron temperatures, which are assumed to be equal to $T_n$ during nighttime. Each of the selected temperatures is fed as $T_\infty$, the exospheric temperature, into the MSIS-86 model. The latitudinal dependence of the neutral densities in the model is not considered in this exercise.

Figs. 4.4a to 4.4d show the decreasing importance of diffusion with decreasing magnetic dip angle. The diffusion curves expand out and the balance level occurs at higher and higher height as the magnetic equator is approached. The important point to be noted is that, at low latitudes, the displacement of the layer for a given change in neutral temperature, is inversely proportional to the dip angle, the magnitude being largest near the dip equator. The sharp rise in the curve of Fig. 4.3 at very low latitudes (the layer displacement for 100 K change in $T_n$ is $\sim 25$ km at a dip angle of 5°) is interpreted to be due to the decreasing influence of plasma diffusion as the geomagnetic field lines become more and more horizontal, which implies reduced opposition on the vertical motion of the layer effected by other applied forcings. This is expected since the $F$ layer response varies as $\sin^2 I$ with dip angle $I$. This raises a basic question on the validity of servo model at low and equatorial latitudes. In this regard, the assumptions made while deriving the ‘servo’ expression (4.16), need to be looked into and the validity checked.

In deriving the servo equation (4.17), the shape of the topside of the $F_2$ layer
is assumed to remain the same. Harper [1979] in his paper on the effect of semi-diurnal tides on the \( F \) layer over Arecibo, found significant changes in the topside semi-thickness. Such changes in the layer shape will affect plasma diffusion near the peak (through the term \( \partial^2 N / \partial h^2 \) in the diffusion equation) and this influences the height of the \( F_2 \) peak [Ganguly et al., 1980]. Large drifts at very low latitudes due to temperature effects seen in the form of layer movements in Fig. 4.3, could as well give rise to changes in layer shape and hence (4.16) might not represent the actual balance height. At very low latitudes, electrodynamic effects are rather important and the large excursion of \( F \) layer observed in the vertical direction is mainly due to the drift associated with electric fields in the equatorial region as was originally shown by Martyn [1956]. A detailed study is thus desirable to determine up to what extent the effects of neutral temperature compete with those associated with electrodynamics at and near the magnetic equator.

Another aspect which has not been discussed yet is the dependence of \( \Delta h_s \) on \( T_n \). Equation (4.18) was derived using the density values at a fixed lower boundary (200 km), from the 1000 K thermopause model of Banks and Kockarts [1973]. Though the model enabled us to express \( \Delta h_s \) in terms of \( T_n \), the effects of changes in composition associated with the solar activity level, diurnal variation of temperature, etc., are not explicit. Equation (4.18) shows a linear relationship between \( \Delta h_s \) and \( T_n \). However, the simulation study suggests that the recombination curves become narrower at higher temperatures and the displacements are smaller, for identical solar-geophysical conditions.

It follows from this simple theoretical simulation of the 'night stationary balance height' at different latitudes that, the region where the servo model is expected to be applicable may well be up to \( \sim 20^\circ \) dip angle (\( \sim 10^\circ \) dip latitude) below which the physical picture becomes complicated. The coordinated experiments, the results

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of which form a part of the present study, provide confirmation to the applicability of the servo principles to the latitudes of Mt. Abu (24.6°N, 72.7°E geographic; 20.3°N dip latitude) and Ahmedabad (23°N, 72.1°E geographic; 18.4°N dip latitude) and these would be discussed in later sections. As a backdrop to the present study, some of the relevant results from midlatitudes obtained by earlier workers are discussed below.

4.4 Results from midlatitudes

Yagi and Dyson [1985] examined the effects of temperature and meridional winds on the \( F_2 \) peak height at midlatitudes using the servo model. They have made use of coordinated measurements of temperatures and winds with a high resolution Fabry Perot spectrometer and the base height of the \( F \) layer, \( h'F \), from ionosondes located Canberra (35.4°S, 149.2°E, geographic) and Hobart (42.9°S, 147.2°E, geographic) in Australia. Data from 16 nights have been used to examine the behaviour of the \( F_2 \) layer in response to changes in neutral temperatures and winds. They found that the 'night stationary level' of the \( F_2 \) layer depends on temperature, with the height changing by \((13 \pm 6) \) km per 100 K and concluded that this agreed well with the prediction of the servo model. A brief description of their analysis is given below.

The expression (4.16) relating the plasma diffusion and chemical recombination coefficients has been solved to determine the relation between the \( F_2 \) peak height and the neutral temperature. Adopting the 1000 K thermopause model of Banks and Kockarts [1973], they solved equation (4.16) for a dip angle \( I = 68^\circ \) to obtain an expression for the peak height given by

\[
h_n = 5.3 \times 10^{-3} T_n (5.5 \ln T_n - 19) + 200 \quad \text{(km)} \number{4.21}
\]

The virtual heights \( h'F \) corresponding to times when the meridional wind was
close to zero were identified, and a plot of \( h'F \) and neutral temperatures \( (T_n) \) at these times showed good correlation between them. The 'night stationary level' in the absence of wind varied by 13 ± 6 km for every 100 K change in temperature, which is in accordance with that expected by the servo model.

It is to be noted in this context that there is a discrepancy in the formula relating \( \Delta h_s \) and \( T_n \), derived by Yagi and Dyson [1985]. According to equation (4.18), the 'night stationary level' at Beveridge (dip angle of 68°) varies by 15 km for every 100 K change in \( T_n \). While solving the expression (4.18) for this location, it has been found that the source of error in the formula used by Yagi and Dyson appears to lie in the value of \( g \) adopted by them for \( F \) layer heights.

Fig. 4.5 shows the result obtained by Yagi and Dyson for midlatitudes. The correlation coefficient was 0.76, indicating that almost 60 % of the variation in \( h'F \) can be accounted for by the variation in neutral temperature. The two important observations are (i) the scatter in the data points and (ii) the dc shift of ~ 45 km in the theoretical and experimental curves. According to Yagi and Dyson, the latter might be due to the fact that the theoretical curve represented the altitude of maximum electron density, while the experimental curve referred to the base of the \( F \) region. The scatter in the data was suggested to be due to the limitations in the model used and the drifts associated with the electric fields not being accounted for and/or due to variations in the parameters like layer shape, time constants of the ionosphere, etc.

A parameter whose effects are most ignored by the current working models on the neutral atmosphere is the turbopause height, the level above the mesopause, above which molecular diffusion is the dominant process, and hence diffusive equilibrium of different atmospheric constituents prevails. It has been shown by earlier workers that the turbopause level has large day-to-day variations [Pokhunkov et al., 1985; Danilov et al., 1979, 1980] and it has an independent control over neutral densities at \( F \) region.
Fig. 4.5. Plot of virtual height $h'F$ and spectroscopically measured temperature at times of zero meridional wind over the midlatitude station, Beveridge (68°S dip). The dashed line corresponds to equation (4.21) in the text. (after Yagi and Dyson, 1985)
heights [Sridharan and Raghavarao, 1984]. Since both $\beta_m$ and $D_m$ are strongly dependent on $T_n$, the neutral composition and the densities, any change in the height of the turbopause would have significant changes in both these parameters, eventually manifesting in the $F$ layer heights. This is an important aspect and might account for the observed scatter in the $h'F$ vs $T_n$ curve obtained by Yagi and Dyson.

4.5 Results from the coordinated measurements from low latitudes

In spite of its limitations and inherent assumptions, it has been demonstrated that the servo model can act as a tool in understanding the nature of the coupling of the thermosphere and the ionosphere [Ganguly et al., 1980; Yagi and Dyson, 1985]. The present study was initiated in order to understand this behaviour in low latitude regions.

Coordinated measurements of neutral temperature and meridional winds obtained from Mt. Abu (24.6°N, 72.7°E geographic; 20.3°N dip latitude) and $F$ region parameters such as layer height deduced from the existing ground-based ionosonde at Ahmedabad (23°N, 72.1°E geographic; 18.4°N dip latitude), are made use of, to provide experimental evidence for the applicability of the servo principles. Specific case studies pertaining to magnetically quiet times were made with the existing data base. The data encompass periods from minimum solar activity in the years 1986 and 1987 upto the present level of activity (1992). Since the stability of Fabry Perot etalon to the desired limit of being able to determine the line of sight winds was achieved only in the winter months of 1989, there exist only temperature measurements in the period 1986–1989. Notwithstanding this limitation, individual case studies utilizing the data for the period 1986–1988 provide credence to the concept that the thermosphere and the ionosphere behave like a fairly well coupled servo system at these
latitudes [Sridharan et al., 1991]. The results are presented in this section.

The ionograms obtained by the ionosonde operating from Ahmedabad are reduced to $N - h$ profiles by the standard Budden Matrix method. An electron density ($N_e$) of $1.2 \times 10^{-5} \text{ cm}^{-3}$ is taken as representative of the base of the $F$ region, whose variation ($h_{N_e}$) is obtained from the reduced $N - h$ profiles.

The two examples presented in Figs. 4.6a and 4.6b show the movement of the $F$ layer as a whole, when there was a simultaneous change in $T_n$, on the nights of 25 and 26, October 1986. Depiction of the variation of two $N_e$ values indicates that the $F_2$ layer retains its shape fairly well. The movement is a physical displacement of the layer and not an apparent displacement that would be seen in the event of the plasma getting neutralised at the base of the $F$ region as these measurements are well after sunset. In the examples presented herein, the whole of the $F$ layer is shown to move up and down with a corresponding change in neutral temperature.

These examples clearly show the strong influence of $T_n$ on the $F$ region height. Another effect of the increase in the neutral temperature would be to increase the vibrational temperature of $N_2$, the dominant neutral species. Due to this, the effective recombination rate of the $F$ region, through the charge exchange reaction of $O^+$ and $N_2$, would get enhanced significantly. For a neutral temperature change from 1000 K to 2000 K, the reaction rate of $N_2$ (vibrational) is known to increase by atleast a factor of 20 [Banks and Kockarts, 1973]. This is expected to have significant effect on the electron densities at any height. Though the decrease of $N_{\text{max}}$ as shown in Figs. 4.6a and 4.6b is expected on the basis of the 'night stationary decay' as discussed earlier, the role of such large changes in $T_n$ in altering $N_{\text{max}}$ densities cannot be ruled out.

The next five diagrams (Figs. 4.6c to 4.6g) depict the behaviour of the thermosphere - ionosphere system on nights of 23, 24 and 27, October 1986, 23 November
Fig. 4.6a. Spectroscopically measured neutral temperature from Mt. Abu and the corresponding movement of the F layer (representative densities of $1.2 \times 10^5 \text{cm}^{-3}$ and $3.6 \times 10^5 \text{cm}^{-3}$) obtained from the ionograms at Ahmedabad along with the peak electron density, $N_{\text{max}}$, with time for 25 October 1986.

Fig. 4.6b. Same as above but for 26 October 1986.
Fig. 4.6c. Neutral temperatures and the $F$ layer base height (corresponding to a density of $1.2 \times 10^4$ cm$^{-3}$) for the night of 23 October 1986. The MSIS-86 model temperature variation is also shown for comparison with the measurements.

Fig. 4.6d. Same as above but for 24 October 1986.
Fig. 4.6e. Same as Fig. 4.6c but for 27 October 1986.

Fig. 4.6f. Same as Fig. 4.6c but for 23 November 1986.
Fig. 4.6g. Same as Fig. 4.6c but for 13 February 1988.
1986 and 13 February 1988 when both thermospheric and ionospheric data are available. For these nights, MSIS-86 model was run to obtain the predicted temperatures for the times when direct measurements are available. The model values are also plotted in these figures. On all the nights in 1986, the $F$ layer showed large rise in its height associated with an increase in temperature but at different times. On 23 October, after a sharp rise at about 2100 h, the layer remained at about 300 km till 2200 h beyond which no temperature data were available. On 24 October, there was an initial rise of 50 km at 2100 h after which the layer started moving down. There was a subsequent increase in its height and the neutral temperature too showed corresponding variations. On both the nights, the airglow intensity was too low to allow any useful data beyond 2230 h.

The examples presented in Figs. 4.6e and 4.6f show contrasting features. The behaviour of the ionosphere on 27 October was similar to that on 23 October but the rise on 27 October was seen only after 2200 h before which the $F$ layer had remained steady. $T_n$ too had shown a nearly steady value except for a singularity at 2100 h. There are no temperature data during the period of steep rise in $h_N$. The $F$ layer on 23 November was located beyond 350 km at about 2100 h and it came down to ~ 270 km by 2145 h. The corresponding change in $T_n$ had been only 400 K. Subsequent variations in base height had corresponding variations in $T_n$. In Fig. 4.6g representing 13 February 1988, the temperature and the $F$ layer height show good correlation. The temperature exhibited a wavy feature which is reflected in the variation of $h_N$. On this night, though the $T_n$ shows a large rise of about 650 K between 2200 and 2300 h, the base height of the $F$ layer shows only a marginal increase.

The measurements of $T_n$ and the base height of the $F$ region for the nights of October and November, 1986, are plotted in Fig. 4.7. The line of best fit is also shown and it has a slope corresponding to $11 \pm 2$ km per 100 K at 95% confidence.
Fig. 4.7. Plot of measured temperatures and the base height of the $F$ layer for different times on the nights covered under study. The slope of the best fit line to the data points has a value of $11 \pm 2$ km per 100 K at 95% confidence limit. The dashed curve shows the result of theoretical calculation carried out using the servo expression (4.16).
level. Using the iteration technique discussed in section (4.3), the balance height for each of the measured temperatures is computed from equation (4.16) and this is also plotted in Fig. 4.7 along with the observations. Since the observed $h_{N_e}$ represents the base height of the $F_2$ region and not the height of the maximum electron density, the difference in the computed peak heights by ~ 65 km is understood. The line of best fit to the data has a correlation coefficient of 0.74, which implies 55% of the variation in $h_{N_e}$ can be accounted for by the variation in neutral temperature alone. The non-linearity in the response of the $F$ layer height at higher temperatures is clearly evident in the computed peak height.

- In spite of meridional winds and electric fields not being taken into account in determining the peak height of the $F$ layer, the agreement in the slope of the theoretical and experimental curves provides confirmation to the belief that the $F$ layer at low latitudes behaves like a servo system and that the 'night stationary level' of the $F_2$ peak depends on temperature in the manner predicted by the servo model.

Since we do not have neutral wind measurements for this period, it was not possible to eliminate the effects of winds in determining the balance height. However, this study indicated the need for examining the thermosphere and the ionosphere as a system, incorporating the effects of all known factors.

4.6 The thermosphere-ionosphere system

Having ascertained the role of neutral temperature in determining the height where the $F_2$ layer is formed, the next step would be to quantify the role played by winds and electric fields in perturbing this 'night stationary level' ($h_s$). Since the work of Rishbeth
and Barron [1960], there were several studies which attempted to deduce the effects induced by these forcings on the F region [Rishbeth, 1967; Rishbeth, 1972; Rishbeth et al., 1978; Chandler et al., 1983; Crary and Forbes, 1986; Forbes and Roble, 1990; Buonsanto, 1990]. Realising the closed cycle of interdependence of thermospheric and ionospheric parameters, various workers have succeeded in the inverse process of deriving meridional winds by making use of this relationship [Miller et al., 1986; Miller et al., 1987; Buonsanto et al., 1989; Krishnamurthy et al., 1990]. Though extremely useful in studying average, systematic, variations, there are certain limitations in the derivation of neutral atmospheric parameters like meridional winds purely based on ionospheric data and model atmospheric parameters. These are brought out in a later chapter on meridional wind and its variabilities.

The action of external forcings such as winds and electric fields on the F region was described in section (4.2) and depicted in Fig. 4.1. When the applied drifts are upward, increased downward diffusion opposes the upward motion of the plasma and when the drifts are downward, increased recombination, leading to the loss of ionization, opposes further lowering. At any instant, the actual height ($h_m$) of the $F_2$ peak approaches the equilibrium level ($h_b$). If the time required for diffusion at the peak is shorter than time scales over which the largest variations in drifts occur, it can be assumed then that the $F_2$ peak relaxes to its equilibrium height ($h_b$) before it is altered further [Forbes and Roble, 1990].

If electric fields are small and for small wind speeds, there exists a linear relationship between the wind speed ($U_p$) and the resulting change in the height of the layer peak [Rishbeth and Barron, 1960; Rishbeth, 1966; Buonsanto et al., 1989]. In this section, this relationship pertaining to our latitudes (dip angle of 33°) is examined. A new method has been evolved to estimate the height of the F layer peak, $h_m$, incorporating the effects of both neutral temperatures and meridional winds. This
balance height is then compared with independently measured peak height \( h_{\text{max}} \) deduced from ionograms. It is then shown that the comparison reveals fairly good agreement reproducing most of the observed features and thus providing experimental evidence for the close coupling of the thermosphere and the ionosphere.

Rewriting the servo equation (4.17) and replacing the reduced height \( z_m \) by the real height \( h_m \), we get

\[
\frac{dh_m}{dt} = \frac{D_m \sin^2 I}{2H} \left\{ \exp\left[-k(h_m - h_0)/H\right] - \exp\left[-(h_m - h_0)/H\right] \right\} + W
\]

Here \( W \) is the vertical drift due to winds and electric fields.

It was shown by Buonsanto et al. [1989] that for most conditions in the \( F \) region, the effects of both the time rate of change of the layer height and the non-linear term on the right hand side of the above equation are small. The above expression then becomes

\[
W = \frac{(k + 1) D_m \sin^2 I}{2H^2} (h_m - h_0)
\]  

Combining equations (4.5) and (4.6), the vertical drift of ionization, being the result of a combination of motion along the magnetic field lines due to a meridional wind \( U_p \) and an ion drift induced by the east-west electric field \( E_E \), is given by

\[
v_z = -U_p \sin I \cos I + \frac{E_E}{B} \cos I
\]  

Equating (4.22) and (4.23) and solving for the layer displacement \( (h_0 - h_m) \),

\[
(h_0 - h_m) = \alpha \left[ U_p - \frac{E_E}{B} \sin I \right]
\]  

where

\[
\alpha = \frac{2H^2 \cos I}{(k + 1) D_m \sin I}
\]
If the electric field is small

\[ h_m = h_0 - \alpha U_p \]  \hspace{1cm} (4.25)

This yields the new balance height of the \( F_2 \) peak in the presence of a meridional wind \( U_p \).

The extent of linearity that holds between the layer displacement (\( \Delta h_m \)) and \( U_p \) has been examined for the location (\( I = 33^\circ \)) under study and it is shown in Chapter 5 (section (5.5)) that the approximation is valid for equatorward wind speeds less than 200 m/s and poleward wind speeds less than 125 m/s. Since the magnitude of the measured meridional wind is less than 150 m/s most of the times, the linear approximation (4.25) to the servo equation is adopted [Gurubaran and Sridharan, 1993] and the effects of meridional winds at a low latitude station, Mt. Abu, are examined and discussed below.

Having seen the importance of neutral temperatures in determining the altitude of the \( F_2 \) layer peak, the measured temperature and its changes are incorporated in the present analysis. These temperatures obtained from the top of the thermosphere by line profile analysis of 6300 Å emissions, are close to the exospheric temperature (\( T_\infty \)) itself [Hays et al., 1970; Hernandez et al., 1975]. The minimum uncertainty in the measurements is estimated to be \( \sim \pm 50 \) K. Based on the simulation done by McCormac et al. [1987], and taking into account the uncertainties in the measurements, the spectroscopically determined \( T_n \) would at the most differ from the actual exospheric temperature (\( T_\infty \)) by 100 K, which would in turn alter the estimated layer height by \( \pm 10 \) km and this could be taken as a steady dc value for one night.

In the present exercise, the neutral atmospheric parameters are deduced from the MSIS-86 model by treating the measured temperature as \( T_\infty \). The same set of
expressions for $\beta$ and $D$ (4.19 and 4.20) is made use of in determining the balance height of the $F_2$ peak by iteration, where equation (4.16) holds. This would represent $h_0$ for this particular time. The meridional wind component along the geomagnetic field lines would alter $h_0$ to a new level $h_m$ satisfying equation (4.25). The $h_m$, i.e., the height of maximum density in the $F$ region, is thus estimated at different times when the $T_n$ and $U_p$ are available in the course of the observations. These estimates are compared with the independently obtained peak height ($h_{\text{max}}$) values from ground-based ionosondes and the results obtained for a few days, indicate fairly good to very good agreement. These are presented below.

The behaviour of the thermosphere-ionosphere system on seven magnetically quiet nights ($A_p < 20$) in the months of February and April, 1991, when we had the complete data on $T_n$, $U_p$ and $h_{\text{max}}$, is depicted in Figs. 4.8a to 4.8g. The top and middle panels show the variation of spectroscopically determined neutral temperature and meridional wind (poleward treated as positive). The dashed line in the top panel represents the $T_\infty$ estimated using the MSIS-86 model. The measurements correspond to emissions emanating from south ($20^\circ$ elevation) of the sky over Mt. Abu. The ionospheric $F_2$ peak height is independently determined from the true height reduction of ionograms obtained by the ionosonde at Ahmedabad (2° south of Mt. Abu) and its variation (stars) is depicted in the bottom panel. Also shown is the estimated height (circled crosses) of the $F_2$ peak. The statistical error of the uncertainty in the estimated height is calculated from (4.25) and is given by

$$\frac{\delta h_m}{h_0 - h_m} = \left[ \left( \frac{\delta U_p}{U_p} \right)^2 + \left( \frac{\delta h_0}{h_0 - h_m} \right)^2 + \left( \frac{\delta \alpha}{\alpha} \right)^2 \right]^{1/2}$$

[Miller et al., 1989]

The uncertainties in $h_0$ and $\alpha$ depend on $T_n$. $\delta U_p$ is the uncertainty in the measured $U_p$ and is determined by the spectrometer characteristics. While estimating the balance height $h_m$, the effect of electric fields is not taken into account. They are
Fig. 4.8a. Spectroscopically measured thermospheric temperatures ($T_a$) and MSIS-86 model predictions for 6 February 1991 depicted in the top panel. The middle panel depicts the variation of measured meridional wind ($U_p$) (positive poleward). The theoretical estimated $F$ layer peak height based on servo principles using $T_a$ and $U_p$ along with ionosonde measurements are depicted in the bottom panel.
Fig. 4.8b. Same as Fig. 4.8a but for 11 February 1991.

Fig. 4.8b. Same as Fig. 4.8a but for 11 February 1991.
Fig. 4.8c. Same as Fig. 4.8a but for 13 February 1991.
Fig. 4.8d. Same as Fig. 4.8a but for 17 February 1991.
Fig. 4.8e. Same as Fig. 4.8a but for 10 April 1991.
Fig. 4.8f. Same as Fig. 4.8a but for 11 April 1991.
Poleward wind (m/s) Temperature (K)

Apr. 14, 1991
Mt. Abu/Ahmedabad
Ap = 6

- - model
•••• Estimated

Observed

--- 1.1
--- 1.9
--- 0.9
--- 0.1

Fig. 4.8g. Same as Fig. 4.8a but for 14 April 1991.
treated as either to be constants or of less significance. The electric fields are estimated separately and the results presented in the next section. In this case study approach, the ionospheric and thermospheric conditions are assumed to be the same over Ahmedabad and the southern sky at Mt. Abu.

Fig. 4.8a shows the results for 6 February, 1991. The measurements are few in number on this night. The neutral temperatures follow closely the model predictions. The wind has remained equatorward all through the observing period. The measured and the estimated $F_2$ peak heights depicted in the bottom panel differ considerably for this night.

Fig. 4.8b shows the results for 11 February 1991. There is a temperature bulge as revealed by the measurements at about 0100 h. The poleward wind of 100 m/s around 2100 h changes its phase to equatorward around 2200 h reversing back to poleward at 0100 h. The layer reaches its minimum at about 2130 h after which it moves upward. The $F_2$ peak is at its highest level of about 370 km between 0000 and 0100 h. The vertical motion of the $F_2$ peak clearly follows the direction of meridional winds. The oscillatory pattern exhibited by the $h_{\max}$ is corroborated well by the meridional wind variation. The estimated and measured heights differ in the range of 30–50 km for this day.

Fig. 4.8c shows the results for 13 February 1991. The measured $T_n$ and the model differ considerably on this day too. The behaviour of the meridional wind has been quite different when compared to that of 11 February. The wind remains mostly poleward except at 2330 h when it either comes down in magnitude close to zero or just has a brief reversal to equatorward. The agreement between the measured and estimated $h_{\max}$ is fairly good. $h_{\max}$ reaches its minimum later at about 2230 h on this night and the poleward wind shows its maximum amplitude at about the same time. The large uncertainty in the estimated layer peak height at 2350 h is due to the large
measurement errors in the spectroscopically determined parameters.

Fig. 4.8d represents the outcome of a similar exercise for 17 February 1991. The neutral temperatures show considerable deviation from those expected by the model at ~ 2100 h and also during midnight. The meridional wind remains equatorward most of the time and the layer is at a higher height when compared to that on previous days. The F layer seems to behave differently between 0100 and 0200 h. Its peak reaches 400 km whereas the temperature deviated from the model only slightly (~ 150 K) and the equatorward wind speeds were of the order of 50 m/s. The agreement between the measured and estimated heights of the F2 peak is reasonably good on this day. The deviation in the expected and the measured heights could be due to the electric fields not being accounted for.

The results from a similar analysis for three nights of data belonging to the coordinated measurements for the month of April 1991, are depicted in the Figs. 4.8e, 4.8f and 4.8g. The measured temperatures on 10 April, agreed with the model. The equatorward wind shows large amplitude at about 2030 h and in the early morning hours. The meridional wind has small speed (~ 50 m/s) in the poleward direction which has resulted in the lowering of the peak height at and immediately after midnight. There is a reasonable agreement between the estimated and measured peak heights for this night.

Coming to the measurements on the night of 11 April, the measured temperatures shown in the top panel of Fig. 4.8f exhibit a peculiar oscillatory feature, fluctuating about the model values, not seen on any of the other nights. The wind has remained steady and equatorward and leads to high estimated F2 peak heights (between 375 and 425 km). The estimated and the measured $h_{max}$ differ by at least 30 km. Such deviations might result from the presence of strong electric fields which will be discussed in the next section.
The results on 14 April are depicted in Fig. 4.8g. The measured neutral temperature closely follows the model values. Because of the rapid intensity changes during the early part of the night, the uncertainties in temperature were very large leading to the rejection of such measurements. The meridional wind shows a tendency of reversing to poleward during the middle of the night, which is well corroborated by the lowering of the $F$ layer to about 300 km. After midnight, the measured height does not show the rapid increase as expected by the 'servo' action of thermosphere-ionosphere system due to the changing meridional wind.

- The case study pertaining to the application of servo model through the seven examples presented, clearly provides experimental evidence for the existence and also the extent of the close coupling that prevails in the low latitude thermosphere-ionosphere system.

4.7 Estimation of electric fields

As had been mentioned earlier, the role of electric fields is not considered in the case study approach presented in the last section, for want of electric field data. However, if the differences in the estimated and actually measured $h_{\text{max}}$ are only due to electric fields, using (4.24), the electric fields could be inferred for the days under discussion. From (4.24), the electric field (positive eastward) and its uncertainty are given by

$$E_E = \frac{B}{\sin I} \left[ U_p - \frac{h_0 - h_m}{\alpha} \right]$$

(4.27)

$$\delta E = \frac{B \sin I}{\alpha} \left[ \alpha^2 (\delta U)^2 + (\delta h_0)^2 + (\delta h_{\text{max}})^2 + \left( (h_0 - h_{\text{max}}) \delta \alpha / \alpha \right)^2 \right]^{1/2}$$

(4.28)

[Gurubaran and Sridharan, 1993]
Fig. 4.9a. Electric fields calculated from the differences between the estimated ($h_m$) and the measured ($h_{max}$) peak heights of the $F$ layer for 6 February 1991.
Figs. 4.9b,c,d. Same as Fig. 4.9a but for 11 (top), 13 (middle) and 17 (bottom), February 1991.
Figs. 4.9e,f,g. Same as Fig. 4.9a but for 10 (top), 11 (middle) and 14 (bottom), April 1991.
Thus evaluated electric fields for the nights belonging to February and April (1991) are depicted in Figs. 4.9a to 4.9g. It is seen in these figures that the electric fields in the month of February are eastward after sunset (at least on 13 and 17 February) and become westward at about 2100 h. They change their direction again near midnight and except on 6 February, continue to be eastward till the end of the observing period. This might represent the winter months. The results shown in Figs. 4.9e to 4.9g suggest that the electric fields in equinoctial months (April) however reveal a different picture altogether. They reach maximum westward amplitude at ~ 0300 h to subsequently become eastward just before sunrise. On 10 and 14 April, there appeared to be a transition from eastward to westward field at about 0100 h. A wavy pattern in the electric field variation is clearly seen on 11 and 13, February, and 10 and 14, April, with periodicities in the range 4 to 6 hours. Variations of such periods are also noticed in the measured temperatures (Chapter 3, section (3.5)) and meridional winds (Chapter 5, section (5.7)) from the same location. The assumptions/limitations involved in the estimation of electric fields are discussed below.

A first look at the electric fields calculated from the differences between the estimated and measured reveals that the values are large when compared to the value in the range of 0.5 to 1 mV/m reported for equatorial region [Woodman, 1970; Namboothiri et al., 1989]. We would rather expect that the electric field at the magnetic equator gets mapped along the field lines towards low latitudes. The fact that estimated electric fields are large, warrants close examination at the physical processes that occur in the low latitude $F$ region.

One of the factors that causes uncertainties in the estimates of electric fields is the explicit assumption of steady state in the servo model. At each instant of time, the $F$ layer has been assumed to be in chemical equilibrium, and the effect of meridional winds was then superposed to find the new balance height. As mentioned
earlier, the diffusion time at the $F_2$ peak height is assumed to be fast enough that the layer soon reaches a balance level before the drift due to a subsequent change in wind can be applied. The assumption of steady state may not be valid for large applied vertical drifts (say, more than 100 m/s), since the height of the ionosphere does not react immediately to wind changes as it has a finite time constant. Thus the electric fields are overestimated for drifts producing large changes in heights by the simplistic servo model approach adopted herein. It becomes necessary that the time delay in the response of the ionosphere needs to be taken into account in this regard.

The physical process which is of relevance to the uncertainties of the electric field estimates over low latitudes, is the equatorial ionization anomaly. The renewal of equatorial fountain resulting from the evening pre-reversal enhancement of upward plasma drifts [Rishbeth, 1971b; Heelis et al., 1974], is known to provide an additional supply of ionization to the nighttime low latitude $F$ region [Sastri, 1982]. Buonsanto [1987, 1988] investigated the behaviour of the $F$ layer at the crest of the equatorial ionization anomaly (Tahiti (17.7°S geographic; 16.6°S dip latitude) in South Pacific Ocean) in the evening and pre-midnight hours. The place of our observations is located under the crest of the equatorial ionization anomaly. The relevance of the fountain effect to the low latitude $F$ region is discussed elaborately in Chapter 6 (section (6.2)). It is suffice to note here that the movement of the crests of the anomaly across the low latitude observing stations, Mt. Abu/Ahmedabad, and the consequent ionization density variation, might have a partial role in inducing vertical motions of the ionization layer and it is possible that the electric fields are slightly overestimated. These are some of the aspects that have not been accounted for in the present study.

- In spite of the coordinated measurements being limited, the case study based on individual nights of observations suggests that there seems to be a distinct phase
difference in the variation of electric field from winter to equinoctial months. The geophysical processes like EIA associated with the electrodynamic properties of the low latitude and equatorial thermosphere-ionosphere system could possibly be the cause for the variabilities exhibited by the electric field.

These aspects need further investigation.