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34100 TRIESTE (ITALY) - P.O.B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONES: 224281/2/3/4/5/6
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AUTUMN COURSE ON GEOMAGNETISM, THE IONOSPHERE
AND MAGNETOSPHERE

(21 September - 12 November 1982)

MIDLATITUDE QUIET IONOSPHERE
(Lectures 5-6)

H. Rishbeth

Rutherford Appleton Laboratory
Chilton
Didcot OX11 OQX
U.K.

LECTURES 5 & 6

H RISHBETH
OCT 1982

§17 Midlatitude Quiet Ionosphere

Fig. 21 shows E, F1, F2 median critical frequency for 50 years at Slough. The E and F1 layers (when visible) show normal solar-controlled variation. This is well understood though numerical computations of solar flux, ionization and loss rates, and chemical reaction rates are not yet highly precise. The E layer has some tidal perturbations which can be understood in terms of dynamo theory.

§18. Some Ionospheric Phenomena

D layer. (Not shown in figure). Basic solar control is shown by absorption and radio propagation (LF, VLF) experiments under quiet conditions, with day/night variations largely due to negative ion formation/destruction.

Winter anomaly in D layer ionization (§3)

- High radio-wave absorption occurs on some days in winter
- Seen at midlatitudes, N & S Hemisph.
- Occurs in patches, few hundred km in extent
- On anomaly days, N_e at 70–80 km increased up to 10 times
- Attributed to chemical changes:
  - ? increased NO, thus increased production by Ly α ?
  - ? decreased hydration, thus smaller effective recombination?
  - ? temperature changes affecting chemical rates?
- Associated with stratospheric warmings — major changes in wave structure and circulation at about 30–50 km.

Sporadic E (Es)

- Thin dense layers, 1 — 3 km thick.
- Midlatitude type commonest in summer
- Attributed to wind shears (vertical variations in wind) acting in conjunction with magnetic field.
- Sometimes develops out of intermediate (E – F) layers stratifications that are dragged down from the lower F layer by tidal winds with downward phase propagation.
- Contain proportion of metallic ions which have long lifetime (recombination is 'radiative' and slow). Ordinary NO^+, O_2^+ ions recombine too fast to be the major ions in a dense Es layer.

Small-scale irregularities Found everywhere in ionosphere. Formation mechanisms not well known in general; (turbulence (only below 100 km), plasma instabilities (spread F; also in electrojets). Much information on size and motion from radio techniques. Elongated along magnetic field in F region.

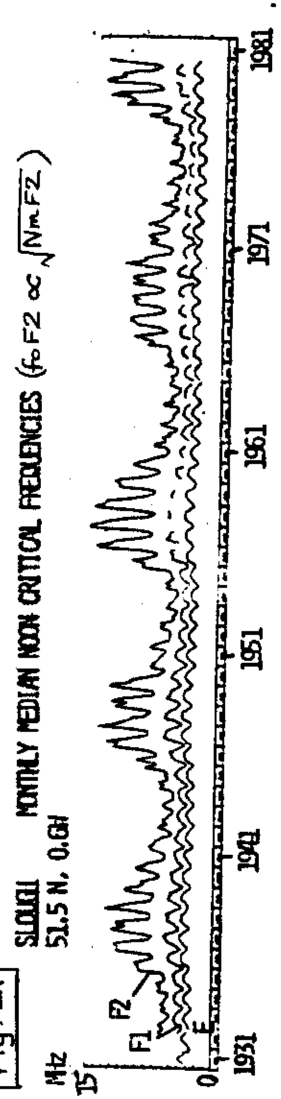


Fig. 21

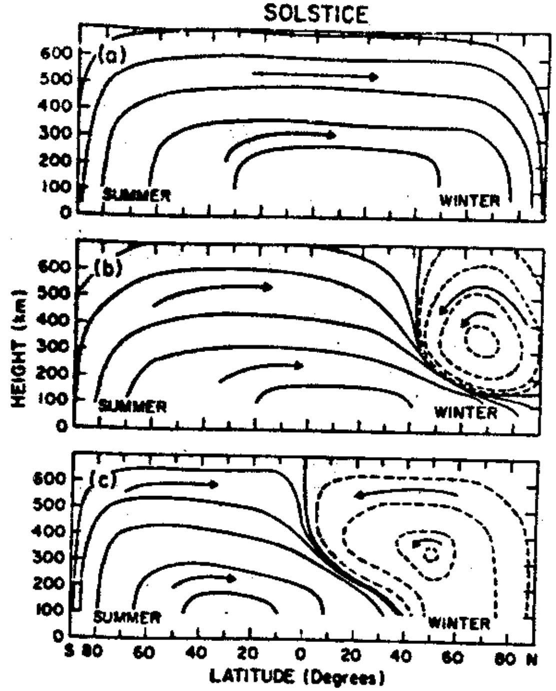
§19. F2 Layer Phenomena and Possible Explanations

- Day/night variations of height : winds towards/away from equator [Fig.17]
- Maintenance at night : winds help by raising F2 layer, but need source : flow from protonosphere? (particles, X-, UV radiation?)
- Seasonal anomaly, with high electron density by day in winter, especially at sunspot maximum ; composition changes, specifically of the O/N_2 ratio, change q/β (because $q \propto [O]$, $\beta \propto [N_2]$) and are caused by a general circulation (§4). [Fig.22]
- 'Noon biteout' of NmF2, espec. in summer : daytime winds blowing towards pole.
- Sunset enhancement of NmF2 : wind turns around [Fig.16] and has a poleward component before sunset in summer.
- Equatorial trough : electric fountain, see §21.
- Semiannual variation : max of neutral and ion density in Apr/Oct.
- Magnetic storm effects : increases/decreases, see §27.
- Eclipse effects : difficult to interpret.
- Solar flare effects : some enhancements have been observed.

Note that the wind direction rotates with LT [Fig.15] ; the F2 layer effect depends on the component of $\underset{\sim}{U} \parallel \underset{\sim}{B}$, and so its phase depends on magnetic declination. This can explain (by considering the detailed magnetic field geometry) some declination effects and UT effects.

§20. Equatorial electrojet

The equatorial electrojet is an intense belt of current driven by a strong polarization field [Fig.12] arising from the equatorial geometry. The polarization field raises the east-west conductivity in the dynamo layer to the 'Cowling' value $\sigma_3 = (\sigma_1^2 + \sigma_2^2)/\sigma_1 \simeq \frac{1}{2}\sigma_0$.
On occasion the electrojet is anomalous, and may even reverse (counter-electrojet) : this has been attributed to changes of wind-shear (due to gravity waves?) and to electric fields transmitted from auroral zones.
The electrojet contains 2 types of small-scale irregularities (two-stream instability mechanism is involved) and these are related to equatorial sporadic E.
['Drift measurements near the electrojet must be treated with caution].



[Fig.22] (Dickinson & Roble) Meridional Circulation in thermosphere, for (a) quiet, (b) slightly disturbed (c) severely disturbed conditions. Upward (downward) motion gives increased (decreased) N_2/O ratio in F2 layer.

§21. Equatorial F2 layer

The equatorial F2 layer trough is a daytime and evening phenomenon [Fig. 23]. It is caused by an 'electrically-driven fountain' [Fig. 24] which raises plasma at the equator by the daytime eastward electric field; the plasma then diffuses down field lines to subtropical latitudes. Ion drag does not cancel out vertical drift at the equator (as it tends to do at midlatitudes, see [Fig. 18] sketch (b)); its effect is to drag neutral air outwards from the dip equator, causing a slight depletion in air density [Fig. 25]. Another effect of the 'equatorial fountain' is the increase in red airglow emission at subtropical latitudes, correlated with F2 layer parameters, attributed to the enhanced plasma recombination arising from the fountain effect which dumps plasma there.

There are often strong vertical motions near sunset; hmF2 becoming very large with spread F developing. Complex sunset effects may be seen over a wide latitude range. ('midnight collapse' and subsequent 'recovery', and complex patterns of wind and pressure have been deduced at night in equatorial and sub-equatorial regions. The airglow phenomena seen at Arecibo are interesting, with complicated structures with strong meridional gradients, attributed to the interaction between 'equatorial' and 'midlatitude' circulation systems in the thermosphere. Another phenomenon sometimes seen at Arecibo are fairly sharply-bounded 'slabs' of plasma, aligned north-south and containing enhanced electric fields.

The spread F and 'radar plumes', seen around and after sunset near the dip equator, are connected with 'plasma bubbles' that arise through an instability in the sunset F2 layer, and sometimes rise to great heights (> 1000 km). The 'bubbles' are depletions of plasma, and have been found to contain heavy ions (molecular and metallic) that differs from the normal F2 layer composition of mainly O^+. They also give rise to intense scintillations of radiowaves (VHF, UHF).

Meridional horizontal winds can affect the F2 layer trough, e.g., a 'converging' wind compresses it [Fig. 26]. 'Transequatorial' wind produces asymmetry (reduced plasma density, especially on 'upwind' side). The wind-driven plasma naturally has to follow a field line; and gets cooled as it is driven upwards and then heated as it descends, producing 'ion temperature troughs'.

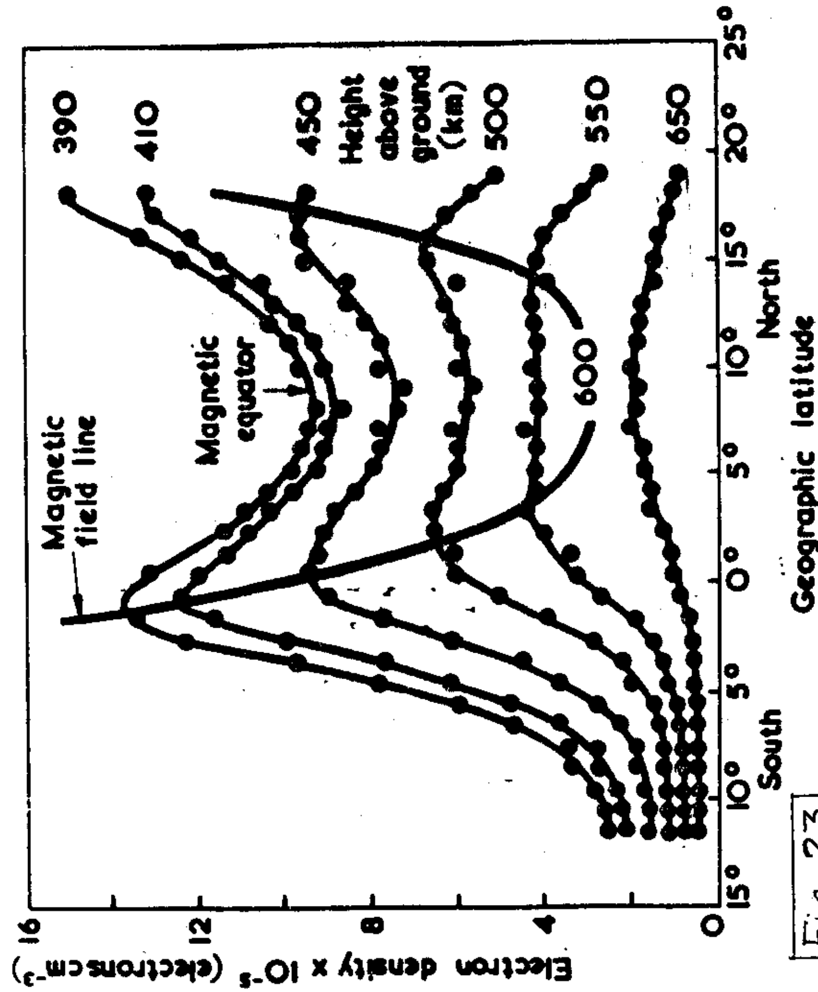


Fig. 23

CURVES OF ELECTRON DENSITY AT FIXED HEIGHTS ABOVE GROUND. 15 SEP. 1963, 1234 L.M.T.

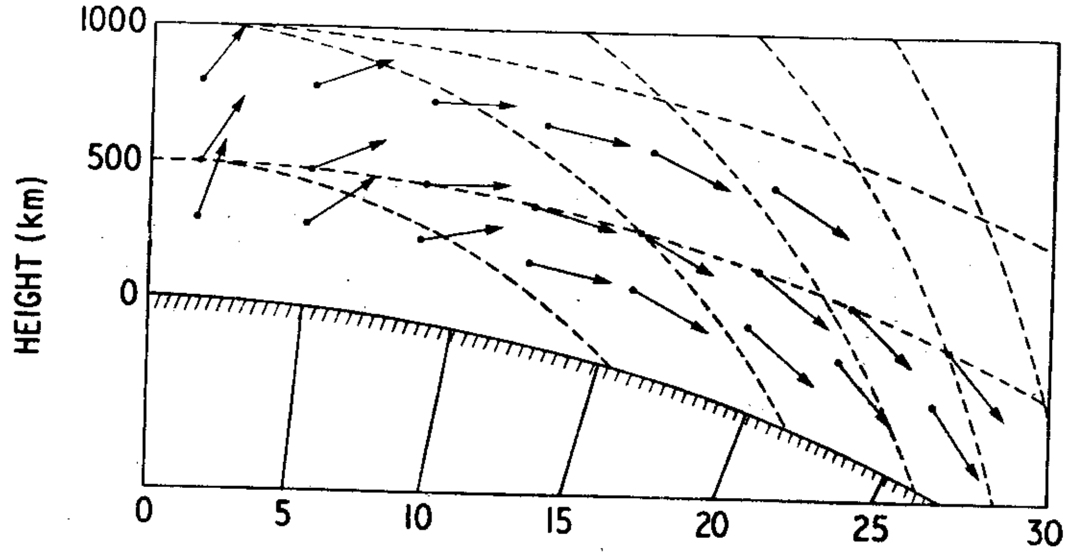
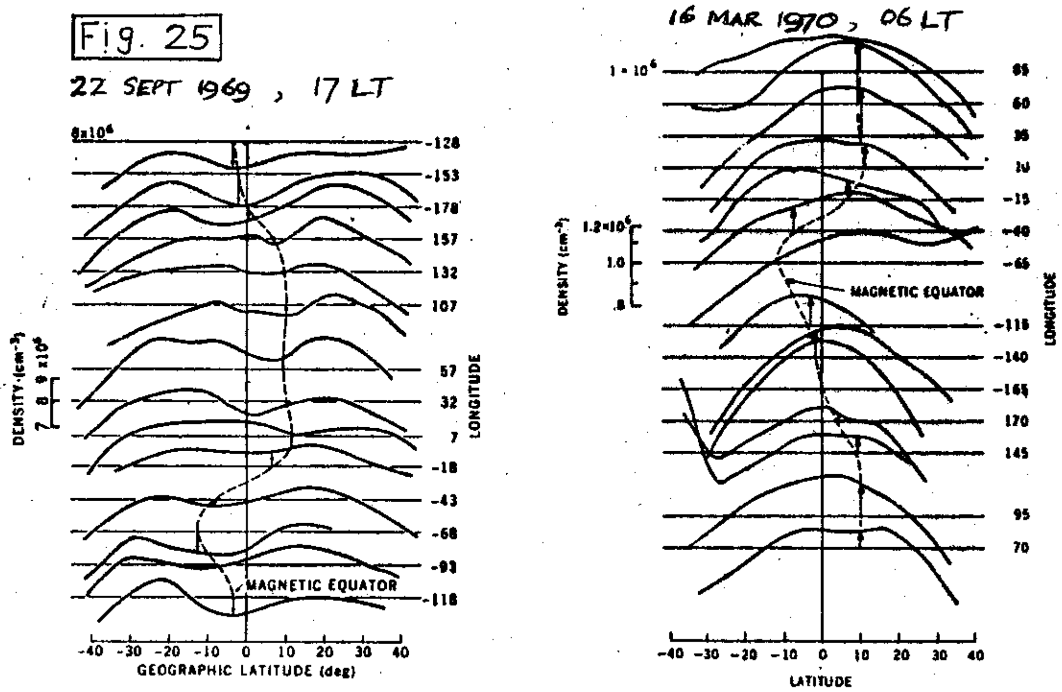


Fig. 24

PLOT SHOWING THE DIRECTION OF MOTION OF ELECTRONS MOVING UNDER THE INFLUENCE OF THE ELECTRIC FIELD (AFTER HANSON AND MOFFETT, 1966)

(7)

Fig. 25



$[N_2]$ concentration measurements, 450 km, OGO-6 (Hedin & Mayr)

(8)

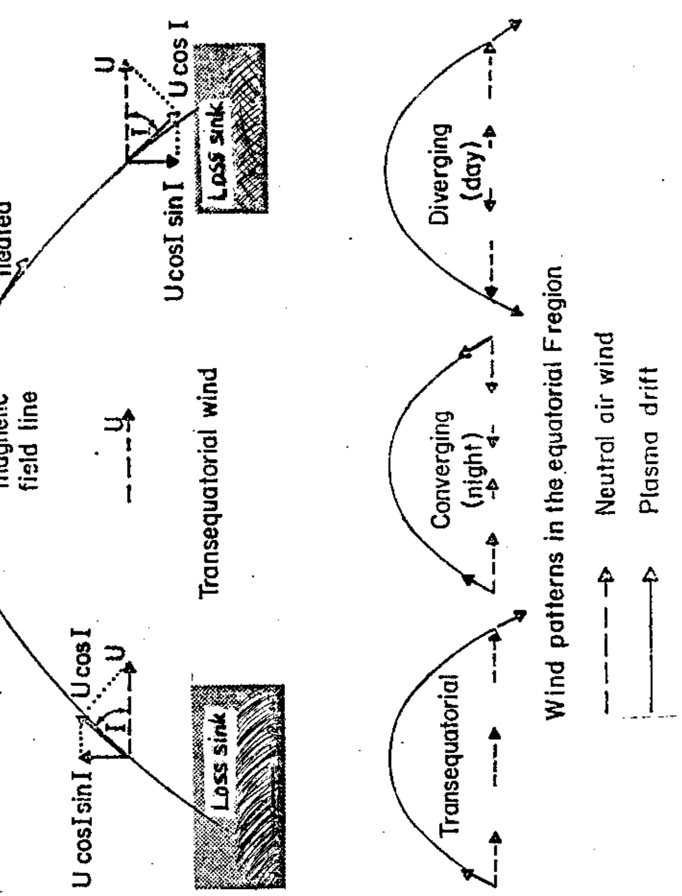


Fig. 26

These effects vary with season – the transequatorial winds blows from summer to winter hemisphere – and with longitude because of the magnetic field (component in magnetic meridian is important). Also varying with longitude are the red airglow enhancements, caused by recombination of plasma driven into the downwind side of the equator. Fig. 27

Other points about equatorial F layer (or E layer)

Differences between Sectors – African, Asian, American. Are they just due to the geomagnetic field geometry? Or are there other reasons?

Topographic effects? Differences between E layer drifts measured at Jicamarca, looking eastward (over Andes) and westward (over Pacific) Fig. 28

Total EW field integral around earth should vanish. But 24-hour integral $\int E_{EW}\, dt$ at one place (Jicamarca) does not. Longitude effect?

Eclipses. Produce good effects in equatorial F layer. Absence of vertical diffusion gives some prospect of analysing $\partial N/\partial t = q - \beta N - \frac{d}{dh}(NW)$ (W is electric field drift). Diffusion makes this unsatisfactory at midlatitudes. Photochemical effect (reduction of q) can give 'eclipse $F1\frac{1}{2}$ layer'.

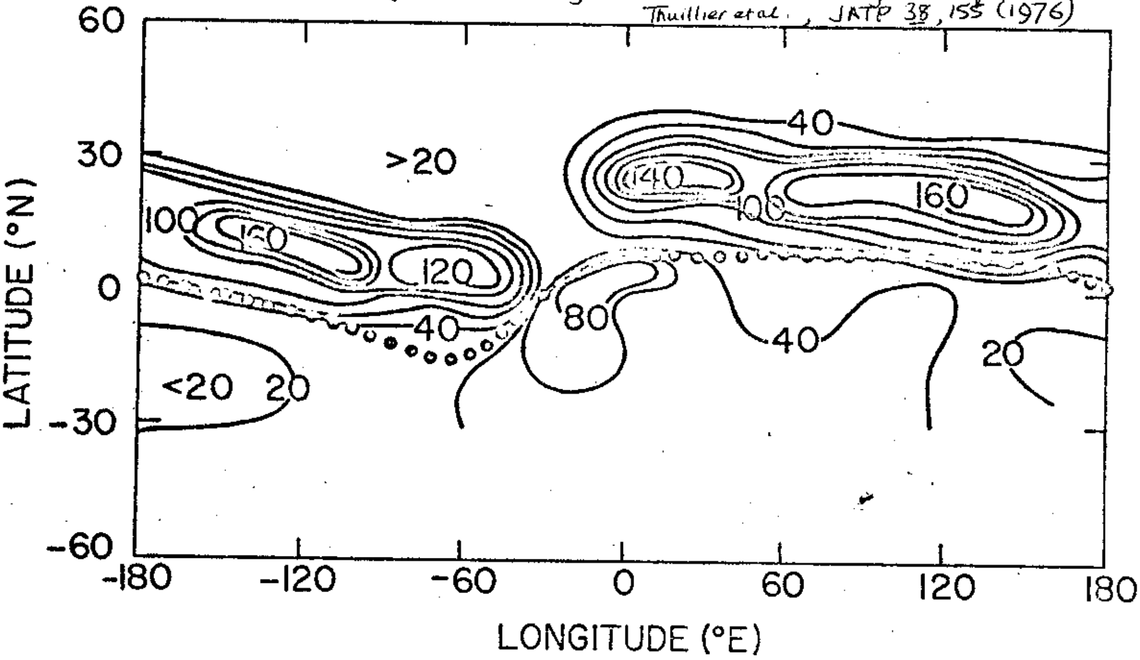
§22. Rotation of the Thermosphere, or Prevailing Zonal Wind

Satellite drag observations have been interpreted as indicating that the earth's thermosphere rotates Λ times as fast as the earth, with $\Lambda \simeq 1.3$ typically. Although some of the data may be explainable in other ways (such as by meridional winds) there seems little doubt that a prevailing eastward (west-to-east) wind does exist in the low latitude thermosphere, mainly at night.

Thermal mechanisms that seem to account for $\Lambda = 60$ in the Venus atmosphere do not work in the earth's thermosphere, because of ion-drag imposed by the geomagnetic field constraint on the ions. Ion-drag so controls the winds (§13) that it damps out most other mechanisms. Fig 29 Only mechanisms that depend on ion-drag for their operation seem likely to succeed. A correlation between the 24-hour components of wind and ion-drag is needed to achieve this.

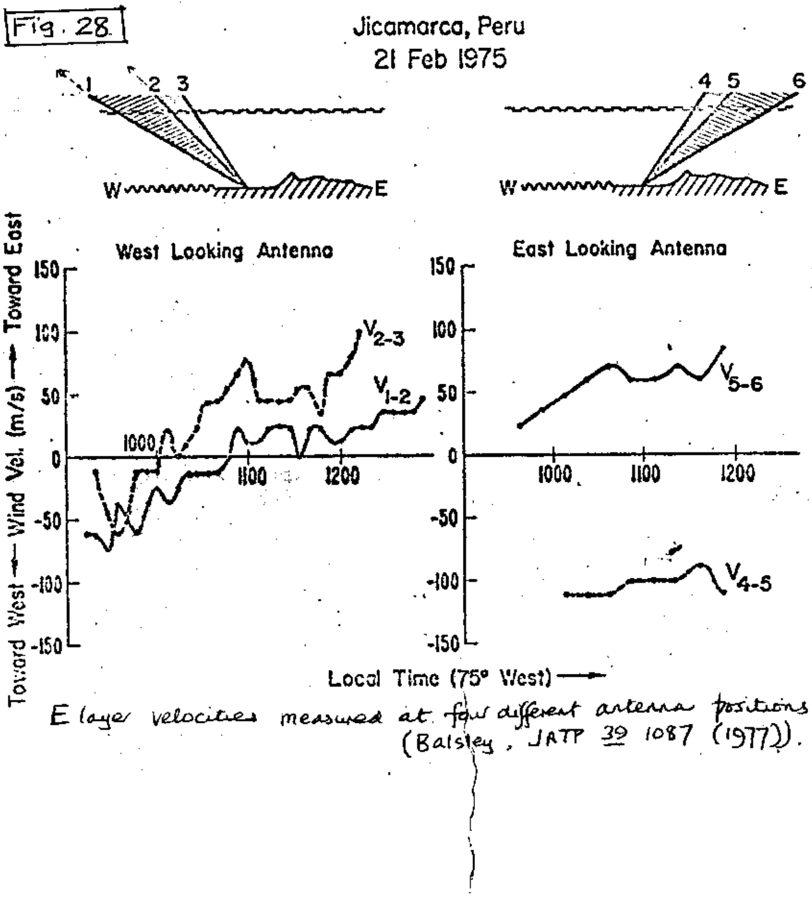
(Some suggestion in literature that this is not necessary: strong polarization field at sunset anyway).

Fig. 27 Alignment of 630 nm Airglow emission with magnetic equator, Thuillier et al., JATP 38, 155 (1976)



(11)

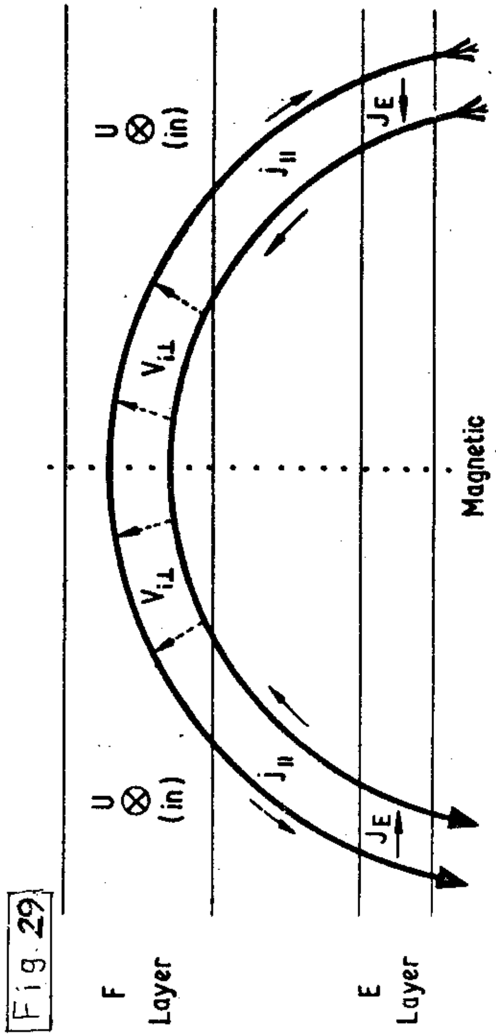
Fig. 28



E layer velocities measured at four different antenna positions (Balsley, JATP 39 1087 (1977)).

(12)

Fig. 29



Looking eastward at magnetic equator. Eastward wind U produces a small ion drift $V_{i\perp} = k_{2i} \cdot m_i \nu_i U$ normal to $\underset{\sim}{B}$. (§8). The circuit is completed by currents $j_\parallel$ and E-layer current J_E. By night a strong polarization $E_\perp$ builds up to drive J_E through the poorly-conducting E layer; it causes ions to drift eastward ($E_\perp \times B$), thus strengthening the eastward wind by ion-drag. No effect by day because $E_\perp$ is short-circuited by highly conducting E layer. Net wind is eastward because U is {eastward by night / westward by day}.

W→E Wind ———— U
W→E Ion Drift ———— V
S→N Wind ———— U'
Ion Drag Parameter ———— $\mathcal{D}$
Driving force/unit mass — $\mathcal{F}$
Vertical/Horiz. eddy velocity ... U^*, W^*

ASSUME

$$U = U_0 + U_1 \cos(\Omega t + \varepsilon)$$
$$\mathcal{D} = \mathcal{D}_0 + \mathcal{D}_1 \cos \Omega t$$

MEAN; 24 hr COMPONENT; PHASE ANGLE

$$\frac{dU}{dt} = \mathcal{F} - \mathcal{D} U \qquad \mathcal{D} = \nu_{ni}(1 - V/U)$$

§ neutral-ion collision frequency ($\propto N$)

Take average over 24 hours; rearrange:

$$U_0 = \frac{\mathcal{F}_0 - \frac{1}{2}\mathcal{D}_1 U_1 \cos \varepsilon}{\mathcal{D}_0}$$

$$\mathcal{F} = \frac{\mu}{\rho}\nabla^2 U - \frac{1}{\rho}\frac{\partial p}{\partial x} + fU' + \frac{\langle U^* W^* \rangle}{H}$$

DRIVING FORCE — VISCOSITY — WEST-EAST PRESSURE GRADIENT — CORIOLIS FORCE — RECTIFIED EDDY MOTION

(Notation as § , with $f = 2\Omega \sin(\text{latitude})$ – Coriolis parameter, U^*, W^* – Horiz/Vert. eddy velocity of air.

Resulting Net W→E Wind Velocity, U_0

CONTRIBUTIONS TO $\mathcal{F}$		$m\,s^{-1}$
Mean pressure-gradient force		+7
Coriolis force due to $U_0 = 40\,m\,s^{-1}$	midlat	+10
	equator	0 (no coriolis force)
Rectification of eddy motion		±10
Zonal wind at base of thermosph...		±10
NON-LINEAR TERM IN dU/dt		±3 ?
EFFECTS ASSOCIATED WITH ION-DRAG		
Diurnal variation of N		+5
Electromagnetic drift V_0	auroral zone ...	+100 ?
	mid- & low latitudes)	±20 ?
Modulation by polarization field ($\mathcal{D}_1/\mathcal{D}_0 \simeq 0.8$ at low latitudes) ...		+30 ← Seems best theory.

§23. High Latitude Ionosphere

The latitudinal structure of the ionosphere is closely linked to the Earth's magnetic field. The polar cap, auroral oval, trough & plasmapause all produce their 'signatures' in the ionosphere. The auroral oval contains persistent luminosity due to particle precipitation, superimposed on which are the discrete auroral substorms that occur every few hours with the release of magnetic energy from the geomagnetic tail — rapidly varying 'splash' events produced by kilovolt particles. The more steady 'drizzle' of harder particles produces diffuse auroral phenomena at somewhat lower latitudes [Fig. 30].

Field-aligned flow

At high latitudes, plasma can escape from the ionosphere along open field lines — the so-called "polar wind". In auroral latitudes, O^+ ions are accelerated by certain waves and escape into the magnetosphere. At lower latitudes, the plasmasphere exchanges plasma with the ionosphere, but is depleted during magnetic storms when the plasmasp shrinks and then recovers [Fig. 31]

Variability

The detailed structure makes the high latitude ionosphere very variable, according to the particular region being measured, as shown by Chatanika data [Fig. 32]. The expansion away from the pole of all the features can lead to high latitude phenomena appearing occasionally at lower latitudes. In particular, the plasmasphere shrinks during storms, then refills slowly.

Auroral arcs have very fine structures (< 1 km) but they are embedded in a much broader region of ionization. Various plasma and wave-particle interactions are involved in auroral phenomena. For example, enhanced electron and ion temperatures observed at Chatanika give evidence of plasma wave generation in an auroral disturbance. Whether auroral particles are accelerated by parallel electric fields or some kind of wave-particle interaction is still controversial. The auroral ionosphere is a superb plasma physics laboratory!

§24. Polar cap drifts and magnetospheric convection

Polar cap field lines become linked to the interplanetary field (reconnection) and are swept from the dayside to the nightside as the solar wind sweeps the interplanetary field past the earth. On the nightside, at some distance down in the tail, the linkage breaks and the magnetic field lines return to the dayside.

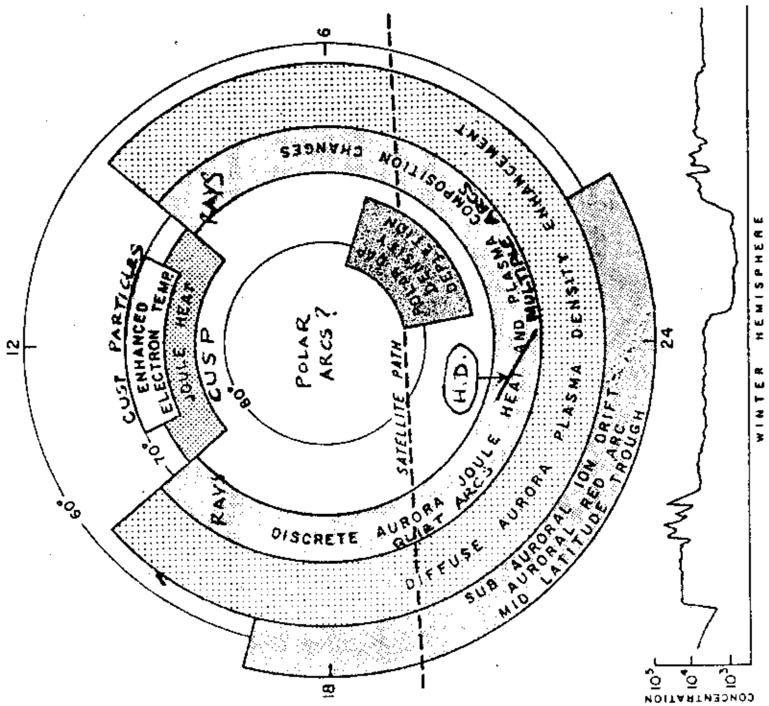


Fig. 30 Schematic illustration of the main features of the plasma and thermal properties of the ionosphere. The diagram does not indicate small- or large-scale ion composition changes, but a typical profile of total ion concentration along a satellite path is shown. (H.D. = Harang discontinuity) (HEELIS, RGSP, 20, 1982)

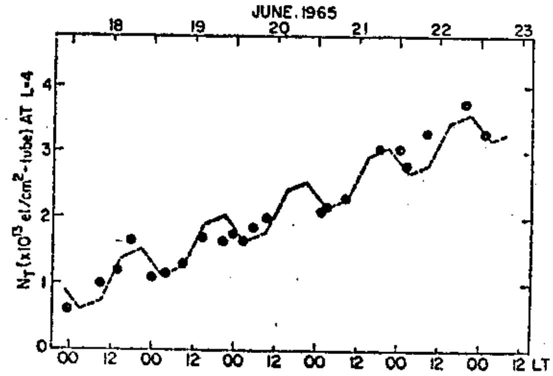
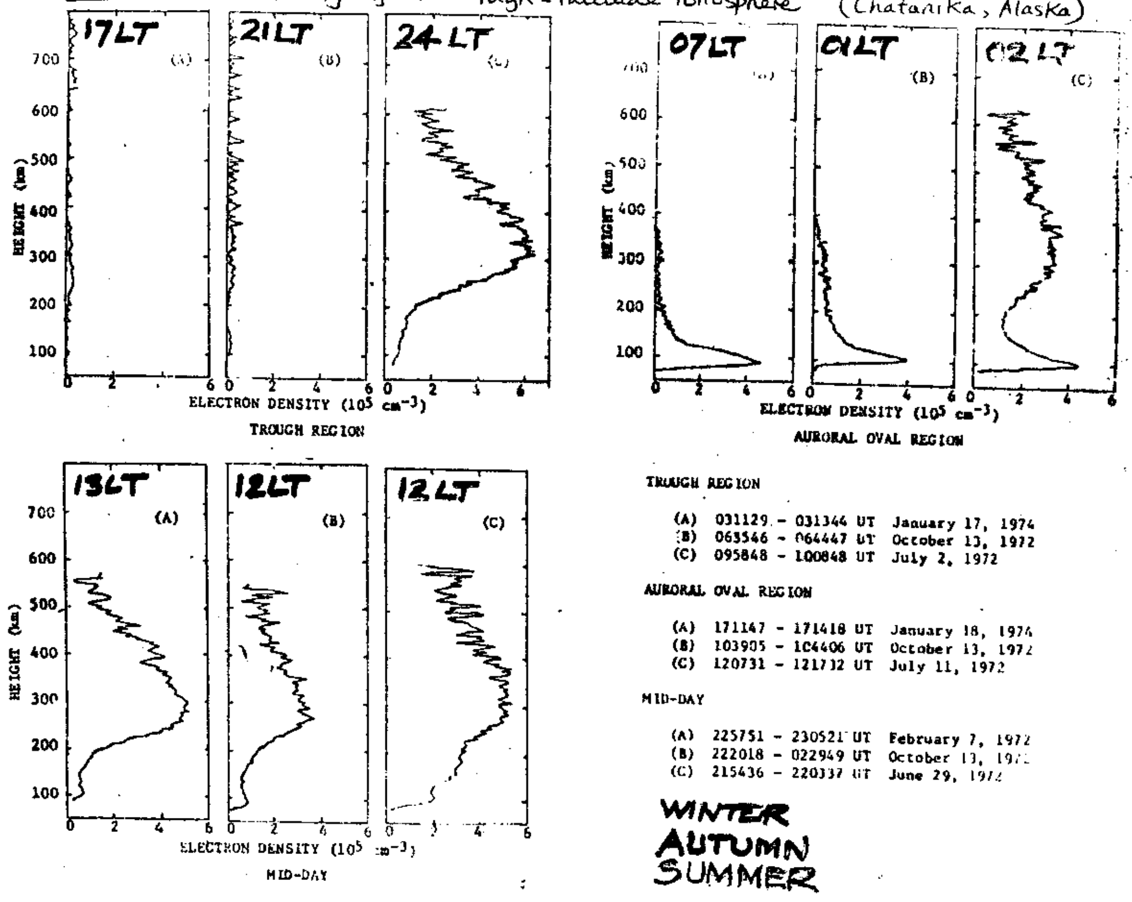


Fig. 31 Refilling the midlatitude protonosphere after a magnetic storm (total content of a field tube)

Fig 32 Variability of the high-latitude ionosphere (Chatanika, Alaska)



In the ionosphere this process of magnetospheric convection appears as an electric field system which causes the plasma to drift with $\underset{\sim}{E} \times \underset{\sim}{B} / B^2$ drift velocity. [Fig. 33] :

Polar cap. The day-to-night or tailward motion is associated with dawn-to-dusk $\underset{\sim}{E}$ field. Drift speeds of some $km\ s^{-1}$ are often produced. This sweeping of plasma from the dayside provides a basic explanation for the maintenance of the polar F2 layer during the winter night. [However, the balance between transport and decay of plasma is a finely-balanced one, since it has been shown that rapid drift under strong electric fields can (a) raise electron temperature, so (b) increase the rate of the $O^+ + N_2 \rightarrow NO^+ + N$ loss reaction, thus (c) – even at the F2 peak – increase the NO^+/O^+ ratio and hence (d) increase the rate of loss of plasma, §4]

Sub auroral return flow. An opposite electric field at lower latitudes (equatorward of the auroral zone) returns the plasma to the dayside. Complicated paths may be followed by the plasma, and the combination of the convection and earth's rotation may lead to stagnation points. If the stagnation point is in darkness, the plasma may there decay to very low ion densities (polar holes). (These may occur even within the polar cap, in more complex situations than that of [Fig. 33])

The auroral oval is therefore a region of {minimum / maximum} electric potential on the {dawn side / dusk side}, and field aligned currents flow {in to / out of} the {dawn / dusk} side. The two sides are separated by the dayside cleft and the nightside Harang discontinuity.

The continuous convection process is not perfectly balanced, in that more magnetic flux is swept into the tail than returns to the dayside, and magnetic energy is stored in the tail. Every few hours this energy is impulsively released in a substorm, accompanied by intense particle precipitation into the auroral oval, and flow of strong electric currents (auroral electrojet [Fig. 12]). Heating: joule effect, particles.

|| The orientation of the Interplanetary Magnetic Field strongly controls the detailed pattern of convection ||

§25 Polar cap winds

The plasma drifting tailwards across the polar cap [Fig. 33] drives the neutral air through ion-drag (§ 15). The equation of motion of the air, neglecting viscosity, is

$$d\underset{\sim}{U}/dt = \mathcal{F} - 2\underset{\sim}{\Omega} \times \underset{\sim}{U} + \nu_{ni}(\underset{\sim}{V} - \underset{\sim}{U})$$

illustrated in [Fig. 34]. This gives a wind pattern which combines the 'magnetospheric convection' drive ($\nu_{ni} \underset{\sim}{V}$) with the thermal drive $\mathcal{F} = -\nabla p/\rho$. Now $\mathcal{F}$ has itself two main contributions — the global temperature and pressure distribution discussed in §12 — and localized auroral zone heating. [Fig. 35] shows observed neutral wind patterns in the polar cap.

These motions are not altogether different from the afternoon-to-early morning wind given by the global thermal heating alone [Fig. 15]. They should produce the systematic LT/UT variations of hmF2 and NmF2 seen at high latitudes. Localized auroral-zone electric fields will of course also contribute to the wind patterns...

§26. Transmission of disturbances from auroral zone to lower latitudes

(Thus excluding storm sudden commencements, which are magnetospheric)

Perhaps three basic types of disturbance:

a. Electric fields [Fig. 36]

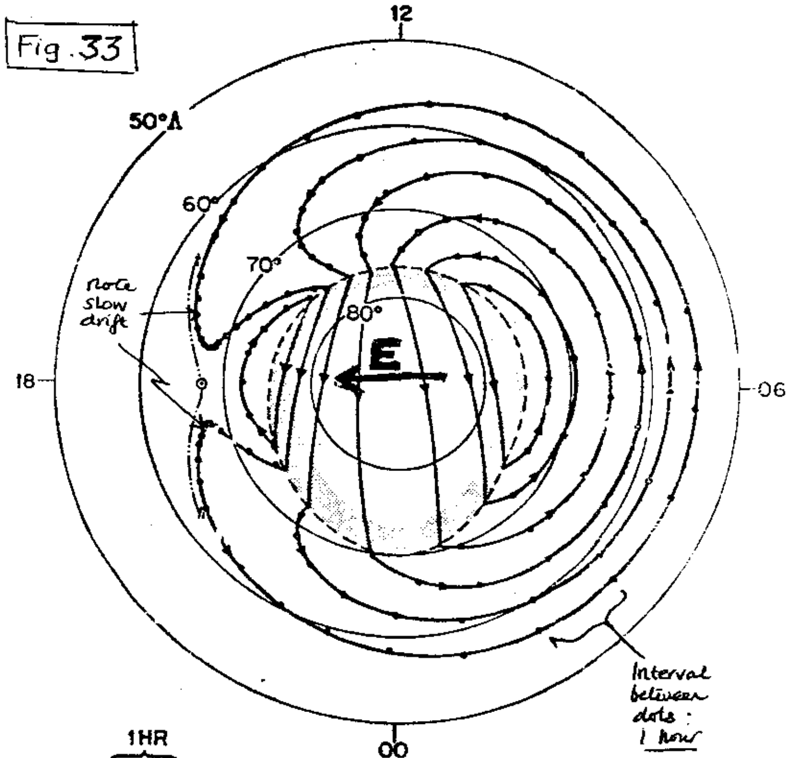
Virtually instantaneous transmission from substorm currents in auroral zone; also to sudden changes in the interplanetary magnetic field. Often seen strongly in equatorial electrojet — is this because of some special linkage, or just because the electrojet is very sensitive? Relationship to counter-electrojet?

b. Atmospheric Gravity Waves * (TID)

Large scale gravity waves (Travelling Ionosp Disturbances) Period ~ ½ – 3 hr., λ ~ 1000 km, velocity ~ ½ km s⁻¹ Generated from auroral substorms.

* Other types → medium scale gravity waves, period 20-30 min, λ ~ 100-200 km. Generated in meteorological storms; topography; eclipses; jetstreams.
→ acoustic waves meteorological infrasonic aurora

Fig. 33



1HR

CONVECTION FLOW LINES IN POLAR IONOSφ

SOFT ELECTRON PRECIPITATION ZONE

LIMIT OF CLOSED FIELD LINES

STAGNATION POINT

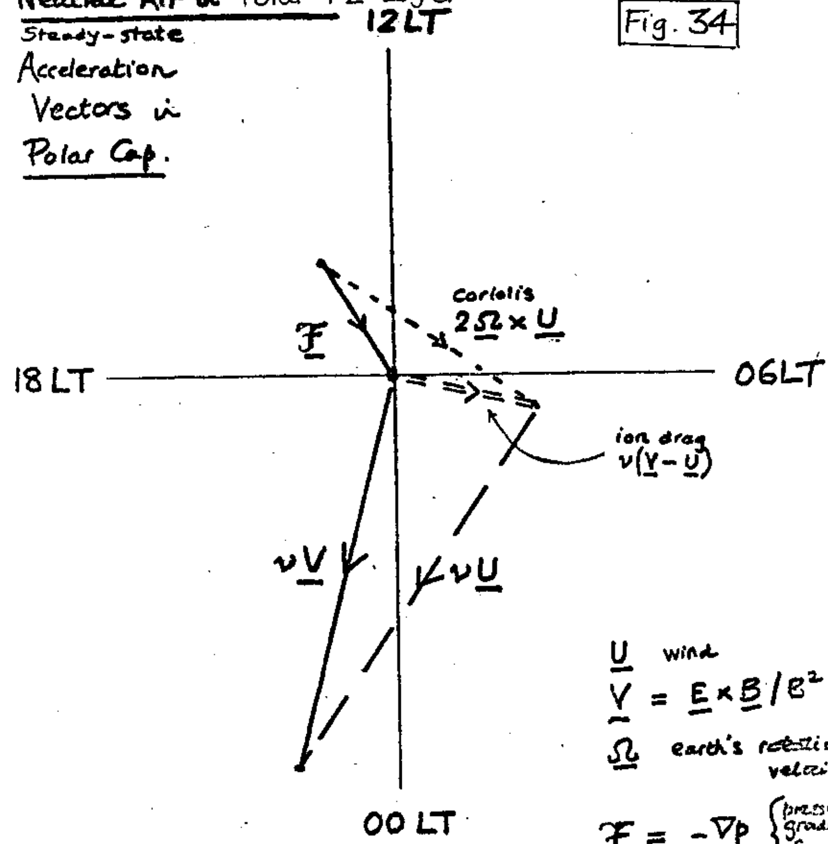
PLASMA PAUSE   Knudsen JGR 79 1046 (1974)

E : DAWN - DUSK ELECTRIC FIELD

Neutral Air in Polar F2 Layer

Steady-state Acceleration Vectors in Polar Cap.

Fig. 34



$\underline{U}$ wind

$\underline{V} = \underline{E}\times\underline{B}/B^2$ plasma drift

$\underline{\Omega}$ earth's rotational velocity

$\underline{\mathcal{F}} = -\dfrac{\nabla p}{\rho}$ {pressure-gradient force per unit mass

==== $\propto$ (V − U)

Contributes to $V_{\parallel}$

$\nu = \nu_{ni}$ neutral-ion collision freq. (recip. of acceleration time)

JATP 39 111 (1977)

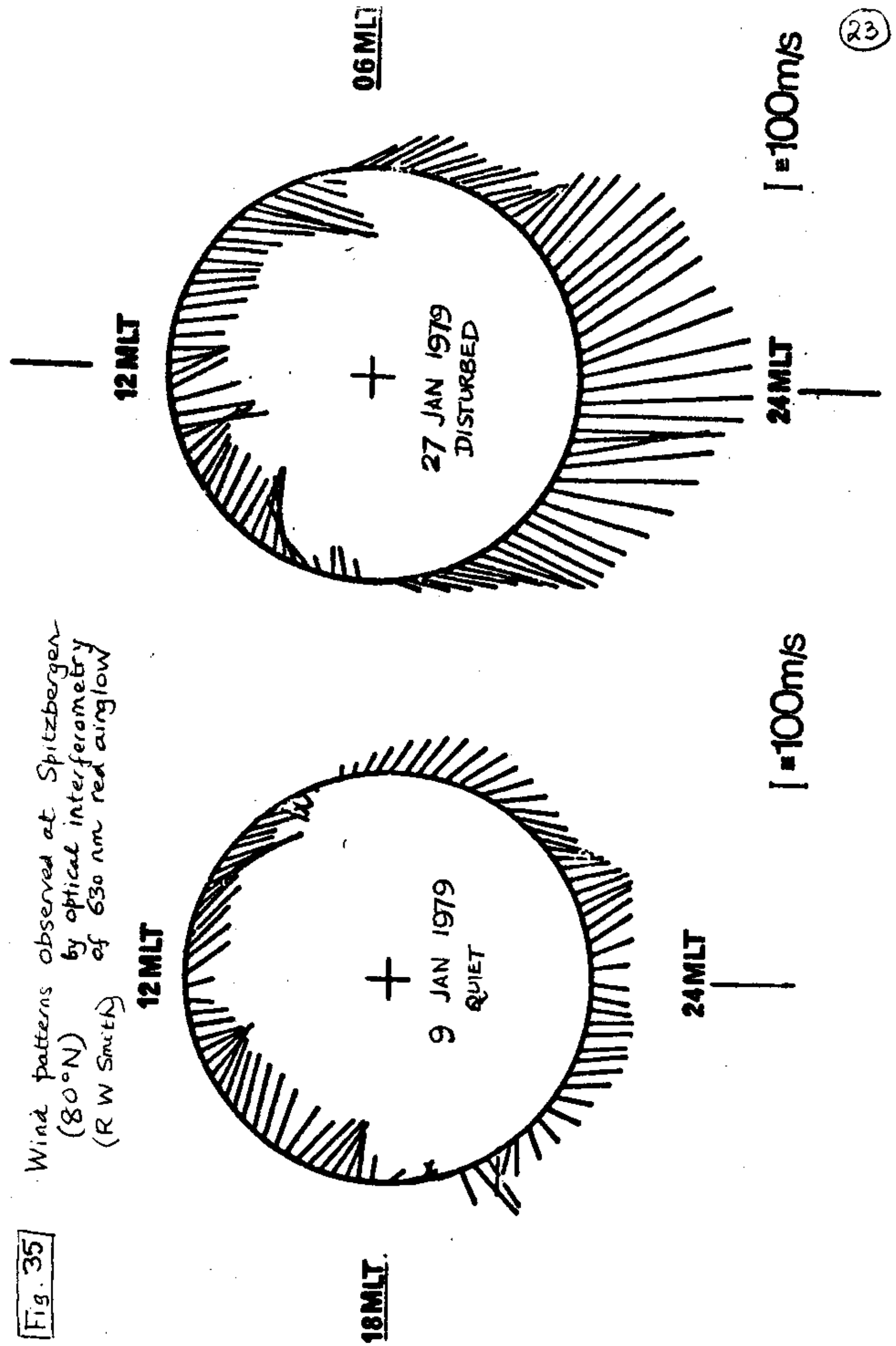


Fig. 35 Wind patterns observed at Spitzbergen (80°N) by optical interferometry of 630 nm red airglow (R W Smith)

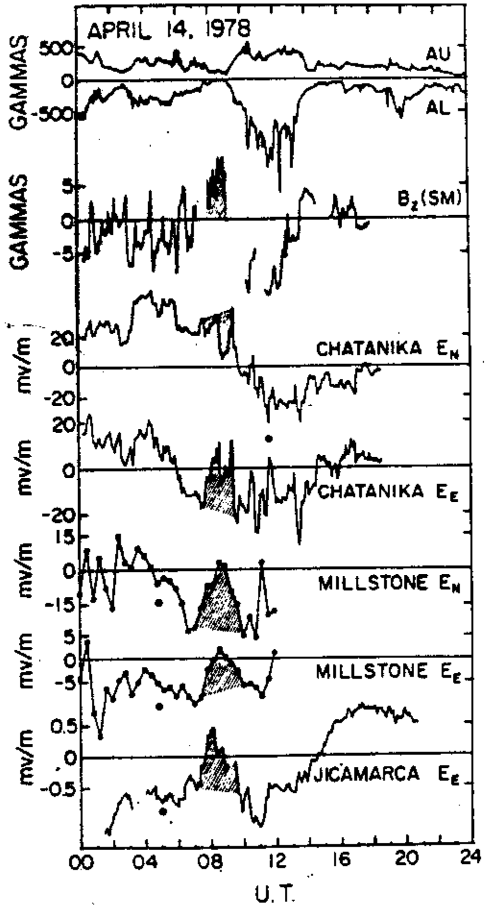


Fig.36 Simultaneous equatorial and auroral electric fields along with auroral indices and IMF data for 14 April 1978. The dots indicate local magnetic midnight (from Kelley et al., 1979).

c. Convection of neutral air — Fig. 37

Heating in auroral zone (especially in strong substorms) causes upwelling of air, which has effect of increasing molecular/atomic gas ratio in then heated region. Outflow to lower latitudes transports gas of higher $[N_2/O]$ ratio, leading to changes in F2 layer chemistry — $N \propto q/\beta$ is therefore decreased (§4). The effects are dissipated by diffusion. This kind of convection combines with the thermal summer–winter system Fig. 22.

§27. Ionospheric Storm Effects — Fig. 38

Typically seen at midlatitudes:

Solar flares often initiate big geomagnetic storms, via
- I. Electromagnetic X radiation from flare. Lasts ≤ 1 hour.
- II. Plasma clouds released from sun, travel to earth in 1–2 days, appear as strengthening and quickening of solar wind; speed up magnetospheric convection and generate frequent, severe substorms, and consequences as in § 26.

I. Solar flare causes very enhanced D layer ionization, strong radio wave absorption and a range of associated 'sudden' phenomena accompanying this SID 'Sudden Ionosph Disturbance'. Some enhancement of F2 layer.

II. Longer time-scale disturbances, following the SC 'Storm sudden commencement' that happens worldwide when the solar plasma cloud impacts on the earth's magnetosphere:

D layer: Short lived disturbance to ordinary day–night variation; sometimes followed after few days by a long lived disturbance, that appears to propagate from the auroral zone. Presumably a chemical effect?

E layer: Very small storm effect, though may get enhanced 'night E' — thick, high nighttime layer

F layer: Often get initial positive phase, big increases of NmF2 attributed to equatorward wind blowing from auroral zone (hence upward drift, §4). Then get main negative phase, NmF2 depresses, probably by chemical effects. The chemical effect sometimes causes the F1 layer visible when it would not otherwise appear (increased β, and G: Fig. 4)

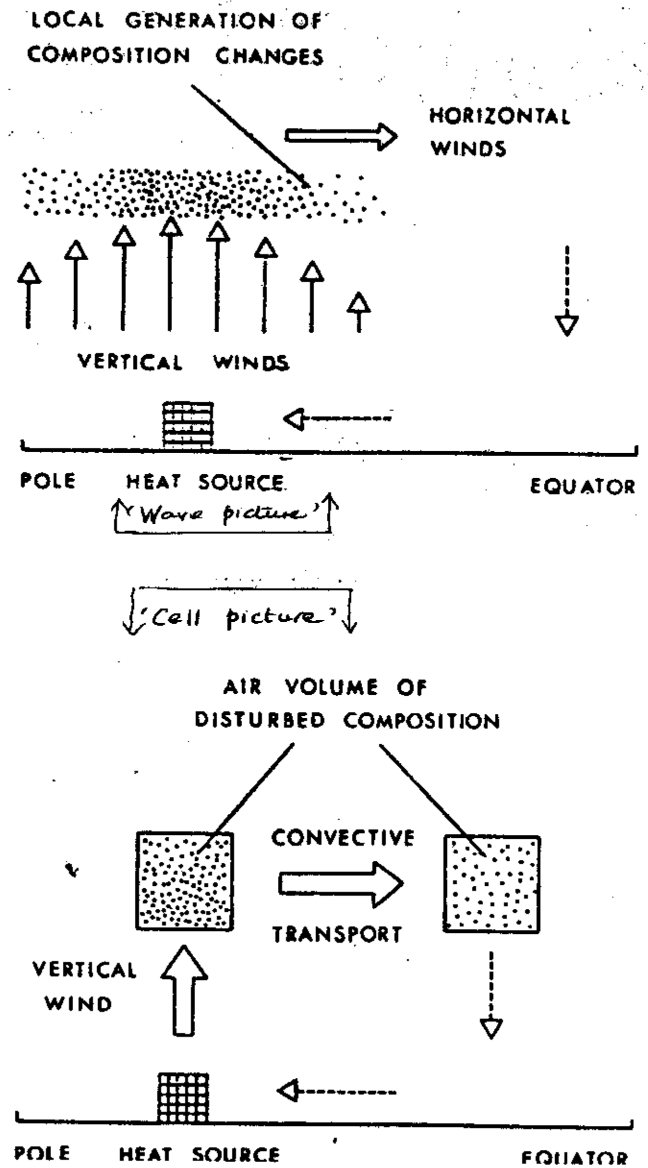


Fig. 37 (Prölss) Two somewhat different pictures of the transport of composition changes from the auroral zone to low latitudes.

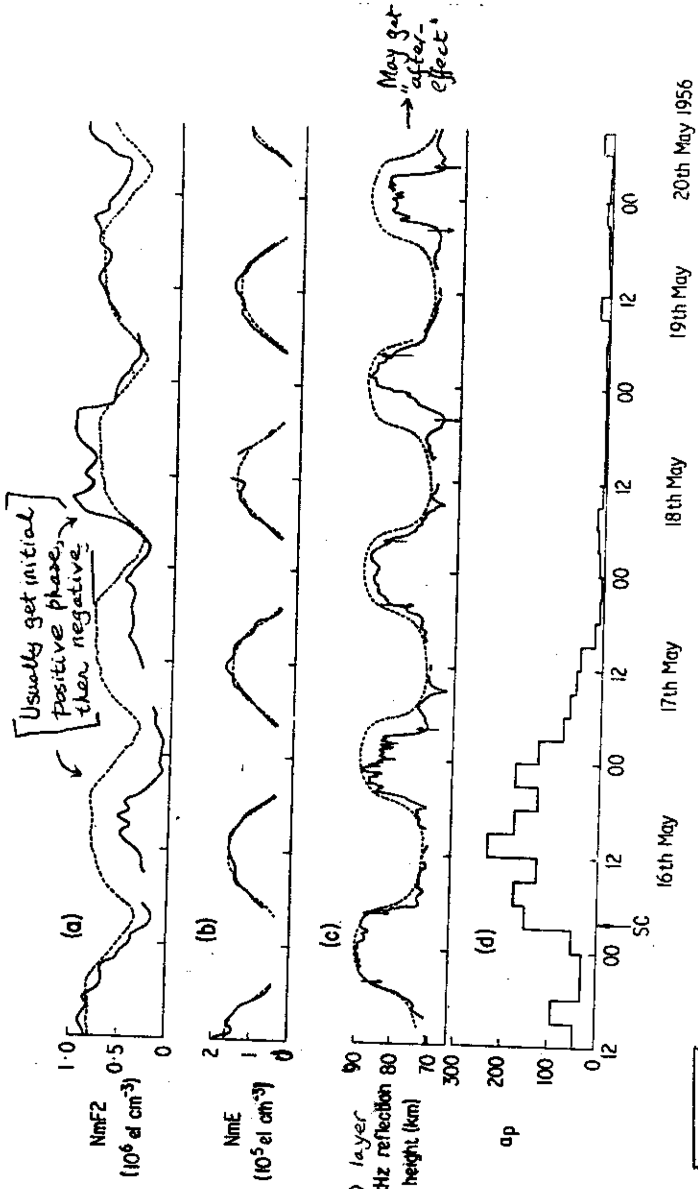


Fig. 38 F2, E & D layer behaviour at Slough during a magnetic storm.

The chemical changes are due to the transport of molecular-enhanced air by a convective mechanism from the auroral zone, or (less probably) stirred up locally by waves transmitted from the auroral oval (c. of §26; Fig. 37). An enhanced neutral $[N_2/O]$ ratio decreases the ratio q/β, (§4). But, sometimes in winter, a storm remains 'positive' (increased NmF2) throughout its course. This must be due to some modification of the circulation.

Equatorial F2 layer. Storm effects are usually 'positive' (increased NmF2). This may be because the winds from the auroral zone produce a 'converging wind' at the equator (Fig. 26). Storm effects are sometimes negative, presumably because the molecular-enhanced air from the auroral zone can penetrate to the equator. Also, account must be taken of electric field modifications; the 'fountain effect' (§21) is weaker during storms.

Storm effects are very complicated, and incompletely understood. No doubt exceptions could be found to most of the statements made in these notes!

§28. Bibliography

Giraud & Petit	Reidel	1978	These cover most of the established "book work". See course book list.
Hargreaves	Van Nostrand Reinhold	1979	
Rishbeth & Garriott	Academic	1969	
Bauer	Springer	1973	

Useful Papers on particular topics, especially relevant to →

Bates	Contemp Phys.	11	105	(1970)	§4
Beynon & Williams	Rep. Prog. Phys	41	909	(1978)	Incoherent Scatter
Briggs	Contemp Phys	16	469	(1975)	Irregularities
Cowley	Space Sci Rev			(1982)	§23
Evans	J A T P	34	175	(1972)	1st dynamics
"	R G S P	16	195	(1978)	Lower thermosp Dynamics
Fejer	R G S P	17	135	(1979)	§23
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Special Issues

JATP	Fifty years of the ionosphere	Dec 1974
JATP	Equatorial aeronomy	Sept 1977
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