INTERNATIONAL ATOMIC ENERGY AGENCY
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COLLEGE ON THEORETICAL AND EXPERIMENTAL RADIOPROPAGATION SCIENCE

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IONOSPHERIC PHYSICS AND RADIO PROPAGATION

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"IONOSPHERIC PHYSICS AND RADIO PROPAGATION"

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I. HOW CAN IONOSPHERIC PHYSICS HELP RADIO PROPAGATION?

Ideally we would like to know the electron distribution N(h,t; lat,long) everywhere and at all times. In principle we could then use radio propagation theory to find possible paths, delay times, signal strength

Can we construct a 'model ionosphere' for this purpose?

We would like to use these models for: (Fig. A)

... Long-term variations (for frequency planning)
... Short term forecasts (must depend on solar-terrestrial conditions)
... Designing real-time adaptive systems

This assumes the ionosphere at any place is reproducible: (in LT, month for any given solar and geophysical conditions S10.7, Kp, etc). [But does the ionosphere depend also on 'recent history'? And can we really reproduce day-to-day variability? (Fig. B) (Fig. C)

II. MODELLING

Two basic types: Empirical, Physical

Empirical — e.g. → IRI (ionosphere); MSIS (neutral air)

Physical — e.g. → USU, Sheffield : NCAR-TGCM, UCL 3DTD

Empirical model deals with 'What is ionosphere like?' [not 'why']

"+++" It does not require the physics to be known. It can usually be reduced to programmable formulas.
"---" It probably has limited space-time resolution (especially if constructed in terms of harmonic functions). In the real ionosphere, sharp boundaries (between different physical regimes) may be important and may affect radio propagation, but are not usually well represented.

Physical model requires equations to be solved:

Conservation of mass [continuity]:

$$\partial N/\partial t = [\text{Production}] - [\text{Loss}] - [\text{Transport}]$$

Conservation of momentum [motion]: (Includes effects of Earth's rotation →)

$$d\underline{V}/dt = [\text{Driving forces}] - [\text{Drag}] - [\text{Viscosity}]$$

Conservation of energy [thermal]

$$\partial T/\partial t = [\text{Heating}] - [\text{Radiative Cooling}] - [\text{Conduction, Convection}]$$

"+++" More physically realistic, but difficult to compute;
"---" boundary conditions; contain many parameters, often poorly-known
We need to understand the physics in order to set them up.

'Hybrid' empirical/physical models exist and may be useful.

e.g. compute NmF2 with physical model, combined with empirical N(h) profile (and derive coefficients for use in empirical model

Neutral Atmosphere parameters essential to physical understanding

III. APPLICATIONS TO IONOSPHERIC LAYERS

Properties of the continuity equation. When trying to explain any phenomenon, it is important to know which term in the continuity equation is involved.

F2 Layer Continuity Equation (loss) = βN

$$\partial N/\partial t = q - \beta N - \text{div}\, N\underset{\sim}{V}$$

(often small)

$$= q - \beta N - \underset{\sim}{V} \cdot \text{grad}\, N - N\, \text{div}\, \underset{\sim}{V}$$

(motion of already-existing gradient) (divergence of velocity)

① General points
[Usually] horiz gradients « vertical
so $\text{div}\, NV \simeq \frac{\partial}{\partial h}(NW)$
[But] Horiz terms are important at high & low latitudes

② $\text{div}\, \underset{\sim}{V} \cong 0$ for electrodynamic drift
$\text{div}\, \underset{\sim}{V}$ small for winds
"Main effect of vertical drift is to move the plasma to a different q/β"

③ "PHOTOCHEMICAL APPROX" $N \simeq q/\beta$ is often good at the F2 peak

See (Fig D) which illustrates the effect of upward & downward drift

Es layers at midlatitudes — Transport term important (otherwise not very important in lower ionosphere)

High latitude ionosphere — See (Fig. E) for possible mapping scheme based on the auroral oval

[Not discussed in lecture]

Equatorial ionosphere — Horizontal & vertical motions are both important

F2 LAYER & NEUTRAL AIR MOTION

"Photochemical approx" $\quad NmF2 \propto \frac{q}{\beta} \propto \frac{I.[O]}{[N_2]}$ $\quad$ (I ← Intensity of solar ionizing radiation)

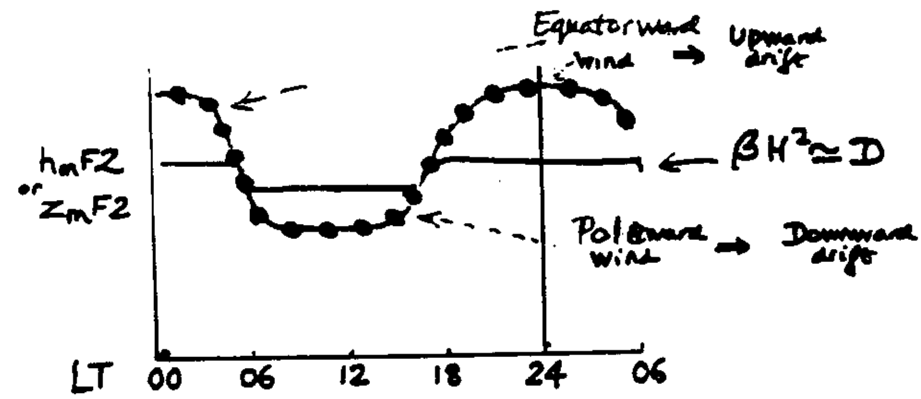
Dynamic studies of the neutral thermosphere show that:

$[O/N_2]$ ratio is $\frac{\text{increased}}{\text{decreased}}$ by $\frac{\text{downward}}{\text{upward}}$ motion of the air

∴ $\frac{\text{"Upwelling"}}{\text{"Downwelling"}} \Rightarrow \frac{\text{Decreased}}{\text{Increased}} [O/N_2] \Rightarrow \frac{\text{Decreased}}{\text{Increased}}$ NmF2

Upwelling requires energy input locally
Downwelling occurs remote from energy inputs
This is basic explanation of F2 seasonal anomaly

The F2 Peak as a Constant Pressure System



hmF2 (at a given LT) increases if the atmosphere gets hotter & expands { winter → summer; quiet → storm; s.s. min → s.s. max }

If we compute hmF2 in terms of "pressure" (zm) instead of real height (hm) we find that the local-time variation is much more consistent with:

① season ② magnetic activity ③ sunspot cycle ④ place to place ?

Pressure coordinate is "Reduced height" [Chapman theory coordinate] *

$$z(h) = \int_{h_B}^{h} \frac{dh}{H} = -\ln p$$

If base height h_B = 80 km then $p(h_B) = 1$ Pa

$$H = \frac{RT}{Mg}$$ Pressure scale height

As T (& M) vary, z at a fixed h changes (with LT, season, s.s. no. →)

'hmF2' can be modelled by using 'zmF2' computed from MSIS

With upper limit hmF2 in above eqn.

*{If H indep of h} $z = \frac{h - h_B}{H}$ but the $\int$ eqn is more general

IV. PROBLEMS OF IONOSPHERIC STORMS

Solar-terrestrial relations

Complex chain of events & linkages } [Flares] ? ⇒ Plasma Streams ⇒ Magnetosφ ⇒ Atmospheric energy input (particles, elec fields)

F2-layer storm phenomena

Complicated patterns {UT LT ST} Initial +ve phase in NmF2 (Fig F)

'+ve & −ve effects   Main −ve phase but may be +ve (winter : low lats)

'AC/DC Effects'

Patterns of ln (N/No)   "DC" (Mean Level (average over LT)) (Fig G)

actual value of NmF2 ↑ / 30-day mean at same LT   "AC" (LT-variation of storm effect)

Possible causes   DC : probably composition changes (which are known to happen)

AC : Winds ? Electric fields ? Compo changes ?

Difficulty with DC effect : The composition changes require a local energy input

Remote energy inputs (in auroral zone) (Fig H) don't produce composition changes at midlatitudes

Possible solution   Need midlatitude energy input to produce midlatitude storm effects

Might be due to precipitation of keV ions from the storm "Ring current"

} STORMS ARE RELATED TO THE THERMOSPHERIC CIRCULATION
MORE INFORMATION FROM ANYWHERE IS NEEDED !

V. OUTSTANDING IONOSPHERIC PROBLEMS

The thermospheric circulation and its ionospheric effects

Still don't fully understand "Thermosφ as engine". Important for ↵

Mechanisms of ionospheric storms, and how effects are transmitted

See Sec IV. Is there a systematic pattern in how storms develop?

Influences of the IMF, solar wind and magnetosphere

Primarily high latitudes : what about low latitude {energy input, elec. fields} ?

Influences of topography and 'terrestrial' events

Gravity waves : effects of mountains & oceans : earthquakes   met. storms ?

The cause of irregular structure on a variety of scales

Scales of m ; km ; Mm ?   Equatorial Es, sp F...   Midlatitudes?

The ionosphere as a physical and chemical laboratory

— active experiments with radio waves, particle accelerators, chemicals

The problem of predictability

Can we predict (or forecast) solar-terrestrial disturbances?
" " " whether a disturbance will cause a serious "storm"?
" " " how an ionospheric storm will proceed — once it has started

¡ Still Lots of Problems to Solve !

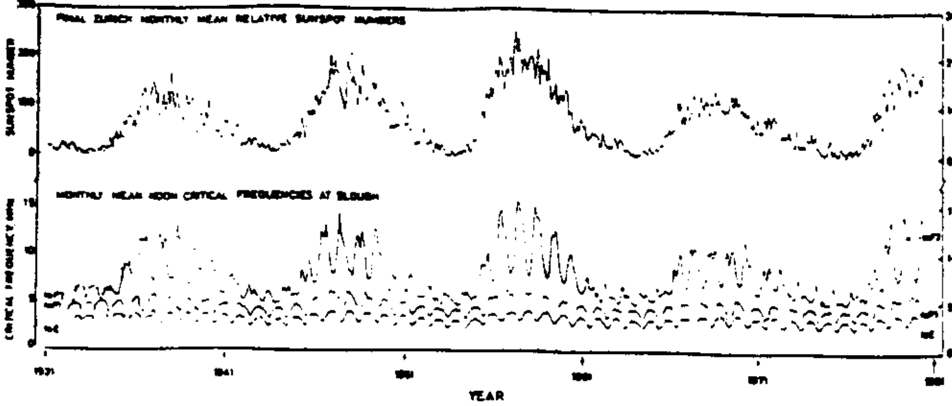


Fig. A Noon monthly mean critical frequencies of the F2, F1 and E layers at Slough (Lat. 52°N, 1931–1981). (*Courtesy of* S.E.R.C. Rutherford Appleton Laboratory.)

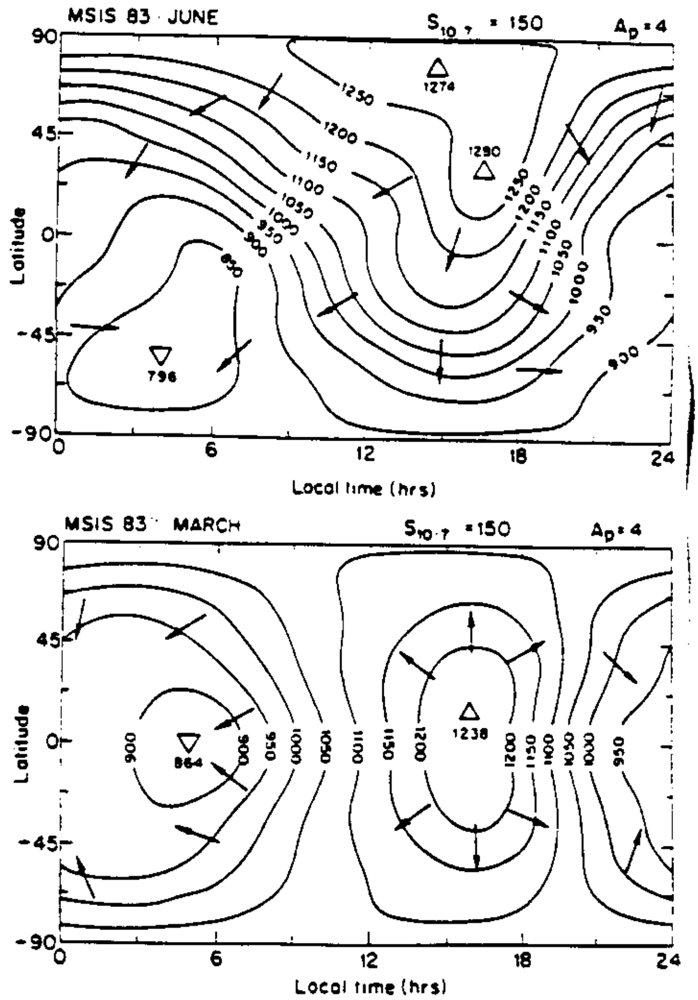


Fig. C Map of exospheric temperature in March & June, for high solar activity and quiet geomagnetic conditions, according to the MSIS83 thermospheric model by A.E. Hedin, *J. Geophys. Res.*, 88, p. 10170, 1983. Arrows show the approximate directions of the thermospheric winds. (*Courtesy of* S.E.R.C. Rutherford Appleton Laboratory.)

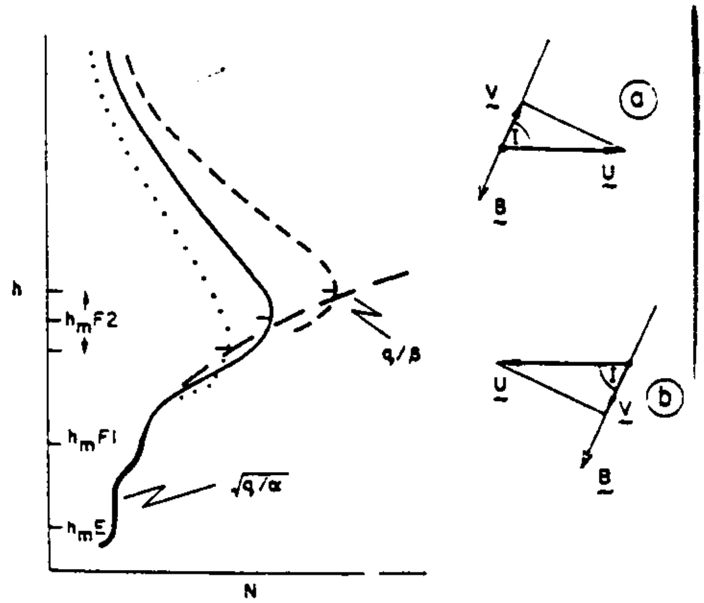
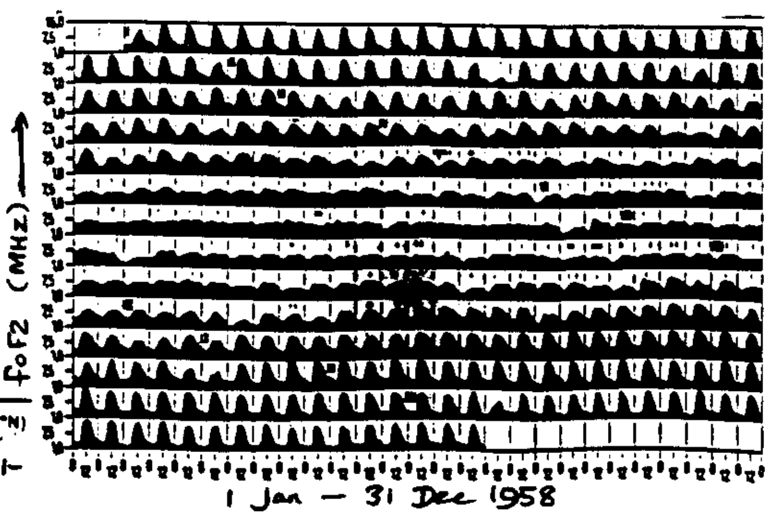


Fig. D Idealized electron density profiles in the E and F1 layers, with square-law loss coefficient; and in the F2 layer, with linear loss coefficient. The effects of upward and downward drift on the F2 peak are shown by dashed and dotted curves, respectively. The sketches on the right show the ion drift V produced by a horizontal wind U in the neutral air, the vector B representing the geomagnetic field (dip angle *I*). (a) Upward field-aligned drift is produced by a wind blowing towards the magnetic equator; (b) downward drift is produced by a wind blowing towards the magnetic pole. (From *Contemporary Physics*, 14, p. 244, 1973, Taylor & Francis.)



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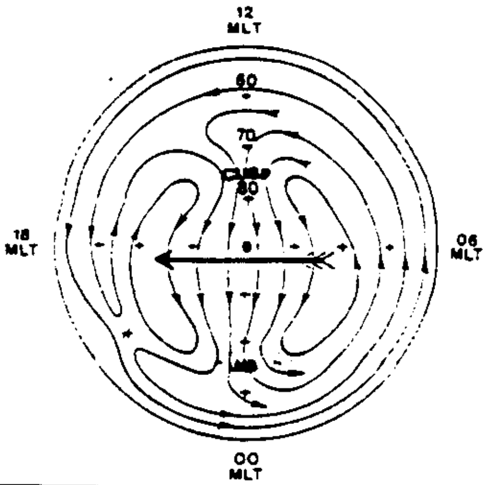


Fig. E. The auroral oval and associated phenomena. View of the North Polar region, centred on the magnetic pole. The bottom of the diagram represents magnetic midnight, 00 MLT; the top represents magnetic noon, 12 MLT; the outer boundary is at 50° magnetic latitude, the crosses being at magnetic latitudes 80°, 70°, and 60°. The outer ring represents the plasmasphere (mid-latitude ionosphere) which co-rotates with the Earth. The stippled ring represents the approximate location of the hard 'drizzle' precipitation. The inner shaded ring is the auroral oval, showing the approximate locations of the 'cusp' in the noon sector and the Harang discontinuity (HD) near midnight. The fine lines represent typical flow lines of the plasma convection pattern (some curves are left incomplete to reduce congestion); note the stagnation point at 20 MLT. The diagram corresponds roughly to moderate magnetic activity ($Kp = 3$) with a southward B_z component of the interplanetary magnetic field. (*Courtesy of* S.E.R.C. Rutherford Appleton Laboratory.)

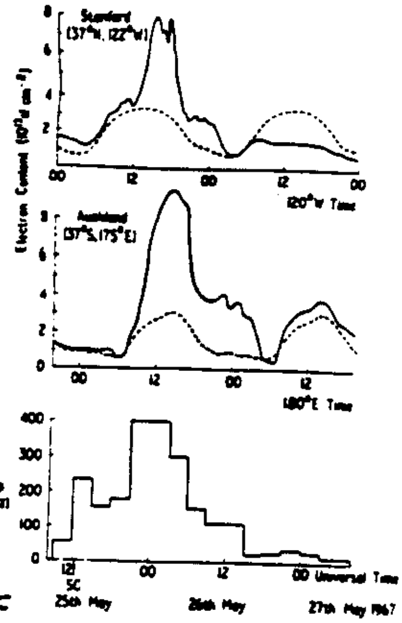


Fig. F Positive and negative storm effects in ionospheric total electron content (mainly F2 layer) at two midlatitude stations. The marked initial increase of electron content in both hemispheres is followed by a negative storm at Stanford (summer hemisphere) but a positive storm at Auckland (winter hemisphere). Dashed curves show monthly average values. The variation of the magnetic ap parameter is shown below (K. L. Jones).

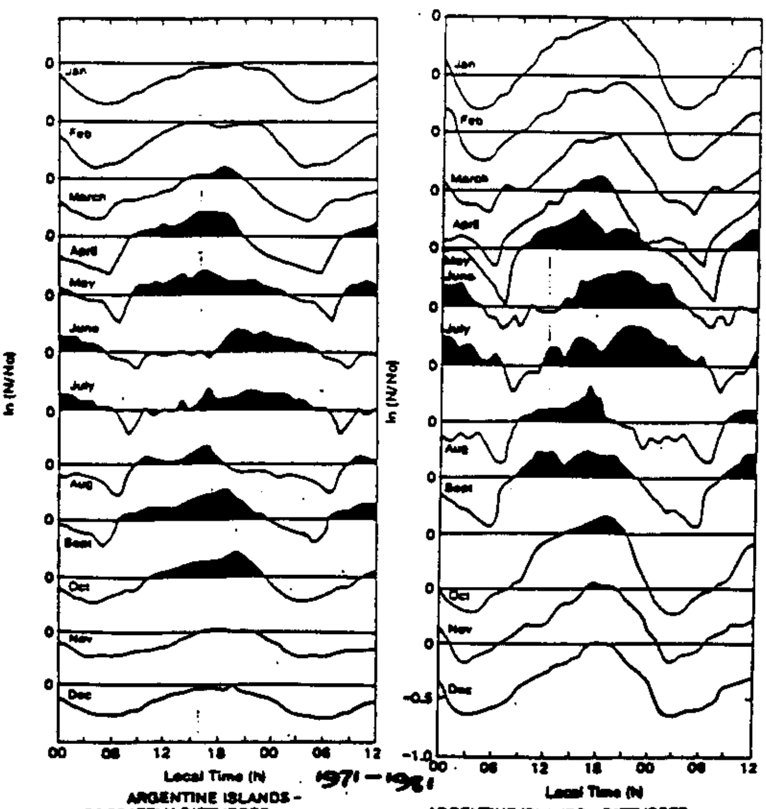


Fig. G. Local time variations of F2 storm effects at an Antarctic Station (Argentine Is./Faraday) (65°S 64°W), showing "mean level" (DC) and LT-dependent (AC) variations. Regions of +ve storm effect are black.

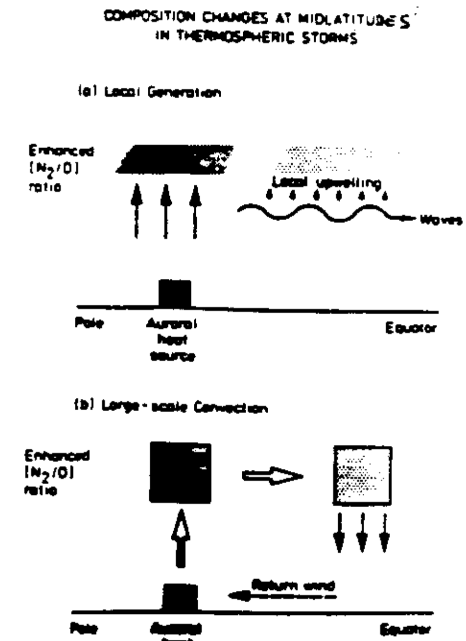
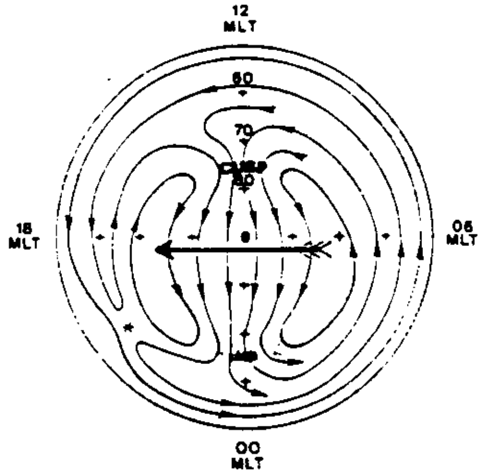


Fig. H Sketch to indicate possible mechanisms by which heat sources in the auroral oval (left) might in principle enhance the $[N_2/O]$ concentration ratio at lower latitudes (right). In (a) the auroral source sets up a disturbance, such as planetary waves [23], gravity waves [24], or convective disturbances [25], which travels to lower latitudes and deposits energy which causes local heating of the thermosphere. In (b) the auroral source drives a large-scale circulation, in which heated air rises in the auroral oval and flows to lower latitudes, carrying its enhanced $[N_2/O]$ ratio with it. Adapted from Prölss

[Unfortunately, neither mechanism seems to work!]



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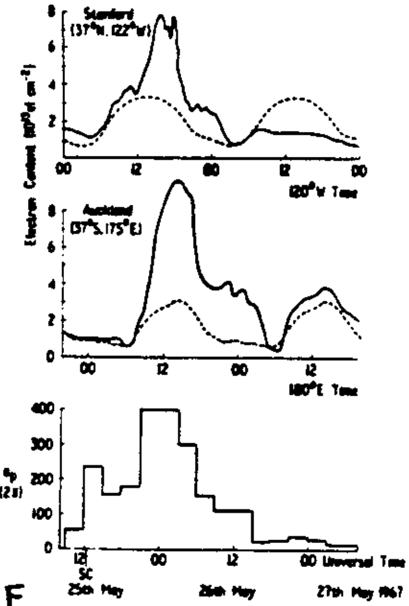

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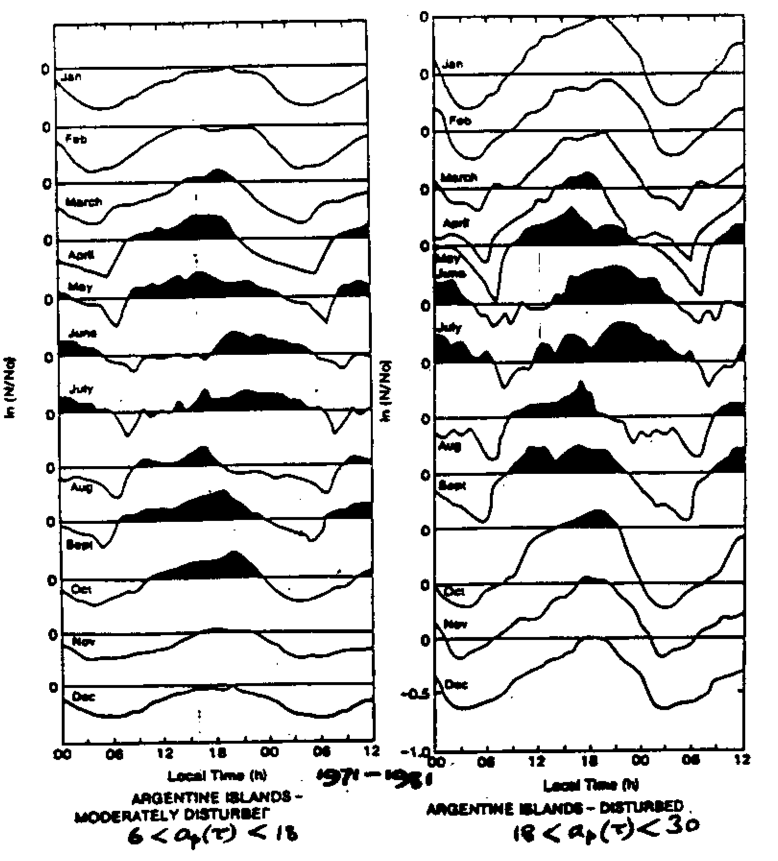

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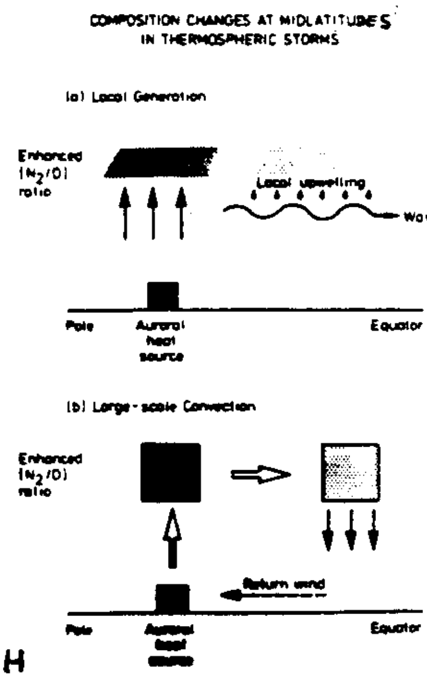

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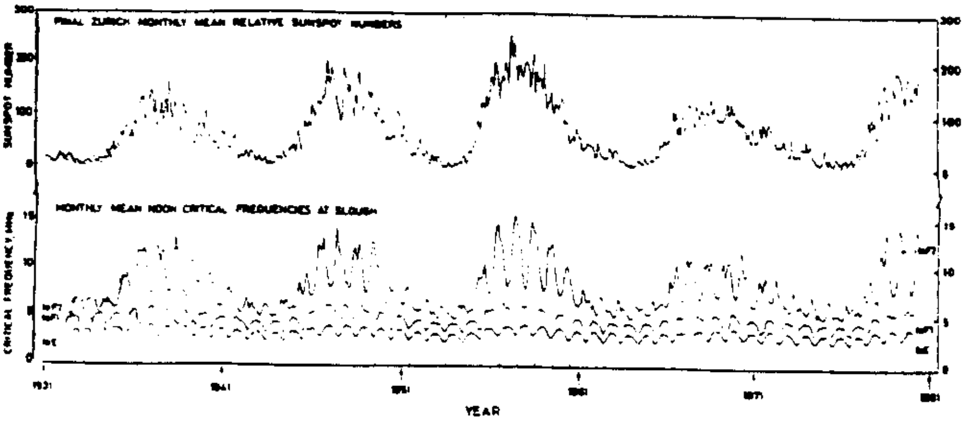

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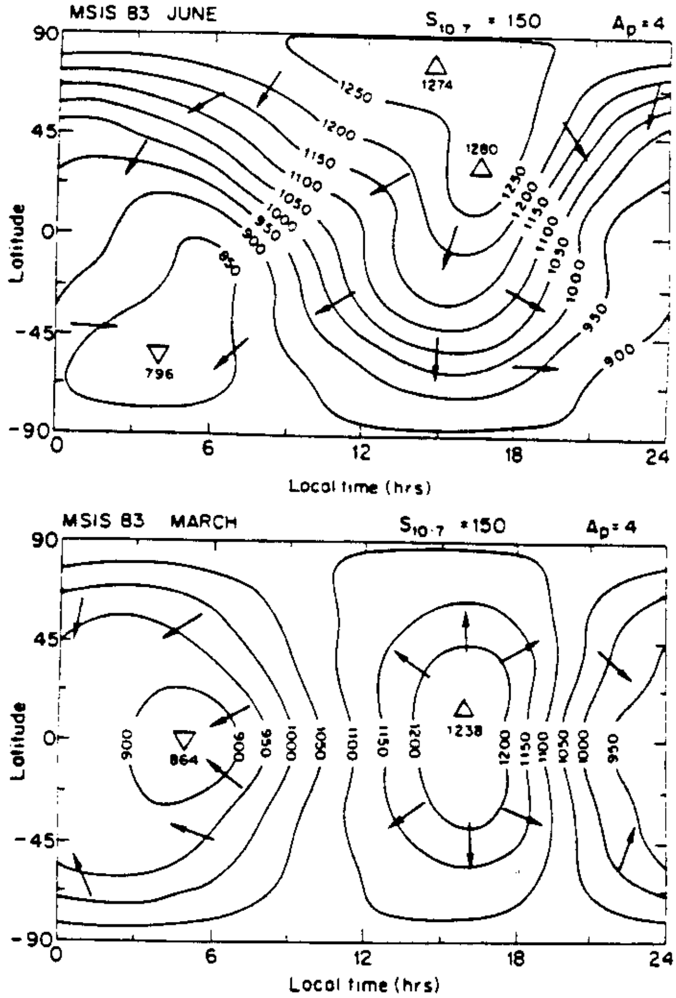

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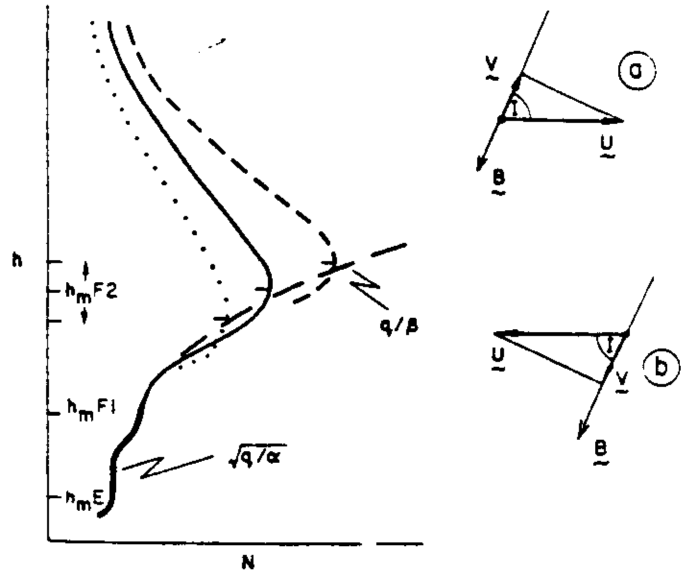

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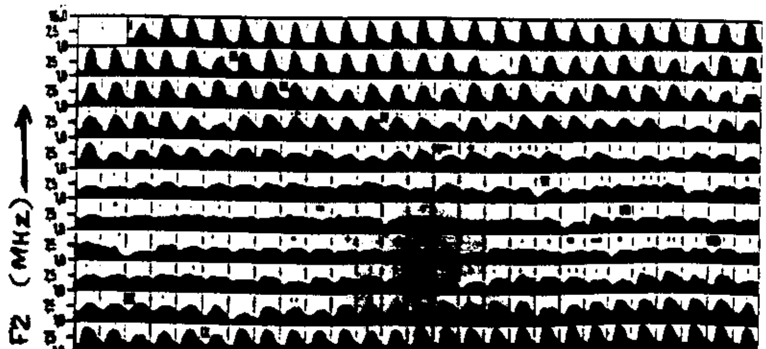

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