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Tutorial Lecture

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Winds and Composition in the Thermosphere

Winds & Composition in the Thermosp

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Mostly about large-scale structure
in the mid-latitude E & F layers

1 General Principles

2 Wind systems

3 Composition Effects – Quiet Days

4 " " – Storms

5 More general principles

FIRST PHYSICAL THEORY OF THE IONOSPHERE ?

Re Mr Marconi's Results in Day and Night Wireless Telegraphy

OLIVER LODGE [1902] : "The observed effect, which if confirmed is very interesting, seems to me to be due to the conductivity ... of air, under the influence of ultra-violet solar radiation."

"No doubt electrons must be given off from matter ... in the solar beams; and the presence of these will convert the atmosphere into a feeble conductor."

THE KEY YEARS

1931	Regular Ionospheric Sounding began at Slough
1931	Chapman's Theory of Ionized Layers
1931	Chapman's Theory of Airglow
1931	Chapman-Ferraro: Solar Particles & the Earth's magnetic field — First idea of Magnetosphere?
1932	Appleton-Hartree Magneto-Ionic Equn
1932	Start of Kp Geomagnetic Index
1933	Slough Swept-Frequency Ionograms

NEW UNDERSTANDING OF THE IONOSPHERE

¶ **GLOBAL CIRCULATION in the upper atmosphere— driven by SUN and MAGNETOSPHERE/SOLAR WIND**

* **Chemical changes → F layer seasonal effects [D layer]**
* **Temp. variations → winds/waves → F layer effects**
* **Auroral heating → winds → F layer storms [D layer]**
* **Electrodynamics → equatorial E & F layers**

¶ **MAGNETOSPHERE — links with ionosphere and IMF**

* **New focus on the high latitude ionosphere :**
[polar caps, auroral zone, "troughs"]

***Ideas* :**

"Vertical structure ⇔ solar radiations"

"Latitude structure ⇔ geomagnetic field"

"Ionosphere as part of interactive solar-terrestrial system"

IONOSPHERIC CONSERVATION EQUATIONS

Continuity equation [mass]:

{Density change} = {Production} − {Loss} − {Transport}

Equation of motion [momentum]:

{Acceleration} = {Force} − {Drag} − {Transport}

Heat equation [energy]:

{Temp change} = {Heating} − {Cooling} − {Conduction}

Plus:

Equation of state [perfect gas equation]

F2 Layer continuity equation

{Plasma diffusion
{Neutral-air winds
{Electric fields

$$\partial N/\partial t = q - \beta N - \mathrm{div}(N\underset{\sim}{V})$$

$$= q - \beta N - \underset{\sim}{V}.\mathrm{grad}\,N - N\,\mathrm{div}\,\underset{\sim}{V}^{*}$$

↑ Motion of existing gradient

↑ Velocity divergence

"Diffusion controls height of peak"

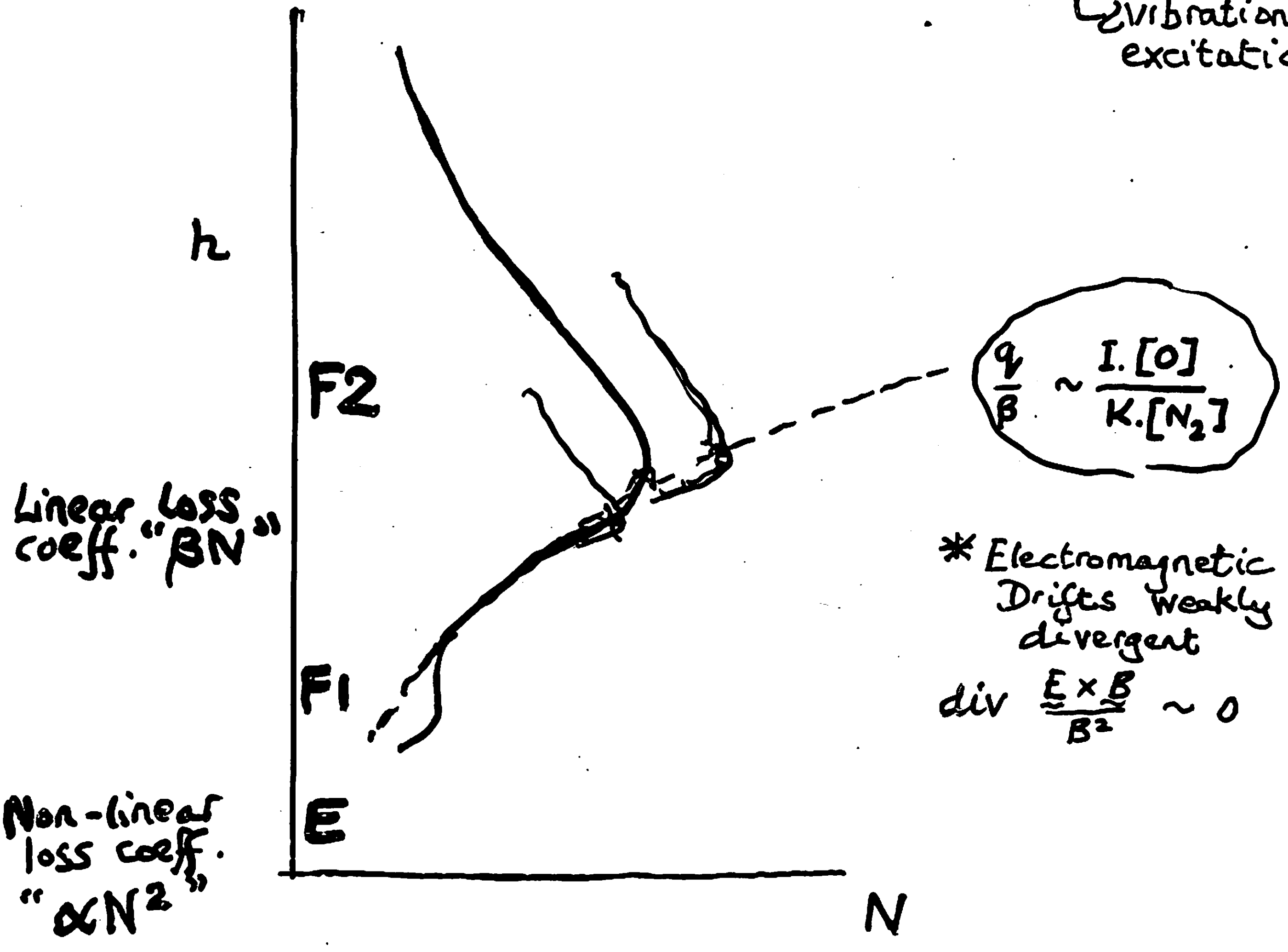
"Main effect of vertical drift is to move the plasma to a different q/β"

"Vertical drift ← Horiz Winds"

$q \propto [O]$

$\beta \propto [N_2, O_2]$

↑ {vibrational excitation?



* Electromagnetic Drifts weakly divergent

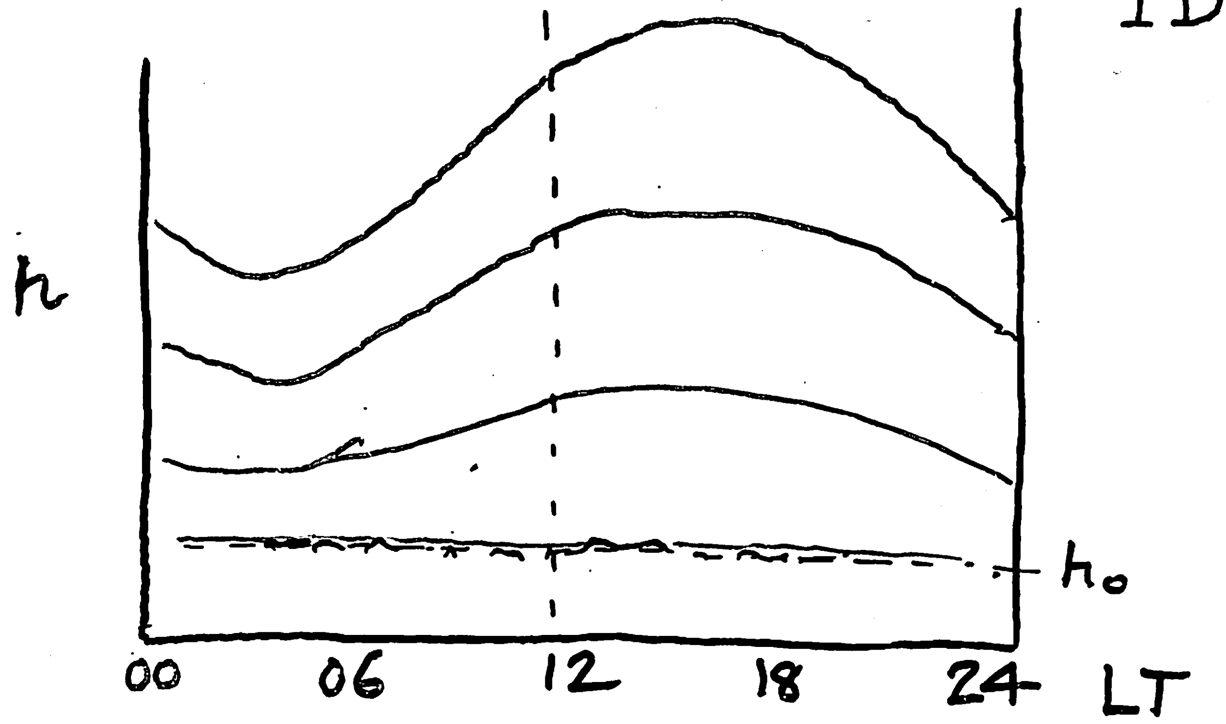
$\mathrm{div}\,\frac{\underset{\sim}{E} \times \underset{\sim}{B}}{B^2} \sim 0$

Variations of ion chemistry:
$\mathrm{Molec}^{+}/\mathrm{Atomic}^{+}$ Ratio

Thermal Expansion

"Barometric" Motion

1D



$$Z = \frac{h - h_0}{H} = \int_{h_0}^{h} \frac{dh}{H} \leftarrow \frac{RT}{Mg}$$

$[O/N_2]$

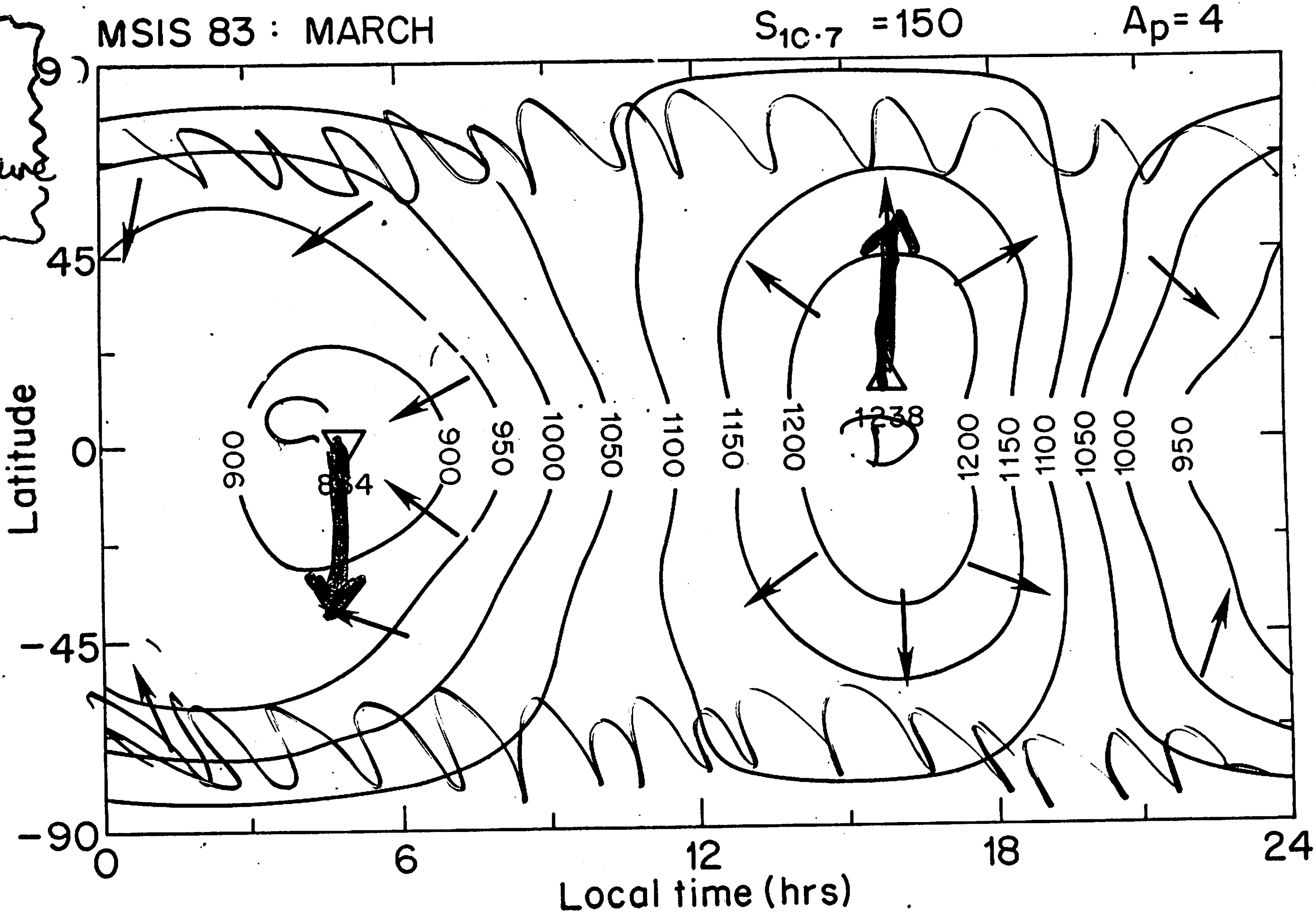
If compo is fixed at lower boundary h_0

then it remains fixed at any fixed Z

Can be changed by

- * Vertical circulation (horiz divergence convergence) "up down welling"
- * Change of mixing at turbopause ?
- * Gravity waves ???

300 km
Wind &
Temperature
Map



Is there a mean
W → E
Wind?

<u>Winds: due to</u> : Solar Heating ("Thermal tide"?)
Magnetospheric Heating (joule heating, particle pptⁿ)
Gravity waves, tides from below

Longitude Averaged Thermospheric Circulations

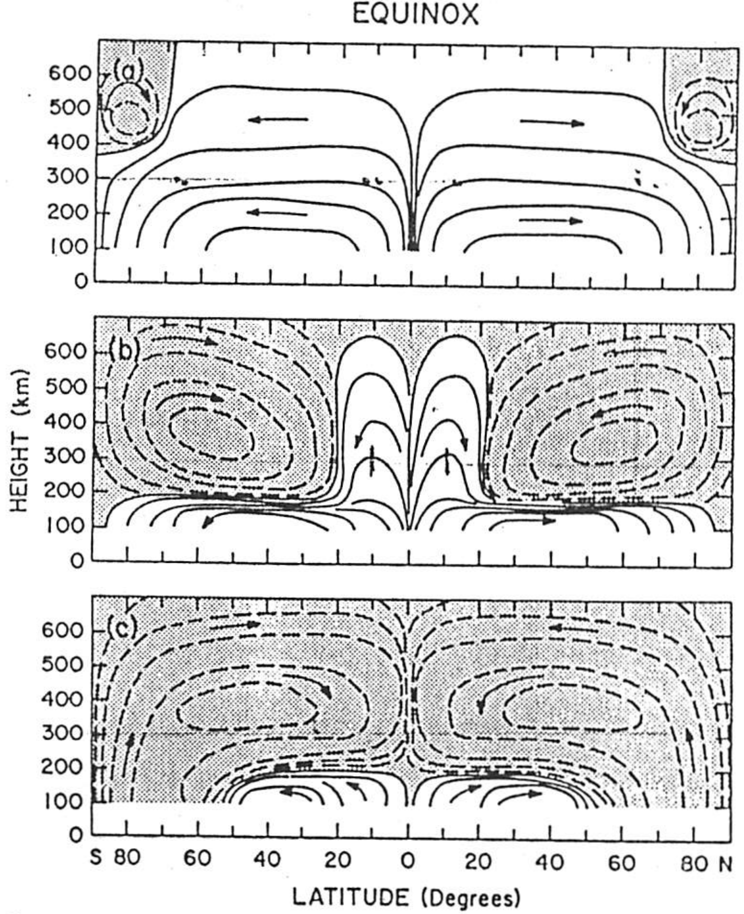


Fig. 1 Schematic diagram of the mean thermospheric circulation during equinox. The upper panel shows the circulation during quiet geomagnetic conditions, the middle panel is for average conditions, and the bottom panel is for geomagnetic storms.

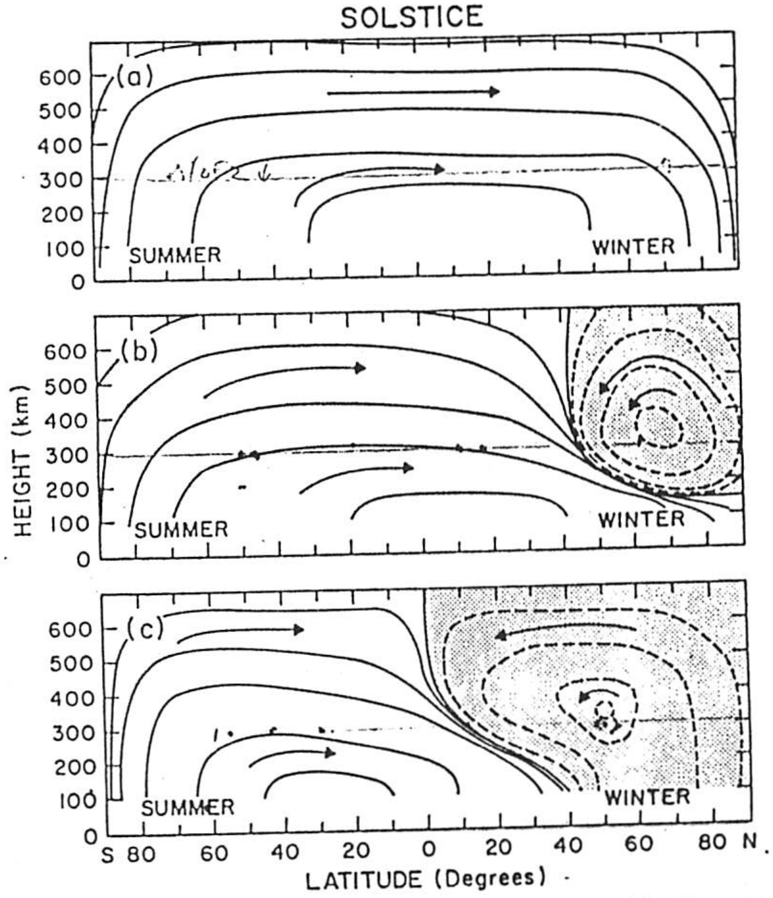


Fig. 2 Schematic diagram of the mean thermospheric circulation during solstice. The upper panel shows the circulation during quiet geomagnetic conditions, the middle panel is for average conditions, and the bottom panel is for geomagnetic storms.

Composition Changes & Vertical Winds

O/N$_2$ ratio is $\frac{\text{decreased}}{\text{increased}}$ by $\frac{\text{upwelling}}{\text{downwelling}}$ of air.

Vertical motion ⇔ energy input / release
↑ ↓

Vertical wind (neutral air)

$$W = W_B + W_D$$

"**BAROMETRIC**" 1-dim^l expansion/contraction

$$W_B = \left(\frac{\partial h}{\partial t}\right)_p$$

(Does not change composition at a fixed pressure-level)

"**DIVERGENCE**" 3-dim^l circulation (linked to horiz. wind by continuity eqn)

$$W_D = -\frac{1}{\rho g}\cdot\frac{Dp}{Dt}$$

Motion of air through pressure levels

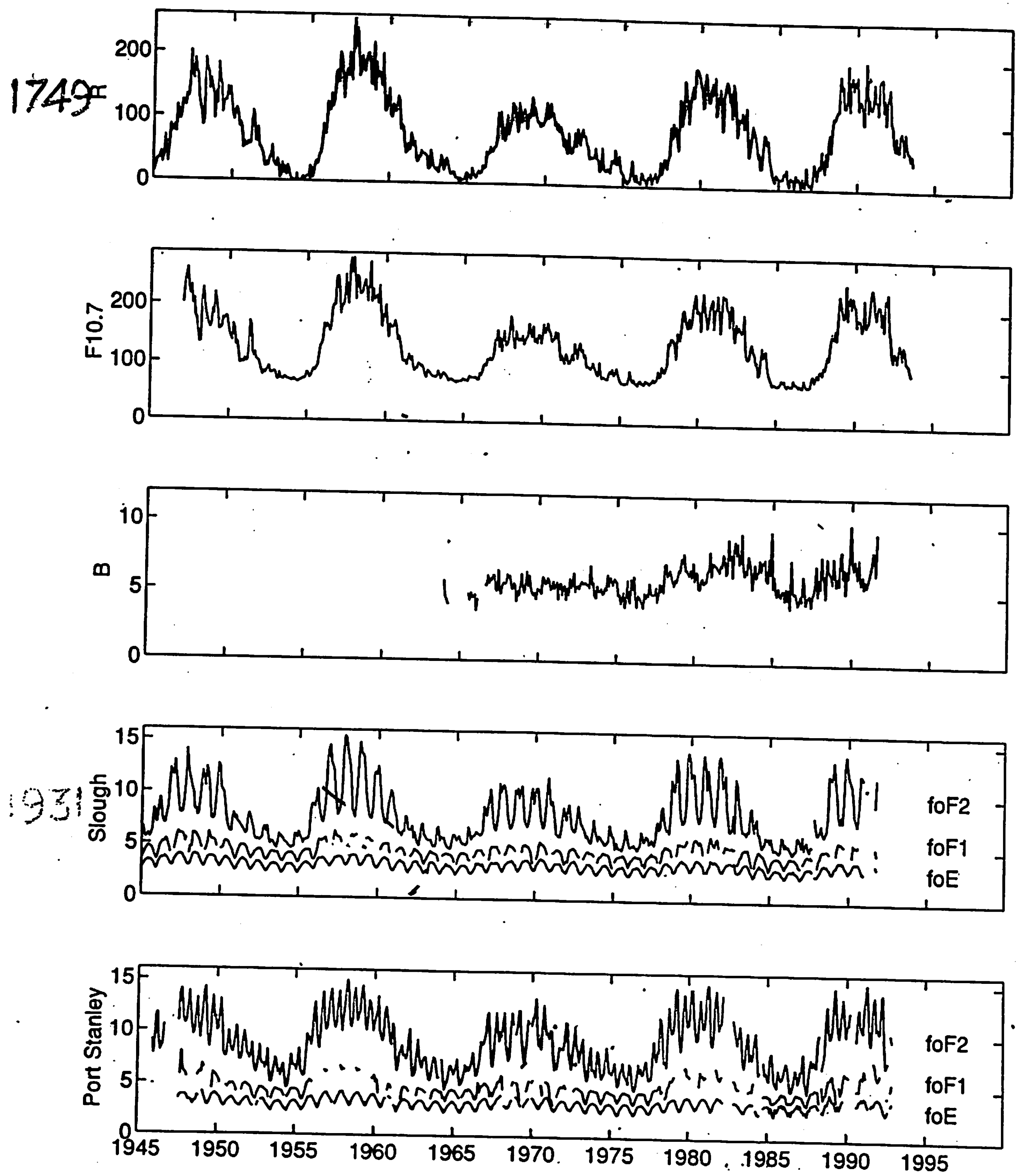
To specify composition of thermosphere

$$P = 28 \ln[O] - 16 \ln[N_2] - 12 \ln T$$

- ✱ Independent of height if thermosϕ is in diffusive equilibrium
- ✱ $\partial P/\partial h \longleftrightarrow W_D$
- ✱ Horiz. variation ⟷ global circulation ("wind induced diffusion")
- ✱ "Think pressure-levels": $Z = \int_{h_0} \frac{dh}{H}$

Effect of gravity waves!

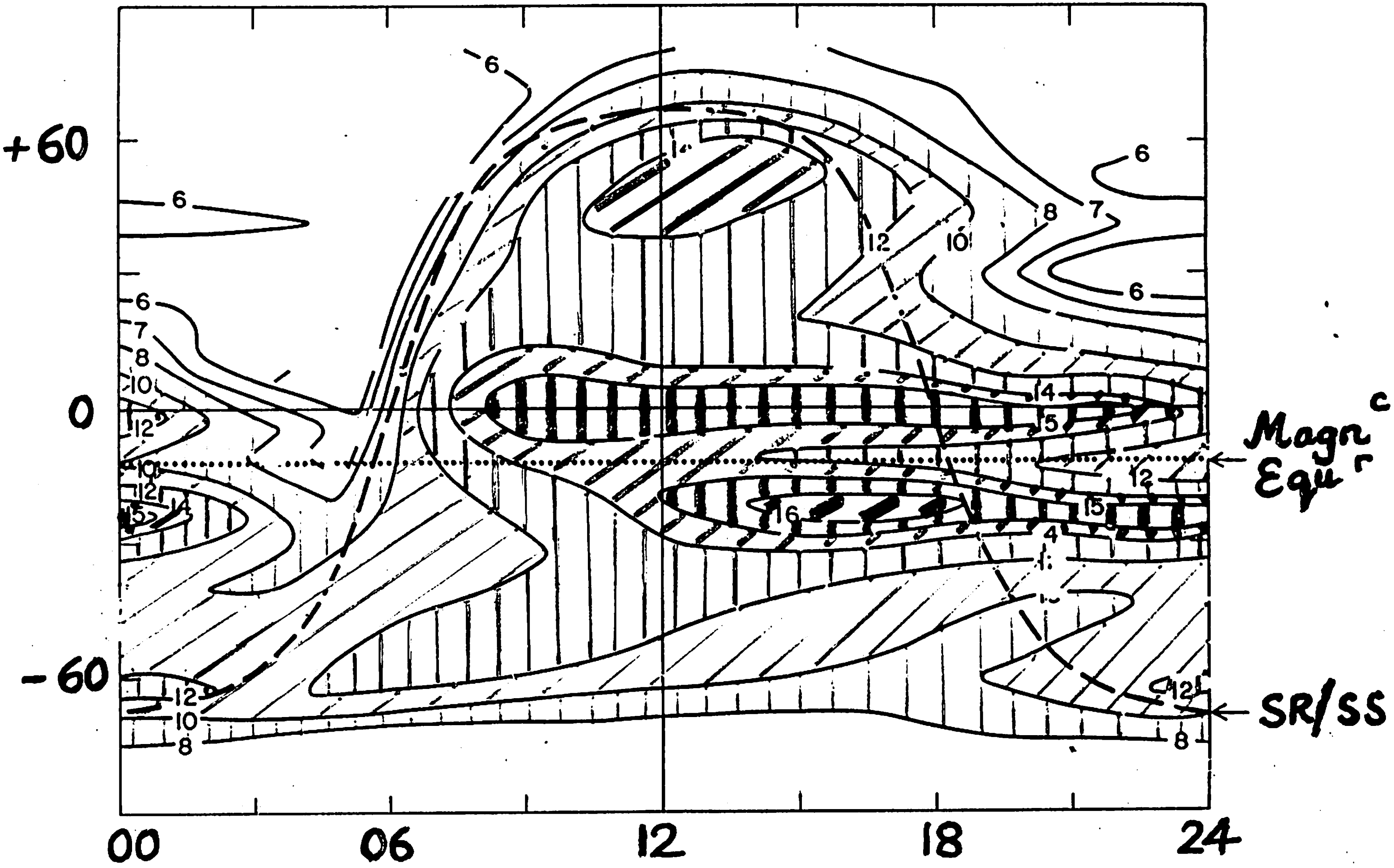
A HALF-CENTURY OF SOLAR & IONOSPHERIC DATA



Willis et al. JATP 1994

IONOSPHERIC F2-LAYER MAP FOR AMERICAN SECTOR

*fx*F2 in Latitude & Local Time : Dec 1957



F2-LAYER ANOMALIES at MID-LATITUDES

"Winter" *or* "Seasonal"	Greatest *N*mF2 in winter
"Annual"	Greatest *N*mF2 in December
"Semiannual"	Greatest *N*mF2 & *h*mF2 at equinox

PHYSICAL CAUSES

Neutral composition changes	$[O/N_2]$ ratio *or* MMM
Horizontal neutral-air winds	Vertical ion drift $U \cos I \sin I$
Solar zenith angle	Ion production $\int q\, dh \propto \cos \chi$

NEUTRAL COMPOSITION is controlled by vertical air motion

"Upwelling" ⇒ Decreased $[O/N_2]$ ratio, increased MMM

"Downwelling" ⇒ Increased $[O/N_2]$ ratio, decreased MMM

Greatest downwelling at ~ 5° equatorward of dayside auroral oval

(Millward et al.)

EXPLANATION of Seasonal & Semiannual Anomaly :

Solar-driven circulation ⇒ seasonal changes of $[O/N_2]$ ratio

Summer midlatitudes : Upwelling ⇒ Decreased $[O/N_2]$
Winter midlatitudes : Downwelling ⇒ Increased $[O/N_2]$

Greatest downwelling at about 5° equatorward of auroral oval
Horiz wind U is weak near downwelling, strong at lower latitudes

Winter at ~50° geog: sectors near magnetic poles: Atlantic / Australasian } sectors

Max downwelling & compo efect – close to auroral oval
Wind effect moderate : *U small, I large, cos I sin I ~ 0.25*

{Compo} > {zenith angle} ⇒ *N*mF2 (winter) > (equx) > (summer) → SEASONAL

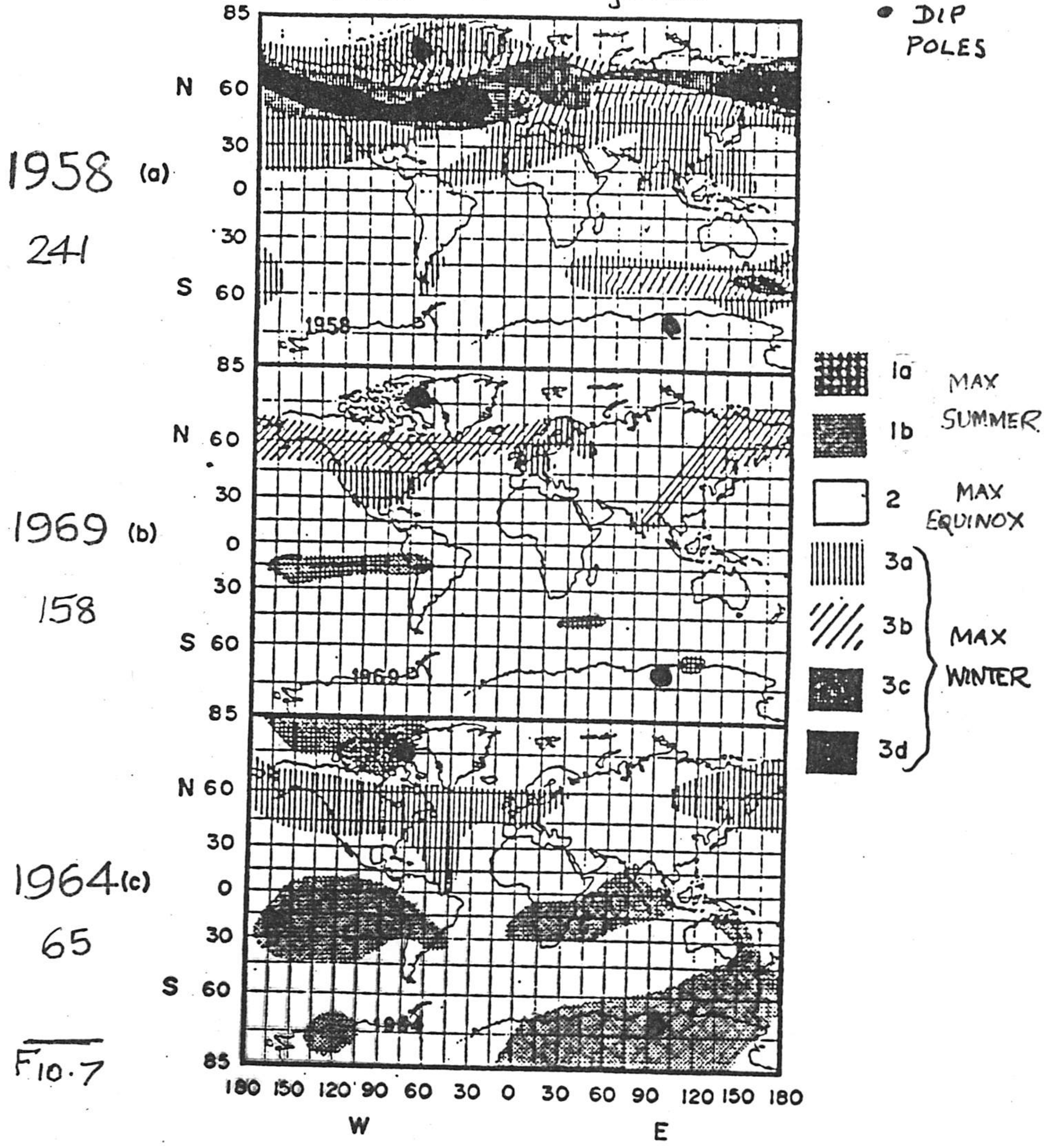
Winter at ~50° geog: sectors remote from magnetic poles: E. Asian / S. American } sectors

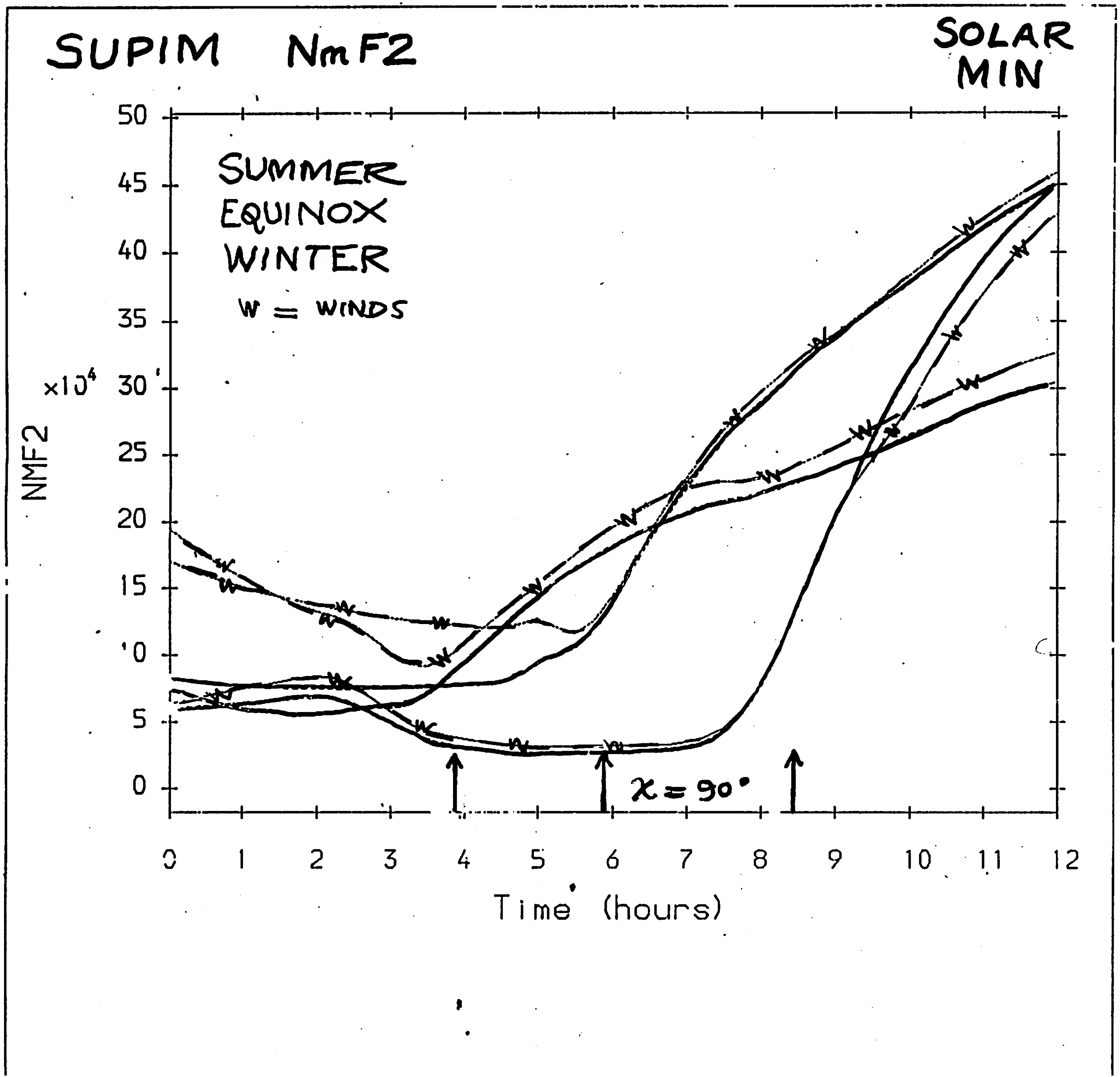
Downwelling & compo effect smaller – far from auroral oval
Wind effect strong : *U large, I moderate, cos I sin I ~ 0.5*

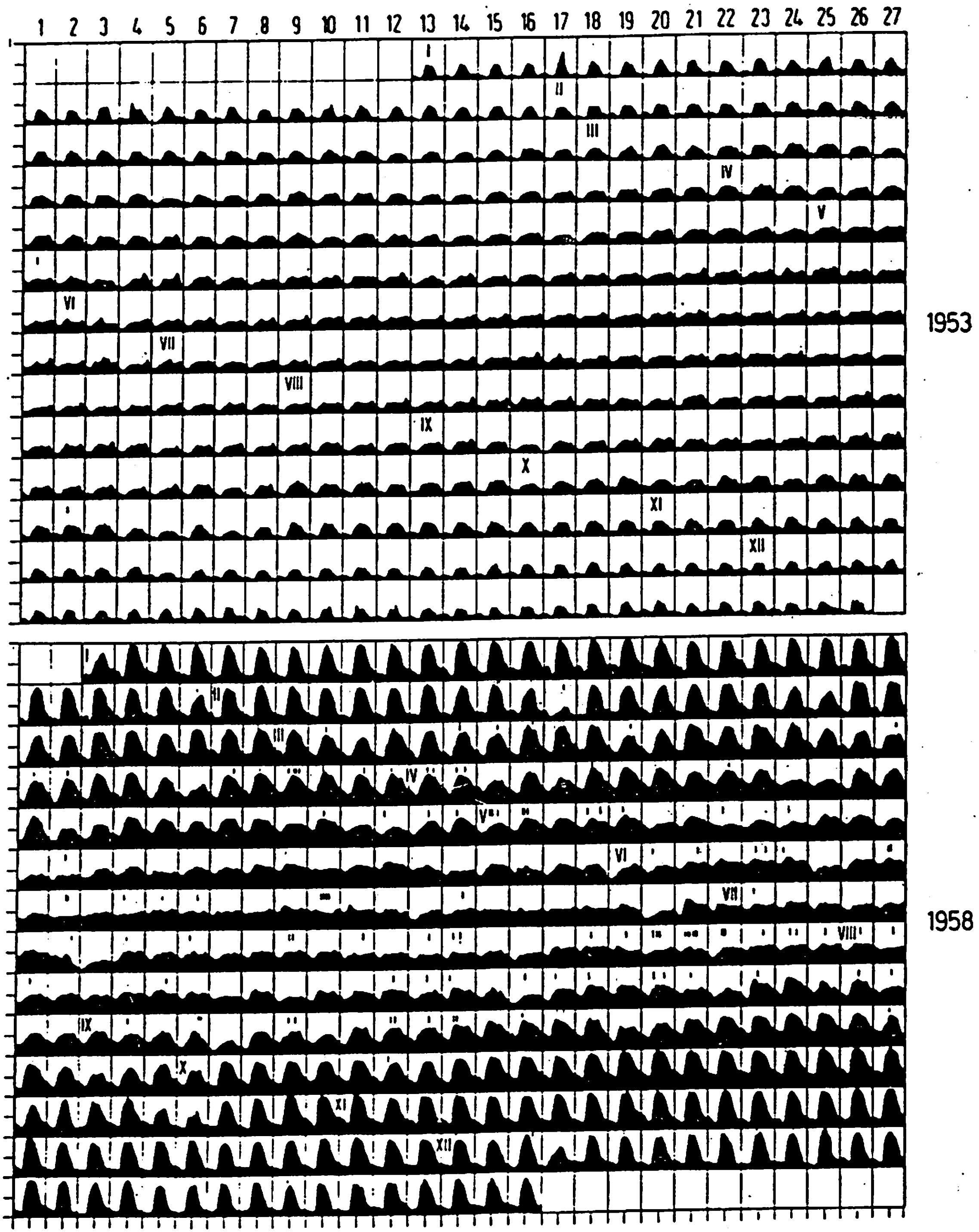
{Compo} < {zenith angle} ⇒ *N*mF2 (winter) < *N*mF2 (equinox) → SEMIANNUAL

Torr & Torr, JATP 1973

Max Noon foF2




SUPIM NmF2
SOLAR MIN
SUMMER
EQUINOX
WINTER
W = WINDS
NMF2
×10⁴
50
45
40
35
30
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
10
11
12
Time (hours)
χ = 90°



Critical Frequency foF2 at Lindau 52°N

for sunspot minimum & maximum

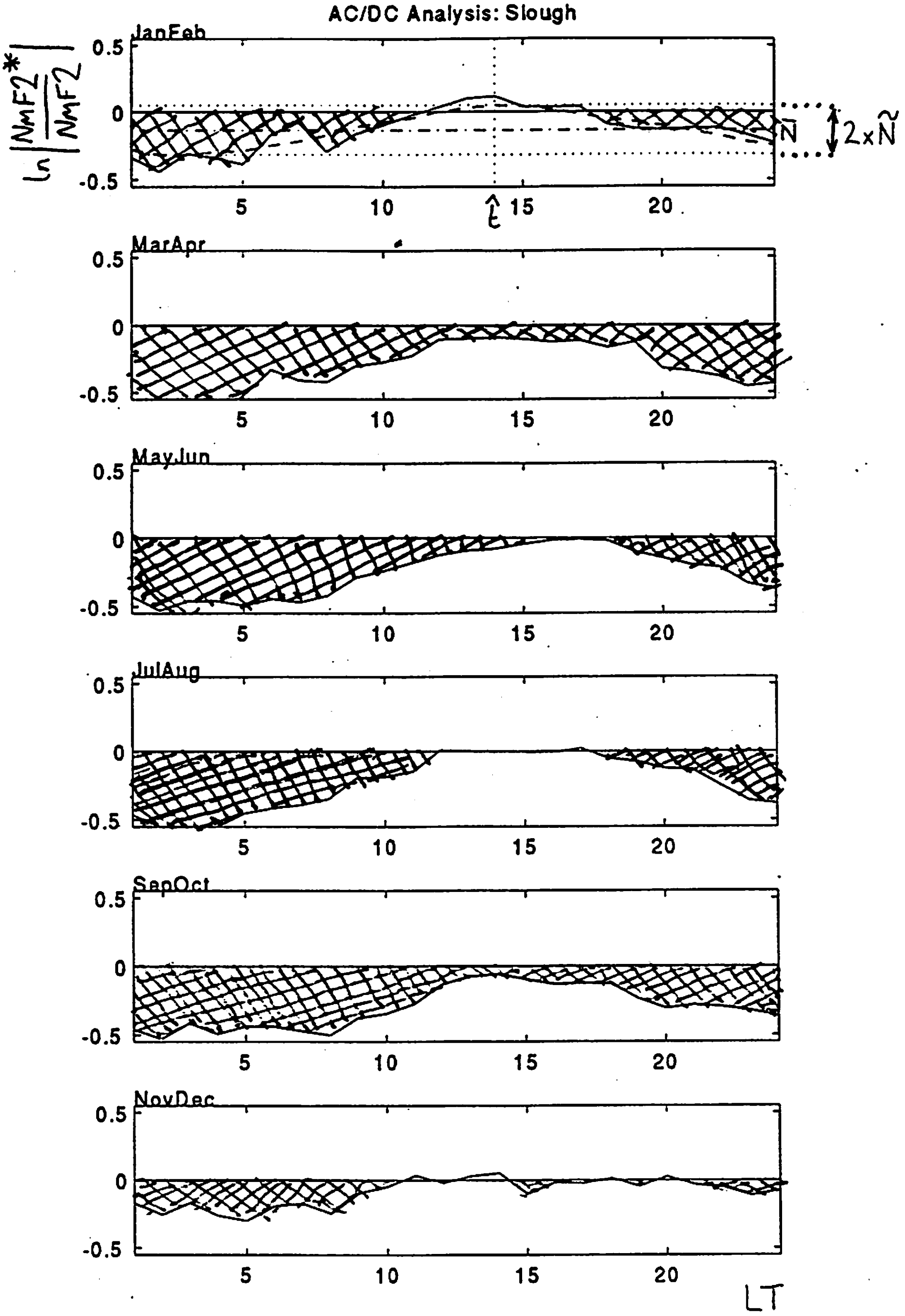
The boxes are 1–16 MHz ↕ 00–24 LT ↔

STORM

$$\ln\left(\frac{NmF2^{*}}{NmF2}\right) = \bar{N} + \tilde{N}\cdot f(t-\hat{t})$$

QUIET DC AC LT phase

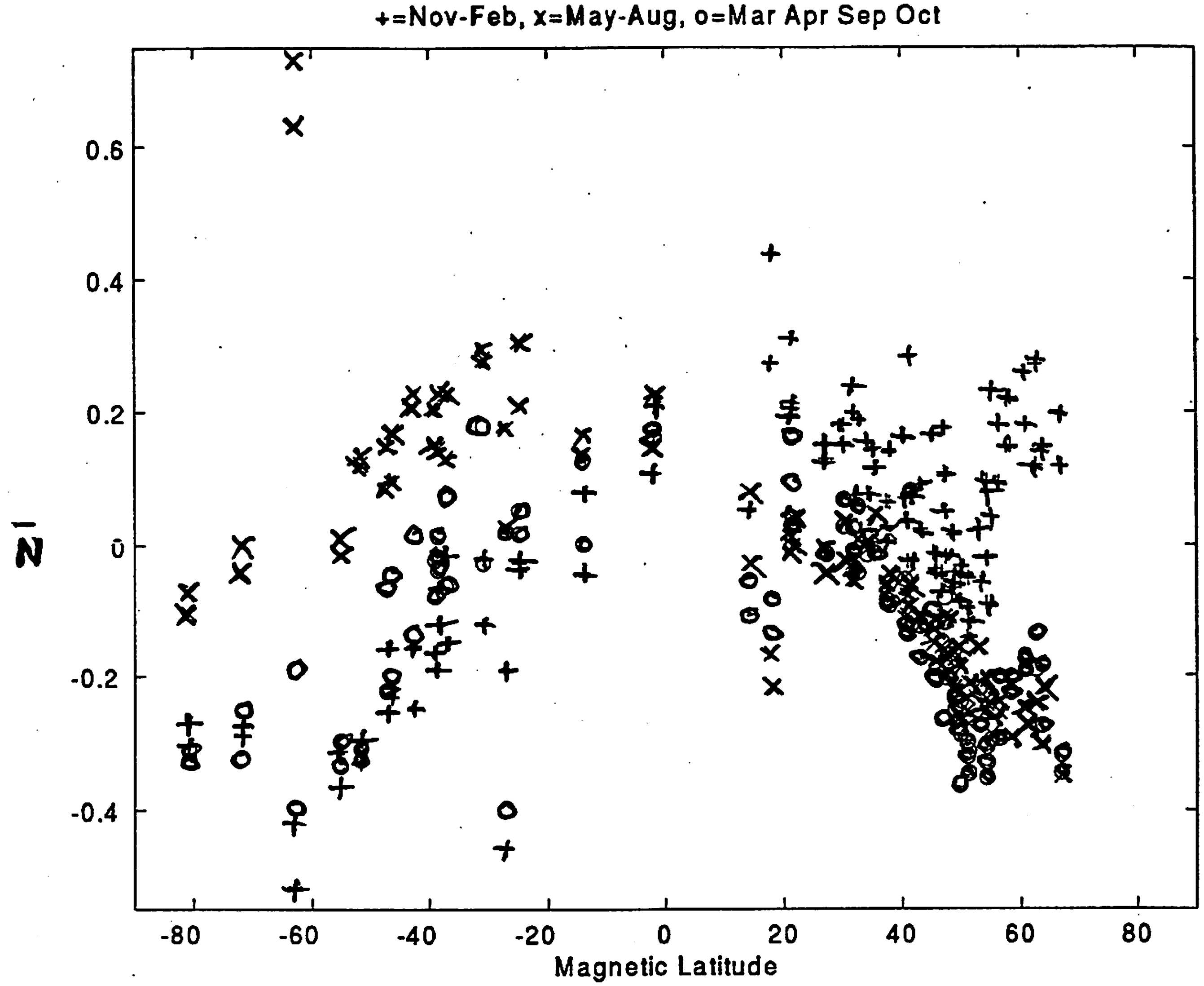
7 hr smoothed data



Rodger Wrenn Rishbeth. JATP 1987/9

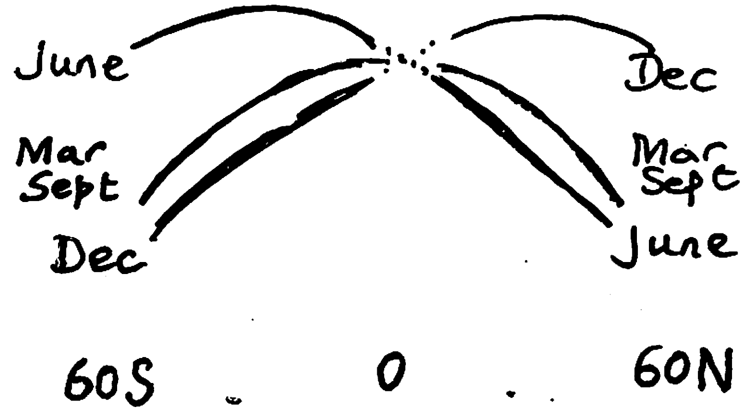
Field & Rishbeth. JASTP 1997

$\boxed{\text{DC}}$ $\ln \frac{NmF2^*}{NmF2}$ · $\frac{\text{storm}}{\text{quiet}}$



SUMMER
EQUINOX
WINTER

$\bar{N}$ vs. lat :



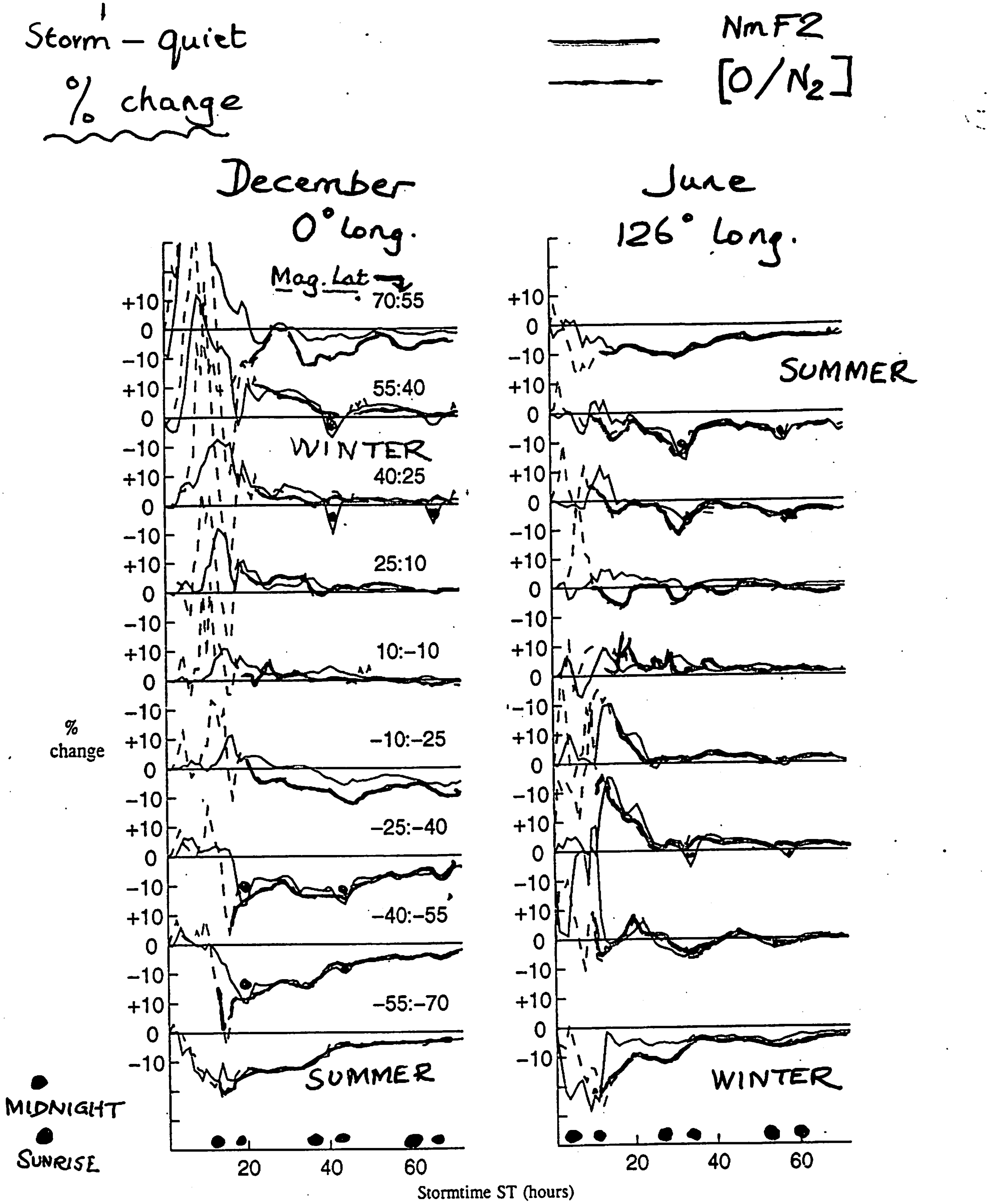


Fig. 1. Percentage changes in NmF2 (full curves) and [O/N2] ratio (dashed curves), computed from the CTIP coupled model for stormtime 0-72 hours, at nine zones of magnetic latitude as shown. Left: December solstice, geographic longitude 0° (European/African sector). Right: June solstice, geographic longitude 126° (Asian/Australian sector). Black dots show local midnight.

{EXCEPT in "INITIAL PHASE"} $$\frac{NmF2^{d}}{NmF2^{q}} = \frac{[O/N_2]^{d}}{[O/N_2]^{q}}$$ AT F2 PEAK

THINGS to THINK ABOUT . . .

- Always consider time & distance scales
  "How long does [a process] take?" "Over what distance does it operate ?"

Vertical scales (tens of km) << Horizontal scales (100-1000 km)
Vertical speeds (~ m s^{-1}) << Horizontal speeds (~ 100 m s^{-1})

But –Vertical motions are very important (structure, energy)

- Difficult to get *absolute* values of parameters from ionospheric observations
  But – modelling is often insensitive to parameters

- Better space/time resolution ⇒ new science

- Importance of routine solar-terrestrial monitoring & WDCs

- Use SI units !

HOW TO USE c.g.s. UNITS [gaussian, e.m.u., e.s.u. etc]

1 Work out numerical values, taking care with powers of 10

2 If it looks wrong, multiply by *c*

3 If it's still wrong, try c^2, $1/c$, $1/c^2$, . . . (etc)

4 If it's still wrong, try a different animal from the c.g.s. zoo

5 Repeat as necessary . . .

HOW TO USE M.K.S.A. [S I] UNITS

1 Work out numerical values, taking care with powers of 10