Introduction to the Ionosphere

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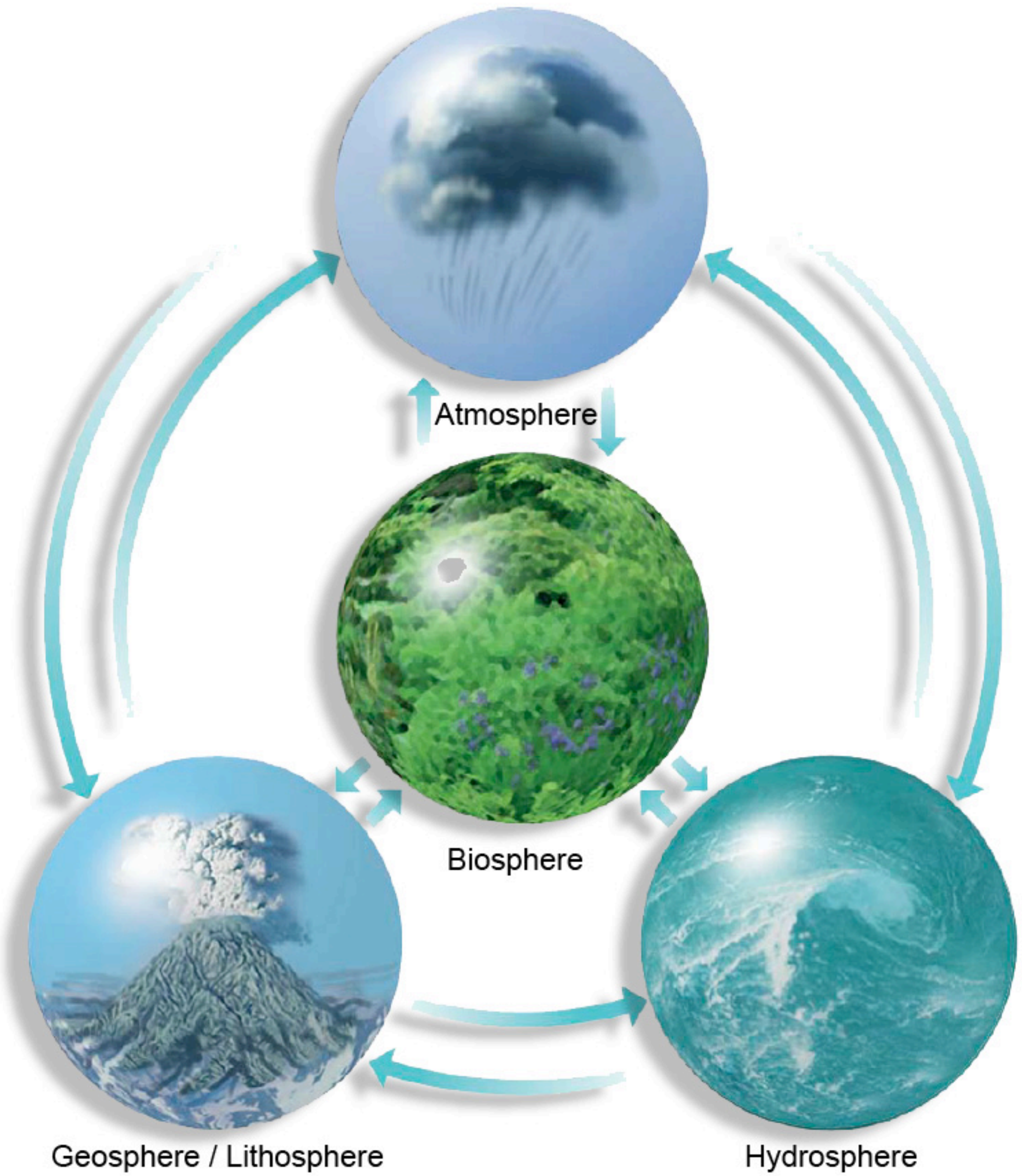
This lecture

- ✓ The atmospheric system
- ✓ Formation of the ionosphere
- ✓ Ionospheric structure
- ✓ Ionospheric variations

The atmospheric system

The Earth System



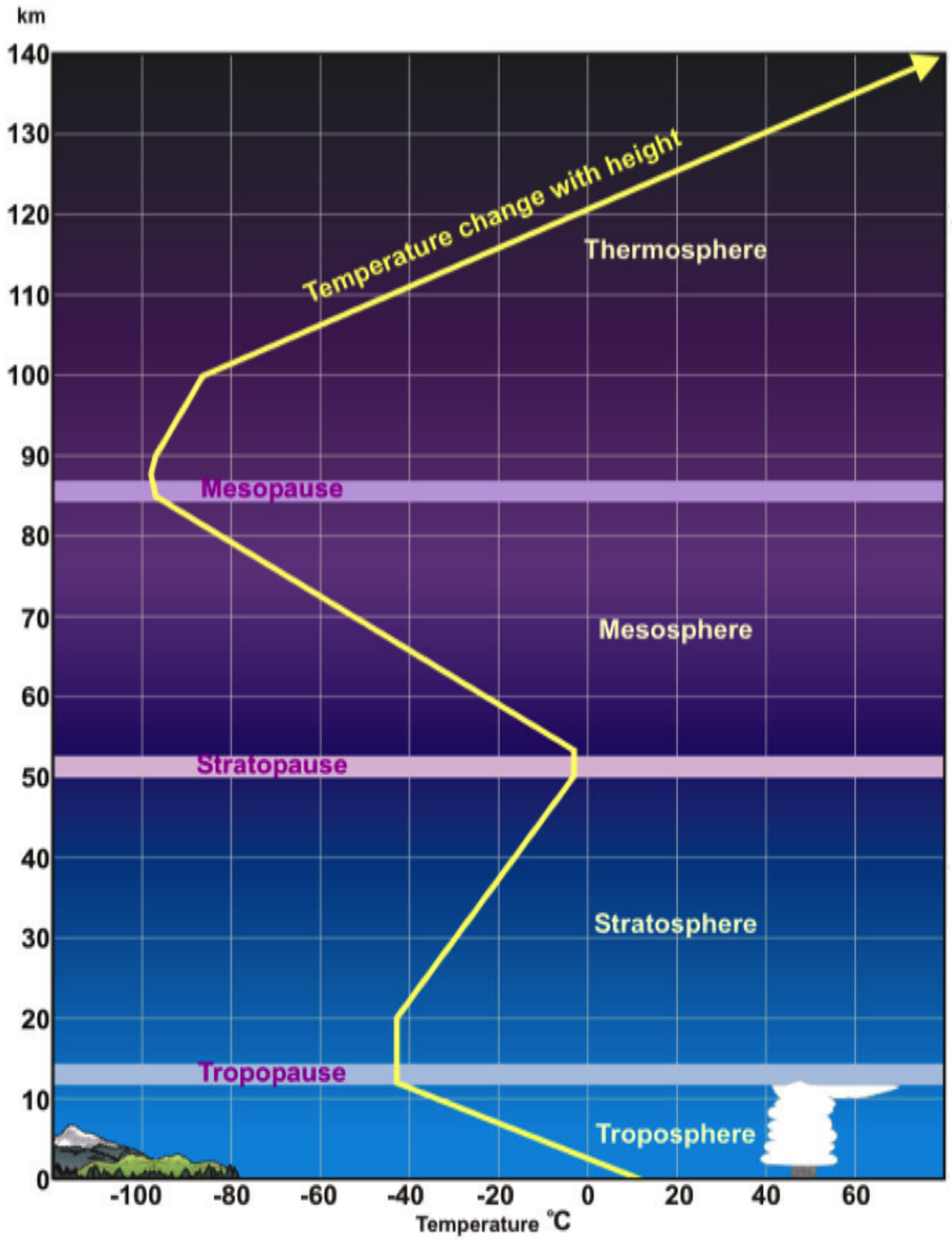
A System of *Interacting Systems*

The atmospheric system

We use a number of variables to describe the atmosphere:

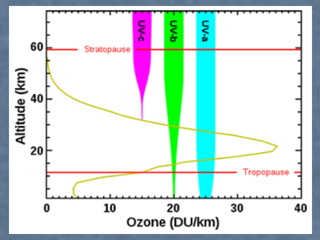
- Temperature
- Mixing ratio
- Ionization
- ...

Temperature



THERMOSPHERE: Temperature increases steadly with altitude because is heated mainly by absorption of EUV and XUV radiation through dissociation of molecular oxygen. Temperature is highly variable with time of day and solar activity.

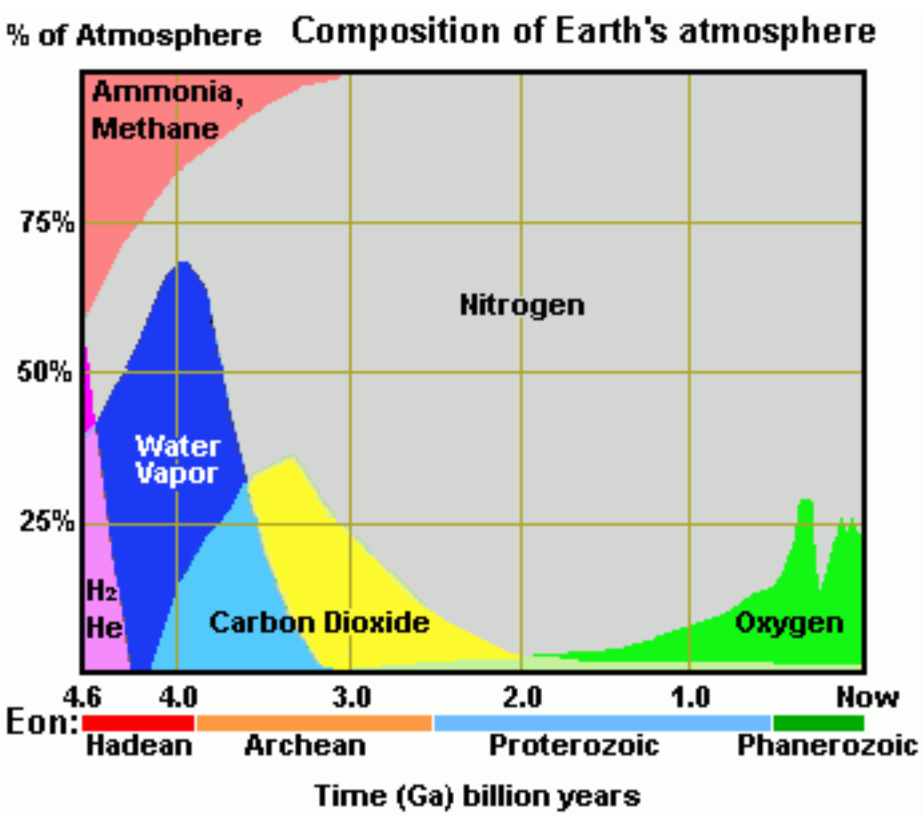
MESOSPHERE: Temperature decreases with altitude because ozone density decreases faster than the increase of incoming radiation.

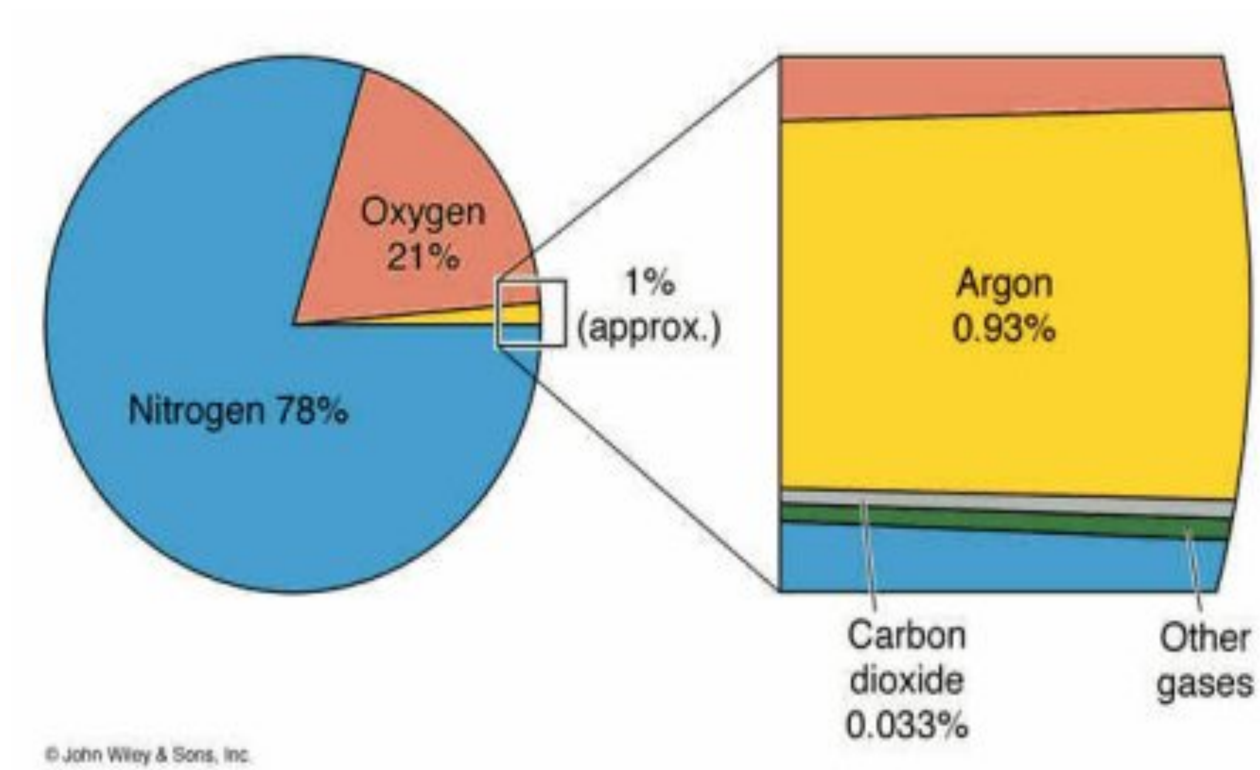


STRATOSPHERE: Temperature increases with altitude due to heating from the *ozone* which absorbs the solar ultra-violet radiation that penetrates down to these altitudes.

TROPOSHERE: Temperature decreases with altitude. Heated mainly by the ground, absorbs solar radiation and re-emits it in the infra-red.

Atmospheric composition: ground level





EVOLUTION IN TIME

NOW

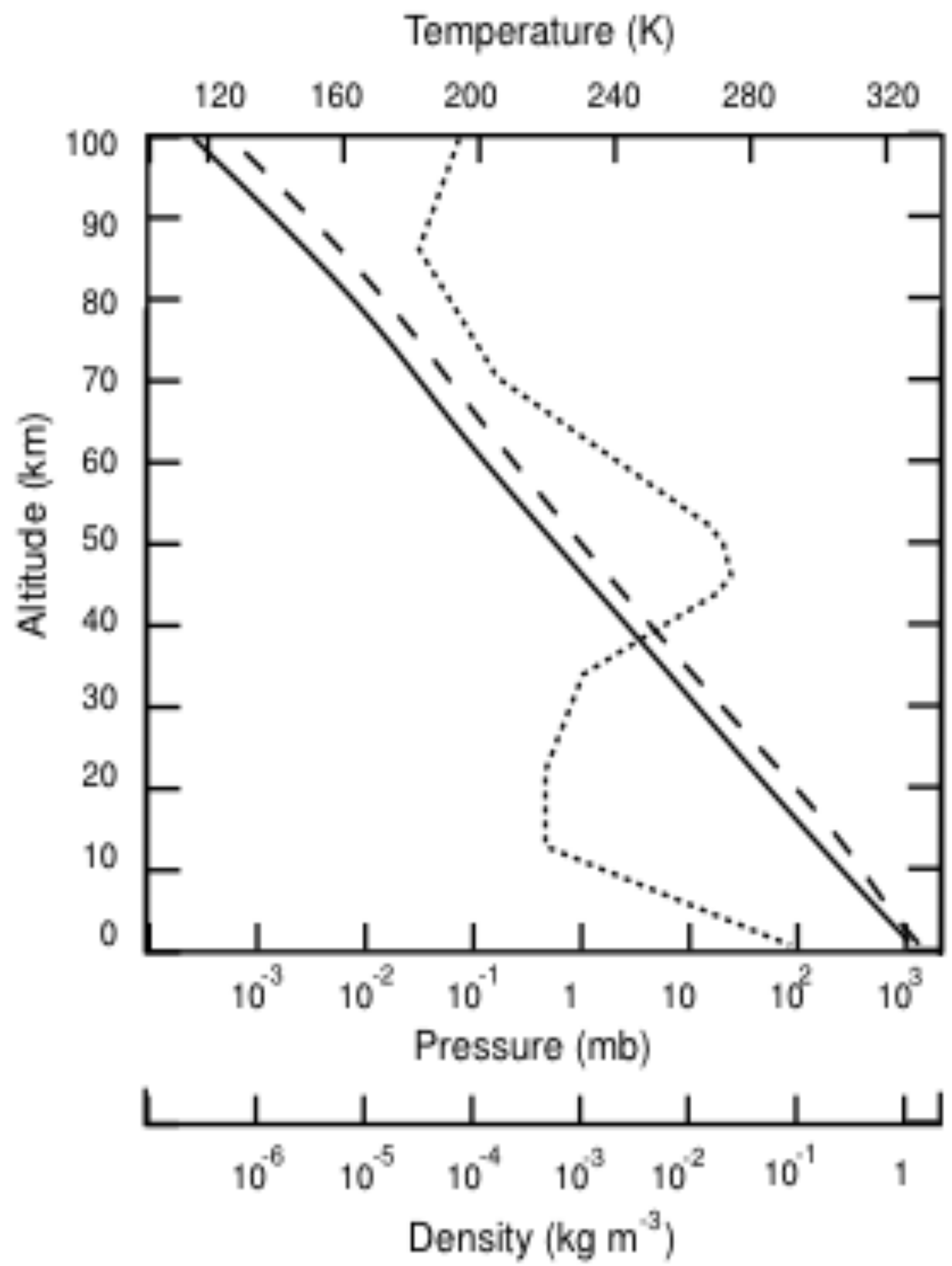
Mixing Ratio

Turbulent mixing: ***lower and middle atmosphere***

- ✓ Does not depend on molecular weight
- ✓ Tends to be independent of height

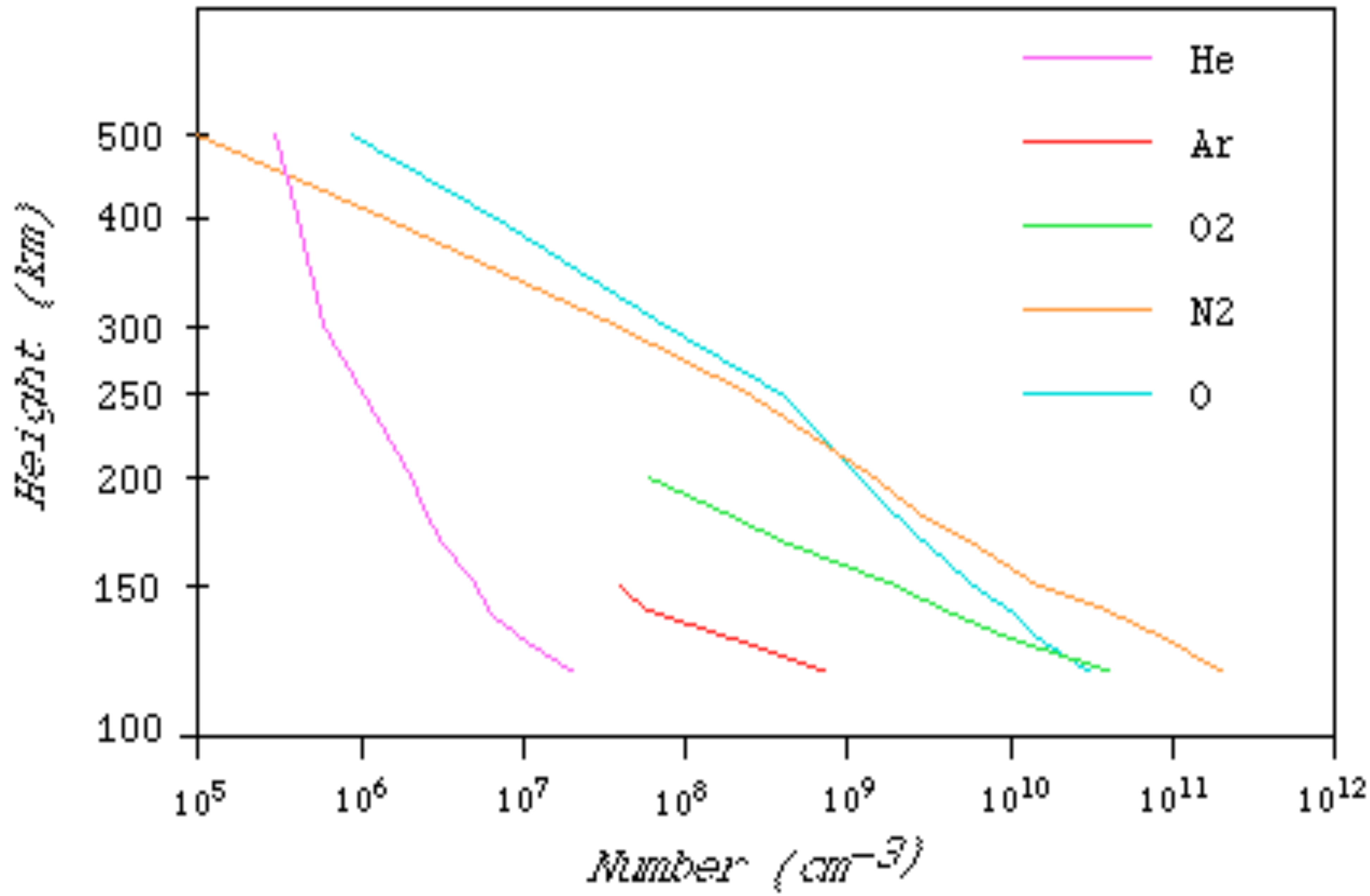
Diffusion: ***upper atmosphere***

- ✓ Mean molecular weight of mixture gradually decreases with height.
- ✓ Only lightest gases are present at higher levels.
- ✓ Each gas behaves as if it were
- ✓ alone.

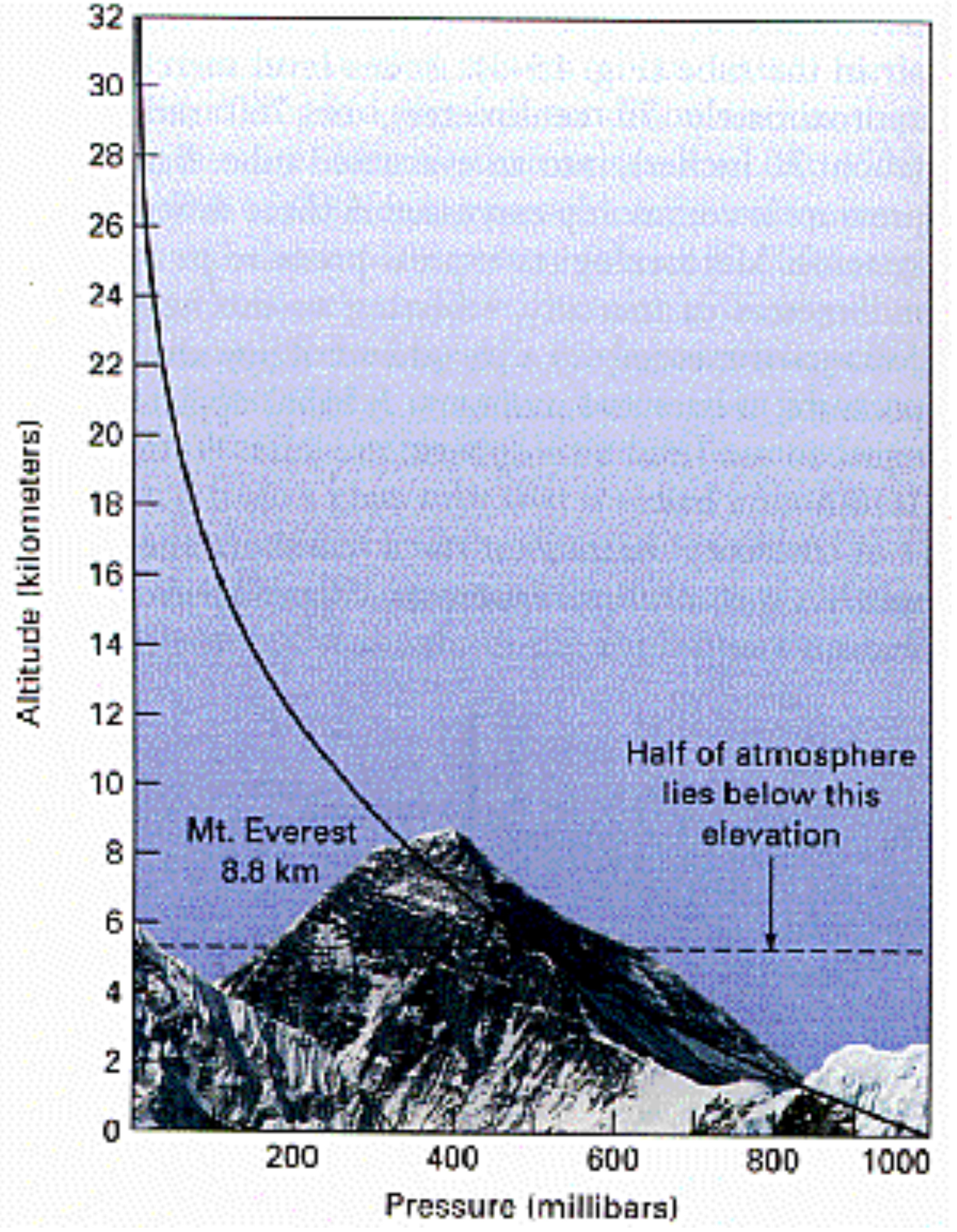


Near 100km: diffusion = turbulent mixing.
Density drops-of exponentially with height

Neutral atmosphere composition in the upper atmosphere



A closer look to the atmospheric pressure



Atmospheric Hydrostatic Equilibrium

Pressure Gradient: $$\frac{dp}{dz} = -g(z)\rho$$ height derivative of pressure equals acceleration of gravity times density

Perfect Gas Law: $$p = nkT = \frac{\rho}{M}kT$$

Approximation: If g and T are not functions of z, then:

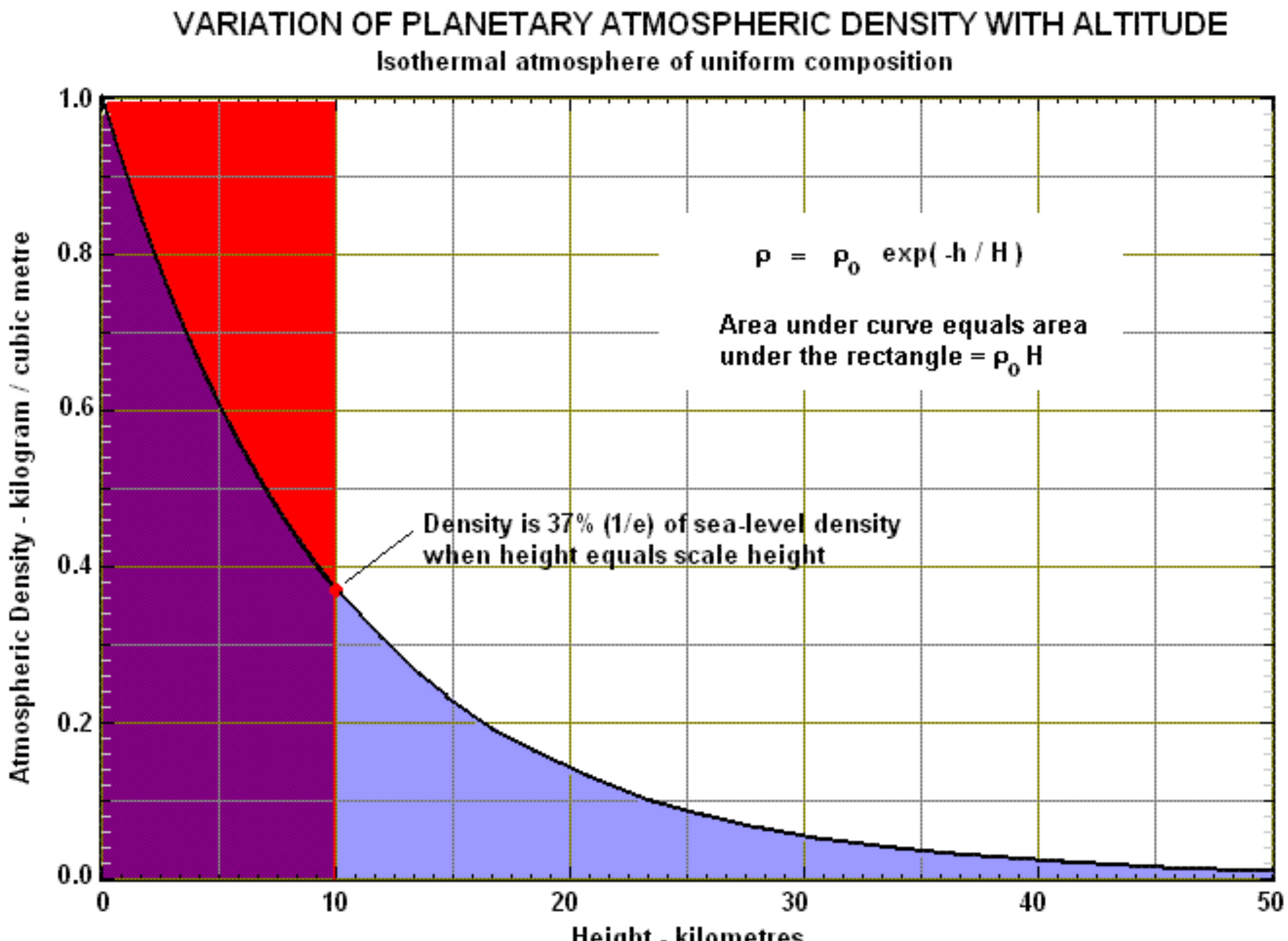
$$\frac{dp}{dz} = -p\frac{Mg}{kT} = -\frac{p}{H} \qquad H = \frac{kT}{Mg}$$

H = scale height (e-folding distance)

$$\frac{dp}{p} = -\frac{dz}{H} \qquad p(z) = p(z_0)\exp\left[-\frac{z - z_0}{H}\right]$$

Scale Height

In various scientific contexts, a "Scale Height" is a distance over which a quantity decreases by a factor of *e*.



The scale height is also a measure of the atmospheric density gradient – a lower scale height implies a higher gradient.

The scale height is the height at which the atmosphere would extend if it were all compressed into one of constant density (the rectangular area in the above diagram)

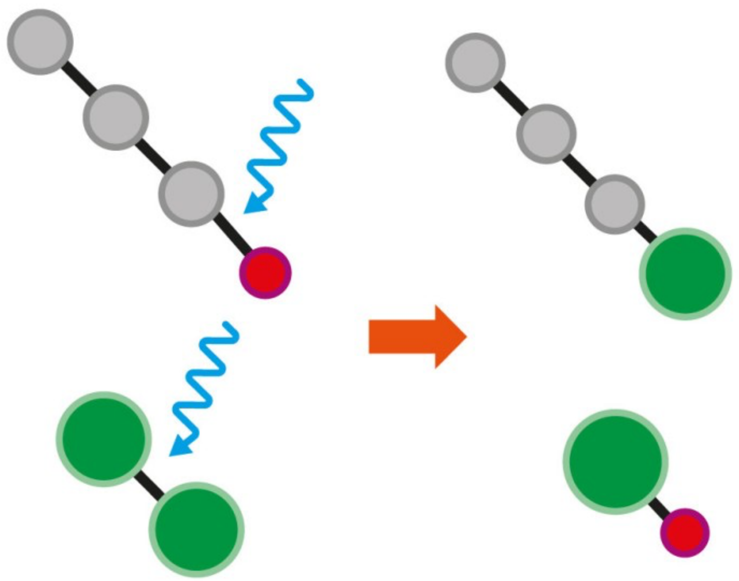
Formation of the ionosphere

Photochemical processes in the atmosphere

The atmosphere of the Earth is made up of a large number of chemical constituents.

Major constituents are N_2, O_2 and Ar, but many more constituents are produced in the atmosphere by *photochemical processes* or at the surface by different natural processes and human activity.

Photochemical processes play a fundamental role in the middle and upper atmosphere including the ionosphere.



Main photochemical absorption processes of solar radiation

Photodissociation $AB + h\nu \rightarrow A + B$

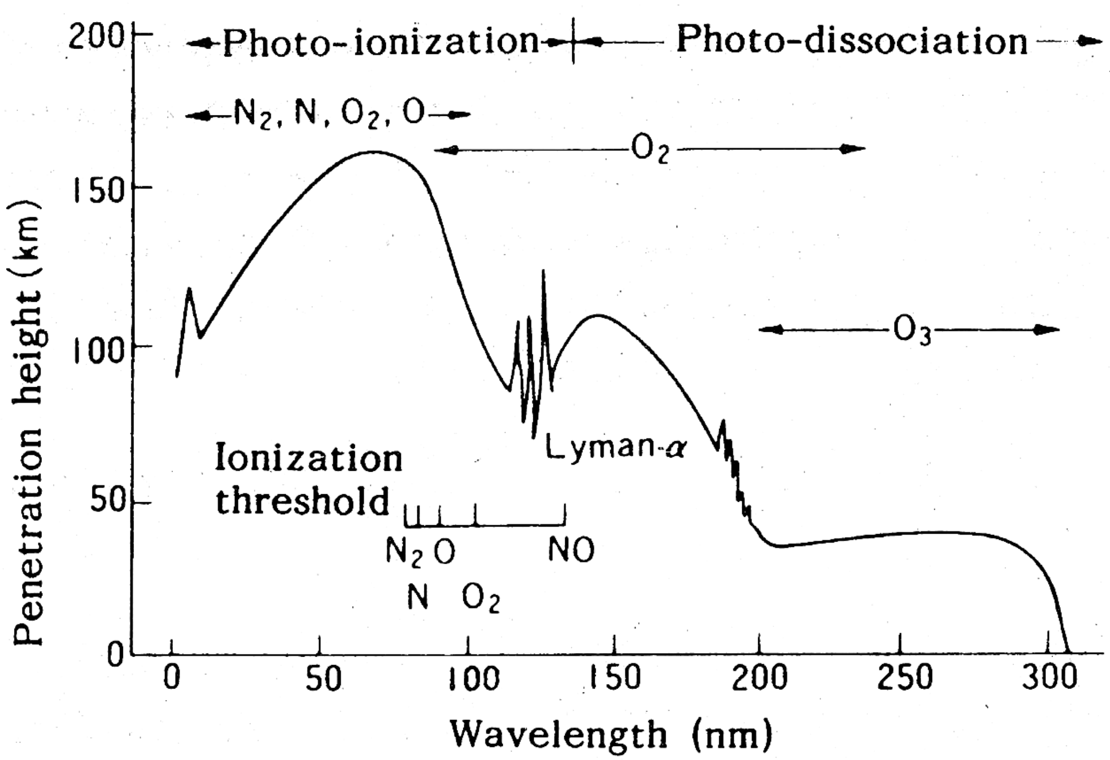
(wavelenght > 130 nm)

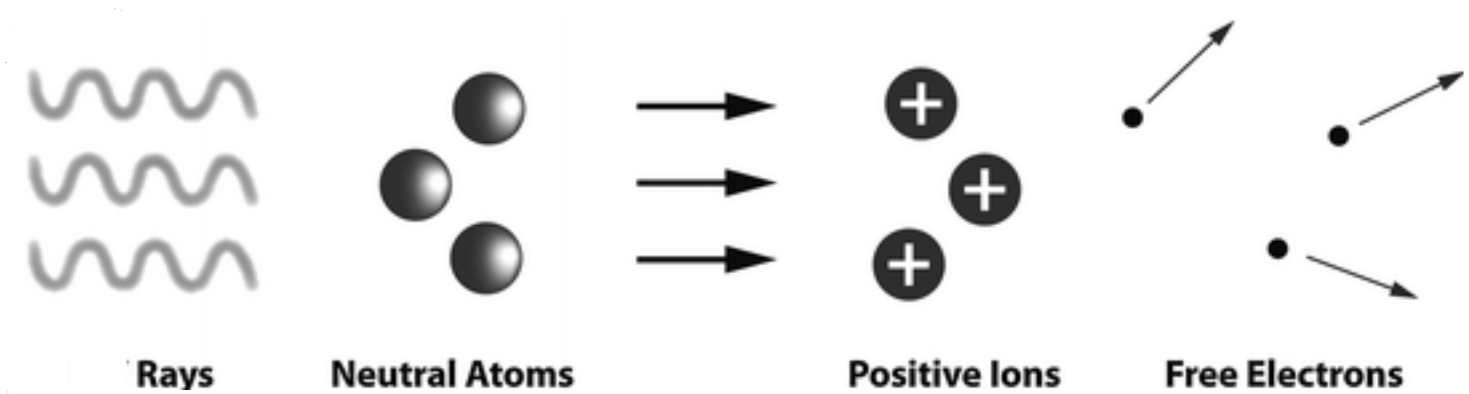
Photoexcitation $AB + h\nu \rightarrow AB^*$

(wavelenght < 130 nm)

Photoionization $A + h\nu \rightarrow A^+ + e$

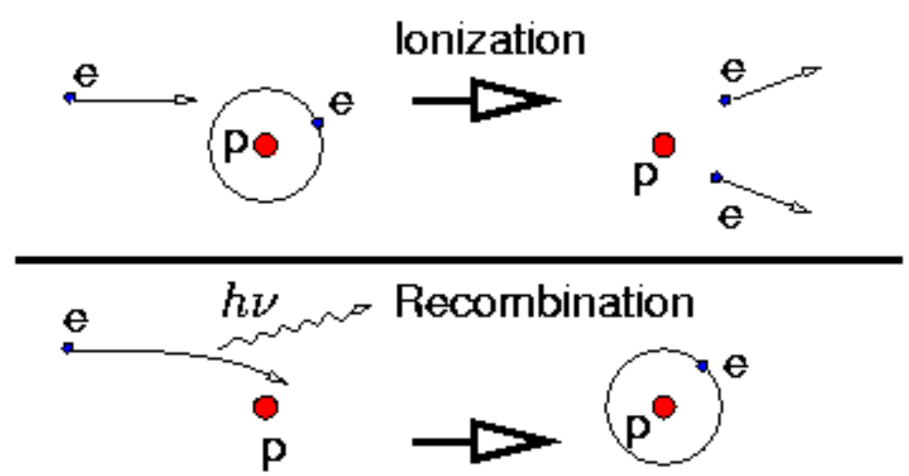
(wavelenght < 100 nm)





Ionic species recombination processes

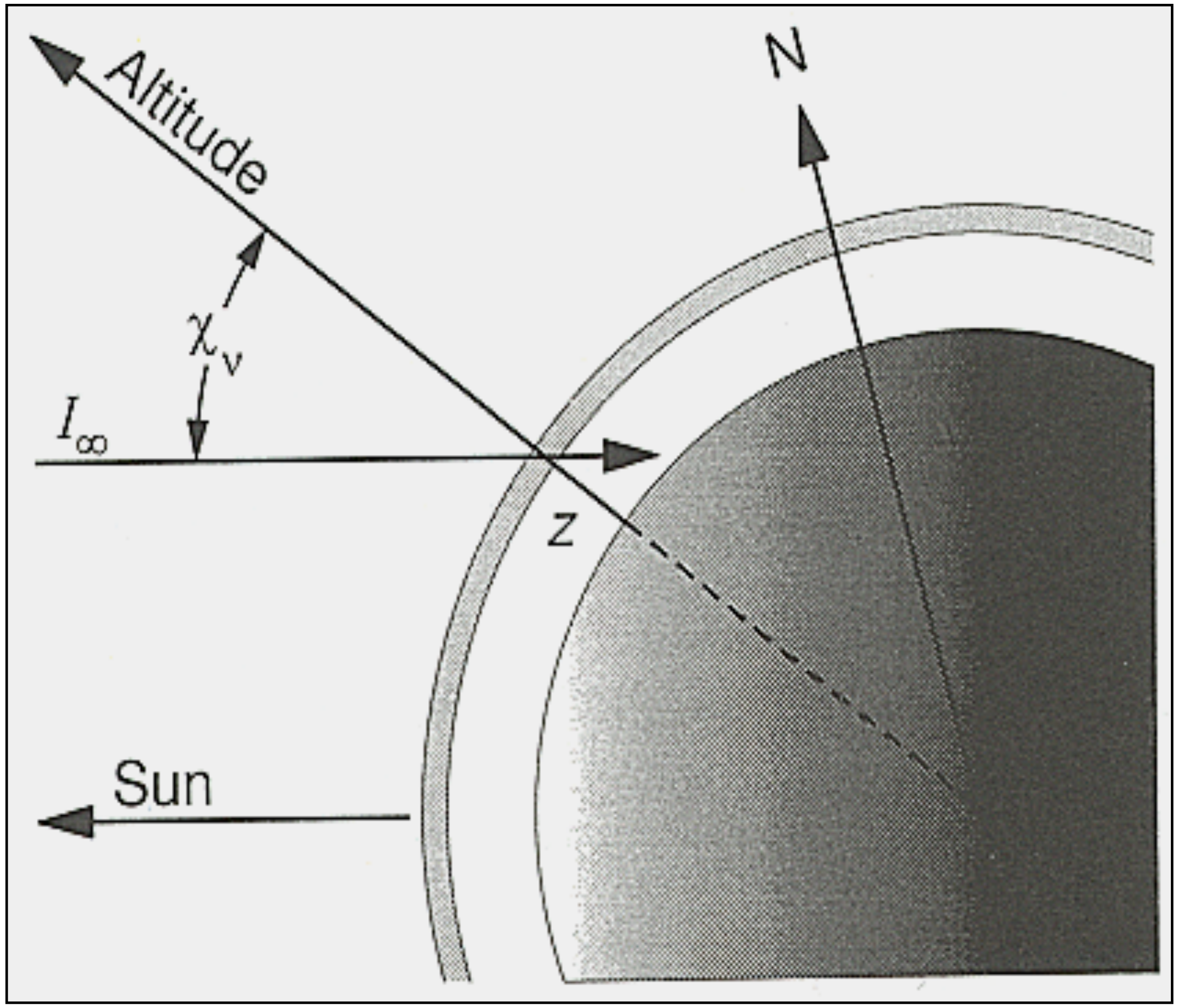
Radiative Recombination	$X^+ + e \rightarrow X + h\nu$ (α_R)
Dissociative Recombination	$XY^+ + e \rightarrow X + Y$ (α_D)
Ion-Ion Recombination	$XY^+ + Z^- \rightarrow$ neutrals (α_I)



Formation of the Ionosphere

Solar UV and X radiation impinges at angle χ_ν and a flux I_∞ on the top of the atmosphere.

Solar radiation is absorbed in the upper atmosphere and ionizes the neutral atmosphere



Chapman layer theory

Named for Sydney Chapman, who first derived mathematically the shape of such a distribution.

The theory assumes:

- A monocromatic ionizing radiation from the sun,
- A single neutral constituent to be ionized distributed exponentially (i.e., with a constant scale height),
- Photochemical equilibrium

Basic equations of solar radiation absorption in the atmosphere (1)

H is the neutral scale height,

$H = k_B T_n / m_n g$,

with *g* being the gravitational acceleration at height $z = 0$, where the density is n_0.

According to radiative transfer theory, the incident solar radiation diminishes with altitude along the ray path in the atmosphere.

σ_ν is the radiation absorption cross section for radiation (photon) of frequency ν.

$$n_n(z) = n_0 \exp(-z/H)$$

$$dI = \sigma_\nu n_n \frac{dz}{\cos \chi_\nu} I$$

Basic equations of solar radiation absorption in the atmosphere (2)

Solving for the intensity yields:

$$I(z) = I_\infty \exp\left[-\frac{\sigma_\nu n_0 H}{\cos\chi_\nu}\exp(-z/H)\right]$$

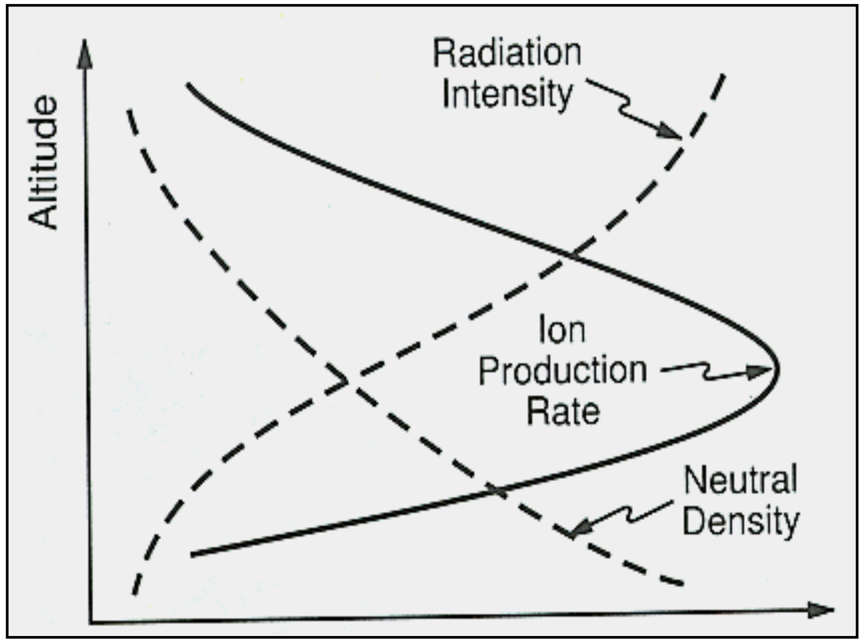
$$q_\nu(z) = \kappa_\nu \sigma_\nu n_0 I_\infty \exp\left[-\frac{z}{H} - \frac{\sigma_\nu n_0 H}{\cos\chi_\nu}\exp(-z/H)\right]$$

The photoionization rate per unit volume $q_\nu(z)$, is proportional to the ionization efficiency, κ_ν, and absorbed radiation:

$$q_\nu(z) = \kappa_\nu \sigma_\nu n_n I(z)$$

This equation describes the formation of the Chapman layer and represents the basis of the theory of the photochemical processes in the atmosphere.

- ✓ Radiation intensity decreases and neutral density increases with decresing altitude.
- ✓ As a consequence ion production reaches a maximum and after that decreases, forming a layer.



Basic equations of solar radiation absorption in the atmosphere (3)

Assuming dissociative recombination and equilibrium quasi-neutrality ($n_e = n_i$),

The continuity equation for n_e reads:

$$\frac{dn_e}{dt} = q_{v,e} - \alpha_T n_e^2$$

Ionospheric structure

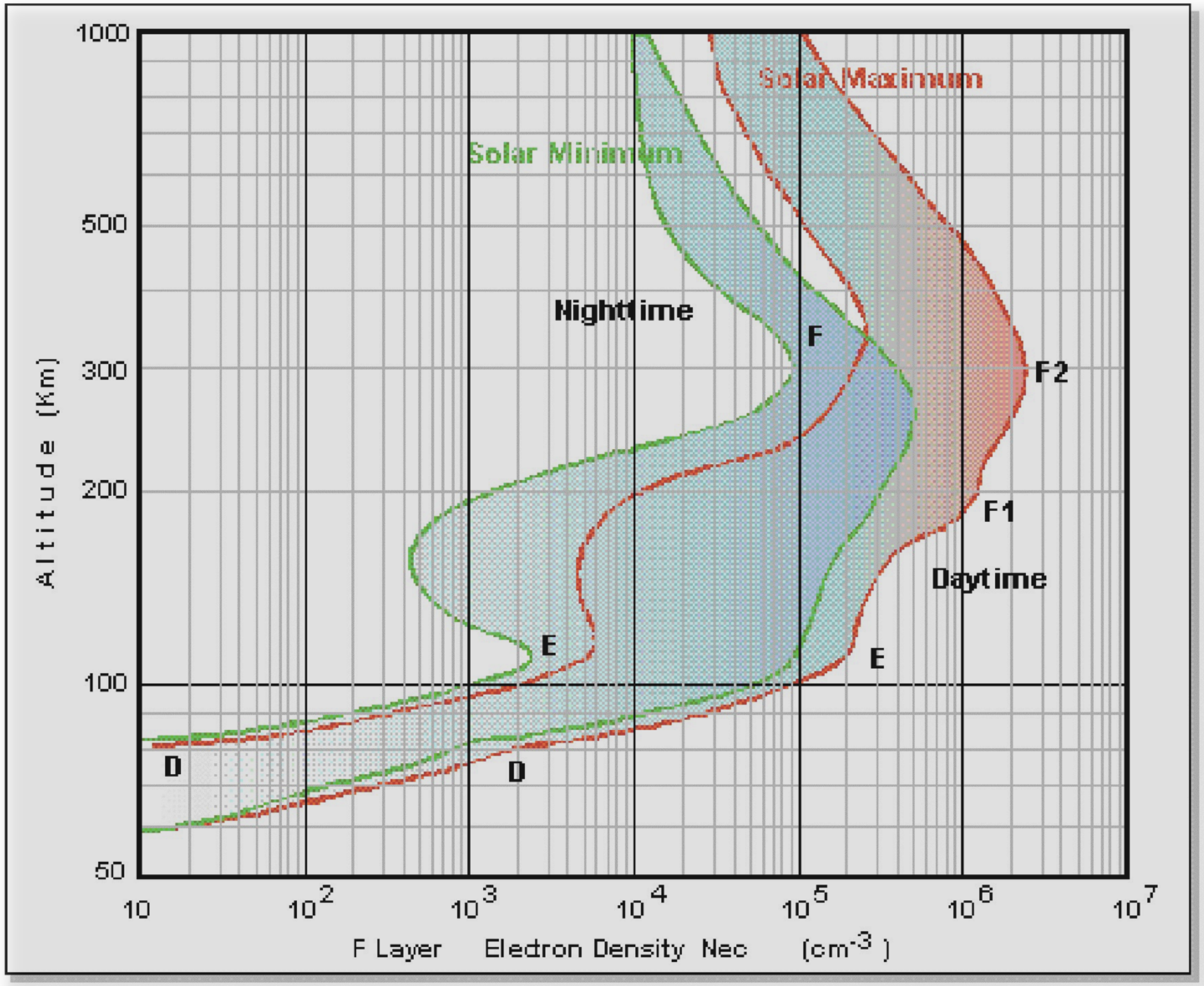
A layered structure

Layered structure varying with time and solar activity due to
different ionization production and loss processes

Transport processes become important in the F2 region and topside, including ambipolar diffusion and wind-induced drifts along B and electromagnetic drifts across B.

E and F1 regions behave as a Chapman layer dominated by photochemical processes.
At the E region heights sporadic thin layers can be formed with electron densities above the background values.

D region is characterized by the presence of negative ions due to the attachment of electrons to neutrals



Continuity equation and Ion transport in the F region

Formed ions and electrons (P), tend to recombine (L) but are also affected by transport with a plasma drift V.

$$\frac{\partial n_e}{\partial t} = P - L - div(n_e V)$$

F region chemistry (1)

Above ca. 150 km ion-electron production is by EUV (10-90 nm)

$$O + h\nu \rightarrow O^{+} + e$$

$$N_2 + h\nu \rightarrow N_2^{+} + e$$

F region chemistry (2)

Recombination is a two-stages process:

$$O^+ + N_2 \rightarrow NO^+ + N \text{ (attachment like), rate} \propto \beta[O^+]$$

This reaction controls the loss rate at high heights

$$NO^+ + e \rightarrow N + O \quad \text{rate} \propto \alpha[NO^+][n_e]$$

This reaction controls the rate at low heights

$$\frac{dn_e}{dt} = q(z,\chi) - \alpha_D n_e^{\,2} - \beta n_e$$

This is the continuity equation (without transport) for electron density

F region chemistry (3)

Continuity equations for the ionized species

$$\frac{dn_e}{dt} = q - \alpha_D n_e [NO+]$$

$$\frac{d[O+]}{dt} = q - \beta[N_2][O+]$$

$$\frac{d[NO^+]}{dt} = \beta[N_2][O+] - \alpha_D n_e [NO+]$$

$$\Bigg\} \quad \frac{1}{q} = \frac{1}{\beta[N_2]} + \frac{1}{\alpha_D n_e^2}$$

$$\beta[N_2] >> \alpha n_e \ ; [NO^+] >> [O^+] \Rightarrow q = \alpha n_e^2$$

$$\beta[N_2] << \alpha n_e \ ; [NO^+] << [O^+] \Rightarrow q = \beta[N_2] n_e$$

F region chemistry (4)

Assuming photochemical equilibrium in the F region

$$q \propto I_\infty [O]$$

At low heights $$n_e = (q/\alpha)^{1/2} \propto (I_\infty [O])^{1/2}$$

At F2 heights $$n_e \propto [O]/[N_2]$$

More exactly :

At F2 heights: $$n_e \propto I_\infty [O]/[N_2]$$

This result is important to explain same aspects of the variability of the F2 electron density

NmF2 and [O]/[N2]

The annual and semi-annual amplitudes (normalized) and phases for NmF2 and [O/N2] at example stations

Yu, T. et al. (2004), Global scale annual and semiannual variations of daytime NmF2 in the high solar activity years, J. of Atmos. and Solar-Terr. Physics 66, 1691-1701

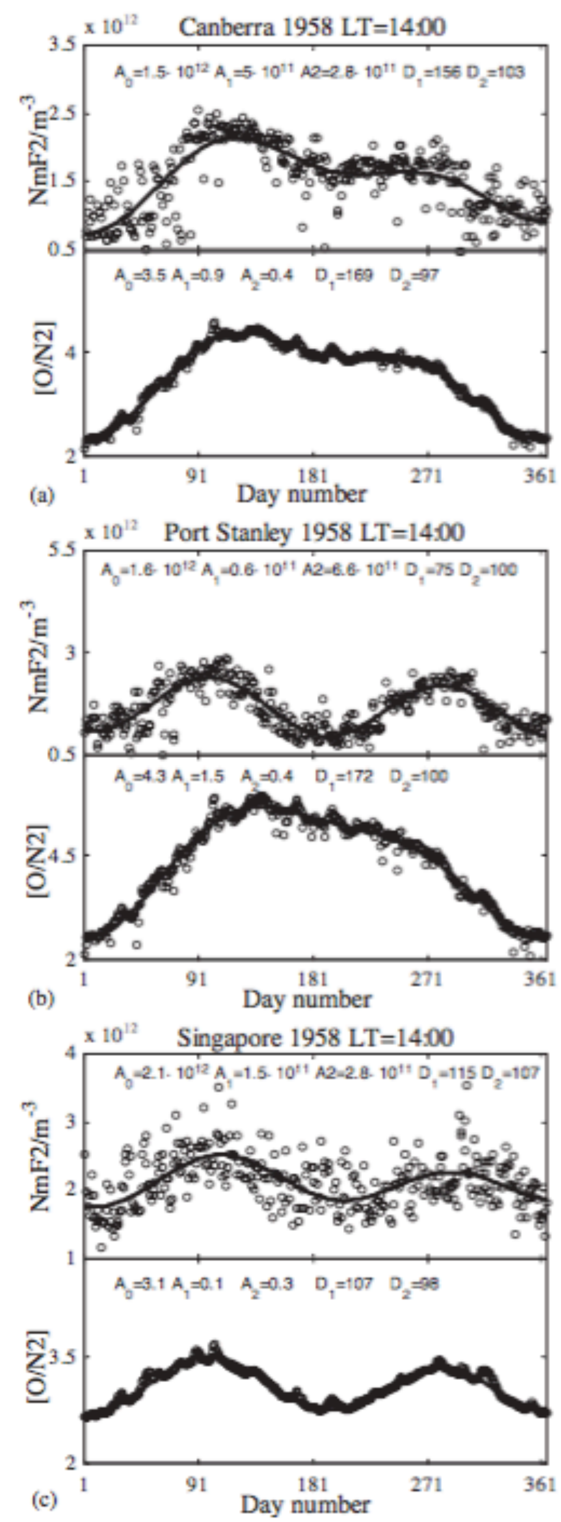


Fig. 8. The variation for the daytime NmF2 at Canberra Station, Port Stanley Station and Singapore Station are respectively, shown in the upper panel of 8(a)–(c), and the [O/N2] at those stations are shown in the bottom panel.

High Latitude

NmF2 shows the same pattern as [O/N2].
NmF2 appears controlled by [O/ N2].

Middle Latitude

Port Stanley, NmF2 shows dominant annual variation, [O/N2] semi- annual one. NmF2 partly controlled by the [O/N2].

Low Latitude

NmF2 and [O/N2] main semi-annual variation but not annual components. [O/ N2] plus other mechanisms contribute to NmF2 variation.

Transport in the F region (1)

Ions and electrons are also affected by transport with a plasma drift *V*

$$\frac{dn_e}{dt} = q(z,\chi) - \beta[N_2]n_e - \frac{d(n_e V)}{dh}$$

W being the upward drift velocity

$$\frac{dn_e}{dt} = q(z,\chi) - \beta[N_2]n_e - \frac{d(n_e W)}{dh}$$

Electron density in the F region

Under day-time equilibrium conditions

$$(1)\ N_m F_2 \approx q_m / (\beta[N_2])_m$$

(2) Below the peak: $N \approx q / \beta[N_2]$

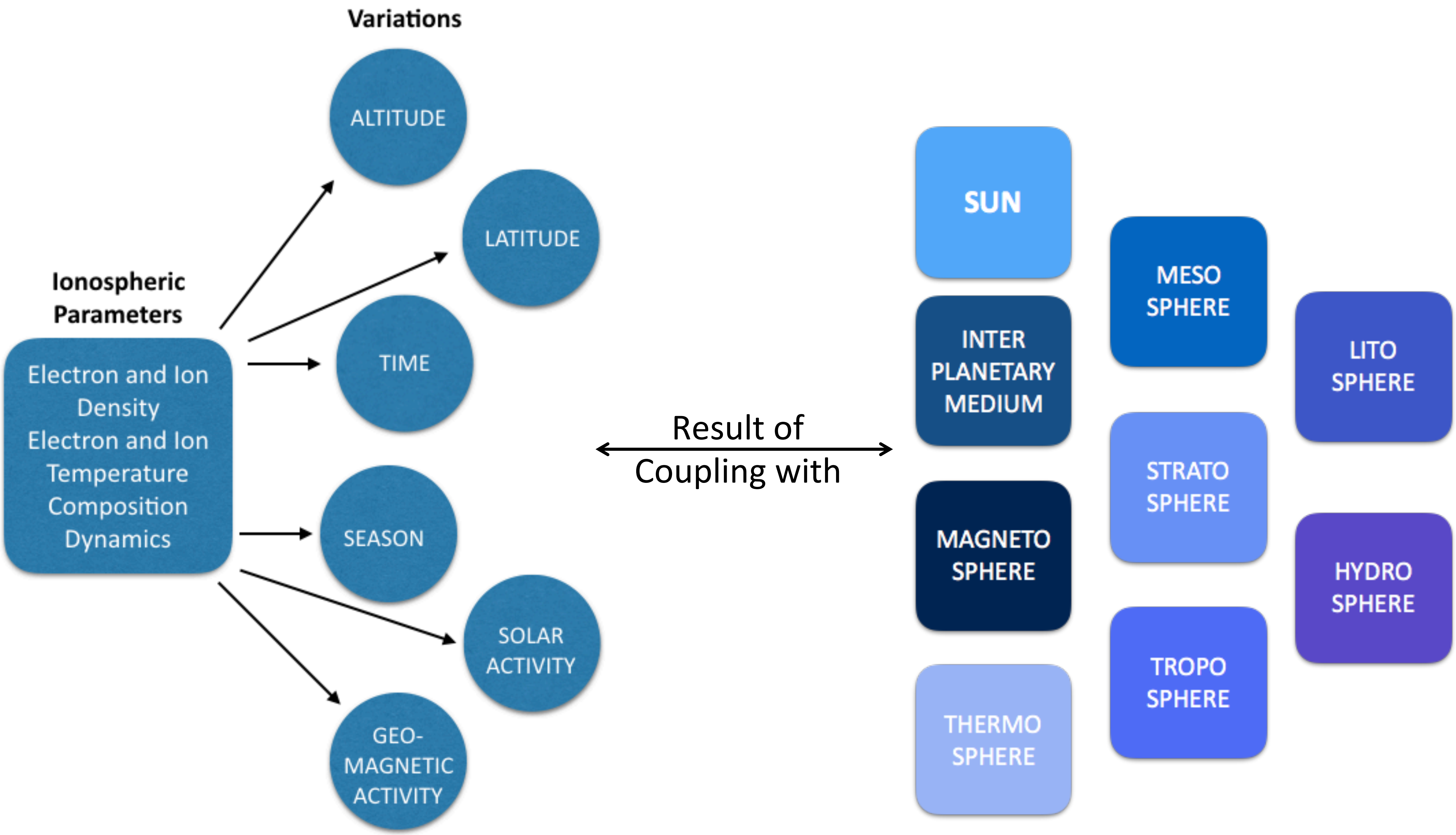
(3) Well above the peak $N \propto e^{-z/2}$

F region in summary

- ✓ The lowest region (F1), where photochemistry dominates.
- ✓ A transition region from chemical to diffusion (lower F2).
- ✓ The upper region, or topside, where diffusion dominates
- ✓ In the F2 (including the topside) the presence of transport processes, influenced by the geomagnetic field, became important.

Ionospheric variations

Ionospheric variations



Two types of variations

Climate
Variations occurring in cycles. Can be predicted with reasonable accuracy

Weather
Variations mostly due to Solar induced Space Weather but also caused by coupling with lower atmosphere

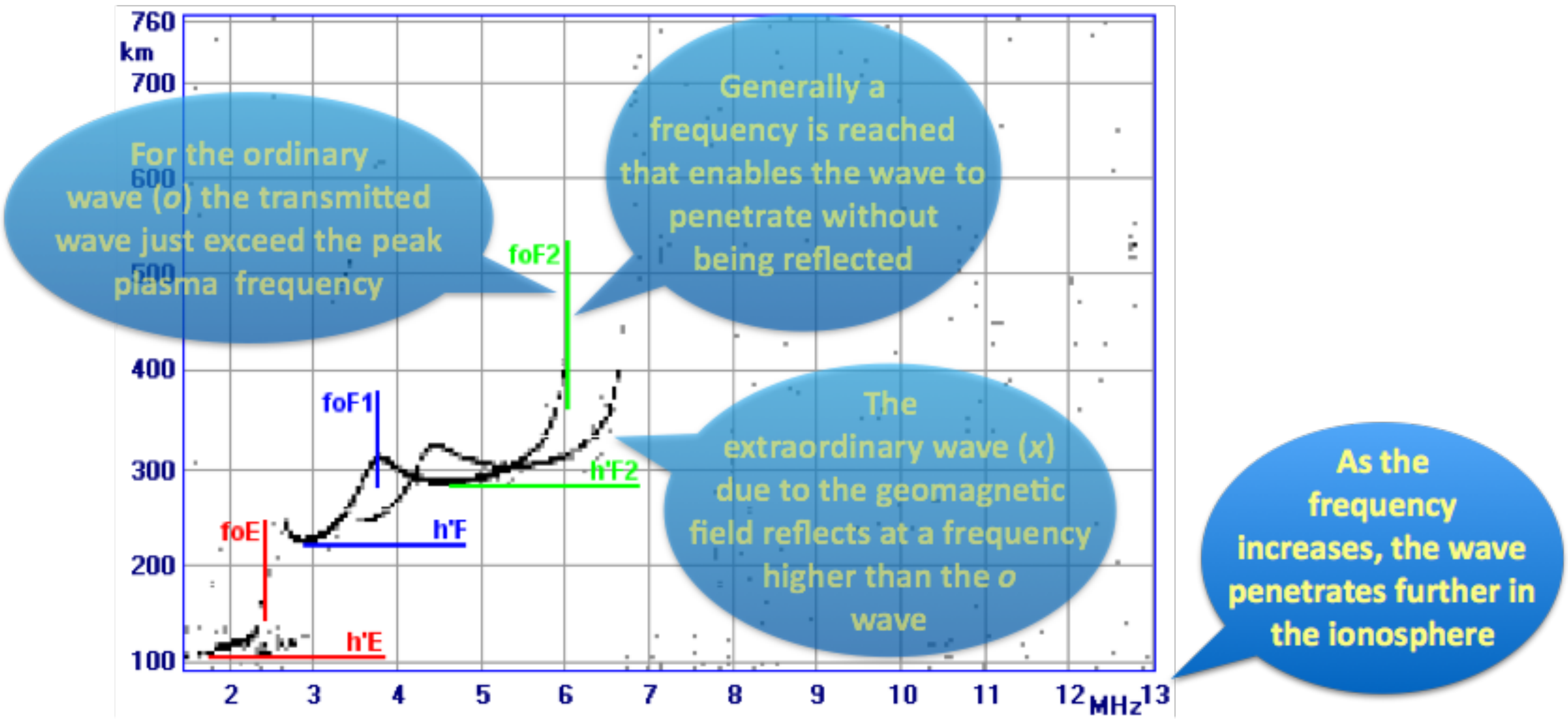
Introduction to the topic

We will concentrate on the variations of the F2 layer through two parameters that are related to the peak electron density and the total electron content in the ionosphere.

The starting point will be a mention to experimental techniques used to derive these parameters.

The ionosonde and the ionogram

A radar that transmits pulses of a sweep of frequencies usually from 1 to up to 20 MHZ

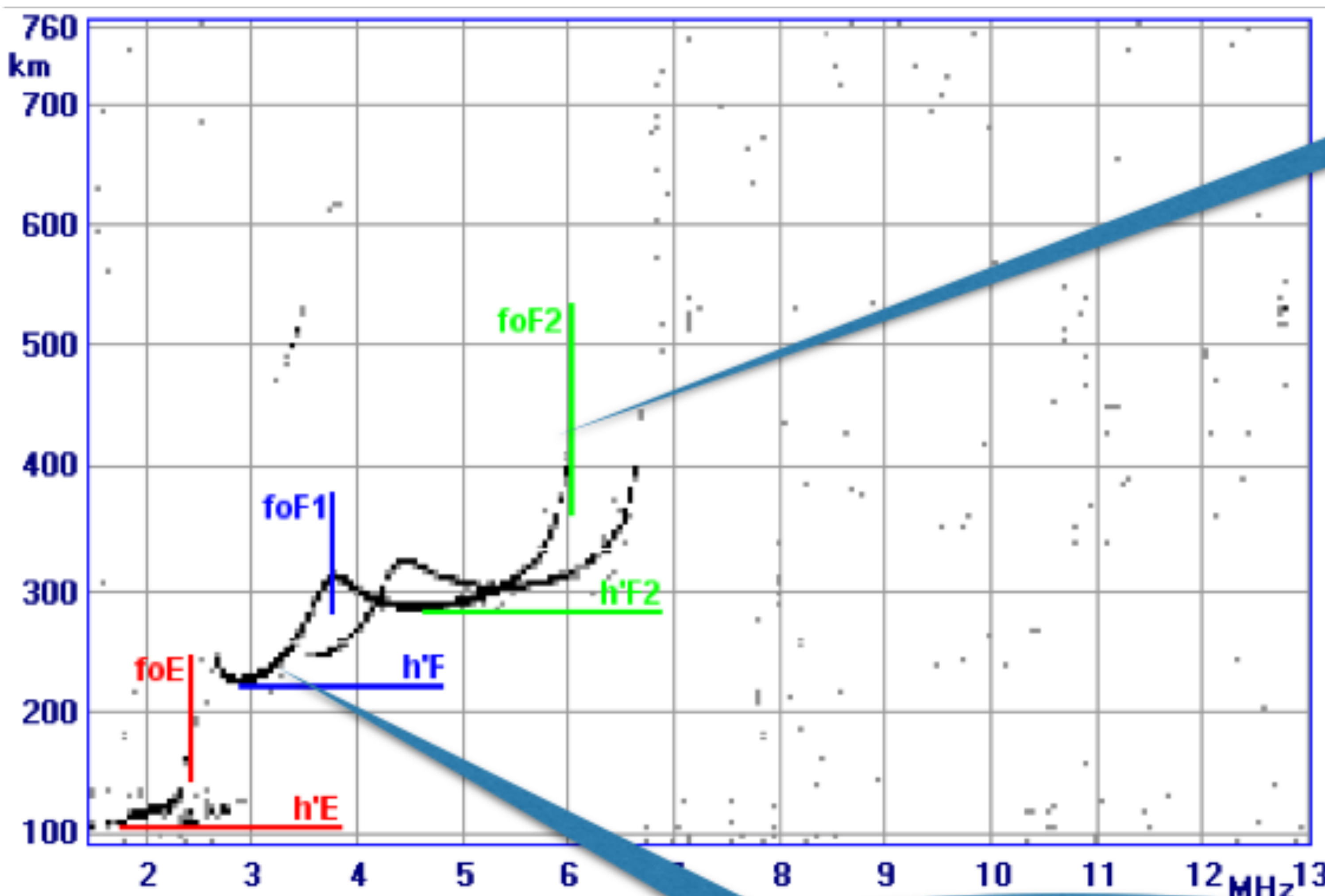


Critical frequencies and virtual heights

CRITICAL FREQUENCY
The frequency at which the wave penetrates the layer
foF2, foF1, foE

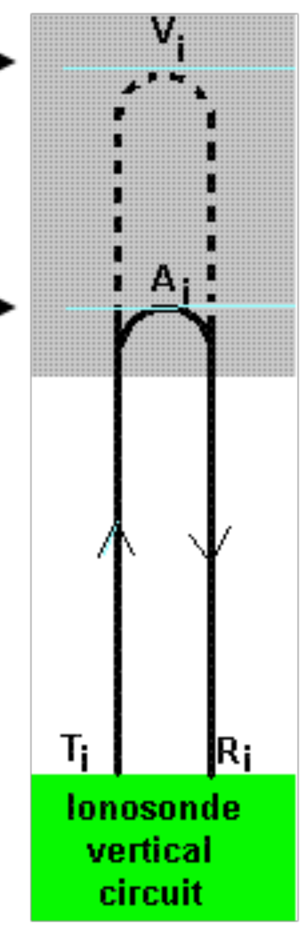
$$N = 0.124 \times 10^{11} \left(f\right)^2$$

$$N\left[m^{-3}\right], f\left[MHz\right]$$



Virtual height →

Real height →

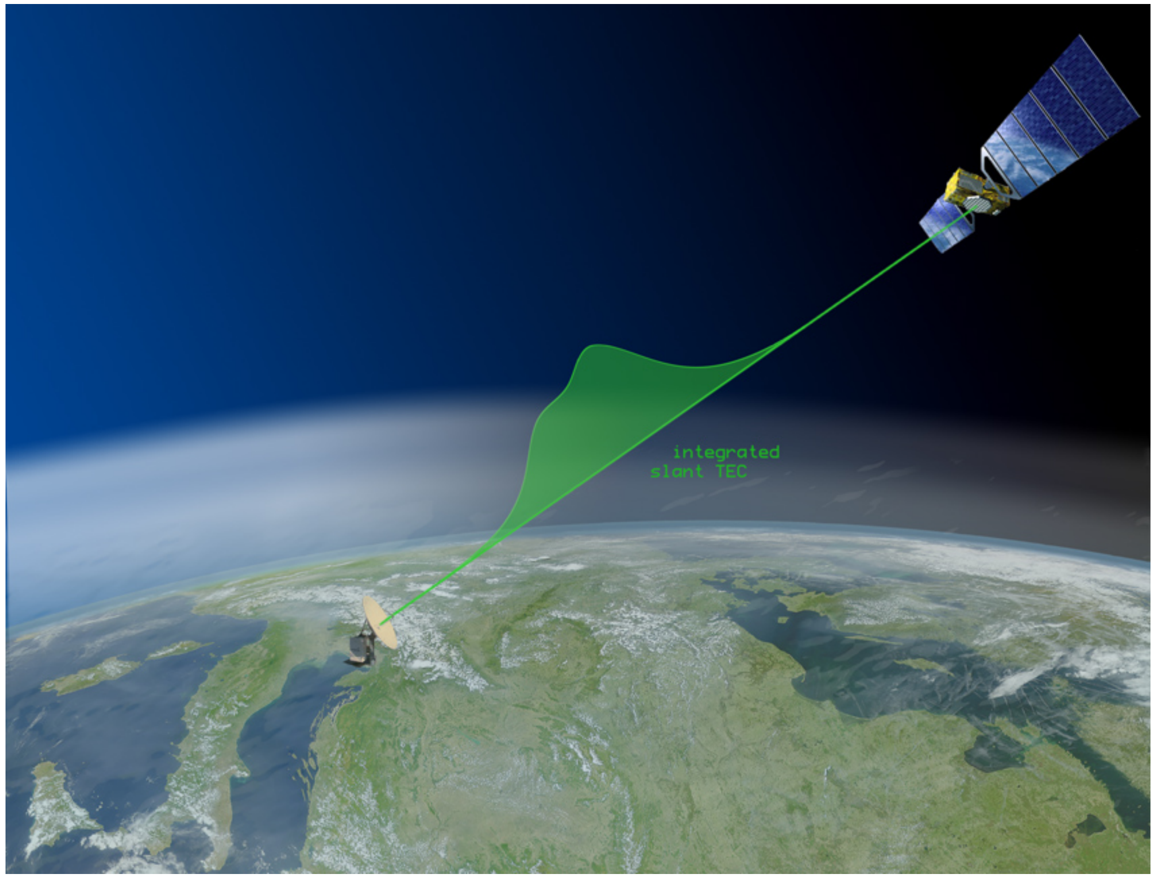


VIRTUAL HEIGHT
The height reached by radio wave if the group velocity is equal to the velocity of light in vacuum.
The presence of the ionosphere slows down the group velocity
h'F2, h'F, h'E

Total electron content

The total electron content (TEC) is the total number of electrons along a path between a transmitter and areceiver

Can be obtained by different means, mainly from GNSS and satellite born altimeters



$$N_T = \int_s N(s)$$

$$1 \text{ TEC unit} = 10^{16} m^{-2}$$

Diurnal, Seasonal and Solar Activity variations of foF2

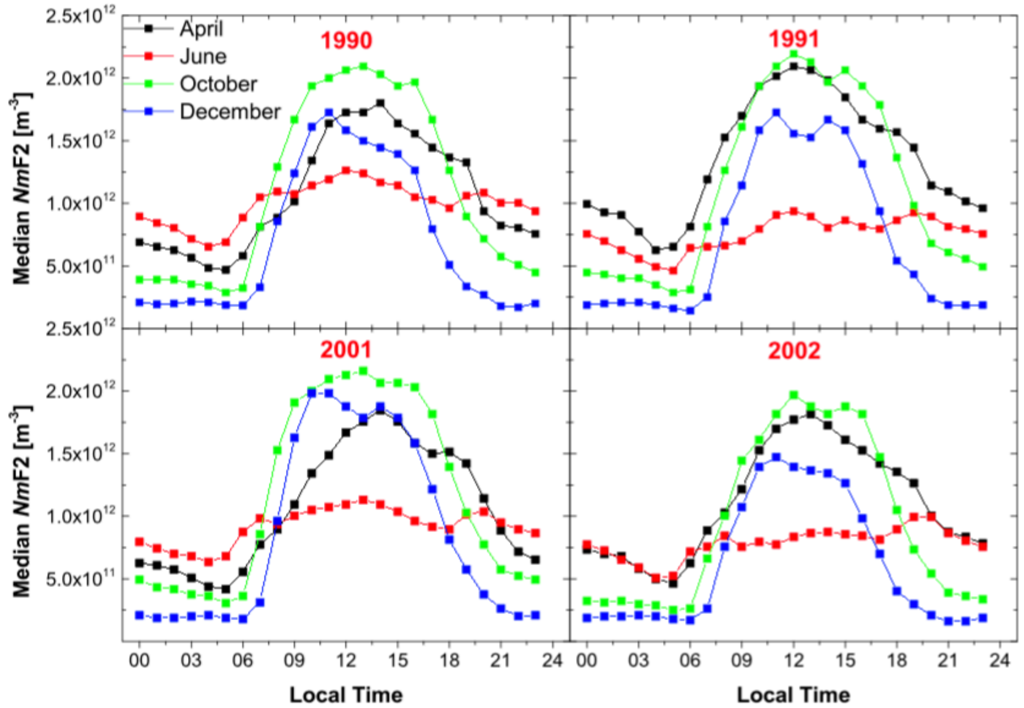
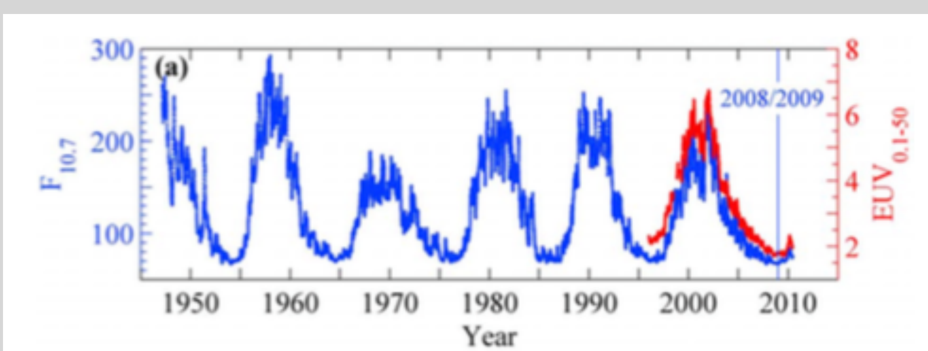


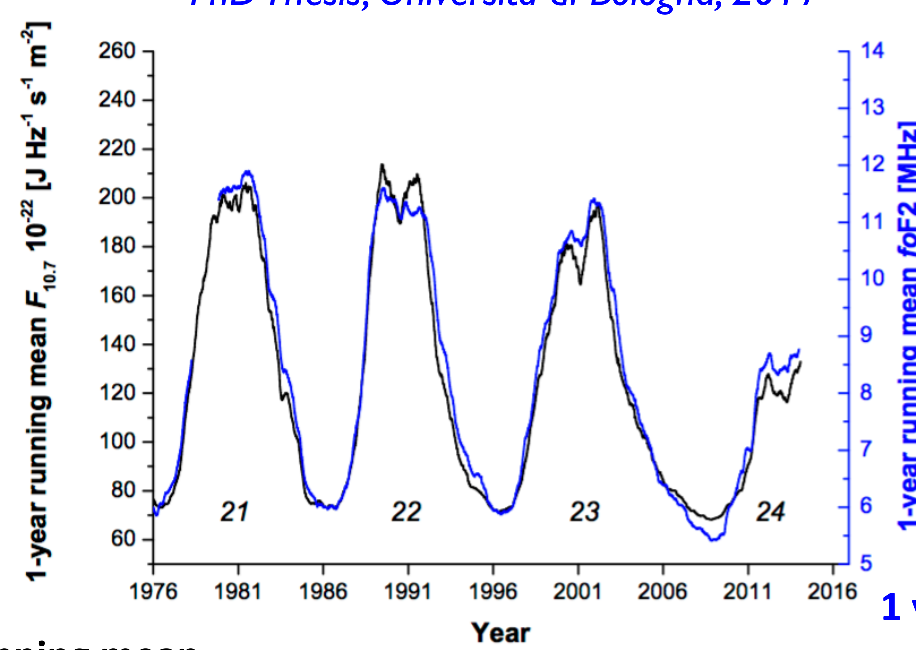
Figure 1.5: Monthly median values of $NmF2$ as recorded at Rome in April, June, October and December for the years of maximum activity 1990-1991 (max of solar cycle 22) and 2001-2002 (max of solar cycle 23).



(a) The 27 day averages of daily F10.7 (in units of 10−22 W/m2/Hz) and SOHO/SEM 0.1–50 nm EUV flux (in units of 1014 photons/m2/s).

Chen, Y., L. Liu, and W. Wan (2011), Does the F10.7 index correctly describe solar EUV flux during the deep solar minimum of 2007–2009?, J. Geophys. Res., 116, A04304, doi:10.1029/2010JA016301.

From: L. Perna, Ionospheric plasma response to the anomalous minimum of the solar cycle 23/24: modeling and comparison with IRI-2012 PhD Thesis, Università di Bologna, 2017



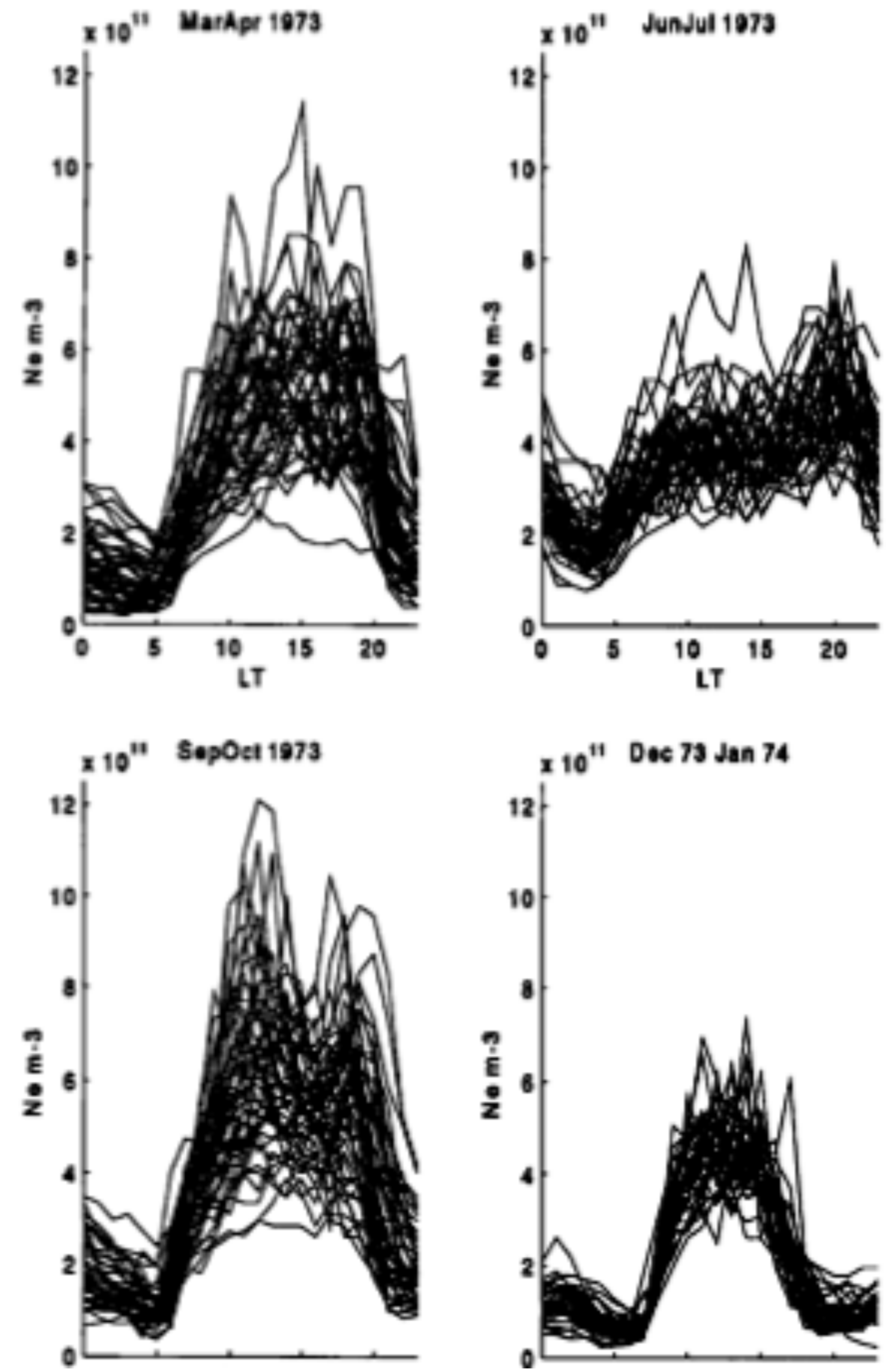
1 y running mean of F10.7

1 y running mean of foF2 at 12 LT in Rome

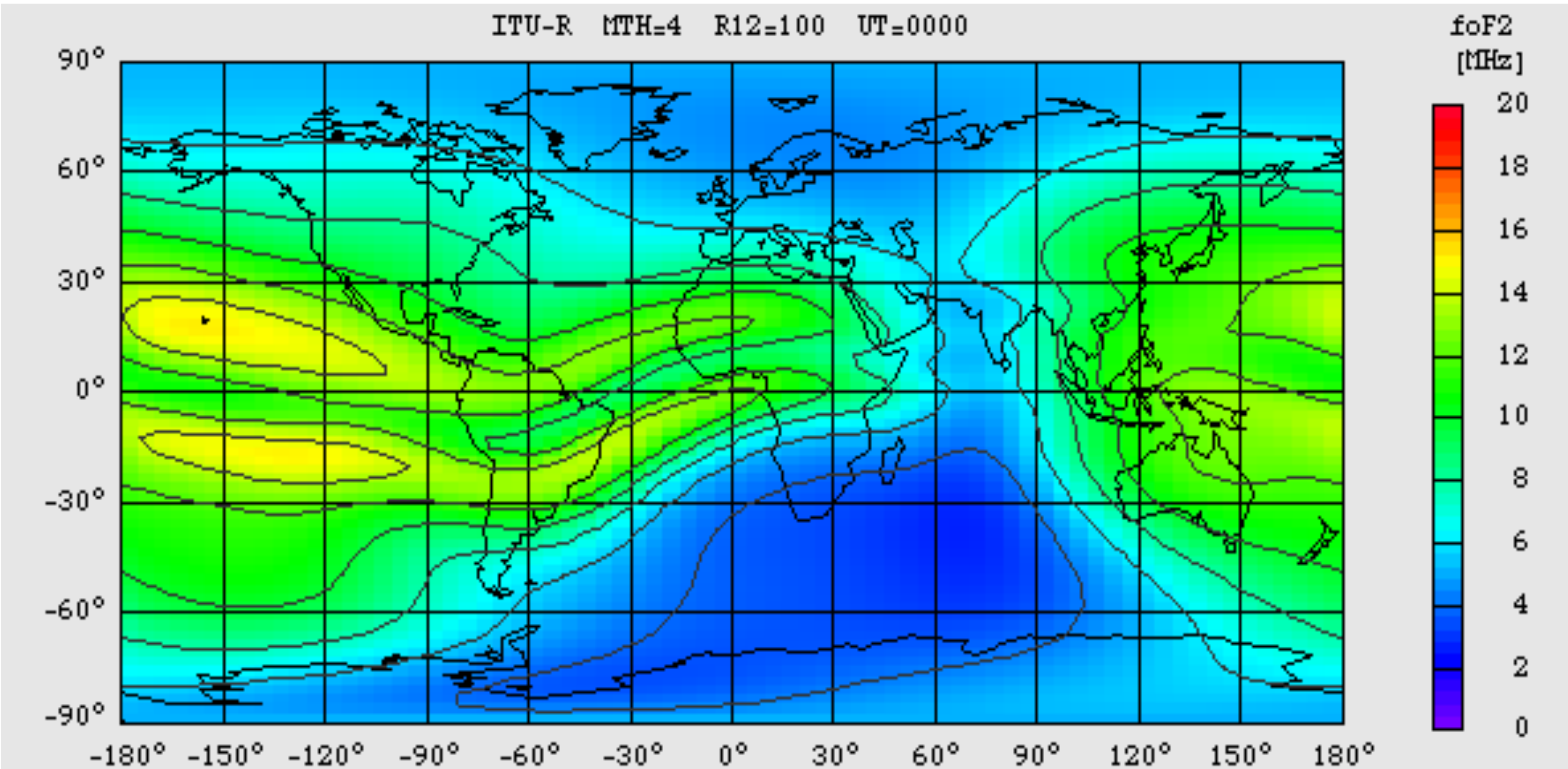
Day-to-day variability of NmF2

Variation of NmF2 at Slough for every day during four 2-month periods in 1973-1974.

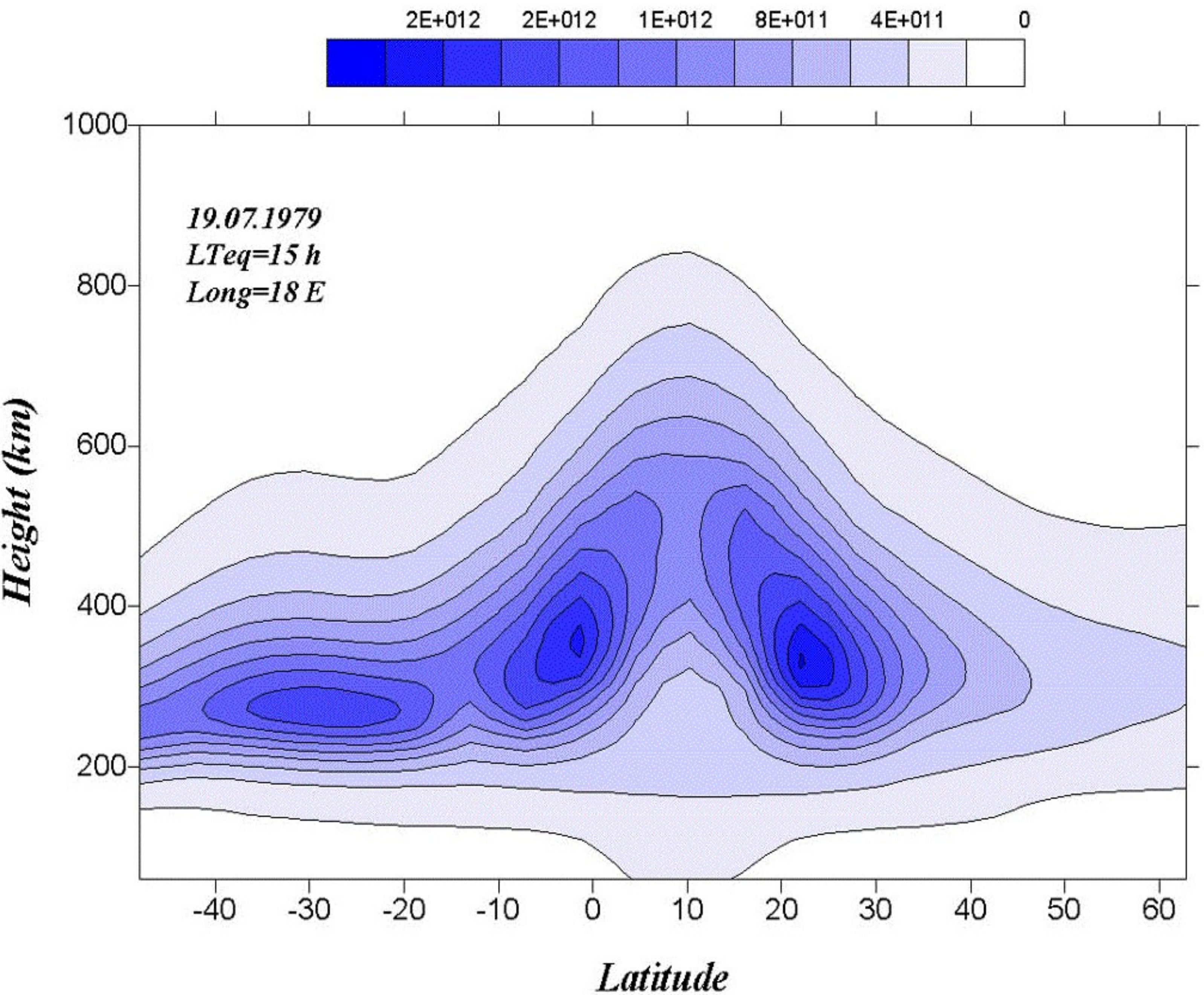
H. Rishbeth, M. Mendillo / Journal of Atmospheric and Solar-Terrestrial Physics 63 (2001) 1661–1680



Global variations of foF2 April (R12=100)



Geographical variations: the equatorial anomaly



Nava B., Radicella S.M., Pulinets S. and Depuev V. "Modelling bottom and topside electron density and TEC with profile data from topside ionograms", Advances in Space Research, V. 27, pp. 31-34, 2001.

From the Chapman theory electron density should maximise over the geographic equator at equinox.

Actually it maximises 15-20 degrees of geomagnetic latitude N and S, with small minimum at the equator

Due to the presence of the geomagnetic field: the 'fountain effect"

Equatorial Anomaly and the "fountain effect"

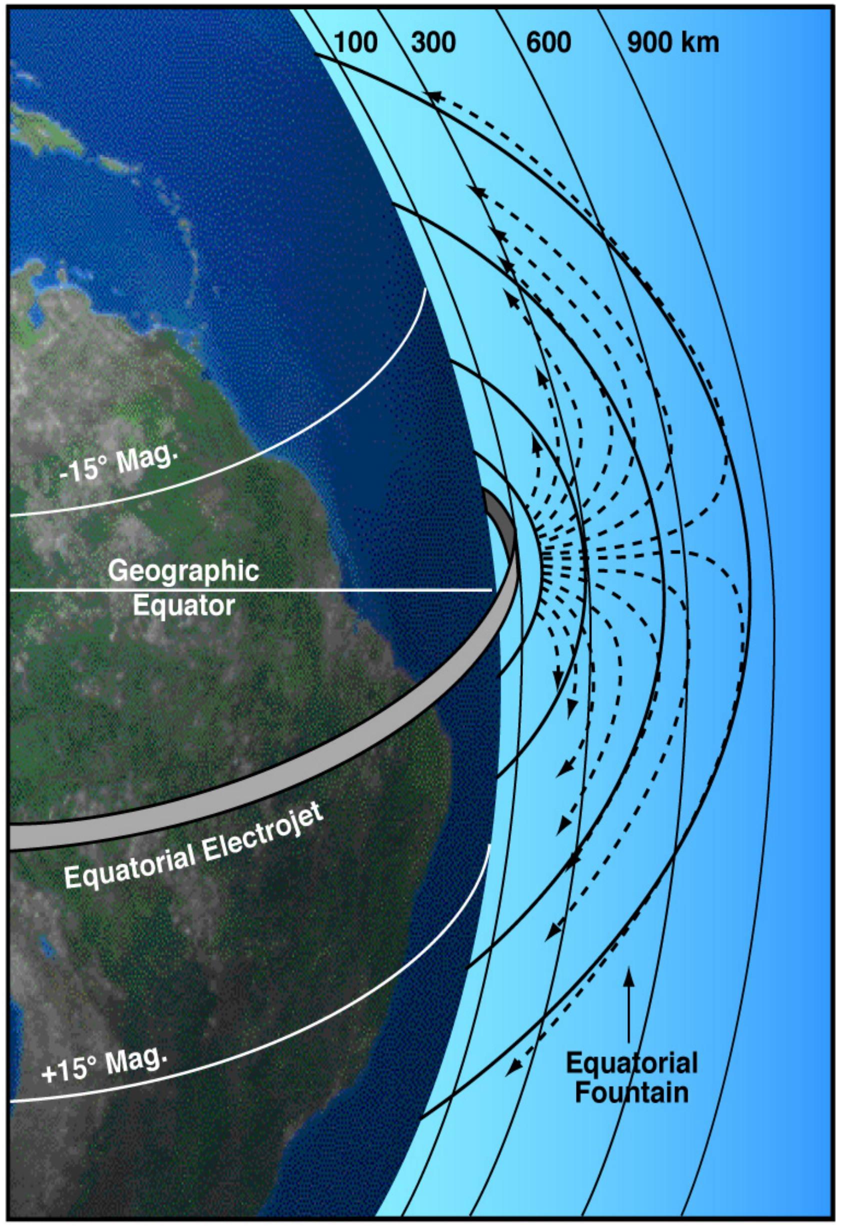
The Equatorial Electrojet drives the F-region behavior

E-field is zonal (along latitude lines)

Magnetic field is meridional (along longitudes)

Plasma drift is vertically upwards

Plasma descends down the magnetic lines N and S of the geomagnetic equator



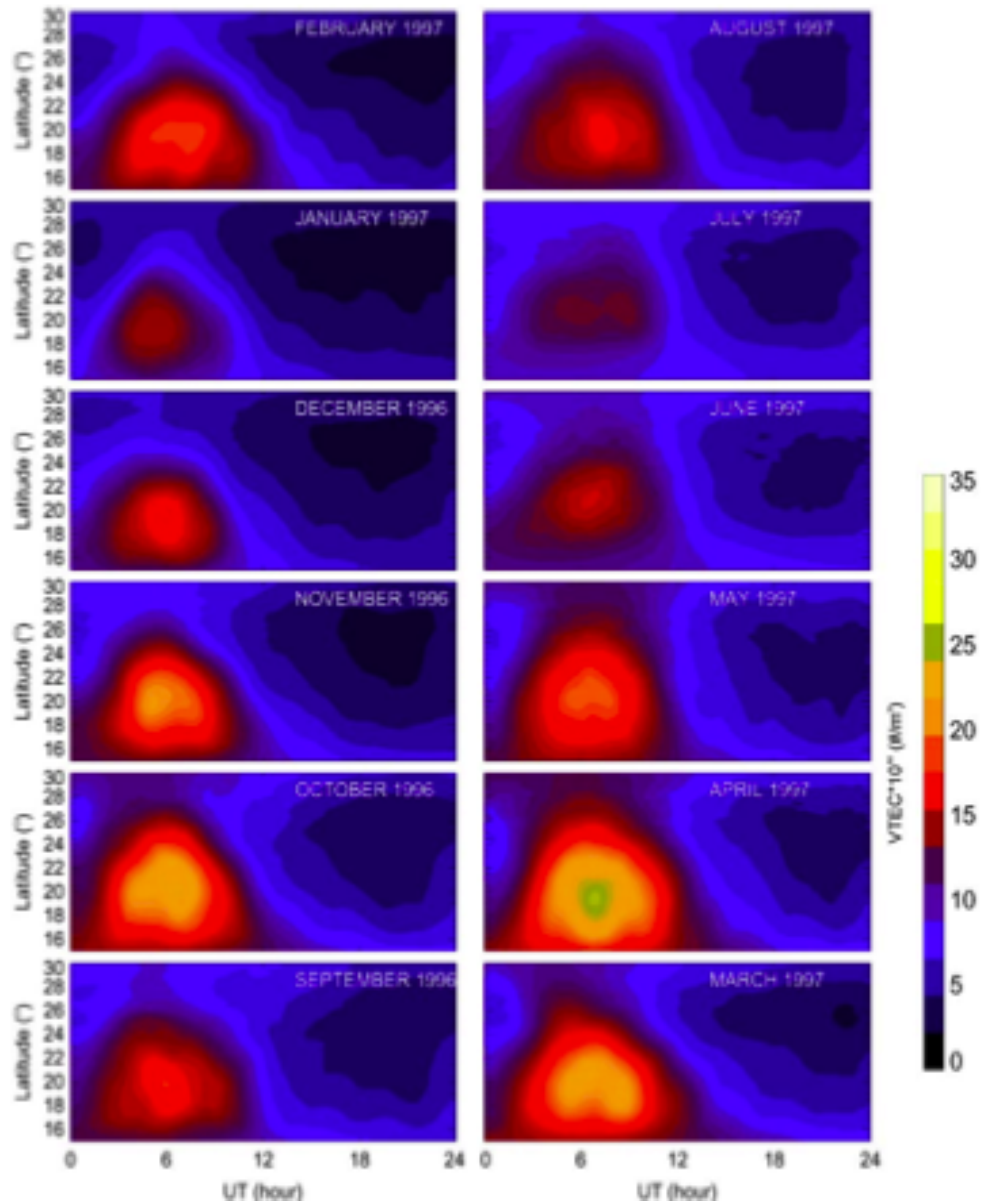
The Equatorial Anomaly of the ionosphere and the "fountain effect"

Diurnal and Seasonal development of the Equatorial Anomaly

The monthly averaged equatorial ionospheric anomaly contour chart of vertical TEC in geographic latitude (Taiwan sector: 6.0 UT = 14.0 LT)

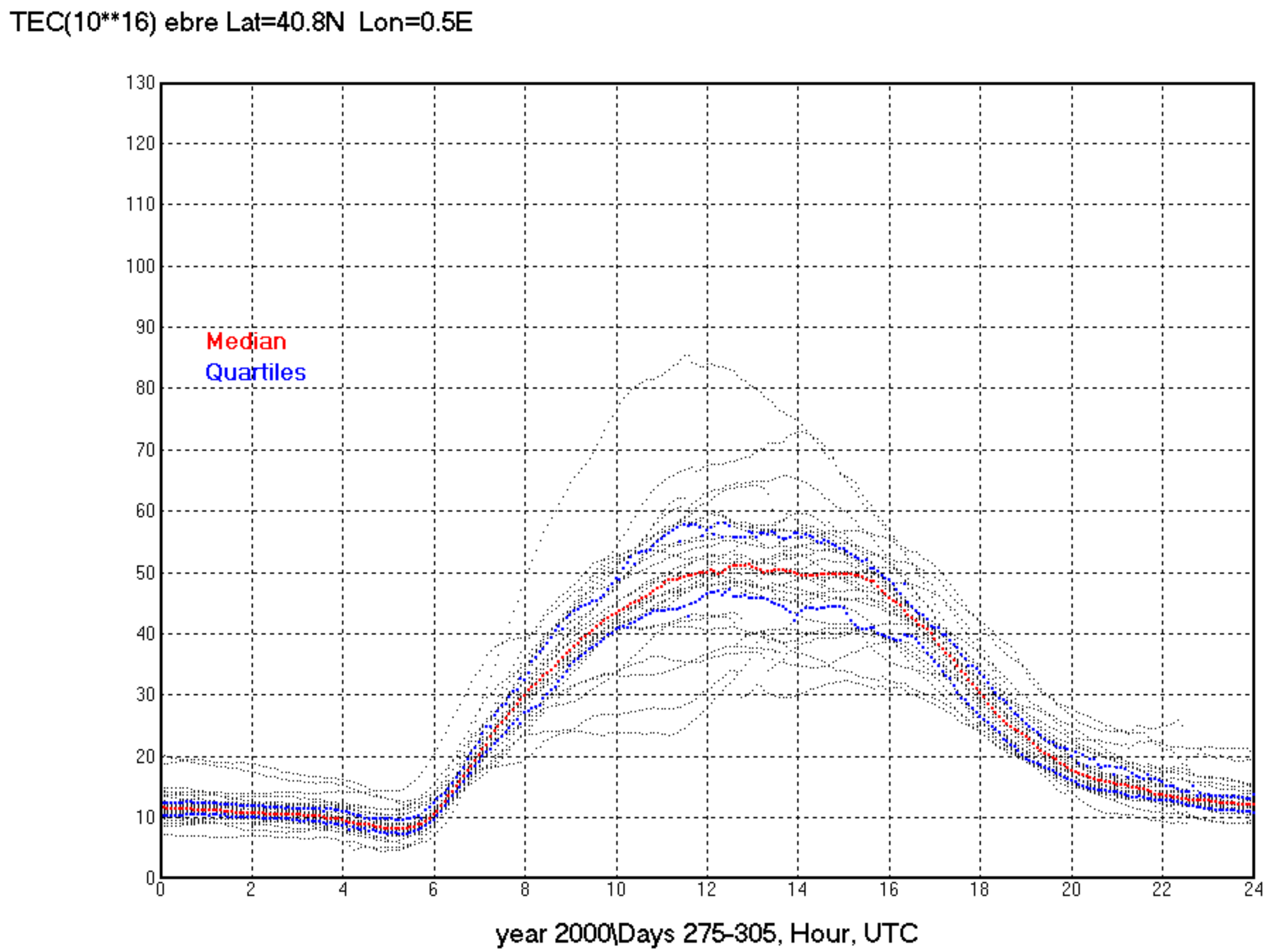
September 1996 - August 1997.

C.-C. Wu et al. / Journal of Atmospheric and Solar-Terrestrial Physics 66 (2004) 199–207



Vertical TEC diurnal and day-to-day variations (1)

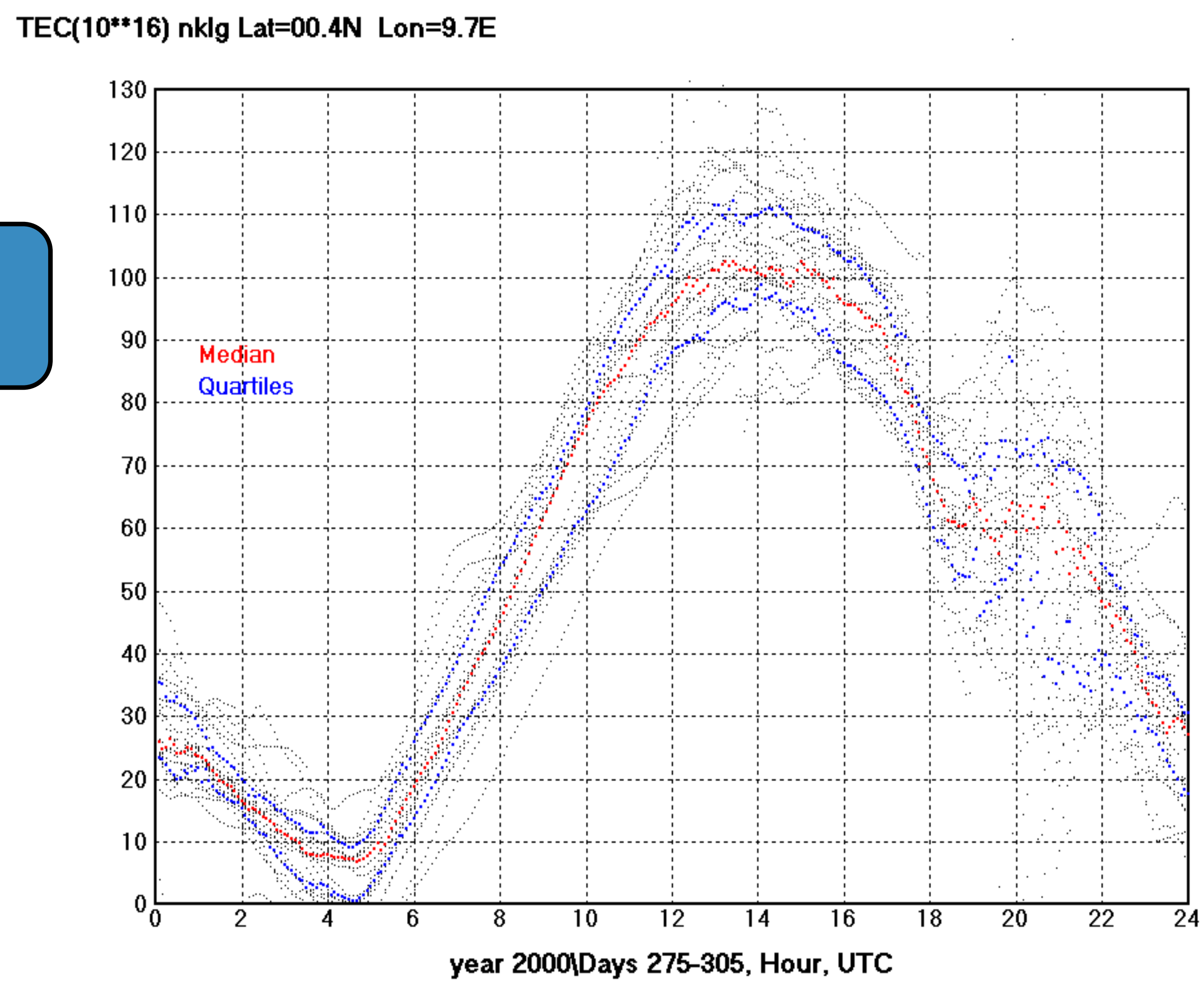
Middle Latutude



GPS derived vertical TEC at 5 min interval for Roquetes (Lat. 40.8°, Lon. 0.5° E, Mag. Dip 57°), October 2000

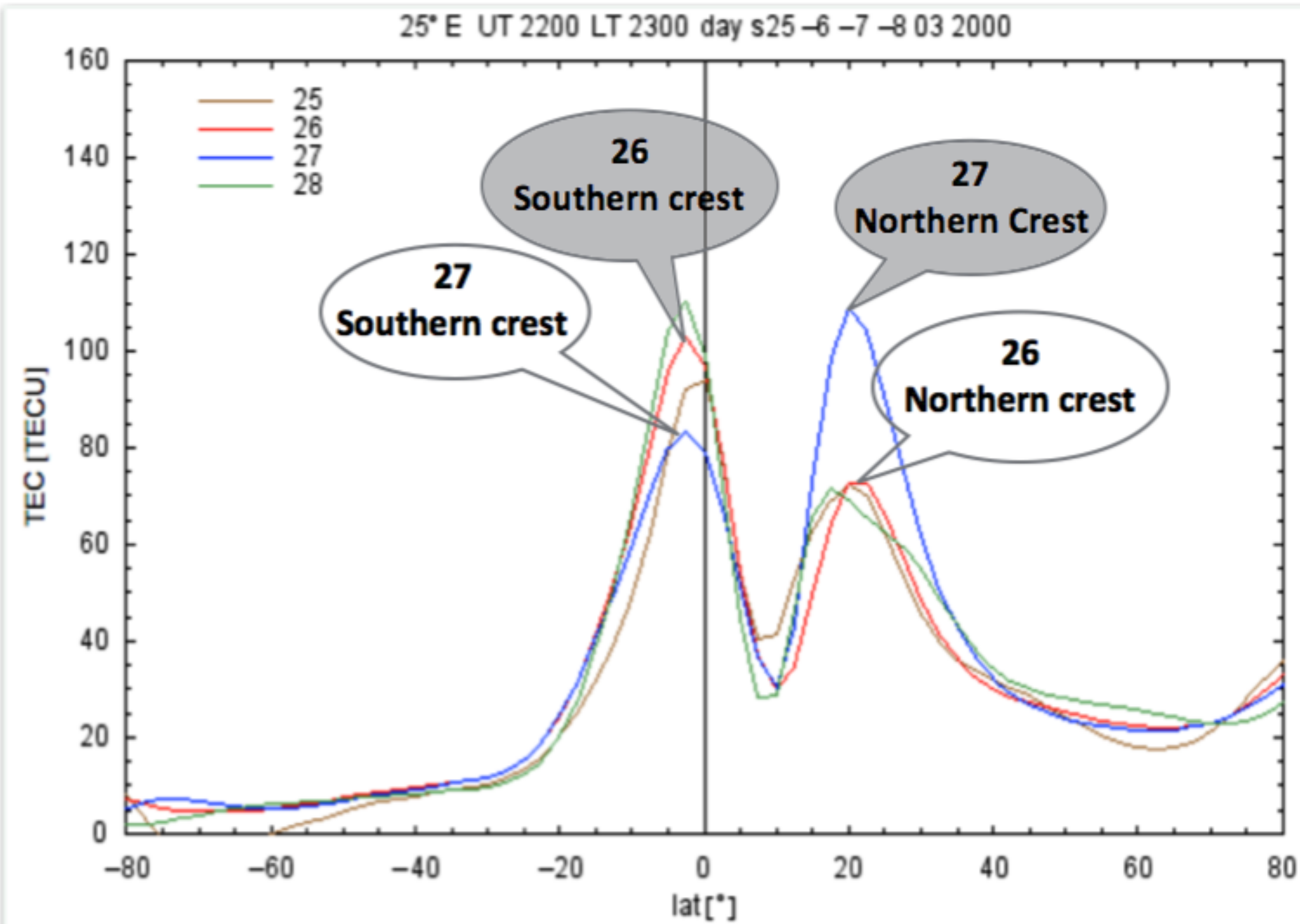
Vertical TEC diurnal and day-to-day variations (2)

Low Latutude



GPS derived vertical TEC at 5 min interval for Libreville (Lat. 0.4° N, Long. 9.7° E, Mag. Dip –25°), October 2000.

Vertical TEC Meridional cross section and day-to-day Variations



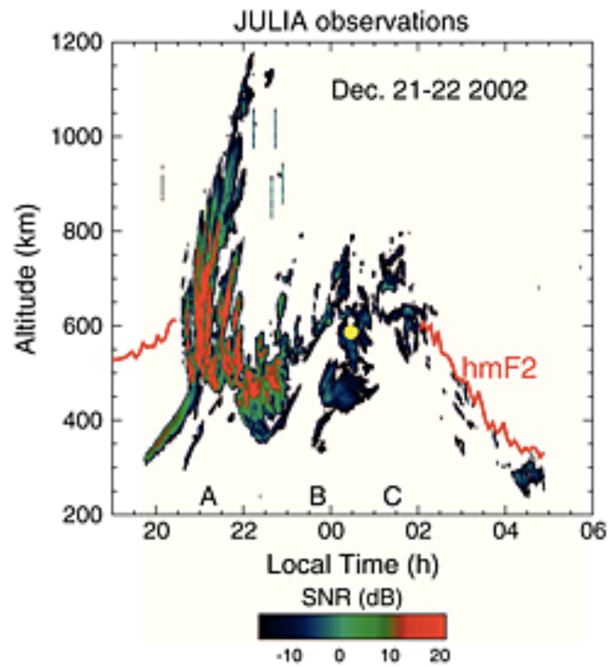
Low latitude Ionospheric irregularities

Radar observations of equatorial night-time F region often reveal rising plumes or bubbles of decreased electron density that penetrate into the topside reaching very high altitudes.

The generation of rising bubbles is initiated by a seed perturbation at the bottomside of a rising F layer.

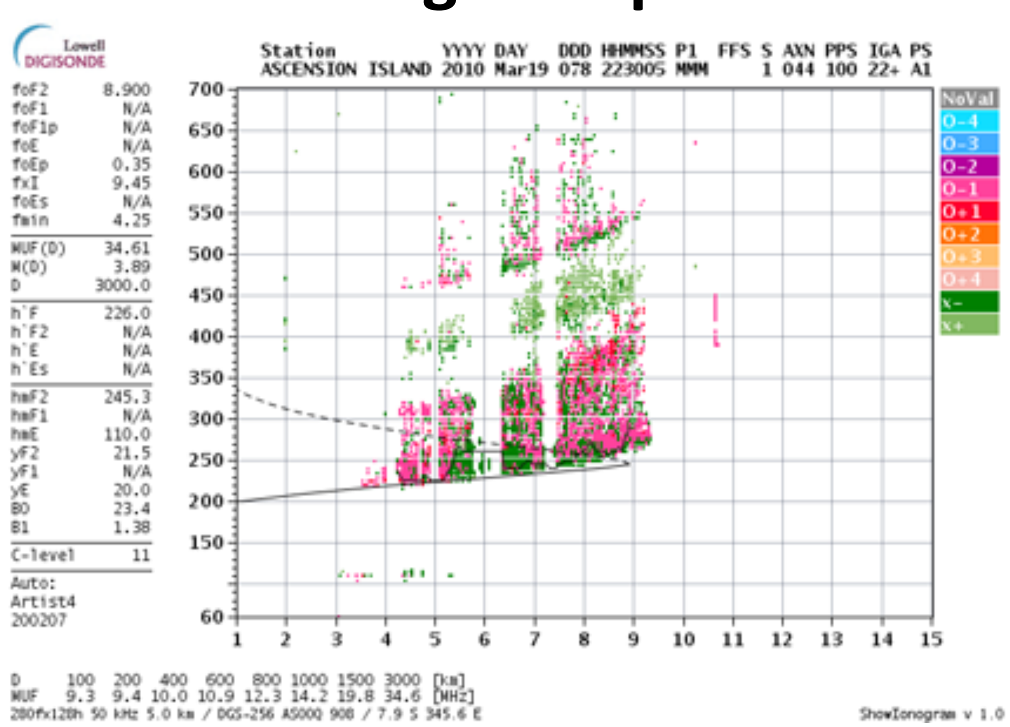
Ionospheric irregularities seen by different techniques

JULIA radar plumes



Hyosub Kil et al., J. Geophys. Res. 119, Issue 7, 2014

Ionogram spread-F



TEC depletion and amplitude scintillation

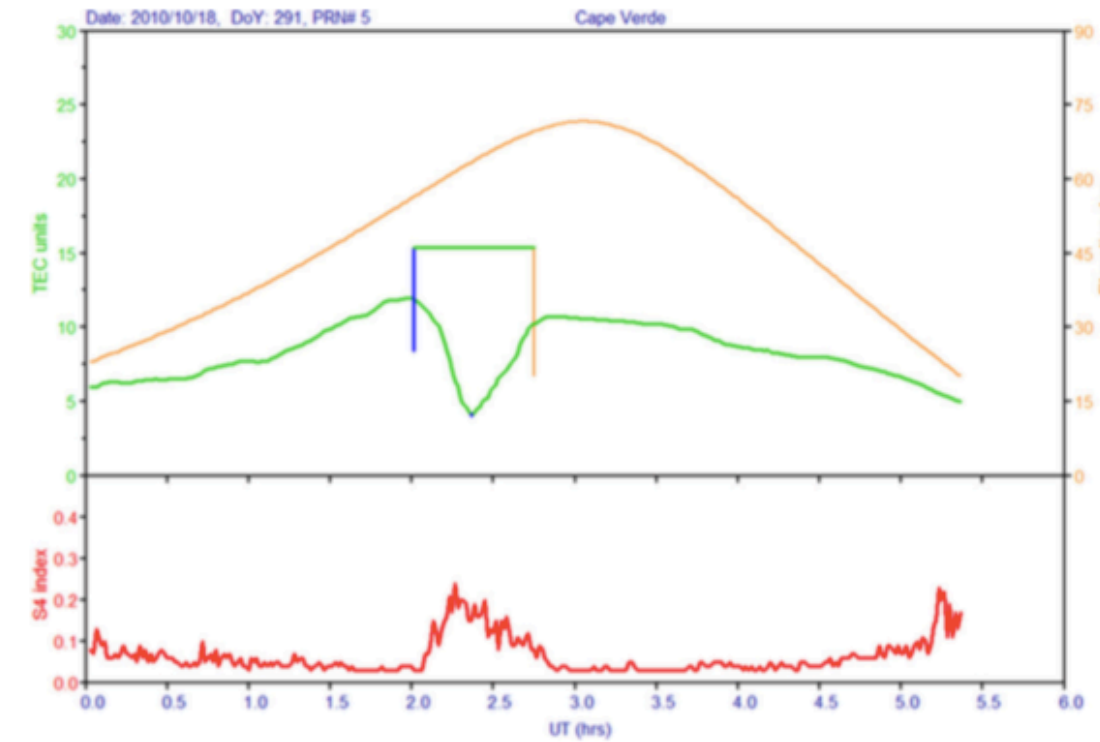
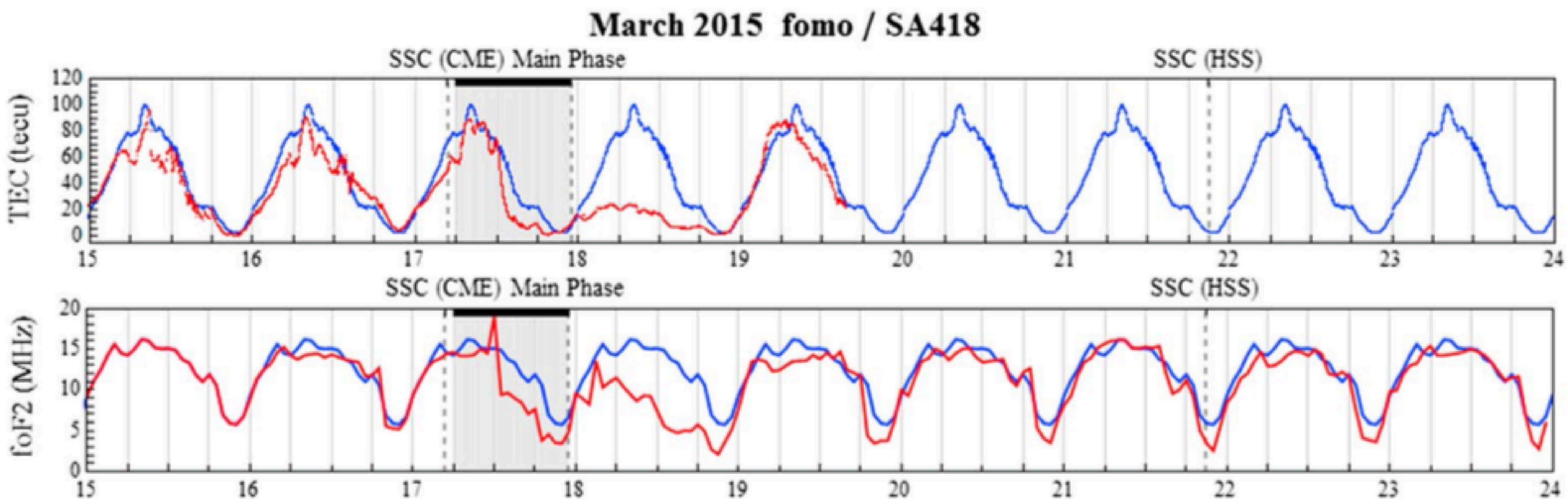


Fig. 2. Example of the measurements at Cape Verde (18 October 2010). The top plot shows the TEC measurements and also the elevation angle of the satellite. Bottom plot shows S4 index measurements at same location. In this example the depletion depth is about 7 TECU.

V. V. Paznukhov et al., Ann. Geophys., 30, 675–682, 2012

Ionospheric Storms

A very complex phenomenon that needs at least a full lecture by itself



Macao
Lat: 22.2 N
Long: 113.5 E

Sanya
Lat: 18.3 N
Long: 109.4 E

Nava, B., J. Rodríguez-Zuluaga, K. Alazo- Cuartas, A. Kashcheyev, Y. Migoya-Orué, S. M. Radicella, C. Amory-Mazaudier, and R. Fleury (2016), Middle- and low-latitude ionosphere response to 2015 St. Patrick's Day geomagnetic storm, J. Geophys. Res. Space Physics, 121, 3421–3438, doi:10.1002/ 2015JA022299.

Tropospheric induced ionospheric variations

From the paper:

“Day-to-day ionospheric variability due to lower atmosphere perturbations” by H.-L. Liu, V. A. Yudin, and R. G. Roble; GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 665–670.

This study demonstrates that the thermosphere-ionosphere-mesosphere electrodynamics general circulation model (TIEGCM) constrained by the atmosphere community climate model (WACCM) simulations is capable of reproducing observed features of day-to-day variations in the F2 region at low latitudes.

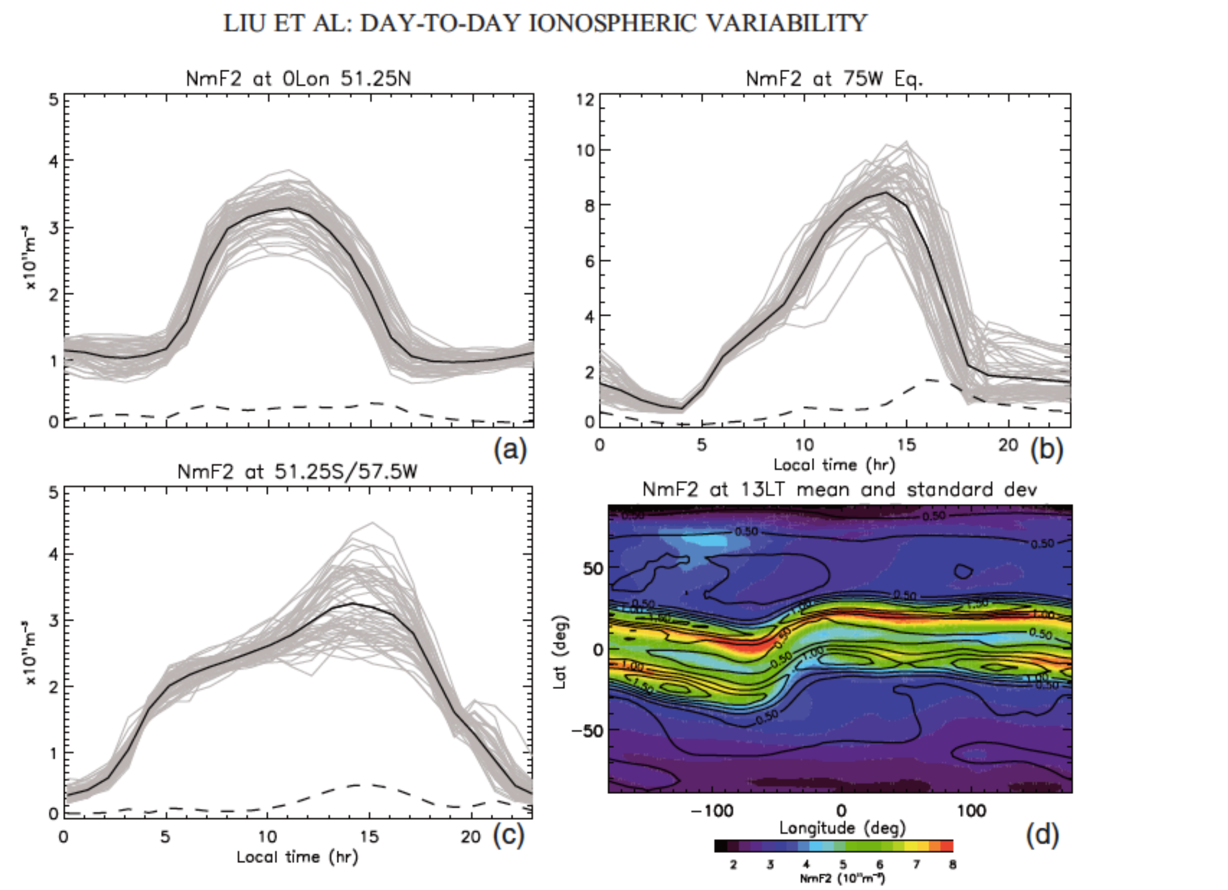


Figure 4. Daily values of NmF2 (gray), their mean values (black solid), and the standard deviation (dashed) for (a) 51.25°N/0 longitude, (b) equator/75°W, and (c) 51.25°S/57.5°W (all geographic). (d) Mean values (shades) and standard deviation (lines) of NmF2 for LT1300. Contour intervals: 2.5×10^{10} m^{-3}.

Under constant solar minimum and geomagnetically quiet conditions the meteorological driving may contribute comparably with geomagnetic forcing to the ionospheric day-to-day variability.

Earthquake and Tsunami ionospheric variations

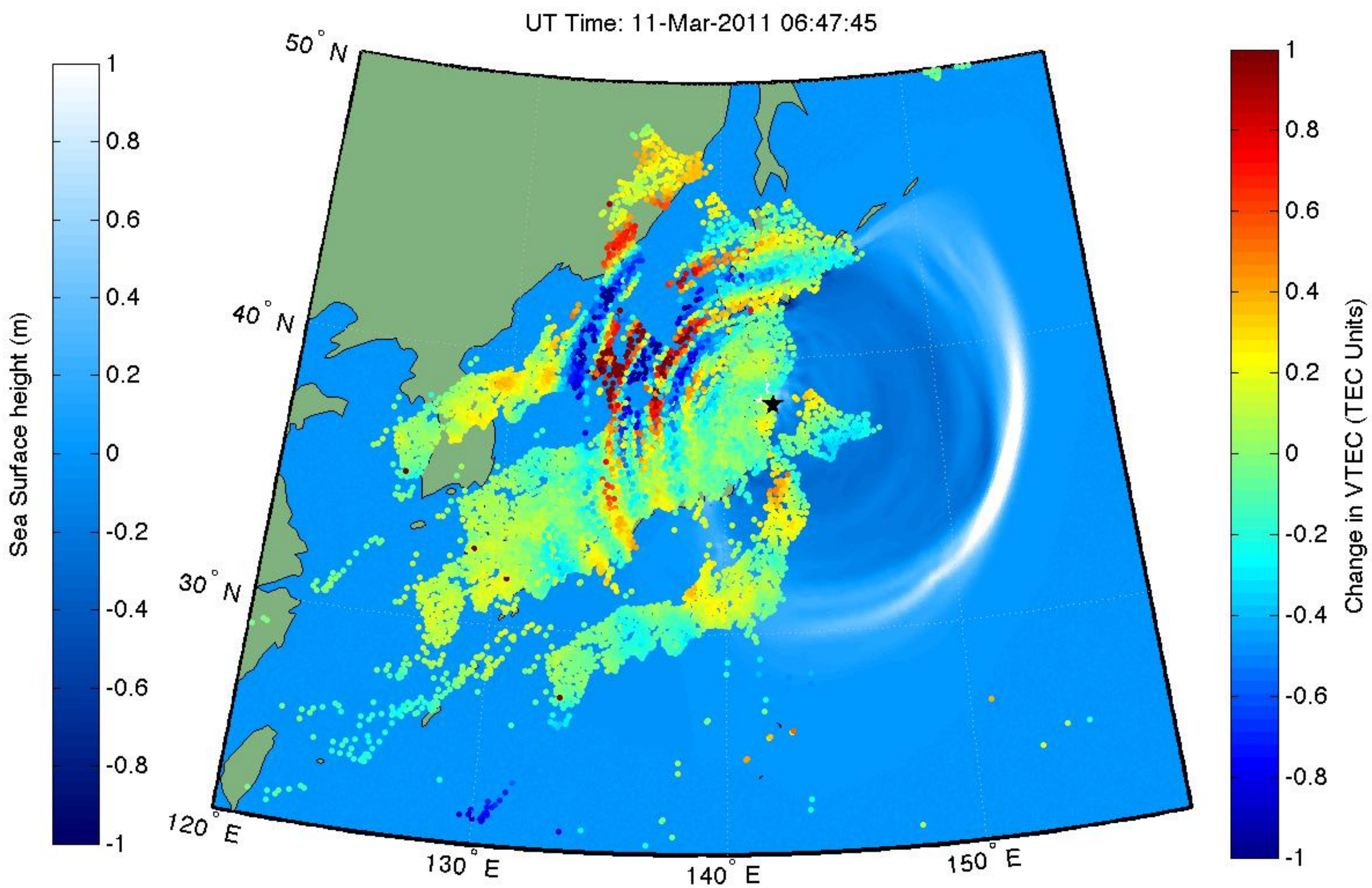


Image by NASA/JPL-Caltech.

Ionospheric variations induced by the Tohoku-Oki earthquake and tsunami of March 11, 2011.

The map shows changes in the Total Electron Content and sea surface heights.

This lecture gives only a pale idea of the complexity of the ionosphere but I hope it awakes more curiosity for this fascinating part of our environment.