Ionosphere and Thermosphere Basics

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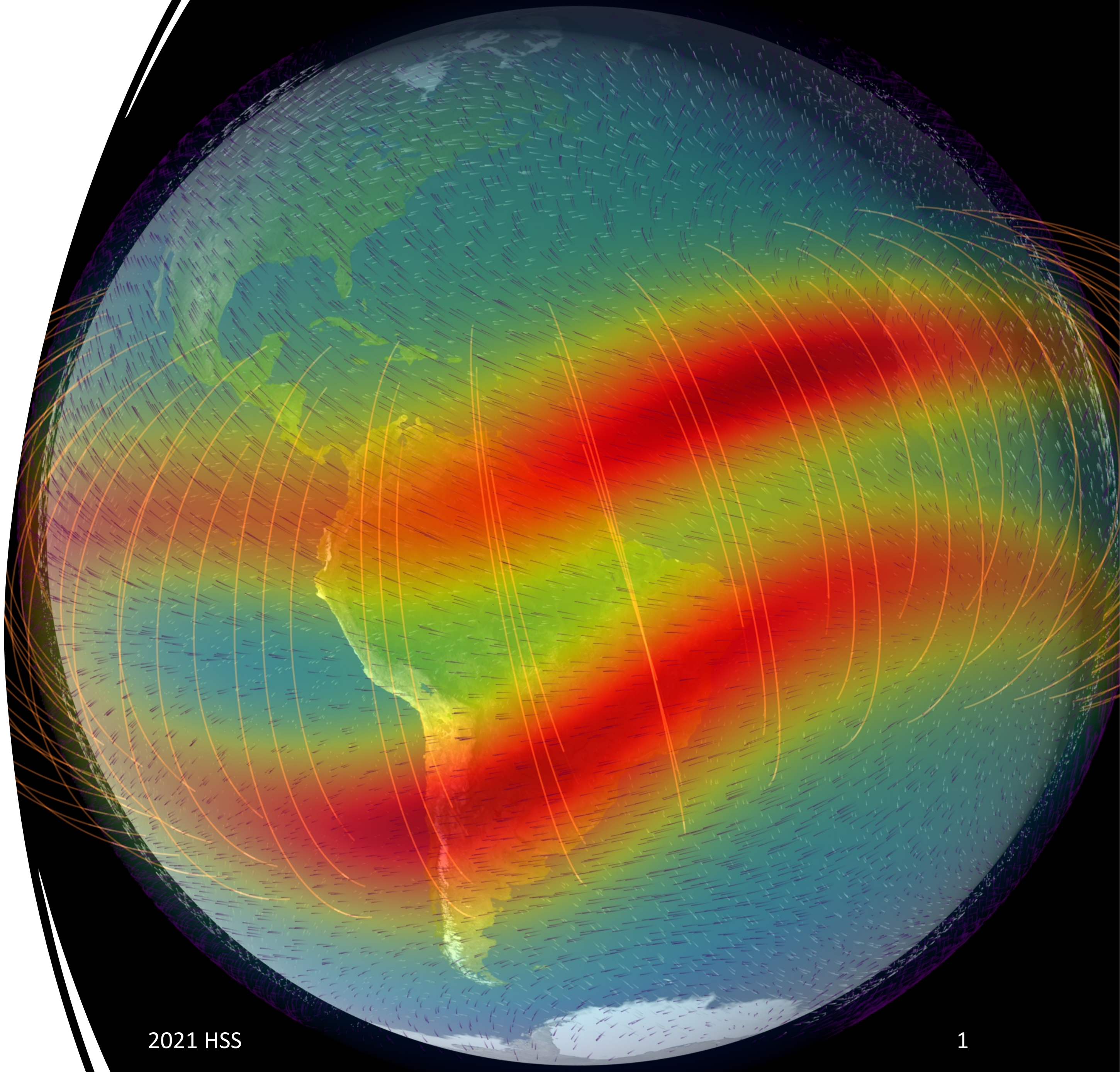
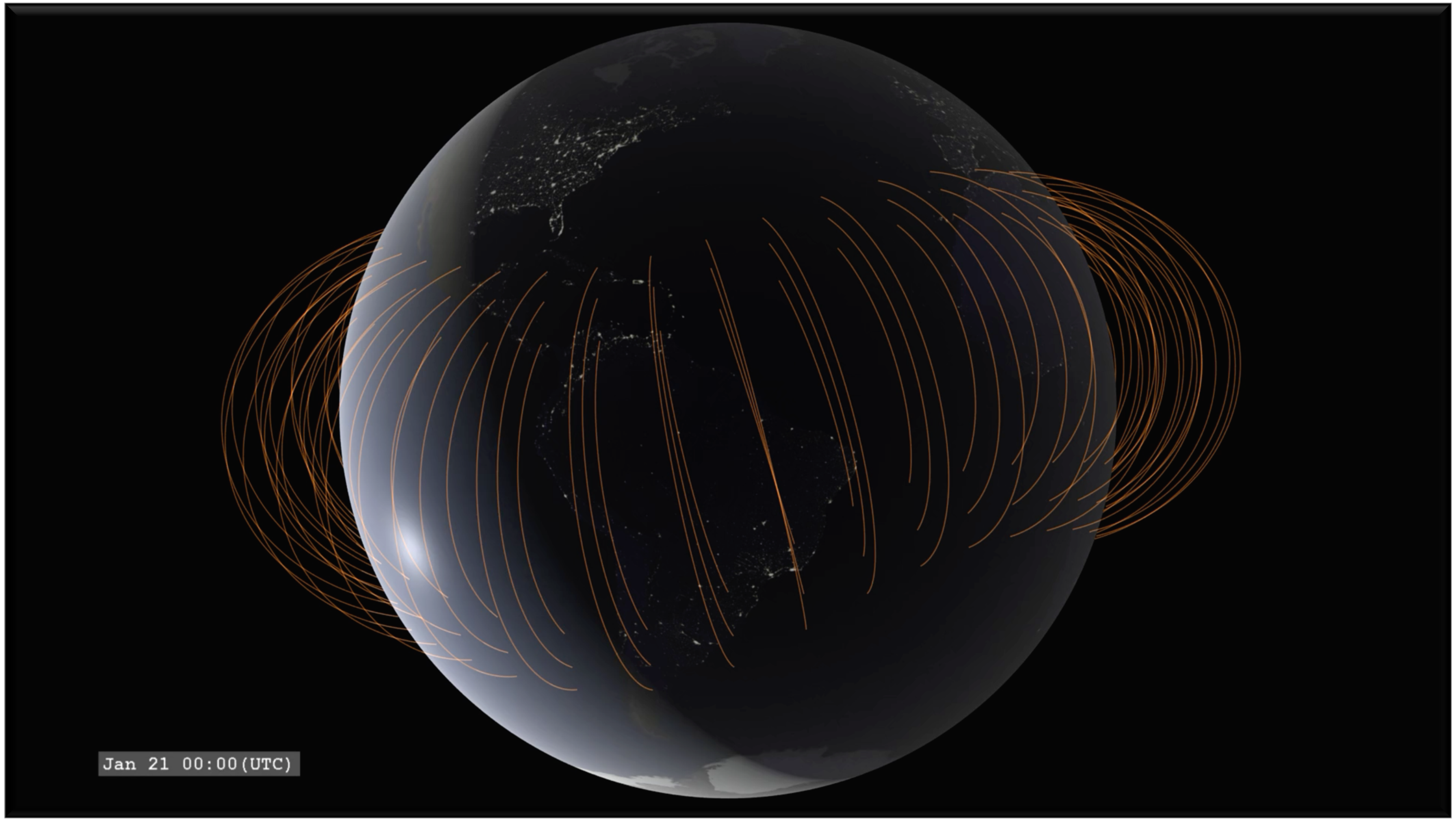


Terrestrial Ionosphere



Credit: NASA's Scientific Visualization Studio

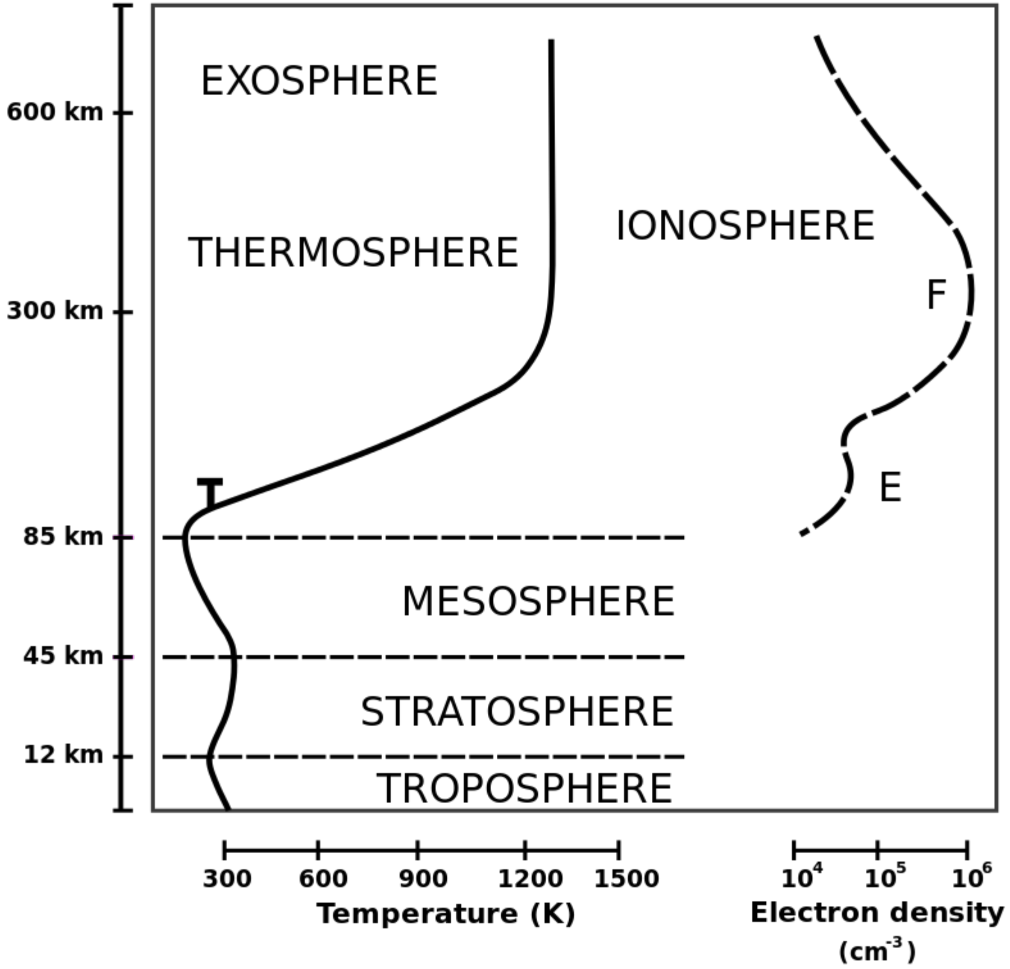
Thermosphere and Ionosphere Definitions

Thermosphere:

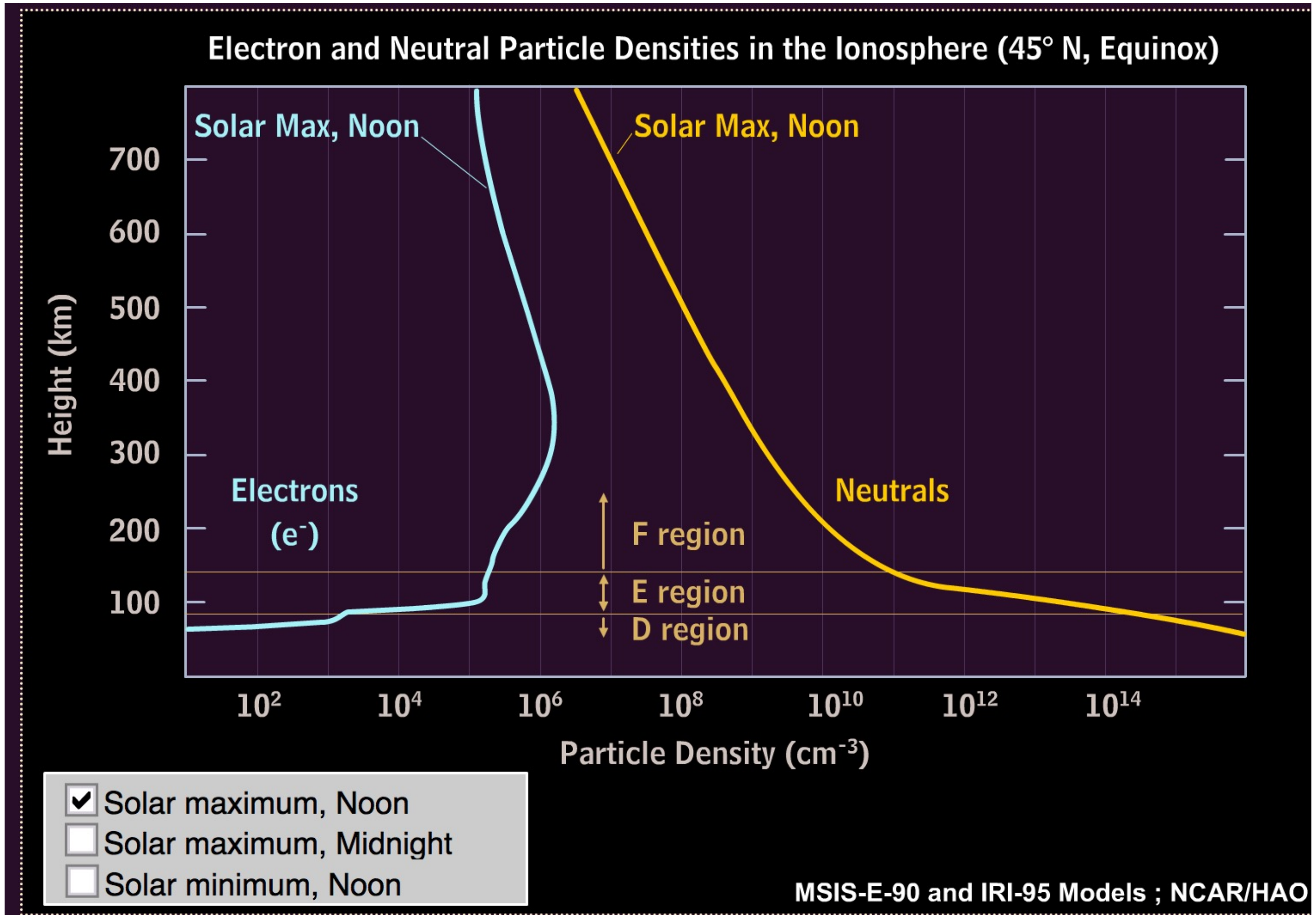
- neutrals
- Layers are divided based on **temperature gradient**
- Starting from the coldest region at mesopause to several hundred km.

Ionosphere:

- plasma
- Layers are divided based on **plasma density**
- Starting from about 80 km to several hundred km.

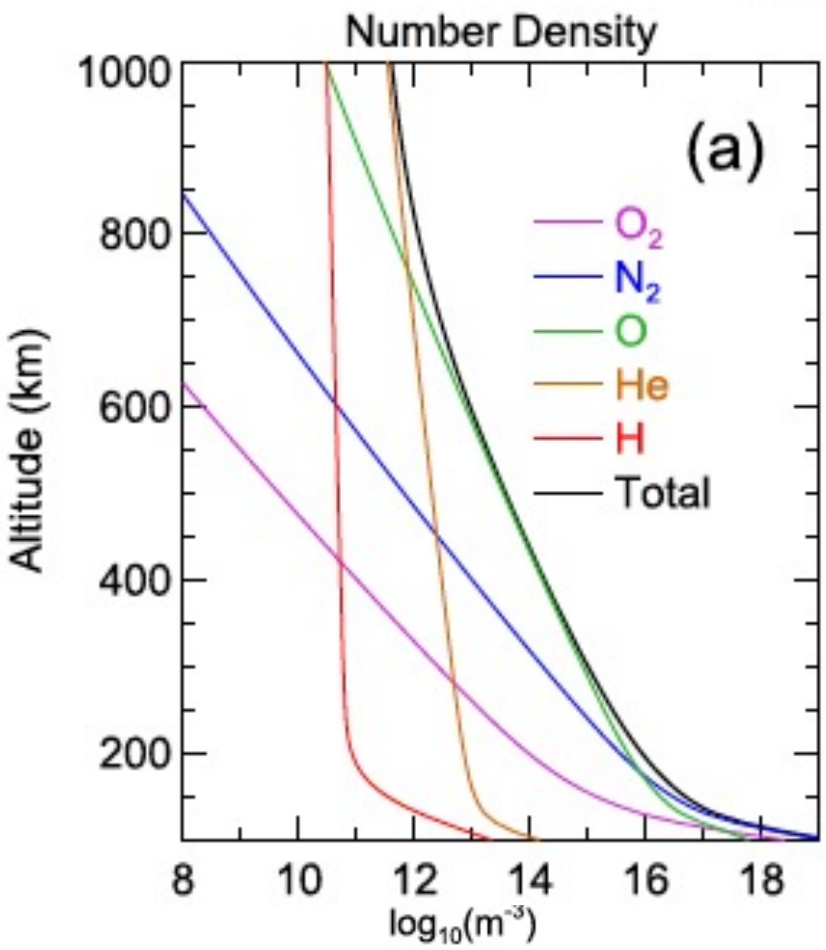


Thermosphere and Ionosphere Density Profiles



- Ionosphere: weakly ionized plasma
- Ion-neutral collisional coupling strongly controls the IT dynamics.

Thermosphere Composition



Global average number density profiles at solar max from the NRLMSISE-00 empirical model. From Emmert, 2015, Advances in Space Research.

- The most abundant neutrals in the lower atmosphere are N_2 and O_2.
- The most abundant neutrals in the thermosphere are O, N_2 and O_2.
- Lighter neutrals, such as H and H_e, become more and more important at higher altitudes.

- All neutral densities decrease exponentially with increasing altitude according to their **scale height (H, in m) above about 100 km**.

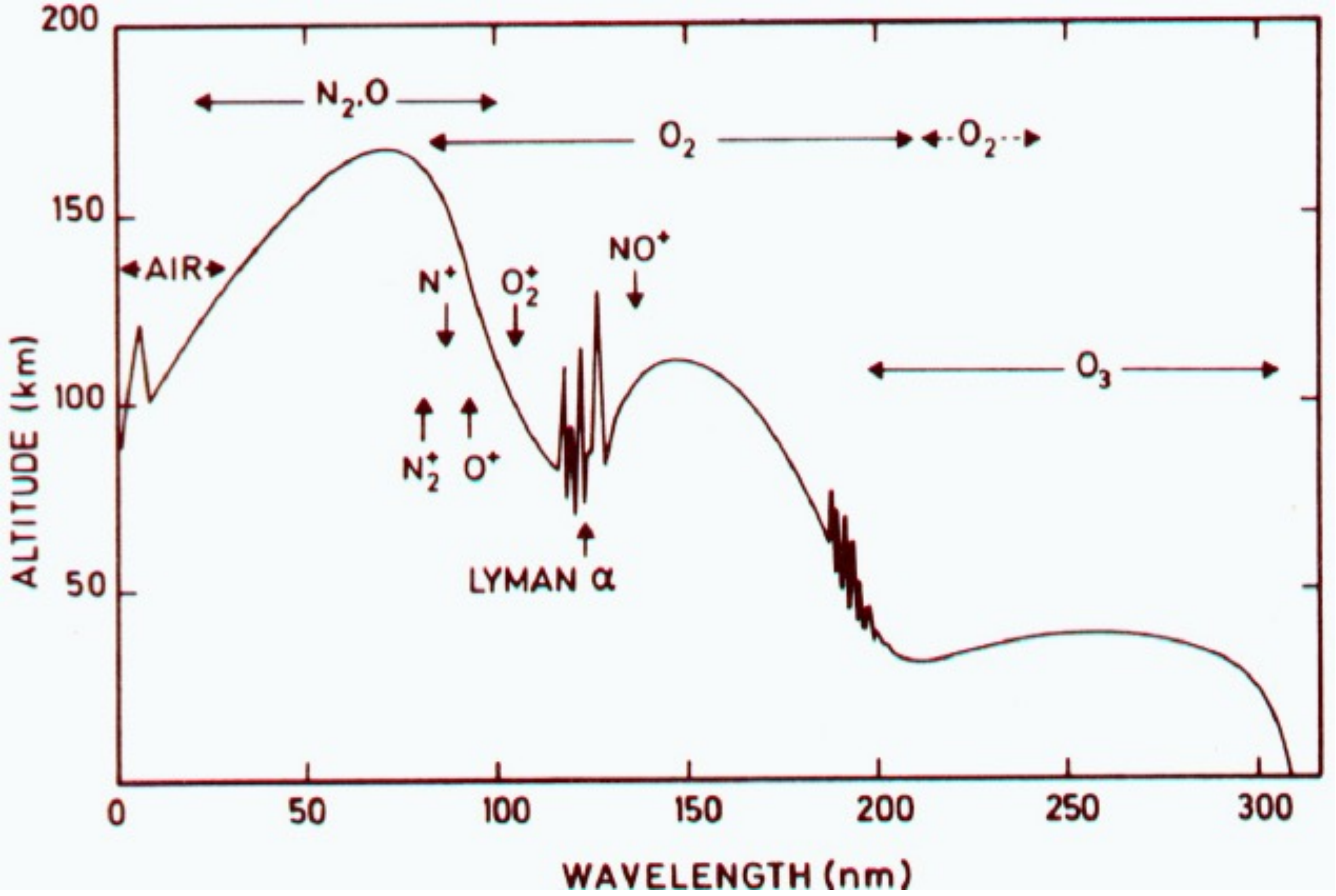
$$n(z) = n(z_0)e^{-\frac{z-z_0}{H}} \qquad H = \frac{kT}{mg}$$

- K is the Boltzmann constant: 1.38 x 10^{-23} J/K
- g is the gravitational acceleration: 9.8 m/s^2
- T is the neutral temperature in Kelvin and m is the neutral mass in Kg.

Absorption of Solar Radiation

- Dissociates molecular gases into atomic gases
- Heats the atmospheric gases
- Ionizes atmospheric gases to produce the ionosphere

Photodissociation due to absorption of solar photons gives different neutral constituents in the upper atmosphere than those in the lower atmosphere.



Photodissociation

- Photodissociation is a chemical reaction in which a chemical compound is broken down by photons.
- The radiation dissociates the molecular species of O_2 and N_2 into atomic species of O and N, thus changing the composition of the thermosphere from a molecular atmosphere near the mesopause around 85 km to an atomic atmosphere.
- O, N, H in the thermosphere are created due to photodissociation.

$$O_2 + h\upsilon \rightarrow O + O$$ ~5.12 eV

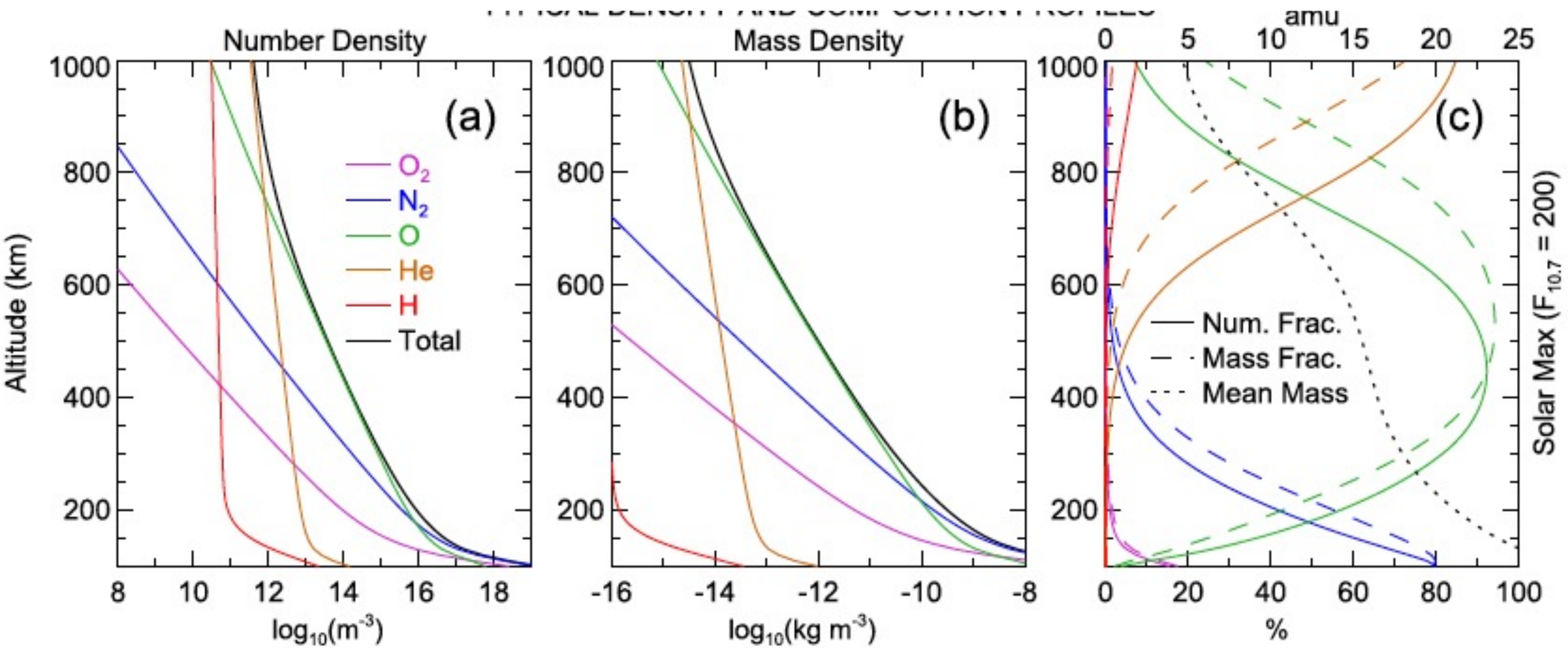
$$N_2 + h\upsilon \rightarrow N + N$$ ~9.8 eV

$$H_2O + h\upsilon \rightarrow H + OH$$

$$OH + h\upsilon \rightarrow O + H$$

~4.77 eV for each bond between O-H

Typical Thermosphere Density and Composition Profiles



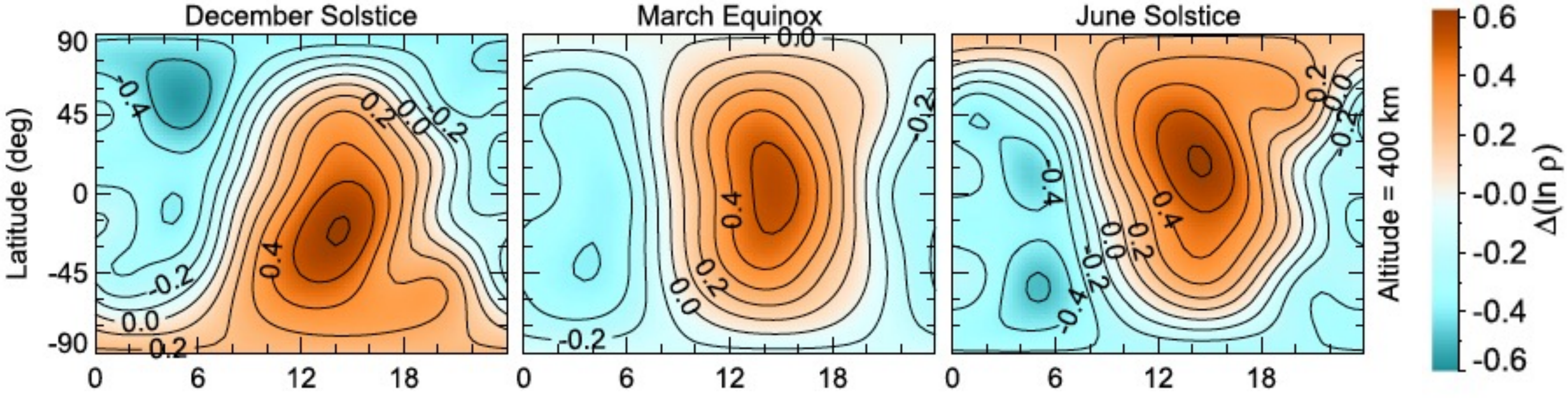
(a) Global average number density profiles at solar maximum (F10.7 = 200 solar flux units from the NRLMSISE-00 empirical model.

(b) Corresponding mass density profiles for each species.

(c) Number mixing ratios (solid lines) and mass mixing ratios (dashed lines) for each species.

From Emmert, 2015, Advances in Space Research.

Typical Thermosphere Density Variation

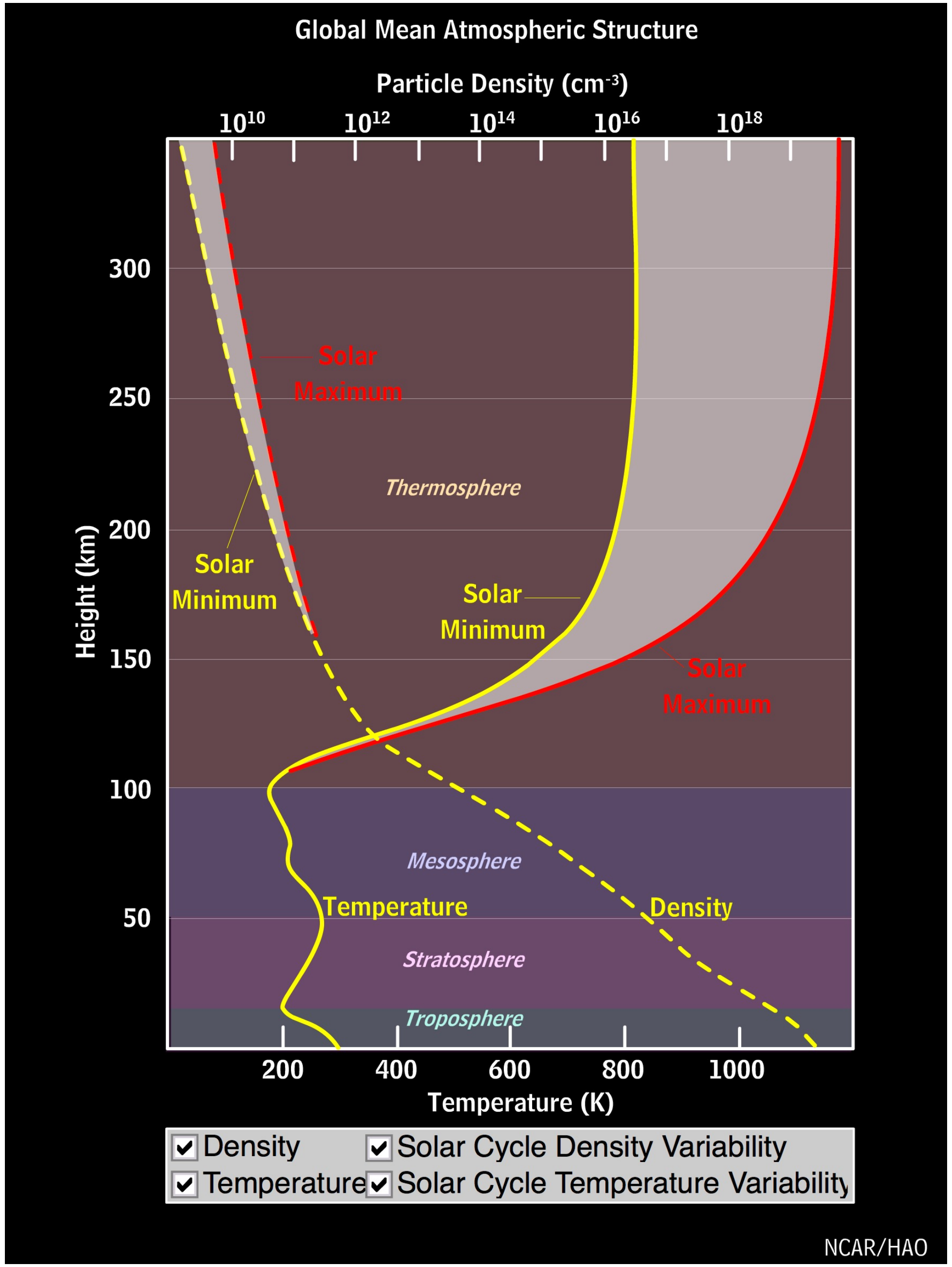


- Solar EUV and FUV irradiance is the primary heating source for the thermosphere (Roble, 1995), and its variation with local time and latitude (including its absence on Earth's night side) produces large variations in thermospheric density at fixed altitudes according to NRLMSISE-00.
- At 400 km the density variation shows a predominately diurnal character, with peak density at 14–15 local time (LT) at the subsolar latitude. Minimum density occurs near 05 LT in the winter hemisphere.

- From Emmert, 2015, Advances in Space Research.

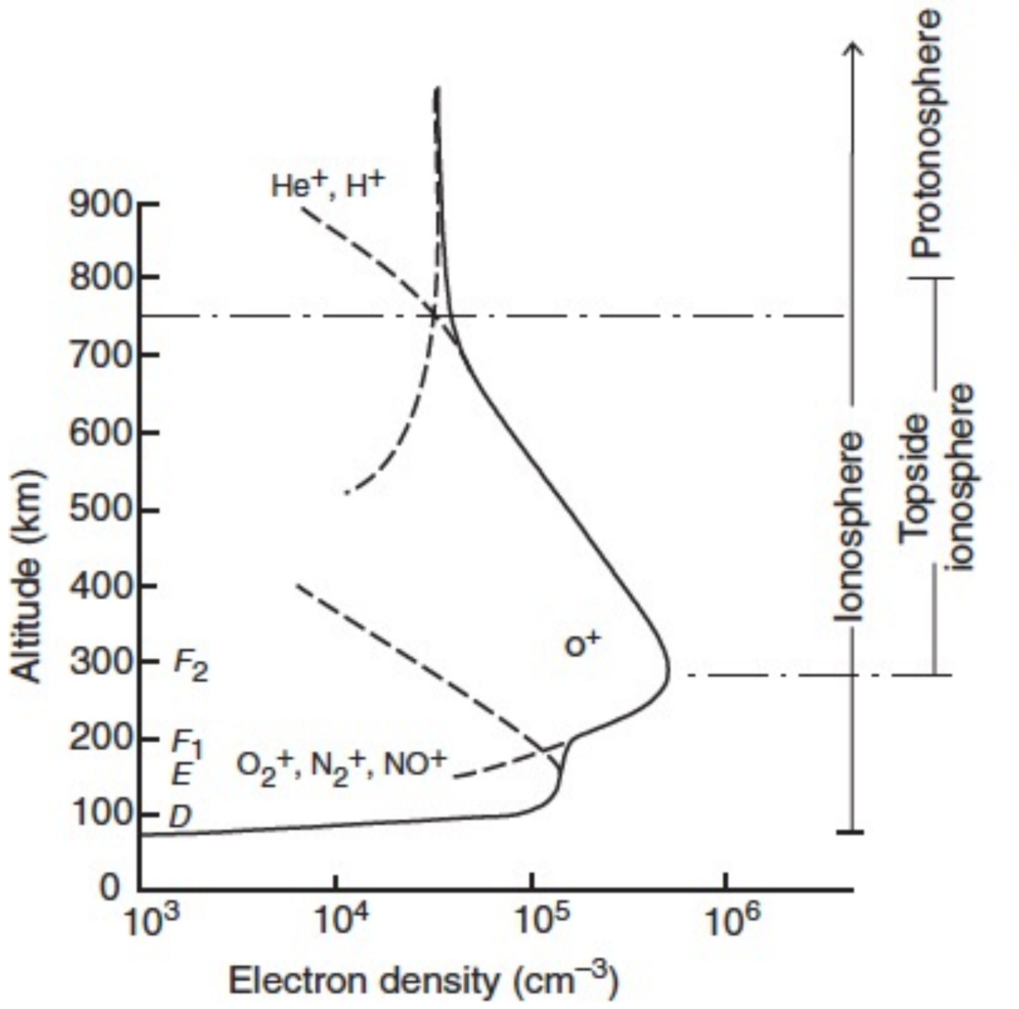
Solar Cycle Variability of Thermosphere

- Near the bottom of the thermosphere (~100 km), the neutrals are well mixed and have the same rate of decreasing.
- Above this height, the neutral densities decrease according to their own scale height.
- During solar maximum, the solar radiation is higher than that during solar minimum. So the thermosphere temperature is higher and the scale height is larger, and then the neutral density is higher.



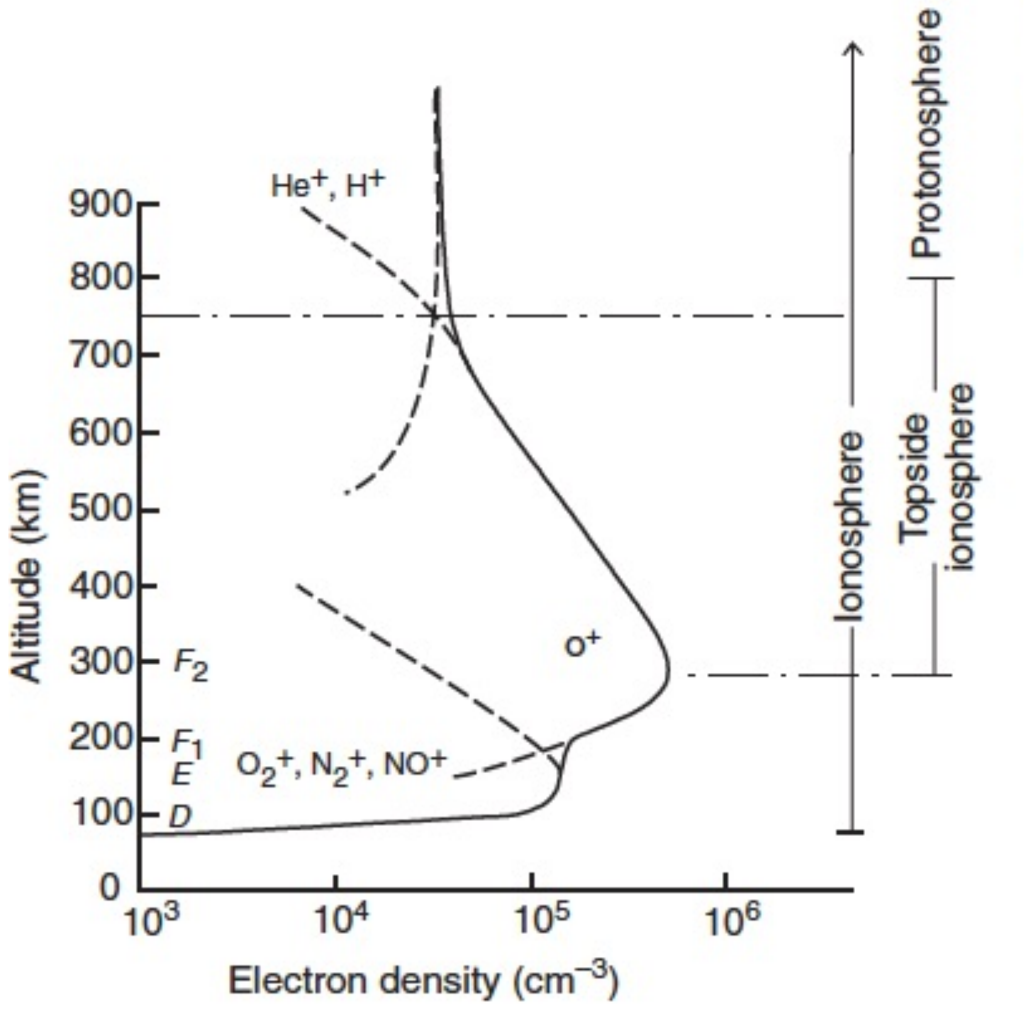
The Earth's Ionosphere

- The ionosphere is the ionized portion of the upper atmosphere and horizontally stratified into different layers.
- It extends from about 60 to beyond 1000 km and completely encircles the Earth but with considerable spatial/temporal variations.
- Most important processes in different layers:
  - Topside/plasmasphere: plasma transport
  - F layer: plasma transport/chemical loss processes
  - D-E layer: chemical processes



The Earth's Ionosphere

- The F2 layer possess the largest plasma density and is the most important layer for radio wave propagation.
  - **NmF2**: peak density of the F2 layer
  - **hmF2**: peak height of the F2 layer
- **Total electron content (TEC)**: integral of the electron density within a column of unit area between the receiver and the transmitter, such as GPS receiver and the GPS satellite. Important parameters to characterize the ionosphere plasma content.
- The most abundant ion in terrestrial ionosphere is O^+ in the F2 layer and molecular ions (O_2^+ and NO^+) in the E layer.

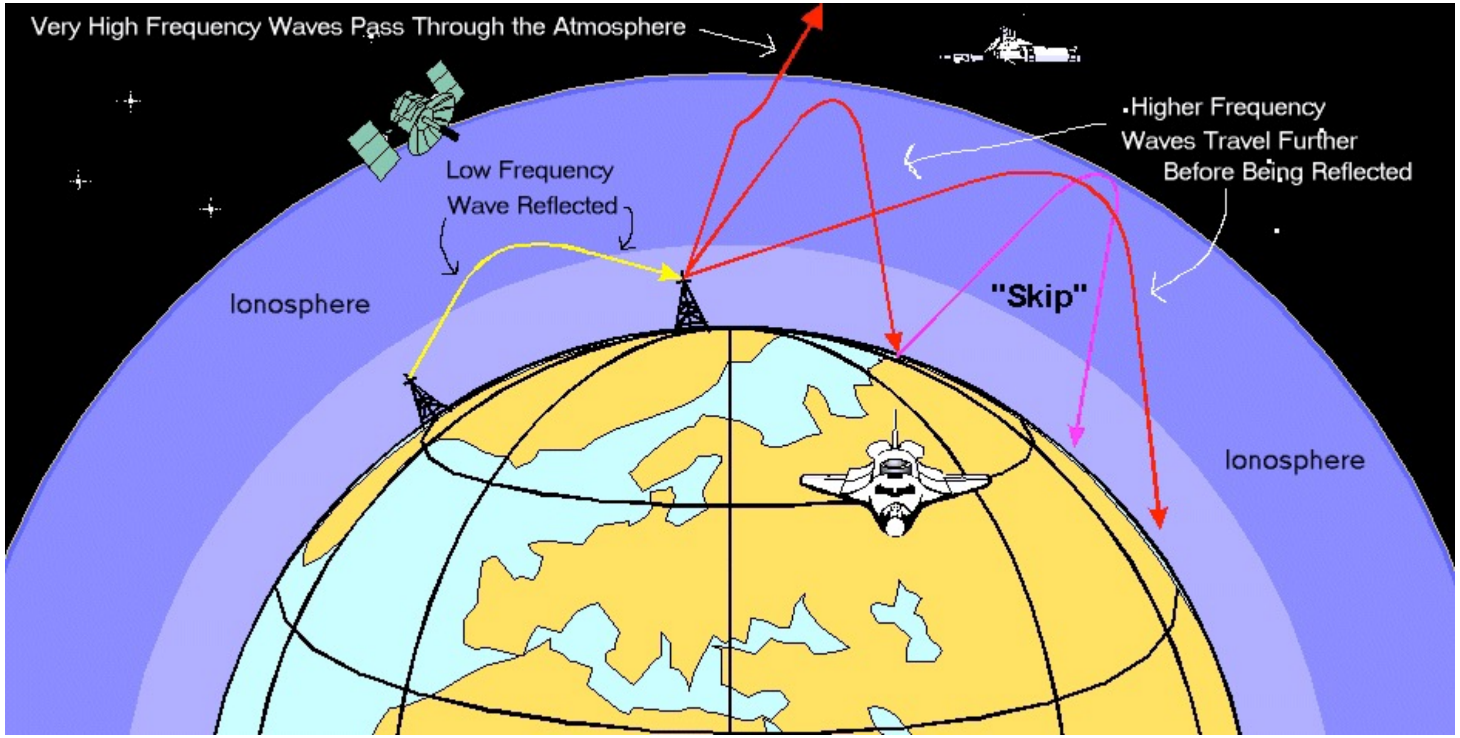


The ionosphere and Radio Wave Propagation

- **Plasma frequency f_0**: The natural resonant frequency of a plasma oscillation, equal to the minimum frequency of electromagnetic waves that can travel through the plasma without attenuation.
- EM waves reflect at the location where the plasma frequency equals the wave frequency.
- This is usually referred to as critical frequency.

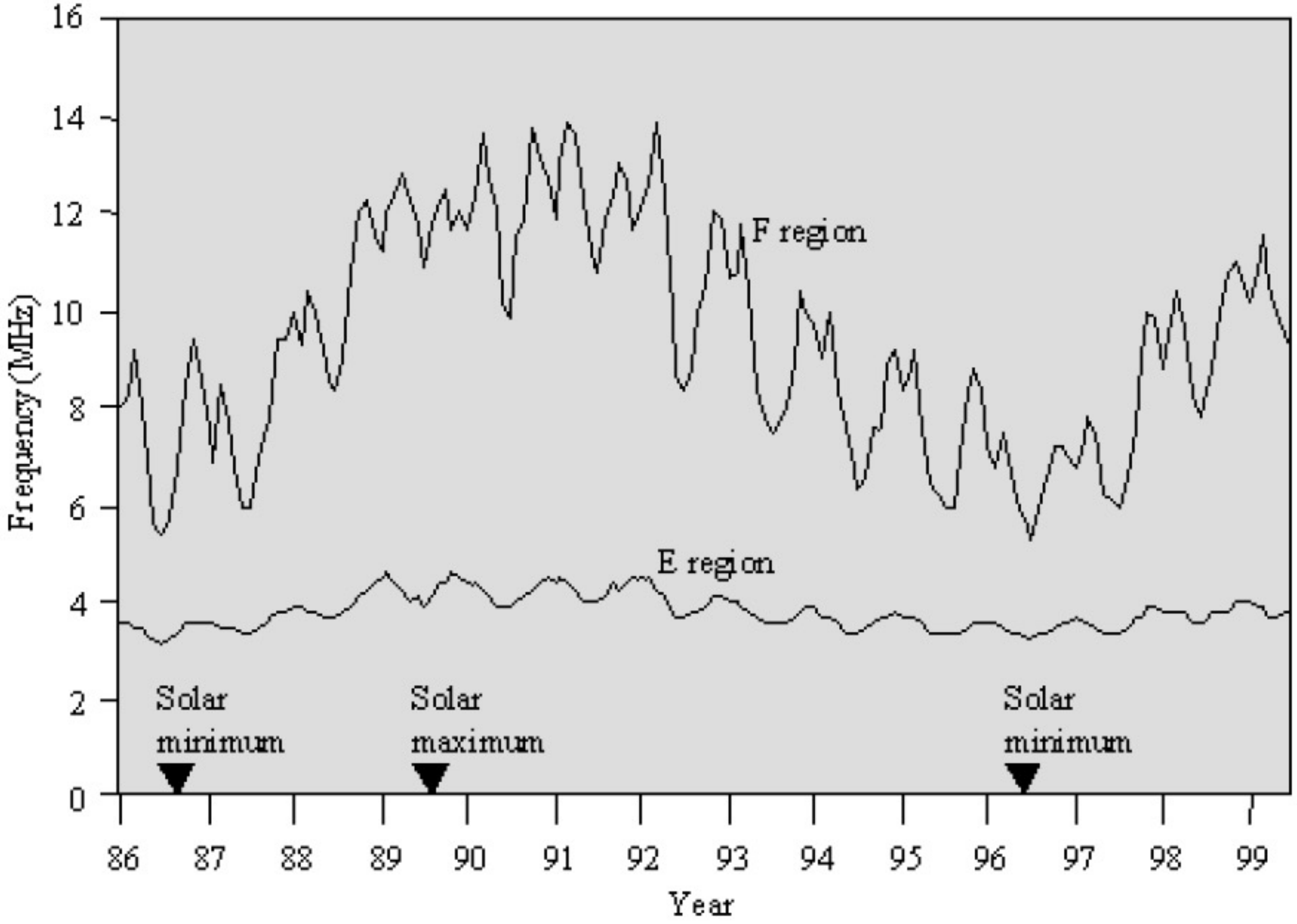
$$f_0 = 9\sqrt{10^{-6} n_e}$$

(f_0 in megahertz, n_e in cm^{-3})



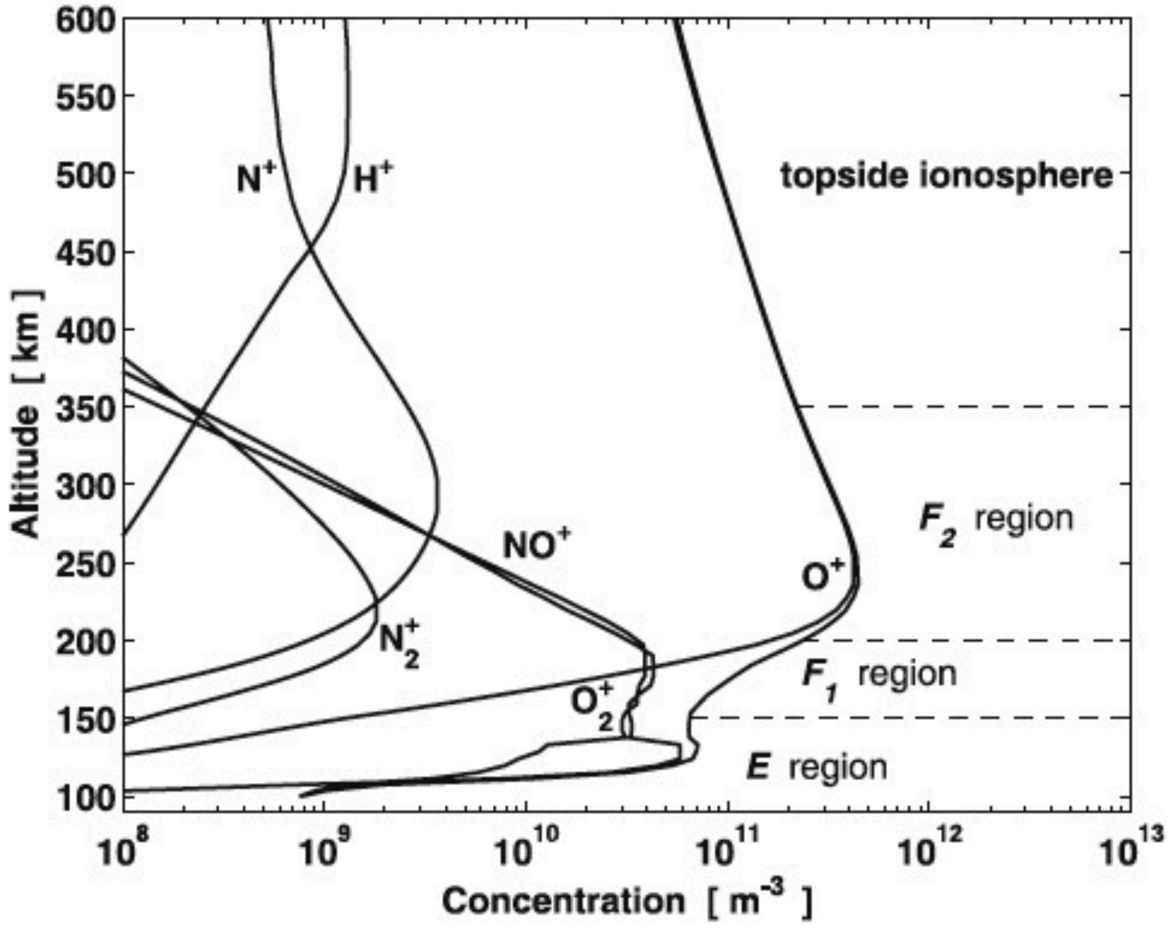
A time series of critical frequency

- Time series of ionosphere E and F region critical frequencies measured by ionosonde are shown above.
- What trends can you see?



Ionosphere Composition

- The E layer is from 90 km to 150 km and is due to soft X-ray (1–10 nm) and far ultraviolet (UV) solar radiation ionization of molecular species. In the auroral zone, particle precipitations also can ionize neutrals here.
- The F_1 layer is the lower sector of the F layer and exists from about 150 to 220 km. It is composed of a mixture of molecular ions O_2+ and NO+, and atomic ions O+.
- In F_2 layer, the O+ atomic ions become the most abundant species.



Chemistry in different ionosphere layers

	Major source	Major loss	
E layer	$N_2 + h\upsilon \rightarrow N_2^+ + e$	$N_2^+ + O \rightarrow NO^+ + N$ $e + N_2^+ \rightarrow N + N$ $NO^+ + e \rightarrow N + O$	Equilibrium determined by photoproduction and chemical loss
F1 layer	$O_2 + h\upsilon \rightarrow O_2^+ + e$	$e + O_2^+ \rightarrow O + O$	Equilibrium determined by photoproduction and chemical loss
F2 layer	$O + h\upsilon \rightarrow O^+ + e$	$O^+ + N_2 \rightarrow NO^+ + N$ $NO^+ + e \rightarrow N + O$	Equilibrium determined by photoproduction and diffusion

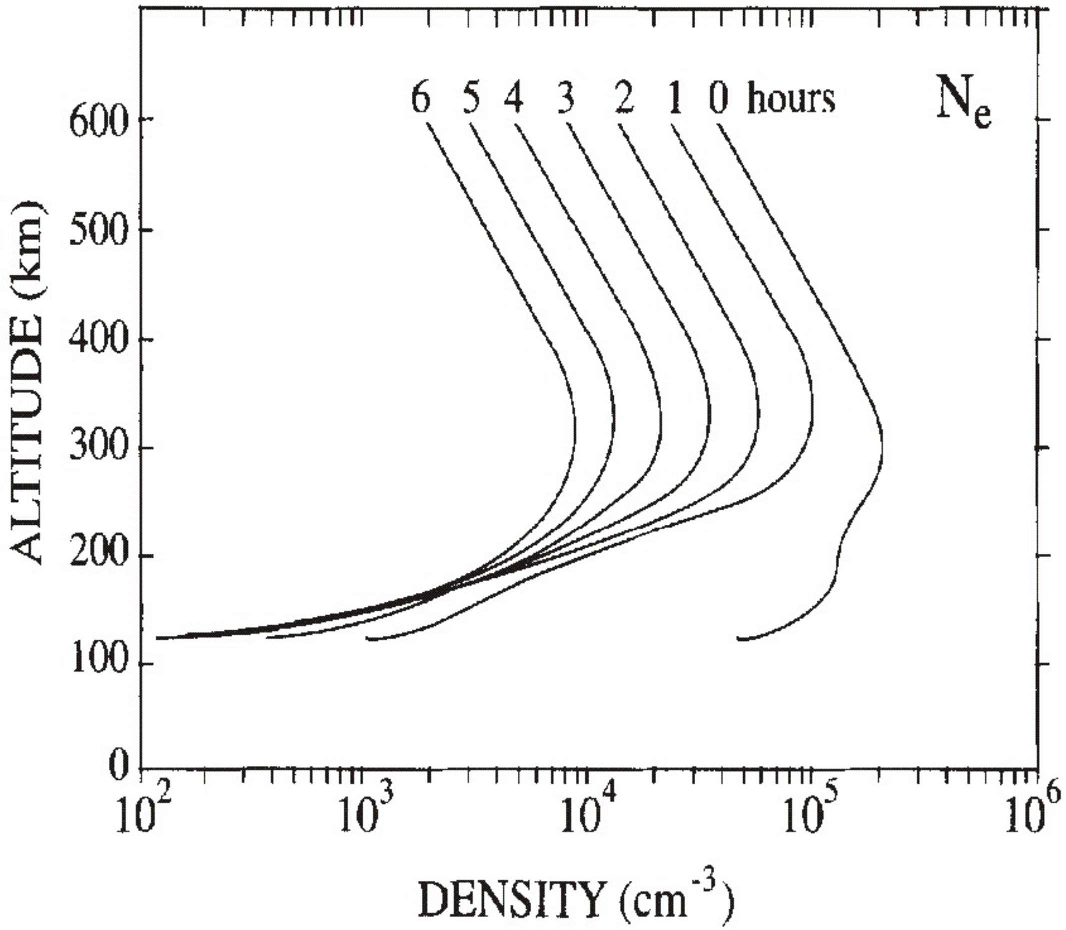
Why O/N_2 ratio important?

The production of ionization depends largely on the [O] density, while chemical loss is determined by the abundance of N_2 and, to lesser degree, O_2.

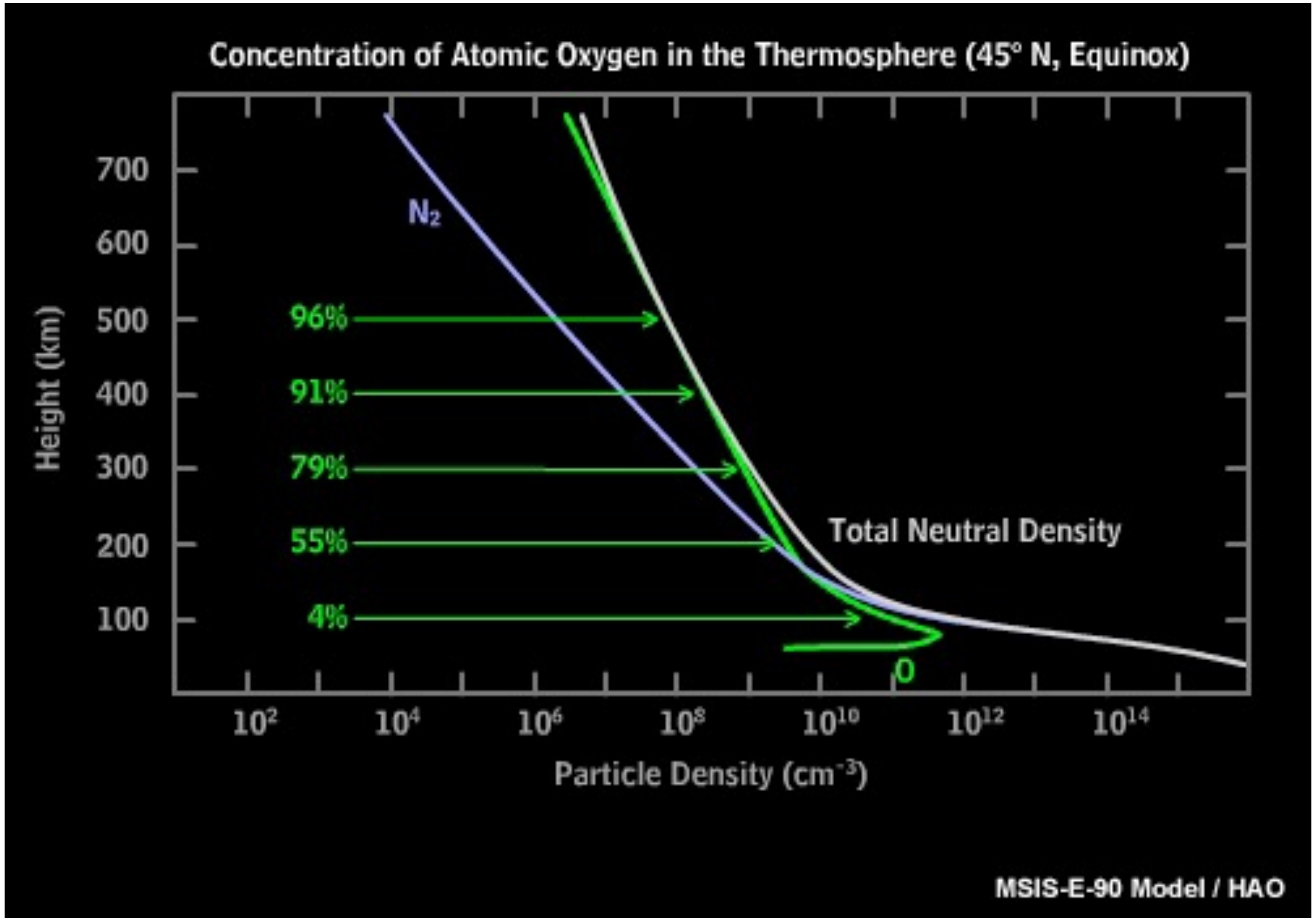
Evolution of electron density due to chemical loss

- This figure shows calculated electron density profiles (Ne) at selected times after photoionization is set to zero.

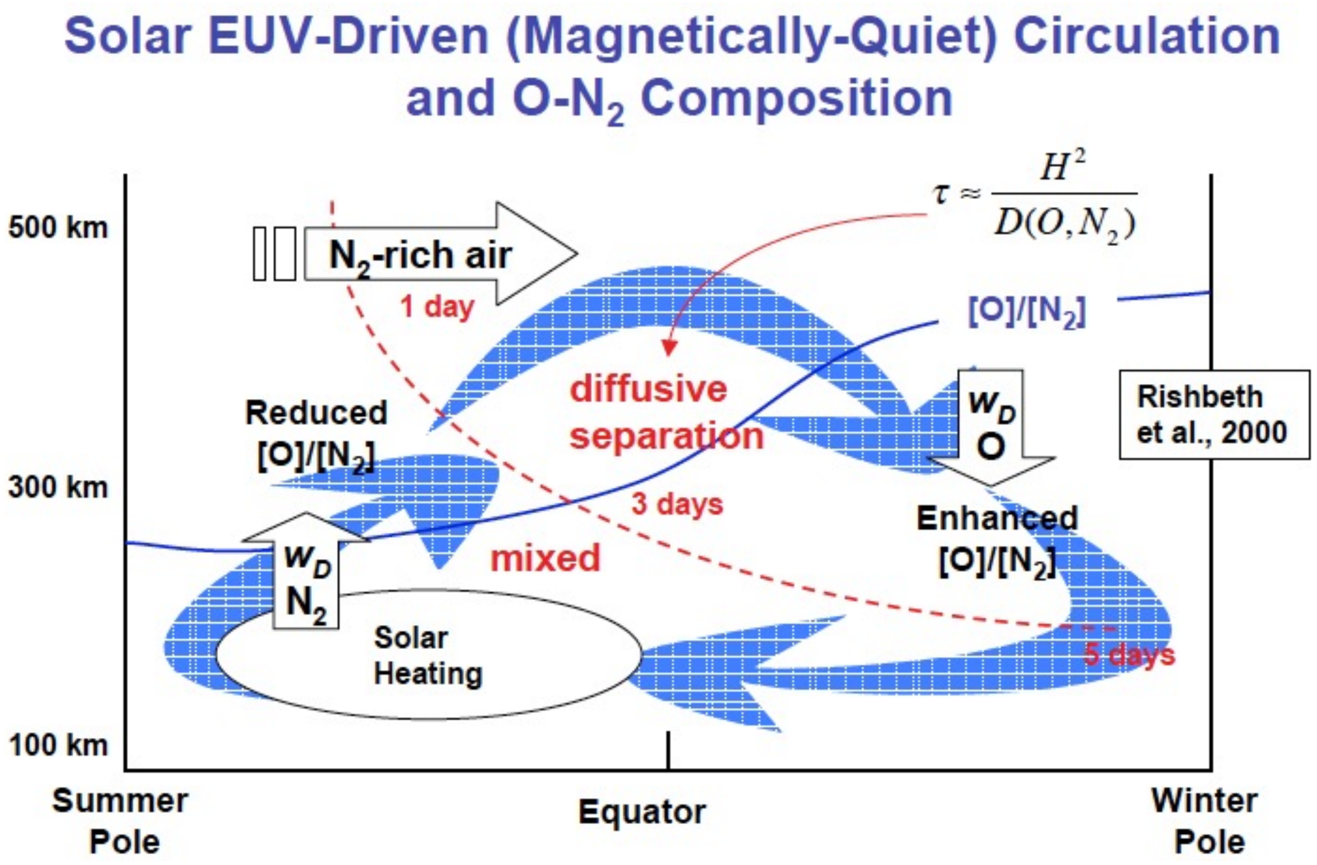
- It shows the different time scales of evolution due to chemical losses at different altitudes.



Ratio of atomic oxygen in the thermosphere



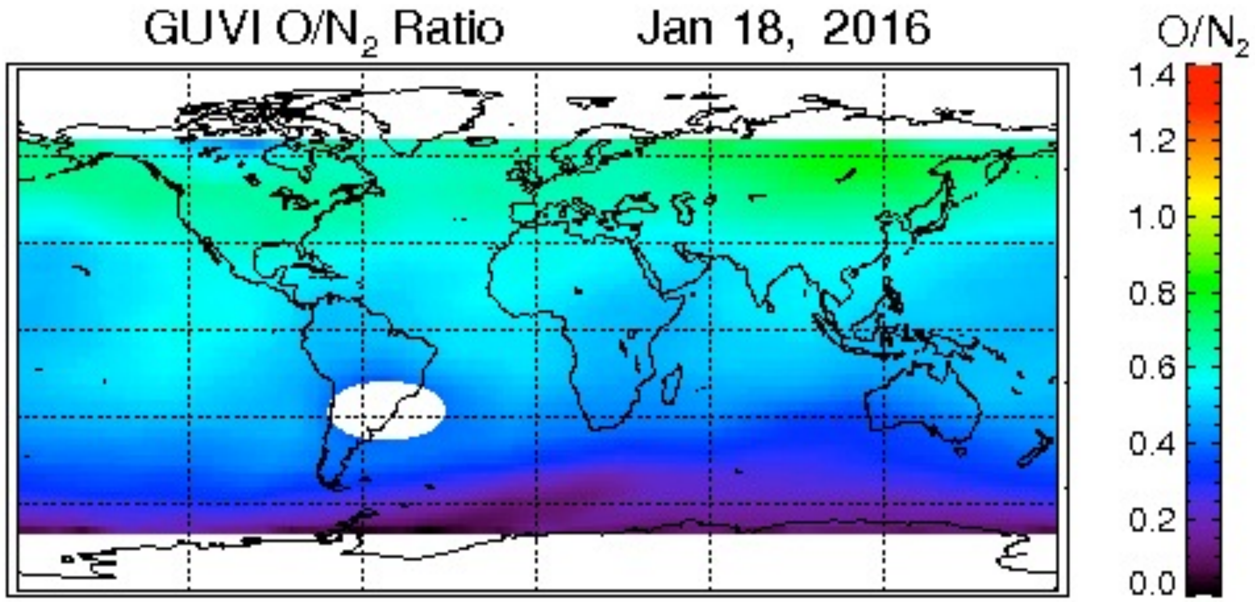
Solar EUV-Driven Circulation during Magnetically Quiet Times



Quiet day O/N_2 ratio

- The thermospheric column number density ratio of O and N_2 referenced at N_2 column number density level of 10^{17} cm^{-2}

- Seasonal thermosphere composition changes can be seen



Plasma thermal structure

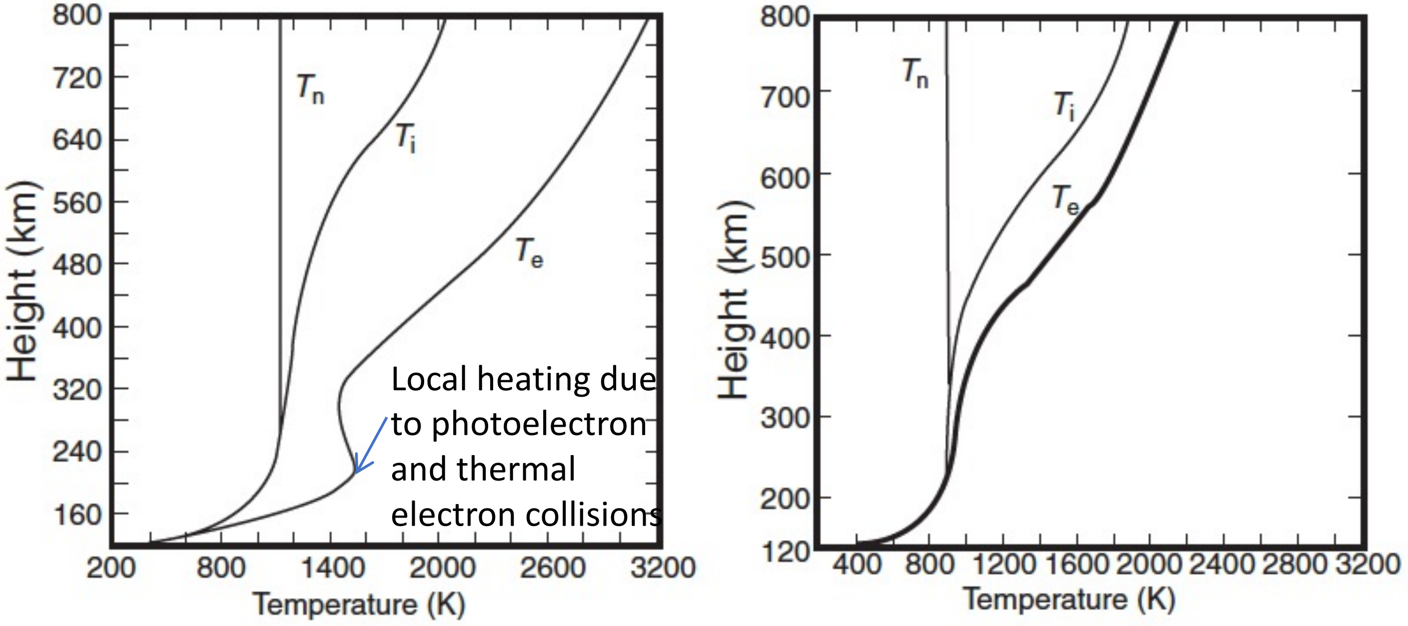


Figure 11.17 Calculated electron, ion, and neutral temperature profiles for the ionosphere over Millstone Hill on March 23–24, 1970. The left panel is for 1422 LT and the right panel for 0222 LT.[22]

Diurnal variation at mid-latitudes

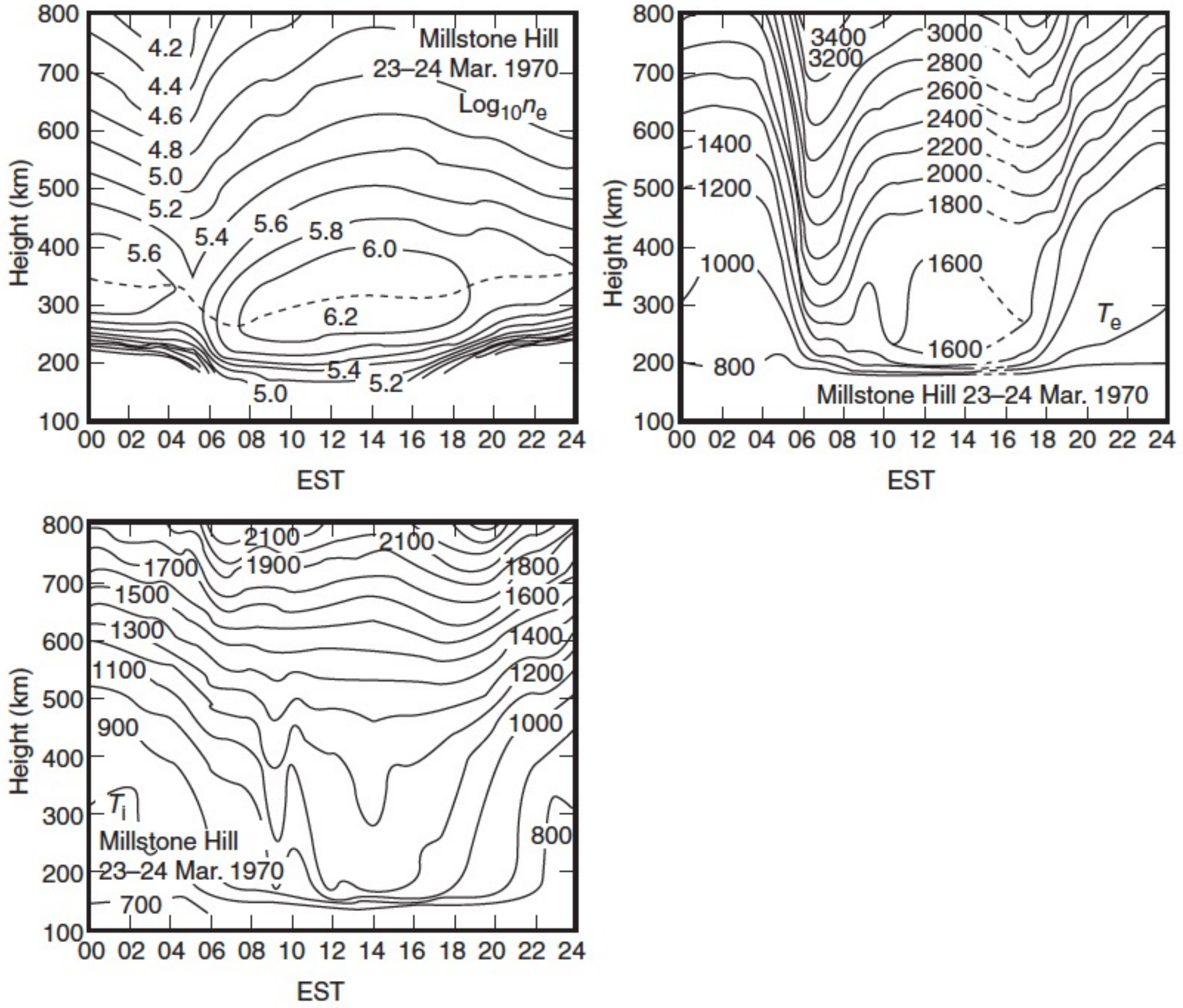


Figure 11.20 Contours of electron density (top left), electron temperature (top right), and ion temperature (bottom) measured by the Millstone Hill incoherent scatter radar on 23–24 March 1970.[28] n_e is in cm^{-3} and the temperatures are in K.

Seasonal variation at mid-latitudes

- The ionosphere's seasonal variation is related to a solar zenith angle change and thermospheric wind pattern change.
- The O/N2 ratio in the winter hemisphere is higher than that in the summer hemisphere.
- The O+ densities in winter are therefore larger than those in summer at F region altitudes. In turn, the higher electron densities in winter result in lower electron temperatures owing to the inverse relationship between the electron density and temperature. This is called **winter anomaly**.

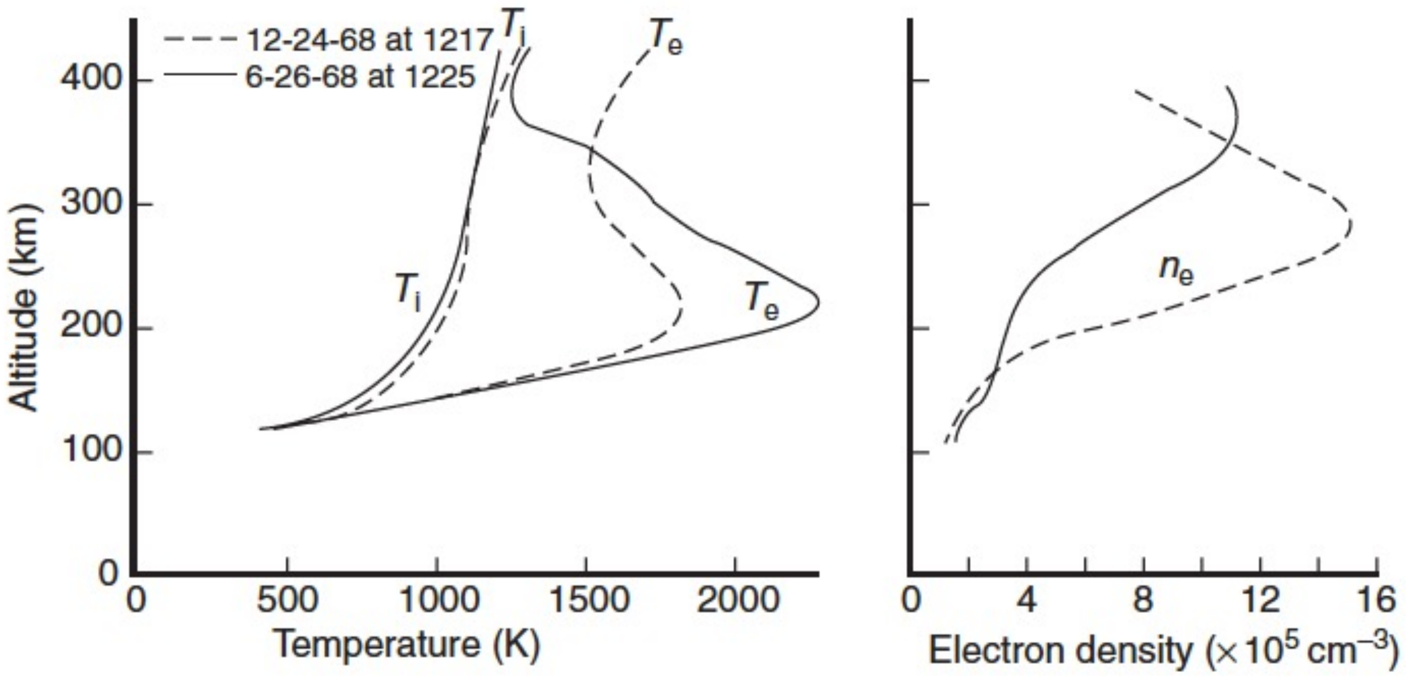


Figure 11.21 Summer (solid curves) and winter (dashed curves) profiles of T_e, T_i, and n_e measured by the Arecibo incoherent scatter radar during the daytime.[29]

Solar cycle variation at mid-latitudes

- At solar maximum, the solar EUV fluxes and the O densities are greater than those at solar minimum, and these conditions lead to higher electron densities and lower electron temperatures.
- The lower electron temperatures are a result of the inverse relationship between the electron density and temperature.

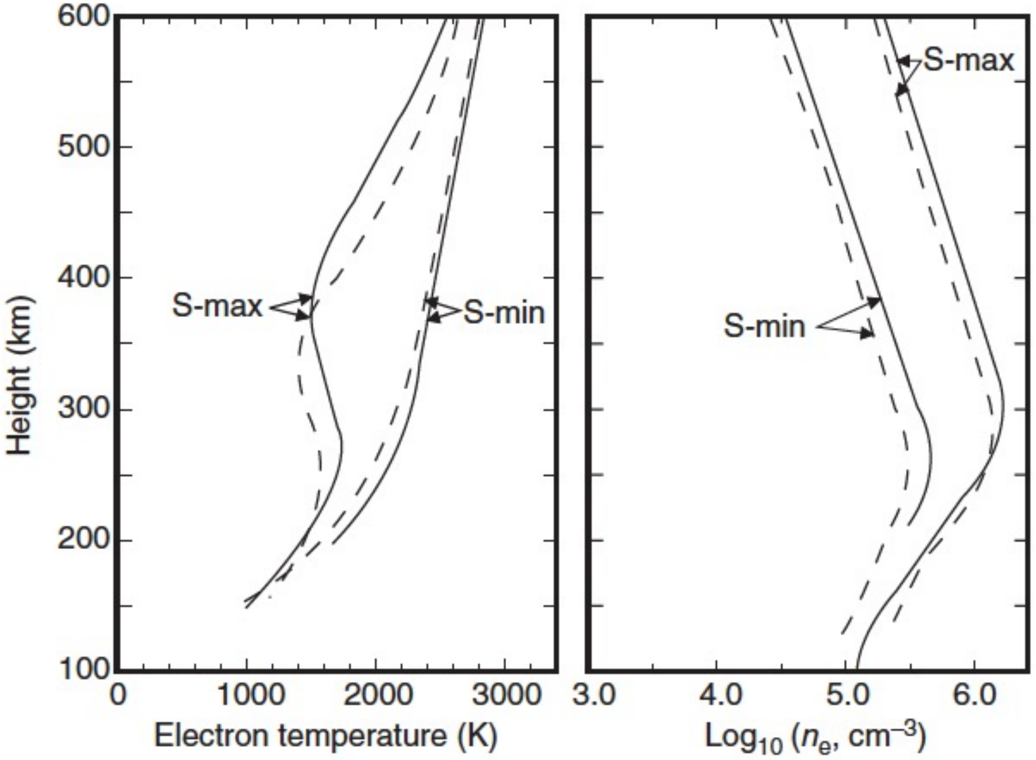


Figure 11.22 Electron temperature and density profiles for the daytime mid-latitude ionosphere at equinox for both solar minimum and maximum conditions. The solid curves are profiles measured by the Millstone Hill incoherent scatter radar, while the dashed curves are calculated.[30]

Ionosphere-Thermosphere Dynamics

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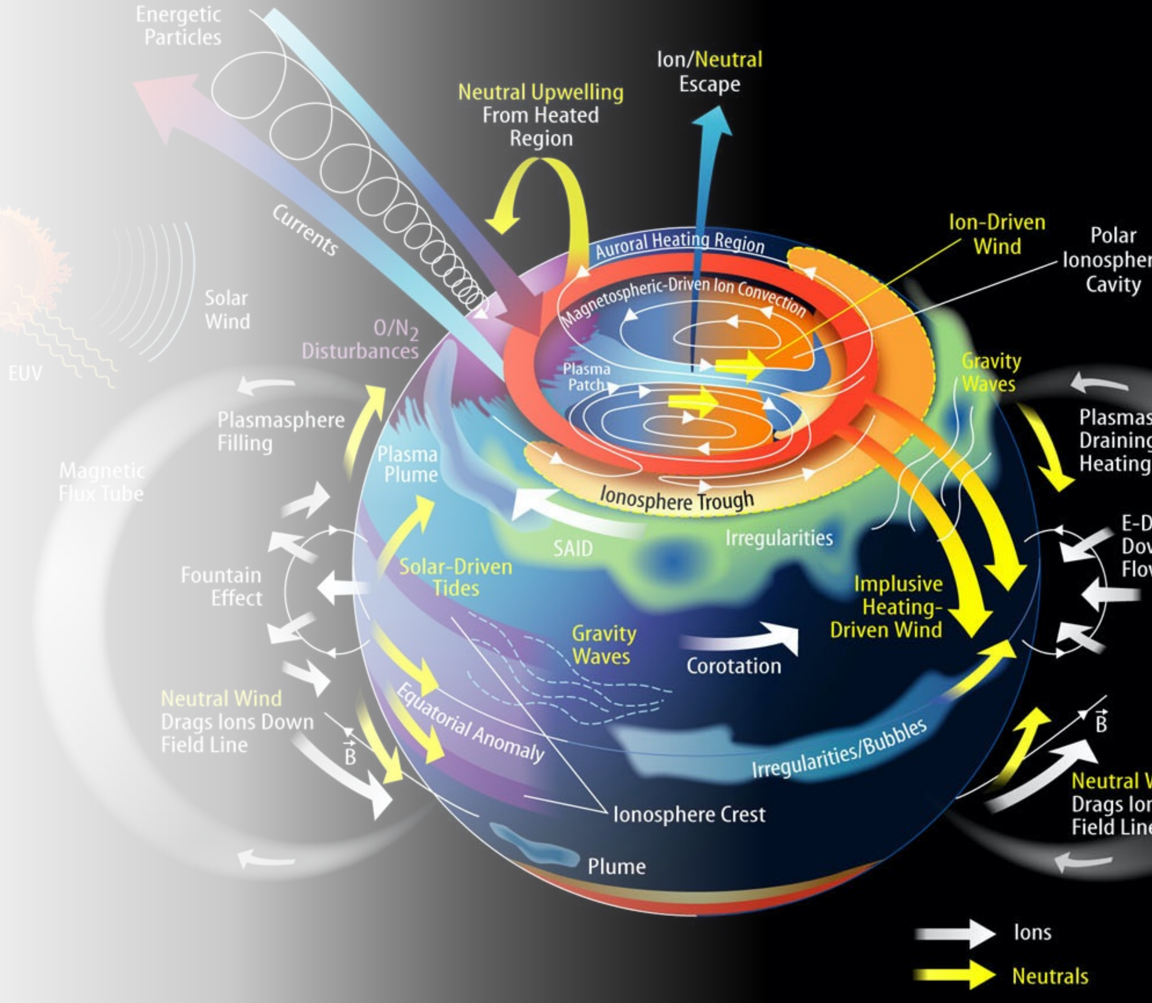
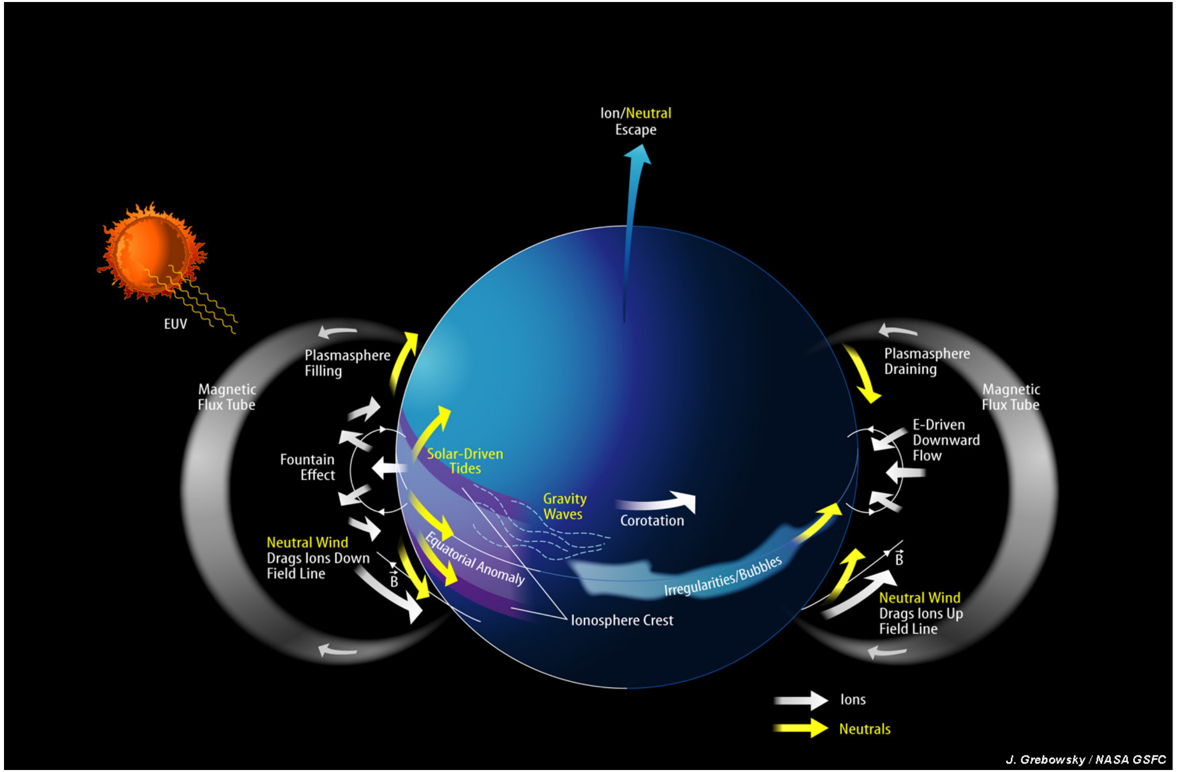


IT System with Solar EUV Forcing Only

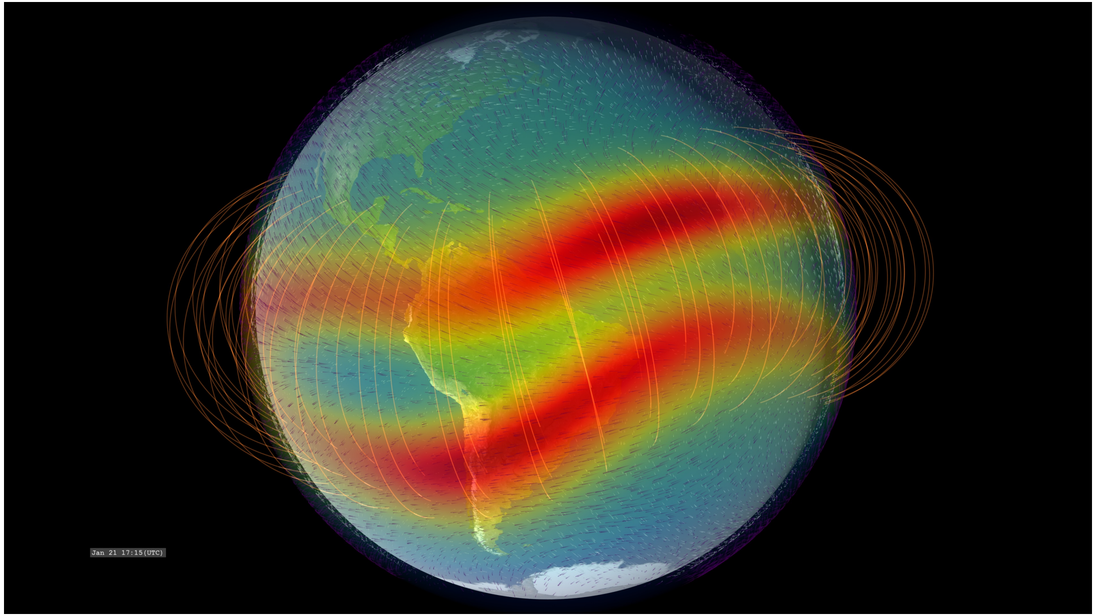


If the solar EUV is the only energy source, most of the IT dynamics would occur in the equatorial to low latitude region.

Dayside Equatorial Ionization Anomaly (EIA)

- EIA or Appleton Anomaly: Large-scale feature in the dayside equatorial and low-latitude region.

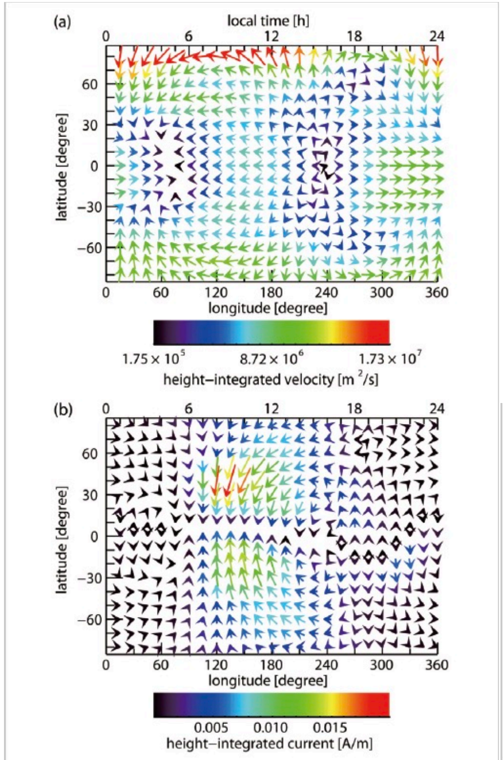
- Edward Appleton won the Nobel Prize in Physics in 1947 for his seminal work proving the existence of the ionosphere.



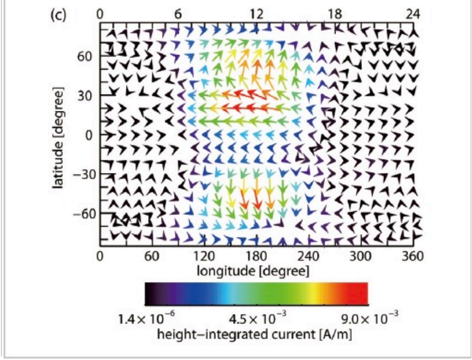
Credit: NASA's Scientific Visualization Studio

E-region Dynamo

An intense convergence of dynamo current to the sunrise sector at the magnetic equator. Here, positive charge is accumulated. In contrast, dynamo current diverges from around the sunset sector at the equator, with negative charge being accumulated.



- Wind velocity field in the thermosphere (September, 0:00 in UT, diurnal component),
- Pedersen dynamo current driven by the neutral winds
- (c) Hall dynamo current.
- The panels (a) to (c) are all integrated over altitudes from 100 to 300 km.



- Jin Hidekatsu

E-region Dynamo

- Effect of poleward winds and Pedersen conductivity near the terminators:
- Eastward electric field (day)
- Westward electric field (night)

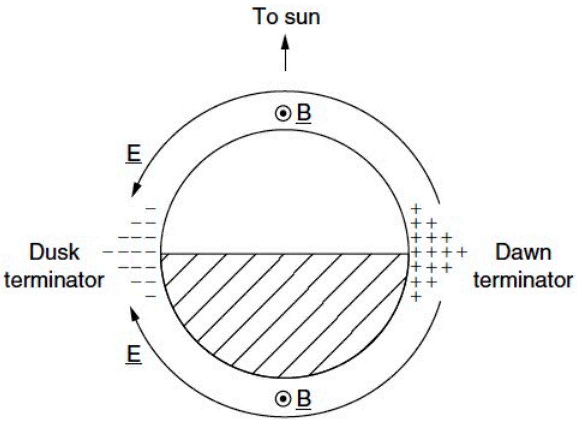
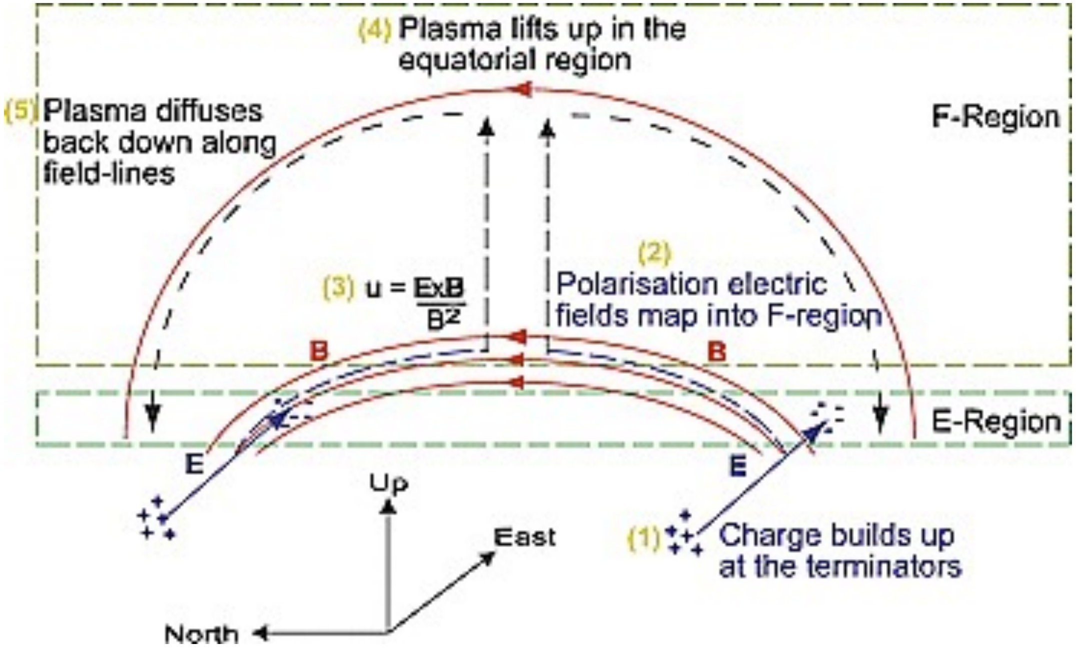


Figure 3.5 Schematic diagram showing the zonal electric field component and its relationship to the charge densities at the terminators. Since the zonal electric field varies slowly with height, the charge density is also a weak function of height from 100 to 500 km.

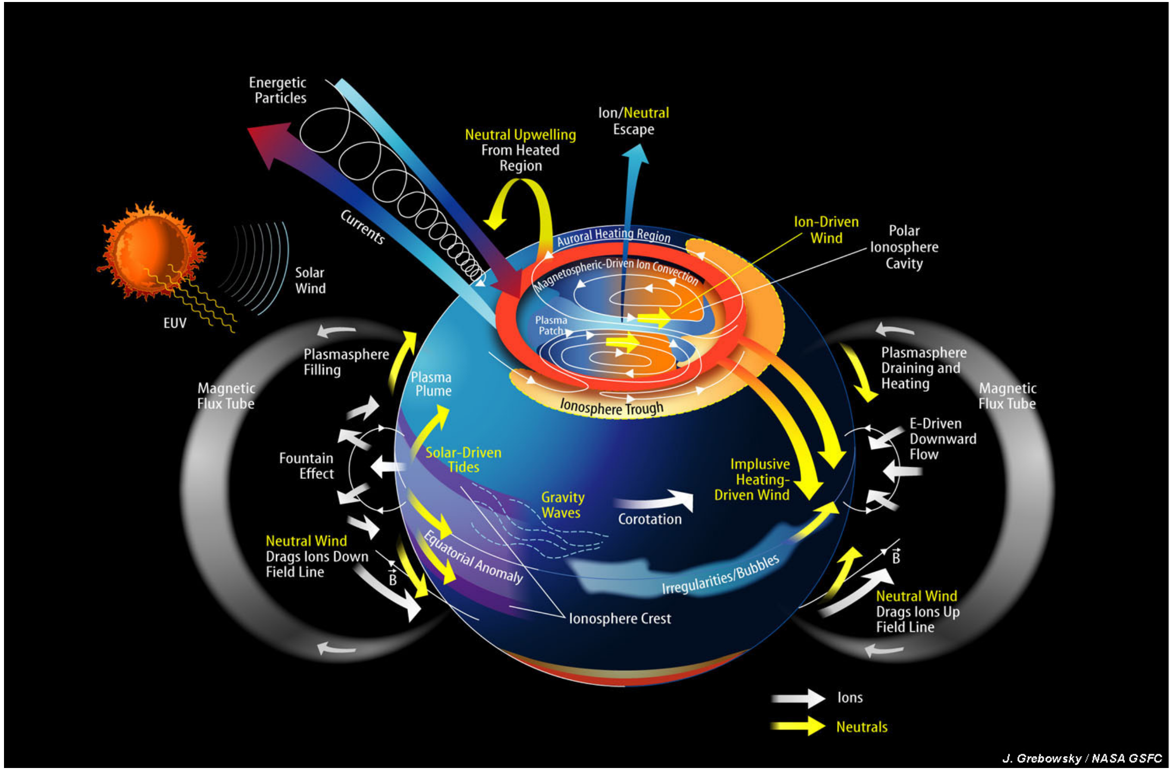
Kelley's Ionosphere book 2009

Appleton anomaly formation mechanism



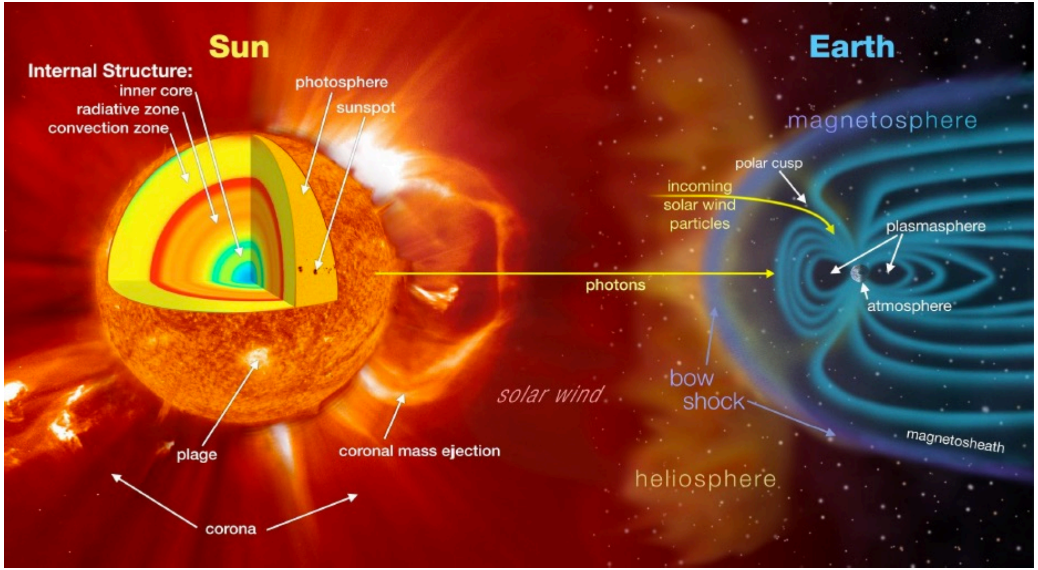
Immel et al. 2006

Adding Solar Wind Forcing



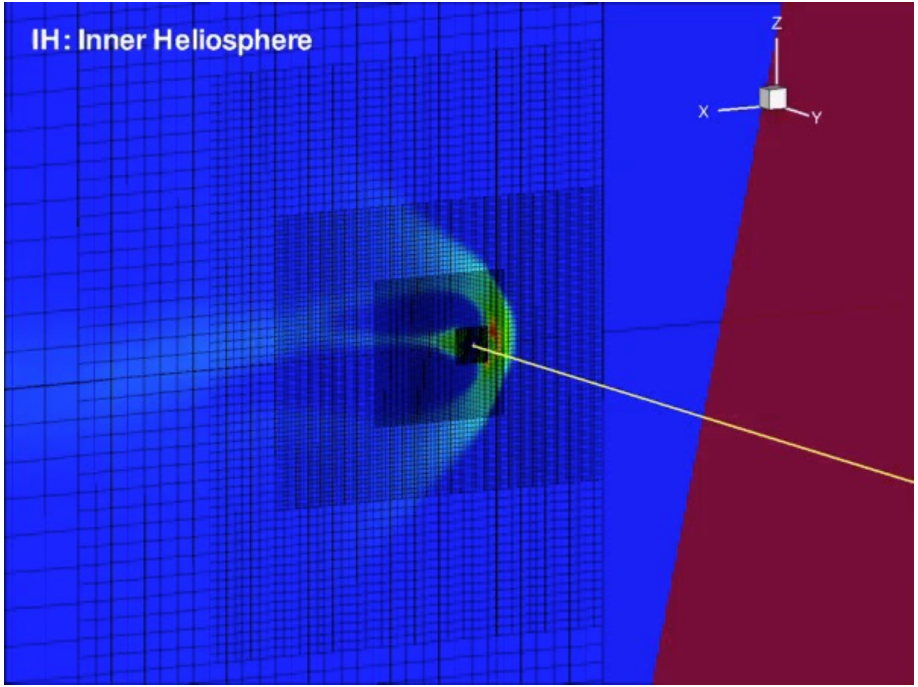
- Adding the solar wind forcing would create various high-latitude dynamics, including convection pattern, FACs and auroral zone.
- During geomagnetic quiet times, the low and high-latitude systems do not interact strongly with each other.

Solar-Terrestrial Relations



- Solar radiation and solar wind are the two ultimate energy sources provided by the Sun to the geospace system.
- The Earth's intrinsic magnetic field deflects much of the solar wind. The solar wind energy entering the magnetosphere drives the dynamics of the geospace system.

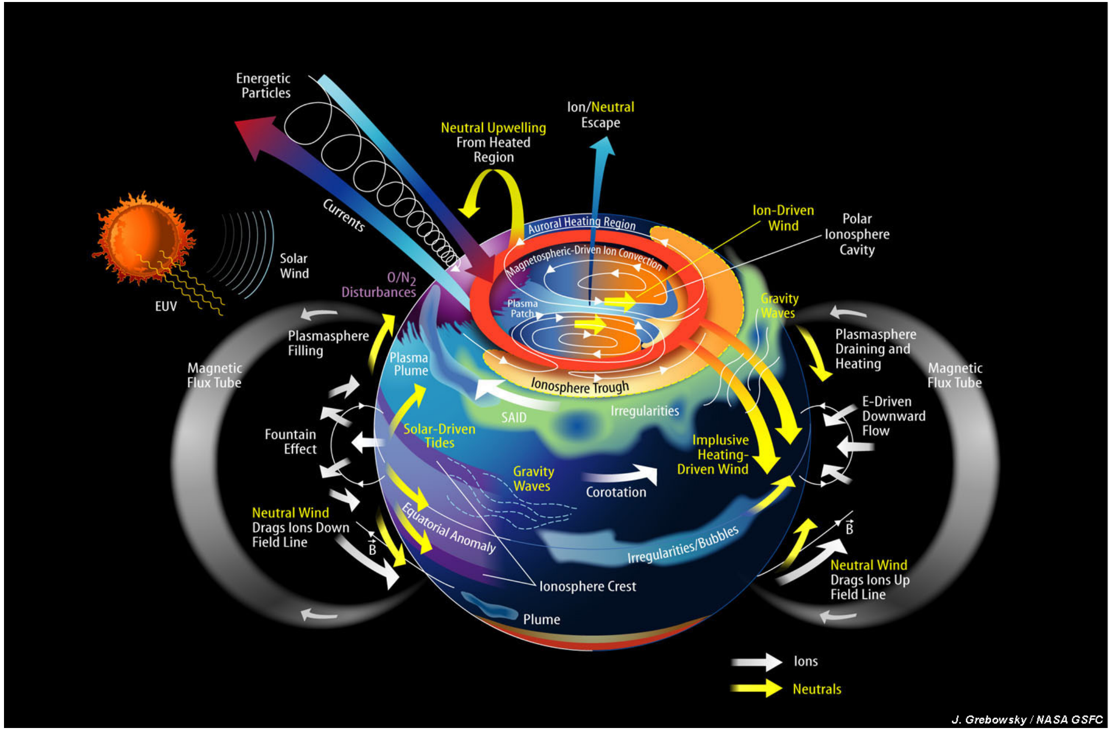
Interaction between Solar Wind and the Earth



Plasma pressure and magnetic fields simulated using University of Michigan Space Weather Modeling Framework (SWMF)

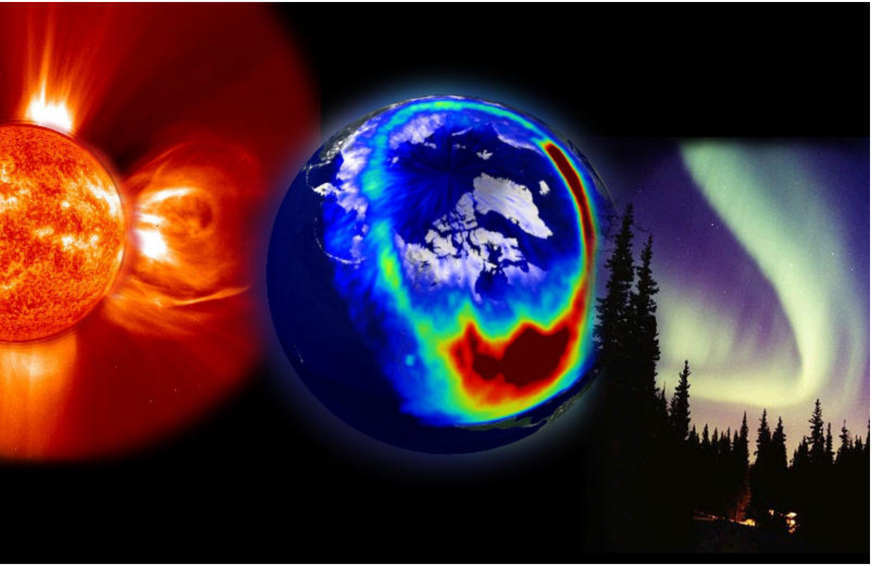
- The geospace system dynamically respond to varying solar wind.

When the Sun “Sneezes”



- Both the solar wind and the solar EUV are highly variable and create “space weather”.
- When they drive the geospace more strongly, for example, during geomagnetic disturbances, the high-latitude system would expand equatorward. At the same time, the equatorial system also expands to higher latitudes. Thus, cross-latitude coupling enhances.

Geomagnetic Disturbances



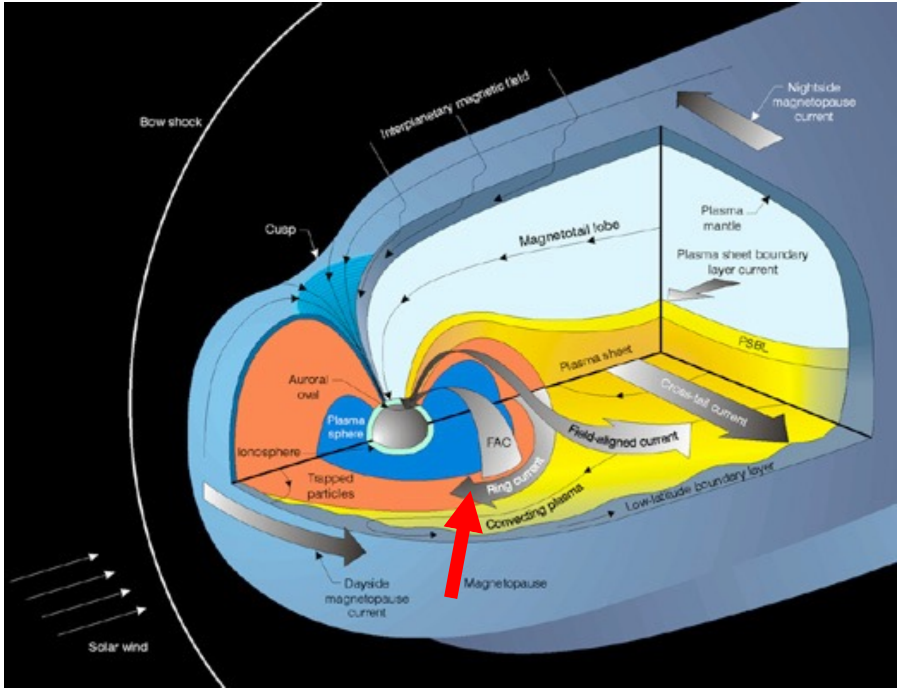
Geomagnetic disturbances are driven by transient solar wind and interplanetary magnetic field structures, such as Coronal Mass Ejection (CME) and Corotating Interaction Region (CIR).

Three major geomagnetic disturbances:

1. **Storm**: largest disturbance; global scale; last a couple of days
2. **Substorm**: nightside disturbance; last a couple of hours
3. **Shock compression**: transient but global disturbance; last several minutes

Geomagnetic Storm

- A geomagnetic storm is a major disturbance of Earth's magnetosphere that occurs when there is a very *efficient energy exchange* from the solar wind into the space environment surrounding Earth.
- There are major changes in the currents, plasmas, and fields in the Earth's magnetosphere.
- Geomagnetic storms are defined by worldwide average of the low-latitude disturbance in the horizontal magnetic field due to *ring current* in the inner magnetosphere.

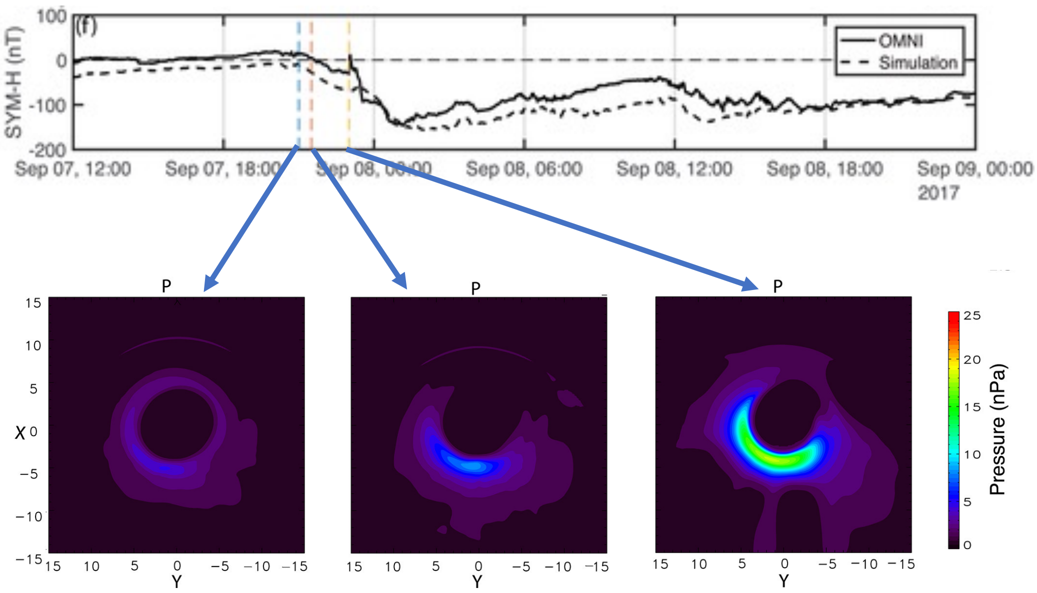


Geomagnetic Storm Identification

- An hourly index D_{st} (disturbance storm-time index) is traditionally used to identify storm and define its magnitude.
  - High temporal resolution version (1-min): Sym-H
  - SuperMAG symmetric ring current index: SMR (Newell and Gjerloev, 2012, JGR)

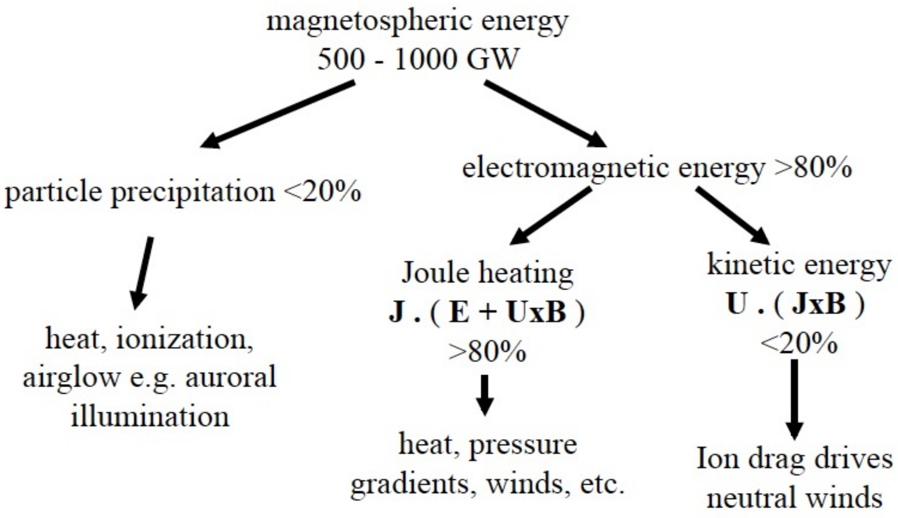
- Geomagnetic storm classification:
  - Minor: -20 nT > D_{st} > -50 nT
  - Moderate: -50 nT > D_{st} > -100 nT
  - Intense: -100 nT > D_{st} > -250 nT
  - Super: -250 nT > D_{st}

Sym-H and ring current evolution



Wang et al. (2019). *GRL*, 46, 7920– 7928.

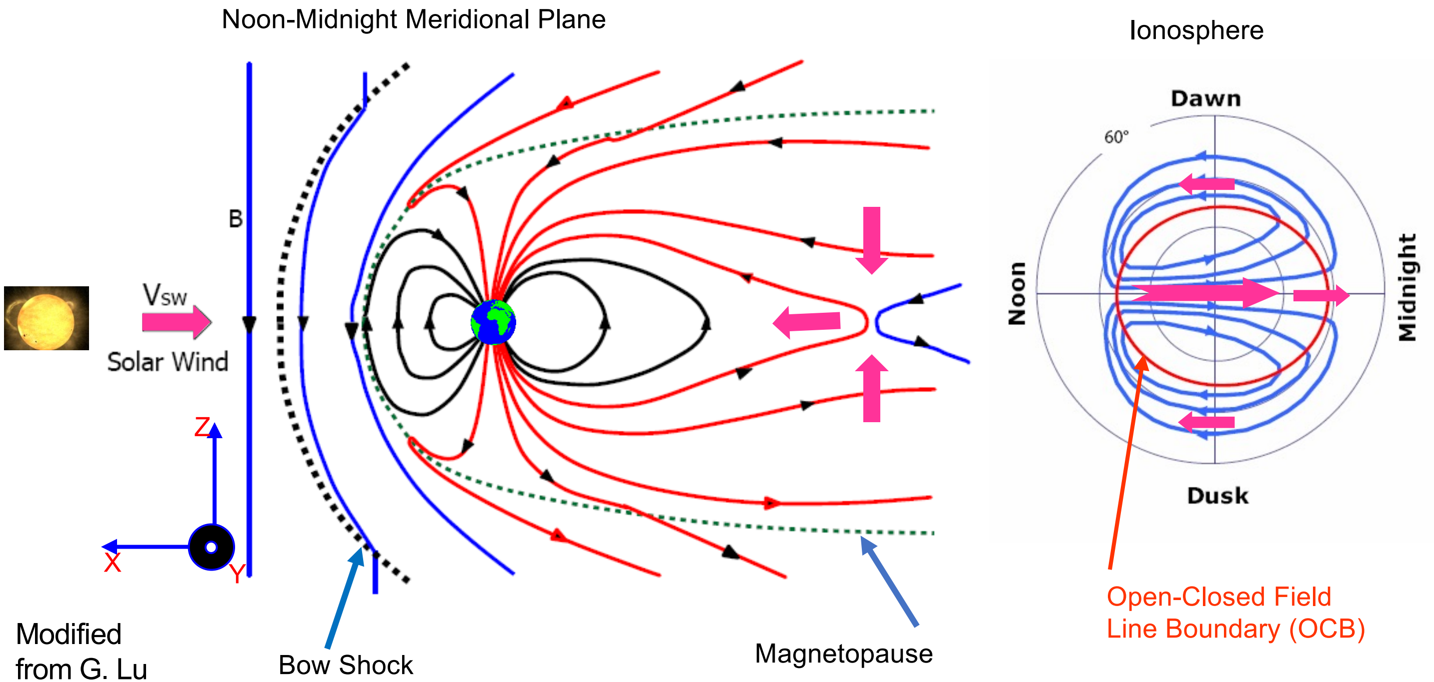
Energy Flow During Storm



See Lu et al., 1995

- Several hundreds GW energies flow into the IT system in the form of electromagnetic energy (Poynting flux) and particle precipitation.
- Electromagnetic energy (Poynting flux) is the dominant energy source.
- Majority of the electromagnetic energy goes to Joule heating.

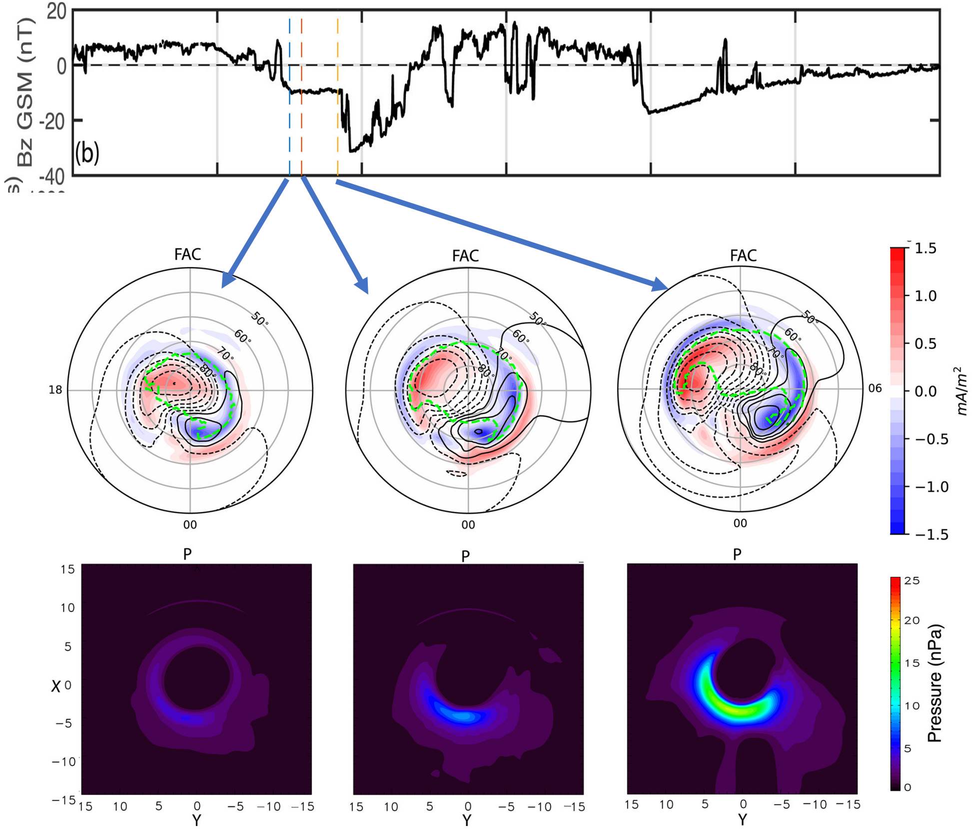
Magnetospheric and Ionospheric Convection: Fluid Description



Modified from G. Lu 2005 GEM Tutorial

- Reconnection model proposed by J. Dungey [1961]
- Major energy and momentum coupling mechanism between the solar wind and magnetosphere.

Storm-time Expansion of Ionospheric Convection



- Dayside reconnection enhances after strong IMF southward turning during storm and efficiently transfers energies into the magnetosphere.
- High-latitude ionospheric convection and FACs expand to lower latitudes.
- Mis-match between convection pattern and FACs => penetrating or shielding electric field
- Penetration electric fields can be established globally nearly simultaneous.
- Ring current evolution modulates the convection and FAC patterns.

Wang et al. (2019). *GRL*, 46, 7920–7928.

Ion-Neutral Coupling

- Convecting ionosphere can be a significant source of momentum and energy for the thermosphere via ion–neutral collisions.
- Resulting interactions act to modify the thermospheric circulation, temperature, and composition, which, in turn, affects the ionosphere.
- Extent of the coupling depends on plasma density. For plasma densities of 10^3 to 10^6 cm^{-3}, the characteristic time constant for accelerating the thermospheric particles ranges from 200 hours (several days) to 10 minutes.

Temporal change of ion temperature:

$$\frac{\partial}{\partial t} T_i = \nu_{in}\left(-T_i + T_n + \frac{M_n}{3k}(\bar{v} - \bar{u})^2\right)$$

Time scale for ions to respond to frictional heating:

$$\tau \propto \frac{1}{\gamma_{in}}$$

A few seconds to a few tens of seconds

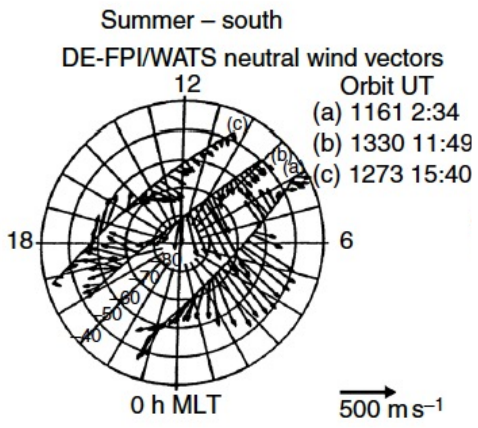
Time scale for neutrals to respond to frictional heating:

$$\tau \propto \frac{1}{\gamma_{ni}} = \frac{n_n m_n}{n_i m_i \gamma_{in}} \gg \frac{1}{\gamma_{in}}$$

Because the neutral density is much higher than the ion density, the time scale for neutrals is much longer than that of ions.

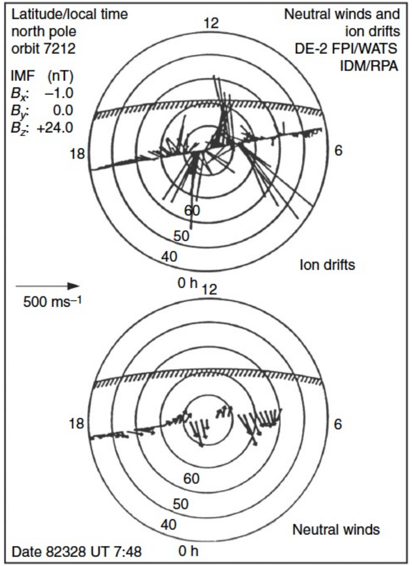
Evidence of Ion-Neutral Coupling at High Latitudes

Southward IMF



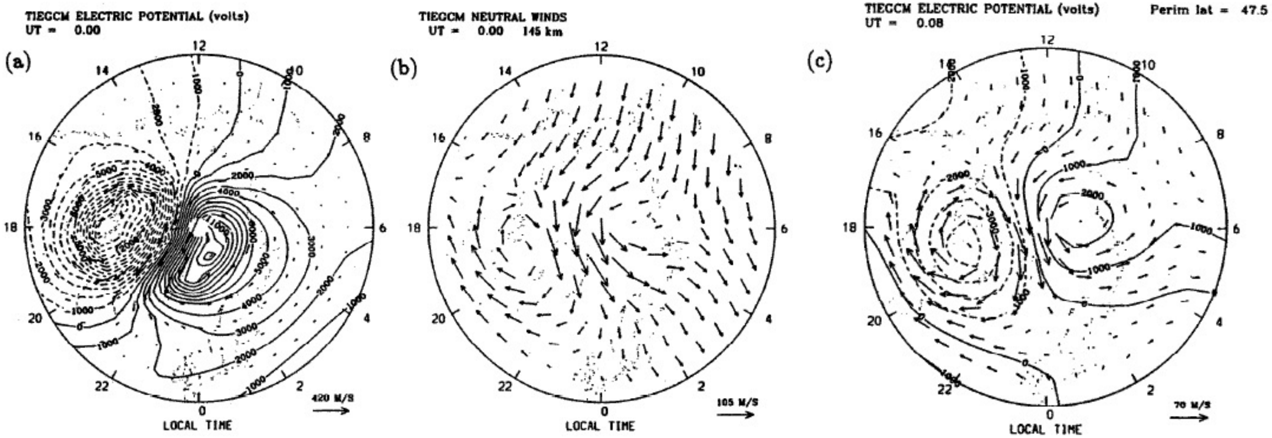
Schunk and Nagy, 2009

Northward IMF



- High-latitude thermospheric wind pattern mimics the plasma convection pattern.
- The wind speed is typically smaller than plasma convection speed but much greater than expected if solar heating was the only process driving the flow.

Neutral Flywheel Effects



Richmond and Roble, 1997

- High-latitude winds on average play a secondary role in the magnetosphere-ionosphere electrodynamic coupling.
- However, they can play a more important role immediately following a period of high magnetic activity.
- Neutral winds tend to maintain the ion convection pattern after the external sources are cut-off.