# The Polar Ionosphere


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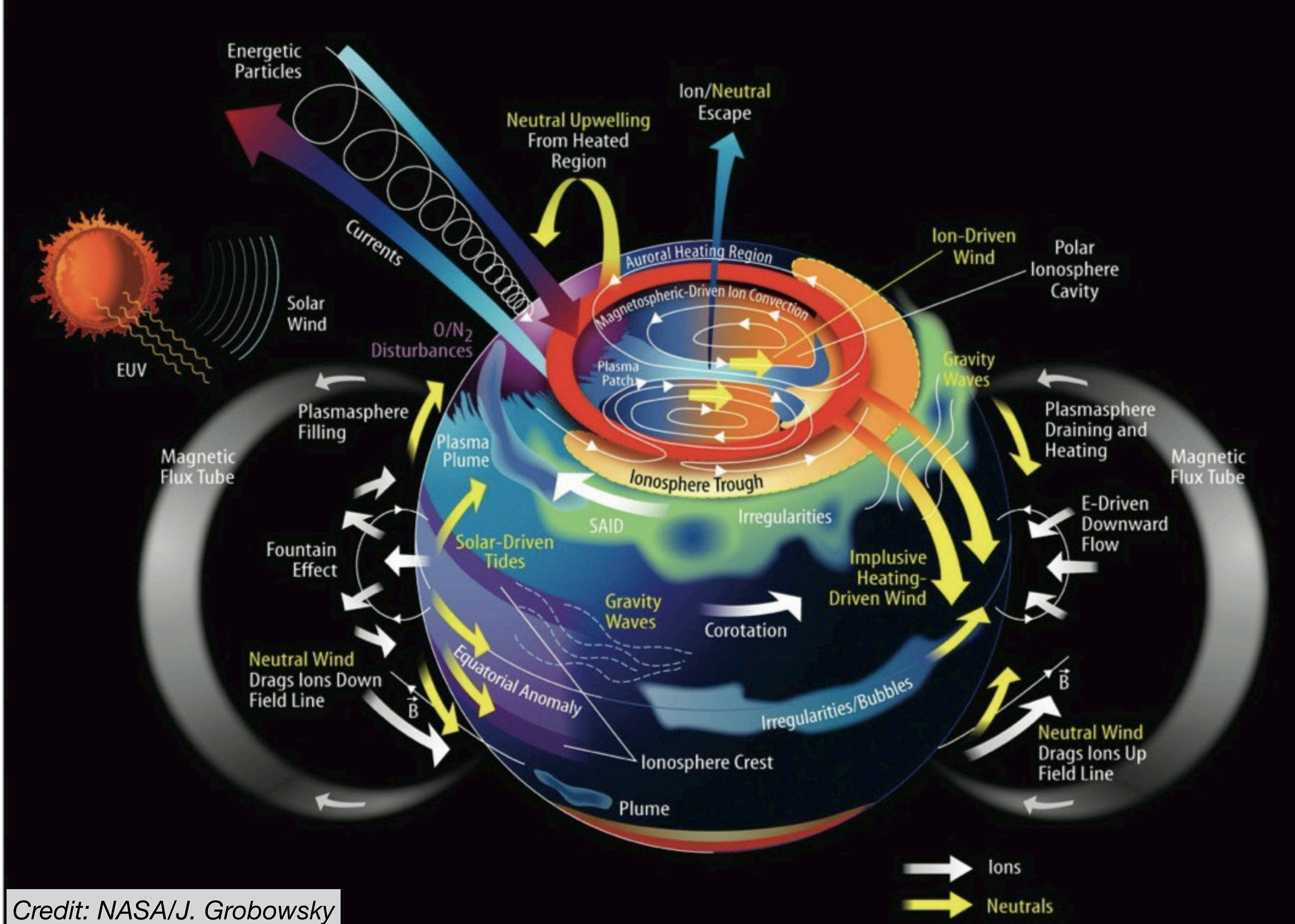
- Some basics on the polar ionosphere
- Vertical density profile of the ionosphere
- Climatology of the polar ionospheric density profile in comparison with the mid-latitude ionosphere

# Ionosphere-thermosphere-mesosphere (ITM) system




Credit: NASA/J. Grobowsky

# The Polar Ionosphere

- It is the '***high-latitude***' ionosphere between about 90 and 2000 km in altitude and ***above about 50° in magnetic latitude***.

- ***The magnetospheric electric field*** provides the dominant force affecting the motion of the charged particles perpendicular to **B** in the polar region.

- There are optical emissions resulting from the absorption of ***energetic particles*** by the neutral gas and ***the field-aligned currents*** in the magnetosphere are closed by horizontal current flow within the ionosphere.

- It includes ***the polar cap, the cusp,*** and ***the auroral oval***.

# M-I-T Coupling

- ***The magnetosphere-ionosphere-thermosphere system in the polar region*** is strongly coupled via electric fields, particle precipitation, field-aligned currents, heat flows, and frictional interactions.

- ***Magnetospheric electric fields*** induce a large-scale motion of the high-latitude ionosphere, which affects the horizontal morphology of the electron density.

- As the plasma drifts through the neutrals, the ion temperature is raised owing to ***ion–neutral frictional heating***.

- The elevated ion temperature then alters the ion chemical reaction rates, topside plasma scale heights, and ion composition.

- Also, ***particle precipitation in the auroral oval*** acts to produce enhanced ionization rates and elevated electron temperatures, which affect the ion and electron densities and temperatures.

# M-I-T Coupling

- These ionospheric changes, in turn, have a significant effect on the thermospheric structure, circulation, and composition.
- At F-region altitudes, the neutral atmosphere tends to follow the convecting ionospheric plasma induced by magnetospheric electric fields.
- The resulting ***ion–neutral frictional heating*** induces vertical winds and thermospheric composition changes.
- These atmospheric changes then further affect the ionospheric densities and temperatures.
- Finally, precipitating auroral electrons produce ***conductivity enhancements***, which can modify the convection electric field, large-scale current systems, and the electrodynamics of the magnetosphere–ionosphere system as a whole.

# M-I-T Coupling

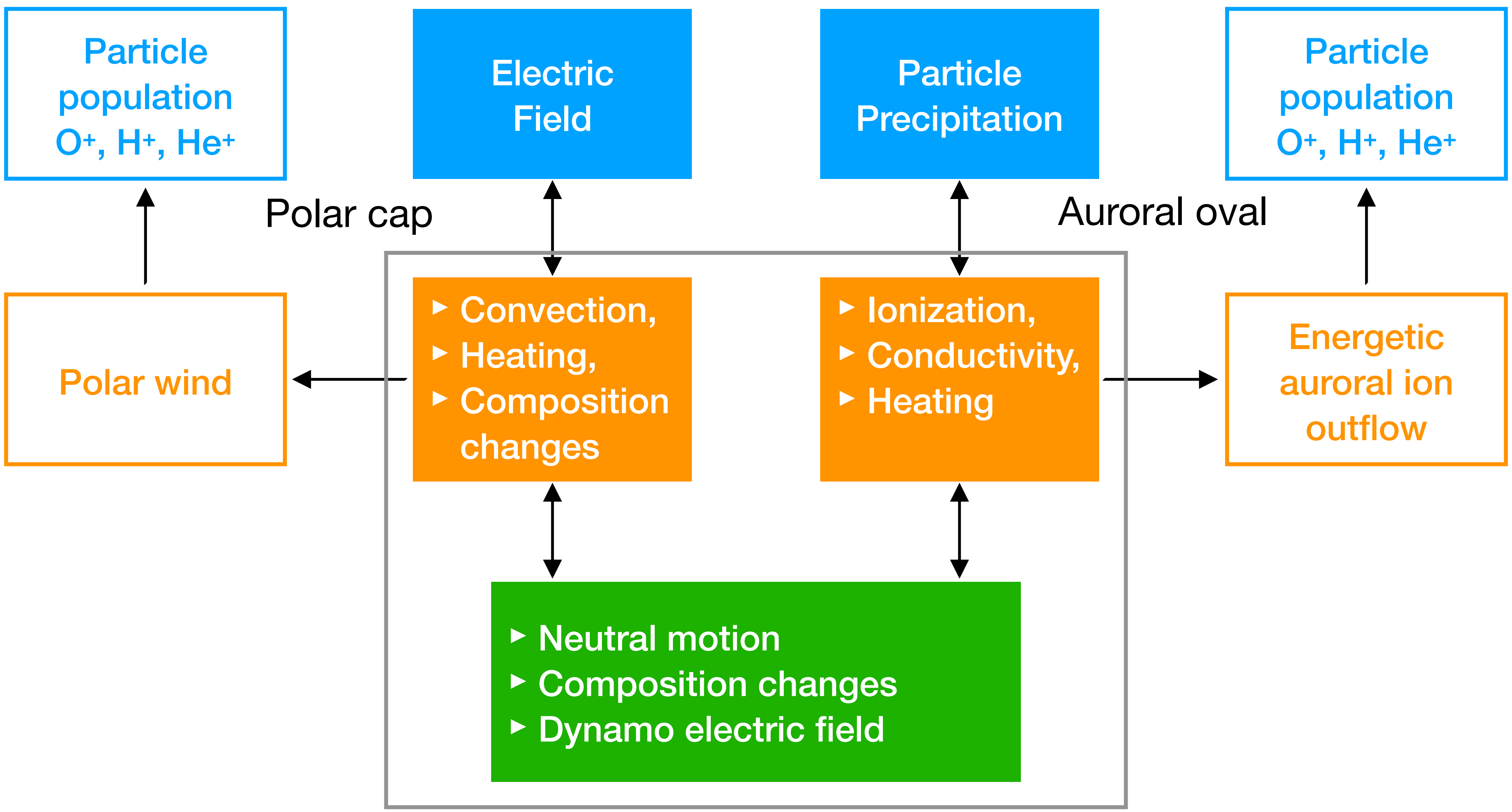
- Once the thermosphere is set in motion by plasma convection via ion-neutral collisions, ***the large inertia of the neutral atmosphere*** will act to produce dynamo electric fields whenever the magnetosphere tries to change its electrodynamic state.

- Additional feedback mechanisms exist on the polar cap and auroral field lines via ***a direct flow of plasma*** from the ionosphere to the magnetosphere.

- In the polar cap, there is a continual outflow of thermal plasma from the ionosphere (i.e., ***the polar wind***) and it represents a significant source of mass, momentum, and energy for the magnetosphere.

- In the auroral oval, energized ionospheric plasma is injected into the magnetosphere via ion beams, conics, rings, and toroidal distributions (i.e., ***ion outflow***).

# M-I-T Coupling




Coupling processes in the Magnetosphere–Ionosphere–Thermosphere system (adopted from *Schunk & Nagy*, 2000)

# Ionospheric density structure in the polar region

- The ionospheric ion/electron density is generally produced by ***solar EUV ionization*** and then can be redistributed by ***transports*** via neutral winds and electric field before they are recombined back to the neutrals.

- In the polar region, in particular, the solar EUV production can exist nearly ***for 24 hours in summer*** or ***nonexistent at all in winter***.

- There are also ***additional productions*** by energetic particle precipitations (electrons 100 eV ~ 100 keV; protons 1 keV ~ 1 MeV) and ***strong transports*** by **E** x **B** drift, which can be particularly severe during disturbed periods.

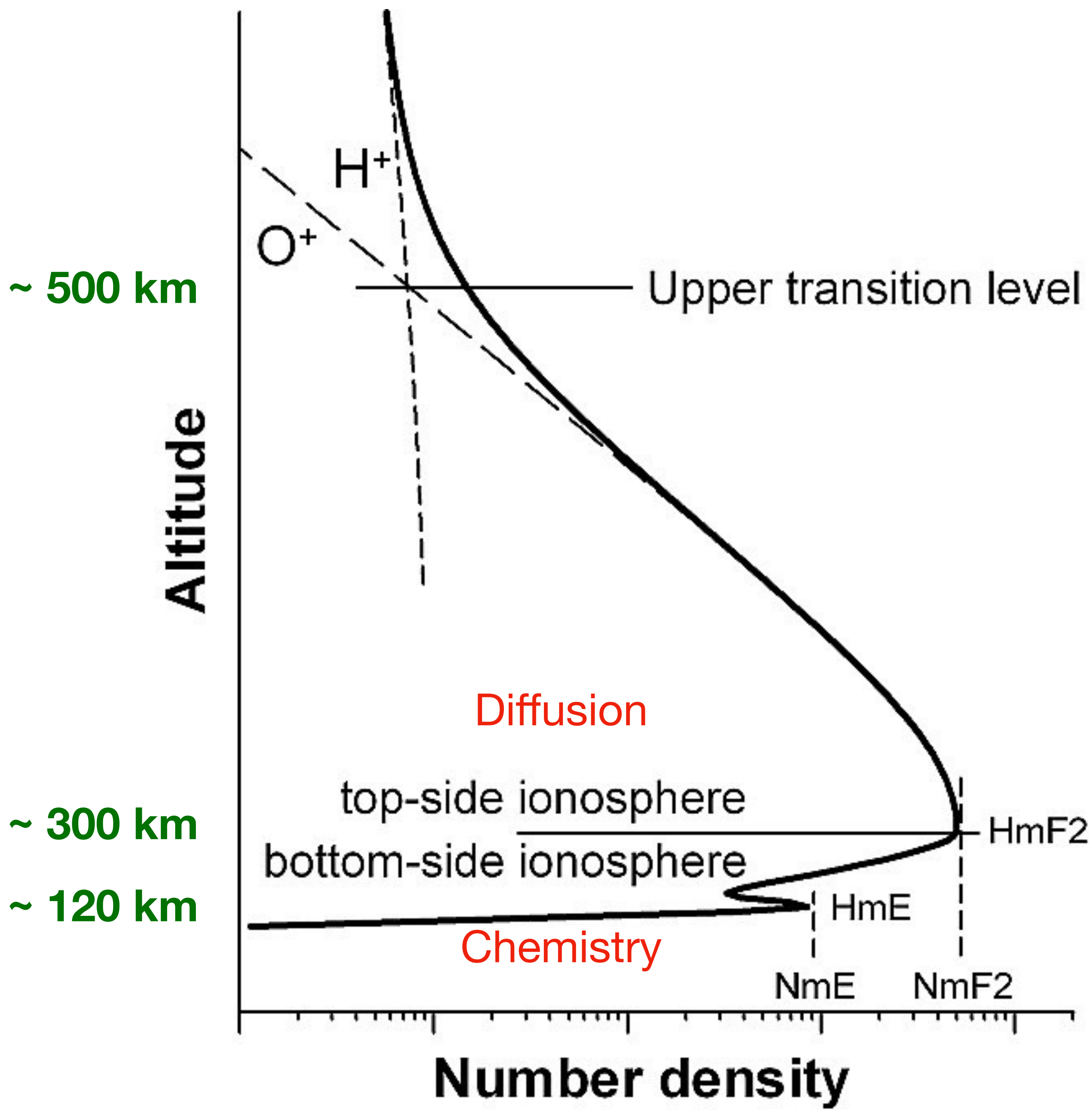
- These unique features of the polar ionosphere result in characteristic density structures.

# Ionospheric density structure in the polar region

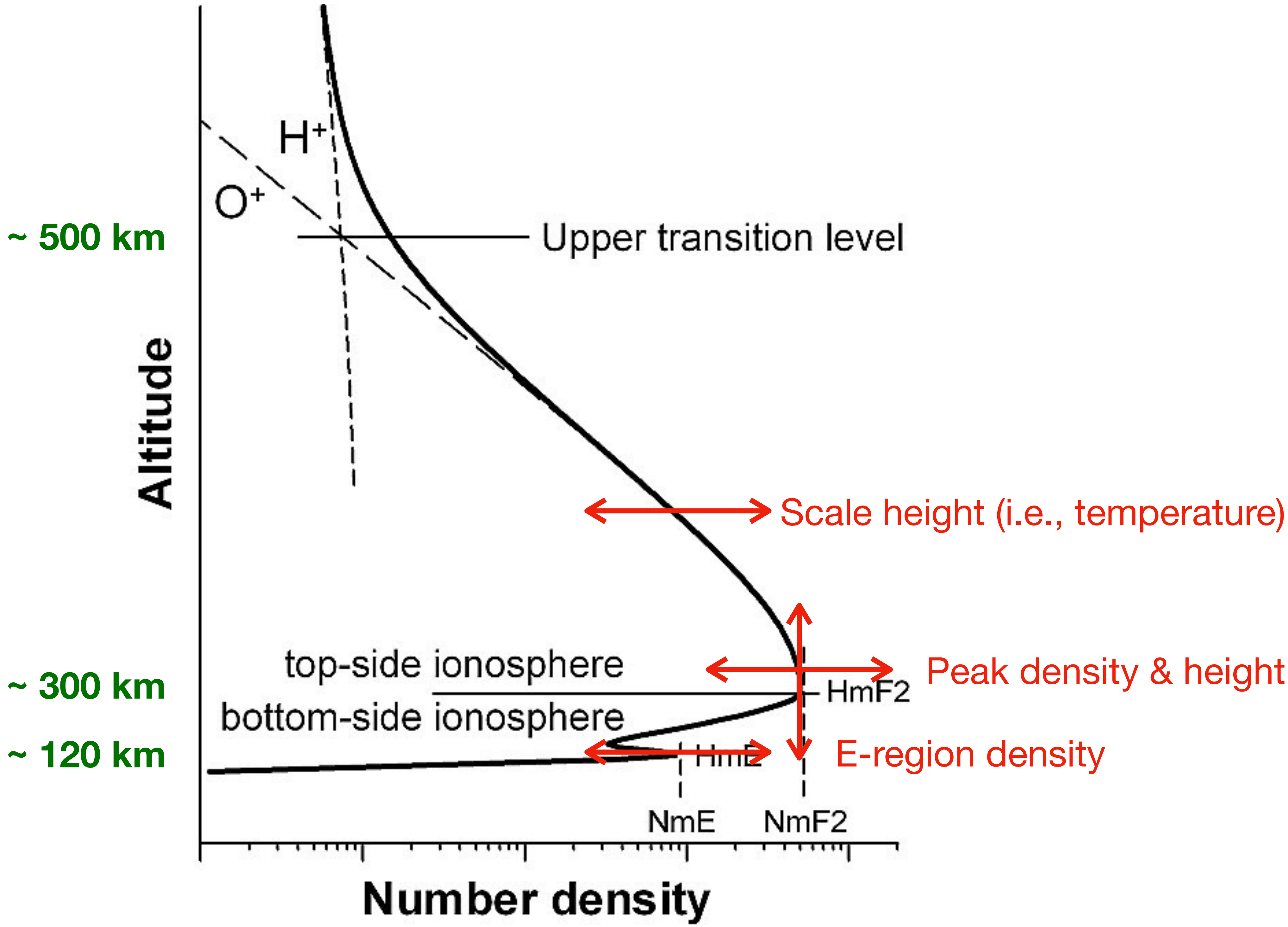
- Most of the studies on the polar ionospheric density have been focused on ***the horizontal density structures*** such as tongue of ionization (TOI), polar cap patch, ionization trough, polar hole, and auroral blobs, which can mostly be observed from the F-region density or total electron content (TEC).

- What about the characteristics of ***the vertical density structure*** in the polar ionosphere?

# Ionospheric density structure in the polar region



# Ionospheric density structure in the polar region



# Ionospheric density structure in the polar region

- **Productions**
  - Solar EUV : global but relatively weak in the polar region
  - Energetic particles: only in the polar region
- **Transports**
  - Diffusion : global
  - Neutral winds : global but negligibly small in the polar region
  - Electric fields : global but particularly important in the equatorial and polar regions
- **Variations of the vertical density profile**
  - Local time & season
  - Solar cycle & magnetic activity

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# Climatology of polar ionospheric density profile in comparison with mid-latitude ionosphere from long-term observations of incoherent scatter radars: A review

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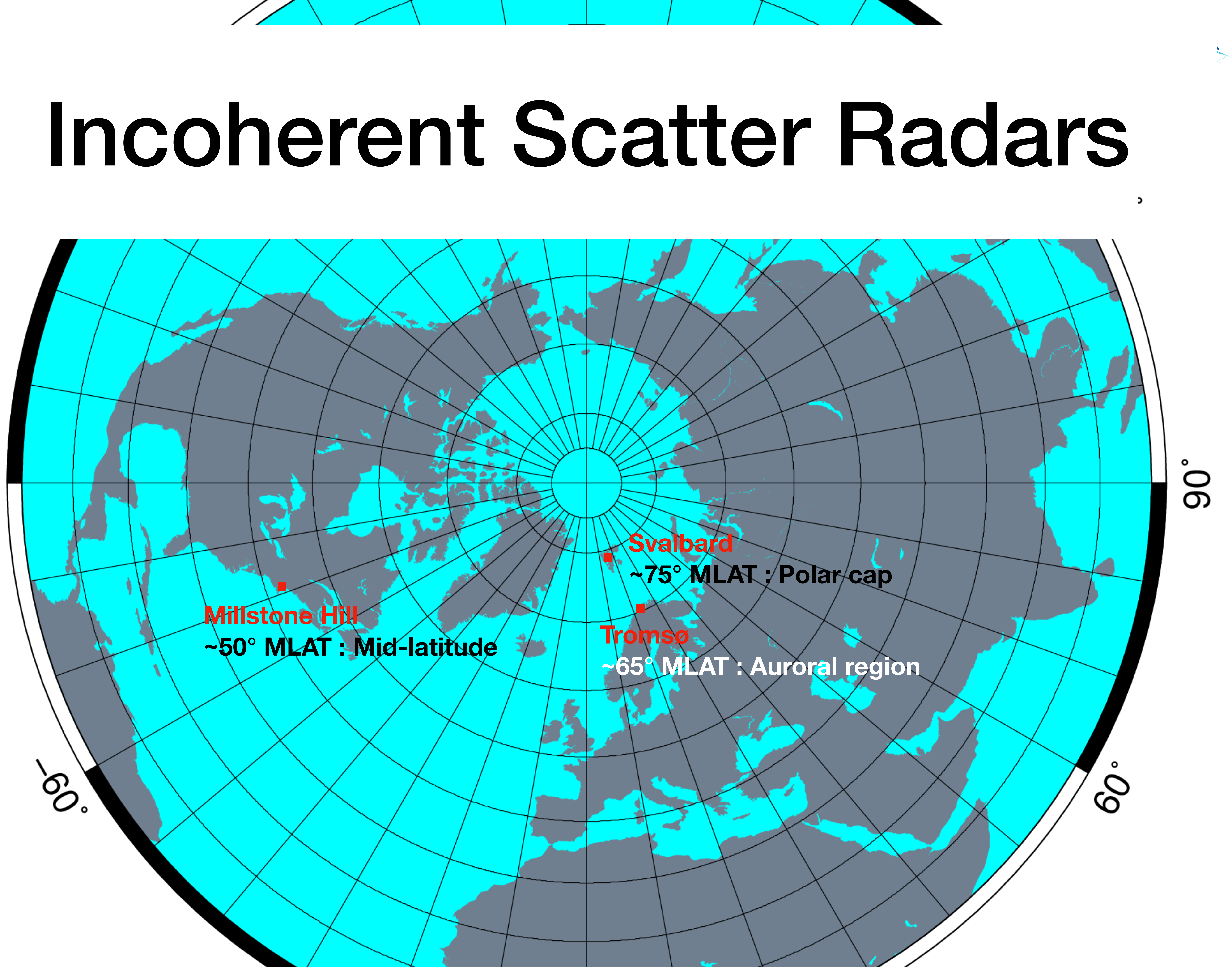
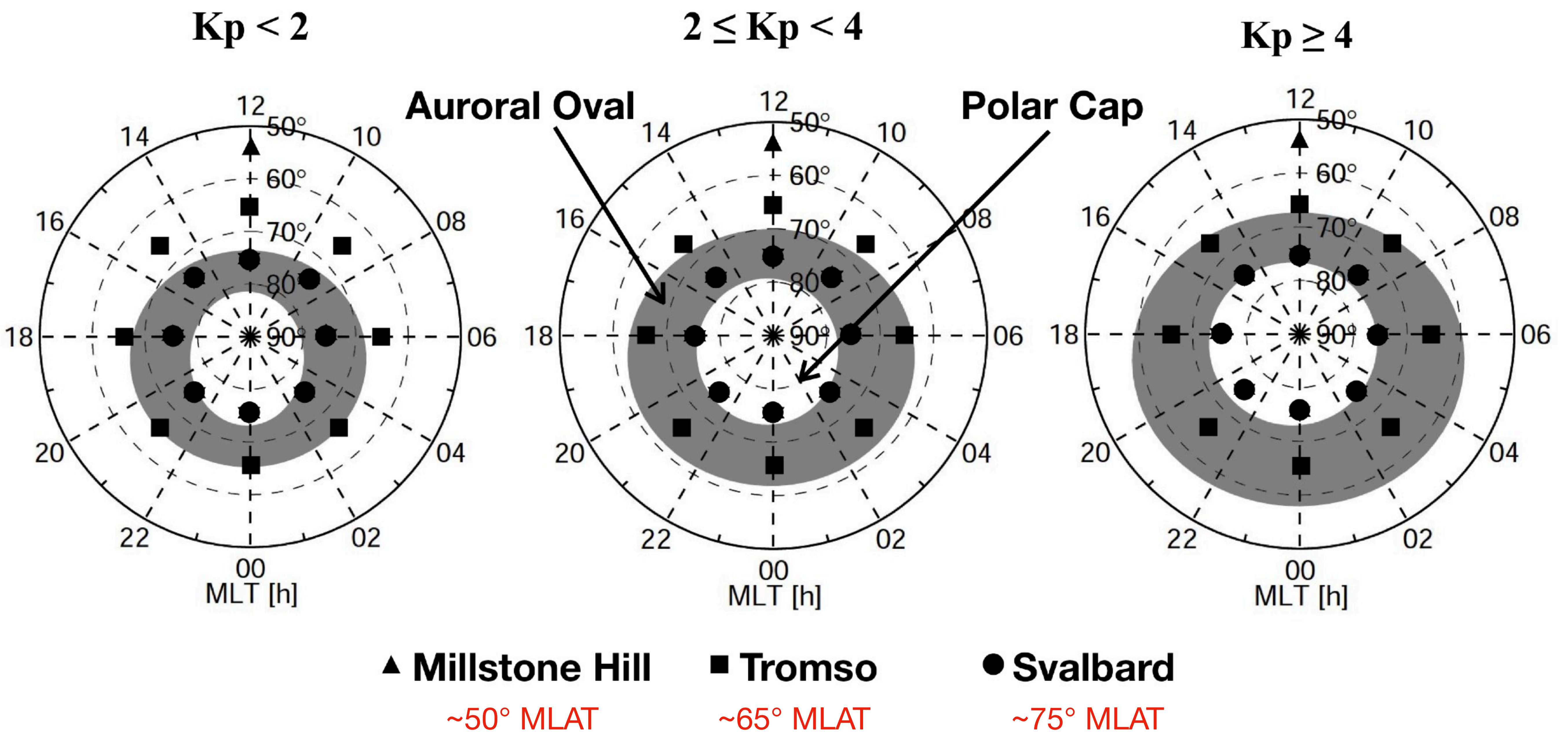
ABSTRACT

Although the horizontal density structures of the polar ionosphere have been extensively studied mostly using the F-region peak density or total electron content, there are relatively few studies on the vertical density structures. In this review, we present the climatology of the polar ionospheric density not only in the F-region but also in the E-region and topside ionosphere, in comparison with the mid-latitude ionosphere, using long-term incoherent scatter radar (ISR) observations at Millstone Hill, Tromsø, and Svalbard. The ISR data during the period of 1995–2015 are analyzed to study on the variations with local time, season, and solar/geomagnetic activity. The diurnal variations of the F-region density are much smaller in the polar region than in the mid-latitude, particularly in summer. At Svalbard, there is a characteristic double-peak structure in the diurnal variation of the polar ionosphere in winter only for high solar activity. The diurnal variation of hmF2 decreases with increasing latitude and eventually disappears at Svalbard for low solar activity but the hmF2 and its diurnal variations in the polar ionosphere are remarkably enhanced for high solar activity. The distinctive irregularity in the mid-latitude F1-layer nearly disappears in the polar region, especially at Svalbard. The anomalous seasonal variations of the F-region density are less evident in the polar ionosphere especially for low solar activity and for high magnetic activity conditions. The polar E-region density shows characteristic nighttime peaks induced by auroral precipitation but it does not necessarily increase with solar activity. The topside ionospheric density variations are much stronger in the polar region for high solar activity. Finally, it is found that the polar ionospheric density profiles more strongly respond to increasing solar activity as well as the magnetic activity compared with the mid-latitude ionosphere.

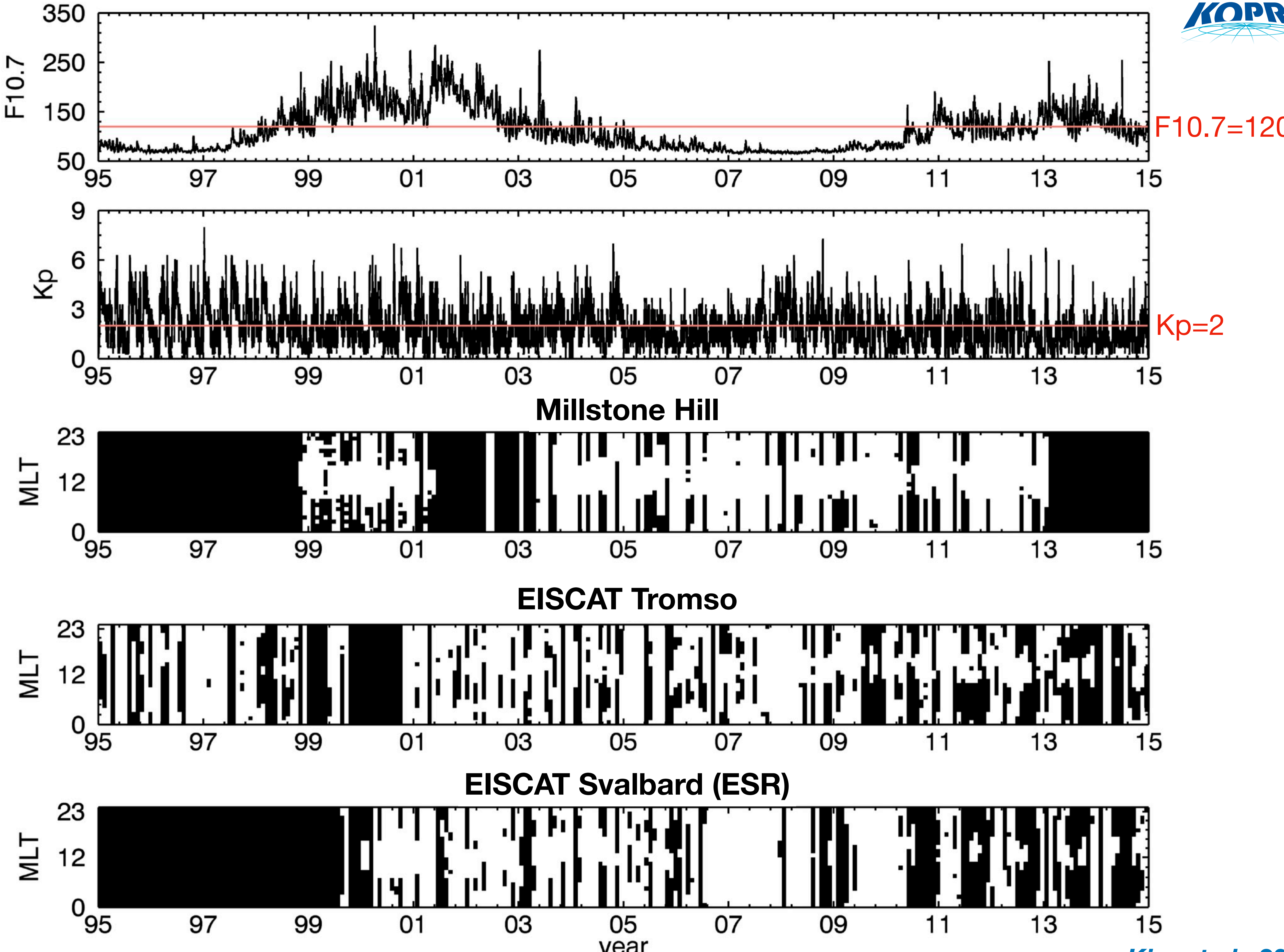
# Incoherent Scatter Radars



# Characteristics of polar ionospheric density




*Kim et al.*, 2020




*Kim et al.*, 2020

# General Characteristics

- Local time variations
- Seasonal variations
- Solar activity variations
- Geomagnetic activity variations
- **Limitations**
  - Not on the specific changes during storm/substorm
  - Only in the northern hemisphere

JGR Space Physics

RESEARCH ARTICLE
10.1029/2022JA031126

# Hemispheric Asymmetry of the Polar Ionospheric Density Investigated by ESR and JVD Radar Observations and TIEGCM Simulations for the Solar Minimum Period

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**Key Points:**

- The polar ionospheric density shows larger magnitude and stronger diurnal and seasonal variations at Jang Bogo Station than in Svalbard
- The daytime density shows an equinoctial asymmetry which is larger in fall equinox than in spring equinox
- Thermosphere Ionosphere Electrodynamic Global Circulation Model significantly overestimates the winter density at high latitudes and shows the opposite equinoctial asymmetry to the observations

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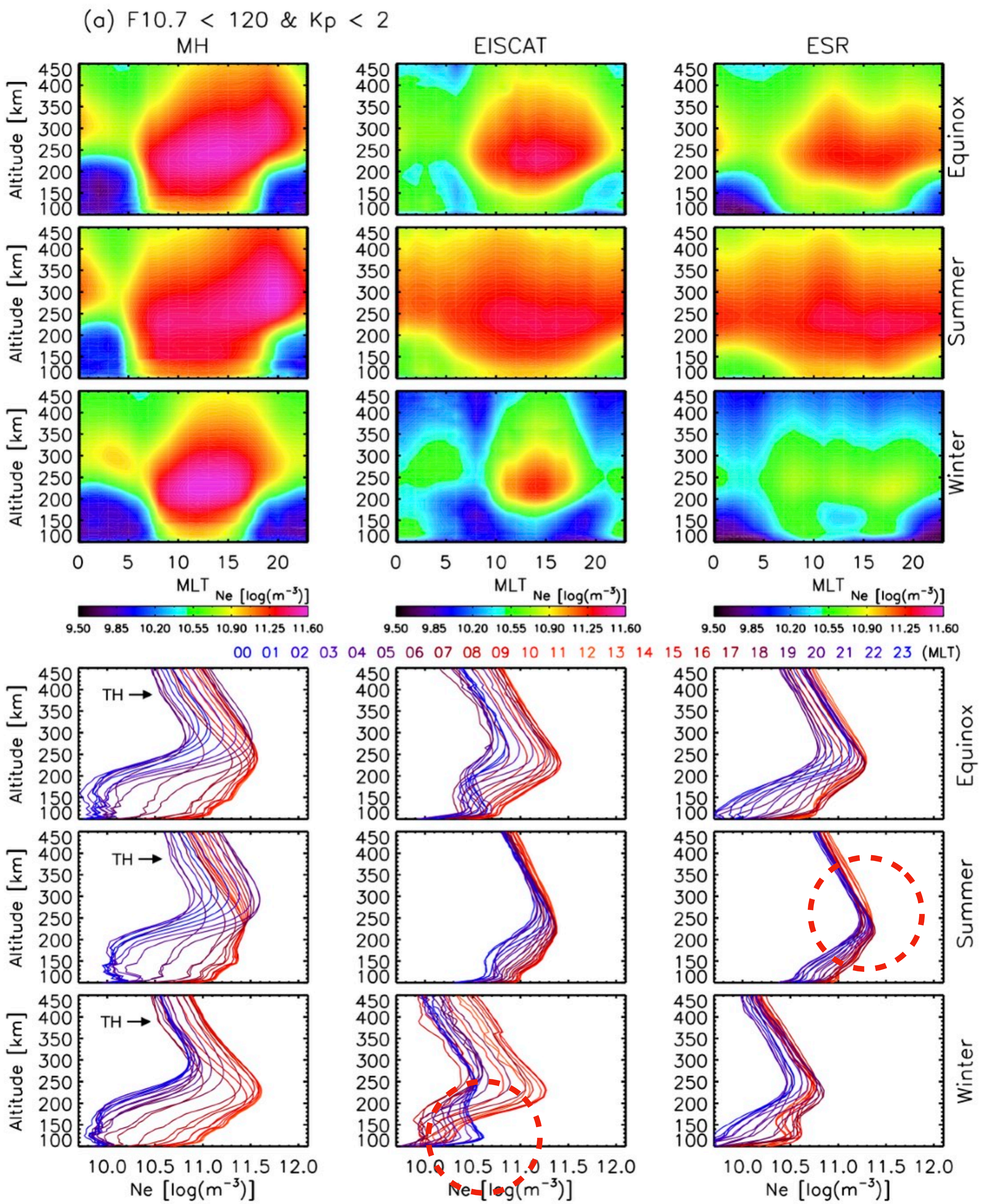
**Abstract** The ionospheric density displays hemispheric asymmetries in the polar region due to various hemispheric differences, for example, in the offset between geographic and geomagnetic poles and in the geomagnetic field strength. Using ground-based ionospheric measurements from Vertical Incidence Pulsed Ionospheric Radar with Dynasonde analysis at Jang Bogo Station (JBS), Antarctica and from EISCAT Svalbard Radar (ESR) where both sites are located mostly in the polar cap, we investigate the hemispheric differences in the ionospheric density between the northern and southern hemispheres for geomagnetically quiet and solar minimum condition. The results are also compared with Thermosphere Ionosphere Electrodynamic Global Circulation Model (TIEGCM) simulations. The observations show larger density and stronger diurnal and seasonal variations at JBS in the southern hemisphere than at Svalbard in the northern hemisphere. The diurnal variations of the density peak height are also observed to be much larger at JBS. In both hemispheres, the ionospheric density is significantly reduced in winter due to the limited solar production at high geographic latitudes, but TIEGCM considerably overestimates winter density, which is even larger than summer density, especially in the northern hemisphere. Also existed are the differences in the equinoctial asymmetry between the observations and the simulations: the daytime F-region density is observed to be larger in fall than in spring in both hemispheres, but TIEGCM shows the opposite. In general, most of the observed asymmetrical density are much weaker in the model simulation, which may result from lack of proper magnetospheric forcings and neutral dynamics in the model.

# Ionospheric density profiles at mid-latitude, auroral and polar cap regions

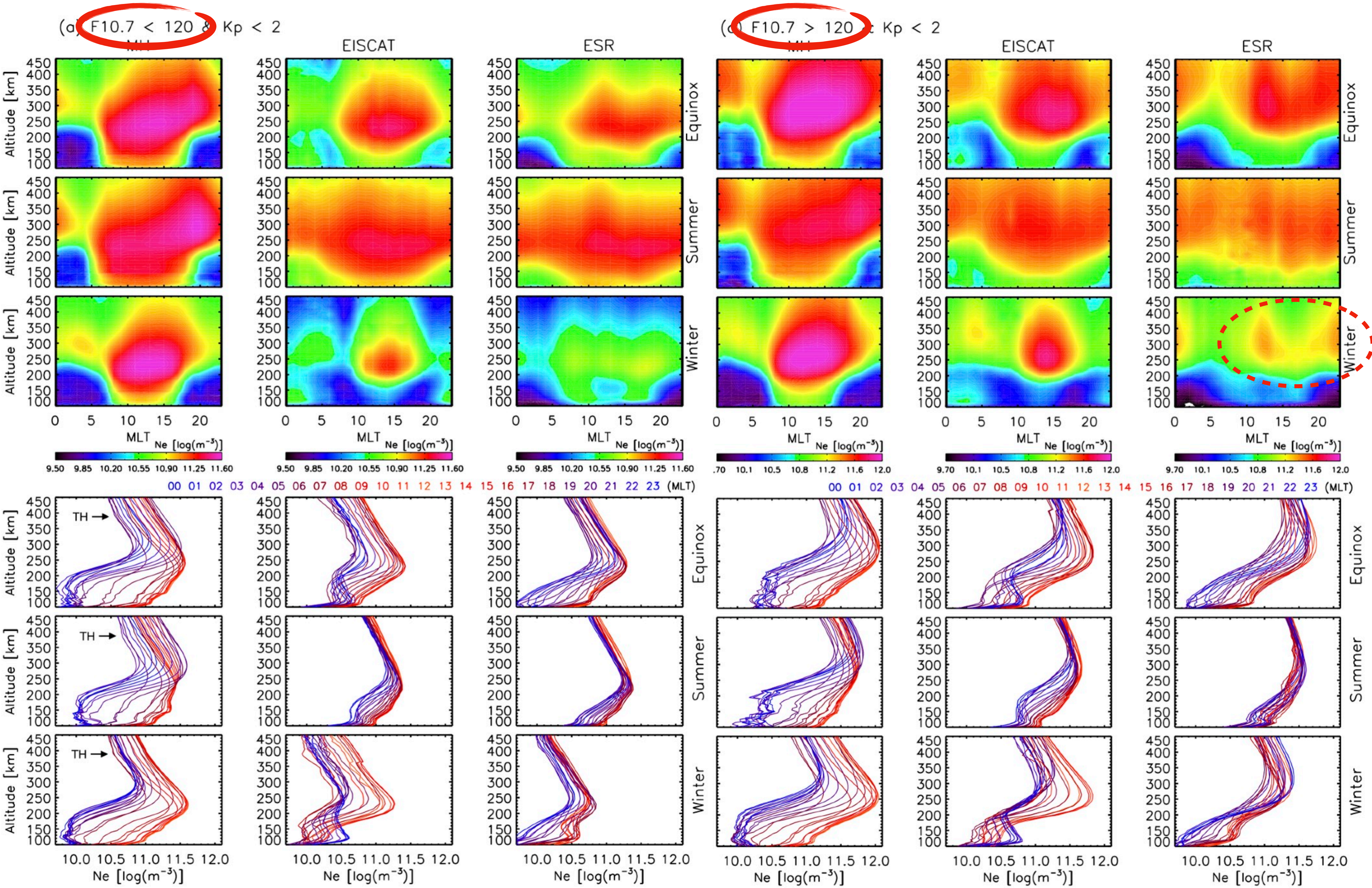



Contour plots of ionospheric density profiles with Altitude vs. Magnetic local time (MLT) coordinate

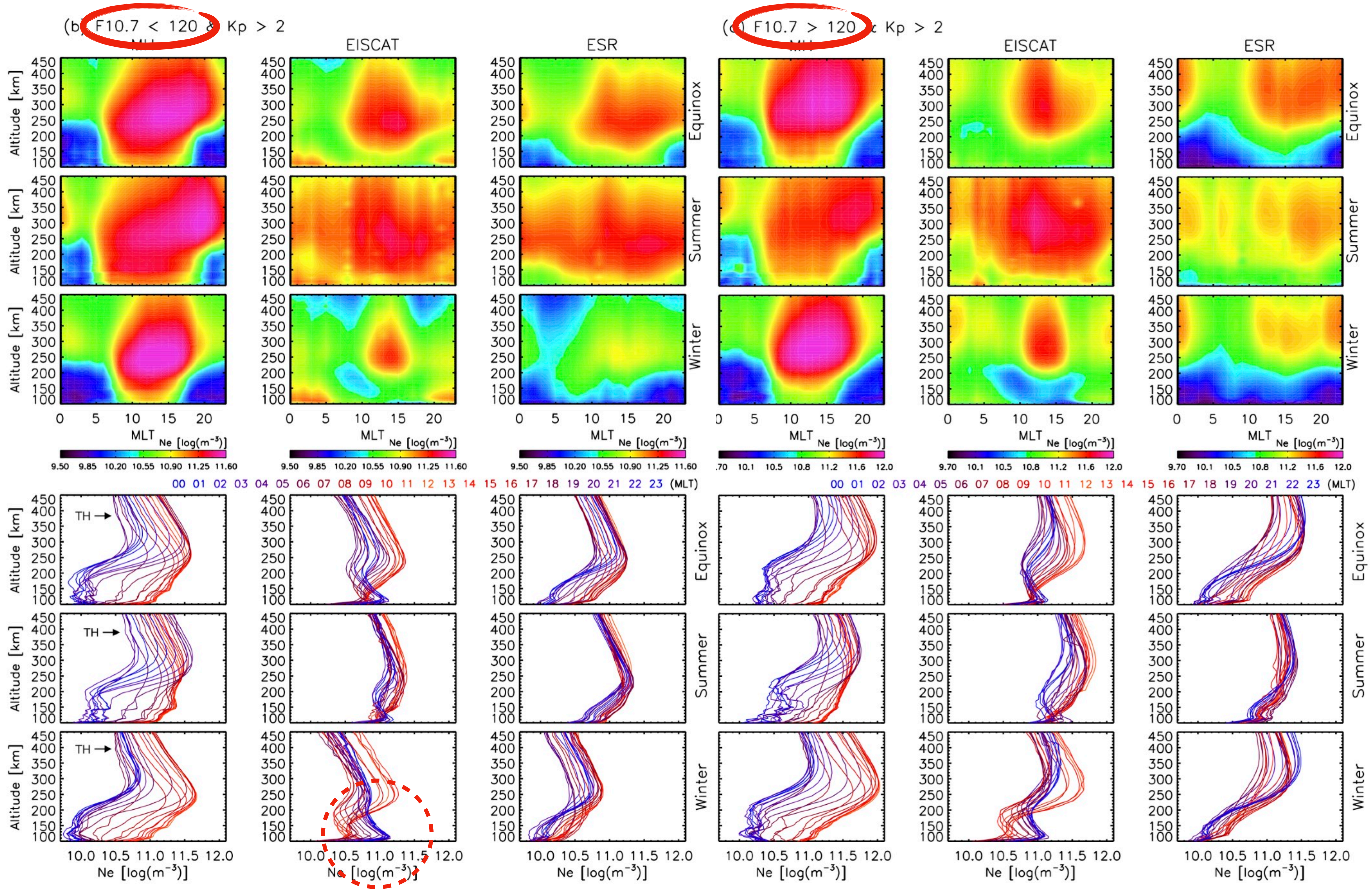
Hourly mean ionospheric density profiles

*Kim et al.*, 2020

# General characteristics
# Low to High Solar activity: Quiet period



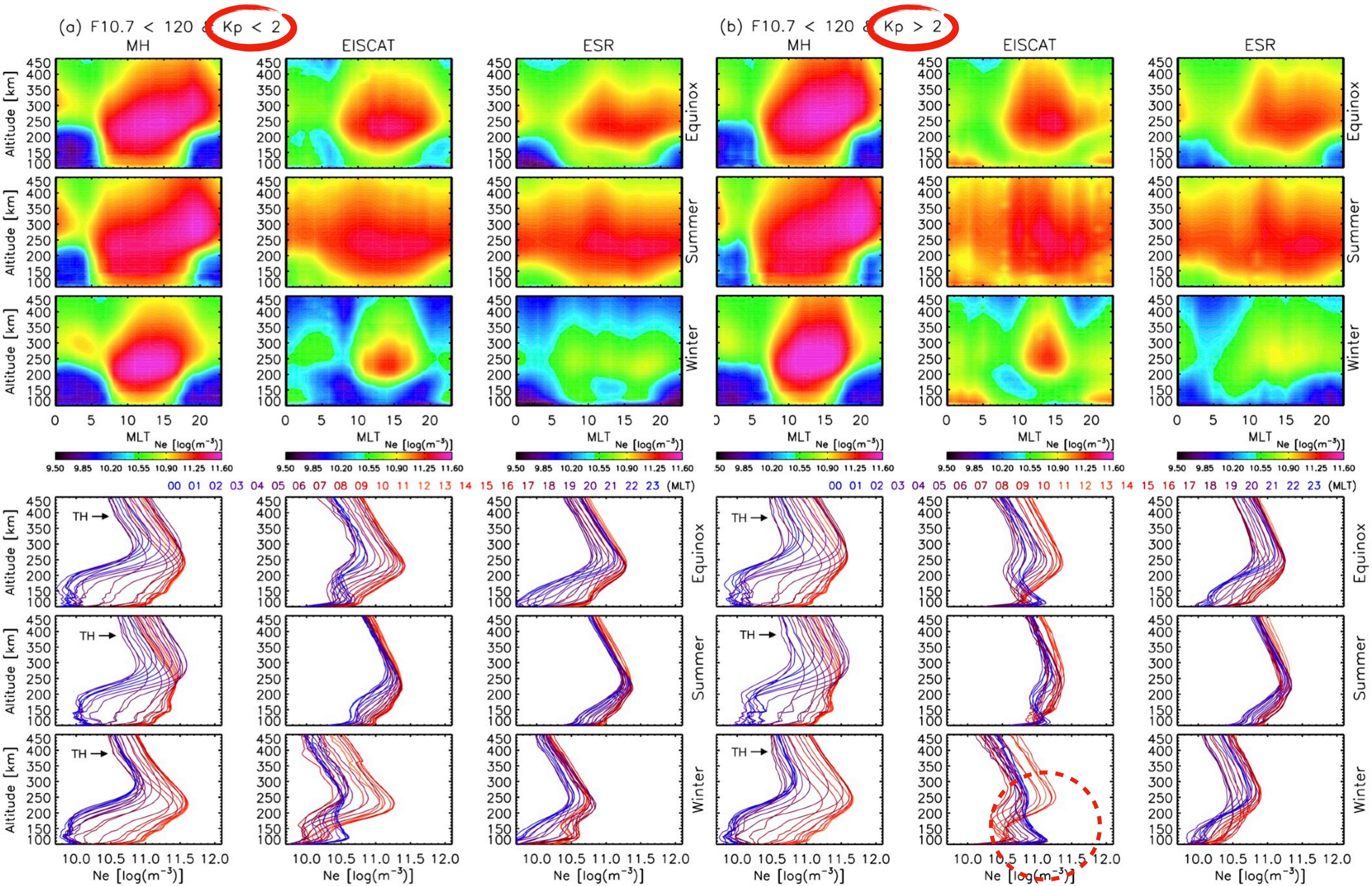
# General characteristics
# Low to High Solar activity: Disturbed period



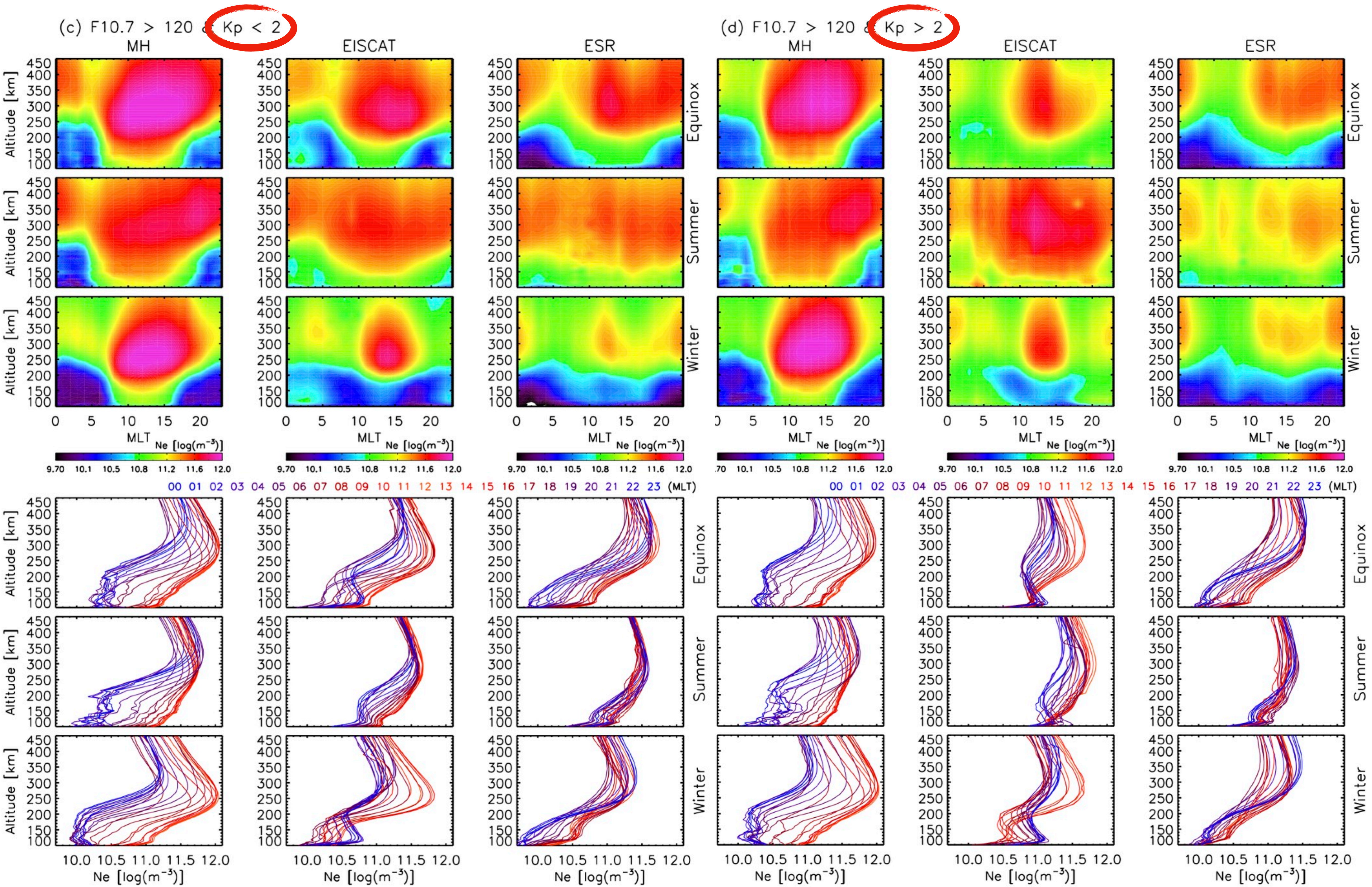
# Variations with Geomagnetic Activity

- Magnetospheric electric field effects
  - Plasma transport from dayside to nightside over the polar cap region
  - Responsible for many 2-D horizontal morphologies of the ionospheric density including TOI, polar cap patch, polar hole, etc.
- Productions by energetic particle precipitations
  - Daytime F-region density enhancement by soft particle precipitation near the cusp region
  - Nighttime E-region density enhancement by auroral electron precipitation

# General characteristics
# Quiet to Disturbed Magnetic activity: Low solar



# General characteristics
# Quiet to Disturbed Magnetic activity: High solar



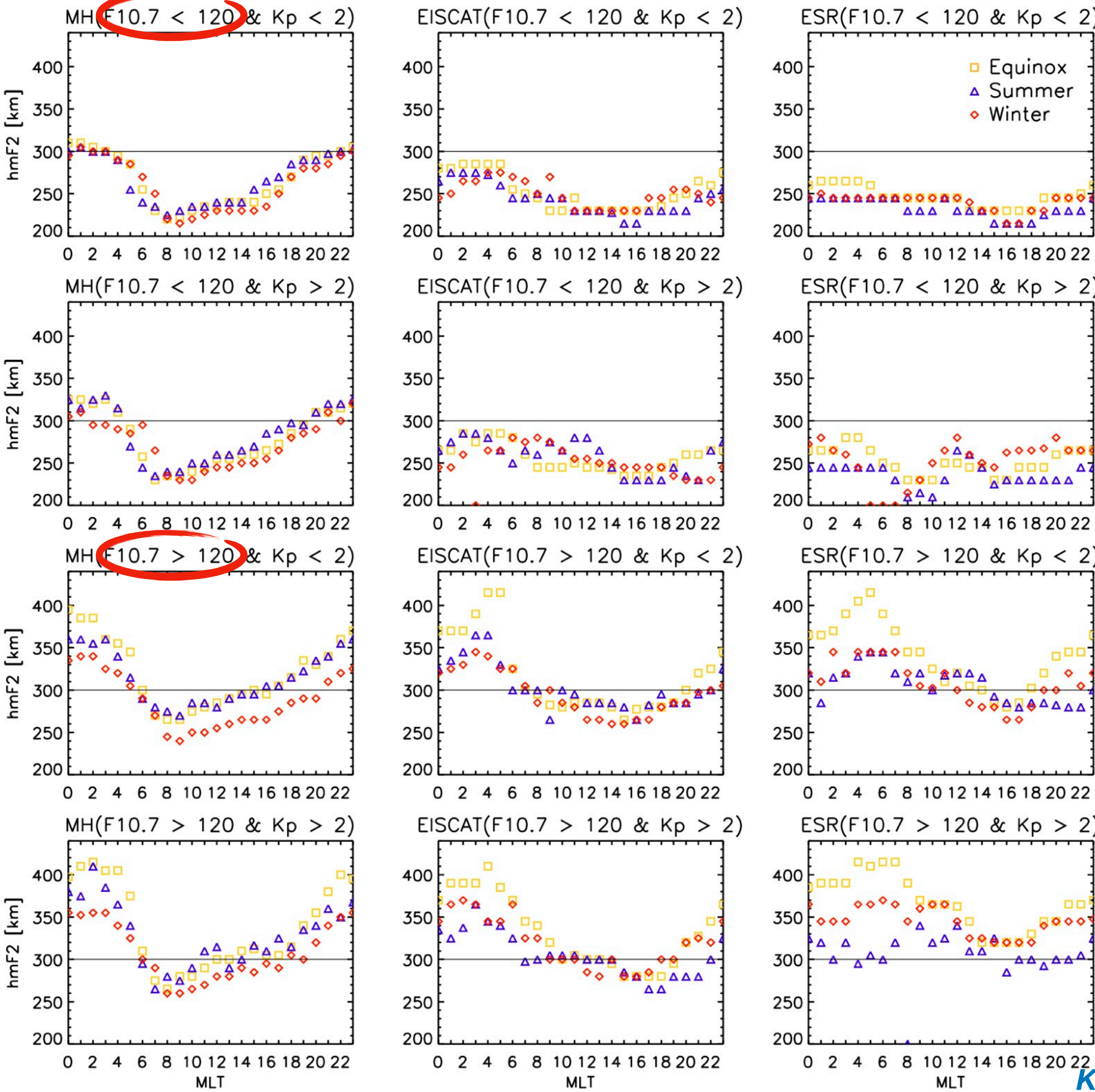
# F-region Peak Height

- The F-region peak height normally occurs at about 200-300 km altitude for low solar activity and 250-400 km altitude for high solar activity ***with significant diurnal variabilities***.

  - E-region density is depleted at night to increase hmF2.

  - Nighttime equatorward neutral wind can also increase hmF2 at mid-latitude.

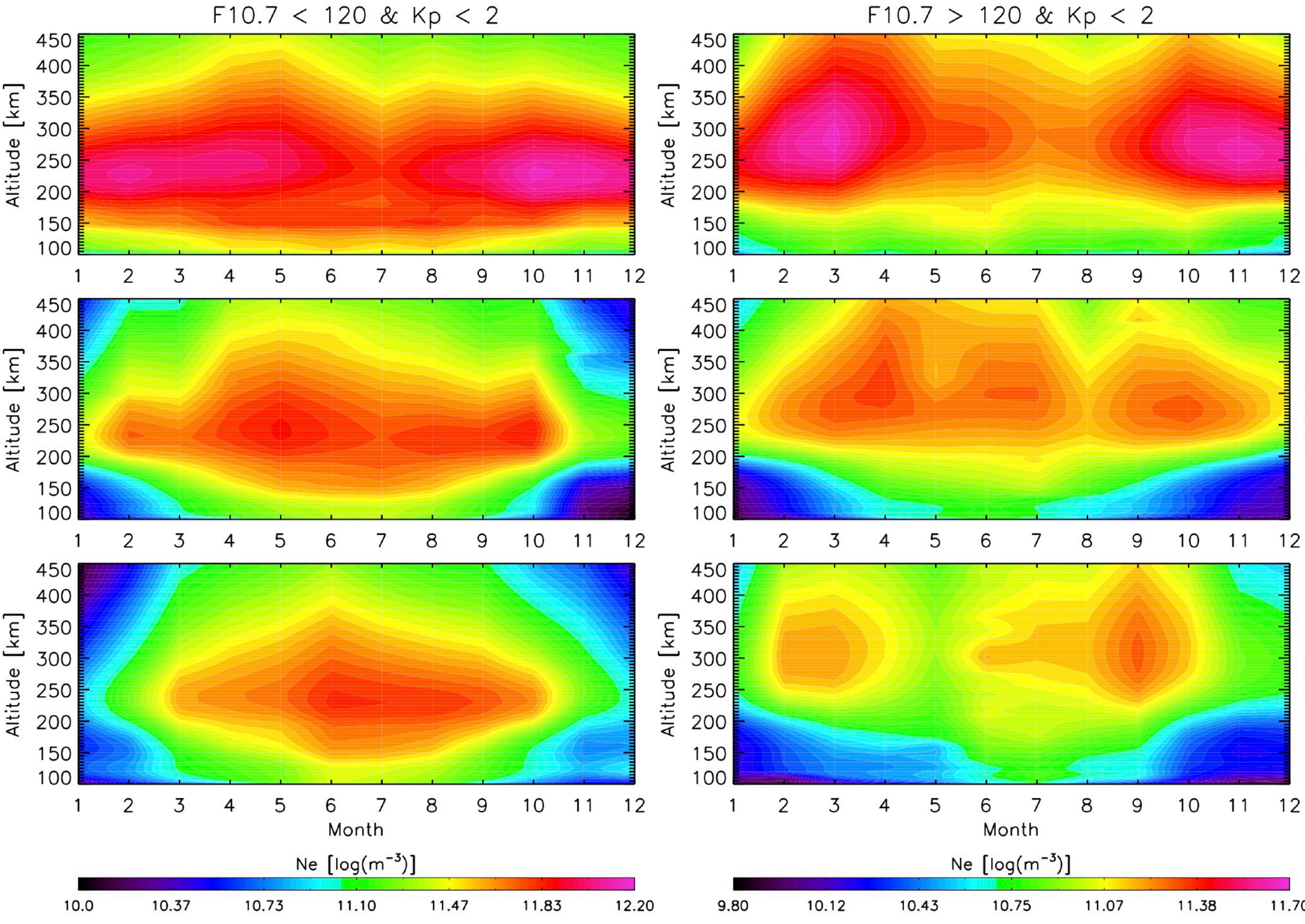
- The local time variations of the peak height should be smaller for solstice in the polar region due to ***the smaller variations of the solar zenith angle*** in summer and winter.




Kim et al., 2020

# Seasonal Variations

- The mid-latitude ionosphere is known to show anomalous seasonal behaviors, being away from the solar-controlled density structures: these include **annual, semiannual, and seasonal (winter) anomalies**.
- These anomalies are mainly related with the ***thermospheric circulation*** and ***composition changes***.
- Do they also exist in the polar region?

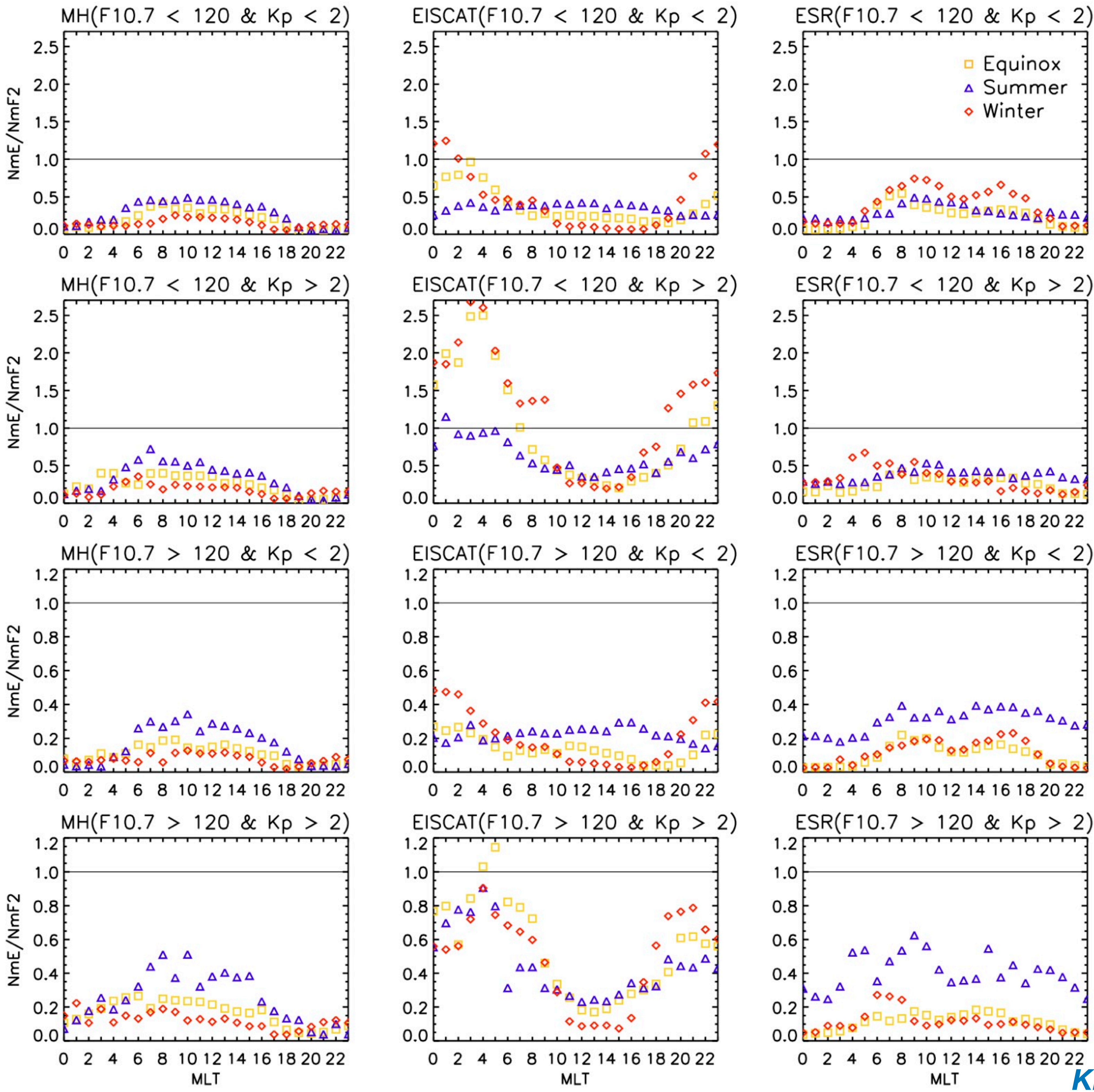



*Kim et al.*, 2020

# E-region ionosphere

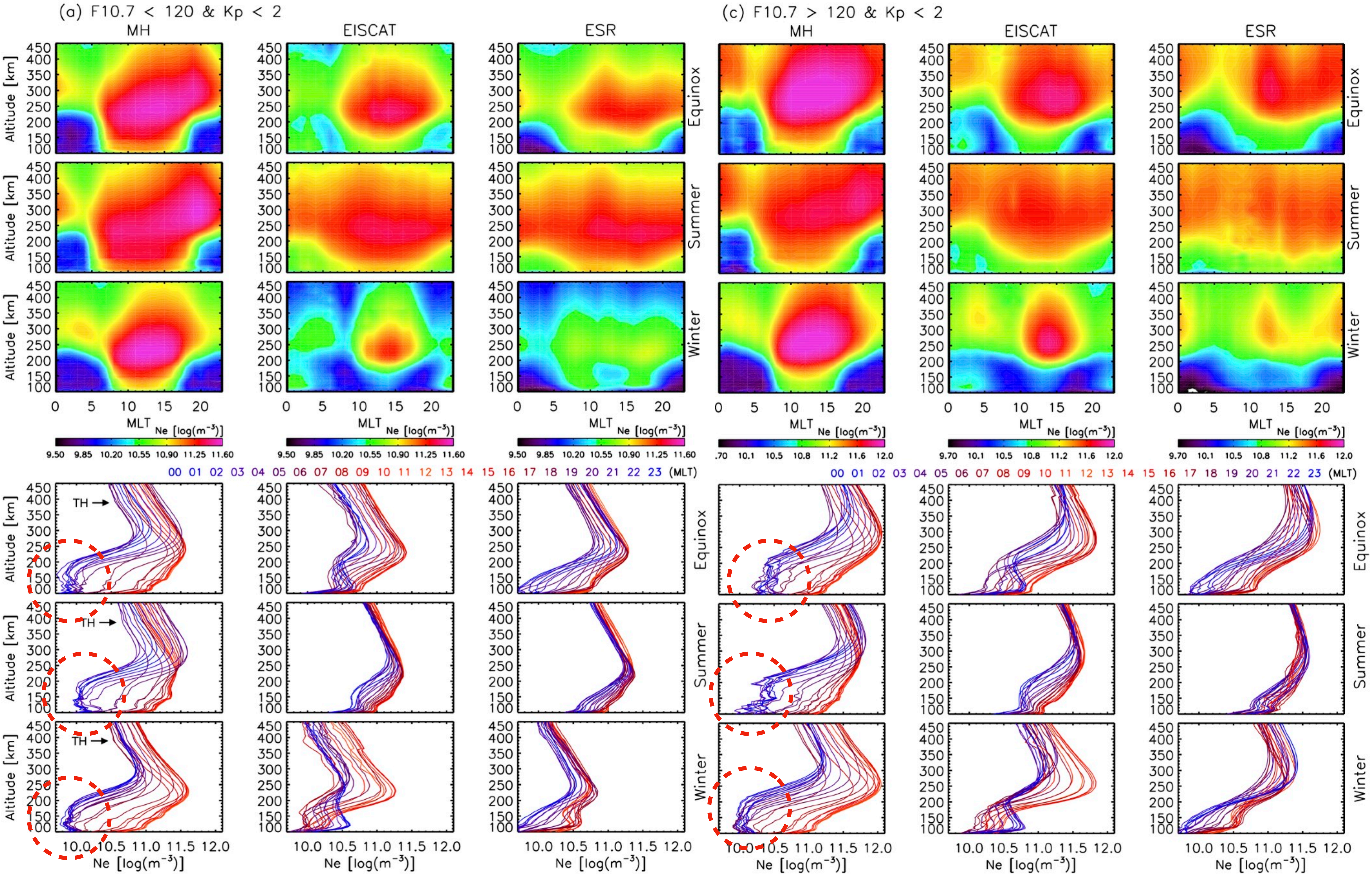
- In the auroral region (Tromsø), there is an additional production by the auroral electron precipitation.

- The E-layer dominated ionosphere (ELDI) appears most prominently in winter for low solar activity and high magnetic activity condition.




Kim et al., 2020

# E-region ionosphere:
## Strong irregularities at mid-latitude



# Topside Ionosphere

- The topside ionosphere is largely controlled by plasma diffusion (i.e., plasma temperature).

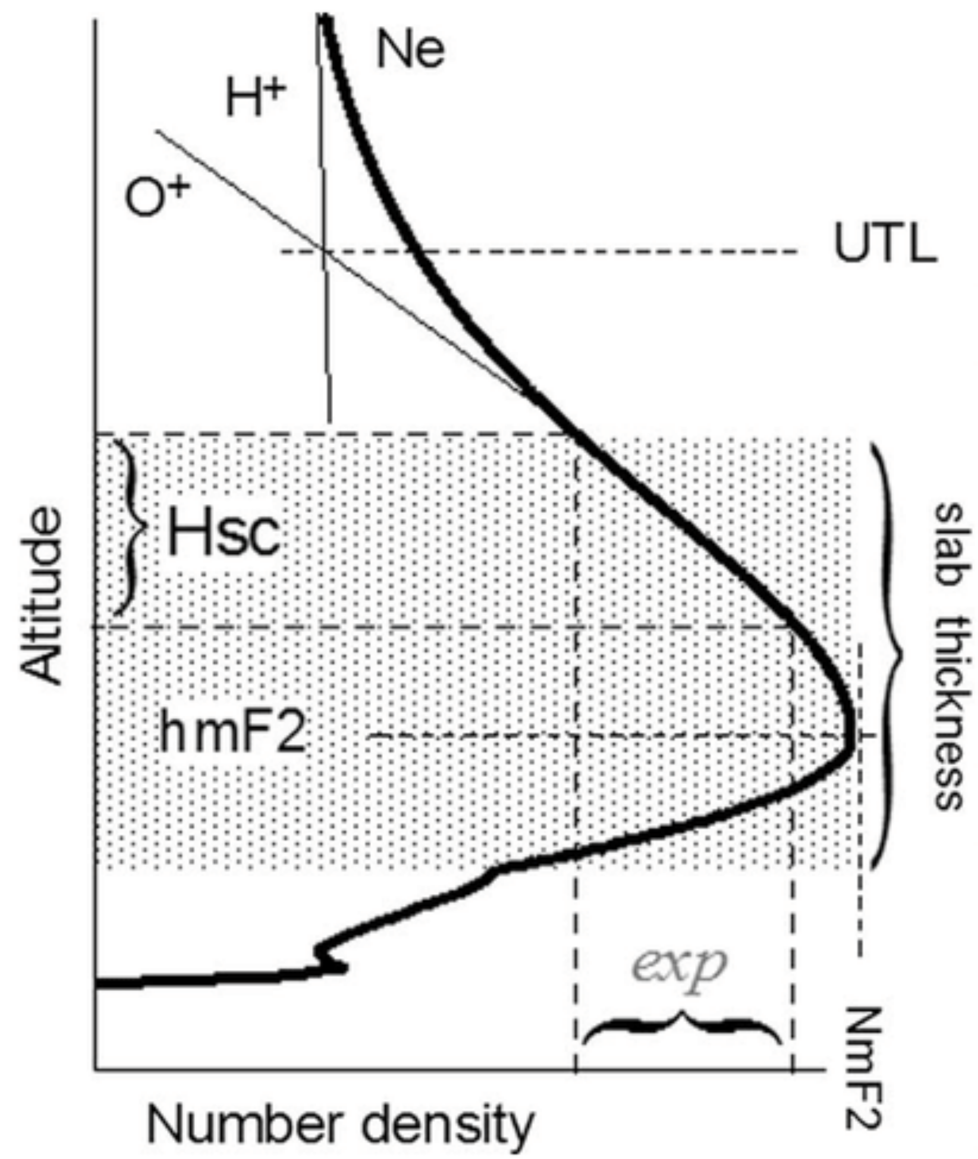
- But it is also strongly affected by the interactions with the magnetosphere.

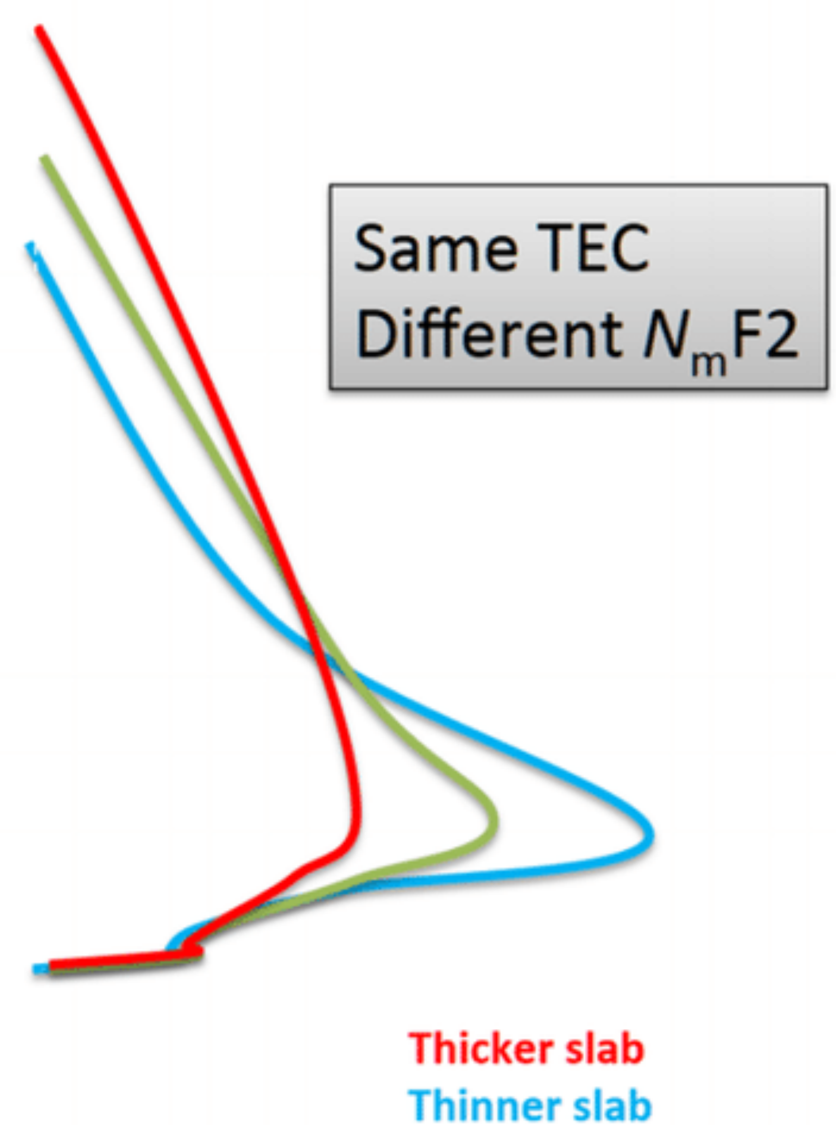
  - At mid-latitude, it is closely coupled with the plasmasphere along the closed magnetic flux tubes, which is very important for the maintenance of the nighttime ionosphere.

  - In the polar region, it also interacts with the magnetosphere along the vertical magnetic field lines (e.g., polar wind and ion out flows into the magnetosphere).

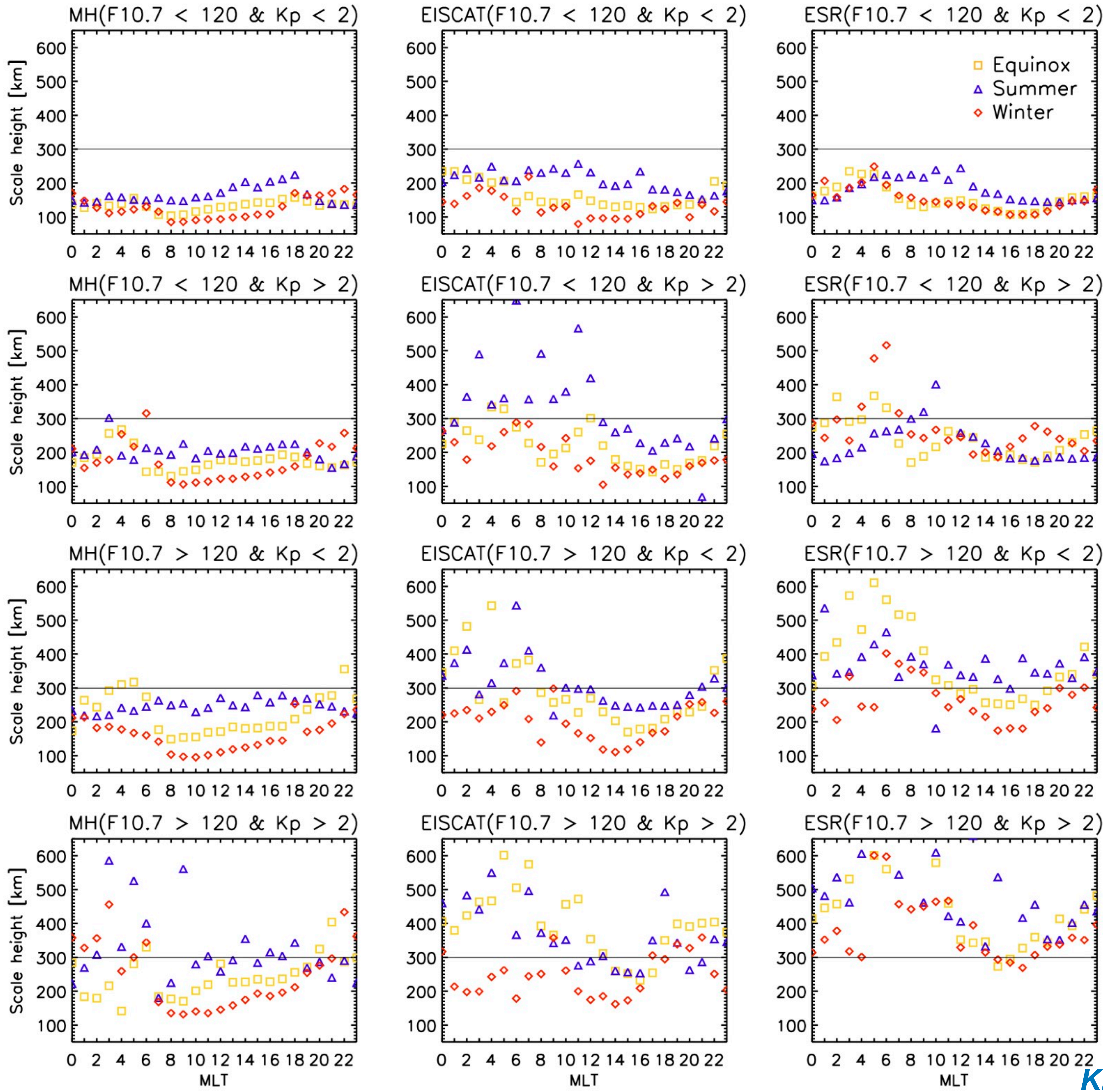
- The topside ionosphere can be represented by **the plasma scale height** and **slab thickness**.

# Scale height & Slab thickness

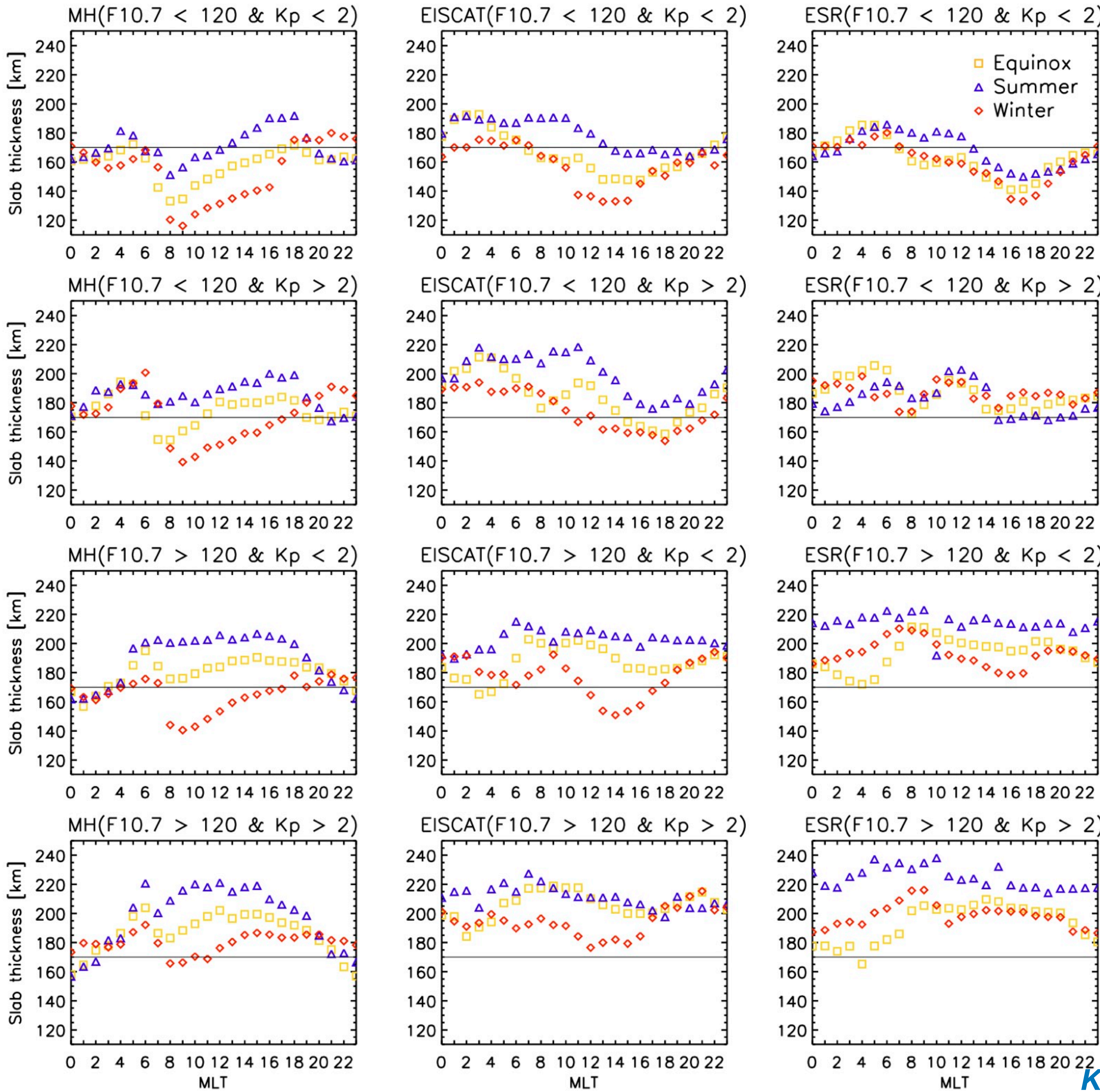



**Equivalent slab thickness ~ TEC/NmF2**




Kim et al., 2020




**Kim et al., 2020**

# Summary

- The polar ionosphere is unique and different from the low and mid-latitude ionosphere mainly due to the coupling with the magnetosphere along the nearly vertical geomagnetic field lines.

- The polar region is where the solar-wind driven magnetospheric energy is directly absorbed into the ionosphere, resulting in characteristic features such as aurora, strong plasma convection, energetic particle precipitations, joule/frictional heating etc.

- The horizontal density structures such as TOI, polar cap patch, polar hole, trough etc. have been extensively investigated in the polar ionosphere.

- However, there are also unique characteristics of the polar ionosphere in the vertical density profile.