Climatology of ionospheric density profiles in the auroral and polar cap regions from long-term incoherent scatter radar observations

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Abstract

Using long-term incoherent scatter radar (ISR) observations, we investigate the climatology of electron density profiles in the high latitude ionosphere in comparison with the mid-latitude ionosphere. The electron density profiles in the E and F regions are compared using the measurements from the three ISRs (Millstone Hill, Tromso, Svalbard) during equinox, summer and winter for different solar and geomagnetic activity periods. The diurnal and seasonal variations of F-region density are mainly controlled by solar zenith angle even in the polar ionosphere. In winter when the solar radiation is absent in the polar cap region, however, it is deviated from the solar controlled ionosphere: the diurnal variation shows two density peaks. The daytime peak is caused by cusp electron precipitation near the magnetic local noon but the nighttime peak is known to be produced by plasma transport from dayside to nightside, particularly during high solar activity. Seasonal variations, commonly occurring in the mid-latitude ionosphere, do not appear in the polar ionosphere during low solar condition but the semiannual anomaly occurs at both Tromso and Svalbard during high solar condition. While the nighttime E-region ionosphere nearly disappears in the mid-latitude and also in the polar cap, the E-region density is significantly enhanced in the auroral region by particle precipitation even during low solar activity or geomagnetically quiet condition. We also found the daytime E-region density enhancement in the polar cusp region in winter, which might be caused by energetic proton precipitation. The diurnal variations of hmF2 are significantly smaller in the polar ionosphere especially for solstices. The hmF2 increases with solar activity for all latitudes but does not vary with magnetic activity. The E-region peak height of about 110 km in the daytime mid-latitude region becomes higher in the polar region, being about 120 km in the nighttime auroral region and about 130 km in the daytime polar cap/cusp region.

1. Introduction

- Since the ionospheric plasma is produced by solar radiation, the plasma density varies with local time, season, solar cycle, latitude and longitude.
- In the **polar region**, however, there is an additional plasma production by **energetic particle precipitation**.
- Furthermore, the ionospheric density is redistributed by **plasma convection flow** over the polar cap region.
- In addition to characteristic horizontal structures of the electron density, the vertical profiles also show somewhat different aspects from the low and middle latitude ionosphere.
- The previous studies have been focused on the F region peak density or a short-period of observations (e.g., *Cai et al., 2007; Xu et al., 2014*).
- In this study, we investigate the characteristics of **density profiles in both E and F region ionospheres**, using long-term ISR observations during equinox, summer and winter for different solar and geomagnetic activity.

2. Incoherent Scatter Radar Observations

- Incoherent scatter radar (ISR) data during 1995 – 2015
  - Millstone Hill (**Mid-latitude**) : 43°N (53°N)
  - EISCAT Tromso (**Auroral region**) : 69°N (66°N)
  - EISCAT Svalbard (**Polar cap/cusp**) : 78°N (75°N)
- We used field-aligned measurements of electron density profiles which are interpolated with a regular altitude step of 5 km within observed altitude range to reproduce the hourly-mean density profiles.
- Then they are sorted by solar activity (F10.7) and geomagnetic activity (Kp) for equinox (3, 4, 9, 10), summer (5, 6, 7, 8), and winter (11, 12, 1, 2).

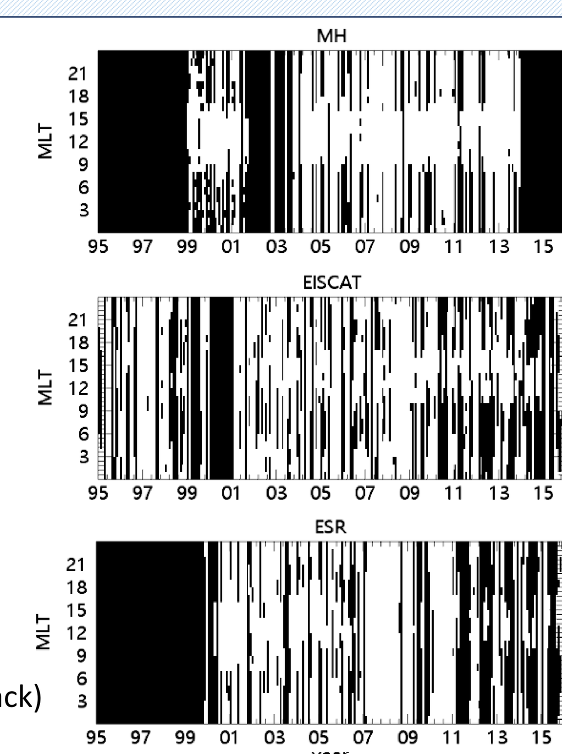

Fig. 1. Data coverage (existence in white and absence in black) in each hour-month grids at MH, EISCAT, and ESR locations.

3. Results and Discussions

Local Time Variations

Mid-latitude : Millstone Hill

- The F region density enhances during daytime and decreases after sunset, but in summer the density peak occurs in the evening.

Auroral region : Tromso

- The daytime density are extended in summer but shrunk in winter, depending on the length of daylight, and the difference of daytime increases with geographic latitudes.
- The F-region peak tends to be higher at night in the mid-latitude ionosphere but it is not in the polar ionosphere.

Polar cap/cusp : Svalbard

- The maximum density occurs at magnetic local noon when the ESR station is located in the cusp region where soft electron precipitation produces plasma.
- Two peaks occur at around magnetic local noon and pre-midnight in winter, especially for high solar activity.
  - *Xu et al. (2014)*: pre-midnight peak is caused by the tongue of ionization and/or polar cap patches
  - *Forster and Haaland (2015)*: the antisunward ion drift decreases with decreasing solar activity
  - *Dandekar (2002)*: the occurrence and strength of polar cap patches decrease with decreasing solar activity

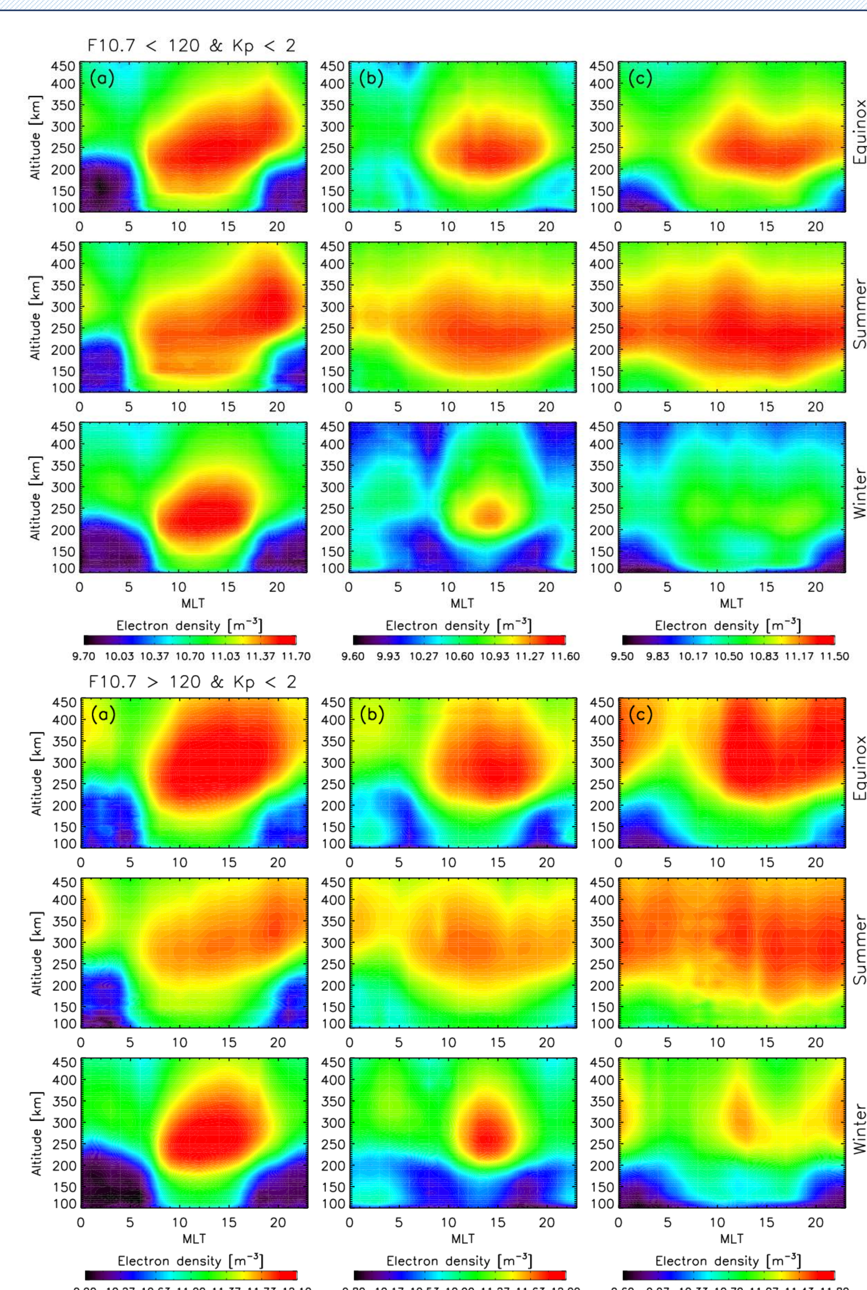

Fig. 2 & 3. Hourly mean of electron density profiles with magnetic local time during low & high solar activity for quiet time at Millstone Hill (a), Tromso (b), and Svalbard (c) stations.

3. Results and Discussions

Seasonal Variations

- Solar zenith angle: Summer < Equinox < Winter
- O/N_2 ratio: Winter > Equinox > Summer
- **Winter anomaly** does not appear in the polar cap/cusp at all
- **Semiannual anomaly** appears only during high solar activity in the polar ionosphere
  - Strong poleward wind decreases density in winter and the summer-to-winter wind is larger during high solar activity (*Hedin et al., 1994*).

Table 1. Annual variations of daytime density at Millstone Hill (MH), Tromso (EISCAT), and Svalbard (ESR) during low and high solar activity.

	Low solar activity	High solar activity
MH	winter ≥ equinox > summer	equinox > winter > summer
EISCAT	summer ≈ equinox > winter	equinox > winter > summer
ESR	summer > equinox > winter	equinox > summer > winter

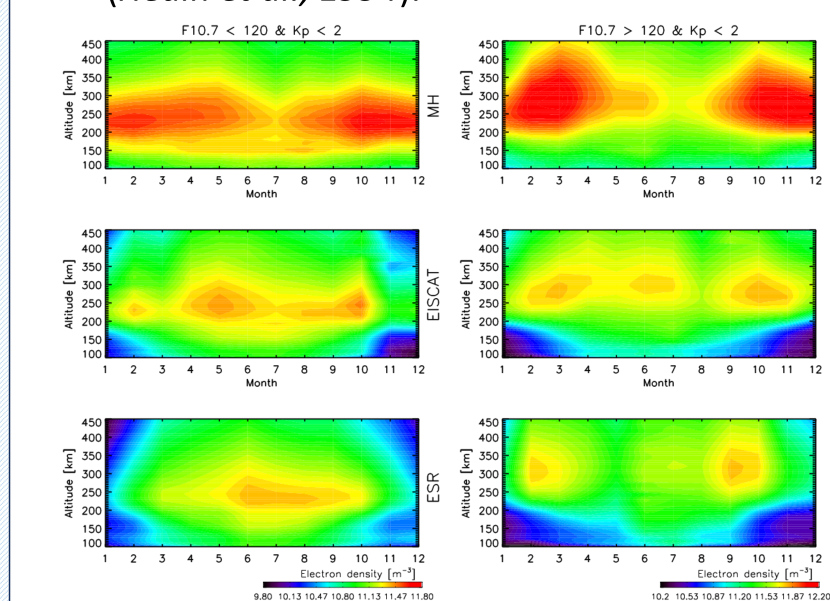

Fig. 4. Monthly mean profiles for daytime (11-13 MLT) at Millstone Hill (MH), Tromso (EISCAT), and Svalbard (ESR) during low and high solar activity.

Variations of F-region peak height

- The diurnal variations of hmF2 become weaker in the polar ionosphere, particularly for solstices.
  - Day-night difference in hmF2: 72 (MH), 42 (EISCAT), 21 (ESR) km
- Diurnal variation of profiles: topside < bottomside ionosphere, due to remaining sun light at higher altitudes
- The F region is much thicker and the hmF2 is 46 (MH), 58 (EISCAT), 75 (ESR) km higher during high solar condition.

E-region density profiles in the polar ionosphere

Auroral region during nighttime

- The auroral particle precipitation causes **E** region density peak at about 123 km even during low solar activity or undisturbed time.
- During low solar activity: E region peak density > F region peak density, called as E layer dominated ionosphere (ELDI) profiles (*Cai et al., 2014*)
  - The ELDI is most prominent in winter during low solar and disturbed conditions, as shown in Figure 7.

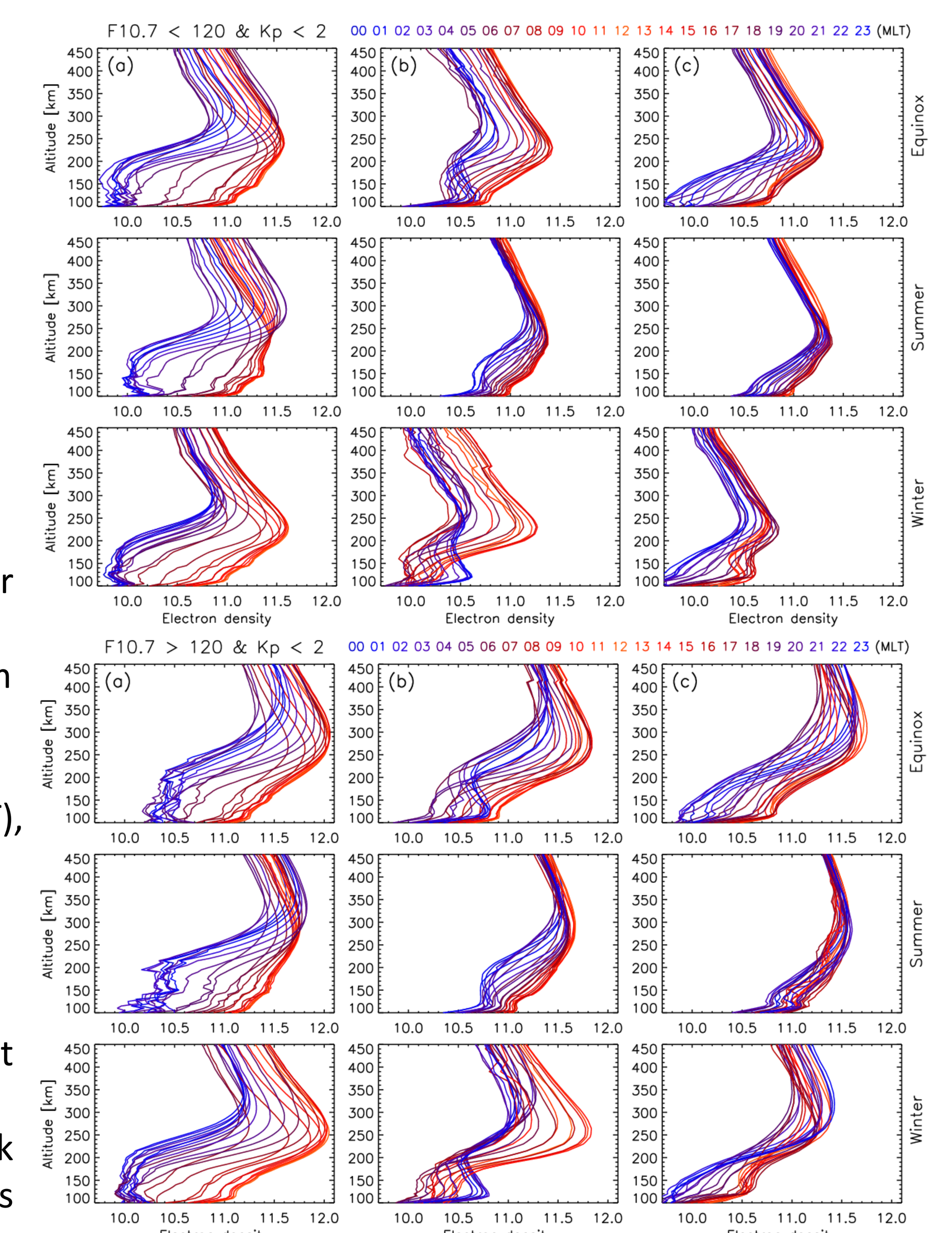

Fig. 5 & 6. Hourly mean of electron density profiles with magnetic local time in different colors during low & high solar activity for quiet time at Millstone Hill (a), Tromso (b), and Svalbard (c) stations.

Cusp region during daytime

- Another E region peak is caused by energetic proton precipitation from cusp to dayside ionosphere.
  - The mean hmE during daytime in winter is about 130 km, while around 110 km in the other latitudes.
- *Vontrat-Reberac et al. (2001)* simulates signature of cusp particle precipitation on the dayside polar ionosphere.
  - Soft electron precipitation → **F** region density
  - Energetic proton precipitation → **E** region density

Table 2. Mean hmE for daytime (09-15 MLT) and nighttime (21-03 MLT) during low/high solar activity conditions.

hmE [km]		Equinox	Summer	Winter
Mid-latitude	Daytime	110.7 / 111.4	135.7 / 120.0	111.4 / 113.6
	Nighttime	105.0 / 120.0	105.0 / 114.3	105.0 / 112.9
Auroral region	Daytime	111.4 / 113.6	107.9 / 108.6	117.1 / 105.7
	Nighttime	120.7 / 124.3	125.7 / 122.1	120.0 / 123.6
Polar cap/ Cusp	Daytime	116.4 / 120.7	108.6 / 115.0	125.0 / 132.1
	Nighttime	108.6 / 111.4	110.0 / 117.9	110.0 / 108.6

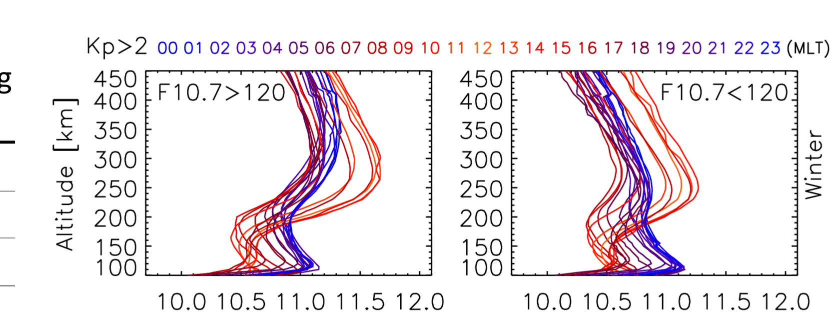

Fig. 7. Hourly mean of electron density profiles with magnetic local time during high (left) and low (right) solar activity for disturbed time in winter at Tromso.

4. Summary and Conclusions

- We investigated the climatological features of the **E and F region density profiles** from long-term ISR observations in the **mid-latitude, auroral region, and polar cap/cusp ionosphere**.

1. **Diurnal variation**: mainly controlled by **solar zenith angle**, but in winter there are two peaks in the polar cap/cusp region, particularly during high solar activity.
   - First peak caused by **soft particle precipitation** from the cusp near magnetic local noon
   - Second peak produced by **plasma transport** from the dayside lower latitude to nightside polar cap
2. **Seasonal Variation**: anomalies do not appear in the high latitude ionosphere during low solar activity. However during high solar activity, the semiannual anomaly exists at both polar stations but the winter anomaly appears only at Tromso.
3. **hmF2**: diurnal variations are smaller in the polar ionosphere especially for solstices
4. **E region density**: enhanced by **auroral particle precipitation** at Tromso during nighttime & by **cusp proton precipitation** at Svalbard during daytime in winter
   - Mean hmE: about 120 km in the auroral region during nighttime and around 130 km in the cusp during daytime, while it is approximately 110 km for the other cases

- Although the high latitude ionosphere is also mainly controlled by solar radiation, particle precipitation and plasma convection flow should be considered even during undisturbed condition.

Reference

- *Cai, H. T., S. Y. Ma, Y. Fan, Y. C. Liu, K. Schlegel, 2007, Climatological features of electron density in the polar ionosphere from long-term observations of EISCAT/ESR radar, Ann. Geophys., 25.*
- *Xu, S., B. Zhang, R. Liu, L. Guo, Y. Wu, 2014, Comparative studies on ionospheric climatological features of NmF2 among the Arctic and Antarctic stations, J. ASTP.*
- *Forster, M., S. Haaland, 2015, Interhemispheric differences in ionospheric convection: Cluster EDI observations revisited, J. Geophy. Res. Space Physics, 120.*
- *Dandekar, B. S., 2002, Solar cycle dependence of polar cap patch activity, Radio Sci., 37, 1.*
- *Hedin, A. E., M. J. Buonsanto, M. Codrescu, M. –L. Duboin, C. G. Fesen, M. E. Hagan, K. L. Miller, and D. P. Sipler, 1994, Solar activity variations in midlatitude thermospheric meridional winds, J. Geophys. Res., 99*
- *Cai, H. T., F. Li, G. Shen, W. Zhan, K. Zhou, I. W. McCrea, S. Ma, 2014, E layer dominated ionosphere observed by EISCAT/ESR radars during solar minimum, Ann. Geophys., 32, 1223-1231.*
- *Vontrat-Reberac, A., D. Fontaine, P. -L. Blelly, M. Galand, 2001, Theoretical predictions of the effect of cusp and dayside precipitation on the polar ionosphere, J. Geophy. Res., 106.*

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