Mid-latitude ionospheric weather & climate

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Role of the ionosphere and space weather in military communications

Outline

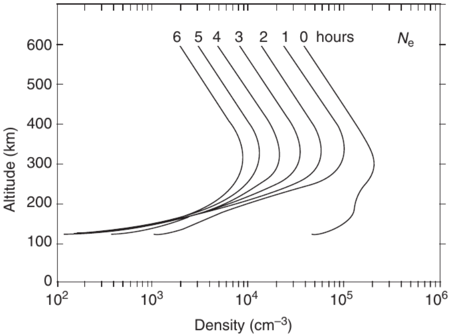
1. Mid-latitude climatology
   - Diurnal cycles
   - Seasonal variations
   - Solar cycle dependencies

2. Ionospheric “weather” & radio applications
   - Introduction
   - Geomagnetic storm effects
   - *D*-layer enhancements
   - Travelling ionospheric disturbances

Mid-latitude climatology

Night-time recombination

- During the night, ionisation disappears due to recombination (note the logarithmic density scale).
- Recombination rate depends strongly on *neutral* density, thus: higher at lower altitude.
- We are ignoring minor sources of ionisation here from *e.g.* cosmic rays.



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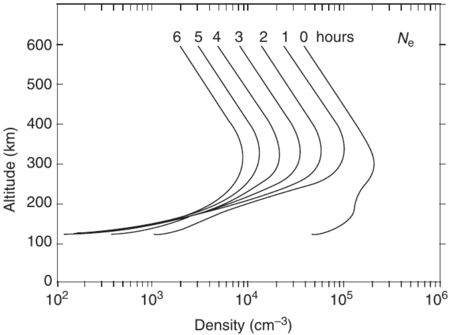


Neutral winds are generally from the subsolar point (noon, summer hemisphere) to its antipode (midnight, winter hemisphere).

Horizontal drift across **B** creates vertical flow, helping to maintain the *F* layer during night (at a higher altitude).

The lower layers

The E and F_1 layers are almost entirely driven by direct photoionization, and thus easily modelled.

The E layer peak density is very well modelled by

$$foE = 3.3\sqrt[4]{(1 + 0.008 \cdot R)\cos\chi}$$

(R = sunspot number, χ = solar zenith angle).

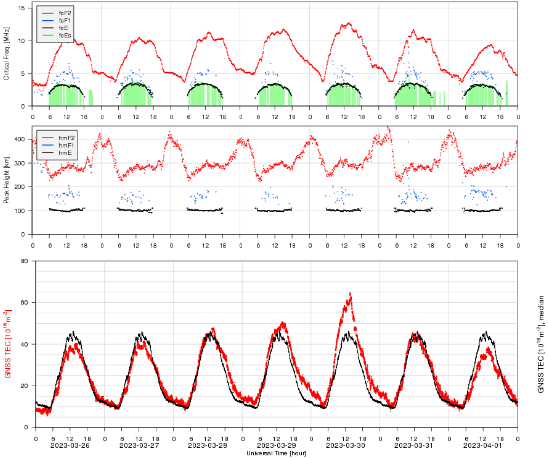
The F_1 layer density, if present, is reasonably well modelled as:

$$foF_1 = 4.25\sqrt[4]{(1 + 0015 \cdot R)\cos\chi}$$

Both layers are well described by the Chapman profile.

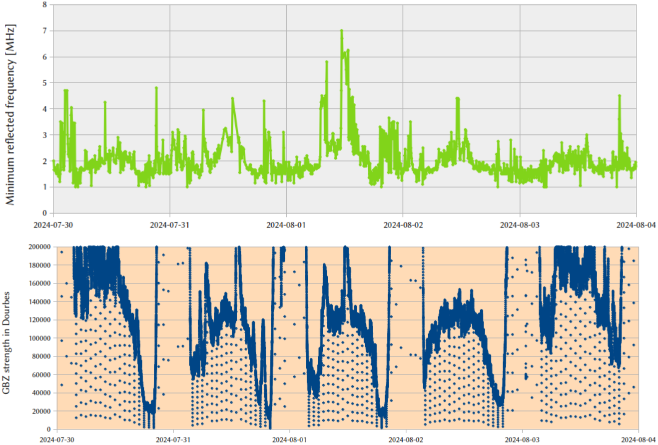
Everything below F_2 peak is (almost) entirely driven directly by irradiation.

Diurnal variations



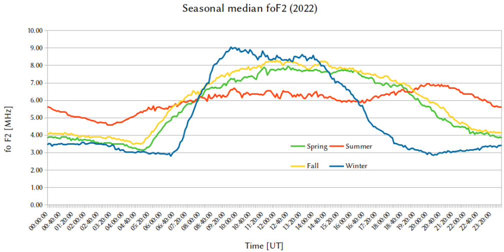
Peak densities and heights of the layers, and total electron content. Main features: foF_2 and $vTEC$ are maximal during day, minimal at night; hmF_2 is highest in the morning hours; E and F_1 layers seen only during the day.

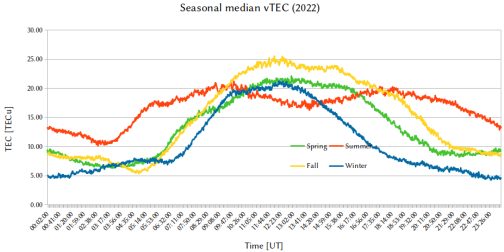
D-layer & influence on radio



D-layer has a similar pattern to *E* and F_1. Opposite effects on HF *vs.* VLF.

Seasonal variations



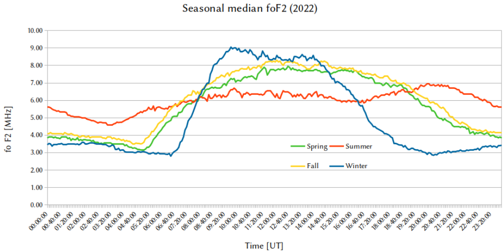


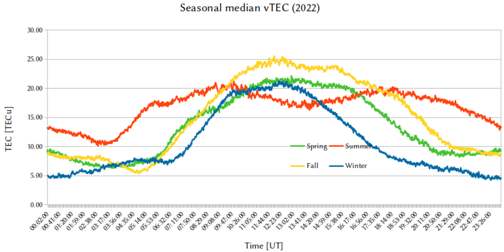
More complicated than expected from irradiation variations alone!

Question:

Why is foF_2 larger in winter than in summer?

Seasonal variations





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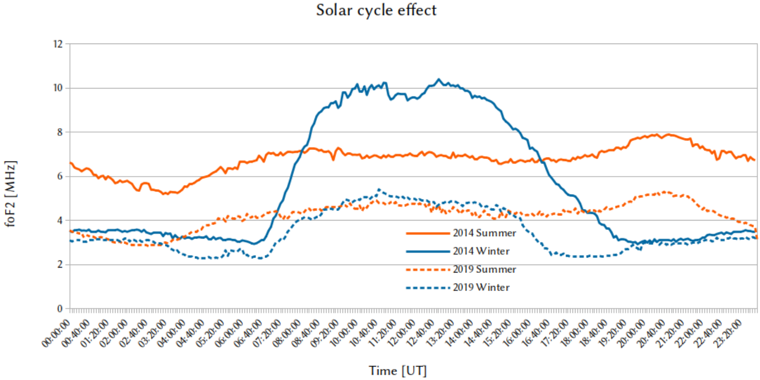
Why is foF_2 larger in winter than in summer?

"Mid-latitude seasonal anomaly" is due to neutral composition changes: more O, less N_2 in winter means more photoionisation, less recombination.

Solar cycle dependencies: foF_2

Solar irradiance also varies with season and solar cycle, leading to very significant cycles in ionisation levels (even for the weak cycle 24).



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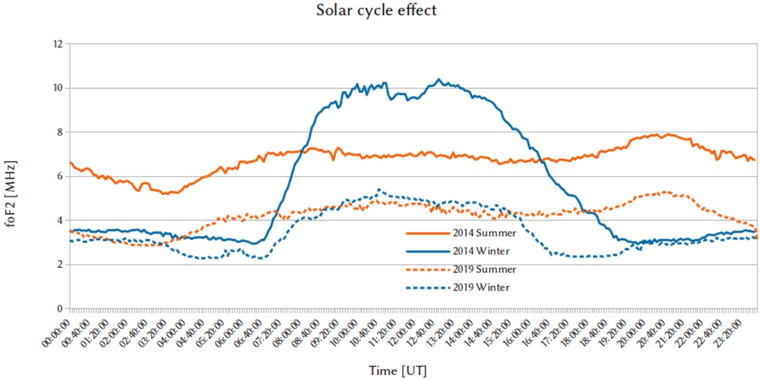
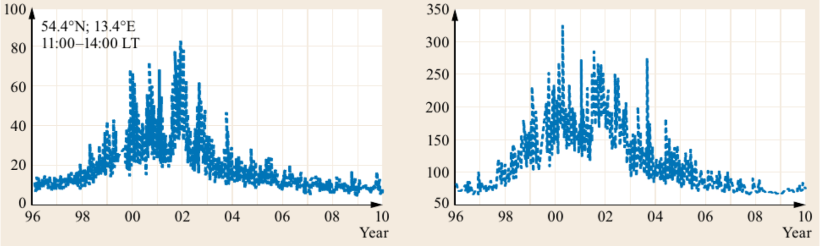


Question:

Why so little variation in foF_2 during summer?

Solar cycle effect: *vTEC*



Total vertical electron content follows $F_{10.7}$ closely, also at shorter time scales (less than a year).

More importantly: (stronger) solar maximum means more solar events like flares and CMEs.

Summary of this part

1. (Mid latitude) ionosphere has typical variations with time of day, season, and solar cycle.
2. Seasonal anomaly: higher ionisation in winter than in summer.
3. Lower layers only depend on solar irradiation, F_2 layer is more complicated.

The same cycles determine frequencies suitable for HF radio communication, and the amount of delays in trans-ionospheric signals.

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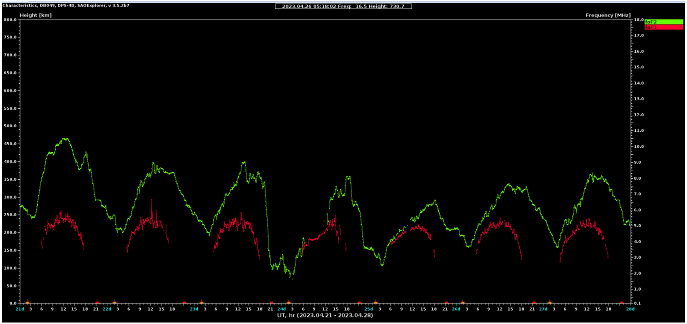
The end of this part.

Questions so far?

Ionospheric “weather” & radio applications

What do we mean by "ionospheric weather"?

The real condition of the ionosphere fluctuates around the climatological, average state (cf. meteorological weather/climate).



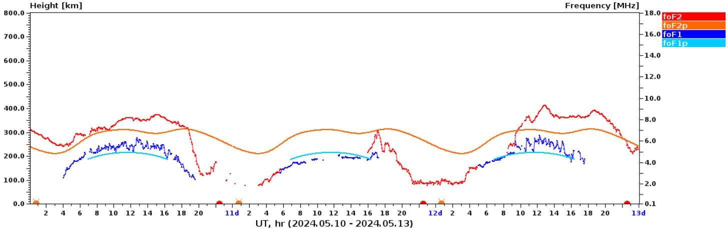
Sources of ionospheric variability include:

- Material from solar eruptions being deposited in the auroral region,
- Solar X-rays flares & high energy particles ionising the *D* layer,
- Bottom-up, thermospheric drivers, such as tides and acoustic waves.

Mechanism of geomagnetic storms

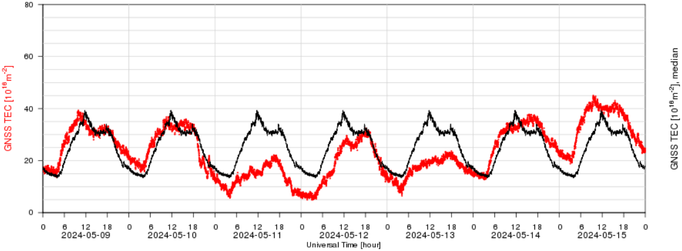
The most significant disturbances come from solar events (CMEs, CIRs), propagating through the solar wind and compressing the magnetosphere.

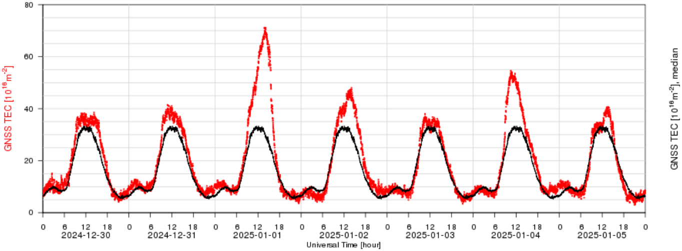
1. Energy injected into the ionosphere, mainly at high latitude.
2. As a result, the auroral oval expands.
3. This causes large scale movement of plasma towards the equator.
4. Drift along the magnetic field lines cause the ionosphere to move up, which can increase electron density ("positive storm phase").
5. Finally, upwelling of N_2 causes increased recombination, leading to a depletion of ionisation ("negative storm phase").



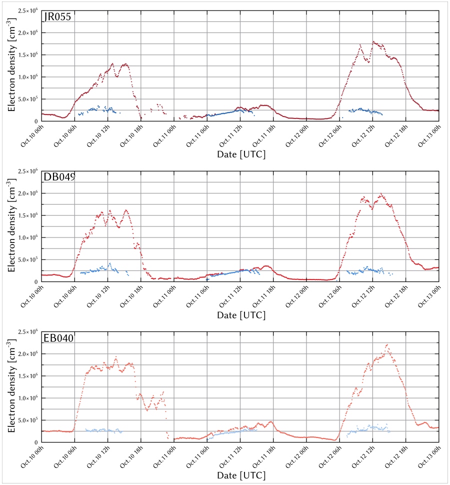
Positive & negative storms

Besides *MUF*, also trans-ionospheric delays are affected, either being decreased or increased, depending on positive or negative storm phase.

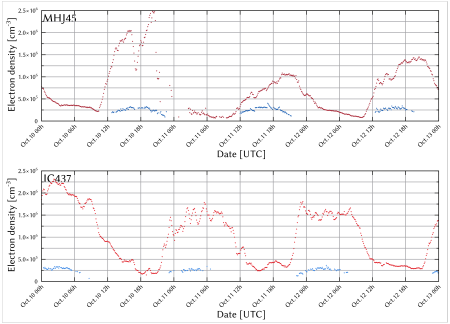




Global storm response

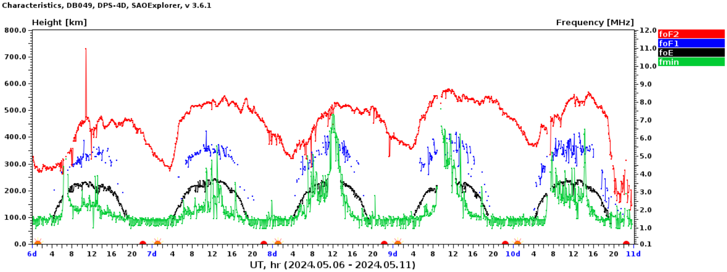


The entire, global ionosphere responds to geomagnetic storms, but effects vary with latitude & longitude.



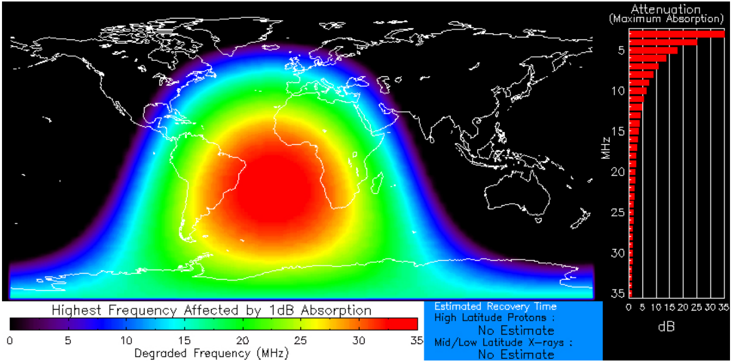
D-layer enhancement (at mid-latitudes)

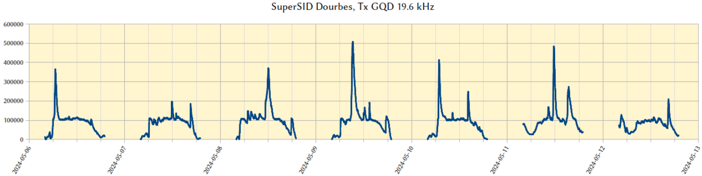
X-rays reach deeper into the thermosphere than EUV, down to the *D* layer.



Solar flares produce burst of enhanced *D* layer ionisation. These enhancements can last up to several hours.

HF blackout, VLF enhancement

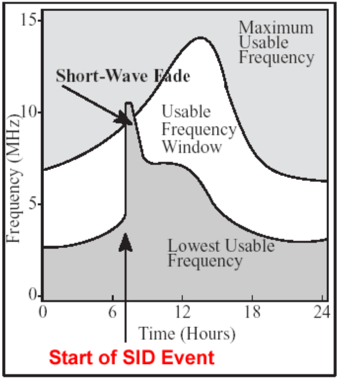




More *D*-layer ionisation: HF blackout in sunlit area, but better VLF transmission (also some possible disturbance of trans-ionospheric signals).

The worst case scenario

- Geomagnetic storms cause the *highest* usable frequency for HF coms to go *down*.
- *D*-layer enhancements cause the *lowest* usable HF frequency to go *up*.



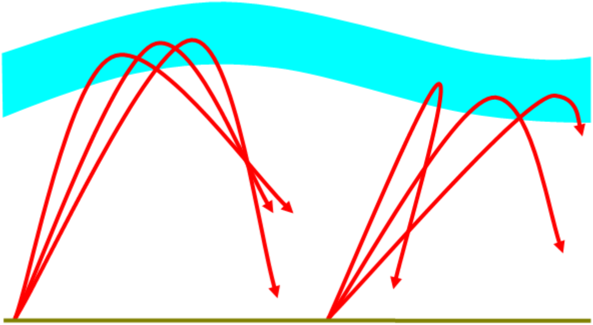
The worst case:

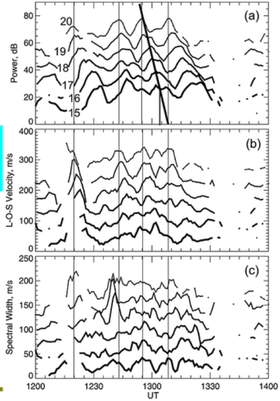
If solar flare during geomagnetic storm, *no* frequency may be usable!

In periods of high solar activity, such coincidences are not rare.

Wave-like disturbances & gradients

The reflecting layers are usually not exactly flat, due to waves and structures in the lower thermosphere.





This can cause issues for HF applications where directionality is important (directional communication, HF radars, radar geolocation systems).

Summary

1. Geomagnetic storms can cause both *positive* and (more importantly) *negative* deviation in electron density (mainly at F_2 altitude) $\rightarrow$ *MUF* depression.
2. Solar X-ray flare cause enhanced *D*-layer ionisation $\rightarrow$ increased HF absorption, but better VLF propagation.
3. Small scale deformations of the bottom of reflecting layer $\rightarrow$ perturbations of directional transmissions.

Note: in mid-latitude, most problems occur for HF band; in high and low latitudes, other mechanisms severely affect trans-ionospheric signals.

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The end!

Questions?