Development of climate of the upper atmosphere and ionosphere and the role of Sun

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The greenhouse gas increase has a cooling effect in the upper atmosphere. Greenhouse gases in the troposphere are optically thick to outgoing longwave (infrared) radiation, which they both absorb and reemit back to the surface to produce the heating effect. In contrast, **greenhouse gases in the much lower density upper atmosphere are optically thin to outgoing infrared radiation**. **In-situ collisional excitation results in atmospheric thermal energy readily lost to space via outgoing infrared radiation (**CO_2 and NO are the two main "coolers" of the thermosphere), while the absorption of radiation emanating from the lower atmosphere plays only a secondary role in the energy balance. **The net result is that the radiatively active greenhouse gases act as cooling agents**, and their increasing concentrations enhance the cooling effect in the upper atmosphere

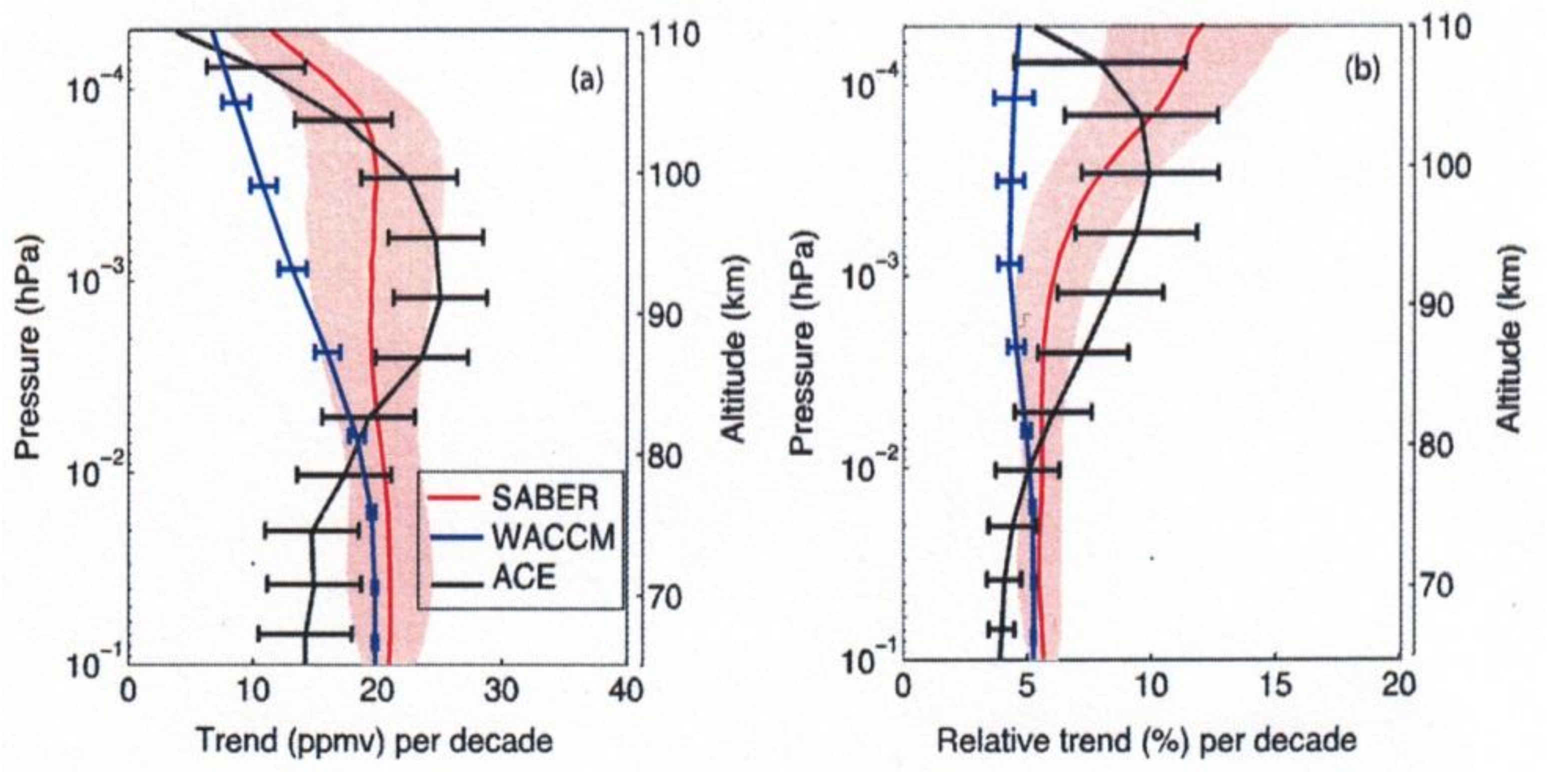
Different drivers of long-term trends

Potential drivers of climatic change (= long-term trends) in the upper atmosphere and ionosphere are long-term changes of:

- **greenhouse gases (CO_2) – main driver**
- **solar activity**
- **geomagnetic activity** (solar wind)
- **secular changes of the Earth's magnetic field**
- **ozone, namely stratospheric ozone**
- **activity of atmospheric waves**
- water vapor

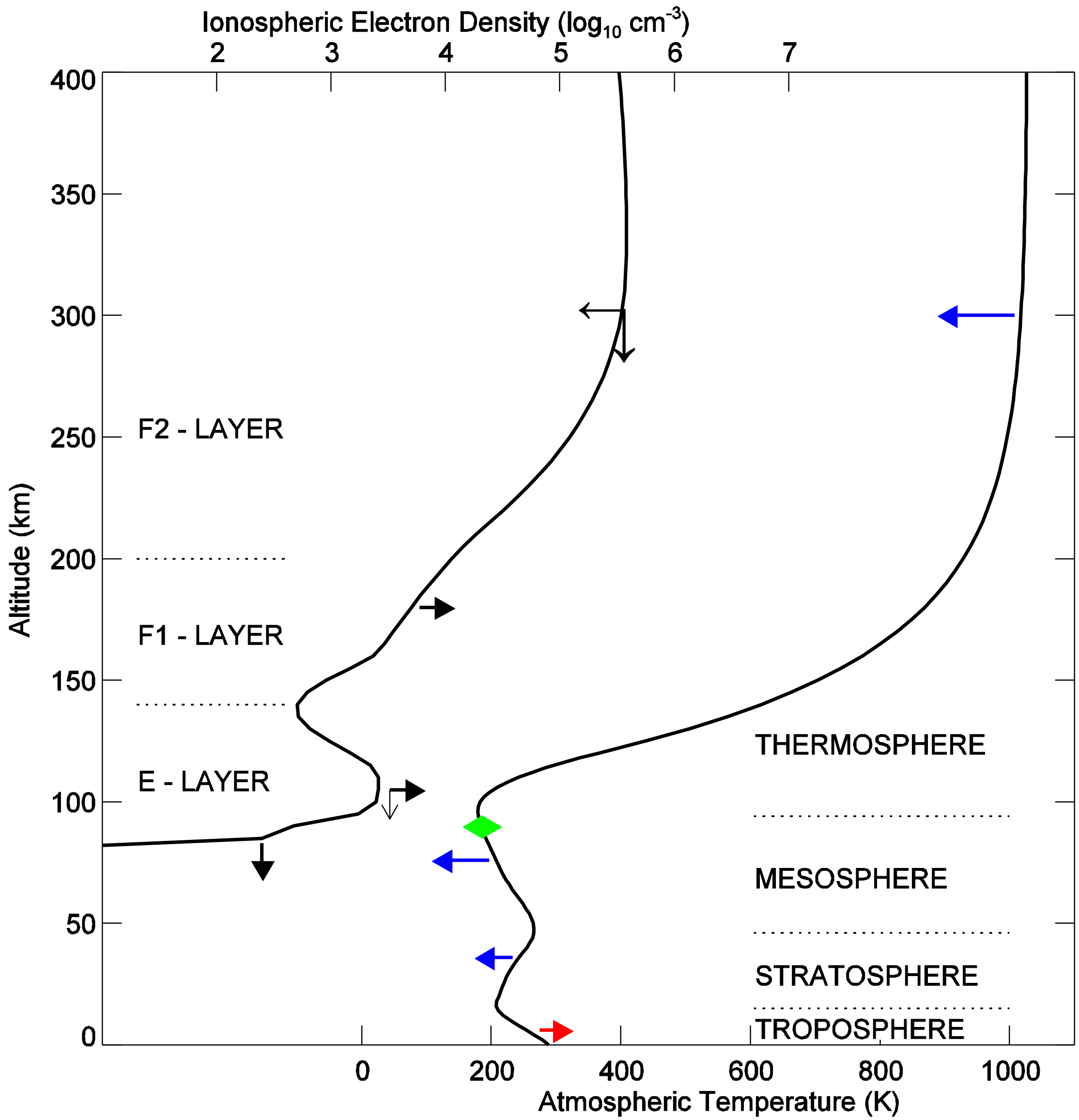
=> **Trends need not be stable, they can change in time and space.**

Vertical profiles of **absolute trends** (left panel) **and relative trends** (right panel, %/decade) **of CO_2 VMR in the mesosphere and lower thermosphere** – SABER red, ACE-FTS black, model SD-WACCM blue. Shaded areas and error bars - 2σ uncertainty. Yue et al. (2015).



Observational trends of CO_2 in 80-110 km are evidently stronger than model trends

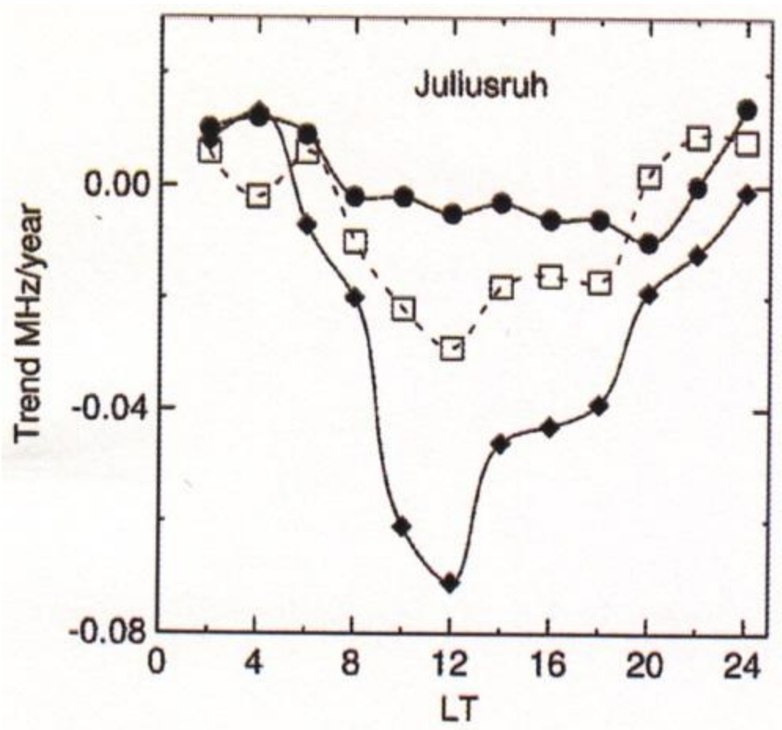
Global scenario of long-term trends



Summary of consistent mesospheric, thermospheric and ionospheric trends, which form the global pattern/scenario based on historical data.

The scenario is qualitatively consistent with expected effect of greenhouse gases.

Trends in foF2 critically depend on local time and season. They are close to no trend at night and in summer daytime and they are negative and not quite small in winter daytime, because hmF2 is close to the boundary where a positive anthropogenic trend in electron density below changes to a negative trend above according to model calculations (Qian et al., 2008). **Therefore foF2 is not a good parameter for studying trends of anthropogenic origin.**



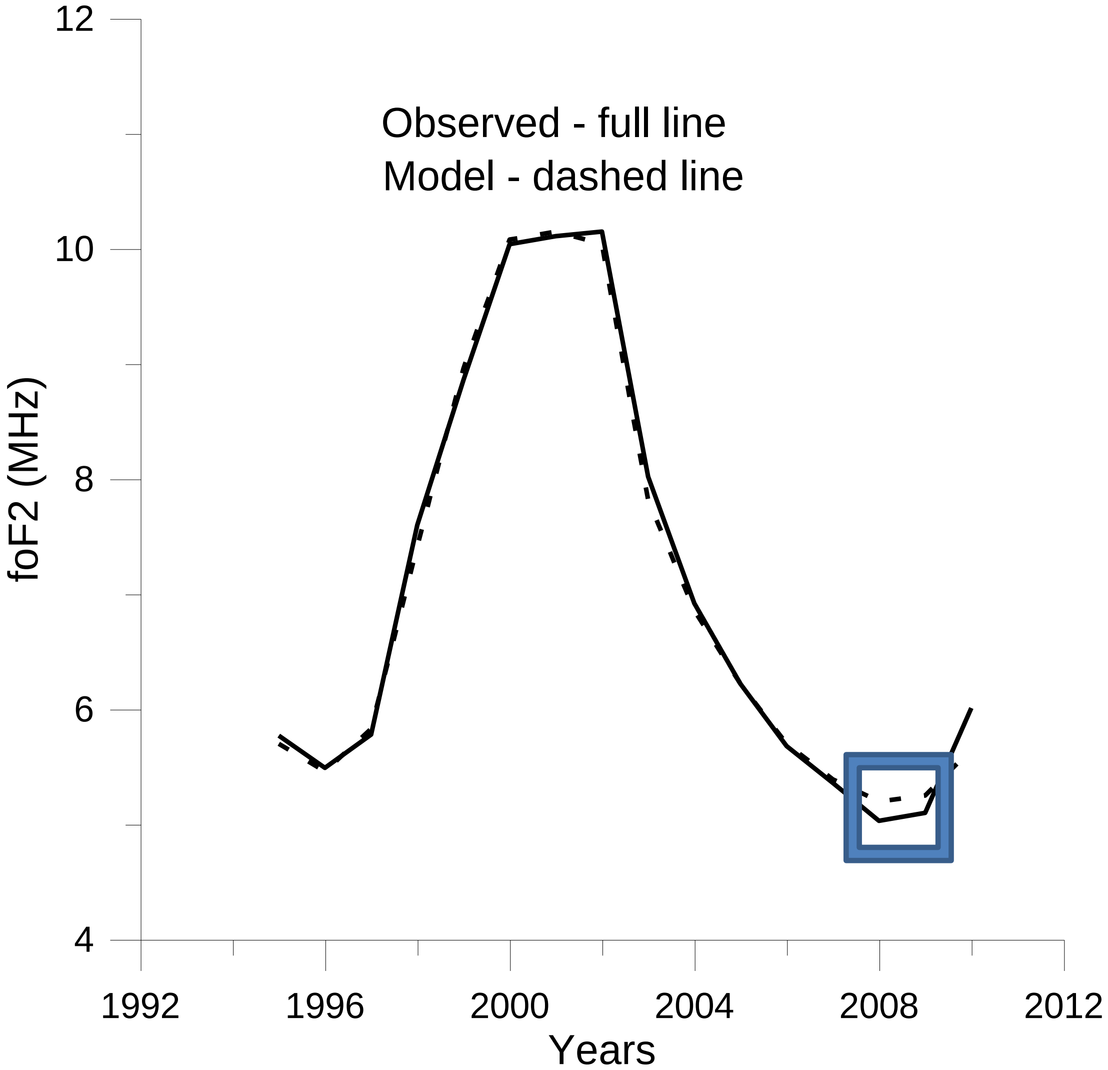
Dependence of trends in foF2 on local time and season for Juliusruh, northernmost Germany. Circles – June; rectangles – September; diamonds – February. Danilov (2015).

Solar activity

Since maximum in 1957/58 solar activity appears to have decreased moderately during the second half of the 20th century, and rapidly in the 21st century, which is a **tendency opposite to what is required to explain the observed predominantly positive ionospheric trends in foE and foF1**. Moreover, the effect of solar activity, on solar cycle time scales, is removed when long-term trends are computed both in the ionosphere and thermosphere. Different corrections to solar activity are one of the sources of differences between different trend results in F2-region parameters, foF2 and hmF2. On the long time-scales like more than four solar cycles (1959-2005), when the effect of solar activity was not removed, it explained 5-40% of total trends in hmF2 and **20-80% in foF2** for various ionospheric stations (Cnossen and Frantzke, 2014).

Solar activity

foF2 (MHz) = A + B x time (year-1994) + C x F10.7

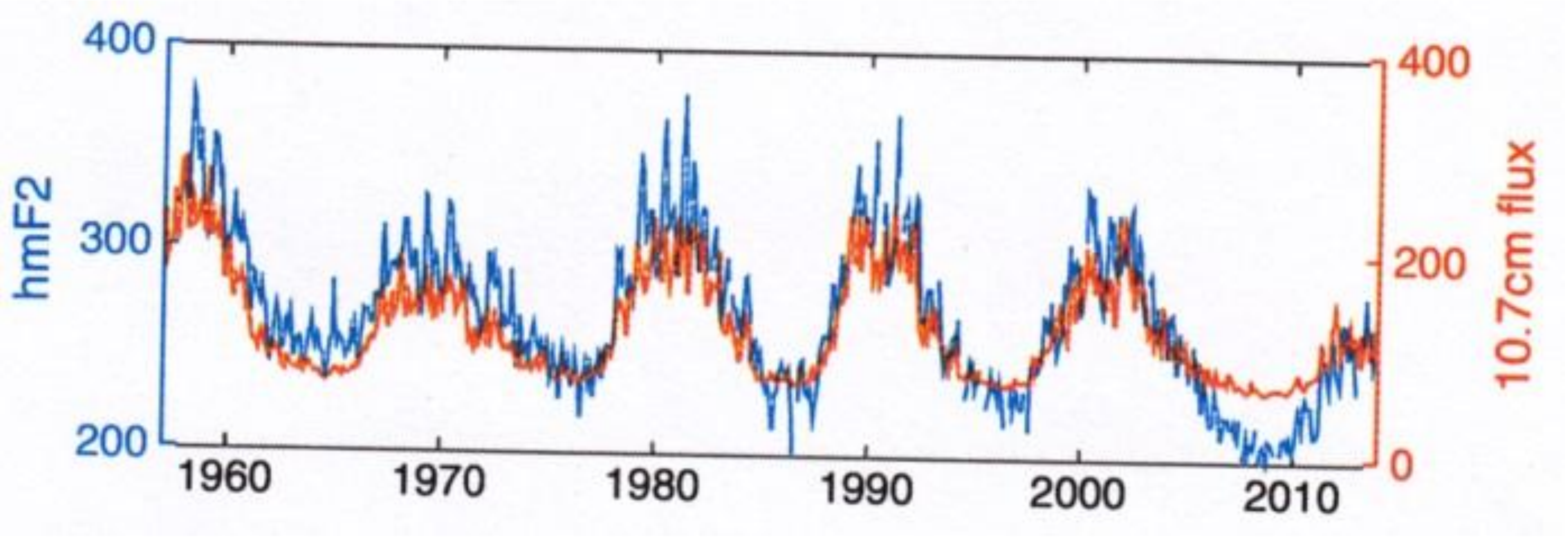


Simple model surprisingly well describes yearly values of foF2 for Pruhonice (50N, 15E) except for **2008 and 2009 – F10.7 does not describe too low EUV flux in these two years**.

This is one of the reasons why we do not have yet reliable information about trends in TEC (for GNSS).

Solar activity

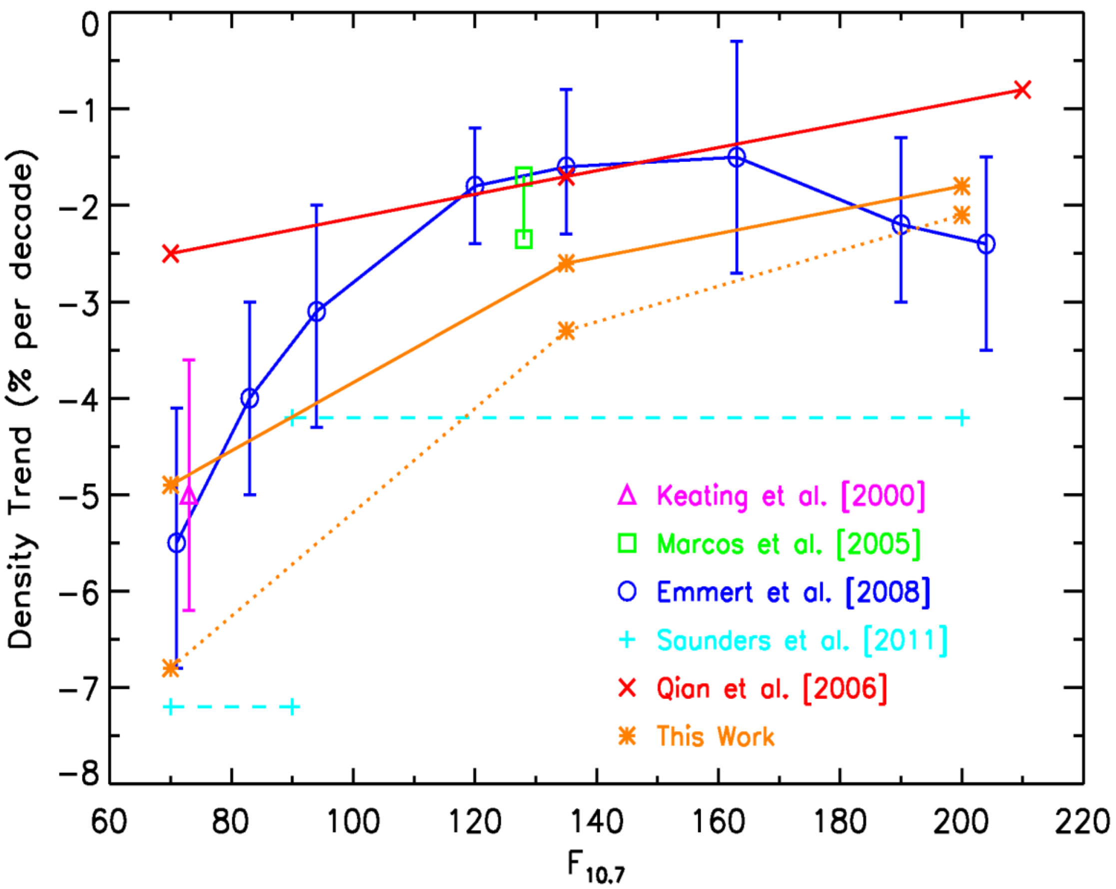
Dependence of hmF2 on solar activity for Sodankylä, northern Finland. Blue – hmF2; red – F10.7. Roininen et al. (2015).



The problem with non-representability of F10.7 in the last solar cycle minimum is even more severe for hmF2. However, we do not know the level of solar EUV flux in this minimum.

Indirect effect of solar activity + Impact of change of CO_2 trends on models

Indirect effect of solar cycle – higher trend in density at solar minimum.



Neutral density trends at 400 km. Crosses – model calculations, middle curve are new calculations with model WACCM and new realistic profile of CO_2 concentration. Other symbols – observational trends from satellite drag measurements. Adopted from Solomon et al. (2015).

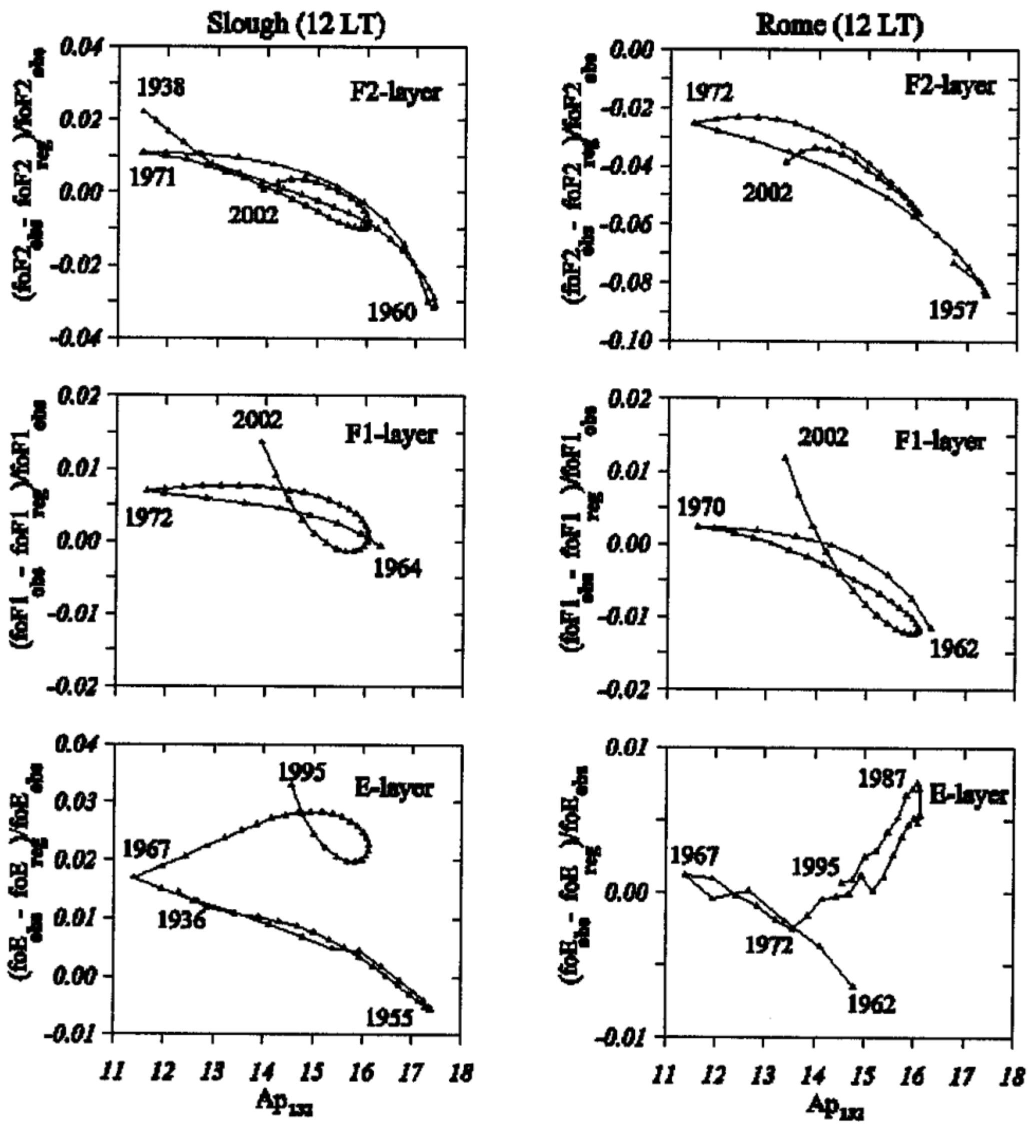
Indirect solar cycle effect is due to a higher role of CO_2 in solar minimum.

Model calculations with new CO_2 trends fit observations evidently better than old calculations.

Geomagnetic activity

Long-term change of geomagnetic activity means its increase almost throughout the 20th century followed by a deep drop in the 21th century. **In the 20th century the role of geomagnetic activity in the observed long-term trends/changes in the atmosphere-ionosphere system was decreasing from its beginning towards its end** (Lastovicka, 2005). Mikhailov and de la Morena [11] found that trends in foE were controlled by geomagnetic activity before about 1970, but not in more recent years. Next slight based on results of A. Mikhailov summarizes effects of geomagnetic activity on ionospheric trends over Europe.

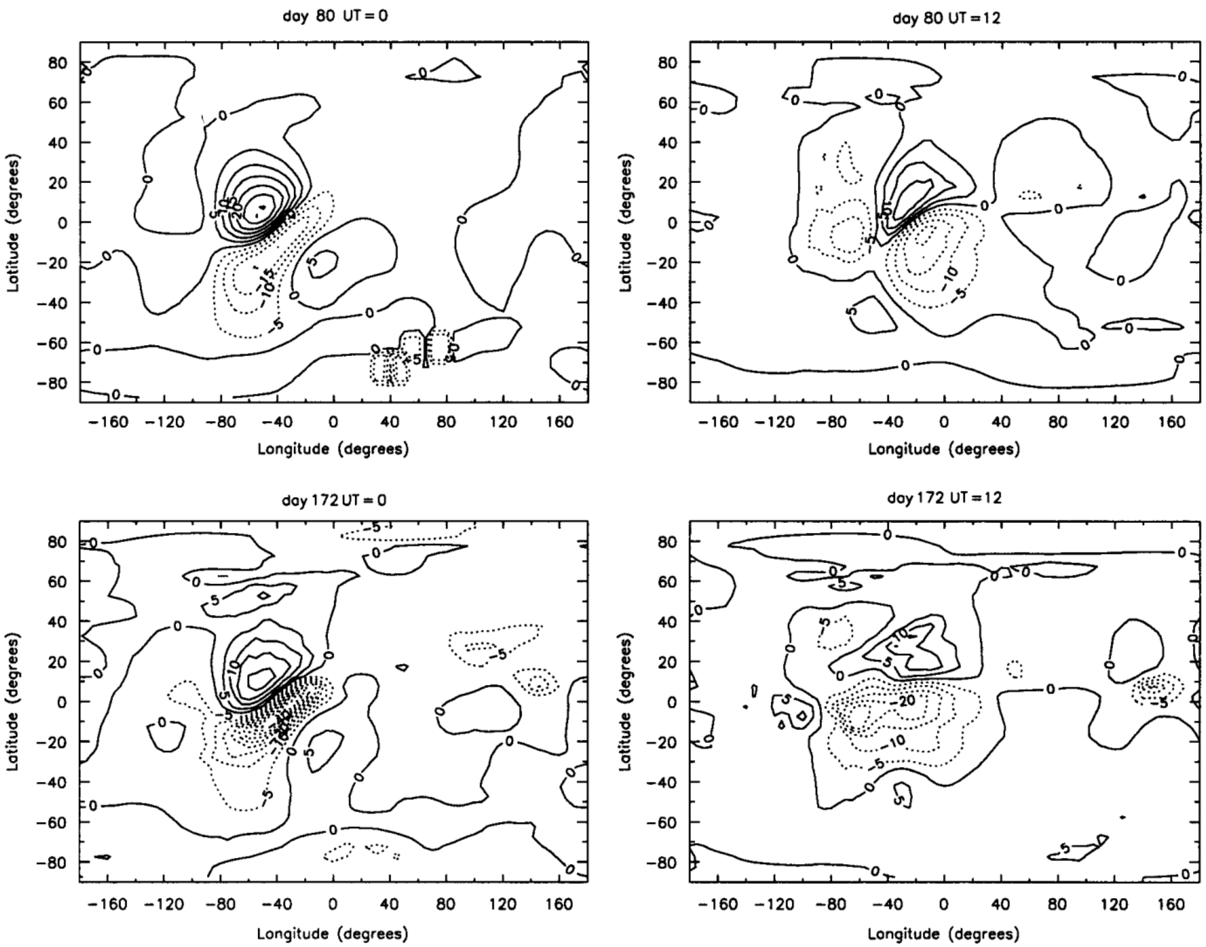
Effect of geomagnetic activity on ionospheric trends



Relationships between δfoF2 (*top panels*), δfoF1(*middle panels*) and δfoE (*bottom panels*), and Ap132 variations for Slough (*left panels*) and Rome (*right panels*).

Past geomagnetic activity control of trends was lost in ~1970 in foE, in the early 1990s in foF1 and in ~2000 in foF2.

Secular change of Earth’s magnetic field



TIE-GCM model simulation of effect of changes of the Earth’s magnetic field in hmF2 (difference between 1997 and 1957 in km) at day 80 (*top*) and day 172 (*bottom*), 00 UT (*left*) and 12 UT (*right*). After Cnossen and Richmond (2008).

Impact on hmF2 is evidently very regional.

Conclusions

1. There is a global scenario of long-term trends in the mesosphere, thermosphere and ionosphere but with some gaps.

2. CO_2 is the main driver of trends but there are important secondary drivers.

3. Solar activity could affect particularly trends in the ionosphere quite significantly but after removal of the solar cycle influence its effect becomes (very) small. There is also an indirect effect of solar activity pronounced in thermospheric density.

4. Geomagnetic activity was probably of primary importance for ionospheric trends in the past; now its role in trends is rather small.