5th Space Climate Symposium
Oulu, Finland
June 15-19, 2013

Solar influence on the long-term change in the ionosphere

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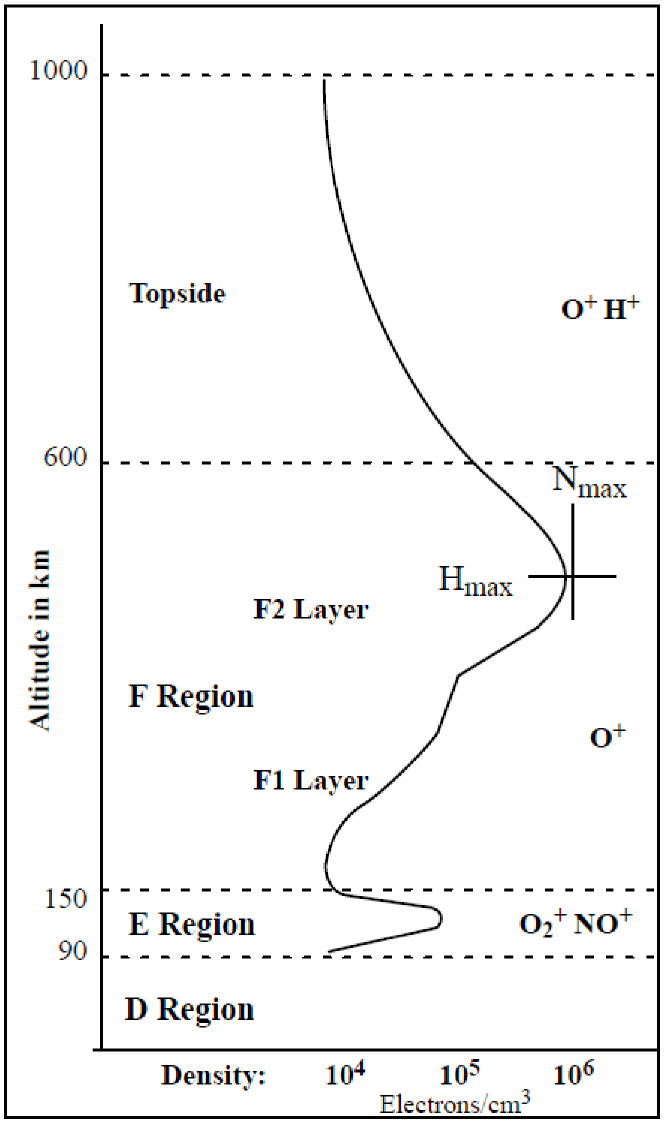
Ionospheric trends

- increase in CO_2 concentration
  (Rishbeth, 1990, 1992; Roble and Dickinson, 1989)
- long-term changes in geomagnetic activity and F2-layer storm mechanisms
  (Danilov and Mikhailov, 1999; Mikhailov and Marin, 2000)
- secular variation of the Earth's magnetic field
  (Foppiano et al., 1999)
- solar influence (long-term changes in solar activity, incorrect filtering, etc.)

Anderson and Fuller-Rowell, 1999



The ionosphere varies greatly because of:

- changes in the sources of ionization (solar EUV radiation)

- changes in the neutral part of the upper atmosphere in which it is embedded (the thermosphere) which also depends on solar radiation

Table 1. Ionospheric Variability

Ionospheric Parameter	Diurnal (Mid-Latitude)	Solar Cycle (Daytime)
N_{max}	1×10^5 to 1×10^6 electrons/cm^3 Factor of 10	4×10^5 to 2×10^6 electrons/cm^3 Factor of 5
Maximum Usuable Frequency	12 to 36 MHz Factor of 3	21 to 42 MHz Factor of 2
Total Electron Content	5 to 50×10^{16} electrons/m^2 Factor of 10	10 to 50×10^{16} electrons/m^2 Factor of 5

Important:

Solar EUV ⇒ dominant influence on ionosphere

Example: Juliusruh: 54.6°N, 13.4°E

foE

foF2

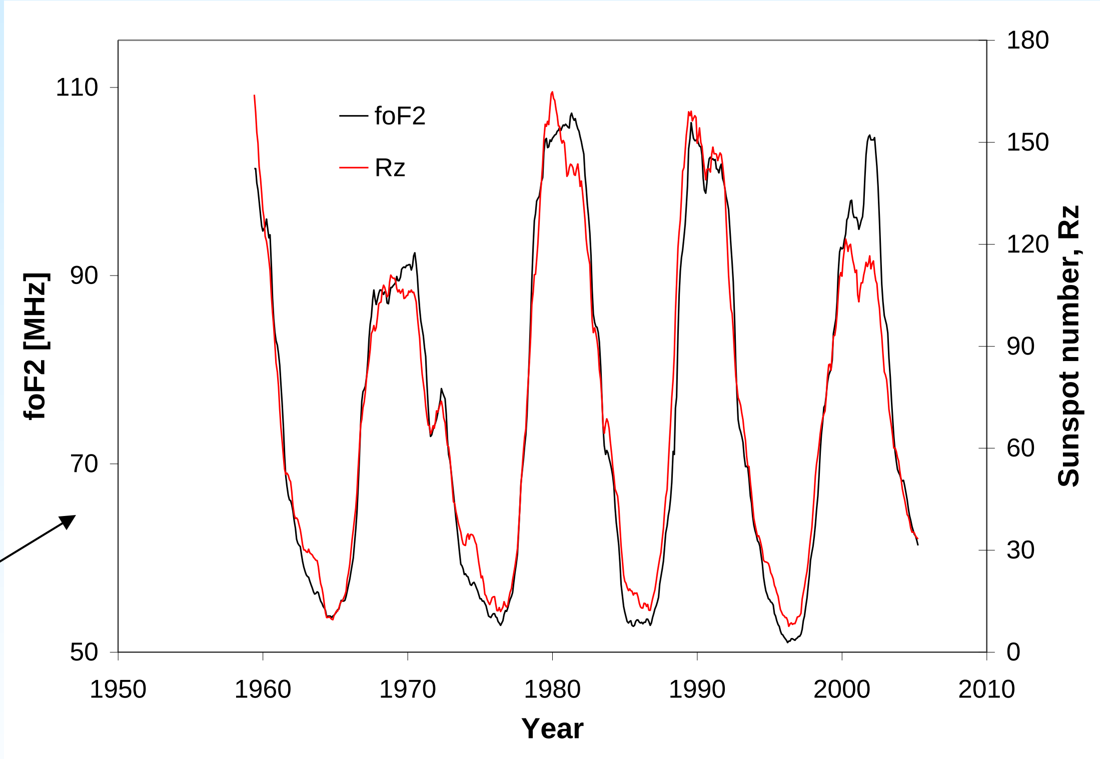
$q_m \propto I_\infty$

hmE

hmF2

conductivities

...



12-month running mean
(annual timescale)

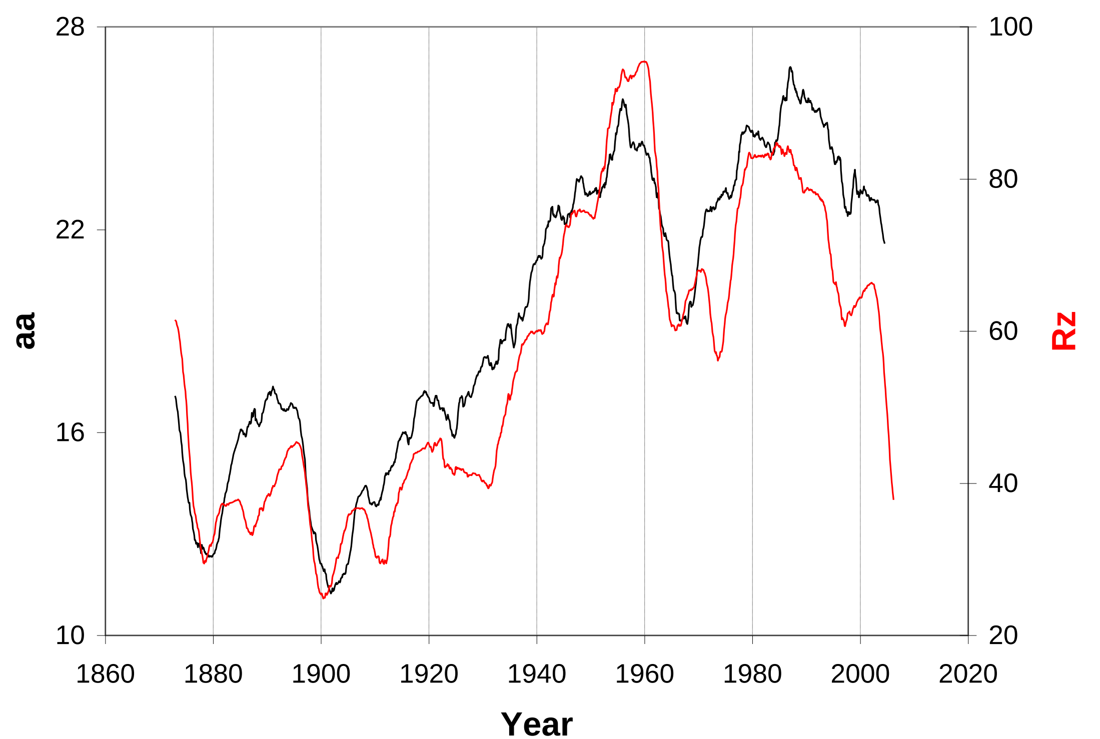
r^2 (foF2, Rz) = 0.963 ⇒ 96% of foF2 variance explained by Rz
r^2 (foF2, F10.7) = 0.969 ⇒ 97% of foF2 variance explained by F10.7

Solar influence on trends in the ionosphere:

1. Inappropriate selection of data, filtering process, proxy used, ...
("non-real influence")

2. Long-term changes of solar and geomagnetic activity, which do contribute to long-term trends

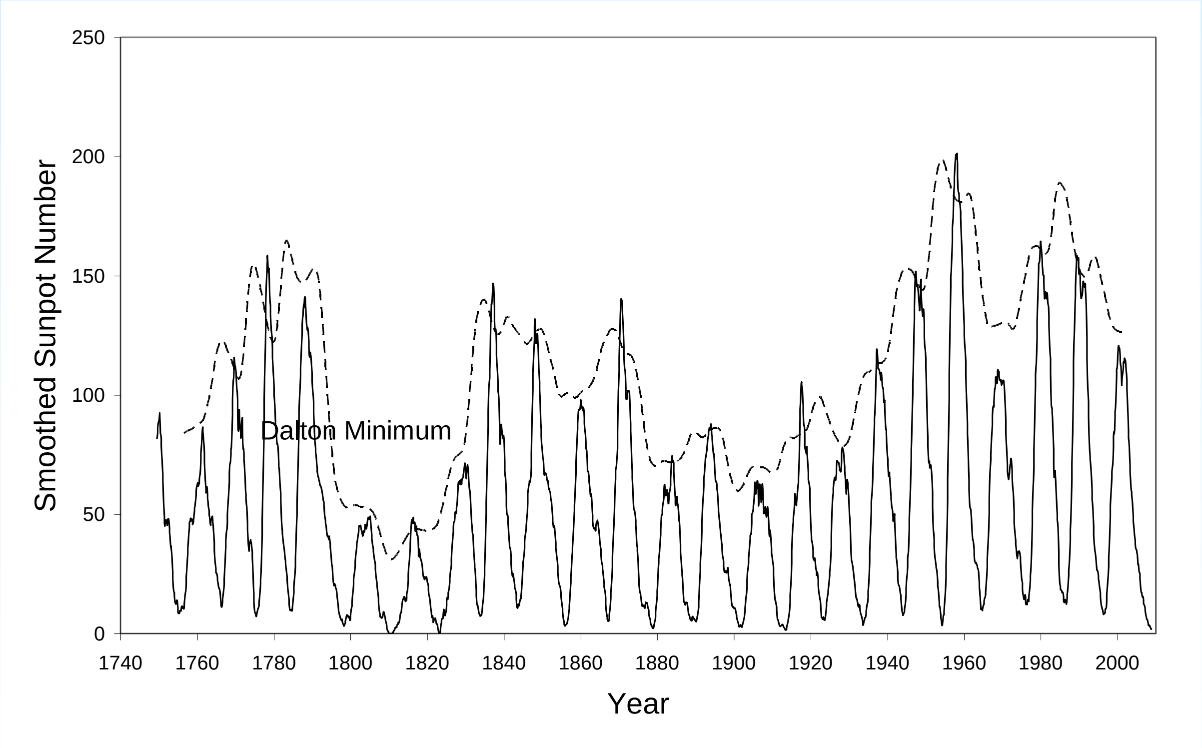
That is, may affect trend determination or cause it.



Note:
Rz is a good proxy for long-term changes, but not the physical quantity that affects ionosphere

Long-term change → variation at time scales greater than 10 years

Solar activity "periodicities"



27-day rotational period

semiannual variation

11-year or Schwabe cycle

22-year Hale magnetic polarity cycle

Gleissberg cycle (~80-90 years)

de Vries or Suess cycle
(~200-210 years)

...

Long-term changes in solar output not shown by traditional indices: Rz, F10.7, ...

SCL ??

Length of the Solar Cycle: An indicator of Solar Activity Closely Associated with Climate, E. Friis-Christensen and K. Lassen, Science 254, 698-700, 1991.

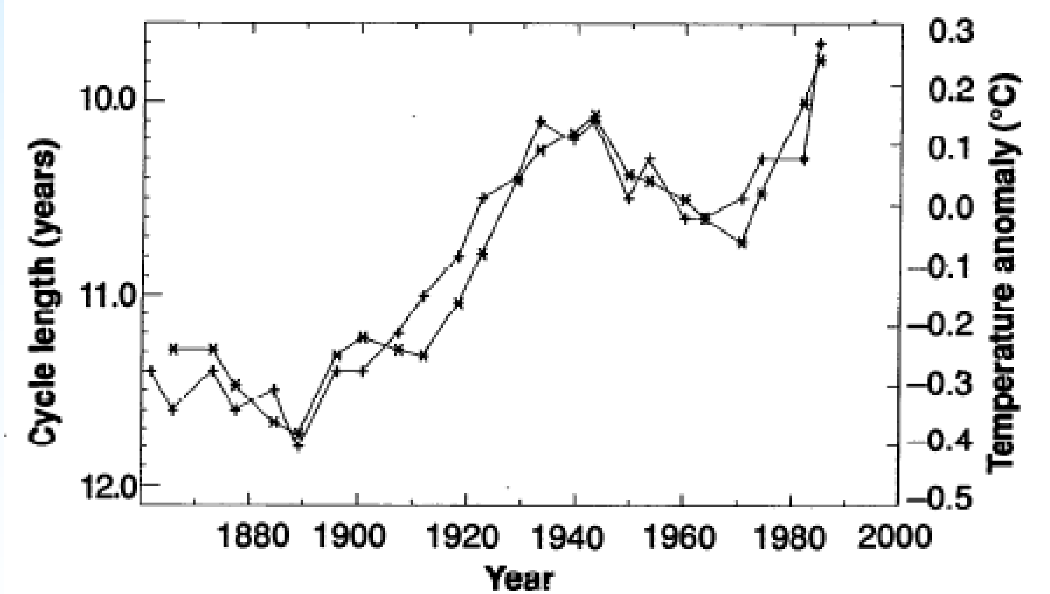


Fig. 2. Variation of the sunspot cycle length (left-hand scale) determined as the difference between the actual smoothed sunspot extremum and the previous one. The cycle length is plotted at the central time of the actual cycle (+). The unsmoothed last values of the time series have been indicated with a different symbol (*) which represents, as in Fig. 1, the Northern Hemisphere temperature anomalies.

Short cycles ⟶ higher activity

Long cycles ⟶ lower activity

Solar influence on trends in the ionosphere:

1. Inappropriate selection of data, filtering process, proxy used, ...
("non-real influence")

An important point in the ionospheric trend analyses is the elimination of the solar and geomagnetic activity-induced parts.

Trend estimation:

Solar activity filtering:

$$foF2A = foF2_{exp} - foF2_{mod}$$

$foF2_{exp}$: experimental foF2 value
$foF2_{mod}$: modeled foF2 value = a Rz + b

$$\mathbf{foF2A = foF2_{exp} - (a\ Rz + b)}$$

Residuals

Linear trend, α, estimated using least squares

$$\mathbf{foF2A = \alpha\ t + \beta}$$

Or you can use: $\mathbf{foF2A = a\ Rz + \alpha\ t + c}$

Solar influence on trends in the ionosphere:
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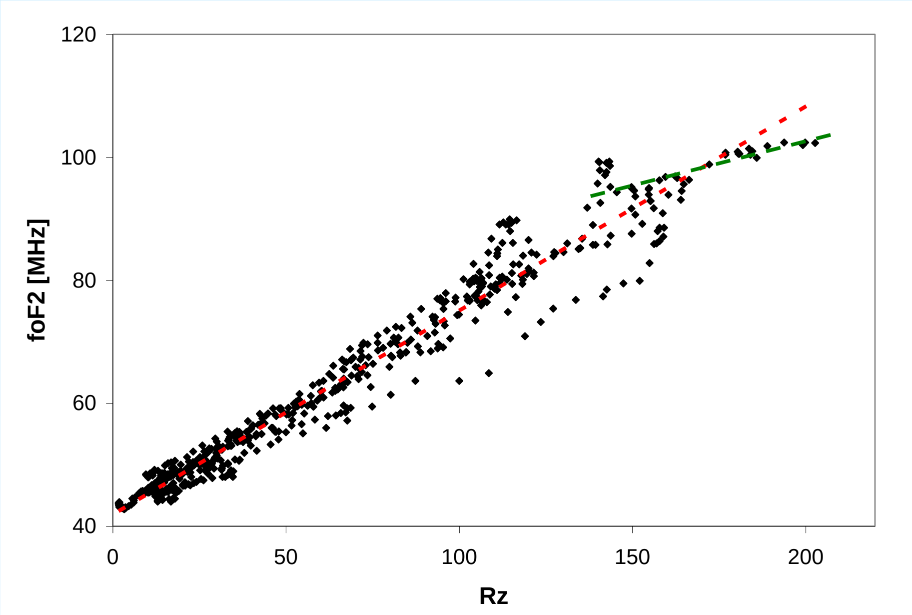
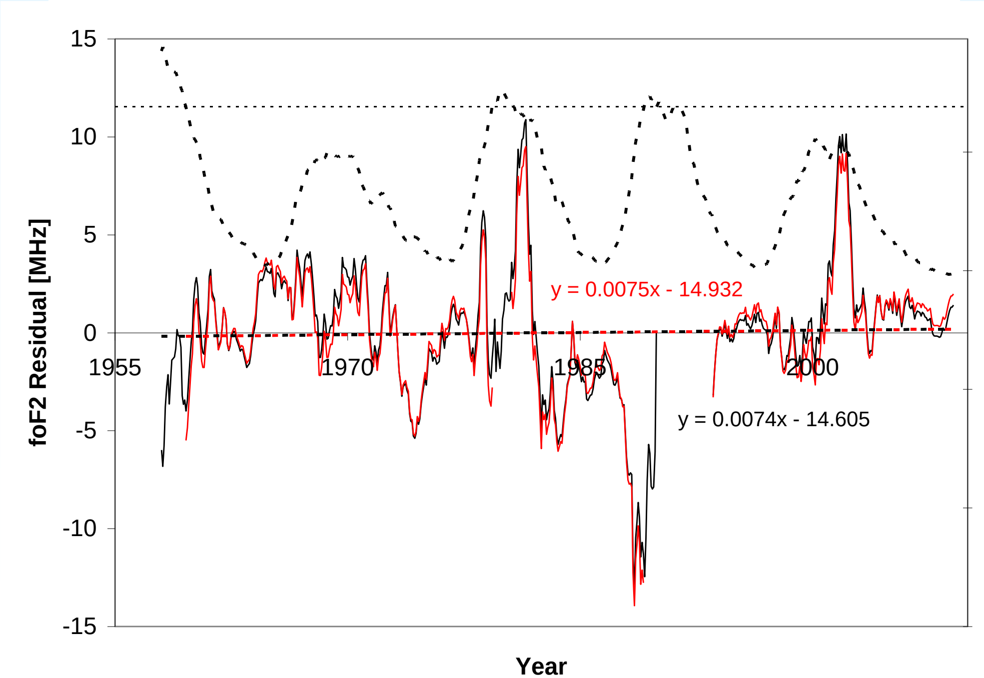
("non-real influence")

Saturation effect

Sodankyla: 67.3°N, 26.3°E

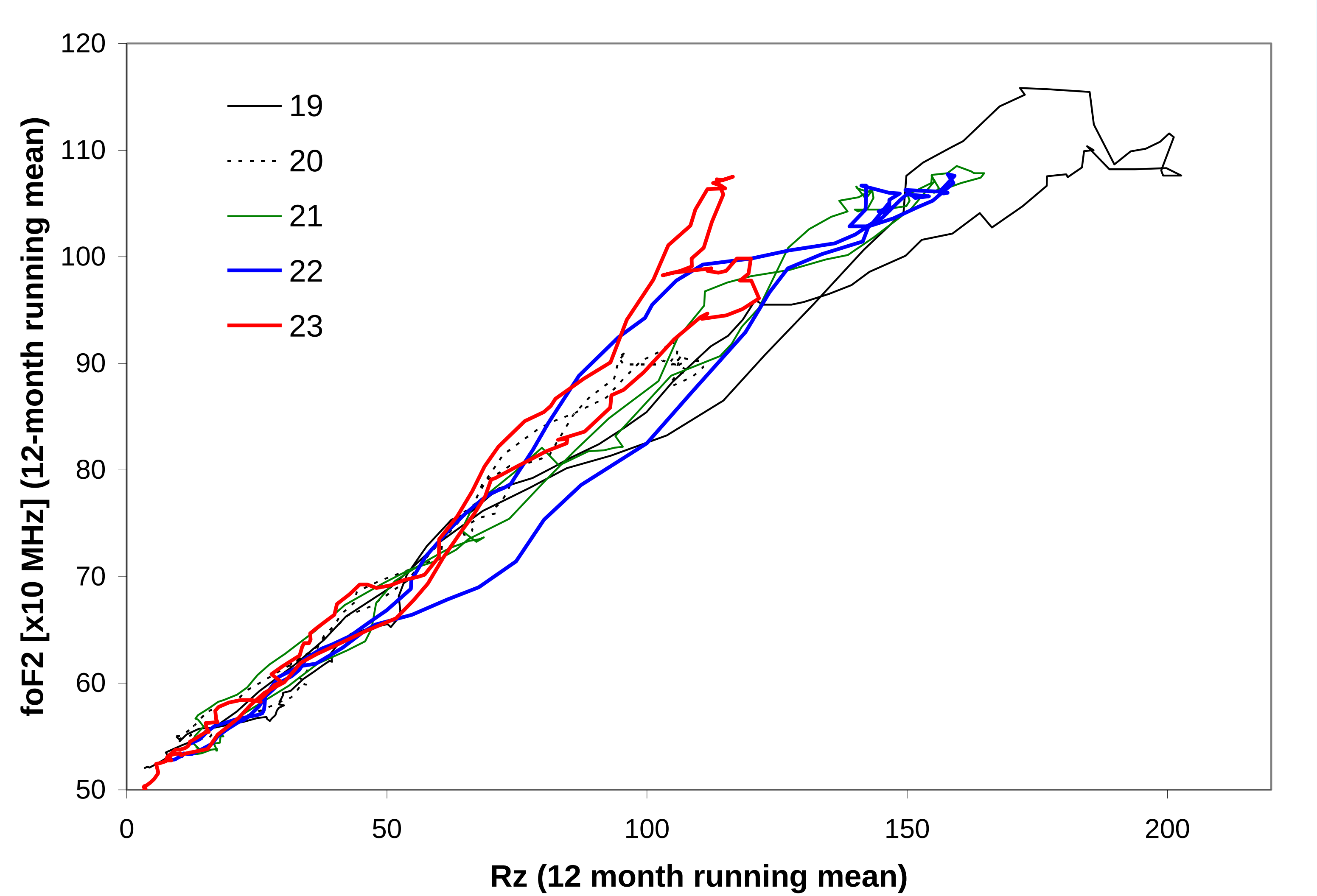




Solar influence on trends in the ionosphere:
1. Inappropriate selection of data, filtering process, proxy used, ...
("non-real influence")

Hysteresis effect

Slough: 51.5°N, 359.4°E



Solar influence on trends in the ionosphere:

1. Inappropriate selection of data, filtering process, proxy used, ...
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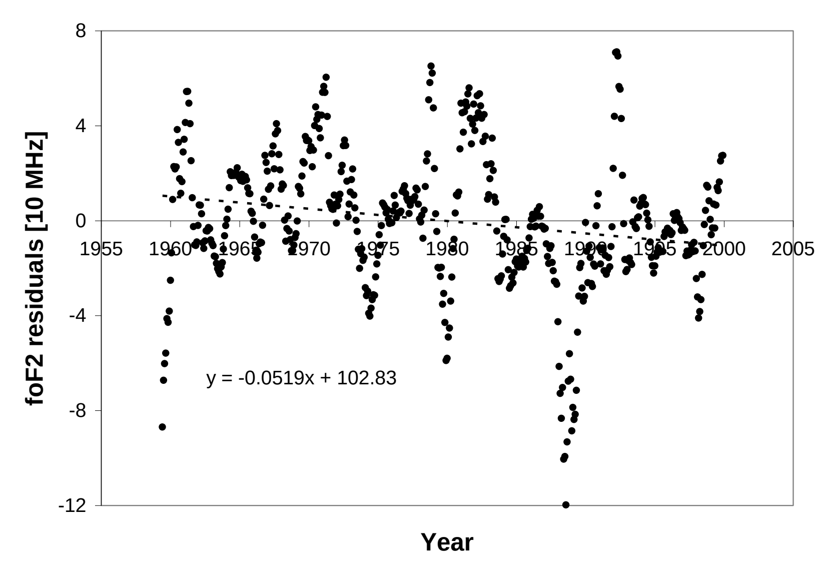
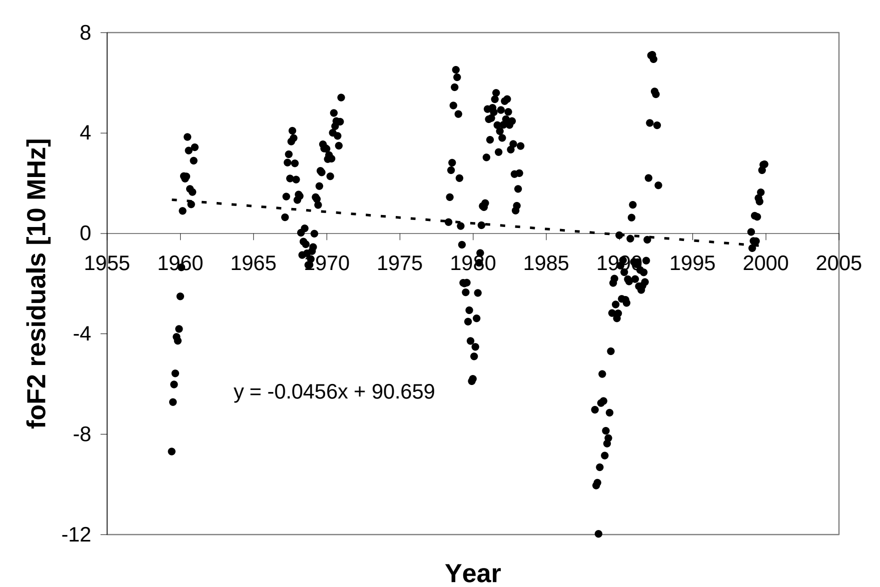
Non-linearity:

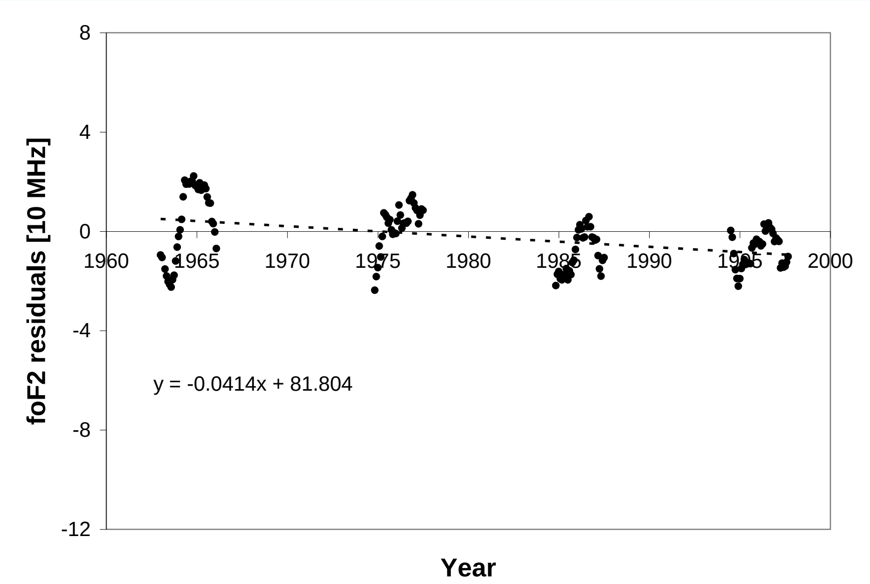
Different trends if we consider only minimum or only maximum

Juliusruh: 54.6°N, 13.4°E

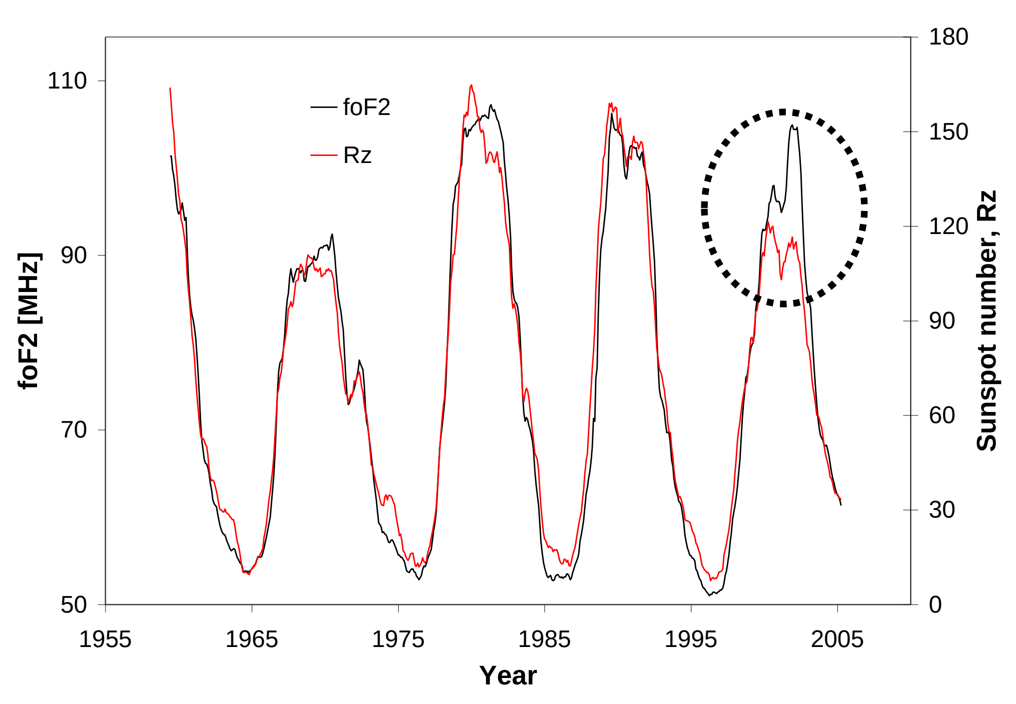


For Cawses II Working Group, Project 2: "The enhancement of the anthropogenic effect on the ionosphere/thermosphere during a quiet sun period"

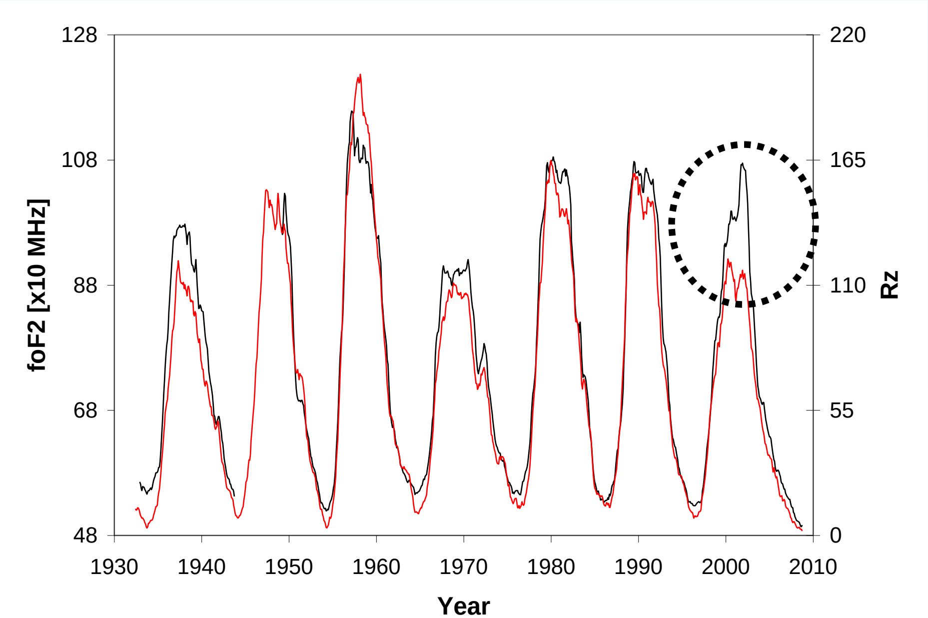




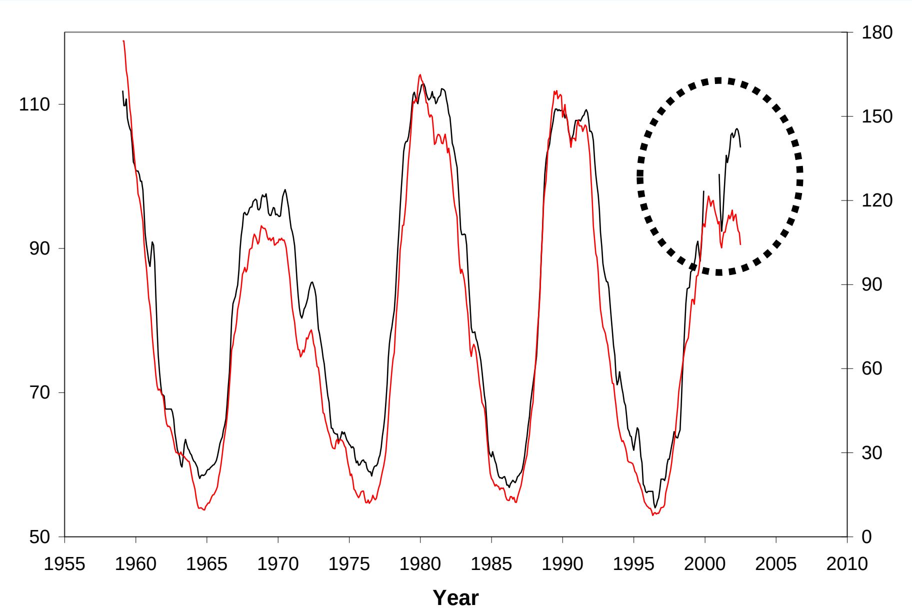
Juliusruh: 54.6°N, 13.4°E



Slough: 51.5°N, 359.4°E



Boulder: 40°N, 254.7°E

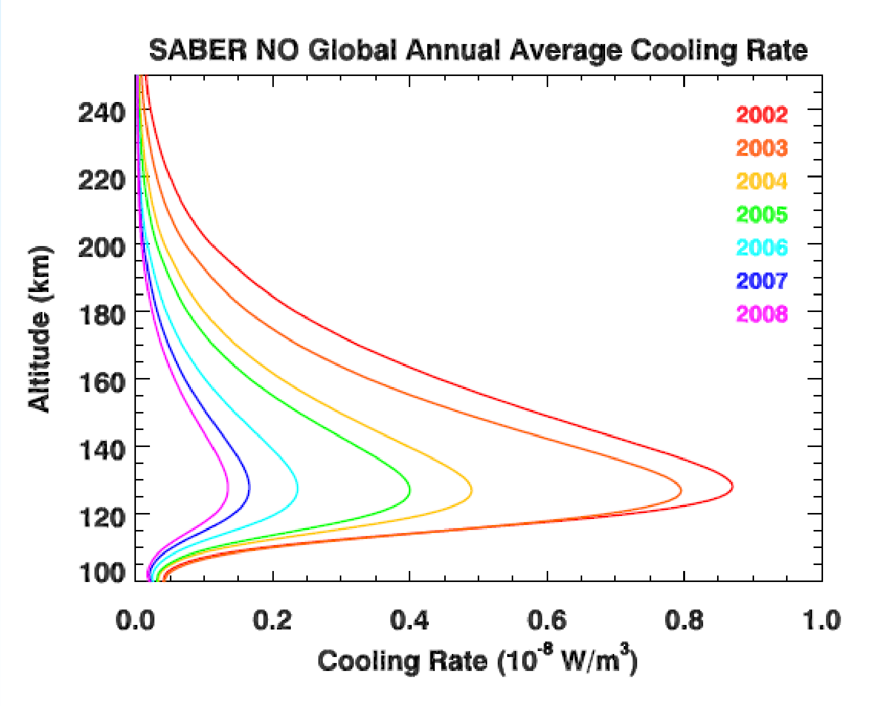


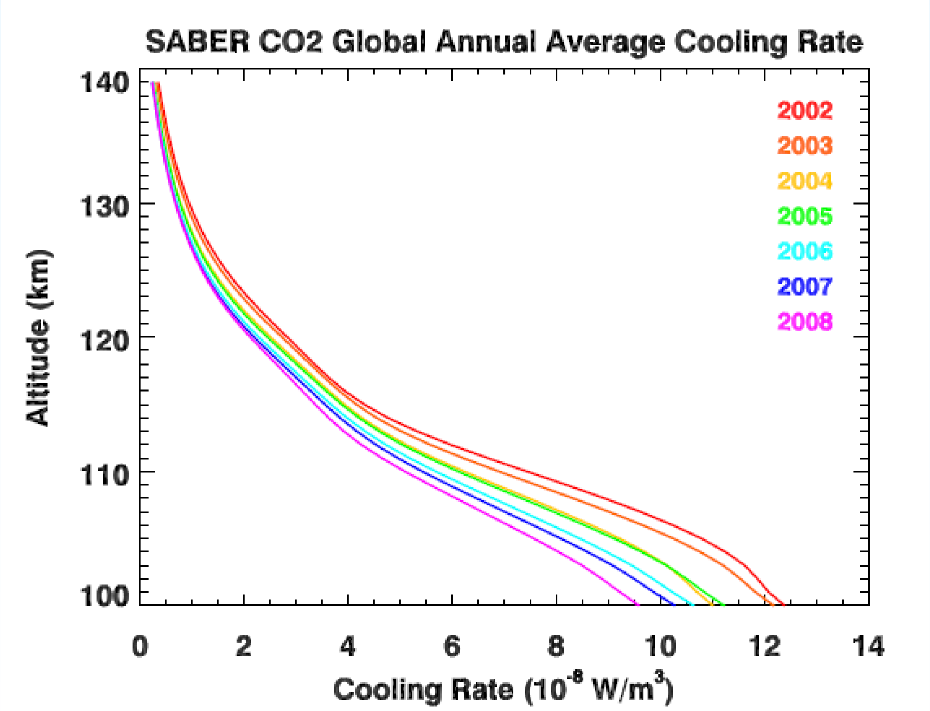
Emmert et al., 2008 - Mlynczak et al. 2010

Thermospheric density trend is different during maximum and minimum solar activity levels

Role of CO_2 radiative cooling compared to NO radiative cooling

- Decrease in radiative cooling by NO and CO_2 in the thermosphere over the last seven years.
- This decrease is consistent with a decrease in the temperature of the thermosphere which affects both NO and CO_2, although the temperature sensitivity of the NO emission is substantially larger than for CO_2.





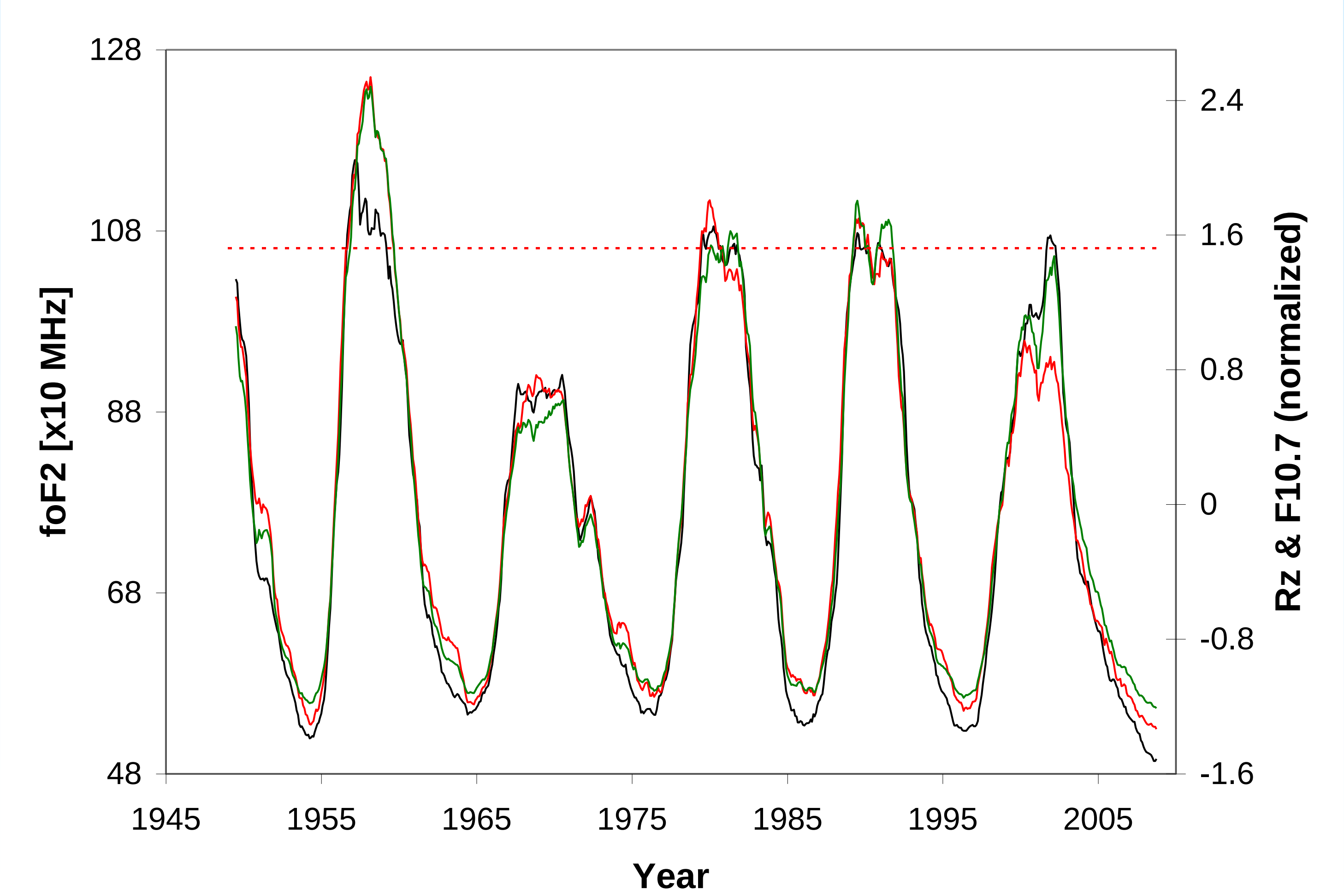
From Mlynczak et al., 2010 & Mlynczak presentation at Trend Workshop 2012

Solar influence on trends in the ionosphere:

1. Inappropriate selection of data, filtering process, proxy used, ...
("non-real influence")

Rz, F10.7, or ...?

Slough: 51.5°N, 359.4°E



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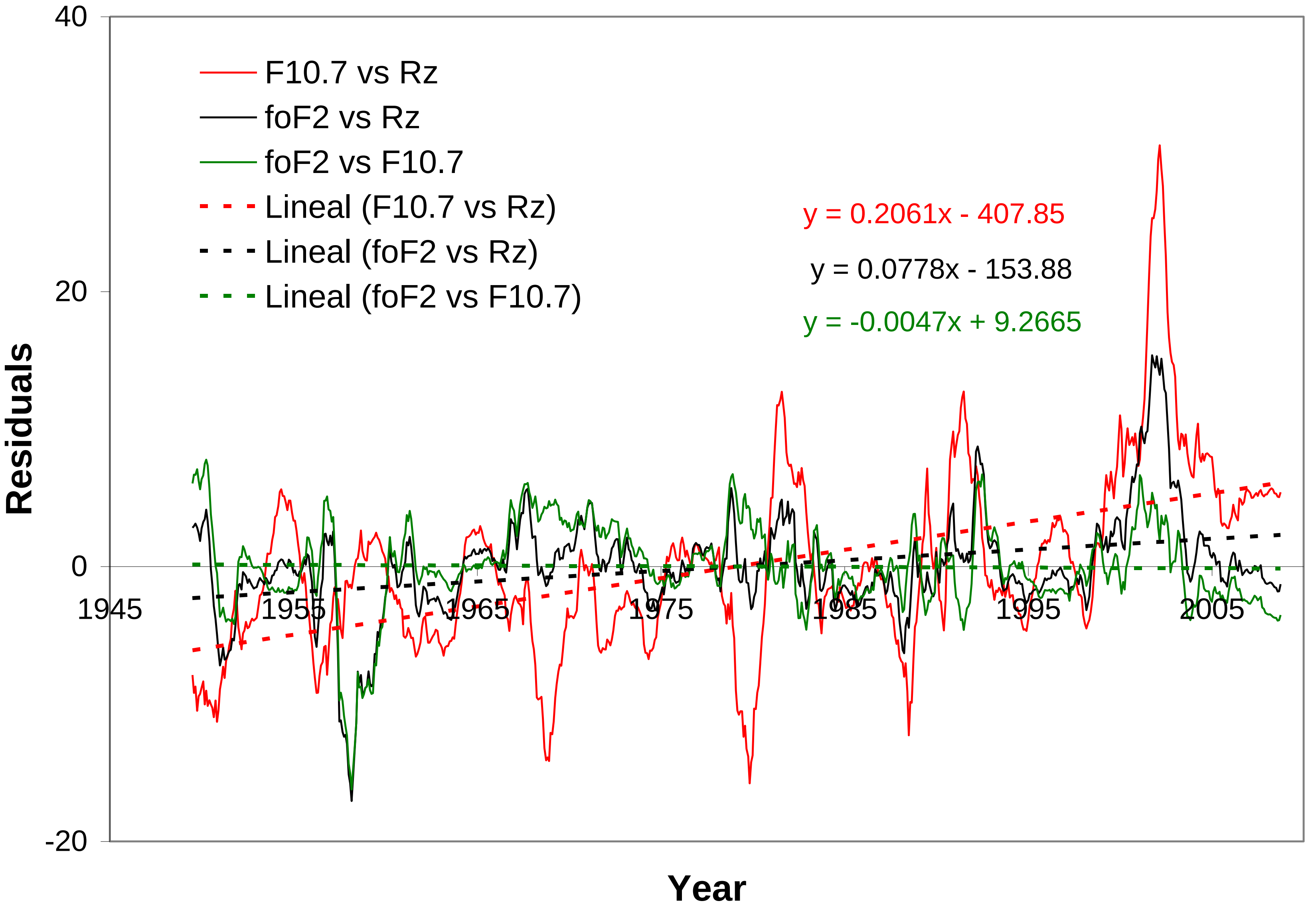
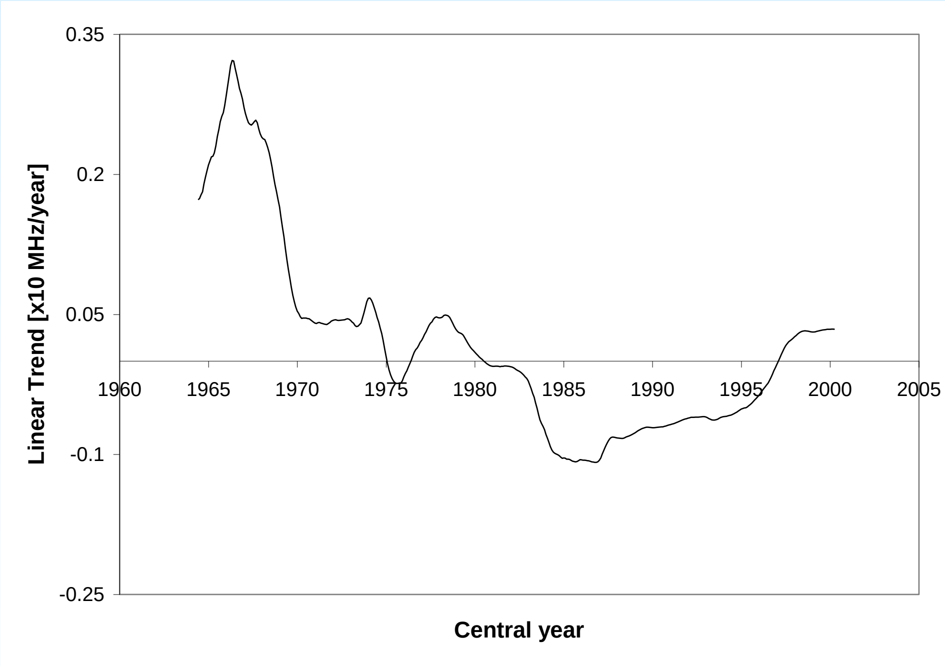


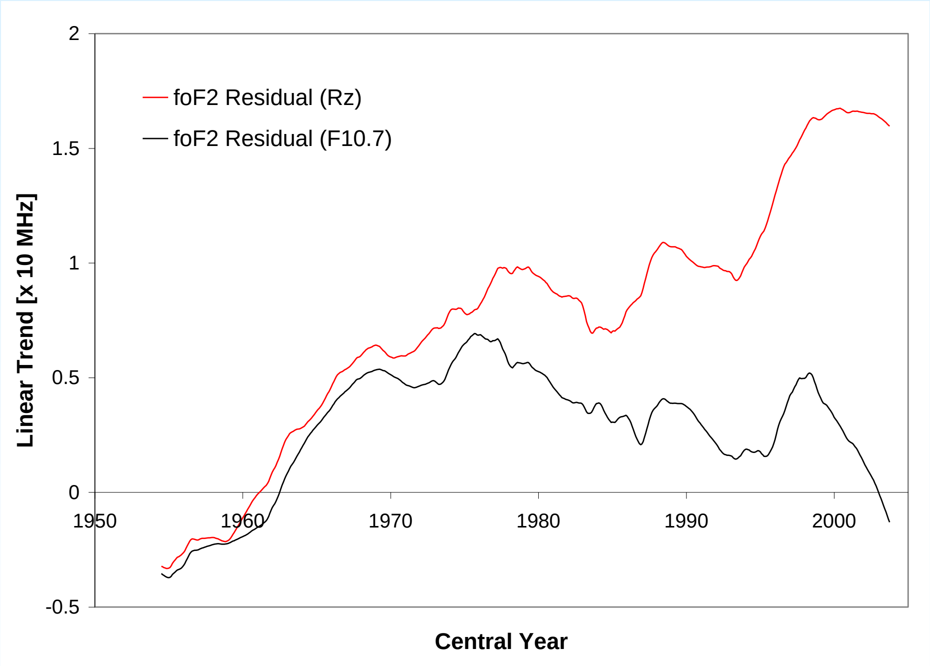
Solar influence on trends in the ionosphere:
1. Inappropriate selection of data, filtering process, proxy used, ...
("non-real influence")

Period analyzed?

Juliusruh: 54.6°N, 13.4°E

Slough: 51.5°N, 359.4°E





Solar influence on trends in the ionosphere:

2. Long-term changes of solar and geomagnetic activity, which do contribute to long-term trends

Solar activity "periodicities"

Gleissberg cycle (~80-90 years)

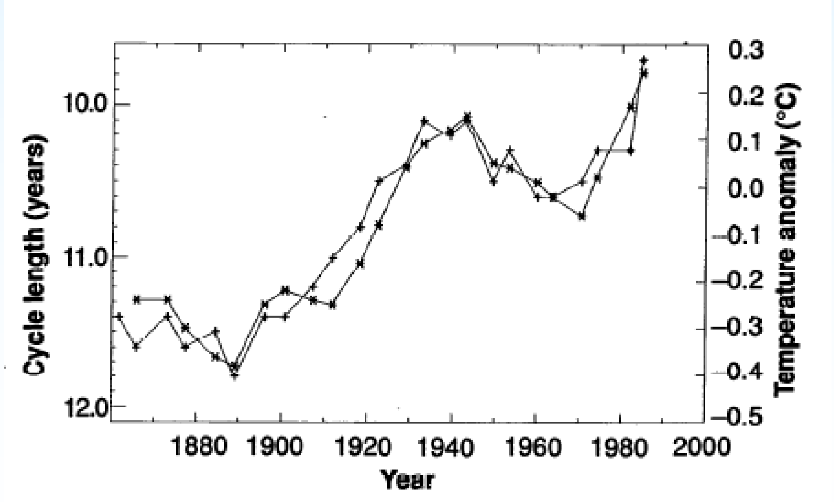
de Vries or Suess cycle
(~200-210 years)

...

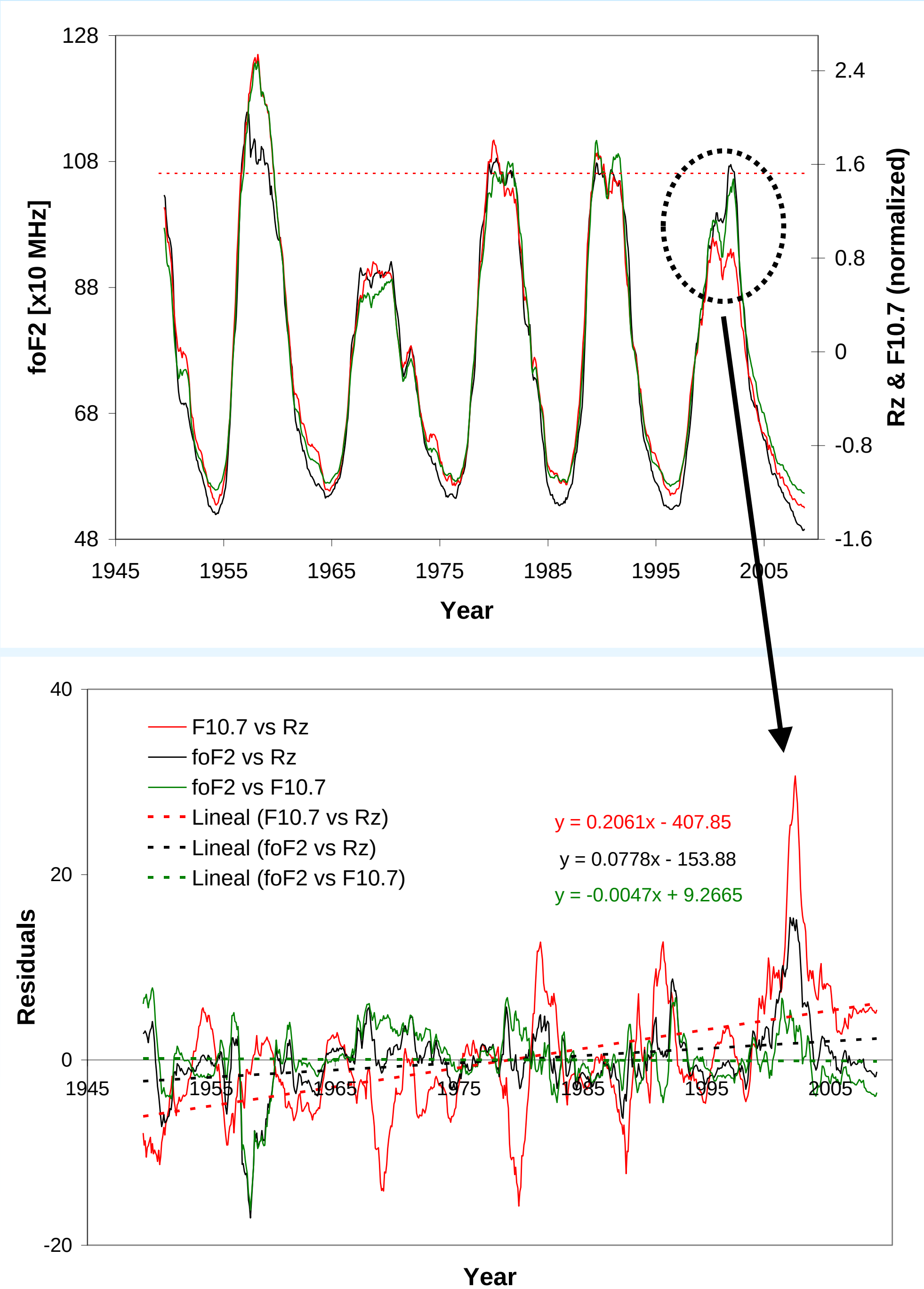
Length of ionospheric parameter time series do not allow resolution

Long-term changes not shown by traditional indices: Rz, F10.7, ...

SCL ??



Livingston et al. 2012 , Decreasing Sunspot Magnetic Fields Explain Unique 10.7 cm Radio Flux, The Astrophysical Journal Letters, 757.



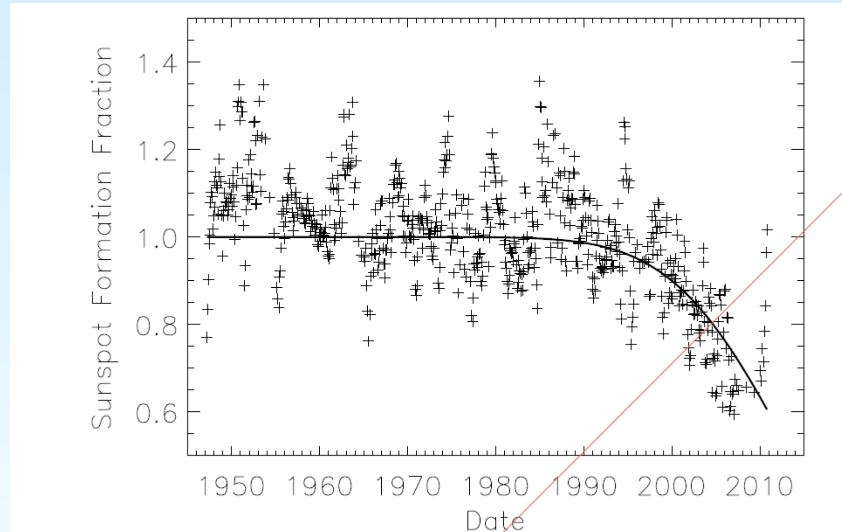


Fig. 4.— The sunspot formation fraction is defined as the number of sunspots seen on the solar surface divided by the number of sunspots predicted by the solar radio emission at 10.7 cm. The value is 1.0±0.11 from 1947 through about 1995, and then it shows a statistically significant decline. It is least-squares fit with an erf(x) function, and it independently confirms the rate of change of the sunspot magnetic field strengths and the 1500 Gauss threshold. Extrapolating this function into the future would predict about 50% fewer spots in Cycle 24 than seen in Cycle 23, and almost no spots in Cycle 25.

Livingston and Penn, EOS, 2009

"... [*Penn and Livingston,Astrophys. J.* 2006], and the observations showed that the magnetic field strength in sunspots were decreasing with time, independent of the sunspot cycle. A simple linear extrapolation of those data suggested that sunspots might completely vanish by 2015."

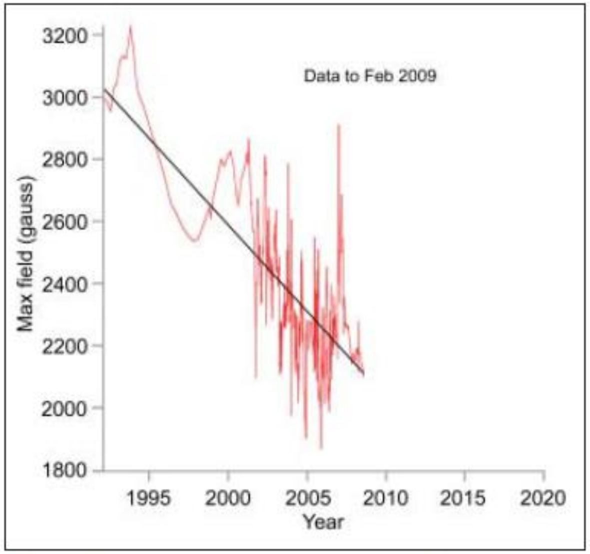


Fig. 3. The maximum sunspot field strength is plotted versus time, during the period from 1992 to February 2009; a 12-point running mean is shown, and a linear fit to the data is plotted. Apart from a few measurements, the linear trend has been seen to continue throughout this solar minimum.

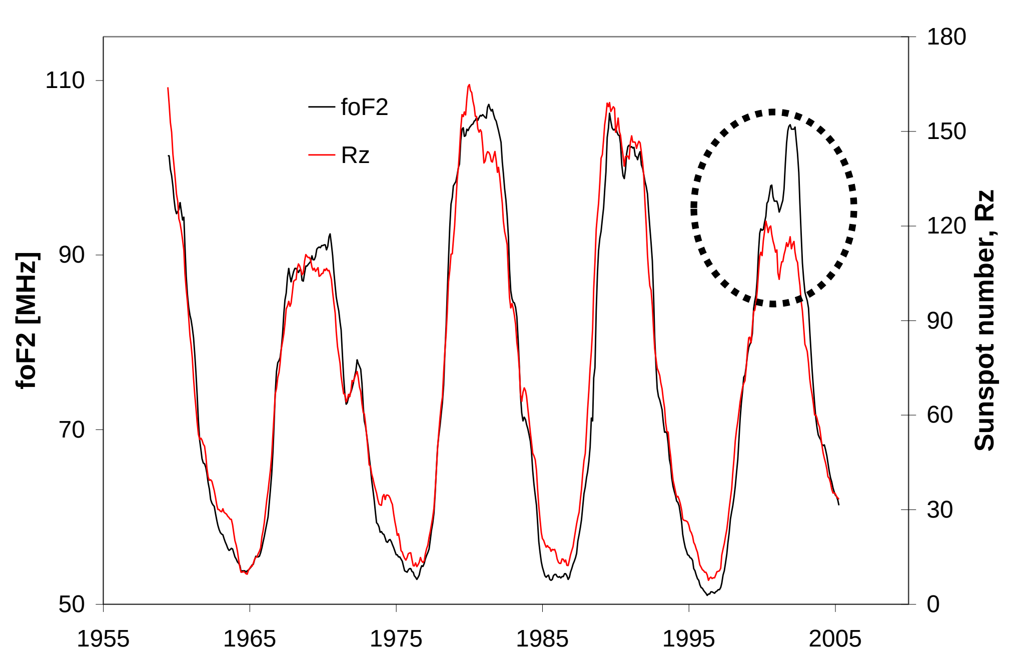
Feynman and Ruzmaikin, Solar. Phys. 2011, "The Sun's Strange Behavior: Maunder Minimum or Gleissberg Cycle?"

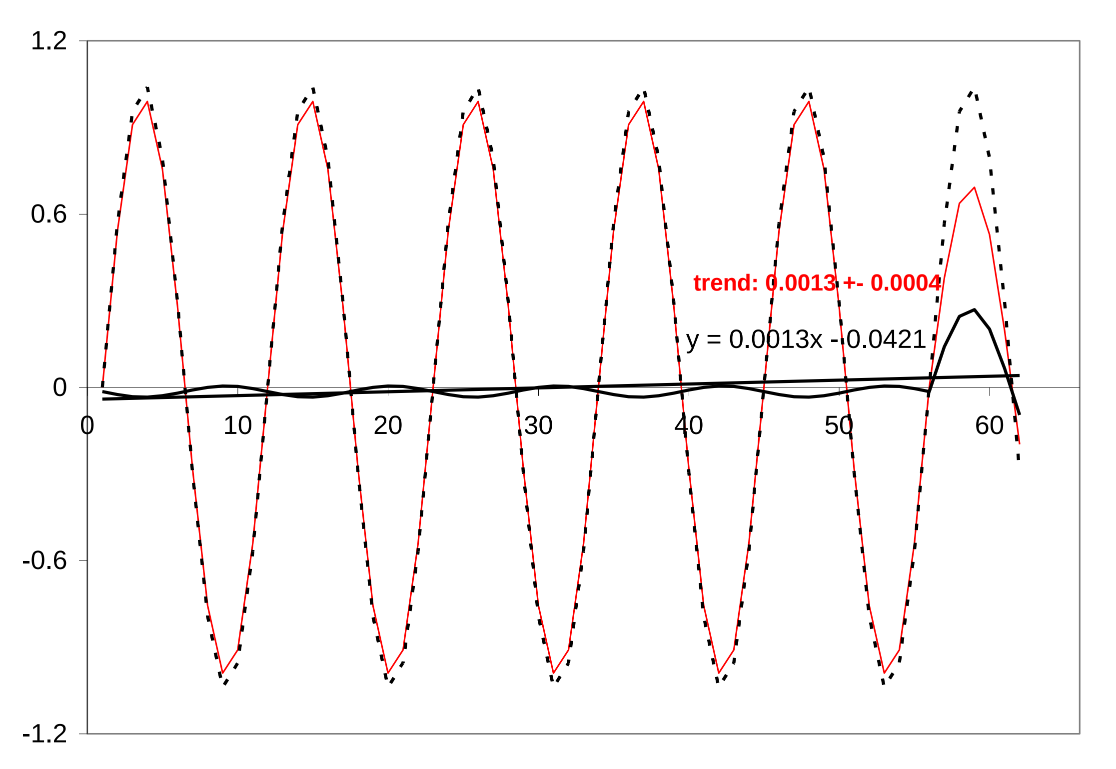
... a minimum of the Centennial Gleissberg Cycle ...

Nagovitsyn, Pevtsov and Livingston, The Astrophysical Journal Letters, 2012

"... we suggest that a gradual decrease in average field strength over the last decade can be explained by a decrease in the fraction of large sunspots with stronger magnetic fields and a corresponding increase in the fraction of small spots with weaker fields ..."

Juliusruh: 54.6°N, 13.4°E





Lean, Emmert, Picone and Meier, JGR 116, 2011.

+0.6 TEC unit/decade in global TEC 1995-2010

These trends are sufficiently large to have been readily detected by ground-based ionosondes but no such trends have been reported. The inference from the TEC data that solar EUV irradiance levels were not 15% lower in 2008 than 1996 consequently invalidates the supposition that the thermospheric density anomaly in 2008 is ascribable solely to this (presumed) irradiance decrease [*Solomon et al.*, 2010].

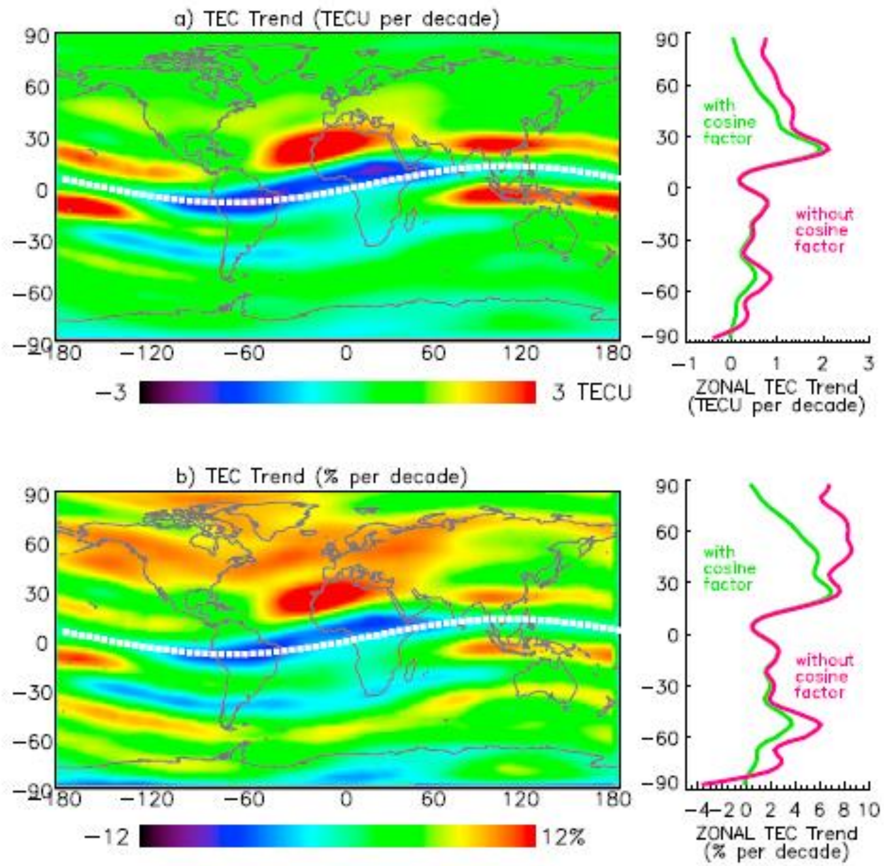


Figure 7. (a) The geographical distribution of 1998–2010 TEC trends obtained using the 3C model of EUV irradiance variability as absolute values in TEC units. The trend values have been normalized so that the global mean trend is +0.6 TECU per decade (the average of the 1995–2010 global trends using the 2C and 3C models). (b) Percentage changes relative to the average ionosphere in Figure 1 (bottom). Also shown are the respective zonal means determined with and without cosine weighting of latitude.

Mielich and Bremer, Long-term trends in the ionospheric F2 region with different solar activity indices, Ann. Geophys., 31, 291–303, 2013

Three main results:
1) F10.7 is a better index for the description of the solar activity than the relative solar sunspot number R as well as the solar EUV proxy E10.7

2) The global mean *fo*F2 and *hm*F2 trends derived for the interval between 1948 and 2006 are in good agreement with model calculations of an increasing atmospheric greenhouse effect (Rishbeth and Roble, 1992).

3) During the years 2007 until 2009, the *hm*F2 values and to a smaller amount the *fo*F2 values strongly decrease. The reason for this effect is a reduction of the thermospheric density and ionization due to a markedly reduced solar EUV irradiation and extremely small geomagnetic activity during the solar cycle 23/24 minimum.

Damboldt and Suessmann, Statistic of long-term ionospheric measurements, Adv. Radio Sci., 10, 255–258, 2012

The solar cycle influence eliminated with CCIR ionospheric prediction model.

Trend reversal in hmF2 in 1963-1964 with negative trend from 1942 to 1963 and positive trend from 1964 to 2005.

This is in contrast to the results reported in most other publications of ionospheric long-term trends.

Discussion and Conclusion

Possible causes for long-term trends in the ionosphere:

1. an increase in CO_2 concentration → Rishbeth (1990) and Rishbeth and Roble (1992): decrease of foF2 between 0.2 and 0.5 MHz for 100% increase in CO_2, for 20% increase in CO_2, decrease of foF2 between 0.001 and 0.003 MHz/year over the Earth

2. long-term changes in geomagnetic activity and F2-layer storm mechanisms

3. long-term changes in the Earth's magnetic field

Trend values according to latitude and LT

4. long-term changes in solar activity → Important now?? Uniform over the Earth??

- **The effect of trend sources (increasing greenhouse gases, Earth's magnetic field secular variation, ...) may not be constant along the solar activity cycle**

- **Filtering procedures normally applied to ionospheric parameters (foF2, hmF2, ...) may not be 100% correct**

- **Index used do not show "all variation" in solar EUV radiation**

Important facts

Why is important to understand and measure the atmosphere response to solar variation?

We live in the Earth and we want to understand and predict the atmosphere behavior which is essential for human life.

And in the present context:

Understanding and interpreting the causes of atmospheric trends requires a fundamental understanding of the atmosphere response to solar variations. This is an essential focus of climate science, which is seeking to determine the extent to which human activities are altering the planetary energy balance through the emission of greenhouse gases and pollutants.

All possible causes (CO_2 , geomagnetic activity, solar activity, Earth's magnetic field, other?) and their interaction should be considered.

Thank you very much for your attention

Lastovicka, JASTP 67, 2005
"On the role of solar and geomagnetic activity in long-term trends in the atmosphere–ionosphere system"

"It is possible to suppress or even avoid the effects of Sun's origin, namely of solar cycle, on trend determination with the use of proper selection of analyzed periods, or with the use of data corrected for solar and geomagnetic activity, or... "

"On the other hand, the solar and geomagnetic activity may be responsible for part of the observed long-term trends due to its secular change during the last century, particularly during its first half."

To this end, the two main conclusions are as follows:

1. The role of solar and geomagnetic activity in the observed long-term trends decreases with decreasing altitude from the F-region ionosphere down to the troposphere, and from the ionized component to the neutral component.

2. In the 20th century the role of solar and geomagnetic activity in the observed long-term trends was decreasing from its beginning (some role even in the troposphere) towards its end (important probably only in the F2 region), and the role of the greenhouse effect was increasing towards the end of the century. This was caused both by a continuous increase of concentration of greenhouse gases in the atmosphere and by much weaker trend in the solar and geomagnetic activity towards the end of the 20th century compared to its first half.