On long-term solar activity impact on ionospheric ionization

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Introduction

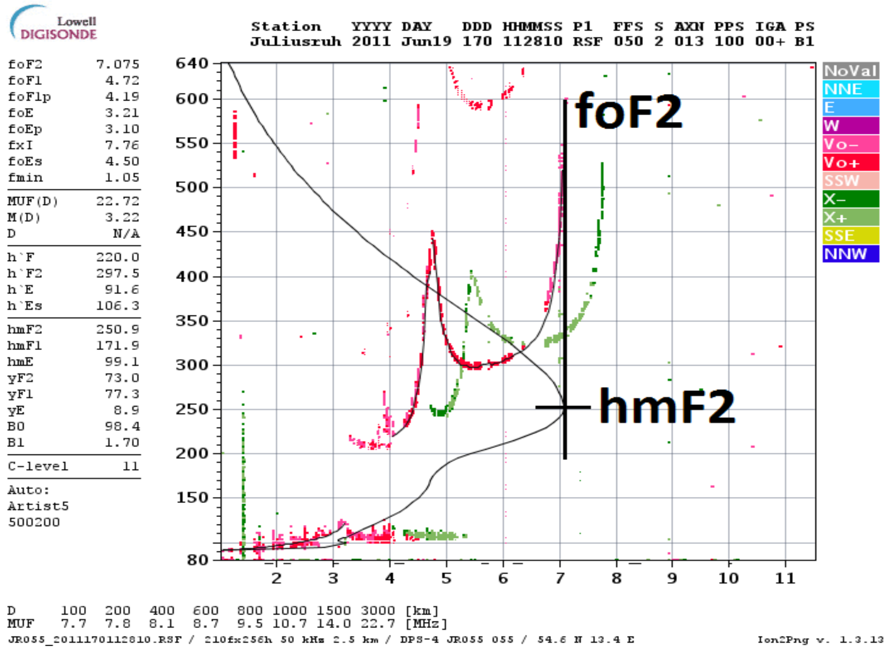
- Structure and dynamics of magnetosphere, ionosphere and thermosphere depend primarily on solar energy input and its variations
- Many other factors have a secondary impact on ionospheric processes in particular on structure and dynamics of the electron density, e.g. trace gases like CO_2, change and variations of the magnetic field, changes of the solar spectrum …
- Detection and interpretation of long-term changes of ionospheric and thermospheric key parameters like electron density and temperature have to address different impact factors adequately.
- One candidate for studying long term trends in the ionosphere is the equivalent slab thickness because it is less dependent from solar activity than NmF2 and TEC
- Since the equivalent slab thickness may be closely related to the thermospheric scale height, there is a potential to estimate the exospheric neutral gas temperature (Jakowski et al., 2017*).

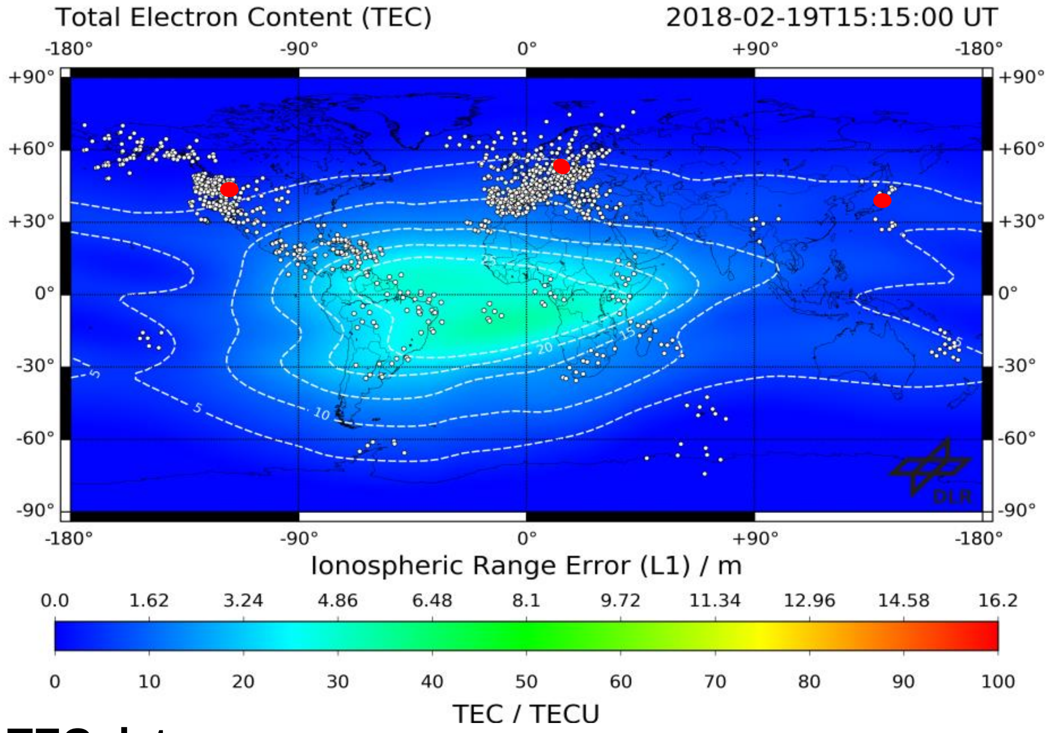
*Jakowski, N., Hoque, M. M. ,Mielich, J., and Hall, C. (2017) Equivalent slab thickness of the ionosphere over Europe as an indicator of long-term temperature changes in the thermosphere, JASTP,. DOI: 10.1016/j.jastp.2017.04.008 ISSN 1364-6826

Data base

Total Electron Content (TEC) derived from ground based GNSS measurements

F2 layer peak electron density NmF2 and height hmF2
derived from vertical sounding data





VS data sources:

i) Ionosonde data from stations Juliusruh, Boulder and Kokubunji

ii) ftp://ftp.ngdc.noaa.gov/ionosonde/data/

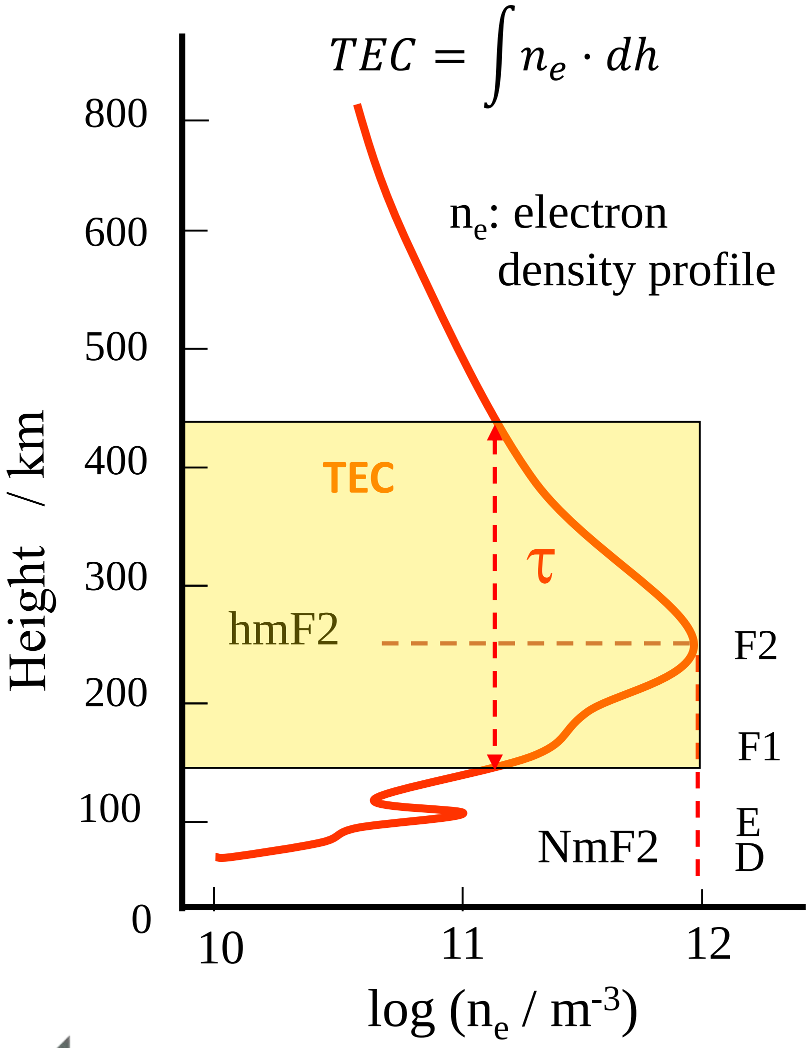
TEC data sources:

i) Post processed TEC maps from DLR/ SWACI

ii) Post processed TEC maps provided by the Center for Orbit Determination in Europe (CODE)

ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex

Equivalent slab thickness of the ionosphere



The equivalent slab thickness τ is an electron density profile shape parameter defined by

$$TEC = \tau \cdot N_m F2$$

According to the Chapman theory the thermospheric scale height is given by

$$H = k \cdot T_n / M \cdot g$$

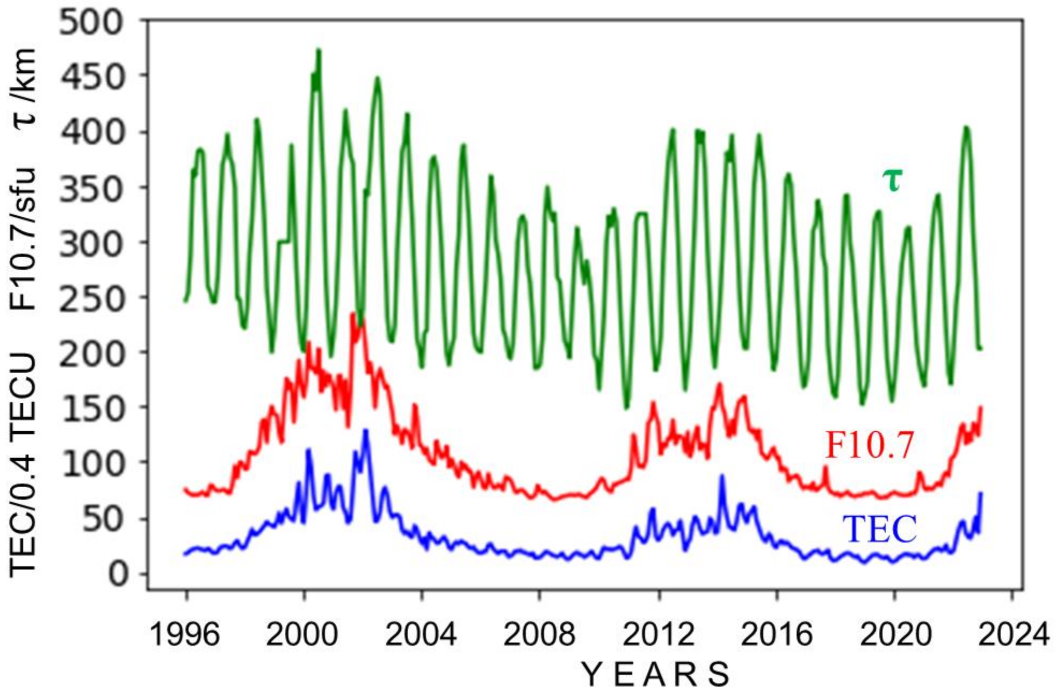
H is related to τ by $TEC \approx 4.13 H \cdot N_m F2 \cdot \sqrt{\cos \chi}$

that means $\tau = \frac{TEC}{N_m F2} \leq 4.13 \; H$

$H \approx 50 \ldots 100$ km ⇨ $\tau \approx 200$ - 410 km

under diffusive equilibrium conditions
(condition best fulfilled around local noon).

Slab thickness τ – a candidate for monitoring thermospheric temperature



Noontime (12-14 LT) values of TEC, F10.7 and the equivalent slab thickness τ over Juliusruh during the period 1996-2022

- Noon time equivalent slab thickness values derived from local foF2 and TEC measurements over Juliusruh behave as expected from Chapman theory

⇨ Chapman theory applicable

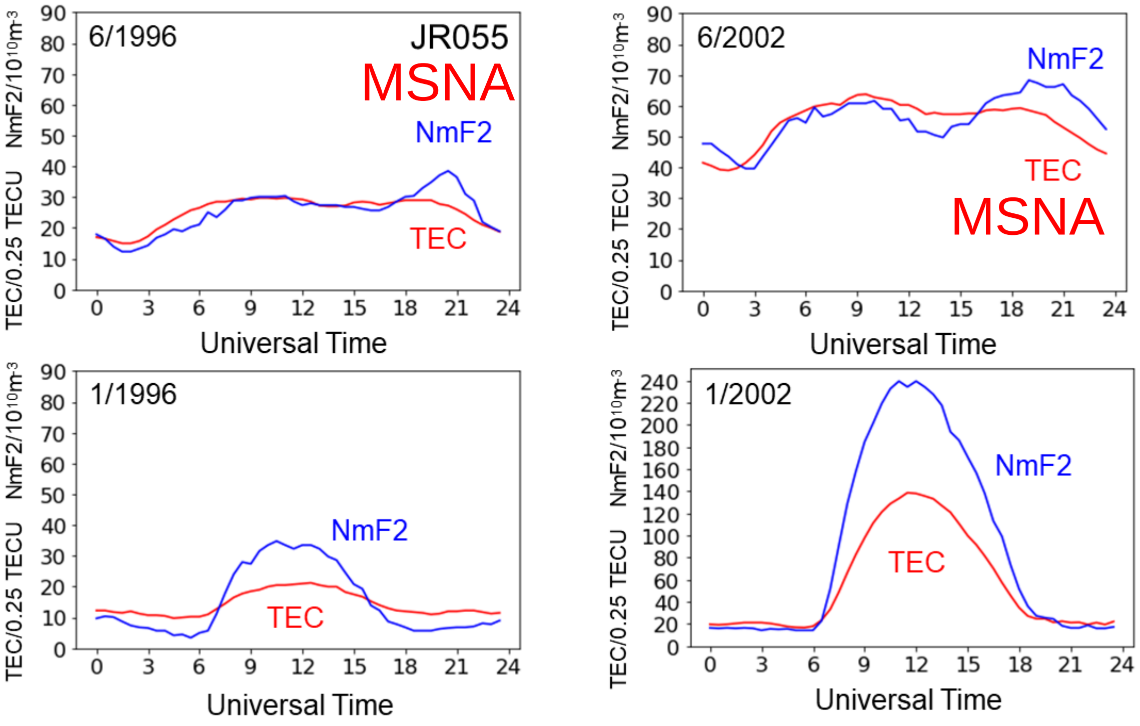
that means:

τ ~ derived neutral gas temperature Tn valid for a height range of 250-400 km height

- Noon time equivalent slab thickness τ is related to solar activity changes as expected but much less sensitive than NmF2 and TEC

- **Noon time equivalent slab thickness** is a candidate for detecting long term cooling effects in the thermosphere - ionosphere system.

Why focusing on noontime equivalent slab thickness?



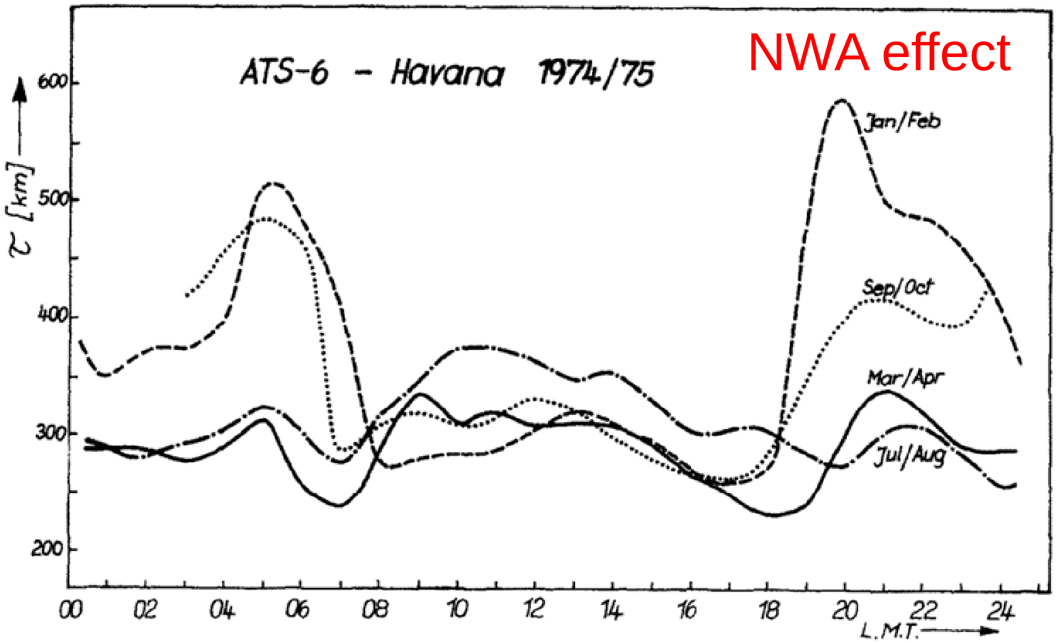


Fig. 2. Diurnal variations of the equivalent slab thickness τ—seasonal dependence.

Mid-latitude Summer Nighttime Anomaly (MSNA)
Thampi, SV, Balan, N, Lin, C, Liu, H, Yamamoto, M. 2011. Mid-latitude Summer Nighttime Anomaly (MSNA)—Observations and model simulations, Ann. Geophys., 29, 157–165, doi:10.5194/angeo-29-157-2011.

Nighttime Winter Anomaly (NWA)
Jakowski, N., Bettac, H.-D., Lazo, B., Lois, L., Seasonal Variations of the Columnar Electron Content of the Ionosphere Observed in Havana from July 1974 to April 1975, J Atmos. Terr. Phys., 43, 7-11, 1981

- Nighttime ionosphere is feeded by plasmaspheric fluxes which maintain the ionospheric ionisation
- Plasmaspheric fluxes may dominate the ionospheric behaviour

⇨ **Nighttime slab thickness values are not suited to study long term effects in direct relation to the solar activity**

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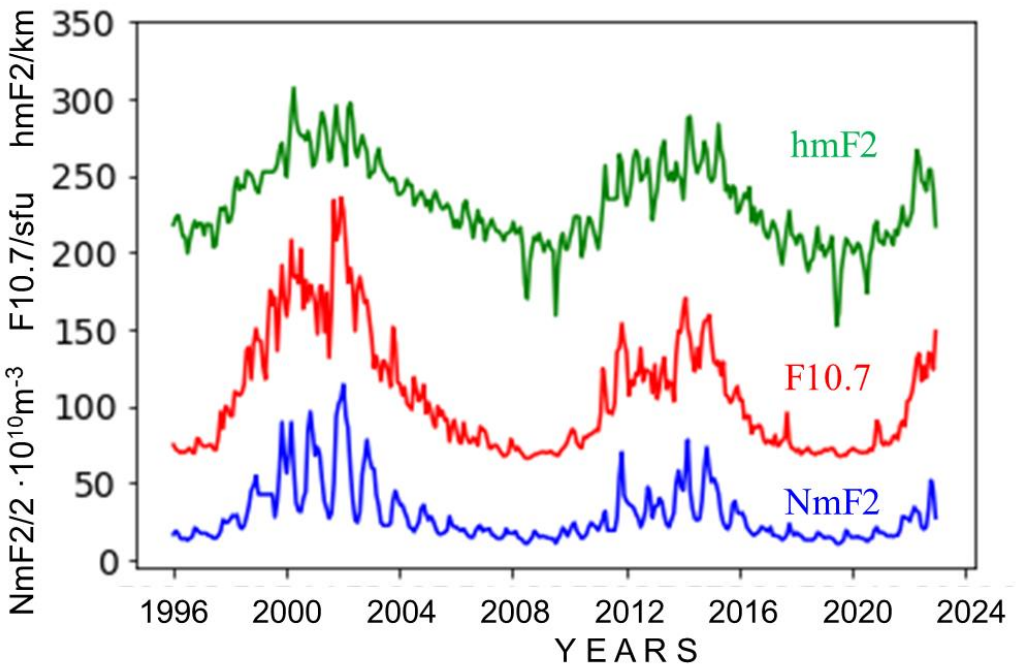
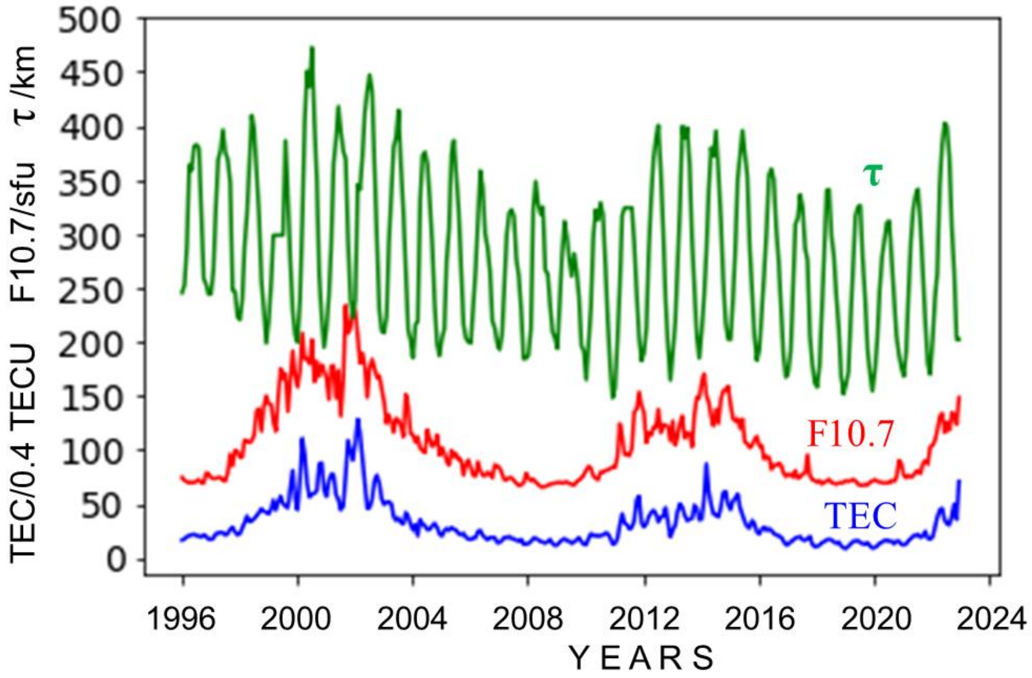
Noontime vertical sounding data and related vertical TEC over Juliusruh





Juliusruh (12:00 – 14:00 LT)

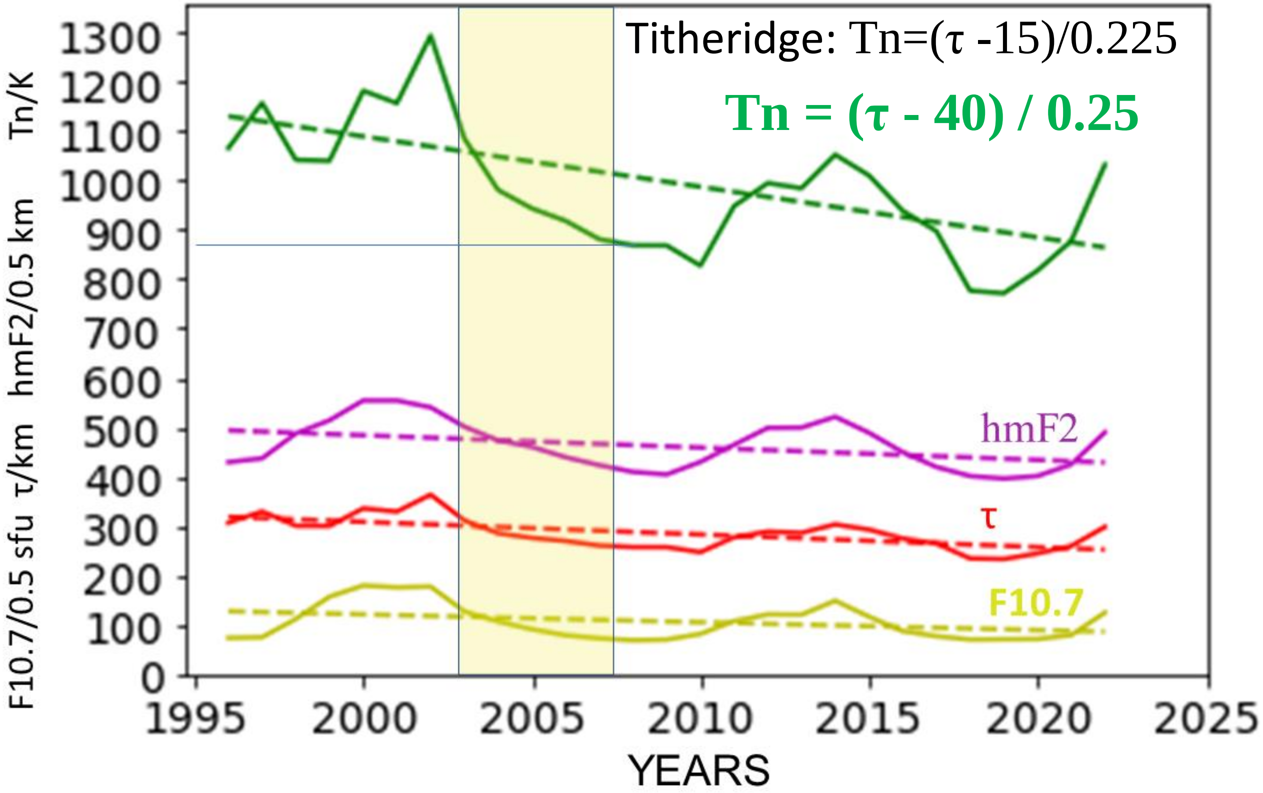
Monthly medians of NmF2, hmF2, TEC and τ are closely related to the solar activity cycles 23-25.

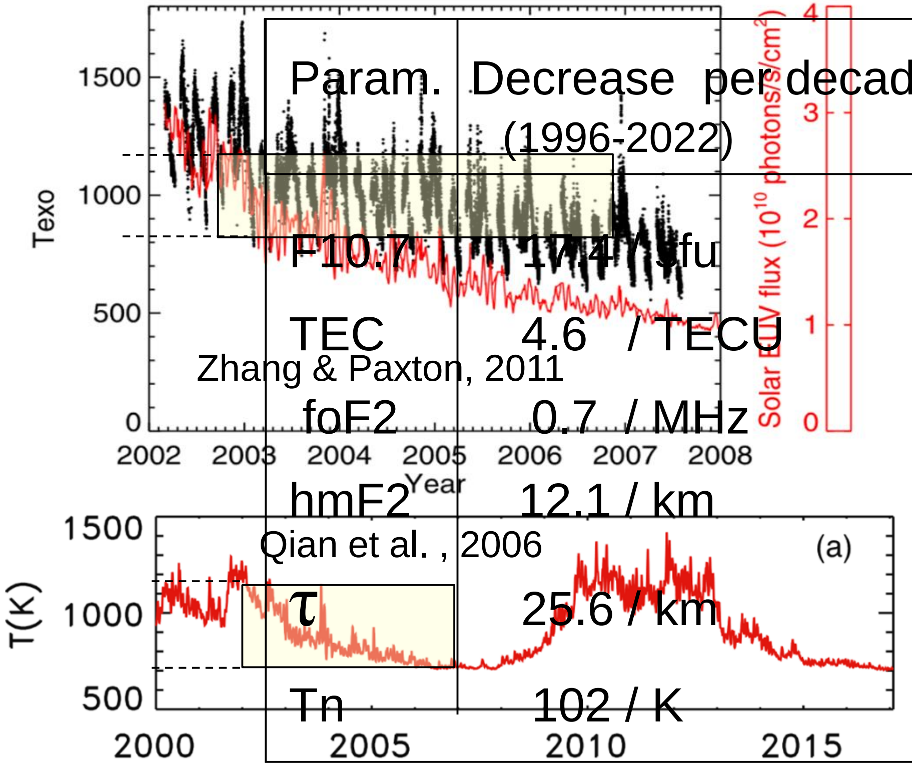
hmF2: no clear seasonal dependence

τ : clear seasonal pattern with minima in winter

Yearly averages of τ cancel out seasonal effects, otherwise separate studies for different seasons are needed.

Equivalent slab thickness and neutral gas temperature over Juliusruh





Param.	Decrease per decade (1996-2022)
F10.7	17.4 / sfu
TEC	4.6 / TECU
foF2	0.7 / MHz
hmF2	12.1 / km
τ	25.6 / km
Tn	102 / K

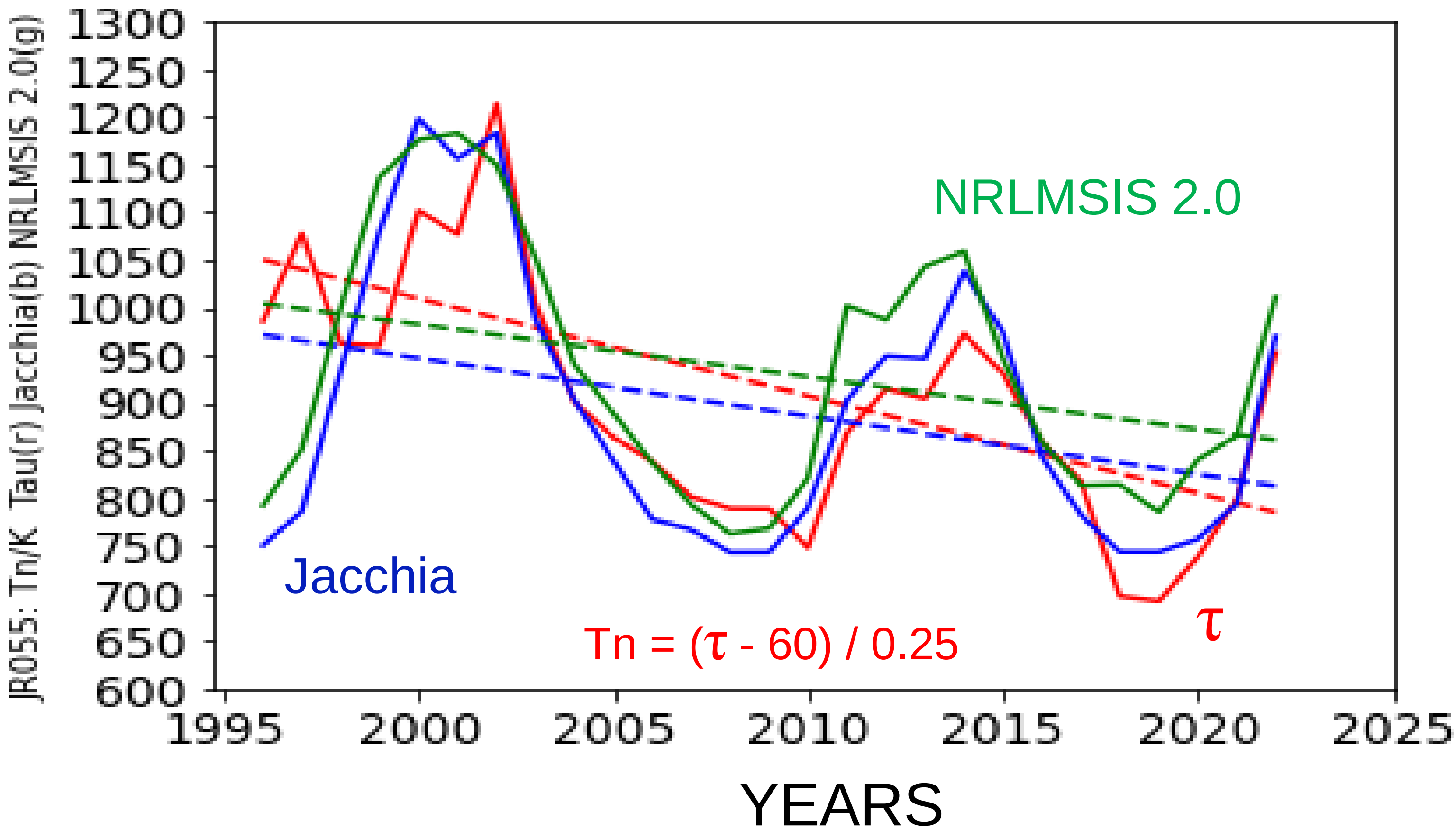
- Tn approach follows an approach made by Titherige in 1972
- Tn derived from τ is able estimating the general behavior of exospheric neutral gas temperature

Titheridge, J.E. (1973) The slab thickness of the mid-latitude ionosphere. Planet. Space Sci. 21 (10), 1775–1793.

Zhang Y.& Paxton, L.J. (2011) J. geophys.Res.,116, A00H02

Qian, L., Roble, R.G., Solomon, S.C.,Kane, T.J. (2006) Geophys. Res. Lett., 33,L23705

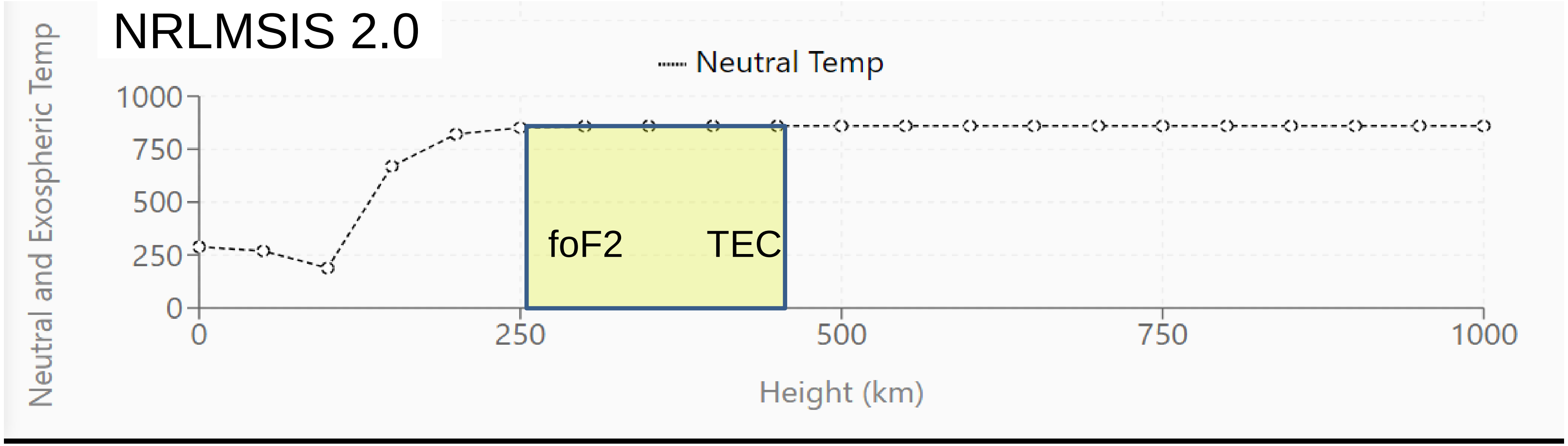
Comparison of τ derived exospheric temperature with neutral gas models



Jacchia, L.G., Smith's Astrophys. Obs., Spec. Rep. 332, 1971

NRLMSIS 2.0 : Community Coordinated Modeling Center (CCMC) at NASA

Use of the NRLMSIS 2.0 thermospheric model to estimate Tn



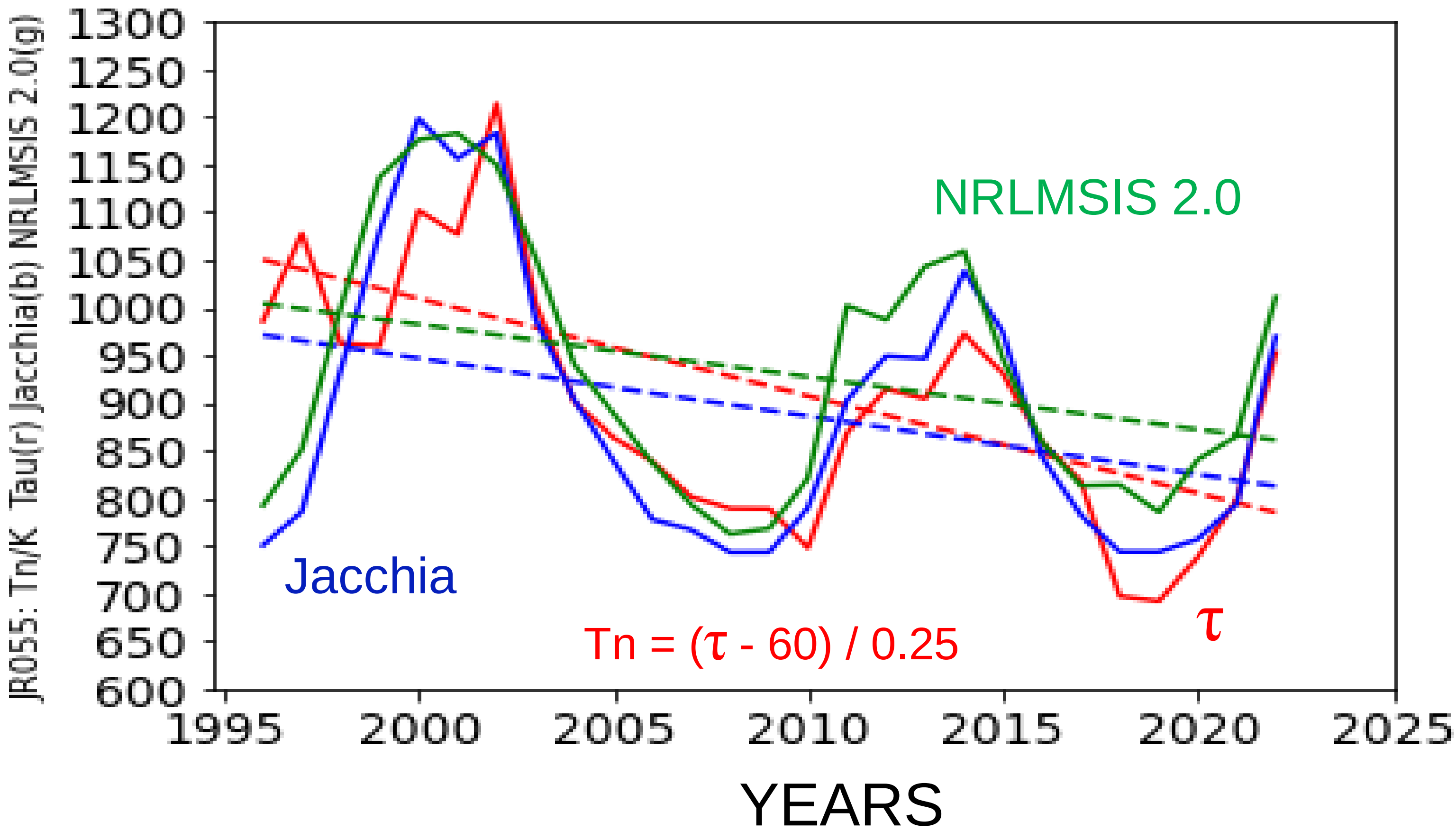
[NRLMSIS | Instant Run | CCMC (nasa.gov)](https://ccmc.gsfc.nasa.gov)

Community Coordinated Modeling Center (CCMC) at NASA

https://ccmc.gsfc.nasa.gov

- Instant runs have been performed for the location of Juliusruh for June and December at 12 UT (around noon at Juliusruh)
- Estimated τ based neutral gas temperature can be considered as exospheric temperature.

Comparison of τ derived exospheric temperature with neutral gas models

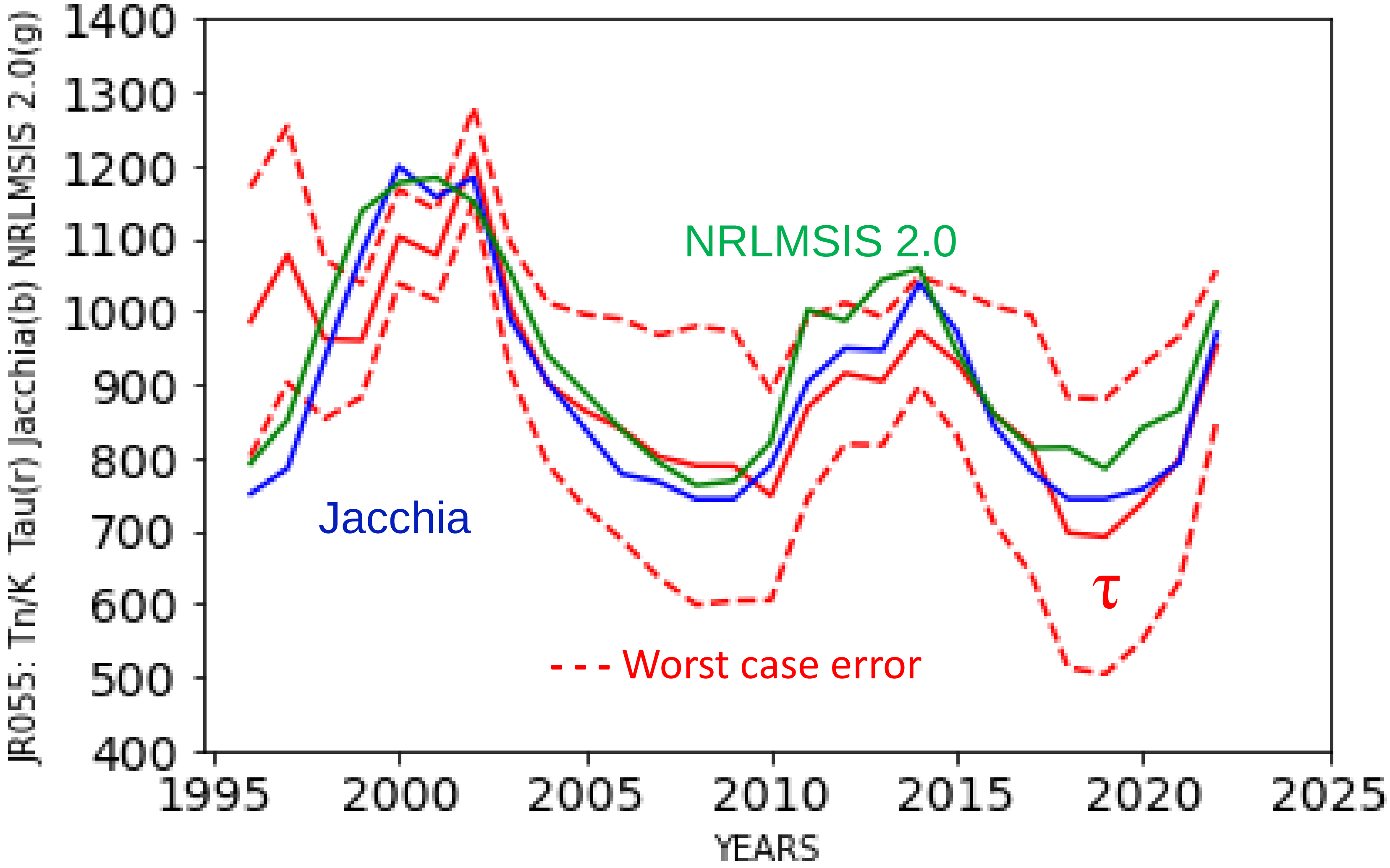


Jacchia, L.G., Smith‘s Astrophys. Obs., Spec. Rep. 332, 1971

NRLMSIS 2.0 : Community Coordinated Modeling Center (CCMC) at NASA

- The general behavior of the τ derived yearly averaged neutral gas model agrees with the Jacchia model and the NRLMSIS 2.0 model in a qualitative manner in the range of about ±100K.
- Both models deviate in the order of about ±50K from each other.
- The current τ derived neutral gas model indicate a faster decrease (cooling) than Jacchia and MSIS models.
- Higher precision of equivalent slab thickess estimation is required to get reliable conclusions.

Worst case error estimation for exospheric temperature determination



Measurement errors

ΔTEC = 1 TECU
ΔfoF2= 0.1 MHz

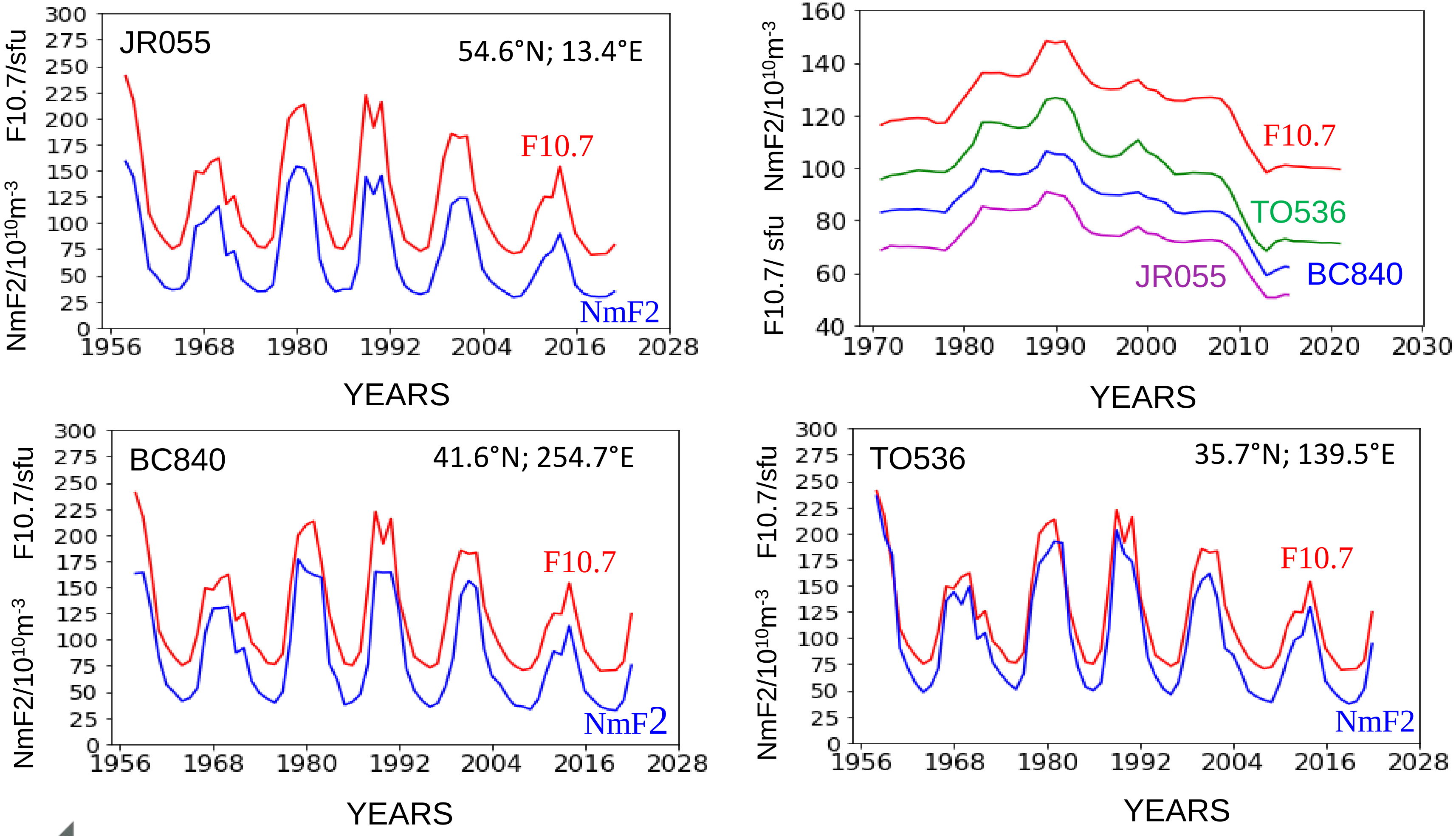
$$\Delta\tau \approx \left|\frac{\Delta TEC}{N_mF2}\right| + \left|\frac{\Delta TEC}{N_mF2} \cdot \frac{\Delta N_mF2}{N_mF2}\right|$$

(cf. Jakowski et al., 2017)

$$\Delta\tau \approx \left|\frac{\Delta TEC}{N_mF2}\right| + \left|2\tau \cdot \frac{\Delta f_oF2}{f_oF2}\right|$$

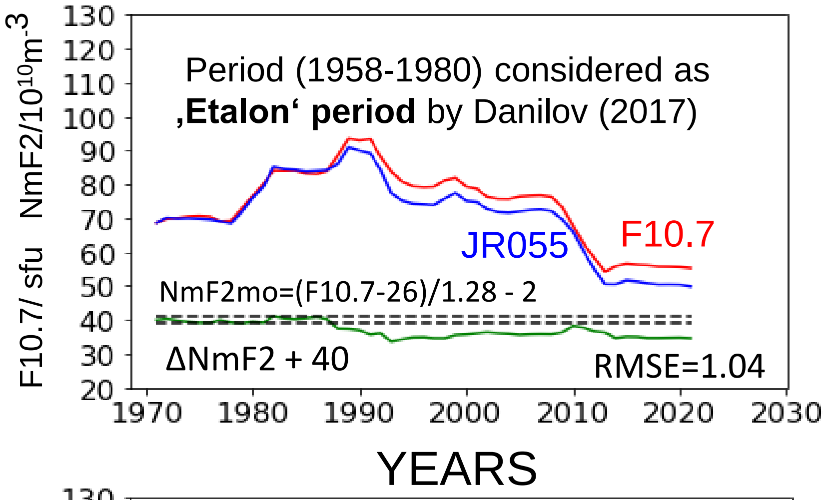
- Precise determination of ionosonde and TEC data required to get reliable conclusions.

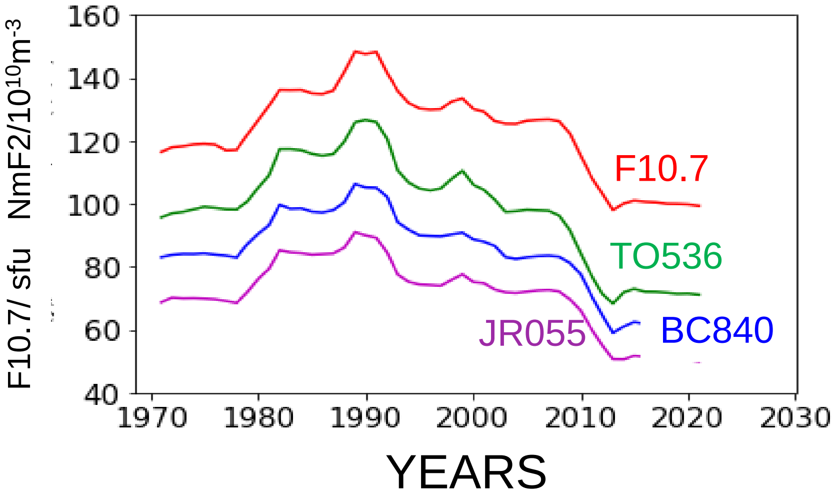
Yearly and 11 years averaged F2 layer peak electron density data

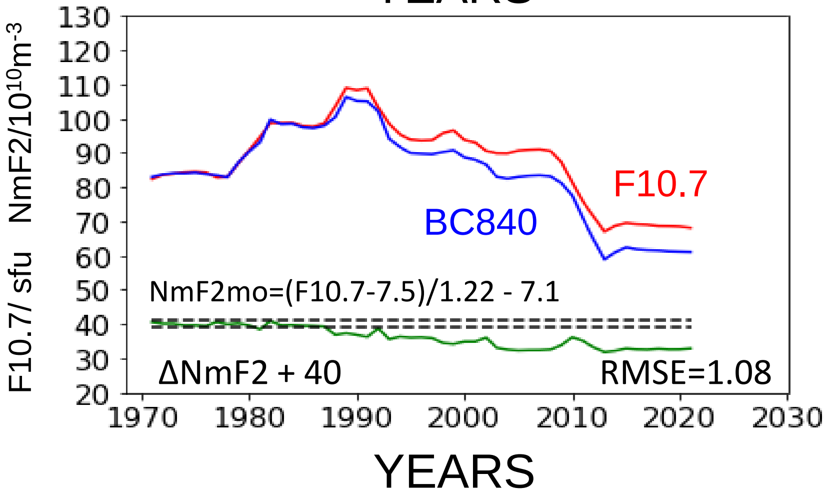


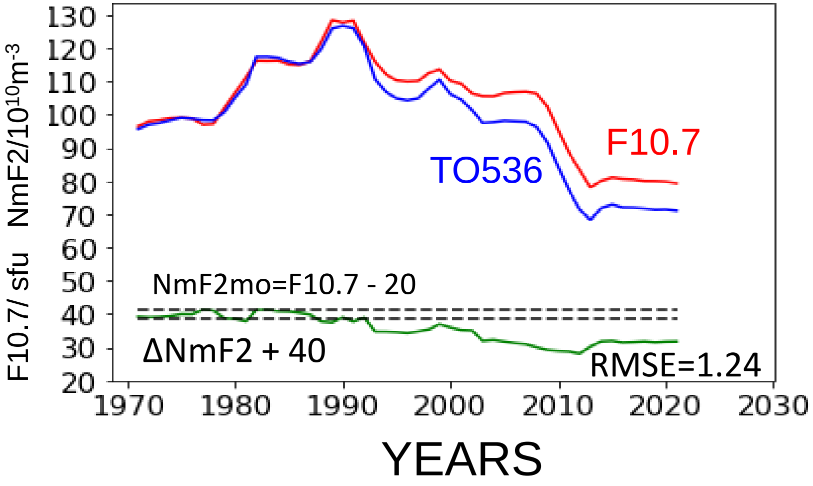
- Yearly averaged NmF2 data over Juliusruh, Boulder and Kokubunji for 1958-2022 show close correlation with the solar radio flux index F10.7.
- The temporal variation of 11 previous years averaged NmF2 data show a very similar behaviour at all three stations.
- Stronger deviations of NmF2 averages from F10.7 are indicated for solar cycles 23 and 24 than for cycles before.

Linear models of NmF2 as a function of F10.7 for 11 years averaged data









- Model approach for period 1970-1990
- RMS errors in the order of only 1 ..1.25·10^{10} m^{-3}
- Model starts to deviate from F10.7 during the decade 1980-1990.
- Physical processes causing the deviation start about 5 years earlier because the 11 years average is computed for previous years.
- Same behaviour at 3 ionosonde stations at differen longitude sectors indicate a **global effect**

(Danilov, A. (2017) JASTP, 163, 103–113, https://doi.org/10.1016/j.jastp.2017.04.002)

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Summary and conclusions

Yearly averages of ionospheric key parameters for years 1996-2022 show decreases of the F2 layer peak electron density NmF2, height hmF2, total electron content TEC and equivalent slab thickness τ.

The equivalent slab thickness τ is an important shape parameter of vertical electron density profiles.

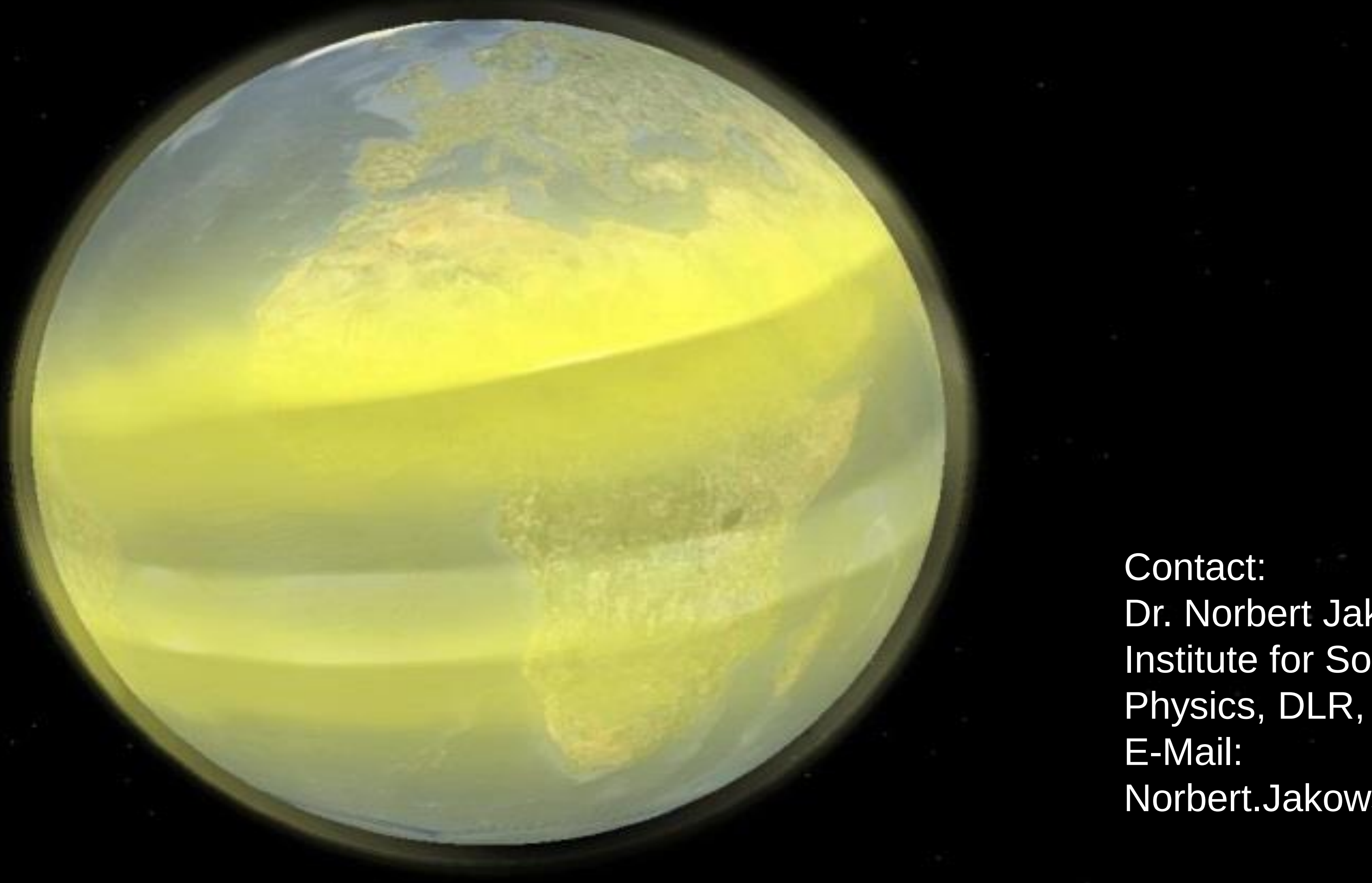
Computations of τ have a principal potential to detect/monitor long-term trends of exospheric temperature but require high accuracy of foF2 and TEC measurements
(ΔfoF2 $\leq$ 0.1 MHz ; ΔTEC $\leq$ 1 TECU).

Long-term modelling approaches for 11 years averaged NmF2 (1958-2022) at ionosonde stations Juliusruh, Boulder and Kokubunji indicate a clear deviation of developed linear models (1970-1990) from F10.7 behavior starting at the end of the 1980-1990 decade.

Similar deviations at all selected stations indicate a global character of the underlying physics. Such a global behavior is required for long-term changes of ionospheric and thermospheric variables that might be caused by cooling and composition changes due to greenhouse gases, changes of magnetic field configuration and activity or solar spectrum.

Ionosphere from space

Electron density
July 23, 2011
14:00 UT



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Thank you for your attention!