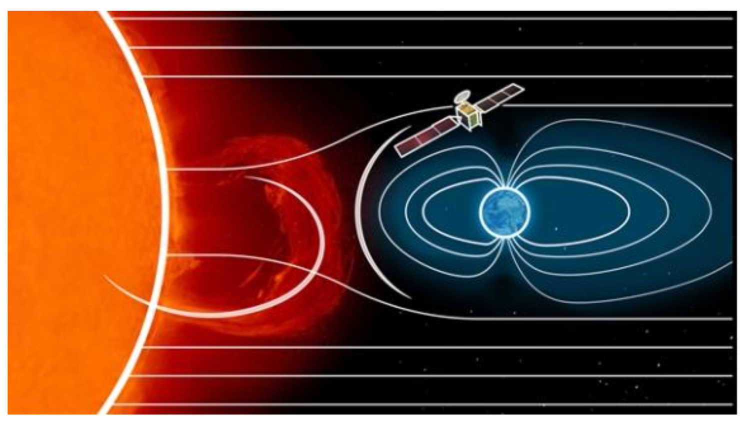

Long-term changes in the dependence of NmF2 on solar flux at Juliusruh

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Introduction

Understanding the ionospheric dependence on solar activity is crucial for the comprehension of the upper atmosphere. The response of the ionosphere to solar EUV flux has been previously considered stable. Subsequent studies have revealed long-term changes that are not yet fully understood. This work evaluates the stability of the NmF2 dependence on solar EUV indices throughout different solar cycles.

The NmF2 response to solar EUV proxies (F10.7 or R) was found to be linear in early studies (Bremer, 1992). However, later studies (e.g., Balan et al., 1994; Liu et al., 2003) discovered that the linear increase of NmF2 with solar EUV proxies at low and moderate solar activity levels breaks down at higher activity levels, indicating a "saturation effect" and a nonlinear dependence. Recent publications (e.g., Danilov and Berbeneva, 2023) show that the dependence of foF2 to solar flux is better represented with a third-degree polynomial regression and that F30 and MgII are the most reliable proxies for long-term analysis (Laštovicka, 2021).

Data/Methods

Solar proxies data

- F10.7, F30 and MgII were considered as proxies. (Toyokawa Observatory).
- Proxies have a daily resolution, we use the value for all hours of the day.
- Determination of the last solar cycles

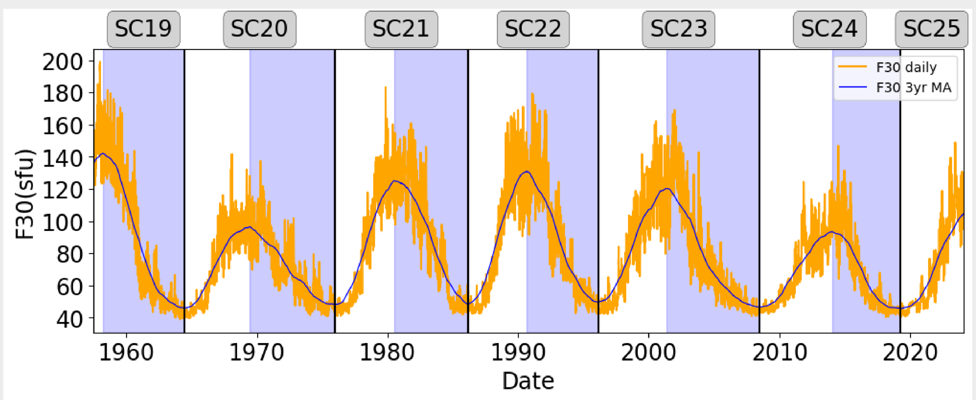

Fig1. F30 (sfu) daily data. The solid-line blue is the 3-year moving window average of F30. The vertical black lines indicate solar cycles and the blue background, the descending part of each solar cycle.

Ionosonde Data – Cleaning Process

- foF2 hourly resolution data from Juliusruh (54.6°N, 13.4°W) ionosonde station was consider. The period used is from 1957 to 2023.
- NmF2 values were derived from foF2 data using the following equation.

$$NmF2[m^{-3}] = 1{,}24.10^{10}(foF2[MHz])^2 \quad (1)$$

- An **ionospheric data cleaning method** with two steps was applied:

1st STEP – Remove all values that fall far outside the natural range of NmF2

NmF2 values exceeding 4.10^{12} e/m^3 were removed.

2nd STEP – Exclude geomagnetic disturbed days

Days where the Kp index is equal to or exceeded 3, as well as the 48 hours succeeding them were removed.

Tab1. Quantified analysis of NmF2 data and corresponding percentage for the cleaning method applied.

Total Values	Initial nan	Natural outliers	Geomagnetically influenced	Total after cleaning
579575	48648	1740	149426	379761
100.0%	**8.4%**	**0.3%**	**25.8%**	**65.5%**

Method: Regression analysis

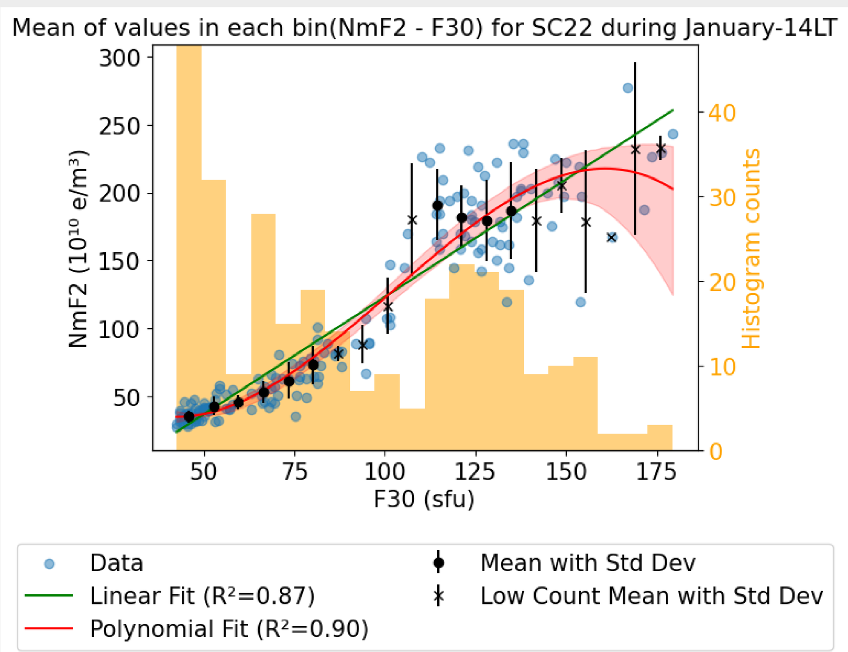

Fig2. Linear (green line) and polynomial fit (red line) dependence between NmF2 and F30 during January at 14 LT for solar cycles 22. Mean values of the bins (black scatter points) and mean values with less than 10 counts in the bin (cruises) with their standard deviation (error bar for each point).

- Cubic polynomial regression:

$$Y = a_0 + a_1X + a_2X^2 + a_3X^3 \quad (2)$$

Where NmF2 is variable *Y* and solar EUV proxy is variable *X*.

- R^2 value indicates the goodness of the description for each fitting.

Results

Seasonal Analysis with different solar EUV proxies

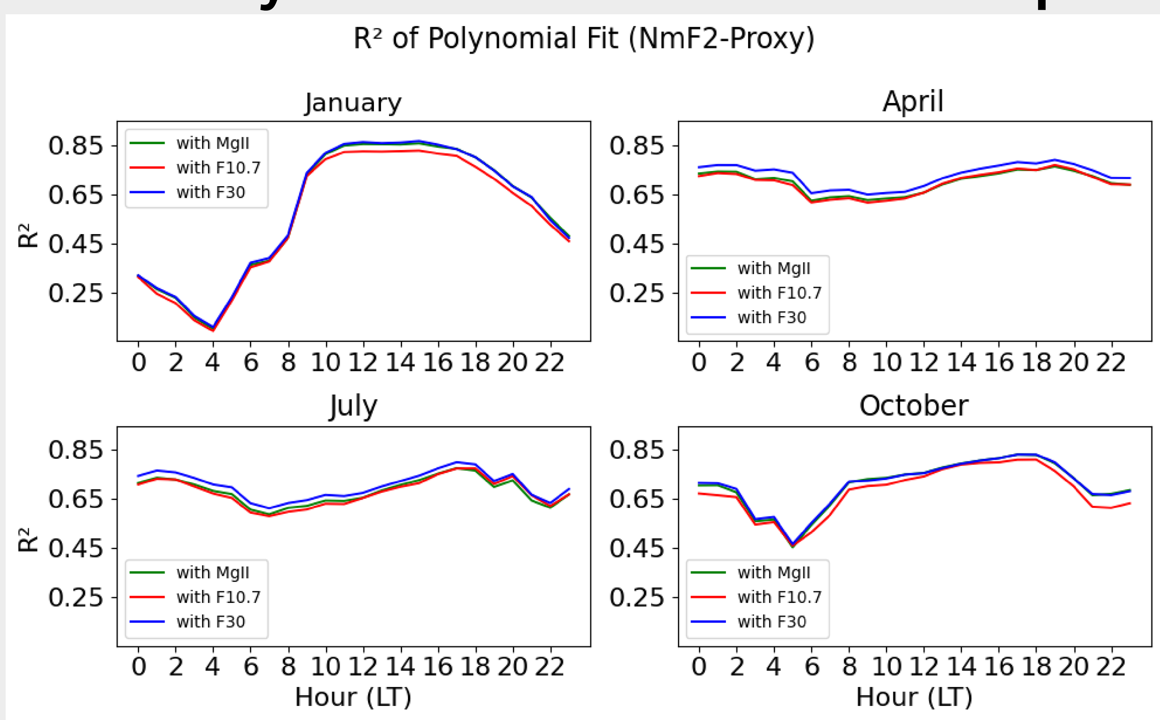

Fig3. Hourly R^2 value of the third-degree polynomial dependence between N mF 2 and solar activity proxies: F30 (blue line), F10.7 (red line) and MgII (green line); a)in January; b)in April; c)in July and d)in October from 1957 to 2023.

Long-term changes

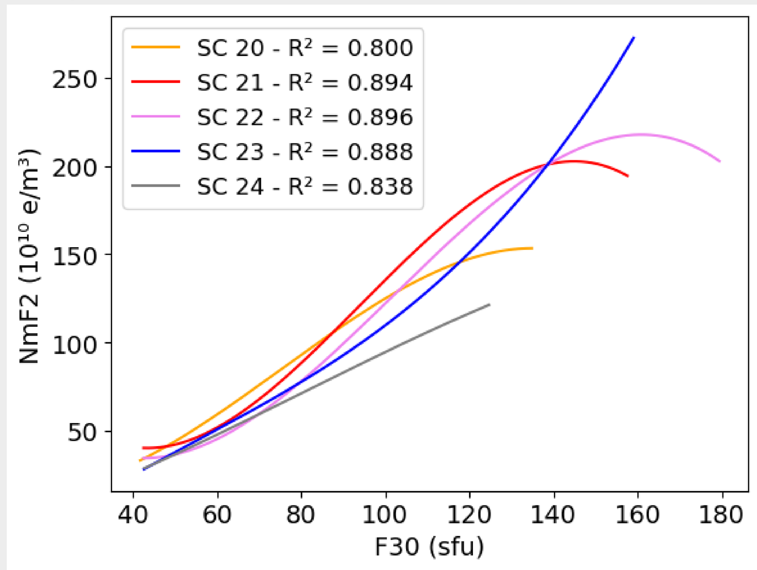

Fig4. Third-degree polynomial dependence between NmF2 and F30 during January at 14 LT for different solar cycles.

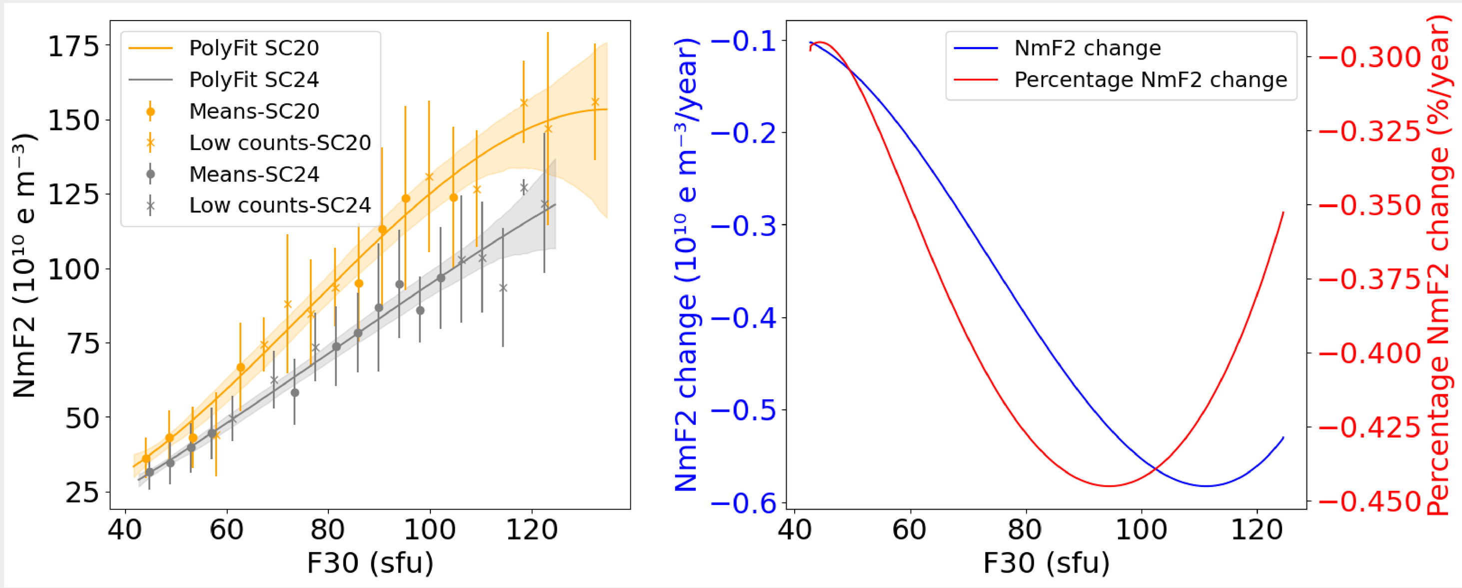

*Fig5. **Left panel:** Polynomial dependence between NmF2 and F30 during January at 14 LT for solar cycles 20 and 24 with their confidence intervals (CI). Mean values of the bins (scatter points) and mean values with less than 10 counts in the bin (crosses) with their standard deviation (error bar for each point); **Right panel:** Absolute and percentage per year differences between the polynomial fitting corresponding to solar cycles 20 and 24.*

Conclusion

The study examined the response of NmF2 from Juliusruh (1957 to 2023) to solar flux by using three different solar EUV proxies (F10.7, F30 and MgII). The analysis was performed for six solar cycles. The following main results were obtained:

- The ionospheric saturation feature is visible in our NmF2 data. This effect begins at lower F30 values in the ascending phase than in the descending phase.
- F30 shows the highest squared correlation value for describing the hourly NmF2 dependence on solar flux over time in Juliusruh in comparison with F10.7 and MgII.
- In January, there is the highest correlation between solar flux and NmF2 during noon conditions, that is explained by the winter anomaly.
- The modeling of the NmF2 response to solar activity for each SC separately revealed a steady decrease of NmF2. A significant discovery is that the long-term variation is influenced by the intensity of the solar activity index. On average, NmF2 decreases by 0.3% to 0.44% per year for low and high solar activity index levels respectively. The long-term decrease becomes more significant with higher solar activity. It changes by approximately 3.2% per solar cycle for small F30, and 4.8% per solar cycle for F30 = 120 sfu.

This study shows that the previously reported long-term decrease of NmF2 at winter noon conditions at the mid-latitude station Juliusruh is reflected in the parametrization of the NmF2 response to the solar activity index F30. This parametrization method is a valuable tool for quantifying long-term change in a meaningful way.

References:

Danilov, A. D., & Berbeneva, N. A. (2023). Statistical analysis of the critical frequency foF2 dependence on various solar activity indices. Advances in Space Research, 72(6), 2351-2361.

Tan Jun Rios, M. G., Borries, C., Liu, H., & Mielich, J. (2024). Long-term changes in the dependence of NmF2 on solar flux at Juliusruh. Annales Geophysicae Discussions, 2024, 1-25.

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