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The strongest solar flares of Solar Cycle 25 and their subionospheric impact: data and modeling

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Abstract. Solar flares, which are powerful explosions on the Sun's surface, are well recognized driving forces that have a significant impact on the near-Earth environment, causing extra ionization within the sunlit Earth's atmospheric layers. Based on how they affect the lower ionosphere and its electron density profile, X-ray solar flares can be categorized. In order to forecast the effects of potential solar occurrences during the waning phase of Solar Cycle 25, this study focuses on the disturbances caused by X-ray solar flares. In this paper we examined Solar Cycle progression i.e. solar activity of highest intensity (strongest 50 solar flares) during the ascending phase of Solar Cycle 25 by conducting numerical ionospheric modeling based on the Geostationary Operational Environmental Satellite (GOES) database on solar X-ray radiation.

Key words: Space weather – Solar activity – Solar X-ray flares – radio signal perturbations – GOES – data – modeling – electron density

1. Introduction

Strong explosions of electromagnetic radiation that come from the Sun's surface are known as solar flares (SFs) (Bothmer et al., 2007; Kahler, 1982; Tandberg-Hanssen & Emslie, 2009; Davidson, 2020; Riley & Love, 2017). The SF classifications range from A to X-class (see e.g. Grubor et al., 2008; Hayes et al., 2021, and references therein). Strong flares have the ability to impair communication and navigation systems and can cause disturbances in the ionosphere, affecting terrestrial communication. SFs emit powerful X-ray and ultraviolet radiation that can ionize the upper atmosphere, resulting in extra free electrons (Khodairy et al., 2020; Le et al., 2013; Šulić et al., 2016; Curto, 2020; Barta et al., 2022). These unbound electrons can affect radio wave propagation by changing the ionosphere's refractive characteristics (Thomson & Clilverd, 2000; Šulić & Srećković, 2014; Kolarski & Grubor, 2014; Srećković, 2023). The density of the ionosphere briefly increases, affecting radio signals going through it (McRae & Thomson, 2004; Kelly, 2009; Nina et al., 2019; Srećković et al., 2024, 2017).

To forecast the impacts of potential solar occurrences during the declining phase of Solar Cycle 25, this study focuses on the disruptions induced by X-ray solar flares. In this paper, we investigated Solar Cycle progression, i.e. solar activity of highest intensity (strongest 50 solar flares) during the ascending phase of Solar Cycle 25 using numerical ionospheric modeling and the Geostationary Operational Environmental Satellite (GOES) (Aschwanden, 1994; Woods et al., 2024) database on solar X-ray radiation (`https://data.ngdc.noaa.gov/platforms/solar-space-observing-satellites/goes`).

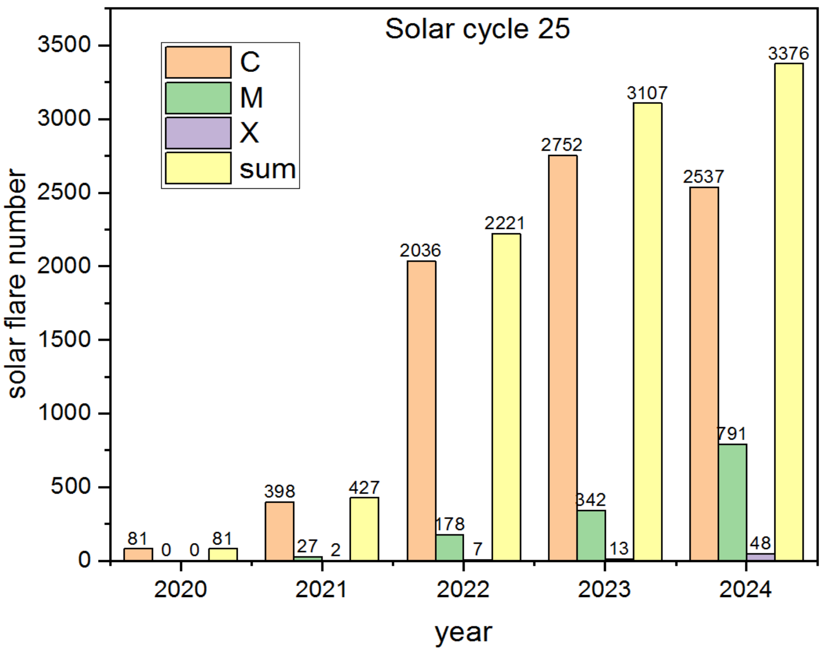

Figure 1. The graph shows the number of C, M and X-class solar flares that were produced during Solar Cycle 25 during the accessing phase, presented by year.

This study's findings may help to improve forecasting models (Gorney, 1990; Lean, 2010; Georgieva & Shiokawa, 2018; Bilitza et al., 2012, 2022), allowing for greater prediction and preparedness for ionospheric disruptions produced by high class SFs. The study of high-class SFs during Solar Cycle 25 and their impact on the ionosphere emphasizes the importance of ongoing research and monitoring of such occurrences to improve our understanding of space weather phenomena and protect technological infrastructure from potential disruptions.

The paper is organized as follows. This Section describes the current state and an introduction to the research problem. Section 2 provides results and analysis concerning the strongest solar flares of Solar Cycle 25 and their subionospheric impact, whereas Section Sec. 3 presents the conclusions and future perspectives of research.

2. Results and discussion

In this paper focus is on the further use of numerical method, so called easyFit that were developed by Srećković et al. (2021a,b) on the cases of high intensity SFs i.e. the strongest ones. We note that initially easyFit methods were developed for SF events of mid to high intensity (upper C-, M- and lower X-class SFs, see e.g. papers Srećković et al. (2021b); Kolarski et al. (2022)).

Datasets from this paper provide an overview of the results obtained by applying the numerical methods easyFit to the examples chosen for investigation, namely the top 50 SF of Solar Cycle 25 from X1.2 to X9. Solar X-ray flux was obtained from the Geostationary Operational Environmental Satellite (GOES) archive database (`https://data.ngdc.noaa.gov/platforms/solar-space-observing-satellites/goes`).

Figure 1 shows the number of C, M and X-class solar flares that were produced during the ascending branch of Solar Cycle 25 presented by year from 2020 to the end of 2024. We observe that, beginning in 2020 and reaching their peak at the end of 2024, the frequency of solar flares is clearly rising. It can be noted that on Jul 3, 2021 X1.59 - class flare occurred as the first X-class flare of Solar Cycle 25 and the first X-class solar flare since September 10, 2017.

Figure 2 upper panel shows sunspot number that were produced during the accessing phase of Solar Cycle 25 presented by year. We note that the number of sunspots is visibly increasing starting from 2020 and reaches its current maximum at the end of 2024. From the listed cases, differences in X-ray flux are associated with solar activity. Lower panel of Figure 2 shows the 50 strongest solar flares of Solar Cycle 25 (black circles) and corresponding reference height ionospheric D-region electron density (red circles). The left axis of the lower panel of Figure 2 shows the soft X-ray flux, while the right axis shows the perturbed values of the ower ionospheric electron density due to solar flares. The electron density is obtained by the easyFit method that was developed by Srećković et al. (2021a,b). One can observe a correlative behavior of increasing solar activity with increasing electron density.

Examining Solar Cycle progression we note that ionospheric disturbances and its parameters are correlated with solar activity during the ascending phase of Solar Cycle 25. These results will allow us to predict and model the ionosphere and its parameters during the waning phase of the Solar Cycle 25.

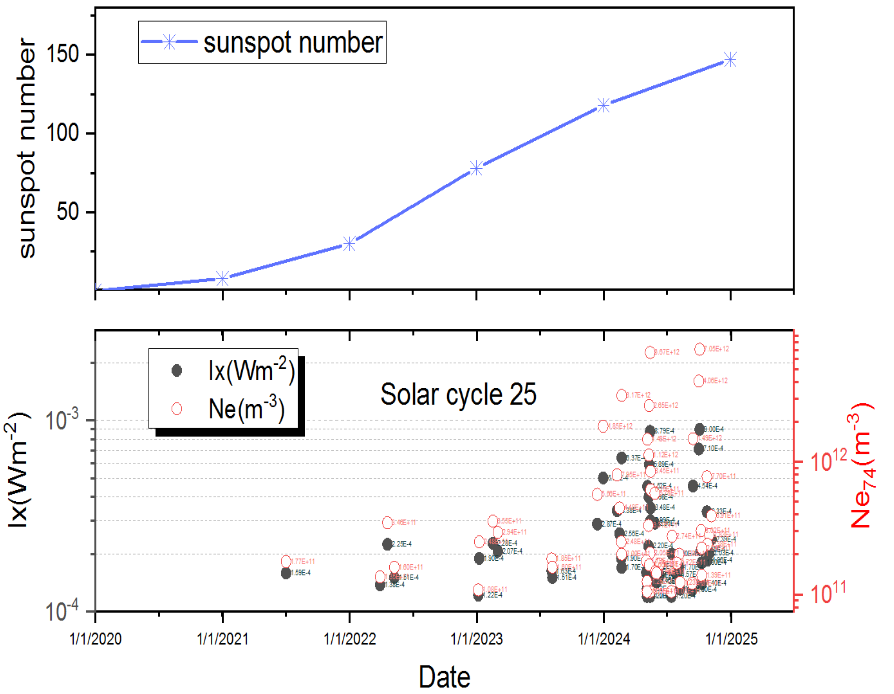

Figure 2. Upper panel: The graph shows sunspot number that were produced during Solar Cycle 25 by year; lower panel: The graph shows the 50 strongest solar flares of Solar Cycle 25 (black circles) and corresponding reference height ionospheric electron density (red circles).

3. Summary and future development

Solar flares, which are powerful explosions on the Sun's surface, are well recognized driving forces that have a significant impact on the near-Earth environment, causing extra ionization within the sunlit Earth's atmospheric layers. In order to forecast the effects of potential solar occurrences during the whole Solar Cycle 25, this study focuses on the disturbances caused by X-ray solar flares from 2020 to the end of 2024.

In this contribution, we investigated Solar Cycle progression, i.e. solar activity of highest intensity (strongest 50 solar flares) during the ascending phase of Solar Cycle 25, using numerical ionospheric modeling and the Geostationary Operational Environmental Satellite (GOES) database on solar X-ray radiation. Numerical method easyFit were applied to research impact of SFs of highest intensity ranging from X1 to X9 during 2020-2024 i.e. the ascending phase of Solar Cycle 25, with the aim to obtain parameters of perturbed lower ionosphere.

The results of this work could aid in the development of forecasting models, enabling better anticipation and readiness for ionospheric disturbances brought on by high-class SFs (see e.g. Gopalswamy, 2022). In order to better understand space weather events and safeguard technological infrastructure from potential disruptions, it is crucial to conduct continuous research and monitoring of high-class SFs during Solar Cycle 25 and their effects on the ionosphere.

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