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New reconstruction of annual integral solar proton fluences between 1984 — 2019

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Accurately determining the long-term fluxes and variability of solar energetic particles (SEPs) is crucial for understanding space physics. However, there are significant uncertainties in assessing average SEP fluxes over the past decades using different methods and datasets. In this study, we aim to re-evaluate annual integral SEP fluences using in-situ measurements from 1984 to 2019, covering three solar cycles 22 – 24. We reconstructed a comprehensive time series of integral SEP fluxes above various energy thresholds (10, 30, 60, 100, and 200 MeV) based on observations from the GOES satellites. To ensure a consistent dataset, we performed intercalibration of the fluxes by establishing linear relations between overlapping observations. Precise calculations of annual SEP fluences were obtained through careful subtraction of galactic cosmic ray (GCR) background and identification of SEP event periods. We calculated annual integral fluences of SEPs for the period spanning 1984 to 2019 at different energy thresholds. Our analysis revealed that solar cycle 24 exhibited a significantly weaker SEP fluence (5 to 8 times lower) compared to cycles 22 and 23.

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1. Introduction

The near-Earth radiation environment consists of two main components: galactic cosmic rays (GCRs) and solar energetic particles (SEPs). GCRs, which are energetic particles from outside our solar system, dominate in the higher energy range, while SEPs are responsible for the lower energy range. SEPs are highly variable and can exceed the GCR background level by several orders of magnitude during sporadic events. Studying SEP events provides valuable insights into solar eruptive processes, particle acceleration, and heliospheric plasma transport [1]. On the other hand, average fluxes of SEPs are important for long-term studies of solar-terrestrial relationships, the near-Earth radiation environment, atmospheric chemistry, and cosmogenic isotopes.

SEP fluences are typically expressed as integrated fluxes of energetic particles (protons) above a specific energy threshold, denoted as F_{E_0}. Commonly considered energy thresholds include 10 MeV, 30 MeV, 60 MeV, and sometimes 100 MeV, denoted as F_{10}, F_{30}, F_{60}, and F_{100}, respectively. The F_{200} fluence has also been identified as representative for ground-based detection of SEP events [2] and cosmogenic isotope production [3]. In addition to direct measurements, average fluxes of SEPs in the 30-80 MeV energy range can be estimated over thousands and millions of years using cosmogenic isotope measurements in lunar rocks [4].

Previous studies have focused on analyzing the strongest SEP events and providing fluence estimates for specific periods or solar cycles. These studies include assessments of fluences for different energy thresholds, analyses of major SEP events, cycle-averaged fluences, and reconstructions of spectra for specific timeframes and events. However, there are uncertainties related to event selection, duration, background levels, and potential biases in spacecraft-borne particle detectors used in these studies.

To address these issues, we conducted a new reconstruction of annual fluences for the period 1984 – 2019 using direct spacecraft data and an updated methodology. Unlike previous studies, we computed the annual fluences directly instead of separating individual SEP events. We also applied improved bias-correction and intercalibration procedures in the data analysis. This approach provides a comprehensive assessment of SEP fluences and addresses previous limitations in the field, contributing to a more accurate and comprehensive understanding of SEP fluences in the near-Earth radiation environment. These proceedings summarizes the main findings of our recent publication [5].

2. Analysis

2.1 Data selection and processing

In this study, we used 5-minute averaged proton flux data[1] obtained from the Energetic Particle Sensor (EPS) onboard the GOES satellites. The EPS instruments were part of the Space Environment Monitor (SEM) subsystem on GOES-1 to GOES-12, and the SEM onboard GOES-13–15 included two units, known as the Energetic Proton, Electron, and Alpha Detectors (EPEADs). The EPS/EPEAD instruments provided seven proton channels (P1 to P7) covering energies from 0.6

[1]Currently available from https://www.ncei.noaa.gov/data/goes-space-environment-monitor/access/avg/

MeV to 500 MeV. For the study, the lowest energy channel P1, which measures low-energy trapped protons, was not used since the focus was on medium and high-energy SEPs.

The data was collected from various GOES satellites from GOES-5 to GOES-15. In case of GOES-5, GOES-6 and GOES-7 two datasets were available: the "original" dataset and a recently revised dataset, denoted with suffix "3s". The data from GOES-16, which was launched in November 2016 and uses a completely new instrument called the Solar and Galactic Proton Sensor (SGPS), was not included in the study. For GOES-13 — 15 we used the orientation information to select fluxes observed by the westward-facing EPEAD. Data from EPS onboard GOES-15 was discontinued in March 2020. This study covers the period up to the end of 2019, which corresponds to the end of solar cycle 24.

The data was downloaded from the National Oceanic and Atmospheric Administration (NOAA) website. After downloading the data, various processing steps were applied to clean and correct the dataset:

- Removal of dropouts and spikes: The proton fluxes, especially from the first generation of satellites (GOES-5 to GOES-7), contain dropouts, spikes, and periods of suspicious values. These were removed by scanning through each channel of each detector and removing datapoints that did not meet certain criteria based on the surrounding datapoints.

- Manual removal of suspicious data: Periods of suspicious data that occurred during times with no detectable SEP activity were identified and removed manually from the time series.

- Comparison between overlapping datasets: A comparison was performed between each two overlapping differential datasets, the agreement between different datasets was quantified by fitting linear relationships between the measured fluxes from different instruments. Decent agreement was found between the fluxes observed by the first generation (GOES-5 to GOES-7) and the later generations of satellites (GOES-8 to GOES-15).

- Correction of first generation data: There was a noticeable difference between the fluxes observed by GOES-7 and GOES-8 in channels P4 to P7, likely due to the use of a different geometric factor in the data processing of the first GOES generation. To better match the later GOES generations, the first generation data (GOES-5 to GOES-7) was corrected by multiplying the fluxes with the geometric factor values GdE derived in the study (see details in [5]) and then dividing the resulting counting rates by the GdE values from previous studies.

Overall, the analysis demonstrated good agreement between the datasets, with the calculated linear relationships providing a reliable means of comparing the measured fluxes from different instruments.

2.2 Integral Fluxes

To determine the integral proton fluxes of solar origin, we subtract the GCR background from the differential fluxes. The background flux is obtained by selecting the minimum daily flux for each 10-day period, separately for each channel of each EPS/EPEAD instrument. To ensure the accuracy of the background estimation, any background value that exceeds 1.5 times or is less than 0.5 times the mean of the three previous background values is replaced with the mean.

PoS(ICRC2023)1242

To achieve uniformity in the data, we choose GOES-8 as the baseline and adjust the differential channels of other selected data sources to the same level using the intercalibration results. We select GOES-8 due to its extensive coverage and high data quality [6]. If there is insufficient overlap, we employ intermediate steps: GOES-8 → GOES-7 → GOES-6 (3s) → GOES-5 (3s) and GOES-8 → GOES-11 → GOES-13 → GOES-15. However, it should be noted that the overlap between GOES-8 and GOES-7 covers only one relatively small solar energetic particle (SEP) event, which increases the overall uncertainty for GOES-5–7.

The integral fluxes are computed using background-subtracted, 1-hour averaged differential fluxes, assuming a piecewise power-law spectrum between the "effective" channel energies E_{ch}. The effective energies are calculated using the following formula:

$$E_{ch} = \left(\frac{(-\gamma + 1)(E_h - E_l)}{E_h^{-\gamma+1} - E_l^{-\gamma+1}} \right)^{\frac{1}{\gamma}}, \qquad (1)$$

where E_l and E_h represent the lower and upper energy limits of the channel, respectively, and γ is the exponent of the power-law spectrum [6, 7]. In this study, we adopt $\gamma = 3$ instead of the commonly used $\gamma = 2$ to provide a more realistic representation of SEP event spectra above ~10 MeV energies [e.g., 8–10].

Due to significant discrepancies observed in channel P4 of GOES-5–8, we exclude this channel and integrate between channels P3 and P5 instead. Additionally, we notice a spectral discrepancy in channel P6 and choose to omit it as well. The integral flux above the highest differential channel P7 is calculated by subtracting 0.86 from the power-law fit between channels P5 and P7, and extrapolating it to infinity. The value 0.86 is calculated as the median of $\overline{\gamma}_{\mathrm{P7,P10}} - \overline{\gamma}_{\mathrm{P5,P7}}$, where $\gamma_{\mathrm{P7,P10}}$ is the power law index between channel P7 and the high-energy GOES/HEPAD channel P10. However, if the resulting value, $\gamma_{\mathrm{P5,P7}} - 0.86$, is smaller than 1.5, we replace it with 1.5 to avoid unrealistically hard spectra. If any channel has zero or negative flux values after background subtraction, we use the next closest channel with a positive value to calculate the power-law fit, excluding the energy range between the lower and upper limits of the non-positive-valued channel from the integration. If fewer than two differential channels have positive flux values, all integral channels for that hour are assigned zero fluxes. The statistical errors of the differential fluxes are propagated into the integral fluxes, including contributions from background subtraction and intercalibration.

An example of integral flux calculation for energy channels 30, 60 and 100 MeV are shown in Figure 1 for solar cycle 24 (data was averaged on monthly basis), where the periods of increased SEP activity can be easily identified. In particular, registration of high-energy SEP particles by ground-based detectors (so-called GLE, Ground Level Enhancement, events [11]) is shown with red arrows while blue arrows correspond to weaker sub-GLEs which were registered only by high-latitude polar NMs (see details about the classification in [12]).

2.3 Integral SEP fluences

To calculate the annual integral SEP fluences, any remaining data gaps in the compiled dataset of 1-hour differential and integral fluxes were filled using logarithmic interpolation. SEP event periods for each of the calculated integral fluxes f_{10}, f_{30}, f_{60}, f_{100}, and f_{200} were then selected based on the set of criteria (see details in [5]), which are intentionally set loose to capture as much of the SEP fluence as possible.

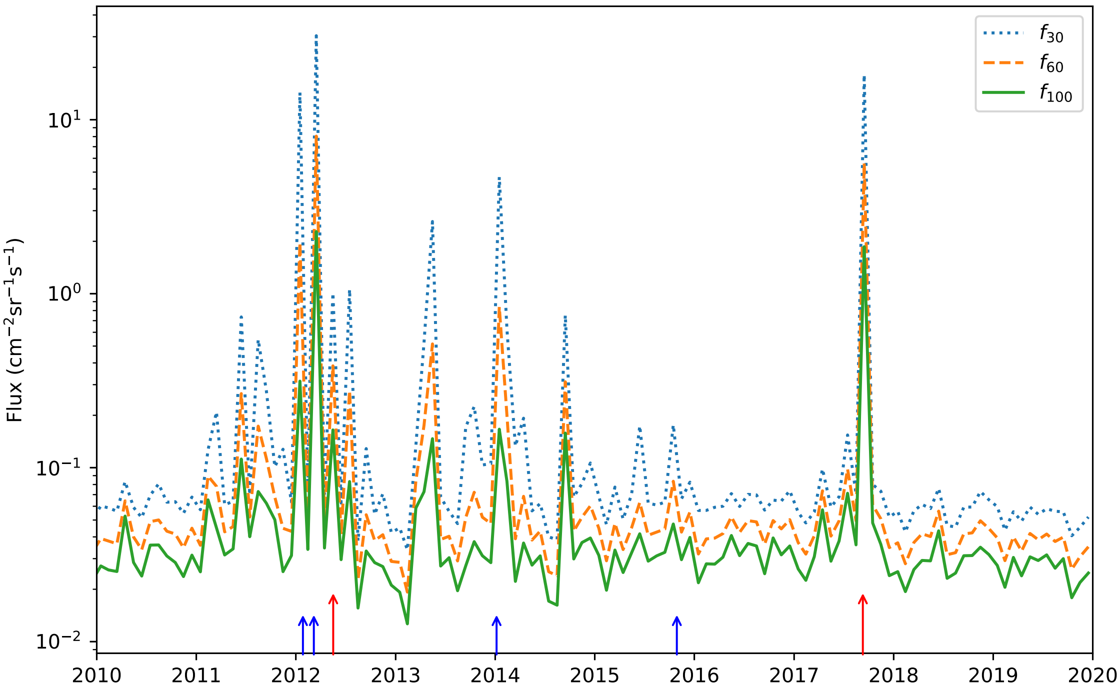

Figure 1: Integral fluxes for energy channels 30, 60 and 100 MeV (doted blue, dashed orange and solid green as denoted in the legend) for solar cycle 24 obtained in this work. Red arrows correspond to GLE events and smaller blue arrows correspond to sub-GLE events.

Comparison with previous results of SEP integral fluences reconstruction shows that significant differences can be observed in some cases. For instance, Feynman et al., 1990 reports a fluence for the event on April 24, 1985, that is 4.7 times higher for F_{10} and 2.2 times higher for F_{30} compared to our calculations. On average, both Goswami et al., 1988 [13] and Feynman et al., 1990 [14] report higher fluences for F_{10}. However, for F_{30}, our results tend to be higher than those in Goswami et al., 1988 [13] and the R-ESC catalogue [15].

It is important to note that the comparison with Goswami et al., 1988 [13] and Feynman et al., 1990 [14] includes the largest events from 1984 to 1986, with most events appearing in both references but with different integration times. Furthermore, only the dates of event onsets are provided in the references, without the exact onset times. Therefore, the start of the integration time for all events was assumed to be the beginning of the day of the event.

Regarding the comparison with the R-ESC catalogue, it includes all events from 1997 to 2017 for which integral fluences up to F_{100} are provided in the catalogue.

Obtained annual SEP fluences exhibit significant variation in fluence levels between individual years. This can be clearly seen in Figure 2, which shows the cumulative solar cycle fluences for energy channels >30, >100 and >200 MeV as function of time. For instance, in solar cycle 22, the year 1989 stands out with the highest annual fluence, contributing to 80–90% of the total cycle fluence. In contrast, during solar cycle 23, the fluence was more evenly distributed over the years 2000–2006, resulting in a gradual fluence accumulation. Notably, solar cycle 24 exhibited a significantly lower fluence, around 5–8 times weaker, compared to the previous two cycles.

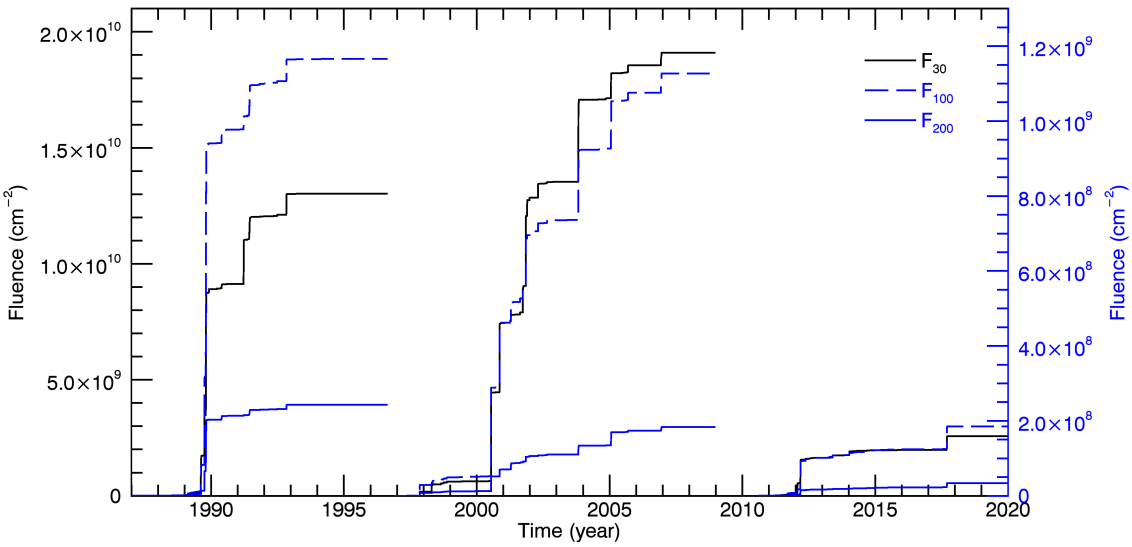

Figure 2: Cumulative solar cycle fluences F_{10}, F_{100} and F_{200} as function of time for the last three full cycles.

These results provide insights into the uneven distribution of SEP fluences across individual years and the varying fluence levels observed throughout different solar cycles.

3. Conclusion

In conclusion, we have reconstructed annual solar energetic particle (SEP) fluences for the period 1984–2019 in five energy ranges. The fluences were derived using revised calibration of in-situ data from GOES-family spacecraft. The fluences exhibit variations over the solar cycle, with peak values occurring during the maximum phase. Solar cycle 24 had significantly lower fluences compared to cycles 22 and 23, with a reduction factor of 5–7. The fluence accumulation is primarily driven by strong SEP events, with a large portion of cycle 22 fluence accumulated during the Autumn of 1989. The cumulative distribution functions of annual fluences follow a Weibull distribution shape, allowing extrapolation to extreme fluences observed in historical events. The findings suggest that the occurrence of fluences an order of magnitude higher than the past 45 years is unlikely on millennial timescales. The improved proton flux data presented in this study will enhance the accuracy of statistical proton models used in various space weather applications and services provided by organizations like the European Space Agency Space Weather Service.

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