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Long-term evolution of the power-law spectrum of galactic cosmic rays in 1953-2016

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1. Introduction

- Fluxes of galactic cosmic rays (GCR) arriving at Earth as recorded by neutron monitors (NM) are modulated by solar activity. The modulation is particularly affected by scattering of GCR on magnetic irregularities whose occurrence varies with the 11-year solar cycle and the 27-day solar rotational period.
- Power spectral densities (PSD) of the neutron monitor data can be used to quantify and study different periodicities and other aspects of GCR variability caused by heliospheric activity.
- We have studied the long-term evolution of spectral slopes of PSDs of the NM count rates.
- Similar long-term studies have been made on the HMF spectrum, e.g., by Starodubtsev & Grigoryev (2011) and Borovsky (2012) who found that the spectral slopes are solar-cycle dependent. However, Starodubtsev & Grigoryev did not consider the change of HMF data source of the OMNI database in 1994.

2. Overview of the neutron data and mean PSD

- Record from 31 NMs spanning years 1953-2016 are shown in Figure 1. They were acquired from the NMDB (http://www.nmdb.eu/nest/) and the Izmiran database (http://cr0.izmiran.ru/common/links.htm) at 1-hour resolution. Outliers were removed using a median filter (±3σ away from the median of 1000 nearest data points).

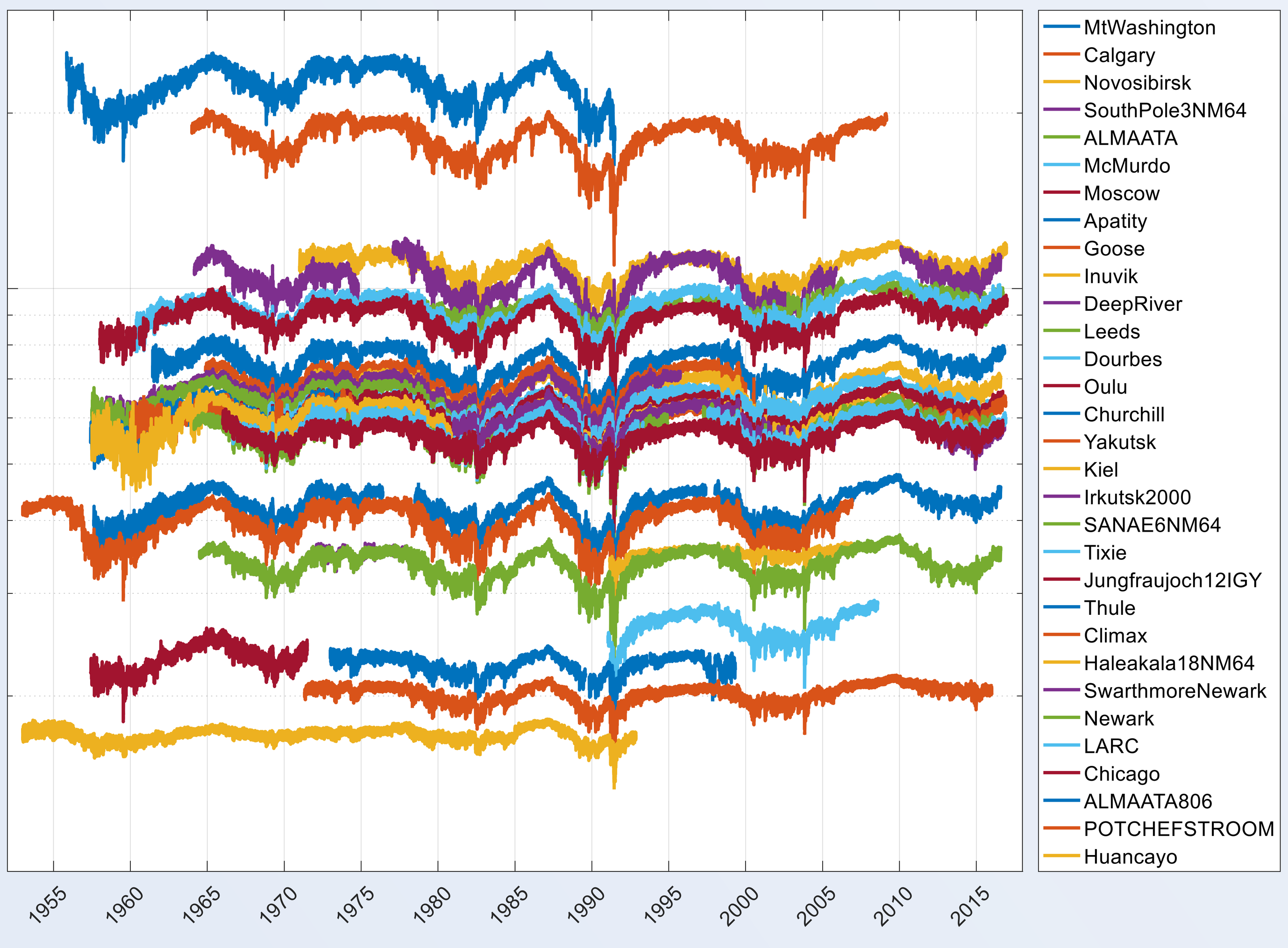

Figure 1. Overview of the hourly data from 31 neutron monitors.

- Missing data points were interpolated linearly. The data was detrended and standardized for each interval individually, before PSD computation .
- An overview mean PSD is presented in Figure 2. One can see the peaks and corresponding harmonics caused by 27-day and 24-hour variations. Between them at timescales from 50 to 130 hours there is a power-law part unaffected by these peaks. Our study focuses on this frequency range.

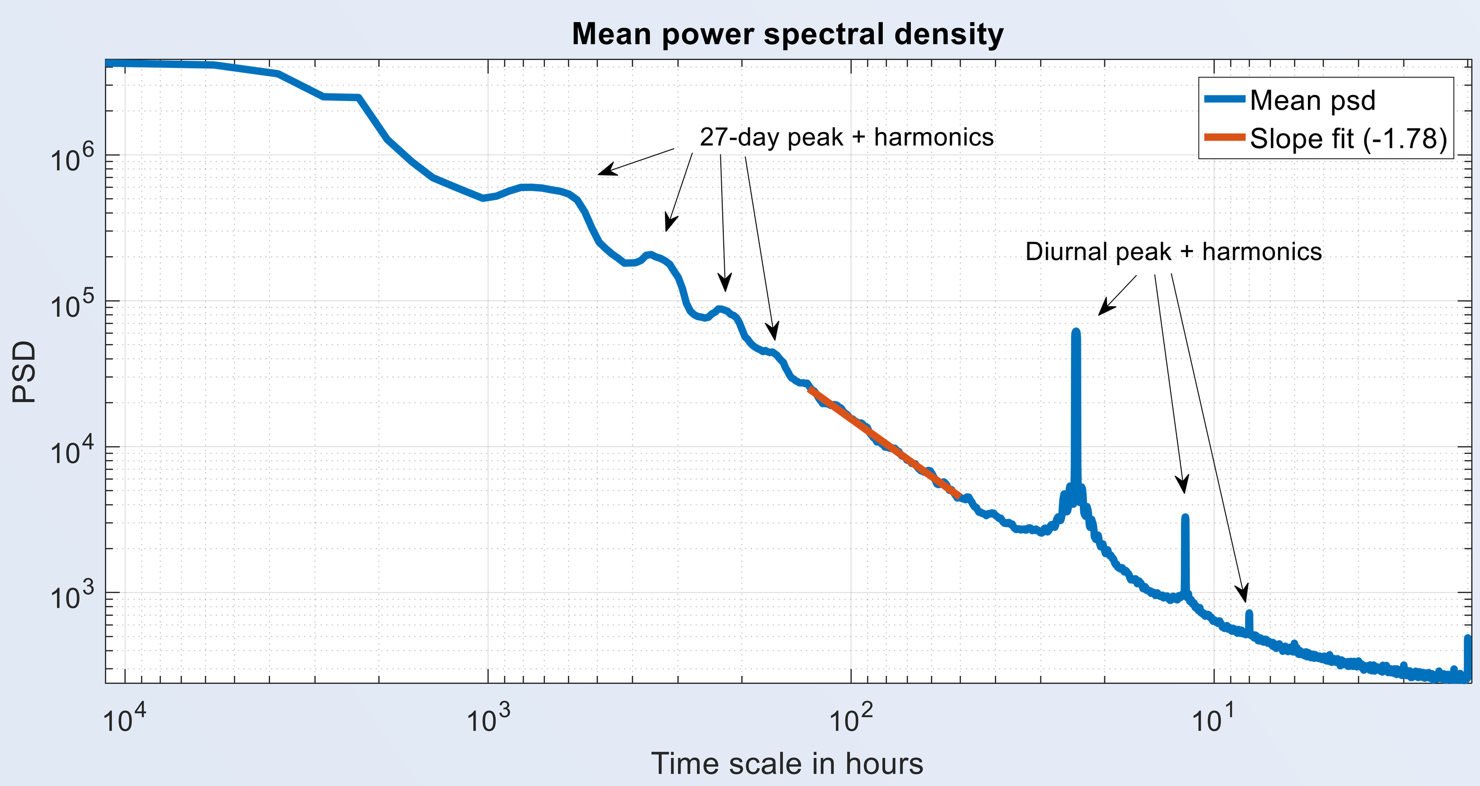

Figure 2. Mean PSD of all 16667 PSDs used in the study.

- We separated the results to different solar cycles and solar cycle phases (see Table 1). The selection using only full years was done based NM count rates, sunspot numbers and geomagnetic data. Some years with unclear solar cycle phase identification were excluded, e.g. the years 1971-1973, when the NM count rate did not have a cyclic behaviour.
- We paired up successive cycles in our cycle-separated study in order to get more reliable statistics compared to using individual cycles.

Table 1. The selected Solar cycle phase years.

Cycle	Ascending	Maximum	Declining	Minimum
18			1953	1954, 1955
19	1956	1957, 1958	1959, 1960, 1961, 1962, 1963	1964, 1965, 1966
20	1967, 1968	1969, 1970	1974, 1975	1976, 1977
21	1978, 1979	1980, 1981, 1982	1983, 1984, 1985	1986, 1987
22	1988	1989, 1990, 1991	1992, 1993, 1994, 1995	1996, 1997
23	1998, 1999	2000, 2001, 2002	2004, 2005, 2006, 2007	2008, 2009
24	2010, 2011, 2012	2013, 2014	2015, 2016	

3. Long-term variation of power spectral index

- The final results of slopes values and their medians are presented in Figure 3.
- The slope values rise higher than -1.5 during 1975, 1986, 1996, 2009, which correspond to declining and minimum years. The steepest slopes of lower than -2 are observed during 1966, 1970, 1978, 1984, 1999, 2014.
- The slope behaviour is different for years 1952-1964, where the number of monitors was small.
- For years 1964-1988, there is a quasi-cyclicity where the median values go from -1.4 to -2.1 to -1.7 to -2.1 to -1.4. This cycle repeats two times with a period of 11 years, with peak years being 1964, 1975 and 1986. Then this behaviour breaks down after 1988, although we can see similar behaviour in the individual (green) slope values (e.g. individual values of over -1.5 in 1997 and 2008).

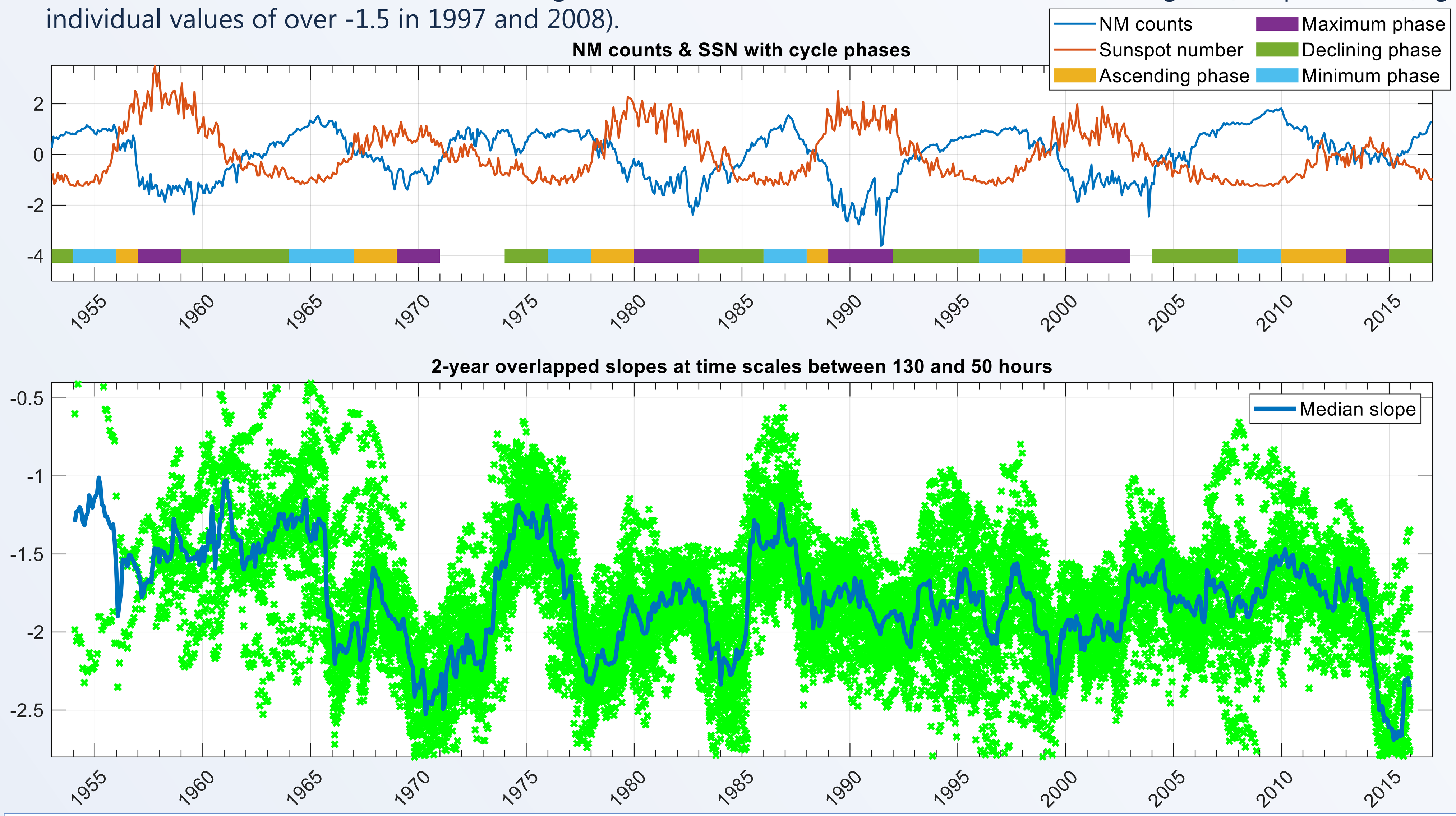

Figure 3. Top: standardized NM counts and sunspot numbers alongside with the selected cycle phase years. Bottom: The spectral slope results, with green 'x's corresponding to slopes from individual neutron monitors, blue line corresponding to median slope

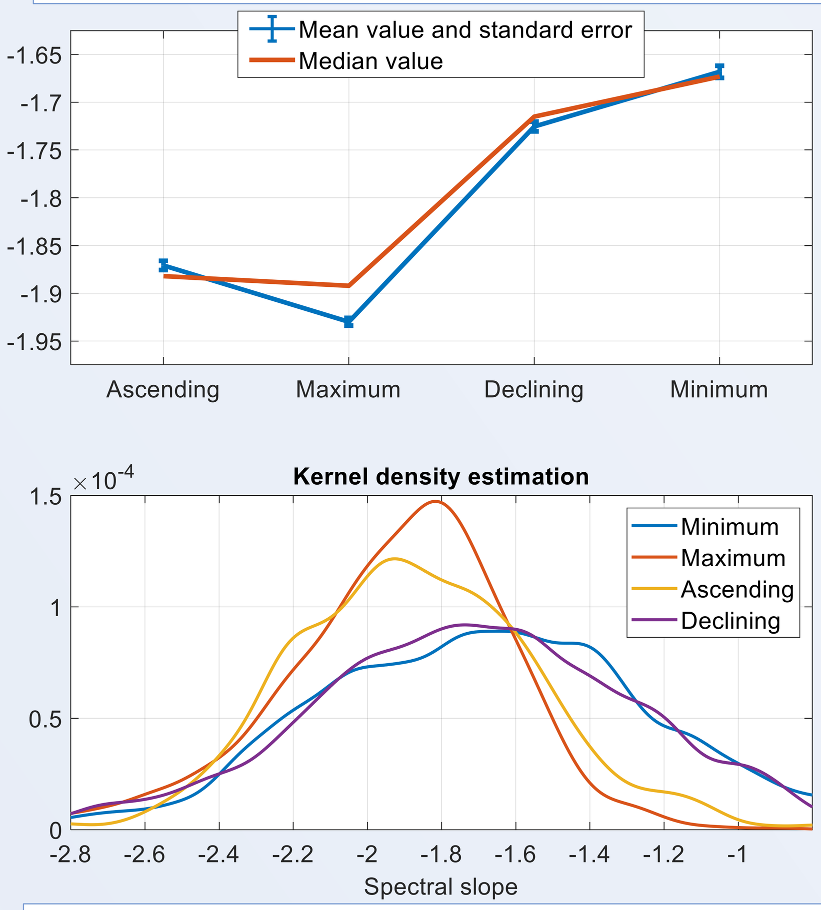

Figure 4. [Top]: Mean values and standard errors of slope values during different solar cycle phases. [Bottom]: kernel density estimation of their slope values of different cycle phases.

- Using Table 1 to separate the results to different solar cycle phases, we computed cycle-specific mean slope values and kernel density distributions, which are depicted in Figure 4.
- The mean slope values are -1.87, -1.94, -1.73 and -1.66 for ascending, maximum, declining and minimum phases, respectively.
- The distribution of slope values (bottom panel) shows that the solar cycle maximum phase has the highest and narrowest distribution, which indicates that the solar maximum has the most well-defined behavior of slopes.
- The ascending phase is similar to the solar maximum, but with a wider distribution.
- The solar minimum and declining phases are very similar, with wide and flat distribution covering values from the whole interval of -2.6 to -0.8, whereas solar cycle maximum and ascending phases do not exhibit many values higher than -1.4.
- Similar results for solar cycle pairs are shown in Figure 5.
- We see that cycles differ from another, although the overall trend of steep slopes at ascending & maximum phases and shallow slopes at declining & minimum phases is preserved for most cases.
- Overall, the distributions are very wide and mixed, halting the detection of underlying physical distributions. We can however infer that the physical slope values of -2 (random processes) and -1.67 (Kolmogorov turbulence) are represented in our results.

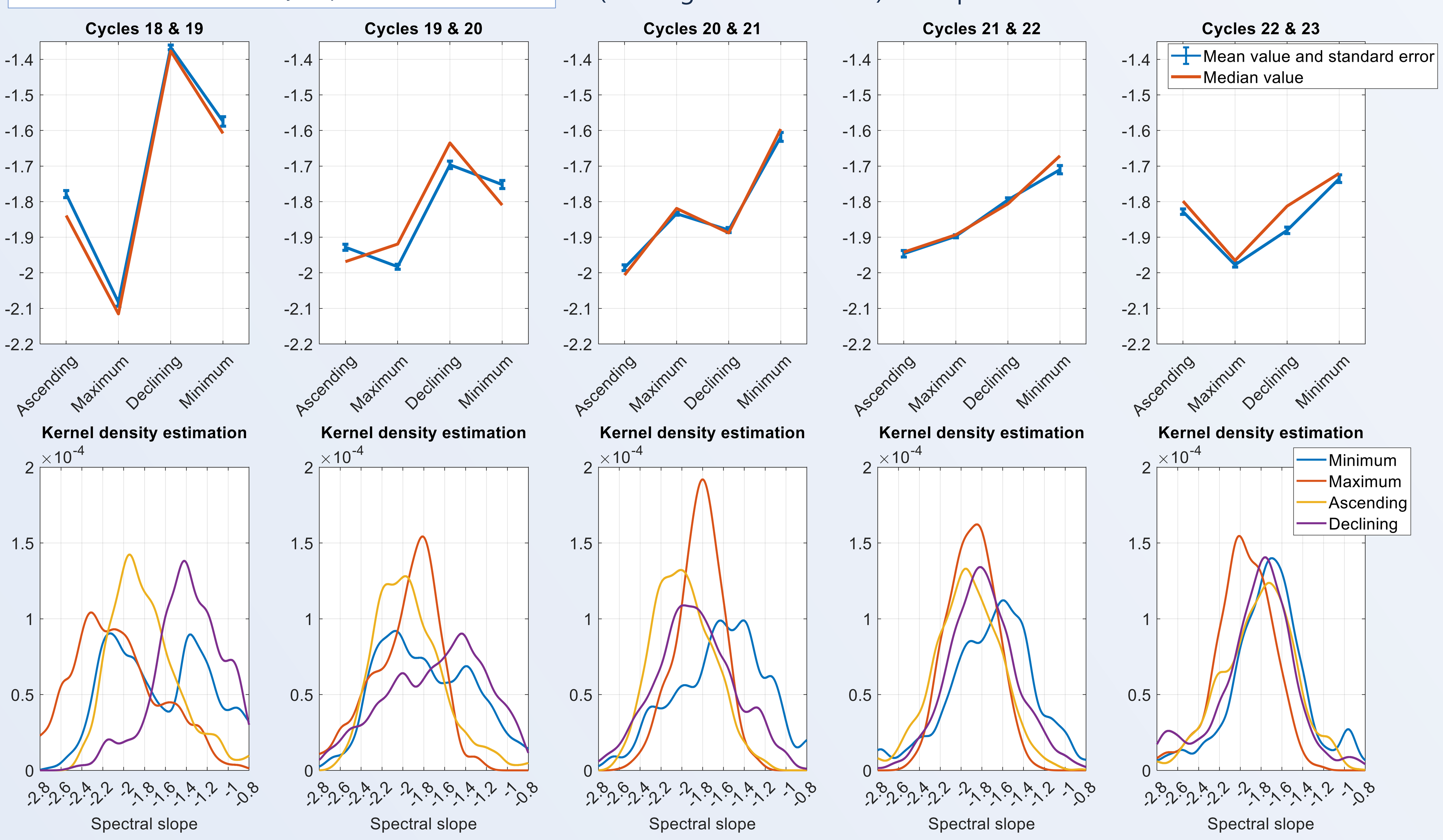

Figure 5. Same as Fig. 4, but with the values of two successive solar cycles separated, for cycles 18 to 23.

4. Summary

- We used 63 years of NM (1953-2016) data from 31 different stations to calculate PSD estimates and cyclic evolution of spectral slopes for time scales between 50 and 130 hours.
- The spectral slopes were found to vary in the course of the solar cycle, with harder spectrum at declining and minimum phases and softer at maximum and ascending phases.
- We note that the distributions tend to be close to the physical power law slope values of -2 and -1.67, although the values are very spread out.

References

- Borovsky, J. E. (2012), The velocity and magnetic field fluctuations of the solar wind at 1 AU: Statistical analysis of Fourier spectra and correlations with plasma properties, J. Geophys. Res., 117, A05104.
- Starodubtsev, S.A. & Grigoryev, (2011) Cosmic rays and solar wind turbulence: Peculiarities of the 23rd solar cycle, V.G. Geomagn. Aeron. 51: 1004.