Updated heliospheric modulation potential of cosmic rays and station-specific scaling factors for 1964-2021

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Introduction

The flux of galactic cosmic rays (GCR) is considered to be constant in the local interstellar medium, but upon arriving in the heliosphere, they experience modulation due to the magnetic activity of the Sun.

This variation can be observed, e.g., when measuring GCR fluxes with neutron monitors (NMs). The modulation is parametrized by the heliospheric modulation potential ϕ, which tells the average energy loss of GCR particles.

This parameter is usually evaluated from the measurements by multiple NM stations by employing models of the cosmic ray yield functions, after correcting for the geomagnetic rigidity cutoff and atmospheric effects.

In this work, we employ the recently updated yield function as presented in Mishev2020 and a new method of minimized root-mean-square errors in order to compute the modulation potential and the station-specific scaling factors.

Data

Stations used are shown in Figure 1. In the selection we focused on good, long-lived stations with P_c < 3 GV.

Table 1 shows basic information and the average scaling factor value obtained.

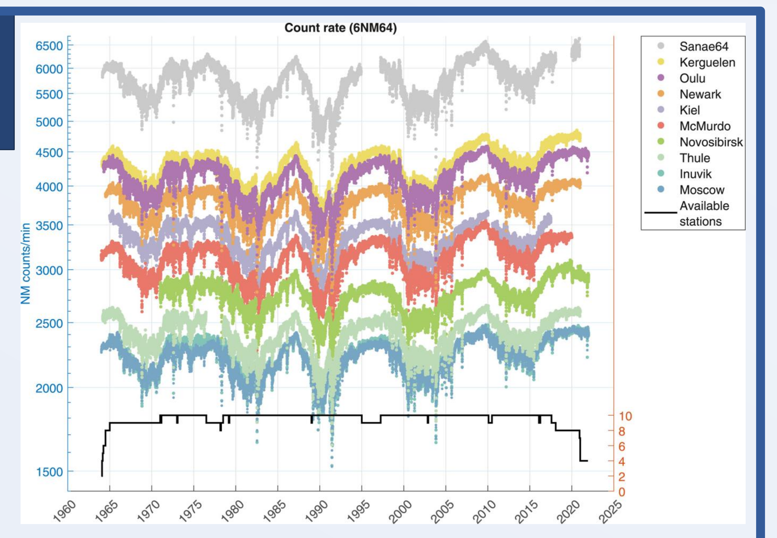

Figure 1. Data from used stations (left) and total coverage (right)

Table 1. Information about the used stations

Station	Latitude	Longitude	h (g/cm^2)	R_c (GV)	# of counters	$\kappa \pm \sigma_\kappa$
Inuvik	68.35	-133.72	1030.51	0.21	18	1.764 ±0.011
Kerguelen	-49.35	70.27	1019.63	1.03	18	0.984 ± 0.009
Kiel	54.3	10.1	1026.43	2.22	18	1.192 ±0.014
McMurdo	-77.95	166.6	1026.85	0	18	1.287 ±0.016
Moscow	55.47	37.32	1019.72	2.23	24	1.885 ±0.016
Newark	39.7	-75.7	1032.97	2.10	9	1.033 ±0.005
Novosibirsk	54.48	83	1014.62	2.64	24	1.575 ± 0.025
Oulu	65.05	25.47	1019.72	0.65	9	1.022 ±0.008
Sanae64	-71.67	-2.85	897.28	0.67	6	1.747 ±0.014
Thule	76.5	-68.7	1025.07	0	18	1.688 ±0.021

Methods

In practical terms, modulation potential ϕ is used in determining the energy spectrum of i-th species GCR

$$J_i(T,\phi) = J_{\mathrm{LIS},i}(T+\Phi_i)\frac{(T)(T+2T_r)}{(T+\Phi_i)(T+\Phi_i+2T_r)},$$

where $\mathbf{\Phi_i} = (\frac{eZ_i}{A_i})\phi$, **T** is the kinetic energy/nucleon, $\mathbf{T_r}$=0.938 GeV is the rest mass of a proton. The local interstellar spectrum (LIS) we use here is by Vos and Potgieter 2015:

$$J_{\mathrm{LIS}}(T) = C \cdot 2700 \cdot \frac{T^{1.12}}{\beta^2}\left(\frac{T+0.67}{1.67}\right)^{-3.93},$$

where we employ the ratio C determined in Koldobskiy et al. 2019, describing the response functions of GCR species, effectively including heavier Z>2 species

$$C = 4.3 \cdot 10^{-9}\phi^2 - 6.2 \cdot 10^{-7}\phi + 0.337$$

Ultimately, using the energy spectrum $\mathbf{J_i}$ and the yield function $\mathbf{Y_i}$,determined by cut-off rigidity $\mathbf{R_c}$ and atmospheric depth **h,** we can compute the theoretical NM count rate

$$N^*(R_c,h,t) = \sum_i \int_{T_{c,i}}^{\infty} Y_i(h,T)\ J_i(E,t)\ dT,$$

The scaling factors are a simple ratio of the theoretical and measured count rates:

$$\kappa = \frac{N^*}{N}.$$

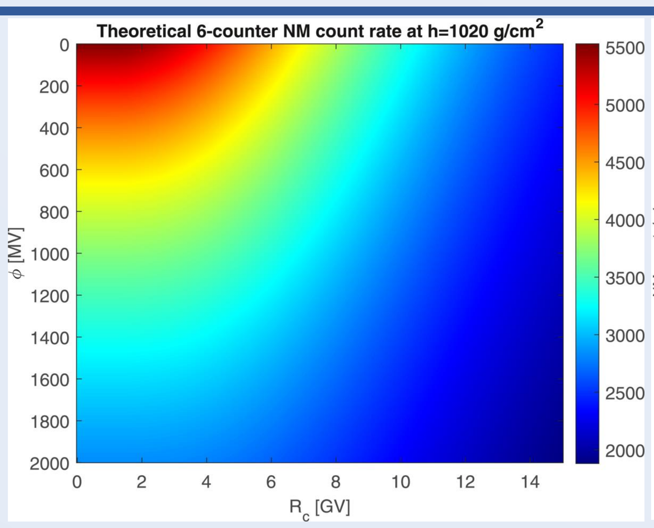

Figure 2. Theoretical count rates at different ϕ and R values for sea level.

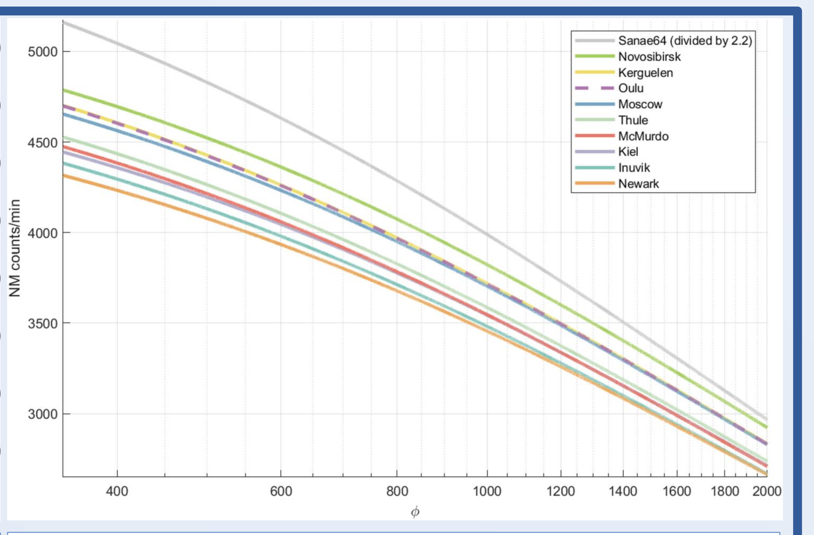

Figure 3. Theoretical count rates of different stations at different modulation potential ϕ

Then, we use a RMSE method to improve the modulation potential estimate.
By minimizing the merit function by employing average scaling factor values of stations

$$M = \sqrt{\frac{1}{X}\sum_{j=NM}^{X}\left(1-\frac{\kappa N_{(j,t)}}{N^*_{(j,t)}(\phi,h,T)}\right)^2}.$$

we then find the best phi value for each timestep at the minimum of the curve (see Figure 4.->)

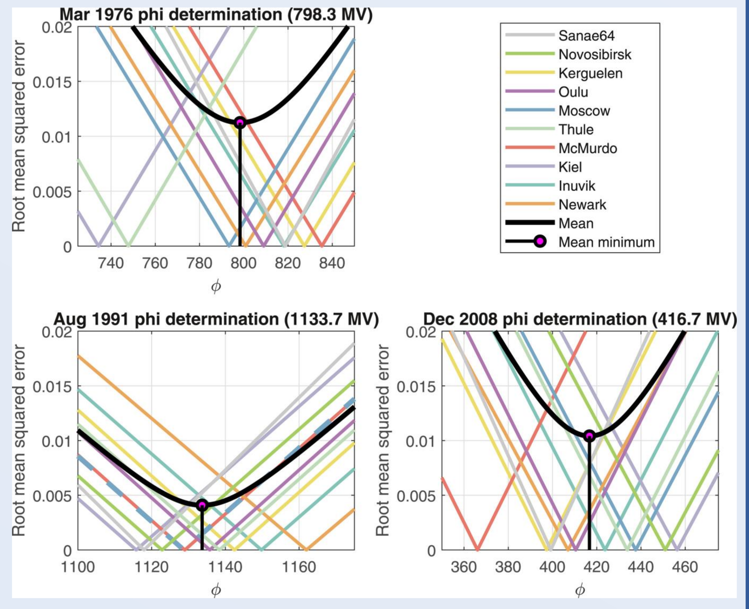

Figure 4. Examples of monthly determination of ϕ using RMSE

Modulation potential (V23)

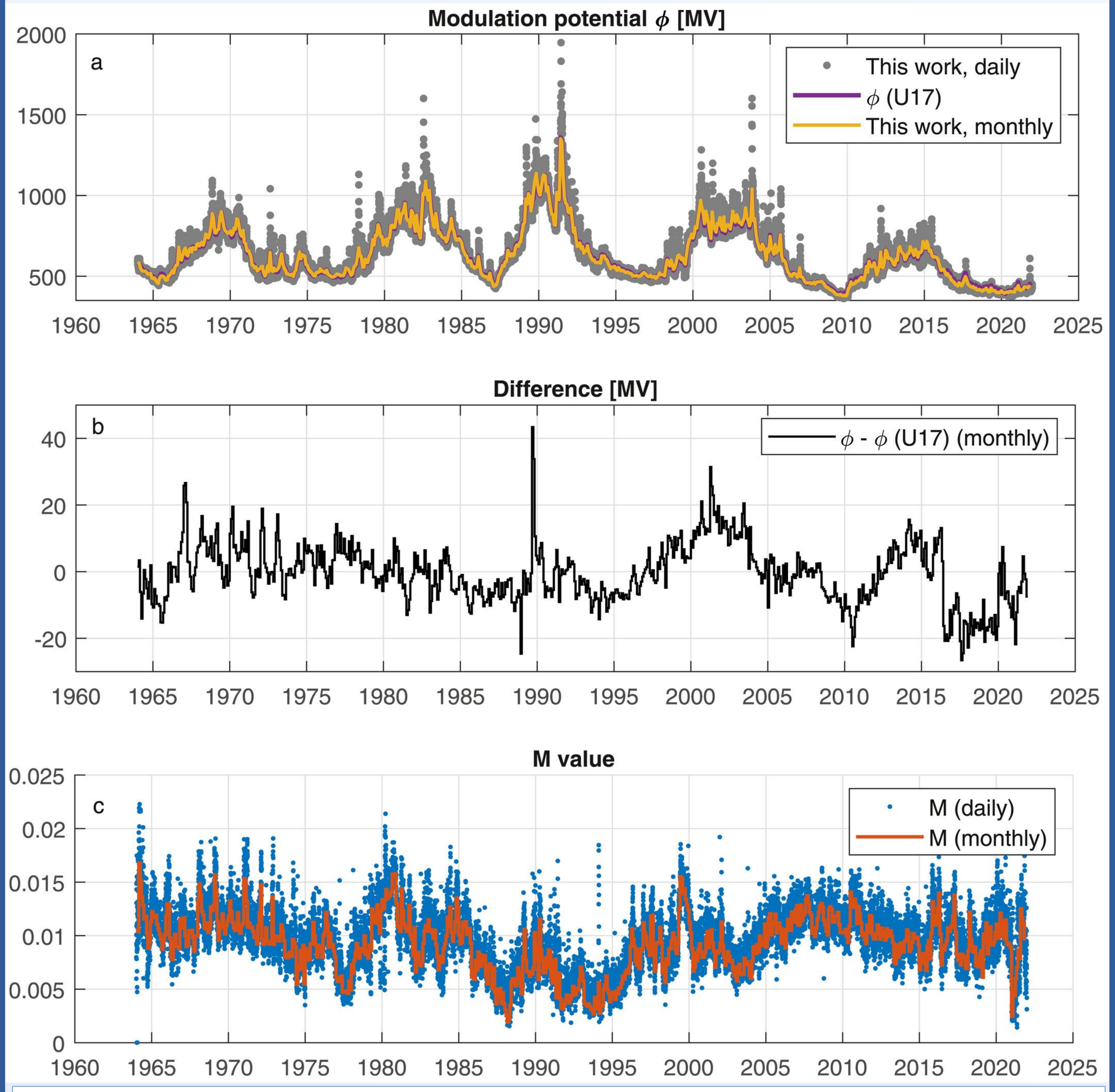

Figure 5. Panel a shows the monthly and daily phi values. Panel b shows the difference between V23 and U17. Panel c shows the residual merit function value, which can be interpreted as an error estimate.

- The new monthly result closely matches U17 with small +-20 MV differences.
- Jump in 2017-2019 is corrected
- Result in Sep-Oct 1989, which had strong solar disturbances, is changed the most.
- Changes in Pre-1973, probably related to some snow effects, will be addressed in future work.
- New daily version (Figure 6) provides more detailed information into short-term modulation and new opportunities for research.

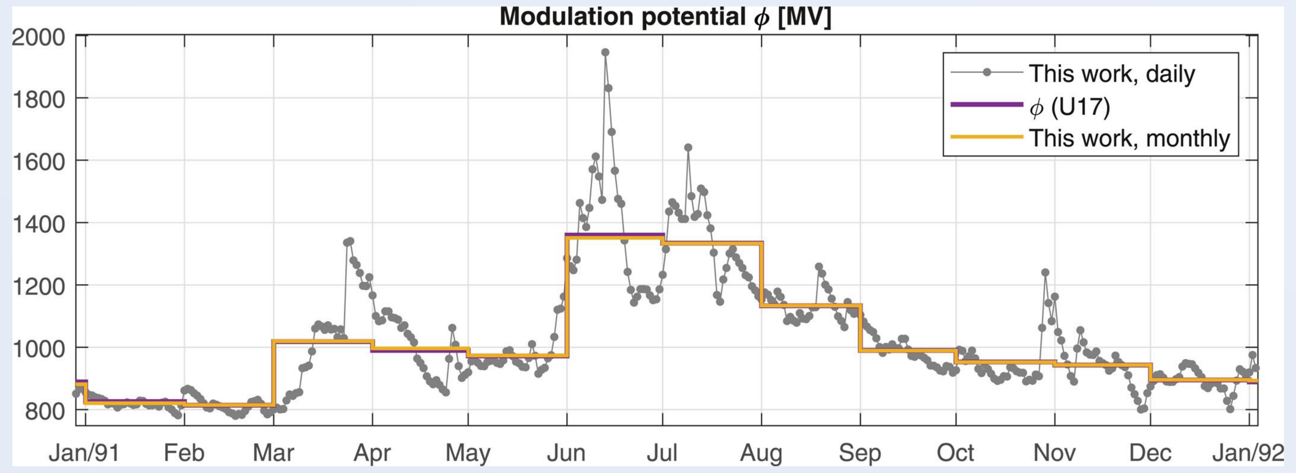

Figure 6. Zoom into 1991 of Figure 5.

Scaling factors

Variation of scaling factors also acts as a measure of reliability for both the model and the data quality of the stations. Station-specific results for both U17 and V23 are shown in Figure 7.

Further spectral analysis can reveal intermittent temporal variations in the scaling factor values, shown in Figure 8.

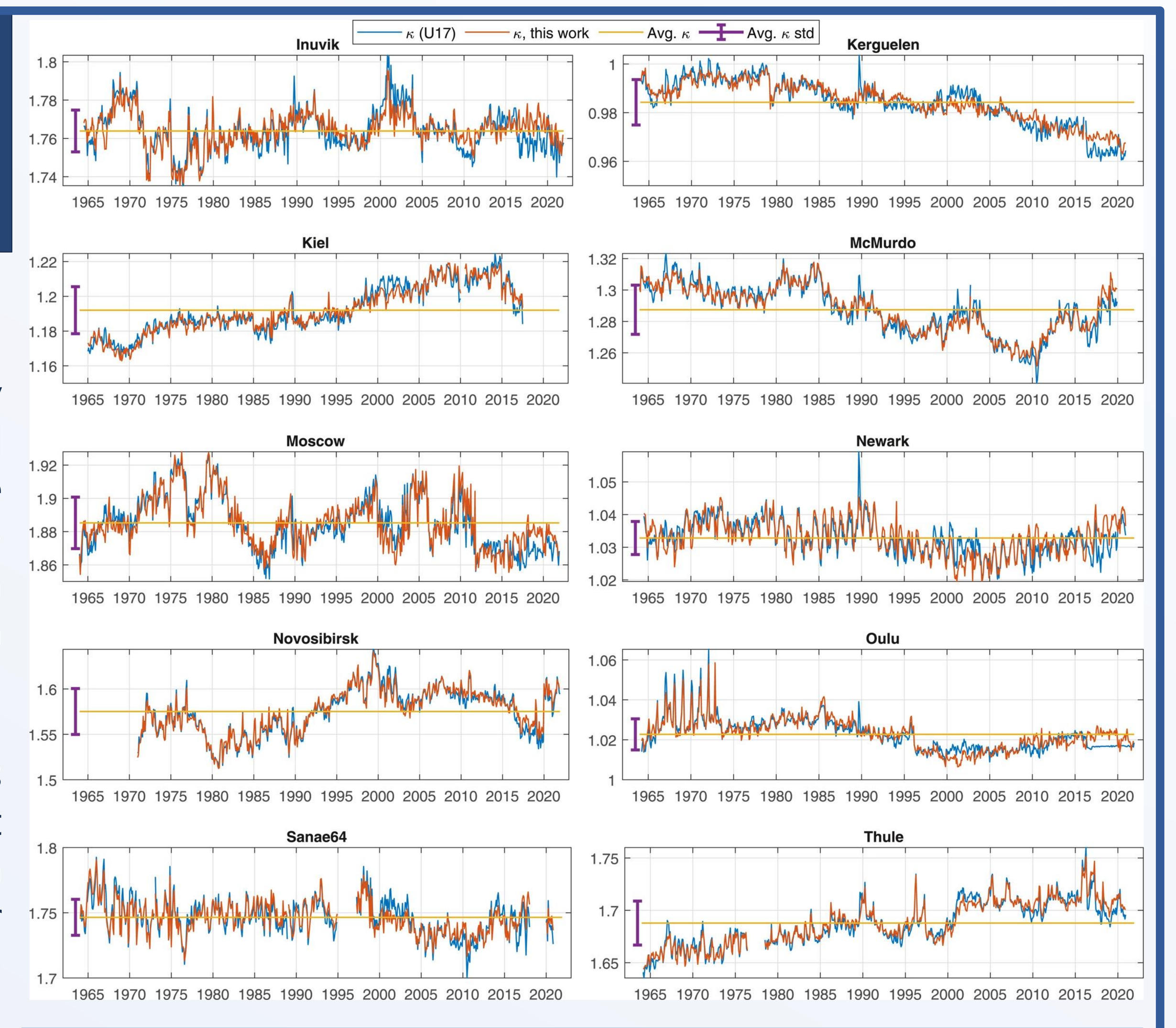

Figure 7. Station-specific scaling factors, blue lines show U17 and red lines V23 results

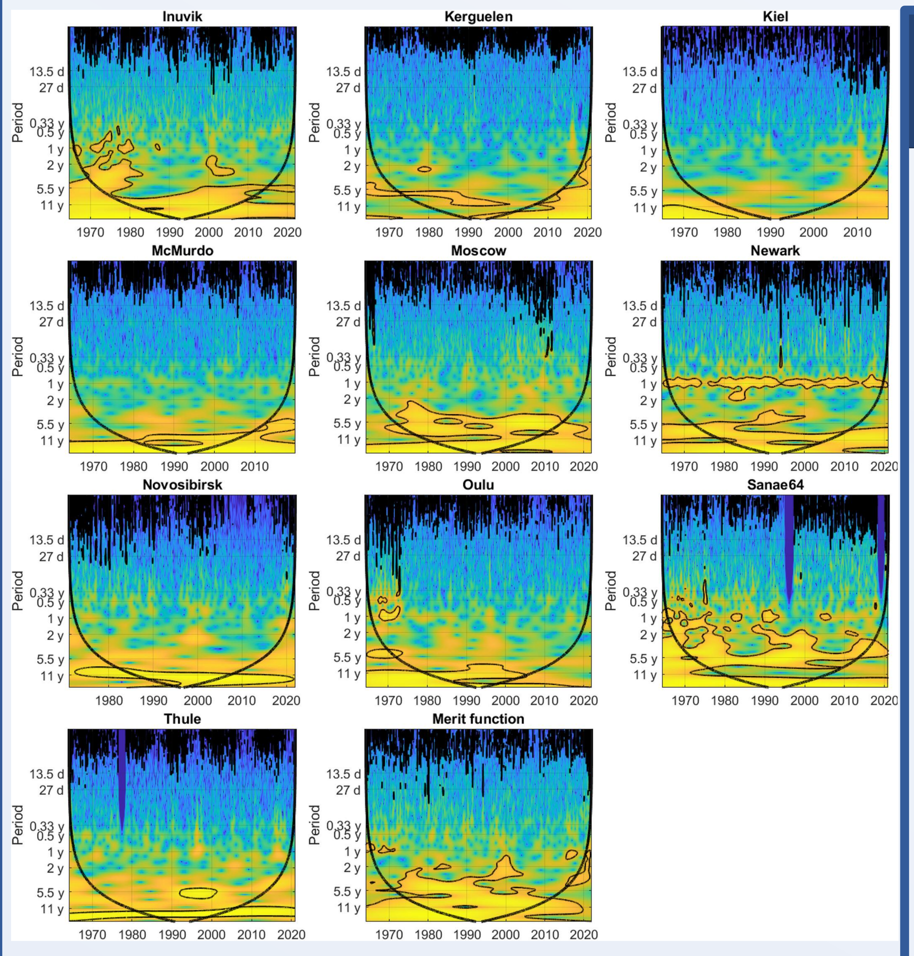

Figure 8: Wavelet scalograms (Morlet with k = 6) of the daily station-specific scaling factors and the merit function, as identified by a title on top of each panel. Y-axis represents the timescale in years and X-axis corresponds to the time where the wavelet is centered on. Red curves bound the cones of influence beyond which the wavelet results are unreliable. The black lines bound the 95% confidence level calculated against AR1 noise.

4. Summary

- We employed parametrized yield functions by Mishev et al. 2020 and a RMSE merit function method to compute new estimate of modulation potential and station-specific scaling factors.
- The method is fast and scalable to include more stations and possible data quality fixes/improvements in the future.
- The scaling factors can be used to check datasets for possible errors, drifts or new/unconsidered physical effects.
- Daily resolution of modulation potential can open new possibilities of research, e.g., on Forbush decreases and other events.
- Analysis was based on low cutoff stations, so future work for increasing number of high cutoff stations is needed.

Reference:

Väisänen, P., Usoskin, I., Kähkönen, R., Koldobskiy, S., & Mursula, K. (2023). Revised reconstruction of the heliospheric modulation potential for 1964–2022. Journal of Geophysical Research: Space Physics, 128, e2023JA031352. https://doi.org/10.1029/2023JA031352