PROCEEDINGS OF SCIENCE

Rigidity dependence of long-term cosmic ray variation

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Investigation of rigidity dependence of long-term cosmic ray variation with cosmic ray muon count rate on the ground requires correction for atmospheric pressure and temperature effect. Although a correction method developed by Mendoça [?] works well, we tried out machine learning technique as an alternative and confirmed it works for several years data[?]. In this study, we apply the machine learning technique to 50 years of long-term muon data. We demonstrate that correction with machine learning technique works well by comparing to Mendoça's method and by showing the variation amplitude is approximately proportional to the reciprocal of the median rigidity.

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1. Introduction

It is commonly known that long-term cosmic ray variation shows 11-year and 22-year periodicity. These variation have been analyzed mostly with cosmic ray data observed by neutron monitors, which observed ~ 10GV rigidity range. On the other hand, cosmic ray muon data remained underutilized due to atmospheric effect on its count rate. Development of correction method [**?**] for the atmospheric effect on muon count rate makes it possible to study long term variation in ~ 50 – 100GV rigidity range[**?**]. Although the correction method, called MSS method, works well, we test out another method using machine learning technique as an alternative. In this report, we perform machine learning on about 50 years of cosmic ray data observed by Nagoya multidirectional muon detector (MD). Rigidity dependence is also checked with Nagoya MD data and several NM data. Analysis period is from 1971 to 2021 covering more than four solar activity cycles.

2. Data

Table 1 shows median primary rigidities of used NM stations and Nagoya MD. Daily averaged count rate recorded between 1971 and 2021 in 17 directional channels of Nagoya-MD and 8 NMs is used. Count rates are corrected for atmospheric pressure and temperature effects and for gaps in the level of count rate caused by instrumentation. For the correction of the temperature effect, high altitude temperature data are acquired from the meteorological data provided by the Global Data Assimilation System (GDAS) at the NOAA's Air Resources Laboratory (ARL). Furthermore, data is available from webpage NMs : https://www.nmdb.eu/data/, Nagoya Station : http://cosray.shinshu-u.ac.jp/crest/DB/Public/main.php

3. Analysis and Result

Echo State Network (ESN), one of the reservoir computing framework, is applied to correct atmospheric effect on cosmic ray count rate on the ground. Detailed description of ESN method on correction of atmospheric effect can be fount in Kataoka et al., (2022)[**?**]. The spectral radius is chosen to be 0.95 following to Kataoka et al.(2022)[**?**]. It is necessary to ensure the legitimacy of

Table 1: used stations and their primary median rigidities

[h] Station	Pm [GV]	
SOPO	13.2	omni directilnal
MCMD	16.7	
THUL	16.7	
OULU	16.7	
INVK	16.7	
KIEL	16.7	
KERG	22.1	
ROME	22.2	
Nagoya	59.4 - 113.7	17 directional channel

this correction method. It is, however, complicated. Therefore, in this study, all period is used as "training period" and trained with 70 nodes to derive the result that gives the highest reproducibility of the result by MSS method, which is chosen to be a reference.

Atmospheric pressure is measured on site and high altitude temperatures at 16 layers, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10 hPa, above the station are down loaded from GDAS. The mass weighted temperature is derived from the same 16 layers data.

After correction, rigidity dependence of cosmic ray variation is inquired with the simple assumption,

$$\Delta I = k \left(\frac{P_m}{10[GV]} \right)^{\gamma}$$

where ΔI is cosmic ray variation, P_m is median primary rigidity, k is constant, γ is spectral index, and 10[GV] is a reference rigidity. Taking ratio $\Delta I_i / \Delta I_{NGO-V}$ for each NM stations and directional channels, indicated by subscript i, gives us,

$$\frac{\Delta I_i}{\Delta I_{NGO-V}} = \left(\frac{P^i_m}{P^{NGO-V}_m} \right)^{\gamma}$$

$\Delta I_i / \Delta I_{NGO-V}$ is derived as slopes of regresstion lines of correlation plots. Then, γ can be determined by LSM. It is expected to be around -1.0 from previous study[**?**]. We aim to obtain γ for each Carrington Rotation, whereas Munakata et al.(2019)[**?**] is derived on a yearly bases.

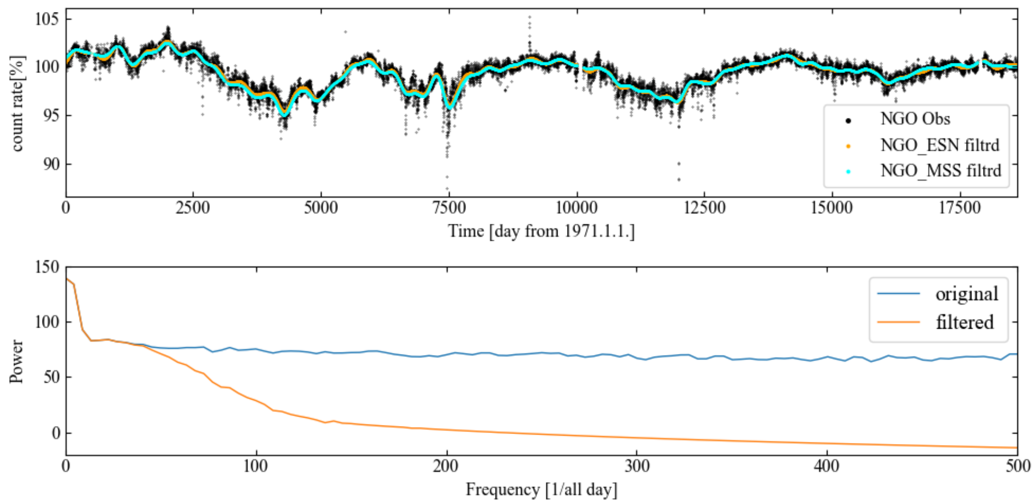

Figure 1: Top : Relative count rate of vertical directional channel at Nagoya MD. Atmospheric effects are corrected. Black dot shows daily average corrected by ESN. Orange and blue dots show filtered daily average by FFT filtering, after correction by ESN and MSS, respectively. Bottom : FFT power before (blue) and after (orange) filtering. The period longer than about 370 days are passed.

Top panel of figure 1 shows net count rate of vertical directional channel at Nagoya Station. Black marker is for daily average. Atmospheric effects are corrected by ESN method. There are several episodic large variations because of space weather events and/or remaining instrumental variation. To remove these variation and to focus on long term variation, we applied FFT filtering instead of removing data itself. The advantage of this method is to remain data points especially

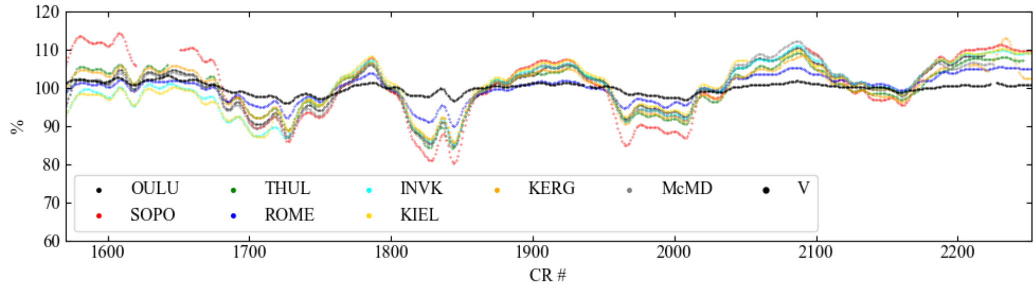

Figure 2: Relative count rate averaged over Carrington Rotation for vertical directional channel of Nagoya and NMs.

in solar maximum periods. It is also desirable for making Carrington Rotation average data. The period longer than about 370 days are passed with this filtering. The bottom panel of figure 1 shows FFT power before (blue) and after (orange) the filtering. Orange marker in the top panel is showing filtered data. The same filtered data corrected by MSS method is also shown as light blue marker. Results by ESN and MSS methods are compatibly. The filtering is also applied to 8 NM stations data. Figure 2 shows Carrigton Rotation average of vertical channel of Nagoya station and 8 NM stations. Although the amplitude of Nagoya station is smaller than NMs, there seems that 11-year and 22year cycle of variation in muon count rate, too.

Since the γ for each Carrington Rotation is not yet derived due to computational difficulty in non-linear fitting, we demonstrate average γ of whole period is reasonable. Figure 3 shows correlations between each NM stations and directional channels of Nagoya and vertical channel of Nagoya station. for total period of analysis. S3 directional channel is exclude because it is not well correlated. The slope of regression lines against median primary rigidities for each station is plotted in Figure 4. Blue line is fitted curve with derived gamma. The gamma is -1.14, and R^2 is 0.89. This result is consistent with Munakata et al.(2019)[**?**].

4. Summary

This study shows the machine learning technique can be applied to correct atmospheric effect on cosmic ray count rate for 50 years of long period. It will be studied to find the best parameters for optimization, training period, number of node, and so on. Result may be different from the result by MSS for higher period of variations. It is necessary to find a method to determine which is the more correct value, ESN or MSS.

Consistent γ value can be derived. Among the correlation diagrams, however, there are several directional channels, in which regression line is not well fitted, such as SW, S2, N2, and W3. Without these channels, γ and R^2 are -1.08, and 0.93, respectively. This may be because of different correlation in different time and may be relevant to cosmic ray modulation. It would be necessary to investigate the Carrington Rotation-by- Carrington Rotation and/or year-by-year variation of γ for resolving this question.

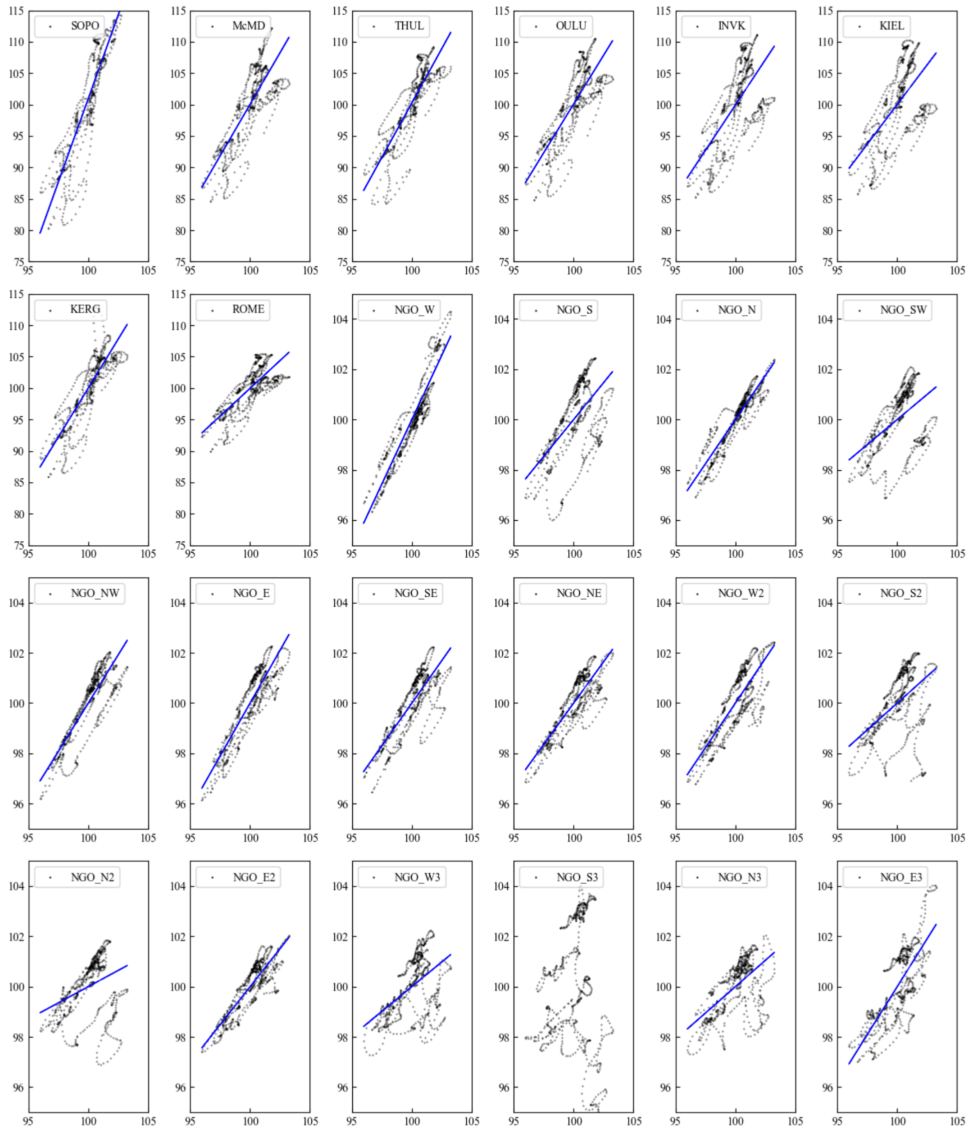

Figure 3: Correlation diagrams for NMs and directional channels of Nagoya to vertical channel of Nagoya Station. Blue lines are regression lines.

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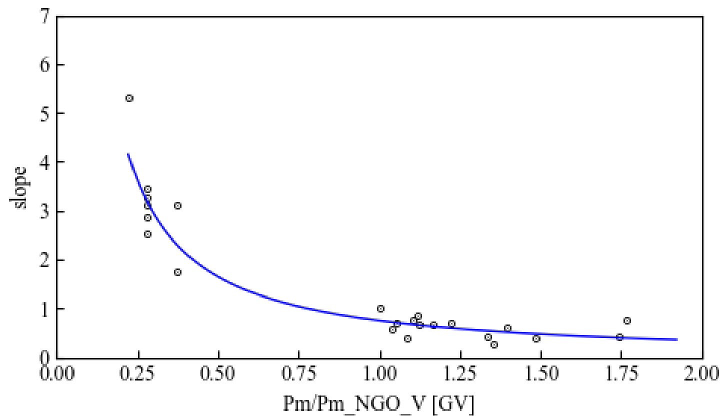

Figure 4: The slope of regression lines in Figure 3 and median primary rigidities relative to vertical channel of Nagoya station. Blue line is fitted curve with derived gamma value.

tron monitor data from South Pole and the South Pole Bares are provided by the University of Wisconsin, River Falls. Kerguelen neutron monitor data were kindly provided by Observatoire de Paris and the French polar institute (IPEV), France. The neutron monitor at Kiel (Germany) is operated by the Extraterrestrial Physics Department of the Institute for Experimental and Applied Physics of the Christian-Albrechts University of Kiel. Oulu neutron monitor data are provided by the Sodankyla Geophysical Observatory (https://cosmicrays.oulu.fi/) We acknowledge the NMDB database (http://www.nmdb.eu), founded under the European Union's FP7 program (contract no. 213007) for providing data.

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