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The Kp Index and Behavior of Quiet Periods

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Abstract

The Kp-index quantifies the electromagnetic effects in the Earth's atmosphere and is used in a variety of scientific fields. Higher Kp values tend to be the focus in these fields as they relate to high solar activity and geomagnetic storms. This study aimed to examine the significance, if any, of lower Kp indices. A simple data analysis was performed on continuous sequences of low Kp values, deemed Quiet Periods. Both the daily average of the values and the full set of Kp data were used. A decaying exponential relationship was discovered between the length of these periods and their frequencies and then probabilities. Higher thresholds on the maximum allowed Kp value during a Quiet Period resulted in more gradual rates of decay. For the daily averages, the time constants of the probability distributions were found to be exponentially related to the threshold values. This relationship was not observed when the full data set was used. Discrepancy between the two data sets is concerning but could simply be due to a smoothing effect of averaging. The resulting probability distributions could prove useful in the prediction of Kp values.

Introduction

The Kp-index is used to quantify electromagnetic effects in the Earth's magnetic field. There are several applications of the Kp-index, including the prediction and measurement of geomagnetic storms, modeling physics-based geospace, and data selection for ionospheric, thermospheric, and magnetospheric studies [1].

Most of the research and interest involving the Kp-index focuses on the higher magnitude values. However, in this new solar cycle there has been a dramatic decrease in large geomagnetic storms and a rise in the number lower Kp values. In examining the intervals of low space weather activity, we hope to better understand the behavior of these periods and their relation, if any, to high magnitude events and the solar cycle. The features of these "Quiet Periods" must first be examined through statistical analysis of Kp-index data over time. That is the principle focus of this study, so future research can work toward discovering what activity these periods truly contain.

Theory

The Kp-index was created in 1949 by Julius Bartels to rank and describe electromagnetic effects and space weather due to solar wind interacting with the Earth's magnetic field. The K-index, introduced by Bartels in 1938, rates the intensity of magnetometer measurements over 3-hour periods (8 measurements per day) on a scale of 0-9. The 'K' label comes from the German word "Kennziffer" which means characteristic digit [2]. The Kp-index averages the standardized K values for each 3-hour window using the data from 13 different geomagnetic observatories around the world (FIG 1).

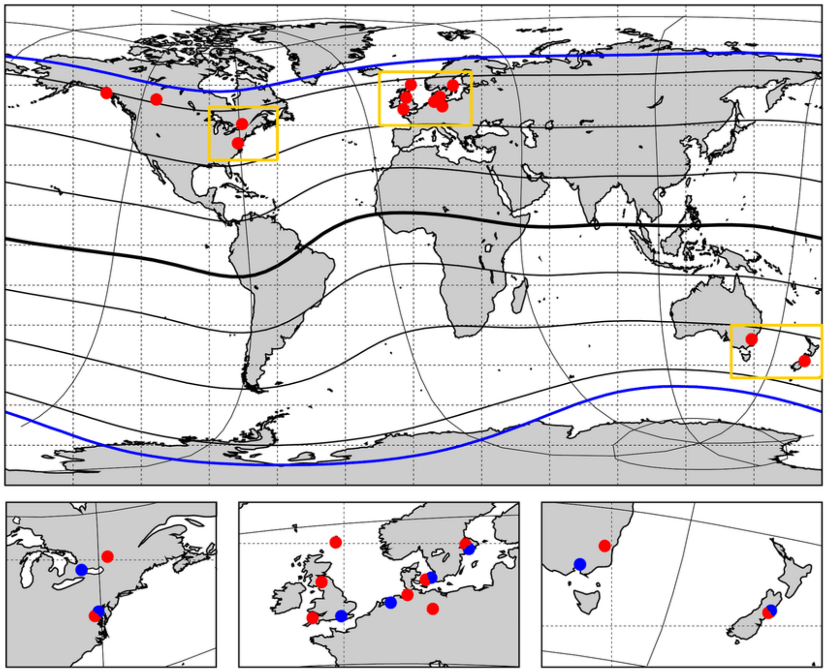

Figure 1. Locations of the 13 Geomagnetic Observatories.

Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Upper-panels-World-map-of-the-13-current-Kp-stations-red-dots-see-also-Table2-with_fig2_350044969

The Kp-index, like the K-index, also ranges from 0-9 with 27 discrete values. A +/- sign indicates adding/subtracting 0.333 to the index. For example, a Kp value of 1.333 can also be written as 1+, and a Kp value of 4.667 can be written as 5-. Values of 0-4 translate to low activity and 5 or greater indicate a geomagnetic storm, with intensity increasing in amplitude to Kp 9. The Kp values of 5-9 correspond to the National Oceanic and Atmospheric Association (NOAA) G-Scale, which ranges from G0 to G5 (G0 meaning no activity or a 0-4 Kp) [3].

The K-index for a 3-hour period is derived from the difference between the maximum and minimum magnetometer reading for that period. This variance is converted from nanoteslas to K indices using a logarithmic scale [3]. Figure 2 shows raw magnetometer data taken at the Reeve Observatory located in Anchorage, Alaska, and the corresponding K values for each period.

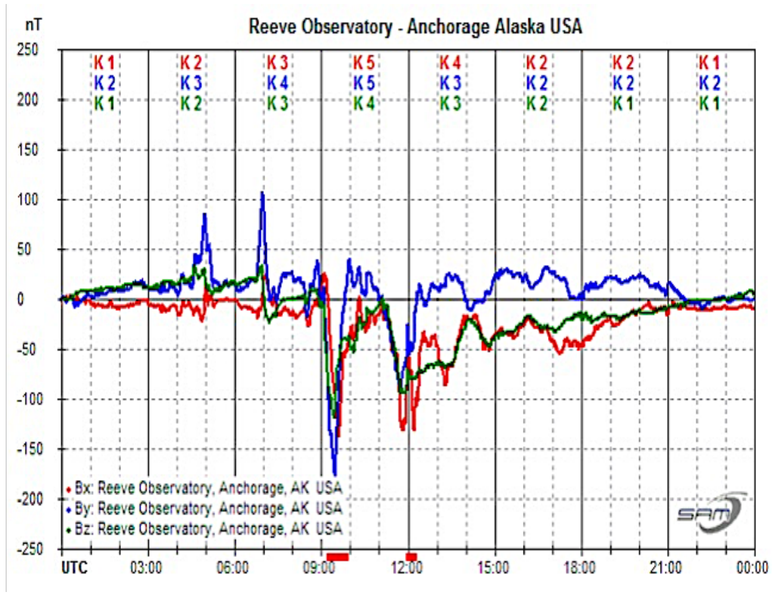

Figure 2. Magnetometer data from the Reeve Observatory in Anchorage, AK USA.
https://reeve.com/MagnetometerM3.htm

Procedures

All the recorded Kp data from January 1st, 1932, to September 20th, 2022, was downloaded from the German Research Centre for Geosciences (GFZ) website [4]. This data was then uploaded into an Excel spreadsheet. In the first part of the analysis, each of the 8 daily Kp values were rounded to their nearest integer value and summed together to get a total daily Kp value. Plots of total daily Kp versus time and the frequency of each value were made in excel.

A threshold of different total daily Kp values were applied to the data set. The length of periods with continuous total daily Kp values at or below the threshold (Quiet Periods) were recorded using loops in python (see supplementary materials). Plots for the frequency as well as probabilities of Quiet Period lengths were created for various thresholds Formulas for the relationships were determined using python curve fitting. The time constant of the probability formulas were then plotted against their threshold values.

Results

Plots for the frequency of daily Kp values are shown in Figure 3. The distribution for the entire dataset is skewed to the right with a mean Kp value of 17 and median 16. The highest total daily Kp of 67 occurred on November 13th, 1960. The plots of the highly active year 1951 and less active year 2001 illustrate the differences between the distributions of total daily Kp. As expected, the less active year is skewed further to the right, with a lower mean, while the active year is closer to a symmetric distribution.

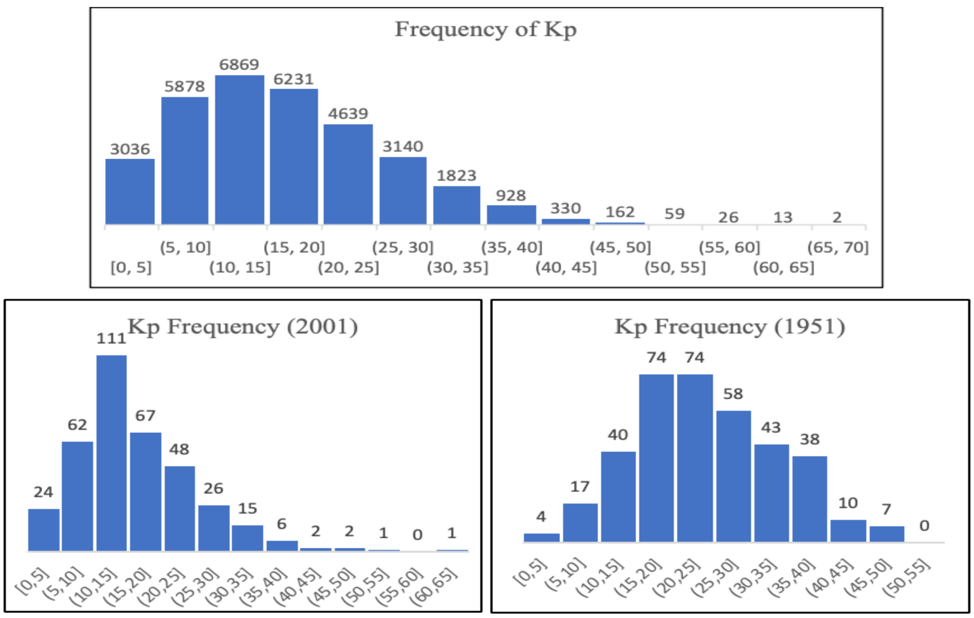

Figure 3. Frequency Distributions of Daily Kp for all data, 2001, and 1951.

A more interesting result comes from observing the distributions of Quiet Periods with daily Kp values less than a given threshold. An exponential decay relationship was noticed between the length of these quiet periods and their frequencies. Curve fitting functions of the form $Ae^{-t/\tau}$ to the plots resulted in little to no noise. From these frequency distributions, probability distributions were easily created (FIG 4).

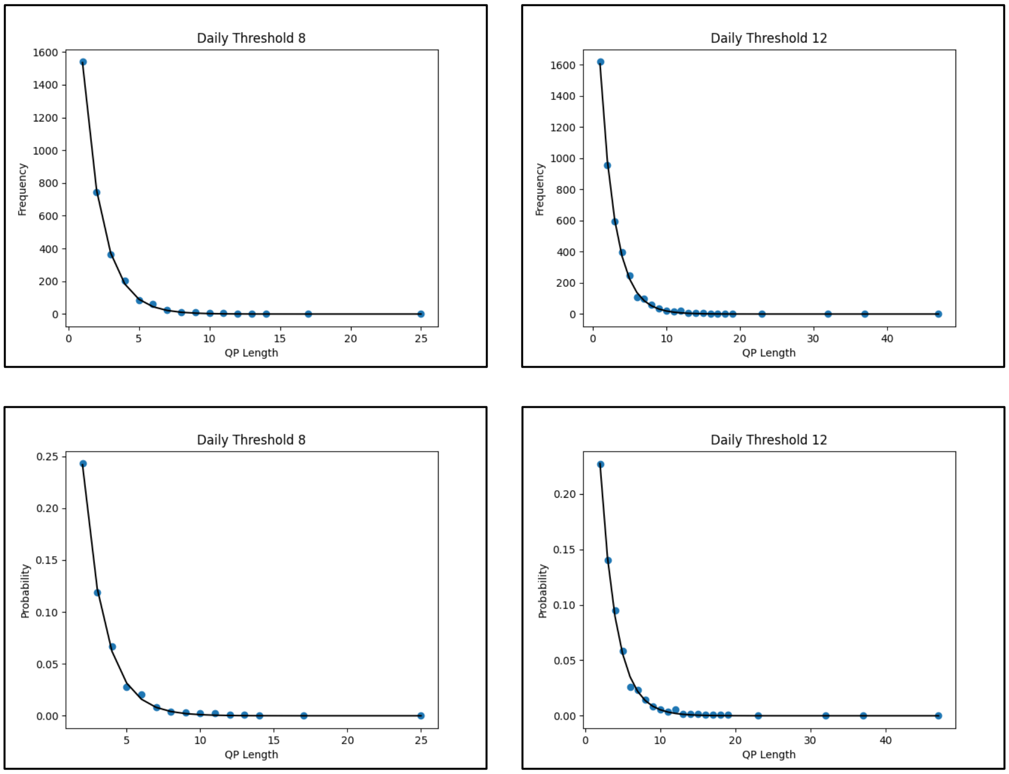

Figure 4. Daily sum frequency vs QP length (above) and probability vs QP length (below) plots.

When using each of the 8 daily Kp values rather than their sum this exponentially decaying relationship is not as strong (FIG 5). There is still a rapid drop in frequency/probability and Quiet Period length increases. However, the distributions do not fit the exponential decay functions as seamlessly.

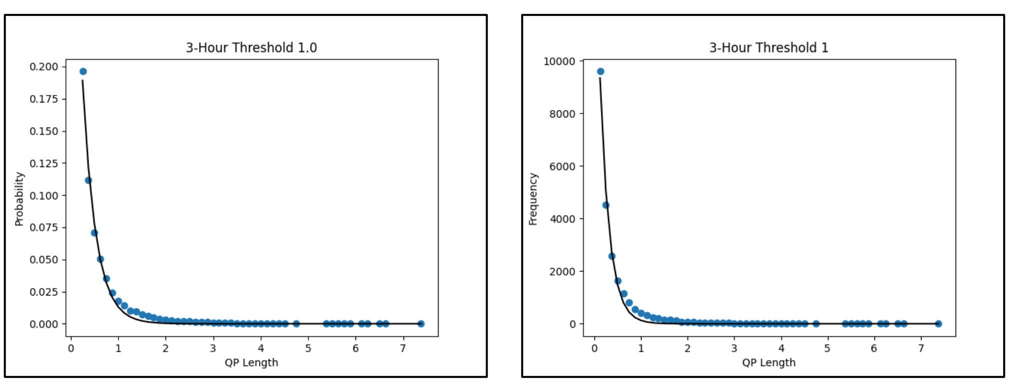

Figure 5. Full data frequency vs QP length (left) and probability vs QP length (right) plots.

From each of the probability functions a time constant (τ), with units of days, was determined and plotted against the Kp threshold values (FIG 6). An exponential trendline is present in the case of the daily sums, but no such relationship exists from the 3-hour data.

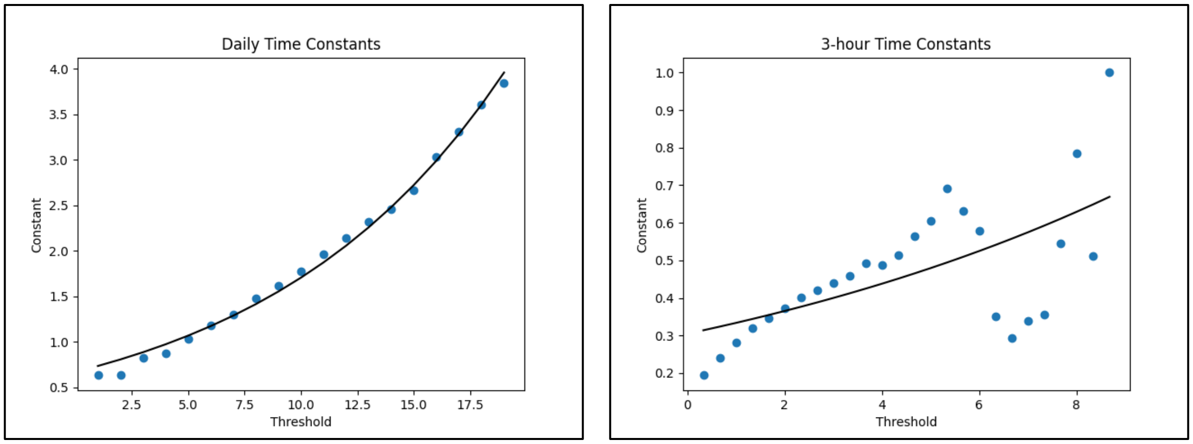

Figure 6. Plots and formulas of the QP threshold and resulting time constants.

Conclusion

The relationship between the length of Quiet Periods and their frequencies/probabilities is quite intriguing. However, the inconsistency in behavior between the daily sum and full 3-hour data is a bit off-putting. What leads the results to differ in this way? One simple explanation could be that using the sum smooths out any irregularities of the 8 discrete values. The variance throughout the day is averaged out when the sum is used. Another explanation is that a different function, with different parameters may be a better fit for the data. Finally, human error within the code that generated these plots could also be the source of this disagreement.

Although it may not be as straightforward as we had hoped, there is some distinct relationship between the frequency/probability and Quiet Period length. At the very least, this research produced probability functions for Quiet Period lengths under a given threshold. How likely a quiet period is to continue could prove useful in the prediction of both high and low Kp values.

So far, our analysis of Quiet Periods has been focused on data manipulation. Future research may wish to uncover what the patterns in the data represent physically. First the disconnect in the results of this study should be resolved. Then the goal is it uncover the underlying implications or causes of this behavior.

Supplementary Materials

Supplementary materials for this report can be found in the file KpDataAnalysis.zip. See the table below for a summary of the archive file contents.

Filename	Content
Kp Data.xlsx	Excel spreadsheets of Kp data and plots
KpDataAnalysis(DailySum)	Folder with all python code for daily sums
KpDataAnalysis(FullData)	Folder with all python code for 3-hour data

Bibliography

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