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Insignificant solar-terrestrial triggering of earthquakes

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[1] We examine the claim that solar-terrestrial interaction, as measured by sunspots, solar wind velocity, and geomagnetic activity, might play a role in triggering earthquakes. We count the number of earthquakes having magnitudes that exceed chosen thresholds in calendar years, months, and days, and we order these counts by the corresponding rank of annual, monthly, and daily averages of the solar-terrestrial variables. We measure the statistical significance of the difference between the earthquake-number distributions below and above the median of the solar-terrestrial averages by χ^2 and Student's t tests. Across a range of earthquake magnitude thresholds, we find no consistent and statistically significant distributional differences. We also introduce time lags between the solar-terrestrial variables and the number of earthquakes, but again no statistically significant distributional difference is found. We cannot reject the null hypothesis of no solar-terrestrial triggering of earthquakes. **Citation:** Love, J. J., and J. N. Thomas (2013), Insignificant solar-terrestrial triggering of earthquakes, *Geophys. Res. Lett.*, *40*, 1165–1170, doi:10.1002/grl.50211.

1. Introduction

[2] In the search for reliable methods for predicting earthquakes, geophysicists have sometimes investigated natural phenomena that might affect their occurrence likelihood. In the context of critical-point accumulation of stress on a fault, a small "nudge" might be all that is needed to trigger an earthquake. The list of unconventional phenomena that might provide such a triggering nudge is long, and their relative importance has historically been controversial [e.g., *Omori*, 1908]. The great solar astronomer *Wolf* [1853] suggested that sunspots could influence the occurrence of earthquakes. Qualitatively, a solar-terrestrial effect on seismicity, if one exists, would almost certainly require some sort of coupling between the Sun, solar wind, magnetosphere, and lithosphere. This coupling might, for example, cause small changes in the Earth's rotation rate, and these could result in more earthquakes [*Sytinskiy*, 1963; *Gribbin*, 1971]. Alternatively, magnetic storms might induce eddy electric currents in rocks along faults, heating them and reducing their shear resistance [*Han et al.*, 2004], or induced currents might cause a piezoelectric increase in fault stress [*Sobolev and Demin*, 1980]. In either case, earthquakes might be triggered. These theories are speculative; they have not yet been sufficiently developed to permit reliable predictions of future earthquake occurrence probability.

[3] A number of published papers have reported, from empirical analysis of historical data, that there is a detectable nonrandom relationship between solar-terrestrial interaction and earthquake occurrence. Some of these reports are inconsistent with each other, and some are based on only selected subsets of the available data. For example, over long time scales, global seismicity has been reported to be highest during solar-cycle sunspot maximum [e.g., *Odintsov et al.*, 2006] and, very differently, highest during the declining phase and minimum of the solar cycle [e.g., *Simpson*, 1967; *Huzaimy and Yumoto*, 2011]. Over shorter time scales, global seismicity has been reported to be correlated with solar-quiet geomagnetic variation [e.g., *Duma and Ruzhin*, 2003; *Rabeh et al.*, 2010], with geomagnetic disturbance [e.g., *Simpson*, 1967], and with enhanced solar wind velocity [e.g., *Odintsov et al.*, 2006]. There have also been reports that regional seismicity is correlated with magnetic-storm occurrence [e.g., *Sobolev et al.*, 2001; *Bakhmutov et al.*, 2007]. Some reports have focused on a few large earthquakes [e.g., *Mukherjee*, 2006; *Anagnostopoulos and Papandreou*, 2012].

[4] The statistical significance of a possible correlation between sunspots and seismicity has occasionally been questioned [e.g., *Jeffreys*, 1938; *Meeus*, 1976], and for certain geographic regions, correlation between solar-terrestrial variables and seismicity has actually been shown to be insignificant [e.g., *Stothers*, 1990; *Yesugey*, 2009]. Still, reports that identify such correlations continue to be published, especially lately. The public finds the possibility of a causal connection between the Sun and earthquakes to be interesting, as evidenced by the speculative accounts that are sometimes published in the popular press [e.g., *Hudson*, 2011] and the need for the U.S. Geological Survey to post responses on its website to related "frequently asked questions." In light of all this, and in recognition of the importance of earthquake prediction, we are motivated to conduct our own retrospective analysis of historical data recording sunspots, solar wind, geomagnetic activity, and global earthquake occurrence. In the spirit of classical hypothesis testing [e.g., *Stuart et al.*, 1999, chapter 20], we seek to reject the null hypothesis that solar-terrestrial interaction plays no role in triggering earthquakes.

2. Inspection and Selection Biases

[5] Given two statistically independent time series of finite duration, it is always possible, with retrospective inspection, to find an illusionary relationship of some type. For example, it has been claimed that stock market performance has, in the past, been correlated with the phases of the moon [e.g., *Yuan et al.*, 2009], a conclusion that some researchers assert was obtained after subjectively searching data sets until something seemingly "interesting" was found [e.g., *Crack*, 1999]. This correlation lacks a known causal basis, and by

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retrospectively focusing attention on its presence, one might be seduced by "inspection bias." To avoid this, the correlation should be shown to be both persistent and detectable in a second "objective" data set that was not used in the original identification of the correlation. Ideally, an entirely new objective data set should be prospectively collected—after—predicting a correlation of the same type as seen in the first data set [e.g., *Feynman*, 1998, pp. 80–81]. "Significance" is assigned if a correlation of the size measured in the objective data set would be an unlikely realization from a null-hypothesis random process. While many published geophysical reports quote retrospective probabilities of correlational "significance" using the very same data used in the identifications of the correlations, technically, these can only support either pessimistic or neutral conclusions. If a retrospective significance probability is large, then the null hypothesis of randomness cannot be rejected, and the persistence of the correlation must be regarded with skepticism, even without consideration of a second objective data set. If a retrospective probability is small, the correlation cannot be regarded as persistent until a significant correlation is shown to exist in a second objective data set.

[6] Related to all of these issues are the the difficulties posed by "selection bias" [e.g., *Mulargia*, 2001]. It is natural for the attention of a scientist to be drawn to rare and unusual occurrences, such as the "clustering" of several geophysical events in time. It is even sometimes tempting to consider more isolated occurrences, such as a single great earthquake that happened to be preceded by a magnetic storm or a longish duration of magnetic disturbance. A pair of unusual events can represent an opportunity for new insight, provided that the temporal relationship of the events has a valid causal explanation. Otherwise, there is the danger of falling for a logical fallacy—just because one event occurs immediately before another does not mean that they are related [e.g., *Woods and Walton*, 1977]. More generally, a correlation that might have seemed interesting in a small and subjectively selected data set will not necessarily be measurably significant in a second objective data set. In which case, the null hypothesis of randomness cannot be rejected, and the persistence of the correlation must be regarded with skepticism. If, for whatever practical reason, a subset of the available data must be selected, then, for objectivity, the selection should be made on the basis of properties that are independent of the statistical properties being analyzed.

3. Data

[7] We analyze four different data time series that span the physical domain of interest: (1) monthly sunspot group numbers G, obtained from NOAA's National Geophysical Data Center for years 1900–2012 [*Hoyt and Schatten*, 1998]; (2) daily average solar wind velocity V measured by near-Earth, extra-magnetospheric spacecraft, 1963–2012, obtained from NASA's OmniWeb project; (3) daily average geomagnetic-activity AA, obtained from the British Geological Survey, 1900–2012 [*Mayaud*, 1980], and (4) earthquake magnitudes $M \geq 7.5$ and their occurrence times (year, month, day), obtained from the USGS National Earthquake Information Center, 1900–2012. The earthquake catalog is known to be biased for small earthquakes; there is, for example, an excess of $7.0 \leq M < 7.5$ events for the first half of the 20th century compared to the second; a difference that is thought not to be geophysical [*Engdahl and Villaseñor*, 2002]. We concentrate our analysis of statistical significance on $M \geq 7.5$ earthquakes. We use an earthquake list derived from the NEIC catalog that has been declustered for aftershocks [*Michael*, 2011]. All the data are shown as time series in Figure 1. Sunspot G records both the familiar ~ 11 year solar-cycle modulation and long-term secular change in cycle amplitude. Geomagnetic AA also records solar-cycle modulation, but because geomagnetic activity is driven by a combination of coronal mass ejections from sunspot active regions and semi-persistent high-speed streams of solar wind that are most prevalent during the declining phase of a solar cycle, peak geomagnetic activity tends to follow peak sunspot number by a couple of years. Enhancements of solar wind V and resulting geomagnetic AA tend to be intermittent; both time series show substantial variance over time.

4. A Few Examples

[8] In Table 1 we list the number N of $M \geq 7.5$ earthquakes in the month and year following the three most geomagnetically active days as measured by AA over the duration 1900–2012. In general, solar-terrestrial conditions are often modulated with the 27 day rotation of the Sun, and, therefore, it is natural to consider average solar-terrestrial conditions over time scales of a month or so. The great magnetic storm of November 1960 had the highest daily average of geomagnetic disturbance since 1900, $AA = 340.74$ nT. In the month that followed, there was one $M \geq 7.5$ earthquake, while the average for 1900–2012 is 0.28/month. Three $M \geq 7.5$ earthquakes followed in the year after the 1960 storm, slightly below the long-term average of 3.38. The seismicity that follows the two other storms listed in Table 1 also does not show any obvious systematic relationship. Of course, without considering data covering longer durations of time and including many earthquakes, it is impossible to draw any definitive conclusion from these few examples.

[9] Conversely, in Table 2 we list the solar-terrestrial conditions in the month preceding the three largest earthquakes during the years 1900–2012. Prior to the 1960 M9.5 Chilean earthquake, the monthly sunspot number $G = 109.60$ was higher than the long-term average of 58.42; the cumulative-exceedance probability $CE = 0.17$ indicates that this was only moderately unusual. No solar wind data are available for 1960. The average level of magnetic activity in the month before the earthquake $\mu_{AA} = 39.69$ nT was higher than the long-term average of 19.83 nT; the cumulative-exceedance probability $CE = 0.02$ indicates that this was rather unusual. The standard deviation of daily geomagnetic-activity levels about the monthly mean, $\sigma_{AA} = 39.75$ nT, indicates that the level of geomagnetic activity was fluctuating quite a bit. In contrast, solar-terrestrial conditions were much more calm during the month preceding the 1964 M9.2 Alaska earthquake and the 2004 M9.1 Sumatra-Andaman earthquake. Note in particular that the standard deviation of solar wind velocity and geomagnetic activity in the month preceding the Sumatra-Andaman earthquake was actually less than the long-term average.

[10] These observations stand in curious juxtaposition with the analysis of *Anagnostopoulos and Papandreou* [2012]. They retrospectively identified a seemingly significant correlation between maxima in the time variation of solar wind velocity and geomagnetic activity with the occurrence of six $M \geq 6.8$ earthquakes during the month of time that culminated with the Sumatra-Andaman earthquake. Given the devastation that resulted from this earthquake, these results might be regarded as possibly important. However, we know of no physical process that would lead

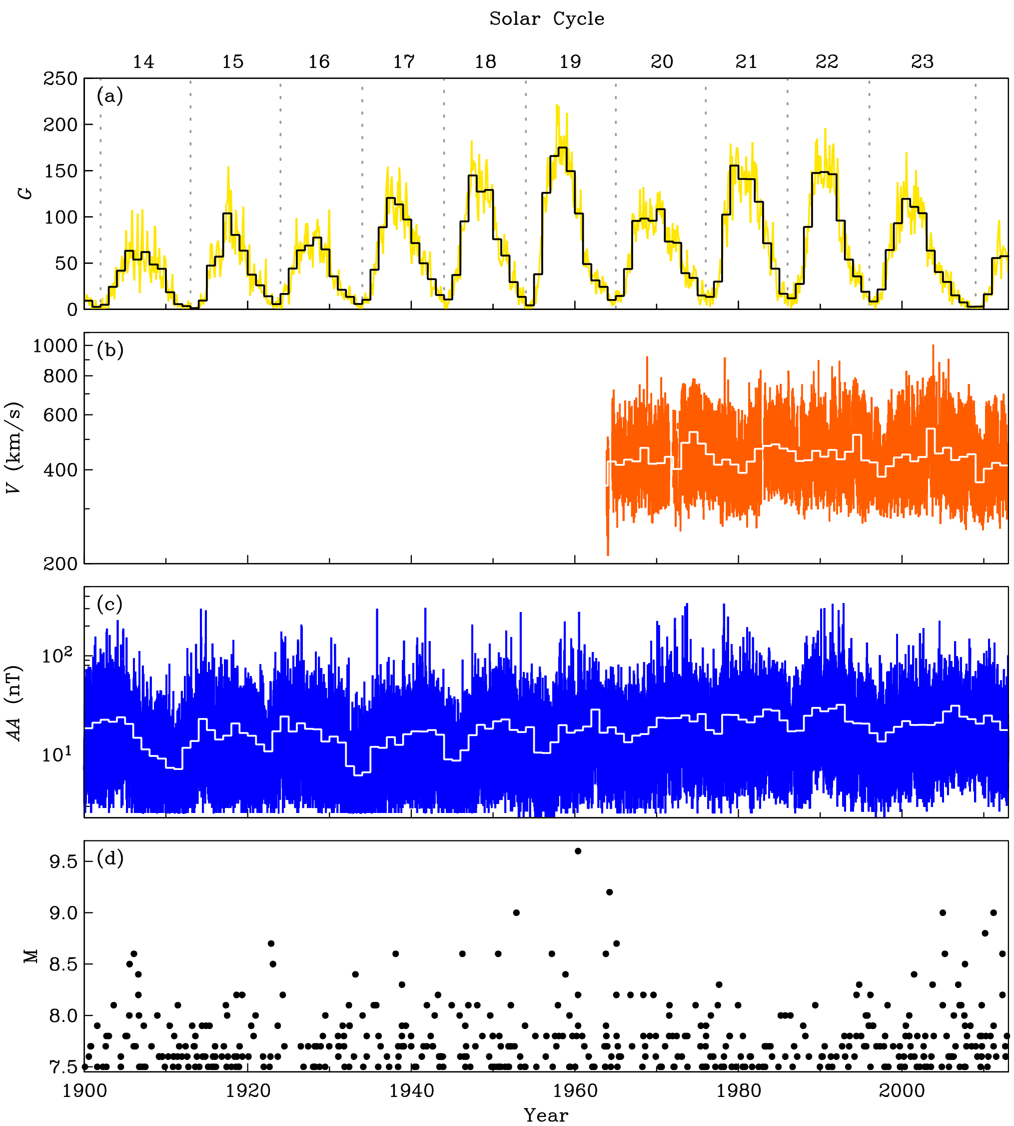

Figure 1. Time series of (a) monthly sunspot group number G (yellow) and annual averages (black), (b) universal-day averages of near-Earth solar wind velocity V (orange) and annual averages (white), (c) universal-day averages of the geomagnetic-activity index AA (blue) and annual averages (white), and (d) global earthquake magnitudes, shown here for $M \geq 7.5$.

Table 1. Number of $M \geq 7.5$ Earthquakes in Month and Year Following Three Great Magnetic Storms

Storm	AA (nT)	Year	Month	Day	N/month	N/yr
	340.74	1960	Nov	13	1.00	3.00
	340.74	1941	Nov	18	1.00	5.00
Québec	338.41	1989	Mar	13	0.00	3.00
μ 1900–2012	19.83				0.28	3.38

to a statistically detectable triggering by the relatively typical solar-terrestrial conditions that preceded these earthquakes. *Anagnostopoulos and Papandreou* [2012] have not yet shown that their correlation can be detected outside of the one month of time that they considered, nor, more stringently, have they used their correlation to successfully predict earthquake probabilities in the future. Until they do, their reported correlation must be regarded with skepticism.

Table 2. Solar-Terrestrial Conditions in the Month Preceding Three Great Earthquakes

Earthquake	M	Year	Month	Day	G	CE	μ_V (km/s)	σ_V (km/s)	CE	μ_{AA} (nT)	σ_{AA} (nT)	CE
Valdivia, Chile	9.5	1960	May	22	109.60	0.17				39.69	39.75	0.02
Alaska, United States	9.2	1964	Mar	28	15.10	0.77				20.18	15.10	0.44
Sumatra-Andaman, Indonesia	9.1	2004	Dec	26	17.90	0.73	457.35	74.04	0.31	21.78	10.35	0.36
μ 1900–2012					58.42		440.51	88.55		19.83	16.98	

5. χ^2 and Student's Hypothesis Tests

[11] Instead of focusing on specific historical anecdotes or short, retrospectively chosen periods of time which encompass only a few earthquakes, we choose to conduct a statistical analysis on the entirety of the long, historical time series summarized in section 3. In Figure 2 we show the number of $M \geq 7.5$ earthquakes per year versus the ordered rank of annual average sunspot number G, 1900–2012 (Figure 2a), solar wind velocity V, 1963–2012 (Figure 2b), and geomagnetic activity AA, 1900–2012 (Figure 2c). So, for example, the lowest (highest) ranked annual sunspot number is 1.60 (175.10) for the year 1913 (1958), when there were five (three) $M \geq 7.5$ earthquakes. Qualitatively, there is no visually obvious relationship between the ranks of annual averages of solar-terrestrial variables and the annual number of earthquakes. More objectively, the difference between the distributions of the annual number of earthquakes for the solar-terrestrial averages falling below the median (green) and those above the median (brown) can be measured by a χ^2 test [e.g., *Press et al.*, 1992, chapter 14.3, "chstwo"]. The difference between the means of the distributions can be measured by a Student's t test [e.g., *Press et al.*, 1992, chapter 14.2, "tutest"]. Statistical significance is given by the probability p that a difference larger than that actually measured could have arisen from random and normally distributed data.

[12] In Table 3 we list the total number of earthquakes N (N_{63}) exceeding given magnitude thresholds, $M \geq 9.0, 8.5, \ldots$ for years 1900–2012 (1963–2012). We also list χ^2 p-value significance probabilities for distributional differences between earthquake counts below and above the median of annual, monthly, and daily averages of the solar-terrestrial variables G, V, and AA. It is important to recognize that none of these probabilities are consistently indicative of statistically significant distributional differences (green versus brown). In Table 4, we list the mean of the annual number of earthquakes exceeding different magnitude thresholds that are below, $\mu_<$, and above, $\mu_>$, the median of the annual averages of G, V, and AA. We also list Student's p-value significance probabilities for differences between these means. For solar wind V and $M \geq 8.5$, we have the smallest probability, $p = 0.04$. Given the number of significance tests performed here, however, this isolated result cannot actually be taken as indicating statistical significance; even random data occasionally will give small p-value measures of significance. Moreover, since solar wind drives geomagnetic activity, one would expect that a small p-value for V would be accompanied by a small p-value for AA. But this is not the case and, therefore, for physical reasons, statistical significance cannot be assigned to the small p-value for V.

[13] Taken together, the p-values listed in Tables 3 and 4 do not support rejection of the null hypothesis of no solar-terrestrial triggering of earthquakes. This evaluation is more quantitative than the assertion by *Meeus* [1976] that sunspots and earthquakes are not significantly correlated. In general terms, our analysis is also consistent with *Jeffreys* [1938], who did not find any significant 11 year solar-cycle modulation in seismicity, and it is consistent with the analysis of *Michael* [2011], who found that the occurrence of large earthquakes is statistically indistinguishable from a time-stationary Poisson process (no clustering, no modulation, no trend). On the other hand, our conclusion is different from that reached

Table 3. Number of Earthquakes and χ^2 p-values

			Year			Month			Day	
M≥	N	N_{63}	G	V	AA	G	V	AA	V	AA
9.0	5	3	0.41	0.39	0.41	0.41	0.36	0.41	0.36	0.41
8.5	17	7	0.52	0.42	0.45	0.45	0.41	0.45	0.40	0.45
8.0	75	34	0.58	0.79	0.58	0.44	0.51	0.54	0.46	0.47
7.5	383	177	0.38	0.48	0.48	0.53	0.65	0.74	0.50	0.43

Table 4. Mean Earthquakes Per Year, Student p-values

	G			V			AA		
M ≥	$\mu_<$	$\mu_>$	p	$\mu_<$	$\mu_>$	p	$\mu_<$	$\mu_>$	p
9.0	0.05	0.03	0.65	0.08	0.04	0.56	0.04	0.05	0.65
8.5	0.14	0.16	0.80	0.23	0.04	0.04	0.19	0.10	0.22
8.0	0.75	0.57	0.20	0.80	0.56	0.23	0.67	0.64	0.80
7.5	3.48	3.30	0.59	3.48	3.59	0.79	3.19	3.55	0.28

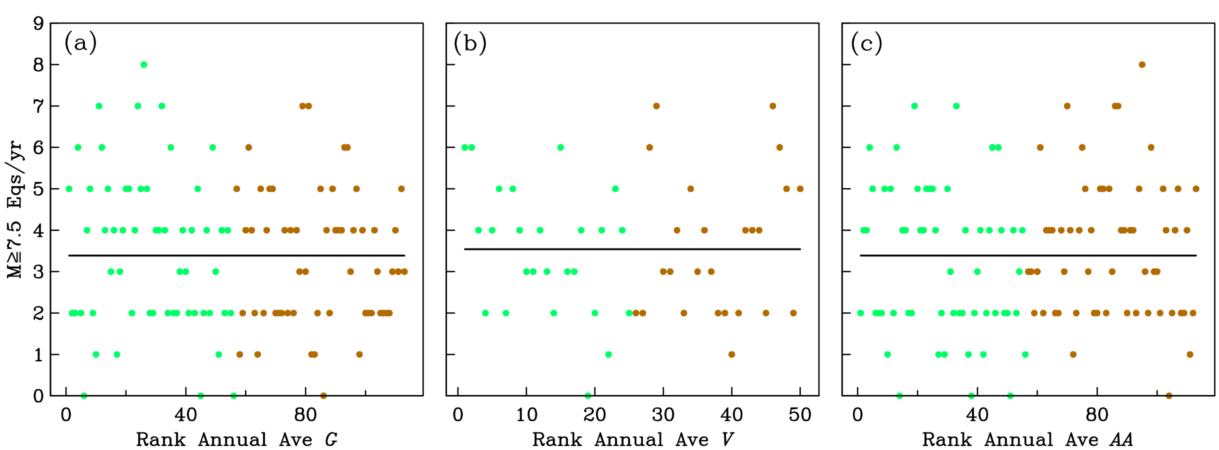

Figure 2. Number of $M \geq 7.5$ earthquakes per year versus the ordered rank of annual average (a) sunspot number G, 1900–2012, (b) solar wind velocity V, 1963–2012, and (c) geomagnetic activity AA, 1900–2012. Earthquake counts for solar-terrestrial averages falling below (above) the median are shown in green (brown). Also shown, as a horizontal line, is the long-term mean of the annual number of earthquakes.

Table 5. χ^2 *p*-values for Lags, $M \geq 7.5$ Earthquakes

	Year			Month			Day	
Lag	*G*	*V*	*AA*	*G*	*V*	*AA*	*V*	*AA*
−5.0	0.81	0.87	0.47	0.63	0.77	0.54	0.48	0.46
−4.0	0.63	0.78	0.54	0.51	0.45	0.65	0.50	0.51
−3.0	0.45	0.79	0.83	0.70	0.71	0.46	0.46	0.47
−2.0	0.65	0.69	0.48	0.79	0.73	0.56	0.46	0.46
−1.0	0.49	0.49	0.23	0.49	0.84	0.63	0.48	0.44
0.0	0.38	0.48	0.48	0.53	0.65	0.74	0.50	0.43
+1.0	0.62	0.77	0.72	0.45	0.45	0.62	0.48	0.44
+2.0	0.85	0.87	0.86	0.51	0.63	0.62	0.46	0.46
+3.0	0.34	0.66	0.94	0.69	0.60	0.70	0.45	0.49
+4.0	0.96	0.71	0.29	0.52	0.41	0.51	0.45	0.47
+5.0	0.80	0.86	0.68	0.52	0.64	0.62	0.45	0.44

by *Odintsov et al*. [2006, Figure 2], who identified a seemingly significant difference between the average number of earthquakes ($M \geq 7.0$, 1900–1999) occurring during sunspot maximum and minimum years (Student's *t* test, $p < 0.05$). In response to the analysis of *Odintsov et al*. [2006], we conducted a Student's *t* test like theirs. We find that the difference between the average number of earthquakes during sunspot maximum and minimum years is insignificant ($M \geq 7.5$, 1900–2012, $p = 0.88$). *Simpson* [1967, Figure 6] reported a correlation between geomagnetic activity and earthquakes that follow a few hours later ($M \geq 5.5$, 1950–1963), but he did not report a traditional measure of statistical significance. Therefore, his retrospective analysis does not even begin to inform a candidate hypothesis, let alone actually test one.

6. Delayed Effects

[14] Next we consider possible time lags between solar-terrestrial variables and seismicity, while, at the same time, bearing in mind the cautious advice of *Mulargia* [1997] for interpreting the significance of parameters that have been empirically determined by retrospective optimization. In Table 5, we list *p*-value significance probabilities for χ^2 distributional differences between $M \geq 8.0$ earthquake counts below and above the median of annual, monthly, and daily averages of the solar-terrestrial variables *G*, *V*, and *AA*, each for a range of lags; negative (positive) lags are for solar-terrestrial averages before (after) earthquakes. None of the probabilities are indicative of statistically significant, lagged distributional differences. Once again, on the basis of these results, we cannot reject the null hypothesis of no solar-terrestrial triggering of earthquakes. Our conclusion, in this section, is different from that reached, for example, by *Huzaimy and Yumoto* [2011, Figure 6], who reported that seismicity (1963–2010) tends to be highest during solar-cycle declining phase and minimum, but they did not report any measures of statistical significance.

7. Future Not Predicted

[15] From retrospective analysis of historical data, we cannot confidently resolve a statistically significant relationship between solar-terrestrial variables and earthquake occurrence. Therefore, we cannot confidently reject the null hypothesis of no solar-terrestrial triggering of earthquakes. This does not mean, of course, that there is no such role—we just cannot detect its presence in historical data. What it does mean is that we have no testable correlation that can be used to objectively predict future earthquakes. In contrast to the work reported here, some advocates of hypotheses in which solar-terrestrial interaction does actually trigger earthquakes have reported the identification of different types of correlations of possible relevance. Before such claims can be regarded as valid, advocates need to demonstrate the statistical significance of their correlations in objectively chosen historical data sets. To guard against inspection and selection biases, advocates of solar-terrestrial triggering of earthquakes also need to demonstrate the persistence and statistical significance of their claimed correlations against future data. This has not been done. And until it is, the hypothesis that solar-terrestrial interaction can trigger earthquakes must be regarded with significant skepticism.

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