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# The Sun's wrath: economic effects of sunspot volatility

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## Abstract

We provide empirical evidence on the negative relationship between sunspot volatility and GDP in OECD countries. Among the different sectors, we find that the information and communication sector is the most adversely affected by space weather.

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# 1. Introduction

Space weather describes the way in which the Sun, and conditions in outer space more generally, impact human activity. The European Space Agency (2018) defines space weather in terms of the "environmental conditions in Earth's magnetosphere, ionosphere and thermosphere due to the Sun and the solar wind that can influence the functioning and reliability of spaceborne and ground-based systems and services or endanger property or human health." Extreme space weather phenomena such as geomagnetic storms represent a significant risk to infrastructures (e.g., telecommunications, broadcasting, navigation, power distribution), especially at northern latitudes (Eastwood, et al, 2017). One of the best-known recent examples of extreme space weather events is a geomagnetic storm on March 9, 1989 which collapsed the Hydro-Québec power network. This event led to a general blackout that lasted more than 9 hours and affected over 6 million people (NASA, 2020).

The earliest mention of the economic impacts of space weather can be attributed to W. Stanley Jevons. Looking specifically at agriculture production in the United Kingdom, Jevons (1878) argued that space weather (measured through the frequency of sunspots) impacts terrestrial weather, which then affects crop production and, ultimately, the overall economy. Moore (1914) connected the transits of Venus to terrestrial economic activity through the business cycles. According to Moore (1914), Venus stands between the Earth and the Sun every 8 years, thereby disrupting the Sun's radiation on its path to Earth.

Modern economic research on the economic impact of space weather has been largely limited to single-country studies. Using data for the U.S. and a variety of econometric methods, Chowdhury (1987) found mixed results on the impact of sunspot activity on GDP and agricultural production. For the case of Japan, Otsu, et al. (2006) found a negative correlation between sunspots and unemployment. One study that looked at a group of countries, Gorbanev (2012) found that the probability of recessions in G7 countries greatly increased around and after the solar maximums, suggesting that they can cause deterioration in business conditions and trigger recessions. Our study is related to the foregoing modern studies in several respects. First, in contrast to Ostu (2006) and Chowdhury (1987), our study covers a panel of OECD-member countries. Second, unlike Gorbanev (2012), our study makes use of econometric methods to study the impact of space weather on terrestrial economies. We also contribute to the larger empirical literature on the social and economic effects of geophysical and meteorological phenomena (e.g., Dell, et al., 2012; Hsiang and Narita, 2012; Cavallo, et al., 2013; Felbermayr and Gröschl, 2014).

It is well-understood that solar activity tends to be more intense the larger the groups of sunspots are. Thus, we use the volatility in sunspot frequency as our measure of solar activity. The evidence we present shows a small but statistically significant effect of sunspot volatility in OECD countries: on average, GDP decreases by at least 0.06 percent for every 1 percent increase in volatility in sunspot activity. Furthermore, this negative effect is amplified for countries in higher latitudes. The qualitative features of these estimates are insensitive to the presence of country fixed effects, year fixed effects, additional control variables, and first differencing. Among different production sectors in OECD economies, the information and communication sector appear to be the most significantly affected by space weather. Precisely, a one percentage point increase in solar activity lowers production in the information and communication sector by 1.34 percentage points. We also find a negative lagged effect that is statistically significant. However, this lagged effect is smaller in magnitude relative to the contemporaneous effect of volatility in solar activity to GDP.

The rest of this paper is structured as follows. In Section 2 we explain how volatility in sunspot frequency affects economic activity on Earth. Section 3 describes the empirical methods and data sources. Section 4 presents our empirical results. Section 5 concludes.

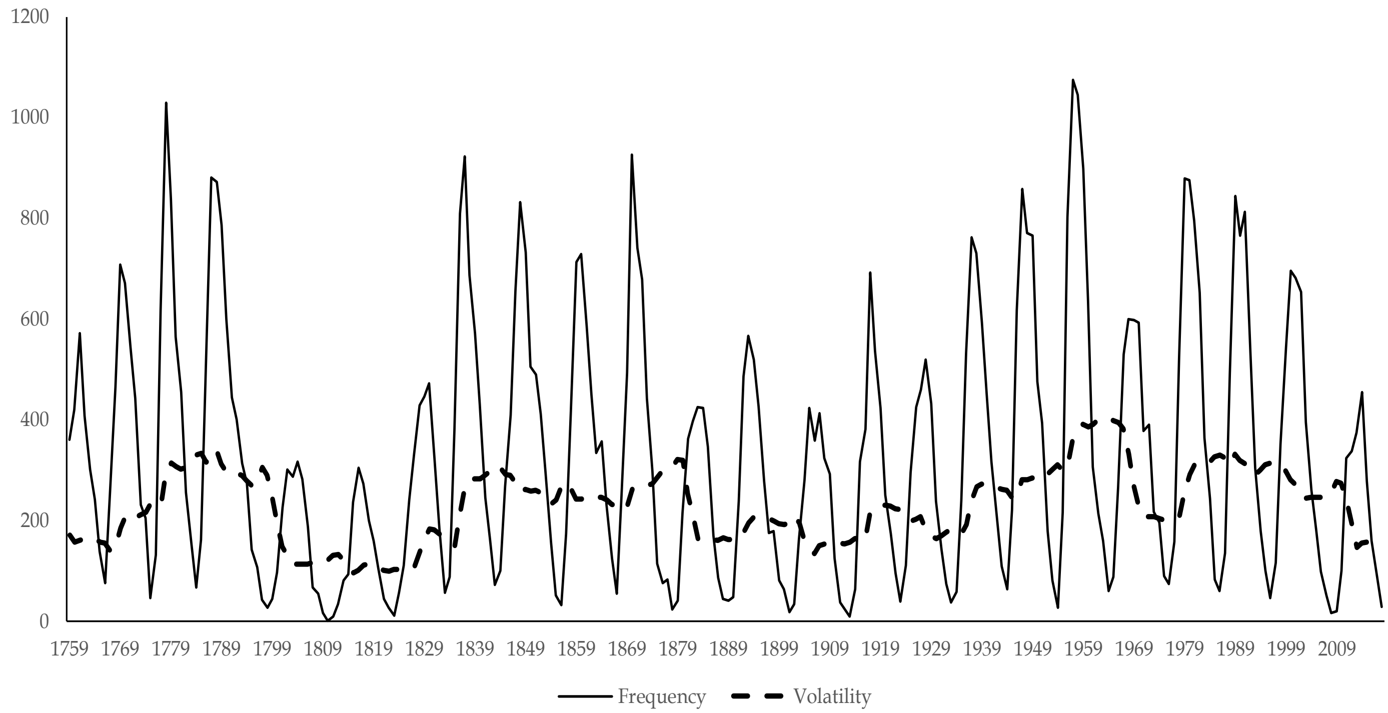


**Figure 1:** Frequency and volatility of sunspots from 1749 to 2017.

## 2. Space weather and its effects

Throughout this study, we use the volatility of sunspots as our measure of solar activity. Sunspots are temporary phenomena on the Sun's photosphere that appear darker than the surrounding areas. Indicating intense magnetic activity, sunspots accompany secondary phenomena such as bursts of electromagnetic radiation (flares) and eruptions of material (coronal mass ejections, CMEs) accompanied by solar energetic particles (SEPs). A solar flare is a sudden release of energy from the Sun, while a CME shoots hot plasma from the Sun into space. The precise mechanisms that trigger flares and CMEs are still being debated, but the bigger the group of sunspots, the more intense such solar activity tends to be. In this study, we use the publicly-available Sunspot Index and Long-term Solar Observations (SILSO) dataset published by the Royal Observatory of Belgium. The data on the frequency of sunspots from 1759 to 2017 is shown in Fig. 1. We can clearly see that solar activity follows a cyclical pattern, known as the solar cycle, lasting about 10-12 years each. Also shown in the figure is the volatility of sunspot activity.

Volatility was computed from the standard deviation in sunspot frequency via a rolling window of 10 years which roughly corresponds to each solar cycle. We find that there is a cyclical pattern in the volatility of solar activity, with peak volatility occurring in 1963.

Flares and CMEs send enormous amounts of energy and charged particles hurtling into collision with the Earth's atmosphere, where they can cause geomagnetic storms. According to Eastwood, et al. (2017), these storms produce numerous effects such as voltage disruptions leading to power outages, changes in oil pipeline to soil voltage that drive enhanced corrosion, disruption in satellite, radio, and cellular communications networks, exposure to elevated levels of radiation, or reduced flights in polar routes. The adverse economic impacts of solar activity on the North American power grid has been well-documented. For instance, 4% of the power disturbances between 1992 and 2010 reported to the U.S. Department of Energy are attributable to strong geomagnetic activity (Schrijver, et al., 2013) . Interestingly, the effects of geomagnetic storms are not restricted to high latitudes and have been documented in the United Kingdom, Finland, Sweden, Spain, the United States and Canada, South Africa, Japan, China, and Brazil (Eastwood, et al., 2017).

## 3. Empirical methods and data

Our identification strategy exploits the fact that the variation in solar activity is entirely exogenous, driven by the solar cycles. The geographical location of the country, and more specifically its latitude, is also important: the effects of an increase in the volatility of solar activity are hypothesized to be stronger in higher latitudes. We can implement this identification strategy by estimating the following equation:

$$y_{i,t} = \beta solar\_activity_t + \gamma solar\_activity_t \times latitude_i + \kappa_i + \tau_t + \varepsilon_{i,t}. \quad (1)$$

The subscript *i* indexes the country and *t* the year. The variable *y* is an economic outcome variable. The variable $solar\_activity$ is the log of the computed volatility in sunspot frequency, our proxy for solar activity. The variable $latitude$ is the log absolute value of the latitude of the country (i.e., a measure of distance from the equator), scaled to take values between 0 and 100, where 0 is the equator. The parameters $\kappa$ and $\tau$ are country and time fixed effects, respectively. For as long as we control for year and country fixed effects, we automatically control for any possible independent effects of solar activity and country latitude. We are then left with the variation due to the interaction of the two factors, and this is what we exploit. It is possible that the economic effects of variation in solar activity take some time to be realized. Thus, we also consider a version of Eq. (1) with the computed volatility in sunspot frequency lagged by one period as the main explanatory variable.

We use two measures for the economic outcome variable. Precisely, we consider an annual panel of GDP and value added from different sectors covering 1995-2017, all in logs, per capita, and expressed in constant 2010 prices, sourced from the OECD online database. The sectors considered are: Agriculture, forestry, and fishing; Industry, including energy; Manufacturing; Transport; Information and communication; and Other sectors. The time period of our analysis is constrained specifically by the availability of data across sectors. While GDP data for OECD-member countries begin in 1960, sectoral data from the OECD online database is available only beginning 1995. Thus, we use the same time period (1995-2017) in our analysis to make the estimation results comparable and consistent across the two economic outcome variables.

In estimating Eq. (1), we consider robust standard errors, clustered at the country level. According to Angrist and Pischke (2008), the use of robust clustered standard errors allows us to effectively deal with correlation of observations in the same group (cross-sectional dependency) and correlation over time of the same units (serial correlation). From a practical standpoint, it is not possible for us to report heteroscedasticity tests as we already use robust clustered standard errors in the estimations which takes into account cross-sectional dependency. In terms of serial correlation tests, however, we report two test statistics (Durbin-Watson and Baltagi-Wu) to check for the presence of panel serial correlation where permissible.

# 4. Empirical results

Table 1 reports the regression results using the specification in Eq. (1) with log real GDP capita as the economic outcome variable. From column (1) we find that a one percentage point increase in sunspot volatility reduces real GDP per capita by 0.91 percentage points. Column (2) then includes country fixed effects, to control for factors that affect GDP and covaries with country latitude. We see a similar negative coefficient, implying that for a given country, years with volatile sunspot activity display on average lower output. Column (3) includes year fixed effects instead, to control for determinants of GDP that also covary with the timing of solar activity. The estimated coefficient is larger in magnitude, suggesting that focusing on the within-country variation if anything underestimates the true negative effect of sunspot volatility. Column (4) then displays the specification which includes both year and country fixed effects. The estimate is again statistically significant, very similar in magnitude to the estimate in column (3) and shows that sunspot volatility has a negative effect on GDP. Column (5) reports the estimated effect with the interaction specification. The interaction term is negative and statistically significant suggesting that the negative effect of sunspot volatility to GDP is amplified in higher latitudes. Column (6) displays the estimated effect with lagged unemployment rate as an additional control variable. The estimate remains negative, statistically significant, and similar in magnitude as in the other specifications.

Previously discussed was the possibility that it may take some time before the effects of sunspot volatility can be realized in the economy. Thus, in columns (7) and (8) we include lagged sunspot volatility as the main explanatory variable. Our results indicate that volatility in sunspot activity has a lagged negative effect to GDP but smaller in magnitude relative to contemporaneous sunspot volatility. There is a statistical concern that the previous estimates are driven by non-stationarity of the volatility in sunspot frequency and GDP, thereby making these results potentially spurious. Hence, we transform the variables to induce stationary by first differencing. Column (9) present the result with first differences and reassuringly we find a coefficient, although very small in magnitude (0.06), that is negative and statistically significant. In all, we find that the negative contemporaneous effect of volatility in solar activity to GDP is statistically significant, with a low of 0.06 to a high of 1.016.

**Table 1:** Effects of solar activity to GDP in OECD countries.

| Dependent variable: Log real GDP per capita (2010 prices) | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|---|
| | Levels | | | | | | | | First difference |
| Solar activity | -0.912*** | -0.912*** | -1.016*** | -1.015*** | -0.596*** | -0.867*** | -0.467*** | | -0.059** |
| | (0. 052) | (0.053) | (0.052) | (0.032) | (0.120) | (0.049) | (0.033) | | (0.011) |
| Solar activity × Latitude | | | | | -0.006** | | | | |
| | | | | | (0.002) | | | | |
| Solar activity(t-1) | | | | | | | -0.441*** | -0.875*** | |
| | | | | | | | (0.026) | (0.050) | |
| Unemployment rate (t-1) | | | | | | -0.009 | | | |
| | | | | | | (0.017) | | | |
| Observations | 792 | 792 | 792 | 792 | 748 | 756 | 756 | 756 | 720 |
| R squared | 0. 204 | 0.852 | 0.310 | 0.959 | 0.842 | 0.960 | 0.193 | 0.184 | 0.024 |
| Country FE | No | Yes | No | Yes | Yes | Yes | Yes | Yes | No |
| Year FE | No | No | Yes | Yes | No | Yes | Yes | Yes | No |
| Standardized effect | -0.452 | -0.452 | -0.503 | -0.503 | -0.311 | -0.662 | -0.235 | -0.430 | -0.156 |
| Durbin Watson stat. | | | | 1.846 | | 1.845 | 1.804 | 1.806 | |
| Baltagi Wu stat. | | | | 1.870 | | 1.869 | 1.830 | 1.832 | |

*Notes:* Robust standard errors in parentheses, clustered at the country level. *** p < .01, ** p < .05, * p < .1. Regressions include a constant (not shown).

**Table 2:** Effects of solar activity across production sectors in OECD countries.

| Dependent variable: Production sector value added (in logs) | Marginal effect of solar activity | Standardized effect of solar activity | R squared | Observations |
|---|---|---|---|---|
| Agriculture, forestry, and fishing | -0.273***<br>(0.079) | -0.136 | 0.902 | 769 |
| Industry, including energy | -0.806***<br>(0.076) | -0.429 | 0.904 | 769 |
| Manufacturing | -0.708***<br>(0.082) | -0.371 | 0.894 | 769 |
| Transportation | -1.003***<br>(0.076) | -0.459 | 0.927 | 769 |
| Information and communication | -1.343***<br>(0.087) | -0.562 | 0.954 | 769 |
| Other | -1.149***<br>(0.063) | -0.496 | 0.961 | 769 |

*Notes:* Robust standard errors in parentheses, clustered at the country level. *** p < .01, ** p < .05, * p < .1. Regressions include a constant (not shown), year fixed effects, and country fixed effects.

All of the coefficients reported in Table 1 were estimated using robust clustered standard errors which takes into account heteroscedasticity and serial correlation. Following Angrist and Pischke (2008), cross-sectional dependency has already been accounted for at least partially since our estimates of the standard errors are clustered at the country level. In terms of serial correlation, we present the results of the Durbin-Watson and Baltagi-Wu test statistics. The values for both test statistics are close to 2 suggesting that the serial correlation is not an issue. Both test statistics fail to reject the null hypothesis of no first order serial correlation.

Table 2 reports the regression results for sectoral production. Here, we use the specification in Eq. (1) with value added from different sectors as the dependent variable including year and country fixed effects. Among the different sectors, we find that the information and communication sector as the most affected by solar weather. Our results indicate that production in the information and communication sector decreases by 1.343 percentage points for every one percentage increase in sunspot volatility. In all regressions we obtain a negative and statistically significant marginal effect for sunspot volatility, which is consistent with the general notion that volatile sunspot activity can produce adverse effects in the economy.

# 5. Discussion and Conclusion

This study provided direct estimates of the economic impact of volatility in sunspot activity. We found a small but statistically significant negative effect of sunspot volatility to GDP in OECD countries. Remarkably, we found that this negative effect is amplified in higher latitudes and is more pronounced in the information and communication sector. While the findings presented in this study are not themselves novel and constrained by availability of data, we should stress that our analysis was able to shed some light on the negative effects of sunspot volatility to a broad set of countries and across various sectors of the economy. Insights from our study can also guide future theoretical and empirical research in further understanding the economic impacts of space weather.

We believe that our findings can be used to inform economic policies related to disaster risk preparedness and mitigation in the following ways: First, our numerical estimates of the impact of volatile sunspot frequency can help improve policymakers' understanding of its economic costs. While our estimated effect of volatility in sunspot frequency is modest, it can represent substantial amounts specially for large technology-dependent OECD-member economies in higher latitudes. Second, our exercise of identifying sectors severely affected by volatility in sunspot frequency can help policymakers better target economic policy. For instance, policymakers should be able to channel investments in risk mitigation in the information and communication sector, the sector identified in this study as most affected by space weather. And third, most importantly, this study raises the awareness to policymakers of the quantifiable risks extreme space weather events pose to the economy.

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