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by

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Economic Effects of Solar Activity: Evidence from Canada

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30 April 2019

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Abstract

This papers uses a three-sector Real Business Cycle model with a stochastic sunspot volatility shock to estimate the adverse effects of intense solar activity to the economy of Canada. To the best of my knowledge this is the first study to measure the adverse effects of intense solar activity in Canada. Calibrating the model for Canada's economy, I found that a solar activity shock leads to lower output, consumption, and investment. These findings are confirmed from an econometric exercise using Canadian data. Precisely, this paper finds that every percentage point increase in solar activity generates a 0.26 percentage point decrease in real GDP per capita.

Keyword: Real-business-cycle model, Solar activity, Consumption, Investment

JEL Classification: E21, E22, E32,

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1 Introduction

Space weather describes the way in which the Sun, and other conditions in outer space, effect 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." It is now well understood that 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 (Batu and Zhao, 2019).

When the Sun becomes active, the occurrences of phenomena such as solar flares, coronal mass ejection become frequent. The amount of high-energy particles and extreme short-wave radiation released, such as X-rays and ultra violet (UV) rays, will also increase. These phenomena affect the ionosphere of the Earth's atmosphere the most. It can disturb Earth's magnetic field, affect communications and create auroras.

According to the National Research Council report on severe space weather events, modern society relies heavily on a variety of technologies that are susceptible to the extremes of space weather-severe disturbances of the upper atmosphere and of the near-Earth space environment that are driven by the magnetic activity of the Sun. Strong auroral currents can disrupt and damage modern electric power grids and may contribute to the corrosion of oil and gas pipelines. Magnetic storm-driven ionospheric density disturbances interfere with high-frequency (HF) radio communications and navigation signals from Global Positioning System (GPS) satellites, while polar cap absorption (PCA) events can degrade-and, during severe events, completely black out-HF communications along transpolar aviation routes, requiring aircraft flying these routes to be diverted to lower latitudes. Exposure of spacecraft to energetic particles during solar energetic particle events and radiation belt enhancements can cause temporary operational anomalies, damage critical electronics, degrade solar arrays, and blind optical systems such as imagers and star trackers (NRC, 2008).

While the study of space weather is a rapidly growing field, academic work to assess its overall social and economic impacts appears to be in its infancy. My objective in this study, therefore, is to provide initial estimates of the impact of space weather on economic variables. To the best of my knowledge, the current paper is the first to use econometric methods and a dynamic stochastic general equilibrium model (DSGE) to study the impacts of space weather in Canada. I choose Canada for several reasons. First, Canada is a country located in northern latitude and is very susceptible to the effects of extreme space weather events. Second, Canada has a reliable data that can be used in the analysis.

In the econometric analysis, I found that Canada's GDP decreases by at least 0.26 percent for every 1 percentage point increase in solar activity. In terms of the different sectors in Canada's economy, I found that the following are adversely affected by intense solar activity: agriculture, mining, utilities, construction, manufacturing, transportation, wholesale trade and other sectors. From the HP filter result, Agriculture and the sun, public utilities and the sun are negatively correlated. Therefore, I choosed the Agriculture and Utilities sectors to build my DSGE model. The results of these econometric analysis are confirmed by the findings from the DSGE model. The model used in the current study is similar to the textbook real business cycle (RBC) model except that it features a stochastic process for the volatility of solar activity and it feature three sectors (agriculture, utilities, and other). The model predicts that a one standard deviation increase in solar activity reduces output, consumption, and investment. The model was calibrated to match Canada's economy.

The rest of this paper is structured as follows. Section 2 presents a review of related literature. Section 3 reports the empirical evidence. Section 4 describes the RBC model part. Section 5 discusses the calibration of the RBC model. Section 6 presents the model results. Section 7 concludes.

2 Review of Related Literature

The literature studying the vulnerability of different industry sectors to space weather rarely extends the analysis to the actual quantification of economic losses resulting from space weather events. Eastwood et al. (2017) provided an initial literature review to gather and assess the quality of any published assessments of space weather impacts and socioeconomic studies.

They found that space weather can affect the economy through various channels:

1. *Power grid*

   Eastwood et al. (2017) found evidence that geomagnetically induced currents associated with geomagnetic storms may damage physical infrastructure (specifically transformers), introduce voltage instabilities that can lead to a blackout without infrastructure damage, and interfere with protection systems and fault detection. For example, 4% of the disturbances between 1992 and 2010 reported to the U.S. Department of Energy are attributable to strong geomagnetic activity (Schrijver and Mitchell, 2013).

2. *Oil and Gas Industry*

   Eastwood et al. (2017) found that geomagnetically induced currents changes in pipe to soil voltage that drive enhanced corrosion.

3. *Communications*

   Mobile network performance can be affected by solar flare radio noise. Certain mobile networks may be affected by the loss of global navigation satellite system (GNSS) timing information (Eastwood et al., 2017).

4. *Ground Transportation*

   Rail networks are in principle susceptible to geomagnetically induced currents. Trams and light railways may be similarly affected, and all mass transit would be severely impacted by power loss (especially for underground mass transit). Finally, a more speculative space weather impact in the future is that on driverless cars (Eastwood et al., 2017).

5. *Satellite Infrastructure*

   Satellites are at risk from the space environment. For instance, during the 2003 Halloween storms, 47 satellites reported anomalies, one scientific satellite was lost, and 10 satellites lost operational service for more than one day (Eastwood et al., 2017). Another example is the outage in January 1994 of two Canadian telecommunications satellites during a period of enhanced energetic electron fluxes at geosynchronous orbit, disrupting communications services nationwide. The first satellite recovered in a few hours; recovery of the second satellite took 6 months and cost $50 million to $70 million (NRC, 2008).

6. *Global Navigation Satellite Systems*

   Eastwood et al. (2017) also finds that disruption to positioning and timing services would occur during a major space weather event, affecting many sectors (e.g., communications, financial trading, energy networks, etc.).

7. *Aviation*

   Solar radiation storms enhance the cosmic ray-generated radiation environment at flight altitude. Reduced flight time at high altitude may be required should a severe energetic particle event to occur during flight, and this would have a commercial/operational impact, including delays and increased fuel use (Eastwood et al., 2017). For instance, the diversion of 26 United Airlines flights to

> non-polar or less-than-optimum polar routes during several days of disturbed space weather in January 2005. The flights were diverted to avoid the risk of radio blackouts during solar storm events. The increased flight time and extra landings and takeoffs required by such route changes increase fuel consumption and raise cost, while the delays disrupt connections to other flights (NRC, 2008).

The current study is very much related to Batu and Zhao (2019) with some important differences. The current study focuses only on the impacts of extreme space weather in the economy of Canada, where as Batu and Zhao (2019) looks at its impacts on a broader set of countries (i.e., OECD). Also, Batu and Zhao (2019) is only empirical whereas the current paper combines both empirical analysis and the development of a DSGE model.

Similar to Batu and Zhao (2019), this paper study also contributes to the larger empirical literature on the social and economic effects of geophysical and meteorological phenomena. Cavallo et al. (2013) examined the average causal impact of catastrophic natural disasters on economic growth by combining information from comparative case studies. For each country affected by a large disaster, they computed the counter factual by constructing synthetic controls. They found that only extremely large disasters have a negative effect on output in both the short and the long runs. However, they also show that this results from two events where radical political revolutions followed the disasters. Once they control for these political changes, even extremely large disasters do not display any significant effect on economic growth.

Dell et al. (2012) used historical fluctuations in temperature within countries to identify its effects on aggregate economic outcomes. They found three primary results. First, higher temperatures substantially reduce economic growth in poor countries. Second, higher temperatures may reduce growth rates, not just the level of output. Third, higher temperatures have wide-ranging effects, reducing agricultural output, industrial output, and political stability. These findings inform debates over climate's role in economic development and suggest the possibility of substantial negative impacts of higher temperatures on poor countries.

The National Research Council's Committee on the Social and Economic Impacts of Severe Space Weather Events report summarizes a 2008 workshop and participants' views on current and future risks and vulnerabilities across different industry sectors.

3 Empirical Evidence

3.1 Econometric specification

Following Batu and Zhao (2019), identification strategy exploits the fact that the variation in solar activity is entirely exogenous, driven by the solar cycles. I can implement this identification strategy by estimating the following equation:

$$y_{i,t} = \beta_0 + \beta_1 solar\_activity_{t-1} + \epsilon_{i,t} \tag{1}$$

The subscript i indexes different sectors and t the quarter. The variable y is an economic outcome variable. The variable $solar\_activity$ is the log of the computed volatility in sunspot frequency per quarter, our proxy for solar activity (lagged one period). The volatility was computed from the 10-year rolling standard deviation of sunspot frequency. I used the publicly-available Sunspot Index and Long-term Solar Observations (SILSO) dataset published by the Royal Observatory of Belgium. I consider time series data for the Canadian economy from the first quarter of 1997 and the last quarter of 2018, in per capita terms and expressed in logs. The data was sourced from Statistics Canada's CANSIM database. The sectors of the Canadian economy considered are as follows: Agriculture, forestry, fishing and hunting; Industry, Mining, quarrying, and oil and gas extraction; Utilities; Construction; Manufacturing; Transportation and warehousing; Information and communication; Wholesale trade; and Other sectors.

3.2 Descriptive statistics

From Table 1 reports the descriptive statistics for variables used in this study. The real value of manufacturing production per capita is at \$5,860, which is the highest among the different production sectors included in this study. Manufacturing is also the most volatile sector since its standard deviation is the highest among the different sectors. The fact that manufacturing has the biggest share in GDP reflects this sector's dominance in Canada's economy. The lowest value of per capita production is agriculture at \$892.

Table 1: Summary of data

Variable	Obs	Mean	Std.Dev	Min	Max
Sunspot frequency	88	70.60	55.56	0.70	194.70
Sunspot volatility	89	57.27	13.31	33.89	78.03
Real GDP per capita	88	47245.56	3568.61	38633.11	52412.84
Agriculture production per capita	88	891.72	64.44	772.31	1039.27
Mining production per capita	88	3660.42	214.11	3125.79	4156.45
Utilities production per capita	88	1114.21	39.28	1018.70	1200.84
Construction production per capita	88	3354.56	513.19	2411.84	4141.69
Manufacturing production per capita	88	5859.99	620.13	4885.15	6976.16
Transportation production per capita	88	2035.95	159.04	1743.72	2389.78
Wholesale production per capita	88	4655.40	611.17	3249.24	5505.34
Other production per capita	88	25342.24	2400.35	20316.04	28689.13

The data on the frequency of sunspots from 1759 to 2017 is shown in Fig. 1. The data and the figure was sourced from Batu and Zhao (2019). 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. I find that there is a cyclical pattern in the volatility of solar activity, with peak volatility occurring in 1963.

3.3 Empirical estimates

The results of the empirical analysis are presented in Table 2. The regression results in the first row of Table 2 follow the specification in equation (1) where the dependent variable is the log of GDP and the main dependent variable is the log of the

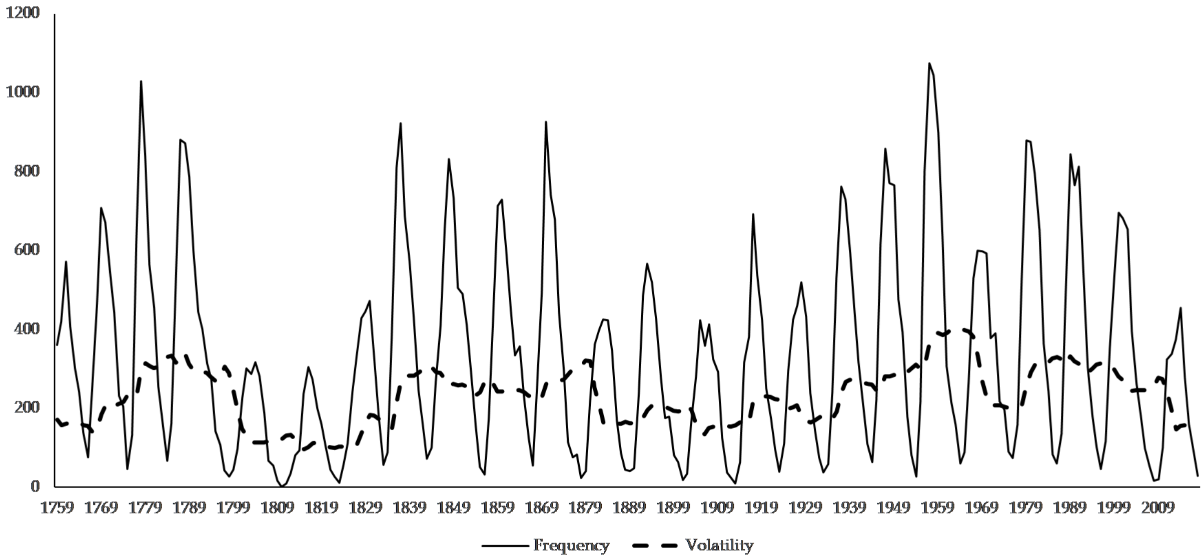

Figure 1: Frequency and volatility of sunspots from 1749 to 2017

volatility of sunspot activity. From the first row I can find that the estimated coefficient for the volatility of sunspot activity is negative which suggests the negative effect of solar activity to economy. The results suggest that for every one percentage point increase in solar activity, the log of real GDP per capita in Canada decreases by 0.261 percentage points, *ceteris paribus.* The estimated coefficient is statistically significant at the 1% level. The model explains about 70% of the variation in GDP per capita in Canada. It is possible that the regression results in Table 2 suffer from a spurious relationship. For instance, the relationship between sunspot volatility and GDP is merely driven by the non-stationarity of the data and not due to any causal relationship between the two. To remove the possibility of a spurious regression, I ran a regression on first differences shown in Table 3. First differencing makes sure that the data become stationary. The results from the first difference regression indi-

Table 2: Bivariate regression of log GDP per capita and log sunspots

Variable	Constant	Lag Sunspot volatility	Obs	R-squared	Durbin-Watson Statistic
Real GDP per capita	11.810***	−0.261***	88	0.692	0.0397
	(0.084)	(0.021)			
Agriculture production per capita	7.635***	−0.210***	88	0.5168	0.2501
	(0.072)	(0.018)			
Mining production per capita	8.867***	−0.165***	88	0.4882	0.3729
	(0.078)	(0.019)			
Utilities production per capita	7.295***	−0.069***	88	0.2385	0.3083
	(0.042)	(0.011)			
Construction production per capita	10.322***	−0.551***	88	0.7381	0.0453
	(0.123)	(0.032)			
Manufacturing production per capita	7.767***	0.225***	88	0.2805	0.0486
	(0.105)	(0.028)			
Transportation production per capita	8.677***	−0.264***	88	0.7184	0.1058
	(0.103)	(0.025)			
Wholesale production per capita	10.277***	−0.457***	88	0.6727	0.0356
	(0.135)	(0.035)			
Other production per capita	11.435***	−0.323***	88	0.6735	0.0282
	(0.102)	(0.026)			

Notes:Robust standard errors in parentheses.$^{***}p < 0.01$,$^{**}p < 0.05$,$^{*}p < 0.1$.

cate that the relationship between sunspot volatility and GDP remain negative but some lost its significance. Also, the R-square decreased significantly. Only 3% of the variation in GDP in Canada is explained by the sunspots. Of the different sectors, only agriculture, construction, and sales production per capita remain significant. The results of the Durbin-Watson statistics is also presented in Tables 2 and 3. The first differencing has improved the model in a way that it took into account the serial correlation in the data.

I also studied the impact of intense solar activity in different sectors of Canada's economy and the regression results for these sectors are reported in the rest of the rows in Table 2. The results indicate that the construction sector is the sector that is most affected by solar activity. Results of the regression indicate that per capita

Table 3: Bivariate regression of log GDP per capita and log sunspots in first differences

Variable	Constant	Δ Log sunspot volatility	Obs	R-squared	Durbin-Watson Statistic
Δ Real GDP per capita	0.003^{***}	−0.040	87	0.028	0.870
	(0.001)	(0.030)			
Δ Agriculture production per capita	0.0004	-0.218^{*}	87	0.050	1.216
	(0.003)	(0.119)			
Δ Mining production per capita	0.001	-0.072	87	0.006	1.743
	(0.003)	(0.126)			
Δ Utilities production per capita	0.001	−0.025	87	0.002	1.710
	(0.002)	(0.061)			
Δ Construction production per capita	0.004^{**}	-0.171^{***}	87	0.092	1.111
	(0.002)	(0.054)			
Δ Manufacturing production per capita	−0.001	−0.084	87	0.015	0.965
	(0.002)	(0.085)			
Δ Transportation production per capita	0.004^{***}	−0.006	87	0.000	1.895
	(0.001)	(0.048)			
Δ Wholesale production per capita	0.005^{***}	-0.087^{*}	87	0.041	1.316
	(0.001)	(0.492)			
Δ Other production per capita	0.004^{***}	0.003	87	0.000	1.113
	(0.000)	(0.016)			

Notes:Robust standard errors in parentheses.$^{***}p < 0.01$,$^{**}p < 0.05$,$^{*}p < 0.1$.

output in the construction sector decreases by 0.551 percentage points for every one percentage point increase in solar activity, *ceteris paribus*. Interestingly, the utilities sector is the least affected with an estimated coefficient at -0.069. The regression models for the different sectors explain about 23% to 74% of the variation in the production for these sectors. Finally and surprisingly, the estimated coefficient for manufacturing is positive at 0.225. All of the estimated coefficients for the different sectors are statistically significant at the 1% level.

4 Model

In this section, I will present a three sector Real Business Cycle (RBC) model. The model economy discussed in this section has the basic structure of the standard RBC model with the addition of shocks related to the volatility in solar activity. Time is discrete and indexed by t=0,...,∞. The empirical evidence presented the previous section showed that production in the Agriculture and Utilities sectors are negatively correlated with volatility in solar activity. The model economy, therefore, includes the following i sectors: $i = 1$ is Agriculture, $i = 2$ is Utilities and $i = 3$ is Others.

The economy is populated by a large number of identical, infinitely-lived agents. The expected lifetime utility, U, of the representative agent is given by:

$$\max \quad E_0 \sum_{t=0}^{\infty} \beta^t U(C_{i,t}) \tag{2}$$

where U is the period utility function, and the preference $\beta \in (0, 1)$ as a discount factor, C_t represents the consumption from sector i, and I assume that labour is inelastic.

The households in our model economy face the following budget constraint:

$$Y_t = C_t + I_t \tag{3}$$

where Y_t is an aggregated production good, C_t is the aggregated consumption and I_t is aggregated investment. The aggregated macroeconomic variables are defined as follows:

$$Y_t = \sum_{i=1}^{3} Y_i \qquad C_t = \sum_{i=1}^{3} C_i \qquad I_t = \sum_{i=1}^{3} I_i \tag{4}$$

4.1 Production Function

The economy's production function is assumed to be concave and satisfy the Inada conditions.

$$Y_{i,t} = e^{A_{i,t}} F(K_{i,t}) \tag{5}$$

where A_t represents a stochastic productivity shock and $K_{i,t}$ is the stock of physical capital in each sector i. The aggregate stock of physical capital can be aggregated as follows:

$$K_t = \sum_{i=1}^{3} K_i \tag{6}$$

The stochastic productivity shock evolves according to:

$$A_{i,t} = \rho_{A,i} A_{i,t-1} + \epsilon_{A,t} \tag{7}$$

where the $\rho_A \in (0,1)$ denotes the persistence of the productivity shock, and the stochastic term $\epsilon_{A,t}$ represents normally distributed and serially uncorrelated innovations.

4.2 Evolution of Capital

The law of motion of capital is given by:

$$K_{i,t+1} = I_{i,t} + [1 - \delta_i(D_t)]K_{i,t} \tag{8}$$

where $\delta_i(D_t) = \bar{\delta}e^{D_t}$ denotes the depreciation rate of capital as a function of the volatility in solar activity, D_t, with the steady state depreciation rate of $\bar{\delta} \in (0, 1)$. The economic intuition as to why the sunspot volatility enters the depreciation function is straightforward. As the sun becomes very active, and it generates geomagnetic storms, it leads to a rapid depreciation of the stock of physical capital such as electronic equipments and satellites.

4.3 Solar Activity

The volatility in solar activity follows an AR(1) process:

$$D_t = \rho_D D_{t-1} + \epsilon_{D,t} \tag{9}$$

where the $\rho_D \in (0, 1)$ denotes the persistence of the solar activity shock, and the stochastic term $\epsilon_{D,t}$ represents normally distributed and serially uncorrelated innovations.

4.4 Firm's Problem

A representative firm chooses its inputs according to the following optimization problem:

$$\max \quad e^{A_{i,t}} F(K_{i,t}) - r_{i,t} K_{i,t} \tag{10}$$

The relative price of input is determined by relative technologies and the relative sectoral capital. Firms in the three sectors rent capital from the households so that in equilibrium the rate of return equals the marginal productivity of capital:

$$r_{i,t} = e^{A_{i,t}} F'(K_{i,t}) \tag{11}$$

where r_i denotes the rental rate of capital in sector i.

4.5 Household's Problem

From the equations above, I can build the Lagrange function:

$$\mathscr{L}_i = \beta^t \Bigg\{ U(C_{i,t}) + \lambda_i \Bigg[e^{A_{i,t}} F(K_{i,t}) - K_{i,t+1} - C_{i,t} + (1 - \delta(D_t)) K_{i,t} \Bigg] \Bigg\} + \beta^{t+1} U(C_{i,t+1}) \tag{12}$$

By taking the derivative of Lagrange with respect to $C_{i,t}$ and $K_{i,t}$, I can get:

$$\{C_{i,t}\}: \quad U'(C_{i,t}) - \lambda_{i,t} = 0$$

$$\{K_{i,t+1}\}: \quad \beta^{t+1} \lambda_{i,t+1} [e^{A_{i,t+1}} F'(K_{i,t+1}) + (1 - \delta(D_{t+1}))] - \beta^t \lambda_{i,t} = 0$$

From the Euler equation, I can find the trade off between the consumption in different period:

$$\beta U'(C_{i,t+1})[e^{A_{i,t+1}}F'(K_{i,t+1}) + (1 - \delta(D_{t+1}))] = U'(C_{i,t}) \tag{13}$$

According to Parker (2008), an Euler equation is a difference or differential equation that is an inter-temporal first-order condition for a dynamic choice problem. It describes the evolution of economic variables along an optimal path. Equations (3) and (13) form a system of two differential equations with two steady-states that has been widely studied as a model of economic growth. Linearization shows that the interesting ($k > 0$) steady state is locally saddle-point stable, and there is a unique feasible convergence path that pins down the dynamic path of consumption and capital.

4.6 Social Planner's Problem

Since there are no externalities and other market imperfections, the competitive equilibrium in this economy can be calculated as the solution to the Social Planner's problem. The Social Planner seeks to maximize the expected lifetime utility if the representative agent by choosing the optimal sequences $\{C_t, K_{t+1}, Y_t, I_t\}$, subject to the resource constraint, the law of motion for capital, the production technology, and the stochastic processes for sunspot volatility and productivity.

5 Calibration

5.1 Data and business cycles

Given the complexity of the baseline specification described in Section 4, I proceed to analyze it numerically. The model is calibrated using quarterly economic data from the Canada for the period 1997Q1-2018Q4, all in logs, per capita, and expressed in constant 2010 prices. As before, I used the publicly-available Sunspot Index and Long-term Solar Observations (SILSO) dataset published by the Royal Observatory of Belgium.

Following Kydland and Prescott (1990), business cycles are are defined as the deviations of macroeconomic aggregates (i.e. out-put, consumption, investment, trade balance) from trend, and business cycle facts are the statistical properties of co-movements of these aggregates with respect to deviations from trend of GDP per capita. When examining business cycle aspects of the data, each data series was detrended using the Hodrick and Prescott (1981) HP filter. For any series $x_t$for $t = 1, 2, ..., T$, the HP filter extracts a trend component and a cyclical component $s_t = x_t - \tau_t$ by minimizing the loss function:

$$\sum_{t}^{T}(x_t - \tau_t)^2 + \lambda \sum_{t}^{T-1}[(\tau_{t+1} - \tau_t) - (\tau_t - \tau_{t-1})]^2 \tag{14}$$

where λ is a weight that reflects the relative variance of the two components.

5.2 Calibration

To quantify the model one must specify functional forms to be used in the simulations. This study abides by the common practice in the macroeconomic literature and specify the utility function to be logarithmic:

$$U(C_{i,t}) = \ln(C_{i,t}) \tag{15}$$

The production function is specified to be Cobb-Douglas:

$$Y_{i,t} = e^{A_{i,t}} K_{i,t}^{\alpha} \tag{16}$$

where, $\alpha \in (0, 1)$ is capital's share parameter.

Supposing that in the Steady State, $C_t = C_{t+1}$, $Y_t = Y_{t+1}$, and $K_t = K_{t+1}$, thus I can get:

$$F'(K_i) + 1 - \delta = \frac{1}{\beta} \tag{17}$$

The model will be simulated numerically following the method described in King et al. (1988). In Table 4 parameter values are set so that the model's properties match averages from data for volatility in solar activity. The discount factor β was set such that the average annual real interest rate r^* is 4%. From Bahadir et al. (2018), the quarterly depreciation rate, δ is set at 0.025. According to Batu (2017), The capital share in production, α, is set at the standard value of 0.33. And $\rho_{A,i}$ denotes the

Table 4: Baseline Calibration Parameters

Calibrated parameters	Description	Value
$r^\star$	rental rate of capital	0.04
β	Rate of time preference	0.98
δ	Depreciation rate for physical capital	0.025
α	Share in capital	0.33
ρ_D	Persistence of the solar activity shock	0.66
$\rho_{A,1}$	Persistence of the productivity shock in the agriculture sector	0.83
$\rho_{A,2}$	Persistence of the productivity shock in the utilities sector	0.64
$\rho_{A,3}$	Persistence of the productivity shock in the others sector	0.87
σ_A	Volatility of TFP shock	0.00001
$\sigma_{D,1}$	Volatility of solar activity shock in agriculture sector	0.0175
$\sigma_{D,2}$	Volatility of solar activity shock in utilities sector	0.081
$\sigma_{D,3}$	Volatility of solar activity shock in others sector	0.45

persistence of the productivity shock in sector i, ρ_D denotes the persistence of the solar activity shock. In order to find the value for ρ_D, I ran a regression model as follows:

$$log(sd_t) = \gamma + \rho_d log(sd_{t-1}) + v_t$$

where $log(sd_t)$ is the volatility in sunspot frequency. Thus, from the data I found ρ_d is equal to 0.66.

The stochastic term $\epsilon_{A,t}$ represents normally distributed and serially uncorrelated innovations. The parameters for standard deviations of the solar activity in the stochastic processes, σ_A, $\sigma_{D,1}$, $\sigma_{D,2}$ and $\sigma_{D,3}$ were set to 0.00001, 0.0175, 0.081 and

0.45, respectively, to match the average annual standard deviations for productivity and solar activity shocks in the sample.

During the calibration, first I change σ_A to match the GDP data in the model to the original data. Next, I calibrated $\sigma_{D,1}$, $\sigma_{D,2}$ and$\sigma_{D,3}$ sequentially to match the volatility of Agriculture, Utilities and Others. The result can be found in the next section.

5.3 Model fit

Table 5 presents the statistics for the benchmark calibration of the model to the Canadian data. The model is able to replicate successfully the Canadian economy as shown by the volatility statistics for the major macroeconomic variables. Moreover, the model was able to replicate most of the business cycle stylized facts with respect to the impact of sunspots to the agriculture and utilities sectors.

Table 5: Data and the benchmark model

	Data	Model
Volatility		
GDP (Y)	0.011	0.11
Agriculture (Y_1)	0.043	0.043
Utilities (Y_2)	0.020	0.02
Others (Y_3)	0.111	0.111
Aggregate consumption (C)	0.005	0.147
Aggregate Investment (I)	0.017	0.041
Solar activity shock in agriculture sector (D_1)	0.489	0.0881
Solar activity shock in utilities sector (D_2)	0.489	0.0408
Solar activity shock in others sector (D_3)	0.489	0.2265
Correlations of sunspots to		
Agriculture	-0.0412	-0.659
Utilities	-0.1332	-0.659
Others	0.2724	-0.659

6 Model Results

In this section, I consider a temporary exogenous shock to solar activity inflows. By introducing shock in our model, I can find the effect in Figure 2 and Figure 3.

Figure 2 plots a positive solar activity shock to depreciation. On impact, the solar activity shock raises the depreciation rate, δ, and then it diminishes as time passes. The shocks follow a similar pattern across the different sectors.

Figure 3 plots the economy's response for an unanticipated, exogenous, but temporary increase in solar activity. On impact, the rate of depreciation δ increases which leads to a decrease in capital in the next period, $K_{i,t+1}$, as well as GDP $Y_{i,t+1}$ in fu-

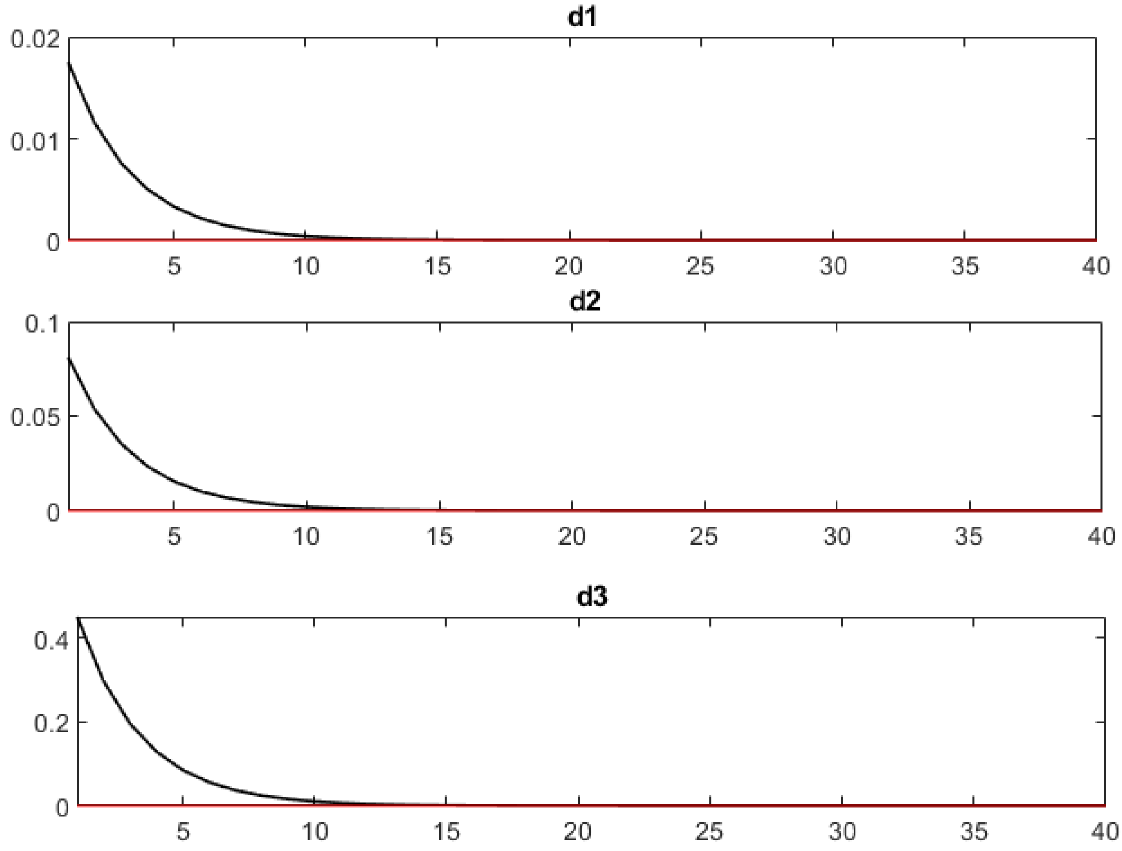

Figure 2: Depreciation shocks

ture periods. Because of diminishing marginal product of capital (MPK), the rental rate of capital goes up as well. In the equilibrium, saving is equal to investment, thus under those conditions, investment $I_{i,t+1}$ and saving $S_{i,t+1}$ will drop. Moreover, as a response, the consumption $C_{i,t+1}$ will increase. Since saving $S_{i,t+1}$ downward, the consumption in the next period $C_{i,t+2}$ decreases. The foregoing description of a how an unanticipated, exogenous, but temporary increase in solar activity affects Canada's economy is true across the different sectors.

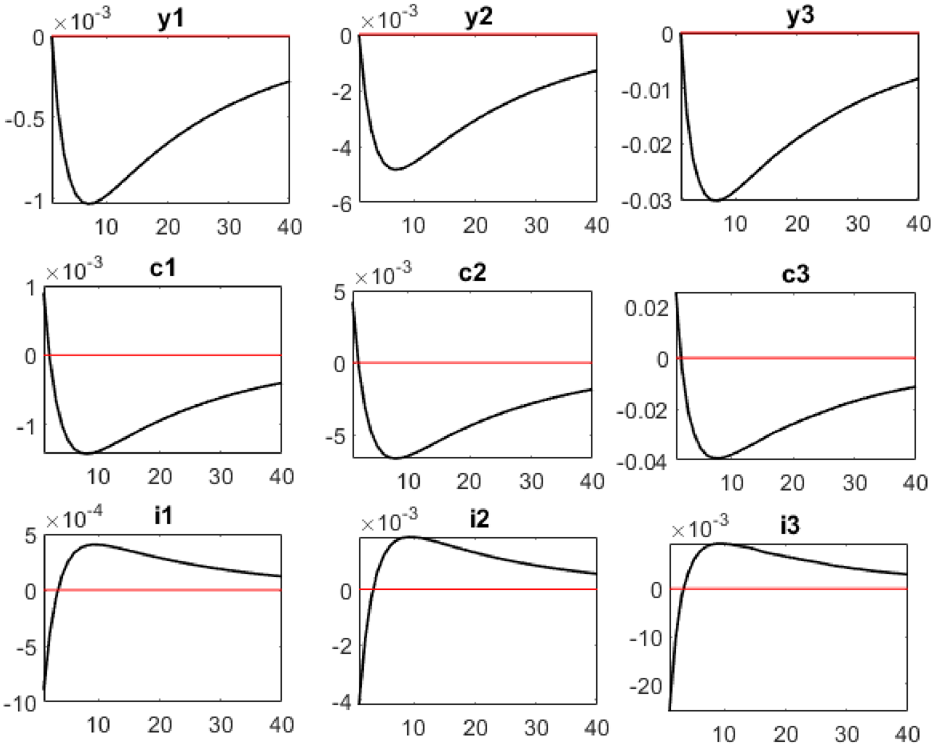

Figure 3: Exogenous shock to solar activity I

The dynamics of the model can be explained using the Euler equation. From the Euler equation right hand side, the decrease in consumption $C_{i,t}$ makes the marginal utility increase at period t. From the left hand side, the increase in $C_{i,t+1}$ leads to the marginal utility of consumption $U'(C_{i,t+1})$ to decrease. Similarly, the decreasing capital $K_{i,t+1}$ makes the marginal product of capital to increase.

Finally, when the time goes to more than 40 periods, I can get the steady state. And

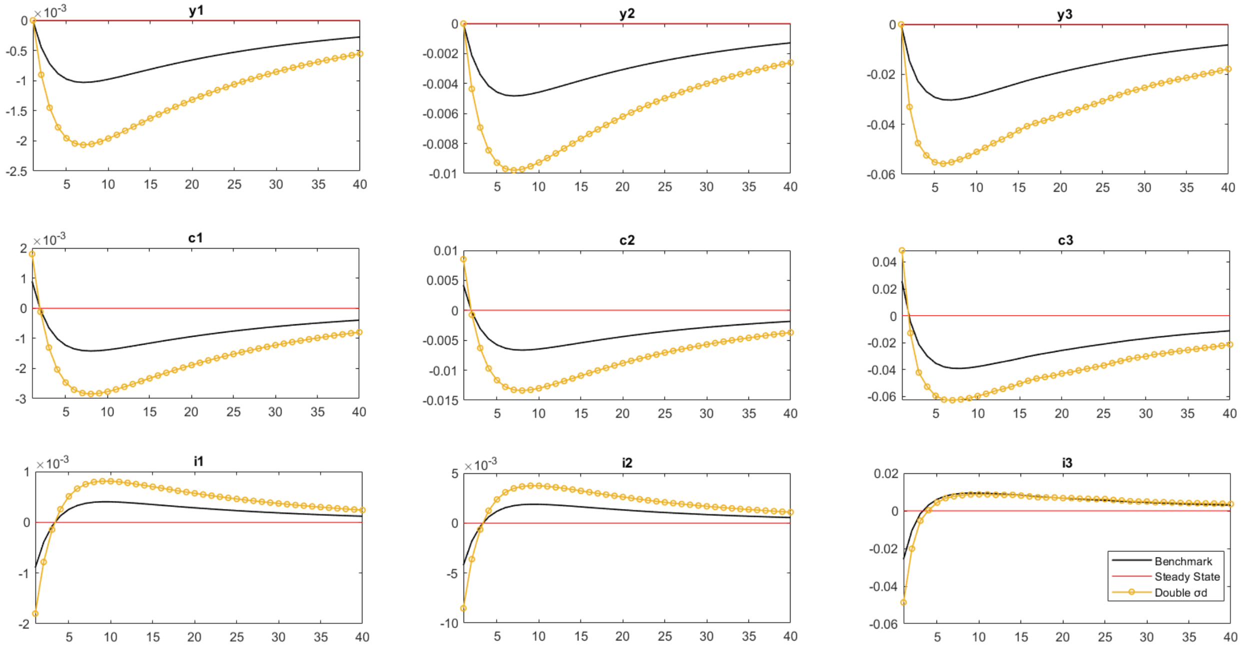

Figure 4: Exogenous shock to solar activity II

the production and consumption begin to recover. As the economy recovers from the shock, it will start to build more capital and that investment, $I_{i,t}$, will begin to increase. Furthermore, the investment will revert back to the steady state in a longer period.

6.1 Sensitivity analysis

In Figure 4, I use the yellow circled line to denote the result after doubled solar activity shock. From the figure I know, double the solar activity shock means double the depreciation rate which makes the capital $K_{i,t+1}$ decreases more as well as

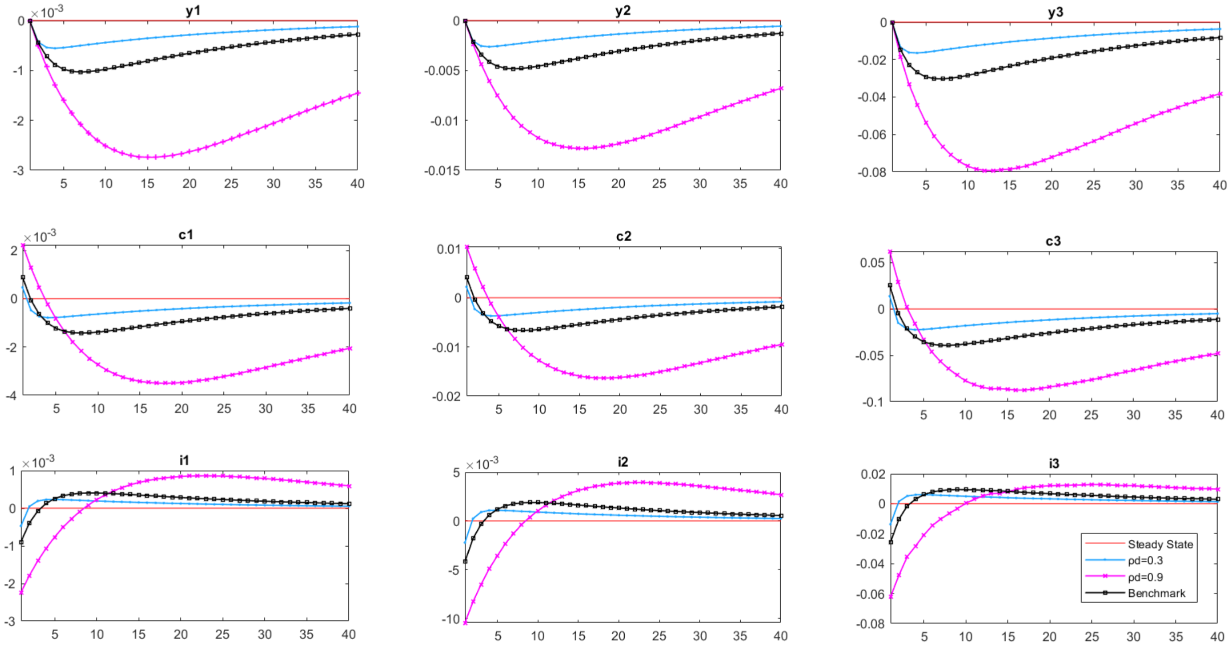

Figure 5: Exogenous shock to solar activity III

investment $I_{i,t+1}$ and saving $S_{i,t+1}$. The same production with less saving makes the higher consumption $C_{i,t+1}$, while the production and consumption downward more deeper than the original data.

From the Figure 5, I changed persistence of solar activity to different number, the blue dote line and pink x line denote ρ_d equals to 0.3 and 0.9, respectively. And the black square line means the benchmark. From the response I can conclude that, the more persistence of solar activity in the system, the much deeper effect to different sectors.

7 Conclusions

By using econometric methods, this paper provides the first direct estimates of the economic impact of intense solar activity in Canada. The volatility of sunspot was found to have a negative impact on the Canadian economy, especially for the construction, sales and transportation.

Also, this paper develops a three-sector RBC model with a stochastic solar activity shock. According to RBC theory, the volatility of solar activity, which temporary in nature, has a negative impact on GDP per capita in the long run. The economy will face a temporary solar activity shock which will increase the depreciation rate significantly. This could lead an initial rise in the consumption but leads to a decrease in capital. Furthermore, from the sensitivity analysis, the more great sunspot volatility, the larger consumption with less capital in different sectors of Canada's economy.

I believe that my findings can be used to guide future theoretical and empirical research in further understanding the economic impacts of space weather in Canada.

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Appendix

```
close all;
var y y1 y2 y3 c c1 c2 c3 k k1 k2 k3 i i1 i2 i3 a1 a2 a3 d1 d2 d3;
varexo ea1 ea2 ea3 ed1 ed2 ed3;
parameters r1star r2star r3star k1star k2star k3star i1star i2star i3star y1star y2star y3star c1star c2star c3star beta1 beta2 beta3 delta1 delta2 delta3 alpha1 alpha2 alpha3 rhoa1 rhoa2 rhoa3 rhod sigmaa1 sigmaa2 sigmaa3 sigmad1 sigmad2 sigmad3;
r1star = 0.04;
r2star = 0.04;
r3star = 0.04;
alpha1 = 0.33;
alpha2 = 0.33;
alpha3 = 0.33;
delta1 = 0.025;
delta2 = 0.025;
delta3 = 0.025;
beta1 = 1/(r1star+1-delta1);
beta2 = 1/(r2star+1-delta2);
beta3 = 1/(r3star+1-delta3);
k1star = ((alpha1/r1star))(̂1/(1-alpha1));
k2star = ((alpha2/r2star))(̂1/(1-alpha2));
k3star = ((alpha3/r3star))(̂1/(1-alpha3));
i1star = delta1*k1star;
```

```
i2star = delta2*k2star;
i3star = delta3*k3star;
y1star = k1starâlpha1;
y2star = k2starâlpha2;
y3star = k3starâlpha3;
c1star = y1star - i1star;
c2star = y2star - i2star;
c3star = y3star - i3star;
rhoa1 = 0.83;
rhoa2 = 0.65;
rhoa3 = 0.87;
rhod = 0.66;
sigmaa1 = 0.0000001;
sigmaa2 = 0.0000001;
sigmaa3 = 0.0000001;
sigmad1 = 0.0175;
sigmad2 = 0.081;
sigmad3 = 0.45;
model;
(1/c1) = beta1*(1/c1(+1))*(alpha1*(k1(̂alpha1-1))*exp(a1(+1))+1-delta1*exp(d1));
(1/c2) = beta2*(1/c2(+1))*(alpha2*(k2(̂alpha2-1))*exp(a2(+1))+1-delta2*exp(d2));
(1/c3) = beta3*(1/c3(+1))*(alpha3*(k3(̂alpha3-1))*exp(a3(+1))+1-delta3*exp(d3));
c1+i1 = y1;
```

```
c2+i2 = y2;
c3+i3 = y3;
y1 = exp(a1)*(k1(-1)âlpha1);
y2 = exp(a2)*(k2(-1)âlpha2);
y3 = exp(a3)*(k3(-1)âlpha3);
i1 = k1-(1-delta1*exp(d1))*k1(-1);
i2 = k2-(1-delta2*exp(d2))*k2(-1);
i3 = k3-(1-delta3*exp(d3))*k3(-1);
a1 = rhoa1*a1(-1)+ea1;
a2 = rhoa2*a2(-1)+ea2;
a3 = rhoa3*a3(-1)+ea3;
d1 = rhod*d1(-1)+ed1;
d2 = rhod*d2(-1)+ed2;
d3 = rhod*d3(-1)+ed3;
y = y1+y2+y3;
c = c1+c2+c3;
k = k1+k2+k3;
i = i1+i2+i3;
end;
initval;
k1 = k1star;
k2 = k2star;
k3 = k3star;
```

```
i1 = i1star;
i2 = i2star;
i3 = i3star;
c1 = c1star;
c2 = c2star;
c3 = c3star;
y1 = y1star;
y2 = y2star;
y3 = y3star;
y = y1star+y2star+y3star;
c = c1star+c2star+c3star;
i = i1star+i2star+i3star;
k =k1star+k2star+k3star;
a1 = 0;
a2 = 0;
a3 = 0;
ea1 = 0;
ea2 = 0;
ea3 = 0;
end;
shocks;
var ea1 = sigmaa1 2̂;
var ea2 = sigmaa2 2̂;
```

```
var ea3 = sigmaa3 ^2;

var ed1 = sigmad1 ^2;

var ed2 = sigmad2 ^2;

var ed3 = sigmad3 ^2;

end;

steady;

stoch_ simul;
```

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