

Do temperature surprise shocks in urban Canada lead to inflationary pressures?

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Abstract

As the consequences of changing temperatures unfold with increasing severity in Canada, understanding the impact of climate change is critical. So far, no consensus has been reached on the magnitude or direction of the effects of temperature shocks. Using monthly data at the census metropolitan area (CMA) level, I create a novel Canadian shock series of the weighted average surprise of extreme temperature realizations in each quarter. I isolate the unexpected component of these weather events by controlling for the adjustments of expectations over time. My empirical analysis provides evidence that adverse temperature shocks lead to mostly deflationary pressures on the Canadian economy. These pressures are persistent, and primarily driven by cold shocks.

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1 Introduction

Rising temperatures unceasingly emphasize the need for improved readiness among market stakeholders. Most of the literature on the subject has considered aggregated, periodic estimates of temperature when quantifying its macroeconomic ramifications. While varying consequences can be explained by specific geographical, wealth, or exposure characteristics,¹ these considerations remain circumscribed. Because temperature is a local feature, using aggregated estimates may fail to capture non-linear variations in its movements (Natoli, 2022). Moreover, the cyclical element of temperature events presupposes that there are anticipated and unanticipated components to its fluctuations (Colacito et al., 2018). Unless differentiated, it is impossible to grasp how both elements affect behaviors, respectively. Recent studies have adopted more of a granular approach to estimating macroeconomic consequences of rising temperatures (Faccia et al., 2021; Choi et al., 2020). However, there still remains a lack of unanimity regarding the direction of the effect of temperatures on prices. To contribute to the apprehension of this global challenge to economic performance, I explore the question: Do temperature surprise shocks in urban Canada lead to inflationary pressures?

Achieving this task requires aggregated high-frequency, infra-annual data at small geographic scales. I draw inspiration from the methodology of Natoli (2022), who takes into account similar issues for the US. His papers exploit aggregated county-level data and gridded daily temperature records to argue that what matters is the magnitude, and not the sign (cold or hot), of unanticipated temperature disturbances. He introduces a time-varying reference for historical average temperatures to capture the degree to which weather events are exceeding updated expectations.

Similarly, I circumvent these challenges to the study of the macroeconomic impact of rising temperatures by considering climate events at the level of census metropolitan areas (CMAs).² In so doing, I allow for the evaluation of temperatures to be as local as possible.

¹In fact, it is well documented that less developed economies are significantly more sensitive to climate shocks for an array of reasons, including weaker infrastructures, greater reliance on exposed industries (such as agriculture, and tourism), less protected working conditions, and poorer health (Laframboise and Loko, 2012; Curtis et al., 2022).

²CMAs are considered to be "large, densely populated centers made up of adjacent municipalities that are economically and socially integrated" StatisticsCanada (2022).

According to the idea of macro shocks, as defined by Ramey (2016), I construct an original time series of the Canadian surprise shocks of temperature. Through building quarterly distributions from three decades of monthly data, I model time-varying adjustments to agent's expectations through experience-based Bayesian learning (Choi et al., 2020; Tran, 2022). I then identify the current quarterly extreme realizations relative to the time-sensitive benchmarks of expectations. Because I use data at a lower frequency than my peers, I set a larger interval for the time-varying reference period. Nevertheless, this process enables my shock series to capture the unanticipated component of temperature occurrences. With a weighted national shock series estimated from realizations in the largest urban centers in Canada, I compute the effect of rising temperature on prices, output, productivity, the policy rate, and more indicators from the business cycle perspective.

My study aims to contribute to the still-scanty repertoire of evaluating the short-term effects of temperature shocks in view of diverse local and seasonal occurrences. Regarding macro consequences, the current consensus regarding the relationship between temperatures and the economy is two-fold: the impact of extreme temperatures is primarily negative, but higher levels of income, and adaptability to local effects critically mitigate the extent of the damages caused (Barreca et al., 2016). Beyond those broad observations, conclusions regarding the behavior of prices are multifaceted.

Indeed, some studies found upward pressures on prices caused by temperature shocks. It is the case of Mukherjee and Ouattara (2021), whose paper exploits panel data of annual average temperature for 107 countries. The authors find that the impact of temperature shocks has inflationary tendencies for all economies, in addition to lasting characteristics for developing ones. They argue that temperature shocks can have effects on the supply-side and demand-side of the economy (Mukherjee and Ouattara, 2021). Moreover, the effects documented on the demand side alone are diverse Choi et al. (2020); Nelson et al. (2010). For instance, more extreme temperatures tend to cause an increase in energy-related costs for agents (McFarland et al., 2015). On the other hand, decreases in aggregate demand, and prices are observed as vulnerable activities, and behaviors are discouraged by unfavorable weather events (Zivin and Neidell, 2014; Griffitt and Veitch, 1971).

Additionally, Faccia et al. (2021) makes a case for effects going in more than one di-

rection. Using panel local projections for 48 advanced and emerging economies, the authors conclude that beyond an increase following the initial shock, the impact across multiple price indices tends to be insignificant or negative in the medium term. The study also denotes the increased magnitude of the effects during the summer and for greater sizes of shocks. Evidence specific to more advanced economies, such as G7 countries, shows that the response induced by temperature shocks on economic growth, price stability, and output is mostly negative across countries Curtis et al. (2022). A US-focused study by Colacito et al. (2018) shows signs of mixed results in the US, largely explained by the component of seasonality. The negative effects are the largest in the summer season during which increases in the seasonal average temperature have significant impacts on the growth rate at the state level.

Across all findings, the various potential implications of temperature change reinforce the urgency for quantification of the impact. To correctly address the question and uncover policy-relevant dynamics, the current body of knowledge points to the need for more depth in the scope of scrutiny. In response to that, this study quantifies the economic challenges of the ambiguous impact of rising temperatures that policymakers and industry stakeholders must contend with in the years ahead.

For that purpose, I take into account the geography of Canadian cities, the aggregation of differences in local effects, and the adaptability of agents' expectations to the broadly observable changes in their environment. My method differentiates itself from previous studies that compared current temperatures to a historical long-run average (Faccia et al., 2021; Mukherjee and Ouattara, 2021). It also aligns my study with the most recent strand of literature involving granular variations to evaluate macroeconomic repercussions. Furthermore, the quarterly considerations of my estimations of the short-term effects of temperature shocks, consistent with Natoli (2022); Ciccarelli et al. (2023), warrant distinguishable seasonal effects.

My results show that temperature shocks exert mostly deflationary pressures on the Canadian economy. In addition, these disturbances erode productivity and induce expansionary monetary responses. Consistent with the literature, I observe that extreme temperatures are detrimental to the economy. For a shock corresponding to 8.8 unfavorable days in a quarter, CPI decreases between 0.02%-0.04% on impact. The same also reduces RGDP by approxi-

mately 0.12% and labor productivity by 0.08%-0.10%. My analysis indicates that the impact of the surprise extends throughout a four-year horizon. I provide evidence that in the case of Canada, temperature surprise shocks push prices in the downward direction and that these effects are driven by extreme cold realizations. My ambition is to provide an empirical assessment relevant to enhance preparedness for the urgent matter of rising temperatures.

I expand on the underlying assumptions I use as foundations in Section 2. Afterward, I start by detailing the process by which I build my innovative shock index and retrieve the surprise from the agent's expectations in Section 3, before presenting the data used in the building of my shock series in Sections 3.1 and 3.2. Then, I expose the course of action I follow for my impulse response analysis in Section 4 and introduce the relevant data in Section 4.1. Section 5 renders the main findings, while Section 6 discusses them. I conduct alternative analyses in Section 7 before drawing my conclusions in Section 8.

2 Methodology

The methodology I employ to build my Canadian shock series is inspired by the one used by Natoli (2022) in his work on the US-based economic impact of temperature shocks. I select and adjust this methodology to sort out the set of assumptions that are best suited to the phenomenon of rising temperatures in Canada.

The first assumption I make is that local temperature shocks could have a non-linear relationship to the typically used country's average temperature. Because temperature is a local phenomenon with sizable sub-national variations, the national mean temperature can be a faulty representation of aggregated local fluctuations. Therefore I work with CMA-level data, which I can then aggregate at the country level using representative weights. Contrary to the broadly used country-wide average, my methodology permits me to detect specific local surprises.

The second assumption is that agents do not anchor their expectations on a fixed long-run average of temperature realizations. Instead, I assume that their beliefs evolve and adjust over time. Documented by Choi et al. (2020) among others, experience-based adjustments in shared beliefs imply that the reference used to determine how much a realization exceeds

expectations must also be time-varying. For that reason, my thresholds are set based on the moving average over 10 years of monthly mean temperatures. This method allows me to identify the unexpected component of the movement of temperature in the short term.

The third assumption is that the seasonal nature of weather variations must be differentiated to capture the true economic impact. By way of explanation, it is reasonable to consider that a surprise, regardless of its direction, can have different economic impacts: a positive surprise - defined as warmer-than-expected months in a quarter - could affect the economy differently if it were to occur in the winter versus the summer. I deal with this subtlety in Section 3.

The fourth assumption is that short-term temperature variations are exogenous to economic activity. This condition allows me to dismiss the case of reverse causality and later on to identify my shock. This condition is critical to my estimation, as it controls for all other influences. The rationale behind it is based on the fact that the impact of economic activities, through the release of GHG emissions, which contribute to the human-induced acceleration of global temperature, only unfolds in the long-term Mikhaylov et al. (2020). This assumption enables me to consider a single type of shock to the system of variables: structural disturbances affecting temperatures. These disturbances are exogenous to contemporaneous developments.

3 Shock construction

To construct the original shock series, I take monthly average surface air temperature records for the 21 largest CMAs in Canada from 1985-2019. I build the CMA surprise measure following the general framework, which gives this expression:

$$cmasurprise_{q,t}^i = \sum_{i=1}^3 [I(T_{m,q,t}^i < lt_{m,q,t}^i) + I(T_{m,q,t}^i > ut_{m,q,t}^i)] - (N_q \times 0.32 \times 0.32) \quad (1)$$

For CMAs determined by $i \in K$, and quarters defined by q , where $K = 1, \dots, 21$ and $q = 1, 2, 3, 4$. Here, $I(x)$ is an indicator function that takes the value 1 if x is true, 0 otherwise. $T_{m,q,t}^i$ the temperature in month m , quarter q , and year t . $lt_{m,q,t}^i$ ($ut_{m,q,t}^i$) lower (upper)

threshold computed monthly by taking plus minus one standard deviation from the average of the previous 10 years of average temperature recorded for month m . N_q number of months of the reference distribution for quarter q . The 10-year expectation-setting period is drawn from the tested learning lengths for expectation adjustment in Pankratz and Schiller (2019). It is the minimal time frame that provides sufficient data points to build a large enough reference distribution.

The term on the right side of the difference in Equation 1 represents the reference distribution constructed by the monthly average realizations of the past 10 years. By construction, by setting the threshold within one standard deviation, I force 32% of realizations beyond those thresholds. This is because approximately 68% of observations are within one standard deviation of a normal distribution. To derive the surprise, in other words, the number of months above (or below) what agents are expecting based on the past 10 years, I must subtract the portion of extreme months beyond those thresholds that were already part of the reference distribution. I multiply twice by 0.32 to account for the monthly and quarterly number of extreme realizations that are expected. This adjustment allows me to determine if the number of months beyond (or below) the thresholds constitutes a positive (or negative) surprise in a given quarter. In this context, a positive surprise represents several extreme months above what is expected. Conversely, a negative surprise is a number of extreme months below agents' expectations for the quarter.

To obtain the country-wide shock series, I calculate the weighted average of surprises that occurred in each CMAs, by quarter:

$$Canadianshock_{q,t} = \sum_{i=1}^K (cma_{surprise}_{q,t}^i \times w_{q,t-1}^i) \quad (2)$$

For a quarter defined by q , and a year defined by t , where $q = [1, 2, 3, 4]$ and t is between 1992 and 2019. Here, $w_{q,t-1}^i$ is the weight computed as the lagged share of the population of CMA i , on the total population of the sample in the same quarter. Using share of the population as weight in my main specification allows my shock to more accurately capture the incidence of exposure to temperature shocks: the denser the population, the greater the number of agents affected by the shock in a given locality. My alternative specification in

Section 7.1 aggregates the shock using employment shares instead of population shares as a proxy for economic activity at the CMA-level. The quarterly frequency of shocks enables me to observe their seasonal impact on output and the extent to which labor productivity, private consumption expenditures, and investment expenditures are affected by unforeseen fluctuations in temperature in the short term.

The time series of the Canadian shock explained above is presented in Figure 2. At its peak, the shock reaches 1.3 months (or 39 days) in a quarter and zero at its lowest. As required for a shock used in an empirical econometric analysis, the mean is approximately zero and the shock is free from serial correlation for various lag lengths, as displayed in Figure 3. While I consider the mean to be roughly equal to zero, I observe that shocks from 1991-2019 are mostly positive, i.e. the aggregated surprise over that period has overwhelmingly been the occurrence of more extreme months (in both directions, cold and hot) than expected. These findings seem to highlight the need for a shorter time frame for the anchoring of agents' expectations. The shock series built upon a 10-year rolling average displays the fact that such expectations, at the pace at which temperature evolves in Canada, will most likely be exceeded. Alternative expectation-setting periods would require data at a higher frequency than monthly, to retain significant predictive power. I introduce in the following sections the data used in the construction of the shock series.

3.1 Temperature data

The air surface average temperature data are taken from the online database initiated by Environment and Climate Change Canada ECCC (2018). Monthly air surface average temperature is obtained by taking the average over a month of the midpoint between the highest and lowest temperature points recorded each day. Specifically, I exploit the Adjusted and Homogenized Canadian Climate Data (AHCCD), which consists of weather station data sets that have been adjusted to correct discrepancies in long-term data records caused by non-climatic factors. I match weather stations with the corresponding census metropolitan areas in which they are located.

Despite having multiple stations for my geographic units, I decided to only consider one

of them per CMA under the assumption that at the macro level, the temperature differences felt within one CMA, are not significant. For instance, I presume that the temperatures on a given day captured at the north, south, east, and west of Vancouver are roughly the same. My monthly weather observations range from 1981-2019.

My source considers a monthly observation as missing if there have been at least eight random days not recorded, or five consecutive days not captured within a month. To circumvent that issue, I reference other stations recording for the same city to fill the gaps. Tables 1 and 2 provide the extensive list and identification number of my stations, the CMA that they represent, and the filler stations used to complete my records.

3.2 CMA-level data

The definition of CMA and the availability of data for high levels of agglomeration limit my sample size of CMAs to the 21 largest in Canada. Natoli (2022) argues that the local component of temperature shocks is best reflected at the most granular geographic unit. With that in mind, I resort to CMA-level data as an alternative to gridded data, to exploit the abundance of data publicly available for this categorization scheme.

These 21 references of urban Canada capture on average, over my 38 years sample: 63% population, 63% of employment, and 67% of GDP nationwide. The trend toward urbanization throughout my period would result in an increase of about 2% in the share of these nationwide measures from 2014-2019. In light of the magnitude of economic activity captured, it is reasonable to regard my sample as a suitable estimate for Canadian economic activity.

My CMA-level data is available for the interval from 1986-2019 and is pulled from the online database of the Conference Board of Canada CBC (2023). I employ quarterly measures of population, and employment as weights to aggregate my CMA-level temperature surprises to the national level. From this point forward, I will consider urban Canada to be the nationwide spectrum of interest in my analysis.

As previously mentioned, I use two different frequencies of data: monthly and quarterly. Monthly data are used in the construction of the surprise shock index, which is then converted

to quarterly. My subsequent analyses of the impulse response of my system of macroeconomic variables are done from a quarterly perspective. As a reminder, the assumption is that each quarter roughly corresponds to a season. To be clear, the first quarter (January to March) is considered winter, and the following sets of 3 months as the consecutive seasons. The source and characteristics of all of my data are summarized in Table 3.

4 Economic methodology

To evaluate the response of my variables of interest to temperature shocks, I follow the work done by Coibion (2012), and almost replicate the methodology used by Mukherjee and Ouattara (2021). I use a VAR system with the following reduced-form equation:

$$y_t = \varphi_0 + B(L)y_{t-j} + \varepsilon_t \quad (3)$$

Here, y_t is an n -dimensional vector of endogenous variables, φ_0 a vector of constant, $B(L)$ is the lag polynomial, and ε_t is an n -dimensional vector of reduced-form disturbances. $E[\varepsilon_t] = 0$ implies that the vector error term is uncorrelated to variables endogenous to the system and unanticipated from the past information. Additionally, $E[\varepsilon_t, \varepsilon'_d] = 0$ for $t \neq d$ implies that the reduced-form errors are uncorrelated with each other and over time. Lastly, $E[\varepsilon_t, \varepsilon'_t] = \sum_\varepsilon$ represents the variance-covariance matrix. The reduced-form errors are correlated across the VAR equation so that this matrix \sum_ε is not diagonal. These properties of the error term are consistent with the theory from Ramey (2016). To address the fact that the primitive shock may be correlated in the reduced form equation, I transform Equation 3 into its structural form in the following manner:

$$B_0 y_t = B_0 \varphi_0 + B_0 B(L) y_{t-j} + A_0 \mu_t \quad (4)$$

Here, $A_0 = B_0 \varepsilon_t$ depicts the relationship between the structural disturbance μ_t and the reduced-form disturbances ε_t such that $E[\mu_t, \mu'_s] = D$ if $t = s$, 0 otherwise. The structural disturbances are assumed to be uncorrelated with each other, thus implying that the variance-covariance matrix of the structural disturbances \sum_μ is diagonal. The contempora-

neous relationships among the variables in the vector of endogenous variables are captured by matrix B_0 with $E[\mu_t] = 0$ implying that the structural disturbances are uncorrelated to any other endogenous variables.

As mentioned in Section 2, our fourth assumption sets the condition for a system where temperature events are exempt from any influences from the other variables of the model in the short term, due to the fact that the impact of economic activities on temperatures is lagged. Using the common lower triangular Cholesky identification strategy, I order the temperature index first in the VAR model and impose zero restrictions on the coefficients of B_0 above the diagonal. Under these constraints, I am able to recursively isolate a single structural disturbance to the system, unanticipated and uncorrelated with other exogenous disturbances. The well-established delayed unfolding of the effects of GHG emissions on climate conditions render the lower triangular Cholesky decomposition a suitable and practical identification strategy to model the system.³

My vector autoregressive model is composed of seven variables based on the referenced works of Mukherjee and Ouattara (2021) and Natoli (2022). I work with four lags⁴ in my baseline specification, as it is customary when working with quarterly data (Deryugina and Hsiang, 2014; Natoli, 2022). The ordering of my variables follows the theory of the Cholesky decomposition and treats them by their respective degree of exogeneity to each other. As mentioned before, my proxy for climate change is considered to be exogenous to every other macroeconomic variable, while every other variable is allowed to be contemporaneously affected by temperature shocks: [TEMP CPI R C I LP GDP]. I expand on each of these variables in the following section.

4.1 VAR model data

My analysis of the response of the economy to the shock series uses quarterly data for Canada from 1991-2019. Seven variables are considered in this analysis: my Canadian temperature surprise shock index (TEMP), a measure of labor productivity (LP),⁵ the consumer price in-

³The lower triangular Cholesky decomposition is best described by the work of Coibion (2012).

⁴I provide in the appendix, Figure 5, the impulse responses for the main specification computed with eight lags. I discuss the results in Section 7.1.

⁵I obtain my measure of labor productivity by calculating the ratio of output and labor force.

dex (CPI), the real gross domestic product (RGDP), the real private household consumption (C), the real gross private investment (I), and the overnight interest rate (R).

All quarterly variables are indexed to prices in the year 2015, and when it applies, seasonally adjusted and expressed in Canadian dollars. Figure 1 shows a visual representation of their evolution over time. For my computations and to simplify interpretation, the log levels for all variables were used, except the overnight interest rate (R) - which is already expressed as a percentage - and the climate change measure, which is expressed in terms of the number of months per quarter.

5 Results

5.1 Short-term response

I present the impulse response over a time horizon of four years within 68% Hall-Wellner confidence bands in Figure 4. I show that in reaction to a transitory, positive one standard deviation shock in a single quarter - equivalent to about 0.292 months or 8.8 days in a quarter - most variables decline on impact.

CPI drops within the -0.02% and -0.04% range in the same quarter, reaching its trough of -0.08% after 3 months. RGDP immediately falls by close to 0.12% and goes slightly past that threshold after six quarters. As expected, labor productivity declines to within the -0.08 to -0.10 range, with a trough close to the -0.12 mark. Private consumption is the only variable not significantly declining on impact. Instead, peaks at 0.06% after three months and remains positive for the rest of the year. Investment experiences the largest drop, of 0.3% in response to the shock. Consistent with the general decline, the monetary approach is expansionary, as the policy rate drops by 0.05% or 5 basis points on impact. It appears that the tendency is to lower the rate within the following two quarters, and in the third quarter, as CPI also rebounds, increasing it again before both variables stabilize at the one year mark.

Since household consumption immediately increases, it seems that temperature shock stimulates demand in the short term. However, the rest of my macroeconomic indicators as a result of the shock, indicating an overall shrinking of economic activities within the year

following an adverse surprise.

5.2 Long-term response

Observing the behavior of the variables beyond one year mark clarifies some of the dynamic effects of temperature shocks. Indeed, as these shocks have diverse effects,⁶ we can draw conclusions on which dominates through the behavior of my variables in the long term. The drop in the CPI persists beyond the one year point. Although the immediate impact on prices is stabilized in the fourth quarter following the shock, the dynamic effects drive the CPI back within a 0.04%-0.06% decline over the four-year horizon. RGDP and labor productivity both experience a persistent decline in the long term. Notably, RGDP decreases by more than twice as much as labor productivity after four years. While private consumption was the only variable increasing in the short term, it suffers the steepest decline in the next three years. Private investment plunges to -0.4% after five quarters and does not revert beyond that threshold in the subsequent quarters. Finally, the overnight interest rate, after responding to prices in the first year, retains an expansionary inclination in the long term to stimulate the deteriorating economic performance.

The long-term effect on output sheds light on the supply-side impact of my climate shock: temperature shock as anticipated⁷ erodes productivity and diminishes production.⁸

As I aim to determine if temperature surprise shocks exert inflationary pressure in Canada, the findings give a clear answer: The subsequent pressures are mostly deflationary. However, in the short term, effects in both directions are felt through the economy. Nevertheless, among these immediate effects, it seems that the deflationary ones dominate. I make this assessment based on the fact that despite private household consumption increasing, CPI declines. Moreover, unfolding after a one year lag, the decrease in household consumption indicates that the aggregate demand is persistently sensitive to extreme temperatures.

In response to the unfavorable surprise, the interaction of my economic indicators points

⁶I discuss in Section 1 the diverse effects on the demand side of the economy that have been identified in the literature. These effects in Canada are, to the best of my knowledge, still to be specified or quantified.

⁷Similar results regarding the decline of GDP as a result of the increase of temperature have been documented by (Colacito et al., 2018; Deryugina and Hsiang, 2014; Natoli, 2022)

⁸By affecting the fragment of hours worked or the work done per unit of time, Somanathan et al. (2015); Cachon et al. (2012) documents some of the ways by which this phenomenon occurs.

toward a lower equilibrium level for Canada's economy. Although relatively small in size, the dynamic effects responsible for the decline of Canada's economic performance seem to persist in the long term. I discuss some of the implicit dynamics behind my results in the next section.

6 Discussions

In line with the literature, my results support the proposition that the impact of extreme temperatures is detrimental to the economy. In my alternative analyses conducted in Section 7.2, I explore the heterogeneity of the impact of the two different types of extremes. My findings allow me to highlight some of the underlying reasons responsible for the deflationary pressure of temperature shocks in Canada.

First, the CPI index is composed of different types of goods and services deemed representative of a consumer's basic basket. Its movements can thus be driven by the price fluctuation of a variety of categories of goods. As we know in the same period, while CPI decreases, private household consumption increases. Although my study is unable to identify the specific behavior of each category, previous findings indicate that the hike in consumption is partially due to higher energy-related expenditures. With that said, my results show that the increase in these costs is small in comparison to the negative impact on labor productivity and output in the same period. In the short term, the negative impact on the supply side of the economy overwhelms the temporary increase in aggregate demand.

Furthermore, in the short term, the decrease in output is largely explained by the drop in of labor productivity. Since labor inputs are by nature more sensitive to this erosion than capital (Baker and Cameron, 1996; Cachon et al., 2012), we can infer that the impact will be accentuated in labor-intensive sectors and weather-exposed/dependent industries.

There are various effects on the demand side. Within the first year, demand-stimulating effects dominate. After that, these effects dissipate as consumption begins to progressively drop. As labor productivity is affected, the marginal product of labor, and thus wages, are likely affected in the same direction. Decreasing wages would reduce the disposable income of households, and at least in part, explain the drop in the levels of private consumption and

investment after the first year.

While the shock is only transitory, its impact seems to persist over multiple years. At the fourth year of the horizon, the level of all of my variables is lower than previously observed before the shock. Without any further interventions, the uncertainty and inconveniences that adverse temperature realizations impose could have a lasting impact on the behavior of economic agents. The acceleration in the pace of change of climate conditions is bound to create even more volatility in temperature occurrences. These mechanisms constitute a significant threat to the well-being of the Canadian economy.

7 Robustness checks

In this section, I investigate the robustness of the results from my baseline specification by expanding the analysis and by testing alternative assumptions.

7.1 Weights

My baseline results exploit population data for my CMAs in order to generate the weights for the aggregation of the local temperature surprise shocks. However, other weights can be used to capture the economic impact of surprises across my sample. I present in Figure 6 the shock series obtained from aggregating the CMA-level surprise by employment. Despite employment being by nature more cyclical than the population, Figure 7 permits me to observe the lack of auto-correlation in the series. This alternative shock is almost the same as the one weighted by population. Naturally, Figure 8 shows that the response of the variables when switching the weighting scheme with employment instead of the population is similar. The results are in line with my main findings: on impact, there are downward pressures on CPI, RGDP, labor productivity, private investment, and the policy rate. During the first year, the overnight interest rate responds to prices, and private consumption increases. However, the impacts on all of the variables are negative afterward.

7.2 Cold vs Heat surprises

The shock series of my main specification is built to capture the number of extreme months, in each season (quarter), exceeding agent's expectations. Extreme realizations are those beyond the thresholds set at one standard deviation from the average, on both sides of the distribution.

I expand the analysis to observe the difference in the way the two types of extremes (cold or heat) affect my variables. The formulas of these alternative shocks have the following form:

$$cmasurprise_{q,t}^{i,cold} = \sum_{i=1}^3 [I(T_{m,q,t}^i < lt_{m,q,t}^i)] - (N_q \times 0.16 \times 0.16) \quad (5)$$

$$cmasurprise_{q,t}^{i,heat} = \sum_{i=1}^3 [I(T_{m,q,t}^i > ut_{m,q,t}^i)] - (N_q \times 0.16 \times 0.16) \quad (6)$$

For CMAs determined by $i \in K$, and quarters defined by q , where $K = 1, \dots, 21$ and $q = 1, 2, 3, 4$.

The right side of Equations 5 and 6 have been adjusted to reflect the quarterly expectations for the left and right tails of the distribution, respectively.

Figures 9 and 10 present the characteristics of both shocks. As one would expect, peaks of extreme temperature surprises in one direction coincide with the troughs in the other. Heat surprises seem to be somewhat correlated with extremely hot occurrences in the previous quarter. Serial correlation in the cold shock series is limited at best. Figure 11 and 12 display the response of my seven variables of interest to events involving colder-than-expected temperatures and higher-than-expected temperatures, respectively. To be clear, the cold surprise shock series unveils the extent to which colder relative extremes - during winter, summer, spring, and fall months - affect the economy. We observe significant differences in the way these shocks impact my variables.

In response to a transitory shock corresponding to approximately nine unexpected cold days in a single quarter, CPI immediately grows by 0.04% before peaking at 0.08% from the first to the third quarter of the same year. RGDP falls by 0.08%-0.10% on impact and reaches -0.35%, six quarters after the fact. Following a similar time frame, labor produc-

tivity first drops by 0.06% then continues its decline by as far as 0.14%-0.16%. After an initial slight increase, private consumption begins a steep decline within the subsequent three months, falling by 0.14% at its trough after a year and a half. Private investments again suffer the most, as it is reduced by 0.2%-0.4%, and by 1.2% at their lowest at the six-quarters mark. When dealing with cold shocks, the policy rate seems to mostly respond to output and consumption, by adopting an expansionary approach. Similar to the findings of my main specification, most variables persistently decline over the four-year horizon, except for the interest rate. After about two years a half years of lowering the rate, monetary authorities adopt a moderate contractionary approach by increasing the rate by as much as 0.04% or 4 basis points. The deflating effects of cold shock begin to drive CPI down with a one year lag.

In the case of a transitory shock equivalent to about 10 unexpected hot days in a single quarter, CPI falls at 0.04% on impact, and declines even more in the following quarter, at nearly 0.16%. However, in the long term, CPI tends to increase. RGDP barely moves on impact but jumps by 0.2% after six quarters. Labor productivity seems to be very slightly positively affected on impact. Nonetheless, dipping at 0.04% after two quarters from the shock, labor productivity jumps by more than 0.08% after six quarters. Outputs are positively impacted in the long term. After an immediate decline of 0.02%, private consumption persistently increases, peaking at 0.14% higher after five quarters. Private investment is stimulated by heat shocks and grows by nearly 1.0% after six quarters. Alongside output, aggregate demand is also positively influenced throughout the four years. In summary, heat shocks seem to drive prices down in the first year, and induce a relaxing of the interest rates by the Bank of Canada.

In the short term, the impact of heat shocks on prices is greater than that of cold shocks. However, after three quarters, the consequences of cold shocks are larger on prices and on every other variable. This alternative analysis reveals that the findings of my main specification are mostly driven by cold surprises. In other words, unexpected extreme cold realizations in Canada are overall more detrimental to economic performance and aggregate demand than warmer days. Strikingly, the impact of both shocks in Canada is heterogeneous. As mentioned earlier, the occurrences of those shocks are mutually exclusive. The implication is that these events with varying effects are most likely to alternate if they are to happen in the

same year, which introduces an added layer of complexity for policymakers.

8 Conclusions

The nature of temperature change differs from that of other climate-related events, in that it is an upward phenomenon instead of a cyclical one. This distinction demands that the phenomenon of rising temperature be considered under a different set of considerations when attempting to measure its repercussions. The growing literature on the topic is starting to develop more fitting approaches to address the matter. The latest works have started to consider the importance of local fluctuations and the evolving expectations of agents regarding the ever-changing climate.

In the same vein, I build an index of the unexpected component of extreme temperature events, thus reducing the likely positive bias of estimations obtained from a historical long-run average of temperatures. Using the 21 largest census metropolitan areas in Canada, I work with the smallest known geographical unit for which macroeconomic indicators are publicly and frequently reported in Canada. After having constructed CMA-specific indicators of temperature shocks, I aggregate them into a nationwide quarterly index of the surprise shocks using their respective population share as weights.

My estimates show that temperature shocks in urban Canada lead to mostly deflationary pressures on the economy in the long term. Moreover, these effects are mainly driven by unexpected colder days over the course of a season. My results for the short and long-term reactions of the economy to temperature shocks are somewhat consistent with the findings of studies focusing on the US. However, I denote more heterogeneity in the impact of cold versus heat shocks in Canada.

My work uncovers the current and upcoming challenges for exposed and labor-intensive sectors, as well as for monetary authorities. Additionally, it provides empirical very preliminary evidence of the productivity-eroding attribute of climate surprises and the lasting consequences of more volatile temperature realizations.

While my results provide indications of the risks caused by rising temperatures, they likely fail to fully display the magnitude of their impact. In fact, due to a lack of available

data, I was unable to capture the size of temperature shocks in the country's rural areas. As I have noted, exploiting higher frequency data would provide the benefit of a more accurate quantification of the economic impact of temperature shocks. Furthermore, an attempt to measure the surprise of agents must typically include considerations for deviations from forecasts. A deeper look into the size of some of the channels of transmission discussed, and similar studies equipped with more extensive sets of current and forward-looking information, are avenues for which this study aims to lay a foundation.

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9 Appendix

Table 1: Representative Canadian stations and coordinates per CMA

Province	CMA	Station ID number	Coordinates
AB	Calgary	3031094	[-114.0 , 51.1]
AB	Edmonton	3012206	[-113.6 , 53.3]
BC	Abbotsford	1100031	[-122.3 , 49.0]
BC	Vancouver	1108380	[-123.1 , 49.1]
BC	Victoria	1018611	[-123.3 , 48.4]
MB	Winnipeg	502S001	[-97.2 , 49.9]
NL	ST. John's	8403505	[-52.7 , 47.6]
NS	Halifax	8202251	[-63.5 , 44.8]
QC	Montreal	7025251	[-73.7 , 45.4]
QC	Quebec city	7024254	[-71.1 , 46.8]
QC	Sherbrooke	7028123	[-71.6 , 45.4]
ON	Hamilton	6153193	[-79.9 , 43.1]
ON	Kitchener	6147188	[-80.4 , 43.3]
ON	London	6144478	[-81.1 , 43.0]
ON	Oshawa	6155878	[-78.8 , 43.8]
ON	Ottawa-Gatineau	6105978	[-75.7 , 45.3]
ON	St. Catherines	6136699	[-79.2 , 43.2]
ON	Toronto	6158355	[-79.4 , 43.6]
ON	Windsor	6139527	[-82.9 , 42.2]
SK	Regina	4016699	[-104.6 , 50.4]
SK	Saskatoon	4057165	[-106.7 , 52.1]

Table 1: The station identification number refers to a specific weather station in a geographic location.

Table 2: Canadian filler-stations per CMA

CMA	Filler station	Station ID number	Coordinates
Calgary	OLDS	3024925	[-114.1 , 51.7]
	Pincher creek	3035198	[-114.0 , 49.5]
Hamilton	Grimsby	6133047	[-79.6 , 43.2]
	Guelph	6143089	[-80.2 , 43.6]
Kitchener	Millgrove	6155183	[-80.0 , 43.3]
London	Lucknow	6124700	[-81.5 , 43.9]
Montreal	Montreal Tavish	7024745	[-73.4 , 45.5]
	Les cèdres	7014290	[-74.1 , 45.3]
Ottawa-Gatineau	Angers	7030170	[-75.6 , 45.6]
	Petawawa	6106396	[-77.3 , 45.9]
Quebec city	Lac ste croix	7065012	[-71.7 , 48.6]
	Donnacona	7011983	[-72.0 , 46.7]
Regina	Fort qu appelle	4016699	[-103.8 , 50.8]
	Weyburn	401HP5R	[-103.8 , 49.7]
Sherbrooke	Sawyerville nord	7027802	[-71.5 , 45.4]
	St hyacinthe	7027361	[-72.9 , 45.6]
St Catherines	Sarnia	7024745	[-82.3 , 43.0]
Toronto	Toronto buttonville	6158409	[-79.3 , 43.9]
	Toronto Ellesmere	6158520	[-79.2 , 43.8]
	Toronto intl A	6158731	[-79.6 , 43.7]
Victoria	Victoria university	1018598	[-123.3 , 48.4]
	Victoria gonzales CS	6158520	[-123.3 , 48.4]
	Victoria	1018621	[-123.4 , 48.7]
Windsor	St thomas	6137362	[-81.2 , 42.8]
	Simcoe	6137730	[-80.3 , 42.9]
	Leamington	6134190	[-82.7 , 42.1]

Table 2: The station identification number refers to a specific weather station in a geographic location. Part of the statistical treatment applied to the Adjusted and Homogenized Canadian Climate Data, consists of grouping data from stations in close range with similar coordinates levels.

Figure 1: Time series of the macroeconomic indicators

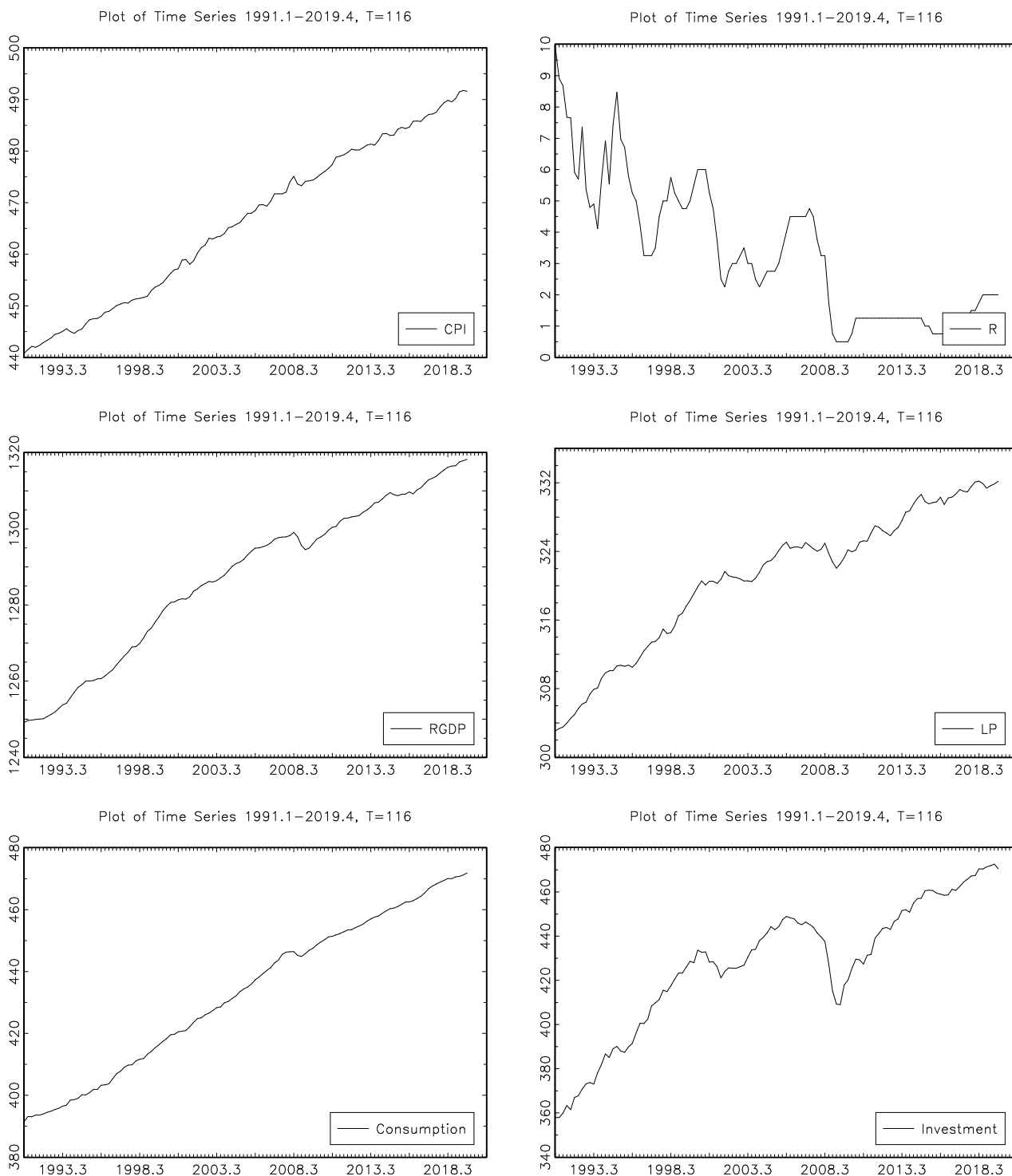


Figure 1: All of the variables above-displayed are in log-level, except for overnight interest rate which is already in percent.

Figure 2: Shock series of unfavorable temperature months per quarter

Plot of Time Series 1991.1–2019.4, T=116

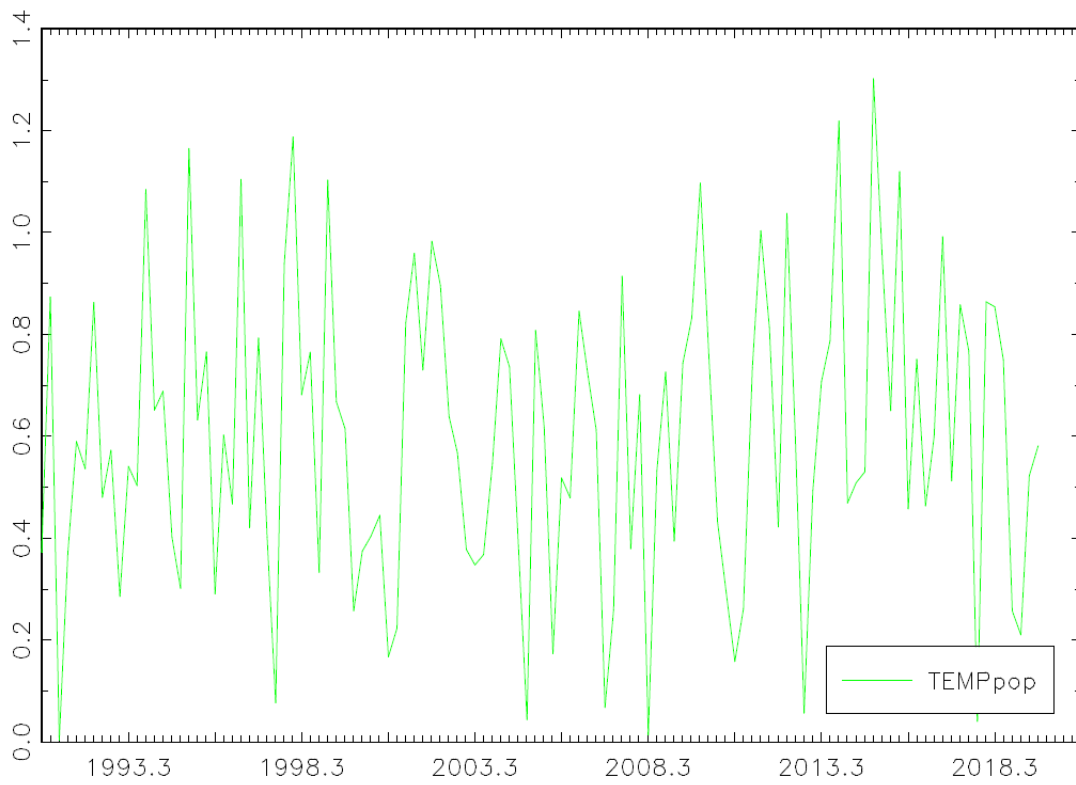


Figure 2: The mean of the population-weighted shock series is set at 0.598 months per quarter, which corresponds to roughly 18 days of adverse temperature occurrences in a season.

Figure 3: Serial correlation in the Canadian shock series

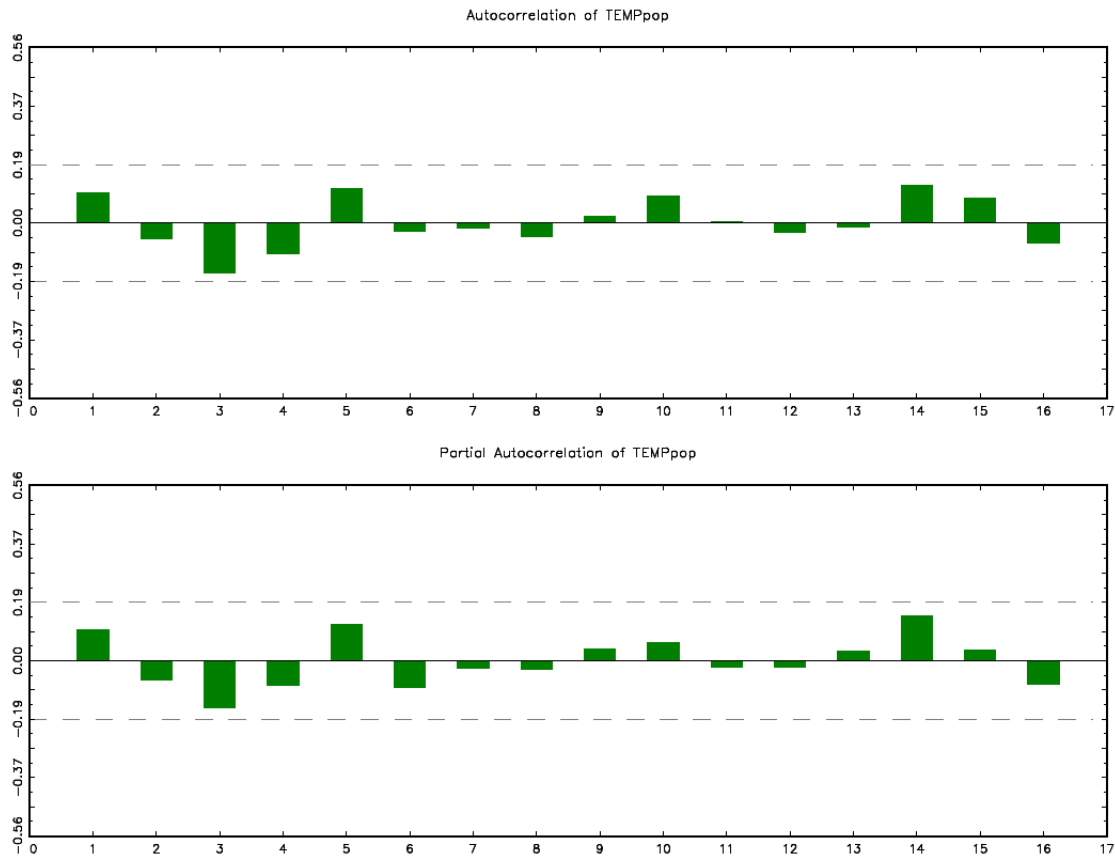


Figure 3: The two graphs above display the relationship between a current population-weighted shock and its lagged values. As it shows, the correlation within the time series is weak.

Figure 4: Impulse response of the baseline specification

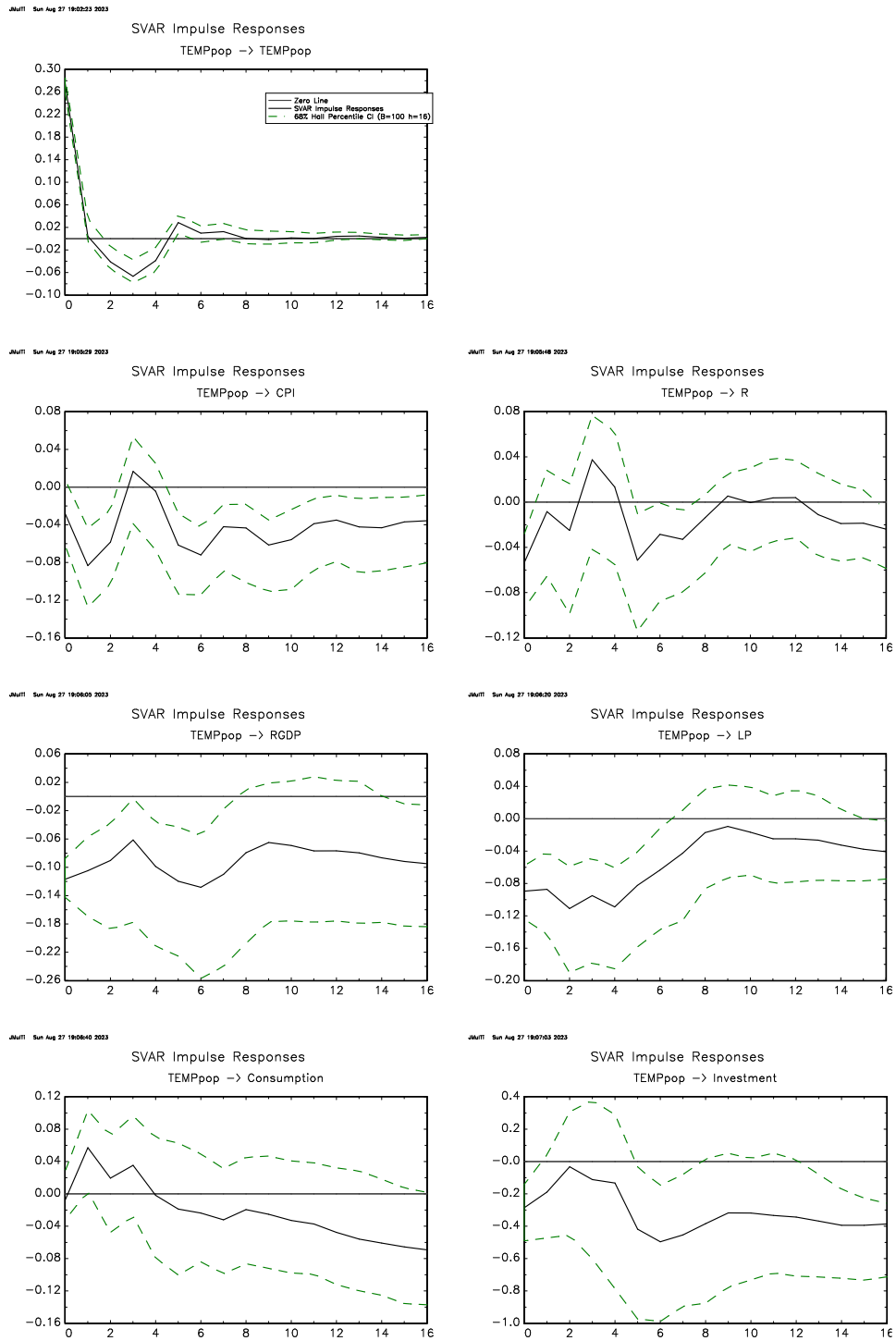


Figure 4: The shock considers four lags and a shock size of one standard deviation from the average. This corresponds to 0.292 extreme months or 8.8 unfavorable days in a quarter. The Hall-Wellner bands are set at a 68 percent confidence level.

Figure 5: Impulse response of a specification with a different lag length

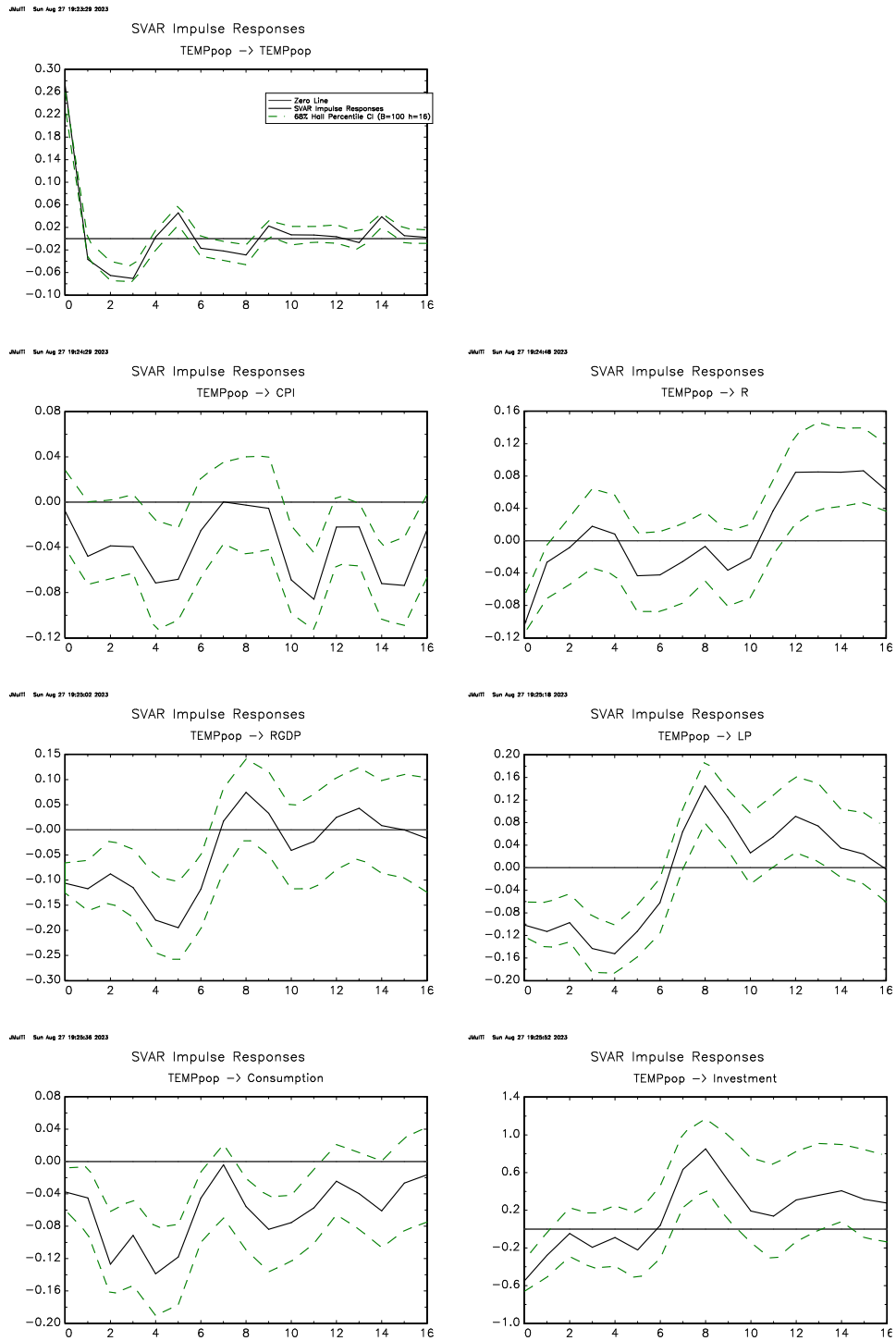


Figure 5: The shock considers eight lags and a shock size of one standard deviation from the average. This corresponds to 0.292 extreme months or 8.8 unfavorable days in a quarter. The Hall-Wellner bands are set at a 68 percent confidence level.

Figure 6: Alternative shock series of unfavorable temperature months per quarter

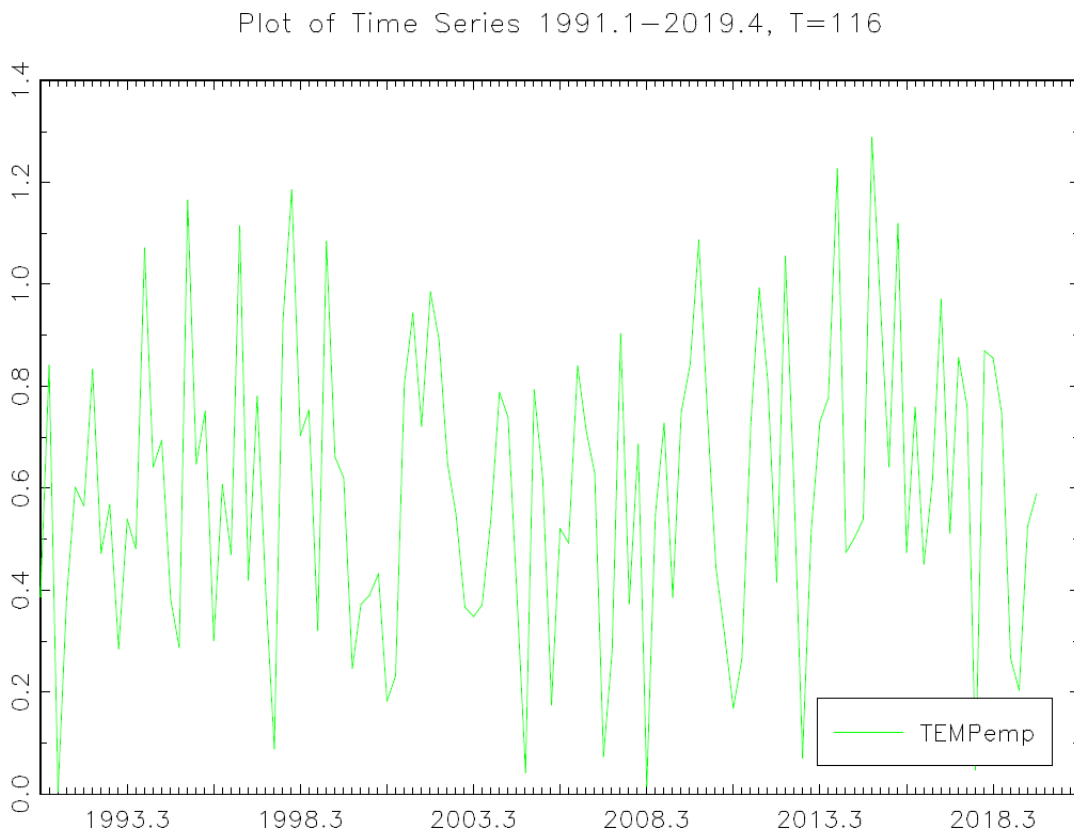


Figure 6: The mean of the employment-weighted shock series is set at 0.597 months per quarter, which corresponds to roughly 18 days of adverse temperature occurrences in a season.

Figure 7: Serial correlation in the alternative Canadian shock series

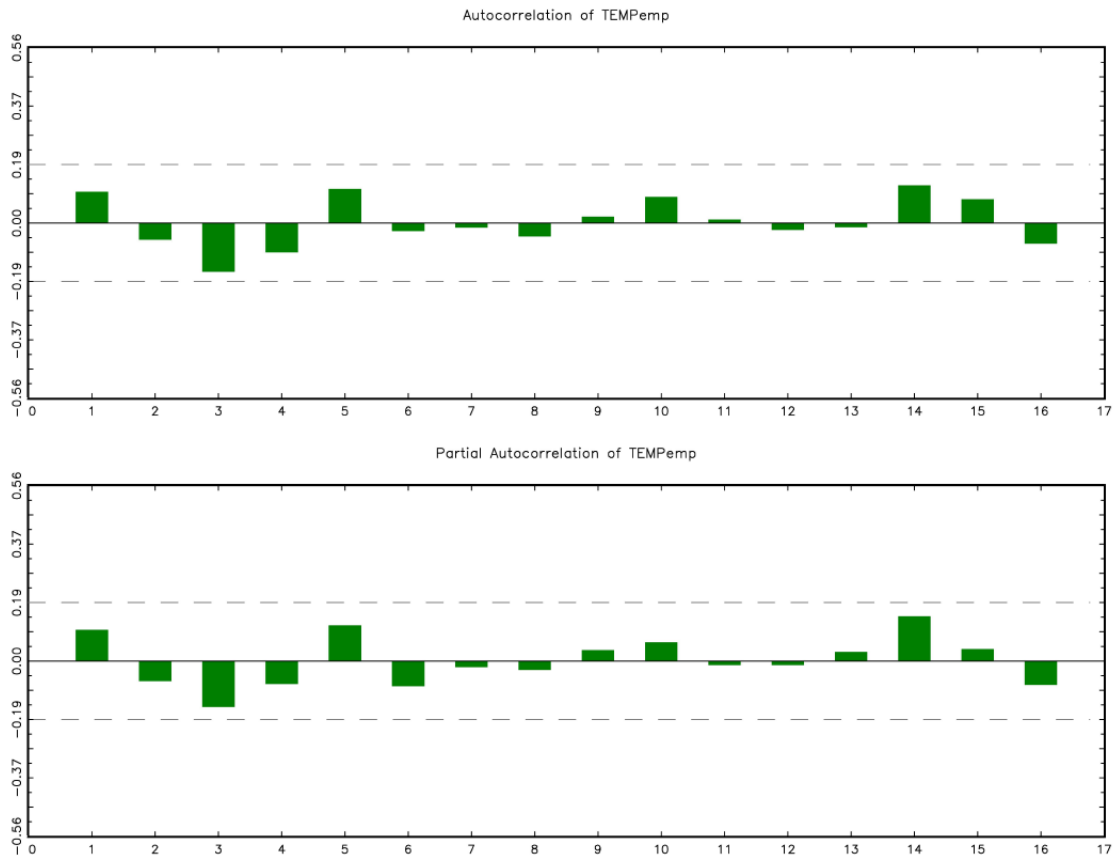


Figure 7: The two graphs above display the relationship between a current employment-weighted shock and its lagged values. As it shows, the correlation within the time series is weak.

Figure 8: Impulse response of a specification with a different weighting scheme

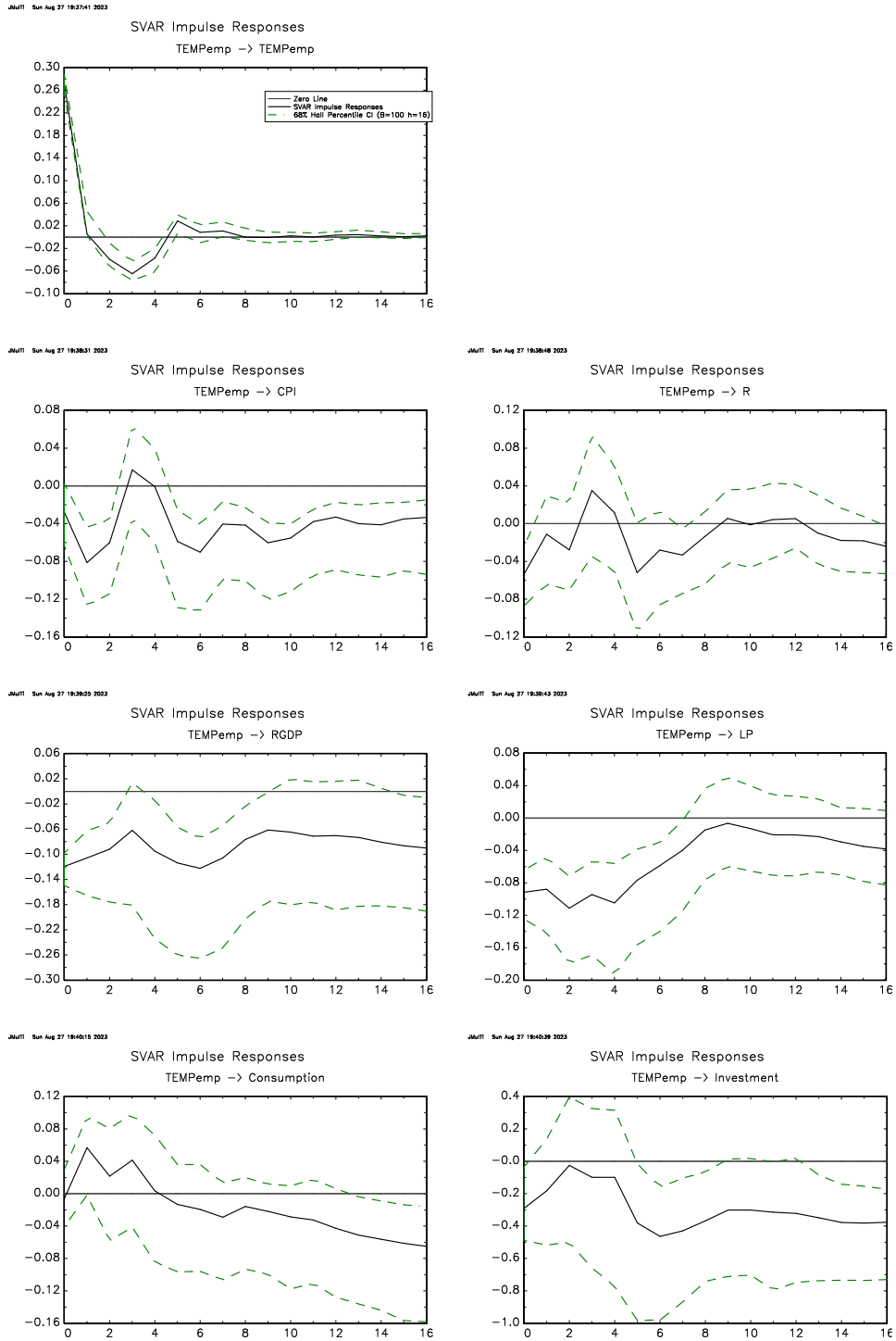


Figure 8: The employment-weighted shock considers four lags and a shock size of one standard deviation from the average. This corresponds to 0.292 extreme months or 8.8 unfavorable days in a quarter. The Hall-Wellner bands are set at a 68 percent confidence level.

Figure 9: Series of shocks below the lower vs beyond the upper threshold

Plot of Time Series 1991.1–2019.4, T=116

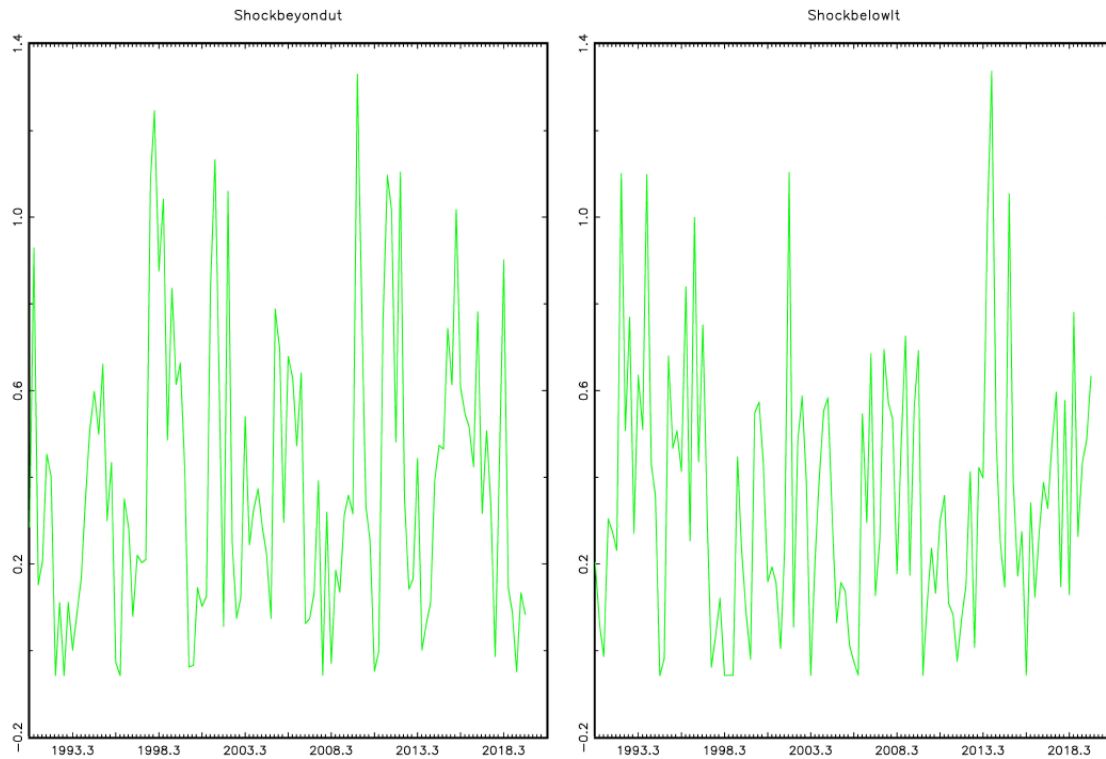


Figure 9: The mean of the population-weighted cold shock series is set at 0.350 months per quarter, which corresponds to roughly 10 days of adverse temperature occurrences in a season. While the mean of the heat shock series is set at 0.392 months per quarter, which corresponds to roughly 11 days of adverse temperature occurrences in a season

Figure 10: Serial correlation of shocks below the lower vs beyond the upper threshold

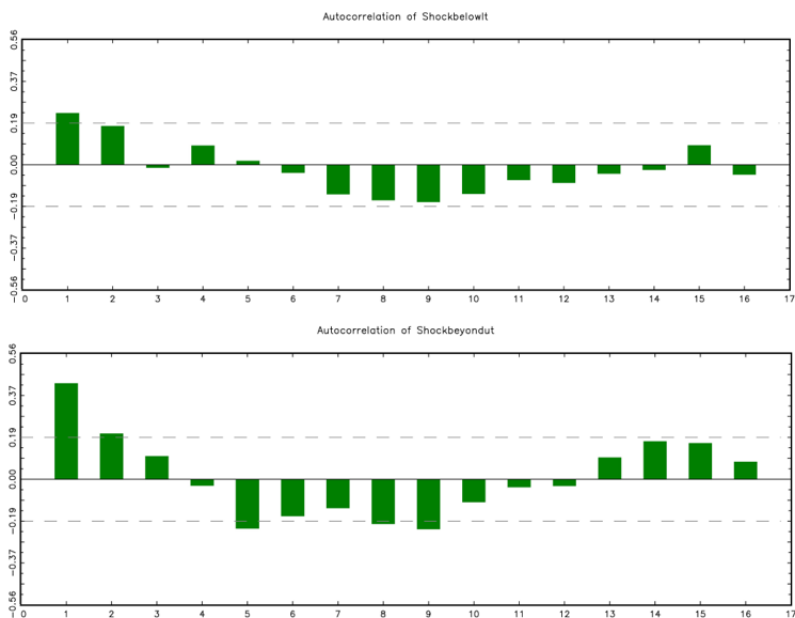


Figure 10: The two graphs above display the relationship between current population-weighted shocks and their lagged values. As it shows, the auto-correlation in the cold shock time series (graph on top) is mostly weak. However, the auto-correlation in the heat shock time series (graph at the bottom) is moderate, with current values and values from the previous quarter having a coefficient of correlation as high as 0.4.

Figure 11: Impulse response of an alternative specification of months below the lower threshold

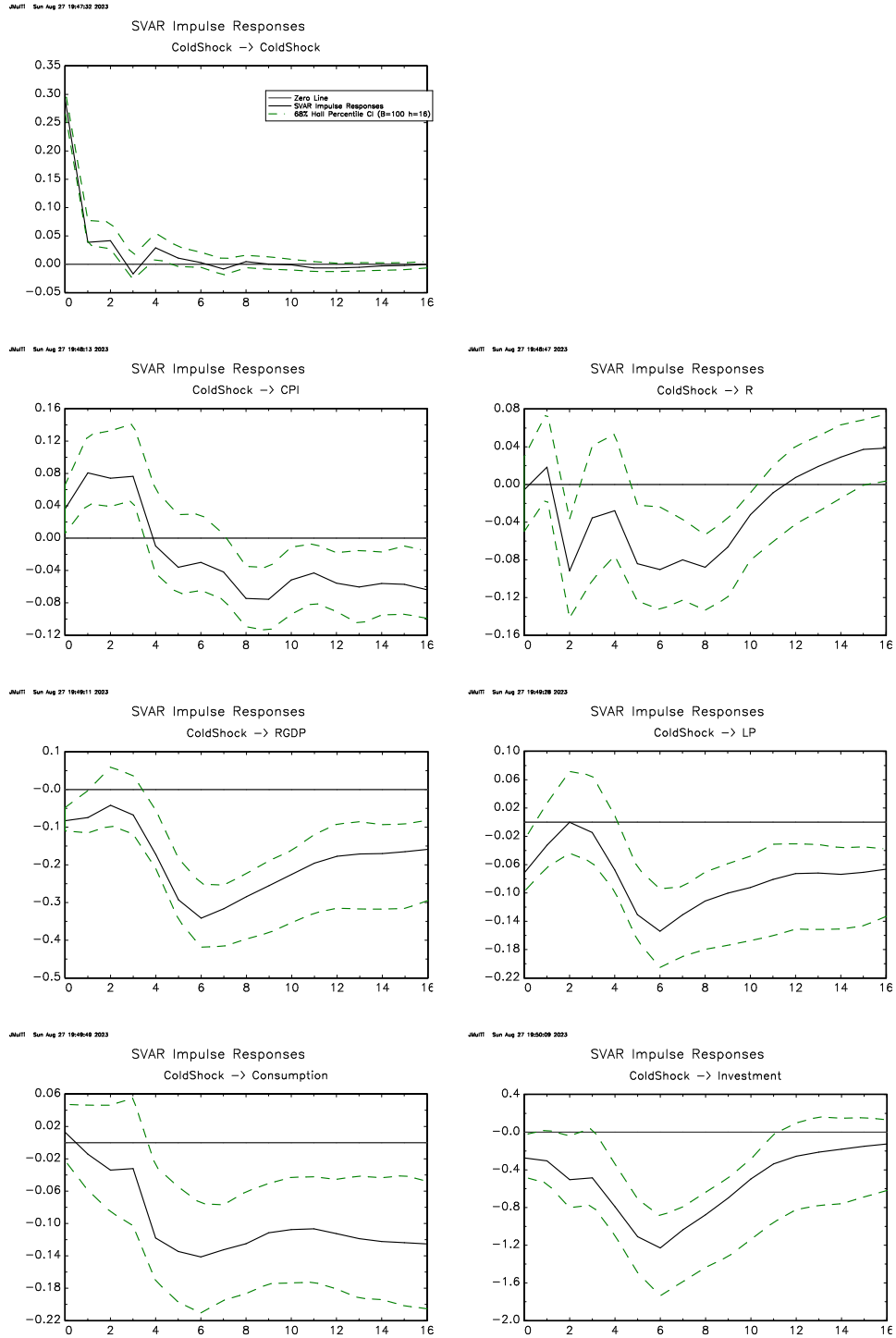


Figure 11: The shock considers four lags and a shock size of one standard deviation from the average. This corresponds to 0.298 extreme months or 9 extremely cold days in a quarter. The Hall-Wellner bands are set at a 68 percent confidence level.

Figure 12: Impulse response of an alternative specification of months beyond the upper threshold

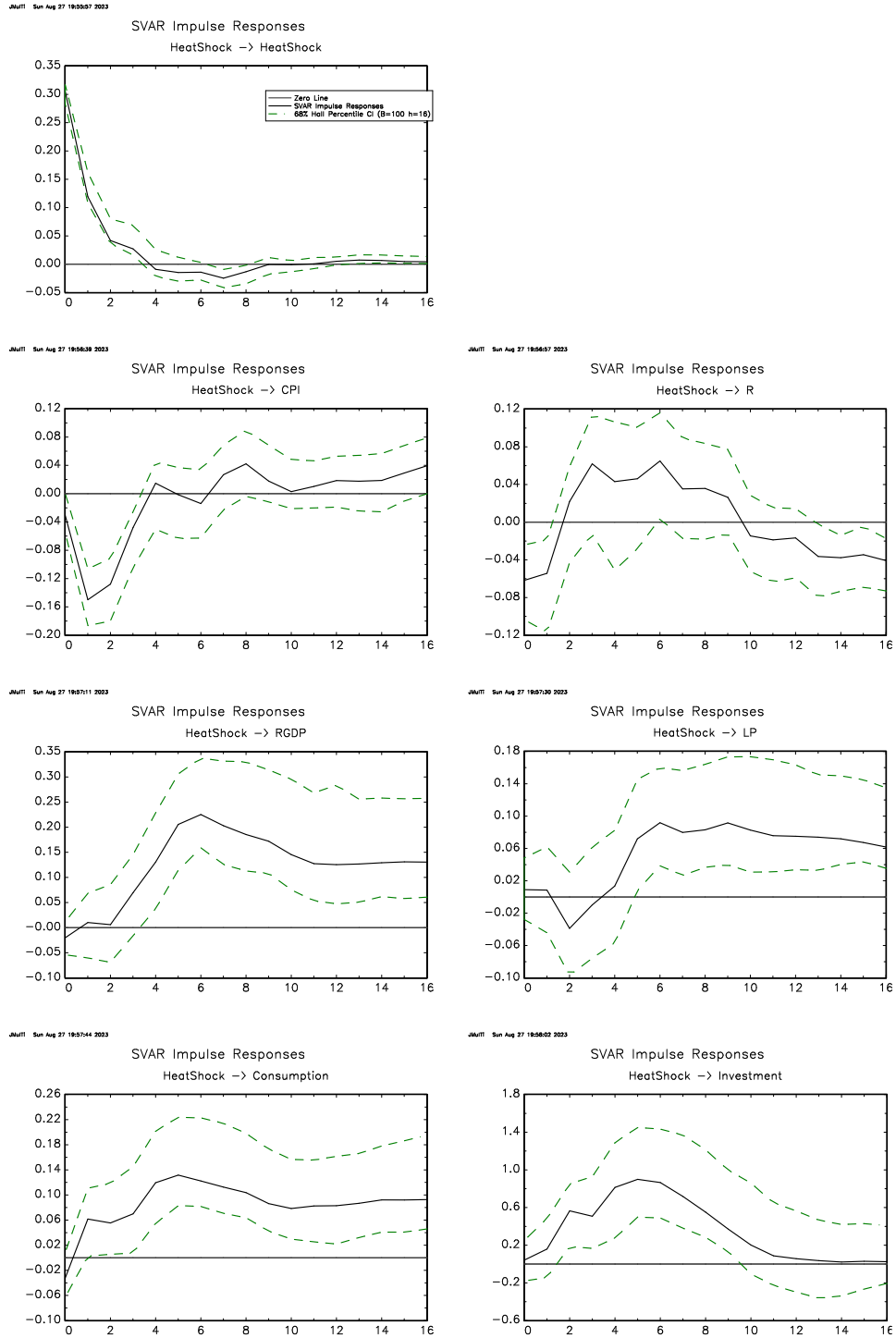


Figure 12: The shock considers four lags and a shock size of one standard deviation from the average. This corresponds to 0.336 extreme months or 10.1 extremely hot days in a quarter. The Hall-Wellner bands are set at a 68 percent confidence level.

Table 3: Data summary

Variables	Source	Frequency	Seasonally adjusted	Sample
<i>Temperature shock</i>				
AHCCD	ECCC (Climate data)	monthly		1981q1 – 2019q4
Population (by CMA)	Conference Board of Canada (e-Data)	quarterly		1985q1 – 2019q4
Employment (by CMA)	Conference Board of Canada (e-Data)	quarterly		1987q1 – 2019q4
<i>Impulse response</i>				
Real GDP (NGDPRSAXDCCAQ)	FRED	quarterly	Yes	1984q1 – 2019q4
Interest rate (IRSTCB01CAQ156N)	FRED	quarterly	No	1984q1 – 2019q4
CPI (CANCPALTT01IXNBQ)	FRED	quarterly	No	1984q1 – 2019q4
Employment (Nationwide)	Conference Board of Canada (e-Data)	quarterly	Yes	1985q1 – 2019q4
Real household private consumption (NCPHIRSAXDCCAQ NBD20150101)	FRED	quarterly	Yes	1984q1 – 2019q4
Real gross private domestic investment (GPDIC1 NBD20150101)	FRED	quarterly	Yes	1984q1 – 2019q4