What Are the Short- to Medium-Term Effects of Extreme Weather on the Croatian Economy?

Tihana Škrinjarić
Bank of England, London, United Kingdom
tihana.skrinjaric@bankofengland.co.uk

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Abstract

This research examines the short- to medium-term effects of weather changes on the Croatian economy by observing a simple model of an economy that includes changes in extreme weather events. Monthly data from 1999 to 2022 on the growth of the index of industrial production, inflation, energy inflation, changes in the unemployment rate, and selected weather variables are utilized to estimate several vector autoregression (VAR) models. The main finding indicates that inflation is mainly affected by weather shocks, especially drought. This means that monetary policy needs to consider this, mainly due to weather extremes being more frequent and of greater magnitudes. Furthermore, the insurance industry

could also benefit from such findings due to the first quantification of such results on Croatian data.

Keywords: climate change, weather effects, extreme weather, inflation

JEL classification: C3, O44, Q54

1 Stylized Facts[1]

Extreme weather effects on the economy have been a research subject in recent decades. The number of papers is consistently growing, and the strands of research are growing as more questions are being explored. Media is also filled with news about climate change, alongside different climate shocks, natural disasters, etc. 2021 alone was a record year regarding extreme weather events (Bloomberg, 2022), with summer temperatures only in Europe being one Celsius above the 1991–2020 average. Moreover, recorded rainfalls in Europe were at a record high, alongside intense and prolonged heatwaves in the Mediterranean region (Copernicus Climate Change Service, 2021). Such events are getting more severe and more significant in numbers. Thus, observing the effects of such weather extremes on the economy is crucial. Understanding such effects is essential for economic policymakers and the insurance industry.

According to the European Environment Agency (EEA, 2022), climate-related extremes caused total economic losses of 487 billion euros in EU-27. Moreover, ECB/ESRB (2020) have stated that the physical risks stemming from extreme weather events are a great source of risk for the financial system and the insurance sector. Knowing this is very important, as only 35 percent of the weather-related losses in the EU were insured in the 1980–2018 period, with some countries being far below the average and Croatia having only 3 percent of insured losses. Some countries had only a few percentage points of insured losses from weather-

1 The views presented in this paper are those of the author and do not necessarily represent the institution the author works at. The paper was written at a time the author was affiliated with the Croatian National Bank.

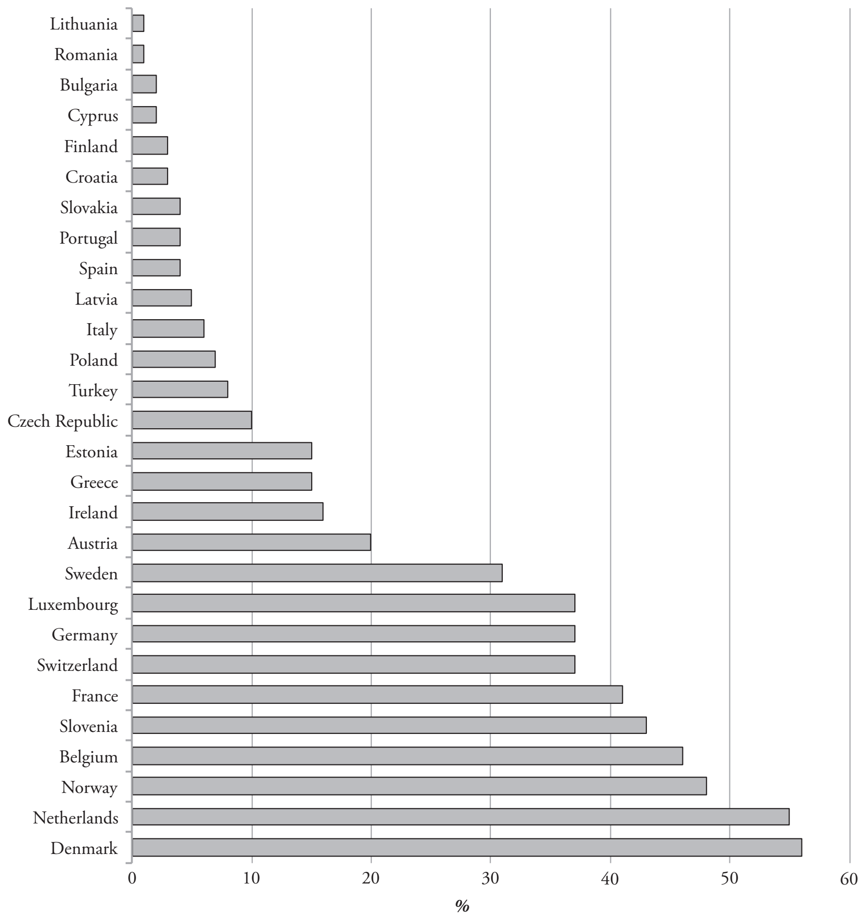
related events (see Figure 1). It was also estimated that from 1980 to 2020, total losses due to weather and climate-related extreme events amounted to 2.860 million EUR, i.e., 643 million EUR per capita, and only 83 million EUR were insured losses. The value and structure of reported weather-related damages in Croatia in the last couple of years are shown in Figure 2. The volatility of those damages is seen alongside the category "other", having an increasing share in total damages over the observed period. Insurance premiums and shares in total insurance in Croatia are depicted in Figure 3.

Moreover, according to the EIOPA (2020a) pilot dashboard on the insurance protection gap for natural catastrophes, Croatia falls in the medium/high-risk category for windstorm, and the high-risk category for earthquake and wildfire inadequate insurance coverage[2], with the overall gap being more significant today compared to the historical average. EEA (2017, 2020) expects the severity and frequency of climate-related extremes in Europe to increase. This means the future economy and the insurance industry will have even more significant consequences. EIOPA (2022) estimated that only in 2021, global losses from weather-related events and natural catastrophes amounted to 280 billion USD, with only 120 billion being insured. As the insurance and pension fund sectors are affected by weather-related effects on the economy, it is essential to evaluate the channels of those effects. Such sectors need to reevaluate their investing strategies, risk evaluation, and other issues relevant to the business[3].

2 Figure A1 in the Appendix depicts the protection gaps in 2020 and a historical gap for 29 European countries, with the averages of individual protection gaps concerning earthquake, flood, wildfire, and windstorm events. However, there were some discussions about earthquakes and the problems surrounding them (see EIOPA, 2020b).

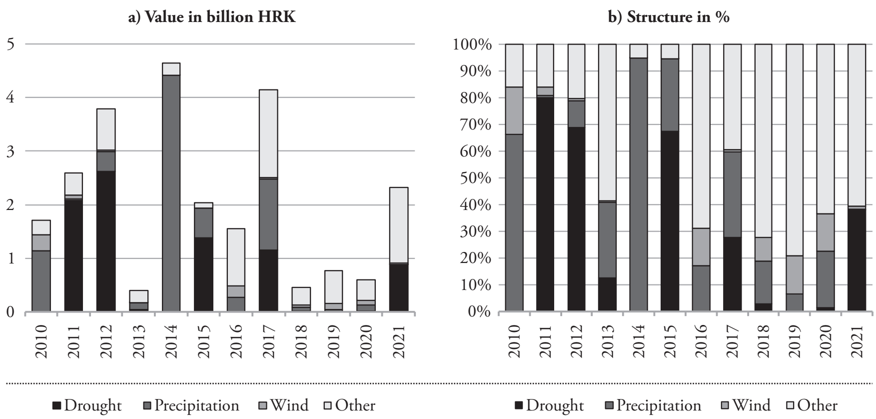
3 Moreover, there is still a dichotomy between words and actions regarding climate issues, especially the circular economy policies (Friant, Vermeulen, & Salomone, 2021). Thus, obtaining concrete results could contribute to better actions of all interested parties.

Figure 1: *Insured Losses for Economic Damage Caused by Weather and Climate-Related Extreme Events, 1980–2020*



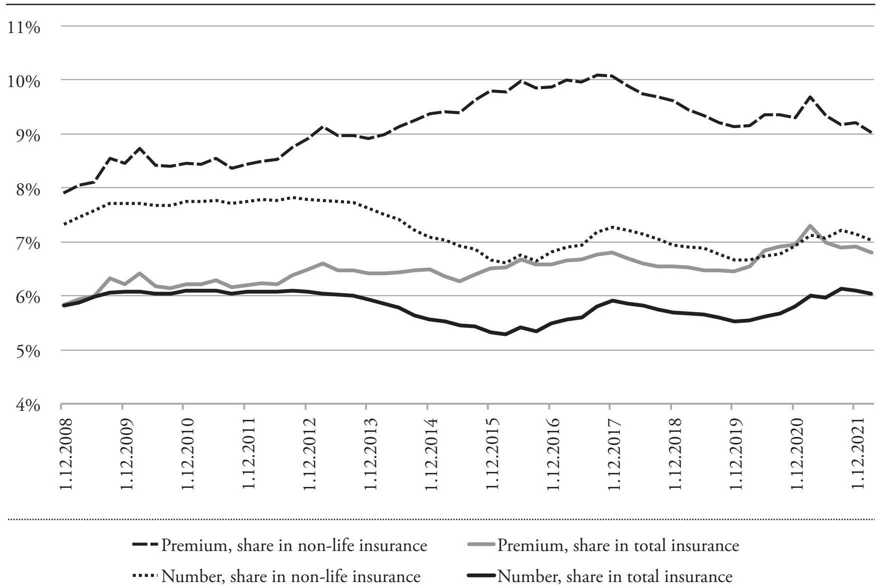
Source: European Environment Agency (2022).

Figure 2: *Reported Weather-Related Damages in Croatia*



Source: Ministry of Finance (2022).

Figure 3: *Insurance Against Fire and Natural Disasters, Number and Premium Shares*



Source: Hanfa (2022).

2 Focus of This Research

This research tries to answer questions regarding the effects of extreme weather events on the macroeconomy for the Croatian case: what are the effects of weather shocks on prices, energy prices, overall growth, and unemployment? The paper employs an autoregressive vector analysis (VAR) and extreme weather variables from IFAB (2022) included in the European Extreme Events Climate Index (E3CI), similar to the ACI (Actuaries Climate Index) that was constructed for North America. The period of the empirical analysis is relatively short, ranging from 1999 to 2022, due to data unavailability of macroeconomic variables. Thus, a short-term analysis is available so far[4]. Based on monthly data on the index of industrial production (IIP), inflation and energy inflation, unemployment rate, and selected extreme weather variables, this paper examines the impulse response functions of the macroeconomic variables to shocks in weather ones. Eurozone IIP growth and the ECB shadow rate are utilized as exogenous variables, as Croatia is a small open economy in the EU, with significant effects of ECB monetary policy on its national monetary policy. The weather variables are collected from a novel dataset from IFAB (2022), where the E3CI synthetic index is constructed based on weather-induced hazards regarding cold and heat stress, intense winds, heavy precipitations, and droughts. Every individual hazard is observed in a separate VAR model to see its individual effects on selected economic variables. In a final model, the E3CI index, which represents an average of individual hazards, is also considered an overall measure of extreme weather events.

Analysis such as this could provide initial insights into the effects of weather extremes on the general economy. If some specific data are still unavailable for analysis, at least a bird's eye view could provide a stepping-stone before future analyses provide better information. As insurance plays an essential role in mitigating the risk materialization of specific weather-related risks, understanding the effects of the weather on the economy is essential.

4 Some other existing approaches observe the long-term effects of weather or climate shocks due to having more data available. However, others also examine the short-term effects (see the Literature Review section). The focus of this paper is the short term due to data unavailability regarding the Croatian economy. Namely, the macroeconomic variables are relatively short time series compared to the weather data.

There are several reasons why the focus is on a single-country analysis, with monthly data for Croatia. First, a single-county analysis could provide better insights into specific results, as previous literature finds differing results across countries and regions of weather effects on macroeconomic variables. For example, Jones and Olken (2010) find that high-temperature shocks significantly affect developing countries' exports more than those of richer ones. The results of Lucidi, Pisa, and Tancioni (2022) indicate that the six biggest eurozone countries experience different future electricity price reactions due to temperature shocks. Faccia, Parker, and Stracca (2021) found that weather shocks affect food price indices differently depending on whether the economies are emerging or advanced. Beirne et al. (2021) also found that weather disasters affect prices differently across countries. Thus, focusing on country-specific analysis could result in better recommendations for policymakers and the insurance industry.

Regarding the monthly frequency of the data, this higher frequency is observed due to the possibility that some weather effects could be short-lived. This is in line with Kim, Matthes, and Phan (2021), who comment that due to unexpected shocks in the weather, and extreme variables being short-lived, aggregating this to a quarterly frequency would lead to a bias in the results. Moreover, Colacito, Hoffmann, and Phan (2019) argue that it would be harder to assess temperature effects yearly due to averaging the data over the year. Findings in Raddatz (2009) also show that extreme temperatures, droughts, floods, and storms significantly adversely affect GDP when a disaster happens. Croatia is examined in this study, as its agriculture and tourism depend significantly on weather shocks' effects. Negative effects in these sectors can spill over to others as well (Liu, Shamdasani, & Taraz, 2021).

Moreover, the idea is to raise awareness of the problems arising from climate change and the consequences of weather shocks in the Croatian economy, a central problem in some countries (see Škrinjarić, 2020). Namely, the adaptation to climate change occurs mainly as a response to extreme weather events, as Adger, Quinn, Lorenzoni, Murphy, and Sweeney (2013) suggested. Therefore, studies like this could increase the responsibility of governments and the insurance industry.

The main findings of this research indicate that the impact of weather shocks is more significant and remarkable on inflation than the other variables. Drought was found to be the weather variable that affects the economy the most. Although the rest of the results are non-significant, they are the correct sign. These results could be due to short time series and data unavailability. However, initial results indicate that if such behavior continues in the future, weather shocks could become more severe and negatively affect growth and unemployment, alongside the already realized impact on prices.

Another way future research could go is to look at long-run effects and include weather effects in the production function to see how total factor productivity, output, and labor productivity are affected. Some effort has already been made both purely empirically (Noy & Nualsri, 2007; Cavallo, Galiani, Noy, & Pantano, 2010) and combining empirical findings with a theoretical model construction (Donadelli, Jüppner, Riedel, & Schlag, 2017). The paper by Donadelli et al. (2017) is interesting, as it examines the welfare costs of temperature shocks and uses the empirical findings to calibrate a DSGE (dynamic stochastic general equilibrium) model to comment on the effects of temperature shocks on both the business cycle and financial markets.

3 Literature Review

The growing body of literature regarding extreme weather effects on the economy, insurance, and related topics has rapidly grown in the last decade. There are many different paths to take when exploring this area. Thus, the focus of this section will be on those closely related to this research. Some of the main findings include the following ones. First, many papers utilize panel data with yearly frequencies; some observe several decades of available data, whereas others focus on shorter periods. A great deal of papers focus on temperature shocks on the economy and especially prices. There are fewer papers on other weather-based variables, such as wind, drought, precipitation, etc. Some of the reasoning could be that indices that track such extreme weather events were not developed and were not made publicly available until recently. Primary variables of interest are usually growth rate, productivity, and inflation[5]. Greater disasters such as earthquakes, floods, and similar happenings have more significant effects on the economy in the short term, whereas some other shocks have medium- to long-term effects due to their gradual build-up over time.

Kim et al. (2021) evaluate the effects of the ACI on the US economy for the period from 1961 to 2019. Monthly data frequency was used to examine a smooth transition VAR model in describing the effects of ACI shocks on the unemployment rate, index of industrial production, inflation, core inflation, and the monetary policy interest rate. The main findings include that increases in extreme weather index that capture different stresses (temperature, drought, wind, precipitation, etc.) have a persistent negative effect on the industrial index growth, as well as increasing inflation and unemployment rate. Thus, the authors advise incorporating the weather variables into macroeconomic models. Lucidi et al. (2022) focus on six countries that represent 70 percent of EA GDP (Belgium, France, Germany, Greece, Italy, and Spain) in their analysis. The authors employed a Bayesian structural VAR model from 2000 to 2022. Temperature shocks are the central weather-related variable observed in this study, affecting energy prices, IIP growth, inflation, and energy production. Cold and hot shocks were divided in the analysis due to potential non-linearities of their effects on prices. The findings indicate that such non-linearities exist, with differing effects across countries, but some typical results are that energy prices are affected by temperature shocks, and the authors conclude that the ECB should pay attention to such climate shocks. Faccia et al. (2021) evaluate the effects of extreme temperatures on consumer and

5 Other variables include trade (Osberghaus, 2019; El Hadri, Mirza, & Rabaud, 2019), budget balance (Lis & Nickel, 2009), agriculture output (Burke, Dykema, Lobell, Miguel, & Satyanath, 2015; De Winne & Peersman, 2018), security and peace (Feitelson & Tubi, 2017; Reiling & Brady, 2015), labor markets (Neog, 2022), welfare (Ngoma, Lupiya, Kabisa, & Hartley, 2021), migration (Kaczan & Orgill-Meyer, 2019), and coastal property (Houser, Hsiang, Kopp, & Larsen, 2105). A variety of different analyses and their results can be found in Dell, Jones, and Olken (2014), where a comprehensive overview of empirical research is given.

producer prices, and the GDP deflator, for a panel of 48 countries and the period from 1990 to 2018. The main findings of this research include the following. Temperature shock effects depend on the year's season, meaning that hot summer temperature shocks have different effects compared to the rest of the year. Moreover, price indices are affected differently, depending on whether the indices track food prices or other goods. Emerging economies have a more significant reaction of food price indices to temperature shocks than advanced ones, with non-linear effects found across the observed sample. One of the main conclusions of the research is that central banks cannot ignore the effects of weather shocks on prices anymore.

Another shorter-term analysis was done by Beirne et al. (2021), where for the 1996–2021 period (monthly frequency), the authors used the structural VAR model to evaluate the effects of disaster events[6] on prices for euro area countries. The analysis included the growth rate of industrial production (and GDP), alongside the unemployment rate and exchange and interest rates. A detailed discussion was provided for France, Germany, Italy, and Spain because these countries are the largest economies in the euro area. Heterogeneous findings include differing reactions of inflations to weather shocks across the four economies, and the authors conclude that differences in supply and demand factors are the reason for such results being obtained. Ciccarelli and Marotta (2021) use a panel VAR approach, where the authors observe 24 countries from 1990 to 2019 to estimate the effects of climate change on the economy. Here, the focus is on the possibilities of mitigating and counteracting those effects. The authors identify four climate shocks based on physical and transition risks. Counteracting these risks has significant effects in the medium term, i.e., between two and eight years. Longer-term analyses include the following papers.

Acevedo, Mrkaic, Novta, Pugacheva, and Topalova (2020) utilize annual data from 1950 to 2015 and 180 economies and, based on a panel regression approach, estimate local projections of the cumulative growth. Temperature and

6 Storms, floods, droughts, heat and cold waves, earthquakes, and volcanic eruptions.

precipitation variables are the main ones for weather event shocks. The authors focus on non-linear model specifications by adding squared terms of weather variables to account for different growth responses based on the initial level of temperature or precipitation of a country in the sample. These non-linear effects were found to be significant, with an increasingly negative impact on growth for economies with high average temperatures. Mukherjee and Ouattara (2021) use panel data from 1961 to 2014 for a sample of developing and developed economies to assess the impacts of climate-related shocks on income, growth, poverty, fiscal response, and inflation. Findings of the empirical analysis show that weather effects are persistent in affecting inflation, especially in developing countries. Thus, the authors concluded that central banks should pay more attention to such shocks and include this information in projections and their objective functions.

Other significant findings include the results in Parker (2018), who focused on disasters and their effects on the inflation and sub-indices of the general price index for the case of 212 countries. Different disasters such as storms, floods, droughts, and earthquakes have heterogeneous effects on the general prices and sub-indices of the consumer price index. The results also depend on the stage of economic development of a country and the timing of the disaster. Short-term effects are also found in Raddatz (2009), where climate disasters only have adverse effects on GDP in the year they happen. Some studies focus on one particular weather-related event or shock, such as Kilimani, van Heerden, Bohlmann, and Roos (2018) looking at drought effects via simulation modeling of an economy, in which the authors show that all relevant variables in the model (GDP growth, industrial output, employment, trade balance, and consumption) are negatively affected by a drought shock; or a specific type of reaction to weather shocks, such as house prices and house demand after a disaster, as in Tran and Wilson (2022); or the "big four" analysis in general (droughts, floods, earthquakes, and windstorms), as in Noy (2009), Fomby, Ikeda, and Loayza (2013), and Felbermayr and Groeschl (2014). Such studies generally agree that the short-term effects of disasters reduce economic activity.

If we focus on papers that look at the Croatian economy, there exist a few in which some aspects of weather shocks are examined in relation to specific issues. Several authors explore the relationship between the economy and pollution, where the environmental Kuznets curve is tested with respect to pollution (see Jošić, Jošić, & Janečić, 2016; Škrinjarić, 2019). However, the results are still inconclusive due to the short time series. This is something to be expected in this research as well. Other studies partially look at weather effects on the economy due to focusing on specific issues. For example, Šverko Grdić and Krstinić Nižić (2017) look at the impact of temperature on tourist arrivals in Croatia and find a positive correlation. The changing temperature was found to be significant for agriculture (Šestak, Vitezica, & Hrelja, 2021) as was precipitation (Marković, Šoštarić, Josipović, & Atilgan, 2021).

4 Methodology and Data Description

4.1 Vector Autoregression (VAR)

The justification for using VAR methodology for this kind of research is as follows. Firstly, the physical risks category in the classification of climate risks (see Batten, 2018) from extreme weather events can be measured in the short to medium run. So, a model that can capture such effects needs to be considered. Moreover, suppose some climate-change adoptions are made. In that case, there could be effects from the macroeconomic variables to the climate ones, as found in Dell et al. (2014), who talk about short-term effects outweighing long-run ones due to those adoptions and resource reallocations. Finally, as the empirical part of this paper deals with a relatively short dataset compared to some other countries, this imposes a limitation on the methodology. Namely, if one had long time series, threshold VAR models could be estimated, as in Kim et al. (2021), to test for possible time-varying effects or non-linearities. Thus, the chosen model for this study is a linear VAR model.

A brief description of VAR models is given, as this is a basic approach of multivariate modeling for impulse response construction. Details are given in Lütkepohl (1993, 2006, 2010). Consider a $(N{\cdot}1)$ vector y_t of endogenous variables in a VAR(p) model:

$$y_t = a + A_1 y_{t-1} + A_2 y_{t-2} + \ldots + A_p y_{t-p} + \varepsilon_t \,, \tag{1}$$

where A_i are $(N{\cdot}N)$ matrices of coefficients, $i \in \{1, 2, \ldots, p\}$, a is the $(N{\cdot}1)$ vector of intercepts, and ε_t is the $(N{\cdot}1)$ vector of white noise process. It is assumed that the VAR model is stable, with $E(\varepsilon_t) = 0$, $E(\varepsilon_t \varepsilon_t') = \Sigma\varepsilon < \infty$, and $E(\varepsilon_t \varepsilon_s') = 0$ for $t \neq s$. The model in (1) is written in a compact form as VAR(1) model: $Y_t = V + AY_{t-1} + e_t$, $Y_t = (y_t\, y_{t-1} \ldots y_{t-p})'$, $V = (v\; 0 \ldots 0)'$, $e_t = (\varepsilon_t\; 0 \ldots 0)'$ and the matrix A has matrices A_i in the first row, with identity matrices on its diagonal from the second row onwards. Now, the MA(∞) representation of the VAR(1) model is written in the following form:

$$Y_t = \mu + \sum_{i=0}^{\infty} A^i e_t = (I_N - AL)^{-1} V + \Phi_i(L) e_t, \tag{2}$$

so that the impulse response functions and the error variance decomposition can be made. L is the lag operator, such that $L^j Y_t = Y_{t-j}$, $j \in \mathbb{R}$, $\Phi(L)$ is the polynomial such that $\Phi_i(L) = JA^iJ'$, $J = (I_N\; 0 \ldots 0)$. Now, the generalized impulse responses are estimated as in Pesaran and Shin (1998): $GI_y(h, \delta_j, I_{t-1}) = E(Y_{t+h} \mid e_{jt} = \delta_j, I_{t-1}) - E(Y_{t+h} \mid I_{t-1})$, where δ_j is the shock given to element j in e_t, I_{t-1} is the information set, and h is the forecast horizon. The GIRF approach does not depend on variable ordering, as generalized impulses integrate the effects of other shocks out of the response (see Koop, Pesaran, & Potter, 1996). We follow this approach in the empirical application, which means that the ordering of the variables is not relevant, as it would be when observing structural VAR.

4.2 Data Description

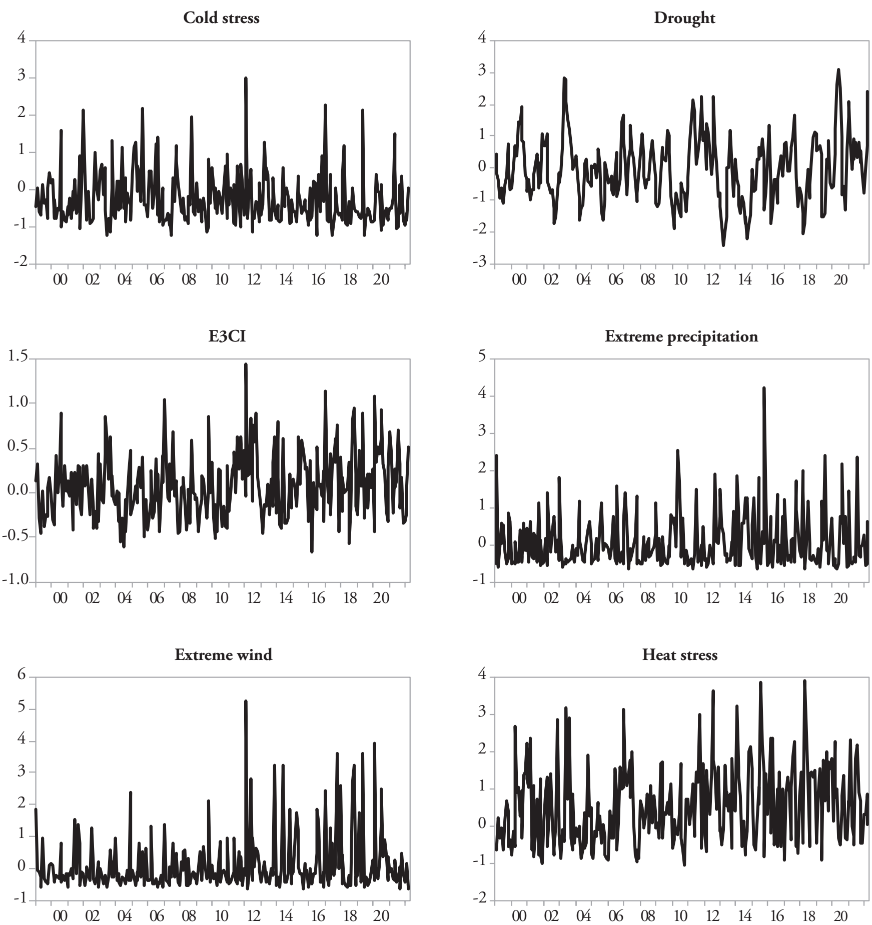
In order to estimate the VAR model, monthly data for the following variables were collected from Eurostat (2022) and IFAB (2022): index of industrial production (IIP), harmonized index of consumer prices (HICP), index of energy prices (En price), unemployment rate, European Extreme Events Climate Index (E3CI) and its components: heat stress, cold stress, drought, extreme wind, and extreme precipitation, and the eurozone IIP. From Wu and Xia (2022), the shadow rate for ECB was collected as the monetary policy control[7] in the model. The eurozone IIP dynamics is an exogenous variable in the model with the policy rate. The IIP indices and the unemployment rate are seasonally adjusted. The period for the data is from January 1998 to March 2022. All economic variables were transformed into year-on-year growth rates or changes (interest rate and unemployment rate). This is a simple description of the economy: real activity has a proxy in the IIP growth rate. Extreme weather events often affect prices, which is why inflation and energy inflation are included in the model. Moreover, unemployment was found to be affected by the weather in previous literature, which is why the change in the unemployment rate is also included in the model.

The extreme weather variables are calculated as described on the IFAB (2022) website, where the deviations from the reference values ranging from 1980 to 2010 are calculated for every month. Figure 4 shows the values of all weather variables, with their respective histograms in Figure 2. Greater values of every variable indicate that the bad deviation from a longer-term average is greater. Moreover, because these indices are calculated, values greater than the unit indicate abnormal values. Histograms in Figure 5 indicate that the distributions are fat-tailed, with a positive asymmetry, meaning that extremes have a significant proportion in the total sample. This is especially true for values greater than one, with drought and heat stress indices exhibiting the greatest number of abnormal values in the observed period. In order to capture the effects of extreme weather

7 Before 1 January 2023, Croatian monetary policy had a managed fluctuating exchange rate of kuna to euro, where the euro price was set based on supply and demand, with the central bank stepping in to intervene when needed. In other words, the regime managed to fluctuate the exchange rate, whereby the rate was kept at a certain interval for specific interventions. Still, the upper and lower bands were never revealed.

events, a rolling 12-month sum[8] was calculated for every indicator from Figure 4. These sums are depicted in Figure 6.

Figure 4: *Dynamics of Weather Variables*



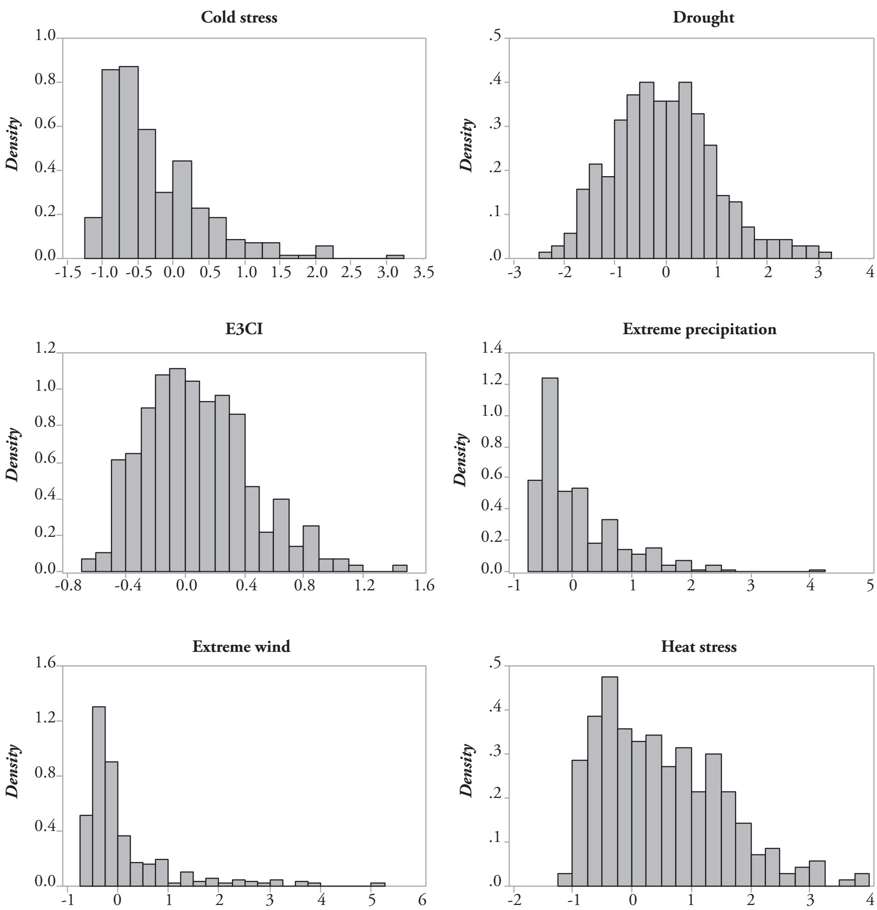
Note: Values beyond 1 stand for "anomalies" with respect to the mean value larger than the "climatological" variability summarized by using standard deviation.

Sources: IFAB (2022) and author's calculations.

8 This transformation was made so that some memory is captured in the model.

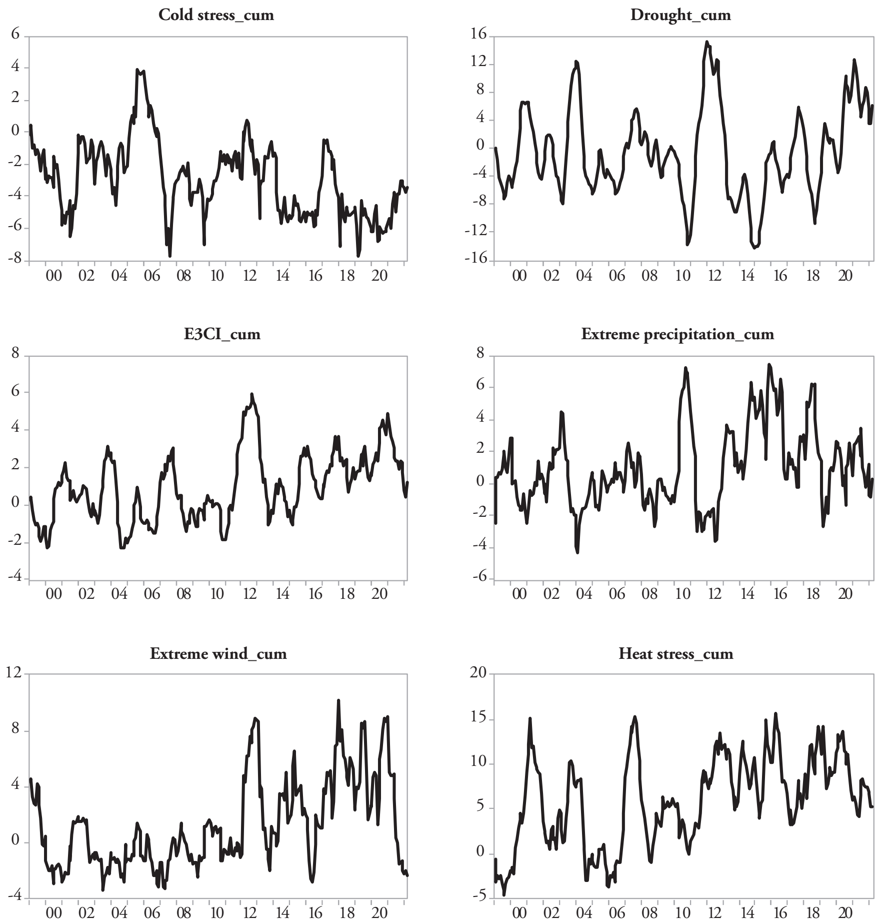
Now, one can see that cold stress has a declining tendency with heat stress rising, which is in line with the global warming ideas, and the total index (E3CI) also has increased in the last couple of years. For the VAR model purpose, values from Figure 6 are utilized, so that the volatility from Figure 4 is reduced. Unit root tests for all variables are shown in the Appendix in Table A1.

Figure 5: *Histograms of Weather Variables*



Sources: IFAB (2022) and author's calculations.

***Figure 6:** Dynamics of Weather Variables, Moving Cumulative*



Sources: IFAB (2022) and author's calculations.

5 Empirical Results

Every weather variable from Figure 6 was included in a VAR(p) model alongside the general inflation, energy inflation, IIP growth, and change of unemployment rate, with exogenous variables of the eurozone IIP growth and the ECB shadow rate. The length of the *p* was chosen based on the information criteria and the usual tests of autocorrelation and heteroskedasticity of error terms[9]. The moving sums of weather shocks are observed in the first specification of the analysis so that the accumulation of weather shocks can be detected. Figures 7–12 depict economic variables generalized impulse response functions to shocks in individual weather variables. The significant results are as follows[10].

Cold shocks increase overall inflation up until one quarter after the initial shock, and drought shocks increase total inflation and energy inflation with a lagged impact from 6 to 18 months after the shock. Greater effects are observed in energy inflation reaction, which could be a result of electricity prices going up due to hydro-energy dependency of electricity production. The lagged response from half a year to one year and a half is expected, as agricultural production that is affected by drought realizes products over time. As droughts are prominent in late spring and over summer, and more and more in autumn, the reduced production of agricultural products in autumn results in higher prices of products in the next couple of months. Precipitation shocks decrease inflation approximately one quarter to one year after the shock and wind shocks decrease IIP growth almost immediately after the shock hits. Other results are not statistically significant, although most are of the correct sign (increases in unemployment and inflation, with decreases in the IIP growth rate). Significant precipitation effects in this study are in line with studies focusing on hydroelectric and related energy production that uses water (Solaun & Cerda, 2017). Positive impulse responses of inflation to weather shocks align with the findings of Lucidi et al. (2022) for individual

9 Table A2 in the Appendix gives a summary of the results of the tests. As the case of lag 2 of each model did not have the usual problems in the resulting tests in the last two columns, this lag was chosen in the analysis.

10 As values greater than one in Figure 4 are interpreted as abnormal events, the corresponding impulse response functions with the specification of including only abnormal values of weather events are shown in the Appendix, in Figure A2. The only significant result is the increase of unemployment change due to extreme wind events. However, as the number of observations declines when only abnormal events are observed, such analysis is not considered reliable. Moreover, robustness checking for some variables has been done in the Appendix in Figures A3 and A4, where the results are similar to the original model for the case of the heat index. Another robustness check was made by following Kim et al. (2021), Lucidi et al. (2022), and Ciccarelli and Marotta (2021), where variable ordering matters due to the structural VAR approach. It is assumed that economic variables cannot affect weather variables contemporaneously. The ordering of the macroblock is as in the aforementioned papers: energy inflation, IIP growth, unemployment change, and inflation. The results are shown in the Appendix in Figure A5, and the resulting IRFs are the same as the ones in the main part of the paper.

eurozone countries. Although non-significant, heat stress index shocks reduce the IIP growth and lower inflation, which is also in line with Lucidi et al. (2022), who explain that the adjustment of these variables is a downward demand-type one.

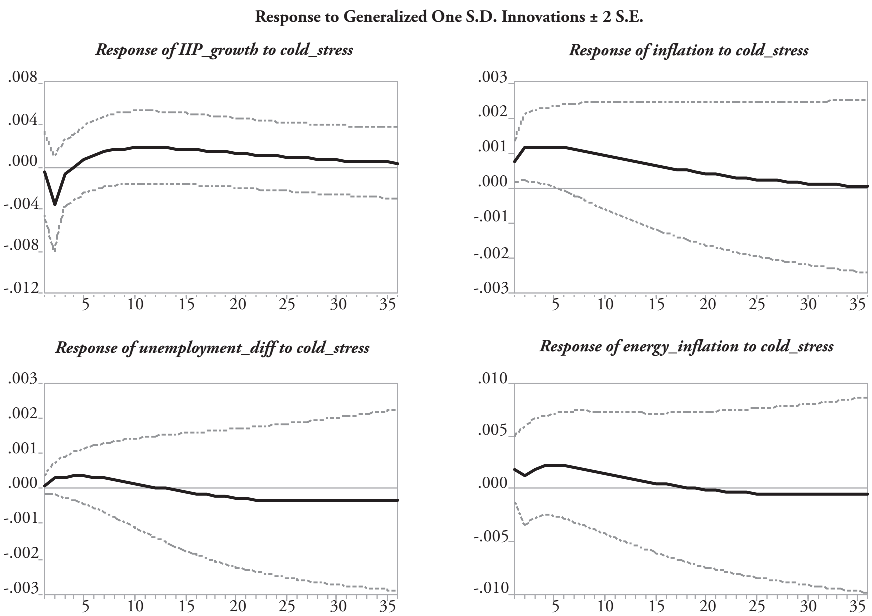
As climate change causes demand- and supply-side adjustments (see Batten, 2018), possible channels of the effects of weather shocks in Croatia could be damage to infrastructure, livestock, and general agricultural shortages. This, in turn, causes increases in the price level (Parker, 2018), as the results here mostly confirm that inflation is the variable that mainly reacts to weather-related shocks. Due to these findings, a particular focus must be placed on them. The monetary policy authority should consider these findings. Some central banks already evaluate the short-term effects of weather events within their work framework (see Bank of England, 2018; and the Fed's analysis in Gourio, 2015). As Batten, Sowerbutts, and Tanaka (2020) conclude, this means that future macroeconomic nowcasting and forecasting will also have to include weather effects. This analysis shows that inflation mainly reacts to drought shocks in Croatia. This could be very problematic due to more significant numbers of droughts in recent years (see Tadić, Brleković, Potočki, & Leko-Kos, 2021) and considering that droughts can have persistent effects on production costs in the medium to long term as well (IPCC, 2014). Moreover, this causes problems of inflationary expectations (Lang, Švaljek, & Ivanov, 2020).

Although non-significant, the only negative effect on unemployment changes (i.e., reducing it) was found to be the case of precipitation (Figure 9). This could be in line with Rutenberg and Diamond (1993), who explain that the local demand for labor could increase due to elevation of on-farm risk, and IMF (2017), where it is demonstrated that more precipitation reduces the probability of droughts, wildfires, and heat shocks.

Long-term temperature projections for Croatia estimate that the average temperature is going to increase (World Bank Group, 2021), which means that the effects in Figure 11 could become significant, as well as have adverse effects on future growth (Dell, Jones, & Olken, 2012; Colacito et al., 2019; Du, Zhao, & Huang, 2017). Home insurance could be a suitable security mechanism for the finance sector, not only individual households (Lucas, Booth, & Garcia, 2021). As the number of exposures to a negative weather event increases, the likelihood of insurance purchase increases (Seifert, Botzen, Kreibich, & Aerts, 2013; Chatterjee & Mozumder, 2014). Liu, Sun, and Tang (2021), North and Schüwer (2017), and Nand and Bardsley (2020) think that climate disasters will lead to increased financial risks, especially in the banking sector. Some believe that is why the role of central banks in fighting climate change needs to be improved (Cœuré, 2018). This could be done via adjusting the collateral and asset purchase policies with respect to climate change risks mitigation (Weidmann, 2020; Schnabel, 2020). Moreover, the economic cost of extreme climate-related events were the highest for Croatia in 2019 in EEA (see Scope Ratings, 2021), which could lead to greater sovereign ratings divergence in the future. Almost 25 percent of the Croatian economy are sectors exposed to adverse weather effects. Primorac and Golub (2019) show how much monetary help has been allocated by year and comment that there are not enough resources to cover these effects.

As weather shocks could negatively affect different sectors, such as the balance sheets of households, non-financial corporations, the insurance industry, and the banking sector, all parties need to consider this. Although studies such as this one and media attention have already existed for a while now, it seems that concrete actions regarding weather shocks and extreme events mitigation are not yet in full swing. It could be said that this is true for the Croatian case, as no related research is found regarding these topics. No formal or empirical studies are found which try to evaluate monetary or other effects of weather effects or different climate-related shocks. Besides raising the awareness of weather-related problems, what needs to be done is ensuring that the risk pricing of such events is done ex-ante and included in the balance sheets of insurers, banks, and individual households. To do so, granular data are needed, and analyses should be done so that location-specific, sector-specific, and other specific characteristics are considered for the risk pricing. A caveat should be stated as well. The central bank could be interested in the results at the end of the analysis, i.e., what the effect is in the medium term, as some effects cannot be observed immediately, and this is especially true for policy instruments and their effects. Thus, with more data in the future, accumulated effects over the medium term could be more interesting to analyze.

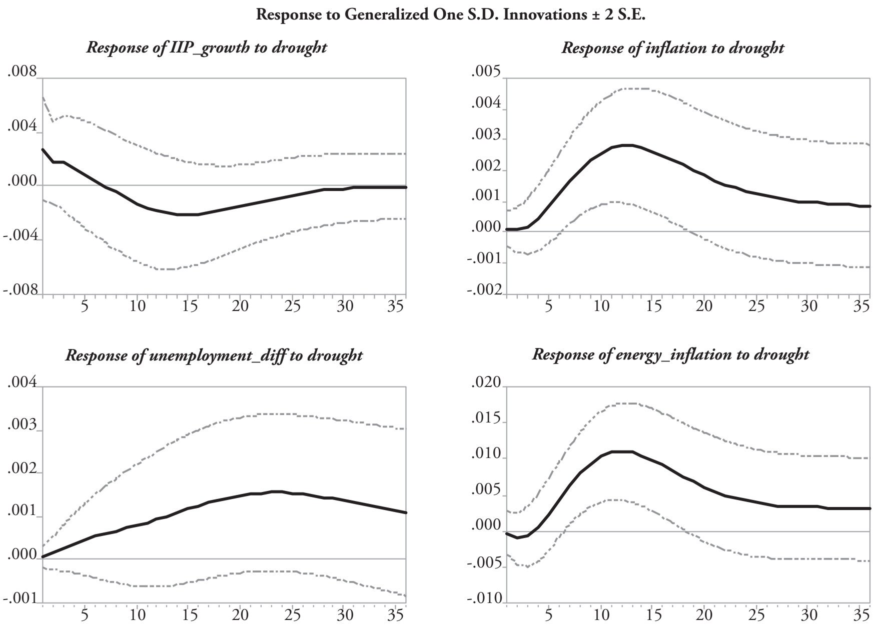
Figure 7: *Impulse Response Functions, Cold Stress Index*



Note: Generalized impulse response functions are depicted, Monte Carlo approach of estimating 95% standard errors with 1,000 repetitions. Full line denotes the average response, with dashed lines representing the upper and lower estimates of the responses.

Source: Author's calculations.

Figure 8: *Impulse Response Functions, Drought Index*



Note: Generalized impulse response functions are depicted, Monte Carlo approach of estimating 95% standard errors with 1,000 repetitions. Full line denotes the average response, with dashed lines representing the upper and lower estimates of the responses.

Source: Author's calculations.

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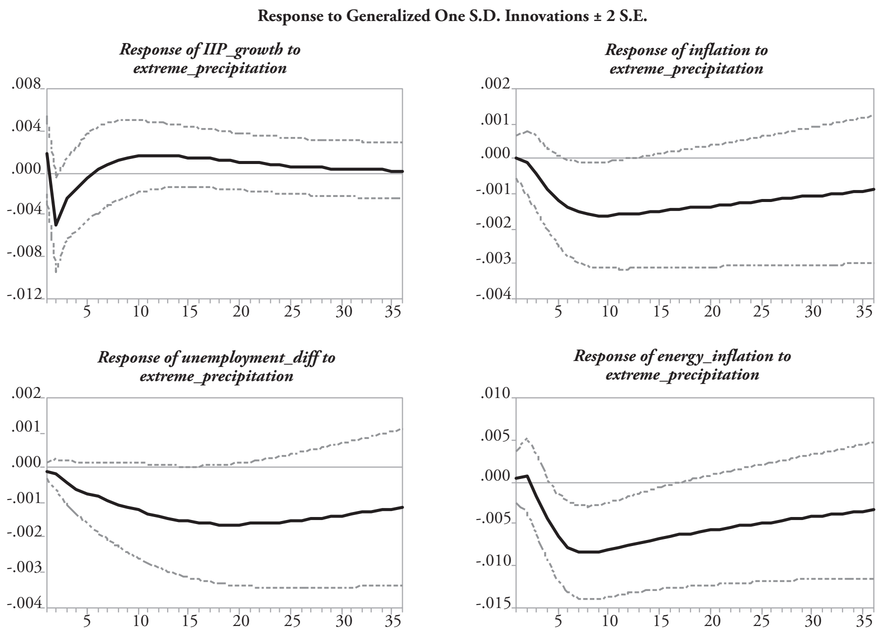
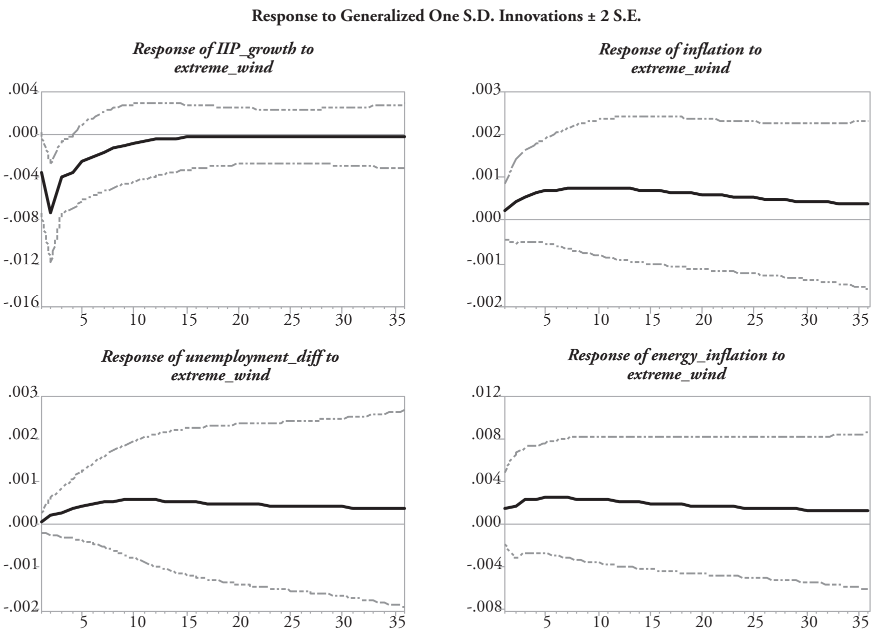
Figure 9: *Impulse Response Functions, Precipitation Index*



Note: Generalized impulse response functions are depicted, Monte Carlo approach of estimating 95% standard errors with 1,000 repetitions. Full line denotes the average response, with dashed lines representing the upper and lower estimates of the responses.

Source: Author's calculations.

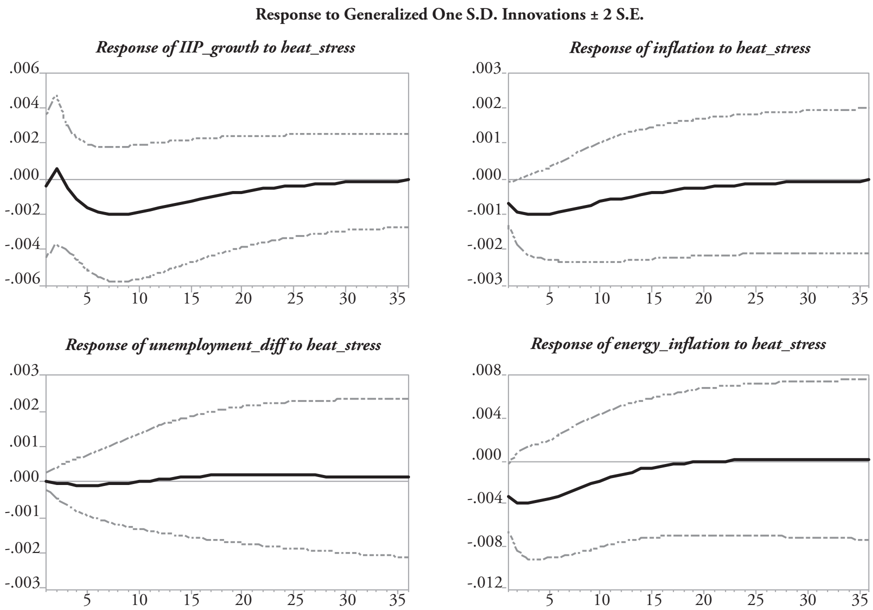
Figure 10: *Impulse Response Functions, Wind Index*



Note: Generalized impulse response functions are depicted, Monte Carlo approach of estimating 95% standard errors with 1,000 repetitions. Full line denotes the average response, with dashed lines representing the upper and lower estimates of the responses.

Source: Author's calculations.

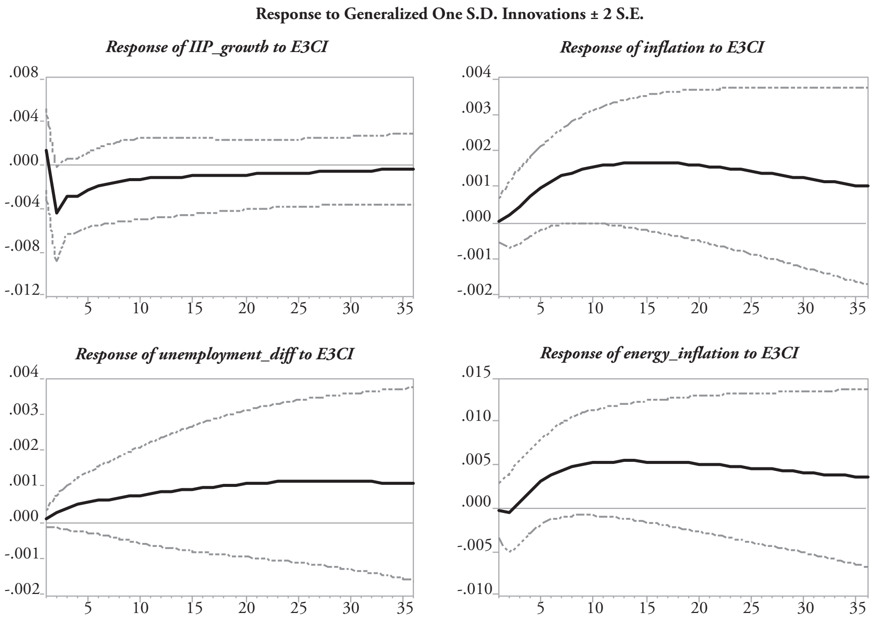
Figure 11: *Impulse Response Functions, Heat Index*



Note: Generalized impulse response functions are depicted, Monte Carlo approach of estimating 95% standard errors with 1,000 repetitions. Full line denotes the average response, with dashed lines representing the upper and lower estimates of the responses.

Source: Author's calculations.

Figure 12: *Impulse Response Functions, E3CI Index*



Note: Generalized impulse response functions are depicted, Monte Carlo approach of estimating 95% standard errors with 1,000 repetitions. Full line denotes the average response, with dashed lines representing the upper and lower estimates of the responses.

Source: Author's calculations.

6 Conclusion

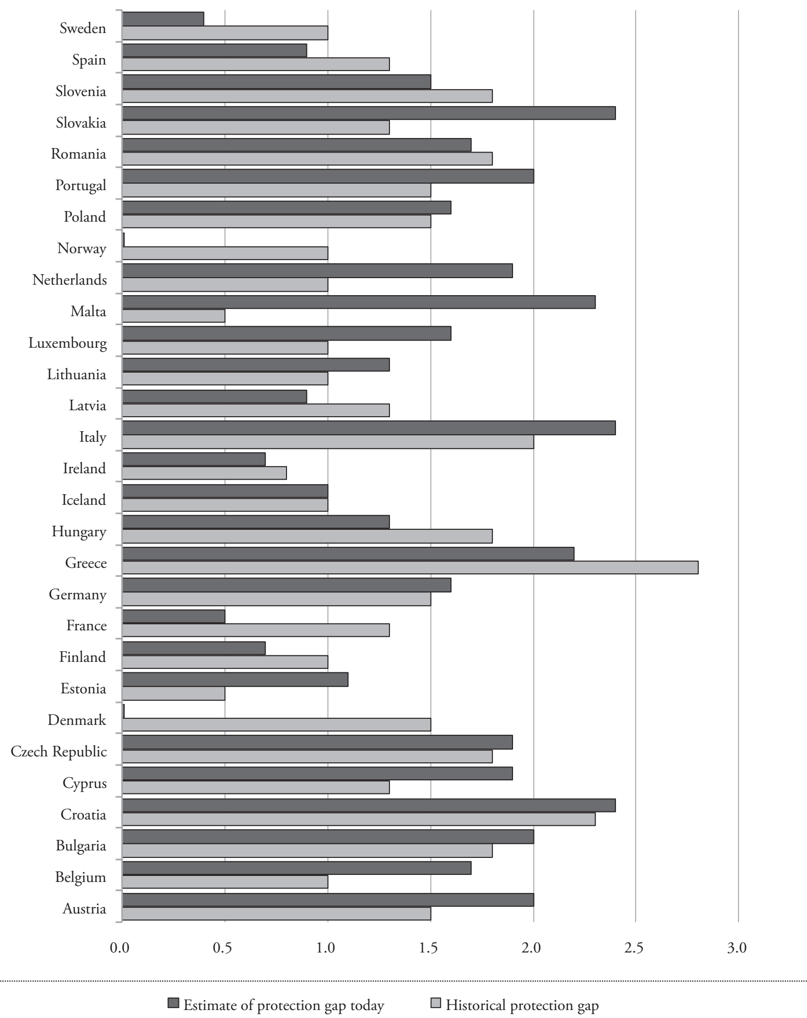
This research examined the average effects of weather-related extreme shocks on selected macroeconomic variables for the case of Croatia. Thus, physical risks were the main focus of this paper, where the main results indicate that inflation is mainly reactive to weather shocks in the observed period. This could have implications for the monetary policy, mainly due to the increasing global warming process. Inflationary pressure of extreme weather events could increase in the future, and this is an additional problem for the current inflation policy due to the global supply chain problems resulting from COVID-19 and the war in Ukraine. The insurance sector will also face some difficulties due to the constant climate changes and increases in the severity and duration of adverse weather shocks, alongside population aging. Physical risks that were observed in this study are already included in insurance business models. However, due to the aforementioned constant weather changes, better resilience must be achieved on all sides: households and firms, the insurance sector, and macroeconomic policymakers. Public finances worldwide, including in Croatia, are faced with increasing weather disasters; governments should consider the possibilities to deal with these problems. Fiscal support is not enough to cover the damage from weather shocks; on the other hand, the insurance coverage in Croatia is still minimal (Figure 1). Coordination between public finance, the insurance sector, and the private sector is needed, and more resources should be directed to education and prevention.

Some of the shortfalls of this study include the following ones. First, the already mentioned short time period resulted in somewhat mixed results. Although the responses of economic variables to weather shocks were of the correct sign, in many cases, they were found to be non-significant. Related studies that rely on shorter periods and a single-country focus in the analysis have similar results (Beirne et al., 2021). One possible reason could be that the VAR modeling is a linear approach. Some related literature utilizes non-linear functional form in panel regressions (see the Literature Review section) and finds significant results regarding the non-linearity. Recent studies show that there could exist non-linear weather effects on the economy (Diffenbaugh & Burke, 2019; Lamperti, Dosi, Napoletano, Roventini, & Sapio, 2018). However, many studies claim that the weather shocks result from human activity. It would not be beneficial to examine a single equation estimation approach as some existing studies have. Due to feedback effects, imposing the assumption that weather variables are always exogeneous could result in biased results. Future analyses should consider this. Moreover, this analysis did not include other weather-related events such as earthquakes, hurricanes, etc., as some are not present in Croatia and due to data unavailability of others. Finally, some variables could not be included in the empirical analysis, as they have an even shorter period than those utilized here. These include the supply side of the economy, such as different energy output variables (available data start in 2008 or 2013), or the activity of the services (the Croatian economy is characterized by a significant share of services that could be affected by extreme weather effects), which also are not long enough. Future analyses should include such information in models when more data become available.

Future analyses should consider the weather effects on specific prices within the monetary policy modeling. As previous research indicates that weather shocks could affect the inflation targeting in the eurozone (Beirne et al., 2021), this could also become a problem for Croatia. The ECB adopted a climate plan in 2021 regarding a new monetary policy strategy that considers climate risks (European Central Bank, 2021a, 2021b). This means national central banks should follow this decision as soon as possible. By taking this into account, the economic impacts of weather disasters could be dampened if we account for relevant risks on time. Moreover, as Batten et al. (2020) state, observing simple mechanisms such as in this research can be too simplistic. Both supply- and demand-side adjustments need to be considered, to fully understand all of the transmission mechanisms of weather-related shocks: investments, exports, changes in infrastructure, etc.

Appendix

Figure A1: *Historical and 2020 Estimated Protection Gap[11] for European Countries*



Note: The historical protection gap is based on the differences between economic and insured historical losses. The estimate of today's gap is based on EIOPA's expert judgement and derived by combining insurance coverage, exposures, vulnerability, and hazard.

Sources: EIOPA (2020a) and author's calculations.

11 The gaps are calculated in a specific way, as annual economic losses normalized by GDP, see technical appendix here: https://www.eiopa.europa.eu/tools-and-data/dashboard-insurance-protection-gap-natural-catastrophes_en

Table A1: *Unit Root Test Results, All Weather Variables*

Critical values	Cold cumulative	Drought cumulative	E3CI cumulative	Precipitation cumulative	Wind cumulative	Heat cumulative
-3.4537; 1%						
-2.8717; 5%	-3.54	-3.57	-3.23	-2.84	-2.22	-3.24
-2.5723; 10%						

Note: Critical values are for the test with only constant included. Although the wind variable test did not reject the null of unit root, we still proceeded with it in the model. Another variant of the model was estimated with a linear trend included, and a third one in which differenced wind index was included. All of them resulted in the same IRFs as the original model. Results are available upon request.

Source: Author's calculations.

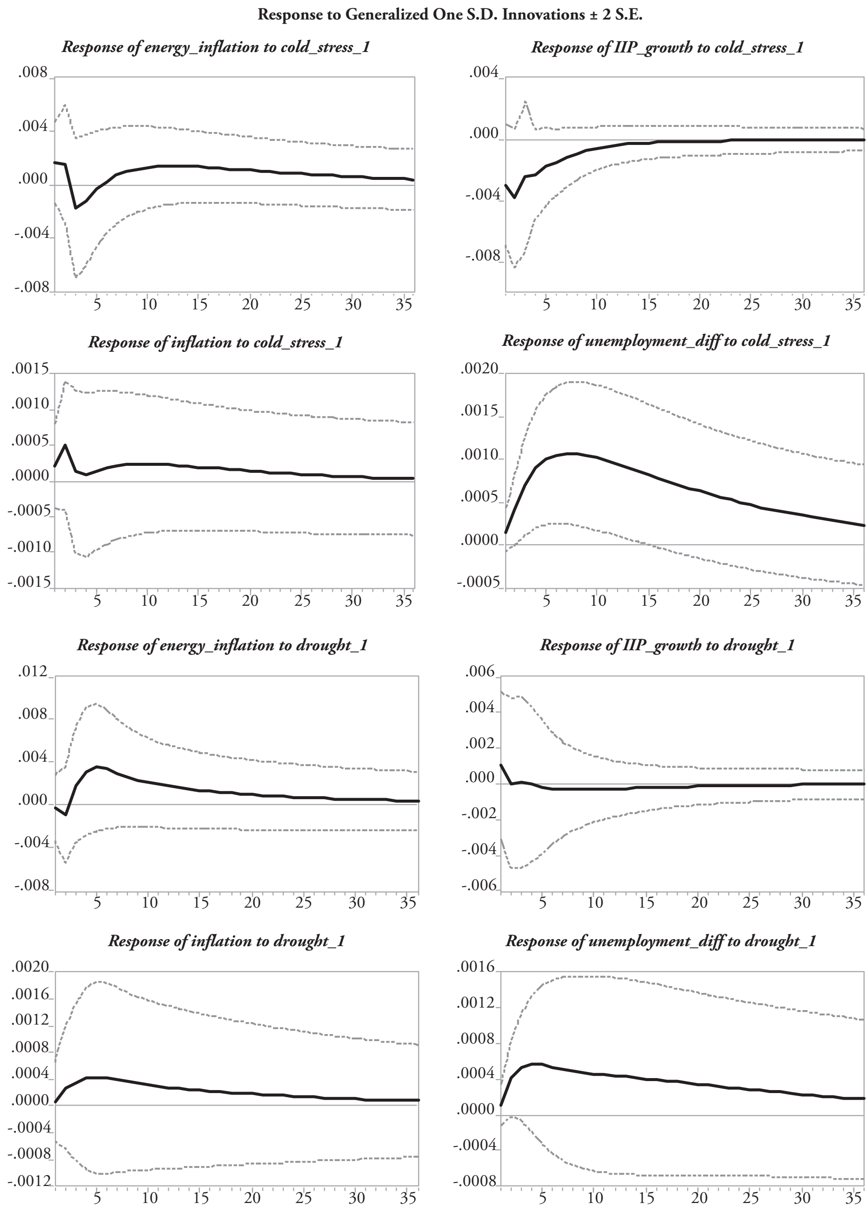
Table A2: *Multivariate Tests and Information Criteria for VAR Models*

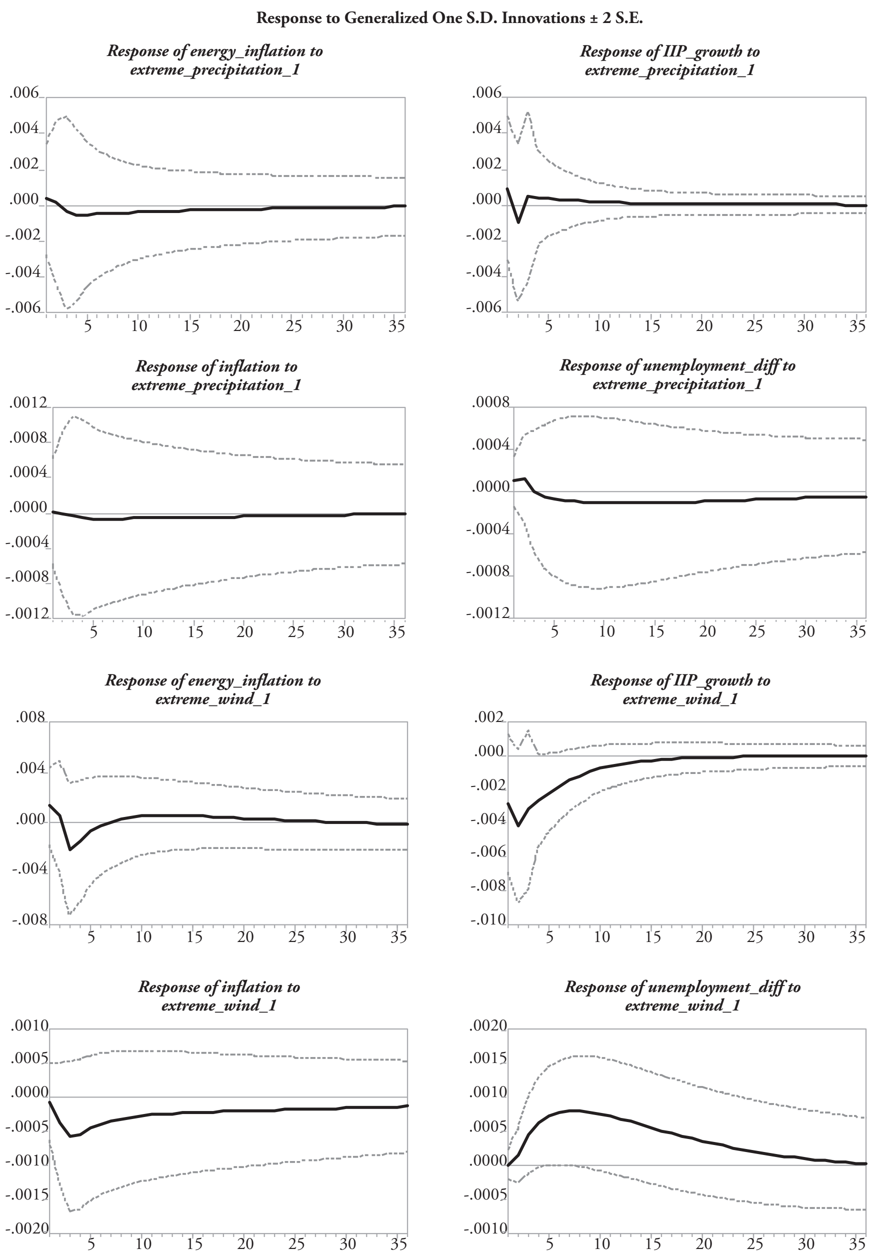
Weather variable in the model	AIC lag selection criteria	SIC lag selection criteria	HQ lag selection criteria	Serial correlation LM test (36 lags)	Heteroskedasticity test
Cold stress	13	2	2	34.53 (0.097)	918.329 (0.989)
Drought	24	2	2	32.41 (0.146)	930.109 (0.979)
E3CI	24	2	2	38.394 (0.042)	923.449 (0.986)
Precipitation	24	2	2	31.009 (0.189)	905.813 (0.996)
Wind	15	2	2	31.499 (0.173)	912.450 (0.993)
Heat stress	24	2	2	31.732 (0.166)	880.689 (0.999)

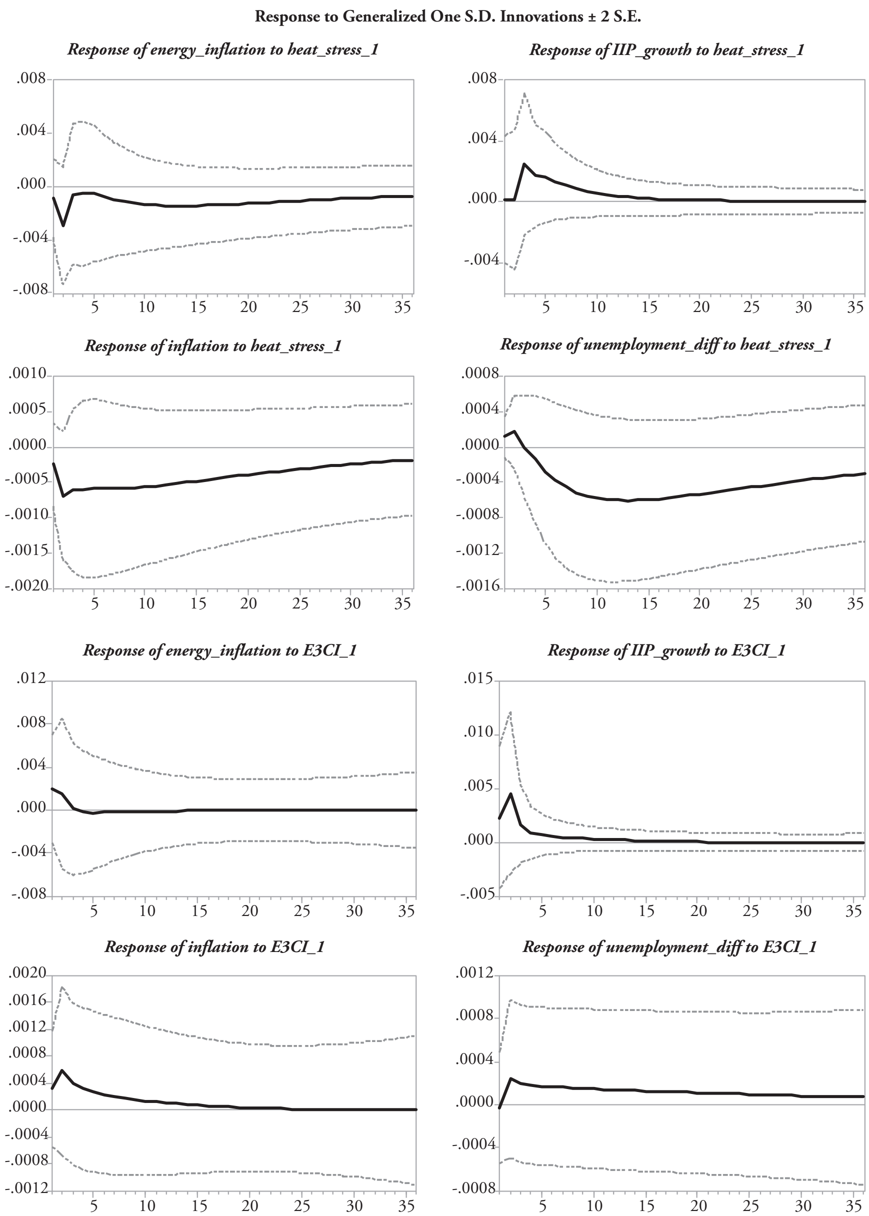
Note: *p*-values are given in parentheses.

Source: Author's calculations.

Figure A2: *Impulse Response Functions, Anomalies Indices*



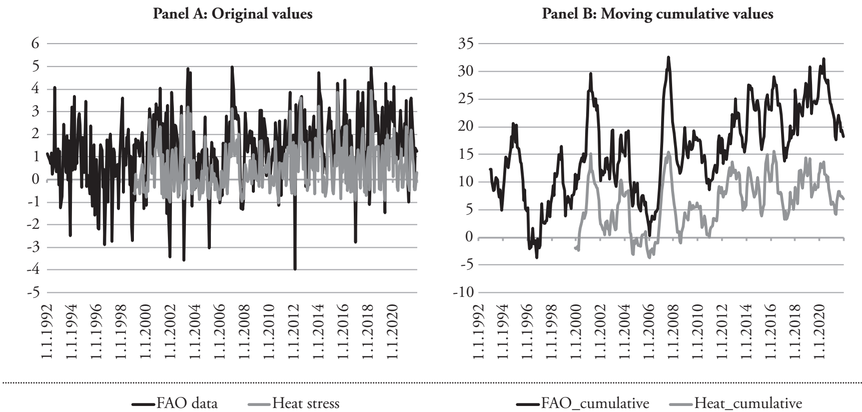

Response to Generalized One S.D. Innovations ± 2 S.E.
Response of energy_inflation to extreme_precipitation_1
.006
.004
.002
.000
-.002
-.004
-.006
5 10 15 20 25 30 35
Response of IIP_growth to extreme_precipitation_1
.006
.004
.002
.000
-.002
-.004
-.006
5 10 15 20 25 30 35
Response of inflation to extreme_precipitation_1
.0012
.0008
.0004
.0000
-.0004
-.0008
-.0012
5 10 15 20 25 30 35
Response of unemployment_diff to extreme_precipitation_1
.0008
.0004
.0000
-.0004
-.0008
-.0012
5 10 15 20 25 30 35
Response of energy_inflation to extreme_wind_1
.008
.004
.000
-.004
-.008
5 10 15 20 25 30 35
Response of IIP_growth to extreme_wind_1
.002
.000
-.002
-.004
-.006
-.008
-.010
5 10 15 20 25 30 35
Response of inflation to extreme_wind_1
.0010
.0005
.0000
-.0005
-.0010
-.0015
-.0020
5 10 15 20 25 30 35
Response of unemployment_diff to extreme_wind_1
.0020
.0015
.0010
.0005
.0000
-.0005
-.0010
5 10 15 20 25 30 35



Note: Generalized impulse response functions are depicted, Monte Carlo approach of estimating 95% standard errors with 1,000 repetitions. Full line denotes the average response, with dashed lines representing the upper and lower estimates of the responses.

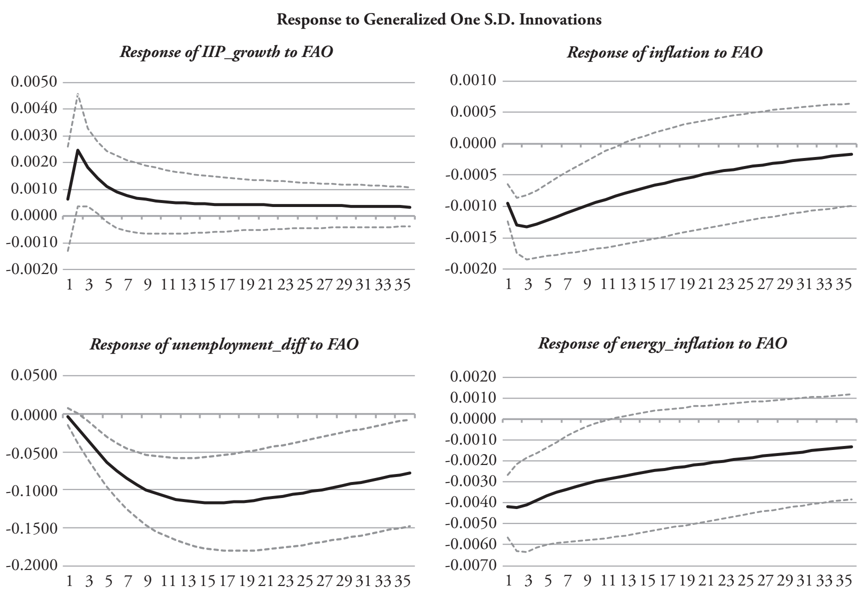
Source: Author's calculations.

Figure A3: *Comparison of Heat Stress to FAO's Database*



Source: FAO (2023).

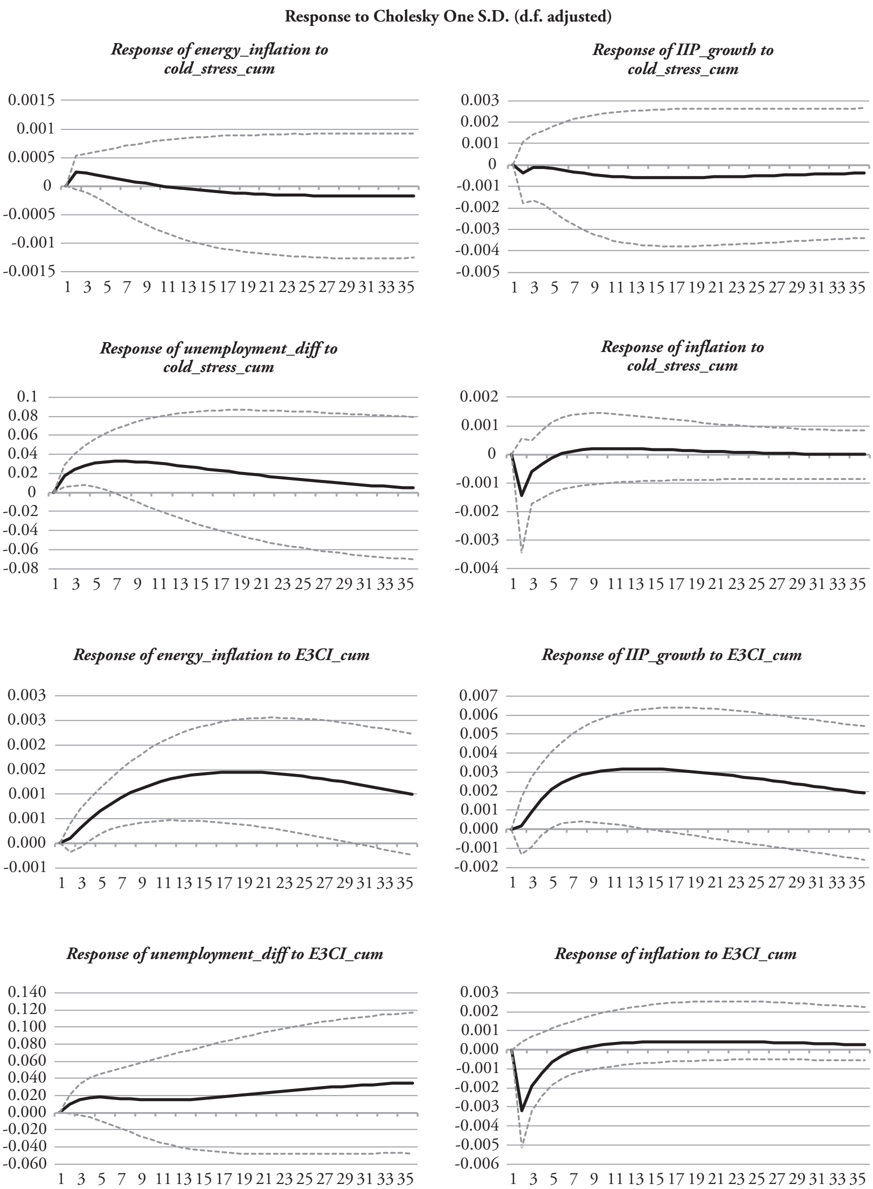
Figure A4: *Impulse Response Functions for Model With FAO Data*

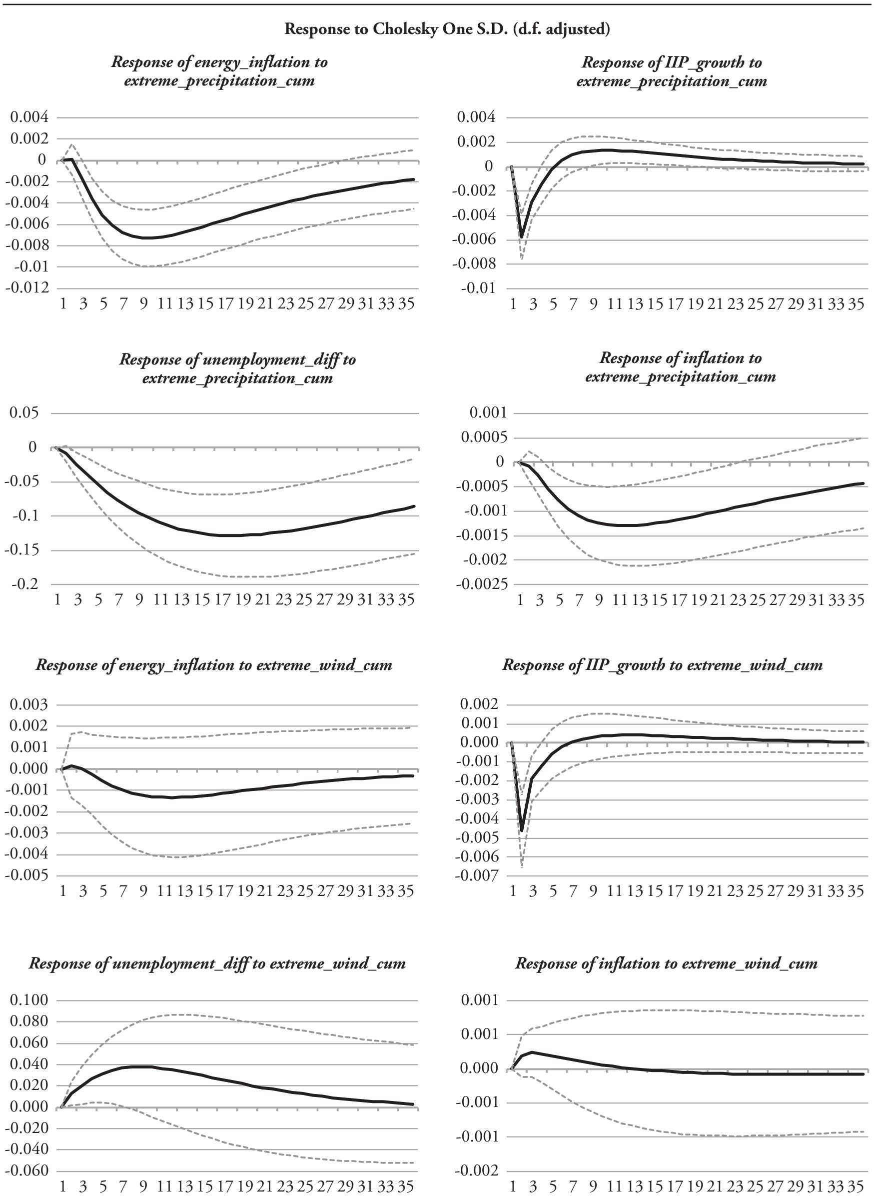


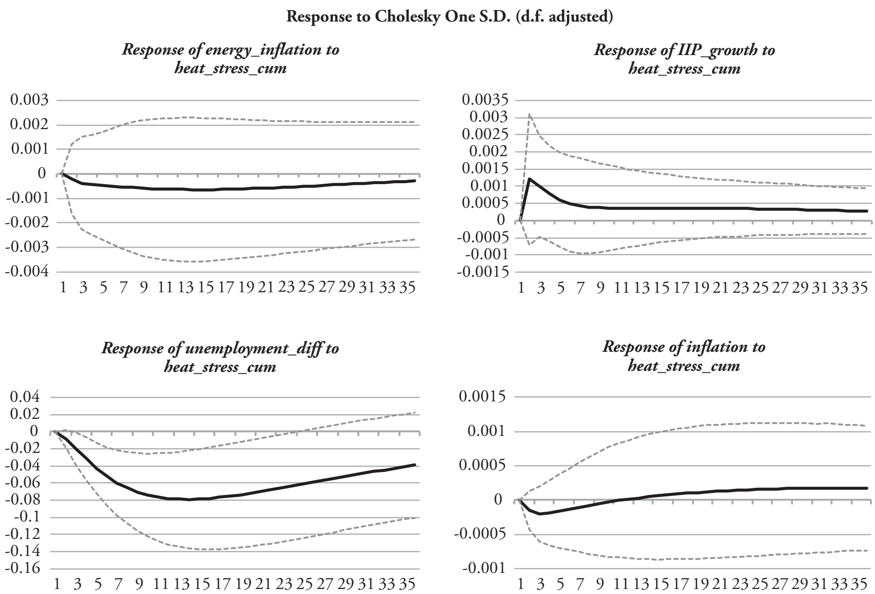
Note: Generalized impulse response functions are depicted, Monte Carlo approach of estimating 95% standard errors with 1,000 repetitions. Full line denotes the average response, with dashed lines representing the upper and lower estimates of the responses.

Source: Author's calculations.

Figure A5: *Impulse Response Functions From a Structural VAR*




Response to Cholesky One S.D. (d.f. adjusted)
Response of energy_inflation to extreme_precipitation_cum
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35
Response of IIP_growth to extreme_precipitation_cum
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35
Response of unemployment_diff to extreme_precipitation_cum
0.05
0
-0.05
-0.1
-0.15
-0.2
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35
Response of inflation to extreme_precipitation_cum
0.001
0.0005
0
-0.0005
-0.001
-0.0015
-0.002
-0.0025
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35
Response of energy_inflation to extreme_wind_cum
0.003
0.002
0.001
0.000
-0.001
-0.002
-0.003
-0.004
-0.005
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35
Response of IIP_growth to extreme_wind_cum
0.002
0.001
0.000
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006
-0.007
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35
Response of unemployment_diff to extreme_wind_cum
0.100
0.080
0.060
0.040
0.020
0.000
-0.020
-0.040
-0.060
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35
Response of inflation to extreme_wind_cum
0.001
0.001
0.000
-0.001
-0.001
-0.002
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35



Note: Generalized impulse response functions are depicted, Monte Carlo approach of estimating 95% standard errors with 1,000 repetitions. Full line denotes the average response, with dashed lines representing the upper and lower estimates of the responses.

Source: Author's calculations.

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