Fresh Evidence from Temperature Effects on Growth and Economic Policy Uncertainty: A Panel Quantile Approach

Flora Leventis
School of Business and Economics
Deree - The American College of Greece
6 Gravias St., Aghia Paraskevi, Athens 15342, Greece
fleventis@acg.edu

Panagiotis Palaios*
School of Business and Economics
Deree - The American College of Greece
6 Gravias St., Aghia Paraskevi, Athens 15342, Greece
ppalaios@acg.edu

*Corresponding author

Abstract

This paper provides fresh evidence of temperature effects on GDP per capita growth and economic policy uncertainty (epu). We apply the quantile via moments methodology (Machado and Santos Silva, 2019) in a sample of 35 countries for the period 1980-2021, the most current time frame of the work we reviewed. To the best of our knowledge, temperature effects on epu, in a panel quantile setting, have not been examined before. Our empirical results provide evidence in favor of asymmetric temperature impacts on both growth rates and epu. Specifically, we find that: First, the impact of temperature and of its interaction with economic policy uncertainty on the growth rate is negative, quadratic, and more intense for poorer countries. Second, the combined temperature and policy uncertainty effect on growth rates is of greater magnitude compared to the simple temperature effect. Third, hotter countries are more vulnerable to economic policy uncertainty, with the effect being more pronounced as uncertainty increases.

Keywords: Climate change; Quantile regression; Economic policy uncertainty; Asymmetric effects

JEL Classification: C33, O13, Q54, Q56.

1. Introduction

Climate change and its consequences for human life is certainly not a new research or policy topic. In fact, it has been studied extensively from environmental and climate scientists as well as economists, among others. It has been, and perhaps surprisingly still is, a controversial and debatable issue, with several groups denying anthropogenic climate change. What's relatively new in the discussion around climate change, is the urgency and force with which measures must be taken, according with several prominent researchers and policy experts. The difference is that the consequences of climate change are no longer something that would be felt in the distant future. We experience them in present time, from rampaging wildfires, to the melting of ice sheets in Antarctica and Greenland, to the deterioration of the population of several species, and to many other adverse outcomes.

From an economics perspective, the contribution of the discipline towards our understanding of how climate change affects several aspects of economic activity and what possible solutions could be implemented in terms of policy, has been considerable, from cap and trade schemes for reducing CO_2 emissions and the Kyoto Protocol to Integrated Assessment Models (IAMs) and damage functions. Recently, there has been a renowned interest both at the academic as well as at the policy level, to enhance and improve some of the theoretical models that have been proposed, but also focus on the empirical framework and econometric modelling to study the relationship between climate change and economic outcomes.

There are several ways to approach the question of how climate change affects economic activity. For example, focusing on extreme weather events and natural disasters, one can distinguish between the direct and indirect effects. Botzen et. al. (2019) define the direct effects of natural disasters as the losses to assets, realized in at the time of the event or shortly after. Indirect effects are those related to changes the level of economic activity. Therefore, one can think of the indirect effects as focusing on the microeconomic dimension and being more centered on the short-run impact, while the indirect effects examine the macroeconomic aspect, using for example GDP or GDP growth. These indirect effects capture both the short run impact on these macroeconomic measures, but can also include long term structural changes in the economy as a result of adjustment and adaptation.

Another important, yet related, classification focuses on the different types of risk stemming from climate change, namely physical and transition risks and their impact on the macroeconomy. Following Batten (2018), physical risks can be broken down to those from an extreme weather event or from the gradual increase in global temperatures. These in turn can be studied by examining the type of shock they produce, i.e. demand or supply. Transition risks on the other hand refer to the risk associated from adopting policies that are less carbon intensive, such as for example a net zero target. Using this framework, several authors have focused on the fiscal implications of both physical as well as transition risks. For example, Agarwala et. al. (2021) present a comprehensive taxonomy linking these two risks on sovereign debt. There is also a growing body of literature focusing on the role of monetary policy and the financial implications of climate change, such as de-carbonizing portfolios and the impact of this on the financial system. Jung et. al. (2023) for instance develop a measure to quantify the climate risk exposure of large global banks.

2. Motivation

Methodologically speaking, some of the more recent approaches focus on using panel regressions to study the impact of weather-related changes on economic conditions. As Dell et. al. (2014) point out, the main advantage of using panel methods lies in the fact that they correct for the omitted variable bias, of which cross-sectional methods are typically subject too. One the other hand, their disadvantage may be their focus on the short-run impact of these weather-related shocks. While long-run impacts and the effects of adaptation are important, in this paper, we decide to follow the panel approach for two main reasons. One relates to the considerable uncertainties with respect to the adaptation mechanism in which economies and societies adjust to new climatic conditions. The other one may be justified by the urgency for action today. In order to tackle the long-term impacts, one first would need to understand and measure the short-run effects on the macroeconomy. As we experience more frequent and more severe extreme weather events, it seems that the definition of what the long-run is has shifted towards the present.

As mentioned above, panel methods have been employed in several studies in the literature. Our work uses panel methods in a quantile framework, following Kiley (2021). Quantile regressions allow us to focus on the effect of a regressor(s) on the entire distribution of the dependent variable including the tails, rather than just the mean outcome, which is the case with simple OLS regressions. This in turn can be useful when examining the effect of say temperature changes on GDP and its growth as it is likely that the effect is not constant. More specifically, extending the Growth at Risk literature[1], Kiley shows that the risk for a severe negative shock to GDP increases at higher temperatures.

Our contributions to the literature can be summarized as follows. First, to the best of our knowledge, quantile regressions on a panel setting have not been widely employed in studying weather and macroeconomic outcomes (with the exception of Kiley (2021)). Thus, one of our contributions is to add to this literature. Second, and perhaps most importantly, we analyze the effect of temperature on economic policy uncertainty, which in a panel quantile setting has not been examined before. Third, our dataset covers the period from 1980 to 2021, the most current time frame of the work reviewed in the next section. Fourth, we find that the impact of temperature on the growth rate of GDP per capita is quadratic, negative and decreases in absolute terms as we move from the lower (bearish economy) to the upper (flourishing economy) quantiles, except for the extreme quantiles, where the temperature effect, as expected, is statistically insignificant. Fifth, concerning our economic policy uncertainty effects, we find that the impact of the interaction between temperature and economic policy uncertainty on growth rate is negative, quadratic and more intense in poorer countries. Further, the combined effect of temperature and policy uncertainty on growth rates are of greater magnitude compared to the simple temperature effect. Lastly, we observe that the impact of temperature on economic policy uncertainty is direct and the magnitude of the impact increases for higher quantiles of economic uncertainty. Our empirical evidence suggests that an increase in temperature due to the climate change

[1] See for example Adrian et. al. (2019), IMF (2017), and Kiley (2022)

poses important threats for the development prospects especially of the poorer countries that usually have both higher temperatures and face severe issues of economic policy uncertainty due to political instability and lack of basic economic infrastructure.

The remainder of the paper is organized as follows. In section 3 we present a brief review of the literature focusing mostly on the relationship between temperature and GDP or GDP growth. Section 4 discusses the data and the econometric methodology used. We present and discuss our results in section 5. Section 6 summarizes the results and concludes.

3. Prior Research

One of the earliest works in this area is the work by Dell et. al. (2009). The authors use cross-sectional regressions and find evidence of a negative relationship between income and temperature using data on 134 countries during the period from 1950 to 2000. In addition, they also perform their analysis using municipal level data on labor income and temperature based on 12 countries in the Americas. The relationship is once again negative and statistically significant; therefore, the effect and direction hold both across as well as within countries. Extending their analysis at the municipal level using more recent and granular data should be an important area for future research, on which we intend to work on.

Focusing on agricultural production, Deschênes and Greenstone (2007) study the impact of changes in temperature and precipitation on the U.S. agricultural sector using county level data in a hedonic cross-sectional model[2] . The paper shows that annual variations in weather have a positive impact of agricultural profits. More specifically using climate change predictions from the Hadley 2 model, they find that climate change will lead to about 4% increase in annual agricultural sector profits. Interestingly enough, they also find that the increases in temperature and precipitation do not seem to have a significant effect on the yields of the two most important crops, namely corn and soybeans.

[2] As the authors point out, the hedonic cross-sectional model has been used extensively in the literature examining the effect of weather changes on economic variables. In this review we chose to focus more on papers using panel techniques.

Eboli et al. (2010) use a multi-regional dynamic general equilibrium model (CGE) to examine the impact of climate change on the level of economic growth. According to their projections they find asymmetrical effects of climate change on economic growth, as developing countries are more affected by environmental changes. It should be noted that according to their findings, although initially Japan and the European Union are expected to experience negative growth effects from climate change, the final effect of climate change is expected to become positive.

Most of the recent literature in this area has moved away from cross-sectional regressions and towards panel methods. As Dell et. al. (2014) point out, cross-sectional regressions are potentially prone to omitted variable bias. In the panel literature, perhaps one of the most cited papers in this area is the one by Dell et. al. (2012). In a sample of 125 countries over the period from 1950 to 2003 the authors find that increases in temperature lead to decreases in growth but only for poor countries. Additionally, the paper shows that economic activity if poor counties is affected both in levels as well as growth rates. In subsequent analysis, they examine the channels through which this negative relationship can be disaggregated. They find that higher temperatures substantially reduce agricultural output, industrial output, and investment while also negatively affecting innovation and political stability. These findings, as they point out, have important implications on the role climate change plays in economic development as well as how it can shape the future climate change policy, especially considering the differences between rich and poor countries.

Lanzafame, M. (2014) focuses on the impact of temperature and rainfall on the per capita GDP growth, using a panel dataset of annual data over the 1962-2000 period which includes 36 African countries. The research finds evidence in favor of both short and long run relations between per capita GDP growth and temperature. On the contrary, the impact of rainfall on GDP growth appears to be less important.

In one of the first papers to examine non-linearities in the weather/growth relationship, Burke et. al. (2015) use data covering the period from 1960 to 2010 for 166 countries to study the effect of temperature and rainfall on economic growth. Their findings indicate that growth is non-linearly related to temperature changes; it increases slowly until the critical point of 13^{o} C, after which it decreases rather rapidly. This key finding of their paper is common for both rich and poor countries, and also for the both the agricultural and non-agricultural sector. Their specification indicates that long-run growth rates could be affected by temperature changes. Moreover, countries with a relatively high starting temperature will experience a stronger negative impact of growth compared to relatively colder counties.

Pretis et al. (2018) further confirm the existence of a non-linear relationship between temperature and GDP growth as they find that temperature changes have statistically significant effects especially for countries that exhibit very high (and low) annual average temperatures. Further, they find evidence that a 2°C warming leads to statistically significant lower economic growth for a large set of countries included in their research.

In an important paper, Burke et. al. (2018) quantify the economic benefits of reducing emissions under different policy targets. Their sample includes 165 countries during the period from 1960 to 2010. Similar to other studies, the link between increases in temperature and loss in output is significant for most countries, with the effect being stronger for countries in the tropics. One of the main contributions of the paper is in terms of quantifying the benefit of meeting the Paris agreement's target. Namely, the authors find that meeting the Paris agreement temperature target of 1.5 degrees Celsius would translate, on average, into an increase in global GDP per capita of 3.4 % at the end of century. On the flip side, under the current trajectory of 3 degrees Celsius, the authors estimate that this would cost the word 5% to 10% of global GDP.

Zhao et al. (2018) use subnational short panel data for 10,597 grid cells across the terrestrial Earth over the period 1990-2005 to examine the relationship between temperature and economic growth. They fit a quadratic model showing the existence of a non-linear relationship between temperature and economic growth, indicating a stronger effect in poorer countries and significant differences of the effect of temperature on growth within countries.

Using also subnational level data, Kalkuhl and Wenz (2020) present a novel dataset with climate and economic data for the period from 1900 to 2014, covering 1500 regions in 77 countries. The authors examine the relationship between climate conditions and changes in productivity levels as well as growth, using different three different estimation approaches: panel regressions, long-difference regressions, and cross-sectional regressions. Similar to other studies, they also find evidence of a non-linear effect of changes in temperature and economic output, where increases in temperature increase gross regional product in cold regions but decrease it in hot regions. In the long-difference specification long run regional growth rates do not seem to be affected by temperature or precipitation levels, as opposed to the cross-sectional model which shows significant negative effects of temperature. Finally, the authors update the 2016 estimates for the social cost of carbon based on the internationally recognized Dynamic Integrated model of Climate and the Economy (DICE) to 73 - 142 US dollars per ton of CO2 - instead of 37 US dollars. In 2030, on the other hand, the damage would be up to 181 US dollars per ton of CO22.

In Acevedo et. al. (2020), the authors use an expanded dataset covering more than 180 countries over the period from 1950 to 2015 to examine the macroeconomic effects of weather changes. In line with previous research, the paper finds that increases in temperature disproportionally affect hotter counties, which also tend to be the most low-income counties. More specifically, their findings indicated that in these countries, an increase in temperature lowers output per capita both in the short and medium terms. Additionally, they show that the effects manifest in variety of channels: lower agricultural and industrial output, lower capital accumulation, poorer human health, and lower productivity in sectors that are exposed to higher temperatures. Finally, using subnational data, they demonstrate that development policies may complement adaptation strategies effectively.

While most of the empirical work concentrates on the effect of average temperature, Kotz et al. (2021) examine the impact of temperature variability on the growth rate of GDP. Specifically, they use daily temperature variability of 1,537 regions worldwide, over 40 years, in fixed effects panel models and find that an extra degree of variability in temperature leads to a five-percentage point reduction, on average, in the regional rate of growth.

Other related work while still employing panel methods, focuses on specific regions. For example, Lee et al. (2020) use a non-linear framework to examine the impact of temperature and precipitation on economic growth, focusing mainly on the

Asian region, during the period 1960-2014. They find evidence that the projected higher temperature could lead to a 10% reduction of the average per capita income in developing Asia, while South Asia, Southeast Asia and the Pacific regions are projected to lose 15.5%, 13.0% and 9.6%, respectively, of their per capita income. Further, they emphasize the role of the government in addressing the challenges that climate change poses, by, among others, developing basic infrastructure and improving the access of at-risk communities to assets, financial capital and markets.

Growth of course is not the only macroeconomic variable of interest. Several of the papers discussed above examine the effect of temperature on different sectors, industrial output, and other outcomes. Another promising area of research which is set to become even more prevalent, looks at the how climate can affect fiscal measures. For example, Beirne et. al. (2021) study the effects of climate related risks on the pricing of sovereign bonds in a panel of 40 advanced and emerging economies using quarterly data from 2002 to 2008. Their findings indicate that both the immediate impact of climate risks (climate vulnerability) and resilience to climate risk have an important effect on the cost of foreign borrowing. They find the former to be more important than the latter. This affects disproportionally emerging economies many of which are more vulnerable to climate risks and may thus face a double challenge.

At a more regional level, Chen and Lu (2022) examine the fiscal implications of climate risk by focusing on the latter's effect on infrastructure investment. More specifically, using data from 2008 to 2015, the authors create a climate risk index based on 31 districts in China, and then use a two-way fixed effects model to quantify the impact of climate risk on fiscal risk. The authors find that climate risk has a statistically significant effect on fiscal expenditures and the deficit ratio. Moreover, through channel analysis, they show that the negative impact of climate risk on infrastructure depreciation can be mitigated through the positive impacts in four other different channels, namely, scale of infrastructure investment, funding source, governance model, and investment structure. Finally, they find that regions that are less economically developed and/or are more vulnerable to climate risk, tend to face a higher fiscal risk.

The empirical literature discussed so far primarily focuses on average expected effects, in other words, the estimation is based on least squares regressions. Kiley (2021) extends previous works by examining the link between temperature and the entire distribution of the percent change in real GDP per capita. Using a panel of 124 countries over the period from 1961 to 2010, he uses quantile regressions linking growth and weather in a number of different specifications. The results suggest that Growth at Risk, defined as the downside risk to GDP growth, are large and robust across different specifications. This implies that climate change may make severe contractions in economic activity more likely.

4. Data Statistical Properties and Econometric Methodology

4.1 Data Sources and Description of Variables

We use the panel quantile methodology with an updated time frame to examine temperature ($temp$) effects on economic policy uncertainty (epu) and GDP per capita growth rates (GDP_{pc_g}). Our sample includes 35 countries during the time period from 1980 to 2021. We collect annual data on the growth rate of GDP per capita from the World Development Indicators. Our temperature data come from the Climate Engine web application and are based on the mean ERA5 climate reanalysis parameter. Data on economic policy uncertainty are from the Economic Policy Uncertainty website[3].

INSERT TABLE 1 HERE

Table 1 presents summary statistics for the variables along with a panel unit root test. We observe that the per capita GDP growth (GDP_{pc_g}) and the economic policy uncertainty (epu) variables provide evidence of a non – normal distribution as they exhibit negative (-0.359) and positive (2.724) skewness, respectively and their kurtosis is 6.963 (leptokurtic) and 13.966 (leptokurtic), respectively. Having detected asymmetrical properties in the distribution of some of our variables we have a sign that nonlinear econometric techniques should be applied to estimate the relationship

[3] https://www.policyuncertainty.com/

between them. The Pesaran (2007) panel unit root test rejects the null hypothesis of non – stationarity for all the variables.

4.2 Econometric methodology

Following Machado and Santos Silva (2019) we develop a location – scale model of the following form:

$$GDP_{pc\_g_{it}} = a_{it} + temp'_{it}\beta + ((\delta_i + Z'_{it}\gamma)U_{it} \quad (1)$$

where $\Pr\{\delta_i + Z'_{it}\gamma > 0\} = 1$ and $(a_i, \delta_i), i = 1, \dots, n,$ capture the individual i fixed effects and Z is vector of known differentiable transformations of $temp$. The sequence $\{temp_{it}\}$ is strictly exogenous, i.i.d for any fixed i and independent across i. U_{it} are i.i.d., statistically independent of $temp_{it}$ and normalized to satisfy that $E(U) = 0$ and $E(|U|) = 1$. Given the above assumptions, equation (1) gives that:

$$Q_{GDP_{pc\_g}}(\tau/temp_{it}) = \left(a_i + \delta_i q(\tau)\right) + temp'_{it}\beta + Z'_{it}\gamma q(\tau) \quad (2)$$

In equation (2) the quantile – τ fixed effect for individual i is given by the coefficient $a_i(\tau) \equiv a_i + \delta_i q(\tau)$ and can be estimated as follows:

$$\widehat{a_\iota}(\tau) = \frac{1}{T}\sum_{t=1}^{T}(GDP_{pc\_g_{it}} - temp'_{it}\hat{\beta}) + \hat{q}\frac{1}{T}\sum_{t=1}^{T}\left(|\widehat{R_{\iota t}}| - Z'_{it}\hat{\gamma}\right) \quad (3)$$

where, R denote the estimated residuals $\hat{R}_{it} = GDP_{pc\_g_{it}} - \hat{a}_i - temp'_{it}\hat{\beta}$. It should be noted that in our empirical analysis we use alternative specifications of the above model with respect to the use of the dependent and the independent variables.

5. Empirical Results and Discussion

We frame our empirical research in two stages. First, we develop a quadratic model to examine the temperature effects on GDP per capita growth rates, in line with Burke et. al (2015) and Kiley (2021), by applying the Quantiles via Moments method of Machado and Marcos Silva (2019), with fixed effects.[4] The main advantage of this method is that it allows the use of methods that are only valid in the estimation of conditional means. Second, using the same econometric methodology, we estimate the effects of temperature and its interaction with economic policy uncertainty on GDP per capita growth rates. Thereafter, we test the temperature effects on economic policy uncertainty.

5.1 Temperature effects on growth

We begin our empirical analysis by applying a quantile panel regression using the quadratic specification, as in line Burke et. al (2015) and Kiley (2021), to model the relationship between the growth rate of GDP per capita in various quantiles and temperature, with the latter variable being the exogenous one. The advantage of the quadratic specification is that it can capture the non – linear effects of temperature on the growth rate of per capita GDP. In addition, since we apply a quantile econometric methodology along with a quadratic specification, our analysis provides a more comprehensive description of the conditional distribution than the econometric ordinary mean approach and the linear modelling specification.

Table 2 two presents the estimation results. The first column shows the estimated coefficient for the OLS location regression and the second column shows the coefficient for the corresponding scale regression. Columns (3) – (11) show the estimated coefficients for each quantile. Following Nusair and Olson (2019) and Lolos et al. (2021), we categorize the quantiles into threes regimes, namely a bearish economy $[\tau = (0.10, 0.20, 0.30)]$, a normal economy $[\tau = (0.40, 0.50, 0.60)]$ and a flourishing economy $[\tau = (0.70, 0.80, 0.90)]$. As we use a quadratic specification, the impact of temperature on the per capita GDP growth rate varies depending on the level of the temperature. Therefore, as in Kiley (2021), to calculate the combined coefficient of temperature we use a temperature threshold, equal to 15.00 ℃ , that distinguishes between colder and hotter countries and corresponds to the 75% percentile of our temperature sample.

[4] As a robustness analysis we also perform an alternative specification estimating the relationship without fixed effects. The results remain qualitatively the same.

According to our results (Table 2), we observe that the impact of temperature on the growth rate of GDP per capita is negative and decreases in absolute terms as we move from the lower (bearish economy) to the upper (flourishing economy) quantiles, except for the extreme quantile $\tau = (0.90)$, where the impact becomes positive.

INSERT TABLE 2 HERE

However, it should be noted that the estimated coefficients of the upper two quantiles $[\tau = (0.80, 0.90)]$ are statistically insignificant. Specifically, in the case of a bearish economy the quantile coefficients are $Q_{temp} =$ (-0.079, -0.066, -0.057), in the case of normal economy the quantile coefficients are $Q_{temp} =$ (-0.051, -0.044, -0.036) and in the case of a flourishing economy the statistically significant coefficient is the coefficient of the 7th quantile, which is equal to -0.028. We further observe that a marginal increase of 1℃ in temperature implies substantially different impacts along the distribution, namely it leads to a 0.079% reduction in the per capita GDP growth rate at the 1st quantile, and to a 0.036% reduction in the per capita GDP growth rate at the 7th quantile. The statistically insignificant temperature effects observed at the 8th and 9th quantiles suggest that for higher levels of GDP per capita growth rates the economy is not affected by the temperature. This result implies that despite the negative impact of extreme temperatures on the GDP per capita growth rates, positive effects from say, structural reforms, advanced technology, investments in human capital and a business-friendly institutional environment, may dominate, leading to the development of a flourishing economy.

Compared to the estimated results of Kiley (2021), our quantile effects appear to be much lower in magnitude as the average temperature of our sample is accordingly much lower (e.g. the 75% percentile temperature in our sample is 15.00 ℃, while in Kiley (2021) it is 25.64℃). Therefore, the GDP per capita growth rates of our sample are higher, and consequently, the impact of temperature is lower, across quantiles. We perform a robustness check by calculating the combined temperature coefficients using a temperature threshold that corresponds to a sample with a higher temperature. The results remain qualitatively the same but, as expected, the absolute values of the coefficients are higher compared to ones that correspond to the lower temperature threshold. The results are shown in the bottom rows of table 2.

The negative relationship between temperature and the per capita GDP growth rate is also confirmed by the OLS location estimation where the temperature coefficient is statistically significant and equal to -0.040. The estimated OLS scale effect of temperature on GDP per capita growth is 0.027. In line with Machado and Santos Silva (2019) we interpret the opposite signs as indicating that higher temperatures reduce the average growth rate of GDP per capita, but also increase the dispersion of the observed per capita growth rates. Comparing the coefficient of the OLS mean approach with the estimated coefficient of the median quantile $\tau = (0.50)$, we find similar effects. However, the statistically significant and lowering in magnitude temperature coefficients, as we move from the lower to the upper quantiles, reveal that the relationship between temperature and per capita GDP growth is indeed asymmetric. Consequently, the mean approach in the presence of conditional heterogeneity and departures form the Gaussian conditions, would lead to spurious results.

INSERT FIGURE 1 HERE

Figure 1 depicts the fitted values of GDP pc growth rates at each quantile for which we have found a statistically significant coefficient, thus showing that growth rates are non-linear and concave in temperature. Further, given the quadratic specification of our model, we calculate, for each quantile, the temperature that corresponds to the maximum fitted value of the per capita growth rate. This temperature also plays the role of a threshold below which the impact of temperature on GDP pc growth rate is direct and above which the relationship becomes inverse. We observe that as the average temperature increases, cold country growth rates increase at a decreasing rate, until the optimum and thereafter they decrease, at an increasing rate, with further warming.

INSERT TABLE 3 HERE

Table 3 reports the relationship between the fitted maximum values of GDP pc growth rates and the corresponding temperature. Our evidence indicates that the threshold temperature for higher quantiles GDP per capita growth rates, corresponds to lower maximum growth rate. Therefore, in poorer countries the maximum growth rates are associated with higher temperatures, compared to the richer countries, or to put it differently, the higher the temperature at which the growth rate of GDP per capita peaks, the lower the growth rate peak value. This evidence is important as it shows that poor countries that are hotter, are more likely to reach their maximum GDP growth rates compared to poor countries that are colder. On the contrary rich countries that are colder, are more likely to reach their maximum growth rates compared to rich countries that are hotter. In addition, the maximum GDP per capita growth according to the mean approach is 2.09%, corresponding to a temperature equal to 8.83 ℃ which is substantially higher than the median growth rate (1.78%), but lower than its corresponding temperature (9.19 ℃). Overall, our empirical evidence is consistent with asymmetric effects as we observe a higher adverse temperature impact on growth rates of poorer countries accompanied with a quadratic relationship between temperature and growth rates along the distribution of the two variables.

5.2 Temperature effects and economic policy uncertainty

The conclusions from the above section made clear that there is a statistically significant relationship between temperature and the per capita GDP growth rate. However, temperature may also have political effects, as stated by Burke and Leigh (2010), Bruckner and Ciccone (2011) and therefore may affect, indirectly, the level of economic activity (Dell et al. (2012)). In this section we develop a political analysis that is framed in two stages. First, we examine the interaction between temperature and economic policy uncertainty on per capita GDP growth rates, and second, we examine the impact of economic policy uncertainty on temperature.

Table 4 presents the results of quantile regression along with the corresponding location and scale OLS estimations for the main impact of temperature and the interaction between temperature and economic policy uncertainty on the growth rates of GDP per capita. Our results, depicted in the last rows of Table 4, show, as expected, a negative relationship between temperature and its interaction with economic policy uncertainty on growth rates. Further, as in the case of the non-political specification of Table 3, we observe that the magnitude of the combined effect of temperature and of its interaction with the *epu* on the growth rate decreases, in absolute terms, as we move from lower to upper quantiles. However, it should be noted that the negative effect on growth rates from the interaction between temperature and economic policy uncertainty are much more intense than in the case of the impact of temperature without the political effects. Therefore, we conclude that the negative effect of temperature on poorer countries that are also characterized by economic policy uncertainty, increases substantially. This poses an important threat for the development prospects particularly of poorer countries that usually have both higher temperatures and higher levels of economic policy uncertainty due to political instability and lack of basic economic infrastructure.

INSERT TABLE 4 HERE

Further, we examine the impact of temperature on economic policy uncertainty applying again the methodology of Machado and Santos Silva (2019). Part A of Table 5 presents the results from the estimation for the location and scale of the OLS model (columns 1 and 2 respectively) and various quantiles of the distribution of economic policy uncertainty. For a better understanding of temperature dynamics on economic policy uncertainty we estimate the lagged models of the temperature impact, presented in Parts B, C and D of Table 5, respectively. The model with no lags shows a positive and statistically significant effect of temperature on *epu*, both in the mean and the quantile approach, in line with the findings of Burke and Leigh (2010) and Brucker and Ciccone (2011), who find that higher temperatures may increase the demand for institutional change. According to our empirical results, we also observe that the magnitude of the impact of temperature increases, as we move from the left to the right tail of the *epu* distribution. This implies that a higher temperature increases economic policy uncertainty in countries with higher economic policy uncertainty that are usually poorer and hotter, a result in line with the findings of Dell et al. (2012). Our findings concerning the impact of temperature on economic policy uncertainty, combined with the results of our previous estimations indicate that hotter countries are more vulnerable to economic policy uncertainty and exhibit lower GDP per capita growth rates. The lagged models, presented in the Parts A, B and C of Table 5 show that the impact of temperature on policy uncertainty follows the same path as we move from the lower to the higher tails of the distribution of GDP per capita growth rates, but the historical effects appear to be statistically significant only in the short (one lag) and medium (5 lags) term, but not in the long run (10 lags). As expected, the magnitude of the impact of temperature on *epu* decreases for the specifications with more lags. For example, the coefficient on *epu* is 0.110 for the first quantile of the non-lagged model, while it becomes 0.0345 for the model with one lag and 0.00308 for the model with two lags. The same path is observed for the rest of the quantiles.

INSERT TABLE 5 HERE

6. Conclusions

This paper provides fresh empirical evidence of asymmetric temperature effects on GDP per capita growth rates and economic policy uncertainty. The econometric methodology applied is the quantile via moments, using quadratic and linear model specifications to a sample of 35 countries during the period from 1980 to 2021, which is the most current time frame of the work who have reviewed. To the best of our knowledge, quantile regressions on a panel setting have not been widely employed in studying weather and macroeconomic outcomes (with the exception of Kiley (2021)). Most importantly, the effect of temperature on economic policy uncertainty, in a panel quantile setting, has not been examined before.

Our empirical results provide strong evidence in favor of asymmetric temperature impacts on both growth rates and economic policy uncertainty. Specifically, in line with the existing literature we confirm that the temperature effect on growth rate is quadratic. Second, we find that the impact of temperature on the growth rate of GDP per capita is negative and decreases in absolute terms as we move from the lower (bearish economy) to the upper (flourishing economy) quantiles, except for the extreme quantiles, where the temperature effect, as expected, is statistically insignificant. Third, concerning our economic policy uncertainty effects, we find that the impact of the interaction between temperature and economic policy uncertainty on the growth rate is negative, nonlinear and, specifically, quadratic. Fourth, the combined negative effect of temperature and policy uncertainty is more intense on poorer countries and most importantly, the effect increases substantially compared to the simple temperature effect. Fifth, hotter countries are more vulnerable to economic policy uncertainty with the effect being more pronounced as uncertainty increases. Finally, historical temperature effects appear to be statistically significant only in the short and medium term, but not in the long run.

Overall, the above results indicate that an increase in temperature due to climate change poses important threats for the development prospects especially, but not exclusively, for the poorer countries that usually have both higher temperatures and face severe issues of economic policy uncertainty due to political instability and lack of basic economic infrastructure.

Although the present study has shed light on crucial temperature effects on growth, among them on the interaction of temperature with economic policy uncertainty, several issues remain open for future research a more in-depth analysis of the asymmetric dynamics between climate change, the economy and political/institutional variables.

References

Acevedo, Sebastian, M. Mrkaic, N. Novta, E. Pugacheva, & P. Topalova (2020). The Effects of Weather Shocks on Economic Activity: What are the Channels of Impact? *Journal of Macroeconomics*, Vol. 65.

Adrian, Tobias, N. Boyarchenko, & D. Giannone (2019). Vulnerable Growth. *American Economic Review*, Vol. 109 (4): 1263-89. DOI: 10.1257/aer.20161923

Agarwala, Matthew, M. Burke, P. Klusak, K. Mohaddes, U. Volz, & D. Zenghelis (2021), Climate Change and Fiscal Sustainability: Risk and Opportunities. *National Institute Economic Review*. Vol. 258 (1), pp. 28 – 46.

Batten, Sandra, (2018), Climate Change and the macroeconomy: a critical review. *Bank of England Working Paper* No. 706.

Beirne, John, N. Renzhi, & U. Volz (2021). Feeling the heat: Climate risks and the cost of sovereign borrowing. *International Review of Economics and Finance*, Vol. 76, pp. 920 – 936.

Botzen, Wouter, W.J., O. Deschênes, & M. Sanders (2019). The Economic Impacts of Natural Disasters: A Review of Models and Empirical Studies. *Review of Environmental Economics and Policy*, Vol. 13 (2), pp. 167 – 188.

Brückner, M., & Ciccone, A. (2011). Rain and the Democratic Window of Opportunity. *Econometrica*, 79(3), 923–947. http://www.jstor.org/stable/41237773

Burke, Marshall, S. M. Hsiang & E. Miguel (2015). Global non-linear effect of temperature on economic production. *Nature*, Vol. 527, pp. 235 - 239.

Burke, Marshall, W. M. Davis & N. S. Diffenbaugh (2018). Large potential reductions in GDP under UN mitigation targets. *Nature*, Vol. 557, pp. 549 – 543.

Burke, Paul J., and Andrew Leigh. (2010). Do Output Contractions Trigger Democratic Change? *American Economic Journal: Macroeconomics*, 2 (4): 124-57.

Carleton, Tamma. A., Hsian, S. M. (2016). Social and economic impacts of climate. *Science*, Vol. 353 (6304).

Chen. Bo. & L. Chu (2022). Decoupling the double jeopardy of climate risk and fiscal risk: A perspective of infrastructure investment. *Climate Risk Management*, Vol. 34.

Choi, I. (2001). Unit root tests for panel data. *Journal of international money and Finance*, 20(2), 249-272.

Dell, Melissa, B. F. Jones, & B. A. Olken. (2009). Temperature and Income: Reconciling New Cross‐Sectional and Panel Estimates. *American Economic Review*, Vol. 99 (2), pp. 198‐204.

Dell, Melissa, B. F. Jones, & B. A. Olken. (2012a). Temperature Shocks and Economic Growth: Evidence from the Last Half Century. *American Economic Journal: Macroeconomics*, Vol. 4 (3), pp. 66 – 95.

Dell, Melissa, B. F. Jones, & B. A. Olken. (2012b). Temperature Shocks and Economic Growth: Evidence from the Last Half Century: Dataset. *American Economic Journal: Macroeconomics*, http://dx.doi.org/10.1257/mac.4.3.66.

Dell, Melissa, B. F. Jones, & B. A. Olken. (2014). What Do We Learn from the Weather? The New Climate‐Economy Literature. *Journal of Economic Literature*, Vol. 52 (3), pp. 740‐98.

Deschênes, Olivier, & M. Greenstone. (2007). The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather. *American Economic Review*, Vol. 97 (1), pp. 354 – 85.

Eboli, F., Parrado, R., & Roson, R. (2010). Climate-change feedback on economic growth: explorations with a dynamic general equilibrium model. *Environment and Development Economics*, 15(5), 515-533.

García-León, David. (2015). Weather and Income: Lessons from the Main European Regions. *Fondazione Eni Enrico Mattei (FEEM)*, http://www.jstor.org/stable/resrep01157

Hsiang, Solomon, R. Kopp, A. Jina, J. Rising, M. Delgado, S. Mohan, D. J. Rasmussen, R. Muir-Wood, P. Wilson, M. Oppenheimer, K. Larsen, & T. Houser. (2017). Estimating economic damage from climate change in the United States. *Science*, Vol. 356 (6345), pp. 1362 – 1369.

IMF (2017). Financial Conditions and Growth at Risk, *Global Financial Stability Report*, October, Chapter 3.

Jung, Hyeyoon, R. F. Engle & R. Berner. (2021, revised 2023). CRISK: Measuring the Climate Risk Exposure of the Financial System. *Federal Reserve Bank of New York Staff Reports*, No 977.

Kalkuhl, Matthias, & L. Wenz. (2020). The impact of climate conditions on economic production. Evidence from a global panel of regions. *Journal of Environmental Economics and Management*, Vol. 103.

Kiley, Michael T. (2021). Growth at Risk from Climate Change. *FEDS Working Paper* No. 2021-54, http://dx.doi.org/10.17016/FEDS.2021.054.

Kiley, Michael T. (2022). Unemployment Risk. *Journal of Money, Credit and Banking*. 54: 1407-1424. https://doi.org/10.1111/jmcb.12888

Kotz, M., Wenz, L., Stechemesser, A., Kalkuhl, M., & Levermann, A. (2021). Day-to-day temperature variability reduces economic growth. *Nature Climate Change*, 11(4), 319-325.

Lanzafame, M. (2014). Temperature, rainfall and economic growth in Africa. *Empirical Economics*, 46, 1-18.

Lee, M., Gaspar, R., & Villaruel, M. (2020). Effects of temperature shocks on economic growth and welfare in Asia. *Resources and Environmental Economics*, 2(2), 158-171.

Lolos, S., Palaios, P. & Papapetrou, E. (2021), Tourism-led growth asymmetries in Greece: evidence from quantile regression analysis, *Portuguese Economic Journal*, Vol. 22, pp. 125-148.

Machado, José A.F., & S. Silva, J.M.C. (2019), Quantiles via Moments, *Journal of Econometrics*, Vol. 213.

Newell, Richard G., B. C. Prest, & S. E. Sexton. (2021). The GDP-Temperature relationship: Implications for climate change damages. *Journal of Environmental Economics and Management*, Vol. 108.

Nusair, Salah A. and Dennis Olson. (2019). The effects of oil price shocks on Asian exchange rates: Evidence from quantile regression analysis. *Energy Economics*, Volume 78, Pages 44-63.

Pesaran, M. H. (2007). A simple panel unit root test in the presence of cross-section dependence. *Journal of applied econometrics*, 22(2), 265-312.

Pretis, F., Schwarz, M., Tang, K., Haustein, K., & Allen, M. R. (2018). Uncertain impacts on economic growth when stabilizing global temperatures at 1.5 C or 2 C warming. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376(2119), 20160460.

Zhao, X., Gerety, M., & Kuminoff, N. V. (2018). Revisiting the temperature-economic growth relationship using global subnational data. *Journal of environmental management*, 223, 537-544.

FIGURES AND TABLES

Figure 1: Fitted quadratic effects of temperature on GDP per capita growth rates for various quantiles [$\tau = (0.10, 0.20, \dots, 0.70)$] and the mean. We have included only the quantiles for which the estimated combined temperature coefficient is statistically significant.

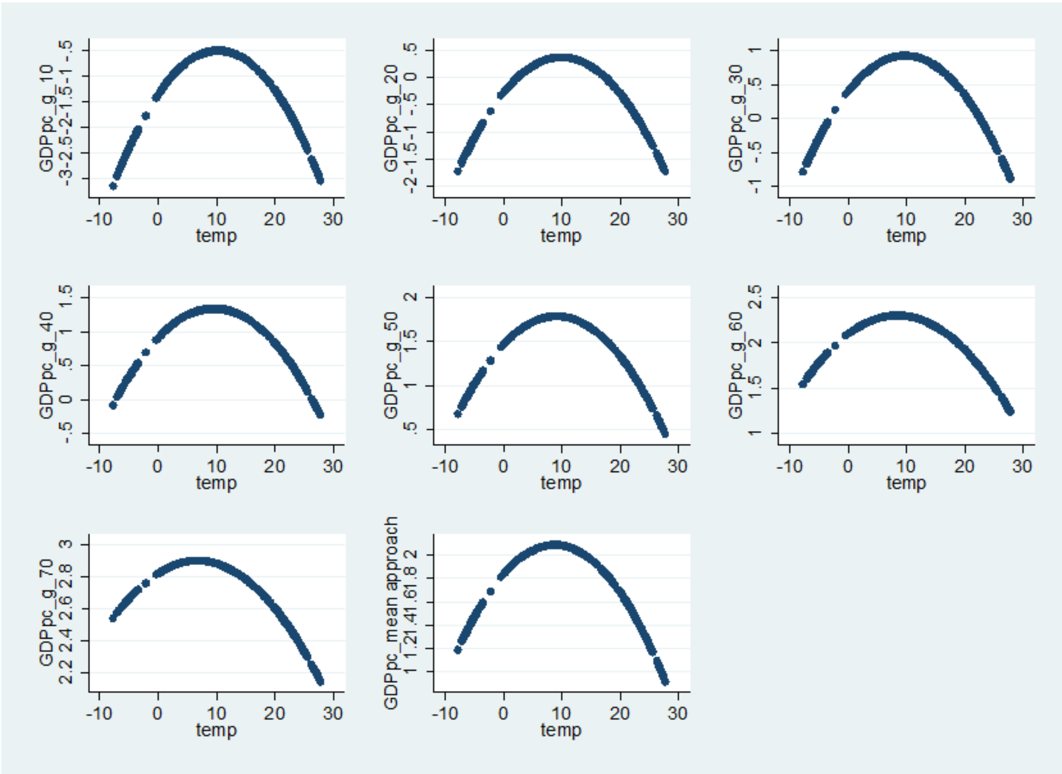

Table 1: Summary statistics for the variables and Unit Root tests

Variable	No. of obs.	Mean	Median	Standard Deviation	Skewness	Kurtosis	Pesaran unit root test
GDP_{pc_g}	1256	1.881	1.903	3.420	-0.359	6.963	-8.633***
$temp$	1333	11.239	10.317	7.798	0.026	2.913	-11.912***
epu	607	123.705	106.122	74.907	2.724	13.966	-1.434*

Notes: *, **, *** denote significance at 10%, 5% and 1% level respectively.

Table 2: Estimation results (Quantiles via Moments) for the quadratic model with fixed effects. Dependent variable is GDP_{pc_g}.

	Mean approach		Bearish economy			Normal economy			Flourishing economy		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Ind. Var.	location	scale	qtile_10	qtile_20	qtile_30	qtile_40	qtile_50	qtile_60	qtile_70	qtile_80	qtile_90
temp	0.0577	-0.0801***	0.170**	0.132**	0.109**	0.0902*	0.0709	0.0486	0.0230	-0.0114	-0.0783
	(0.0457)	(0.0262)	(0.0683)	(0.0587)	(0.0532)	(0.0497)	(0.0465)	(0.0437)	(0.0433)	(0.0447)	(0.0549)
temp_sq	-0.00326**	0.00360***	-0.00830***	-0.00662***	-0.00555***	-0.00472***	-0.00386**	-0.00285*	-0.00170	-0.000157	0.00285
	(0.00166)	(0.00105)	(0.00246)	(0.00209)	(0.00188)	(0.00176)	(0.00166)	(0.00159)	(0.00163)	(0.00178)	(0.00230)
Constant	1.836***	2.278***	-1.350***	-0.288	0.391	0.913***	1.461***	2.096***	2.822***	3.800***	5.704***
	(0.271)	(0.182)	(0.483)	(0.384)	(0.331)	(0.304)	(0.272)	(0.256)	(0.267)	(0.276)	(0.426)
Obs.	1,251	1,251	1,251	1,251	1,251	1,251	1,251	1,251	1,251	1,251	1,251
Cumulative Temperature Effects											
(temp.=15℃)											
Coef.	-0.0401***	0.0279***	-0.0793***	-0.0662***	-0.0579***	-0.0515***	-0.0447***	-0.0369***	-0.0280*	-0.0160	0.0073
	(0.0143)	(0.0102)	(0.0210)	(0.0180)	(0.0164)	(0.0152)	(0.0144)	(0.0143)	(0.0149)	(0.0166)	(0.0214)
(temp.=25.64℃)											
Coef.	-0.1096***	0.1046***	-0.2560***	-0.2072***	-0.1760***	-0.1520***	-0.1268***	-0.0976**	-0.0643*	-0.0194	0.0680
	(0.0399)	(0.0297)	(0.0685)	(0.0562)	(0.0496)	(0.0451)	(0.0408)	(0.0385)	0.0389	0.0414	0.0536

*, **, *** denote significance at 10%, 5%, 1* level respectively, standard errors in parentheses

Table 3: Relationship between estimated maximum GDP per capita and temperature

	Quantile	Fitted maximum GDP pc growth rate	Temperature
Bearish economy	$Q_{0.1}$	-0.48%	10.22℃
	$Q_{0.2}$	0.37%	10.00℃
	$Q_{0.3}$	0.92%	9.77℃
Normal economy	$Q_{0.4}$	1.34%	9.55℃
	$Q_{0.5}$	1.78%	9.19℃
	$Q_{0.6}$	2.30%	8.51℃
Flourishing economy	$Q_{0.7}$	2.90%	6.74℃
	mean	2.09%	8.83℃

Table 4: Political effects**.** Estimation results (Quantiles via Moments) for the quadratic model with fixed effects. Dependent variable is GDP_{pc_g}.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Ind. Var.	location	scale	qtile_10	qtile_20	qtile_30	qtile_40	qtile_50	qtile_60	qtile_70	qtile_80	qtile_90
tempXepu	-0.0491*	0.0419*	-0.1136**	-0.0823**	-0.0682*	-0.0528*	-0.0402	-0.0316	-0.0225	-0.0108	0.0131
	(0.2901)	(0.0233)	(0.0561)	(0.0408)	(0.0351)	(0.0303)	(0.0270)	(0.0259)	(0.0257)	(0.0278)	(0.0332)
tempXepu_sq	-0.0002*	2.01e-06	-0.0002	-0.0002	-0.0002	-0.0002	-0.0002*	-0.0002	-0.0002	-0.0002	-0.0002
	(0.0001)	(0.0001)	(0.0002)	(0.0002)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0002)
Constant	5.4888***	-0.0682	5.5937**	5.5427***	5.5199***	5.4947***	5.4743***	5.4602***	5.4454***	5.4263***	5.3874***
	(1.0413)	(0.8565)	(2.2504)	(1.6288)	(1.3479)	(1.1173)	(0.9536)	(0.8698)	(0.8206)	(0.8636)	(1.0424)
Observations: 577											
Cumulative Temperature Effects											
Coef.	-0.0577**	0.0420**	-0.1223**	-0.0909**	-0.0769**	-0.0614**	-0.0488**	-0.0402*	-0.0310	-0.0193	0.0045
	(0.0245)	(0.0206)	(0.0492)	(0.0355)	(0.0303)	(0.0257)	(0.0226)	(0.0215)	(0.0211)	(0.2300)	(0.0277)

*, **, *** denote significance at 10%, 5%, 1* level respectively, standard errors in parentheses

Table 5: Political effects**.** Estimation results (Quantiles via Moments) with fixed effects. Dependent variable is epu.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Ind. Var.	location	scale	qtile_10	qtile_20	qtile_30	qtile_40	qtile_50	qtile_60	qtile_70	qtile_80	qtile_90
Part A: 1 year lag model											
temp	0.174***	0.0438**	0.110***	0.125***	0.143***	0.159***	0.172***	0.187***	0.202***	0.225***	0.247***
	(0.0302)	(0.0180)	(0.0356)	(0.0326)	(0.0303)	(0.0296)	(0.0301)	(0.0318)	(0.0347)	(0.0403)	(0.0469)
Constant	2.902***	-0.106	3.058***	3.022***	2.977***	2.940***	2.909***	2.872***	2.835***	2.779***	2.726***
	(0.308)	(0.184)	(0.363)	(0.332)	(0.308)	(0.301)	(0.306)	(0.323)	(0.352)	(0.410)	(0.478)
Part B: 1 year lag model											
tempL1	0.0822***	0.0313**	0.0345	0.0471**	0.0596***	0.0714***	0.0807***	0.0915***	0.103***	0.117***	0.134***
	(0.0217)	(0.0132)	(0.0259)	(0.0233)	(0.0216)	(0.0212)	(0.0216)	(0.0230)	(0.0252)	(0.0289)	(0.0341)
Constant	3.849***	0.0232	3.814***	3.823***	3.833***	3.841***	3.848***	3.856***	3.865***	3.875***	3.888***
	(0.220)	(0.134)	(0.263)	(0.236)	(0.218)	(0.214)	(0.218)	(0.232)	(0.255)	(0.293)	(0.346)
Part C: 5 years lag model											
tempL5	0.0316**	0.0185**	0.00308	0.0104	0.0181	0.0247*	0.0304**	0.0370**	0.0435***	0.0525***	0.0619***
	(0.0138)	(0.00823)	(0.0171)	(0.0154)	(0.0142)	(0.0137)	(0.0138)	(0.0144)	(0.0156)	(0.0179)	(0.0208)
Constant	4.368***	0.155*	4.129***	4.190***	4.254***	4.310***	4.357***	4.413***	4.467***	4.543***	4.621***
	(0.139)	(0.0827)	(0.173)	(0.155)	(0.142)	(0.137)	(0.138)	(0.145)	(0.157)	(0.179)	(0.209)
Observations: 607											

*, **, *** denote significance at 10%, 5%, 1* level respectively, standard errors in parentheses