Weather and Income: Lessons from the main European regions

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Abstract

Some recent papers by Dell et al. (2009) and Dell et al. (2012) (DJO) relating weather and economic outcomes, have delivered meaningful messages with clear implications to the effects of a changing climate. In a nutshell, the authors claim that a $1^{\circ}\mathrm{C}$ increase in global average temperatures would harm both the level and growth capacities of relatively poor countries, leaving rich countries basically unaffected. In this study, we make use of a detailed weather and economic dataset covering the main regions of the five largest economies in the Euro area in an attempt to refute the previous affirmation. In particular, we find in our sample that global warming affects, although in a modest manner, all regions within well-developed countries in the long-term (level effect). As in DJO, the level effect in poor regions is exacerbated. The latter regions also suffer from a slight negative short-term effect (growth effect). We claim also that the larger short-time response of these regions to a climate shock is partially adapted in the long-run.

Keywords: economic growth, weather, Ricardian analysis, developed economies, climate change, adaptation, NUTS

JEL Classification: O1, O4, Q51, Q54, Q59, R11

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1 Introduction

> *"People are part of the Earth system and they impact and are impacted by its materials and processes."*

Over the centuries, the risk-averse human being has focused in minimising the adverse consequences of the second part of the previous statement and, indeed, has successfully been able to decouple the economic system from the uncertain environmental conditions up to a great extent. This has been done by means of gradually switching away from environmentally exposed technologies and systems of production to less exposed activities. And the strategy has paid off for a decent amount of time. Unfortunately, this has been carried out without paying much attention to the transitive part of the sentence, that is, without caring about the impacts that human behaviour causes in the system, the result being an anthropogenically warming process of the Earth that poses into serious threat the delicate equiilibrium upon which the system rests. The gradual warming of the system, widely known as *climate change*, has brought about a great amount of questions and concerns that have to be addressed in the very near future. For most of them a careful, categorical and scientific response is required. This is what occupies us in this paper.

In light of the more than likely increase of the global mean surface temperature[1] one would like to know up to which extent the economic system is exposed to environmental conditions and how the changing nature of those variables affect its performance. In particular, we would like to measure whether a relationship between weather and income exists and determine its sign and magnitude and assess whether projected increases in temperatures will undermine the ability of our economies to grow.

Melissa Dell (Harvard), Benjamin Jones (MIT) and Benjamin Olken (Northwestern) (DJO, henceforth) have very recently delivered a series of papers [Dell et al. (2009, 2012, 2014)], in which they link meteorological and economic data. The relationship between temperature and aggregate economic activity has traditionally been quantified using two approaches. One approach, emphasized in the growth and development literatures, has examined the relationship between average temperature and aggregate economic variables in cross-sections of countries. This is the so-called *hedonic* or *Ricardian* approach and was first applied to weather variables and economic outcomes by Mendelsohn et al. (1994). Further examples of this methodology applied to different fields and regions are the case studies of Sachs and Warner (1997); Gallup et al. (1998); Nordhaus (2006) and Fisher et al. (2006).

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[1] The 5th Assessment Report of theIPCC (2013) points out that "Surface temperature is projected to rise over the 21st century under all assessed (emission) scenarios". The increase in temperatures would range from 0.3 to 4.8ºC according to different greenhouse gases emssion pathways.

For example, In contemporary data, considering sub-national data at the municipality level for 12 countries in the Americas, Dell et al. (2009) find that a negative relationship between income and temperature exists when looking within countries, and even looking within states within countries. The authors claim that hot countries tend to be poor, with national income falling 8.5% per degree Celsius in the countries' cross-section. Other studies, like the one performed by Albuoy (2009) find a negative correlation between temperature and firm productivity within the United States. However, many argue that this correlation is driven by spurious associations of temperature with national characteristics such as institutional quality (e.g., Acemoglu et al. (2002); Easterly and Levine (2003); Rodrik et al. (2004)). Their reasoning against the relation between temperature and income hinges on the role of omitted variables, by which other correlated variables, such as a country's institutions or trade policy, drive prosperity in contemporary times, leaving no important role for geography. DJO disprove this in Dell et al. (2009). Doubtless, however, weather variables can be considered as exogenous variables in almost any context and thus, are particularly suitable for reduced-form analyses.

On the other hand, there exists a second and novel approach to climate and economic data. Dell et al. (2012) take an approximation to climate data different from cross section data and micro evidence. They first construct temperature and precipitation data for each country and year in the world from 1950 to 2003 and combine this dataset with data on aggregate output. They then examine the historical relationship between changes in a country's temperature and precipitation and changes in its economic performance. Their main identification strategy uses year-to-year fluctuations in temperature and precipitation. They find a significant, large, negative effect of higher temperatures not only on the level of output but also on growth, but only in poor countries[2]. In particular their estimates identify that a 1ºC rise in temperature in a given year reduced economic growth in that year by about 1.3 percentage points, which is quite substantial. For rich countries, changes in temperature do not have a robust, discernable effect on economic growth. Our point here is that the whole effect of temperature on income may be swept away by the fact that the data employed is at the country level, averaging thus the possible heterogeneity present within countries.

The findings in Dell et al. (2009), though remarkable, are susceptible to controversy since in the event of harmful consequences following a continued global warming of global temperatures, most of the developed world would be left aside or hardly affected, which seems quite a bit optimistic, especially, after caring about the messages delivered by the *IPCC* in their successive series of reports. Even if their claim were to be flawless, this is a major issue that is worth sheding some more light

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[2] The use of annual variation to estimate the impact of climate change was first proposed by Schlenker and Roberts (2009) and Deschênes and Greenstone (2007), who use annual county-level U.S. data to estimate the impact of weather on U.S. agricultural output

into. Determining faithfully the exposure of well-developed economies to the increase in temperatures is a major issue within the economics of climarte change. Should wealthy economies be affected by temperature, then a much larger fraction of the global economy may be disturbed by climate change than previously thought. The message in Dell et al. (2009) was not new. Several examples in the literature of the economic implications of climate change, among which we can find Schelling (1992); Poterba (1993); Stern (2006); Nordhaus (2008); Tol (2009) point in that direction.

However, a continously growing body of evidence suggests that even in well-developed countries some economic vulnerabilities remain, implying that adapting to all climatic conditions along all margins is too costly. Most studies are based primarily in the analysis of the response of agricultural yields to extreme weather events (Roberts and Schlenker (2011); Burke and Emerick (2013)). In non-agricultural contexts, Graff Zivin and Neidell (2014) document a negative response of temperature-exposed labor supply and Hsiang et al. (2013) claim that high temperatures continue to elicit costly personal conflicts even in wealthy populations. More recently, A very novel study by Deryugina and Hsiang (2014) relate daily temperatures with annual income in the United States counties finding that this single environmental parameter still happens to play a significant role in the overall economic performance, with a decline in average productivity of roughly 2% per additional 1ºC over 15ºC. Similarly, Colacito et al. (2014) document empirical evidence on the negative effect of temperature in the economic growth of the United States, especially in summer. Again, they make use of nationally disaggregated weather and income data from 135 U.S. weather stations. Even a negative relationship between rising temperatures and economic growth has been recently estimated using equity markets data (see Bansal et al. (2014)).

We follow the spirit of Deryugina and Hsiang (2014); Colacito et al. (2014) and try to apply it to the case of Europe[3]. Having a quick glance at the European mainland map and looking at the larger countries in economic terms, that is, Germany, France, UK, Italy and Spain, and given the geographic dimensions of those countries, it is possible to find the heterogenous (exogenous) variation in climate-related variable that enables us to exploit its relation with economic variables. We will benefit from the statitical classification enacted by the EU, called NUTS, through which the whole EU is parcelled in different levels and regions. This framework is generally used by Member States to apply their regional policies and is therefore the appropriate level for analysing regional/ national problems. In particular, environmental policies within the EU are formulated in a regional (NUTS 2) level[4]. On

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[3] Contrary to the US case, there exists no centralised agency that gathers all the national weather records. Our main drawback will be to retrieve all the meterological data and make it hoomogenous for comparison

[4] The regular report on the social, economic and territorial situation and development of the regions of the EU, which the Commission is required to produce every three years under Article 31 of Council Regulation (EC) No 1083/2006 concerning the European Regional Development Fund, has so far been drafted mainly for the NUTS 2 level.

basis of that, it turns necessary to delve into the main results and refine them.

Noting that climate change is not about a permanent climate shock but rather about a stochastic warming process along an upward trend, recent historical experience, which has occurred on such a stochastic warming trajectory, provides a highly relevant setting to understand warming effects. Thus, while attention and beliefs about warming may change, causing changes in responses, and while non-linear global effects (like sea level rise) continue to sit outside recent historical experience, recent “long differences” provide an important opportunity to maintain the strength of identification from panel methodologies while studying time scales that bear more directly on longer-run responses. So far, research using longer time scales does not suggest substantial adaptation compared to shorter-run estimates over this type of time scale, but these analyses are still relatively few and much work remains ahead. Note, however, that in this paper we will not try to draw any relevant conclusions around the process and effects of climate change on these regions. In order to do so, we would need to have series ranging in the interval of 30 to 50 years to distinguish a proper variation in the climate pattern, which is not our case. We will simply exploit the stochastic variations occuring in the available period.

In possession of the previous results, we will try to reconcile the possible differences between the two magnitudes by making use of a simple framework derived in Dell et al. (2009) by which, we will attempt to disentangle the differences in both figures responding to the action of two specific mechanisms, namely, convergence and adaptation. convergence forces may pull lagging countries and regions toward the frontier. Convergence effects offset temperature effects, so that convergence limits the cross-sectional income differences that can be sustained. Second, over longer periods, regions may adapt to their climate. The panel growth estimates reflect responses to climate shocks. To the extent that individuals adjust their behavior to permanent temperature changes, e.g., by switching to more appropriate crops, industries, and technologies estimates may be larger than the longer-run response. Adaptation is a concept particularly relevant in the climate change literature and is one of the main focus of the *IPCC* in terms of alleviating the pernicious effects of climate change in various fields, including the economic.

All in all, this paper will aim to shed light into some insights of the climate-income relationship**.** First, we provide novel cross-sectional evidence using subnational data for a set of well-developed countries. In particular, we will try to refute partially the findings of DJO, insofar as within-country heterogeneity in temperatures should be accounted for when performing cross-country analyses. The immediate implication of the above is striking because if we happen to observe regions that are more prone to weather sensitivity, policy makers should develop regional-level policies that protect those regions to extreme weather events. As a byproduct of the previous point, when modelling the climate change the researcher should take into account the possible regional heterogeneity and thus, propose models that incorporate this feature[5]. Second, we will complement the previous approach with the short-term impact of weather fluctuations occurring in the very same set of regions and will analyse, to tie up all loose ends, how these two magnitudes relate. As far as we are concerned, that would be the first attempt to do so for the sample set of European countries/regions.

The remainder of the paper is organized as follows. In Section 2, we describe all the data employed in this study. Section 3 obtains the long-term relationship betwen weather income and income by studying the cross-section dimension of our dataset. Section 4 goes large in the T dimension so as to study the dynamics of the short-term relation of our variables of interest. In section 5, we try to reconcile the previous magnitudes by the use of a simple framewrok of convergence and adaptation and Section 6 concludes.

2 Data

For this study an on-purpose dataset must be constructed. As already mentioned, there exists no European-broad agency that assembles all the weather data required for this study. Besides that, the offical European statistical agency, EUROSTAT, does not provide either a detailed breakdown of regional economic accounts prior to year 2000. Thus, the strategy amounts to retrieve data from national statistical offices and national climate agencies in order to construct a wide-region database as longitudinally largest as possible. The unit of reference we have opted for is the NUTS classificaton. The NUTS classification (Nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the EU for the purpose of the collection, development and harmonisation of EU regional statistics. Socio-economic analyses of the regions. We can identify different level of NUTS (see Figures 1 to 3): NUTS 0 correspond to counties; NUTS 1, to major socio-economic regions; NUTS 2, to basic regions for the application of regional policies; and NUTS 3, to small regions for specific diagnoses Framing of EU regional policies. A full breakdown of NUTS at the different levels can be observed in Table (3).

The purpose of the creation of the NUTS classification is the socio-economic analyses of the regions. At the same time as establishing a correlation between regions in terms of size, NUTS also provides several analytical levels. The 1961 Brussels Conference on Regional Economies, organised by the Commission, found that NUTS 2 (basic regions) was the framework generally used by Member States to apply their regional policies and is therefore the appropriate level for analysing regional/national problems. For the purpose of appraising eligibility for aid from the Structural Funds,

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[5] In this sense, Krusell and Smith in their yet unpublished manuscript "A Global Economy-Climate Model with High Regional Resolution" are about to propose such a mechanism by adapting the Aiyagari model to an IAM context

regions whose development is lagging behind (regions covered by the Convergence Objective) have been classified at the NUTS 2 level. The areas eligible under the other priority Objectives have mainly been classified at the NUTS 3 level.

As mentioned in the introduction we have headed to the study of the five largest economies in the EU for various reasons. Especifically, these countries present the variability both in terms of economic and weather patterns that make them suitable for a detailed econometric analysis. The heterogeneity in economic figures and weather variables (temperatures and precipitations) can be easily spotted looking at the various cloropeth maps displayed in the appendix. Accordingly, we have decided to set the NUTS 2 level as the reference for comparison except for one case, the spanish. If we look at Table (3), it can be observed that the overlapping between the Spanish NUTS 3 and the different NUTS 2 for the rest of countries both in terms of area and average population is more than palpable. Moreover, this feature is corroborated also in their weather pattern, which is again very heterogenous, as it could be seen in Figure (8) or Figure 10. Additionally, the relativelly reduced number of Spanish NUTS 3 (51 regions) make them fairly manageable. It is worth mentioning that, for the case of France, it could also have been advisable to resort to the study of NUTS 3. Unfortunately, such breakdown in the conomic figures is not elaborated by the French statistical office.

As of the economic variables, all of them are collected from their homeland national statistical offices. Their time span, fully described at Table 4, varies depending on the availability, ranging from an early start for the Spanish varibales dated back at 1980 to a more recent of the Italian at year 1995. Note also that British economic data come originally expressed in Sterling pounds. Hence, some conversion to constant Euros using historical exchange rates has been necessary. As of weather variables, all of them have been provided also by the official weather organisms of each country (see more details at Table 4).

Several features differ our study from that of Dell et al. (2009) in terms of data. Firstly, they base their cross-section study on countries based on the western hemisphere whereas all our sample is located in the eastern hemisphere, which makes this one, as fars as we know, the first attempt to a major study relating weather and economic varibles carried out for the eastern hemisphere.

Another relevant feature of our meteorological data is that all figures correspond to real observed values collected directly from weather stations located within the NUTS of reference. In this respect, we have tried to match each NUTS with a weather station located in a geographic node where most of the economic activity is agglomerated[6]. Meanwhile, DJO make use of gridded weather data, which is the result of interpolated real weather data. In particular, they use the Matsuura and Willmott (2007) gridded dataset, which has a resolution of $1^{\text{o}} \times 1^{\text{o}}$, that is, $111km \times 111km$. The use of gridded data

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[6] Tipycally, this node corresponds to the capital or main city of the specific NUTS.

in weather analysis arise some potential pitfalls, see for instance Aufhammer et al. (2013), including the creation of a ficticious correlation between weather measures that could bias our conclusions. With our dataset, this issue is resolved by construction.

3 Cross-sectional evidence at the regional level

The theoretical background in which this section is embodied is the Ricardian (or *hedonic*) method applied to climatic variables that stems from the original work by Mendelsohn et al. (1994). These authors were the first to apply this methodology to measure the impacts of climate change in economic outturn. It does not rely on complex crop-yield models, but rather is a cross-sectional technique that estimates the empirical relationship between value and climate. Let us assume that the net present value of a unit of business, say, a company or a farm is determined in the following way

$$V_i = \int \left[\sum P_j Q_{ij}(X_{ik}, Z_i) - \sum M_k X_{ik} \right] e^{-\varphi t} dt \tag{1}$$

where P_j are the market prices of each output produced by company/sector i, Q_{ij} are the quantities of each output produced at firm i, X_{ik} is a vector of purchased inputs, M_k is a vector of input prices, Z_i is a vector of exogenous variables and φ is the interest rate.

The firm chooses the outputs Q_{ij} and inputs X_{ik} that maximise net revenues. By solving (1) to maximise net revenues and by folding the vector of prices of outputs and inputs P_j, M_k into the vector of exogenous variables Z_i,V_i can be expressed as a function of only exogenous variables

$$V_i = f(Z_i) \tag{2}$$

The cross sectional Ricardian regressions estimate equation (2). In our case, net present values are proxied by gross value added per year. Further examples of this methodology for Europe are mainly focused on agricultural output. See, for example, van Passel et al. (2012) for an analysis of EU-15 countries at the farm level, Lippert et al. (2009) for Germany or Kurukulasuriya and Mendelsohn (2008) for a sample of African countries.

3.1 Empirical framework

In order to examine the weather-income relationship at the regional level, we make use of the Ricardian regression analysis in a multi-region level[7]. In a similiar fashion to Dell et al. (2009) and, following the spirit of the above technical background, we estimate the cross-sectional relationship between geographic variables, climate variables—mean temperature, mean precipitaion levels and mean sun hours—and per capita income, i.e.,

$$LOGY_r = \alpha_r + \beta_1 TEMP_r + \beta_2 PRECIP_r + X_r^{'}\gamma + \varepsilon_r \tag{3}$$

where X represents a vector of specific geographic variables, such as elevation and distance to the sea. We estimate (3) for the whole sample of NUTS regions using OLS. Standard errors are calculated clustering observations by larger NUTS level.

3.2 Results

The results from estimating (3) are presented in Table 5. As a benchmark, we begin in column 1 of Table 5 with a basic raw regression of income on temperature for the whole sample of regions. We observe a negative, significant effect of temperature on per capita GDP, namely, an increase of $1^{\circ}\mathrm{C}$ would represent *cæteris paribus* a decrease of 2.2 percentage points of per capita GDP. In accordance with DJO, we find a negative response of the economic activity following a raise in temperatures, but much more modest than that estimated by these authors (8.5%), which can be partly attributed to the fact that we are focusing on a sample of well-developed countries that could possibly accomodate an increase in temperatures better than less developed regions. In fact, this figures are pretty much in accordance with those obtained by Deryugina and Hsiang (2014), who estimate a decline in productivity of 1.7% following an increase of $1^{\circ}\mathrm{C}$ for the United States. In column 2, we simply replicate the first regression but, this time, robust standard errros are obtained. To do so, we cluster observations via the immediate upper-level NUTS. As we observe, standard errors increasemarginally. Robust standard erros will be calculated thoroughout the rest of specifications.

In column 3, we add some geographic variables we reckon it is important to control for, namely, distance to the seaside and average elevation. They result to be both significant but quantitatively

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[7] It may well be the case that the reader could pose objections to the use of this methodology for a small subset of countries but asBryan and Jenkins (2013) point out: "The only estimates that are unaffected by the small number of countries are the fixed parameters on individual-level predictors (the number of individuals per country is typically large): provided there is not also a random component attached to the slope, these parameters are estimated without bias and with the correct standard errors (and non-coverage rate)".

of a very scarce importance [8].The point estimate for the effect of temperature remains quite stable, taht is, negative and of the same order of magnitude. In column 4, precipitations are incorporated into the regression. Its associated point estimate is slightly positive albeit not significant —pretty in accordance with what other studies report— whereas the rest of estimates remain qualitatively the same.

Columns 5 and 6 examine the relationship between weather conditions and income within countries. In column 5, we include country fixed effects. The point estimate of temperature preserves its sign and magnitude, that is, an increase in $1^{\circ}\mathrm{C}$ results in a decrease of around 3.1% of pc GDP. These results confirm that the the sign of the cross-sectional relationship between temperature and income holds within countries, as well as across countries. The reader should note that these compact bunch of variables already explain a remarkable 60% of the variation of pc GDP in the sample.

In their paper on the relation between economic growth and weather conditions (Dell et al. (2012)), the authors claim that poor countries are more prone to suffering the consequences of an increase of temperatures. Our last regression (column 6) represents an attempt to test for the validity of the previous afirmation. In this case, in line with their findings we find a qualitatively similar result but applied to our sample. We find that *poor regions*[9] are relatively more affected by an increase of temperatures in income terms. Actually, the effect is highly significant, observing a decrease of 3.8% of their pc GDP when $1^{\circ}\mathrm{C}$ is to be observed. The corresponding figure for rich regions remains significant, though, but halves with respect to the previous specification, indicating that are poor regions who drive most of the effect. We interpret this as a structural weakness of poor regions to coping with increases in temperatures. Interestingly, this feature of poor regions in the sample occurs inside a group of countries that, overall, are highly developed. At this point, I would like to draw the attention of the reader on how different the conclusions can be whether you are analysing a group of regions encapsulated in a country framework or you take them separatedly. Indeed, we find regions that are more prone to suffer from the global warming although they belong to well established economies. Not only are poor countries the weakest link in the climate change process, but also poor regions within rich countries can suffer the consequences of global warming. As it can be infered from the results, the effect of temperatures on poor regions is three times larger than that observed in relatively more developed regions. On a broader temporal perspective and considering the benchmark scenario projected by the *IPCC* for year 2100[10], would represent a decrease of additional 6% attributed to the sole effect of weather conditions.

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[8] Detailed results regarding these variables may be supplied upon request to the author

[9] We define *poor regions* as the ones that are below the median pc GDP of the whole sample

[10] This organism forecasts, under the scenario of a total cut-off of Greenhouse Gases, an increase of the world air temperature of $2^{\circ}\mathrm{C}$

3.3 Robustness and channels

In an attempt to gently check for the validity of the results obtained in the previous paragraphs, many exercises have been carried out. In particular, we have modified the reference year in a window of 5 years above and below the reference year (2000) and the same qualitative and quantitave results were obtained[11]. Another aspect that could be of interest is to gauge which branch of activity is harmed the most by weather conditions. With the purpose of checking this statement, we proceed with the breakdown of *pc GDP* in branches of activity, namely, agriculture, industry and services and regress each of them on our control variables. The results are presented in Tables 6 through 8.

Surprisingly (or not) a positive and quite significant response to an increase in temperatures is observed when looking at agricultural output. In particular, an increase of $1^{\circ}\mathrm{C}$ represents an average increase in agricultural activty ranging from 9% to 13% depending on the specification. Other authors find a similar result. For instance,Deschênes and Greenstone (2007) find a positve response of warming to the productivity level of certain crops in the United Sates. Note that the effect is reasonably stable across regions, regardless their level of income. As one could easily expect, temperatures explain solely more than 8% of the variation of agricultural activity across regions. Again, the effect of precipitations is limited but eminently positive. The negative effects of temperature in activity accrued in *pc GDP* are esentially due to industry and services according to our results. This can cearly be seen in Tables7 and 8. It can also be noted in both tables that the negativity is exacerbated in poor regions, which is the main feature that we have obtained in our benchamark regression.

4 The effects of weather fluctuation in the economic activity

In this section, we are going to make use of the longitudinal dimension of our dataset in order to try comprehend the dynamic effects of weather variation in economic activity. Our main identification strategy uses year-to-year fluctuations in temperature and precipitation to identify changes in economic performance. We can then use panel data econometric techniques to inform whether temperature impacts regional groeth rates or simply the level of income.

Although our time span is not as large as the one used by Dell et al. (2012), we still fufill the minimum requirement of having at least $T \geq 20$ for all the 169 regions observed, which is a kind-of self-imposed pre-requisite to accept the validity of the results. Looking at Table 9, we can document the extent of temperature and precipitation fluctuations within countries. It can be easily seen that precipitations are quite more volatile (almost double) than temperatures and that, along our sample,

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[11] These results can be obtained from the author upon request

it can hardly be seen a deviation of more than $1°\mathrm{C}$ of average values once we control for year or reginal effects. This feature of the data can also be spotted quite straight forward in Figures 12 and 13, respectively.

4.1 Empirical framework

The suggested empirical framework follows the derivation in Bond et al. (2010). Let us consider the simple economy[12]

$$Y_{it} = e^{\beta T_{it}} A_{it} L_{it} \tag{4}$$

$$\Delta A_{it}/A_{it} = g_i + \gamma T_{it} \tag{5}$$

where Y is aggregate output, L measures population, A measures labour productivity, and T measures weather. Equation (4) captures the level effect of weather; e.g. the effect of current temperature on crop yields. Equation (5) captures the growth effect; e.g. the effect of temperature on features such as institutions that influence productivity growth.

Taking logs in (4) and differencing with respect to time,

$$\frac{d}{dt}(\log Y_{it}) = \frac{d}{dt}(\beta T_{it}) + \frac{d}{dt}(\log A_{it}) + \frac{d}{dt}(\log L_{it}) \Rightarrow$$

$$g_{it} = \beta(T_{it} - T_{it-1}) + g_i + \gamma T_{it} \Rightarrow$$

$$g_{it} = g_i + (\beta + \gamma)T_{it} - \beta T_{it-1} \tag{6}$$

we have the dynamic growth equation, where g_{it} is the growth rate of per capita output. The level effects of weather shocks on output, which come from equation (4), appear through β.The growth effects of weather shocks, which come from equation (5), appear through γ.

The growth equation in (6) allows separate identification of level effects and growth effects throught the examination of transitoury weather shocks. In particular, both effects influence the growth rate in the initial period of the shock. The difference is that the level effect eventually reverses itself as the weather returns to its prior state. By contrast, the growth effect appears during the

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[12] this reasoning can be extended to more general dynamic panel models that incorporate richer lag structures and lagged dependent variables

weather shock and is not reversed. The growth effect is identified in (6) as the summation of the temperature effects over time. This reasoning extend to models where temperature effects play out more slowly. This would be the standard distributed-lag approach

$$\Delta y_{it} = g_i + \alpha_1 \Delta y_{it-1} + \ldots + \alpha_p \Delta y_{it-p} + \sum_{j=0}^{p+1} \rho_j T_{it-j} + \Delta\varepsilon_{it} \tag{7}$$

To estimate the above effects, panel regressions of the form

$$g_{it} = \theta_i + \theta_{rt} + \sum_{j=0}^{L} \rho_j T_{it-j} + \varepsilon_{it} \tag{8}$$

are run, where θ_i are region fixed effects, θ_{rt} are (regional) time fixed effects, ε_{it} is an error term clustered simulatenously by region and region-year (following the two-way clustering of Cameron et al., 2011), and T_{it} is a vector of annual average temperature and precipitation with up to L lags included.

We begin by estimating (8) with no lags, focusing on the null hypothesis that temperature does not affect growth

$$H_0(L = 0) : \rho_0 = 0$$

A failure to reject this hypothesis would indicate an absence of both level and growth effects. In subsequent regressions with lags, following the conventions in the distributed-lag literature, we separately test the immediate effect of temperature

$$H_0^1(L > 0) : \rho_0 = 0$$

and the cumulated effect of temperature:

$$H_0^2(L > 0) : \sum_{j=0}^{L} \rho_j = 0$$

The summation of the lag coefficients corresponds to the parameter γ, the growth effect.

4.2 Results

In the previous section we have identified that poor regions within Eurpoe are more prone to suffer the harmful consequences of an overall increase in average temperatures with a subtle but significant response of around 3 precentage points per additional degree. We have also documented that the channels through which this pernicious effects are manifested are the industrial and services branches, not the agricultural, whch would benefit from a warmer atmosphere. Once said that, one would like to look at the ability of weather conditions to alter the year-to-year economic performance of regions, that is, their ability to grow.

Column 1 of Table 10 shows a positive and statistically significant relationship between temperature fluctuations and growth on average across all regions. Note, though, that this is a very simplistic regression in which we relate growth with temperaures and nothing else. Note also that the goodness of the fit is fairly low. In column 2, once when we account for country fixed effects, the estimate attached to temperatures already recovers a sign familiar to us from the previous section. In particular, an increase of average temperatures of 1 degree today hampers the growth potential of regions almost by 0.06 pp, which turns out to be of a modest nature but, once accumulated, yields remarkable figures[13].

Next, in column 3, we interact temperature with a dummy for a country being "poor", defined as having below-median per-capita GDP in a year of reference[14]. The coefficient on the interaction between the "poor" dummy and temperature is negative and statistically significant, indicating substantial heterogeneity between poor and rich regions. As shown in the last row of the table (which reports the sum of the main effect of temperature and its interaction with the poor dummy), the net effect of a $1^{\circ}\mathrm{C}$ rise in temperature is to decrease growth rates in poor regions by 0.086 percentage points. Put another way, since the standard deviation of annual temperature once country fixed effects, region × year, and poor country × year fixed effects are removed is 0.70 degrees (see Table 9 for more detail), the estimates in Table 10 imply that a one standard deviation increase in annual temperature is associated with a reduction in growth of about 0.059 percentage points. Ours and the results from Colacito et al. (2014) are the first to document a negative and statistically significant relationship between rising temperatures and economic growth in a developed economy.

Lastly, in column 4, we incorportate precipitations to our specification. We decide to include it only in the last specification as this variable proved to be ambiguous in the previous section. No matter what, it is always advisable to control for it in order to cross-check the results obtained in the previous column. As it can be observed, the point estimates remain very stable, both qualitatively and quantitatively. We have to remark now that the point estimate of temperatures for rich regions is now not statistically significant, in other words, not distinct from zero which confirms the findigns

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[13] For instance, the level effect of this result is of almost 2% in 25 years time, nearly 4% in 50 years time and of 7.5% in 100 years. Under the *IPCC*'s scenario of an average increase of temperatures of $2^{\circ}\mathrm{C}$, that would cost to European regions two-digit figures (more than 11% assuming a further increase in temperatures in 50 years) in terms of per capita income

[14] 1995 in our case. Similar results obtained when this is altered

obtained in the cross-section dimension (see Table 5), and those of Dell et al. (2012), that is, in rich regions (countries) typically a positive but rarely statistically significant temperature effects is found.

4.3 Robustness and channels

A set of robustness exercises may be carried out[15]. Firstly, we can modify quite easily the panel specification and the lags of the variables involved. We can also investigate alternative formulations of the temperature and precipitation variables. For instance, we can consider using logs rather than levels of annual average temperature and precipitation. The large and persistent effects of temperature shocks on aggregate output in poor regions suggest further investigation. Thus, regarding the channels through which the effect of temperature on poor regions is manifested, we can resort ourselves to the study of the different branches of activity in which pc GDP is split in a manner similar to that used in Section 3.

In order to disentangle the channels through which the negative short-term effect of weather fluctuations in the economy we repeat the above exercise substituting the dependent variable by its branches' equivalent, namely, agriculture, indistry and services. Those results are presented in Tables 11 through 13. We identify a very negative, contundent impact of increasing temperature in agricultural value added of almost 0.23 percentage points less growth per additional degree in poor regions. Again the effect is exacerbated in poor regions as opposed to rich regions,in which the decay in growth represents an equivalent of nearly 0.14pp. Studying the industry output, we cannot identufy any discernable effect of weather variables in activity. Up to some extent, this sector represent *ex ante* a branch one may think to be less affected by environmental conditions. Thus, the results seem to be logical. On the other hand, we find a positive significant impact of temperature on services only in poor regions. This result could be attached to the plausible benefitial effects of some warming to the tourism industry. In any respect, our conclusions do not differ much from that obtained by Dell et al. (2012).

We also try to check the robustness of the results by including lags of the regressors to the benchmark specification. Accordingly, we consider more flexible models with up to 5 lags of temperature and precipitations. Table 14 presents the results from estimating (7) with no lags, 1 lag, 3 lags and 5 lags. All temperature and precipitations are interacted with poor region dummies. We also report the cumulative effect of temperature for poor regions. As it can be observed, the effect remains stable and statistically significant across specifications at around -0.07-0.09pp. However, from 3 lags

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[15] Note that these analyses are reduced-form, and therefore do not identify the possibly complex structural relationships between temperature, growth, and other outcomes.

onwards the cumulative effect dilutes, which can be plausibly attributed to the still scarce longitudinal dimension of our dataset. Surely, a cross-check of this excercise should be attempted once we are in possession of a more balanced, extense dataset.

5 A way to reconcile short- and long-term effects: Adaptation and convergence

All in all, we have found a permanent effect of temperatures in the level of GDP of about 3% in poor regions whereas the short-term effect of temperatures on growth represent a -0.08% which if accumjlated to a longer horizon implies a slightly higher total effect of temperatures on income. To reconcile the long-run cross-sectional relationships documented in Section 3 with the short-run growth effects of temperature estimated in Section 4, we consider two mechanisms: convergence and adaptation. First, convergence forces may pull lagging countries and regions toward the frontier. Convergence effects offset temperature effects, so that convergence limits the cross-sectional income differences that can be sustained. If rates of convergence are larger within regions than across them, then the long-run effect of climate will be more muted within regions than across them.

Second, over longer periods, regions may adapt to their climate. The panel growth estimates reflect responses to climate shocks. To the extent that individuals adjust their behavior to permanent temperature changes, e.g., by switching to more appropriate crops, industries, and technologies and by migrating away from difficult environments altogether, the short-run estimates may be larger than the longer-run response.

Imagine that growth in per capita income proceeds as

$$\frac{d\log y_i(t)}{dt} = g + \gamma(T_i(t) - \bar{T_i}) + (\gamma + \rho)\bar{T_i} + \varphi(\log y_*(t) - \log y_i(t)) \; for \, t \geq 0, \tag{9}$$

where $\log y_i(t)$ is the log per capita income in geographic area i, $T_i(t)$ is the temperature in area i at time t, $\bar{T_i}$ is the average temperature level in area i, and $\log y_*(t)$ is the relevant frointier level of income to which the area converges. The parameter γ captures the causative short-run effect of temperature shocks on growth, as would beidentified in a panel specification such as (7). The parameter ρ captures the degree of adaptation over the long-run to average temperature levels, potentiallt offsetting the short-run temperature effects. the parameter $\varphi \in (0, 1)$ captures the rate of convergence. We further assume that all countries start, at time zero, with the same level of per capita income, $\log y_i(0) = c$ for all i. Note that since equation (9) applies to all regions, including region *, $\mathbb{E}[\log y_*(t)] = c + (g + (\gamma + \rho)\bar{T}_*)t$.

Integrating the differential equation (9) with the initial condition and taking expectations, we have

$$\mathbb{E}[\log y_i(t)] = \mathbb{E}[\log y_*(t)] + \frac{\gamma + \rho}{\varphi}(\bar{T}_i - \bar{T}_*)(1 - e^{\varphi t}) \tag{10}$$

Therefore, in the long run, as $t \to \infty$, the cross-sectional relationship between income and temperature is

$$\frac{d\,\mathbb{E}[log y_i]}{d\bar{T}_i} = \frac{\gamma + \rho}{\varphi} \tag{11}$$

Equation (11) is an inequality with four unknowns, and we already have estimates for three of them. The left-hand side of (11) is the cross-sectional regression parameter in the regression of income on temperature, i.e.,$\beta = -0.022$ (see Table 5). As discussed above, the short-run growth coefficient is approximately $\gamma = -0.0058$.

5.1 Convergence

We first consider turning off the adaptation channel (setting $\rho = 0$ in (11)) to examine the implications of convergence alone. In this setting, reconciling the short-run and long-run temperature effects is achieved when $\varphi = \frac{\gamma}{\beta}$. At a within-country level, then we require $\varphi = \frac{-0.0058}{-0.022} = 0.2636$. This estimate appears extremely high.[16] These calculations suggest that adaptation is likely to be important in reconciling the data.

5.2 Adaptation

Over the long run, areas may adapt to difficult geographic conditions. Technologies, skills and physical capital can all be tailored to a given climatic regime. Moreover, population can react altering the local per capita intensity of the factors of production.

We now relax the strong assumption of no adaptation ($\rho = 0$), and instead estimate ρ using our own findings for β and γ, and a chosen convergence rate, φ. Rearranging (11) shows that $\rho = \beta\varphi - \gamma$. In the within-country context, taking an upper-bound cross-country convergence estimate $\varphi = 0.05$, we find $\rho = 0.0047$ so that 81 percent of the short-run growth effect is offset in the long-run, so that the long-run growth rate effect of being 1 degree warmer is -0.0011, i.e., 0.1 p.p. per annum. Note,

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[16] For example, in developed countries (United States, Japan, Europe) Barro and Sala-i-Martin estimate within-country convergence coefficients of approximately 0.02–0.03.

however, that this value depends critically on the chosen convergence rate that we choose. Thus, we have to adopt these values with caution.

6 Conclusion

DJO have successfully documented a negative relation of temperatures on income for poor countries working with a cross-country sample of sub-national data of 12 countries in the Americas in which relatively less developed countries were sampled. In particular they find national income falling 8.5% per degree Celsius. On a separate exercise, the same authors study a panel formed by more than 150 countries around the world by looking at the dynamics of the relation of temperatures and income along the period 1950-2003 finding a negative, significant effect of temperatures in economic growth only for poor countries of around -1.1% per additional degree. Two straight forward messages derive from those results: first, the increase in temperatures that we are witnessing due to global warming will be benevolent with rich countries/regions. Second, for the sake of comparison and consistency, it would be advisable to reproduce both exercises for the same set of countries/regions. In light of the above, we have attempted to gently respond to the first statement and overcome the drawbacks of the second.

To do so, we have constructed and on-purpose dataset covering income variables and meteorological variables at the NUTS level for the main European countries. This dataset present some features that are worth mentioning: first, all weather data correspond to real observed weather stations matched with the NUTS unit of reference. In this way, we avoid the use of gridded weather data, which could result in biased interpretation of the results as pointed out in the text. Second, and equally important, the fact of resorting to the NUTS level present unvaluable advantages, since this is the level at which regional policies, like environmental, are formulated.

In the cross-section analysis, we find qualitatively similar results to DJO. Specifically, we distinguish a negative, significant but tempered effect of temperatures on income within our sample. More precisely, an additional degree is attached to a decrease of 1.6-2.2% of personal income. This negative effect is amplified for poor regions within the sample. Other authors, like Deryugina and Hsiang (2014) find similar results for the United States. These findings pose into series threat the afirmation that wealthy countries easily decouple their economy from the environmnent based on the use of resources to adapt to a changing environment.

In general, and in accordance with DJO, the effect of precipitations is difuse but eminently positive, altough not significant. Other geographic variables, such as elevation and distance to the sea happen to be quite significant but of a residual importance. Besides, it is through industry and services that the negative effect of temperature on income is manifested. What trascends the results in this section is that, unlike DJO claim, well-developed countries would probably be harmed if temperatures are to increase. This poses further risks to weatlhy regions when facing climate change.

If we treat our dataset entirely as a panel, we now have the chance to exploit the stochastic variation in weather variables and try to estimate their effect on the short-term dynamics of income. This is covered in Section 4. Overall, we find that an increase of average temperatures of 1 degree today hampers the growth potential of regions almost by 0.06 pp, which in accumulated terms represents an overall effect in the long-run slightly larger than the one estimated in the previous section. As of poor regions, the net effect of a $1^{\circ}\mathrm{C}$ rise in temperature is to decrease growth rates in poor regions by 0.084 percentage points, where again poor regions are a bit more penalised than rich regions. Our results together with those of Colacito et al. (2014) are the first to document a negative, significant relationship between rising temperatures and economic growth in the context of developed economies. Once again, we find no relevant statistical evidence about the effect of precipitations in the short-term economic performance of regions. These findings go in parallel with the general findings of some other authors in the literature. Surprisingly, and opposed to the previous section, we find a robust, negative effect of temperatures and precipitations in the agricultural output, as if it was measuring the adverse effects of sudden and abrupt deviations of average weather values, namely, floods, droughts or frost damages, on the performance of crops.

In Section 5 we develop a very stylised framework to reconcile the differences existing between the estimates obtained for the short-run and the long-run. We build on a basic growth model devised by Bond et al. (2010) and decompose the gap between the level and growth impact of weather into a convergence and adaptation behaviour. We discard the dominance of a convergence period and opt for the existence of an adaptation behaviour of region to changing weather conditions, via reassignation of crops, mobility, switch of industries and technologies,... The figures obtained range in an interval of 10% to 60% of the short-term variation absorved or adapated in the long run. Note, however, that this results depend crucially on the *ad hoc* election of some convergence rates. Surely, more work in this are has to be done and there is scope for further dedicated research.

Nowadays, adaptation plays a vital role in the climate change literature and is one of the main concerns of institutions, like the *IPCC*, that fight against climate change. Currently, very few serious studies have benn carried out avbout this issue. Without a doubt, this is a topic that it is worth deepening into and deserves some further analytical and numerical research. Some of my future projects will be headed to try address this important feature of the implications of climate change.

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A Data description and descriptive statistics

Table 3: NUTS description

NUTS 0	NUTS 1	NUTS 2	NUTS 3
FRANCE			
	ÎLE DE FRANCE		
		Île de France	
	BASSIN PARISIEN		
		Champagne-Ardenne	
		Picardie	
		Haute-Normandie	
		Centre	
		Basse-Normandie	
		Bourgogne	
	NORD - PAS-DE-CALAIS		
		Nord - Pas-de-Calais	
	EST		
		Lorraine	
		Alsace	
		Franche-Comté	
	OUEST		
		Pays de la Loire	
		Bretagne	
		Poitou-Charentes	
	SUD-OUEST		
		Aquitaine	
		Midi-Pyrénées	
		Limousin	
	CENTRE-EST		
		Rhône-Alpes	
		Auvergne	
	MÉDITERRANÉE		
		Languedoc-Roussillon	

Table 3: NUTS description

		Provence-Alpes-Côte d'Azur
		Corse
DEUTSCHLAND		
	BADEN-WÜRTTEMBERG	
		Stuttgart
		Karlsruhe
		Freiburg
		Tübingen
	BAYERN	
		Oberbayern
		Niederbayern
		Oberpfalz
		Oberfranken
		Mittelfranken
		Unterfranken
		Schwaben
	BERLIN	
		Berlin
	BRANDENBURG	
		Brandenburg
	BREMEN	
		Bremen
	HAMBURG	
		Hamburg
	HESSEN	
		Darmstadt
		Gießen
		Kassel
	MECKLENBURG-VORPOMMERN	
		Mecklenburg-Vorpommern
	NIEDERSACHSEN	
		Braunschweig

Table 3: NUTS description

		Hannover
		Lüneburg
		Weser-Ems
	NORDRHEIN-WESTFALEN	
		Düsseldorf
		Köln
		Münster
		Detmold
		Arnsberg
	RHEINLAND-PFALZ	
		Koblenz
		Trier
		Rheinhessen-Pfalz
	SAARLAND	
		Saarland
	SACHSEN	
		Dresden
		Chemnitz
		Leipzig
	SACHSEN-ANHALT	
		Sachsen-Anhalt
	SCHLESWIG-HOLSTEIN	
		Schleswig-Holstein
	THÜRINGEN	
		Thüringen
ITALIA		
	NORD-OVEST	
		Piemonte
		Valle d'Aosta/Vallée d'Aoste
		Liguria
		Lombardia
	SUD	

Table 3: NUTS description

		Abruzzo	
		Molise	
		Campania	
		Puglia	
		Basilicata	
		Calabria	
	ISOLE		
		Sicilia	
		Sardegna	
	NORD-EST		
		Provincia Autonoma di Bolzano/Bozen	
		Provincia Autonoma di Trento	
		Veneto	
		Friuli-Venezia Giulia	
		Emilia-Romagna	
	CENTRO (IT)		
		Toscana	
		Umbria	
		Marche	
		Lazio	
ESPAÑA			
	NOROESTE		
		Galicia	
			A Coruña
			Lugo
			Ourense
			Pontevedra
		Principado de Asturias	
			Asturias
		Cantabria	
			Cantabria

Table 3: NUTS description

NORESTE		
	País Vasco	
		Araba/Álava
		Gipuzkoa
		Bizkaia
	Comunidad Foral de Navarra	
		Navarra
	La Rioja	
		La Rioja
	Aragón	
		Huesca
		Teruel
		Zaragoza
COMUNIDAD DE MADRID		
	Comunidad de Madrid	
		Madrid
CENTRO (ES)		
	Castilla y León	
		Ávila
		Burgos
		León
		Palencia
		Salamanca
		Segovia
		Soria
		Valladolid
		Zamora
	Castilla-La Mancha	
		Albacete
		Ciudad Real
		Cuenca
		Guadalajara

Table 3: NUTS description

		Toledo
	Extremadura	
		Badajoz
		Cáceres
ESTE		
	Cataluña	
		Barcelona
		Girona
		Lleida
		Tarragona
	Comunidad Valenciana	
		Alicante / Alacant
		Castellón / Castelló
		Valencia / València
	Illes Balears	
		Eivissa y Formentera
		Mallorca
		Menorca
SUR		
	Andalucía	
		Almería
		Cádiz
		Córdoba
		Granada
		Huelva
		Jaén
		Málaga
		Sevilla
	Región de Murcia	
		Murcia
	Ciudad Autónoma de Ceuta	
	Ciudad Autónoma de Melilla	

Table 3: NUTS description

	CANARIAS		
		Canarias	
			Palmas (Las)
			Sta. Cruz de Tenerife
UNITED KINGDOM			
	NORTH EAST (ENGLAND)		
		Tees Valley and Durham	
		Northumberland and Tyne and Wear	
	NORTH WEST (ENGLAND)		
		Cumbria	
		Greater Manchester	
		Lancashire	
		Cheshire	
		Merseyside	
	YORKSHIRE AND THE HUMBER		
		East Yorkshire and Northern Lincolnshire	
		North Yorkshire	
		South Yorkshire	
		West Yorkshire	
	EAST MIDLANDS (ENGLAND)		
		Derbyshire and Nottinghamshire	
		Leicestershire, Rutland and Northamptonshire	
		Lincolnshire	
	WEST MIDLANDS (ENGLAND)		
		Herefordshire, Worcestershire and Warwickshire	
		Shropshire and Staffordshire	
		West Midlands	
	EAST OF ENGLAND		

Table 3: NUTS description

	East Anglia
	Bedfordshire and Hertfordshire
	Essex
LONDON	
	Inner London
	Outer London
SOUTH EAST (ENGLAND)	
	Berkshire, Buckinghamshire and Oxfordshire
	Surrey, East and West Sussex
	Hampshire and Isle of Wight
	Kent
SOUTH WEST (ENGLAND)	
	Gloucestershire, Wiltshire and Bristol/Bath area
	Dorset and Somerset
	Cornwall and Isles of Scilly
	Devon
WALES	
	West Wales and The Valleys
	East Wales
SCOTLAND	
	Eastern Scotland
	South Western Scotland
	North Eastern Scotland
	Highlands and Islands
NORTHERN IRELAND	
	Northern Ireland

Table 1: Data Summary

country	NUTS				Income		Temperature		Precipitation		Sun hours	
	level	regions	avg. area	avg. population	mean	sd	mean	sd	mean	sd	mean	sd
full sample	2/3	171	11102	1751	45065	11905	13.147	3.69	7.454	3.67	19.176	6.00
France	2	22	24340	2455	55109	5771	12.755	1.54	8.653	1.94	18.399	4.30
Germany	2	39	9398	2165	49808	7879	10.453	0.65	7.220	1.69	15.714	1.46
Italy	2	22	14352	2829	48793	5209	18.947	4.29	6.360	6.07	na	na
Spain	3	51	8576	761	35234	3388	15.286	2.76	5.588	3.91	26.352	4.55
United Kingdom	2	37	6574	1648	45629	17785	10.290	0.94	10.122	1.97	14.363	1.11

Notes: Data describing NUTS regions come from the NUTS 2010 classification (see NUTS on Eurostat). The average area is expressed in square kilometres. Average population population is in thousands. All the remaining figures date from the year 2000. Total personal income is in constant euros. Temperatures are conveyed in $^\circ\mathrm{C}$, precipitations in 100mm/year and sun hours in 100h/year.

Table 2: NUTS summary

country	NUTS 2			NUTS 3		
	area	population	regions	area	population	regions
France	24340	2455	22	6328	638	100
Germany	9398	2165	39	867	200	412
Italy	14352	2829	22	2740	541	110
Spain	26631	2362	18	8576	761	51
United Kingdom	6574	1648	37	1750	438	139

Notes: Area and Population at year 2007. Source: Eurostat.

Table 4: Data sources

country	economic variables	period	weather variables	period
France	INSEE	1990-2012	Meteo France	1949-2013
Germany	DESTATIS	1992-2013	DWD	1900-2014
Italy	ISTAT	1995-2012	METEOAM	1995-2013
Spain	INE	1980-2013	AEMET	1948-2014
United Kingdom	ONS	1995-2012	Met Office (UKCP09)	1981-2012

Notes: This table reflects the total availability of data. Note that not all data, especially the meteorological, intervene in this study.

B Theory: Adaptation and convergence

Consider the growth specification

$$\frac{d\log y_i(t)}{dt} = g + \rho\bar{T}_i + \gamma T_i(t) + \varphi(\log y_*(t) - \log y_i(t))\ for\, t \geq 0, \tag{12}$$

which is a rewritten version of equation (9) in the main text. Here we provide a formal derivation of equation (11), which is the integrated form of (12).

First, we observe from (12) that

$$\frac{d\log y_*(t)}{dt} = g + \rho\bar{T}_* + \gamma T_*(t)$$

Next, define a variable $\hat{y}(t) = \log y_i(t) - \log y_*(t)$, and rewrite (12) as

$$\frac{d\hat{y}(t)}{dt} = \frac{d(\log y_i(t) - \log y_*(t))}{dt} = \rho(\bar{T}_i - \bar{T}_*) + \gamma(T_i(\tau) - T_*(\tau)) + \varphi\hat{y}(t)$$

If we integrate the above expression once, we find

$$\hat{y}(t) = bt + \gamma \int_0^t h(\tau)\,\mathrm{d}\tau - \varphi \int_0^t \hat{y}(\tau)\,\mathrm{d}\tau$$

where $b = \rho(\bar{T}_i - \bar{T}_*)$ and $h(\tau) = T_i(\tau) - T_*(\tau)$ (which is stochastic). Since this is linear we can take expectations and change the order of integration, producing

$$\mathbb{E}[\hat{y}(t)] = bt + \gamma \int_0^t \mathbb{E}[h(\tau)]\,\mathrm{d}\tau - \varphi \int_0^t \mathbb{E}[\hat{y}(\tau)]\,\mathrm{d}\tau$$

Noting that $\mathbb{E}[h(\tau)] = \bar{T}_i - \bar{T}_*$, this integrated differential equation can be wrtitten as

$$\mathbb{E}[\hat{y}(t)] = mt - \varphi \int_0^t \mathbb{E}[\hat{y}(\tau)]\,\mathrm{d}\tau \tag{13}$$

where $m = (\gamma + \rho)(\bar{T}_i - \bar{T}_*)$. Equation(13) can be solved by repeated substitution of $\mathbb{E}[\hat{y}(t)]$. In particular, substituting once provides

$$\mathbb{E}[\hat{y}(t)] = mt - \varphi \int_0^t (m\tau - \varphi \int_0^\tau \mathbb{E}[y(\tau')]\,\mathrm{d}\tau')\,\mathrm{d}\tau =$$

$$mt - \varphi m \frac{t^2}{2} - \varphi^2 \int_0^t \int_0^\tau \mathbb{E}[y(\tau')]\,\mathrm{d}\tau'\,\mathrm{d}\tau$$

With an infinite set of substitutions and integrating all terms in m we have

$$\mathbb{E}[\hat{y}(t)] = m \sum_{j=0}^{\infty} (-1)^j \varphi^j \frac{t^{j+1}}{(j+1)!} + \lim_{n\to\infty} \varphi^n \int_0^t \int_0^\tau \int_0^{\tau'} \cdots \int_0^{\tau'\{n\}} \mathbb{E}[\hat{y}(\tau'^{\{n\}})]\,\mathrm{d}\tau'^{\{n\}} \ldots \mathrm{d}\tau'\,\mathrm{d}\tau$$

The second term on the right hand side limits to zero. This follows because (i) $\varphi < 1$, and (ii) $\mathbb{E}[\hat{y}(\tau'^{\{n\}})] < c$ where c is a positive definite constant. The limit is thus less than $\lim_{n\to\infty} \varphi^n \frac{c^n}{n!} = 0$. The integrated form can therefore be written

$$\mathbb{E}[\hat{y}(t)] = \frac{m}{\varphi} \sum_{j=1}^{\infty} (-1)^{j+1} \varphi^j \frac{t^j}{j!}$$

which is equivalently recognised as

$$\mathbb{E}[\hat{y}(t)] = \frac{m}{\varphi}(1 - e^{-\varphi t})$$

Recalling the definitions of $\hat{y}(t)$ and m, we have

$$\mathbb{E}[\log y_i(t) - \log y_*(t)] = \frac{\gamma + \rho}{\varphi}(\bar{T}_i - \bar{T}_*)(1 - e^{-\varphi t})$$

which is equation (11) in the text.

C Tables and Figures

Figure 1: Map of NUTS 1 regions

Figure 2: Map of NUTS 2 regions

Figure 3: Map of NUTS 3 regions

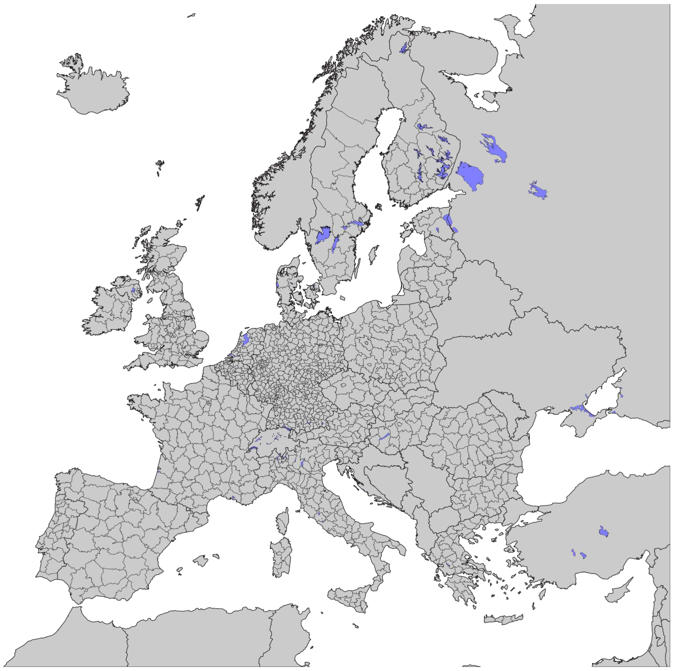

Figure 4: Average GDP per capita in NUTS 2 regions. Year 2000

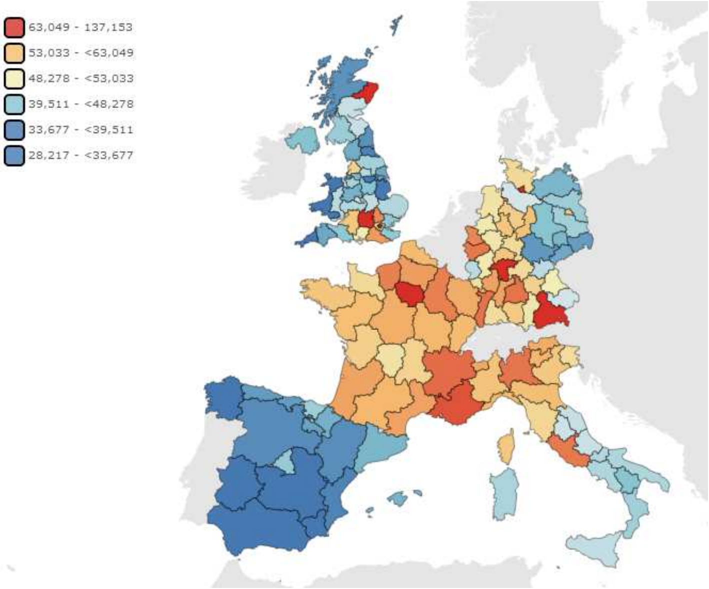

Figure 5: Average GDP per capita in Spanish NUTS 3 regions. Year 2000

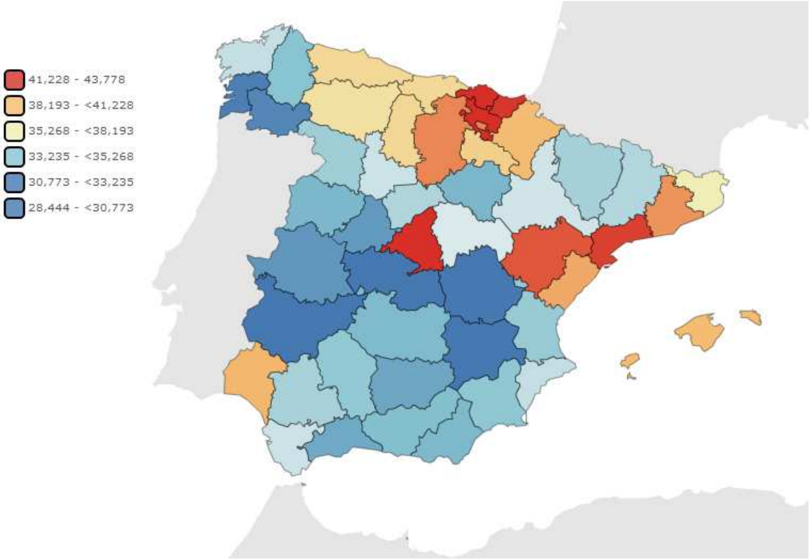

Figure 6: Average temperature in NUTS 0 regions. Year 2000

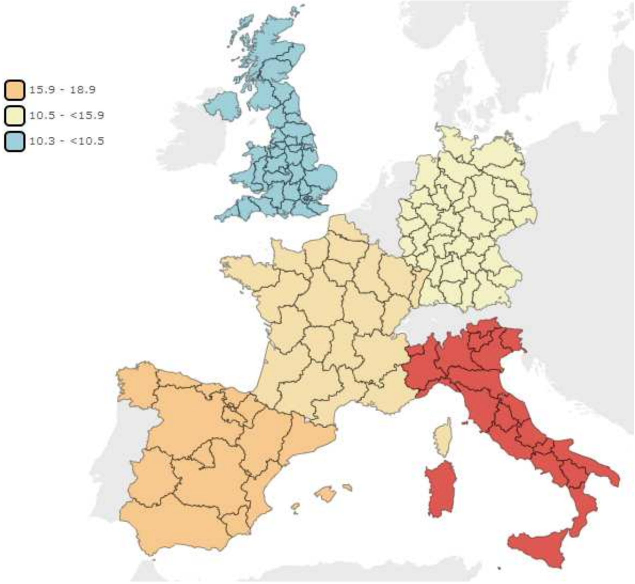

Figure 7: Average temperature in NUTS 2 regions. Year 2000

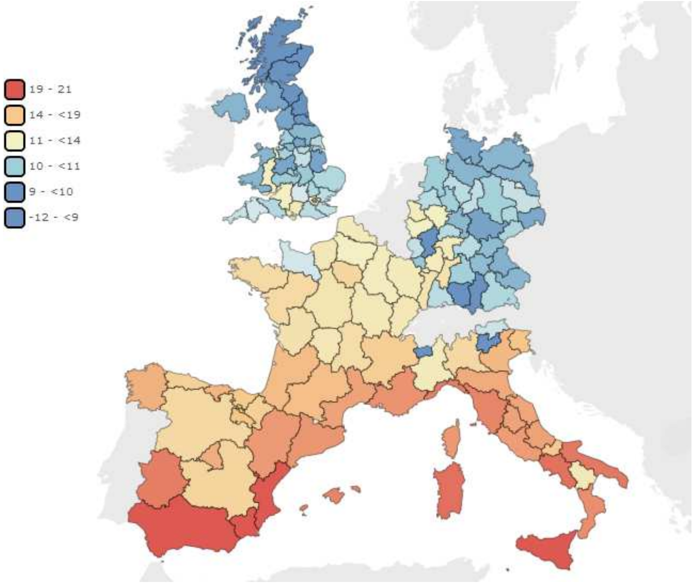

Figure 8: Average temperature in Spanish NUTS 3 regions. Year 2000

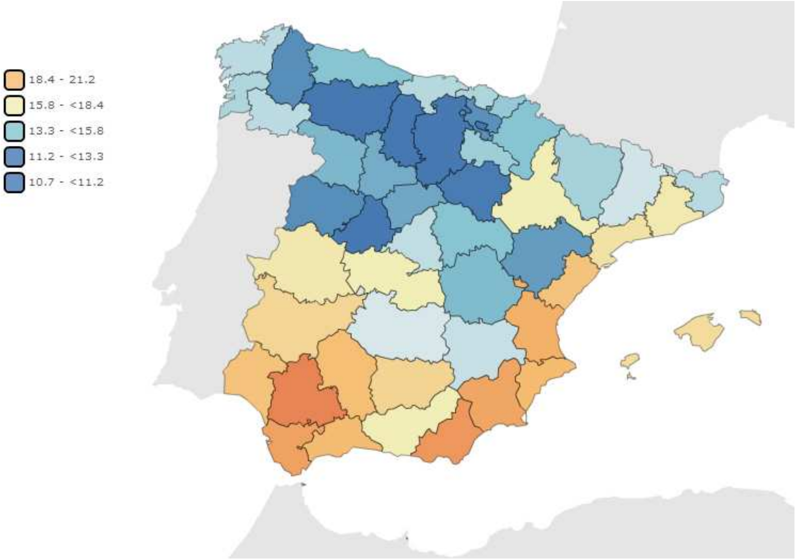

Figure 9: Average precipitations in NUTS 2 regions. Year 2000

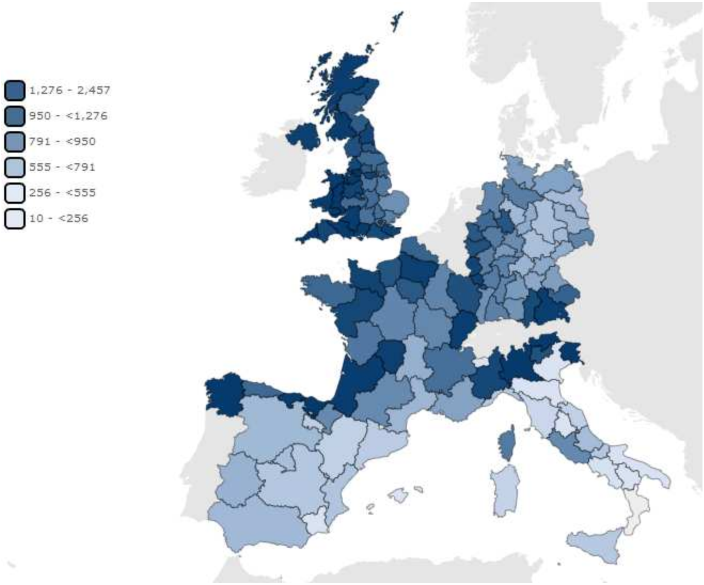

Figure 10: Average precipitations in Spanish NUTS 3 regions. Year 2000

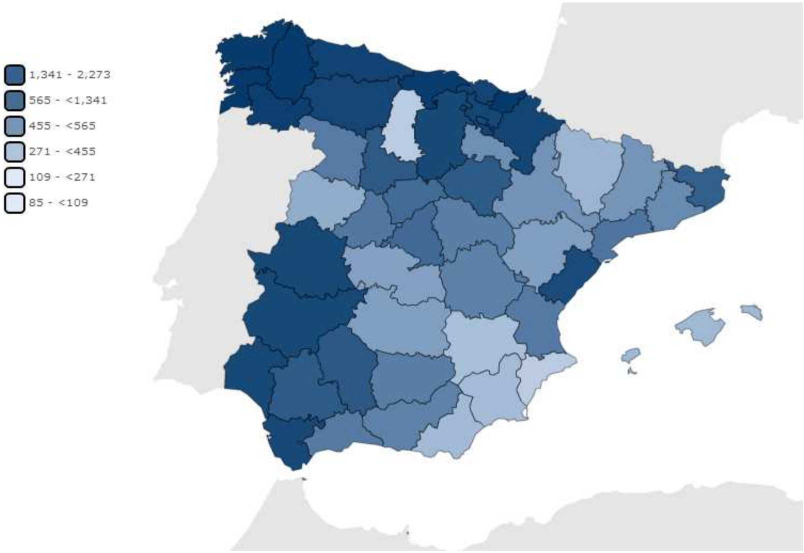

Figure 11: Average temperature variation in NUTS 2 regions. Decade 2000 against decade 1990

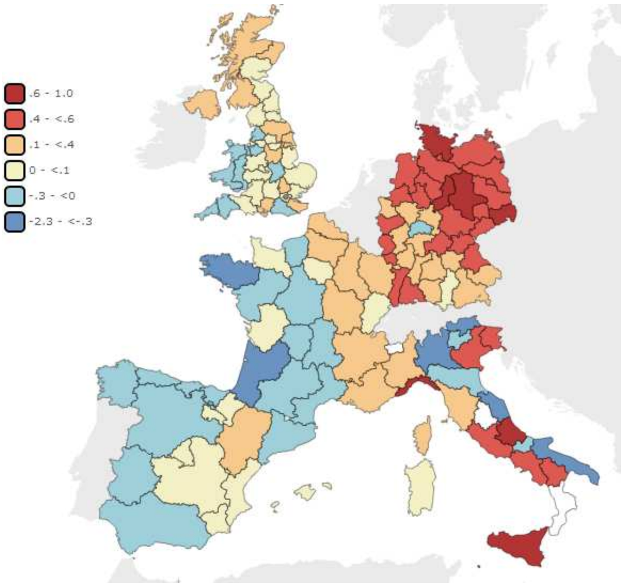

Table 5: Long-term Relationship. All Regions

	(1)	(2)	(3)	(4)	(5)	(6)
temperature	-0.022***	-0.022***	-0.023***	-0.021**	-0.031***	-0.016*
	(0.006)	(0.007)	(0.008)	(0.010)	(0.009)	(0.009)
temperature x poor regions						-0.022***
						(0.004)
precipitations				0.002	0.005	0.000
				(0.007)	(0.005)	(0.003)
Geographic variables	No	No	Yes	Yes	Yes	Yes
Country FE	No	No	No	No	Yes	Yes
Observations	168	168	168	168	168	168
Number of clusters	-	59	59	59	59	59
R-squared	0.085	0.085	0.196	0.197	0.599	0.712
Temp. effect on poor Nuts						-0.038***
						(0.010)

Notes: In all the regressions, the dependent variable is the logarithm of the regional *GDP per capita*. Under *Geographic variables* we find elevation and distance to coasy. The reference year is 2000. Column (1) depicts a simple OLS regression of the dependent variable on temperature. Column (2) replicates column (1) but calculates robust standard errors by Nuts 1 level (Nuts 2 for the case of Spain). Column (3) adds a set of georgraphic variables as controls. Column (4) incorporates precipitations. Columns (5) and (6) include country fixed effects. Column (6) incorporates the interaction effect of temperature in poor regions. * denotes significance at 10 pct., ** at 5 pct., and *** at 1 pct. level.

Table 6: Agriculture. Long-term Relationship. All Regions

	(1)	(2)	(3)	(4)	(5)	(6)
temperature	0.099***	0.099***	0.114***	0.126***	0.099	0.087
	(0.026)	(0.033)	(0.035)	(0.038)	(0.073)	(0.076)
temperature x poor regions						0.017
						(0.020)
precipitations				0.017	0.031	0.035
				(0.032)	(0.054)	(0.056)
Geographic variables	No	No	Yes	Yes	Yes	Yes
Country FE	No	No	No	No	Yes	Yes
Observations	168	168	168	168	168	168
Number of clusters	-	59	59	59	59	59
R-squared	0.079	0.079	0.096	0.099	0.435	0.438
Temp. effect on poor Nuts						0.075
						(0.168)

Notes: In all the regressions, the dependent variable is the logarithm of the regional *agricultural GDP per capita*. Under *Geographic variables* we find elevation and distance to coasy. The reference year is 2000. Column (1) depicts a simple OLS regression of the dependent variable on temperature. Column (2) replicates column (1) but calculates robust standard errors by Nuts 1 level (Nuts 2 for the case of Spain). Column (3) adds a set of georgraphic variables as controls. Column (4) incorporates precipitations. Columns (5) and (6) include country fixed effects. Column (6) incorporates the interaction effect of temperature in poor regions. * denotes significance at 10 pct., ** at 5 pct., and *** at 1 pct. level.

Table 7: Industry. Long-term Relationship. All Regions

	(1)	(2)	(3)	(4)	(5)	(6)
temperature	-0.127*** (0.033)	-0.127*** (0.048)	-0.124*** (0.045)	-0.111*** (0.055)	-0.127* (0.074)	-0.106 (0.074)
temperature x poor regions						-0.031* (0.017)
precipitations				0.020 (0.046)	0.025 (0.080)	0.018 (0.081)
Geographic variables	No	No	Yes	Yes	Yes	Yes
Country FE	No	No	No	No	Yes	Yes
Observations	168	168	168	168	168	168
Number of clusters	-	59	59	59	59	59
R-squared	0.082	0.082	0.345	0.347	0.632	0.638
Temp. effect on poor Nuts						-0.137** (0.076)

Notes: In all the regressions, the dependent variable is the logarithm of the regional *industrial GDP per capita*. Under *Geographic variables* we find elevation and distance to coasy. The reference year is 2000. Column (1) depicts a simple OLS regression of the dependent variable on temperature. Column (2) replicates column (1) but calculates robust standard errors by Nuts 1 level (Nuts 2 for the case of Spain). Column (3) adds a set of georgraphic variables as controls. Column (4) incorporates precipitations. Columns (5) and (6) include country fixed effects. Column (6) incorporates the interaction effect of temperature in poor regions. * denotes significance at 10 pct., ** at 5 pct., and *** at 1 pct. level.

Table 8: Services. Long-term Relationship. All Regions

	(1)	(2)	(3)	(4)	(5)	(6)
temperature	-0.052* (0.029)	-0.052 (0.034)	-0.066* (0.036)	-0.056 (0.047)	-0.007 (0.069)	0.016 (0.065)
temperature x poor regions						-0.033* (0.019)
precipitations				0.015 (0.040)	0.044 (0.062)	0.037 (0.062)
Geographic variables	No	No	Yes	Yes	Yes	Yes
Country FE	No	No	No	No	Yes	Yes
Observations	168	168	168	168	168	168
Number of clusters	-	59	59	59	59	59
R-squared	0.018	0.018	0.312	0.314	0.617	0.627
Temp. effect on poor Nuts						-0.018 (0.071)

Notes: In all the regressions, the dependent variable is the logarithm of the regional *services GDP per capita*. Under *Geographic variables* we find elevation and distance to coasy. The reference year is 2000. Column (1) depicts a simple OLS regression of the dependent variable on temperature. Column (2) replicates column (1) but calculates robust standard errors by Nuts 1 level (Nuts 2 for the case of Spain). Column (3) adds a set of georgraphic variables as controls. Column (4) incorporates precipitations. Columns (5) and (6) include country fixed effects. Column (6) incorporates the interaction effect of temperature in poor regions. * denotes significance at 10 pct., ** at 5 pct., and *** at 1 pct. level.

Figure 12: 171 Regions. Observed variability in temperatures

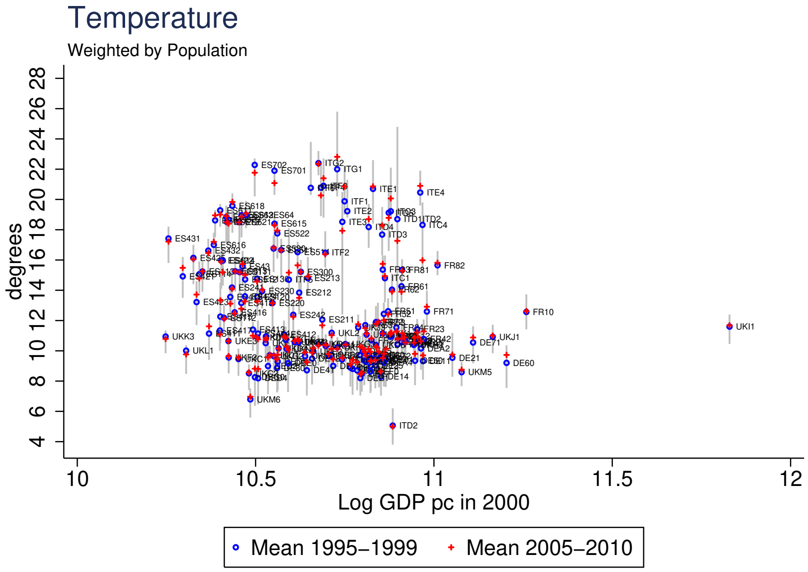

Figure 13: 171 Regions. Observed variability in precipitations

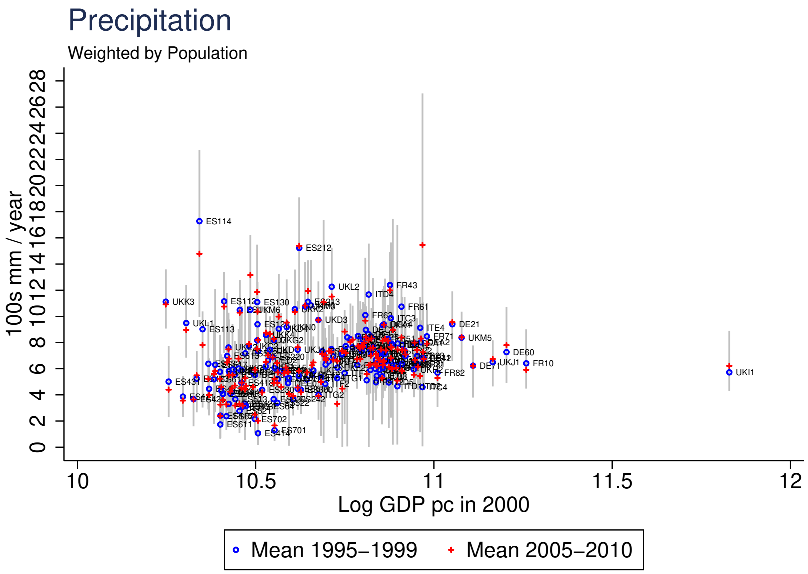

Figure 14: 39 German Regions. Observed variability in temperatures

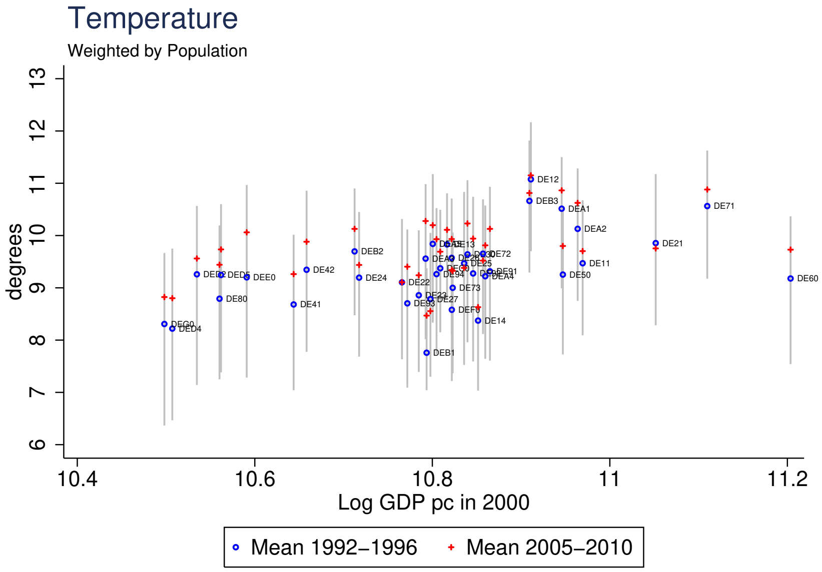

Figure 15: 39 German Regions. Observed variability in precipitations

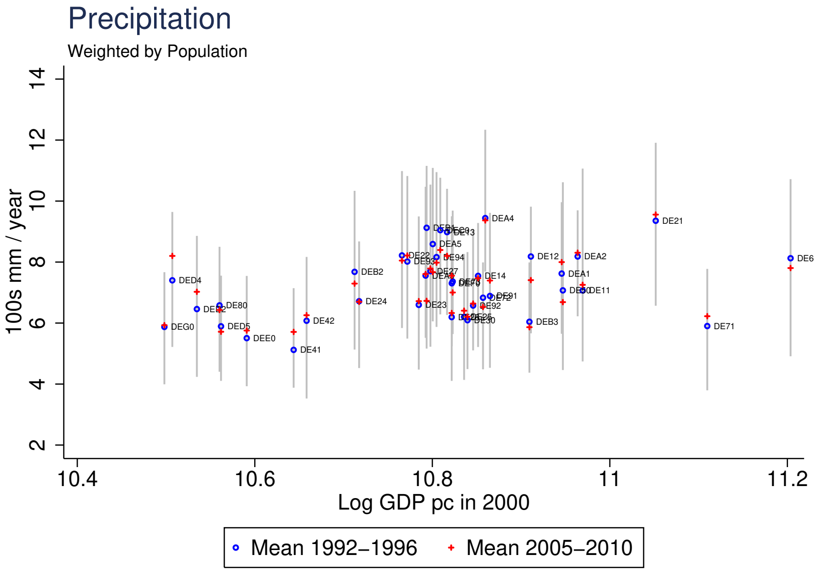

Figure 16: 51 Spanish Regions. Observed variability in temperatures

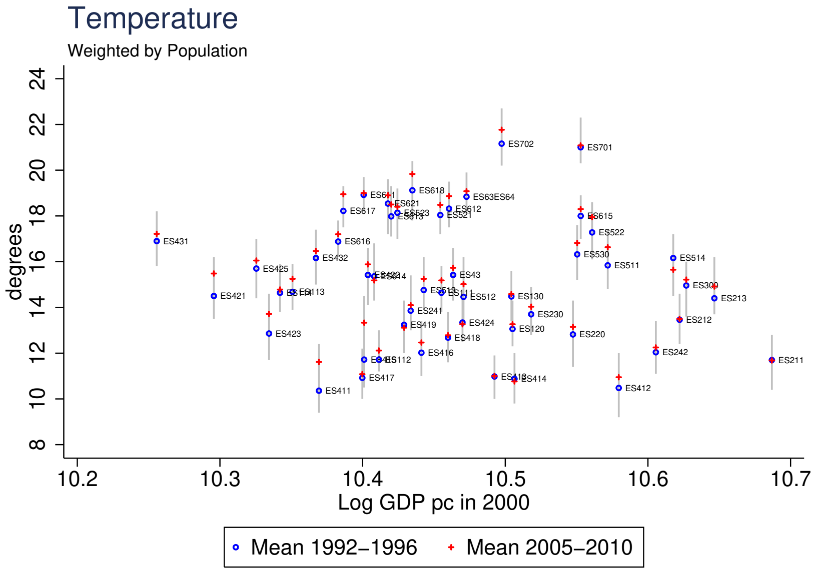

Figure 17: 51 Spanish Regions. Observed variability in precipitations

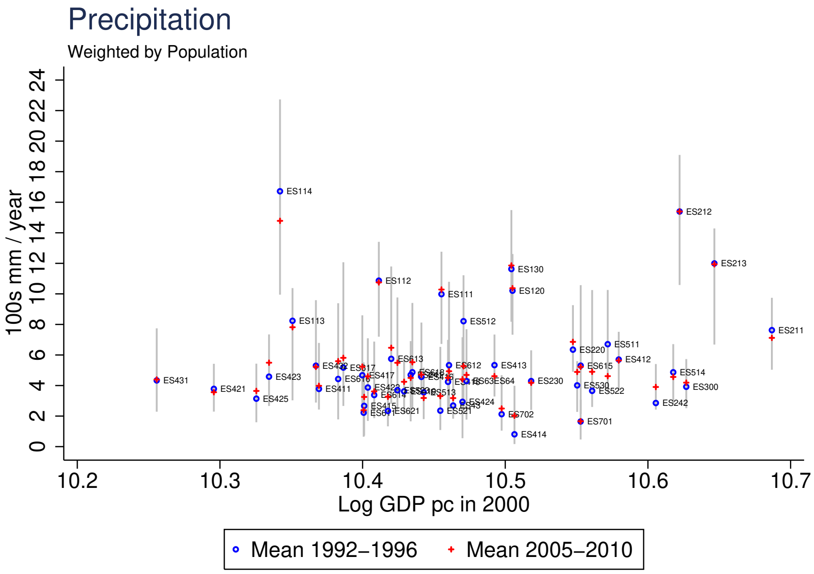

Figure 18: 37 British Regions. Observed variability in temperatures

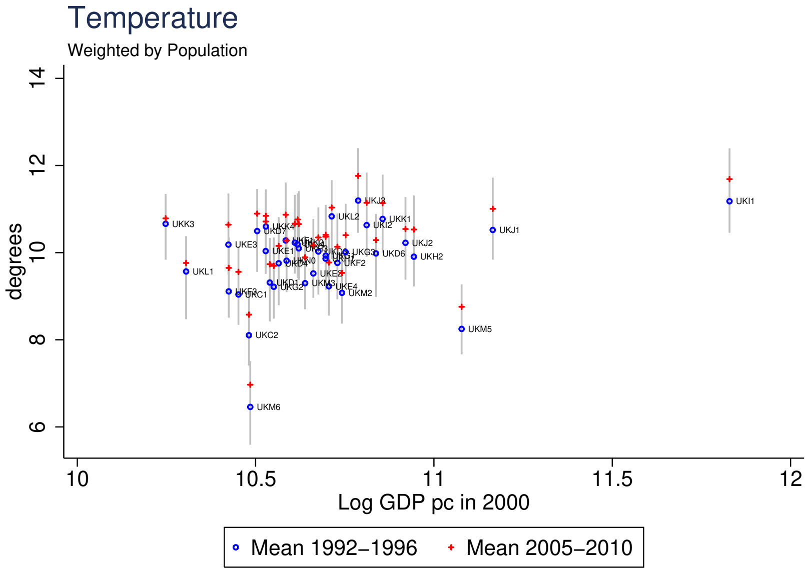

Figure 19: 37 British Regions. Observed variability in precipitations

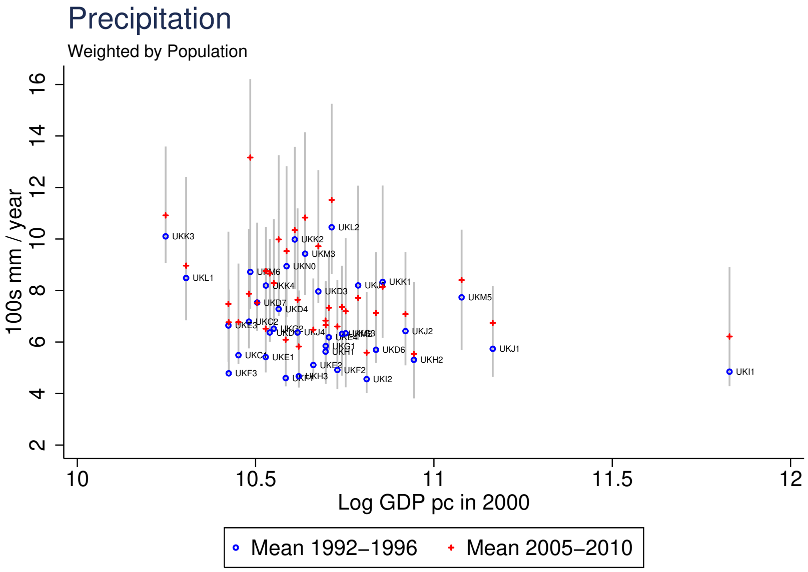

Figure 20: 22 French Regions. Observed variability in temperatures

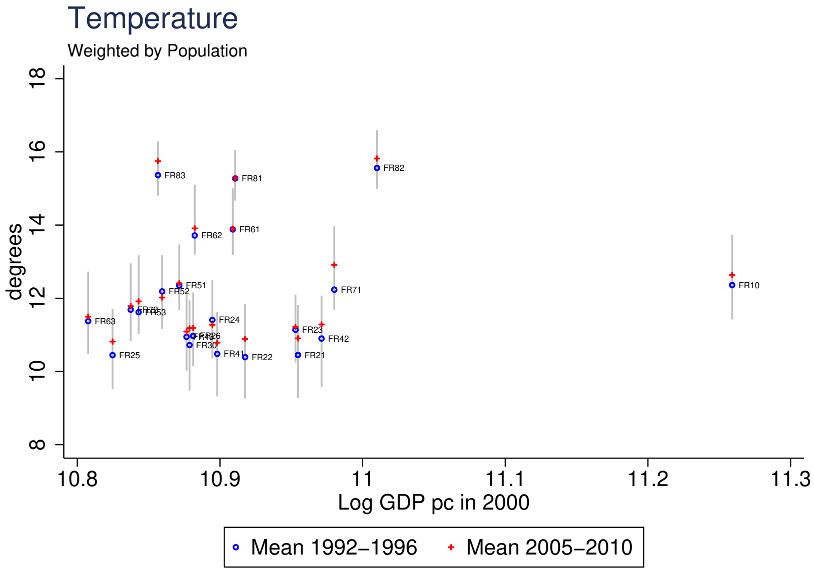

Figure 21: 22 French Regions. Observed variability in precipitations

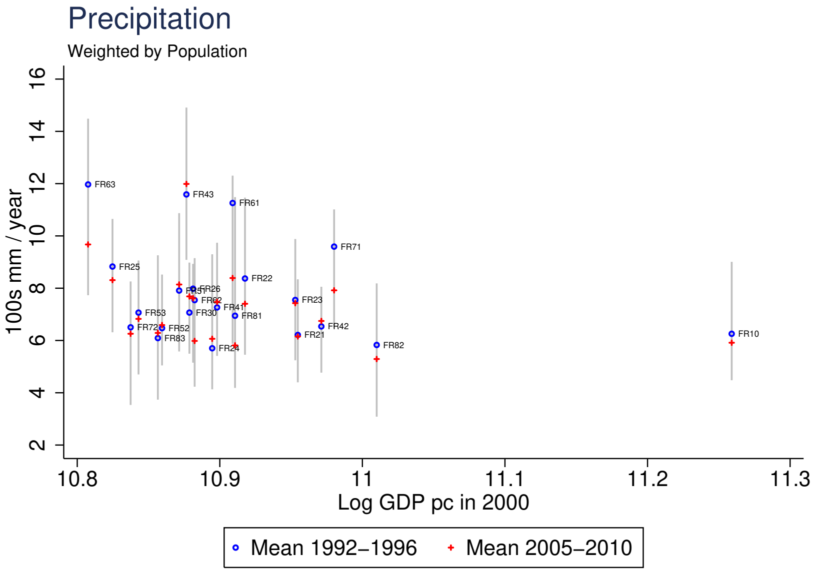

Figure 22: 22 Italian Regions. Observed variability in temperatures

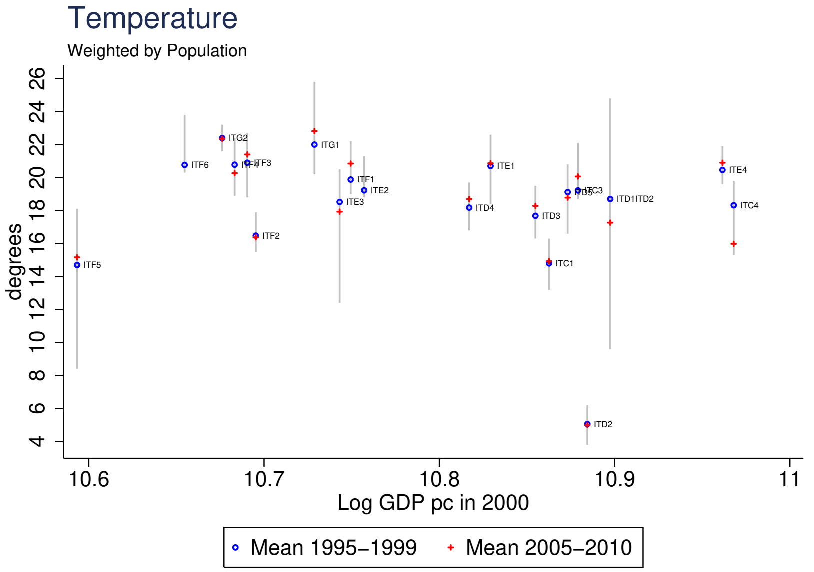

Figure 23: 22 Italian Regions. Observed variability in precipitations

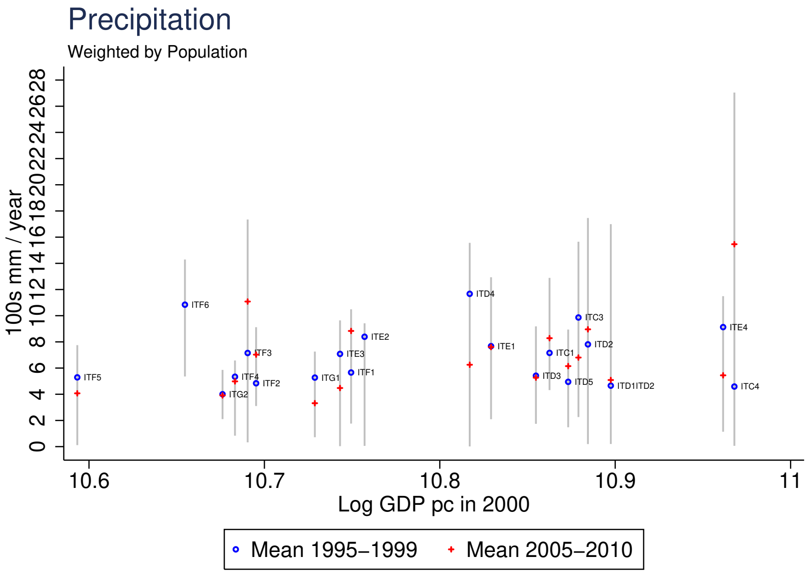

Figure 24: Changes in growth and temperatures between the decades 1990 and 2000

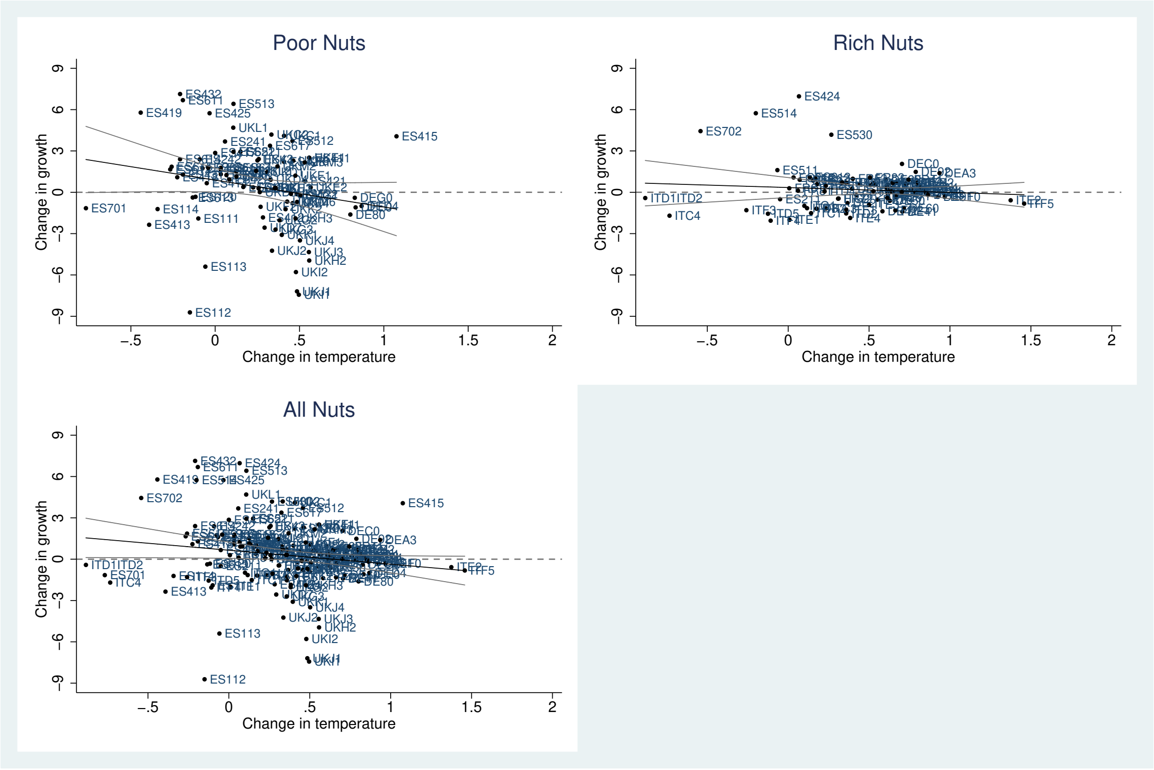

Table 9: Observed temperature and precipitation variation (1990-2011)

Proportion of Nuts-years with temperature (...) degrees above/below total mean temperature						
	0.2	0.4	0.6	0.8	1	1.2
Raw data	0.721	0.463	0.293	0.176	0.104	0.055
After removing Nuts-year fixed effects	0.366	0.122	0.048	0.022	0.012	0.007
Proportion of Nuts-years with precipitations (...)*100 mm above/below total mean precipitations						
	0.5	1	1.5	2	2.5	3
Raw data	0.705	0.445	0.256	0.145	0.078	0.049
After removing Nuts-year fixed effects	0.666	0.392	0.215	0.113	0.067	0.043

Table 10: Short-term Relationship. All Regions

	(1)	(2)	(3)	(4)
temperature	0.178** (0.038)	-0.064*** (0.023)	-0.034* (0.019)	-0.022 (0.017)
temperature x poor regions			-0.052** (0.026)	-0.058** (0.026)
precipitations				0.036 (0.028)
Country FE	No	Yes	Yes	Yes
Observations	3246	3246	3246	3241
Number of clusters	59	59	59	59
R-squared	0.029	0.469	0.469	0.470
Temp. effect on poor Nuts			-0.086*** (0.029)	-0.080*** (0.026)

Notes: bla bka * denotes significance at 10 pct., ** at 5 pct., and *** at 1 pct. level.

Table 11: Agriculture. Short-term Relationship. All Regions

	(1)	(2)	(3)	(4)
temperature	0.202** (0.078)	-0.152** (0.060)	-0.093 (0.070)	-0.135** (0.067)
temperature x poor regions			-0.104 (0.105)	-0.095 (0.102)
precipitations				-0.158** (0.062)
Country FE	No	Yes	Yes	Yes
Observations	3282	3282	3282	3277
Number of clusters	59	59	59	59
R-squared	0.001	0.400	0.400	0.401
Temp. effect on poor Nuts			-0.196*** (0.084)	-0.229*** (0.084)

Notes: bla bka * denotes significance at 10 pct., ** at 5 pct., and *** at 1 pct. level.

Table 12: Industry. Short-term Relationship. All Regions

	(1)	(2)	(3)	(4)
temperature	0.275*** (0.055)	-0.065 (0.043)	-0.056 (0.050)	-0.055 (0.049)
temperature x poor regions			-0.015 (0.069)	-0.020 (0.069)
precipitations				-0.010 (0.033)
Country FE	No	Yes	Yes	Yes
Observations	3282	3282	3282	3277
Number of clusters	59	59	59	59
R-squared	0.017	0.338	0.338	0.337
Temp. effect on poor Nuts			-0.071 (0.057)	-0.075 (0.060)

Notes: bla bka * denotes significance at 10 pct., ** at 5 pct., and *** at 1 pct. level.

Table 13: Services. Short-term Relationship. All Regions

	(1)	(2)	(3)	(4)
temperature	0.438*** (0.062)	0.066** (0.028)	0.025 (0.026)	0.024 (0.028)
temperature x poor regions			0.072** (0.030)	0.074** (0.030)
precipitations				0.002 (0.016)
Country FE	No	Yes	Yes	Yes
Observations	3282	3282	3282	3277
Number of clusters	59	59	59	59
R-squared	0.065	0.765	0.765	0.765
Temp. effect on poor Nuts			0.097*** (0.026)	0.098*** (0.027)

Notes: bla bka * denotes significance at 10 pct., ** at 5 pct., and *** at 1 pct. level.

Table 14: Short-term Relationship. All Regions

	(1) No lags	(2) 1 lag	(3) 3 lags	(4) 5 lags	(5) No lags	(6) 1 lag	(7) 3 lags	(8) 5 lags
temperature	-0.034*	-0.034*	-0.027	-0.033	-0.028	-0.030	-0.018	-0.026
	(0.019)	(0.019)	(0.020)	(0.023)	(0.019)	(0.020)	(0.020)	(0.023)
temperature x poor regions	-0.052*	-0.133	-0.062	0.169	-0.051*	-0.126	-0.065	0.157
	(0.026)	(0.206)	(0.0275)	(0.299)	(0.026)	(0.216)	(0.262)	(0.307)
L1: temperature x poor regions		0.081	0.036	-0.158		0.077	0.048	-0.146
		(0.211)	(0.403)	(0.382)		(0.217)	(0.412)	(0.396)
L2: temperature x poor regions			0.134	0.234			0.199	0.339
			(0.558)	(0.568)			(0.579)	(0.595)
L3: temperature x poor regions			-0.168	-0.292			-0.237	-0.327
			(0.503)	(0.549)			(0.525)	(0.558)
precipitations	No	No	No	No	Yes	Yes	Yes	Yes
Observations	3246	3237	3055	2794	3241	3230	3043	2779
Number of clusters	59	59	59	59	59	59	59	59
R-squared	0.014	0.469	0.475	0.482	0.470	0.470	0.478	0.486
Temp. effect on poor Nuts	-0.086***	-0.087***	-0.053	-0.022	-0.079***	-0.079***	-0.035	-0.014
	(0.029)	(0.030)	(0.437)	(0.410)	(0.025)	(0.025)	(0.432)	(0.440)

Notes: bla bka * denotes significance at 10 pct., ** at 5 pct., and *** at 1 pct. level.