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Geographical Spread of Global Emissions: Within-country Inequalities Are Increasing

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Geographical Spread of Global Emissions: Within-country Inequalities Are Increasing

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Abstract

The major greenhouse gases, CO_2 and CH_4 , are uniformly mixing, but spatial inequalities in emissions do matter in terms of both efficiency and equity of environmental policy formation and implementation. As the recent evidence has mainly focused on convergence issues between countries, this paper extends the empirical analysis by taking into account within-country inequalities in emissions of three major atmospheric pollutants: CO_2 , SO_2 and CH_4 over the 1970-2008 period. Using Theil-index decompositions, we show that within-country inequalities account for the bulk of global inequality, and tend to increase over the sample period, in contrast with diminishing between-country inequalities. An original extension to include differences across sectors reveals that between-sector inequality matters more than between-country inequality, and becomes the dominant source of global inequality at the end of the sample period in the CO_2 and SO_2 cases. A final exercise suggests that social tensions arising from the disconnection between emissions and future damages are easing for CO_2 but rather stable for CH_4 . These orders of magnitude should be kept in mind while discussing the efficiency and fairness of alternative paths in combating global warming.

Keywords: Global spatial emission inequality, sub-national emission inequality, CO_2 , SO_2 , CH_4

1. Introduction

The different emission sources of gases contributing to global warming are unevenly spread across the Earth surface. For a climate analyst, this may seem relatively benign given that the major greenhouse gases (GHG), carbon dioxide and methane, are uniformly mixing and thus deploy their effects worldwide. However, from a politico-economic perspective, the attribution of polluting emissions to specific locations is crucial for a variety of reasons. Everything else equal especially monitoring possibilities fixed, the more widespread pollution sources are, the larger the costs of implementing and monitoring reductions in emissions. This efficiency argument must be refined to include marginal abatement costs, which do differ strongly across locations. Moreover, and even

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more importantly, even though one additional ton of CO_2 equivalent has the same warming effect whatever its origin, its long lasting impact varies widely across locations. This has generated heated debates about who should be made accountable for these damages. While consumption-based accounting focuses on the responsibility of the final consumer, independently of the production site, the location of emission sources determines the responsibility in terms of the applied regulation. It is largely acknowledged that differences in responsibilities should be taken into account in policy negotiations such that the final outcome can be considered as fair.¹ Finally, asymmetries in both exposition to damages and historical responsibilities are crucial in shaping not only the national stance in terms of climate policy, but also lobbying activities within each nation. In short, spatial differences in emissions are critical in shaping the efficiency and fairness of international and national environmental policies and need to be better understood.

Recognizing the importance of patterns of spatial distributions of GHG emissions for environmental policy making, the literature started to analyze them in the late 20th century (see for instance Grunewald et al. (2014), Arora (2014), Duro et al. (2013), Duro (2012), Ordas and Grether (2011), Clarke-Sather et al. (2011), Groot (2010), Cantore and Padilla (2010), Coondoo and Dinda (2008), Duro and Padilla (2006), Padilla and Serrano (2006), Heil and Wodon (2000), Heil and Wodon (1997)). Most of the work dealing with emission inequalities focused so far solely on inequalities between countries and on only one particular gas, carbon dioxide. This is probably due to data availability, the importance of carbon dioxide in the context of climate change and to the perception that negotiating units are countries or groups of countries. The contribution of Arora (2014) and Clarke-Sather et al. (2011) which analyze inequality patterns at the sub-national level in India and China constitute a notable exception, with a focus on only one particular country and gas. To our best knowledge, no study exists which analyzes global emission inequality using sub-national disaggregated data.

Accounting for within-country spatial inequality of emissions may improve our understanding for at least three reasons. First, from an analytical point of view, using national instead of sub-national basic units will result in an important underestimation of global geographic inequality. After all, within country inequalities may even be stronger than between country inequalities. Second, the literature on the political economy of environmental policies emphasizes the important role of lobbying groups in the formation of environmental policies (see for instance Oates and Portney (2003) or Aidt (1998)). Hence spatial within country inequalities are important because they might shape national environmental policies via the interaction of different sub-national interest groups. As Clarke-Sather et al. (2011) put it: “internal dynamics of carbon inequality have the potential to shape future energy policies”. Finally, we observe today an emerging trend towards sub-national and or sectoral policies regarding greenhouse gases. Scott Barrett for instance proposed to break the problem up and to rely on separate agreements addressing different gases and sectors (Barrett,

¹The theoretical and empirical literature on climate change policy negotiations emphasizes clearly the importance of fairness as a criteria for successful international and national negotiations (see for instance Rübbelke (2011), Kverndokk and Rose (2008), Lange et al. (2007), Paavola and Adger (2006), Barrett and Stavins (2003) Ringius et al. (2002) and Rose et al. (1998)). Using the words of Barrett and Stavins (2003), p.358: “Concerns for fairness are not merely abstract notions. They are important for negotiations. People often refuse offers they perceive to be unfair, even when doing so comes at significant personal cost. In principle, it should be possible to negotiate a treaty that is both efficient and fair.”

2008). Another example would be the World Bank which recently launched its idea of a global network of carbon markets (see World Bank (2013)).

This paper proposes an in-depth analysis of spatial inequalities in global warming related emissions for three gases, two direct GHG, carbon dioxide (CO_2) and methane (CH_4) and one acidifying (cooling) gas, sulfur dioxide (SO_2). To measure inequality we use a spatial Theil index, which captures how polluting emissions per square kilometre are unevenly spread across the Earth's surface. This index allows to analyze structural determinants of inequalities, as it can be decomposed into the contribution of geographical groups on different hierarchical levels (e.g. continents, countries) and emission sources (e.g. sectors). It thereby attempts to provide answers to the following questions: By how much do we underestimate global emission inequality by choosing countries as basic units of analysis? How do the contributions of between and within country inequality evolve over time? Which specific sector/country combinations contribute more than proportionally to global emission inequality? And finally, as an illustration of the importance of these measures in the policy debate, what is the degree of overlapping between the geographical distribution of current emissions and the geographical distribution of future damages?

This paper contributes in several ways to the existing literature. It estimates for the first time global emission inequality using a sub-national basic unit of analysis. Moreover, instead of limiting ourself to the carbon dioxide case, we extend the analysis by including methane and sulfur dioxide as additional gases. On top of that we extend existing Theil index decomposition methods in two directions, to be able to determine first which part of total inequality is due to differences between countries and between sectors and which part is due to differences within countries and sectors, and second how far is the geographical distribution of damages disconnected from the distribution of emissions. In order to implement these estimations, we use a unique database on spatial emissions that we combine with several other databases.

2. Data

The selected source of emissions is the Emission Database for Global Atmospheric Research (EDGAR, see European Commission (2011)), which provides sectoral grid emission data (in tons) covering the years 1970 to 2008. To the best of our knowledge, this is the most comprehensive source of disaggregated emissions, as data is available for each bottom left centred 0.1 degree latitude longitude grid on the surface of the planet. In this paper we take two direct greenhouse gases into account: carbon dioxide (excluding short-cycle organic carbon from biomass burning) and methane as well as one acidifying gas: sulphur dioxide. Using the IPCC sector classification, EDGAR also provides the emissions for each grid-cell by sector. Note that the sectors might differ for different gases, as reported in table (A2) in the Appendix, which also displays shares in total world emissions of each sector by gas in 1970 and 2008.

We merged the EDGAR database with the GADM Global Administrative Area database (see Global Administrative Areas (2012)) to attribute each grid-cell to a given country and UN-region². In the case where a grid-cell corresponds to more than one country we attributed the cell to the

²For an overview of the different UN regions and their share in world emissions refer to table (A1)

country in which the majority of the cell is located.

Note that the large majority of the literature used either GDP or population data as weights. We however use area in square kilometres as a weight. This choice is conceptual: we aim to analyze the spatial distribution of emissions, hence emissions per square kilometre are the appropriate measure. We calculated the planimetric area A of each grid cell by treating the planet as a sphere: $A = \frac{\pi}{180} R^2 \left| \sin\left(\text{lat} \frac{\pi}{180}\right) - \sin\left((\text{lat} + 0.1) \frac{\pi}{180}\right) \right| |\text{lon} - (\text{lon} + 0.1)|$. $R = 6371$ km is the radius of the Earth while lat and lon correspond to the bottom left grid-cell corner latitude and longitude in decimal degrees. Given that economic activity also takes place on non-land covered areas (transport, fishing, etc.) the surface variable which is used is the total area of the grid-cell, whether partially covered by water or not.

For our proposed extension to compare between-sector with between-country inequalities, we need a sector area variable. We don't directly observe sector production area but we know how many sectors produce in a given year-cell combination. So we first made the most straightforward hypothesis that all sectors present in a cell share the area equally. As a second way to go we attribute the cell area proportionally to cell sector emissions. The implications of those two hypotheses will be discussed in the result section.

To measure geographical inequalities in damages, we rely on the results from the Global Circulation Models made available by the World Bank on its Climate Change Portal (see World Bank (2014a)). This choice is dictated by our objective to capture geographical distribution at the highest degree of disaggregation. As data on damages is only available for grid-cells at the 1 degree level, emissions had to be aggregated to that level for comparison purposes. The selected proxy for damages is the average estimated share of very warm days over the 2046-2065 period (a very warm day is defined as having a temperature exceeding the 90th percentile bound over the 1961-1990 reference period) times the estimated human population of the cell in 2050 (obtained by multiplying the population figures at the country level for 2050, which come from the World Bank (see World Bank (2014b)), by the 2005 grid-level population shares derived from the G-Econ database (Nordhaus et al. (2006))). The representative scenario is the A2 scenario of the list elaborated by the IPCC (Randall et al. (2007)), which describes a heterogenous world with slow rates of convergence and technological change.

For each grid-cell we aggregate all sectoral emissions of a particular gas and obtain the total emissions of the gas for the given grid-cell³. Finally we drop all grid-cells which are not located within country borders (i.e. we drop all cells which are in international waters). This choice is necessary because we are interested in the between and within contribution of different countries to total emission inequality. The coverage of the final sample in 2008 is larger than 96.4% of world emissions for CH_4 , 93.5% for CO_2 emissions, and 89.2% for SO_2 emissions. We end up with roughly 1.5 million observations per year and gas for a total of 38 years, three gases (CO_2 , CH_4 and SO_2), more than ten sectors and 228 countries. Due to space constraints we cannot present all detailed

³EDGAR provides a variable capturing total emissions of a given grid-cell. We don't use this variable because the computation of sectoral emissions and total emissions has been done using slightly different methodologies. This leads to a few cases where the sum of sectoral emissions does not correspond to the total emission variable provided by EDGAR.

results in the result section. They are however available upon request to the authors.

3. Methodology

3.1. The basic spatial Theil index of emission inequality

Assume the world is composed of a total of I cells indexed by i . Variable y is used to denote total world emissions ($y = \sum_{i=1}^I y_i$) and variable n to denote total world area ($n = \sum_{i=1}^I n_i$).

Our main objective is to analyze inequality of emissions per square kilometre hence our basic units are geographic cells.⁴ The overall Theil index can then be defined as follows:

$$T = \sum_{i=1}^I \frac{y_i}{y} \ln \left(\frac{\frac{y_i}{y}}{\frac{n_i}{n}} \right) \quad (1)$$

Where equation (1) is a reformulation of the originally proposed index by (Theil, 1967). Note that a cell is contributing positively to overall inequality when its emission share in total emissions ($\frac{y_i}{y}$) is larger than its area share in total area ($\frac{n_i}{n}$). The bigger the positive contribution to overall inequality is, the dirtier is the cell and hence the higher is the cell's responsibility in polluting the globe. Analogically, a cell which has a negative contribution to the overall index is a relatively clean cell.⁵ By defining the Theil index in this way we also underestimate inequality - because we assume perfect equality within a given 0.1 degree cell - but to a considerably lower extent compared to the case where the basic unit is the country.

3.2. Geographical decomposition of the basic Theil index

We now start decomposing equation (1). First we use the two-stage decomposition proposed by Akita (2003). This approach allows to decompose total emission inequality into:

- between UN-region inequality;
- between country inequality within a given UN-region;
- within country inequality within a given UN-region.

The globe is composed of R UN-regions indexed by r . Each UN-region r can itself be divided into C^r countries indexed by c . Each country c in region r contains $I^{r,c}$ cells. Where $y = \sum_i y_i = \sum_{r=1}^R \sum_{c=1}^{C^r} \sum_{i=1}^{I^{r,c}} y_i^{r,c}$ and $n = \sum_i n_i = \sum_{r=1}^R \sum_{c=1}^{C^r} \sum_{i=1}^{I^{r,c}} n_i^{r,c}$.

⁴A basic unit of analysis corresponds to the smallest unit for which data is available and which is used to compute the inequality index. The income inequality literature commonly refers to this as the basic social unit of analysis which might be for instance an individual, a household, a nuclear family or an extended family (Cowell, 2011).

⁵For an excellent intuitive interpretation of the Theil index and its various decompositions refer to (Conceicao and Ferreira, 2000).

Having this notation in mind, we can rewrite (1) as follows:

$$\begin{aligned}
T = & \underbrace{\sum_{r=1}^R \frac{y^r}{y} \ln \left(\frac{\frac{y^r}{n^r}}{\frac{y}{n}} \right)}_{\text{Between UN-region inequality} \equiv BR} + \underbrace{\sum_{r=1}^R \frac{y^r}{y} \sum_{c=1}^{C^r} \frac{y^{r,c}}{y^r} \ln \left(\frac{\frac{y^{r,c}}{n^{r,c}}}{\frac{y^r}{n^r}} \right)}_{\text{Between countries inequality, within UN-regions} \equiv BCwr} \\
& + \underbrace{\sum_{r=1}^R \frac{y^r}{y} \sum_{c=1}^{C^r} \frac{y^{r,c}}{y^r} \sum_{i=1}^{I^{r,c}} \frac{y_i^{r,c}}{y^{r,c}} \ln \left(\frac{\frac{y_i^{r,c}}{y^{r,c}}}{\frac{n_i^{r,c}}{n^{r,c}}} \right)}_{\text{Within country inequality, within UN-regions} \equiv WCwr} = BR + BCwr + WCwr
\end{aligned} \tag{2}$$

Where y^r (n^r) denotes total emissions (total area) of UN-region r and $y^{r,c}$ ($n^{r,c}$) denotes total emissions (total area) of country c in UN-region r . Equation (2) allows to analyze the contribution of each UN-region to the between region, between country and within country inequality terms. As an example, if a region has a positive contribution to the between region term its emission share in total emissions is higher than its area share in total area and the region can be considered to be relatively dirty. At the same time this region's contribution to the between country term might be zero, indicating that all countries within this region are equally dirty. Finally, the contribution of this region to the within country term might be highly positive, indicating that there are important differences between clean and dirty cells within the region's countries. This two-stage decomposition method provides also a first insight on the magnitude of importance of between country and within country inequalities.

3.3. Integration of sectoral contributions in the geographic decomposition

Equation (2) allows to analyze the contributions of different geographical entities to total inequality. As a next step we refine this analysis by applying the methodology proposed by Giammatteo (2007) to equation (2). Giammatteo (2007) took the classical between country and within country decomposition and extended it by his pseudo Theil approach, allowing to analyze the contribution of each sector to the between and the within country term. We apply the pseudo Theil approach proposed by Giammatteo (2007) to equation (2). We have a total of S sectors, indexed by s . So for a given cell i in UN-region r and country c we have $y_i^{r,c} = \sum_{s=1}^S y_i^{r,c,s}$. Hence by combining the approach of Akita (2003)(equation (2)) with the one by Giammatteo (2007) we obtain:

$$\begin{aligned}
T &= \sum_{s=1}^S \underbrace{\sum_{r=1}^R \frac{y^{r,s}}{y} \ln \left(\frac{y^r}{\frac{n^r}{n}} \right)}_{\substack{\text{s}^{th} \text{ source contribution to BR} \\ \equiv Tbr(s)}} + \sum_{s=1}^S \underbrace{\sum_{r=1}^R \frac{y^r}{y} \sum_{c=1}^{C^r} \frac{y^{r,c,s}}{y^r} \ln \left(\frac{y^{r,c}}{\frac{n^{r,c}}{n^r}} \right)}_{\substack{\text{s}^{th} \text{ source contribution to BCwr} \\ \equiv Tbc(s)}} \\
&+ \underbrace{\sum_{s=1}^S \sum_{r=1}^R \frac{y^r}{y} \sum_{c=1}^{C^r} \frac{y^{r,c}}{y^r} \sum_{i=1}^{I^{r,c}} \frac{y_i^{r,c,s}}{y^{r,c}} \ln \left(\frac{y_i^{r,c}}{\frac{n_i^{r,c}}{n^{r,c}}} \right)}_{\substack{\text{s}^{th} \text{ source contribution to WCwr} \\ \equiv Twc(s)}} \\
&= \sum_{s=1}^S Tbr(s) + \sum_{s=1}^S Tbc(s) + \sum_{s=1}^S Twc(s)
\end{aligned} \tag{3}$$

The interpretation of the terms in equation (3) is identical to the one in equation (2). But we are now also able to analyze the contribution of each sector to each of the three terms. The sectoral contributions can be positive (relatively dirty sectors) or negative (relatively clean sector).

3.4. Analyzing the sectoral dimension in more details

As a last step we analyze the sectoral dimension in more detail by proposing an original extension. Instead of analyzing the contributions of each sector to the geographical components (as we do in (3)) we want to be able to not only separate between and within geographical group contributions but also between and within sector contributions. In order to do so we need to change our basic unit replacing emissions per square kilometer in country c (y_c^c) by emissions per sectoral production area ($y_i^{s,c}$), assuming this later information is available.⁶ Instead of analyzing T , the inequality of emissions per square kilometres as we do with (1)-(3), we now analyze inequality of sectoral emissions per sectoral production area, T' :

$$T' = \sum_{s=1}^S \frac{y^s}{y} \sum_{i=1}^I \frac{y_i^s}{y^s} \ln \left(\frac{y_i^s}{\frac{n_i^s}{n}} \right) = T + \sum_{s=1}^S \frac{y^s}{y} \sum_{i=1}^I \frac{y_i^s}{y^s} \ln \left(\frac{y_i^s}{\frac{n_i^s}{n_i}} \right) \tag{4}$$

Note that T' equals T plus the inequality between sectors within a given 0.1 degree cell. Given that we ignore UN-regions in this specification, the world is composed of a total of C countries, and each country c is composed of I^c cells. Where $y_i^c = \sum_{s=1}^S y_i^{s,c}$. Using the standard properties of the Theil index, we can rewrite T' as follows:

⁶For more information refer to the discussion on the impossibility of simultaneously decomposing T into source and group contributions in Giammatteo (2007)

$$\begin{aligned}
T' &= \underbrace{\sum_{c=1}^C \frac{y^c}{y} \ln \left(\frac{y^c}{n^c} \right)}_{\substack{\text{Between country inequality} \\ \equiv BC}} + \underbrace{\sum_{c=1}^C \frac{y^c}{y} \sum_{s=1}^S \frac{y^{c,s}}{y^c} \ln \left(\frac{y^{c,s}}{n^{c,s}} \right)}_{\substack{\text{Between sector inequality within a country} \\ \equiv BSwc}} \\
&+ \underbrace{\sum_{c=1}^C \frac{y^c}{y} \sum_{s=1}^S \frac{y^{c,s}}{y^c} \sum_{i=1}^{I^c} \frac{y_i^{c,s}}{y^{c,s}} \ln \left(\frac{y_i^{c,s}}{n_i^{c,s}} \right)}_{\substack{\text{Within sector inequality within a country} \\ \equiv WSwc}} = BC + BSwc + WSwc
\end{aligned} \tag{5}$$

Analogically, we can also express T' as follows:

$$\begin{aligned}
T' &= \underbrace{\sum_{s=1}^S \frac{y^s}{y} \ln \left(\frac{y^s}{n^s} \right)}_{\substack{\text{Between sector inequality} \\ \equiv BS}} + \underbrace{\sum_{s=1}^S \frac{y^s}{y} \sum_{c=1}^C \frac{y^{s,c}}{y^s} \ln \left(\frac{y^{s,c}}{n^{s,c}} \right)}_{\substack{\text{Between country inequality,} \\ \text{within sectors} \equiv BCws}} \\
&+ \underbrace{\sum_{s=1}^S \frac{y^s}{y} \sum_{c=1}^C \frac{y^{s,c}}{y^s} \sum_{i=1}^{I^c} \frac{y_i^{s,c}}{y^{s,c}} \ln \left(\frac{y_i^{s,c}}{n_i^{s,c}} \right)}_{\substack{\text{Within country inequality,} \\ \text{within sectors} \equiv WCws}} = BS + BCws + WCws
\end{aligned} \tag{6}$$

Taking the average of equations (5) and (6), we obtain the following decomposition:

$$T' = \overline{W} + \overline{BC} + \overline{BS} \tag{7}$$

Equation (7) - our newly proposed decomposition - has a unique interpretation: Given that $WSwc = WCws$ we can interpret $\overline{W} = WCws = WSwc = \frac{1}{2}(WCws + WSwc)$ as an overall within country/sector component representing inequalities which are due to the differences in emission intensities across cells of a given country and a given sector. $\overline{BC} = \frac{1}{2}(BC + BCws)$ can be interpreted as an average between country effect capturing the part of inequality due to differences in average emissions intensities among countries. And $\overline{BS} = \frac{1}{2}(BS + BSwc)$ can be interpreted as an average between sector effect, representing inequalities which are due to the differences in average emissions intensities among sectors.

3.5. Linking emissions with damages

Part of the political tensions affecting the climate change debate is due to the fact that damages fall in locations which are not necessarily the major sources of emissions. This subsection establishes and discusses the formal links between emissions and damages inequalities from a spatial perspective. We first re-note the Theil index of spatial inequalities in emissions (equation (1)) by T^y , in order to tell the difference with the Theil index of spatial inequalities in damages, T^d . If d denotes world damages ($d = \sum_{i=1}^I d_i$), we have:

$$T^d = \sum_{i=1}^I \frac{d_i}{d} \ln \left(\frac{\frac{d_i}{d}}{\frac{n_i}{n}} \right) \quad (8)$$

Let us define the damage gap as $\Delta_i \equiv (d_i/d) - (y_i/y)$. Rewriting d_i/d as $(y_i/y) + \Delta_i$, and replacing $\ln[(d_i/d)/(n_i/n)]$ by $\ln[(d_i/d)/(y_i/y)] + \ln[(y_i/y)/(n_i/n)]$, it is straightforward to obtain, from equations (1) and (8):

$$T^d = T^y - \underbrace{\sum_{i=1}^I \frac{y_i}{y} \ln \left(\frac{\frac{y_i}{y}}{\frac{d_i}{d}} \right)}_{\text{Disparity index, } DSP} + \underbrace{\sum_{i=1}^I \Delta_i \ln \left(\frac{\frac{d_i}{d}}{\frac{n_i}{n}} \right)}_{\text{Overdamage index, } OVD} = T^y - DSP + OVD \quad (9)$$

The first term on the RHS of equation (9) is the Theil index of spatial inequality in emissions. It may be considered as an initial benchmark assumption which is bound to be incorrect (and thus in need of corrections) because in the majority of cases damages are not spread spatially the same way as emissions. So the next two elements on the RHS are correction terms. The first one is also a Theil index of inequality in emissions, but not with respect to geographic area, but with respect to damages. In other words, while T^y picks up by how much emission shares are different from area shares, the first correction term indicates by how much emission shares are different from damage shares, so we will call that term the *disparity* index (DSP). Note that a given value of DSP may be obtained from an array of totally different distributions of damages on the Earth's surface. So we need an additional correction to make the link between damages and geography. This is the intuition behind the second correction term, a covariance which indicates by which extent over-damaged cells, i.e. those where Δ_i is large, also tend to be those where damages are intense, i.e. those where the logarithmic term is positive. Therefore, we will refer to that second correction term as an index of *over - damage* (OVD).⁷

Both indices matter in terms of social tensions, but to illustrate why the DSP (OVD) index enters negatively (positively) into the equation, let us consider a simplified stylized world where emissions and damages are spread over equalized cells, ranked by decreasing order of emission density. In the three panels of Figure 1, the solid decreasing line represents the emission share of each cell. Damages shares are represented by the dashed line, which differs across panels. Damages and emissions have identical distributions in the top panel, damages are equally spread across all cells in the medium panel, and damages and emissions have opposite distributions in the bottom panel. We consider below each panel to unveil the interpretation of the two correction terms.

(i) victims=polluters i.e. damages and emissions shares are equal across all countries (top panel). In this obvious case $T^y = T^d$. The two correction terms are zero, both because damages and emissions are evenly spread.

(ii) damages evenly spread across all cells (medium panel). In that case $T^d = 0$. How do we obtain that? The overdamage index is zero because even if some countries emit and others do not, damages per square kilometer are constant. So the compensation comes 100% from the disparity

⁷Formally, OVD is I times the covariance between Δ_i and $\ln[(d_i/d)/(n_i/n)]$, due to the fact that $\sum_{i=1}^I \Delta_i = 0$

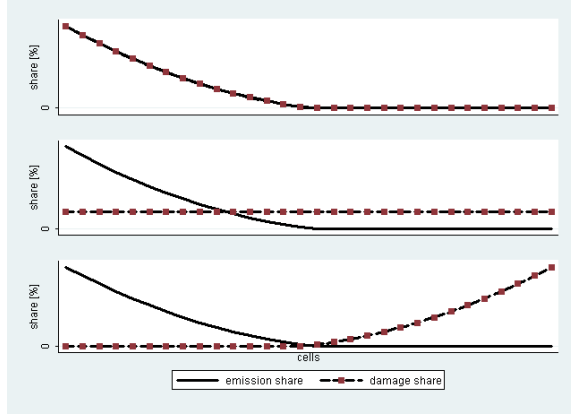


Figure 1: Stylized worlds

index, which is both nonzero, as emissions and damages are unequally spread across countries, and necessarily equal to T^y , as damage shares and spatial shares are identical for each country in that particular case.

(iii) perfect opposition between victims and polluters (bottom panel). In this case damages occur precisely in cells which do not emit pollution. With respect to the previous case, disparity has increased, so that the addition of the first two terms on the RHS leads to a negative value. However, overdamage is large, with damages biased towards those areas which do not emit to such an extent that spatial inequality in damages (captured by T^d) just mimics spatial inequality in emissions (captured by $T^y = T^d$), although on a completely different subset of cells.

Every element of equation (9) can be decomposed into the sum of a between-region (BR), between-country ($BCwr$) and within-country ($WCwr$) term. For T^d and DSP , the corresponding terms are direct extensions of those appearing in equation (2). For OVD , it is straightforward to show that $BR = \sum_{r=1}^R \Delta^r \ln \left(\frac{d^r/d}{n^r/n} \right)$, $BCwr = \sum_{r=1}^R \sum_{c=1}^{C^r} \Delta^{r,c} \ln \left(\frac{d^{r,c}/d^r}{n^{r,c}/n^r} \right)$, and $WCwr = \sum_{r=1}^R \sum_{c=1}^{C^r} \sum_{i=1}^{I^{r,c}} \Delta_i^{r,c} \ln \left(\frac{d_i^{r,c}/d^{r,c}}{n_i^{r,c}/n^{r,c}} \right)$, where $\Delta^r = (d^r/d) - (y^r/y)$, $\Delta^{r,c} = (d^{r,c}/d) - (y^{r,c}/y)$ and $\Delta_i^{r,c} = (d_i^{r,c}/d) - (y_i^{r,c}/y)$.

4. Results

Results are reported on the basis of figures and summary tables, starting from the description of global patterns, and then focusing on the identification of the major inequality drivers between countries or between sectors. Comments mainly refer to the CO_2 case, but the other two gases are also discussed in case of important differences.

Beforehand, based on the affinity between polluting emissions and specific sectors, let us mention two roughly expectable outcomes. First, as illustrated by the world shares reported in table A2, carbon dioxide and sulphur dioxide emissions are mainly released by fuel consumption for power generation and manufacturing, while methane is more linked to agriculture. As agriculture is more

evenly spread, we may expect a lower spatial inequality index for methane. Second, whether based on factor endowments or economies of scale, trade between different locations allows for specialization and industrial clustering, which tends to increase spatial inequalities. As barriers to trade are typically less important within countries, everything else equal, we may expect more trade intensity, and thus larger spatial inequalities within countries than between them.

However, sectoral affinity is far from being the unique contributor to spatial inequalities. Differences in technology and environmental policies also matter. As we may expect more homogeneity along those dimensions within a given country, these effects work oppositely to trade forces, leading to less spatial inequalities within countries, not more. Further complications appear when considering the evolution over time, in particular economic growth during the last four decades. This phenomenon has been accompanied by both increased specialization and trade on the one hand, and by more technological, economic and policy convergence on the other hand. The net impact of these different forces on spatial inequalities in emissions is unclear, which increases the interest in the empirical analysis below.

4.1. Global patterns

Theil indices decomposed according to equation (2) are reported in Figure (2). Our two major expectations are confirmed. First, of the three gases, methane turns out to be more evenly spread, with an overall index slightly above 2, versus 3 for CO_2 and 4 for SO_2 . This is consistent with the view that CH_4 anthropogenic emissions are mainly due to rural activities. Second, there is a striking similarity among the three gases regarding the dominance of within-country inequalities, which represent between 66% and 75% of the total. According to the above-mentioned arguments, this suggests that the agglomeration and specialization forces generated by freer trade within countries tend to overcome the influence of a unique regulatory framework.

Regarding changes over time, although the order of magnitude is small, there is again a strong similarity across gases. Between-region and between-country inequalities are on average declining over the period, while within-country inequalities tend to increase, in particular at the end of the time interval. Again, this appears consistent with a period of globalization and growth during which, on the one hand, countries tend to converge in income per capita, which is positively correlated with environmental consciousness and policies, and on the other hand with increased specialization through trade, which leads to larger spatial inequalities within countries. For CO_2 and CH_4 two peaks can be identified in the years 1997/1998. Those peaks are the results of the enormous forest fires in those two years in Indonesia (probably the largest forest fires ever recorded in history).

Figure (2) illustrates the importance of the basic unit used to compute global emission inequality. By choosing countries as basic units, i.e. by making the assumption of perfect equality within countries, one underestimates global spatial emission inequality by a large amount. The dominant approach in the literature underestimates global spatial emission inequality on average by roughly $\frac{2}{3}$ - for the case of CO_2 - to $\frac{3}{4}$ for the cases of SO_2 and CH_4 . Taking countries as basic units not only results in an important underestimation of global emission inequality, but impacts also on the observed overall trends. While previous studies find a decrease of global (carbon dioxide) inequality since the 70ties (see for instance Grunewald et al. (2014) or Duro and Padilla (2006)), we show that global emission inequality is either roughly constant (CO_2) or even slightly increasing (SO_2

and CH_4).

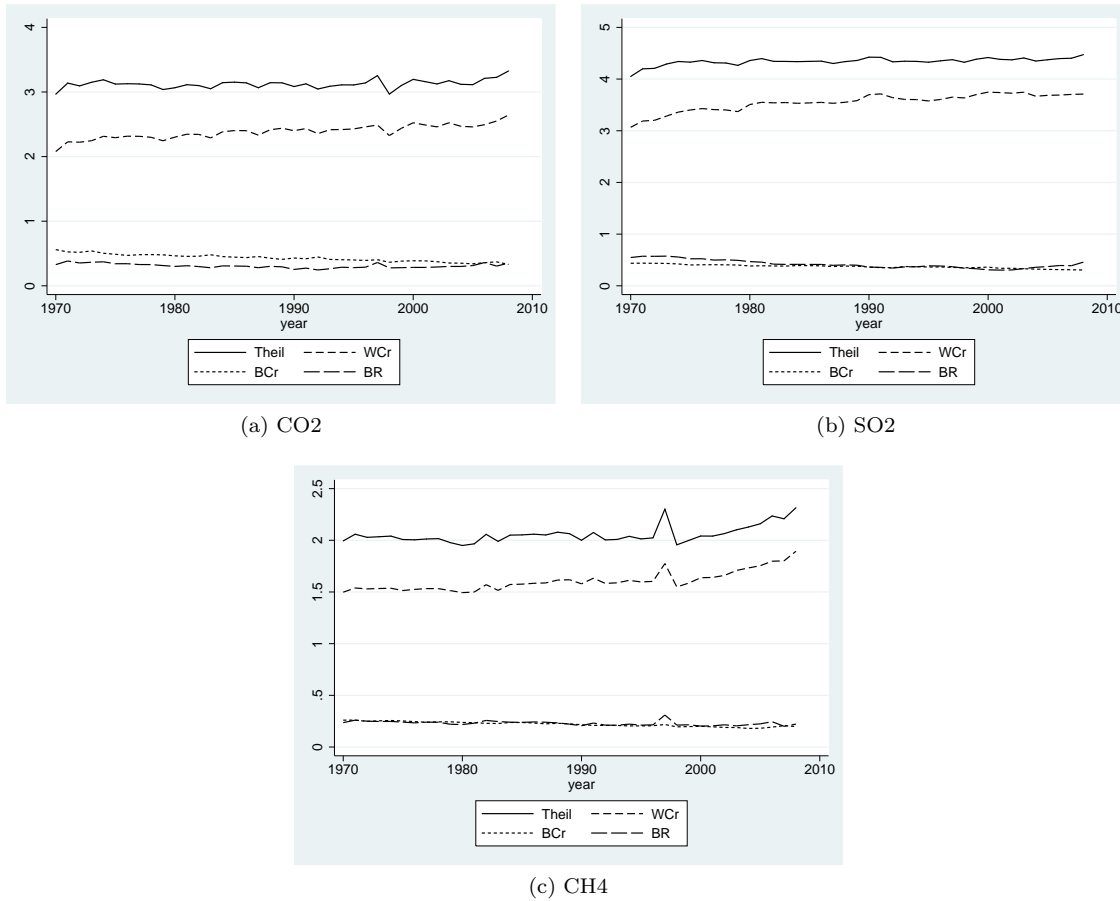


Figure 2: Geographic Decomposition of the Theil index T

4.2. Which regions/sectors contribute more to inequality?

The above-mentioned global patterns may hide important differences across regions and sectors. This calls for a more detailed analysis at the disaggregated level. Two reminders are in order to avoid misunderstandings while interpreting the results.

First, some contributions are negative, as every element of the Theil index is reported for the between-region part of the index (column BR of table (1)). In that case, a negative(positive) figure just indicates that this particular region has an emission density which is smaller(larger) than average.

Second, what we measure here are spatial inequalities of emissions, not emission shares. That is, if the results below suggest a particular region or sector does not contribute much to overall inequality, it does not mean that its share in global emission is commensurate. It just means that emissions in that particular region or sector are rather evenly spread geographically.

Table (1) provides absolute contributions to inequality by regions for 1970 and 2008. Based on column "Theil", the major contributors for CO_2 and SO_2 turn out to be the four most industrialized regions i.e. Europe, North America, Former Soviet Union and East Asia, which represent together on average a rough 85% of total inequality. This common average contribution to inequality drops to 70% for CH_4 , as South Asia and South East Asia are more important, a difference which could have been expected on the basis of the sectoral affinity argument.

For a given region, a large contribution may be due to three different factors: (i) because this region has a larger density of emissions per square kilometre than the average (column "BR") or (ii) because the countries in this region are strongly dissimilar between them (column "BCwr") or still (iii) because there are large spatial inequalities within the countries of this region (column "WCwr"). On average, for the four major industrialized regions, and whatever the gas, the most important factor is always the within-country component, while the less important factor is either the between-country component for the two smaller and more homogenous regions (Europe and East Asia) or the between-region component for the other larger regions (North America and the Former Soviet Union).

Regarding changes over time, reported in the last columns of Table (1), there again, and whatever the gas, the larger changes are experienced by the four major industrialized regions, with an increase for East Asia and a decrease for the other three regions. The only exception is methane in the case of the Former Soviet Union, for which there is practically no change over the 1970-2008 period. Moreover, the major components of these temporal changes are the between-region component and the within-country component. The important change of the between-region component suggests a strong redistribution of world emission shares among three of these large industrialized regions, while the important change of the within-country component reflects increased specialization and clustering within the countries of the regions.

The contributions of each sector to global spatial inequality (equation (3) above) are reported in Table (2). Energy production and use is the major contributor but with important differences across gases (see "Theil" column). Carbon dioxide and sulphur dioxide emissions are basically linked to fuel consumption, which accounts on average for more than 80% of spatial inequalities for both gases. Within that broad category, public electricity and heat production is the most important subsector, representing on average close to 50% (70%) of spatial inequalities sources for CO_2 (SO_2). In the case of methane, the contributions are more equally spread across three broad categories: fugitive emissions (related to coal, gas and oil production, by decreasing order), agriculture (due to enteric fermentation and soil management) and waste management. Whatever the gas, for each major sector, the most important average contribution comes from the within-country component, which is always at least twice as large as the other two components. The only exception is agriculture in the case of methane, where the average between-country (between-region) component is less than 30% smaller than the average within-country component for enteric fermentation (agricultural soils).

Table 1: Absolute contributions to between region, between country, within country and total inequality by UN-region and gas.
(Note: Numbers might not add up due to rounding)

Gas	UN-Region	Absolute contributions, 1970				Absolute contributions, 2008				Absolute difference, 2008-1970			
		BR	BCwr	WCwr	Theil	BR	BCwr	WCwr	Theil	BR	BCwr	WCwr	Theil
CO2	East Asia	0.01	0.08	0.14	0.22	0.31	0.07	0.76	1.15	0.30	-0.01	0.62	0.93
	Europe (excl. FSU)	0.39	0.11	0.35	0.85	0.16	0.04	0.24	0.45	-0.23	-0.07	-0.11	-0.40
	Former Soviet Union	-0.02	0.05	0.57	0.59	-0.06	0.01	0.39	0.35	-0.04	-0.04	-0.18	-0.24
	Middle East and North Africa	-0.03	0.01	0.03	0.02	-0.03	0.03	0.13	0.13	0.00	0.02	0.10	0.11
	North and Central America	0.10	0.13	0.74	0.97	0.02	0.08	0.62	0.72	-0.08	-0.05	-0.12	-0.25
	Oceania and Pacific Islands	-0.02	0.00	0.04	0.02	-0.02	0.00	0.07	0.05	0.00	0.00	0.03	0.03
	South America	-0.04	0.01	0.05	0.02	-0.05	0.00	0.07	0.03	-0.01	-0.01	0.02	0.01
	South Asia	-0.01	0.04	0.07	0.10	0.02	0.01	0.22	0.24	0.03	-0.03	0.15	0.14
	South East Asia	-0.01	0.01	0.02	0.01	0.05	0.01	0.06	0.13	0.06	0.00	0.04	0.12
	Sub-saharan Africa	-0.04	0.13	0.07	0.15	-0.06	0.07	0.07	0.08	-0.02	-0.06	0.00	-0.07
SO2	East Asia	0.03	0.06	0.17	0.27	0.58	0.07	1.27	1.93	0.55	0.01	1.10	1.66
	Europe (excl. FSU)	0.52	0.12	0.58	1.21	0.06	0.02	0.23	0.31	-0.46	-0.10	-0.35	-0.90
	Former Soviet Union	0.01	0.04	0.87	0.91	-0.05	0.02	0.51	0.48	-0.06	-0.02	-0.36	-0.43
	Middle East and North Africa	-0.02	0.02	0.04	0.04	-0.02	0.05	0.28	0.31	0.00	0.03	0.24	0.27
	North and Central America	0.17	0.12	1.03	1.32	-0.04	0.04	0.51	0.51	-0.21	-0.08	-0.52	-0.81
	Oceania and Pacific Islands	-0.02	0.00	0.08	0.05	-0.02	0.00	0.14	0.12	0.00	0.00	0.06	0.07
	South America	-0.05	0.02	0.10	0.08	-0.05	0.02	0.14	0.11	0.00	0.00	0.04	0.03
	South Asia	-0.02	0.00	0.05	0.03	0.05	0.03	0.35	0.44	0.07	0.03	0.30	0.41
	South East Asia	-0.01	0.00	0.02	0.02	0.01	0.01	0.12	0.13	0.02	0.01	0.10	0.11
	Sub-saharan Africa	-0.06	0.05	0.13	0.12	-0.06	0.04	0.16	0.13	0.00	-0.01	0.03	0.01
CH4	East Asia	0.12	0.03	0.26	0.41	0.20	0.03	0.61	0.84	0.08	0.00	0.35	0.43
	Europe (excl. FSU)	0.17	0.05	0.20	0.42	0.05	0.02	0.07	0.13	-0.12	-0.03	-0.13	-0.29
	Former Soviet Union	-0.05	0.02	0.33	0.30	-0.05	0.01	0.38	0.34	0.00	-0.01	0.05	0.04
	Middle East and North Africa	-0.03	0.02	0.07	0.07	-0.03	0.02	0.12	0.11	0.00	0.00	0.05	0.04
	North and Central America	-0.02	0.06	0.33	0.36	-0.05	0.03	0.24	0.22	-0.03	-0.03	-0.09	-0.14
	Oceania and Pacific Islands	-0.02	0.00	0.03	0.02	-0.02	0.00	0.05	0.03	0.00	0.00	0.02	0.01
	South America	-0.04	0.01	0.06	0.03	-0.03	0.01	0.13	0.11	0.01	0.00	0.07	0.08
	South Asia	0.12	0.04	0.11	0.27	0.14	0.03	0.14	0.31	0.02	-0.01	0.03	0.04
	South East Asia	0.04	0.01	0.05	0.11	0.05	0.01	0.08	0.15	0.01	0.00	0.03	0.04
	Sub-saharan Africa	-0.06	0.02	0.04	0.01	-0.05	0.04	0.08	0.07	0.01	0.02	0.04	0.06

Table 2: Absolute contributions to between region, between country, within country and total inequality by IPCC-sector and gas, 1970-2008. (FC = Fuel consumption, FE = Fugitive emissions; Note: Numbers might not add up due to rounding)

CO2	Sector	Absolute contributions, 1970				Absolute contributions, 2008				Absolute difference, 2008-1970				
		BR	BCwr	WCwr	Theil	BR	BCwr	WCwr	Theil	BR	BCwr	WCwr	Theil	
Energy	FC in electricity and heat production	0.109	0.104	0.848	1.061	0.155	0.118	1.665	1.938	0.046	0.014	0.817	0.877	
	FC in other energy industries & waxes	0.014	0.022	0.161	0.197	0.012	0.006	0.079	0.097	-0.002	-0.016	-0.082	-0.100	
	FC in manufacturing	0.109	0.094	0.351	0.554	0.087	0.033	0.276	0.395	-0.022	-0.061	-0.075	-0.159	
	FC in international and domestic aviation	0.007	0.004	-0.002	0.006	0.006	0.003	0.006	0.006	-0.001	-0.001	-0.001	-0.002	
	FC in road transportation	0.043	0.040	0.186	0.269	0.004	0.049	0.190	0.279	-0.003	0.009	0.004	0.010	
	FC in non-road ground transport	0.005	0.006	0.000	0.011	0.000	0.001	-0.005	-0.004	-0.005	-0.005	-0.005	-0.015	
	FC in international and domestic shipping	0.002	0.001	-0.003	0.001	0.002	0.000	-0.003	0.000	0.000	-0.001	0.000	0.001	
	FC in residential	0.097	0.061	0.213	0.372	0.041	0.029	0.153	0.223	-0.056	-0.032	-0.060	-0.149	
	FE from oil production	-0.003	0.017	0.157	0.171	0.000	0.006	0.097	0.104	0.003	-0.011	-0.060	-0.067	
	Non-metallic mineral processes	0.013	0.007	0.046	0.066	0.026	0.006	0.130	0.162	0.013	-0.001	0.084	0.096	
Chemical processes solvents	0.006	0.005	0.026	0.037	0.006	0.006	0.044	0.056	0.000	0.001	0.018	0.019		
Metal processes	0.006	0.002	0.033	0.041	0.002	0.001	0.016	0.019	-0.004	-0.001	-0.017	-0.022		
Agriculture	Agricultural soils	0.001	0.001	-0.002	0.000	0.001	0.001	-0.004	-0.002	0.000	0.000	-0.002	-0.002	
Land use	Large scale biomass burning	-0.083	0.196	0.058	0.171	-0.030	0.073	0.004	0.047	0.053	-0.123	-0.054	-0.124	
Waste	Waste incineration	0.000	0.001	0.001	0.003	0.001	0.001	0.002	0.003	0.001	0.000	0.001	0.000	
Others	Fossil fuel fires	0.000	-0.001	0.005	0.004	0.001	0.000	0.001	0.003	0.001	0.001	-0.004	-0.001	
SO2	Sector	BR	BCwr	WCwr	Theil	BR	BCwr	WCwr	Theil	BR	BCwr	WCwr	Theil	
		0.256	0.189	1.829	2.273	0.271	0.202	2.678	3.151	0.015	0.013	0.849	0.878	
		0.150	0.104	0.357	0.610	0.169	0.042	0.321	0.533	0.019	0.062	-0.036	-0.077	
		0.010	0.010	-0.006	0.014	0.013	0.003	-0.002	0.014	0.003	-0.007	0.004	0.000	
		0.006	0.004	0.010	0.021	-0.001	0.002	0.004	0.005	-0.007	-0.002	-0.006	-0.016	
		0.114	0.099	0.094	0.266	0.034	0.009	0.013	0.057	-0.080	-0.050	-0.081	-0.209	
		0.009	0.018	0.055	0.055	0.024	0.010	0.092	0.125	0.015	-0.008	0.037	0.049	
		0.021	0.007	0.093	0.121	0.007	0.007	0.069	0.082	-0.014	0.000	-0.024	-0.039	
		0.013	0.049	0.638	0.700	-0.039	0.027	0.535	0.522	-0.052	-0.022	-0.103	-0.178	
		-0.001	0.000	-0.001	-0.003	0.000	-0.001	-0.003	-0.004	0.001	-0.001	-0.002	-0.001	
Agriculture	Agricultural waste burning	-0.029	-0.003	-0.008	-0.041	-0.023	0.004	0.000	-0.019	0.006	0.007	0.008	0.022	
Land use	Large scale biomass burning	0.000	0.000	0.006	0.006	0.003	0.001	0.003	0.007	0.003	0.001	-0.003	0.001	
Others	Fossil fuels fires	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.001	-0.003	0.000	
CH4	Sector	BR	BCwr	WCwr	Theil	BR	BCwr	WCwr	Theil	BR	BCwr	WCwr	Theil	
		0.001	0.002	0.013	0.016	0.001	0.002	0.022	0.025	0.000	0.000	0.009	0.009	
		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
		0.000	0.001	0.007	0.009	0.000	0.000	0.002	0.003	0.000	-0.001	-0.005	-0.006	
		0.022	0.008	0.015	0.044	0.016	0.007	0.010	0.033	-0.006	-0.001	-0.005	-0.011	
		0.043	0.043	0.565	0.651	0.073	0.026	0.177	0.876	0.030	0.017	0.212	0.225	
		FE from oil production	-0.019	0.013	0.253	0.247	-0.011	0.002	0.174	0.165	0.008	-0.011	-0.079	-0.082
		FE from gas production	-0.004	0.016	0.206	0.218	-0.015	0.017	0.488	0.490	-0.011	0.001	0.282	0.272
		0.000	0.000	0.001	0.002	0.000	0.000	0.002	0.002	0.000	0.000	0.001	0.000	
		0.032	0.054	0.070	0.157	0.034	0.051	0.085	0.170	0.002	-0.003	0.015	0.013	
0.013	0.011	0.004	0.028	0.008	0.008	0.006	0.023	-0.005	-0.003	0.002	-0.005			
0.127	0.057	0.214	0.398	0.084	0.026	0.081	0.191	-0.043	-0.031	-0.133	-0.207			
0.001	0.001	0.000	0.000	0.001	0.001	0.000	0.002	0.000	0.000	0.000	0.000			
Land use	Large scale biomass burning	-0.030	0.019	-0.004	-0.015	-0.015	0.025	0.002	0.012	0.015	0.006	0.006	0.027	
Waste	Solid waste disposal & incineration	0.025	0.029	0.074	0.129	0.010	0.018	0.114	0.142	-0.015	-0.011	0.040	0.013	
Waste water	Waste water	0.023	0.008	0.077	0.108	0.034	0.015	0.131	0.179	0.011	0.007	0.054	0.071	
Others	Fossil fuel fires	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	

Temporal changes are reported in the last columns of Table (2). For the two gases related to fuel consumption, CO_2 and SO_2 , electricity and heat production becomes more important, while residential and manufacturing are losing ground. This probably reflects both growth in energy demand (scale effect) and abatement activities (technical effect). Note that the relative change of the between-region component is the larger one in those subsectors with decreasing importance, suggesting abatement efforts have been biased towards the "old" industrialized regions, which exhibit declining shares in global emissions. For methane, the evolution is more complex, with an increase in the contribution of gas production and a decrease in agriculture soil of similar magnitude, and a similar compensation pattern between coal (increase) and oil (decrease) production.

4.3. Which source of inequality matters most: between countries, between sectors or within them?

Although the analysis above reported contributions for specific sectors, the decomposition of the inequality index itself remained spatially-oriented, i.e. according to the between-region or within-region components. In fact, when emissions on a specific spot of the Earth's surface are particularly large, this may be because they arise from a highly polluting country, or a highly polluting sector, or still a highly polluting spot within that particular country-sector combination. The last decomposition exercise provides an estimate of which of these three sources of inequality matters more for each gas.

To perform that decomposition, based on equation (7), in the absence of additional information, we need to make assumptions regarding the spatial distribution of sectoral emissions within each cell. We consider two extreme scenarios: under hypothesis 1, cell area is split equally between sectors ($n_i^s = \frac{1}{S}n_i$), whereas under hypothesis 2, cell area is split in proportion to reported emissions ($n_i^s = \frac{y_i^s}{y_i}n_i$). Hypothesis 2 may appear more intuitive at first, but has the important drawback of assuming away any within-cell inequalities across sectors (the second term of equation (4) becomes zero and hence $T'=T$). Unfortunately, we do not have any empirical evidence which could guide us towards the best assumption. Hypothesis 1 seems however more realistic. Therefore, we will focus on results under hypothesis 1 and only consider hypothesis 2 as a robustness check.

The patterns reported in Figure (3) are reminiscent of the above-commented results. First, for all gases, the between-country component is the smallest one, and is declining over time. Second, the two gases strongly linked to fuel consumption, CO_2 and SO_2 , exhibit a similar trend, with a growing between-sector component which becomes the dominant source of spatial inequalities at the end of the period. Third, for methane emissions, which are more evenly spread across sectors, it is the within-country-within-sector element which is the growing and dominant component. Results under hypothesis 2 are reported in Appendix Figure (A1). They confirm these broad trends. Confirming results from section 4.2, this suggests that recent decades have been characterized by more specialization across sectors than across countries, particularly for carbon dioxide and sulphur dioxide. Moreover, even after controlling for differences across sectors, within-country inequalities remain important.

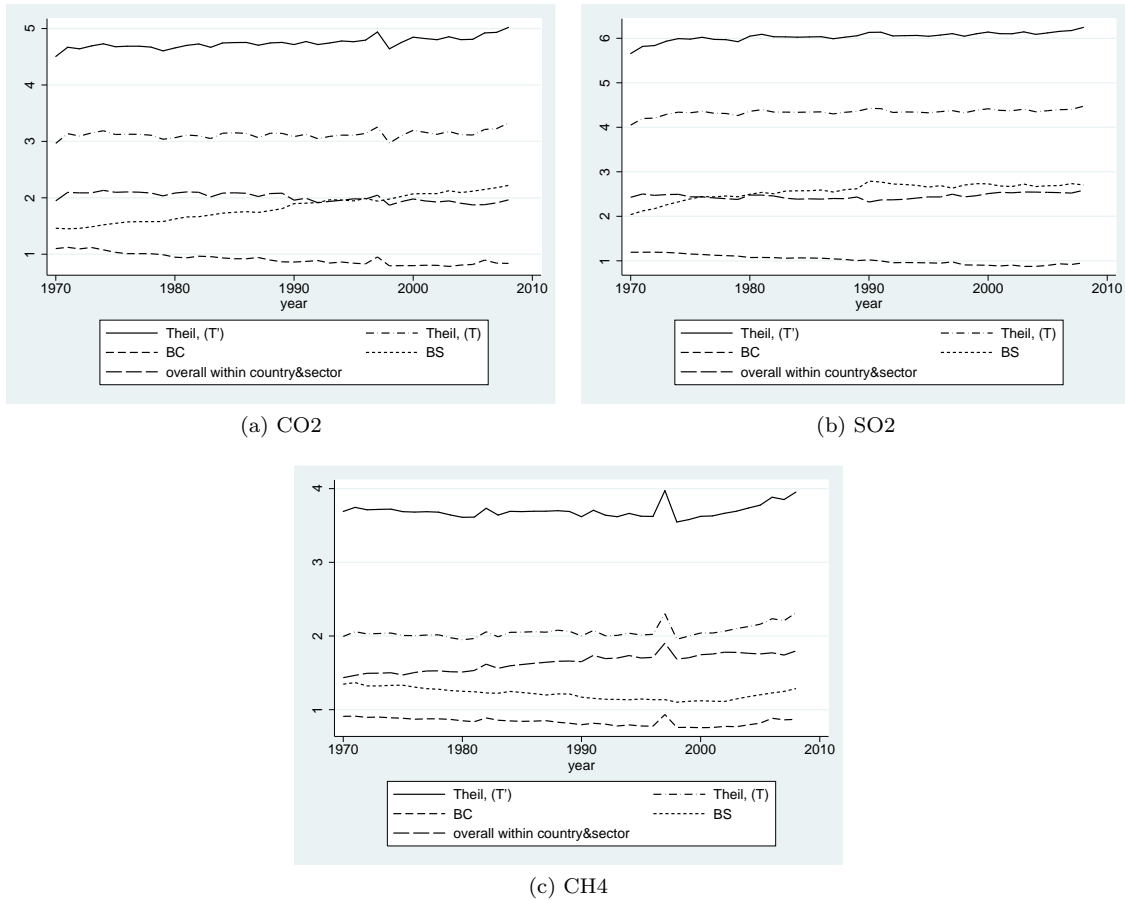


Figure 3: Average decomposition of the Theil index T' , H1

4.4. Where does the damage fall?

As a final exercise, we want to compare produced emissions with potential future damages from climate change, relying on the decomposition provided by equation (9). Local damages from emissions, such as local air pollution take place around the emission source and therefore inequalities of these local damages are the same as our reported inequalities of emission sources. In this section we extend the inequality analysis to damages from climate change and hence limit the analysis to CO_2 and CH_4 . This allows us to investigate the discrepancy between emitters of greenhouse gases and places suffering most from negative effects from climate change.

Three introductory comments are in order. First, generally speaking, damages may come from a variety of phenomena, and are characterized by huge uncertainties. A detailed analysis being out of scope for this paper, we simply focus on a single and very rough proxy for damages: the product between hot days and estimated human population in 2050. The combination of these two

elements in the proxy for damages means that most damages happen in densely populated regions of emerging economies in low latitudes (in particular South Asia and Sub-saharan Africa, see table A1 in the Appendix) rather than in the temperate zones where developed countries locate. This will be important regarding interpretations. Second, as both damages and emissions are linked to demography, we might expect a certain degree of similarity between the two spatial distributions. However, this similarity is far from perfect, because the intensity of the demographical link is conditioned by climate regarding damages, and by economics regarding emissions, the latter effect depending on the type of gas considered (CO_2 or CH_4). Third, due to data availability, we have to re-aggregate emissions at the 1-degree latitude and longitude grid cells (see above data section). This leads to smaller estimates of spatial inequalities in emissions than in the rest of the paper. In other words, to compare emissions with damages, we have to relax one of our main objectives, which is to capture within-country inequalities with the largest possible details. Still, the obtained results suggest this avenue of research may be promising.

The main results are reported in Figure (4). Note first that emission inequalities are not rising any more, but rather decreasing for CO_2 and stable for CH_4 . This is due to the fact that by working at the 1-degree grid cell level, an important part of within-country inequalities has vanished. Second, the Theil index of spatial inequalities in damages, constant as it refers to the assumed situation in 2050, is in between the emission Theil index for the two greenhouse gases considered. As already mentioned above, this is due to the fact that CO_2 emissions are essentially related to fuel combustion, and therefore income levels, while CH_4 emissions are more related to agriculture and fuel extraction, the latter activities being more widespread at the Earth's surface. According to equation (9), this also means that the disparity index (DSP) is larger (smaller) than the over-damage index (OVD) for CO_2 (CH_4).



Figure 4: Decomposing the emission-damage link

For CO_2 , we observe a decreasing trend of all time-varying indices. This is essentially due to the economic catch-up of large emerging economies, in particular in Asia, which makes emissions

more equally spread around the globe. In the case of the *DSP* index, for which the between-region share is larger than 50%, most of the change is due to the decreasing influence of Europe and the Former Soviet Union, and the increasing influence of East Asia.⁸ Although the evolution of the *OVD* index is similar, there are two important differences. First, the major contributors are South Asia and Sub-Saharan Africa, two populous regions which are strongly exposed to heat waves and emit relatively few emissions. Second, for that index, within-country inequalities matter as much as between-region ones, and the major source of change happens within China, where large portions of its territory switch from over-damaged to under-damaged areas *vis-à-vis* their emission shares.

Emissions of CH_4 being less connected to income levels, they are both more equally spread across the Earth's surface and less sensitive to the structural changes that followed the economic convergence of emerging economies in recent decades.

5. Discussion and Conclusion

This paper estimates for the first time spatial inequalities in emissions, using the Theil index at the world wide level and decomposes overall inequalities into between region, between country and within country inequalities. We take full advantage of disaggregated grid-level emission data to identify a number of interesting stylized facts, of which three at least deserve a particular mention.

First, although the political stalemate on climate change has much to do with opposition between large regions, in particular between the old industrialized world and emerging economies, we show that inequalities across regions are the less important component of global spatial inequalities. Inequalities within countries matter much more, as they account between two-third and three-quarter of total inequality, and they are on the rise. After all, this could be expected in a period of globalization that exacerbates both specialization and agglomeration forces. However, and quite surprisingly, this aspect has been fairly neglected by the literature over the last decades, which implies that additional empirical and theoretical work is needed.

Second, we have shown that an important part of within-country inequality is due to differences across sectors. Although the major sectors are generally all related to energy, there are important contrasts between gases. On the one hand, carbon dioxide and sulphur dioxide, with opposite effects on global warming, are both strongly linked with fuel consumption, in particular with the electricity and heat production subsector. This particular subsector is a growing source of spatial inequalities in recent decades, contrarily to emissions from manufacturing and residential, which are more evenly spread geographically, and where abatement activities may have been more prevalent. On the other hand, methane is not linked to fuel consumption, but to fugitive emissions from fuel production and to two other sectors unrelated to energy i.e. agriculture and waste management. In that case, the growing sources of spatial inequalities over the period are coal and gas production, whereas oil production and agricultural soils exhibit a downward trend.

Third, although sectoral differences do account for a substantial part of within-country spatial inequalities, they also leave unexplained an important share of those, in particular in the case of

⁸results at the regional level are not reported due to space constraints. They are available from the authors upon request

methane. This may be due to a number of reasons, from topography to sectoral disaggregation, and calls for further investigation.

To illustrate the link between these stylized facts and the (regulatory) responsibility debate, we compared the Theil indices of spatial inequalities of contemporaneous emissions with the corresponding Theil index of future damages, using very warm days estimated for 2050 as a crude proxy for these damages. It turned out that results depend a lot on the type of gas. For CO_2 , damages are more widespread than emissions, and the social tensions arising from the emission-damage gap tend to soften over time. For CH_4 , damages are more concentrated than emissions, and social tensions remain roughly stable over the last four decades.

These novel results suggest that within-country inequalities matter as much as between-country ones, and that they are on the rise. This should be kept in mind when discussing the efficiency of pollution controls or alternative regulatory strategies. The analysis should also be refined to include larger time-spans or better sectoral coverage.

6. Acknowledgements

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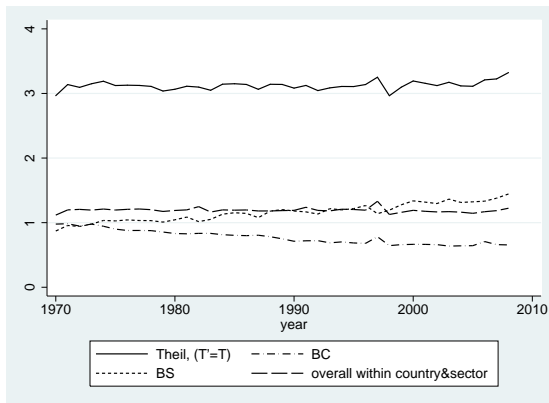
8. Appendix

Table A1: UN-regions
(Note: Numbers might not add up due to rounding)

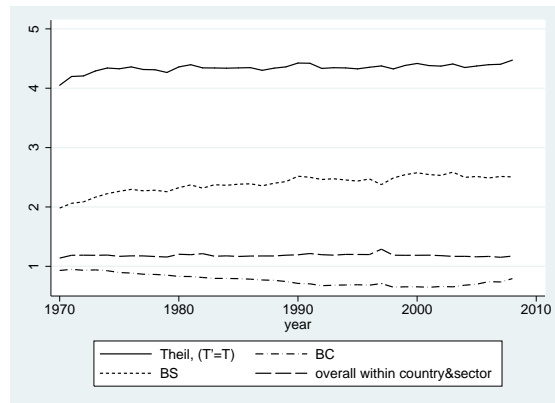
Gas	UN Region Code	UN Region Name	Emission share, 1970	Emission share, 2008	Damage share, 2046
CO ₂	EAA	East Asia	0.0934	0.2748	0.1494
	EUR	Europe (excl. FSU)	0.2173	0.1276	0.0424
	FSU	Former Soviet Union	0.1424	0.086	0.0254
	MNA	Middle East and North Africa	0.0162	0.0445	0.0676
	NAM	North and Central America	0.2531	0.1909	0.0714
	OCE	Oceania and Pacific Islands	0.0091	0.0136	0.0038
	SAM	South America	0.0761	0.0465	0.0491
	SAS	South Asia	0.0476	0.07	0.2829
	SEA	South East Asia	0.0171	0.0703	0.0764
SSA	Sub-saharan Africa	0.1279	0.0759	0.2315	
SO ₂	EAA	East Asia	0.1166	0.3905	0.1494
	EUR	Europe (excl. FSU)	0.2638	0.0781	0.0424
	FSU	Former Soviet Union	0.1734	0.0924	0.0254
	MNA	Middle East and North Africa	0.012	0.0622	0.0676
	NAM	North and Central America	0.3004	0.1188	0.0714
	OCE	Oceania and Pacific Islands	0.0166	0.0265	0.0038
	SAM	South America	0.0384	0.0451	0.0491
	SAS	South Asia	0.0214	0.0959	0.2829
	SEA	South East Asia	0.011	0.0411	0.0764
SSA	Sub-saharan Africa	0.0465	0.0494	0.2315	
CH ₄	EAA	East Asia	0.176	0.2205	0.1494
	EUR	Europe (excl. FSU)	0.1317	0.0708	0.0424
	FSU	Former Soviet Union	0.1049	0.1037	0.0254
	MNA	Middle East and North Africa	0.0377	0.045	0.0676
	NAM	North and Central America	0.1447	0.1098	0.0714
	OCE	Oceania and Pacific Islands	0.0227	0.0198	0.0038
	SAM	South America	0.0834	0.0996	0.0491
	SAS	South Asia	0.1362	0.1453	0.2829
	SEA	South East Asia	0.0617	0.0702	0.0764
SSA	Sub-saharan Africa	0.101	0.1153	0.2315	

Table A2: IPCC sectors
(FC = Fuel consumption; FE = Fugitive emissions; Note: Numbers might not add up due to rounding)

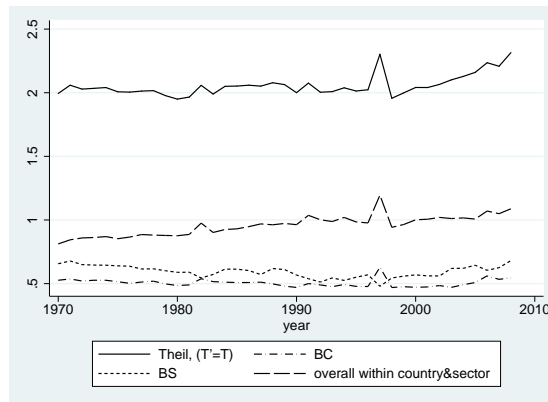
CO2	Sector	IPCC-code	Share of world total, 1970	Share of world total, 2008
Energy	FC in electricity and heat production	1A1a	0.1865	0.3347
	FC in other energy industries & waxes	1A1c+2G	0.0354	0.0276
	FC in manufacturing	1A2	0.1855	0.1459
	FC in international and domestic aviation	1A3a	0.0130	0.0167
	FC in road transportation	1A3b	0.0870	0.1346
	FC in non-road ground transport	1A3c+1A3e	0.0167	0.0084
	FC in international and domestic shipping	1A3d	0.0049	0.0038
	FC in residential	1A4	0.1455	0.0939
	FE from oil production	1B2a	0.0381	0.0238
Industrial processes	Non-metallic mineral processes	2A	0.0211	0.0391
	Chemical processes solvents	2B+3	0.0088	0.0138
	Metal processes	2C	0.0118	0.0053
Agriculture	Agricultural soils	4C+4D	0.0026	0.0032
Land use	Large scale biomass burning	5A+C+D+F+4E	0.2401	0.1470
Waste	Waste incineration	6C	0.0006	0.0009
Others	Fossil fuel fires	7A	0.0024	0.0014
SO2	Sector	IPCC-code	Share of world total, 1970	Share of world total, 2008
Energy	FC in electricity and heat prod & waste	1A1a+6C	0.3653	0.4982
	FC in manufacturing	1A2	0.2183	0.2011
	FC in non-road transportation	1A3a+c+d+e	0.0266	0.0221
	FC in road transportation	1A3b	0.0126	0.0089
	FC in residential	1A4	0.1477	0.0749
	FE & FC in other energy industries	1B1+1B2+1A1b+c	0.0172	0.0355
Industrial processes	Non-metallic paper chemical industry	2B_2D	0.0264	0.0196
	Metal processes	2C	0.1561	0.1128
Agriculture	Agricultural waste burning	4F	0.0019	0.0034
Land use	Large scale biomass burning	5A+C+D+F+4E	0.0249	0.0205
Others	Fossil fuels fires	7A	0.0029	0.0029
CH4	Sector	IPCC-code	Share of world total, 1970	Share of world total, 2008
Energy	FC in energy production & manufacturing	1A1+1A2	0.0123	0.0170
	FC in non-road transportation	1A3a+c+d+e	0.0001	0.0001
	FC in road transportation	1A3b	0.0033	0.0017
	FC in residential	1A4	0.0402	0.0343
	FE from solid fuel	1B1	0.1027	0.1323
	FE from oil production	1B2a	0.0590	0.0414
	FE from gas production	1B2b	0.0596	0.1320
Industrial processes	Industrial process and product use	2	0.0007	0.0007
Agriculture	Enteric fermentation	4A	0.2844	0.2833
	Manure management	4B	0.0363	0.0325
	Agricultural soils	4C+4D	0.1881	0.1043
	Agricultural waste burning	4F	0.0034	0.0044
Land use	Large scale biomass burning	5A+C+D+F+4E	0.0856	0.0499
Waste	Solid waste disposal & incineration	6A+6C	0.0645	0.0812
	Waste water	6B	0.0593	0.0846
Others	Fossil fuel fires	7A	0.0006	0.0004



(a) CO2



(b) SO2



(c) CH4

Figure A1: Average decomposition of the Theil index T^i , H2