How unequal are global emissions?
Alternative measures of spatial inequalities 1970-2008

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University of Neuchâtel, February 2013

PRELIMINARY VERSION

Abstract

Using the EDGAR grid-cell database, we measure spatial inequalities in emissions of CO2, CH4 and SO2 at the world wide level over the 1970-2008 period. It turns out that emissions of methane and carbon dioxide are more disperse than emissions of sulfure dioxide, with a widening gap between the two categories of emissions until the beginning of the years 2000. Since then, all three emission sources tend to become more concentrated. A novel decomposition of the geographical Theil index into a between-country, a between-sector and a within-country&sector component is developed. It shows that between-country inequalities are decreasing, suggesting convergence across countries, at least before 2000. However, they are a minor component of total inequalities, and between-sector inequalities are getting larger in the case of sulfur dioxide, suggesting divergence across sectors. The analysis is complemented by a measure of word-wide centers of gravity of polluting emissions. These alternative estimates confirm that the decreasing trend in spatial inequalities tends to reverse around 2000, and illustrate the South-Eastern shift of polluting emission sources across the sample period.

Keywords: spatial inequalities, structural decomposition, Theil index

We thank Caspar Sauter for excellent research assistance, Stefano Puddu and Jim de Melo for very helpful comments, and the Swiss National Science Foundation for financial support under project 138625. The usual disclaimers apply.

1. Introduction

The different emission sources of gases contributing to global warming are unevenly spread across the Earth surface. This may seem relatively benign given that the major greenhouse gas (GHG), carbon dioxide, is uniformly mixing and thus deploys its effects worldwide. However, another important gas, sulfur dioxide, which has a cooling effect, is more regional in diffusion. Most importantly, the attribution of polluting emissions to specific locations is crucial in determining responsibilities and identifying where actions are needed. Thus, they are critical in international negotiations, and may also shape the national stance in terms of environmental policy. In spite of that, to the best of our knowledge, little effort has been devoted up to day to the actual measurement of spatial inequalities of polluting emissions at the worldwide level.

This paper proposes two simple measures of spatial inequalities in global warming related emissions for three gases, two direct GHG, carbon dioxide (CO2) and methane (CH4) and one acidifying (cooling) gas, sulfur dioxide (SO2). The first indicator is a spatial Theil index, which captures how polluting emissions per square kilometer are unevenly spread across the Earth's surface. This index allows for analyzing structural determinants of inequalities, as it can be decomposed into a between-country, a between-sector and within-country/sector component. Second, we apply the concept of the world's gravity center to polluting emissions, which encapsulates into a single point the myriad sources of emissions (see Grether and Mathys (2010) for an application of that concept to GDP). The trajectory of the projection of this center upon the Earth's surface is an indicator of global shifts in the distribution of GHG.

We apply these indicators using the Emission Database for Global Atmospheric Research (EDGAR, see European Commission (2011)), which provides information over the 1970-2008 period for our three selected gases. At the aggregate level and in a nutshell, it turns out that the two uniformly mixing pollutants (i.e. CO2 and CH4) and the regional pollutant (SO2) tend to become more evenly spread over the period 1970-2000 but that the recent trend is towards larger geographical concentration. Structural decompositions allow to characterizing which forces are shaping these global trends.

Data and methodology are presented first, followed by a discussion of results and a conclusion.

2. Data and methodology

2.1. Data sources

The Emission Database for Global Atmospheric Research (EDGAR, see European Commission (2011)) reports data on pollutants (in tons) per year, IPCC sector and grid cell at a 0.1° level of resolution in terms of latitude and longitude. IPCC sectors depend on the type of pollutant (see table A1 in the Appendix, which also reports the abbreviations used in the diagrams). These data are available for 1970-2008 and have been aggregated at the 1° level of resolution to allow matching with the GEcon database (Nordhaus et al, 2006) to allocate each grid cell to a specific country (see table A2 for country names and abbreviations).[1]

Regarding the measure of cell surface, we could have used the land variables reported by the GEcon database. But this would have biased the results as economic activity also takes place on non-land covered areas (transport, fishing, etc). Thus the surface variable which is used is the total area of the cell, whether partially covered by water or not. This surface depends on the latitude angle (α) of the cell, which varies between 0° (equator) and 89° or -89° (close to the North or South pole). As the surface of a spherical cap is given by $2\pi rh$, where r is the sphere's radius and h the height of the cap, the surface of each grid cell is given by: $2\pi r^2[\sin(\alpha+0.5)-\sin(\alpha-0.5)]/360$ for $\alpha \neq 0$ and by $4\pi r^2[\sin(0.5)]/360$ for $\alpha = 0$. It is assumed that the Earth is a perfect sphere with a radius equal to 6371km.[2]

2.2. Theil index of spatial inequalities

Countries are indexed by c ($c=1,\dots,n$), sectors by k ($k=1,\dots,m$) and the world by w. In country c, for each cell i ($i=1,\dots,N_c$), emissions of sector k are denoted by E_{ick} (in tons), surface area by A_{ic} (in square kilometers), and emissions per square kilometer $e_{ick} \equiv E_{ick} / A_{ic}$. The share of emissions x in total emissions y is noted s_x^y, so that for example s_{ick}^w represents the share

[1] Some oceanic cells did not correspond to any country and were dropped from the analysis. The coverage of the final sample is larger than 99.5% of world emissions for CO2 and CH4, and larger than 97.5% for SO2 emissions. Also, some cells correspond to several countries. We allocate emissions according to the arithmetic average share of each country (averaged over three dimensions: land area, population and gross cell product).

[2] For cells shared between several countries, this surface was split according to the average country shares defined in footnote 1.

of cell i of country c, sector k in world emissions. Year and pollutant subscripts are omitted to ease notation. The world Theil index of spatial inequality is given by:

$$T = \sum_{c=1}^{n}\sum_{k=1}^{m}\sum_{i=1}^{N_c} s_{ick}^{w} \ln\left[\frac{e_{ick}}{e_w}\right] \qquad [1]$$

where e_w are emissions per square kilometer at the world-wide level ($e_w \equiv E_w / A_w$).

Based on the usual properties of the Theil index, equation [1] can be decomposed into the following expressions:

$$T = \sum_{c=1}^{n} s_c^w T_c + \sum_{c=1}^{n} s_c^w \ln\left[\frac{e_c}{e_w}\right] = WC + BC \qquad [2a]$$

$$T = \sum_{k=1}^{m} s_k^w T_k + \sum_{k=1}^{m} s_k^w \ln\left[\frac{e_k}{e_w}\right] = WS + BS \qquad [2b]$$

where T_c and T_k are the Theil indices for country c, sector k ($T_c = \sum_{k}^{m}\sum_{i=1}^{N_c} s_{ick}^{c} \ln\left[\frac{e_{ick}}{e_c}\right]$, $T_k = \sum_{c}^{n}\sum_{i=1}^{N_c} s_{ick}^{k} \ln\left[\frac{e_{ick}}{e_k}\right]$). These expressions illustrate the traditional decomposition into within-country (*WC*) and between-country (*BC*) inequalities ([2a]) or within-sector (*WS*) and between-sectors (*BS*) inequalities ([2b]).

Along similar lines, country and sector-specific indices can be further decomposed into:

$$T_c = \sum_{k=1}^{m} s_{ck}^{c} T_{ck} + \sum_{k=1}^{m} s_{ck}^{c} \ln\left[\frac{e_{ck}}{e_c}\right] = WS_c + BS_c \qquad [3a]$$

$$T_k = \sum_{c=1}^{n} s_{ck}^{k} T_{ck} + \sum_{c=1}^{n} s_{ck}^{k} \ln\left[\frac{e_{ck}}{e_k}\right] = WC_k + BC_k \qquad [3b]$$

where T_{ck}, represents the Theil index for country c and sector k $T_{ck} = \sum_{i=1}^{N_c} s_{ick}^{ck} \ln\left[\frac{e_{ick}}{e_{ck}}\right]$.

A few manipulations lead to a unique decomposition formula of the aggregate Theil index. Fist, by multiplying equation [3a] by s_c^w and summing up over countries, and exploiting equation [2a], one obtains $T - BC = \sum_{c=1}^{n} s_c^w WS_c + \tilde{BS}$, where $\tilde{BS} \equiv \sum_{c=1}^{n} s_c^w BS_c$ is an alternative definition of the between-sector component of global inequalities. Second, by similarly combining [3b] and [2b] one obtains: $T - BS = \sum_{k=1}^{m} s_k^w WC_k + \tilde{BC}$, where $\tilde{BC} \equiv \sum_{k=1}^{m} s_k^w BC_k$ is an alternative definition of the between-country component. Third, after realizing that $\sum_{c=1}^{n} s_c^w WS_c = \sum_{k=1}^{m} s_k^w WC_k = \sum_{c=1}^{n}\sum_{k=1}^{m} s_{ck}^w T_{ck}$, and averaging alternative definitions of the between components, one obtains the following decomposition:

$$T = \overline{W} + \overline{BC} + \overline{BS} \qquad [4]$$

where $\overline{W}$ is the overall within component ($\overline{W} \equiv \sum_{c=1}^{n}\sum_{k=1}^{m} s_{ck}^w T_{ck}$), $\overline{BC}$ the average between-country component ($\overline{BC} \equiv (BC + \tilde{BC})/2$) and $\overline{BS}$ the average between-sector component ($\overline{BS} \equiv (BS + \tilde{BS})/2$).

The first RHS term of equation [4] represents the *within* component of world inequalities, i.e. the inequalities which are due to differences in emission intensities (i.e. tons per square meter) across cells of a given country and a given sector. But even if that component of world inequalities is absent because all cells of a given country-sector combination report identical emission intensities, one must still control for the fact that average emission intensities may vary across country and sectors, which is captured by the other two *between* components of the formula.

2.3 World's emission center of gravity

We apply here the methodology previously introduced for calculating the economic world center of gravity (see the general description in the Appendix to Grether and Mathys (2011)). First the Polar coordinates (i.e. latitude and longitude) of each grid cell are converted into their corresponding Cartesian coordinates (denoted by *x*, *y* and *z*). Second, the coordinates of the world center of gravity (WCG), are obtained as weighted averages of the Cartesian coordinates of each grid cell, using emission shares as weights.

Using the same conventional notations as above regarding subscripts and shares, this leads to calculating the following expressions:

$$x = \sum_{c=1}^{n}\sum_{i=1}^{N_c} s_{ci}^{w} x_{ci}\ ,\ \ y = \sum_{c=1}^{n}\sum_{i=1}^{N_c} s_{ci}^{w} y_{ci}\ ,\ \ z = \sum_{c=1}^{n}\sum_{i=1}^{N_c} s_{ci}^{w} z_{ci} \qquad [5]$$

The length of the associated vector with its origin in the Earth's center is an indicator of the concentration of polluting emissions on the Earth's surface.

The Polar coordinates given by equation [5] can be converted back to Polar coordinates in order to represent the projection of the WCG upon the Earth's surface. The annual distance covered by this projection on the Earth's surface is an indicator of the speed of the changes affecting the spatial distribution of emissions.

3. Results

3.1 Theil indices

The overall Theil indices for the three pollutants are reported Figure 1(a). Three broad comments are in order. First, SO2 emissions are more geographically concentrated than CO2 and CH4 emissions. Second, the evolution of CO2 and CH4 concentration is bumpier than SO2, with two peaks occuring in 1982 and 1997. As can be appreciated by the evolution of emission shares reported in Figure A1 in the Appendix, this is mainly due to large scale biomass burning occuring in Indonesia during these particular years. Third, over the 1970-2000, SO2 concentration remains stable, while CO2 and CH4 emissions become more evenly spread. More recently, since 2000, all emission sources tend to become more concentrated.

< Figure 1: Theil index and decomposition 1970-2008 >

The decomposition of equation [4] allows to unveiling which type of structural forces are shaping these aggregate outcomes. Results appear in the remaining panels of Figure 1. Whatever the pollutant, two stylized facts seem to emerge. First, more than 40% of total spatial inequality is attributable to the within component, which is fairly constant over time. Second, the between-country component is decreasing before 2000. This suggests that economic convergence across countries leads to more evenly spread polluting emissions during that subperiod. By contrast, the evolution of the between-sector component is pollutant-specific. For CO2 and CH4, it is either stable or decreasing, wherehas it is increasing for SO2. This suggests that the overall stability of the inequality index in the case of sulfur dioxide is the result of a compensation between countries becoming more similar on the one hand and sectors becoming more dissimilar on the other hand.

3.2 World's centers of gravity

Projections of the world gravity centers of emissions are reported in Figure 2. The evolution for CO2 and SO2 are broadly similar, with a long Eastward trajectory starting North of Scandinavia in the 70s and approaching Kazakhstan in recent years. The trajectory for CH4 is shorter, mainly located between Russia and the Aral sea, and rather Southward oriented. These trajectories are reminiscent of those reported by Grether and Mathys (2011) for the world economic center of gravity (similar to CO2 and SO2) and for the world demographic center of gravity (similar to CH4). This is not totally surprising, as methane emissions are more linked to labor-intensive primary sector activities, wherehas carbon dioxide and sulfur dioxide emissions are strongly influenced by energy consumption, itself a positive function of aggregate economic activity.

< Figure 2: World centers of gravity 1970-2008 >

As an alternative indicator of geographic concentration, the length of the gravity vector is reported in Figure 3. The downward trend of CO2 and CH4 concentrations is confirmed. What is slightly surprising is the decrease of the SO2 vector's length as well. This may be due to compensations occuring between the two antipodal locations of North America and East Asia. The increase in concentration for all pollutants since 2000 is confirmed.

< Figure 3: Length of the gravity vectors 1970-2008 >

Figure 4 reports the average speed of the projection of the world center of gravity upon the Earth's surface. A 5-year moving average is applied to avoid the extreme values for years 1982 and 1997 already mentioned above. In spite of that smoothing procedure, average speed is a more volatile for CO2 and CH4 emissions than for CO2. Overall, the trend seems to be towards a larger speed, in particular since 2000, suggesting an acceleration of the strucural rebalancing.

< Figure 4: Annual distance covered 1970-2008 >

4. Conclusions

(TO BE COMPLETED)

References

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Nordhaus, W., Azam, Q., Corderi, D., Hood ,K., Makarova, N., Mohammed ,M., Miltner, A. and J. Weiss (2006), "The G-Econ Database on Gridded Output: Methods and Data", data is available at http://gecon.yale.edu/

Appendices

Table A1: IPCC sectors, codes and abbreviations

CH_4 data:

Sector	IPCC-code
Agricultural waste burning	4F
Energy manufacturing transformation	1A1+1A2
Enteric formation	4A
Fugitive from solid	1B1
Gas production and distribution	1B2b
Industrial process and product use	2
Manure management	4B
Oil production and refineries	1B2b
Residential	1A4
Road transportation	1A3b
Solid waste disposal	6A+6C
Waste water	6B
Agricultural soils	4C+4D
Non-road transportation	1A3a+c+d+e
Fossil fuel fires	7A
Large scale biomass burning	5A+C+D+F+4E

CO_2 data:

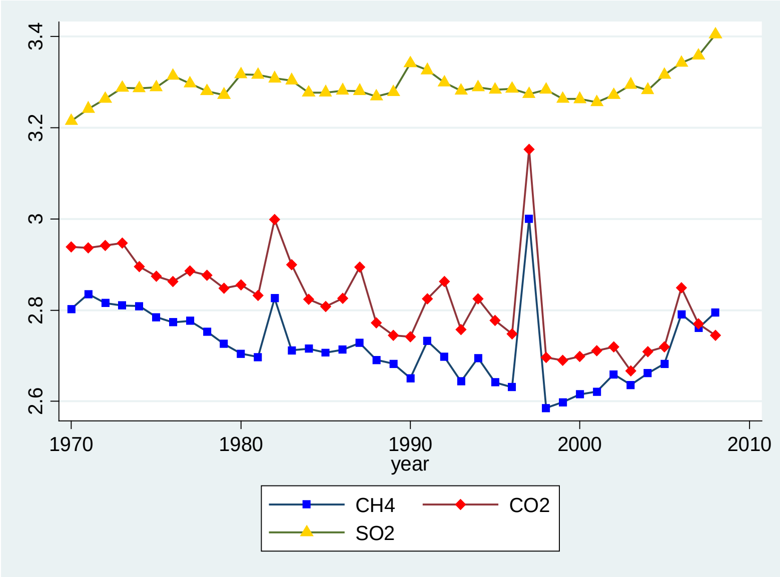
Sector	IPCC-code
Oil production and refineries	1B2a
Residential	1A4
Road transportation	1A3b
Solid waste disposal	6A+6C
Agricultural soils	4C+4D
Fossil fuel fires	7A
Large scale biomass burning	5A+C+D+F+4E
Chemical processes solvents	2B+3
Combustion in manufacturing industry	1A2
Energy industry	1A1a
International and domestic aviation	1A3a
Metal processes	2C
Non-metallic mineral processes	2A
Non-road ground transport	1A3c+1A3e
Transformation non-energy use	1A1c+2G
International and domestic shipping	1A3d

SO2 data:

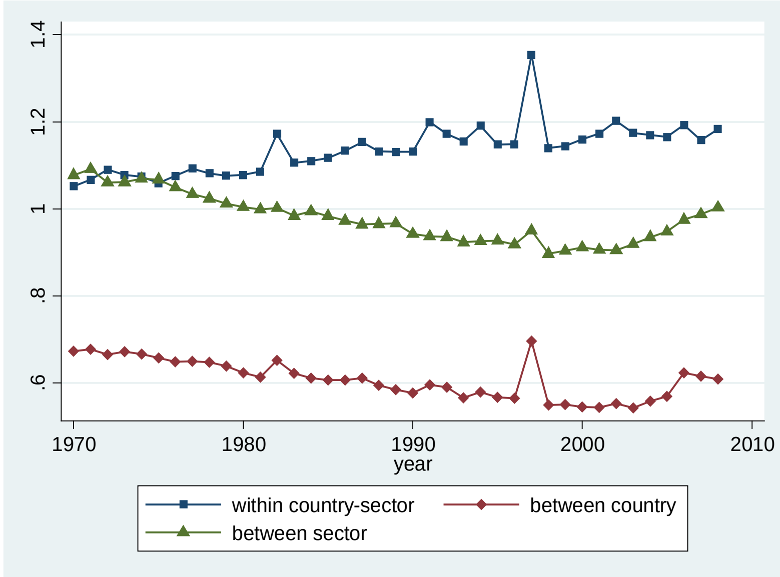
Sector	IPCC-code
Combustion in manufacturing industry	1A2
Residential	1A4
Road transportation	1A3b
Non-road transportation	1A3a+c+d+e
Fossil fuels	7A
Large scale biomass burning	5A+C+D+F+4E
Metal processes	2C
Energy industry and waste incinerator	1A1a+6C
Non-metalic paper chemical industry	2A+2B+2D
Transformation, oil production and refinering	1B1+1B2+c+1A1b+c
Agricultural waste burning	4F

Table A2: Country names and abbreviations (TO BE COMPLETED)

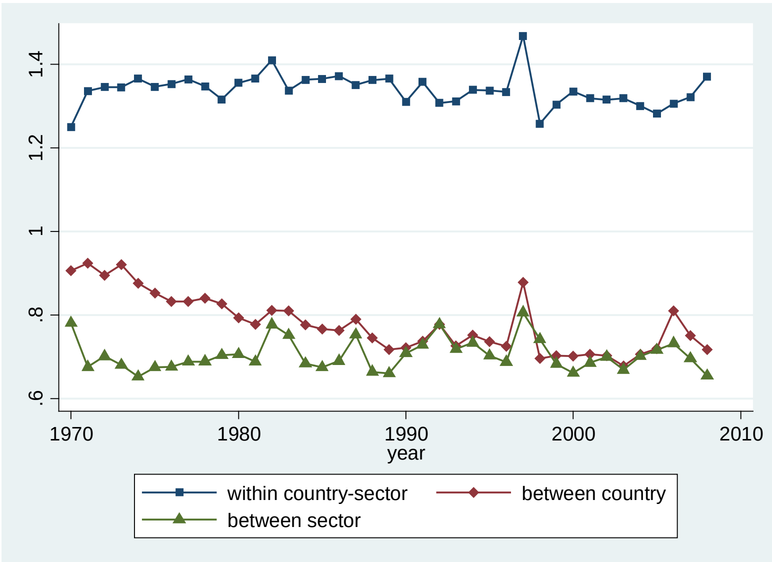
Figure 1: Theil index and decomposition 1970-2008



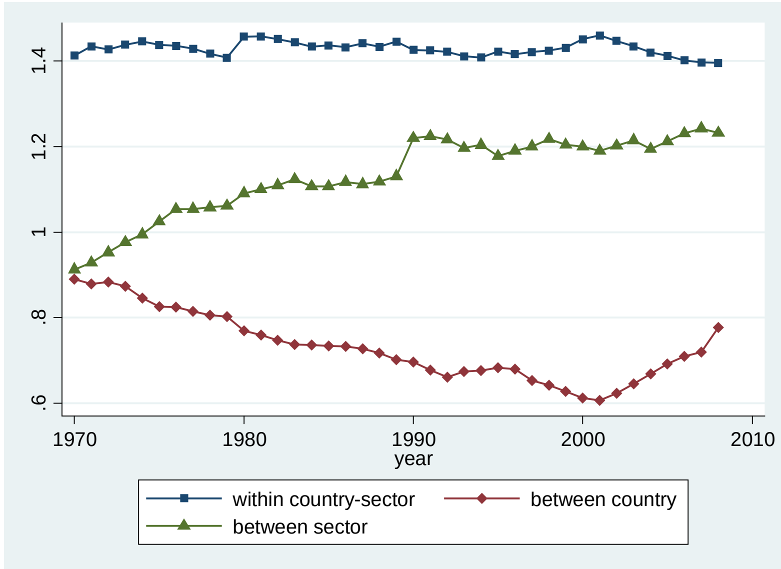
(a) Overall index



(b) CH4



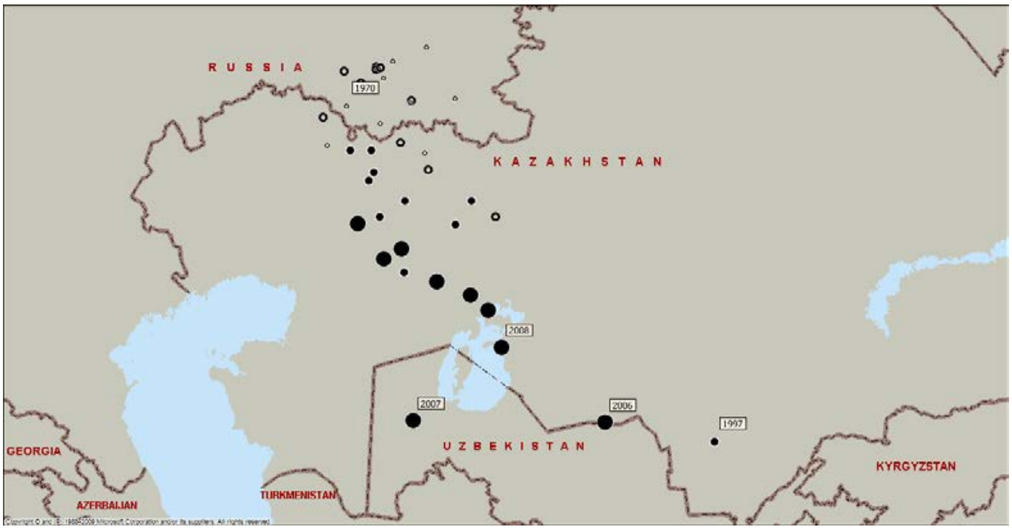
(c) CO2



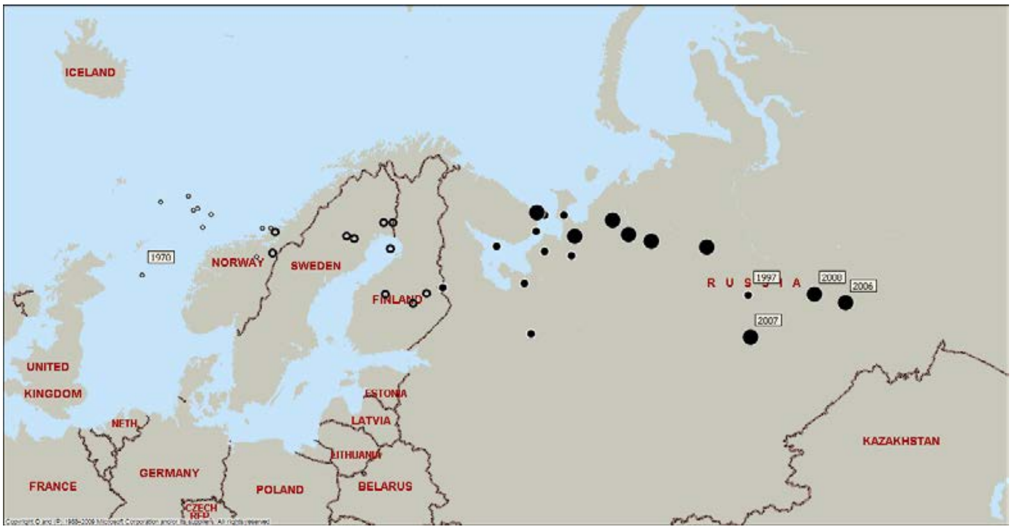
(d) SO2

Figure 2: World centers of gravity 1970-2008

CH4



CO2



SO2

o : 1970-1979 ○ : 1980-1989 • : 1990-1999 ● :2000-2008

Figure 3 : Length of the gravity vectors (concentration)

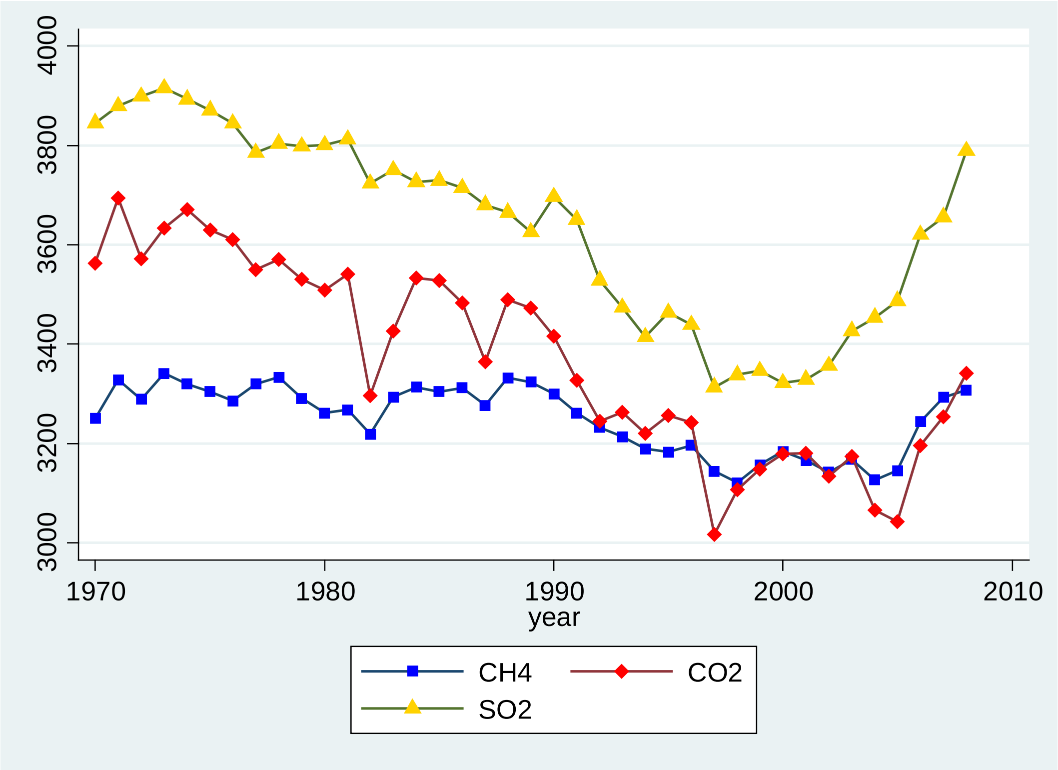
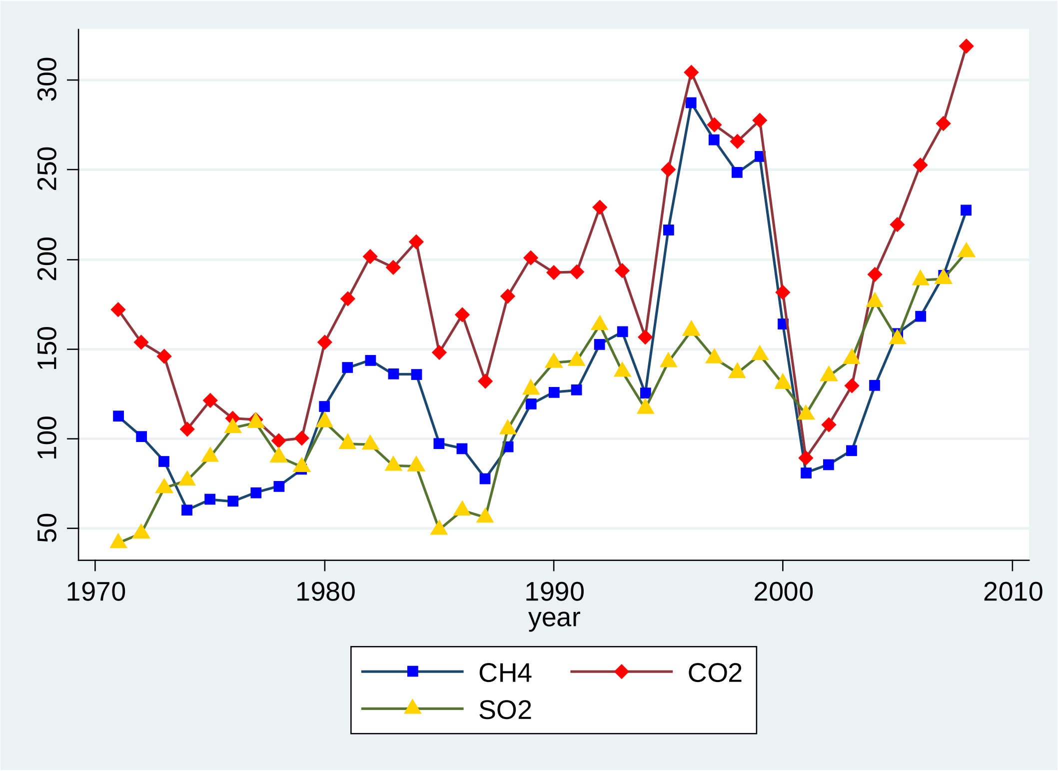


Figure 4: Annual distance covered (speed of adjustment)



Note: moving averages over 5 years

Figure A1(a): Country shares 1970-2008

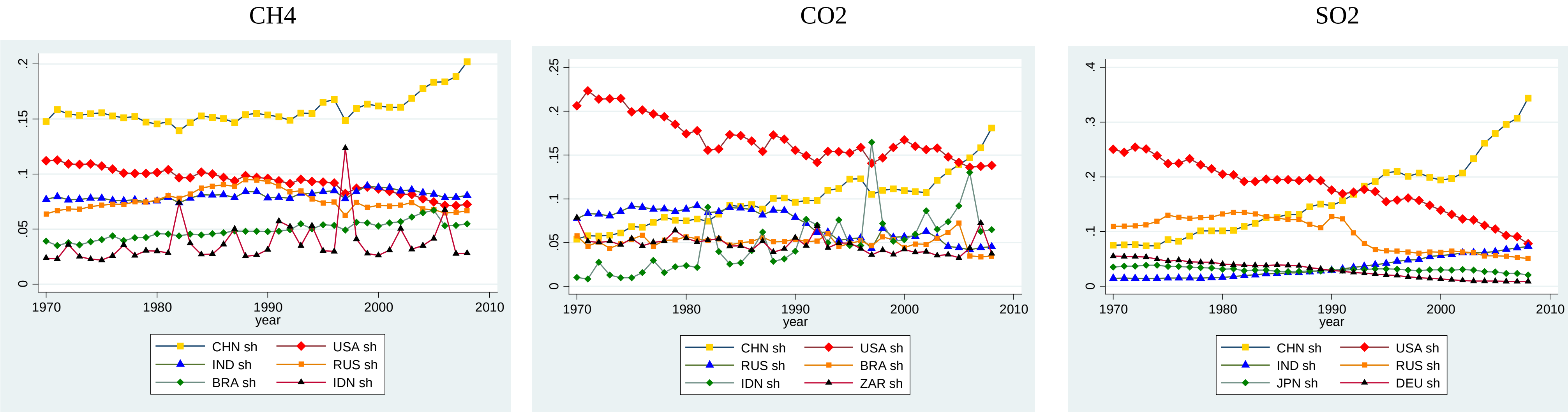


Figure A1(b): Sector shares 1970-2008