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Global sulfur emissions from 1850 to 2000

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Abstract

The ASL database provides continuous time-series of sulfur emissions for most countries in the World from 1850 to 1990, but academic and official estimates for the 1990s either do not cover all years or countries. This paper develops continuous time series of sulfur emissions by country for the period 1850–2000 with a particular focus on developments in the 1990s. Global estimates for 1996–2000 are the first that are based on actual observed data. Raw estimates are obtained in two ways. For countries and years with existing published data I compile and integrate that data. Previously published data covers the majority of emissions and almost all countries have published emissions for at least 1995. For the remaining countries and for missing years for countries with some published data, I interpolate or extrapolate estimates using either an econometric emissions frontier model, an environmental Kuznets curve model, or a simple extrapolation, depending on the availability of data. Finally, I discuss the main movements in global and regional emissions in the 1990s and earlier decades and compare the results to other studies. Global emissions peaked in 1989 and declined rapidly thereafter. The locus of emissions shifted towards East and South Asia, but even this region peaked in 1996. My estimates for the 1990s show a much more rapid decline than other global studies, reflecting the view that technological progress in reducing sulfur based pollution has been rapid and is beginning to diffuse worldwide.

Keywords: Pollution; Acid rain; Aerosols; Climate change; Estimates; Inventory

1. Introduction

Data on sulfur emissions are important for analyzing and understanding three important environmental problems: local air pollution and smog, acid rain and dry deposition, and global climate change. In the latter case, sulfate aerosols derived from emissions have a cooling effect on a continental scale due to the reflection and absorption of radiation by the aerosol particles. The additional information provided by the most recent temperature data is critical to the power of tests to detect and attribute climate change (Kaufmann and Stern, 1997). Exploiting these data requires up to date data on the variables that may be causing changes in climate. Hence, developing up to date time series and spatial data sets of sulfur emissions is vital to the investigation of global change.

ASL and Associates (ASL and Associates, 1997; Lefohn et al., 1999) produced a data base of sulfur emissions for individual countries for the period

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1850–1990, which has been used in a number of climate studies (e.g. Stern and Kaufmann, 2000). I refer to this source in the following as ''ASL''. These estimates were superior to all previous estimates published in the academic literature and by national and international agencies (e.g. Cullis and Hirschler, 1980; Möller, 1984; Varhelyi, 1985; Dignon and Hameed, 1989; Hameed and Dignon, 1992; Spiro et al., 1992; Kato, 1996) in terms of their spatial and temporal resolution and extent. However, the cut-off point of 1990 is an impediment to continued use of these estimates in climate change research.

Smith et al. (2001) developed estimates of global sulfur emissions from 1980 to 2000. But they do not provide data for individual countries, only regions (gridded data is available for 1990) and estimates are only given for five year intervals. Additionally, the estimate for 2000 is a forecast and is not based on any observed data. Also, by comparison with Carmichael et al. (2002) and other sources of information on developments in Asia, they underestimate the control of sulfur emissions in East Asia and particularly in China. Olivier and Berdowski (2001) provide country by country estimates for 1990 and 1995 for all countries in the World. These are used to develop some of the estimates in this paper and are referred to as ''Edgar''.

This paper aims to provide global and individual country estimates of sulfur emissions for each year from 1991 to 2000 combined with estimates from existing published sources for 1850–1990. Estimates are obtained in two ways. For countries with published data I compile the data from the available sources. For the remaining countries, depending on the availability of data, I use the econometric emissions frontier model developed by Stern (2002), an environmental Kuznets curve model (see Stern and Common, 2001), or simple interpolation or extrapolation of the growth rate of emissions. Time series are also provided for the period from 1850 to 1990 based on these estimates, the ASL database, and a variety of other published sources for the years 1970–1990. The preferred series uses the individually published estimates for years before 1990 where these are available in North America, Europe, and Asia. For earlier years the growth rates in the ASL database are used. Finally, the main movements in emissions in the 1990s are discussed and the estimates in this study compared to those of other studies.

I emphasize that the majority of datapoints and the large majority of emissions estimates are accounted for by previously published data though that data has been adjusted in many cases to develop smooth time series. Most of the estimates produced by the econometric models are for small emitters or interpolate the years 1998–1999 for East Asia and 1991–1994 for parts of the former Soviet Union.

2. Estimating emissions for the 1990s

2.1. Compiling published estimates

Published estimates for the 1990s are available in time series form for around 70 countries in Europe, the former Soviet Union, North America, East and South Asia, Australia, and New Zealand. These are used in preference to any other estimates. For the remaining countries, Olivier and Berdowski (2001) (I refer to this source as ''Edgar'') have computed estimates for 1990 and 1995. These are used for these dates for most other countries. In a few cases, raw ASL estimates are used for 1990. The sources are described in detail in Appendix A. The Asian source is referred to in the following as Carmichael et al., the source for Europe (including the former Soviet Union) and Canada is referred to as EMEP, and the US and Australian sources are referred to as EPA and AGO, respectively. Husain (1994) provides an estimate of emissions from the oil fires in Kuwait in 1991. All published estimates are first converted to the common unit of metric tonnes (Mg) of sulfur per annum. Appendix C describes the treatment of countries that split apart or merged or faced other boundary changes, as well treatment of the Russian Federation and Turkey, countries that cross the Europe–Asia boundary. The remainder of this section describes the three methods used to estimate emissions datapoints (year, country) without previously published data.

2.2. Estimating emissions in the remaining countries and years

Appendix D lists the methods used in each country and year. These methods were used to determine the growth rate of emissions. When used to interpolate estimates, for example between the 1990 and 1995 Edgar estimates, the rates were adjusted by subtracting or adding a constant to each year so that the final period level was predicted correctly. This is equivalent to adjusting the rate of technological change, which is assumed before adjustment to simply be the average rate in the previous period.

2.2.1. Econometric emissions frontier method

The econometric emissions frontier model described in Stern (2002) is used to estimate emissions with an expanded number of explanatory variables, countries, and years and the updated data described in Appendices A and B. The model is based on a multi-output production function that produces pollution emissions in addition to desirable economic outputs. This model estimates sulfur emissions S in country i and year t using the following function of economic outputs y and inputs x:

$$S_{it} = \gamma_i A_t \prod_{j=1}^{J} y_{jit}^{\alpha_j} \left(\sum_{k}^{K} \beta_k x_{it} \right) \varepsilon_{it} \quad (1)$$

where the α's, β's, γ's, and A's are regression coefficients to be estimated using non-linear panel data estimation and ε is a random error term. The outputs are value-added in services, manufacturing, non-manufacturing industry, and agriculture in country i and year t. The inputs are the primary energy inputs: coal, refined oil, natural gas, hydroelectric power, nuclear energy and biomass; primary crude oil supply which is equal to oil refined in country; and primary smelting of copper, lead, zinc, and nickel. The α_j coefficients sum to zero. γ_i represents a country specific effect that models the relative efficiency of each country compared to the best practice frontier and A_t a time specific effect that is intended to model technological change.

The model assumes that the relative effects of each of the variables are common to all countries but emissions intensity in each country can differ by the factor γ_i. This factor accommodates for the effects of omitted variables and for differences in the degree of adoption of emissions reducing technology A in different countries. γ_i can be considered as reflecting the relative distance of each country from the best practice frontier. Also, it is assumed that emissions-specific technological progress is common to all countries. The actual innovations adopted at any time may be different in different countries. The level of total factor productivity in producing outputs y is different in each country and across time. The model assumes that other inputs such as capital and labor do not have an effect on emissions, ceteris paribus. A referee suggested including data on technology or abatement expenditures. While theoretically attractive, this would severely limit the data points that could be used and render the model useless for predicting emissions for datapoints without observations on those variables. A linear functional form is chosen for the inputs because some inputs are zero in some countries (e.g. nuclear power, copper smelting, etc.). This function imposes constant returns to scale, infinite substitutability between inputs, and non-diminishing returns to each input. The power function of outputs is linear in logarithms and is very common in econometric applications. Zero degree homogeneity is imposed on this function as increasing output in the absence of increasing inputs should not affect the production of emissions. Instead such a change indicates an increase in total factor productivity.

The sample includes data for 73 countries for the period 1971–1990. The results of the econometric estimation are presented in Table 1. It is important to note that these effects represent partial derivatives. Therefore, a small coefficient on copper smelting, for example, could indicate that the ore types and technologies differ substantially across countries and that this effect is largely picked up in the country effects. Similarly, the refined oil coefficient is negative and reflects a relative effect holding oil refining (crude oil) constant. Also, all effects are relative to the base case, which is Algeria in 1971. Given these caveats, the overall pattern of results is somewhat expected with large effects from coal use and oil refining. The total technological change effect is a 40% decline in emissions, ceteris paribus, from 1974 to 1990, which is around double my previous

Table 1
Econometric emissions frontier model

Variable	Coefficient	Standard error
Coefficient estimates		
Agricultural GDP	−0.0854	0.0309
Manufacturing GDP	0.1641	0.0361
Non-manufacturing GDP	0.0003	0.0231
Coal	9.2366	1.4608
Refined oil	−0.0177	0.0026
Natural gas	1.4779	0.4485
Hydropower	0.4275	0.3089
Nuclear power	−2.2298	0.2866
Biomass	1.2638	0.2006
Crude oil	4.7223	0.3724
Copper smelting	0.0625	0.0284
Lead smelting	0.1302	0.0434
Nickel smelting	0.2105	0.0779
Zinc smelting	−0.0265	0.0623
Maximum time effect (1974)	0.006534	0.03708
Minimum time effect (1990)	−0.3929	0.0407
Maximum country effect (Zambia)	2.8932	0.3268
Minimum country effect (Singapore)	−0.9396	0.1327
Statistics		
R bar squared	0.985	
Pedroni cointegration test	−3.9033	[a]
Average change in time effect	−2.07% p.a.	

Sample: 1971–1990, Algeria, Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China Colombia, Costa Rica, Cote D'Ivoire, Denmark, Dominican Republic, Ecuador, Egypt, El Salvador, Finland, France, Gabon, Germany, Ghana, Greece, Guatemala, Honduras, Hong Kong, India, Indonesia, Iran, Ireland, Israel, Italy, Jamaica, Japan, Jordan, Kenya, Korea South, Kuwait, Luxembourg, Malaysia, Mexico, Morocco, Mozambique, Nepal, Netherlands, New Zealand, Nicaragua, Nigeria, Norway, Paraguay, Peru, Philippines, Portugal, Saudi Arabia, Senegal, Singapore, South Africa, Spain, Sri Lanka, Sweden, Switzerland, Taiwan, Tanzania, Thailand, Trinidad and Tobago, Tunisia, Turkey, United Kingdom, USA, Uruguay, Venezuela, Zambia, Zimbabwe.

[a] The significance level of the Pedroni cointegration test is 0.000095.

estimate (Stern, 2002). The most emissions efficient country in the sample is Singapore and the least is Zambia, which makes sense. The implied relative efficiencies are very large. Singapore emits 46 times less sulfur, *ceteris paribus*, than Zambia. The Pedroni cointegration statistic is a model diagnostic that rejects the hypothesis that the relation between the non-stationary variables in the model is spurious and purely due to stochastic trending behavior in the variables included in the model.

To project emissions into the 1990s, I assume that the rate of change in the time specific effect, ΔA_t, in the prediction period is the same as the mean over the estimation period except where published data allowed the fine tuning of the rate of technological progress. For example, for the East Asian countries, I use this model to interpolate estimates for 1998 and 1999.The rate of technological progress is set so that emissions in 2000 are predicted correctly given the 1997 base year. For many other countries, I interpolate between the Edgar estimates for 1990 and 1995.

2.2.2. Environmental Kuznets curve method

When insufficient data are available to use (1) to predict emissions, I use an environmental Kuznets curve model (EKC). An environmental Kuznets curve is a quadratic in logarithms relating emissions or concentrations of a pollutant to national income per capita. Such a model also includes country and time specific effects with the latter representing technological progress in reducing emissions. Sulfur emissions in year t and country i are given by

$$\ln(S/P)_{it} = \alpha_i + \gamma_t + \beta_1 \ln(Y/P)_{it} + \beta_2(\ln(Y/P)_{it})^2 + \varepsilon_{it} \quad (2)$$

where *Y*/*P* is GDP per capita in 1995 US dollars adjusted for purchasing power parity (PPP dollars). *S*/*P* is sulfur emissions per capita in kilograms *S*. The α_i are country specific constants or effects and the γ_t are time specific constants or effects that represent technological progress in reducing emissions that is common to all countries. ε_{it} is a random error term. The EKC model assumes that the percentage response of emissions to a given percentage change in per capita income is equal for all countries at a common income level. Also, it is assumed that technological progress occurs at a common rate across all countries but that the level of technology in each country can differ by a fixed proportion. Furthermore, it assumes that only these income and time effects are needed to explain the distribution of emissions across countries and time.

The sources for the GDP and population data are described in Appendix B. The sample includes 82 countries for the period 1971–1990. The results are presented in Table 2. As estimated by Stern and Common (2001) and Stern (2002) with different data and samples, the EKC is monotonic in income within the income range of the sample as the turning point where emissions begin to decline with increasing income is at $79 500 per capita. The effect of a one percent increase in income is a 0.87% increase in emissions at the sample mean. The reduction in emissions due to time effects is more than twice as great as in my previous estimates for this period—a 45% total reduction, ceteris paribus. The most efficient country is Hong-Kong and the least Zambia, which are not surprising results.

Table 2
Environmental Kuznets curve estimate

Variable	Coefficient	Standard error
Coefficient estimates		
ln(GDP/P)	3.6128	0.5892
$(\ln(GDP/P))^2$	−0.1601	0.0341
Maximum time effect (1971)	0.2033	n.a.
Minimum time effect (1990)	−0.2477	n.a.
Maximum country effect (Zambia)	−12.76	n.a.
Minimum country effect (Hong Kong)	−20.45	n.a.
Statistics		
R bar squared	0.1012	
Hausman statistic	4.1477 ($p = 0.1256$)	
Pedroni cointegration test	−3.6570 ($p = 0.000255$)	
Turning point	$79 499	
Mean income elasticity	0.87	
Average change in time effect	−2.37% p.a.	

Sample: 1971–1990, Algeria, Argentina, Australia, Austria, Belgium, Bolivia, Brazil, Canada, Chile, Colombia, Costa Rica, Cote D'Ivoire, Cyprus, Denmark, Dominican Republic, Ecuador, Egypt, El Salvador, Ethiopia, Finland, France, Gabon, Germany, Ghana, Greece, Guatemala, Honduras, Hong Kong, Hungary, India, Indonesia, Iran, Ireland, Israel, Italy, Jamaica, Japan, Jordan, Kenya, Korea South, Kuwait, Luxembourg, Malaysia, Mexico, Morocco, Mozambique, Namibia, Nepal, Netherlands, New Zealand, Nicaragua, Nigeria, Norway, Panama, Paraguay, Peru, Philippines, Portugal, Romania, Saudi Arabia, Senegal, Singapore, South Africa, Spain, Sri Lanka, Sweden, Switzerland, Syrian Arab Republic, Taiwan, Tanzania, Thailand, Trinidad and Tobago, Tunisia, Turkey, United Kingdom, USA, Uruguay, Venezuela, Zaire, Zambia, Zimbabwe.

The Hausman statistic indicates that any potential omitted variables problem is not significant in this case as it does not reject the hypothesis that the explanatory variables are not correlated with the time and country effects (see Stern, 2004 for discussion). The cointegration test statistic (Pedroni, 1997) rejects the null hypothesis of no cointegration, which means that the estimated relation is statistically valid despite the stochastically trending nature of the variables involved (see Stern, 2004).

Emissions are projected using the sample mean rate of technological progress of −2.37% per annum. Raw predictions were modified as necessary as described for the emissions frontier model.

2.2.3. Growth rate method

In cases where the data to use even model (2) to predict emissions are not available, I use the mean growth rate of sulfur emissions in the previous decade in the country in question to estimate the growth in emissions. In other cases where data for some years are available values are interpolated using a simple linear curve.

2.3. Validation exercise for the emissions frontier model

To check the validity of the approach for estimating emissions, I applied the emissions frontier model method to predicting emissions in all OECD countries with published emissions for all years from 1991 to 2000 and sufficient data to forecast the frontier model for each year. These countries are: Australia, Austria, Belgium, Denmark, Finland, France, Germany, Greece, Italy, Japan, Luxembourg, Netherlands, Portugal, Spain, UK, and USA. Fig. 1 compares predicted and published emissions. The fit seems very good. Of course, for each country, the 1990 and 1995 emissions are predicted exactly due to the "fine tuning" method used. The largest residuals are for Denmark for recent years (below the main trend) and Finland (above the trend). Apparently the rate of technological change accelerated significantly in the latter years in Denmark and slowed in Finland. In a regression of the logarithm of published emissions on the logarithm of predicted emissions the R-squared is 0.99 and the slope coefficient is insignificantly different from unity ($t = 0.19$). A tougher test is comparing the predicted and published percentage changes from year to year. These are presented in Fig. 2. The R-squared is 0.43. However, the slope coefficient is 0.79, which is significantly less than unity ($t = -2.81$). This could be partly due to measurement error bias or accelerated technical change in the second half of the 1990s. The biggest percentage changes and errors occur in Luxembourg and Denmark. Errors are much smaller for the major emitters.

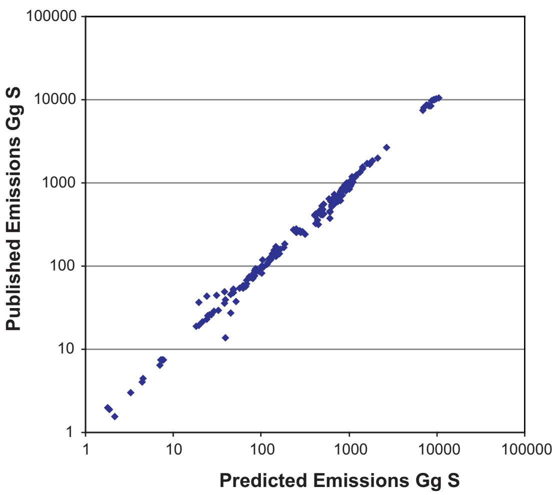

Fig. 1. Predicted and published emissions for sixteen OECD countries, 1990–2000.

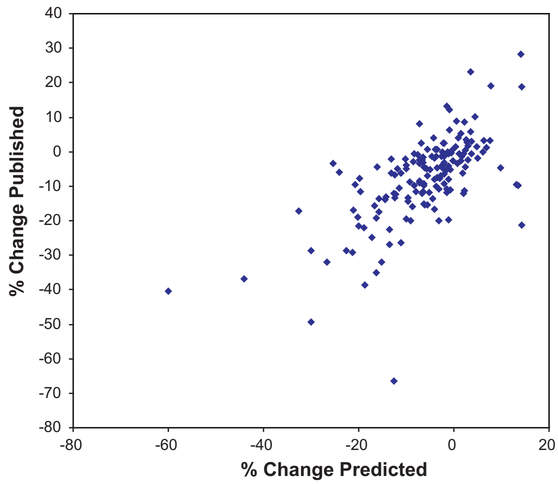

Fig. 2. Predicted and published percentage changes in emissions: sixteen OECD countries 1991–2000.

3. Estimates for 1850–2000

Though the focus in this paper is on the estimates for 1991–2000, I also provide estimates for the period 1850–1990. The primary source for this period is the ASL database. However, my preference is for the alternative published estimates where they are available. This is because individual country estimates take account of more detailed data than used by ASL. This is a point conceded by Lefohn et al. (1999). For example, ASL assume that the sulfur content of fuels is constant in each country over time, with the exception of the US. ASL estimates for many developing countries do not include emissions from oil burning and, therefore, are lower than other estimates. Additionally, Street's et al. (2000b) show that their estimates for Asia are congruent with official estimates for those countries and previous estimates for the region by for example Kato (1996).

My aim is to produce continuous and reasonably smooth time series of emissions for each country for use in global climate modeling. I achieve this with the following methods:

(a) There are numerous periods of missing data for specific countries in the ASL database and I interpolate these using a simple linear function.

(b) For the vast majority of countries that have alternative published data for the 1990s or before I use the growth rates of emissions implied in the ASL database to extrapolate estimates backward from the first year with such estimates. For the other countries I use unmodified ASL data.
(c) I also extrapolated estimates for each country back in time to 1850 for countries without ASL data for those years assuming that the growth rate in each year in each such country was the average for its region. I use the following regions:
W. Europe, E. Europe and the Soviet Union, Middle East and North Africa, Asia, Africa, Oceania, Anglo America, Latin America.

The composition of the regions is described in Appendix D. This problem was solved iteratively in Microsoft Excel.

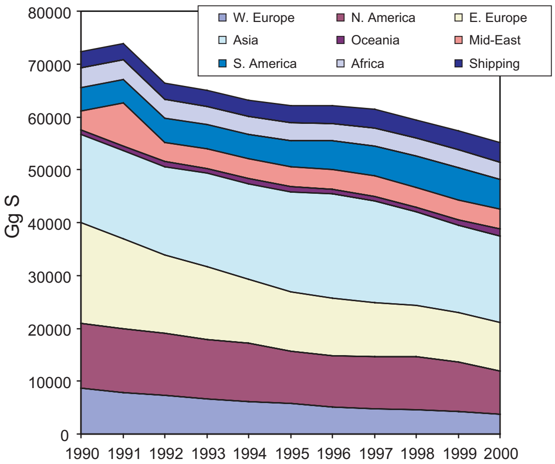

Fig. 4. Global and regional sulfur emissions 1990–2000.

4. Trends and developments in emissions

The detailed estimates are available at:
http://www.rpi.edu/~sternd/datasite.html

Fig. 3 presents the global and regional totals for the full 1850–2000 period. Maximum emissions were reached in 1989 at 74.1 Tg (million tonnes). An initial peak occurred in 1980 at 73.2 Tg. The recession following that year and the beginning of a secular decline in Western Europe (North America peaks in 1973 but Europe was only 200 Gg (thousand tonnes) below its 1973 level in 1980) lead to a decline in total global emissions in the first half of the 1980s. Emissions then recovered to the slightly higher high in 1989 mainly as a result of rising emissions in Asia (Fig. 6).

After 1989 a precipitous decline sets in, only punctuated by the Kuwait oil fires, which contributed around 4.7 Tg of sulfur (Husain, 1994), as the Soviet Union and Eastern European economies collapse. Fig. 4 presents a close up view of the 1990s showing the relentless fall over the decade. Asia peaks in 1996 and starts to add to the decline. The effects of the Asian crisis in 1997 obviously have an impact, but changes in China appear to be more deep-seated (Street's et al., 2001; Dasgupta et al., 2002; Stern, 2004). The Chinese government has adopted a variety of policies aimed at reducing emissions from cars, powerplants, industry, and households. Additionally, structural changes in the economy are reducing energy intensity (Zhang, 2002). Carmichael et al. (2002) also estimate that emissions continued to fall through 2000 in many countries including India, Indonesia, South Korea, Thailand, and Vietnam.

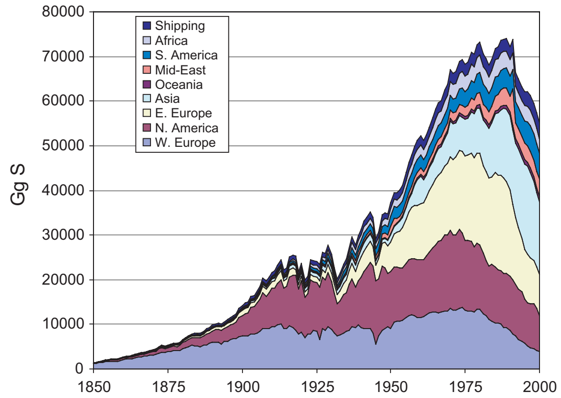

Fig. 3. Global and regional sulfur emissions 1850–2000.

Thus after going through a topping out period in the 1970s and 1980s the direction of change has reversed on a decadal scale. At the regional level, the 1990s continue the process of change already evident in the previous 140 years. In 1850 Europe accounted for 88% of non-shipping emissions (Fig. 5). The locus of emissions shifted first to North America, then the share of Eastern Europe and the Soviet Union increased followed by the rise of Asia as a substantial emitter. In the 1990s Asia became the largest source area. Chinese emissions overtook US emissions in 1987 to make China the largest single emitter. Chinese emissions peak in 1996 and then fall. Fig. 5 also shows that emissions in the minor regions—Africa, South America, Middle East, and Oceania are an increasing share of global emissions and this trend accelerated in the 1990s. In fact since 1996 Asia's share of global emissions started to decline.

Table 3 lists the peak year of emissions and emissions shares in each region. The first four regions were each the World's largest emitter in their peak year. Asia is still the largest emitter in 2000—none of the other four regions has yet emerged as a new focus of pollution. Over

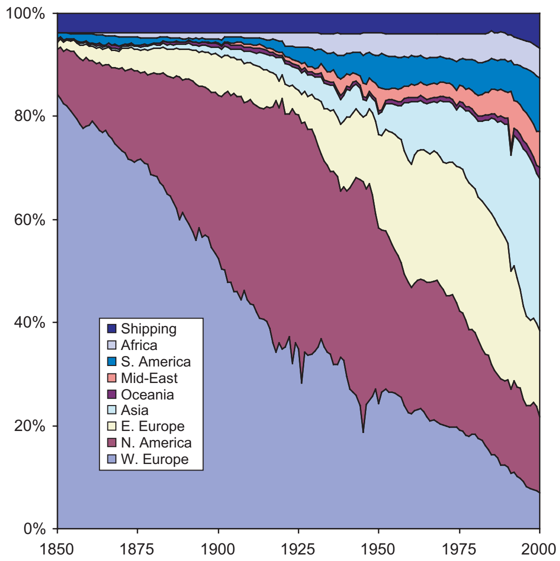

Fig. 5. Shares of global sulfur emissions.

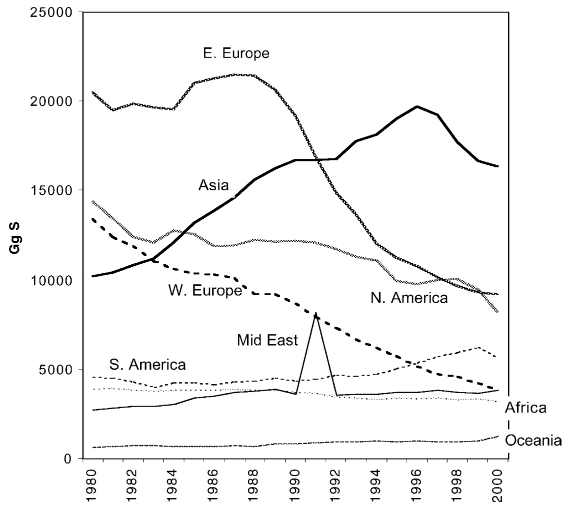

Fig. 6. Regional trends in the 1980s and 1990s.

time the distribution of emissions is becoming more even across the world.

Fig. 6 presents regional estimates for just the 1980s and 1990s in order to show more detail of the regional changes. Emissions in Western Europe are now less than in South America and about the same as in the Middle East. In fact, the UK now has lower emissions than in 1850 when it emitted more than half the global total. British emissions have been declining since 1955.

Emissions in Oceania are dominated by Australia and are showing a relentless increase despite Australia's developed country status. Australia does not have near neighbors and most power stations, etc. are in the narrow strip of development along the south and east coasts between the arid interior and the ocean in either a dominant westerly (in Victoria, for example) or easterly (in NSW and Queensland) air flow. Pressure to reduce emissions in North America, Europe, and East Asia seems to have come mainly as a result of transboundary or inter-regional pollution problems and such pressure is largely absent in the Australian case.

Developments in both Australia and China contradict the environmental Kuznets curve theory that proposes that emissions are a quadratic function of national income per capita. According to this theory emissions should be rising in developing countries and falling in developed countries. There is extensive other evidence to refute this idea first made popular in the early 1990s (Stern, 2004). In this paper, I use an EKC model as a last resort to estimate emissions where there is minimal data available. The empirical estimate reported above also contradicts the "EKC theory" that emissions will decline after income reaches moderate levels.

The reversal in emissions in Fig. 1 might be thought to have negative implications for future climate change. That is, if sulfate aerosols will decline in future (and have already declined) their effect in offsetting future

Table 3
Peak shares in global emissions

Region	Year of peak emissions	Peak emissions (Tg)	Year of peak share	Peak percentage of global emissions (%)
Western Europe	1974	13.7	1850	87.6
North America	1974	17.6	1926	52.4
Eastern Europe	1987	21.5	1986	30.6
Asia	1996	19.7	1996	33.5
South America	1999	6.2	1999	11.6
Middle East (does not include Kuwait oil fires in 1991)	2000	3.8	2000	7.5
Africa	1987	3.9	2000	6.3
Oceania	2000	1.2	2000	2.4

Note: these figures do not include emissions from shipping.

warming may be less than had previously been expected. In fact this is one key factor behind higher rates of temperature increase in the 21st century predicted in the most recent IPCC Report (Schneider, 2001). Zhang (2002) documents the relative contributions of the decrease in carbon and sulfur emissions in China to potential global warming.

5. Comparison with other studies

Table 4 compares my global estimates with other estimates for the 1990s. My estimates for 1990 are similar to Lefohn et al. (1999) and Smith et al. (2001) and lower than Olivier and Berdowski (2001). This is despite my inclusion of emissions from shipping which are not included by Lefohn et al. This is because the official totals produced by governments and used in my estimate are almost always smaller than the ASL and Edgar estimates. Even in the case of the US, the ASL estimate for 1990 is 2 Tg higher than the EPAs estimate. This is because the global academic estimates generally have underestimated the degree of sulfur pollution control.

Table 5 presents alternative regional estimates for 1990. Turkey is included in Smith et al.'s (2001) Western Europe total, while I have included it in the Middle East for the other two estimates and split it between Western Europe and the Middle East in my own estimates. North Africa is included in the Middle East in all the estimates apart from Smith et al.

Table 4
Alternative estimates of global sulfur emissions in the 1990s (Tg S)

Year	Lefohn et al.	Olivier and Berdowski	Smith et al.	Present study
1990	71.5	77.1	72.0	72.3
1991				73.8
1992				66.4
1993				65.1
1994				63.2
1995		70.9	67.0	62.1
1996				62.1
1997				61.4
1998				59.5
1999				57.4
2000			68.0	55.2

Table 5
Regional estimates 1990 (Tg S)

Region	Lefohn et al.	Present study	Smith et al.	Olivier and Berdowski
W. Europe	9.1	8.7	9.1	11.8
E. Europe	18.2	19.2	17	20.8
N. America	14.0	12.2	11.7	12.5
S. America	3.4	4.4	5.5	4.4
Asia	20.4	16.7	19.9	20.6
Africa	2.3	3.7	3.0	3.4
Middle East	3.2	3.6	1.2	2.9
Oceania	0.9	0.9	0.9	0.8

Comparing my estimates to ASL's, in Asia, Street's et al. (2000b) estimate for China is 3.1 Tg lower than ASL's. This explains much of the difference in Asia. My estimate for Eastern Europe is higher than ASL mainly due to the higher estimate in the Edgar data for the former Soviet Union, which I use. As explained above, official estimates for Western Europe and North America are lower than ASL's. For Australia the official estimate coincides with the ASL estimate. For the remaining regions, I mainly use the Edgar estimates which include more emissions sources than ASL do, particularly in the case of low-income countries. The estimates for Nigeria, for example, differ by a factor of fifty. The higher Edgar estimate is much more plausible given my econometric results.

Olivier and Berdowski's (2001) estimate is highest. They include a number of emissions sources that are omitted from the other databases. Excluding non-industrial emissions their estimate for 1990 is 72.8 Tg S, which is very close to Smith et al. (2001) and Lefohn et al. (1999).

The most significant difference between my estimate and Smith et al. (2001) is the estimate for China, which they place at 13 Tg. Again, I favor the regional focus of the Street's et al. (2000b) estimate. Smith et al. (2001) project strongly rising emissions in Asia through 2000. Possibly their estimate of sulfur retention before the 1990s is too low as well. They note that the only adjustment they make for emissions control in developing Asia is a 3% retention due to coal washing in China.

Going forward from 1990, I show a decline in emissions of 14% to 1995. Olivier and Berdowski (2001) and Smith et al. (2001) both indicate a decline of only 7%. Both the official estimates I use, the Street's et al. (2000b) estimates for Asia, and my own model estimates all predict rapid adoption of strategies to reduce sulfur emissions that the other sources do not seem to be taking into account. Between 1995 and 2000 I predict another 11% fall in emissions while Smith et al. (2001) predict an increase.

6. Conclusions

This study has developed continuous time series of sulfur emissions for the period from 1850–2000 for most countries in the world. Despite inherent uncertainties, these data should be useful in global change research.

This study has also revealed that changes in the pattern of global sulfur emissions were more dramatic than previously believed (e.g. Smith et al., 2001). Emissions shifted southward and eastward on a global basis but

East Asia is already seeing a declining trend in emissions. Since 1990 global emissions have fallen at an average rate of 2.7% per annum. If these trends continue they will have important implications for the problems of acid rain and deposition and global warming. But they may also have political implications due to what they indicate about the potential to solve environmental problems.

Success in reducing emissions and concentrations of pollutants such as sulfur dioxide in the developed countries in the 1970s and 1980s helped generate the idea of the environmental Kuznets curve in the early 1990s. The concept that pollution first rose and then fell with increasing income strengthened pre-existing beliefs that developing countries were "too poor to be green" (Martinez-Alier, 1995) and that the only way to attain a decent environment in most countries is to become rich (Beckerman, 1992). These views have also permeated media and policy debates (Stern, 2004). The fact that emissions of some pollutants are already falling in East Asia, particularly in China, partly as a result of explicit environmental policies (Dasgupta et al., 2002; Stern, 2004), will eventually have to result in a change in these attitudes.

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Appendix A. Sources of published sulfur data

The countries and sources of the published data are as follows:

East and South Asia: Streets et al. (2000b) report data for 23 countries in East and South Asia: Bangladesh, Bhutan, Brunei, Cambodia, PRC, Hong Kong, India, Indonesia, Japan, North Korea, South Korea, Laos, Malaysia, Mongolia, Myanmar, Nepal, Pakistan, Philippines, Singapore, Sri Lanka, Taiwan, Thailand, and Vietnam. The data are reported in Gg of SO_2. The period of the data is 1985–1997. Carmichael et al. (2002) update this data for 2000 and also include data on emissions from ships in Asia. These data are available online at: http://www.cgrer.uiowa.edu/people/carmichael/ACESS/Emission-data_main.html

Data for emissions from *ships* in Asian waters for 1988, 1990, 1993, 1994, and 1995 are available in Street's et al. (2000a). Earlier figures that appear in a chart in Carmichael et al. (2002) were supplied by David Streets.

For *Japan* there are also partial OECD data for 1970–1989 and for 1990–2000 Japan has data submitted to the UNFCCC. I interpolate this data using the Streets and ASL data to derive a consistent series.

Europe and the Former Soviet Union: Data is available from the EMEP website (www.emep.int) for 1980–2001 for the following countries: Armenia, Austria, Belarus, Belgium, Bosnia and Hercegovina, Bulgaria, Canada, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Kazakhstan, Latvia, Liechtenstein, Lithuania, Luxembourg, Macedonia, Moldova, Monaco, Netherlands, Norway, Poland, Portugal, Romania, Russian Federation, Slovakia, Slovenia, Spain, Sweden, Switzerland, European Turkey, Ukraine, United Kingdom, Yugoslavia.

Most Western European countries have a complete data set as does the Russian Federation and many other eastern European and former Soviet Union countries. Coverage in others is variable, from a few missing years to only a few years of observations.

Additional data for the 1970s is available from earlier OECD publications for: Denmark, France, Finland, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom. This data was interpolated where necessary in the same manner as the data for Japan.

Canada: Canadian data for 1970–2001 are also reported on the site providing the European estimates.

United States: Data for 1940–1998 are available from US EPA (2000) and updated to 2001 from the EPA website.

Australia: Estimates for 1990–2000 are from the Australian Greenhouse Office (2002).

New Zealand: Estimates for 1990–2000 are from the UNFCCC website.

Shipping: Carmichael et al. (2002) provide estimates of emissions from shipping in Asian waters. Estimates for the world as a whole are provided by Smith et al. (2001).

Global: Olivier and Berdowski (2001) provide estimates for all countries for 1990 and 1995. These are used for 1990 and 1995 for all countries not mentioned above. These data are available online at:

http://arch.rivm.nl/env/int/coredata/edgar/data32_so2.html

and are referred to as Edgar data. For years from 1850 to 1990, data are available from the ASL database described by Lefohn et al. (1999). The growth rates implied by this database are used for all observations where the other published estimates described above are not available.

Appendix B. Data sources for explanatory variables

B.1. Energy use

Data are from the International Energy Administration (2002, 2003) for 1986–2000 for non-OECD and for OECD for 1999–2001 (both have select earlier years) and IEA online data. Data were collected for total primary energy supply of crude oil, refined petroleum products, natural gas, coal, hydropower, nuclear power, and biomass fuels. Other energy use categories were considered small enough to ignore. Primary supply of refined petroleum products is equivalent to actual end use oil consumption in a country, while primary supply of crude oil is the quantity of oil refined in a country. Some countries such as the Netherlands carry out extensive oil refining for export, while other countries, such as Germany import significant amounts of refined product.

B.2. GDP and population

I obtained the data from the Penn World Table version 6.1 (Heston et al., 2002). Any gaps were filled from the *World Development Indicators Online*.

B.3. Economic structure

The structure of value added by industry for non-OECD countries was obtained from the *World Development Indicators Online* published by the World Bank (2003). For OECD countries I used data obtained from the *SourceOECD* website.

B.4. Metal smelting

Data on primary production of refined copper, lead, zinc, and nickel for 1980–2000 were received from the United Nations Industrial Development Organization. These data are reported in the *Yearbook of Industrial Statistics*. For copper, lead, and zinc I obtained the same data for 1971–1979 from the hardcopy version. For nickel I obtained data for 1971–1979 from the US Bureau of Mines *Minerals Yearbook*.

Appendix C. Boundary changes and related issues

My general approach is to make borders as comparable as possible to those of the present day. Therefore, where countries have merged—for example Germany—I report the figures for the merged country for all years. Where countries have split I report separate figures as far back as possible. This section also reports on methods of interpolation in these countries that were not reported above.

C.1. Korea

The ASL database gives separate figures for North and South Korea from 1947.

C.2. Pakistan

Bangladesh and Pakistan are treated as separate countries starting in 1972 and a single country before that date. Pakistan is included in India for years before 1948.

C.3. Yugoslavia

Estimates are primarily based on EMEP data. I interpolate values for Croatia for 1981–1989 and for Bosnia and Macedonia for 1980–1989 as a constant proportion of Yugoslavia's total emission solved iteratively. In the 1990s for Bosnia-Hercegovina I use the Edgar estimate for 1995 and the EMEP value for 2000 and interpolate the other values in the missing years based on the rate of change in the former Yugoslavia as a whole. For Macedonia I use Edgar estimates for 1990 and 1995 and EMEP for 1997 and 2000 and the same method of interpolation. I report estimates for all these countries separately from 1980 on. Emissions for Serbia for 1851–1912 are attributed to Yugoslavia.

C.4. USSR

For 1990 and 1995 I use the Edgar estimates for those republics/countries without EMEP estimates (Tajikistan, Turkmenistan, Kazakhstan, Azerbaijan, Uzbekistan) and interpolate using the frontier and EKC methods. EMEP data for Russia only cover European Russia. To estimate Asian Russia or Siberia in 1990 and 1995 I subtract the EMEP estimate for Russia from the Edgar estimate for Russia. Total Russian emissions are then interpolated using the EKC and frontier methods. The Edgar estimate for Russia looks very plausible-using the frontier method it would imply that Russia has a similar emissions efficiency to other middle income countries and some less emissions efficient high income countries. Data are reported for the USSR and for constituent republics where available. Estimated emissions for the Soviet Union in 1990 are 23% greater than the ASL estimate.

C.5. Czechoslovakia

From 1980 I report the Czech Republic and Slovakia separately and as a single country before 1980. Estimates for Slovakia for 1981–1984 were interpolated from the EMEP data using an exponential growth rate.

C.6. Vietnam, Germany, and Yemen

Are each reported as a single country in all years.

C.7. Turkey

As is the case for Russia, EMEP data for Turkey only cover the European portion (Smith et al., 2001). However the ASL and Edgar estimates are for the entire country of Turkey. I, therefore, use ASL estimates for total Turkish emissions up till 1990. I estimate emissions for 1991–2000 for Turkey as a whole using the emissions frontier method. For 1980–2000 I also provide separate series for Asian and European Turkey by subtracting the EMEP figure from the estimate for Turkey as a whole.

C.8. Others

I added Cape of Good Hope to the ASL estimates for South Africa between 1926 and 1935. French Equatorial Africa is attributed to Gabon during 1950–1957. French-Indo China refers to Laos. Emissions for French West Africa are attributed to Senegal. Estimates for the Leeward Islands are attributed to Antigua and Barbuda. Emissions for Rhodesia–Nyasaland are split between Zimbabwe and Malawi from 1950 to 1963 (mostly attributed to Zimbabwe, but allowing for exponential growth in emissions in this period in Malawi). The various states of Malaysia, which appear separately in the ASL database, are reported as a single country. Japan includes the Ryuku Islands when these are listed separately by ASL. Newfoundland data are included in Canada when they are listed separately by ASL. Rwanda and Burundi are reported as separate countries.

C.9. Shipping

Data for shipping in Asian waters were subtracted from the estimates of Smith et al. (2001) for global shipping to derive an estimate for shipping in the rest of the World.

Appendix D. Methods used to estimate emissions

In this section I note which of the three methods was used to estimate emissions in each country in each year. When not otherwise specified, the data for that country and those years is from the published sources.

D.1. Emissions frontier method

1971–1989, 1991–1994, and 1996–2000 Benin, Cameroun, Congo, Cote d'Ivoire, Gabon, Ghana, Kenya, Mozambique, Nigeria, Senegal, Tanzania, Zambia, Zimbabwe
1971–1976, 1981–1989, 1991–1994, 1997–2000 Togo
1971–1989, 1991–2000 Zaire
1975–1976, 1991–1994, and 1996–2000 UAE
1981–1989, 1991–1994, and 1996–2000 Ethiopia
1985–1989, 1991–1994, and 1996–2000 Angola
1991–1993 and 1996–2000 Jamaica
1991–1993, 1995–1997, 1999–2000 Uruguay
1991–1994 and 1996–1998 Nicaragua
1991–1995 Bahrain
1991–1994 and 1996–2000 Albania, Algeria, Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Dominican Republic, Ecuador, Egypt, El Salvador, Guatemala, Honduras, Iran, Jordan, Kuwait, Mexico, Morocco, Namibia, Panama, Paraguay, Peru, Saudi Arabia, South Africa, Syria, Trinidad and Tobago, Tunisia, Turkey, Venezuela, Yemen
1992–1993 and 1995–2000 Uzbekistan
1992–2000 Tajikistan
1992–1994 and 1996–2000 Azerbaijan
1996–2000 Cuba, Kazakhstan, Lebanon, Macedonia, Siberia
1998–1999 Bangladesh, China, Hong Kong, India, Indonesia, Malaysia, Myanmar, Nepal, Pakistan, Philippines, Singapore, South Korea, Sri Lanka, Taiwan, Thailand, Vietnam

D.2. EKC method

1958–1989, 1991–1994, and 1996–2000 Guyana
1960–1964 Togo
1960–1989, 1991–1994, and 1996–2000 Rwanda
1961–1989, 1991–1994, and 1996–2000 Cape Verde
1969–1984 Angola
1971–1980 Ethiopia
1971–1989 Namibia
1971–1989, 1991–1994, and 1996–2000 Botswana, Madagascar, Malawi, Mauritania, Mauritius, Niger, Sierra Leone, Swaziland
1972–1989, 1991–1994, and 1996–2000 Haiti
1975–1979, 1991–1994, and 1996–2000 Malta, Sudan
1977–1989, 1991–1994, and 1996–2000 Antigua and Barbuda
1978–1989, 1991–1994, 1996–2000 Uganda
1982–1988 Liberia
1985–1989 and 1991 Tajikistan
1986–1989, 1991–1994, and 1996–2000 The Bahamas
1987–1989, 1991–1994, and 1996–2000 Turkmenistan, Oman
1991 Uzbekistan
1991–1993 Cuba, Lebanon
1991–1994 Kazakhstan, Macedonia, Siberia
1991–1994 and 1996–2000 Israel, Barbados, Fiji, Malta, Papua New Guinea, Qatar, Surinam
1996–2000 Bahrain
1998–1999 Bhutan, Cambodia, Laos, Mongolia

D.3. Growth rates method

1989, 1991–1994 1996–2000 Liberia
1991–1994 Kazakhstan, Tajikistan
1991–1994 and 1996–2000 Afghanistan, Bermuda, Burkina Faso, Central African Republic, Chad, Djibouti, Eritrea, Faeroe Islands, Gibraltar, Greenland, Guam, Guinea, Guinea-Bissau, Iraq, Libya, Macao, Mali, Martinique, Netherlands Antilles and Aruba, New Caledonia, Puerto Rico, Reunion, Saint Pierre and Miquelon, Somalia, US Virgin Islands
1996–1999 Bosnia and Hercegovina
1998–1999 Brunei, North Korea

Appendix E. Regions

The regions include the following countries:

W. Europe: Austria, Belgium, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Malta, Monaco, Netherlands, Norway, Poland, Portugal, Spain, Sweden, Switzerland, European Turkey (1980–2000), United Kingdom.

E. Europe and the Former Soviet Union: Albania, Armenia, Asian USSR, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Czechoslovakia, Estonia, European Russia, FYR Macedonia, Georgia, Hungary, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Romania, Serbia, Serbia-Montenegro, Siberia, Slovakia, Slovenia, Tajikistan, Turkmenistan, Ukraine, USSR, Uzbekistan, Yugoslavia.

Middle East and North Africa: Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syria, Tunisia, Turkey (1979), Asian Turkey (1980–2000), UAE, Yemen.

Asia: Afghanistan, Bangladesh, Bhutan, Brunei, Cambodia, China, Hong Kong, India, Indonesia, Japan, Korea, Laos, Macau, Malaysia, Mongolia, Myanmar, Nepal, North Korea, Pakistan, Philippines, Singapore, South Korea, Sri Lanka, Taiwan, Thailand, Vietnam.

Africa: Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Congo, Cote d'Ivoire, Djibouti, Eritrea, Ethiopia, Gabon, Ghana, Guinea, Guinea-Bissau, Kenya, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda, Zaire, Zambia, Zimbabwe.

Oceania: Australia, Fiji, Guam, New Caledonia, New Zealand, PNG.

Anglo America: Bahamas, Bermuda, Canada, Greenland, Puerto Rico, St Pierre et Miquelon, USA, US Virgin Islands.

Latin America: Antigua and Barbuda, Argentina, Barbados, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Rep., Ecuador, El Salvador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles and Aruba, Nicaragua, Panama, Paraguay, Peru, Surinam, Trinidad, Uruguay, Venezuela.

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