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Estimation of Global SO_2 Emissions: An Economist's Perspective

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Despite evidence of sulfur dioxide's adverse effects on the environment, few governments outside of the OECD have taken steps to significantly reduce emissions in their country. Combined natural and anthropogenic deposition of sulfur from the atmosphere are as much as fifty percent greater now than during the pre-industrial age. Virtually all of the increase is attributed to anthropogenic activities and a vast majority of these anthropogenic emissions are from coal combustion. In aggregate terms, the largest emitters are the USSR, Eastern Europe, and China; on a per capita basis, the USSR, Eastern Europe, and North America stand out; and on a per GNP basis, Eastern Europe and China lead. Japan and the developing world are small emitters in all three categories. Establishment of global emissions limits would have profound effects on the economic growth potential of different regions due to the diverse emissions patterns.

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[1] The author is a Ph.D. candidate in Resource Economics in the Department of Agricultural Economics at Cornell University. Thanks are due to Professor Duane Chapman and to Thomas Drennen, both of the Department of Agricultural Economics at Cornell, for their many helpful comments during earlier drafts of this paper. The author takes responsibility for the content and any remaining errors in this paper.

I. INTRODUCTION

Sulfur dioxide emissions have adverse effects on human health and the environment but contemporary economies have not adequately internalized these costs. The market's apparent inability to encourage "appropriate" (sic lower) pollution levels has induced government intervention for emissions reductions, primarily through direct restrictions on emissions rather than taxes or incentives.

Several OECD nations took steps in the nineteen-seventies and early eighties to reduce their emissions and both West and East European countries began co-operation under the 1979 UN-ECE Convention on Long-Range Transboundary Air Pollution to promote information exchanges, research, and development of strategies to reduce emissions of air pollutants. The convention was strengthened by the 1985 Helsinki Protocol[1] under which several countries agreed to reduce sulfur levels by 30 percent from 1980 levels by 1993.

In China, urban air quality levels are at a level comparable to the worst of the developed countries in the 1950s and 1960s. Ambient air pollution levels in several of the country's cities are among the worst in the world. Mindful of this problem, the Chinese government has introduced efforts to reduce pollution, including modernization of obsolete boilers, compulsory installation of coal scrubbers, provision of cleaner coal, and fines.[2]

Despite the Protocol and various government statements, there is little evidence of implementation of plans or actual reductions in countries outside the OECD.

The success of any plans or policies to reduce sulfur pollution will require cooperation across wide regions. Cooperation, in turn, depends on adequate information about regional sulfur emissions and costs of emission abatement. The following estimates are an attempt to shed some light on regional emissions.

II. ESTIMATES OF GLOBAL EMISSIONS

A. Natural Emissions

Sulfur compounds are released into the atmosphere through a variety of naturally occurring (i.e., non-anthropogenic) processes, including wind erosion, biogenic emissions from micro-organisms and plants, sea spray, and volcanic activity.

The literature on biogeochemical cycles includes several studies of the global sulfur cycle, with wide variation among estimates of sulfur emissions. The results of the SCOPE study[3] illustrate this variation. The mean sulfur flux into the atmosphere from natural sources is estimated to be the equivalent of 457 million metric[4] tons (Mtons) SO_2. With incorporation of the report's confidence intervals for the terrestrial and biogenic marine sources[5], emissions range from 369 Mtons to 543 Mtons, and incorporation of other reports' results further widens the range.

B. Anthropogenic Emissions

Comprehensive data on SO_2 emissions from OECD nations is publicly available. For countries outside of the OECD, information about emissions and specific air quality protection programs are unavailable, requiring that emissions be estimated. These estimates are based on fuel consumption and industrial production according to the following general equation.

$$E = 2\,\Sigma_k C_k s_k x_k + .02P + \Sigma_i Q_i u_i$$

k = Coal type (hard, coke, brown/lignite, briquets)
i = Industry i.d.
E = SO_2 emissions, million metric tons (Mtons)
C = Coal combustion, Mtons
s = Sulfur content, fraction
x = Sulfur oxidation factor, fraction
P = Petroleum consumption, Mtons
Q_i = Industrial output in industry i, own units
u_i = SO_2 emission in industry i, Mtons/unit of output

Coal, coke, and oil consumption data are taken from the UN 1985 Energy Statistics Yearbook. Assumptions of sulfur content for coal consumed in each region are based on regional estimates of sulfur content of coal produced in Survey of Energy Resources 1974 and on trade flow data. These results are shown in Table A-1.[6]

The assumed rates of sulfur oxidation[7] are 95% for coke, and 90% for hard coal, and 85% for brown coal/lignite. An implicit assumption in the calculation of emissions is that no flue gas desulfurization occurs. The impact of this on regional estimates is not minor. Depending on the emission limits imposed and the quality of coal consumed, there could be as much as an order of magnitude difference between emissions from a controlled boiler and an uncontrolled boiler.

For example, emissions restrictions for newly installed large coal-fired boilers in OECD countries generally fall in the range of 0.15 - 0.74 kg SO_2 per million Btu (kg/mmBtu)[8], while potential SO_2 emissions might range from 0.73 kg/mmBtu to 4.44 kg/mmBtu, depending on the quality of the coal.[9]

Emissions from consumption of petroleum products are assumed to derive from residual oil. Since the greatest effort to reduce sulfur in oil is concentrated at the refinery stage; flue gas desulfurization efforts by utilities and industry and the variability of sulfur levels of stocks both have small impacts on SO_2 emissions from oil, relative to coal. The sulfur content of consumed residual fuel is set at one percent, globally. Emissions from industrial processes are calculated separately, based on average emissions limits in U.S. industry[10] and regional industrial production levels.

Global and regional estimates are shown in Table 1. Global SO_2 emissions in 1985 are estimated to be 164.5 million tons. This is in the middle of the range of estimates made within the past fifteen years. For example, Almquist reported 160 Mtons in 1973, Friend reported 130 Mtons in 1973, Cullis and Hirschler reported 188.2 Mtons in 1975 and 220 Mtons in 1980, Möller estimated 1977 emissions at 149.8 million tons SO_2, and the OECD estimated 110 Mtons of SO_x emissions for 1980.[11] Figure 1 shows Möller's estimated time series and several cited estimates.[12]

Table 1[13]

Global SO_2 Emissions Estimates for 1984 (million metric tons)

	Total	Metric Tons per GNP	Kilograms per Capita
World	164.45	12.09	34.46
USA	21.60	5.52	91.25
Canada	3.67	10.57	145.63
Latin America	4.41	6.33	11.19
Africa	2.76	7.29	4.95
Western Europe	15.60	5.28	44.16
Eastern Europe	41.22	102.84	300.00
USSR	32.51	16.89	118.22
Japan	1.08	0.84	8.99
China	30.51	95.68	29.02
rest of Asia	9.93	8.41	6.22
Oceania	1.17	5.82	47.78

Sources:

SO_2 emissions for USA, Canada, Western Europe, and Japan are from Table 2.1C of OECD Environmental Data Compendium 1989. All data is 1985 except: Japan (1983), Belgium (1983), Greece and Spain (1980), Switzerland (1984). All other SO_2 estimates are derived according to the method described on the previous page.

GNP estimates for all regions except Japan are from Encyclopedia Britannica, 1988 Britannica Book of the Year, pp. 770-774; GNP estimate for Japan is the 1983 estimate from the 1986 Britannica Book of the Year, converted to 1985 US$ using the implicit GNP deflator from the Economic Report of the President.

Population estimates are 1984 levels taken from Table 18 of United Nations, 1983/84 Statistical Yearbook.

Comparisons of this and other reports' regional estimates are limited by the scarcity of other such studies. In fact, this author found only one report for non-OECD countries, a review of estimates for Eastern Europe. The United Nations Environment Programme (UNEP) reports calculations[14] of annual emissions of 7.713 million metric tons sulfur from the East European countries for the year 1983. That level, 15.426 Mtons SO_2 equivalent, is substantially lower than the estimate of 41.22 Mtons presented in this paper. Assuming that most anthropogenic sulfur emissions are from coal combustion, inspection of the estimates in the UNEP report presents a picture of either a cleaner coal combustion technology in the East than in the West or of coal supplies with significantly less initial sulfur content. Given that sulfur emissions restrictions for OECD nations had generally not been instituted nor proposed until after 1983 and assuming that environmental concern and action has been more pronounced in the West than in the East, it is unlikely that East European countries had substantive sulfur emissions restrictions in place during 1983. Comparisons between the two Europes, then, should be based on the coal's sulfur content instead of the emissions technology. Dividing sulfur emissions by coal consumed, in each country, yields a maximum effective sulfur concentration in the coal. Summary results for Eastern and Western Europe are shown in Table 2.

Figure 1. Estimated Global Anthropogenic SO_2 Emissions (million metric tons)

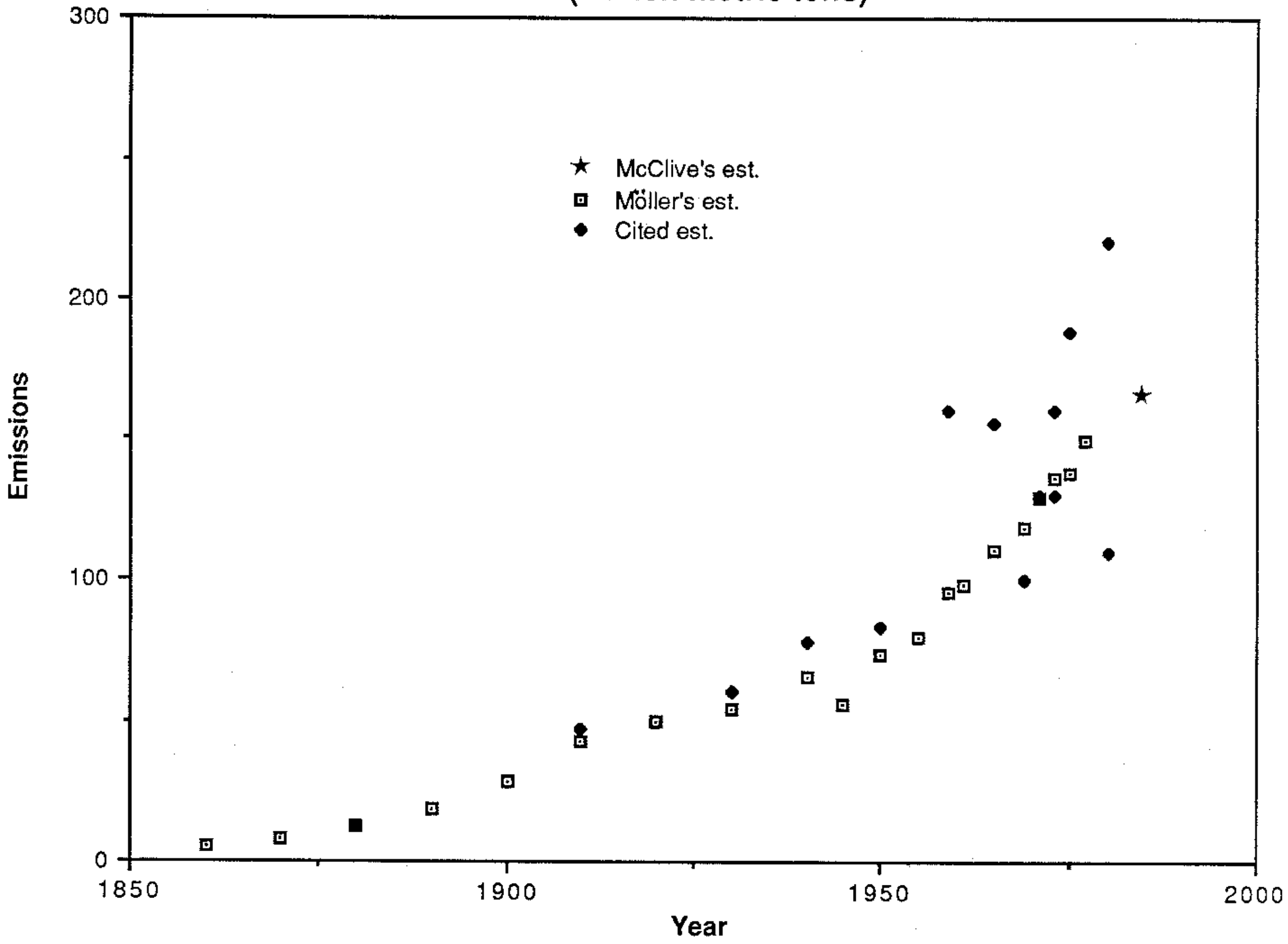


Table 2
Implied Sulfur Content of Coal

	Sulfur emissions (million metric tons)	Coal consumed (million metric tons)	Sulfur (%)
Eastern Europe	7.71	664.23	1.16
Western Europe	9.51	434.55	2.19

Sources:
Sulfur emissions data from Environmental Data Report.
Coal data from UN, 1985 Energy Statistics Yearbook.

The clearest implication of these results would be that East European countries use coals which have considerably less sulfur content than do West European countries. This contradicts the coal quality survey information published by the World Energy Conference and used in this paper.

A third, and perhaps more plausible, explanation for the discrepancy would be that coal combustion in the East is significantly less efficient than assumed in this paper.

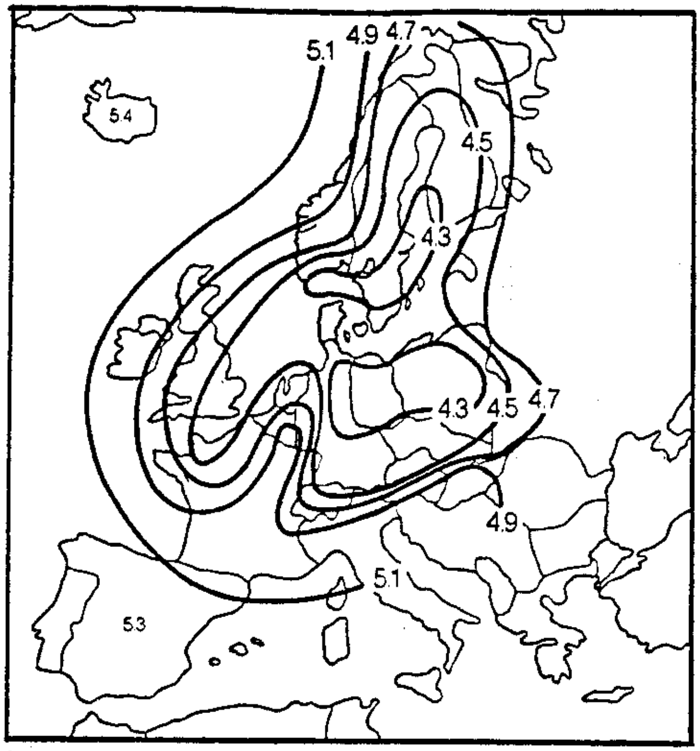
III. Comments

A. Global Implications

Natural emissions are clearly a major source of atmospheric sulfur. Compared with the estimates of anthropogenic emissions, the natural emissions comprise roughly three quarters of the total.[15] The relative concentration of natural emissions is markedly different between continental and oceanic sources. As less than 25 percent of natural emissions are continental but virtually all anthropogenic emissions are landbased, it is probable that an absolute majority of land based emissions are manmade.

The SCOPE study assessed global sulfur balances for both the preindustrial and present eras and estimated that deposition of atmospheric sulfur on land has increased 90% from 44 Mtons sulfur (S) to 84 Mtons S and the deposition in the oceans has increased by 40% from 184 Mtons S to 258 Mtons S[16], for a total increase in deposition of 50%. The increased deposition is due solely to anthropogenic sources; that is, SCOPE indicates that there is no increase of natural emissions. The report's analysis and results imply that approximately two thirds of anthropogenic emissions eventually fall over the oceans. Policies intended to reduce deposition across large regions will have to consider the great distance that airborne sulfur can travel. For example, efforts to reduce deposition in a coastal region that is upwind from the ocean must be predicated on the understanding that the amount of sulfur reaching land in the region may be only one third of the amount being emitted upwind of the region.

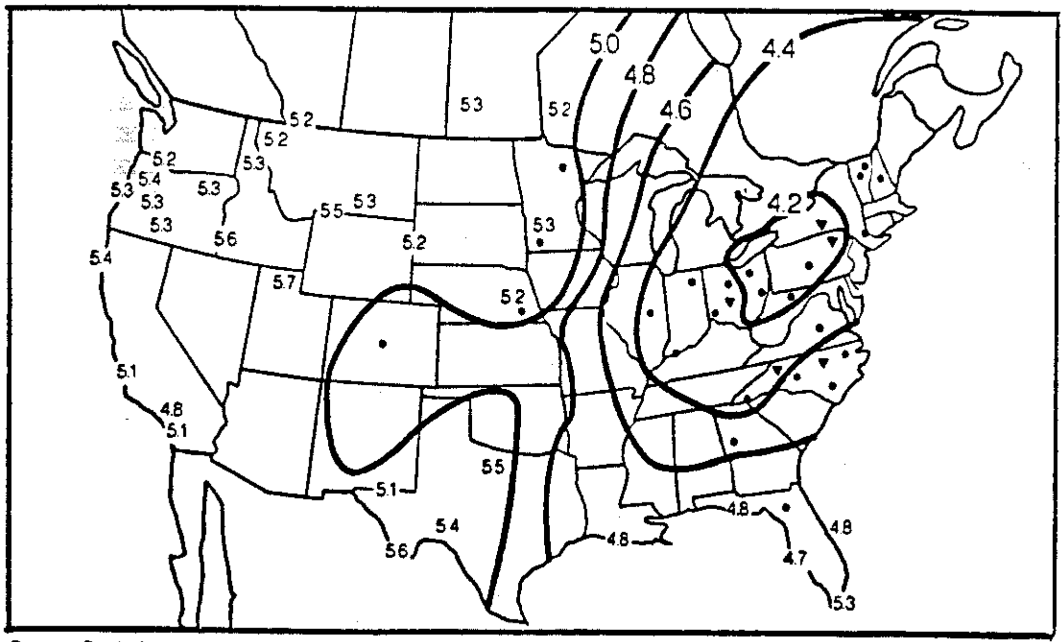
Figure 2
Acidity of European Precipitation, 1985 (pH units)



Source: Co-operative Program for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe
For additional information, see Sources and Technical Notes.

Reproduced from World Resources 1988-89, page 23.

Figure 3
Acidity of North American Precipitation, 1985 (pH units)



Source: Pacific Northwest Laboratory
Note: ● = station showing no trend in acidity, 1979-84. ▼ = station showing decreasing acidity, 1979-84
For additional information, see Sources and Technical Notes

Reproduced from World Resources 1988-89, page 23.

B. Regional Implications

1. Relative concentration

The aggregate global measures do not reflect the diverse regional concentrations of atmospheric SO_2.

Oceanic concentrations are around 0.1 micrograms S per cubic meter (ugS/m^3) and mean continental values range from 0.1 ugS/m^3 to 3 ugS/m^3.[17] Average daily urban concentrations range[18] from under 15 ugS/m^3 (eg. Toronto, Bogota, Bombay, or Auckland) to levels above 100 ugS/m^3 (eg. Beijing, Tehran, or Milan), while more typical values are in a range of 20 - 70 ugS/m^3. Peak levels are predictably higher, reaching 625 ugS/m^3 in residential Beijing, over 1000 ugS/m^3 in industrial Shenyang, 800 ugS/m^3 in residential Milan, and between 200 and 500 ugS/m^3 in several other cities.

Regional patterns are also apparent in rainfall's acid concentration, as shown in Figures 2 and 3.[19]

2. Policy implications

Regional differences in emissions have strong implications for environmental policy considerations. Future negotiation of global environmental laws or codes will likely address sulfur restrictions' impacts on regional and national economies. Two common types of pollution reduction schemes have been considered: percentage reductions of current emission levels and maximum allowed emission rates. The latter would be tied to population or economic measures. Table 1 shows SO_2 emissions in per GNP (million US$) and per capita terms.

With little exception (Japan and Canada), the emissions per GNP are uniform across the non-communist world. The clearest difference exists for emissions per capita. Except for Japan, all industrialized nations have a significantly higher emission per capita ratio than do the developing nations.

Rules based on emissions per GDP would be difficult to implement or enforce, largely because of the complexities of measuring economic output in comparable units. Various alternatives of rules based on per capita emissions would have profound implications for growth potential. For example, percentage rollbacks would severely limit the growth potential of the under-developed economies of Latin America, Africa, and Asia which already have low emissions ratios. If instead, ceilings were set that would allow growth by those countries yet not increase global emissions rates, then the heavier emitters (primarily Eastern Europe and Canada) would face strong pressure on their industrial sectors.

Table A-1
Assumed Sulfur Content of Coal Consumed
(percent by weight)

Region/country	Hard coal	Coke	Brown coal
USA	2.00	1.79	0.80
Canada	1.56	1.42	0.60
Latin America	1.52	1.52	0.60
Africa	0.60	0.54	n/a
Westerm Europe			
UK	1.90	1.69	n/a
West Germany	1.22	1.13	2.50
France	0.87	0.89	0.60
Spain	1.78	1.59	4.00
Other	1.48	1.39	2.49
Eastern Europe			
Albania	2.00	1.79	0.00
Bulgaria	2.47	2.21	4.00
Czechoslovakia	2.06	1.84	2.00
East Germany	2.17	1.94	3.00
Hungary	2.00	1.79	2.00
Poland	2.00	1.79	2.00
Romania	1.90	1.71	3.95
Yugoslavia	2.49	2.23	2.00
USSR	2.49	2.23	2.50
Asia			
Japan	1.02	0.92	n/a
China	2.00	1.79	2.00
India	0.60	0.54	0.60
Other	1.51	1.16	1.78
Oceania	0.60	0.54	0.60

Table A-2
Coal Consumed
(~~thousand~~ metric tons)
million

Region/country	Hard coal	Coke	Brown coal
USA	674.02	26.54	62.61
Canada	21.55	5.21	26.86
Latin America	35.05	11.77	0.04
Africa	136.91	3.22	0.00
Westerm Europe			
UK	105.70	9.12	0.00
West Germany	87.48	21.34	123.18
France	36.38	10.42	2.44
Spain	24.70	3.61	23.73
Other	80.60	23.77	42.30
Eastern Europe	225.07	40.97	627.29
Albania	0.22	0.03	1.79
Bulgaria	8.28	1.75	30.66
Czechoslovakia	28.31	9.04	98.25
East Germany	4.80	2.99	312.36
Hungary	4.55	2.01	21.07
Poland	159.87	15.08	57.57
Romania	13.96	6.64	37.92
Yugoslavia	5.09	3.43	67.67
USSR	478.77	82.76	185.76
Asia			
Japan	109.46	49.76	0.00
China	804.54	37.60	34.63
India	152.77	11.64	7.70
Other	1186.21	12.90	58.79
Oceania	46.15	3.60	38.53

ENDNOTES

1. See the bibliography under 'United Nations.' As of Autumn 1988, the following countries had signed the protocol: Austria, Bulgaria, Canada, Czechoslovakia, Denmark, Finland, France, West Germany, Hungary, Liechtenstein, Luxembourg, Netherlands, Norway, Sweden, Switzerland, and USSR.

2. These comments are drawn from articles and news stories of the BBC's "The Far East; Weekly Economic Report", the Xinhua General Overseas News Service, and the Kyodo News Service.

3. See Table 7.1 of Ivanov, M.V. and J.R. Feney (editors), The Global Biogeochemical Sulphur Cycle. This is referred to as the SCOPE study.

4. All emissions data in this paper are in metric tons.

5. The terrestrial and biogenic sources account for 57.5 million tons of the 228.5 million tons of natural sulfur emissions. The confidence intervals are summarized on pages 233, 234, and 239 of SCOPE.

6. There are indications that the estimates of sulfur content used in this analysis are lower than actual values for some regions, particularly the CMEA countries and China. Information conveyed orally by Duane Chapman indicates that the brown coal burned in Czechoslovakia has sulfur levels exceeding 10 percent and reaching as high as 20 percent. The level of sulfur assumed for coal in China (2% S by weight) is based on point estimates from two mines and one field. The notation accompanying those estimates suggests that that coal is representative of only the better coal available. Endnote 13 contains revised sulfur emissions estimates for Eastern Europe which incorporate higher sulfur levels for brown coal in Czechoslovakia and East Germany.

7. A portion of the sulfur will bond with ash, thus reducing the potential for airborne sulfur. Möller's levels of sulfur oxidation for coal and coke are adopted here. See Table 6, page 22 of Möller.

8. This estimated range is adapted from information in Coal Information 1988, pages I.63 - I.75.

9. Potential emissions (in kg/mmBtu) are compared for coal with high- and low-sulfur content and for high- and low-heat content.

	Sulfur Content	
	Low (1%)	High (4%)
High-heat coal (27,500 Btu/kg)	0.73	2.91
Low-heat coal (18,000 Btu/kg)	1.11	4.44

10. The lone exception is the copper industry, where emissions/production ratios are based on international data provided by Duane Chapman, Cornell University. Use of US emissions rates is probably inaccurate for non-industrialized nations or for countries with substantially different pollution control regimes. However, it is also likely that industrial sources comprise a small portion of emissions in most regions. This contention is supported by the estimates for all regions except Latin America, where copper production in Chile is a major source of sulfur pollution. Also, OECD estimates of emissions from Canada are significantly higher than the estimates from this model. The reason may lie in a failure of the model to fully capture emissions from the Canadian smelting industries.

11. See [Möller], page 23, for references to all but the OECD and the 1980 Cullis and Hirschler estimates. The OECD estimate is from its 1987 Environmental Data Compendium, Table 2.1A on page 17. The second Cullis and Hirschler estimate is from SCOPE, page 245.

12. Except as noted in the previous footnote, all cited estimates are in [Möller].

13. When the sulfur content of brown coal consumed in Czechoslovakia and East Germany is set at five percent by weight, the level of SO_2 emissions rises substantially:

	Total	Metric Tons per GNP	Kilograms per Capita
World	179.91	13.23	37.70
Eastern Europe	56.68	141.41	412.52

14. See Table 1.16, page 28 of Environmental Data Report. The data are attributed to: Lehmhaus, J., Saltbones, J and Eliassen, A. 1986: A Modified Sulphur Budget for Europe for 1980. Norwegian Meteorological Institute, Oslo, 1986.

15. SCOPE's estimate of natural emissions is equivalent to 457 million (metric) tons SO_2, with a range of 368 - 543 million tons. The estimate of anthropogenic emissions is 164 million tons, which falls in a range of 110 - 220 million tons. One can deduce that natural emissions are in a range of 65% to 83% of total emissions.

16. See Tables 4.9 and 4.10 on pages 273 and 277, respectively, of SCOPE.

17. Ibid, Table 4.2, pages 211-13.

18. See World Resources 1988-89, Table 23.4, pp. 338-340.

19. Note that the acidity of rainfall is also increased by nitric acid from NO_X emissions. Hence, the information conveyed in the figures is not wholly attributable to SO_2.

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