Is Free Trade Good For The Environment?
TECHNICAL APPENDIX

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Contents

A Capital Intensity and Pollution Abatement

We argue in our paper that capital-intensive industries are also pollution-intensive. To support this claim, figure A-1 illustrates the relationship between capital intensity and the pollution abatement costs (per unit of output) for a set of U.S. industries in 1988.

A regression through the 122 data points based on the logarithmic transformations of abatement cost ratio and capital intensity reveals a positive relationship with an R^2 of 0.3, indicating that a 1% increase in the capital intensity increases the abatement cost ratio by 0.7%. Data were only available for manufacturing industries. Thus, a particularly interesting industry—electricity generation—is not included in the sample. From other sources it is known that pollution abatement costs and capital intensity are both extremely high in that industry.

Pollution abatement data are as reported in Patrick Low "Trade Measures and Environmental Quality: The Implications for Mexico's Exports", chapter 7 in: Patrick Low (ed.) "International Trade and the Environment", World Bank Discussion paper 159, The World Bank, Washington/DC, 1992, pp. 113-114. Additional capital and labour figures for the 3-digit SIC manufacturing industries were taken from the U.S. Annual Survey of Manufacturing. The i123-type labels next to each data point indicate the 3-digit US-SIC industry.

B Data Set Description

B.1 Dependent Variable

The dependent variable in our study is the concentration of sulphur dioxide at observation sites in major cities around the world as obtained through the GEMS/AIR data set supplied by the World Health Organization. Measurements are carried out using comparable methods. Each observation station reports annual summary statistics of SO_2 concentrations such as the median, the arithmetic and geometric mean, as well as 90th and 95th percentiles.

We have chosen to use a logarithmic transformation of the median SO_2 concentration as our dependent variable. Figure B-4 shows that the distribution of concentrations is highly-skewed towards zero when viewed on a linear scale. In this diagram, the horizontal axis shows ranges of median SO_2 concentrations in parts per million per cubic metre [ppm/m3]. As was pointed out in the WHO (1984) report about the GEMS/AIR project, concentrations are more suitably described by a log-normal distribution with a number of observations concentrated at

Figure A-1: Pollution Abatement and Capital Intensity in the U.S. (1988)

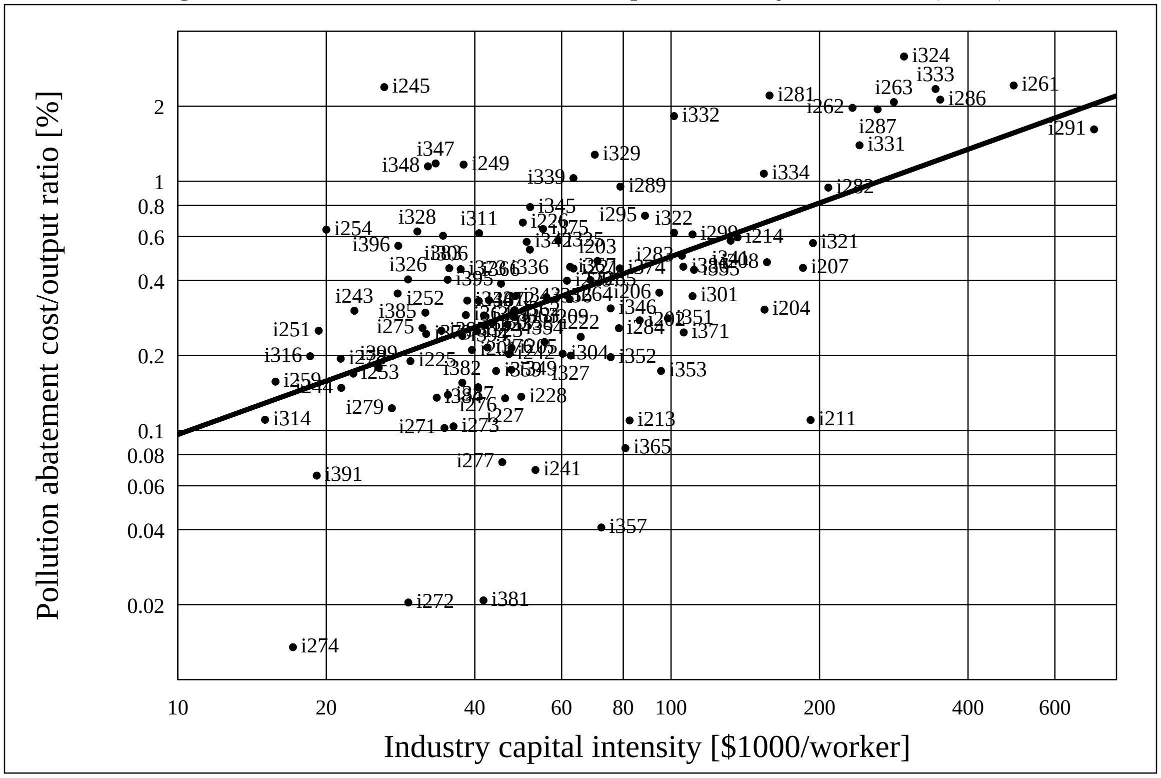
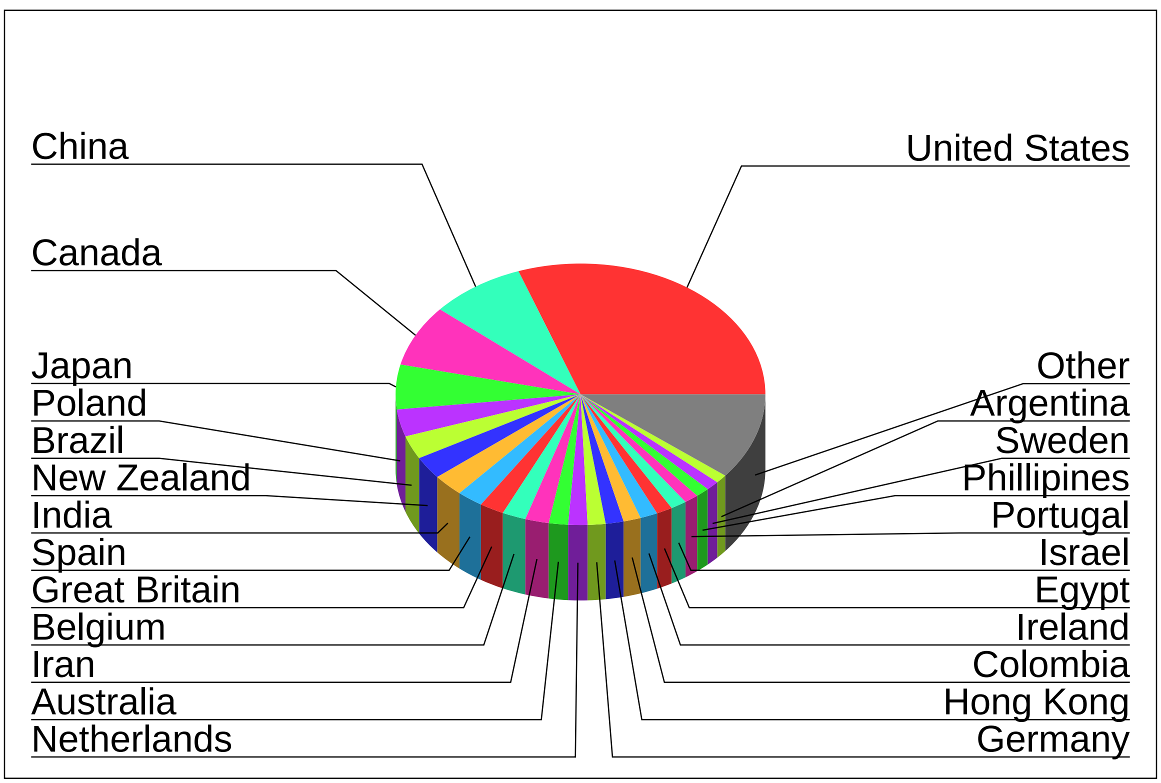


Figure A-2: Composition of GEMS/Air Data Set (Observations per Country)



the measurement threshold of the measurement devices. These instruments cannot measure arbitrarily low concentrations. This is apparent in figure B-5 where the horizontal axis is logarithmic. There is also an ambient level of SO_2 in the air that has natural causes.

The composition of the data set by contributor countries is shown in the pie diagram of figure A-2. A large share of observations were from the United States due to this country's extensive network of air quality measurement stations. Other large contributor countries were China, Canada, and Japan. Many of the other observation stations provided short or discontinuous streams of data while participating in the GEMS/AIR project. All in all, our analysis is based on over 2,600 observations from 293 observation stations in 109 cities around the world; these cities are located in 44 countries.

Figure B-3 reveals the time period during which individual countries participated in the GEMS/AIR project. The countries are ranked by length of participation. Numerous countries provide more than fifteen years of observations, among them the United States, Canada, Germany, and Japan. In addition, table B-1 lists the cities in which the observation stations were located along with the number of stations in each city and the minimum and maximum concentrations measured at any of the stations in a given city.

The primary source for our data is the *AIRS Executive International database* that contains information about ambient air pollution in nations that voluntarily provide data to the GEMS/AIR program sponsored by the United Nations World Health Organization.[1] We had problems with the identification of several observation stations. The longitude and latitude information provided in one of the ancillary files was in some cases incorrect and was corrected case-by-case based on the the description of the location.

B.2 Regressors

Additional data sources for our regressors include the *Penn World Tables*[2] for macroeconomic data, the CIESIN *Global Population Distribution Database*[3] for population density data, the World Resources Insititute *World Resources Database*[4] for natural resources and physical endowments, and data from the *Global Historical Climatology Network*[5] (GHCN) for weather conditions at the observation stations. Yet more time series were obtained for real world oil prices,[6] for tariff and non-tariff trade barriers,[7] and educational attainment.[8]

Summary statistics for the major variables appear in table B-2. Some of the variables warrant further explanation. First, our scale measure of economic activity GDP per square kilometre is calculated by multiplying a country's real per-capita GDP ($/person) with each city's population density (people/km^2). Extrapolations for per-capita GDP were carried out for the years past 1993 based on real growth rates obtained from the IMF/IFS statistics. Population densities were available only for 1990.

The capital abundance (K/L) of countries was obtained from the physical capital stock per worker variable in the Penn World Tables. Relative capi-

1. This package is available from the United States Environmental Protection Agency (US-EPA) at http://www.epa.gov/-airs/aexec.html. The US-EPA kindly provided a much more complete version of this dataset that included not only averages but also median and other percentiles of SO_2 concentrations. We would like to express our gratitude to Jonathan Miller of the US-EPA for providing additional GEMS/Air data not contained in the public release of the database, and for patiently answering our numerous technical questions.

2. Robert Summers and Alan Heston, "The Penn World Table (Mark 5): An Expanded Set of International Comparisons, 1950–1988", Quarterly Journal of Economics, Vol. 106, May 1991, pp. 327–368. Available in revision 5.6 from the NBER ftp site at ftp://ftp.nber.org/pwt56/.

3. This data set from the Consortium for International Earth Science Information Network (CIESIN) is only available for 1990. It can be obtained freely from the United Nations Environmental Programme server maintained by the U.S. Geological Survey at http://grid2.cr.usgs.gov/globalpop/1-degree/-description.html.

4. World Resources 1998-1999: A Guide to the Global Environment", Oxford University Press, Oxford: 1998.

5. Information is available on monthly average temperatures, monthly precipitation, and atmospheric pressure. The raw data and description file are available from the National Climatic Data Center of the U.S. National Oceanic and Atmospheric Administration at ftp://ftp.ncdc.noaa.gov/pub/data/ghcn/v1/.

6. This series from the U.S. Energy Information Administration (at http://www.eia.doe.gov/price.html) has been calculated by dividing the landed costs of crude oil imports from Saudi Arabia (Arabian Light) in US$ per barrel by the US GDP deflator (1990=100).

7. See Sachs and Warner (1995).

8. These figures were obtained from Robert J. Barro and Jong-Wha Lee 1994 study, available from the NBER web site at http://www.nber.org/pub/barro.lee/ZIP/BARLEE.ZIP.

Figure B-3: GEMS/Air Participation by Country and Time Period
(Countries are sorted by decreasing number of contributing years)

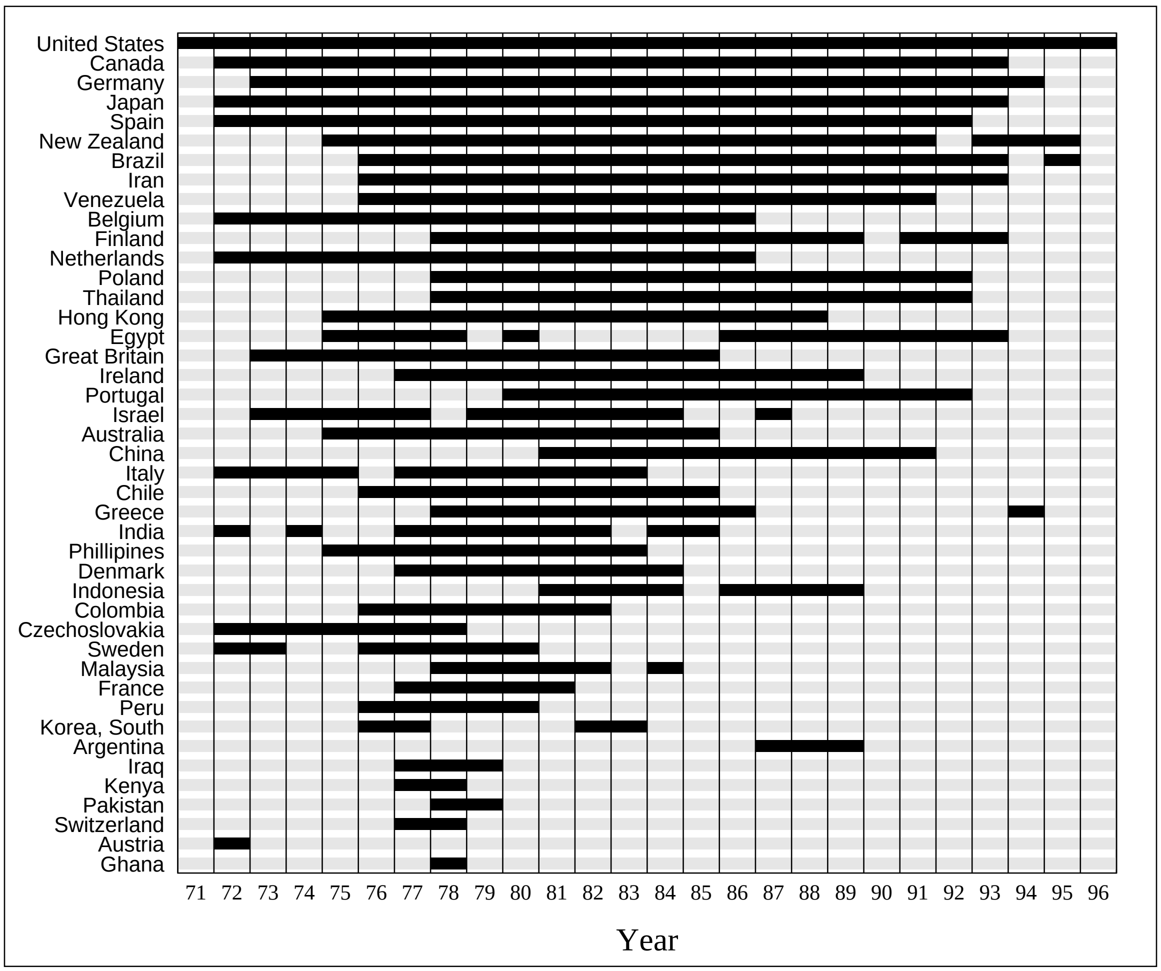


Figure B-4: Distribution of the Dependent Variable (linear scale)

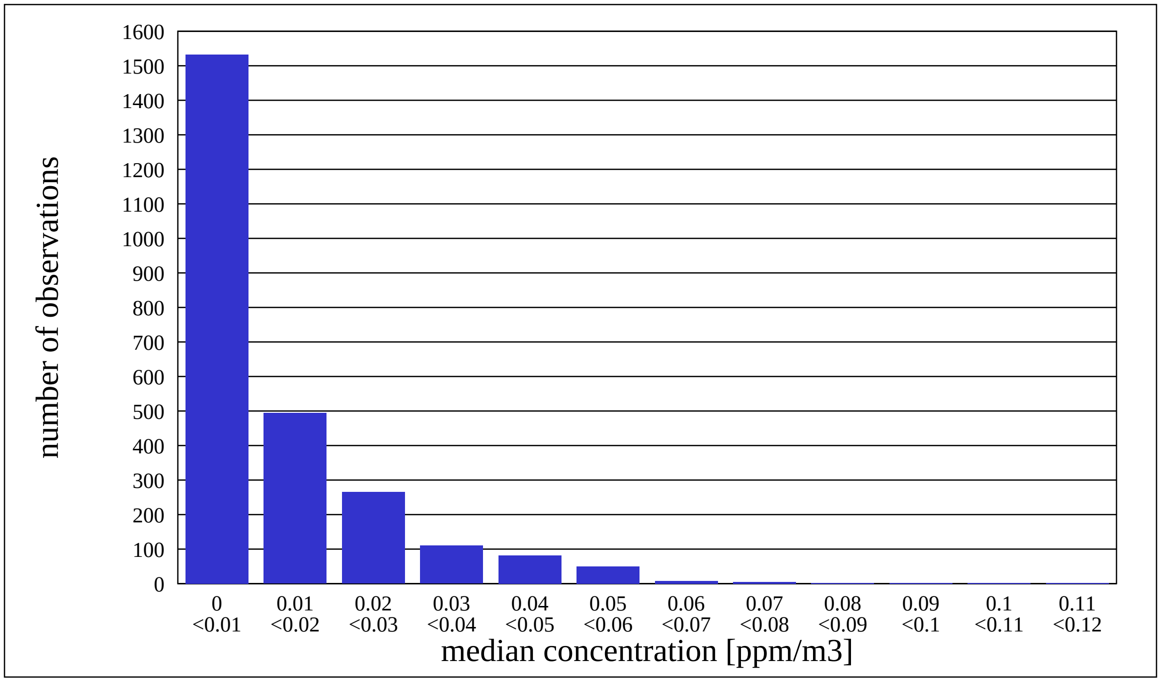


Figure B-5: Distribution of the Dependent Variable (logarithmic scale)

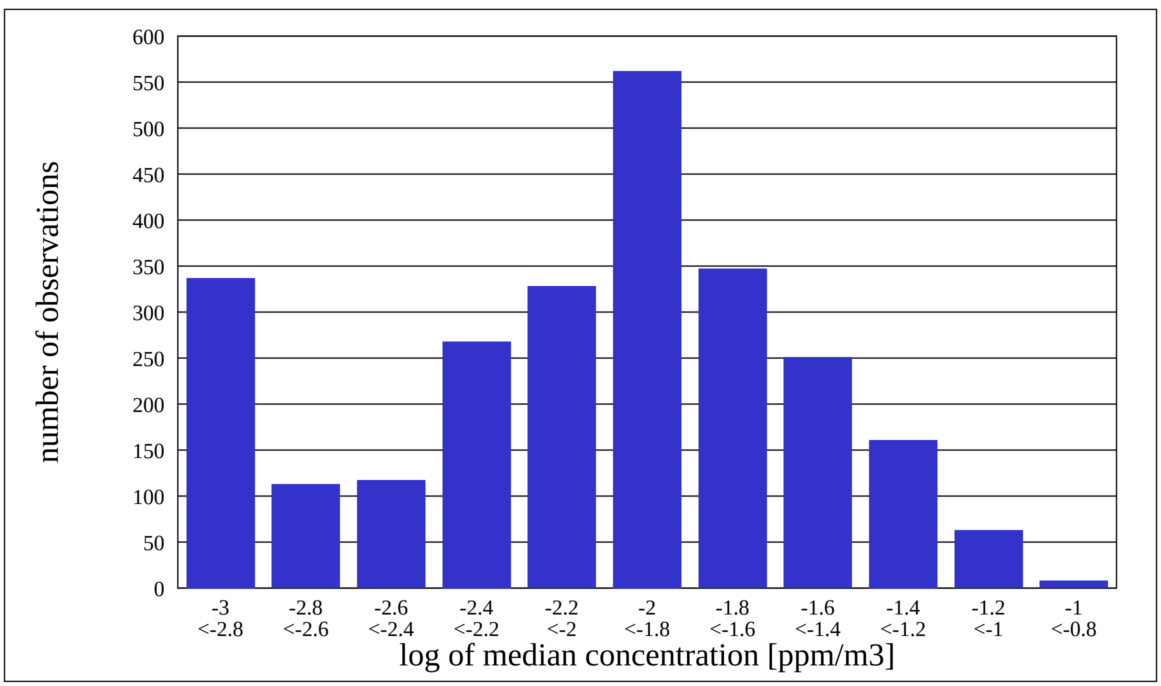


Table B-1: Cities by descending maximum of annual median SO_2 concentration

Country & City	n	min	max	Country & City	n	min	max	Country & City	n	min	max
KOR Seoul	6	25	115	CHE Zurich	1	17	26	USA Houston, TX	3	1	10
ITA Rome	3	2	103	IRL Dublin	3	4	26	USA Long Beach, CA	1	1	10
ITA Milan	2	17	100	MYS Kuala Lumpur	4	1	25	USA Seattle, WA	1	1	10
IRN Tehran	3	7	93	USA Alexandria, VA	1	5	25	NZL Auckland	3	1	9
CHN Shenyang	4	1	89	POL Wroclaw	3	6	24	IRQ Baghdad	3	1	8
AUT Vienna	3	40	80	COL Medellin	3	1	22	USA Chelsea, MA	1	4	8
ESP Madrid	5	2	73	ISR Tel Aviv	5	1	22	USA Tampa, FL	3	1	8
CSK Prague	3	13	65	HKG Hong Kong	6	1	21	COL Cali	3	1	7
BEL Brussels	4	9	64	CAN Hamilton	5	1	20	GHA Accra	3	4	6
EGY Cairo	4	1	61	CAN Montreal	4	1	20	THA Bangkok	4	1	6
GBR London	3	11	58	SWE Stockholm	5	1	20	USA Allen Park, MI	1	2	6
JPN Tokyo	3	5	58	USA Philadelphia, PA	5	1	20	USA St Ann, MO	1	4	6
JPN Osaka	4	5	56	USA St Louis, MO	3	3	20	USA River Rouge, MI	1	3	6
CHN Guangzhou	4	2	55	CAN Vancouver	7	1	19	DEU Munich	1	5	5
BRA Sao Paulo	5	8	51	PAK Lahore	2	15	19	IDN Jakarta	3	1	5
PHL Manila	3	2	50	DNK Copenhagen	3	3	18	PER Lima	3	1	5
CHL Santiago	3	11	49	USA Detroit, MI	2	2	18	USA Atlanta, GA	2	2	5
BRA Rio De Janeiro	2	20	46	KEN Nairobi	2	7	17	USA Waltham, MA	1	1	5
CHN Beijing	5	1	44	USA Chester, PA	1	6	17	PHL Davao	2	1	4
CHN Xian	4	3	41	NZL Christchurch	4	1	16	ARG Buenos Aires	1	1	3
CHN Shanghai	4	1	40	FRA Paris	3	2	15	ARG San Lorenzo	1	2	3
USA Boston, MA	2	3	40	SWE Oxelosund	1	11	15	USA Chula Vista, CA	1	1	3
DEU Frankfurt	3	5	38	USA Washington, DC	2	7	15	USA Dallas, TX	1	2	3
FRA Toulouse	4	19	38	USA Cicero, IL	1	2	14	USA Livonia, MI	1	1	3
NLD Amsterdam	3	6	37	VEN Caracas	3	3	14	USA St Petersburg, FL	1	1	3
IND Bombay	6	3	36	SWE Nykoping	2	5	13	USA Adams Co, CO	1	1	3
COL Bogota	3	1	35	USA Chicago, IL	3	1	13	USA Burbank, CA	1	1	2
PRT Lisbon	3	1	35	USA East St Louis, IL	1	5	13	USA Los Angeles, CA	1	1	2
IND Calcutta	3	4	33	POL Warsaw	3	3	12	USA San Diego, CA	1	1	2
GBR Glasgow	3	11	32	USA Camden, NJ	1	5	11	USA Tarpon Springs, FL	1	1	2
ARG Mendoza	3	10	30	USA Wood River, IL	1	2	11	ARG Cordoba	2	1	1
AUS Melbourne	1	1	30	CAN Toronto	5	1	10	ARG San Miguel de Tucuman	7	1	1
IND New Delhi	3	1	30	FIN Helsinki	3	1	10	ARG Santa Fe	1	1	1
GRC Athens	5	7	29	USA Baytown, TX	1	1	10	ISR Ashdod	2	1	1
USA New York City, NY	2	7	28	USA Blue Island, IL	1	1	10	USA Azusa, CA	1	1	1
AUS Sydney	3	2	27	USA Denver, CO	1	2	10	USA El Cajon, CA	1	1	1

Note: The column n is the number of observation stations in each city. The columns min and max show the lowest and highest measured level of the annual median SO_2 concentration in each city, measured in parts per billion. Note that a maximum or minimum concentration of "1" is equivalent to the measurement threshold of the measurement device. Countries appear with their ISO-3166 codes.

Table B-2: Summary Statistics

Variable	Dimension	Obs.	Mean	Std.Dev.	Min.	Max.
Log of SO2	log(ppm)	2555	-2.112	0.481	-3.000	-0.939
City Economic Intensity	\$m per km^2	2555	0.790	0.878	0.010	5.934
Capital abundance	\$10k/worker	2555	5.612	2.497	0.829	17.189
GDP per capita, 3yr avg.	\$10k	2555	1.430	0.839	0.113	2.636
Education Attainment	0-1 range	2555	0.540	0.226	0.088	0.799
Trade Intensity (X+M)/GDP	[—]	2555	0.409	0.322	0.088	2.617
Relative Income	World=1.00	2555	2.500	1.392	0.221	4.138
Relative (K/L)	World=1.00	2555	1.357	0.605	0.203	4.174
Communist Country	[—]	2555	0.125	0.331	0.000	1.000
C.C. $\times$ Income	\$10k	319	0.302	0.208	0.127	0.716
Population Density	1000p/km^2	2555	0.063	0.055	0.001	0.276
Avg. Temperature	°C	2555	14.689	5.600	2.617	28.967
Precipitation Coeff. of Var.	[—]	2555	0.011	0.006	0.001	0.054
Price of crude oil	\$/barrel	2555	28.136	12.047	13.470	49.670
Hard Coal Reserves	GJoule/worker	2555	0.040	0.043	0.000	0.146
Soft Coal Reserves	GJoule/worker	2555	0.038	0.052	0.000	0.348

Note: All monetary figures are in 1995 US Dollars. The interaction term for income with the communist countries dummy only shows the case where the the dummy is equal to one; thus the mean for this line is the mean for the communist countries only.

tal abundance is obtained by dividing each country's capital abundance by the corresponding world average for the given year, where "world average" is defined by all the countries in the Penn World Tables. In computing the capital abundance figures, we use a measure of human capital instead of the labour force. The size of the labour force is adjusted by a 0–1 average education index in which 1 represents 16 years of schooling. The education attainment data were obtained from the Barro/Lee study.

Our income (I) variable is the three-year average of lagged GDP per capita. That is, for a given year t, $I_t = (y_{t-1} + y_{t-2} + y_{t-3})/3$. Relative income is constructed in the same fashion as our relative capital abundance measure.

The suburban and rural location type dummy variables are from the oiriginal GEMS/AIR dataset. The third (default) location type is 'central city'.

Our trade intensity measure is calculated as the sum of exports and imports expressed as a percentage of gross domestic product. Our alternative measure of country openness are black market premia of foreign exchange rate, available for 1970 and 1980. Data points for other years were constructed through interpolation and flat extrapolation. From Sachs and Warner (1995) we have taken measures of average tariff and quota levels for the time period 1985-88, as well as an indicator variable for openness available for the entire time period of our sample. This inidicator is 1 for open economies and 0 otherwise.

The communist country dummy used in our study identifies the following countries: China, Czechoslovakia, Poland, and Yugoslavia. The country dummy for the Helsinki Protocol identifies Austria, Belgium, Bulgaria, Canada, Czechoslovakia, Denmark, Finland, France, Germany, Hungary, Italy, Luxembourg, The Netherlands, Norway, and Switzerland, in the years after 1985.

C Sensitivity Analysis

C.1 Model Specification

In table C-3 we start with a formulation where our capital to labor ratio is not corrected for effective labor measures. We then consider site-specific fixed effects estimation in column (2) 'Base', consider a different time period for the analysis in column (3) 'Time', allow for a more general specification for scale effects in column (4) 'ISca', introduce several new possible factor endowments in column (5) 'FEnd' and employ a different measure of openness in column (6) 'SaWa'.

While there are naturally some differences across these specifications, the consistency with the results in Table 1 is quite remarkable. For example, the fixed-effects estimates in column 2 offers perhaps stronger evidence in favor of our approach. Both fixed-effects and random-effects models deliver significant estimates for the scale, technique, and trade-intensity elasticities.[9]

In column (3) we have restricted the time period to the years 1976–91 because of concerns over data quality and sample selection. The GEMS/Air study was carried out primarily throughout the years 1976-1991 when the United Nations Environment Programme (UNEP) provided funding to the participating countries. Before 1976 there are only few countries that provide measurements of SO_2 concentrations, and after 1991, the number of countries that report such observations drop rapidly. By 1996 data are only available from the United States. This is also shown in table B-3. To allow for a possible participation bias due to funding, we repeat our base-line regression by excluding observations from before 1976 and from after 1991. This shortened period has 489 (or roughly 20%) fewer observations but the results are very similar both in terms of coefficient estimates and statistical significance. Our experiments with other subsets have not revealed any discernible problems with the the data set.

Another sensitivity test is shown in column (4) 'ISca'. Our linear formulation rules out the constant elasticity given by theory. A simple way to investigate both of these possibilities is to allow the scale variable to differ across income classes. Accordingly we have divided the world into three income classes: the bottom thirty percent, the top thirty percent and the remainder. We use as our universe of countries all of those included in the Penn World Tables. Taking the middle group as our excluded category, the estimates in column (4) show that the scale variable does indeed differ significantly across income classes. The estimates now imply a point elasticity of scale of 0.55 for the bottom income group, 0.46 for the middle-income group, and 0.54 for the high-income group. The point elasticities indicate that the scale elasticity may fall with income as sug-

Table C-4: Elasticities at Sample Means

Elasticity	Estim.	S.E.	95%-C.I.
Random Effects – Base Model			
Scale	0.27	0.03	0.20, 0.33
Composition	0.90	0.20	0.50, 1.29
Technique	−1.55	0.17	−1.88, −1.21
Trade Intensity	−0.40	0.10	−0.59, −0.21
Fixed Effects – Base Model			
Scale	0.26	0.06	0.15, 0.37
Composition	0.80	0.36	0.10, 1.50
Technique	−1.13	0.38	−1.87, −0.40
Trade Intensity	−0.83	0.16	−1.15, −0.50
Random Effects – Sachs/Warner			
Scale	0.25	0.03	0.20, 0.31
Composition	−0.24	0.22	−0.68, 0.19
Technique	−1.06	0.19	−1.42, −0.70
Trade Intensity	0.13	0.11	−0.08, 0.35
Random Effects – Factor Endowments			
Scale	0.24	0.03	0.18, 0.30
Composition	0.41	0.13	0.16, 0.66
Technique	−1.18	0.18	−1.54, −0.82
Trade Intensity	−0.35	0.09	−0.53, −0.16
Random Effects – Time Period			
Scale	0.31	0.03	0.24, 0.37
Composition	0.95	0.22	0.52, 1.37
Technique	−1.43	0.19	−1.79, −1.07
Trade Intensity	−0.23	0.10	−0.43, −0.03
Random Effects – Scale-Income Interaction			
Scale (poor 30%)	0.55	0.12	0.32, 0.78
Scale (middle)	0.46	0.10	0.27, 0.65
Scale (rich 30%)	0.54	0.07	0.40, 0.67
Composition	0.79	0.21	0.38, 1.21
Technique	−1.24	0.19	−1.61, −0.87
Trade Intensity	−0.32	0.10	−0.52, −0.12

Note: Elasticity calculations use the Delta method and are based on the random effects version (last column of table 1) and the fixed effects version (first column of appendix table B) of our base-line regression. The Sachs/Warner and factor endowment random-effects regressions correspond to table B. Instead of the sample mean for the Sachs/Warner openness measure across countries, the indicator value '1' was used to measure the effect of openness. Column S.E. contains standard errors, and column 95%-I.V. contains the 95% confidence interval.

9. Elasticities are calculated using the Delta method for functions of the least squares estimator. See William H. Greene, "Econometric Analysis", third edition, Prentice-Hall: 1997, section 6.7.5, pp. 278ff.

Table C-3: Sensitivity Analysis & Specification Tests

Model	Base	Time	ISca	FEnd	SaWa
Intercept	-4.55^{**}	-2.56^{**}	-4.18^{**}	-3.39^{**}	-4.07^{**}
$\xi =$ City GDP/km^2	0.06^{**}	0.07^{**}	0.14^{**}	0.06^{**}	0.06^{**}
$\xi\times$ rich countries			-0.09^{**}		
$\xi\times$ poor countries			0.19^{**}		
Capital abundance (K/L)	0.38^{*}	-0.12	0.28^{*}	0.25^{*}	0.17
$(K/L)^2$	0.00	0.03^{**}	0.01	0.02	0.00
Lagged p.c. income (I)	-0.63	-1.98^{**}	-1.05^{**}	-1.37^{**}	-0.48
I^2	0.56^{**}	0.61^{**}	0.59^{**}	0.70^{**}	0.54^{**}
$(K/L)\times(I)$	-0.28^{**}	-0.12	-0.24^{**}	-0.30^{**}	-0.29^{**}
$\theta =$ Openness	-2.57^{**}	-2.73^{**}	-0.44	-0.62	0.16
$\theta\times$ relative (K/L)	-1.75	0.88	-1.94^{*}	-1.63	-0.70
$\theta\times$ relative $(K/L)^2$	-0.01	-0.81^{**}	-0.06	-0.27	0.01
$\theta\times$ relative (I)	1.94^{**}	1.73^{**}	1.16^{**}	0.93^{*}	0.04
$\theta\times$ relative $(I)^2$	-0.34^{*}	-0.31^{*}	-0.30^{*}	-0.25^{*}	-0.11^{*}
$\theta\times(K/L)\times(I)$	0.50	0.25	0.66^{**}	0.80^{**}	0.49^{**}
Suburban Dummy		-0.26	-0.47^{*}	-0.42^{*}	-0.54^{**}
Rural Dummy		-0.49	-0.70	-0.64	-0.78^{*}
Communist Country		-1.34^{**}	-0.80	-0.41	-0.26
C.C. $\times I$	13.85^{**}	9.55^{**}	7.37^{**}	5.08^{*}	5.26^{**}
C.C. $\times I^2$	-11.83^{**}	-10.22^{**}	-8.55^{**}	-5.70^{**}	-6.76^{**}
Soft Coal (per worker)				3.57^{*}	
Hard Coal (per worker)				-2.00	
Oil Price (real, log)				-0.10^{*}	
Average Temperature	-0.06^{*}	-0.06^{**}	-0.05^{**}	-0.06^{**}	-0.05^{**}
Precipitation Variation	5.75	7.38	3.15	4.36	3.81
Time Trend	-0.03^{**}	-0.04^{**}	-0.04^{**}	-0.03^{**}	-0.04^{**}
Helsinki Protocol	0.01	-0.20^{*}	-0.07	-0.12	-0.07
Observations	2555	2066	2555	2555	2555
Groups	290	274	290	290	290
R^2 (overall)	0.114	0.318	0.378	0.369	0.349

Note: Significance at the 95% and 99% confidence levels are indicated by * and **, respectively. The dependent variable is the log of the median SO_2 concentration.

gested by a shift to cleaner non-traded services but we cannot reject the hypothesis of a constant elasticity across income classes. The remaining estimates in this column are very similar to their previous values and none of our conclusions are altered.

In column (5) 'FEnd' we allow for a wider set of factor endowments to affect pollution concentrations. Our model is parsimonious in the extreme: we assume the division of production between dirty and clean goods is only affected by a country's capital to labor ratio and its existing pollution regulations. We have implicitly restricted the impact of other factor endowments to indirect effects on the scale of output and on incomes per capita. This assumption seems a poor one for factor endowments known to be highly complementary with either dirty or clean good production. To investigate whether our simple two factor assumption has seriously affected our results we add several new regressors. We add the endowment of soft and hard coal per worker as well as the real price of oil to our analysis. As the results in column (5) show the inclusion of the other potentially relevant endowments appears to make very little difference to the results.

Finally in column (6) 'SaWa' we adopt another measure of "openness." It is well known that trade intensity is a poor measure of the "openness" of trade policy, is negatively correlated with country size, and is positively correlated with the peculiarity of a country's resource endowments. Accordingly we replace our measure of trade intensity with the Sachs and Warner (1995) measure of openness. Overall the results are surprisingly similar. The sign pattern is almost identical to those in Table 1 of the paper. However, the estimate of the composition-effect elasticity is negative (but not significant). Similarly, the trade-intensity effect is inconclusive for a country in the middle of the sample.

C.2 Fixed Effects vs. Random Effects

Table 1 in the paper presents our key regression in column (6) in addition to nested versions of this model in columns (1) through (5). In each of these cases we use random effects to estimate the regression coefficients. The use of random-effects estimation allows us to exploit both the cross-sectional and longitudinal variation in the data set. By comparison, the fixed-effects model completely supressess the cross-sectional variation. A critical assumption in the random effects model is that the individual effects are not correlated with the regressors. This type of estimation therefore suffers from possible inconsistency due to omitted variables. The fixed-effects estimator, however, does not suffer from this problem. When the aforementioned orthogonality assumption fails, the GLS estimator is biased and inconsistent. The Hausman test provides a method to compare the fixed-effects and random-effects estimators; it tests the orthogonality between regressors and random effects. The resulting Wald statistic is distributed χ^2 with the degrees of freedom equal to the number of regressors in themodel. When the Hausman test is significant, the hypothesis that the individual effects are uncorrelated with the regressor should be rejected.

Fixed effects are useful when dealing with an entire population. By comparison, random effects are more suitable when one is dealing with a sample of an underlying population. In our case, the observation stations, cities, and countries represent a sample of the entire population of urban areas around the world. We thus feel that the use of random effects estimation is appropriate, notwithstanding the results from the Hausman test. As an intermediate step or compromise, we have also investigated the use of mixed effects (where we employ fixed effects at the country level and random effects at the station level). In practice, this is accomplished by adding country dummies to our full random-effects model. The results from this approach, not shown in this appendix, solidly confirm our findings we obtain from the random effects model.

Table C-5 in this appendix repeats the regressions shown in Table 1 of our paper; however, all results are based on fixed effects instead of random effects. The regressors that do not change over time (the location dummies and the communist-country dummy) are excluded from the regression. The Hausman test favours the fixed-effects model when the three excluded regressors are ignored in this test. Because of the dropping-out of the time-constant regressors, this result has to be interpreted with caution.

Comparing the results from the random-effects estimation of our model with the results from the fixed-effects estimation of our model, it is apparent that the

Table C-5: Sensitivity Analysis for Specification — Fixed Effects

Model	SOE (1)	TII (2)	PPH (3)	PFE (4)	Convex (5)	Full (6)
Intercept	-4.27^{**}	-4.32^{**}	-2.97^{**}	-5.59^{**}	-4.23^{**}	-4.55^{**}
City GDP/km^2	0.04^{**}	0.03^{**}	0.05^{**}	0.03^{*}	0.04^{**}	0.06^{**}
Capital abundance (K/L)	0.12	0.11	0.23^{**}	0.49^{**}	0.58^{**}	0.38^{*}
$(K/L)^2$	-0.01^{*}	-0.01^{*}	-0.01^{**}	-0.03^{**}	-0.03^{**}	0.00
Lagged p.c. income (I)	-0.52	0.06	-2.05^{**}	0.22	-1.96^{**}	-0.63
I^2	0.10	-0.01	0.29^{*}	-0.06	0.24^{*}	0.56^{**}
$(K/L) \times (I)$						-0.28^{**}
$\theta =$(X+M)/GDP		-0.81^{**}	-4.22^{**}	1.50	-1.97^{*}	-2.57^{**}
$\theta\times$ relative (K/L)				-2.84^{**}	-2.80^{**}	-1.75
$\theta\times$ relative $(K/L)^2$				0.73^{*}	0.61^{*}	-0.01
$\theta\times$ relative (I)			2.07^{**}		2.40^{**}	1.94^{**}
$\theta\times$ relative $(I)^2$			-0.21		-0.28^{*}	-0.34^{*}
$\theta \times (I) \times (K/L)$						0.50
Suburban Dummy						
Rural Dummy						
Communist Country						
C.C. $\times I$	11.21^{**}	11.86^{**}	16.49^{**}	9.93^{**}	14.59^{**}	13.85^{**}
C.C. $\times I^2$	-11.07^{**}	-11.01^{**}	-13.13^{**}	-10.12^{**}	-12.49^{**}	-11.83^{**}
Average Temperature	-0.06^{*}	-0.06^{*}	-0.06^{*}	-0.06^{*}	-0.06^{*}	-0.06^{*}
Precipitation Variation	7.23	7.81	6.19	8.76^{*}	7.99	5.75
Time Trend	-0.04^{**}	-0.04^{**}	-0.03^{**}	-0.04^{**}	-0.03^{**}	-0.03^{**}
Helsinki Protocol	-0.20^{*}	-0.19^{*}	-0.18^{*}	-0.15	-0.10	0.01
Observations	2555	2555	2555	2555	2555	2555
Groups	290	290	290	290	290	290
R^2 (overall)	0.138	0.074	0.135	0.068	0.155	0.114
Log Likelihood	-4078	-4065	-4011	-4054	-3996	-3973
LR Test Statistic (λ)	208.5	184.0	75.52	161.8	45.16	0.00
$\chi^2(0.99, df)$	16.81	15.09	11.34	11.34	9.21	
Hausman Test	35.85	45.20	75.34	49.73	75.52	86.09

Note: To conserve space, no standard errors or t-statistics are shown. However, significance at the 95% and 99% confidence levels are indicated by * and **, respectively. The dependent variable is the log of the median of SO_2 concentrations at each observation site. The "SOE" model tests our small open economy hypothesis. The "TII" model tests our trade intensity hypothesis. The "PPH" model tets the pure pollution haven hypothesis. The "PFE" model tests the pure factor endowment hypothesis. "Convex" is a convex combination of the PFE and PPH models. These five models are compared through a log-likelihood test against the "Full" model of our base-line regression.

sign pattern of our estimates is very stable across both methods. The significance of some of the estimates changes slightly. We are thus satisfied that our qualititative conclusions are not driven by the estimation method we use.

C.3 Alternative Dependent Variables

In a further set of sensitivity analyses we explore the choice of our dependent variable. We have argued before—based on the observations expressed in figures B-4 and B-5 that a logarithmic transformation of the dependent variable is appropriate. However, there is a menu of different SO_2 concentrations to choose from. We opted for the median SO_2 concentration because it is more "robust" with respect to outlier observations than the arithmetic mean. The U.S. Environmental Protection Agency kindly supplied us with a variety of concentration statistics. We explore all of them in tables C-6 and C-7 for our fixed-effects and random-effects baseline model. In addition to the median (column 'Base'), we use the arithmetic mean (column 'Mean') and the 90th, 95th, and 99th percentile of SO_2 concentrations (columns 'P90%', 'P95%', and 'P99%'). All of these measures were transfomred into logarithms when they were used as a dependent variable.

The first observation is that the intercept term is increasing from left to right, as the higher percentiles have higher average SO_2 concentrations. The regression that used the median concentration has a higher intercept than the regression based on the mean concentration. This is probably a result of the non-normal distribution of the (linear) SO_2 cocentrations, which can be seen in figure B-4 to be highly-skewed to the left.

All five specifications produce results that are broadly in line with our previous findings. In particular, all signs remain the same, the estimates remain significant, and the overall magnitudes change only to a small extent. We take these results as a confirmation of the regularity of the distribution of SO_2 concentrations. Recall that these numbers are *annual* summary statistics that tend to mitigate the effect from single-day outliers.

C.4 Box-Cox Transformation

We have argued earlier that the appropriate transformation of the dependent variable is to take the logarithm, based on our observations expressed in figure B-5. However, in table C-8 we explore the possibility of other transformations, notably, a linear transformation and a Box-Cox transformation. All of these are based on our fixed-effects model.

We apply a Box-Cox transformation as a generalization to our fixed-effects model (where ν_i is a site-specific fixed effect). The model can be specified as

$$\begin{aligned} y_{it}^{(\lambda)} &\equiv \begin{cases} y_{it} - 1 & \text{for } \lambda = 1 \\ (y_{it}^{\lambda} - 1)/\lambda & \text{for } 0 < \lambda < 1 \\ \log(y_{it}) & \text{for } \lambda = 0 \end{cases} \\ &= \mathbf{X}_{it}\beta + \nu_i + \epsilon_{it} \end{aligned} \quad (1)$$

which assumes that there exists a λ for a transformation of the dependent variable so that $\epsilon_{it} \sim \mathrm{N}(0, 1)$. The transformation parameter λ is determined by maximizing the concentrated log-likelihood function

$$L(\lambda) = -\frac{N}{2} \ln \hat{\sigma}^2(\lambda) + (\lambda - 1) \sum_t \ln(y_t) \quad (2)$$

where

$$\hat{\sigma}^2(\lambda) = \frac{1}{N} \left(y^{(\lambda)} - \mathbf{Xb}\right)' \left(y^{(\lambda)} - \mathbf{Xb}\right) \quad (3)$$

With the results from the Box-Cox regression we can also peform two likelihood-ratio tests, $2[L(\lambda) - L(0)] \sim \chi^2(1)$ and $2[L(\lambda) - L(1)] \sim \chi^2(1)$, that allow us to test the Box-Cox transformation against the log-linear (our baseline) model and the simple linear model.

We find that the signs of our estimates remain stable and significant. The optimal Box-Cox transformation parameter is approximately 0.2. When we test this specification against either the log-linear or pure-linear case, the log-likelihood test statistics reject both the log-linear and pure-linear specifications in favour of the Box-Cox transformation. Observe, though, that the pure-linear model is rejected by a much larger margin than the log-linear model. Also note that the interpretation of the parameters changes and cannot be compared across the three models.

C.5 Simultaneous-Equation Approach

Yet another concern in our work has been the possibility of a simultaneous determination of pollution

Table C-6: Sensitivity Analysis for Dependent Variable — Fixed Effects

Model	Base (1)	Mean (2)	P90% (3)	P95% (4)	P99% (5)
Intercept	-4.55^{**}	-4.71^{**}	-3.82^{**}	-3.28^{**}	-3.00^{**}
City GDP/km^2	0.06^{**}	0.06^{**}	0.08^{**}	0.07^{**}	0.05^{**}
Capital abundance (K/L)	0.38^{*}	0.68^{**}	0.77^{**}	0.72^{**}	0.57^{**}
$(K/L)^2$	0.00	-0.02^{*}	-0.03^{**}	-0.02^{*}	-0.01
Lagged p.c. income (I)	-0.63	-0.63	-1.04^{*}	-1.11^{*}	-0.50
I^2	0.56^{**}	0.60^{**}	0.66^{**}	0.69^{**}	0.69^{**}
$(K/L) \times (I)$	-0.28^{**}	-0.33^{**}	-0.32^{**}	-0.31^{**}	-0.36^{**}
$\theta =$(X+M)/GDP	-2.57^{**}	-0.75	-1.76^{*}	-1.41	-0.91
$\theta\times$ relative (K/L)	-1.75	-2.87^{**}	-2.99^{**}	-2.86^{**}	-2.84^{**}
$\theta\times$ relative $(K/L)^2$	-0.01	0.44^{*}	0.70^{**}	0.67^{**}	0.22
$\theta\times$ relative (I)	1.94^{**}	0.58	0.77	0.50	1.08^{*}
$\theta\times$ relative $(I)^2$	-0.34^{*}	-0.13	-0.11	-0.05	-0.37^{**}
$\theta \times (I) \times (K/L)$	0.50	0.63^{**}	0.53^{*}	0.49^{*}	0.91^{**}
Suburban Dummy					
Rural Dummy					
Communist Country					
C.C. $\times\ I$	13.85^{**}	11.02^{**}	12.41^{**}	12.12^{**}	10.84^{**}
C.C. $\times\ I^2$	-11.83^{**}	-8.99^{**}	-9.13^{**}	-8.81^{**}	-9.20^{**}
Average Temperature	-0.06^{*}	-0.06^{**}	-0.06^{**}	-0.07^{**}	-0.07^{**}
Precipitation Variation	5.75	3.44	2.38	3.36	4.22
Time Trend	-0.03^{**}	-0.03^{**}	-0.03^{**}	-0.04^{**}	-0.04^{**}
Helsinki Protocol	0.01	0.11	0.11	0.07	0.14^{*}
Observations	2555	2555	2555	2555	2555
Groups	290	290	290	290	290
R^2 (overall)	0.114	0.165	0.166	0.158	0.157
Hausman Test	86.09	101.8	139.6	145.3	85.90

Note: To conserve space, no standard errors or t-statistics are shown. However, significance at the 95% and 99% confidence levels are indicated by * and **, respectively. The dependent variable is as specified in the Model line: Base = the log of the median of SO_2 concentrations at each observation site; Mean = the log of the arithmetic mean of SO_2 concentrations; P90%, P95%, P99% = the log of the 90th, 95th, and 99th percentiles of SO_2 concentrations.

Table C-7: Sensitivity Analysis for Dependent Variable — Random Effects

Model	Base (1)	Mean (2)	P90% (3)	P95% (4)	P99% (5)
Intercept	-3.84^{**}	-4.20^{**}	-3.43^{**}	-3.00^{**}	-2.75^{**}
City GDP/km^2	0.06^{**}	0.06^{**}	0.06^{**}	0.06^{**}	0.05^{**}
Capital abundance (K/L)	0.30^{**}	0.46^{**}	0.50^{**}	0.45^{**}	0.31^{**}
$(K/L)^2$	0.01	-0.00	-0.01	-0.01	0.01
Lagged p.c. income (I)	-1.34^{**}	-1.04^{**}	-1.24^{**}	-1.21^{**}	-0.58^{*}
I^2	0.66^{**}	0.64^{**}	0.66^{**}	0.69^{**}	0.72^{**}
$(K/L) \times (I)$	-0.27^{**}	-0.29^{**}	-0.27^{**}	-0.27^{**}	-0.34^{**}
θ =(X+M)/GDP	-0.43	0.43	-0.03	-0.06	0.01
$\theta\times$ relative (K/L)	-2.02^{*}	-2.88^{**}	-3.08^{**}	-2.91^{**}	-2.59^{**}
$\theta\times$ relative $(K/L)^2$	-0.13	0.12	0.32	0.28	-0.12
$\theta\times$ relative (I)	1.04^{*}	0.71^{*}	1.01^{**}	0.97^{**}	1.35^{**}
$\theta\times$ relative $(I)^2$	-0.27^{*}	-0.27^{**}	-0.29^{**}	-0.28^{**}	-0.52^{**}
$\theta \times (I) \times (K/L)$	0.75^{**}	0.86^{**}	0.77^{**}	0.74^{**}	1.05^{**}
Suburban Dummy	-0.42^{*}	-0.14	0.01	0.05	0.15
Rural Dummy	-0.65	-0.17	-0.02	0.12	0.28
Communist Country	-0.64	-0.37	-0.33	-0.43	-0.18
C.C. $\times\ I$	6.52^{**}	6.03^{**}	6.39^{**}	6.52^{**}	6.49^{**}
C.C. $\times\ I^2$	-7.41^{**}	-6.56^{**}	-6.64^{**}	-6.62^{**}	-7.43^{**}
Average Temperature	-0.05^{**}	-0.05^{**}	-0.05^{**}	-0.05^{**}	-0.05^{**}
Precipitation Variation	3.98	5.90^{*}	6.78^{*}	7.79^{*}	7.88^{**}
Time Trend	-0.03^{**}	-0.03^{**}	-0.04^{**}	-0.04^{**}	-0.04^{**}
Helsinki Protocol	-0.05	0.07	0.07	0.04	0.12
Observations	2555	2555	2555	2555	2555
Groups	290	290	290	290	290
R^2 (overall)	0.362	0.338	0.288	0.261	0.238
Hausman Test	86.09	101.8	139.6	145.3	85.90

Note: To conserve space, no standard errors or t-statistics are shown. However, significance at the 95% and 99% confidence levels are indicated by * and **, respectively. The dependent variable is as specified in the Model line: Base = the log of the median of SO_2 concentrations at each observation site; Mean = the log of the arithmetic mean of SO_2 concentrations; P90%, P95%, P99% = the log of the 90th, 95th, and 99th percentiles of SO_2 concentrations.

Table C-8: Sensitivity Analysis for Dependent Variable Transformation

Model	Base (1)	linear (2)	Box-Cox (3)
Intercept	-4.55^{**}	-1.47	2.48^{*}
City GDP/km^2	0.06^{**}	1.02^{**}	0.10^{**}
Capital abundance (K/L)	0.38^{*}	16.23^{**}	1.09^{**}
$(K/L)^2$	0.00	-0.50^{**}	-0.02
Lagged p.c. income (I)	-0.63	-30.81^{**}	-1.68
I^2	0.56^{**}	10.98^{**}	1.04^{**}
$(K/L) \times (I)$	-0.28^{**}	-4.31^{**}	-0.51^{**}
θ =(X+M)/GDP	-2.57^{**}	6.18	-2.60
$\theta \times$ relative (K/L)	-1.75	-52.81^{**}	-4.42^{**}
$\theta \times$ relative $(K/L)^2$	-0.01	11.13^{**}	0.44
$\theta \times$ relative (I)	1.94^{**}	11.63	2.79^{**}
$\theta \times$ relative $(I)^2$	-0.34^{*}	-0.78	-0.48
$\theta \times (I) \times (K/L)$	0.50	1.07	0.74
Suburban Dummy			
Rural Dummy			
Communist Country			
C.C. $\times$ I	13.85^{**}	68.75^{*}	19.44^{**}
C.C. $\times$ I^2	-11.83^{**}	-60.12^{*}	-16.94^{**}
Average Temperature	-0.06^{*}	-0.42	-0.09^{*}
Precipitation Variation	5.75	-74.62	4.38
Time Trend	-0.03^{**}	-0.29^{**}	-0.05^{**}
Helsinki Protocol	0.01	3.75^{**}	0.14
Observations	2555	2555	2555
Groups	290	290	290
R^2 (overall)	0.114	0.238	0.127
Log Likelihood	-3973	-16675	-3464
LR Test Statistic (λ)	1019	26422	0.00
$\chi^2(0.99, df)$			

Note: To conserve space, no standard errors or t-statistics are shown. However, significance at the 95% and 99% confidence levels are indicated by * and **, respectively. λ is the transformation parameter of the Box-Cox transformation as defined in equation (1).

and (current-period) per-capita income. We did not pursue a simultaneous-equations approach for our main analysis because it is our belief that the likely effect of pollution on per-capita income is rather small. This belief appears to be validated by Dean (1998), who finds no significant relationship in her 2SLS procedures. Contemporaneous per-capita income only enters through our scale variable but not through our technique variable; recall that we use lagged per-capita income to determine the technique effect because income increases will typically take a number of years to translate into policy changes.

To address the simultaneity of income (y) and pollution (z) determination in our scale effect we have experimented with a fixed-effects 2-stage least squares estimator using as a second estimating equation a simple approximation of a production function

$$\log(y) = \gamma_1 \log(z) + \gamma_2 \log(K) + \gamma_3 \log(L) + \gamma_4 (t - 1980) \quad (4)$$

where K and L denote capital stock and labour force, and t is a linear time trend. In addition, we decompose a city's economic intensity measure into the product of per-capita income and population density. Taking logs of the resulting expression, we can additively separate these two effects in our regression equation. As our measure of population density is constant over time, it does not appear as a regressor in the fixed-effects implementation. In contrast to our baseline model, the estimated coefficient corresponding to income is a constant-elasticity estimation of the scale effect.

Results from the fixed-effects 2SLS regression, shown in table C-9, indicate that the parameters in our baseline model remain stable. However, we estimate the scale effect from a city's economic intensity to be much higher than in our baseline model: around 2. In the GDP regression we find that pollution has a negligible (negative) effect on per-capita income with an estimated elasticity of 0.03, ie, a 10% increase in pollution will decrease per-capita income by 0.3%. The elasticities for the composition and trade intensity effects (as usual evaluated at sample means) are consistent with our other work. The technique-effect elasticity is much higher in magnitude (around –3.2). Consistent with our other empirical work the sum of scale and technique effect remains negative.

Table C-9: Simultaneity Analysis: 2SLS Regression

Dependent Variable	$\ln(SO_2)$	
log of city GDP/sq.km.	1.45	(1.51)
Capital abundance (K/L)	0.37	(1.83)
$(K/L)^2$	0.00	(0.19)
Lagged p.c. income (I)	-1.76	(1.32)
I^2	0.57^*	(2.20)
$((I) \times (K/L)$	-0.20^{**}	(3.27)
C.C. $\times I$	11.79^{**}	(4.37)
C.C. $\times I^2$	-11.4^{**}	(4.77)
θ =(X+M)/GDP in %	-2.58^*	(2.47)
$\theta\times$ relative (K/L)	-1.49	(1.27)
$\theta\times$ relative $(K/L)^2$	-0.18	(0.43)
$\theta\times$ relative (I)	1.56^*	(2.53)
$\theta\times$ relative $(I)^2$	-0.20	(1.19)
$\theta\times$ relative $(K/L) \times (I)$	0.42	(1.29)
Average Temperature	-0.06^*	(2.40)
Precipitation Variation	9.18^*	(2.27)
Time Trend	-0.04^{**}	(5.16)
R^2	0.143	
Dependent Variable	ln(GDP/sq.km.)	
log of SO_2 concentration	-0.04^{**}	(3.48)
log of capital stock	0.49^{**}	(25.71)
log of labour fource	-0.81^{**}	(17.08)
Time Trend	0.01^{**}	(5.12)
R^2	0.731	
Elasticities		
Scale	1.453	(1.51)
Composition	1.257^{**}	(3.69)
Technique	-1.722^*	(2.05)
Trade Intensity	-1.054^{**}	(5.85)

Note: T-statistics are shown in parentheses. Significance at the 95% and 99% confidence levels are indicated by * and **, respectively. Regression is a fixed-effects modification of 2SLS (ie, site averages have been subtracted).