ACDIS

Research Report

Extrapolation of Regional Historical Trends of Anthropogenic Atmospheric Carbon Emissions

Clifford E. Singer
Program in Arms Control & Domestic and International Security
University of Illinois at Urbana-Champaign

Research of the Program in Arms Control
& Domestic and International Security

University of Illinois at Urbana–Champaign

August 2022

The research for this publication is supported by the University of Illinois. It is produced by the Program in Arms Control & Domestic and International Security at the University of Illinois at Urbana-Champaign.

The University of Illinois is an equal opportunity/ affirmative action institution.

ACDIS Publication Series: ACDIS *Swords and Ploughshares* is a periodic journal of collected articles aimed at a general audience. The ACDIS *Occasional Paper* series is the program's principal publication for circulating the scholarly analytical results of faculty, students, and visiting researchers associated with ACDIS. The ACDIS *International Security Policy Brief* series highlights ongoing academic research at ACDIS and the University of Illinois that serves to inform U.S. and international policy decisions. The ACDIS *Research Reports* series publishes technical reports and the findings from contracted grant research. For additional information and to download publications, visit the ACDIS home page at: http://acdis.illinois.edu/

Published 2022 by ACDIS//ACDIS SIN:1.2022

University of Illinois at Urbana–Champaign 359 Armory Building, 505 E. Armory Ave.
Champaign, IL 61820-6237

Series Editor: Jazmin Tejeda

Extrapolation of Regional Historical Trends of Anthropogenic Atmospheric Carbon Emissions

CLIFFORD E. SINGER
csinger@illinois.edu
Program in Arms Control & Domestic and International Security
University of Illinois at Urbana Champaign

Abstract: Functional fits to historical data on the fraction of global anthropogenic atmospheric carbon emissions from each of sixteen geographic regions multiply an extrapolation of global carbon emissions. The global extrapolation uses fits to historical estimates of emissions from industrial sources and due to land use changes. That extrapolation is modified by accounting for impact of depletion of fluid fossil fuel resources as influenced by their elasticity of demand. Extrapolated emissions are plotted on figures displaying results for four regions each.

1. Introduction

A starting point for analyzing policy options for limiting future anthropogenic atmospheric carbon emissions contained in carbon dioxide (here referred to as carbon emissions) is an extrapolation of such emissions absent of implementation of new policy options. Impacts of different reductions of global emissions have been analyzed in a previous report [1]. The present report provides a start on analysis of policy options that do not require uniform application of emissions limits across the globe. To this end, historical trends in the fraction of global emissions from sixteen different geographical regions are fit with convenient functional forms for use in extrapolation exercises. Those functions are then multiplied by an extrapolation of global emissions to provide region by region extrapolations. That provides a starting point for possible future work involving region by region analysis of costs and benefits of limiting emissions.

The regional decomposition used here is illustrated in Figure 1. The composition of the regions is close to that in the framework for uncertainty, negotiation and distribution (FUND) model [2]. Of the various models reviewed by Stanton, Ackerman, and Kartha [3] and chosen for study by Gillingham et al. [4], other than RICE [5] and FUND, many were very complex. The FUND model was chosen over a recent version of the RICE model as a starting point because the FUND model allows for separate analysis of the impacts of changes in global average temperature and atmospheric carbon dioxide concentration. Such separation is needed in a model used for examination of solar radiation management options that decouple limitation of increases in global average temperature from limits on carbon emissions.

Table 1 lists three-letter abbreviations for the regions and some notable constituents of several of them. (The table also lists the long-term limits of percentages of global carbon emissions discussed below.) Puerto Rico is placed in the Small Island States (SIS) region. Central and Eastern Europe includes the three former Soviet Union Baltic countries that subsequently joined the European Union. The Former Soviet Union (FSU) region thus excludes those three Baltic countries. Turkey is included in the Middle East (MDE). South Asia (SAS) includes Afghanistan. The Chinese province of Taiwan is included in the Southeast Asia in view of the way its energy mix has been administered. Mongolia and North Korea are included with China (CHI) in view of mutual trade relations. In view of its relationship with Morocco, Western Sahara is included with North Africa (NAF). Sub-Saharan Africa (SAS) includes the other African countries that are at least partly continental, and also Madagascar.

With three small exceptions, the Small Island States (SIS) group includes everything that has EDGAR [6] carbon emissions estimates but is not in the other fifteen regions. Those exceptions are the Falkland, Faroe, and St. Pierre and Miquelon islands. They are included with Western Europe (WEU) in view of their small populations and close association with European countries.

(The word States in the name of the SIS region is not meant to imply that everything included in that region conforms to the formal definition of a state.) Small islands without EDGAR entries are given the same colors in Figure 1 as the regions containing countries that those islands are most closely associated with. Complete lists of the constituents of each of the 16 regions are given in Appendix A below.

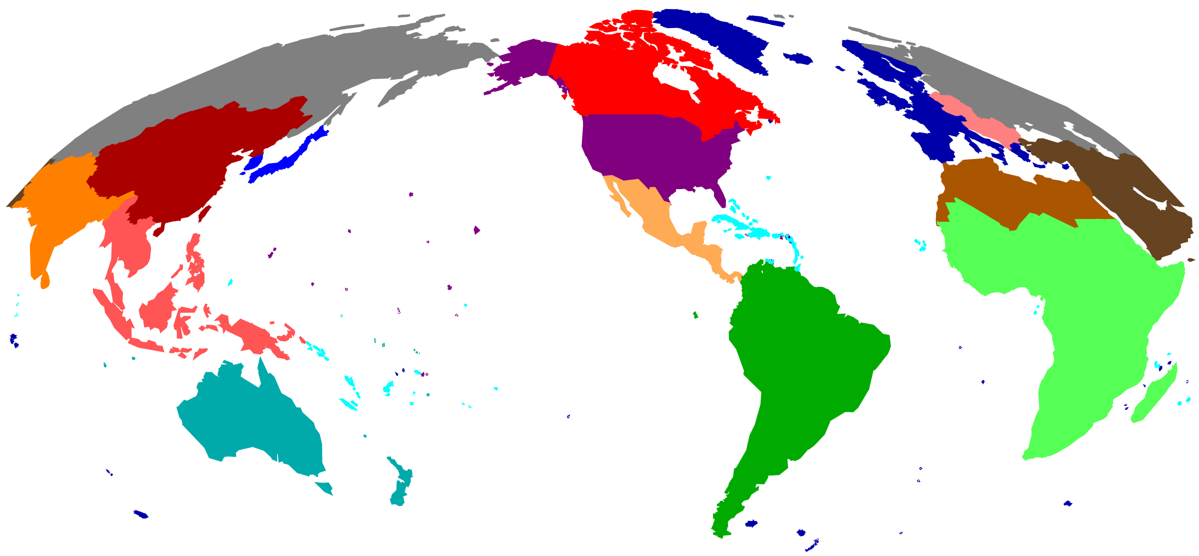

Figure 1. Global regions.

Table 1. Regions

Region	f_∞(%)	Name	
USA (Developed)	8.88	USA	(without Puerto Rico)
CAN (Developed)	2.55	Canada	
WEU (Developed)	7.38	Western Europe	(with Greenland)
JPK (Developed)	6.54	Japan and South Korea	
ANZ (Developed)	1.42	Australia and New Zealand	
CEE (Developed)	1.99	Central and Eastern Europe	(including Baltics)
FSU (FSU)	7.90	Former Soviet Union	(without Baltics)
MDE (Other)	7.32	Middle East	(with Turkey)
CAM (Other)	1.40	Central America	
SAM (Other, South)	3.26	South America	
SAS (Other)	8.21	South Asia	(with Afghanistan)
SEA (Other)	5.41	Southeast Asia	(with Taiwan)
CHI (CHI)	33.48	China	
		(without Taiwan Province,	with North Korea and Mongolia)
NAF (Other)	1.53	North Africa	(Mediterranean + Western Sahara)
SSA (Other, South)	2.30	Sub-Saharan Africa	
SIS (Other, South)	0.42	Small Island "States"	(includes Puerto Rico)

2. Fits to Historical Fractions of Global Emissions

Carbon emissions estimates are from the 1970–2019 portion of annual time series from for 1970–2020, with the exceptions of North Korea and Western Sahara. To avoid the complication of temporary pandemic-related changes, entries after 2019 were not used. For North Korea and Western Sahara, Carbon Dioxide Information Analysis Center (CDIAC) estimates were used [7]. For North Korea, the ratio 0.0775 of its and the rest of the CHI region cumulative emissions for the overlapping years 1970—1984 was multiplied by the other annual CHI region emissions and then added to the other annual CHI emissions. For Western Sahara, the ratio 0.0008 of its and the rest of the CHI region cumulative emissions for the overlapping years 1970—2018 was multiplied by the other annual NAF region emissions and then added to the other annual NAF emissions.

The starting point for extrapolation of historical regional carbon emissions is fitting the global fractions of the CHI and FSU, emissions, and that of the sum of the regions with the word “Other” included in parentheses in Table 1. Those fractions and fits to them are plotted in Figure 2. The sum of those fractions is then subtracted from 1 to get the points and curve labeled “Developed” in Figure 2. The least squares fitting functions used are listed in Table B2.

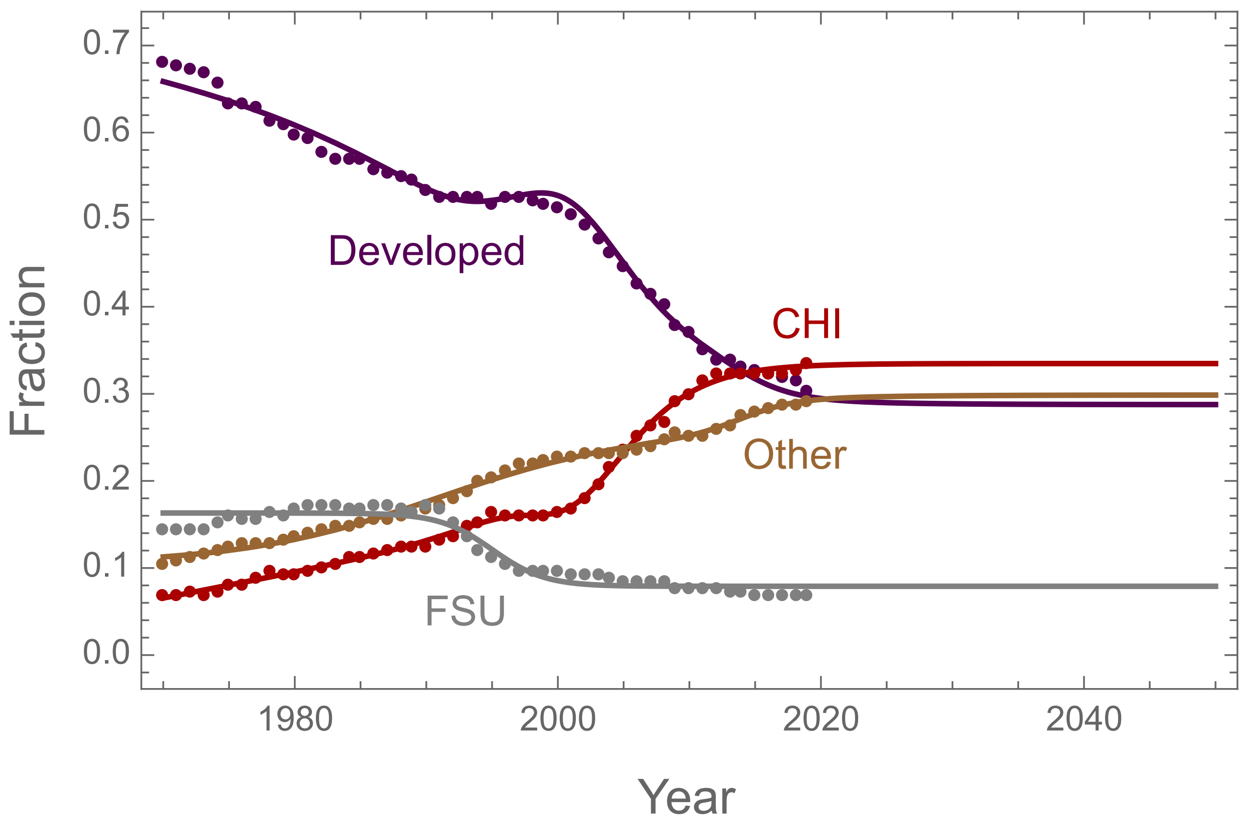

Figure 2. Data and fits for fractions of global carbon emissions for the CHI and FSU regions and the Developed and Other groups.

The fractions of the “Developed” results shown in Figure 1 for all but the USA are then fit, with the results shown in Figure 3a. The USA result is the “Developed” result shown in Figure 1 less the sum for the regions except for USA shown in Figure 3a. Similarly, the fractions of the “Other” result shown in Figure 3 for all but the “South” (SAM+SSA+SIS) group are fit with the result shown in Figure 3b. The result for the “South” group shown in Figure 3b is 1 minus the sum of the regions except for the “South” group. Finally, the CEE fraction of CEE+WEU and each of the SAM and SSA fractions of the "South" group are fit, with the results (and their complements for WEU and for SIS) are shown respectively in Figures 4a and 4b.

Long-term limits of the percentages of global emissions are listed in Table 1. The fitting functions used for Figures 3 and 4 are also listed in Table B1. Threaded throughout these fits is the unit logistic function $u(h, y) = 1/(1+e^{-(t-h)/y})$. In this function, h is the time (in Julian years) at which u is equal to 1/2 of its long-term limit of 1. Use of the unit logistic function u and its complement $1-u$ avoids unphysical results that extrapolate to emissions fractions that are negative or greater than 1. The rate in yr^{-1} at which $1-u$ decays to 0 in the long-term limit is $1/y$. The minimum value of y used for all of the fitting functions is 2 years.

Of particular note are the fitting functions used for global emissions fractions of the CHI and "Other" groups plotted in Figure 1. For CHI, the fitting function is approximately

$$0.30(t-1948)(1-u(1999,2)+0.33u(2003,3.4) \tag{2.1}$$

(For potential use for independent applications of these results, more exact values for the fitting parameters are listed in Appendix B). For CHI, a command economy period of linear growth in emissions less unconstrained by concerns about environmental effects of emissions is replaced in the twenty-first century by an initially rapid increment that transitions to a longer term evolution of the global fraction of emissions with an upper limit of about 33.5%.

The fitting function for the "Other" group of regions is approximately

$$0.1+0.15u(1991,7.5)+0.04u(2014,2) \tag{2.2}$$

One limitation of this approach is that use of a limited number of logistic functions to get a convergent least squares fit for the "Other" group precludes the possibility of a future increase similar to the ones centered around about 1991 and 2014. As a result, each of the curves plotted in Figure 2 rapidly approaches a constant for extrapolations after 2019.

Use of a constant plus a single logistic function appears to capture the consequences of an FSU region economic disruption in the 1990s, with a transition to a lower global carbon emissions fraction centered around about 1995. An additional fitting procedure is not required to address the complications of the evolution of the global carbon emissions fraction of the Developed group, since that fraction is necessarily what makes the total of the curves plotted in Figure 2 add to 1.

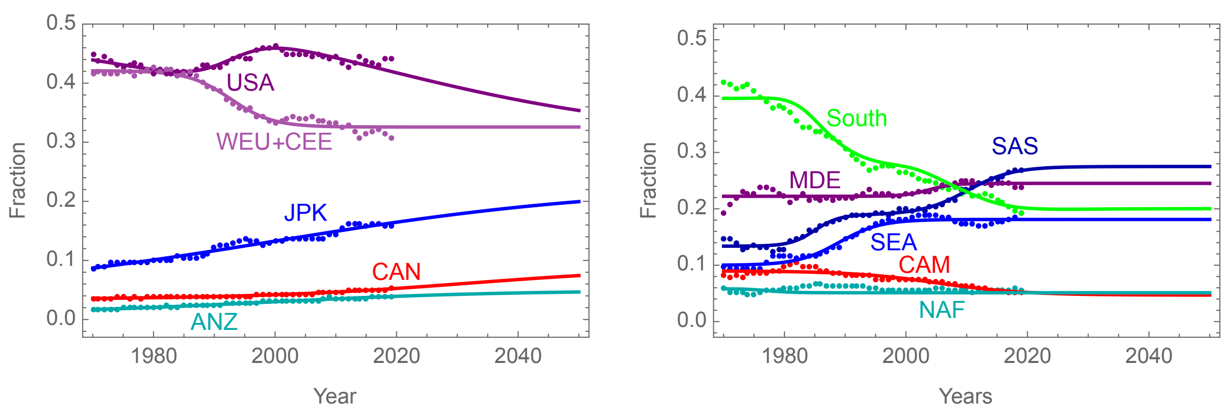

Figure 3. Data and fits for fractions of (a) Developed and (b) Other groups of regions.

The other four plots in Figure 3a are all for constants plus a single logistic function. For Canada, the fit is approximately $0.034+0.055u(2032,18)$. The half-maximum year of 2000 for the Japan and South Korea region (JPK) logistic contribution to the fraction of "Developed" plotted in Figure 3a is earlier than for Canada, but its timescale of about 28 years for approach to saturation is longer. It will be seen below that the CAN and JPK sum of extrapolated growth in total GtonneC/yr (annual billions of metric tons of anthropogenic carbon) emissions after 2019 more than compensates for an extrapolated USA decline in TtonneC/yr emissions.

The decline of the WEU+CEE curve shown in Figure 3a reaches its halfway point in 1993 and correlates with a similar decline in the above-mentioned FSU fraction of global emissions. Figure 4a shows that there was a transient growth in the CEE fraction of the WEU+CEE total, which faded as Eastern European countries joined the European Union. As detailed in Appendix A, that transient is fit with a function of the form $(1-u)u$, which is proportional to the time rate of change of the unit logistic function.

The SAM and SSA fractions of the "South" group are each fit with a constant plus a logistic function. The logistic contributions are small compared to the constant terms. The difference from a constant is a larger fraction of that constant for the SIS fit shown in Figure 4b, which is 1 less the sum of the SAM and SSA fits. It will be seen below that the total extrapolated SIS GtonneC/yr is very small. This suggests policies aimed at changing it would, not surprisingly, have very little effect on total global carbon emissions.

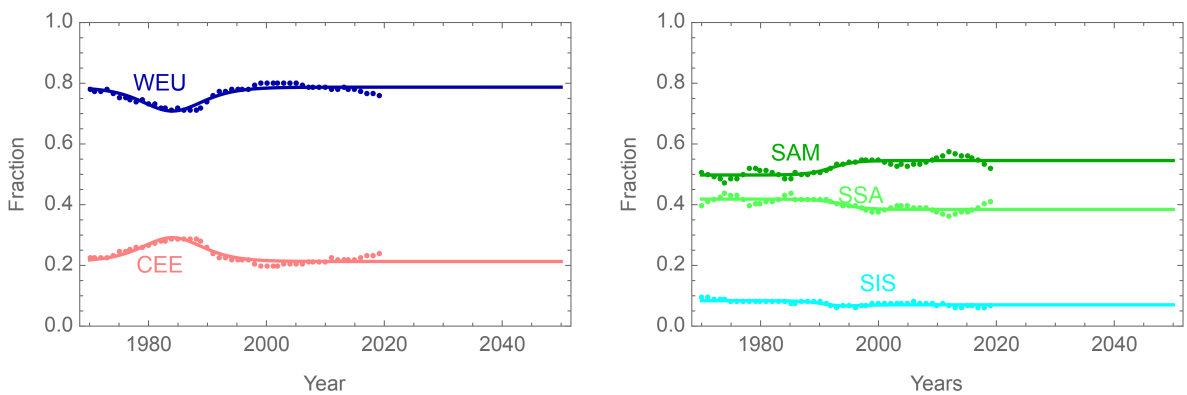

Figure 4. Data and fits for fractions (a) WEU+CEE and (b) South group of regions.

3. Extrapolations of Global Emissions

Formulas for fractions of total global emissions for each region are found by multiplying appropriate combinations of the functions plotted in Figures 2–4. To use those results to extrapolate carbon emissions for each region, it is also necessary to have formulas for extrapolation global emissions. A starting point for that was fitting increases in global industrial emissions from 1750–2019 with a logistic function, and fitting evolution of emissions from deforestation and other land use changes with two terms proportional to the time rate of change of logistic functions. To account for effects on use of fluid fossil fuels from depletion of their easier to extract resources in the context of a globalizing market for such fuels, a correction term for the extrapolations is applied. This overall approach is detailed in a previous report [8] and also summarized for completeness here at the end of Appendix B.

To plot the results of this exercise, the sixteen regions summarized in Table 1 are divided into four groups. Plotted in Figure 5a are the results accounting for about 52% of the total long-term-limit emissions fractions listed in Table 1. The logic for using this grouping is that just three coordinated policy implementations, (in China, the European Union, and the United States) could in principle affect up to about half of total long-term emissions. Because the CHI region alone accounts for over a third of the long-term limit fraction of emissions, that region could realize calculated economic benefit from reducing environmental impacts of climate change that more than offset the cost of implementing partial emissions reductions [9]. The EU could have perceived security benefits of reducing fossil fuel use that it sees compensating for costs associated with carbon emissions reductions. Combined with noting that the USA has a larger near-term extrapolated GtonneC/yr of carbon emissions than any of the other regions except for CHI, this way of plotting the extrapolations draws attention to the question of how U.S. policy on emissions will in fact evolve.

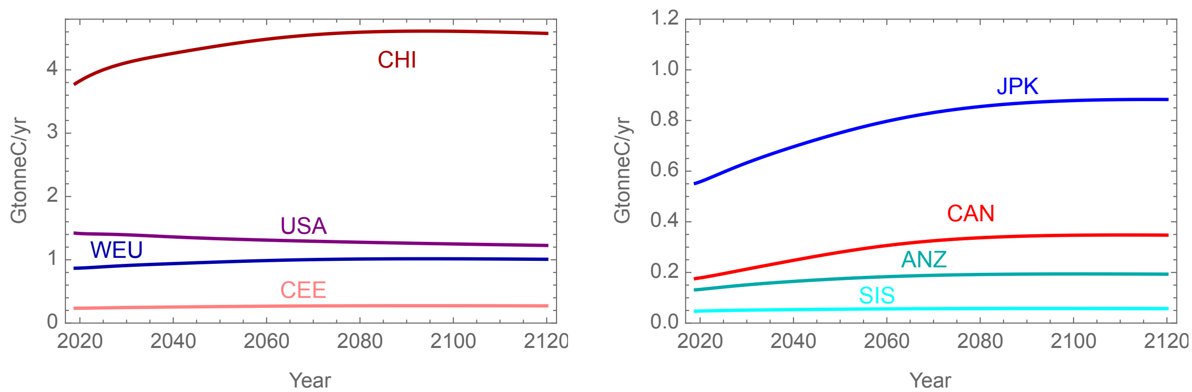

Figure 5. Extrapolated carbon emissions for (a) CHI, USA, WEU, and CEE and (b) JPK, ANZ, CAN, and SIS.

Plotted in Figure 5b, with a three-fold smaller vertical scale than in Figure 5a, are extrapolated GtonneC/yr emissions from three "Developed" regions and for Small Island States (SIS). Together, these account for about 11% of the long-term fractions of total carbon emissions listed in Table 1. Having either high-latitude populations or substantial populations in maritime-influenced climate these regions, these regions may have less financial incentive to cooperate with substantial emissions reductions if direct impacts of warming on productivity and cooling costs dominate impacts of warming on economic productivity. This observation suggests that the comparative importance of other impacts of globally more minor such as storm damage and coral reef destruction may merit particular attention for one or more of these regions. Historical alliance relations, a limited number of decision makers in the comparatively prosperous CAN, JPK, and ANZ regions, and the possibility of effective delivery of foreign aid to politically stable components of the SIS regions may also facilitate cooperation on emissions reductions by some or even all of the regions plotted in Figures 5a and 5b. That observation is a motivation for plotting extrapolated emissions from these four regions on the same figure.

Figure 6a plots extrapolated carbon emissions from South Asian States (SAS) and a set of three middle income regions. Together, these account for about 18% of the total fractions of long-term extrapolated emissions listed in Table 1. Formally, most of the components of these are participants in regional cooperation organizations. These are the Organization of American States (OAS, with twenty founding members in addition to the United States), the Association of Southeast Asian Nations (ASEAN with ten members), and the South Asian Association for Regional Cooperation (SAARC, with six continental members, Sri Lanka, and the Maldives). In practice, organizing effective cooperation of carbon emissions reductions across the entire set of four regions listed with results plotted in Figure 6a could be more challenging than for the three "Developed" regions plotted in Figure 5b.

Figure 6b plots results for the SSA region of Africa that contains 44 countries, and for three fluid fossil fuel exporting regions. Together, these account for about 19% of the total fractions of long-term extrapolated emissions listed in Table 1. The political challenges of arranging and implementing coordinated carbon emissions reductions amongst 44 mostly low per capita income countries and a set of fluid fossil fuel exporters could be particularly daunting.

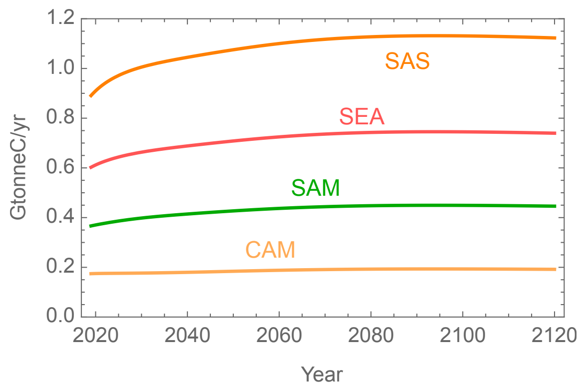

Figure 6. Extrapolated carbon emissions for (a) SAS, SEA, SAM, and CAM and (b) FSU, MDE, SSA, and NAF.

4. Implications

The underlying approach here to extrapolating anthropogenic atmospheric carbon emissions is to first extrapolate global emissions and then multiply the result by extrapolations of regional fractions of those emissions. This layered approach allows exploring the consequences of global emissions first [1], without immediately delving into regional variations. Implications of economic, political, and environmental homogeneity can then be explored, using results presented herein, at a somewhat deeper level of analysis.

As noted above, the way that logistic contributions to fitting functions are used here automatically guarantees that extrapolations of emissions fractions will have physically reasonable bounds. A possible disadvantage is that extrapolations of emissions fractions approach constants on time scales determined by the range of historical data used, with relaxation time constants here ranging up to only about 28 years. The possibility that there might be longer term trends is thus not accounted for. One such possibility is the evolution of implementing different emissions limitation policies for different regions, which may be explored in a subsequent report.

That countries in different regions might develop and implement substantially different carbon emissions limitation policies is foreshadowed by the groupings of extrapolations of total regional GtonneC/yr emissions shown in Figures 5 and 6. The f_∞ long-term fractions limits listed in Table 1 can provide a starting point for considering what options for reducing extrapolated global carbon emissions by different factors might plausibly be implemented either by implicit or explicit agreement on actions within different geographic regions. The results presented here and in the provide an update of some of what is needed to extend previous work along these lines [9].

Appendix A. Geographic Regions

Table A1 lists International Standards Organization abbreviations [10] for all of the components of each region. Table A2 lists full names of what is included in the SIS (Small Island States) region. Some, but not all, reporting units not recognized by the United Nations as sovereign states are assigned to regions containing countries that they are associated with. (A small darker dot east of Haiti on Figure 1 does not correspond to an island and appears to be a software rendering glitch.) Following the FUND model assignments, Puerto Rico is included in the SIS region. The assignment of islands was generally based on geography for cases where adequate data on economic production was available and by political association otherwise.

Table A1. Region Components

Region	ISO Code											
USA	USA											
CAN	CAN											
WEU	AUT	BEL	CYP	CHE	DNK	FLK	FRO	FIN	FRA	DEU	ESP	GIB
	GBR	GRC	GRL	ISL	IRL	IMN	ITA	LIE	LUX	MLT	MCO	NLD
	NOR	PRT	SMR	SPM	SWE							
JPK	JPN	KOR										
ANZ	AUS	NZL										
CEE	ALB	BIH	BGR	CZE	EST	HRV	HUN	LVA	LTU	MKD	MNE	POL
	SRB	SVK	SVN	UVK								
FSU	ARM	AZE	BLR	GEO	KAZ	KGZ	MDA	RUS	TJK	TKM	UKR	UZB
MDE	ARE	BHR	IRN	IRQ	ISR	JOR	KWT	LBN	OMN	PSE	QAT	SAU
	SYR	TUR										
CAM	BLZ	CRI	GTM	HND	MEX	NIC	PAN	SLV				
SAM	ARG	BOL	BRA	CHL	COL	ECU	GUF	GUY	PRY	PER	SUR	URY
	VEN											
SAS	AFG	BGD	BTN	IND	LKA	NPL	PAK					
SEA	BRN	IDN	KHM	LAO	MYS	MMR	PNG	PHL	SGP	TWN	THA	TLS
	VNM											
CHI	CHN	HKG	MAC	PRK	MNG							
NAF	DZA	ESH	EGY	LBY	MAR	TUN						
SSA	AGO	BEN	BWA	BFA	BDI	CMR	CAF	COD	COG	CIV	DJI	GNQ
	ERI	ETH	GAB	GMB	GHA	GIN	GNB	KEN	LSO	LBR	MDG	MWI
	MLI	MRT	MOZ	NAM	NER	NGA	RWA	SEN	SLE	SOM	TCD	SSD
	SDN	SWZ	TZA	TGO	UGA	ZAF	ZMB	ZWE				
SIS	AIA	ATG	ABW	BHS	BRB	BMU	BES	VGB	CYM	COM	COK	DJI
	GNQ	ERI	ETH	GAB	ETH	GAB	GMB	GHA	GIN	GNB	KEN	CUB
	CUW	DMA	DOM	FJI	PYF	GRD	GLP	GUM	HTI	JAM	KIR	MDV
	MHL	MTQ	MUS	MYT	FSM	NRU	NCL	MNP	PLW	PRI	REU	SHN
	KNA	LCA	VCT	BLM	MAF	WSM	STP	SYC	SXM	SLB	TON	TTO
	TCA	TUV	VUT	VIR	WLF							

Table A2. SIS, Small Island States

Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Bermuda, British Virgin Islands, Cayman Islands, Comoros, Cabo Verde, Cook Islands, Cuba, Curaçao, Dominica, Dominican Republic, Fiji, French Polynesia, Grenada, Guadeloupe, Haiti, Jamaica, Kiribati, Maldives, Martinique, Mauritius, New Caledonia, Palau, Puerto Rico, Réunion, Saint Helena and Ascension and Tristan da Cunha, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Samoa, São Tomé and Príncipe, Seychelles, Solomon Islands, Tonga, Trinidad and Tobago, Turks and Caicos Islands, Vanuatu

Appendix B. Fitting Functions

Using the notation $u_{mn} = 1/(1+e^{-(t-b_m)/b_n})$, Table B1 lists the fitting functions and their parameter values used to produce the graphs above. The numbers less than 1 in Table B1 are dimensionless fractions; the units of the numbers greater than 1900 are Julian years, and the units of the numbers between 1 and 30 are years.

Table B1. Carbon Emissions Fraction Functions and Parameters

Who	Fit b_0	b_1	$b2$	b_3	b_4	b_5	b_6
World							
CHI							
$b_1(t-b_0)(1-u_{23})+b_4u_{56}$	1947.86	0.2956	2	1998.83	0.3348	2002.59	3.425
Other $b_0+b_1u_{23}+b_4u_{56}$	0.1040	0.1546	1991.01	7.485	0.0401	2013.98	2
FSU $b_0+b_1u_{23}$	0.1631	-0.0841	1995.01	2			
Developed							
CAN $b_0+b_1u_{23}$	0.0342	0.0546	2031.82	17.72			
WEU+CEE $b_0+b_1u_{23}$	0.4210	-0.0952	1992.68	3.47			
JPK $b_0+b_1u_{23}$	0.0386	0.1887	2000.15	28.43			
ANZ $b_0+b_1u_{23}$	0.0093	0.0400	1998.42	19.61			
Other							
MDE $b_0+b_1u_{23}$	0.2223	0.0229	2003.77	2.002			
CAM $b_0+b_1u_{23}$	0.0090	0.0429	2005.25	7.12			
SAS $b_0+b_1u_{23}+b_4u_{56}$	0.1338	0.0556	1984.98	2	0.0856	2010.08	3.73
SEA $b_0+b_1u_{23}$	0.0999	0.0813	1989.00	3.43			
NAF $b_0+b_1u_{23}$	0.0582	-0.0071	1977.40	2			
WEU+CEE							
CEE $b_0+b_1u_{23}(1-u_{23})$	0.2129	0.3144	1984.04	3.48			
South							
SAM $b_0+b_1u_{23}$	0.4978	0.0476	1992.02	2			
SSA $b_0+b_1u_{23}$	0.4184	-0.0339	1993.84	2			

Note that the maximum value of $b_1u_{23}(1-u_{23})$ in the row starting with CEE is $b_1/4 = 0.0786$, so the rise in CEE/(WEU+CEE) shown in Figure 4a is smaller than the base value of $b_0 = 0.2129$.

Global extrapolated carbon emissions in GtonneC/yr used here are $1000e_c$ [8], where

(B.1) $$e_c = f_c e_{\text{ind}} + (1-f_c)f_d e_{\text{ind}} + e_{\text{land}}$$

Here e_{land} is the sum of the last two formulas listed in Table B2, and

(B.2) $$f_d = \left(1 + \frac{1+b_d\text{Max}[U, U_{2019}]}{1+b_dU_{2019}}\right)^{\beta_f}$$

The formula for cumulative sum of industrial atmospheric carbon emissions is

(B.3) $$U = -b_1b_2 + b_1b_3\ln[e^{b_2/b_3} + e^{t/b_3}] + b_0(t-1750)$$

(The units used in this section are in TonneC to avoid large numbers in GtonneC for cumulative carbon emissions.) Here, b_0, b_1, b_2, and b_3 are from the first row of numbers in Table B2 and values of the other parameters are listed in Table B3.

Table B2. Global Carbon Emissions Constants

Type, with Units in TtonneC/yr	b_0	b_1	b_2 (Julian Year)	b_3 (yrs)
Industrial $b_0 + b_1 u_{23}$	-0.000002	0.015285	2002.57	27.82
Land Use Early $b_0 + b_1 u_{23}(1 - u_{23})$	-0.000075	0.005940	1950.98	46.20
Land Use Late $b_1 u_{23}(1 - u_{23})$	0	0.002967	2021.63	8.91

Table B3. Fluid Fossil Fuel Depletion Effect Constants

Symbol	pp4	Value	Units	Description
f_c	0.41	1		coal fraction of 1965–2019 carbon emissions
b_d	0.68	1/TtonneC		fluid fossil fuel depletion effect coefficient
β_f	-0.35	1		fluid fossil fuel demand elasticity exponent
U_{2019}	0.44	TtonneC		cumulative industrial emissions through 2019

References

[1] Ding, C., and C. Singer, 2002. Extrapolations of Global Average Temperature, Sea Level Rise, and Ocean pH Change, University of Illinois at Urbana-Champaign Program in Arms Control & Domestic and International Security Research Reports ACDIS//ACDIS DIN:5, https://acdis.illinois.edu/outreach/research/research-reports, 2022.

[2] Anthoff, D., and J. Tol, 2014. The climate framework for uncertainty, negotiation and distribution (FUND), technical description, version 3.9, http://www.fund-model.org/versions, accessed May 18, 2019.

[3] Stanton, E., F. Ackerman, and S. Kartha. 2009. Inside the integrated assessment models: Four issues in climate economics. *Climate and Development* **1**, 166–184, doi: 10.3763/cdec.2009.0015.

[4] Gillingham, K., W. Nordhaus, D. Anthoff, G. Blanford, V. Bosetti, P. Christensen, H. McJeon, J. Reilly, and P. Sztorc. 2015. Modelling uncertainty in integrated assessment of climate change: A multi-model comparison, MIT Joint Program on the Science and Policy of Climate Change Report 290. https://globalchange.mit.edu/publication/16235.

[5] Nordhaus, W. 2010. Economic aspects of global warming in a post-Copenhagen environment. *Proceedings of the National Academy of Sciences* **107**, 11721-11726, doi/10.1073/pnas.1005985107.

[6] Crippa, M., D. Guizzardi, E. Solazzo, M. Muntean, E. Schaaf, F. Monforti-Ferrario, M. Banja, J. Olivier, G. Grassi, S. Rossi, E. Vignati, GHG emissions of all world countries - 2021 Report, EUR 30831 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-41547-3, doi:10.2760/074804, JRC126363.

[7] Boden, T., G. Maria, B. Andres. 2011. Index of /ftp/trends/emissions, Oak Ridge National Laboratory Carbon Dioxide Information Analysis Center, https://cdiac.ess-dive.lbl.gov/ftp/trends/emissions/, accessed May 23, 2022.

[8] Ding, C., and C. Singer, 2002. Calibration and Extrapolation of a Simple Global Carbon Balance Model,2 University of Illinois at Urbana-Champaign Program in Arms Control & Domestic and International Security Research Reports ACDIS//ACDIS DIN:2, https://acdis.illinois.edu/outreach/research/research-reports, 2022.

[9] Yang, B. 2021. Economic analysis of international climate cooperation. University of Illinois at Urbana-Champaign PhD Thesis, https://www.ideals.illinois.edu/handle/2142/110488.

[10] International Standards Organization. 2019. Country Codes Collection. https://www.iso.org/publication/PUB500001.html, accessed December 15, 2019.