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Historic Patterns of CO_2 Emissions from Fossil Fuels: Implications for Stabilization of Emissions

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INTRODUCTION

Global carbon dioxide (CO_2) emissions from fossil fuel consumption (CO_2 emissions from cement manufacture are also included) have been documented by several workers.[1,2,3] Emissions grew at a remarkably constant 4.3% per year from 1950 until the time of the 1973 oil crisis (Figure 1). Another disruption in the pattern of growth followed the oil price increases of 1979. Although the earlier growth rate has not been resumed, global total emissions have been increasing steadily since the 1982-1983 minimum and have grown by more than 20% since then.

At present, emission of CO_2 from fossil fuel burning is dominated by a small number of countries. In 1990, emissions from the U.S., the former Soviet Union, and China comprised over 50% of the total emissions from all countries and the developed countries of Europe and Japan were major contributors. Only 20 countries emit 84% of emissions from all countries. However, rates of growth in many of the developed countries are now very low. In contrast, energy use has grown rapidly over the last 20 years in some of the large, developing economies.

Emissions from fossil fuel consumption are now nearly 4 times those from land use change[4] and are the primary cause of measured increases in the atmospheric concentration of CO_2.[5] The increasing concentration of atmospheric CO_2 has led to rising concern about the possibility of impending changes in the global climate system.

In an effort to limit or mitigate potential, negative effects of global climate change, 154 countries signed the United Nations Framework Convention on Climate Change (FCCC) in Rio de Janeiro in June, 1992. The stated objective of the FCCC is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system".[6] Specifically the FCCC asks all countries to conduct an inventory of their current greenhouse gas emissions and it sets non-binding targets for some countries to control emissions by stabilizing them at 1990 levels by the end of the present decade. The FCCC also acknowledges the "specific needs and concerns of developing country Parties...with economies that are vulnerable to the adverse effects of implementation of measures to respond to climate change".[6]

This paper examines the historical record of greenhouse gas emissions since 1950, reviews the prospects for emissions into the future, and projects what would be the short-term outcome if the stated targets of the FCCC were in fact achieved. The examination focuses on the most important of the greenhouse gases, CO_2. The extensive record of historic CO_2 emissions is explored to ascertain if it is an adequate basis for useful extrapolation into the near future. This is not intended as a critique of the FCCC, for the challenges of this first step are appreciated: it is rather an attempt to gauge the length of this first stride. If the world judges it is important to control CO_2 emissions, how ambitious was the target which emerged from the negotiations leading up to the Rio accord?

BACKGROUND

The FCCC commits all Parties to develop and make available national inventories of anthropogenic emissions of greenhouse gases and to formulate and implement national programs to mitigate climate change by addressing anthropogenic emissions of greenhouse gases. Further, those countries specifically listed in Annex I are committed to adopting national policies and taking corresponding measures to limit anthropogenic emissions of greenhouse gases. Although the phrasing of Article 4, Paragraphs 2a and 2b is, purposefully, a bit convoluted, the key phrases are "...return by the end of the present decade to earlier levels of anthropogenic emissions of carbon dioxide and other greenhouse gases..." and "...with the aim of returning individually or jointly to their 1990 levels of these anthropogenic emissions...".[6] Although the extra words of this text allow the reader to render these into targets rather than commitments, it is clear that the objective is returning greenhouse gas emissions to 1990 levels by 2000 (note that the FCCC always refers to "greenhouse gases not controlled by the Montreal Protocol" in order to avoid conflicts with controls already adopted under international agreements for protection of stratospheric ozone). The FCCC provides that this target be reviewed at the first session of the Conference of Parties and again not later than the end of 1998 and that the list of countries in Annex I also be reviewed prior to the end of 1998. Paragraph 7 of Article 4 specifically acknowledges that "economic and social development and poverty eradication are the overriding priority of the developing country Parties".[6] Annex I lists the 24 Organization for Economic Cooperation and Development (OECD) countries plus 6 of the former republics of the USSR, 5 additional countries in Eastern Europe (Bulgaria, Czechoslovakia, Hungary, Poland and Romania), and the European Community.

It is interesting to note the role of the Annex I countries in terms of the magnitude of current emissions of CO_2 from fossil fuel combustion for all countries. In 1990, 10 countries accounted for more than 70% of the total CO_2 emissions and all but two of these countries, China and India, are Annex I countries. Seventeen countries emit 80% of global CO_2 emissions and 11 of these are Annex I countries. By the time 90% of emissions are accounted for, the list includes 16 countries which are Annex I signees and 14 which are not. The data show that current and historic emissions have been dominated by countries which have now endorsed the goal of stabilizing emissions. Figure 2 illustrates the extent to which historic CO_2 emissions have been dominated by OECD (see North America; Western Europe; and Oceania, dominated by Japan and Australia) and Eastern European countries.

Figure 2 also illustrates that the relative contributions of regions to global CO_2 emissions have changed markedly over time. As early as 1984 it was noted that growth in emissions was most vigorous in some of the developing countries and that, over time spans beyond a couple of decades, growth would be dominated by the developing countries.[7] Edmonds and Barns showed in 1990 that some emissions control objectives, even within the next 2 decades, could not be achieved without developing country participation.[8] Figure 3 shows that CO_2 emissions have grown slowly in some regions, mostly those containing Annex I countries, since the early 1970's, while growth has continued in other regions. Thus the current situation is that emissions are dominated by one set of countries while others are experiencing rapid growth in energy consumption and greenhouse gas emissions. Although, as the FCCC acknowledges, economic development and convergence is a desired objective, it creates challenges in confronting greenhouse gas emissions.

With a data set that provides a 41-year time series of CO_2 emissions for most countries, it is enticing to speculate on the consequences of continuing current trends. The capacity also exists to examine the potential consequences of the FCCC by calculating along current trends for most countries while freezing emissions from those specifically listed in Annex I.

Extrapolating current trends into the future is hardly an elegant way to generate scenarios. Analysis of the future of greenhouse gas emissions has taken great strides over the last decade, moving from simple extrapolations of time trends to complex models of the global economy. It is increasingly possible to create "what if" scenarios to examine the interactions of growth in population, changes in economic variables and potential control strategies to see their implications for greenhouse gas emissions.[9, 10, 11, 12] The various models have different levels of national or regional resolution and disaggregation by economic activity. They provide a consistent framework to examine the possibilities. Modeling tools can represent the interrelationships among technological development, resource depletion, human activities and political decisions; but they cannot capture the capriciousness of human motivation. The record of global CO_2 emissions since 1950 (Figure 1) demonstrates both the regularity of recent growth and that projections made prior to 1973 would have seriously missed the current state. Yet, models of any sophistication are unlikely to anticipate the kinds of dislocations in energy consumption that were observed in the middle to late 1970's.

Nevertheless simply extrapolating current trends a short distance into the future is unlikely to go too far astray and in the text below it is shown that the simple projections do closely approximate some of the most commonly cited model results. Although the value of extrapolations decreases with their length, the projections were extended to 2025 to facilitate comparison with scenarios like those produced by the Intergovernmental Panel on Climate Change (IPCC).

METHODS

Recognizing that the agreements in the FCCC place stabilization goals primarily on countries that already have low, or in some cases negative, rates of growth, the extrapolations show how much the current path would be altered if the FCCC objectives were fully implemented. This has been done by taking data on CO_2 emissions in the recent past, solving the linear regression equations, and extrapolating a short distance into the future. This was done individually for each of 191 countries. The second step was to assume that Annex I countries had CO_2 emissions stabilized at the 1990 level. Although the FCCC discusses achieving 1990 levels by the year 2000, the extrapolations considered the case of stabilization at 1990 levels out to the year 2025. A linear regression was chosen for all countries because a linear model provides a good fit for the global total and for many countries, and because exponential extrapolations quickly get out of hand as shown in studies like "The Limits to Growth".[13]

Because the historic data show that growth of emissions from many countries was disrupted during the late 1970's and that the global total resumed relatively uniform growth in the early 1980's, linear regressions were done on the 1981-1991 data series for each country. Preliminary experiments showed surprisingly little difference in the extrapolations when years 1979 to 1984 were chosen as the starting point for the regression analyses. All data series end in 1991, the last year for which United Nations energy data are available as the basis for CO_2 emissions calculations.[3]

In four cases country data were aggregated because of political splitting or unification during the interval analyzed, e.g. the unification of Germany in 1990. For the Soviet Union there is only a single historic time series despite the current presence of 15 independent republics. Because 6 of these republics have consented to be Annex I countries, and because these 6 republics accounted for 85.5% of total CO_2 emissions from the USSR in 1985,[14] the combined former USSR was treated as if it were a single Annex I country.

The analysis was duplicated for 191 countries plus one additional data grouping. Largely because emissions from bunker fuels (i.e. those fuels used in international commerce) are not assigned to any country, the sum of emissions from all countries is always less than the global total of emissions.[15] This difference between the estimate of global total CO_2 emissions and the sum of all country emissions is labeled "BUN" in the figures and the emissions were treated as if they were emissions from country number 192. After obtaining the slopes and intercepts for all 192 linear regressions, projections were made by extrapolating each data series out to 2025. The individual country emissions were summed to yield regional and global totals.

Review of the slopes and intercepts for the 192 regression lines (Table 1) revealed that a number have negative slopes, i.e. CO_2 emissions have been decreasing over the last decade. Primarily these are small countries, with very low rates of CO_2 emissions and political and/or economic problems. Other nations suffering economic difficulties and undergoing negative CO_2 emissions growth rates are important Eastern European countries (Hungary, Poland, Romania, Czechoslovakia and Bulgaria). Also France, with its successful movement away from fossil fuels; Germany; Belgium and Sweden are undergoing negative growth rates. Only for France and Poland has the decline been greater than 1 million metric tonnes C per year. Although declining emissions are unlikely to continue for very long, for consistency of the analysis, the extrapolations were continued as described for the current-trends scenario and emissions were frozen at 1990 levels in the second computation. The 37 countries with declining emissions were responsible for emissions of 767 x 10^6 tonnes C in 1981 and only 373 x 10^6 tonnes C in 2025, a fact that needs to be considered when comparing output from the two scenarios. Of the 394 x 10^6 tonnes C reduction, 174 x 10^6 tonnes C are from France and Poland and 357 x 10^6 tonnes C from all Annex I countries. For a couple of small countries, extrapolation of declining emissions actually leads to negative values of CO_2 emissions by 2025, but the sum of all negative values never exceeds 0.3% of global, total emissions and they are ignored here.

Another defect of simple extrapolations needs to be emphasized before the numbers generated are considered. Emissions from Annex I countries have been mathematically frozen while emissions continue current trends in other countries. In fact, it is inevitable that emissions-reduction targets in Annex I countries would have repercussions in other countries as well. Whether freezing emissions would cause a shift of energy-intensive activities such as petroleum refining and metals processing away from Annex I countries, or cause a spreading depression of economic growth, or some combination of the two, can only be examined with the more sophisticated models being developed to examine emissions futures. A recent analysis suggests a "leakage rate" of about 10% by 2025 as unilateral emissions reductions in OECD countries result in emissions elsewhere rising by 10% more than in the business-as-usual (BaU) case.[16] Leakage in the Manne and Rutherford model occurs because the unilateral emissions controls put downward pressure on international oil prices and stimulates oil consumption elsewhere. Such leakage is not considered in the results presented here.

Simple, short-term extrapolations can produce interesting comparisons with the outcome of more complex models. The current-trends, linear extrapolation for the U.S. passes through

1351 x 10^6 tonnes C in 1990 and reaches 1576 x 10^6 tonnes C by the year 2000. By contrast, President Clinton's Climate Change Action Plan is targeted against a that passes through 1367 x 10^6 tonnes C in 1990 and reaches 1474 x 10^6 tonnes C in 2000.[17] The model exercised for Clinton's BaU scenario envisions much slower growth in CO_2 emissions than has been the case for the last decade. Even freezing emissions at 1990 levels, the U.S. remains, in the linear extrapolations, the largest, single, CO_2 source until exceeded by China in 2012.

RESULTS AND COMPARISON WITH OTHER PROJECTIONS

Figure 4 shows the results of the extrapolation of global CO_2 emissions from fossil fuel consumption based on 192 linear regressions. The upper curve represents projected emissions if current trends continue. The lower curve represents projected emissions if the FCCC objective is fully implemented. Freezing CO_2 emissions at 1990 levels in Annex I countries produces a 34% decrease in the amount of emissions in 2025. Emissions reach 10,365 x 10^6 tonnes C in 2025 in the current-trends extrapolation but only 8,800 x 10^6 tonnes C when growth is denied in Annex I countries. Recall, however, that the current-trends case has 37 countries with declining emissions, including 9 Annex I countries with emissions that are held constant in the second scenario but declined by 357 x 10^6 tonnes C when allowed to follow current trends.

The CO_2 emission projections developed herein have been based solely on the recent, historical record of CO_2 emissions from individual countries. Other, and more sophisticated, bases for making CO_2 emission projections are being widely employed. It is important to note that projections, based on current trends and ideas, decrease in utility the further they are projected into the future and the probability of changing or unforseen circumstances increases; including social, political, economic and technological developments. The extrapolations presented in Figure 4 have been extended, with some trepidation, out to 2025 in order to facilitate comparison with other projections.

In 1992, the IPCC developed six, new scenarios of CO_2 emissions which embody widely varying economic, social, and environmental trends (Figure 5). These scenarios were intended to span the range of credible anthropogenic impacts on the climate. They are not predictions, rather they are the input into climate models. The scenarios extend to the year 2100, but in 2025, CO_2 emissions vary by a factor of 1.7. Of particular interest here is scenario IS92a which is their BaU scenario. IS92b is similar to IS92a but embodies some proposed limitations in greenhouse gas emissions.

The IPCC specifically notes that "Population and economic growth, structural changes in economies, technological advance, fossil fuel supplies, nuclear and renewable availability are among the factors which could exert a major influence on future levels of CO_2 emissions".[18] In fact, the IPCC developed its 1992 scenarios after only 2 years of evolving events suggested a revision of the "underlying assumptions" in its 1990 scenarios. For all of the discussion of scenario building, population projections, and gross domestic product per capita, the IPCC BaU scenario is very little different from the linear extrapolation of historical trends of CO_2 emissions. IPCC scenario IS92a had 2025 emissions of CO_2 at 11.1 x 10^9 tonnes C, 7% larger than the current-trends, linear extrapolation and very close to the linear extrapolation if the negative slopes were set to zero. IS92b has 2025 emissions of 10.7 x 10^9 tonnes C, 20% larger than the frozen emissions extrapolation. The IPCC recognizes that their BaU scenario, IS92a, has GNP growth rates "substantially below those experienced by most world regions in the past 34 years, from 1955 to 1989" and that it "fall(s) well below the aspirations of many countries".[18] Interestingly, Jesse Ausubel has shown that the long-term historic trend of decreasing intensity of CO_2 emissions per unit of primary energy use is not captured in the IPCC scenarios.[19] The clear implication is that in building scenarios for the future which include complex parameters, the scenarios are very much limited by the imaginations of their creators. In IS92a, fossil energy represents over 85% of primary energy use until 2025.

Dean and Hoeller[20] have described CO_2 emissions from 6 global economic models as part of an OECD Model Comparison Project. Even for the BaU scenarios, there is a wide range of estimates of CO_2 emissions over the next century. For the 4 models which generate CO_2 emissions values for 2020, the values range from 8180 to 10,800 with a mean value of 9460×10^6 tonnes C (the extrapolated current-trends value for 2020 is 9752×10^6 tonnes C) (Figure 5). Despite large uncertainties, the different models agree that emissions are likely to grow substantially over the next century, that emissions will grow fastest over the next decades before slowing later in the century, and that growth will be faster in developing than in developed countries.[21]

Figure 5 shows the extrapolations superimposed on the range of emissions for the 6 IPCC scenarios. Figure 5 also shows the 2025 emission endpoints of other projections. The time trend of these other projections have not been shown for clarity.

Figure 6 shows the regional distribution of emissions in both current-trends and annex I-freeze scenarios. The surprising feature is the relative lack of difference between the two scenarios. The major difference is in the emissions from North America. This is because all included countries, the United States and Canada, are under a freeze in emissions. Their relative loss in emissions is spread over the other regions with no region gaining excessively.

CONCLUSIONS

Increasing concern over rising levels of greenhouse gas emissions to the atmosphere led 154 countries to sign The Framework Convention on Climate Change in June, 1992. Among other things, the FCCC aims to have developed countries limit their emissions to 1990 levels by the year 2000. Many of these developed countries are among the major emitters of CO_2. This study examined the possible effect of a fully implemented FCCC on emissions of CO_2, the most important of the greenhouse gases.

Limiting emissions in developed countries produces a significant reduction in global total emissions, but a large portion of growth is now in developing countries. Compared to a current-trends scenario, the FCCC would lead to a 34% decrease in the amount of emissions in 2025. Whether or not emissions controls are implemented, distribution of emissions among economic regions is changing with time. The majority of growth in emissions is occurring in developing countries who are trying to meet their goals for economic and social development.

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Table 1. Range of slopes of the 192 linear regressions of CO_2 emissions from fossil fuel consumption and cement manufacture. All slopes are reported in million tonnes C/year. The number of Annex I countries are included in parentheses where appropriate.

Range of Slopes	Number of Regressions
< -1	2 (2)
-1 - < 0	35 (7)
0 - 1	137 (15)
1 - 2	8 (3)
2 - 3	2
> 3	8 (3)

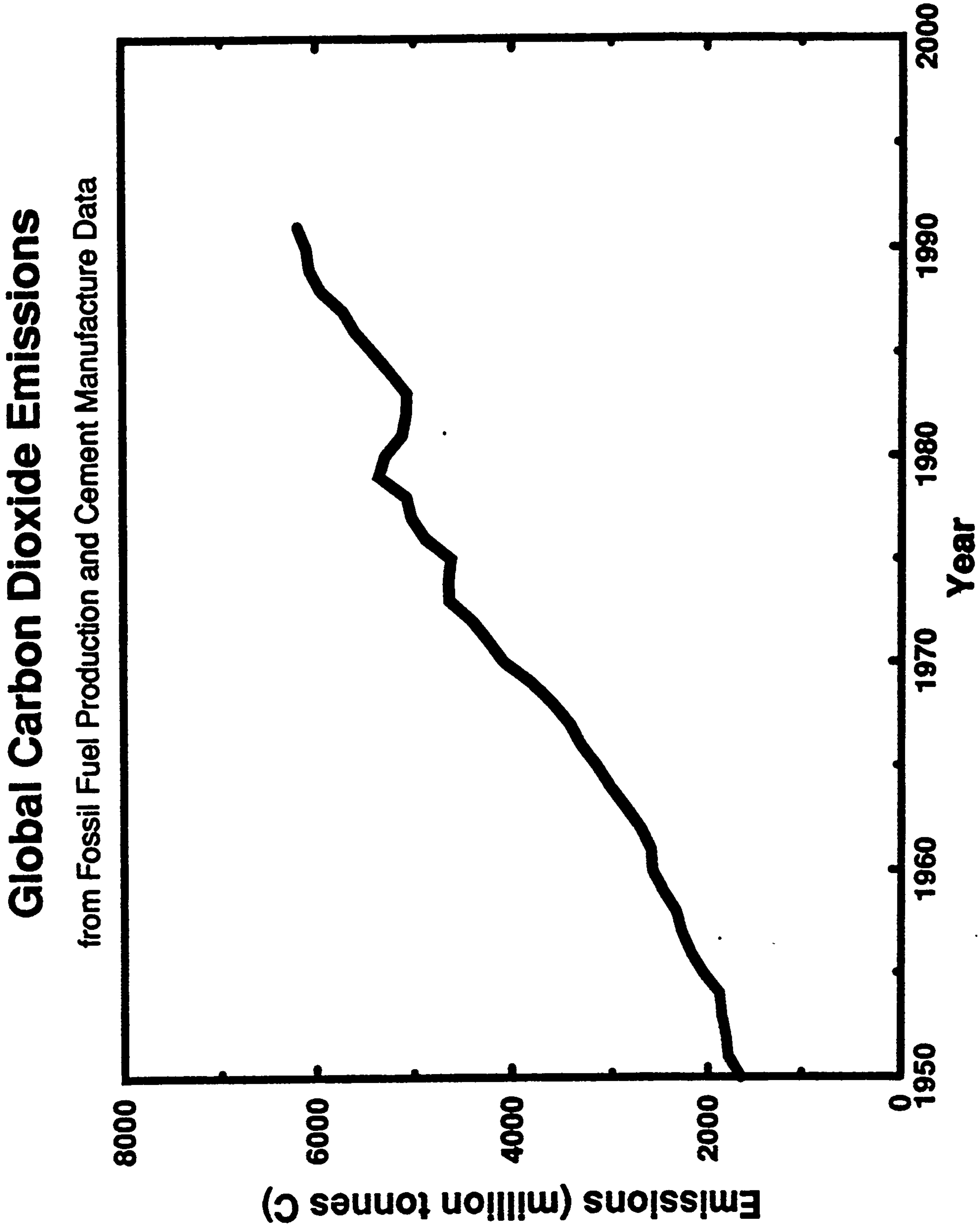

Figure 1. The growth in total CO_2 emissions with time.

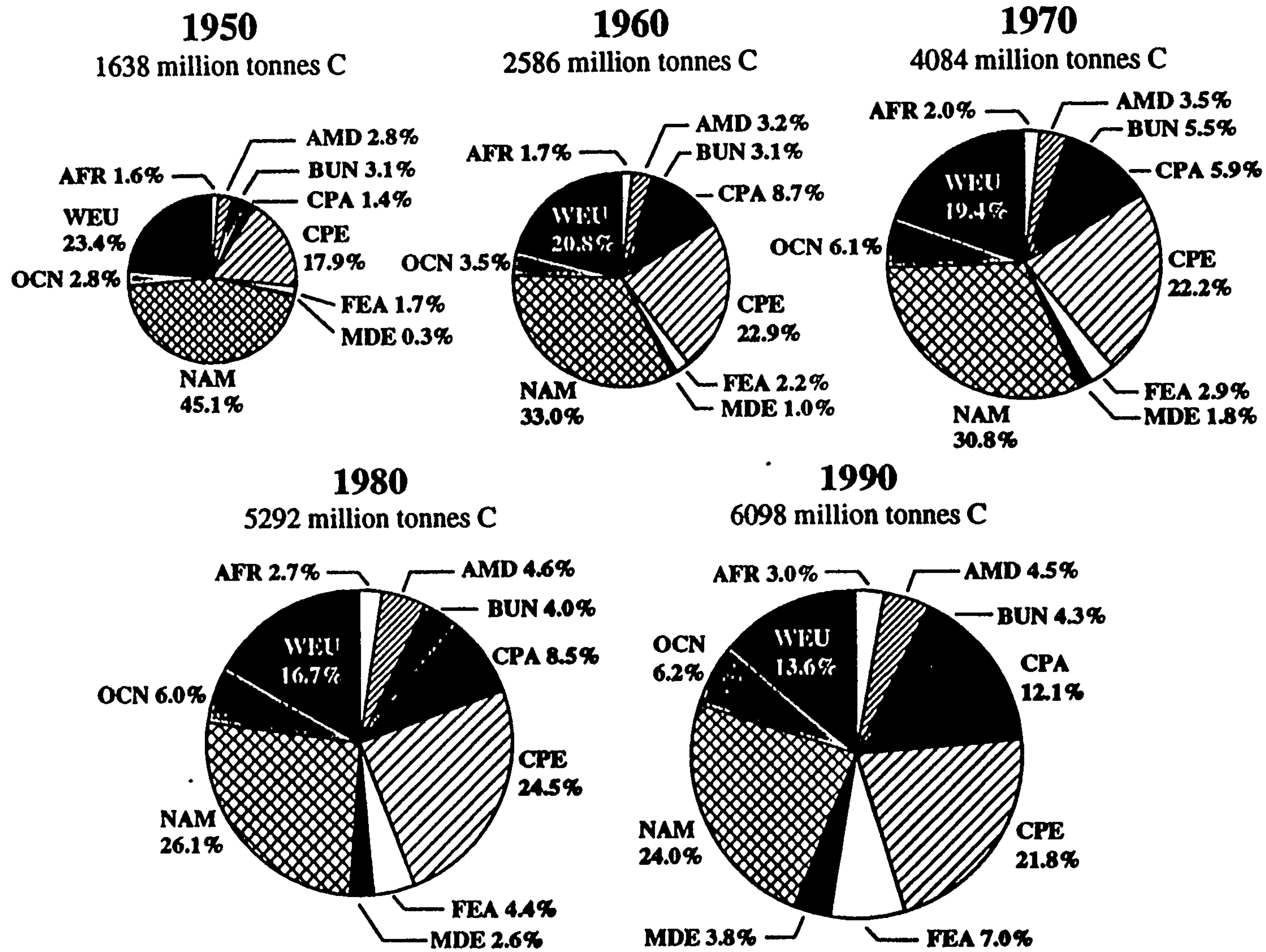

Figure 2. The regional distribution of historical CO_2 emissions. Total emissions are given below the year. The area of the pie diagram is proportional to the total emissions represented. Regions are abbreviated as AFR (Africa), AMD (Other Americas), BUN (bunkers), CPA (Centrally Planned Asia), CPE (Centrally Planned Europe), FEA (Far East Asia), MDE (Middle East), NAM (North America), OCN (Oceania), WEU (Western Europe).

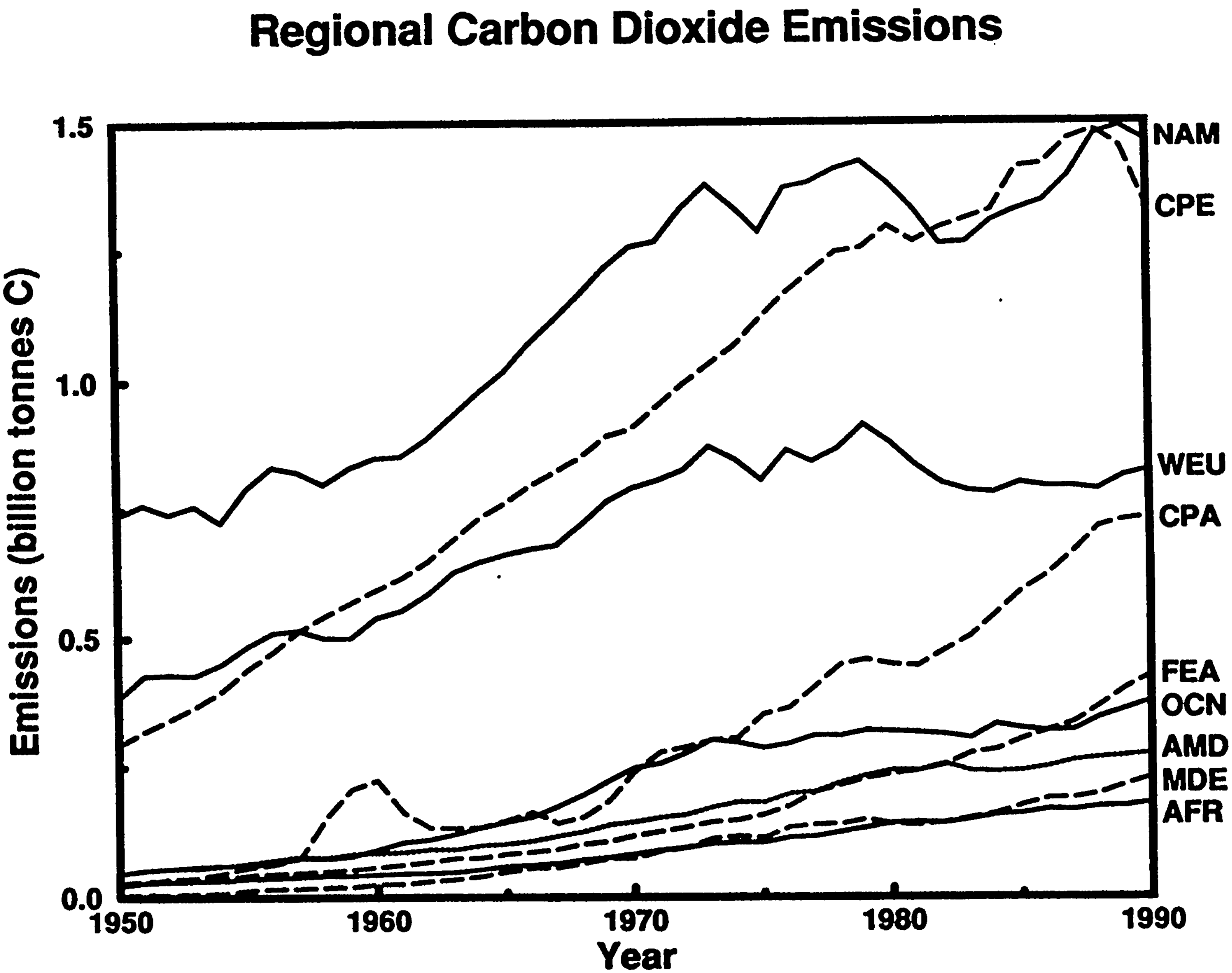

Figure 3. The growth in regional CO_2 emissions with time. Same regional abbreviations as in Figure 2.

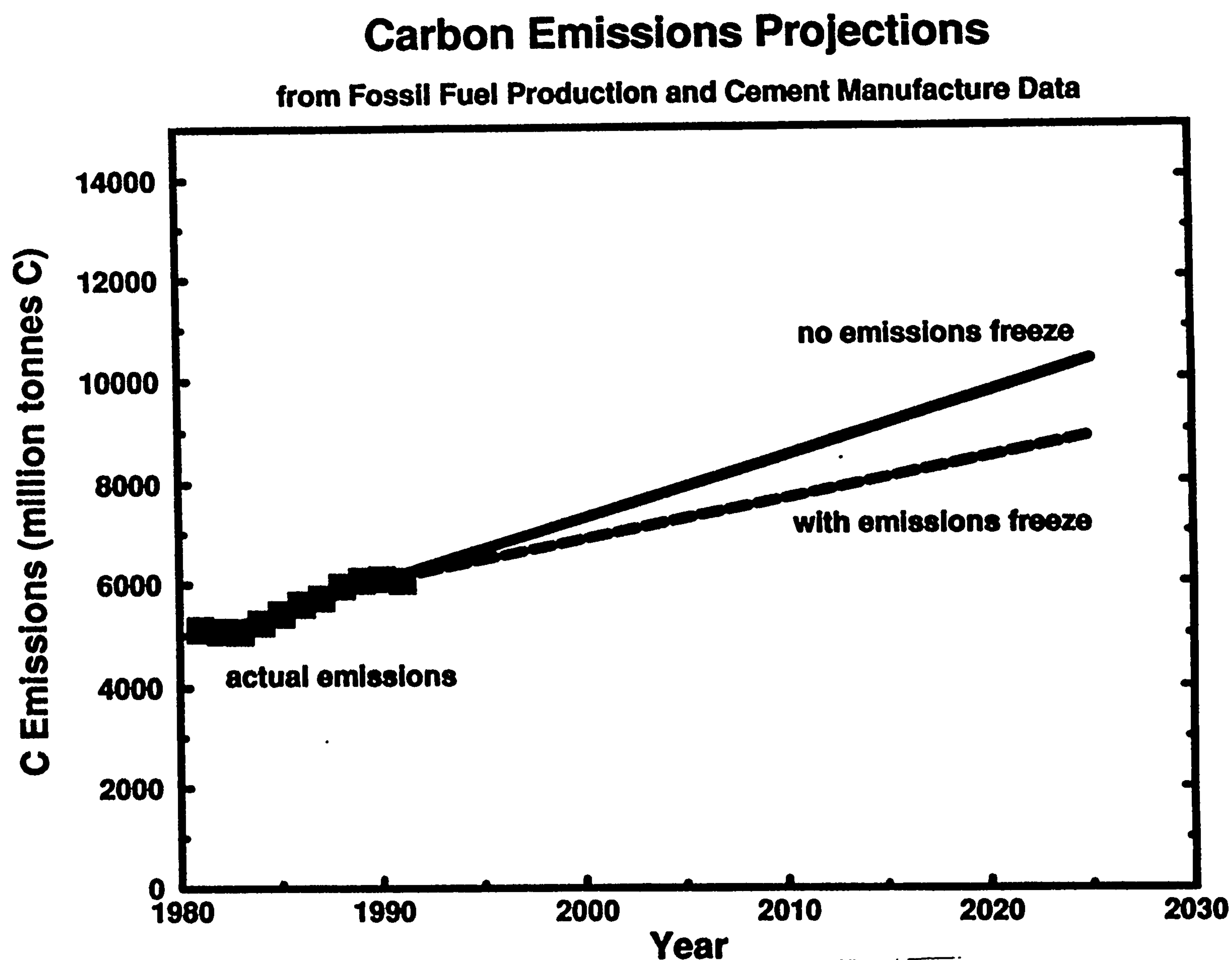

Figure 4. Projections of CO_2 emissions from fossil fuel consumption and cement manufacture based upon 192 linear regressions. The upper curve represents projected emissions if current trends continue. The lower curve represents projected emissions if the FCCC is fully implemented. Actual emissions for 1981 to 1991 are indicated by the boxes.

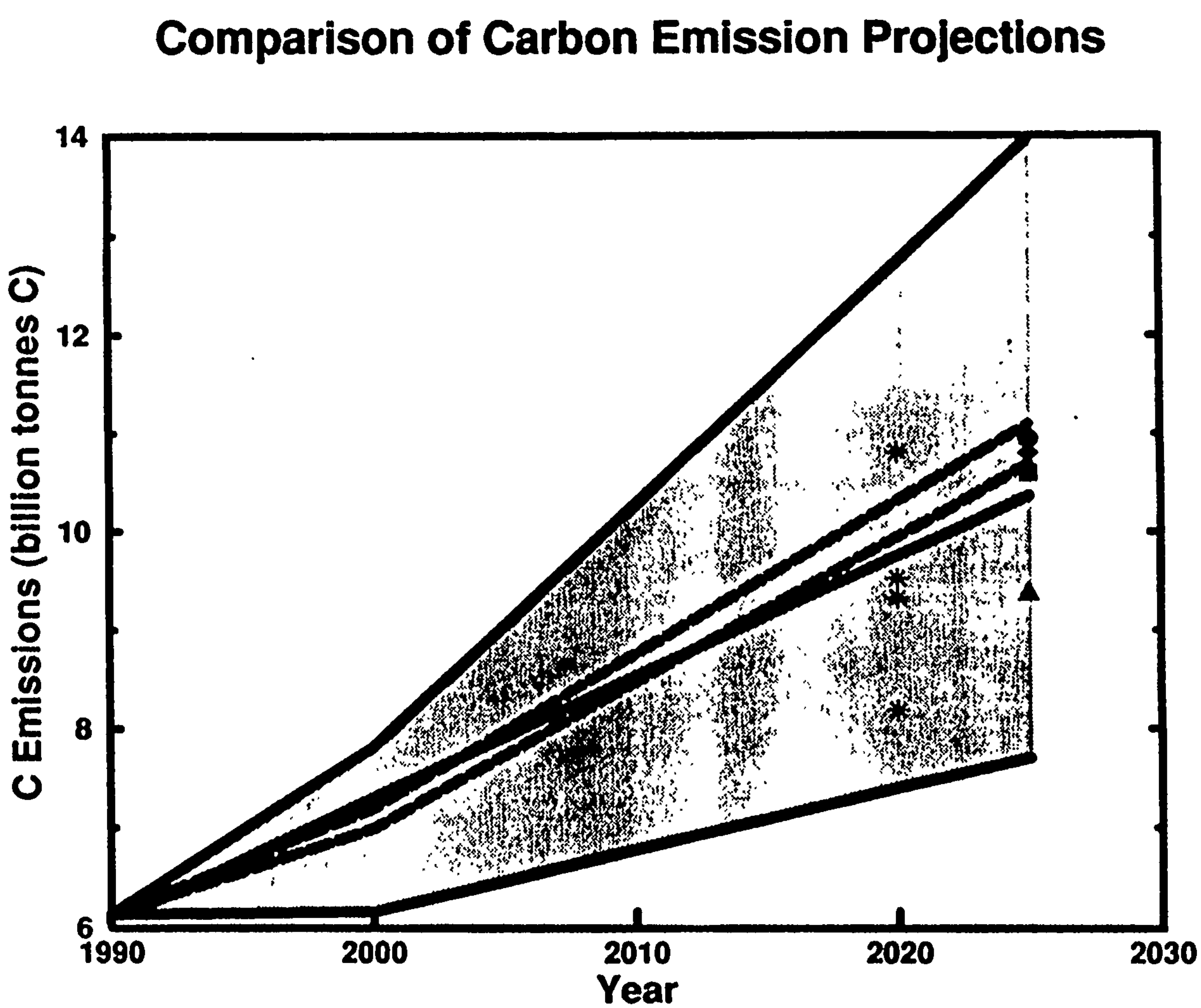

Figure 5. Comparison of CO_2 emission projections. The shaded area shows the range in IPCC IS92 scenarios. IS92a (the upper dashed line) is the IPCC business-as-usual (BaU) scenario which continues modern day emissions and trends. IS92b (the lower dashed line) makes provisions for some CO_2-limiting proposals.[18, 22] The current-trends, linear extrapolation is shown by the central, solid line. Endpoints of some other BaU scenarios are also shown (● Global 2100,[10] ♦ CETA,[11] ■ Edmonds-Reilly (mean of 400 runs with non-zero correlation of the parameters),[9] ▲ World Energy Council Case B,[12] and * Dean and Hoeller (4 different models)[20]), the full lines of these scenarios are not shown for clarity, but generally fall within the shaded region. Since some scenarios lacked emissions from cement, the contribution from cement as used in IS92a has been added to the ●, ♦, ■ and ▲ data.

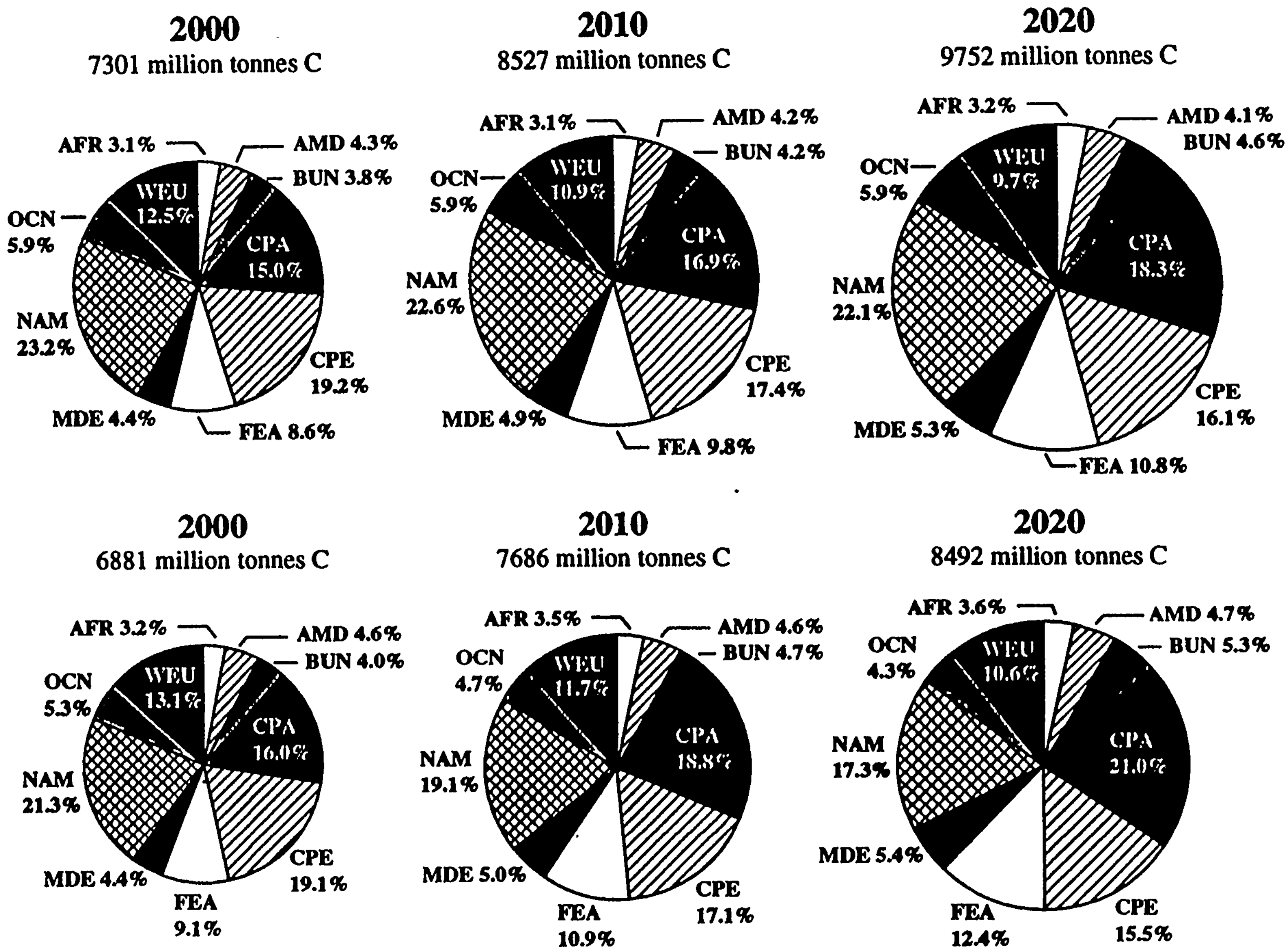

Figure 6. The regional distribution of extrapolated CO_2 emissions. The upper set represents current trends and the lower set represents a fully implemented FCCC. Total emissions are given below the year. The area of the pie diagram is proportional to the total emissions represented. Same regional abbreviations as in Figure 2. WEU contains all of the emissions from a unified Germany; this results in less than a 1% loss in emissions from CPE because of the exclusion of emissions from the former East Germany.