Working Paper

An Assessment of the Responsibility for the Increase in the CO_2 Concentration and Inter-generational Carbon Accounts

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WP-90-55
October 1990

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Preface

Evidence is accumulating that it will be necessary to reduce global carbon dioxide emissions and other anthropogenic sources of greenhouse gases. Most of the proposed measures appear to be insufficient in causing a sufficient reduction by themselves and in very few cases a stabilization of global carbon dioxide emissions. Thus, it would be prudent in the future to expand the range of policy options that can help reduce the emissions. Furthermore, most of the proposed reduction measures such as carbon taxes, tradable permits, national or per capita emission quotas are all associated with numerous and complex global tradeoffs and important equity issues.

This paper by Yasumasa Fujii represents an attempt to develop a yardstick for establishing equitable criteria for greenhouse gas reduction strategies. The timeliness and policy relevance of such research is illustrated by ongoing discussions about international and intergenerational inequalities that can be expected to result from climate change and possibly also from many of the proposed response strategies. For example, if such policies were only based on current per capita emission levels, they would place an unequal burden on the developing countries and their future populations. Industrialization has brought hitherto unknown wealth to the developed parts of the world but also high carbon dioxide emission levels since the 19th century. Much of these emissions from last century still remain in the atmosphere due to long residence time for carbon dioxide. Thus, a significant share of current atmospheric concentration of anthropogenic carbon dioxide is due to historical emissions above and beyond the factor of ten difference in current per capita emissions between developed and developing countries. Therefore, future generations especially in the developing countries will have to bear a potential burden of our current and inherited emissions.

This is certainly not equitable for humanity as a whole. A possible criterion of equity would be that every human being, past or "future", is allowed the same emission quota on annual basis. This could provide for intergenerational and interpersonal equity throughout the world, but would also imply that some of the developed regions would have an excess of historical carbon emissions or a "deficit" of future annual per capita quotas. Consider further that there exist an ultimate carrying capacity limit to the total (hypothetical cumulative) gigatons of carbon that can be "deposited" in the atmosphere as a global "resource" or "carbon credit" available to the humanity. How large would this resource have to be in order to fulfill the suggested intergenerational and interpersonal equity criterion? Fujii's analysis shows that the hypothetical resource would have to be in excess of 1,000 gigatons, probably way too much from the perspective of potential global warming.

This analysis reveals significant regional and intergenerational disparities in historical contributions to current atmospheric carbon dioxide concentration and to cumulative emissions. In terms of cumulative person-years, the developed countries have contributed the lion's share to current concentrations, while the majority of "future" person-years will be in the now developing countries that would be forced to offset the large historical emission "deficit" of past generations in the industrialized countries. These disparities in per capita annual emissions ought to be considered in negotiations on greenhouse gas reductions, in the corresponding policies and any international carbon accounting system. Even if it turns out that equity does not necessarily imply interpersonal and intergenerational equality of emission permits on annual basis, the analysis in this paper can provide a yardstick for the assessment of other equity criteria that would extend beyond the current generation and current emissions.

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Contents

An Assessment of the Responsibility for the Increase in the CO_2 Concentration and Inter-generational Carbon Accounts

Yasumasa Fujii

1 Introduction

The possibility of global warming problem which is associated with anthropogenic emissions of greenhouse gases (GHGs) is one of the most crucial issues in the world. These GHGs are principally CO_2, CH_4, N_2O, O_3, and CFCs. The Intergovernmental Panel on Climate Change (IPCC) has concluded that GHGs could increase the global mean temperature of 1.5 to 4.5 K sometime around the middle of the next century (Bolin *et al.*, 1986). This global warming is thought to cause serious climate changes which will have great impacts on humanity. Some of these GHGs have potentially greater effects on global warming than others. Many researchers have studied the relative contributions of these gases (Lashof and Ahuja, 1990). Although CO_2 causes the least effects on a per mole basis, recent studies show that CO_2 has been responsible for over half the total additional greenhouse forcing because of its large absolute increase in concentration (Rodhe, 1990).

This CO_2 related problem has lately attracted considerable attention all over the world, and has developed from a merely scientific subject into an international political issue. Many efforts towards a settlement of this problem have already been made through internationally organized meetings, such as IPCC. It is likely that in the near future certain targets will be set for reductions in the CO_2 emissions of individual countries.

In such a context, the purpose of this study is to obtain a first insight into the following questions.

- Who is responsible for the observed rising in the level of atmospheric CO_2 concentration, and to what degree?
- What are "fair" allocations for how much carbon each of us is allowed to emit annually by fossil fuel burning considering past, present and future generations?

We propose, in this paper, a new carbon accounting system which takes into consideration inter-generational carbon accounts. This is, in principle, based on the cumulative population of different regions. We also show some interesting computational results of this new accounting system. We believe that it is meaningful to examine the CO_2 problem from such inter-generational aspects as well as international ones, because unquestionably this problem cannot be resolved solely by the present generation.

2 New Accounting System

The relative contributions of different energy consuming regions to the increasing atmospheric CO_2 concentration is not only a function of current emission levels but also that of the profiles of historical emissions. This is because the atmospheric lifetime of CO_2 absorbed by the oceans and the biosphere is supposed to be almost a couple of centuries (IPCC, 1990). Most developing countries have increased their emission levels only over the last few decades. On the other hand, the industrialized countries of Europe and North America have been emitting CO_2 ever since the beginning of the Industrial Revolution. This means that if we calculate the contributions of different regions on the basis of current emission levels, we will obviously underestimate those of developed countries. For instance, England has emitted huge amount of the carbon emissions compared to other countries during the 19th century and most of the emitted carbon is supposed to be still in the atmosphere.

In addition to the historical profiles of carbon emissions, the growth patterns of regional populations also play an important role in assessing the responsibilities of each region for the observed increase in the atmospheric CO_2 concentration. Other reasonable criteria, such as emission per GDP or emission per land area, have already been proposed for this kind of assessment. However, in this study we adopted the per capital criteria as the most appropriate one, since such criteria enable us to see the problem more intuitively from the viewpoint of inter-generational and inter-regional equity.

This approach is, however, inadequate if the measurement is based only on the present populational situation. As mentioned above, the current level of increased CO_2 concentration is the outcome of almost 200 years of emissions. These are not entirely caused by the activities of the present generation. This inter-generational nature of the CO_2 problem requires that we should also take into account the responsibilities of the past generation. For this we decided to adopt cumulative populations for each region as the denominators of the criteria. However, the growth patterns of regional populations are noticeably different from each other, pointing out the necessity of taking into consideration their historical profiles.

If we turn our eyes to the future, we easily recognize that this population based analysis can also suggest new guidelines for the future policies of national emission quotas or tradeable CO_2 permits. No one can discuss global environment problems without taking account of future demographic trends. Most forecasts indicate that the populations of developing countries will expand enormously, whereas those of developed countries will be constant or even decline in the next century. It is clear that if CO_2 related policies are based on current emission levels, such policies would place an unequal burden on developing countries as compared to developed countries.

To deal with such a long-term problem which intrinsically includes the concept of inter-temporal carbon allotments, we introduce the following postulate into the accounting system.

Everyone has an equal emission quota irrespective of both the country he or she lives in and the generation he or she belongs to.

This may be an extremely equalitarian postulate, but it can be used as a guideline for an ideal allocation of emission quotas from the viewpoint of equity. Under the above postulate, we propose a new accounting system with which we are able to determine inter-generational carbon accounts. First, we calculate the ideal contribution trajectories of the different regions (under our equity criteria) to the additional CO_2 concentration within a certain period. We do this through the use of a carbon cycle model. These contributions are, in principle, derived from the cumulative population of each region. Next, we evaluate the difference between the ideal contributions and real ones which were derived from historical carbon emission data.

3 Data on Regional Population and Fossil Fuel Consumption

In order to both assess the responsibility of the observed increased in CO_2 concentration and to develop possible future emission profiles, it is necessary to identify individually the different energy consuming regions. We divided the whole world geopolitically into nine regions: Western Europe, Eastern Europe, North America, USSR, Japan, Oceania, Asia, Africa, and Latin America. In the above framework, we estimated the regional populations between 1800 and 2100 (*Figure 1*), and regional fossil fuel consumption by type between 1800 and 1987 (*Figures 2, 3* and *4*). In the case where national borders have changed, this study generally goes by the borders of the year in question and not by the present ones.[1]

The population data for most of the regions between 1800 and 1920 was derived from J.D. Durand's work (Durand, 1967). Since he did not disaggregate Europe into western part and eastern one, we estimated the historical population data for Western Europe by using the censuses of the individual countries listed in B.D. Mitchell's European Historical Statistics (Mitchell, 1981). The population data between 1920 and 1980 was derived from United Nations' World Population Prospects (UN, 1966, 1989), and that between 1990 and 2100 was derived from World Bank's World Population Projections (Zachariah and Vu, 1988). The projections which we adopted here were comparatively optimistic by anticipating that the world population by 2100 would be stabilized at the level of about 10.4 billion people.

The data for regional consumption of coal and petroleum in Western Europe, Eastern Europe, North America and USSR (Russia) between 1800 and 1920 was calculated by counting both the domestic production and the net imports of the individual countries. We obtained this data from B.R. Mitchell's Historical Statistics (Mitchell, 1981, 1983) at intervals of 10 years. From this we deduced the annual consumption by exponential interpolations (or extrapolation for the case where there was no data available for the beginning of 19th century). The consumption from 1860 to 1920 of coal and petroleum for the remaining regions (i.e., Japan, Oceania, Asia, Africa, and Latin America) was estimated by allocating the difference between the total consumption of the above leading regions such as Western Europe and that of the whole world (Nakićenović, 1988) in proportion to their respective consumption share in 1925. We assumed that fossil fuel consumption in these remaining regions was negligible before 1860. In the same way, we allocated the world consumption of natural gas before 1920 among all nine regions proportionally on the basis of their consumption share in 1925. The absolute consumption of natural gas during this period was so small that errors here will not significantly affect the results.

The consumption data of all 3 types of fossil fuels between 1921 and 1987 were estimated in the following way. We obtained the energy consumption data of 1925, 1929, 1933, and 1937 from Darmstadter's Statistics (Darmstadter, 1971). The annual energy

[1] For example, GDR is included in Western Europe until 1945, and present day Austria is included in Eastern Europe until 1919.

consumption data since 1950 were obtained from United Nations' World Energy Supplies 1950–1974 (UN, 1976), IEA's Energy Balances of OECD countries 1960–1987 (IEA, 1987, 1989a), and IEA's World Energy Statistics and Balances 1971–1987 (IEA, 1989b). Annual consumption of each fuel between 1921 and 1949 was estimated by exponentially interpolating the fragmented data we obtained. It is to be noted that we revised the energy data obtained from the United Nations. We multiplied it by appropriate factors so as to make it consistent with the IEA. There are noticeable discrepancies between these data sources which might have been caused by the differences in the assumed thermal conversion factors such as the coefficients used to convert other fuels into a coal equivalent.

Using the fossil fuel consumption data estimated above, we calculated the regional profiles of the historical carbon emissions from fossil fuel consumption since 1800. The carbon emissions from coal equivalent units were assumed to be 0.683 ton of carbon for coal, 0.520 ton for petroleum, and 0.411 ton for natural gas (Ausubel *et al.*, 1988). For a more detailed analysis, it would be advisable to use the national emissions data between 1950 and 1987 which Marland *et al.* (1990) recently estimated using a more sophisticated method.

4 Atmospheric Concentration Model

We developed a simple atmospheric concentration model to evaluate the contributions of carbon emissions from the different regions. Roughly speaking, there are two kinds of simplified approaches to describe a complex terrestrial carbon cycle between the atmosphere, the ocean and the biosphere. One is an airborne fraction approach (Bolin *et al.*, 1986) and the other is a linear response function approach (Maier-Reimer and Hasselmann, 1987). Here we adopted a, so to speak, hybrid method based on the two different approaches. The model we developed is given by the following first order linear differential equation.

$$\begin{aligned} \frac{dM(t)}{dt} &= 0.471 \times AF \times X(t) - \frac{M(t)}{T_0} \\ M(t) &= C(t) - C(1800) \end{aligned} \tag{1}$$

where AF: Airborne Fraction, $X(t)$: Carbon Emission, $C(t)$: Concentration Level, $C(1800)$: Pre-industrial Concentration Level, T_0: Time Constant of Oceanic Uptake.

This is almost the same model that Nordhaus used in his previous work (Nordhaus and Yohe, 1983). In this study, however, $M(t)$ is an additional concentration defined as the difference between the concentration level of the year in question and that of pre-industrial days. The coefficient with a value of 0.471 is a conversion factor for a gigaton of carbon to an atmospheric concentration unit of ppm. The last term of the right-hand side of equation (1) represents an effect of long-term oceanic uptake. We adopted a time constant T_0 of 300 years.[2] Maier-Reimer and Hasselmann (1987) approximated their inorganic ocean-circulation carbon cycle model by a linear response function of multi-time constants and they said in their paper that the largest amplitude exponential has a time constant of 300 years. Indeed, our single-time-constant model is physically less realistic than a multi-time-constant variant, but the above model enables us to account for carbon

[2]Equivalent time constants for carbon emissions in 1800, 1900 and 2000, which are calculated on the basis of decay rates in 2100, are about 160 years, 130 years and 83 years, respectively. The equivalent time constants are much shorter than 300 years because the airborne fraction AF in equation (1) is not equal to 1. And the time taken for the added carbon to decay to 37% (1/e) of the initial value is only 40 years.

emissions in a practically more accustomed manner. We can interpret our model simply as an accounting system in which historical emissions of carbon are discounted at an annual rate of 0.333% (1/300). This is because the discounted cumulative carbon emissions are in proportion to the corresponding additional concentrations. This means that 1 ton of carbon emission in 1800 has only 37% (1/e) of the weight of 1 ton of carbon emission in 2100.

The airborne fraction was estimated by a least-square fitting of the model outputs to the observed concentration data measured at Mauna Loa in Hawaii since 1958 (Bolin *et al.*, 1986) (*Figure 5*). We obtained an airborne fraction of 42 percent on the basis of estimated historical data of carbon emissions from fossil fuel consumption, cement production, gas flaring (Marland *et al.*, 1990), and deforestation (forest and soil) shown in *Figure 6*. However, it should be noted that carbon emissions from deforestation have a large degree of uncertainty and are still in controversy. There have been three kinds of principal approaches used to analyze how the forest-soil reservoir affects the CO_2 content of the atmosphere. These approaches are as follows: direct estimates based on data showing changes in the area of ecosystems with different amounts of carbon per unit area, indirect estimates based on changes in the ratios of carbon isotopes ($^{13}C/^{12}C$) in tree rings, and other indirect estimates based on the difference between the amount of carbon emissions from industry and the expected amount of carbon emission computed by oceanic uptake models. Unfortunately the three approaches do not yield similar carbon fluxes between the biosphere and the atmosphere, and of course historical carbon emission profiles.

The emission data we adopted in this study are the result of direct estimates between 1860 and 1980 made by Houghton *et al.* (1983)[3]. In their analysis, the cumulative carbon emission from forest and soil between 1860 and 1980 is estimated to be 180 gigaton and the annual carbon emission in 1980 is 2.6 gigaton including emissions from non-tropical forests. The latest research, however, shows that the cumulative carbon emission from land-use change is 115±35 gigaton between 1850 and 1985 (IPCC, 1990). Assuming high historical carbon emissions from forest and soil, our analysis will sketch possible future emission profiles which is advantageous to the use of fossil fuel.

We assumed that the emissions from deforestation between 1980 and 1987 were the same levels as that in 1980, and also extrapolated the emissions before 1860 along a least squares fit of those between 1860 and 1920. Historical atmospheric CO_2 concentrations before 1958 were calculated by solving the equation (1) backward from 1957 to 1800. Consequently we obtained the pre-industrial concentration level of 278 ppm[4] and a historical concentration profile which is almost identical with the results of CO_2 measurements such as analysis of the ancient air occluded in natural ice of known age (WMO, 1983).

Since our concentration model is described as a linear differential equation, it is possible to evaluate the respective contributions of different carbon sources or different regions to the atmospheric CO_2 concentration. *Figure 7* shows that 47 percent of the additional concentration from 1800 to 1987 is due to fossil fuel consumption.

[3]We also examined the emission data estimated by Peng *et al.* (1983). They computed profiles of historical carbon emissions on the basis of the observed $^{13}C/^{12}C$ change in tree rings through the use of a modified multi-box ocean model. Although they used the above advanced methodology, their estimated values seem most unlikely because they estimated a pre-industrial CO_2 concentration level to be as low as 250 ppm.

[4]We obtained the pre-industrial concentration level by iterative calculation. It is natural that the extrapolated value should be equal to $C(1800)$ in equation (1).

5 Assessment of the Responsibilities

In this section, we examine the profiles of historical carbon emissions from fossil fuel burning by region. We then assess the responsibilities for the observed increase in the atmospheric CO_2 concentration with the per capita criteria.

Figure 8 shows the regional historical carbon emissions from fossil fuel consumption between 1800 and 1987. In the beginning of 19th century, Western Europe was the only emitter in the world (most of the carbon was emitted from the United Kingdom) but its absolute emission was not so large in comparison to current levels. North America started to increase its carbon emission in the middle of the 19th century, partly (because there was an unprecedentedly rapid growth of the population in this region, but) mainly because there was a significant increase in coal consumption probably caused by the shift in fuel from wood to coal. [The absolute amount of wood, as a fuel, consumption in the United States began to decline since 1871, and was surpassed by that of coal consumption in 1885 (Marchetti and Nakićenović, 1979).] The other developed regions increased their carbon emissions several decades later. Therefore, the cumulative emissions of these regions which developed later are relatively smaller than those of Western Europe and North America.

Figure 9 shows both the current emission shares and the contributions to the increases in the atmospheric CO_2 concentration by region in 1987. As seen in this figure, the residence time of CO_2 in the atmosphere is so long that we cannot assess the responsibilities only by the current emission levels. The past emission profiles have significant influence on the assessment. For instance, though the current emission share of Asia is as much as 20 percent, the contribution to the concentration is less than 10 percent.

The above share analysis, however, is not appropriate for the assessment of the responsibilities because the populations of these regions and their growth patterns are quite different from each other. *Figure 10* shows both current (in 1987) and cumulative (from 1800 to 1987) per capita carbon emissions by region. Through the use of the concentration model, we made sure that the long-term oceanic uptake of CO_2 does not affect the computational results of the concentration considerably. In other words, the cumulative criteria have almost the same meaning as per capita contributions to the concentration for the assessment of the responsibilities. We can say that the region which has emitted more cumulative carbon per capita is more responsible for the additional CO_2 concentration. The cumulative emission per capita was calculated as follows.

$$CE_i = \frac{\sum_{t=1800}^{1987} E_{ti}}{\sum_{t=1800}^{1987} POP_{ti}} \tag{2}$$

where i: Index for regions, t: Index for years, CE_i: Cumulative Per Capita Emission, E_{ti}: Annual Carbon Emission, POP_{ti}: Regional Population.

Examination of *Figure 10* provides some intriguing information on the regional characteristics of carbon emissions up to the present. They are summarized as follows:

1. North America has emitted pronouncedly the largest amount of carbon per capita in terms of both the current value and the cumulative one. Its per capita emission level is much higher than those of other developed regions, not to mention developing regions. In addition to that, it also occupies the largest share (35%) of the contribution to the concentration in all regions (*Figure 9*).

2. The per capita cumulative emissions from Western Europe is not so large in spite of the fact that it has emitted a substantial amount of carbon since the beginning of the 19th century and that it occupies the second largest share of the contribution to the CO_2 concentration of 1987 (*Figure 9*). This probably is due to the relatively large size of its population which had already expanded to some degree in the beginning of the 19th century.

3. Though USSR and Eastern Europe are currently emitting considerable amounts of carbon per capita, their cumulative emissions are rather smaller than those of other developed regions except Japan. These two regions began to increase their carbon emissions rapidly after World War II.

6 Inter-generational Carbon Accounts

6.1 Why do we need a new accounting system?

In the previous section, we discussed the historical carbon emissions. From this we found that there are great differences in the per capita carbon emissions from fossil fuel burning between the developed regions and the developing ones. We might call this the North–South dimension of the global environmental issues.

Consequently, we need to ask ourselves whether it is right or not to freeze emission levels of all regions as they are now, before setting the targets. Most developing regions have increased their emission levels only over the last decades and their populations are expected to expand enormously over the next century. If their emissions are required to be frozen at the current levels, they will obviously have to shoulder much more burden than the developed regions. That is why we propose a novel carbon accounting system which enables us to keep inter-generational carbon accounts. The system is, in principle, based on the cumulative population and it eliminates the unfairness among different countries or regions.

6.2 A per capita emission quota

The first step we should take is to calculate a per capita quota of carbon emission under the postulate that everyone has an equal amount of emission quota irrespective of both the country (i.e., region) he or she lives in and the generation he or she belongs to. We can obtain the emission quota by solving the following equation.

$$\begin{aligned} M(2100) &= 0.471 \times AF \times \sum_{i=1}^{9} \sum_{t=1800}^{2100} \\ &\quad \left\{ POP_{ti} \times C_0 \times \left(1 - \frac{1}{T_0}\right)^{2100-t} \right\} \end{aligned} \tag{3}$$

where $M(2100)$: the increase in the CO_2 concentration by 2100, C_0: the per capita emission quota.

As seen in equation (3), the emission quota is proportional to the resultant increase in the concentration in 2100. If we assume that the CO_2 concentration level rises from 280 ppm to 560 ppm by 2100, we obtain the per capita emission quota of 1.37 tons of carbon per year. It should be noticed that this value is entirely dependent on the future population prospects.

6.3 Break-even lines and historical emissions

Once the emission quota is derived, we can draw a break-even line of inter-generational carbon accounts which is illustrated in *Figure 11*. The line indicates the permitted cumulative carbon emissions by the year in question, when we assume a certain increase (in this case, 140 ppm) in the atmospheric CO_2 concentration in 2100. We note that the vertical axis was converted to the equivalent amount of carbon emissions in 2100 at the annual discount rate of 0.333 percent. We computed the break-even lines of the different regions as well as that of the world total by solving the following equation.

$$IC_{Ti} = \sum_{t=1800}^{T} \left\{ POP_{ti} \times C_0 \times \left(1 - \frac{1}{T_0}\right)^{2100-t} \right\} \tag{4}$$

where IC_{Ti}: Ideal Cumulative Carbon Emission by the Year T.

Let us explain illustratively how to figure out the inter-generational carbon accounts. As can be seen in *Figure 11*, typically there are two cases (A and B) with regard to the relative position between the historical emission path and the break-even line. If the former is above the latter, just as case "A" in the figure, we have emitted a larger amount of carbon than is expected from the viewpoint of inter-generational equity. In this case we are supposed to be in debt to the future generation. On the other hand, if the historical emission is below the break-even line as case "B", we are still supposed to be in the black and to have an additional emission quota inherited from the past generation.

Figures 12–15 show the historical emission paths of Western Europe, North America, Asia and the whole world, respectively. It should be noticed that the historical emissions in these figures do not include carbon emissions from biota.

Western Europe is arriving at the break-even line for a concentration increase of 280 ppm. This means that it has neither a debt nor an inheritance of carbon emissions, if our target for the concentration is set at the level of 560 ppm (280 + 280 ppm) in 2100. North America is far beyond the line for the increase of 420 ppm. Although we only took into account the emissions from the burning of fossil fuels, we discovered that its present position of the historical emission was in the vicinity of the line for an increase of 800 ppm. This means that North America had already emitted the total amount of carbon which was allocated for it under the assumption of an increase of 200 ppm by 2100. This shows that the target of the concentration being 480 ppm (280 + 200 ppm) in 2100 is infeasible for this region without carbon disposal or permits for international trade of carbon. In comparison with the developed regions, Asia has emitted a smaller amount of carbon than is expected on the basis of its historical population data. As can be seen in *Figure 15*, the whole world is just reaching the break-even line for an increase of 140 ppm. It seems that the excessive amount of carbon emissions from the developed regions is offset by the carbon credit of the developing regions.

6.4 Possible future emission profiles

Through the use of the accounting system we proposed here, it is possible to sketch outlines of regional future emission profiles. This will eliminate the unfairness of the contributions of different regions. According to the number of the assumed constraints, we made the three kinds of projections listed in *Table 1*. The problem was formulated by the following equations.

Table 1.

1) A zero order projection Equity of the regional contributions during the period between 1800 and 2100	$CP_{ti} = \exp(\alpha_i)$
2) A first order projection + Smooth shift from the present state	$CP_{ti} = \exp(\alpha_i + \beta_i \times t)$
3) A second order projection + Stabilization of the concentration in 2100	$CP_{ti} = \exp(\alpha_i + \beta_i \times t + \gamma_i \times t^2)$

$$\begin{aligned} M(2100) \quad & \times \sum_{t=1800}^{2100} POP_{ti} \times \left(1 - \frac{1}{T_0}\right)^{2100-t} \Bigg/ \sum_{j=1}^{9} \sum_{t=1800}^{2100} POP_{tj} \times \left(1 - \frac{1}{T_0}\right)^{2100-t} \\ & = 0.471 \times AF \times \left[\sum_{t=1988}^{2100} \left\{ POP_{ti} \times CP_{ti} \times \left(1 - \frac{1}{T_0}\right)^{2100-t} \right\} \right. \\ & \left. + \sum_{t=1800}^{1987} E_{ti} \times \left(1 - \frac{1}{T_0}\right)^{2100-t} \right] \end{aligned} \tag{5}$$

where CP_{ti}: Carbon Emission Per Capita in the Year t.

The forms of CP_{ti} are defined as follows with respect to a number of the constraints. We estimated the above parameters by solving the equation (5) iteratively.

1. A zero order projection
   We obtained the average annual carbon emission quotas with respect to per capita. *Figure 16* shows the emission quotas by region under three scenarios. These scenarios assume a concentration increase of 140 ppm, 280 ppm, and 420 ppm, respectively, by fossil fuel burning from 1800 to 2100. It is to be noted that these values are not the absolute concentration levels. In order to get the absolute levels, we have to not only add the pre-industrial level (280 ppm) to the respective values but also take into account the carbon emissions from biota. It is interesting that in the medium (+280 ppm) and high (+420 ppm) concentration scenarios, there were little differences between the quotas of the developing regions and those of the developed ones except for North America. Indeed the developing regions have some amount of additional emission quotas inherited from their past generation, but the huge size of their future populations seem to reduce the value of the additional quotas on the per capita basis. Under the low (+140 ppm) concentration scenario, North America is requested not to emit any carbon for the sake of equity.

2. A first order projection
   We calculated average annual reduction rates of carbon emission per capita under the above two constraints. The reduction rates of the developed regions are shown in *Figure 17*. (It is not necessary for the developing regions to reduce per capita carbon emission.) Under the medium concentration scenario, the necessary carbon reduction rates of most developed regions are around 1 percent a year, whereas that of North America is more than 7 percent a year. North America seems to be requested to make greater efforts at reducing its carbon emission than the other developed regions. There was no solution for North America in the case of a 140 ppm increase.

3. A second order projection
   The above two projections do not necessarily mean the stabilization of the atmospheric CO_2 concentration by 2100. Through the use of our simple concentration model, we made a calculation for possible emission profiles which lead to the stabilization of CO_2 concentration. (Again please note that we do not have a thorough knowledge of the terrestrial carbon cycle yet.) By letting the left-hand side of equation (1) equal zero, we obtained a sustainable carbon emission level of 4.7 gigaton per year under the medium concentration scenario. In this case, we have 0.46 ton of carbon emission quotas per person in 2100.

Figure 18 shows the historical and possible future profiles of carbon emissions from 1800 to 2100 for the selected regions. All emission paths converged at the level of 0.46 ton in 2100. As can be seen in the figure, most developed regions would need to reduce their carbon emissions monotonously over the next century. Asia has a large enough carbon quota to raise its emission level beyond 2 ton of carbon per capita in the middle of the next century.

It is to be noted that this figure just shows possible future profiles under the equity postulate. These are far from predictions, they are hypothetical calculations designed to illustrate equity issues inherent in any emissions reduction strategy. Therefore, we are not implying that North America must reduce its carbon emission by 90% immediately or that Asia must increase its present per capita emission as high as those of the developed regions.

7 Concluding Remarks

The purpose of this study was to obtain the first insight into the questions "*Who is responsible for the increase in CO_2 concentration?*" and "*How much carbon each of us could be allowed to emit over the next century?*".

The results are summarized as follows:

1. With the cumulative per capita criteria which we used as a measure in the assessment of the responsibilities, we found that North America has emitted CO_2 (from fossil fuel consumption) outstandingly higher than any other regions. The cumulative per capita emissions of the USSR, Eastern Europe and Asia (including China) were rather small in comparison with their respective current emissions.

2. We could not find significant differences in per capita future emission quotas between the developing regions and the developed ones with the exception of North America. The huge size of the future populations in the developing regions seemed to reduce the value of the additional quotas inherited from their past generation.

3. This kind of equity consumption shows that the developed regions would need to reduce their per capita carbon emissions by about 1 percent a year over the next century, if we assume 280 ppm for the increase in concentration in 2100. In the case of North America, the reduction rate would need to be more than 7 percent.

The above observation indicates that the accounting system in this paper will provide us with new guidelines for future policies concerning the CO_2 problem. However, we should also note the limitation of this method in the following sense.

1. We did not evaluate the carbon emissions from biota which were supposed to have contributed over half the increase in the atmospheric CO_2 concentration. Even though the analysis in this study was based only on the carbon emissions from fossil fuel consumption, this does not reduce the usefulness of the results obtained. This is because the carbon emissions from fossil fuel are large enough to raise the concentration to an unacceptable level before 2100. In other words, the results of this study suggest some of the necessary conditions of our future efforts, and not sufficient ones.

2. We described the terrestrial carbon cycle as a first order linear differential equation. However, the real carbon cycle must have non-linear characteristics and also it must be desperately complicated. Moreover, we have to resolve the so-called missing sink problem before developing a complete carbon cycle model.

Acknowledgment

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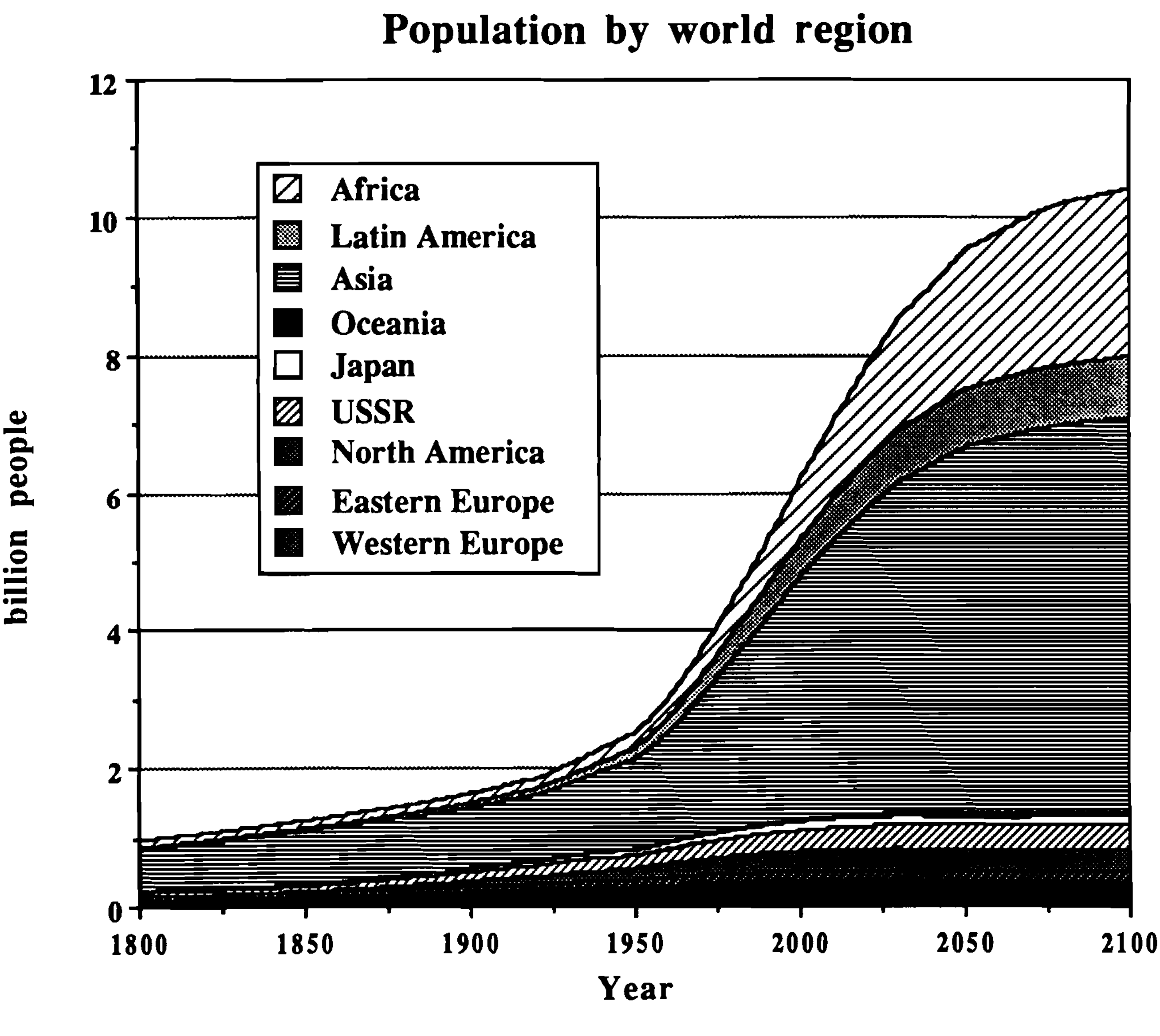

Figure 1. Population by world region 1800–1985 and World Bank projection to 2100.

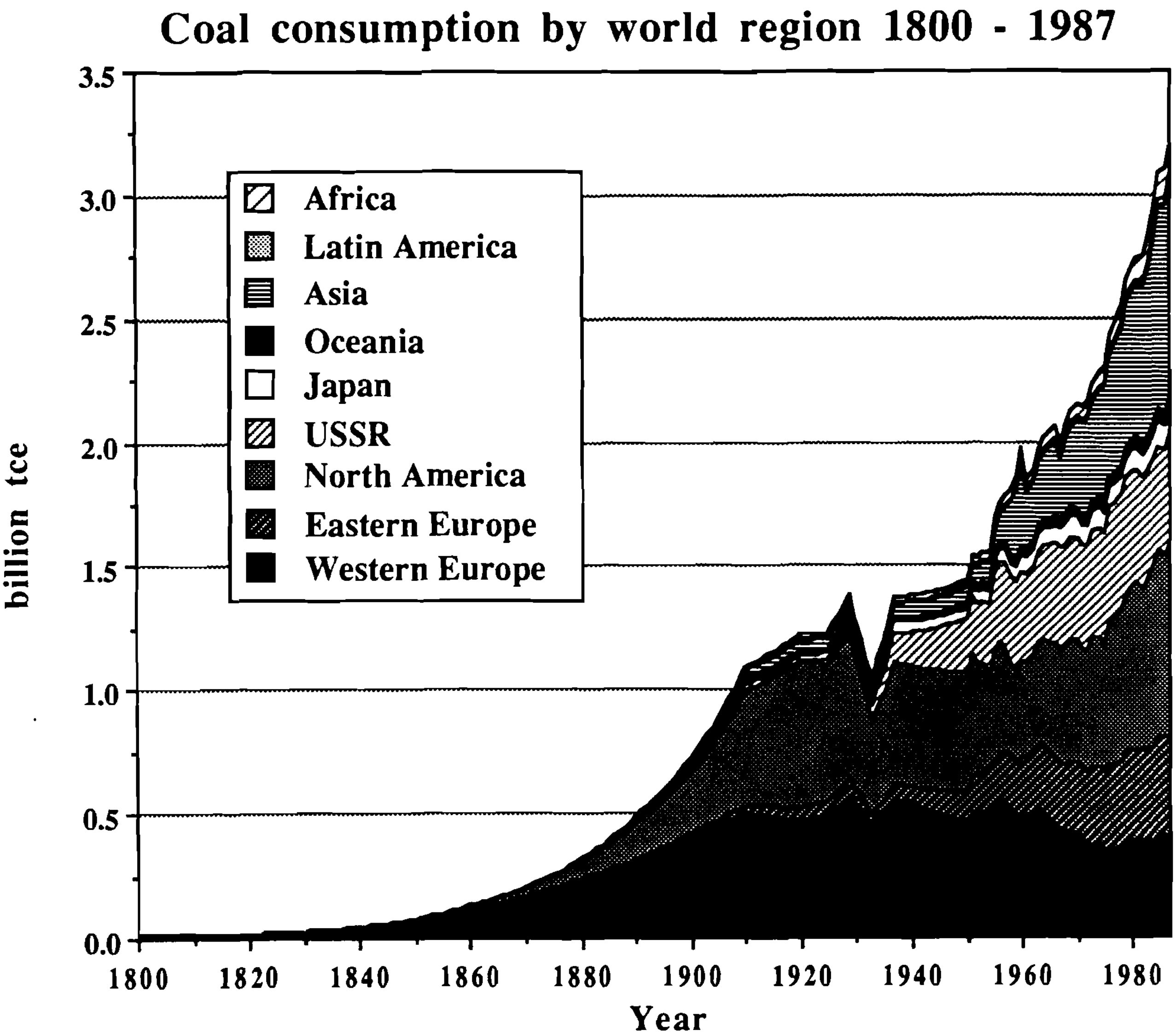

Figure 2. Coal consumption by world region 1800–1987 (in billion tce).

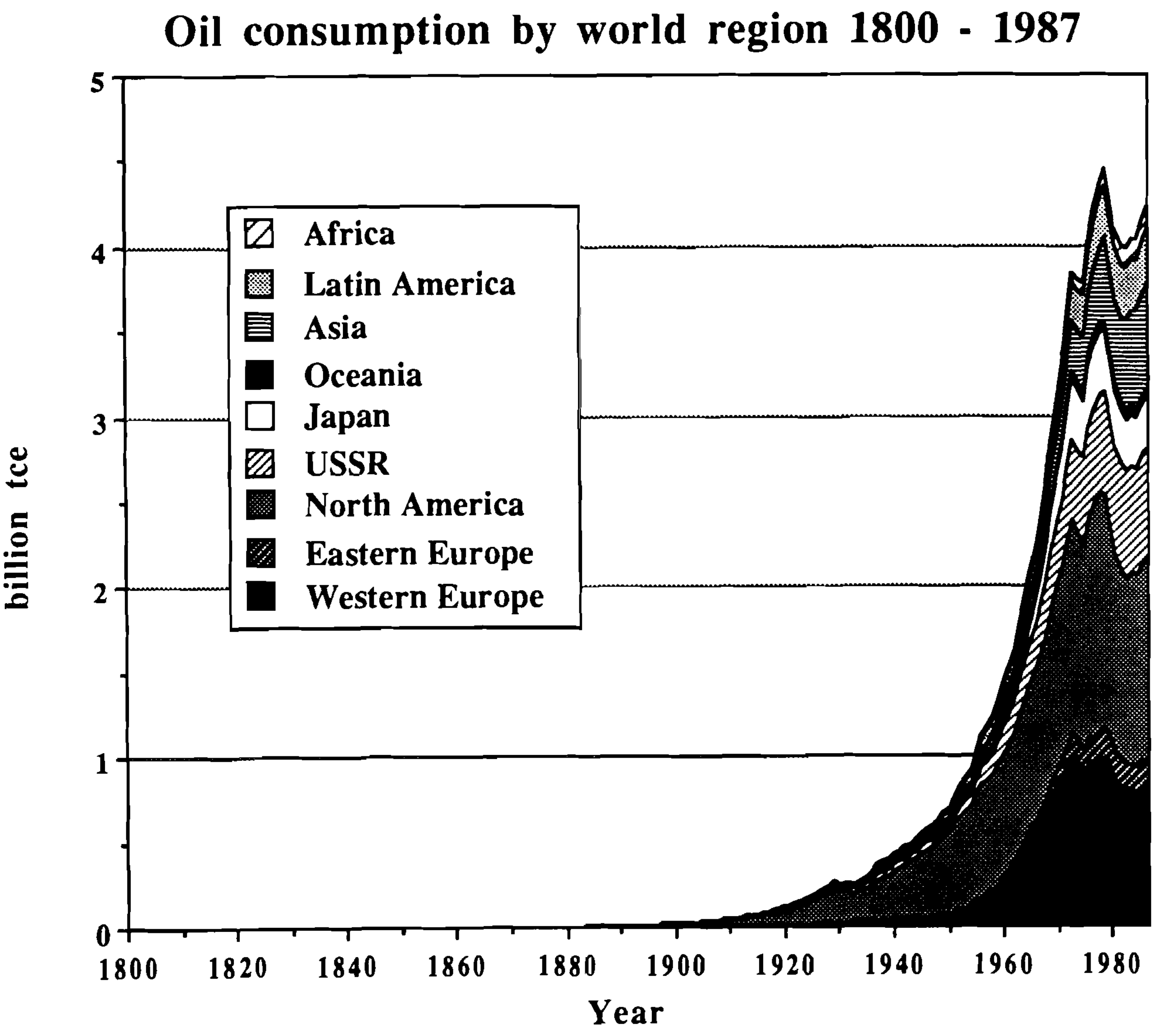

Figure 3. Oil consumption by world region 1800–1987 (in billion tce).

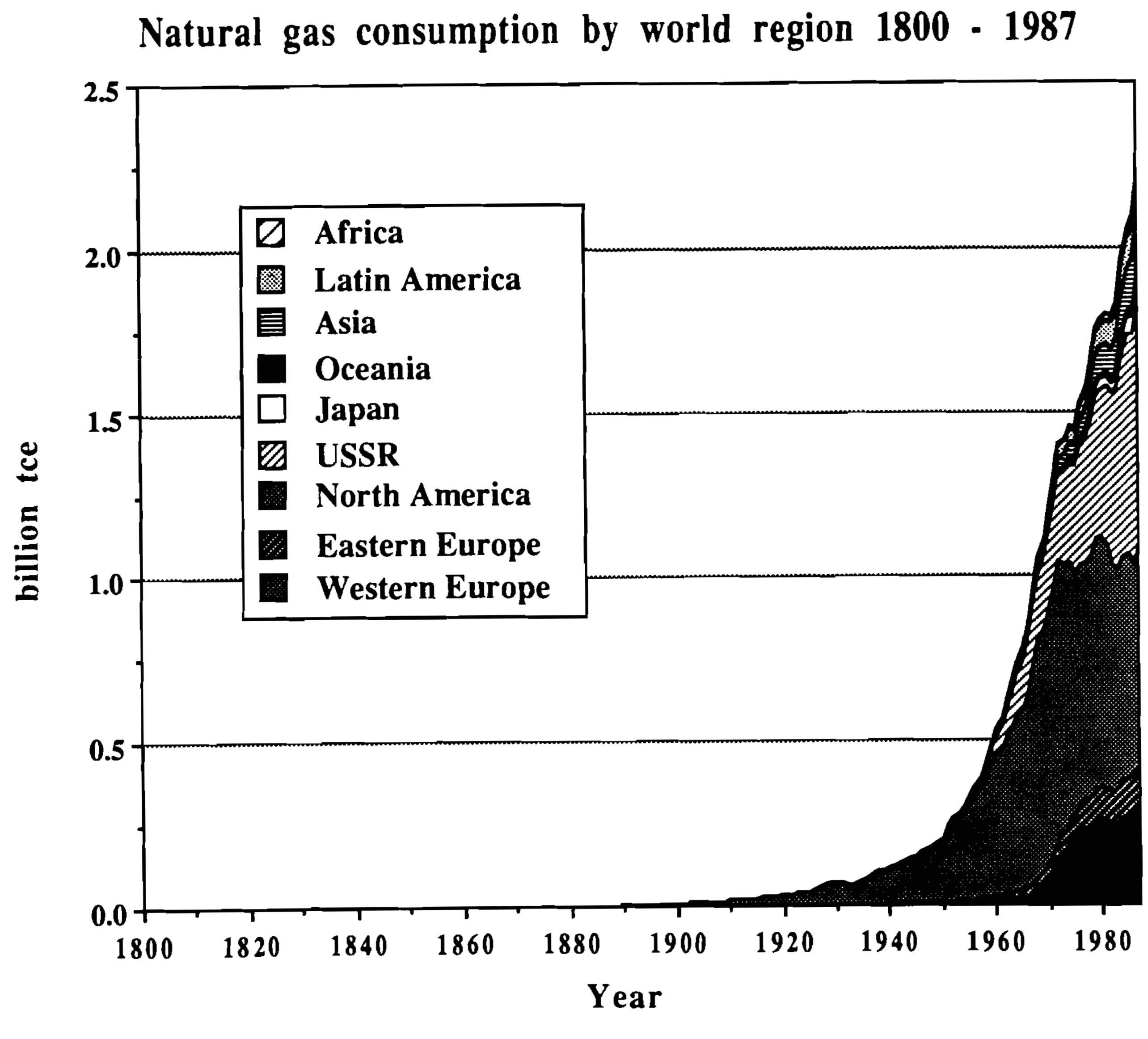

Figure 4. Natural gas consumption by world region 1800–1987 (in billion tce).

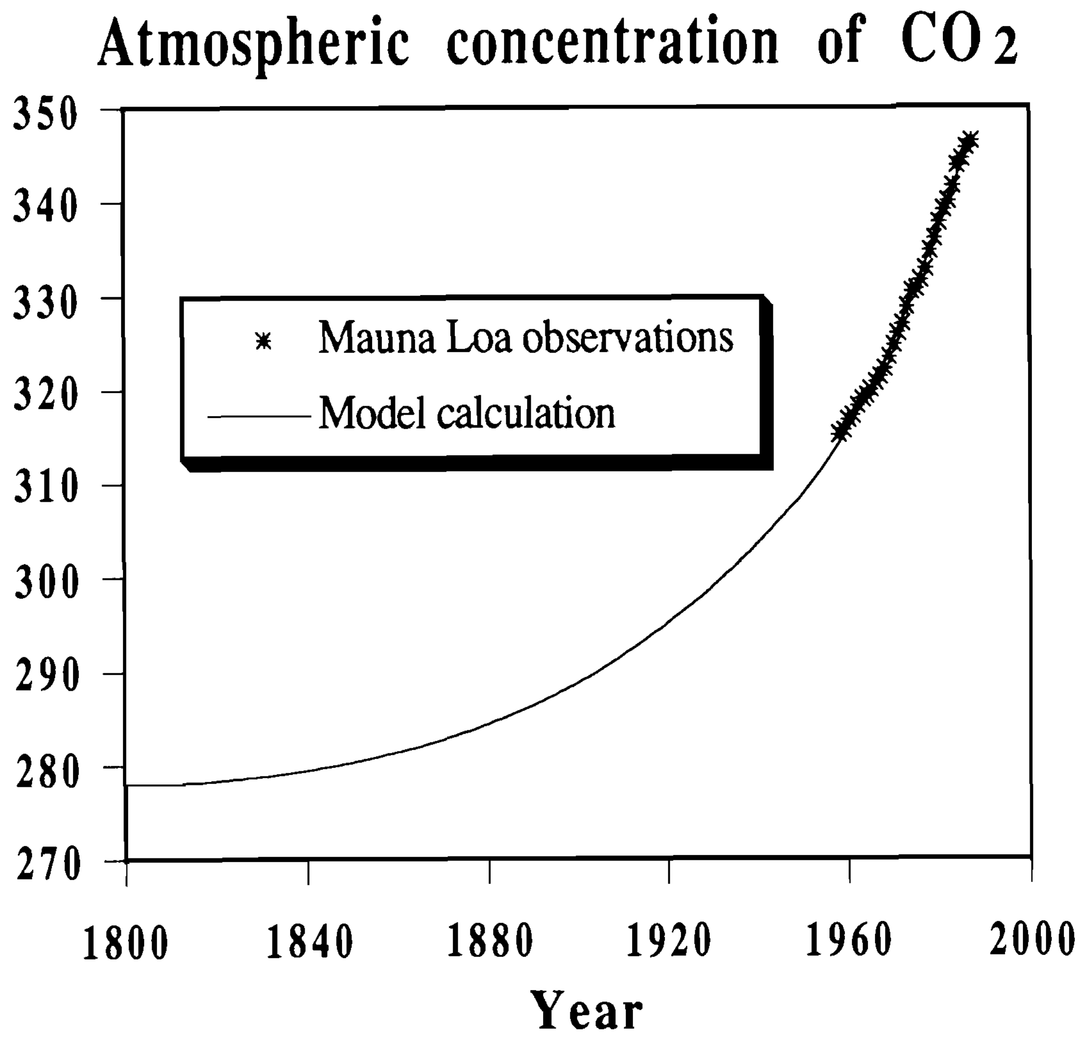

Figure 5. Atmospheric concentration of CO_2, Mauna Loa observations and calculation based on historic emission profiles and simple atmospheric concentration model (in ppm).

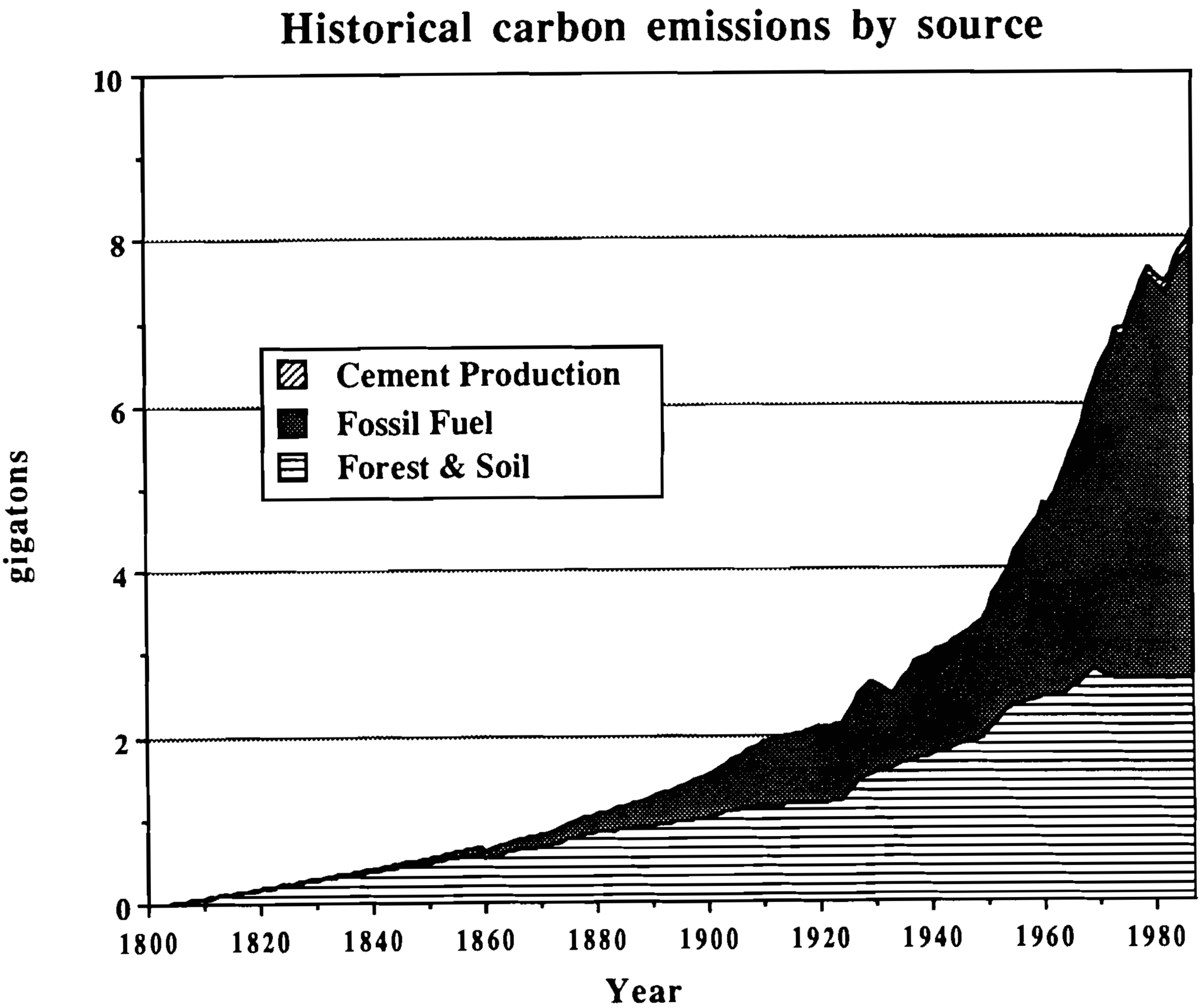

Figure 6. Historical carbon emissions from fossil fuel use, and forest and soil (Houghton *et al.*, 1983) 1800–1987 (in gigatons).

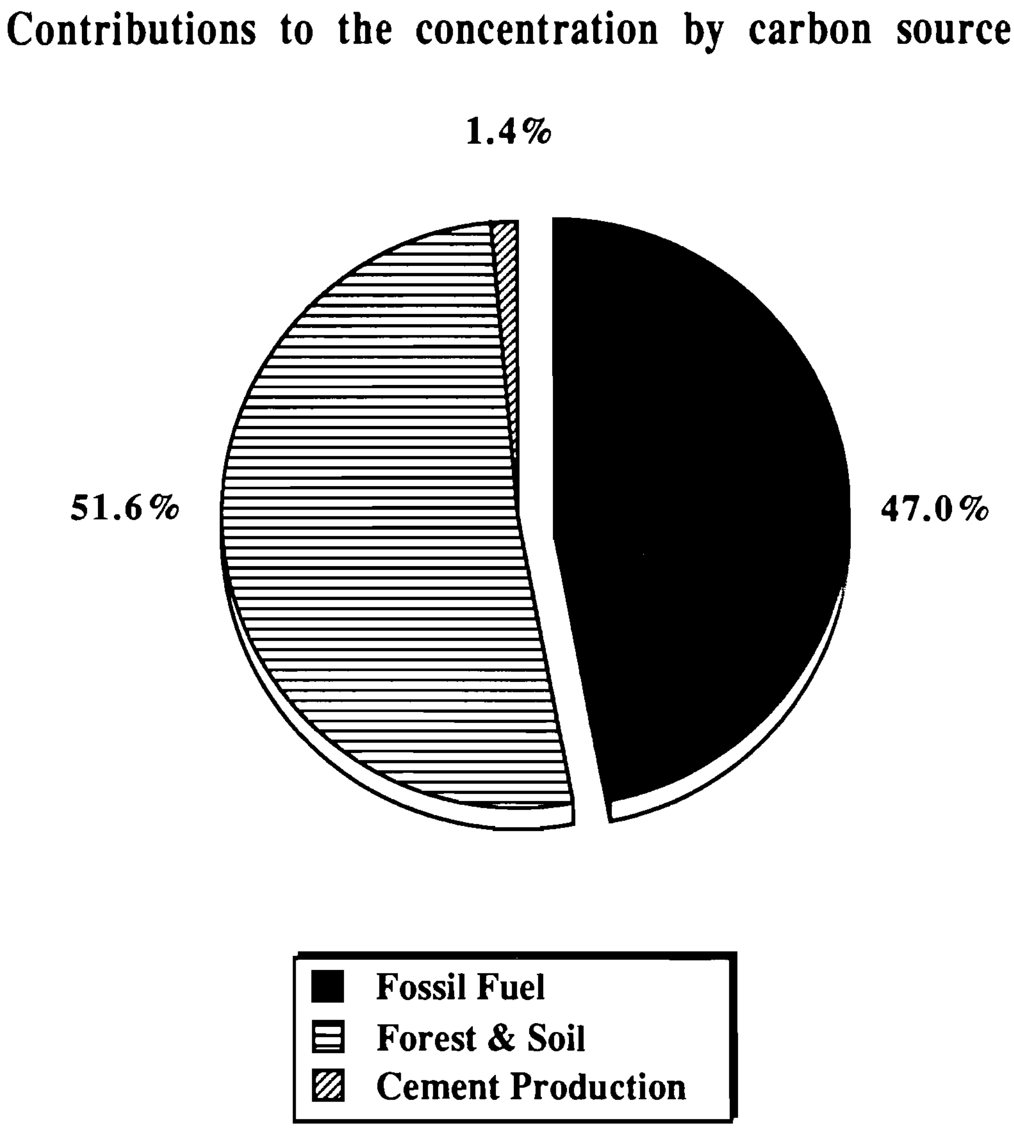

Figure 7. Contribution to increase in atmospheric CO_2 concentration since 1800 by carbon source (in percent).

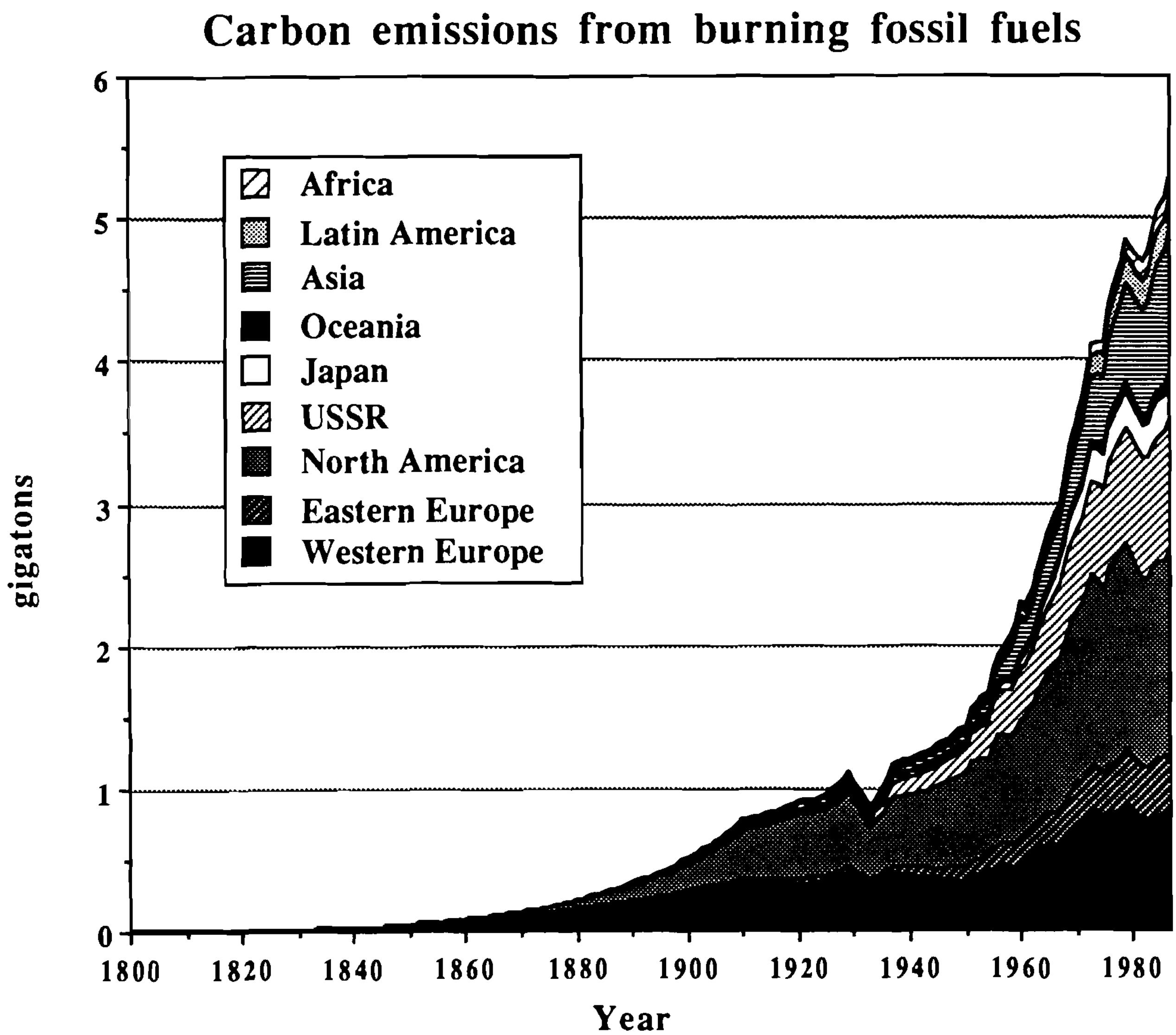

Figure 8. Carbon emissions from burning fossil fuels by world region 1800–1987 (in gigatons).

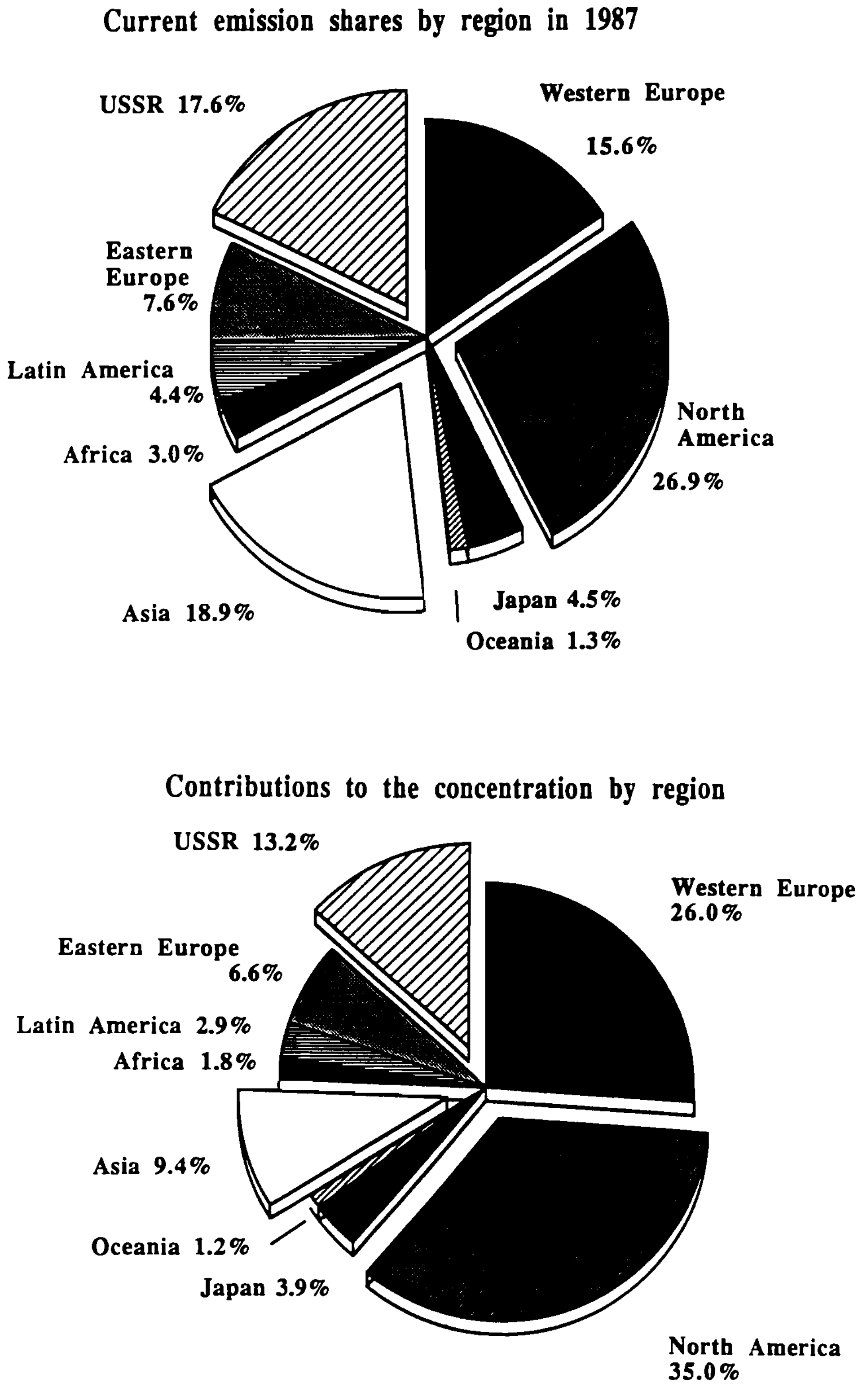

Figure 9. Share of different regions in current CO_2 emissions (top) and in contribution to the increases in atmospheric concentration since 1800 (bottom), in percent.

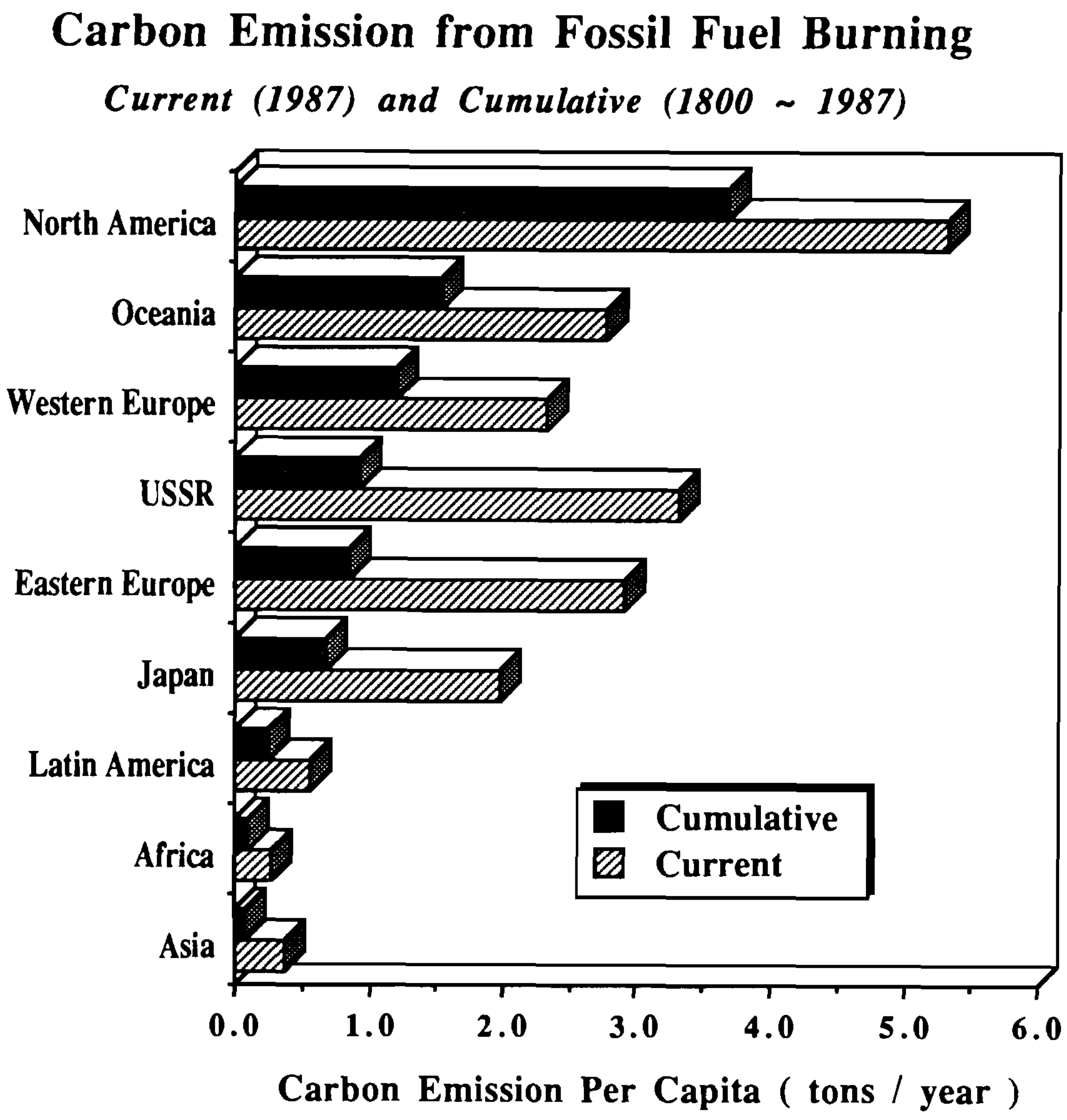

Figure 10. Current (1987) and cumulative (1800–1987) carbon emissions per capita by world region (in tons carbon/year per capita).

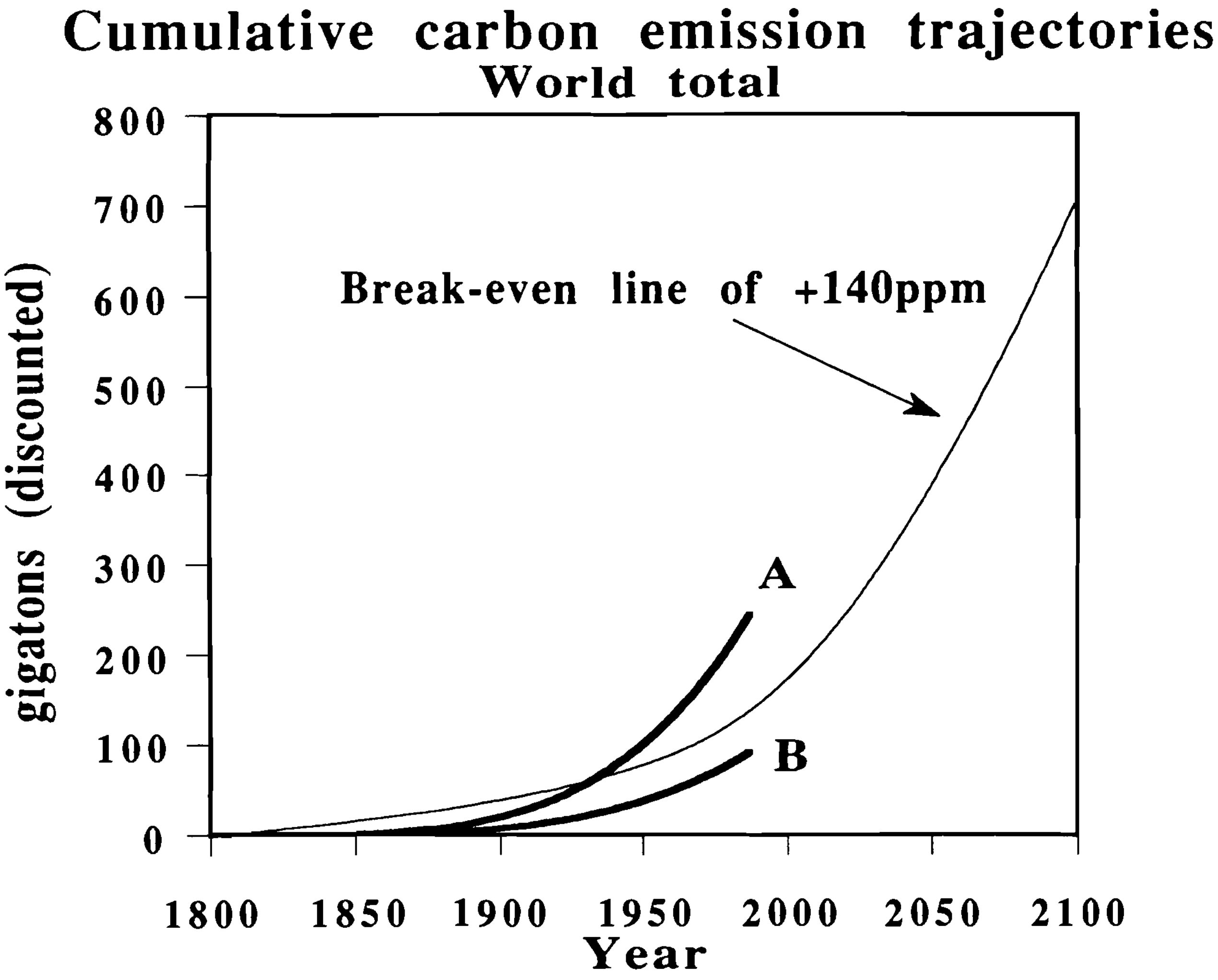

Figure 11. Cumulative carbon emission trajectories in a scenario allowing an increase of atmospheric CO_2 concentrations of 140 ppm by 2100. Break-even line of inter-generational equity emission trajectory; inter-generational emission debt (A) and credit (B) emission trajectories.

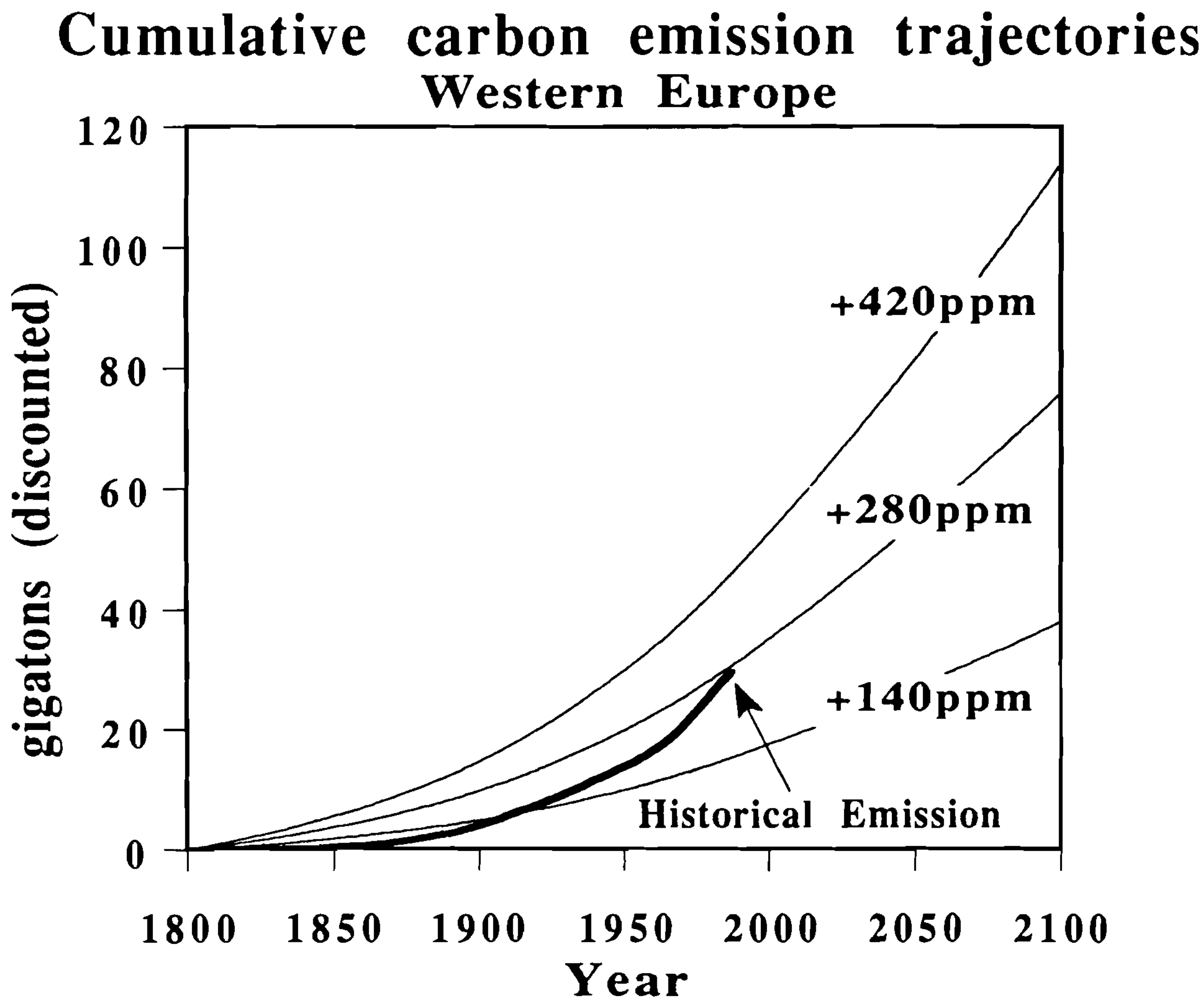

Figure 12. Cumulative carbon emission trajectories, historical emissions and inter-regional inter-generational equity emission paths for three scenarios of increases in atmospheric CO_2 concentration (additional 140, 280 and 420 ppm, respectively, by 2100): Western Europe.

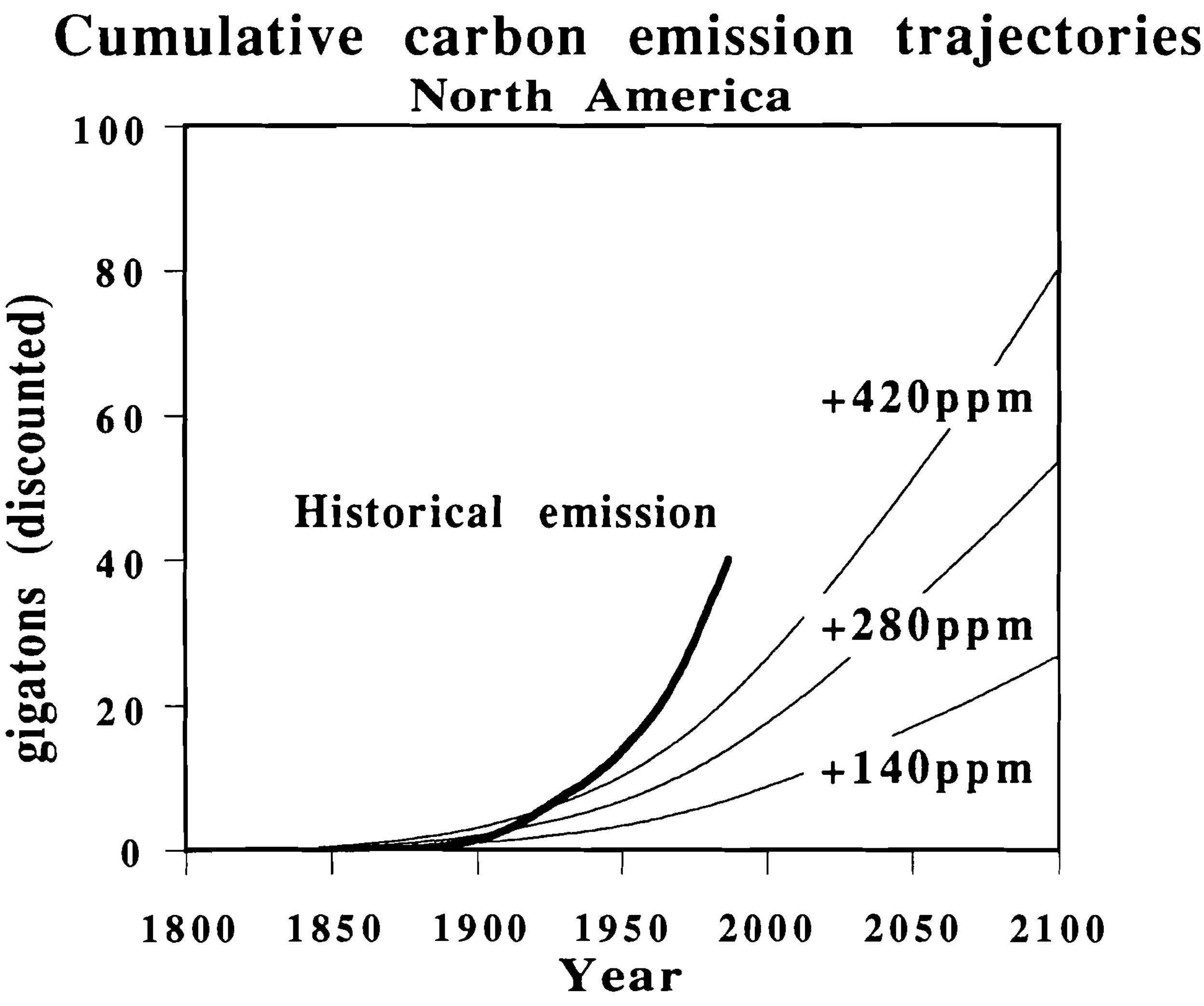

Figure 13. Cumulative carbon emission trajectories, historical emissions and inter-regional inter-generational equity emission paths for three scenarios of increases in atmospheric CO_2 concentration (additional 140, 280 and 420 ppm, respectively, by 2100): North America.

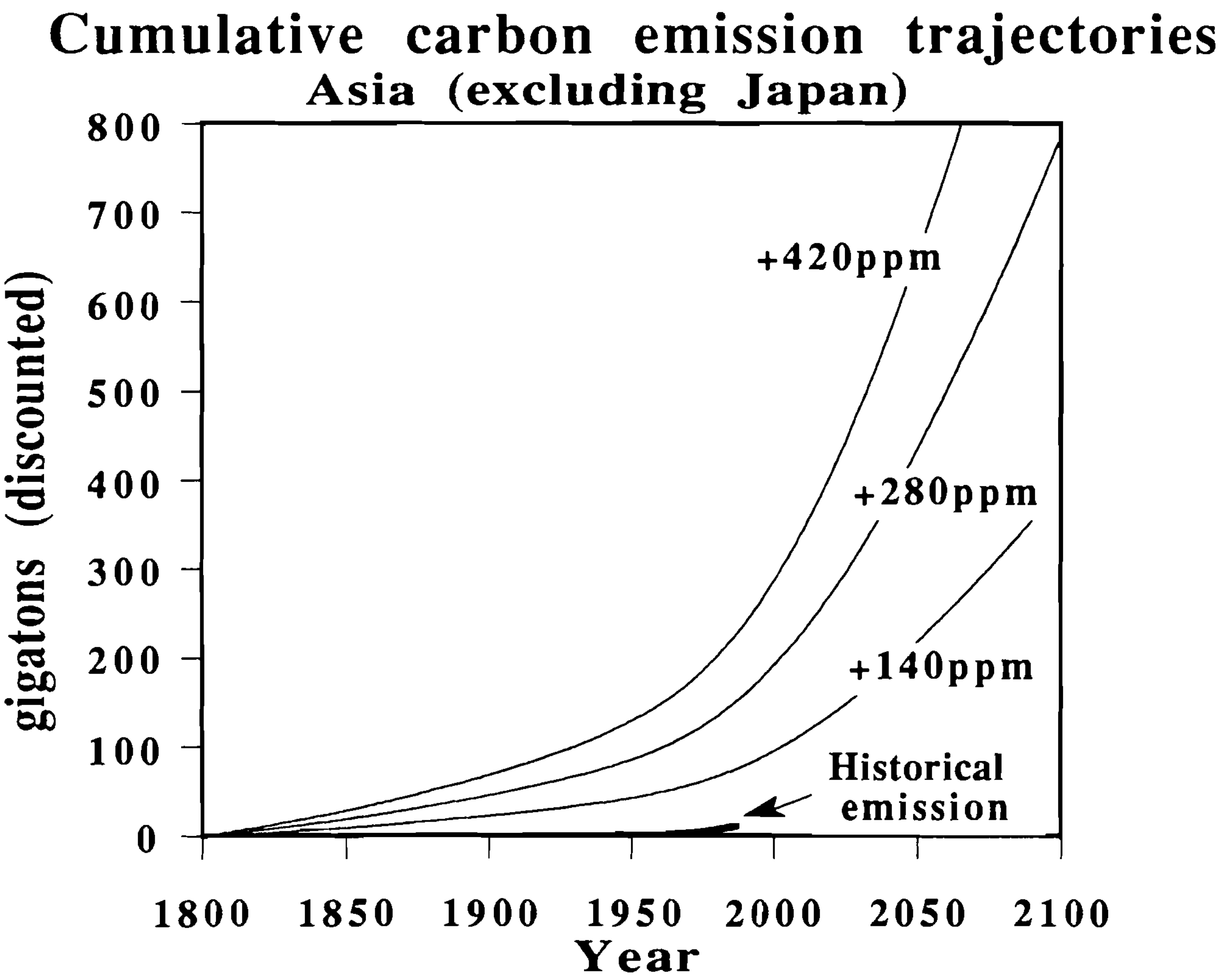

Figure 14. Cumulative carbon emission trajectories, historical emissions and inter-regional inter-generational equity emission paths for three scenarios of increases in atmospheric CO_2 concentration (additional 140, 280 and 420 ppm, respectively, by 2100): Asia (excluding Japan).

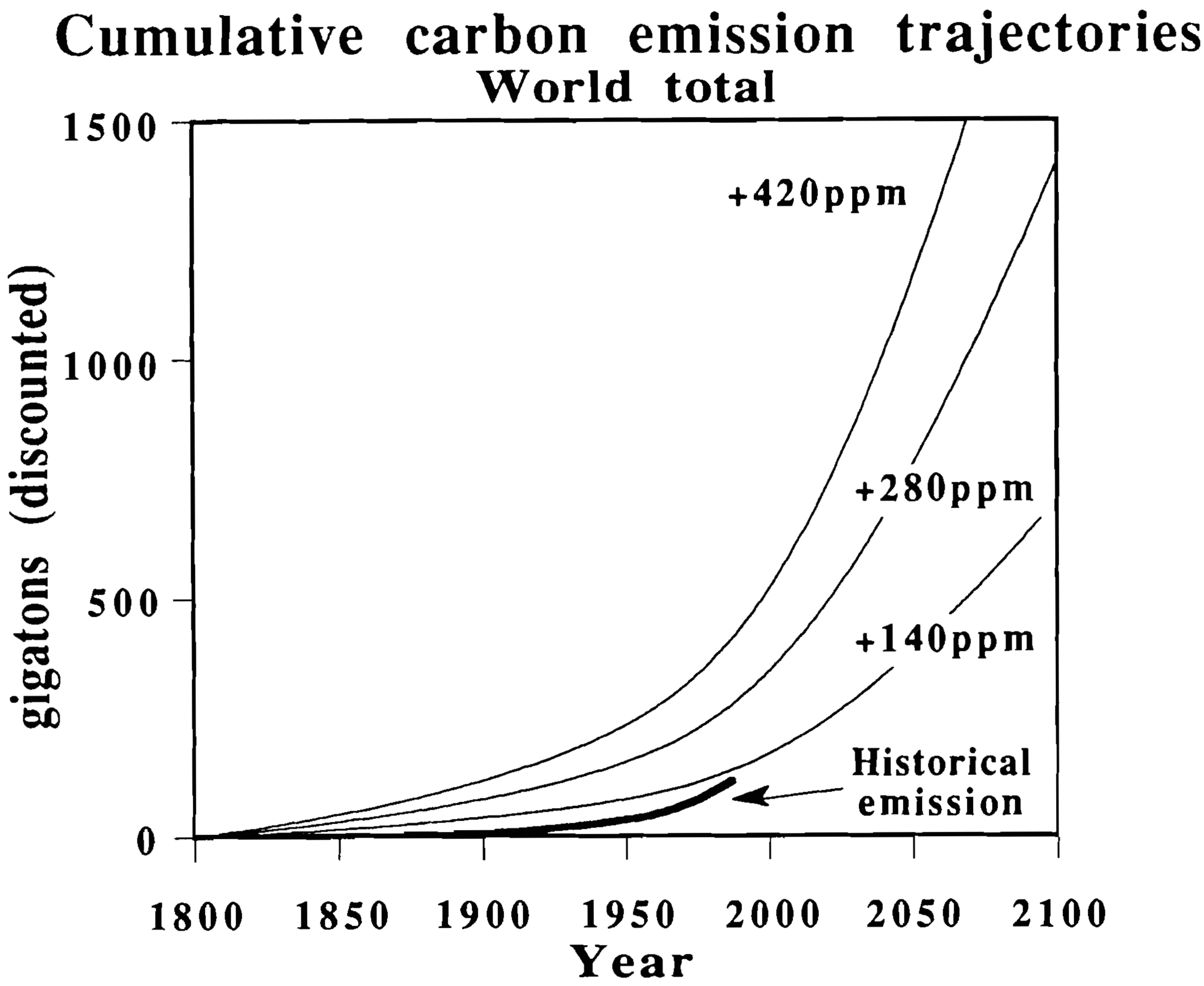

Figure 15. Cumulative carbon emission trajectories, historical emissions and inter-regional inter-generational equity emission paths for three scenarios of increases in atmospheric CO_2 concentration (additional 140, 280 and 420 ppm, respectively, by 2100): World total.

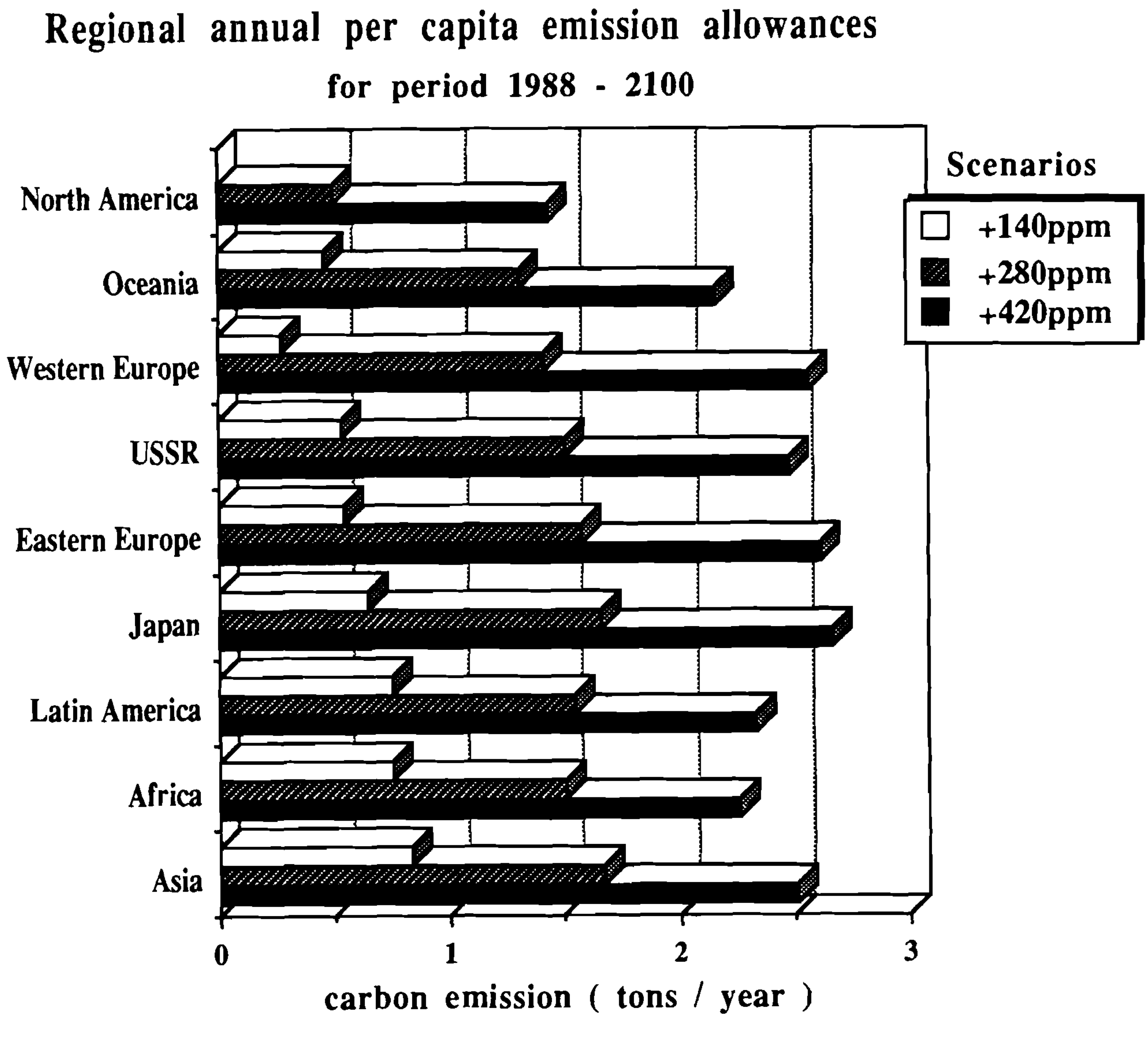

Figure 16. Regional annual per capita CO_2 emission allowances for period 1988–2100 assuming inter-regional and inter-generational equitable emission allowances for three scenarios of increases in atmospheric CO_2 concentrations (in tons carbon/year per capita).

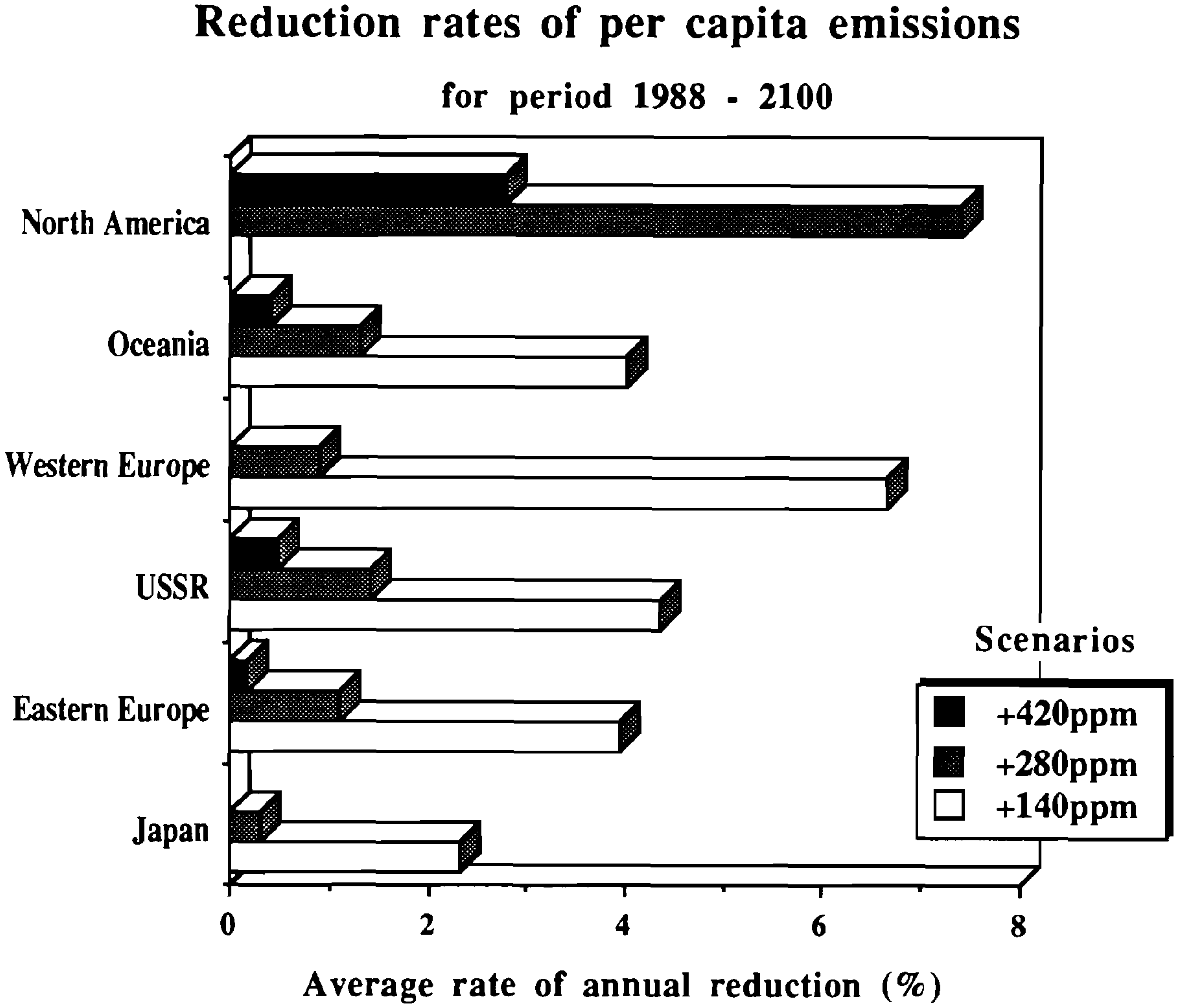

Figure 17. Average rate of annual reduction in per capita CO_2 emissions under equity consumption for three scenarios of increases in atmospheric CO_2 concentrations.

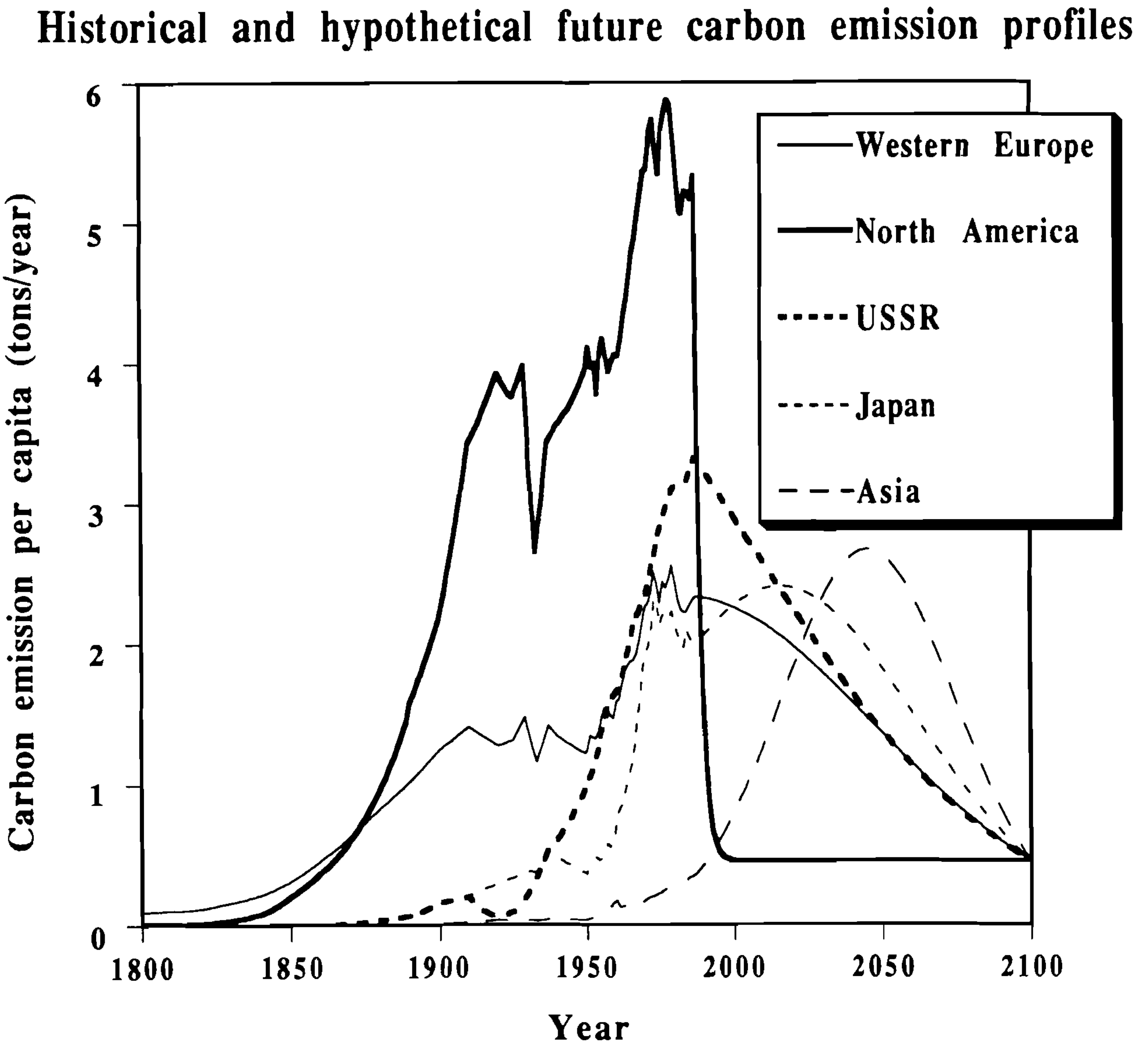

Figure 18. Historical and hypothetical future carbon emission profiles per region under inter-regional and inter-generational equitable emission allowances in a scenario aiming at stabilizing atmospheric CO_2 concentrations of twice the pre-industrial level by the year 2100 and onwards. Note that hypothetical future emission paths do not consider trading of carbon emission allowances, reforestation or CO_2 abatement technologies.

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