# SULFUR EMISSIONS

ARNULF GRÜBLER
*IIASA, A-2361 Laxenburg, Austria*

**Abstract.** The paper reviews base year emission inventories, driving forces, and long-term scenarios of sulfur emissions as background material for developing a new set of IPCC emissions scenarios. The paper concludes that future sulfur emission trends will be spatially heterogeneous (decline in OECD countries, rapid increase particularly in Asia) and therefore cannot be modeled at a global scale only. In view of ecosystems and food production impacts future sulfur emissions will need to be increasingly controlled also outside OECD countries. As a result, future sulfur emissions are likely to remain significantly below the values projected in the previous IPCC IS92 high emissions scenarios.

**Key words:** sulfur emissions, climate modeling, energy, emission driving forces, emission inventories, long-term scenarios, sulfate aerosols, energy.

## 1. Introduction

The purpose of this paper is to review briefly base year and scenario assumptions on sulfur emissions in the IS92 IPCC scenarios; advances in knowledge and modeling of future sulfur emission scenarios since IS92; as well as to discuss some key relationships of sulfur emissions to other scenario driving forces. The objective is to provide background information with respect to trends in future sulfur emissions to be used in the ongoing process of constructing a set of new IPCC emission scenarios. Throughout this paper emissions of sulfur are reported in million tons elemental sulfur (MtS; to convert to $SO_2$ multiply by a factor of 2). The central metric to discuss long-term sulfur emission trends is the relative evolution of sulfur emissions to that of carbon, as quantified by the sulfur to carbon (emissions) ratio (in kg S per ton C).

## 2. Sulfur Emissions in IS92

### 2.1. GLOBAL SULFUR EMISSIONS

The treatment of sulfur emissions in the IS92 scenarios was comprehensive. In addition to the dominant energy sector emissions, sulfur emissions from industrial processes and biomass burning and (a constant flow) of natural sources were also included in the scenarios.

1990 base year values in IS92 were as follows (based on Pepper *et al.*, 1992:102), in MtS:

| | |
|---|---|
| Energy Sector | 65 MtS |
| Other Industry | 8 MtS |
| Biomass burning | 2 MtS |
| Anthropogenic | 75 MtS |
| Natural | 22 MtS |
| TOTAL | 98 MtS |

These global base year values are within the range given by global sulfur emission inventories of 4 to 45 MtS natural sources and 65 to 90 MtS anthropogenic sources in 1990 (IPCC, 1995:135–141, Benkovitz *et al.*, 1996, Olivier *et al.*, 1996, WMO, 1997). As pointed out by Streets (1997) however, it remains unclear if the IPCC estimates of natural sulfur flows refer to S or $SO_4$. The numbers also refer to volcanic sources only. Therefore some uncertainties remain as regards the natural sulfur emission budgets used in the IS92 assessment. Because these natural emissions are not influenced by anthropogenic activities, they are not subject to scenario variations and therefore not of direct relevance to the scenario exercise for a new set of IPCC emissions scenarios.

### 2.2. 1990 BASE YEAR VALUES (ANTHROPOGENIC EMISSIONS)

A comparison of 1990 base year anthropogenic sulfur emission values from all available inventories and global and regional emissions scenarios and integrated assessment models (Table I) yields the following main conclusions.

Global IS92 values are well within the range of estimates in the literature. Global IS92 values are also identical to those aggregated from best available 1990 inventory data at the regional level (cf. discussion below).

However, as observed in the evaluation of the IS92 scenarios (Alcamo *et al.*, 1995), regional sulfur emissions assumed in IS92 (e.g., for China) are more uncertain than global numbers. IS92 values for 1990 are quite different from more recent inventories and studies of regional sulfur emissions. Based on an assessment of all global and regional sulfur emission inventories available, (subjective) "best available inventory" (BAI) data for 1990 are suggested below and compared to the values retained in the IS92 scenarios. (The criteria for retaining particular BAI values were a) consistency between alternative inventory sets, and b) agreement with most recent inventory data. Note that this overview, does not include data from the 1 × 1 gridded sulfur inventory of the GEIA data set (Benkovitz *et al.*, 1996). No published estimates exist for this data set to compare it at a regional level to the other sulfur inventories available. Note also that the regional definition retained in the IS92 scenarios for "OECD Europe" is especially problematic, as it includes sulfur emissions from Canada, a region where there is practically no transboundary emissions/deposition flows with the remainder of the region. (The various detailed inventory data analyzed to derive BAI data are available upon request from the author.)

The BAI data summarize the most important data sources of regional and global sulfur emissions including the European inventories EMEP and CORINAIR, NAPAP for North America, and for Asia the most recent inventories, in particular from the World Bank sulfur project (Foell *et al.*, 1995), as well as the detailed bottom-up estimates of Akimoto and Narita, 1994, and Kato, 1996.

The overall conclusion for the assessment of 1990 base year data of sulfur emissions is that, whilest global totals are in excellent agreement, regional emissions as portrayed in the IS92 scenarios are outdated in view of more recent information from sulfur emission inventory studies. In particular, base year emissions by FCCC-Annex-I countries are seriously overestimated (by 20 percent) in IS92, whereas those from Non-Annex-I countries are underestimated by one third. Considering recent emission trends (to 1995) that invariably show further decreases in emissions in Annex-I countries (as they are showing further increases in Non-Annex-I countries), these discrepancies in base year data compound misleading emission trends as projected in IS92.

Despite an attempt to analyze all available emissions inventories and studies and to recommend BAI estimates for 1990 base year values, it needs to be stressed that important uncertainties remain. To illustrate the uncertainty underlying sulfur emission inventories that persist for many developing countries, emissions estimates for the CPA region and China are summarized in Table II. The year to which the estimates apply is indicated in parenthesis.

Emissions inventories outside the OECD therefore continue to be uncertain. Despite uncertainty, one can conclude that the values retained

Table I. 1990 IS92 sulfur emissions (all anthropogenic sources) and comparison with 1990 BAI (best available inventory) data, in MtS (%)

| | IS92 | BAI | %-Diff. |
|---|---|---|---|
| USA | 10.5 | 10.2 | +3% |
| OECD-EUROPE-IS92 | 14.0 | 9.9 | +41% |
| OECD-Europe w/o Canada | 12.4 | 8.3 | +49% |
| EEFSU | 18.5 | 18.8 | −2% |
| OECD-ASIA | 7.2 | 2.6 | +277% |
| ANNEX-I | 50.2 | 41.5 | +21% |
| CPA | 9.8 | 13.2 | −26% |
| other Asia | 4.5 | 6.1 | −26% |
| Middle East | 2.8 | 2.4 | +17% |
| Africa | 0.9 | 5.9 | −85% |
| Latin America | 5.3 | 4.6 | +15% |
| NON-ANNEX-I | 23.3 | 32.2 | −27% |
| WORLD | 73.5 | 73.7 | −0% |
| WORLD (incl. bunkers) | n.a. | 76.2 | −4% |

*Note*: EEFSU: Central and Eastern Europe and Former Soviet Union, i.e. Difference between FCCC Annex I and Annex II (OECD) countries; CPA: China and Centrally Planned Asia; OECD-EUROPE-IS92 includes Canada as assumed in IS92 scenarios. BAI data have been adjusted accordingly. OECD-Europe data excluding Canada as also shown.

in the IS92 series in all likelihood are too low for Asia and Africa in light of more recent estimates and inventory data. Surprisingly, IS92 emission data show a systematic overestimation of 1990 sulfur emissions for OECD countries, leading to especially large differences in the case of Europe, even after correcting for the inclusion of Canada in the IS92 OECD Europe region, and OECD Asia (Japan, Australia, New Zealand). Part of this discrepancy is certainly due to the fact that IS92 1990 values were projected to increase from a base year 1985, whereas actual emissions have dropped significantly in all OECD countries. For instance, emissions have declined by some 24 percent between 1990 and 1994 in Western Europe and in the EEFSU region (ECE, 1997) as a result of continued sulfur reduction policies or economic recession (and resulting decline in coal use) respectively. Conversely, emissions in Asia have increased significantly over the same time period, as indicated by the estimates for CPA and China given above.

These scenario base year emissions data discrepancies become especially pronounced when comparing most recent (1995) emission inventories with global, gridded (1 × 1) sulfur emissions inventory

Table II. Recent sulfur emission estimates for China and the CPA (China and Centrally Planned Asia) Region, in MtS.

| | | |
|---|---|---|
| IS92a | (CPA 1990) | 9.700 (9.5 energy + 0.2 industry) |
| Spiro *et al.* | (CPA 1980) | 10.920 |
| Spiro *et al.* | (China 1980) | 9.893 |
| Akimoto & Narita | (China 1987) | 9.995 |
| Kato | (China 1987) | 9.994 |
| EDGAR | (CPA 1990) | 14.146 (12.5 energy, 1.7 non-energy) |
| China Env.Yrbk | (China 1980) | 8.000 |
| China Env.Yrbk | (China 1987) | 7.100 |
| China Env.Yrbk | (China 1994) | 9.100 |
| Dadi *et al.* | (China 1990) | 8.400 (7.6 energy + 0.8 other) |
| Dadi *et al.* | (China 1995) | 11.900 (11.0 energy + 0.9 other) |
| IIASA | (CPA 1990) | 11.100 |
| IMAGE-2 | (CPA 1990) | 11.687 |
| AIM | (CPA 1990) | 18.060 |
| RAINS Asia | (China 1990) | 10.950 |
| RAINS Asia | (CPA 1990) | 11.300 |
| Smith *et al.* | (CPA 1990) | 12.000 |

*Sources*: Inventories: Spiro *et al.*, 1992; Akimoto and Narita, 1994; Kato, 1996; Sinton, 1996 (China Environmental Yearbook). Olivier *et al.* (EDGAR), 1996; Dadi *et al.*, 1998. Models: IS92 (Pepper *et al.*, 1992); IIASA (energy sources only, Amann *et al.*, 1995); IMAGE-2 (Posch *et al.*, 1996); AIM (Morita *et al.*, 1994); RAINS Asia (excluding international shipping, Foell *et al.*, 1995); Smith *et al.*, 1998.

data developed for climate modeling purposes. With exception of the EDGAR database referring to 1990, other global gridded data sets available refer to yet earlier years (e.g., the Spiro *et al.*, 1992 inventory refers to the year 1980; the GEIA gridded sulfur emission data update the Spiro *et al.*, data set for 1985 for a number of regions, most of them Annex-I countries.) Due to differential sulfur emission growth trends, discrepancies between gridded inventory data and most recent emission data widen increasingly.

*To summarize, 1990 base year estimates of the IS92 scenario series are outdated and need to be replaced by more recent data (cf. BAI data given above). New scenarios need also take into account recent trends indicating significant sulfur emissions declines in Europe and substantial increases in Asia that were misrepresented in the IS92 scenario series (cf. discussion on regional scenarios below).*

## 2.3. GLOBAL, REGIONAL, AND GRIDDED $(1 \times 1)$ SULFUR EMISSION INVENTORIES

Most scenario information about $SO_2$ emissions are in the form of annual emissions from world regions or globally averaged. In order to use this information as input to global atmospheric chemistry and climate models, these emissions must be downscaled to a finer spatial and temporal scale. Downscaling can also be a useful device for harmonizing regional emission estimates computed by different groups that use different regional aggregations of countries in their calculations.

There are apparently no global approaches for a temporal downscaling of emission scenarios (from yearly averages to seasonal variations, for example). Climate researchers have developed a number of spatially disaggregated emissions data sets at a high degree of spatial resolution, typically at a one by one degree resolution (e.g., Dignon and Hameed, 1989, or Spiro *et al.*, 1992). Spiro *et al.* (1992) took a "top down" approach and distributed country estimates onto a global grid by using population density and other data. The GEIA data base (Benkovitz *et al.*, 1997) improves upon this effort by using detailed gridded inventories recently developed for some regions (most notably the regions covered by the European CORINAIR inventory, inventories for North America, as well as from some Asian countries and regions). These 1985 values complement the default 1980 values retained from the Spiro *et al.* (1992) emissions inventory. Recently, an alternative data set (the EDGAR) gridded emissions inventory (Olivier *et al.*, 1996) has become available using 1990 as base year values, covering emissions of the most important direct and indirect greenhouse gases and halocarbons in addition to sulfur emissions. The data quality of these emissions inventories at the regional level varies considerably. Older inventories, e.g., such as that by Spiro *et al.* (1992) have been found to be especially uncertain (or rather inaccurate) with respect to energy-related emission sources (Streets, 1997). These earlier global emission inventories moreover end in 1980, and empirical data suggests that regional sulfur emission patterns have changed drastically since. They have declined in the OECD, in Eastern Europe and the ex-USSR, and they have increased markedly in non-OECD Asia.

This is contrasted in the following Table III for the trends in sulfur emissions since 1980 in the emissions inventory compiled by the United Nations Economic Comissions for Europe (ECE, 1997) given in Table III: For the entire ECE region, where sulfur emission inventories are well developed, the difference between 1980 and 1995 data amount to 46 percent. The differences are particularly large in Western Europe, where 1995 emissions are some 60% less than in 1980, i.e. an emis-

Table III. Sulfur emissions (in MtS), 1980, 1990, and 1995 for the ECE region.

| | 1980 | 1990 | 1995 | % change 1980–1995 |
|---|---|---|---|---|
| Western Europe | 14.1 | 8.5 | 5.8 | −59% |
| Eastern Europe | 6.0 | 4.7 | 3.8 | −37% |
| Russia | 3.6 | 2.2 | 1.5 | −58% |
| Other CIS | 2.6 | 2.0 | 1.1 | −58% |
| Total Europe | 26.3 | 17.4 | 12.2 | −54% |
| USA & Canada | 14.2 | 11.8 | 9.6 | −32% |
| Total ECE Region | 40.5 | 29.2 | 21.8 | −46% |

*Note*: For Russia only emissions for stationary sources are available, actual emissions therefore are larger than indicated. 1980 GDR emissions are included in Western Europe.

sions decrease of 5.8% per year. Such differences become compounded when rescaling global (rising) sulfur emission scenarios linearly based on gridded sulfur emissions data for a region where emissions decline at some 6 percent per year.

For developing countries the situation is the opposite: emissions continue to rise markedly, compounded by additional uncertainties in base year emissions data. For instance, the Chinese Environmental Yearbook (translated by Sinton, 1996) indicates sulfur emissions in China have risen from 6.6 MtS in 1985 to 9.1 MtS in 1994 (by 38 percent), or by 3.6 percent annually. The most recent inventory by Dadi *et al.* (1998) indicate a rise in Chinese sulfur emissions from 8.4 to 11.9 MtS between 1990 and 1995, corresponding to a growth rate of some 7 percent annually.

Continuous updating of global gridded emission data is thus required to accurately reflect different regional trends on emissions patterns. Evidently, more recent data sets (GEIA, or EDGAR) are preferable over earlier estimations, but even these need to be regularly assessed and updated. In any case, downscaling global emissions trends uniformly would introduce large margins of error. Fortunately, a number of models are already available that base their downscaling calculations on a number of different regions separately (cf. Hulme, 1997, Schlesinger, 1997). This needs to be incorporated into the requirements for regional detail in the new IPCC scenarios. At a minimum, emissions need to be separated by Annex-I and Non-Annex-I countries, and need to put special emphasis on Asia, where sulfur emission growth is particularly high.

*To summarize, climate modelers are cautioned against using outdated gridded global sulfur emission inventory data and especially against rescaling techniques that use uniform time trends of future emissions growth across all regions. Emissions have been declining rapidly, especially in Europe and North America, and are increasing rapidly in Asia.*

## 2.4. OTHER OBSERVATIONS FOR MODELS

The above discussion strongly suggests that global emission estimates should be constructed "bottom-up" using detailed regional inventories reflecting most recently available data as well as trends in regional emissions, rather than deploying any linear downscaling from global numbers. For instance, there is up to a factor two difference between regionalized estimated of global inventories and aggregates of national and regional emissions inventories. Thus, the good agreement of global base year values of IS92 or similar estimates used in climate models masks important differences, uncertainties, and time trends at the regional level.

Improved modeling of regional sulfur emissions (and deposition, i.e. impacts) patterns also requires a high degree of regional detail, which is impossible to provide in models of global coverage. Thus, "top-down" spatial rescaling techniques will ultimately also be needed to translate world regional sulfur emissions data into detailed spatially disaggregated emission and deposition patterns for use in impact analysis. Currently, two emissions models have been linked to the spatially disaggregated acidification impact modules of the RAINS model (IMAGE and IIASA), with both models covering Asia and Europe (Posch *et al.*, 1996, and Nakicenovic *et al.*, 1998).

To ease data transfer and compatibility, a redefinition of the world regions as used in the IS92 scenario series is required. For instance, Canada is included in the region OECD-Europe, and the IS92 region "South Asia" includes both the Indian subcontinent and Indonesia. The important differences in resource endowments in these regions lead to different patterns of sulfur emissions. Their differing predominant weather patterns and distinct ecosystems also lead to differing acidic deposition patterns and impacts. These factors together preclude their aggregation into one single regional model for the purposes of sulfur emission scenarios and modeling, as was done for IS92.

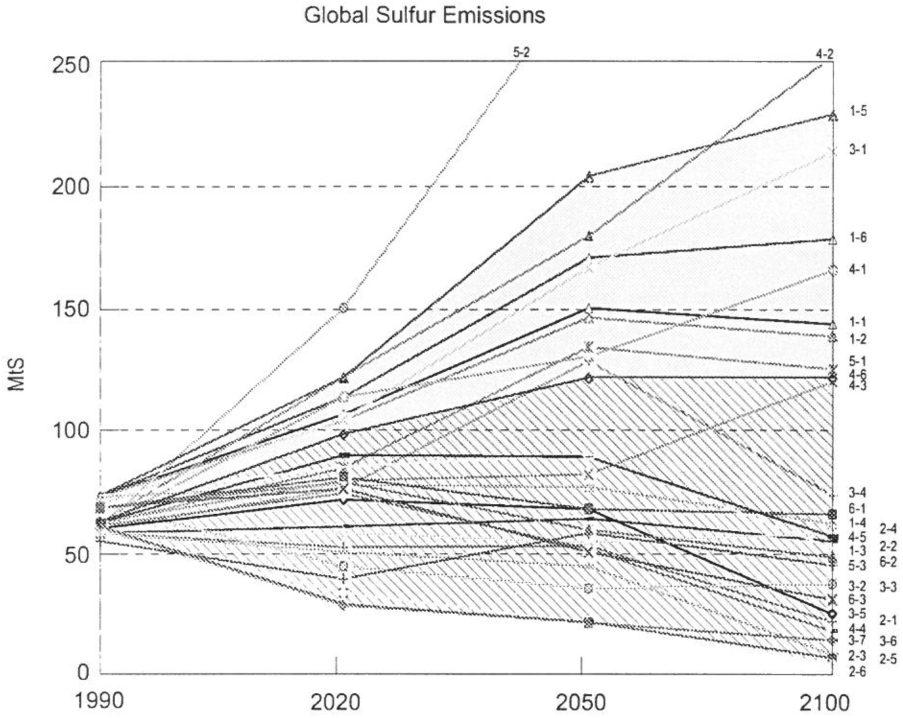


*Figure 1.* Global sulfur emission scenarios (in MtS): a comparison of scenarios. Range of IS92 scenarios (grey) and range of sulfur control scenarios (cross-hatched). For explanation of scenario coding see the Appendix.

## 2.5. FUTURE GLOBAL EMISSIONS: IS92 AND OTHER SCENARIOS

Concerning future emissions of sulfur, the IS92 scenarios project global anthropogenic emissions of between 150 to 200 MtS by 2050 and between 140 to 230 MtS by 2100 in the high growth cases, and of around 80–90 and 60 MtS in the two low energy demand scenarios (IS92c and IS92d) by 2050 and 2100, respectively (Figure 1).

In the global aggregate, the IS92 sulfur emissions scenarios are partly representative of other sulfur emissions scenarios developed within integrated assessment (IA) models and exercises that deal specifically with GHG and sulfur emissions at the same time. Recently, integrated assessment models have been developed which are able to model in greater detail driving forces of sulfur emissions as well as acidification impacts (cf. discussion in Section 3 below). These model simulations suggest that acidification impacts would require substantial sulfur emission control measures already much earlier than 2050, particularly in Asia. The resulting global sulfur emissions are therefore substantially

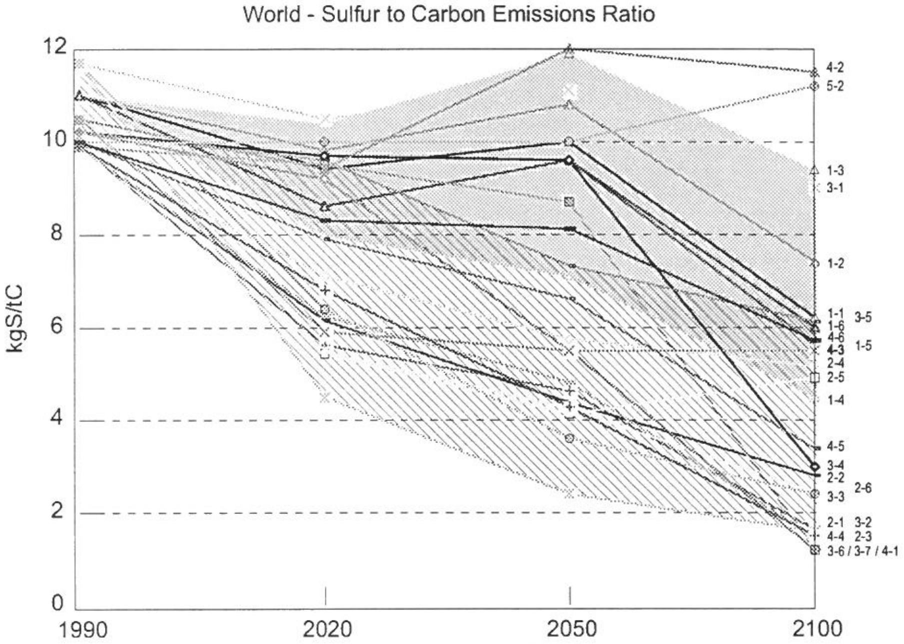


*Figure 2.* Ratio of sulfur to carbon emissions (kgS/tC), world: a comparison of scenarios. Range of IS92 scenarios (grey) and range of sulfur control scenarios (cross-hatched). For explanation of scenario coding see the Appendix.

lower than suggested by the IS92 scenarios, leading to rapidly declining sulfur to carbon emission rations (Figure 2).

Only the two lowest IS92 scenarios (IS92c and IS92d) approach the higher end estimates of the global sulfur emissions of latest sulfur emissions scenarios. These have a special focus on mitigation of acidification and other environmental impacts of unabated high sulfur emission levels. Sulfur control (only) policy scenarios developed with models such as AIM, IMAGE, IIASA, or MiniCam indicate that global sulfur emissions are likely to be lower than IS92c or IS92d. (Note that all these scenarios are sulfur control scenarios only. None assumes any climate policy measures.)

These sulfur control policy scenarios were developed based on recent findings of acidification impacts studies (cf. discussion in the following Section 3 below) and indicate global sulfur emission levels in the range of 20 to 80 MtS by 2050, and 15–60 MtS (120 MtS in the IMAGE S50 scenario) by 2100 (Figure 1). These scenarios are confirmed also by energy industry perspective scenarios, such as those developed by IIASA–WEC (1995) and the results reported in Nakicenovic *et al.* (1998), where global sulfur emissions as a rule remain below 65 MtS by

2050 and 2100, even in the highest scenarios. These values are greatly exceeded in the IS92 series outside IS92c and IS92d.

The differences between no-sulfur-controls scenarios and sulfur control scenarios are best illustrated by analyzing the sulfur to carbon ratio of global emissions scenarios (Figure 2). Such an analysis confirms that, compared to more recent scenarios, all of the IS92 scenarios (except the two low demand scenarios IS92c and IS92d) have sulfur emission profiles that de facto correspond to the no-sulfur-control scenarios of more recent studies.

## 2.6. FUTURE REGIONAL EMISSIONS: IS92 AND OTHER IA MODELS

The IS92 scenario evaluation (Alcamo *et al.*, 1995:281–282) concluded that the IS92 scenario series only to a limited degree reflects recent legislation to reduce sulfur emissions (e.g., the Amendments to the Clean Air Act in the US or the Second European Sulfur Protocol). Hence, regional sulfur emissions projected in IS92 are much higher than more recent scenarios that account for these legislative changes, particularly in the OECD countries (as also discussed by IPCC, 1995:155–156). The discussion below summarizes regional sulfur emissions trends for three representative regions: OECD-Europe, EEFSU, and China and Centrally Planned Asia (CPA).

### 2.6.1. *OECD-EUROPE*

Invariably, IS92 sulfur emissions for Europe increase (cf. Figure 3), not least because 1990 base year data are substantially overestimated in the IS92 scenarios. For 2020 projected emissions (including Canada) span the narrow range of 10.9 to 11.7 MtS and for 2050 an again narrow range of 10.2 to 11.9 MtS. The recent scenarios of the Commission of the European Communities (EC, 1996) indicate that sulfur emissions by 2020 will be between 64 to 77 percent below 1990 emissions levels, or between less than 2 to 3 MtS, compared to 8 in 1990. These numbers correspond to the levels of sulfur emissions as agreed in the Second Sulfur Protocol, amounting to 2.4 MtS for all countries in Western Europe by the year 2010. This European view is also confirmed by recent scenarios such as IIASA–WEC (1995), where emissions range between 1 to 3 MtS, consistent with the sulfur control scenarios developed with IA models (AIM, IMAGE, IIASA, and MiniCam).

### 2.6.2. *EEFSU*

The situation for the EEFSU region is very similar to that of OECD Europe (cf. Figure 4). IS92 project regional sulfur emissions between 17 and 22 MtS (compared to $< 15$ MtS in 1990) and between 12

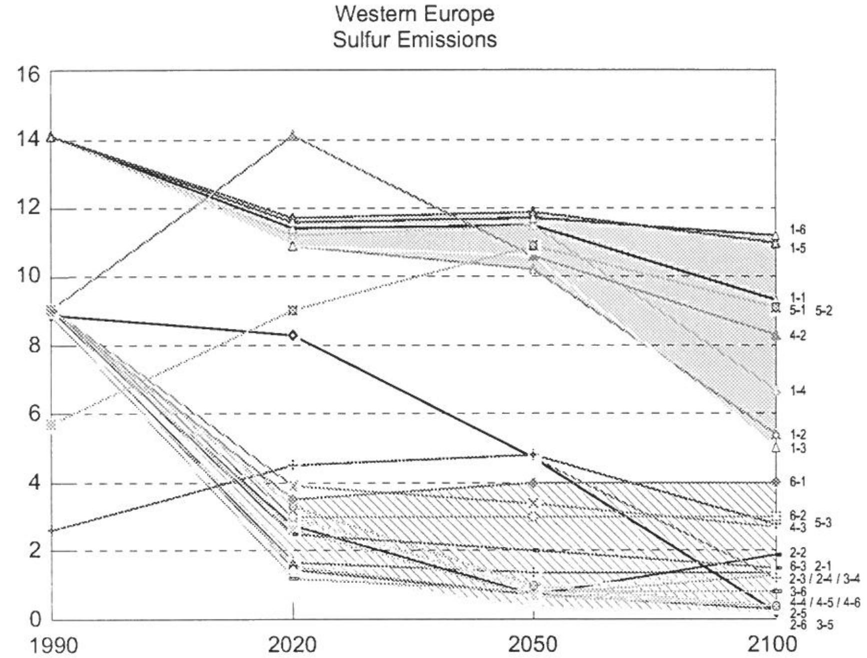


*Figure 3.* Sulfur emission scenarios for OECD-Europe (in MtS): a comparison of scenarios. Range of IS92 scenarios (grey) and range of sulfur control scenarios (cross-hatched). For explanation of scenario coding see the Appendix.

to 26 MtS by 2050. This compares to sulfur emissions projected by IIASA–WEC (1995, Nakicenovic *et al.*, 1998) of 5–8 and 2–12 MtS by 2020 and 2050 respectively, taking into account the drastic reduction in economic activity and energy use since the early 1990s. These baseline emissions compare to sulfur control scenarios in the range of 3–15 MtS by 2020 and 2–15 MtS by 2050. The higher range of sulfur control scenarios assume only partial fulfillment of the legal emissions reduction requirements under the Second European Sulfur Protocol (The protocol requires a 54 percent reduction in sulfur emissions compared to 1990 levels by the year 2010). Only the lowest of the IS92 scenarios (IS92c and IS92d) even approach that range.

### 2.6.3. *CPA (China and Centrally Planned Asia)*

For the CPA region (Figure 5), where no agreements for limiting sulfur emissions are in place yet, the IS92 series cover well the mid-range of future sulfur emissions scenarios, reaching up to 24 MtS by 2020, 49 MtS by 2050 and over 50 MtS (i.e. approaching current GLOBAL sulfur emissions) by 2100. In the meantime however, the ecological and economic impacts, such as damage to foodcrops, of such high emissions scenarios have been evaluated in more detail (cf. Section 3 below),

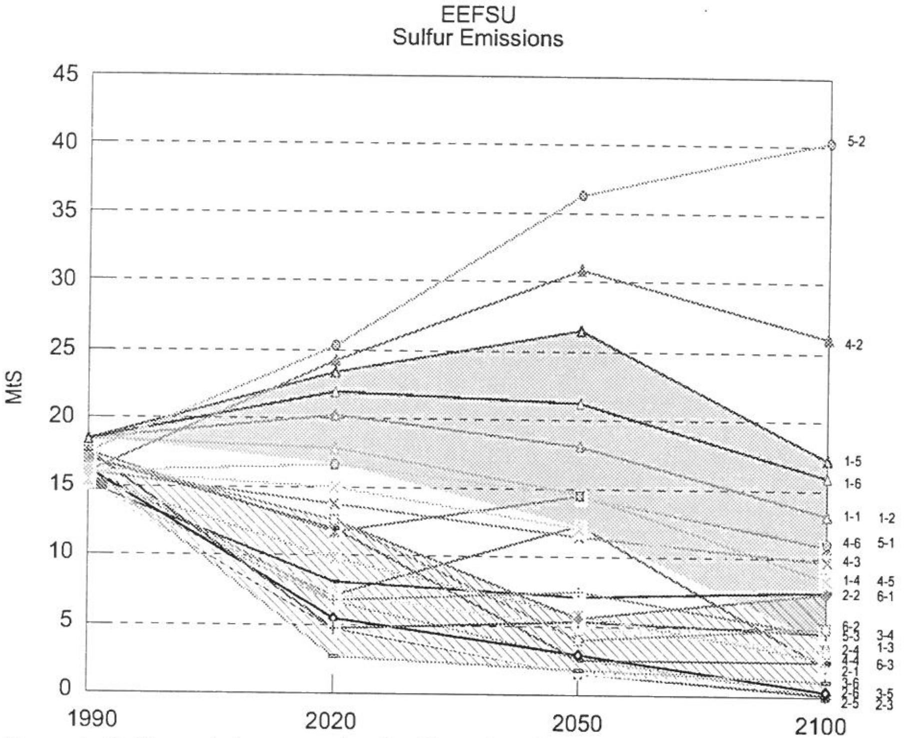


*Figure 4.* Sulfur emission scenarios for Central and Eastern Europe and the former USSR (in MtS): a comparison of scenarios. Range of IS92 scenarios (grey) and range of sulfur control scenarios (cross-hatched). For explanation of scenario coding see the Appendix.

suggesting that such high emission scenarios would be inconsistent with the projected food demands and a minimum degree of protection for human health, especially in urban areas, as well as natural and man-managed ecosystems. Representative sulfur control scenarios indicate a possible range of emissions of 10 to 30 MtS by 2020, and 7 to 30 MtS by 2050, depending on timing and scale of sulfur reduction efforts implemented. This range is more representative of the two low scenarios, IS92c and IS92d. Yet higher emission scenarios are representative of no sulfur control cases, which, in view of projected impacts on human health, food security, and ecosystems impacts, should be considered as hypothetical model calculations rather than scenarios with a higher degree of probability of actual occurrence.

### 2.6.4. *Summary*

*Regional sulfur emissions scenarios of IS92 do not reflect the impacts of recent international agreements and national legislation, such as the European Second Sulfur Protocol or the Clean Air Act Amendement in*

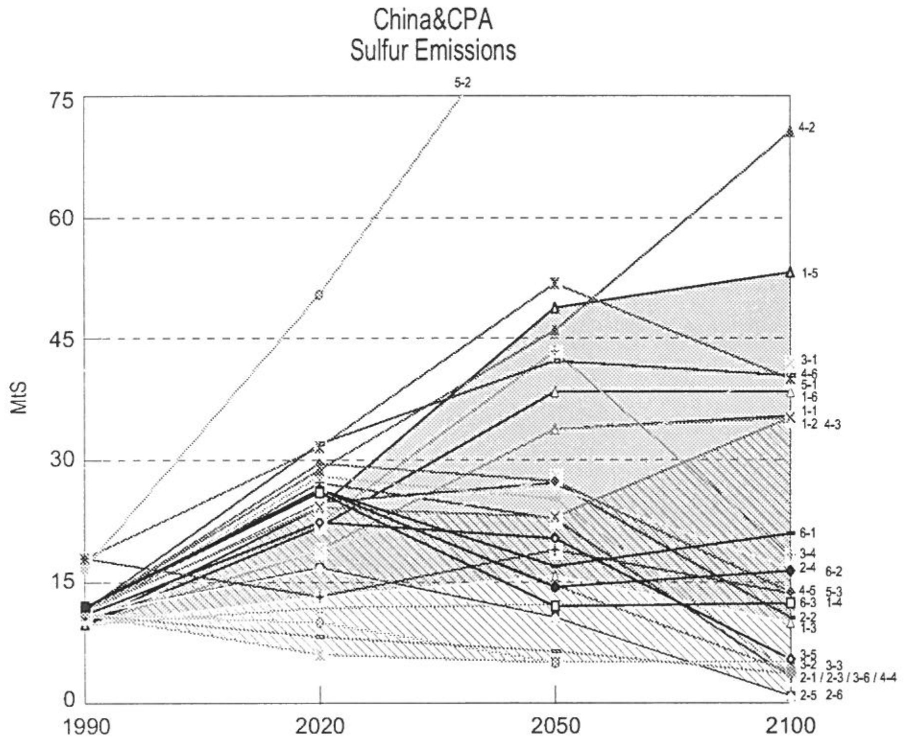


*Figure 5.* Sulfur emission scenarios for China and Centrally Planned Asia (in MtS): a comparison of scenarios. Range of IS92 scenarios (grey) and range of sulfur control scenarios (cross-hatched). For explanation of scenario coding see the Appendix.

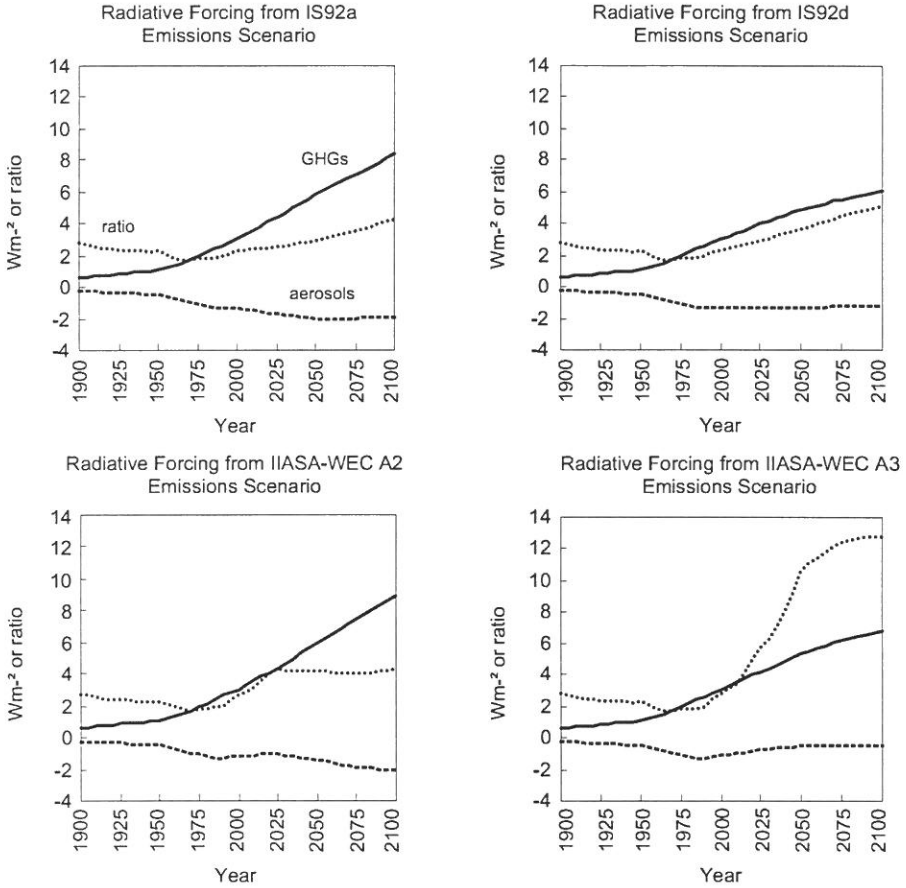
*North America. As a result, IS92 ANNEX-I countries sulfur emissions projected are much higher than in scenarios that take these recent changes into account. For EEFSU and North America sulfur emissions are likely to remain below levels as projected by the lowest IS92 scenarios, IS92c or IS92d; for OECD Europe, emissions are likely to remain substantially below these two scenarios, not least because IS92 base year emission data are overestimated by close to a factor of 2 for the OECD Europe region. Emissions in developing countries are also likely to follow at least IS92c or IS92d pathways in view of recent evidence of the high impacts of unabated high sulfur emissions on human health, food security, and ecosystems, particularly in Asia. As a simplified modeling assumption a persistently declining sulfur to carbon ratio is recommended across all scenarios, the timing and magnitude of which would be scenario specific between a range of minimum sulfur control and environmental protection to high degrees of sulfur control, e.g. following recent OECD sulfur emission trends also in other regions.*

## 3. Scientific (Sulfur) News Since IS92

The importance of aerosols, including those from sulfur emissions influencing the climate system that came to fore at the time of the preparation of the IS92 scenarios, is by now widely recognized (IPCC WGI, 1996). Simplified IA models are now available to model in detail sources of sulfur emissions and to assess their impacts on temperature changes (cooling) at the global level. Examples of such IA models include AIM, IIASA, IMAGE, and MiniCam, among others. Many of these models draw on simplified climate models such as MAGICC for estimation of the aggregate radiative forcing impacts of sulfate aerosols. (For a recent quantification see Subak *et al.*, 1997.) Some progress has also been made to quantify effects on regional climate. However, substantial uncertainties continue to persist regarding magnitude and the exact impacts of sulfate aerosol cooling on regional climate. Thus, the importance of sulfur emissions as input to climate models is larger than ever. Yet GCM runs are unavailable for a range of plausible sulfur emission scenarios. Therefore, regional impact assessments need to rely on outputs from simplified models that are just starting to become available.

Work within the Energy Modeling Forum (EMF-14) is in progress based on a 6-region disaggregation of sulfur emissions that can be combined with a wide range of future sulfur emissions scenarios for six world regions. Simplified climate model runs are also available for spatially gridded regional climate impacts for these scenarios (Schlesinger, 1997). In principle, the MAGICC/SCENGEN model is likewise able to deal with regionally different sulfur emissions for a disaggregation into three world regions. For the time being, however, only their impacts on *global* mean temperatures can be calculated. Regional climate impacts have not yet been implemented owing to the lack of appropriate GCM experiments (Hulme, 1997). The integrated assessment model IMAGE-2 has also been expanded to include a relatively simple regional coupling of sulfur emissions, sulfate air concentration, and the cooling effect of sulfate on climate (Alcamo *et al.*, 1995, Posch *et al.*, 1996).

Thus, a variety of simplified approaches exist on which regional climate assessment and impact studies can draw upon in principle to assess the differential impacts of alternative sulfur emission scenarios. Hulme (1997) argues, however, that especially for impact assessments one needs to consider that the cooling effect from sulfate aerosols is a *transient* phenomenon and that at the global level the maximum relative aerosol/GHG forcing already has been passed (cf. Figure 6, Hulme, 1997, and Subak *et al.*, 1997). Thus, considering that climate change and impact studies generally refer to distant future time horizons (mid-



Radiative Forcing from IS92a Emissions Scenario

Radiative Forcing from IS92d Emissions Scenario

Radiative Forcing from IIASA-WEC A2 Emissions Scenario

Radiative Forcing from IIASA-WEC A3 Emissions Scenario

*Figure 6.* GHG (solid lines) and sulfate aerosols (dashed lines) forcing obtained with the MAGICC model for three scenarios: IPCC IS92a and IIASA–WEC A2 and A3 scenarios. The ratio (i.e. relative forcing impact) of GHG to aerosl forcing (dotted lines) is also shown, illustrating the transient nature of the cooling effect of sulfate aerosols. Source: Subak *et al.*, 1997.

21st century), the immediate need to quantify the shorter-term effects of differential sulfate aerosol cooling effects appears less pressing, provided this transient "signal" would indeed slowly disappear throughout the 21st century under various scenarios of stepped up sulfur controls for reasons unrelated to climate change.

Such trends appear highly probable, considering continued sulfur reduction policies in the OECD and the likely emergence of similar trends in other regions toward the middle of the next century. Obviously, sulfur emissions profiles in the new IPCC scenarios need to be both plausible and consistent with the overall scenario storylines.[1] But out of consideration of recent trends, results from acidification impact studies, as well as the transient nature of the sulfate "cooling signal," it makes little sense to postulate hypothetical sulfur scenarios that could "compensate" permanently GHG-induced changes in radiative forcing. Hence, for climate impact assessment the focus should rather be on the long-term, where the anthropogenic signal on the climate system will be essentially a GHG forced pattern of climate change (Hulme, 1997). This releases pressure to choose a particular profile of the transient sulfur signal (sulfur emission profiles) emerging from the scenario exercise, as long as the long-term values (e.g., the S/C ratio) remain arguable, especially from a human health and ecological impact perspective. Transient scenarios could also remain consistent with the sulfur emission scenarios developed within the framework of short- to medium-term sulfur policy analysis. Initially, sulfur emissions could continue to rise, pass through a peak, in order to decline as progressively tighter emission standards are implemented.

Since the publication of the IS92 scenarios several detailed sulfur impact studies have become available that call into question the high sulfur emissions profiles assumed in the IS92 scenario exercise. In particular, recent studies have yielded new information on:

(a) implications in acidic deposition levels of high sulfur emissions scenarios such as IS92a (cf. Amann *et al.*, 1995, Posch *et al.*, 1996)

(b) aggregate ecosystems impacts, especially exceedence of critical loads for acidification (taking into account deposition levels and different buffering capacities of soils) (cf. Amann *et al.*, 1995, and Posch *et al.*, 1996)

(c) direct vegetation damage, particularly on foodcrops (Fischer and Rosenzweig, 1996).

These studies provide new information on the impacts of high concentrations and deposition of sulfur emissions above those extensively documented in the literature. (For a review cf. Crutzen and Graedel, 1986; WHO and UNEP, 1993; and WMO, 1997.) These studies assume particular importance, because they document environmental changes resulting from high emissions scenarios with the help of detailed representations of the numerous non-linear dose-response relationships at work between emissions, atmospheric concentrations, deposition, ecosystems sensitivity threshholds, and finally, impacts.

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[1] A scenario storyline is an overall qualitative description of the main causality links and driving forces of a possible future development path.

All recent studies agree that unabated high sulfur emissions along the lines of IS92a or above would yield high impacts not only for natural ecosystems and forests but also for economically important foodcrops and human health, especially in Asia, where emissions growth is projected to be particularly high. Magnitude and exact timing of impacts remain uncertain, indicating the need to explore a variety of short- to medium-term emission scenarios for sulfur control policy analysis. Nonetheless, the magnitude of sulfur emissions projected in "no control" scenarios over the long-term is such as to dwarf uncertainties on impact levels associated with short- to medium-term emission levels.

A representative result (based on Amann *et al.*, 1995) is shown in Figure 7 contrasting 1990 European sulfur deposition levels with those of Asia by 2050 from a high sulfur emission scenario (very close to IS92a). Sulfur deposition exceeding 5 grams per $m^2$ per year occurred in Europe in 1990 in an area at the border of the Czech Republic, Poland, and the former GDR, a region denoted as "black triangle," which, in view of its ecological impacts, has been officially designated by UNEP as and "ecological disaster zone". In a scenario like IS92a similar high sulfur deposition would occur over more than half of Eastern China, large parts of South Korea, and some smaller parts of Thailand and Southern Japan.

In such a scenario significant impacts on agricultural crops in the region would emerge. In a detailed study Fischer and Rosenzweig (1996) have assessed the combined impacts of climate change and acidification of agricultural crops in Asia for a scenario similar to IS92a. The overall conclusion of the study was that the projected likely regional climate change would largely benefit agricultural output in China, whereas it would lower agricultural productivity on the Indian subcontinent, with the combined effect of projected temperature and precipitation changes would have differential impacts across various crops and subregions. However, the projected high levels of acidic deposition would reduce agricultural output to such an extent as to more than offset any possible beneficial impacts of regional climate change. This is primarily due to the fact that sulfur and nitrogen deposition, while acting as fertilizer for plant growth at lower deposition levels, negatively affects plant growth at higher deposition levels. These threshhold levels are projected to be surpassed between 2020 to 2050 for all major Asian foodcrops in a scenario like IS92a.

These results strongly suggest that impacts are so substantial as to preclude any high sulfur emissions scenario in the range of IS92a or even above. Representative sulfur control scenarios (Amann *et al.*, 1995, Posch *et al.*, 1996) rather suggest a range of global emissions below 100 MtS by 2050 and below 120 MtS by 2100.

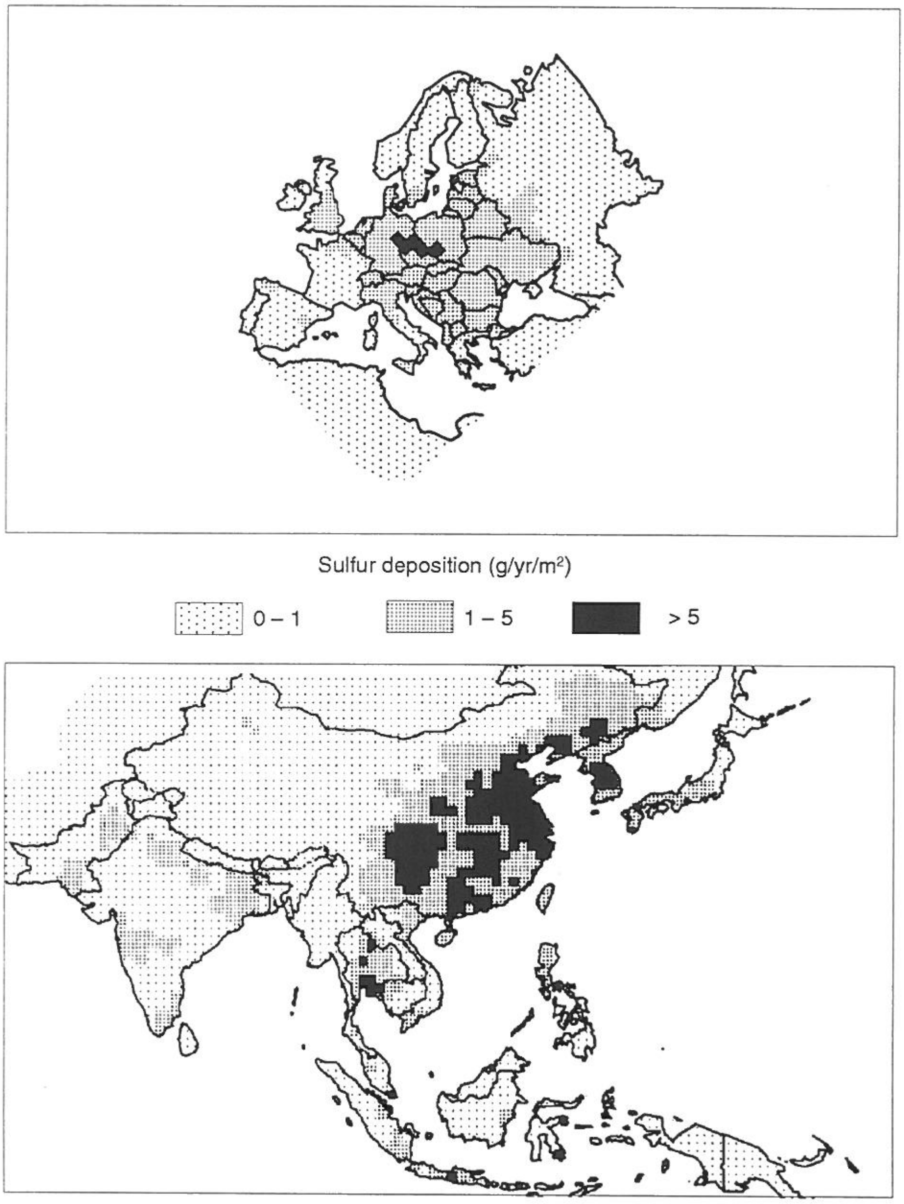

*Figure 7.* Current sulfur deposition in Europe (top) and projections for a high growth, coal-intensive scenario similar to IS92a for Asia in 2020 (bottom) in grams sulfur (S) per m$^2$. Source: Grübler, 1998 based on Amann *et al.*, 1995.

Increasingly, energy sector and integrated assessment models are able to link regional acidification models with simplified climate models, enabling joint analysis of sulfur and climate policies and impacts. Examples include the IMAGE model (Posch et al., 1996) and the IIASA model (Rogner and Nakicenovic, 1996) that are linked with the acidification model RAINS for Europe and Asia, or the AIM (Morita *et al.*, 1994) model for Asia. These models extend earlier energy sector models that dealt with a comparative costs assessment of isolated sulfur and carbon reductions, and joint mitigation respectively, such as the OECD GREEN model (Complainville and Martins, 1994). The state of knowledge and availability of models to study the joint benefits of sulfur and carbon emission reductions was reviewed in the 1995 IPCC WG III report (IPCC, 1996:215–218) and is expanding rapidly (cf. CIRED *et al.*, 1997, Nakicenovic *et al.*, 1997).

## 4. Scenario Driving Forces and Relationships

### 4.1. DRIVERS OF SULFUR EMISSIONS

There are two major sets of driving force variable that influence future sulfur emissions: (1) Level and structure of energy supply and end use, and (2) degrees of sulfur control assumed. (Because of the dominance of energy related sulfur emissions, they receive particular attention here. Industrial sources can be included in the scenarios based on much a simpler driving force models, e.g., coupling to industrial output.)

Historically both clusters of variables are linked to the level of economic development. With increasing affluence, energy use per capita rises and its structure changes away from the use of traditional solid fuels (fuelwood and coal). This structural shift, combined with greater emphasis on urban air quality that goes along with rising incomes, results in a kind of inverted U-shaped pattern of sulfur emissions/concentrations rising initially (with growing per capita energy use), passing through a maximum, and then declines at higher income levels owing to structural change in the end-use fuel mix and also control measures for large point sources. This pattern emerges also from the literature on environmental Kuznets curves (cf. e.g. World Bank, 1992, or IIASA–WEC, 1995) and is corroborated by both longitudinal and cross-sectional empirical data (cf. Figures 8 and 9).

Thus, in the process of industrialization and economic development, emissions and ambient concentrations initially rise, pass through a maximum, and decline thereafter with rising per capita incomes and the resulting preference for cleaner end-use fuels, valuation of clean environments, etc. Typically, ambient concentration levels for $SO_2$ reach

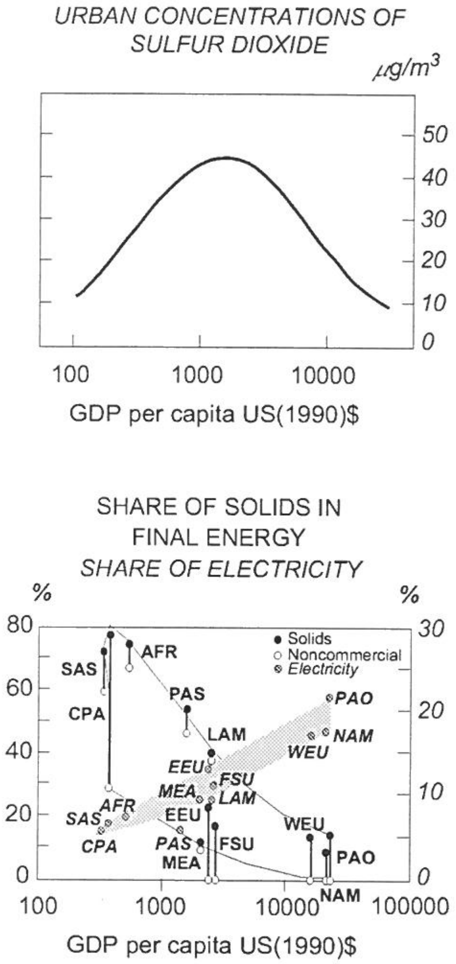

*Figure 8.* Urban concentration of sulfur dioxide (top) and changing structure of final energy mix as a fucntion of per capita income (bottom). Source: Nakicenovic *et al.*, 1998, based on World Bank, 1992, and IIASA–WEC, 1995.

their peak at levels around 2000 \$/capita income, and decline thereafter (Figures 8 and 9). A comparison of the situation in the 1970s to that of mid- to late-1980s confirms this pattern. Indeed, ambient concentrations in low income countries have increased, whereas they have decreased in middle- and high-income countries. Equally striking is the decline in the difference between the most polluted and the cleanest cities in high income countries over this period.

Initially, the decline in sulfur pollution levels, at least historically, was simply achieved by dispersion of pollutants (tall stacks policy). Subsequently, actual emissions started to decline, both as a result of structural change (substitution of solids by gas and electricity as end

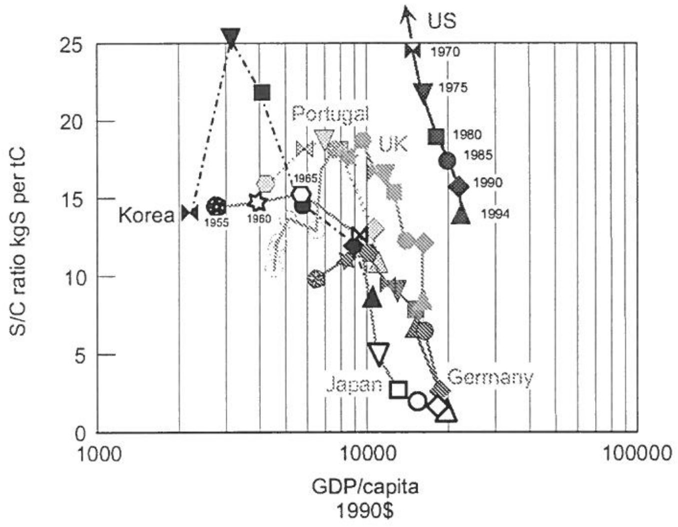

*Figure 9.* Ratio of sulfur to carbon emissions (in kg S per ton C) as a function of GDP per capita (in constant 1990$ per capita) for selected OECD countries, 1970–1994. Data sources: GDP: Maddison, 1995; carbon emissions CDIAC, 1997; sulfur emissions: Mylona, 1993 and 1996, EPA, 1995, Tonooka, 1998 (Japan), Korean Energy Economics Institute, 1998 (Korea).

use fuels, cf. Figure 8) and sulfur reduction measures (oil product desulfurization and flue gas scrubbing of large point sources). This structural change is best visible in time series of sulfur to carbon emissions ratios (Figure 9). Historically, in the early industrializing countries (UK, Germany, France, USA) this trend reversal occurred at income levels around 10,000 $/capita. Later industrializing countries, most notably Japan, experienced a similar trend reversal at already lower income level of some 6,000 $/capita; a similar trend break occurred in South Korea (a typical "newly industrializing" country) at income levels of around 3,000 $/capita.

In terms of scenario driving force variables, sulfur emission profiles are therefore linked to both income and time, as well as to policy measures implemented. The linkage to income is explained through the structural change in favor of cleaner and more convenient energy forms that goes along with income growth (Grübler and Nakicenovic, 1996), as well as the increasing valuation of clean environments (indoor air and urban air), which again is linked to rising incomes. In other words, willingness and ability to pay for environmental amenities are closely linked. Time enters as a scenario driving force in form of a learning externality (frequently referred to as technological "leapfrogging", cf. Goldemberg, 1991). Late industrializers undergo a similar structural change as early industrializers, but generally much faster and with the availability of more modern and better technology. This explains why the peak in relative sulfur emissions occurred at lower income levels in Japan compared to the UK, and at yet lower income levels in Korea compared to Japan and the UK. Finally, of course, active sulfur control measures constitute an important driving force variable, as do general environmental policies that have an indirect emissions reduction effect, e.g., through induced energy conservation and/or structural change.

### 4.2. SULFUR EMISSION SCENARIOS

Future sulfur emissions are, ceteris paribus, highest in scenarios of high demand growth, rapid resource depletion, limited technological change and absence of sulfur control measures, especially outside OECD countries. In terms of energy supply structures, such scenarios imply a massive use of coal, including synfuel production. Typical examples would include the IS92e and IS92f scenarios. Up to ca. 2050 sulfur emissions in such scenarios roughly grow in line with fossil fuel use and resulting carbon emissions, i.e. a roughly constant sulfur to carbon emissions ratio. Post 2050, still in absence of sulfur control measures, growth rates of sulfur emissions start to fall short of growth in fossil fuel use owing to the internal technology logic of synfuel production: synfuel production requires prior coal conversion (e.g., gasification) and removal of sulfur prior to further conversion to synliquids. Ceteris paribus, therefore, sulfur emissions relative to those of carbon decline even without any active sulfur control measures assumed.

Sulfur emissions are lower in scenarios with: (1) lower demand; (2) more ample resource availability (especially natural gas); (3) higher rates of technological change (especially for non-fossil energy technologies); and (4) extent and timing of sulfur control measures especially outside OECD countries (itself function of income effects and projected environmental impacts like acidification); and finally, (5) level of other environmental control measures and valuation of environmental goods (e.g., sulfur emissions are also lower in scenarios imposing limits on particulate and GHG emissions).

A scenario taxonomy along the dimensions of demand, resource availability, and technological change is in any case necessary to respond to the critique on the IS92 series that these important driving forces were not varied appropriately to reflect uncertainty as well as scientific knowledge and empirical evidence. They form part of the overall scenario design process and the scenario "storylines," and need not to be addressed specifically in this paper on sulfur emissions. Separate "sulfur stories" can be developed in addition, based on overall relationships between sulfur emissions and levels of affluence, industrial structure, etc., existence (or absence of environmental policies) etc. Three such illustrative sulfur control "stories" and their embedding within the overall scenario taxonomy are illustrated below, based on recently published and ongoing scenario work.

A key variable remains the timing and extent of sulfur control measures to be assumed for the new scenarios, independent of whether they are driven by income and structural change effects, or by environmental policy. First, the scenarios need to reflect recent trends and changes in actual policies implemented. As noted above, IS92 did not take full account of recent environmental legislation in North America, the Second European Sulfur Protocol, nor the effects of economic restructuring in Central and Eastern Europe, which have lead to drastic declines in sulfur emissions. New scenarios need to reflect these recent developments. Recent scenarios are available, and corresponding assumptions can simply be taken from the reviewed literature (Amann *et al.*, 1995, IIASA–WEC, 1995, Posch *et al.*, 1996) as summarized above.

Second, future sulfur emission trajectories also need to reflect recent scientific findings, in particular the very large local and regional impacts on agricultural crops and ecosystems of unabated high sulfur emission scenarios, particularly in Asia. Therefore, all scenarios should assume faster and deeper reductions in sulfur emissions outside OECD countries than were assumed for IS92 in light of this recent scientific evidence. This is important for both scenario plausibility and for scenario consistency. The exact timing and extent of sulfur control measures would then be scenario dependent. Furthermore, no specific reference to individual policy measures needs to be made to avoid normative policy elements, or recommendations, in the IPCC scenario exercise. Reference to general emission control measures that would be feasible in various regions would be sufficient to justify particular sulfur control scenarios. Alternatively, reduction profiles could be adopted from existing sulfur reduction scenarios in the scientific literature, e.g. the control scenarios evaluated with the AIM, IIASA, and IMAGE models.

As a summary, it is suggested that:

1. No scenario assumes absence of sulfur control policies;
2. Assumed OECD and EEFSU emission profiles reflect most recent developments, resulting in substantial emissions reductions;
3. The timing and extent of sulfur control measures outside OECD reflects recent findings of increasing valuation of environmental quality with rising income levels and the large environmental and economic impacts of non-intervention. In particular all scenarios would assume

sulfur control measures beyond the ones assumed in IS92 but with timing and extent being scenario dependent.

Implementation of emissions reductions would be either a function of particular income level threshholds assumed in the scenarios or would simply be time dependent, e.g., the timing is varied between 2020 to (latest) 2050, and the degree of abatement varied in conformity with the income levels postulated in the scenarios and in due consideration of the results of impact model calculations. E.g., a minimum control level would protect production levels of important foodcrops, whereas a maximum protection level would minimize exceedance of critical loads in order to protect also natural ecosystems.

As a convenient and simple shorthand to structure the discussion and quantification of sulfur control scenarios, the simple metric of global and regional sulfur to carbon emission ratios is suggested.

## 5. Sulfur control scenarios: An overview of the literature

The following section provides an overview of recent sulfur mitigation scenario analyses. Three different approaches are illustrated, ranging from ecological targets (critical loads), to "pollutant burden" and income driven approaches for determining sulfur emission scenarios and reduction targets.

### 5.1. Ecological Targets

Amann *et al.*, (1995) and Nakicenovic *et al.*, (1997) report on an integrated assessment exercise of the combined climate change and acidification impacts of long-term emission scenarios. As a first step, the analysis drew up a reference scenario with unabated emissions (cf. Scenario F in Figures 1 to 5) As a second step, alternative scenarios of control of various pollutants were developed. The discussion here focuses on the sulfur control scenario (labeled FS scenario in Figure 1) Four different approaches were followed to determine regionally specific sulfur emissions reduction profiles. For North America, simply the regulation as postulated by the Clean Air Act of 1990 (Title IV requiring a reduction of emissions by 10 million tons $SO_2$) was adopted and imposed as a medium term (2015) emission constraint. Thereafter, emissions were assumed to remain at least at that level.

For Europe and Asia, where detailed model linkages between energy sector and regional acidification models were developed within the framework of the study, the RAINS model and the concept of critical acidification loads was adopted to determine sulfur reduction levels.

For Asia, critical loads as evaluated by Foell *et al.*, (1995) using a steady mass balance approach for different ecosystems (cf. Hettelingh *et al.*, 1995) were adopted. Recognizing the high costs of achieving complete ecosystems protection in a region where emissions are bound to rise markedly, a 25th percentile critical load was defined, i.e. a level of deposition where, given the critical load estimates of ecosystems sensitivity to acidic deposition 25 percent of ecosystems in a particular area would be left unprotected, but 75 percent would remain protected. In addition, exceedence of the thus determined critical loads up to a level of 2 mg $SO_2$ per $m^2$ meter were allowed in isolated "hot spots", defined at the level of grid cells with a spatial resolution of 150 times 150 km (i.e. up to 2050, exceedence of critical loads in individual grid cells as allowed up to a level of 2 $mg/m^2$, provided that the threshhold level was also not exceeded in adjacent areas, provoking thus large-scale ecosystems deterioration. After 2050, deposition levels had to remain below above defined 25th percentile threshhold). Using this approach, labeled "minimum level of ecosystems protection," the RAINS model was used to determine maximum allowable sulfur emissions levels for the region. In the resulting sulfur reduction scenario, emissions in Asia range below 11 MtS by 2020 and 2050 and are further reduced to less than 7 MtS by 2100, compared to projected emission levels in the unabated reference scenario of some 30 MtS by 2020 and 60 MtS by 2050.

For Europe, a more sophisticated approach was adopted, defining critical loads on basis of the joint effects of sulfur and nitrogen deposition, as developed by the Working Group on Effects under the auspices of the UN-ECE Convention on Long-Range Transboundary Air pollution (cf. Posch *et al.*, 1995). Critical loads were defined on the basis of a cumulative distribution function for all critical loads within each grid cell, setting the target value at the 5th percentile. In other words, a maximum of 5 percent of ecosystems would remain unprotected, but 95 percent remain protected. This more stringent assumption reflects the target values underlying the Second Protocol of sulfur emission reductions in Europe. As a result, the maximum allowable sulfur emissions levels in the region (comprising Western and Eastern Europe plus the European part of the former USSR) were determined with help of the RAINS model at below 4 MtS by 2020 and 3 MtS by 2050 (compared to some 16 MtS in 1990 and 12 MtS in 1994).

For all other regions where information on ecosystems vulnerability and models of acidic deposition are unavailable a simple analog approach to the one adopted for Asia was used. Maximum allowable sulfur emission levels were calculated based on the sulfur emission density per unit country area of the sulfur control scenario developed for Asia.

The resulting global sulfur emission reduction scenario projects global sulfur emissions of 30 MtS by 2020 and some 20 MtS by 2050. With exception for the more stringent assumptions deployed for Europe following the Second Protocol, the approach is considered by Nakicenovic et al. (1997) as a definitively cautious scenario of minimum ecosystems protection rather than an extreme policy scenario.

### 5.2. "POLLUTANT BURDEN" SULFUR CONTROL SCENARIOS

A "pollutant burden" approach was taken by Alcamo *et al.* (1997) to generate $SO_2$ emissions scenarios for 13 world regions up to 2100. The two basic assumptions of this analysis were: (1) The point in time when emission reductions begin: developing regions are assumed to begin to reduce sulfur dioxide emissions when their "pollutant burden" reaches the same magnitude as the pollutant burden of industrialized regions at the time when they began to reduce their emissions; (2) The tempo of emission reduction: once emission reductions begin in developing regions, they are assumed to proceed at a pace similar to that observed in industrialized regions.

The annual rate of emissions of sulfur dioxide per unit area is used as an indicator of pollutant burden. Developing regions are assumed to begin to reduce their emissions when the emission flux over a critical percentage of their land area exceeds a critical level of emission flux. Sulfur emission fluxes are used as an indicator of pollutant burden, rather than more direct measures such as sulfur deposition or sulfur dioxide air concentration, because models for calculating deposition and concentration are not available outside North America, Europe, or Asia. By contrast, estimates are available for the temporal trends and gridded patterns of sulfur emissions globally. Hence, for global consistency, emission fluxes are used as a surrogate of pollutant burden.

Once emission reductions begin, the reductions are assumed to follow a logistic trend over the long run. The rate of this logistic trend is estimated from current trends in industrialized regions. Somewhat different assumptions are required regarding the start time and rate of emissions reductions in industrialized regions, because they have already begun reducing emissions. Their current policies to decrease emissions are assumed to continue over the long run by extrapolating their reduction trend with a logistic function.

Since all parameters in this analysis – the critical pollutant burden, the critical area, and the rate of emissions reductions are highly uncertain, the authors used probability distributions rather than discrete numbers to describe them. The authors report results for the mean and 5th and 95th percentiles, respectively, based on a simulation of 50 scenarios. It remains unclear however, on which basis these probability distributions were derived. Moreover, in their analysis Alcamo *et al.* also took into account the uncertainty of future population and economic growth and their effects on estimated emissions. These input uncertainties were combined and propagated through an emissions model (IMAGE2) by using stochastic simulations, and resulting distributions of future sulfur emissions were computed for 13 world regions.

Using this approach Alcamo *et al.* (1997) arrive at a median global sulfur projection of some 90 MtS by 2020 and 2050, a level that would fall to below 60 MtS by 2100. The (low) 5th percentile scenario yields 75, 50, and 20 MtS by 2020, 2050, and 2100 respectively, whereas the (high) 95th percentile yields some 100 MtS by 2020, and 120 MtS by 2050 and 2100. It is interesting to note that the mean scenario falls in the range of the two low demand IS92 scenarios, IS92c and IS92d, whereas the high emission profile of the 95th percentile range remains significantly below any other IS92 scenario, including IS92a. Assuming that Alcamo *et al.*'s probability distributions reflect subjective expert judgment, there is thus a chance of less than 5 percent that sulfur emissions would indeed reach levels as high as depicted in IS92a, not to mention IS92e.

This approach has the advantage of explicitly taking into account one of the driving forces that stimulate policies ("pollutant burden") as well as the change in these forces over time. It also provides for estimates of confidence intervals of future emissions that represent some of the uncertainties for making long term estimates. Among its simplifications is that it assumes that all societies respond similarly to high levels of sulfur emissions. In addition, the model used does not take fully into account the fact that emission reductions will also be achieved by structural change in the fuel mix towards low and zero-sulfur fuels.

### 5.3. SULFUR CONTROL SCENARIOS BASED ON ENVIRONMENTAL KUZNETS CURVES

In a recent study Smith *et al.* (1998) have deployed the concept of environmental Kuznets curves to derive alternative scenarios of future sulfur control levels. In a first step of the analysis a high growth, coal intensive scenario similar to IS92a was developed using the MiniCam model. Subsequently three alternative sulfur emission control scenarios were developed. All scenarios assume that levels of sulfur emissions controls are a function of the degree of economic development, measured by GDP per capita (expressed in purchasing power parities). Starting from low levels of emissions control, the percentage of emissions controlled in developing countries was assumed to increase along a logistic function to some 42 percent at GDP per capita levels of 23,000 $, in order to rise asymtotically to between 75 and 95 percent, with 85 percent being assumed for their "business as usual" (BAU) scenario (cf. scenarios PNL-75%, PNL-BAU, and PNL-95% in Figures 1 to 5). For CPA a somewhat accelerated introduction of emissions control levels was assumed.

The approach is somewhat similar to the "pollutant burden" approach discussed above. The quantifications of Smith *et al.* (1998) also include industrial emission sources in addition to the dominant energy sector emissions. Nonetheless, the empirical basis for estimating the shape of the particular emission control levels as a function of per capita income is not discussed in the paper. Even if the assumed control levels as a function of per capita income can be interpreted as rather pessimistic when compared to the historical experience of Western Europe or Japan, the approach provides a useful upper boundary estimate of future sulfur emissions based on an environmental Kuznets curve approach.

The results for global sulfur emissions are consistent with those obtained with alternative approaches. Even in the most pessimistic case, global sulfur emissions rise to some 80 MtS by 2020 and decline to some 65 MtS by 2050 (and 2100), which is significantly below sulfur emission levels usually assumed in BAU-type scenarios such as IS92a. In all control level scenarios global emissions by 2020 do not differ markedly (75 MtS). Over the longer-term the spread is larger as a function of the ultimate asymptotic control levels assumed. In the high control case emissions are 50 MtS by 2050 and about 30 MtS by 2100.

### 5.4. A SCENARIO TAXONOMY FOR SULFUR EMISSIONS

As discussed above, alternative approaches have recently been published in the literature describing possible driving forces and magnitudes of sulfur emissions. Recent evidence also suggests that sulfur emissions will become increasingly controlled outside the OECD region as well to mitigate negative impacts on human health, crop productivity, and ecosystems. Rate and timing of such sulfur emission reduction efforts are evidently scenario dependent. For instance, a minimum control level would protect human health and production levels of important foodcrops, whereas a maximum protection level would minimize exceedance of critical loads in order to also protect natural ecosystems. Implementation of sulfur control policies can then be either a function of the scenario specific impact minimization, or alternatively, could be approximated as a function of particular income level threshholds assumed in the scenarios. In a most simple case, sulfur control levels could also be assumed to be time dependent, e.g., the timing is varied between 2020 to (latest) 2050, and the degree of abatement varied in conformity with the income levels postulated in the scenarios and in due consideration of the results of impact model calculations. For instance, in a high growth scenario without any direct environmental policies, sulfur emissions could be defined entirely based on income effects only, peaking at income levels of some 3,000 $/capita, or alternatively, at some 6,000 $/capita in a scenario of more modest economic growth, without resorting to any specific measures or policy assumptions concerning sulfur emissions. Alternatively, sulfur emissions control could also be included in general environmental policies (e.g., on water quality, urban traffic related pollutants, forest protection etc.) assumed to be characteristic of a particular scenario "storyline".

Based on the current draft versions of the scenario storylines, the following scenario taxonomy with respect to sulfur emissions is suggested in Table IV (for comparison: 1990 emission levels from anthropogenic sources totaled some 75 MtS). An entirely hypothetical sulfur emissions scenario without any control measures (IS92a or higher) could be developed, as additional scenario variant, if required for the purposes of climate models or for shorter-term sulfur impact analysis (e.g., a high sulfur emission sub-variant of the fossil fuel variant of the high-growth scenario A1).

## 6. Data requirements

The most obvious data requirement is comprehensive sulfur emissions by major source category (anthropogenic and natural, energy sector and other industrial sources). Here the data model of the IS92 scenarios appears appropriate and only requires a reassessment in view of most recent data of regional emissions (cf. Section 1 above).

Evidently, the scenarios need to incorporate most recent data and trends of sulfur emissions by region, instead of simply relying on increasingly outdated global sulfur emission inventories. For example, as a result of a major World Bank study on acid rain in Asia, improved national and regional sulfur emissions inventories have become available (Foell *et al.*, 1995). Improved recent data also exist for North America and Europe (including the European part of the former USSR). Improved emissions inventories outside North America, Europe, and Asia (excluding Oceania, for which only sparse data seems to be available)

Table IV. Suggested taxonomy of new IPCC sulfur emissions scenarios, in MtS.

| Scenario | Driving force of sulfur controls | Control level | Illustrative global emissions, MtS by 2020 | Illustrative global emissions, MtS by 2050 |
|---|---|---|---|---|
| A1 | income driven | high | ≈50 | ≈50 |
| A2 | region specific:<br>income, and pollution burden | moderate (DCs)<br>medium (OECD) | <100 | <80 |
| B1 | ecologically driven | very high | ≈30 | ≈20 |
| B2 | ecological, and pollution burden | high (but delayed) | <50 | ≈30 |

*Note*: Four classes of scenarios have tentatively been designated. Within each scenario there are a number of subscenarios embedded within the overall scenario storylines. The four main scenario families include:
A1: rapid development leading to high incomes, high productivity, and low population (A1 is subdivided into a number of technological bifurcation subscenarios)
A2: fragmented world, with regional drive for self-suffciency and heterogenous, high fertility (i.e. high population)
B1: emergence of new values and resulting focus on quality of life: low fertility, high valuation of environmental amenities and rapid dematerialization.
B2: intermediate scenario (imperfect realization of Scenarios A1 and B1)

have not been made available since publication of IS92. As a result, models and scenarios continue to rely on rough estimates only, largely based on approximate mass and sulfur balance approaches in the world regions for the Middle East, Southern Africa, and Latin America. A first order assessment has been made in comparing all major emissions inventories for these regions, and "best available inventory" base year data (for 1990) have been suggested above for use and verification by the modeling community in the open scenario quantification process.

A more difficult question concerns spatial disaggregation. Independent from the question of which formal models are being used to check for scenario consistency, the greatest spatial detail currently available in driving force models with global coverage is at the level of world regions (typically around 10, but going up to 20 world regions). Both climate and acidification models require inputs at finer spatial resolution. It is unclear at present what would constitute a "minimum" or "desirable" level of spatial disaggregation for the variety of user communities of new IPCC scenarios. Existing model links (like with the RAINS model) could be used in some regions like Europe and Asia to generate spatially highly disaggregated sulfur emission and deposition maps as inputs for climate models and for impact assessment studies (e.g., for agricultural crop yield models). In their most advanced versions the model links even incorporate regionalized differential growth trends and thus improve on the standard practice of renormalizing base year spatial emission and deposition patterns linearly with a particular sulfur emissions scenario. However, in view of the time constraints involved in the scenario exercise, it seems impossible to ask modeling teams to perform such elaborate calculations. At the same time, simplified climate models like MAGICC/SCENGEN or the model runs performed by Michael Schlesinger for the EMF 14 require only a high degree of spatial detail (3 to 6 world regions). Therefore, from the perspective of sulfur emissions scenarios and their potential user communities a pragmatic two step approach appears desirable: use higher spatial resolutions that at least separate the northern from the southern hemisphere, single out the critical region of Asia in the initial scenario exercise, and ask modeling teams to provide greater geographical detail with their models in the open scenario process.

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Table A-I. Appendix: Overview of sulfur scenarios analyzed.

| No. | Scenario | Reference | Specific sulfur controls | Global emissions, MtS | |
|---|---|---|---|---|---|
| | | | | 2050 | 2100 |
| 1-1 | IS92a | Pepper *et al.*, 1992 | ? | 150 | 144 |
| 1-2 | IS92b | Pepper *et al.*, 1992 | ? | 146 | 139 |
| 1-3 | IS92c | Pepper *et al.*, 1992 | ? | 90 | 52 |
| 1-4 | IS92d | Pepper *et al.*, 1992 | ? | 77 | 63 |
| 1-5 | IS92e | Pepper *et al.*, 1992 | ? | 204 | 229 |
| 1-6 | IS92f | Pepper *et al.*, 1992 | ? | 171 | 179 |
| 2-1 | WEC-A1 | Nakicenovic *et al.*, 1998 | yes | 54 | 23 |
| 2-2 | WEC-A2 | Nakicenovic *et al.*, 1998 | yes | 64 | 55 |
| 2-3 | WEC-A3 | Nakicenovic *et al.*, 1998 | yes | 45 | 9 |
| 2-4 | WEC-B | Nakicenovic *et al.*, 1998 | yes | 55 | 58 |
| 2-5 | WEC-C1 | Nakicenovic *et al.*, 1998 | yes | 22 | 7 |
| 2-6 | WEC-C2 | Nakicenovic *et al.*, 1998 | yes | 22 | 5 |
| 3-1 | IIASA-HER | Rogner & Nakicenovic, 1996 | no | 167 | 214 |
| 3-2 | IIASA-MIS | Rogner & Nakicenovic, 1996 | yes | 36 | 38 |
| 3-3 | IIASA-MOM | Rogner & Nakicenovic, 1996 | yes | 36 | 38 |
| 3-4 | IIASA-F | Nakicenovic *et al.*, 1997 | no | 128 | 74 |
| 3-5 | IIASA-FC | Nakicenovic *et al.*, 1997 | no | 68 | 26 |
| 3-6 | IIASA-FS | Nakicenovic *et al.*, 1997 | yes | 22 | 15 |
| 3-7 | IIASA-FSR | Nakicenovic *et al.*, 1997 | yes | 22 | 15 |
| 4-1 | IMAGE-CW | Posch *et al.*, 1996 | no | 130 | 166 |
| 4-2 | IMAGE-A | Posch *et al.*, 1996 | no | 180 | 253 |
| 4-3 | IMAGE-S50 | Posch *et al.*, 1996 | yes | 82 | 120 |
| 4-4 | IMAGE-PB_5% | Alcamo *et al.*, 1997 | yes | 52 | 18 |
| 4-5 | IMAGE-PB_M | Alcamo *et al.*, 1997 | yes | 89 | 57 |
| 4-6 | IMAGE-PB_95% | Alcamo *et al.*, 1997 | yes | 121 | 121 |
| 5-1 | AIM-pl2 | Morita *et al.*, 1994 | ? | 134 | 125 |
| 5-2 | AIM-pl3 | Morita *et al.*, 1994 | ? | 289 | 443 |
| 5-3 | AIM-pl4 | Morita *et al.*, 1994 | yes | 59 | 46 |
| 6-1 | PNL-75% | Smith *et al.*, 1998 | yes | 68 | 66 |
| 6-2 | PNL-BAU% | Smith *et al.*, 1998 | yes | 59 | 49 |
| 6-3 | PNL-95% | Smith *et al.*, 1998 | yes | 51 | 31 |