Historical evolution of radiative forcing of climate

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Abstract

We have compiled the evolution of the radiative forcing for several mechanisms based on our radiative transfer models using a variety of information sources to establish time histories. The anthropogenic forcing mechanisms considered are well-mixed greenhouse gases, ozone, and tropospheric aerosols (direct and indirect effect). The natural forcing mechanisms taken into account are the radiative effects of solar irradiance variation and particles of volcanic origin. In general there has been an increase in the radiative forcing during the 20th century. The exception is a decline in the radiative forcing in the 1945–1970 period. We have found that the evolution of anthropogenic particle emissions in the same period may have been a major cause of this decline in the forcing. We have discussed uncertainties in the various forcings and their evolution. The uncertainties are large for many forcing mechanisms, especially the impact of anthropogenic aerosols. In particular the indirect effect of aerosols on clouds is difficult to quantify. Several evolutions of their effect may have been possible, strongly influencing the evolution of the total anthropogenic radiative forcing. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

A large number of different climate forcing mechanisms may influence the climate (IPCC, 1996a; Hansen et al., 1998; Shine and Forster, 1999). The external climate forcing mechanisms are of both natural and anthropogenic origin. The complexity and uncertainties of the forcing mechanisms vary substantially. For some of the radiative forcing mechanisms observations of high quality can be used to estimate their change, whereas for other components their change must almost entirely rely on model experiments. Hansen et al. (1997) have shown that radiative forcing is a valuable concept for prediction of surface temperature change and in particular for comparative studies of different forcings.

Hansen et al. (1993) established an evolution of the radiative forcing since 1850. They considered well-mixed greenhouse gases, stratospheric ozone, direct and indirect effects of tropospheric aerosols as well as changes in the total solar irradiance and contributions from volcanoes. Since their paper, there has been new work in many of these fields, in particular regarding the radiative forcing due to tropospheric aerosols. Wigley et al. (1997) provided another evolution of the radiative forcing including well-mixed greenhouse gases, direct and indirect effects of tropospheric aerosols as well as changes in solar irradiance.

The General Circulation Models (GCMs) are used to study not only the future climate, but also the climate of the past (Tett et al., 1999; Delworth and Knutson, 2000). This is important in validation of the GCMs and in studying the interplay between the many processes that are coupled within the climate system. It is evident that several forcing mechanisms have had an impact on the climate since preindustrial times. When running the GCMs in this period, it is important to have an accurate representation of the evolution of the forcing. Until now, several studies have been published on the current radiative forcing for each of the forcing mechanisms. In

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our opinion, there is now a need for increased emphasis on the evolution of the forcing, since GCMs have matured to allow a meaningful comparison with observed climate change. A natural starting point is to work out the evolution of the global mean forcing. Eventually, however, the evolution of the spatial distribution will be needed.

This work extends the two previous studies (Hansen et al., 1993; Wigley et al., 1997) by including also tropospheric ozone, and also by considering new development in the general understanding of many of the forcing mechanisms. Whereas the two previous studies included calculations of the evolution of the global mean-surface temperature, we do not offer such estimates in this study.

In this paper we present time evolution of various external radiative forcing mechanisms. We focus on the period since industrialization, from 1750 up to 1995. The data that we report are mainly our own calculations, but partly also compilations of other work. Our study regards both the 1995 radiative forcing of individual forcing mechanisms and approximations for their time evolution. We have made an effort to construct plausible time evolutions of radiative forcing of individual mechanisms based on our best judgement. Significant uncertainties are inherent in the presented results. In order to study implications of uncertainties in some of the results, we have performed several sensitivity experiments. We have then strictly studied dependency of the radiative forcing on certain parameter values. One should therefore not regard the extreme values to represent the uncertainty range. We also therefore refrain from estimating the extreme plausible range of the total radiative forcing.

A short description of the radiative transfer models is given in Section 2. Results for each of the individual contributions to the radiative forcing are presented in Section 3. In addition to presenting time evolutions of the various mechanisms we describe the basis of the results, e.g., whether it stems from previous work or it is based on original work. The main focus of this paper is the total radiative forcing. Results for the time evolution of the total radiative forcing are given in Section 4, where we point out that our estimated forcing for the direct and the indirect effect of aerosols is a major driver of the evolution of the total forcing in certain time periods. Our sensitivity experiments are presented in Section 5.

2. Radiative transfer models

For the anthropogenic forcing mechanisms their radiative forcing is calculated using radiative transfer models, either performed as a part of this study or in already published papers. We use an emissivity/absorptivity broad band model for thermal infrared radiation (Myhre

Table 1
Global mean-radiative forcing in 1995 since industrialization (in $W\,m^{-2}$), reference case[a]

Component	Radiative forcing	
CO_2	1.38	
CH_4	0.47	
N_2O	0.12	
CFCs	0.33	
Well-mixed greenhouse gases		2.30
Stratospheric ozone	− 0.10	
Tropospheric ozone	0.38	
Ozone		0.28
Sulfate	− 0.36	
Soot	0.14	
Organic carbon	− 0.09	
Biomass	− 0.20	
Direct effect of aerosols (external mixing)		− 0.51
Indirect effect of aerosols		− 1.00
Solar irradiance variation		0.12
Stratospheric aerosols		− 0.33

[a]The numbers are either calculated explicitly for 1995 or they are established by extrapolation from estimates in 1985 or 1990, see text for details. Note also that the anthropogenic forcings in most cases maximize in 1995 this is not the case for the natural forcing mechanisms (solar irradiance variation and stratospheric aerosols of volcanic origin) which have been fluctuating during the period of investigation.

and Stordal, 1997). The model includes about 50 absorption bands including all the major greenhouse gases. Clouds are included in the model. For solar radiation a multi-stream model using the discrete ordinate method (Stamnes et al., 1988) is used. Absorption by O_2, O_3, CO_2, and H_2O, Rayleigh scattering, aerosols, and clouds are taken into account. The spectral resolution varies from 1 nm to dividing the spectral interval into 70 regions (see Berntsen et al., 1997; Myhre et al., 1998b for more details).

3. Forcing mechanisms

In this section we present the basis of our estimates of the evolution of various individual forcing mechanisms. Their current global radiative forcings since industrialization are shown in Table 1, and all contributions are discussed in the following. Anthropogenic changes in well-mixed greenhouse gases (CO_2, CH_4, N_2O, and halocarbons), ozone (tropospheric and stratospheric), direct effects of aerosols (sulfate, soot, organic carbon, and biomass), and indirect effects of aerosols are taken into account in addition to the natural changes in solar irradiance and stratospheric aerosols of volcanic origin. All
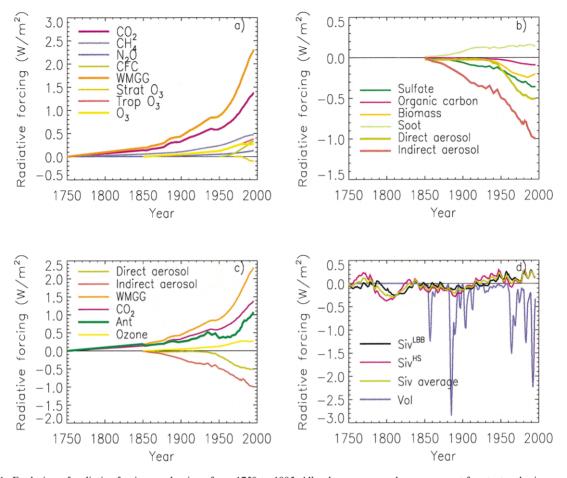
Fig. 1. Evolution of radiative forcing mechanisms from 1750 to 1995. All values are annual means except for stratospheric aerosols, where 3 years running mean is used. (a) Radiative forcing due to CO_2, CH_4, N_2O, CFCs, all well-mixed greenhouse gases (WMGG), tropospheric ozone, stratospheric ozone, and total ozone. (b) Radiative forcing due to soot, sulfate, organic carbon, biomass aerosols, total direct aerosol effect, indirect aerosol effect. (c) Radiative forcing due to WMGG, CO_2, ozone, direct aerosol effect, indirect aerosol effect, and total anthropogenic radiative forcing mechanisms (Ant). (d) Solar irradiance variation (Siv) based on Lean et al. (1995) (Siv^{LBB}), Siv based on Hoyt and Schatten (1993) (Siv^{HS}), the average of Siv^{LBB} and Siv^{HS} (Siv average), and radiative forcing due to stratospheric aerosols of volcanic origin (Vol) (1850–1995).

results are given for global mean, however their regional patterns differ substantially (see Shine and Forster, 1999). Of course there are uncertainties associated with the given numbers, varying substantially between the forcing mechanisms (we refer to IPCC, 1996; Hansen et al., 1998; Shine and Forster, 1999, for discussion of uncertainties). The radiative forcings shown in Table 1 are calculated for 1995. However, for some components the radiative forcing calculations are performed for either 1985 or 1990 and thereafter scaled to 1995 values. This is described for each forcing mechanism in the following.

We have neglected some known anthropogenic effects, which are considered too uncertain, especially when it comes to establishing a time evolution, such as dust aerosols (Tegen et al., 1996), land surface albedo change

(Hansen et al., 1998), and aircraft contrails and aviation-induced cirrus clouds (Fahey et al., 1999; Boucher, 1999).

3.1. Well-mixed greenhouse gases

In Myhre et al. (1998a) we established formulas for global radiative forcing as a function of atmospheric concentrations for the well-mixed greenhouse gases based on calculations with the models described in Section 2. In this work we have applied these functions along with changes in the concentrations of well-mixed greenhouse gases specified in Hansen et al. (1998) to establish the evolution of the radiative forcing (Fig. 1a). In Table 1, we show estimates of all near-current (1995) radiative forcings since industrialization (1750), including

contributions from CO_2, CH_4, N_2O, and halocarbons. In 1995 the radiative forcing due to all well-mixed greenhouse gases is 2.30 $W m^{-2}$, out of which CO_2 contributes with 1.38 $W m^{-2}$. About 20% of the 1995 forcing was obtained already by the year 1900. The strongest increase has been from 1950, when about 50% of the forcing has occurred. The increase in the radiative forcing due to CO_2 has been almost monotonic, but with a short period of decrease around 1940.

3.2. Ozone

The radiative forcing due to changes in ozone is shown for changes in tropospheric ozone and stratospheric ozone as well as total change in ozone (also in Fig. 1a). The tropospheric ozone forcing is taken from a recent study where we investigated the evolution from 1850 to 1990 (Berntsen et al., 2000), based on the same models as in Berntsen et al. (1997). Regional differences in the evolution in the tropospheric ozone precursors were taken into account and were found to be significant for the evolution in radiative forcing. Stevenson et al. (1998) made a similar study, but they used only global emissions for the ozone precursors. The current radiative forcing adopted in this study (Berntsen et al., 2000) is slightly higher than in Berntsen et al. (1997) due to updates in emissions and chemical reaction rates. The estimate of the current forcing in Berntsen et al. (2000) compares well to other recent estimates (see discussion in Berntsen et al., 1997, 2000). In Berntsen et al. (2000) we calculated "time slices" up to 1990. In this work we have extrapolated the forcing linearly after 1990 from the calculated trend from 1980 to 1990. Calculations where changes in surface and aircraft emissions were also included showed that this is a reasonable assumption (Karlsdottir et al., 2000). Effects of reduced stratospheric ozone are known to have influenced the tropospheric ozone, but they are not considered here.

Global radiative forcing calculations due to changes in stratospheric ozone have been performed for this study. We have adopted the ozone data from the work of Randel and Wu (1999); who developed zonal mean stratospheric ozone changes based mainly on satellite observations, but ozone sonde measurements in the polar regions. Long-wave and short-wave calculations are performed with the models described in Section 2. Stratospheric temperature adjustment is included in the calculations. The strongest radiative forcing is found around 70 and 80°S with values around -1.0 $W m^{-2}$. At northern high latitudes the radiative forcing is between -0.3 and -0.4 $W m^{-2}$. In the tropical region the radiative forcing is close to zero. The global and annual mean radiative forcing due to change in stratospheric ozone (Table 1) is calculated to -0.10 $W m^{-2}$ (long wave -0.26 $W m^{-2}$ and solar 0.16 $W m^{-2}$) for the period 1979–1997. Randel and Wu (1999) rather arbitrarily

set the ozone changes in the tropics in the lower stratosphere to zero, even though the satellite data indicated a small positive change. Forster (1999) performed a calculation taking all the ozone changes into account with a result of -0.02 $W m^{-2}$, whereas he found that when using only statistically significant stratospheric ozone changes the best estimate was in the range -0.08 to -0.12 $W m^{-2}$. Changes in stratospheric ozone prior to 1979 are not well quantified. The vertical distribution of the changes in this period was probably quite different from the distribution since 1979, when, e.g., the Antarctic stratospheric ozone hole started to develop (Shine and Forster, 1999). In this study we have neglected stratospheric ozone changes before 1979, and the evolution of stratospheric ozone has been taken from an assumption of IPCC (1996a), based on scaling of stratospheric ozone depletions after 1979 to tropospheric chlorine loading.

3.3. Aerosols

3.3.1. Direct effect

A number of different aerosol components are of climatic importance, and we have included the direct effect of four types of aerosols currently believed to yield the largest contributions to the radiative forcing; sulfate, soot, organic carbon, and biomass aerosols. We have chosen here to use this classification of aerosols, which has been adopted by IPCC (1996a) and used in several papers. It is worth noting that whereas the three former components are classified in terms of their chemical composition, the latter is rather classified according to its origin. As we point out below aerosols from biomass burning largely consist of soot and organic carbon.

The value -0.36 $W m^{-2}$ is used for the 1995 forcing due to sulfate based on our previous results presented in Myhre et al. (1998b). Several recent estimates of the forcing due to sulfate are performed, some in line with this estimate (see discussion in Myhre et al., 1998b) and some with stronger radiative forcing (Haywood and Ramaswamy, 1998; Penner et al., 1998) (-0.63 and -0.81 $W m^{-2}$, respectively). Uncertainties in the representation of hygroscopic effects of the sulfate aerosols and forcing in cloudy areas are major reasons for the large differences found. Likewise, a soot forcing of 0.14 $W m^{-2}$ based on Myhre et al. (1998b) is included. This estimate is slightly lower than other estimates (Haywood et al., 1997; Haywood and Ramaswamy, 1998; Penner et al., 1998) (0.20 $W m^{-2}$ in all cases). Large uncertainties for this aerosol component also exist, mostly related to the mass and the distribution of the soot, optical properties, and mixing with other types of aerosols (Haywood et al., 1997; Myhre et al., 1998b).

Field studies indicate that organic carbon aerosols yield a major contribution to the total aerosol mass (Hegg et al., 1997), but information on their distribution and radiative properties is scarce. For this study, we have

now estimated the 1995 radiative forcing due to fossil fuel organic carbon aerosol to $-0.09\,\mathrm{W\,m^{-2}}$ for 1995. The calculation is performed based on Mie theory for the optical properties and a linear mass relationship between organic carbon and soot as suggested in Liousse et al. (1996). We used the same soot distribution as in Myhre et al. (1998b). Hygroscopic growth is taken into account for the organic aerosols. In lack of better data, we have used refractive indexes for organic carbon as for sulfate aerosols. The estimate for fossil fuel organic carbon is somewhat stronger than in Penner et al. (1998) and Hansen et al. (1998), and uncertainties are probably mostly related to the mass and the distribution of the aerosol species, optical properties (most important their single scattering albedo), hygroscopic effects, and mixing with other aerosol types.

We have not performed any model calculations for biomass aerosols, but rather use an estimate of $-0.2\,\mathrm{W\,m^{-2}}$ based on Penner et al. (1998) and Hobbs et al. (1997). In Penner et al. (1998) optical properties were calculated with Mie theory for soot and organic carbon. The radiative forcing due to aerosols from biomass burning depends on assumptions regarding size distribution and mixing, with values within $\pm\,30\%$ of $-0.2\,\mathrm{W\,m^{-2}}$. Hobbs et al. (1997) used air-borne measurements to estimate an upper limit of $-0.3\,\mathrm{W\,m^{-2}}$ for global mean radiative forcing due to aerosols from biomass burning.

Establishing the evolution of the direct aerosol effect is difficult. For the radiative forcing due to sulfate, we have chosen to follow assumptions made in Wigley et al. (1997). The evolution of the sulfate aerosol forcing (Fig. 1b) is calculated with scaling to global mean SO_2 emissions, which are taken from Schlesinger et al. (1992). Fossil fuel consumption (IPCC, 1996b) is used to scale the evolution of the radiative forcing due to organic carbon aerosols. We regard this only as a first estimate, as it is known that also other processes contribute to organic carbon aerosols. Furthermore there has been a change in the composition and use of fuel over time. For the evolution of the radiative forcing due to soot, consumption of coal, diesel, and oil (http://www.iea.org/stats/files/keystats/p_0303.htm) and soot emission coefficients from Cooke and Wilson (1996) are used. Notice that the forcings for sulfate and soot calculated in Myhre et al. (1998b) were made for the year 1985. We used the method outlined in this paragraph to establish the evolution of the radiative forcings both prior to and after 1985, including the 1995 forcings (given in Table 1).

The evolution of the radiative forcing from aerosols from biomass burning is scaled to the gross tropical deforestation. Several data sets for deforestation exist (World Resources Institute, 1996; Houghton, 1999; Ramankutty and Foley, 1999). There are large differences between data sets. We have chosen to use a combination of the data of World Resources Institute (1996) and Houghton (1999), representing central values among the existing data sets. We have assumed a linear trend before 1940 (Ramankutty and Foley, 1999). The deforestation is one anthropogenic influence on the biomass burning. Man-made activity can also alter the biomass burning in other ways, e.g., in altering the Savanna burning. However, quantification of such effects are difficult and not included here.

3.3.2. Indirect effect

The indirect aerosol effect is probably the most uncertain anthropogenic forcing mechanism. Previous estimates yield large variations (Lohmann and Feichter, 1997; Chuang et al., 1997; Rotstayn, 1999). We have performed calculations where the relationships between sulfate mass, cloud droplet number concentration, and effective radius have been treated as in Boucher and Lohmann (1995). The relation between cloud droplet number concentration N_d and the sulfate mass is based on the equation

$$N_d = 10^6 am^b,\tag{1}$$

where m is the sulfate concentration and a and b are constants that differ over land and ocean, see Boucher and Lohmann (1995). Further the relationship between the cloud droplet number concentration and the effective radius (Boucher and Lohmann, 1995) is

$$r_e = \left(\frac{3W_1}{4\pi\rho_1\kappa N_d}\right)^{1/3},\tag{2}$$

where W_1 is the liquid water content, ρ_1 is the density of liquid water, and κ is a constant that differs over ocean and land. We have adopted the sulfate mass used in Myhre et al. (1998b). For the 1985 calculations, the distributions of cloud amount and optical depth from ISCCP (Rossow and Schiffer, 1991) are used. The asymmetry factor and single scattering albedo are calculated based on the relationship between effective radius and the optical properties in Slingo (1989).

For the time evolution, the effective radius and the relationship in Slingo (1989) between effective radius and optical properties are used. For the optical depth τ this relationship is

$$\tau_i = \mathrm{LWP}(a_i + b_i/r_e),\tag{3}$$

where LWP is the liquid water path and a_i and b_i are constants given for each spectral interval (i). It is assumed in all our calculations that the LWP is constant in time so the change in τ is only due to the change in r_e.

Our estimate of the indirect effect includes only the change in the effective radius of cloud particles (first indirect effect). We have taken into account neither the effect of an increased lifetime of the cloud particles (second indirect effect), which would probably give a stronger

cooling, nor effects of aerosols other than sulfate (e.g., sea salt) that may alter the magnitude of the forcing.

The basis for our estimate of the evolution of the indirect effect is the global distribution of the mass of sulfate calculated for the year 1985 used in Myhre et al. (1998b), which is based on chemistry transport model calculations. Prior to that and after that, we have assumed an evolution in the sulfate mass which is proportional to the SO_2 emissions.

As pointed out by Hegg (1994); Kogan et al. (1997) we find that the indirect aerosol effect is not linear with increase in sulfate mass. Anthropogenic sulfate is most efficient for low concentrations of sulfate. Two strong non-linear effects exist; between sulfate mass and cloud droplet number concentration, and between cloud droplet number concentration and effective radius. However, the radiative forcing is nearly proportional to the change in effective radius. In total the radiative forcing due to the indirect aerosol effect, which is negative, grows faster for smaller masses of sulfate. Therefore, it is important to emphasize even areas with relatively small changes in the mass of sulfate. For the indirect effect we have therefore considered four regions of SO_2 emissions; North America, Europe, Asia, and the Southern hemisphere. The SO_2 emissions for these four regions are constructed based on Dignon and Hameed (1989). For each of the four regions we have adopted the procedure given by Eqs. (1)–(3), to establish an evolution of the effective radius, and thereafter calculated the radiative forcing every 5 years with a horizontal resolution of 10×10 degrees.

We arrive at a forcing of $-1.0 \, \mathrm{W\,m^{-2}}$ in 1995, which also seems to be a central value among previous estimates. It has been shown that an indirect forcing of $-1 \, \mathrm{W\,m^{-2}}$ may account for the observed decrease in the diurnal temperature variation (Hansen et al., 1998). The strongest forcing calculated in this study is found over oceans close to industrialized regions.

Our estimated evolution of the radiative forcing due to the indirect aerosol effect is shown in Fig. 1b. The growth of the negative forcing is rather strong up to about 1910, when it slowed. After 1940 there has again been a strong increase in the forcing up to 1995. In the period from about 1910 to 1940, the growth in SO_2 emissions was relatively weak compared to the rest of the period since 1850. In the period up to 1910, weak increases in the emissions of SO_2 in Asia and the Southern hemisphere contributed significantly to the forcing. Likewise emissions in the Southern hemisphere have had a large effect during the last two decades, when the radiative forcing due to the indirect effect of sulfate has not changed in the same manner as the global emissions of SO_2.

3.4. Total anthropogenic forcing

Fig. 1c summarizes the evolution of the anthropogenic forcing mechanisms considered in this paper. The evolu-

tions of the radiative forcing mechanisms vary, as their lifetime and the evolution of their sources differ. Components with long lifetime accumulate in the atmosphere and the radiative forcing depends on the emissions over a long time period, whereas components with short lifetime depend largely on their actual emission. The main source of CO_2 is from fossil fuel, but also deforestation is important. The overall lifetime for CO_2 is long, but it has multiple sink mechanisms operating on a variety of time scales. CH_4 has several sources and the atmospheric chemistry removal may vary over time (Karlsdottir and Isaksen, 2000). The CFCs have been only emitted to the atmosphere in significant amounts after the 1950s. Whereas the well-mixed greenhouse gases have lifetimes of many years, the aerosol lifetimes are typically less than a week. Most of the SO_2 emissions are from fossil fuel, but over the last decades emission reductions of SO_2 in the industrialized regions of the world have been implemented. The soot is dependent on emissions of coal, diesel, and oil. In conclusion, all the various radiative forcing mechanisms differ in their evolution, and the anthropogenic radiative forcing is a complex combination of the various mechanisms.

A decline in the total anthropogenic forcing around 1950 is evident, with a strengthened negative aerosol (direct and indirect) forcing as the main cause. The direct aerosol effect is important in this respect; it is very weak before 1950 and grows stronger thereafter. This is due to the difference in the evolution of the radiative forcing from soot compared to the other aerosol components. In support of this, the ice core measurements of Lavanchy et al. (1999) indicate that the soot abundance in the atmosphere has grown faster before 1920 and slower after 1920 than that of organic carbon. The different evolutions in the aerosol components may therefore have altered an important optical property of the aerosols; the single scattering albedo (Haywood and Shine, 1995; Hansen et al., 1997). In our calculations the single scattering albedo would probably be lower before 1950 than after.

3.5. Natural forcing mechanisms

To complete the picture of external forcing of the climate system, we have compiled evolutions of radiative forcings of natural origin. Variability in the solar energy output as well as stratospheric aerosols of volcanic origin are known to yield a radiative forcing varying on relevant time scales.

We show solar irradiance variations from Hoyt and Schatten (1993) and Lean et al. (1995) in Fig. 1d. Differences in the two data sets are due to use of different proxy parameters for the reconstruction of the solar irradiance variation. The most noticeable difference after 1850 is in the period from about 1900 to 1970. An average of Hoyt and Schatten (1993) and Lean et al. (1995), which in the

following is used as a reference case, is shown in the figure as well. We have taken into account that the largest solar variation is at short wavelengths which are absorbed at high altitudes, inhibiting a direct effect on the tropo-sphere–surface system using the procedure established by Hansen et al. (1997). Indirect effects of solar irradiance variations are not taken into account in this presentation, such as influence on stratospheric ozone and clouds.

Volcanic aerosols have long been known to yield significant climate impact. Aerosols reaching the stratosphere reside there for more than a year during which they impact the radiative balance by scattering the solar radiation and to some extent also by increasing the greenhouse effect. There exist a few data sets of the evolution of the optical depth of volcanic particles. We have used results from Sato et al. (1993) (and updated values from the web site, http://www.giss.nasa.gov/), who have compiled data from 1850 based on a variety of methods. Based on radiative transfer modelling Lacis et al. (1992) established a relationship between optical depth and radiative forcing which we have adopted to derive a time series of the radiative forcing (Fig. 1d). The forcing due to volcanoes varies on a shorter time scale than the other forcings considered in this work. Volcanoes therefore presumably impact the climate in a different manner, so that a comparison should be made with caution.

4. Total forcing

The main purpose of this paper is to establish a time evolution of the total radiative forcing. Fig. 2 summarizes the forcing due to all mechanisms considered in this study. The figure shows the total anthropogenic forcing, the anthropogenic forcing in combination with solar irradiance variation, and the anthropogenic forcing in combination with solar irradiance variation and stratospheric aerosols of volcanic origin. The total anthropogenic contribution in 1900 is about 25% of the 1995 value. There are two periods with marked increase during the 20th century. From 1900 to about 1945 it increases substantially. The solar irradiance variations and volcanoes further strengthen this development with low solar irradiance and strong volcanic activity around 1900 and vice versa near 1945. The solar forcing over this period is rather similar to the total anthropogenic forcing, in which aerosols offset half of the greenhouse gas forcing.

The total radiative forcing due to all anthropogenic forcing mechanisms declines after about 1945 and retains the same value around 1970. A strong increase in the negative aerosol forcing (due to SO_2 emissions) in this period offsets much of the greenhouse gas forcing. The solar irradiance variation strengthens the decline in this period. However, the radiative forcing due to aerosols dominates over the solar irradiance variation. Strong volcanic activity in the latter part of the period from 1963 to 1995 has further given a strong decline in the natural radiative forcing. In the last 25 years period, the positive greenhouse gas forcing has dominated strongly over the negative aerosol forcing. In the beginning of this period, solar irradiance variation also contributed to the increase in the total forcing. Two strong volcanic eruptions have occured in this period.

It can be viewed as an interesting coincidence that the natural forcing has strengthened the time evolution of the total anthropogenic forcing in the 20th century, with one major exception; the strong volcanic activity after 1960, a period with strong increase in the total anthropogenic forcing.

In general the evolution of the total forcing developed in this paper resembles the evolution described by Hansen et al. (1993) and Wigley et al. (1997). We have estimated an increase in the period 1970–1990 which is somewhat weaker than in the Wigley et al. (1997) paper. Our calculations also differ somewhat from the two previous papers in the estimate of a decline in the 1945–1970 period. Hansen et al. (1993) estimated a decline in parts of the period due to volcanic activity, whereas Wigley et al. (1997) found a weak reduction in the forcing, stemming almost exclusively from the reduction of solar irradiances estimated by Hoyt and Schatten (1993). In this work we find that the radiative forcing due to aerosols may also have contributed significantly to a decline in the forcing, as discussed above.

5. Discussion and sensitivity tests

A wide range of uncertainties exist for the 1995 radiative forcings and approximations for their evolutions. In this section we assess and discuss some uncertainties in our results. We have performed sensitivity tests using the time evolution of the radiative forcing of the anthropogenic effects and solar irradiance variation shown in Fig. 2 as the reference case.

We first consider the large uncertainty in the forcing due to changes in stratospheric ozone. Fig. 3a shows effects of altering the forcing between -0.35 and -0.05 W m^{-2}, which is the range suggested by WMO, 1999. This shows to have a noticeable effect on the total radiative forcing, especially after 1985.

Several estimates of the global radiative forcing due to the direct aerosol effect of sulfate have been made (see discussion in Myhre et al. (1998b) in addition to estimates in Haywood and Ramaswamy (1998) and Penner et al. (1998)). The range of the estimates are large; from about -0.3 to -0.8 W m^{-2}. There are many reasons for the large variation between the estimates of the radiative forcing. The most important ones are probably different estimates in sulfate mass and its distribution, hygroscopic
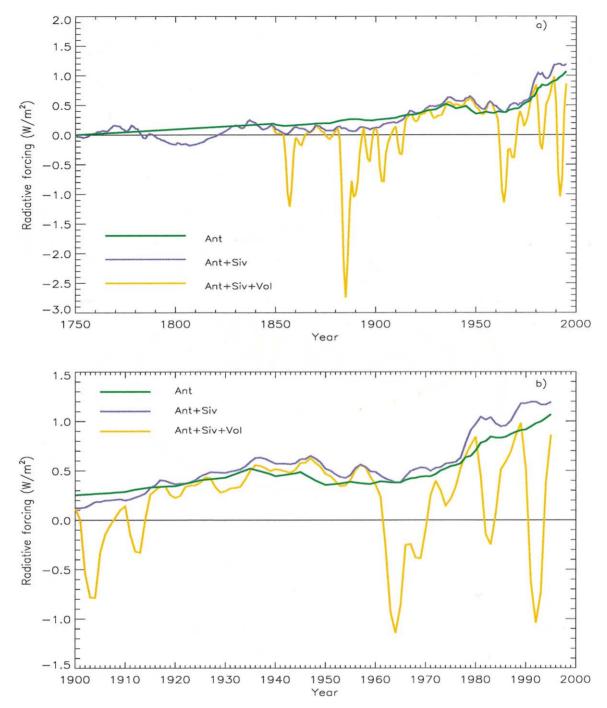
Fig. 2. Evolution of radiative forcing for anthropogenic forcing mechanisms (Ant) (from Fig. 1c), anthropogenic forcing mechanisms in addition to solar irradiance variation (Siv) (Siv average from Fig. 1d), and anthropogenic forcing mechanisms in addition to solar irradiance variation and stratospheric aerosols of volcanic origin. Results are shown for two time periods; (a) 1750–1995, (b) 1900–1995.

effects, optical properties, the radiative effect in cloudy regions, and different radiative transfer schemes used. In most previous studies the sulfate aerosols have been specified with certain size distributions and not mixed with other aerosol types. Fig. 3b shows a case where we have assumed the sulfate direct radiative forcing to be -0.80 W m^{-2} as opposed to -0.36 W m^{-2} in the reference case.
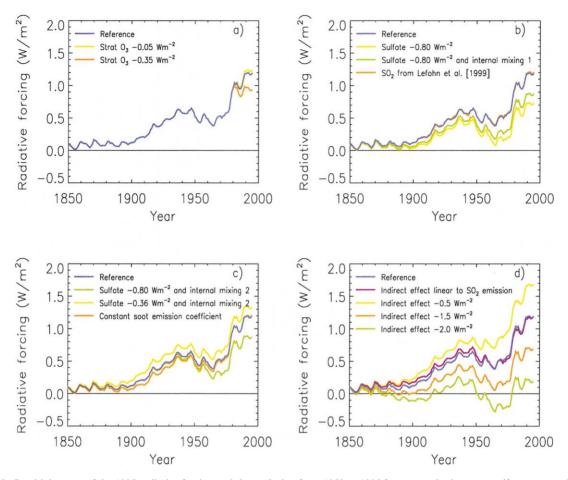
Fig. 3. Sensitivity tests of the 1995 radiative forcing and the evolution from 1850 to 1995 for stratospheric ozone, sulfate, soot, and the indirect aerosol effect. All sensitivity tests are performed as perturbations to the reference case including all anthropogenic forcing mechanisms and solar irradiance variation (shown in Fig. 2). (a) 1995 radiative forcing due to change in stratospheric ozone of -0.05 and -0.35 W m^{-2}. (b) Two cases with 1995 radiative forcing due to sulfate of -0.80 W m^{-2}. In the first case this is the only change compared to the reference case. In the second case the 1995 radiative forcing due to soot has been set to 0.28 W m^{-2}, mimicing the effect of internal mixing of sulfate and soot. Internal mixing 1 assumes that the evolution of the effect of internal mixing follows the evolution of the radiative forcing due to sulfate. One case shows the effect of using a data set of SO$_2$ emissions from Lefohn et al. (1999) for the evolution of the radiative forcing due to sulfate. (c) The 1995 radiative forcing due to sulfate is assumed to be -0.80 or -0.36 W m^{-2} and for soot 0.28 W m^{-2} to take into account internal mixing of sulfate and soot. Internal mixing 2 assumes that the evolution of the effect of internal mixing follows the evolution of the radiative forcing due to soot. One case shows the effect of neglecting variation in the emission coefficient for coal use for the forcing due to soot. (d) 1995 radiative forcing due to the indirect aerosol effect of -0.5, -1.5, and -2.0 W m^{-2}. One case shows the effect of the radiative forcing due to the indirect aerosol effect scaled linearly to the global SO$_2$ emissions.

Haywood et al. (1997) and Myhre et al. (1998b) found that internal mixtures of sulfate and soot give a substantially different forcing than an external mixture, thereby increasing the importance of the soot. Other cases in Figs. 3b and c therefore assume internal mixing of sulfate and soot. We have only performed explicit radiative forcing calculations for internal mixing in the case of the concentrations of sulfate and soot in 1985. The difference between the internal and external mixing cases has been chosen to be $+0.14$ W m^{-2}, which

corresponds to a doubling of the soot contribution. This is based on results from Haywood et al. (1997) and Myhre et al. (1998b). For mixing between the two components at other times, we determine the deviation between the radiative forcing in the internal and external mixing cases by simple scaling approximations, either according to concentrations of sulfate (assumption 1, results in Fig. 3b) or soot (assumption 2, results in Fig. 3c). Experiments with internal mixing have been performed in combinations with two different

forcings from sulfate alone, namely -0.36 and -0.80 W m^{-2}.

Using a stronger radiative forcing for sulfate aerosols has a marked, but slowly evolving effect (Fig. 3b). The evolution is particularly dependent on the sulfate forcing after about 1945, when there was a strong increase in the SO$_2$ emissions. In the period 1945–1970 there is only a slight downward trend in the total radiative forcing in the reference case, but a strong sulfate forcing yields a marked downward trend in the total radiative forcing. In the case where the effect of the internal mixing follows the evolution of the radiative forcing due to sulfate, the evolution of the forcing differs from the reference case in magnitude, but the patterns in the evolution are similar.

An experiment with another time history of global sulfur emissions (Lefohn et al., 1999) is included as well in Fig. 3b. In this case the radiative forcing due to the direct effect of sulfate differs only for a few years by more than 10% from the reference case, and the difference in the total radiative forcing can hardly be recognized.

Fig. 3c illustrates effects on the time evolution of radiative forcing from including the positive effect of an internal vs. an external mixing, now in terms of an increased soot contribution. Two such cases are shown. In the experiment adopting the reference case for sulfate and internal mixing, a difference relative to the reference case occured during a few decades around year 1900, only very slowly evolving since then. However, in the case with stronger sulfate forcing and internal mixing with soot there is a strong decline in the total radiative forcing from 1945 to about 1970. Thereafter the increase in the total radiative forcing is similar to the one in the reference case.

The differences between using SO$_2$ emissions and soot emissions in determination of the internal mixing of soot and sulfate can be seen comparing the two cases in Fig. 3b and c. The difference between these two assumptions yields the largest effect before 1950. An additional curve shows a case where we have assumed that soot grows according to the emissions from combustion of coal diesel, and oil, but neglecting the evolution of the soot emission coefficients for coal. This is shown to have a small effect from 1900 to about 1950.

The largest uncertainty is in the indirect aerosol effect. We have performed experiments reflecting the large spread in estimates of this effect. Estimates of the radiative forcing due to the indirect aerosol effect are mostly within the range between -0.5 and -2.0 W m^{-2} (Chuang et al., 1997; Jones and Slingo, 1997; Lohmann and Feichter, 1997; Rotstayn, 1999). We have therefore included in Fig. 3d cases where the 1995 forcing is assumed to be -0.5, -1.5, and -2.0 W m^{-2} in addition to the reference value of -1.0 W m^{-2}. The uncertainty in the radiative forcing due to the indirect effect of aerosols has a large influence on the total radiative forcing

from the end of the 19th and throughout the 20th century. The strongest indirect forcings yield a marked decline in the total forcing in the 1945–1970 period, whereas the weakest indirect forcing only results in a total forcing which is leveling off in this period. We have also included a case where we have assumed a linear relationship between the indirect forcing and the SO$_2$ emission. In this case the indirect forcing is weaker than in the reference case before 1945, but the differences are relatively small after 1945.

Finally we have tested the impact of calculating the indirect effect in four separate regions. We have performed a control experiment with emissions evolving at the same rate in all emission regions, resulting in more than 20% stronger radiative forcing before 1945 and 10% weaker in 1995.

6. Summary

In this paper we have estimated the evolution of anthropogenic climate forcing mechanisms (well-mixed greenhouse gases, ozone, and direct and indirect effect of aerosols) as well as natural forcing mechanisms (solar irradiance variation and stratospheric aerosols of volcanic origin).

We have found that the 20th century can be divided in three periods with different characteristics. The periods up to about 1945 and from about 1970 to 1995 show increase in the total radiative forcing caused by changes in the anthropogenic as well as the natural forcing mechanisms. In the period from about 1945 to about 1970 the total forcing declines at various rates (or at best stabilizes), depending on the values of the several uncertain parameters in the study. The contribution from anthropogenic aerosols (direct and indirect effect) is the major reason for this decline, but the two natural forcing mechanisms considered also contribute. Whether this decline in the total radiative forcing may have given rise to a surface temperature decrease in accordance with the observations (Jones et al., 1999) needs to be investigated in comprehensive climate models.

The uncertainties are large for some of the components regarding their 1995 radiative forcing and many approximations made for their time evolution. They are particularly large for the contributions from anthropogenic aerosols. On the other hand the estimates of the radiative forcing due to well-mixed greenhouse gases is less uncertain. Consequently the total radiative forcing consists of large positive radiative forcing due to well-mixed greenhouse gases with low uncertainty and a large number of other forcing mechanism with much larger uncertainty and with varying sign.

It has been an improvement in the understanding of the radiative impacts of aerosols from recent measurement campaigns (ACE-1, TARFOX, SCAR-B). However,

with the large spatial variation in aerosols, future campaigns are also needed to further improve the estimates of radiative forcing due to aerosols. Haywood et al. (1999) showed, by using a combination of satellite data and models over oceans, that the direct effect of aerosols is substantial.

The 1995 total radiative forcing and the evolution since industrialization depends strongly on the radiative forcing due to the indirect effect of aerosols. According to the spread in the estimates for the indirect aerosol effect, it may even be the single largest forcing mechanism in 1995. The indirect aerosol effect has two contributions; change in the size of the cloud droplets and increase in cloud lifetime. Only the former effect is considered in this study. Han et al. (1994) showed that the effective radius of cloud droplets is very inhomogeneous, with larger sizes in the Southern hemisphere than in the Northern hemisphere as well as over the ocean than over land. Further investigations with observations and models are needed in order to quantify these differences. Observations of changes in cloud lifetime, and therefore the cloud amount from anthropogenic aerosol emissions, may be complicated by the fact that a climate feedback may also alter the cloud amount. Hansen et al. (1998) indicated that anthropogenic aerosols are a dominating factor. The two aerosol effects may further not be additive (Rotstayn, 1999). Another complicating factor is that the indirect aerosol effect may also alter the aerosol burden and the amount of water vapor (Lohmann and Feichter, 1997). The indirect effect depends also much on whether the anthropogenic sulfate generates new particles or the sulfate is condensed on existing particles. Further it also matters whether other aerosol types are involved (see Shine and Forster, 1999).

We have pointed to the fact that the radiative forcing due to the indirect aerosol effect is not proportional to the SO_2 emissions, and shown that this has important implications for the evolution of the forcing, especially before 1950. An important consequence of this is that future global SO_2 emission reductions may not reduce the indirect radiative forcing in a proportional manner. E.g., SO_2 emission reductions in regions with high SO_2 emissions will have a relatively smaller effect than increases in the SO_2 emissions in regions with low SO_2 emissions.

Satellite observations after the late 1970s show variation in the total solar irradiance over a solar cycle, however long-term trends in the total solar irradiance are much more uncertain. Estimates of the long-term trend differ by different use of proxy parameters. Trends in the total solar irradiance over the satellite era are also uncertain (Willson, 1997; Fröhlich and Lean, 1998). Future continued satellite measurements will extend the basis for detecting a long-term trend in the total solar irradiance and lead to a better use of proxy parameters (Fröhlich and Lean, 1998).

For stratospheric aerosols of volcanic origin satellite observations have also been used to identify the radiative impact of the Mt. Pinatubo eruption (Minnis et al., 1993; IPCC, 1994). The net anomaly the some few months after the eruption was about $-4\ Wm^2$. However, records of historical information for stratospheric aerosols are much more uncertain.

Our investigation clearly points to the fact that the total radiative forcing of the climate is constituted by a wide range of contributions of similar magnitude. Modelling surface temperature variations over the 20th century therefore requires consideration of variety of anthropogenic as well as natural forcing mechanisms.

Our radiative forcing data set is available by contacting the authors.

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