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Scientific note

Radiative forcing due to anthropogenic activities

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Abstract: A wide range of anthropogenic as well as natural forcing mechanisms may lead to climate change. We present calculations of the radiative forcing due to anthropogenic emissions leading to changes in the concentrations of several trace gases and aerosols. Increase in all major well mixed greenhouse gases are included as well as changes in tropospheric and stratospheric ozone. The radiative forcing due to certain aerosols is also estimated. The calculations have been performed for the Northern Hemisphere, and the main focus in this scientific note is on high latitudes.

1. Introduction

Several climate forcing mechanisms may lead to climate change (IPCC, 1996; Hansen *et al.*, 1998; Shine and Forster, 1999). At present the known anthropogenic forcing mechanisms include well mixed greenhouse gases, ozone, aerosols (direct and indirect effects), and land surface albedo. In this scientific note we point to work that we have already published on the radiative forcing due to several forcing mechanisms. We include also a short description of the radiative transfer models which we have used, in Section 2.

Our results have previously mainly been seen in a global context, whereas we here briefly discuss matters of particular interest for high latitudes in the Northern Hemisphere. Results for each of the individual contributions to the radiative forcing are discussed in Section 3.

2. Radiative transfer models

The radiative forcing is calculated using radiative transfer models. We use an emissivity/absorptivity broad band model for thermal infrared radiation (Myhre 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. Radiative forcing due to anthropogenic forcing mechanisms

In Table 1 we show estimates of all near present (1995) radiative forcings since industrialization (1750). The numbers are global and seasonal averages. The global distribution of the radiative forcing due to all the anthropogenic contributions discussed in the following is shown in Fig. 1 for seasonally averaged conditions.

3.1. Well mixed greenhouse gases

We have previously established formulas for global radiative forcing as a function of

Table 1. Global-mean radiative forcing in 1995 since industrialization.

Species	Radiative forcing (Wm^{-2})
CO_2	+1.38
CH_4	+0.47
N_2O	+0.12
CFCs	+0.33
Total for well mixed greenhouse gases	+2.30
Stratospheric ozone	−0.15
Tropospheric ozone	+0.38
Total for ozone	+0.23
Sulfate	−0.36
Soot	+0.14
Total for sulfate and soot aerosols (external mixing)	−0.22

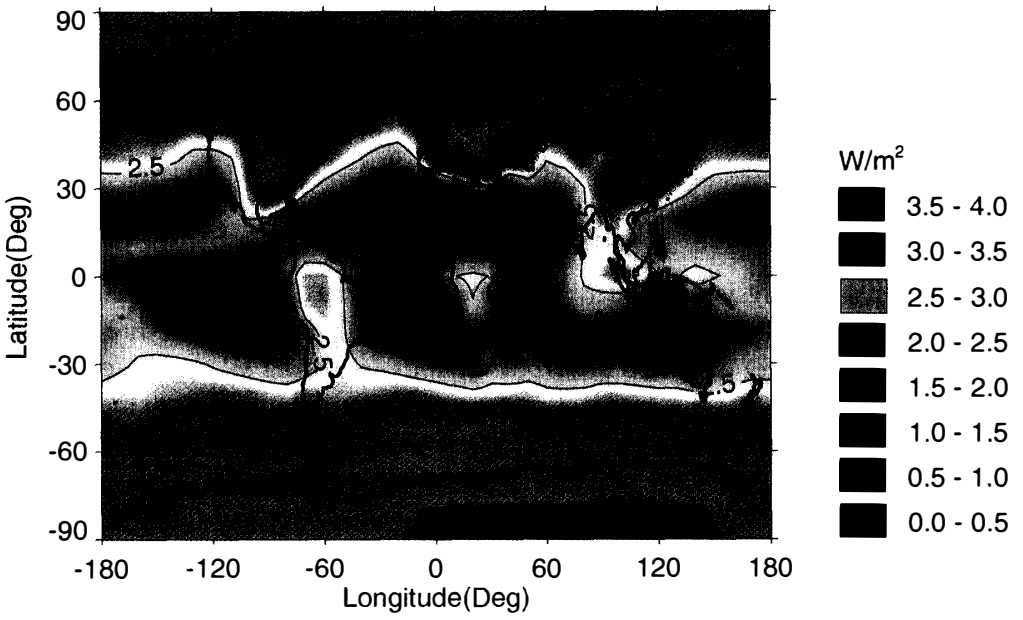

Fig. 1. Radiative forcing due to anthropogenic activity (in Wm^{-2}). The results are for changes in well mixed greenhouse gases, tropospheric and stratospheric ozone, sulfate and soot aerosols from pre-industrial to 1995 conditions.

atmospheric concentrations for the well mixed greenhouse gases (Myhre *et al.*, 1998a) based on calculations with models described in Section 2. 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 radiative forcing in 1995. CO_2, CH_4, N_2O and a group of halocarbons yield a forcing of 2.30 Wm^{-2}, out of which CO_2 contributes with 1.38 Wm^{-2}. There is a marked latitudinal gradient in the forcing, with largest values in the tropics, due to the large temperature between the warm surface and the cold tropopause region (Myhre and Stordal, 1997). This pattern can clearly be seen in Fig. 1. The forcing at high latitudes in the Northern Hemisphere is about 70% of the global average.

3.2. Ozone

In a recent study we have investigated the evolution of tropospheric ozone and its radiative forcing from 1850 to 1990, due to emissions of ozone precursors (Berntsen *et al.*, 2000), based on the same models as in Berntsen *et al.* (1997). Regional differences in the radiative forcing due to tropospheric ozone are marked, with maxima at longitudes near the regions of maximum emissions of the ozone precursors. The maxima in radiative forcing, which are displaced towards lower latitudes, *e.g.* due to the larger difference in the vertical temperature gradient, as for the well mixed greenhouse gases, can also be seen in Fig. 1. Consequently, the radiative forcing is weak at high northern latitudes. The global radiative forcing is 0.38 Wm^{-2}.

In a recent calculation of the radiative forcing due to change in stratospheric ozone (Myhre *et al.*, 2000), we have adopted the ozone data from the work of Randel and Wu (1999); who developed zonal mean stratospheric ozone changes based on satellite observations and ozone sonde measurements in the polar regions. Long wave and short wave calculations are performed with the models described in Section 2. Strong radiative forcing is found at northern high latitudes, with values between -0.3 Wm^{-2} and -0.4 Wm^{-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 is calculated to -0.15 Wm^{-2}.

3.3. Direct effect of aerosols

Several different aerosol components are of climatic importance, and we have included the direct effect of two types of aerosols in this scientific note, namely sulfate and soot. These are important components of the Arctic ambient particulate matter, e.g. in Arctic haze (see *e.g.* Shaw *et al.*, 1993).

We have previously calculated the value -0.36 Wm^{-2} for the present (1995) forcing due to sulfate (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). Uncertainties in 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 Wm^{-2} based on Myhre *et al.* (1998b) was estimated. This estimate is slightly lower than other estimates (Haywood *et al.*, 1997; Haywood and Ramaswamy, 1998; Penner *et al.*, 1998). Large uncertainties for this aerosol component also exists, 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).

Thus, large uncertainties also exist for the forcing at high northern latitudes. In general, the radiative forcing due to the largely scattering sulfate aerosol is reduced at very high latitudes due to the high surface albedo in the areas covered with ice and snow. Conversely, the radiative forcing due to the absorbing soot aerosols is enhanced in the same region.

4. Discussion

There are several features which make radiative forcing values at high northern latitudes deviate from the global averages. The well mixed greenhouse gases are of somewhat less importance due to the lower vertical gradient between the surface and the tropopause. This is the case also for tropospheric ozone, in this case also because of the distance to the regions of emissions of ozone precursors.

Stratospheric ozone changes, on the other hand, maximize at high latitudes and in particular in the Arctic, so the radiative forcing due to depletion of the ozone layer is largest there. Whereas the well mixed greenhouse gases have increased in atmospheric burden since the time of industrialization, the most significant ozone depletion has taken place over only about two decades. Consequently, at high northern latitudes, the heating due to well mixed greenhouse gases has been nearly been balanced by the cooling due to reductions in stratospheric ozone over the last two decades.

Aerosols also play a role in the radiative balance at high northern latitudes, in the so-called Arctic haze events. The uncertainties in the radiative forcing estimates are large, but it is clear that the effect of scattering sulfate aerosols is reduced and the effect of the absorbing soot aerosol is enhanced relative to the globally averaged conditions due to the high local surface albedo.

In the Arctic there is a large seasonal variation in the radiative forcing. This is most noticeable for the forcing due to Arctic haze and changes in stratospheric ozone. The Arctic haze maximizes during the winter and spring. The radiative effect is largest in the visible wavelengths. Consequently it peaks during spring after the winter time polar night (Shaw *et al.*, 1993). Likewise, the radiative effects of changes in stratospheric ozone maximize during spring, which is the time of the strongest ozone depletion, which also depends on solar radiation (see WMO, 1999 and references therein).

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