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Publication Date
2009-10-01

Manuscript prepared for Atmos. Chem. Phys.
with version 1.3 of the LaTeX class copernicus.cls.
Date: 2 October 2009

Total aerosol effect: forcing or radiative flux perturbation?

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Abstract. Uncertainties in aerosol forcings, especially those associated with clouds, contribute to a large extent to uncertainties in the total anthropogenic forcing. The interaction of aerosols with clouds and radiation introduces feedbacks which can affect the rate of rain formation. Traditionally these feedbacks were not included in estimates of total aerosol forcing. Here we argue that they should be included because these feedbacks act quickly compared with the time scale of global warming. We show that for different forcing agents (aerosols and greenhouse gases) the radiative forcings as traditionally defined agree rather well with estimates from a method, here referred to as radiative flux perturbations (RFP), that takes these fast feedbacks and interactions into account. Thus we propose replacing the direct and indirect aerosol forcing in the IPCC forcing chart with RFP estimates. This implies that it is better to evaluate the total anthropogenic aerosol effect as a whole.

1 Introduction

Aerosols affect climate directly by scattering and absorption of shortwave and thermal radiation (direct effect). The global-mean net direct effect at the top-of-the-atmosphere (TOA) is a cooling that partly offsets the warming due to greenhouse gases. It is estimated as -0.5 W m^{-2} with a 5 to 95% confidence range of -0.1 to -0.9 W m^{-2} (Forster et al., 2007). In addition, aerosols modify the radiation budget indirectly by acting as cloud condensation nuclei and ice nuclei. The cloud albedo enhancement (first indirect effect, cloud albedo effect or indirect aerosol forcing) of warm stratiform clouds refers to an increase in cloud droplet number concentration due to anthropogenic aerosols for a constant liquid water content (Twomey, 1977). These more numerous and smaller cloud droplets increase the total surface area and thus cloud albedo. The cloud albedo effect can be calculated as a forcing because of the assumption of a constant liquid water content. Global-mean model estimates of the cloud albedo effect have remained rather constant over time (see figure 1) and amount to roughly -0.9 W m^{-2}. The -0.9 W m^{-2} estimate that is obtained from the average over all published estimates, treating each of them equal (one paper one vote) is slightly larger than the estimate of the cloud albedo effect in the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) where a different weighting procedure was used. There the median value of the indirect aerosol forcing was estimated as -0.7 W m^{-2} with a 5 to 95% range of -0.3 to -1.8 W m^{-2} (Forster et al., 2007). The rather large uncertainty in both the direct and indirect (cloud albedo effect) forcing accounts for a large fraction of the uncertainty in the total anthropogenic forcing (Kiehl, 2007).

In addition to the cloud albedo effect, there are multiple other effects such as the cloud life-time effect, the semi-direct effect and aerosol effects on mixed-phase, convective and cirrus clouds (Lohmann and Feichter, 2005; Denman et al., 2007). These effects need to be evaluated as radiative flux perturbation (RFP) (Haywood et al., 2009) or climate forcing (Forster and Taylor, 2006) because these effects do not act ”instantaneously”. This means that the difference in the top-of-the-atmosphere radiation budget between two simulations, one with pre-industrial emissions and one with present-day emissions is evaluated. RFP estimates thus involve fast feedbacks and interactions in the climate system that induce changes in the meteorology. This does not conform to the usual definition of ”radiative forcing” Forster et al. (2007), in which only one thing is changed while leaving everything else constant.

Also, telling the multitude of different effects that refer to different physical processes apart is not easy as different interactions can take place at the same time. Also, if aerosols and/or cloud droplet number concentrations are calculated interactively in the model, the calculation of the aerosol radiative forcing is not straightforward because aerosols will then also influence the precipitation formation and with that cause an additional change in cloud properties. If these interactions and feedbacks are taken into account, then the difference between simulations with different aerosol emissions is a radiative flux perturbation (RFP) . The advantage of the RFP method over the strictly defined forcing is that it allows the radiative impact of aerosols on both cloud albedo and precipitation efficiency to be evaluated. As shown in figure 1, if estimates of other aerosol-cloud interactions are considered next to the cloud albedo effect, then these estimates are mostly larger than the cloud albedo effect alone. This suggests that most of the model-calculated additional effects do not offset the cloud albedo effect, but rather constitute an additional cooling. Although the total indirect effect shows more scatter than the cloud albedo effect, more recent estimates indicate smaller (less negative) values (see supplement). Some of the smallest estimates result from estimates of the indirect aerosol forcing from satellite data or result from general circulations model (GCM) estimates that constrained the indirect aerosol effect by satellite data. Also, some aerosol interactions with mixed-phase clouds can partly offset the forcing due to the cloud albedo effect.

A complementary approach to estimate either the indirect aerosol effect or the total anthropogenic aerosol effect is to infer it as a residual using the observed temperature record over land, and estimates of the ocean heat uptake and the evolution of greenhouse gas and solar radiative forcing (Anderson et al., 2003; Hegerl et al., 2007). These so-called inverse estimates constrain the total cooling forcing over the 20th century, attributable to anthropogenic aerosols, to a likely range[1] of -1.7 to -0.1 W m^{-2} (Hegerl et al., 2007). A total anthropogenic aerosol effect that is more negative than -1.7 W m^{-2} would thus be inconsistent with the observed warming.

The question that remains is how the total aerosol effect that includes fast feedbacks and interactions due to the cloud lifetime effect, semi-direct effect or aerosol interactions with mixed-phase and ice clouds can be compared with the forcings from the well-mixed greenhouse gases (GHG). The difference between the forcing (as strictly defined) and the RFP (change in TOA net radiation between two GCM simulations with pre-industrial versus present-day aerosol emissions, see also below) due to the aerosol indirect effect was first investigated by Rotstayn and Penner (2001). They found from their atmospheric GCM coupled to a mixed layer ocean model that the differences in the climate sensitivity due to using the RFP method were smaller than the differences in the climate sensitivity due to different forcings. They hence argued that RFP estimates from aerosols should be compared to forcing estimates from GHG. Put differently, given that cloud responses to aerosol perturbations are much quicker compared with the timescale of global warming, it makes sense from an energy balance perspective (Murphy et al., 2009) and is more suitable in the conceptual framework of radiative forcing and climate sensitivity (Gregory et al., 2004; Knutti and Hegerl, 2008; Quaas et al., 2009a) to include the radiative impact of fast feedbacks and interactions in estimates of the effects of aerosols.

The issue of how to include fast feedbacks and interactions is not new. One approach suggested by Joshi et al. (2003) and Hansen et al. (2005) is to obtain an efficacy (E) and to display it next to forcing estimates. E is defined as the ratio of the climate sensitivity parameter for a given forcing agent to the climate sensitivity parameter for CO_2. A comparison of E for different forcing agents from different models is given in Forster et al. (2007). Instead of introducing E in addition to forcing estimates, we suggest to replace the total anthropogenic aerosol forcing by its RFP as detailed below.

2 Radiative forcing versus radiative flux perturbation

In this paper we compare the forcings due to two well-mixed greenhouse gases, the direct aerosol forcing and the cloud albedo effect as described in Table 1 from five atmospheric GCMs with the

[1] likely refers to a $>$ 66% probability of occurrence

respective RFP that take fast feedbacks and interactions into account. Indirect aerosol effects beyond the cloud albedo effect cannot be compared this way because they comprise fast feedbacks and interactions and thus no forcing calculation can be done for them. The versions of the participating GCMs are: CSIRO in low resolution (Rotstayn et al., 2007; Rotstayn and Liu, 2009), EC-Earth (Storelvmo et al., 2009), ECHAM5 (Lohmann et al., 2008), GISS (Menon et al., 2008), and HadGEM2 (Collins et al., 2008). These models vary in the complexity with which they describe aerosol-cloud interactions and thus provide a reasonable spread in radiative forcing and radiative flux perturbation estimates. All models include anthropogenic emissions of sulfate precursors, organic and black carbon. Therefore the direct aerosol effect accounts for black carbon in all models and the semi-direct effect of black carbon is accounted for in the RFP calculations. However, only in the CSIRO and ECHAM5 GCMs does hydrophilic black carbon also contribute to the number of cloud droplets and thus to the cloud albedo effect. The radiative forcing and RFP calculations are conducted by using prescribed sea-surface temperature and sea ice extent, which is also referred to as the Hansen-style method to estimate forcing (Hansen et al., 2002).

For the forcing calculations using the traditional forcing definition, denoted F, the radiation code of the models was called twice keeping the meteorology fixed. The differences between two radiative transfer calculations due to pre-industrial GHG or aerosol concentrations versus their present-day values were extracted at the top-of-the-atmosphere and at the tropopause (or at 100 hPa which some GCMs took as a surrogate for the tropopause). The forcing calculation at the tropopause is necessary to account for the fast stratospheric temperature adjustment as a response to the warming due to molecular absorption by greenhouse gases (Hansen et al., 1997). In the second set of experiments, the simulations were run for 5-10 years each after a spin-up period of several months under conditions appropriate for the present-day climate. As the meteorology is different when varying greenhouse concentrations or aerosols, here the radiative effects of the forcing agents will be evaluated as RFP, defined as the difference in the net TOA radiation balance between the pre-industrial and present-day simulations.

In cases where GCMs have aerosols that interact with cloud microphysics and where the aerosols are radiatively active at the same time, RFP calculations for individual aerosol effects are more complicated. Here the interaction between aerosols and cloud droplets is artificially deactivated by prescribing a cloud droplet number concentration N_c for the calculation of precipitation formation. Moreover, aerosol concentrations were put to zero for the time evolution of the model. Then the forcings due to the direct aerosol effect and the cloud albedo effect are obtained from the difference of the forcing calculations in a simulation with present-day and one with pre-industrial emissions. Taking the difference between present-day and pre-industrial forcing is necessary as in each simulation the total forcing (present-day minus zero aerosols and pre-industrial minus zero aerosols) is calculated. RFP calculations are performed as for GHGs. For all radiative flux perturbations, the interannual standard deviation was calculated (Snedecor and Cochran, 1989).

The estimates of RFP vs. F at TOA and at the tropopause for the different forcing agents from the five GCMs are shown in Figure 2. The difference between tropopause and TOA forcing is only important for CO_2 as an increase in CO_2 warms the troposphere but cools the stratosphere. If a stratospheric temperature adjustment would have been allowed in these simulations, then F at TOA would equal F at the tropopause. Therefore for CO_2 RFP at TOA needs to be compared to F at the tropopause as shown in the right panel.

For the majority of these different estimates, the F values for the net radiation at the tropopause fall within the $RFP \pm$ their interannual standard deviation. Deviations occur mainly for the larger forcings (carbon dioxide and the first indirect effect) especially for those models with larger forcings for a given species. For individual models explanations can be found that relate to the way the cloud feedback differs in these simulations. The negative F and RFP values for the aerosol effects and their deviations from the one-to-one line are reflected in the shortwave F and RFP values. The positive F and RFP values for the greenhouse gases and their deviations from the one-to-one line are dominated by their longwave signals (Figure 2). The scatter plot of the net radiation tropopause forcing versus RFP also includes a literature estimate of the direct aerosol effect by Hansen et al. (2005).

Deviations between the forcing and RFP estimates are smaller in the clear-sky case where the influence of cloud feedbacks is much smaller (Figure 3). Unfortunately the clear-sky results are only available for the TOA forcing but not for the tropopause forcing. Changes in total cloud cover, liquid and ice water path remain below 1% of their present-day values in all RFP simulations and models (not shown). Thus, the zonal and annual mean pattern of the RFP estimates are a noisy version of the forcing distributions because of the inclusion of fast interactions and feedbacks in the latter but are not fundamentally different (Figures 4, 5, 6).

This is a very powerful result as it shows that RFP estimates are consistent with forcing calculations using the traditional approach for all the species/effects considered here. This implies that in the global mean fast interactions due to aerosol-cloud interactions but also the water vapor, lapse rate and land surface temperature feedbacks are not that important for the investigated species/effects.

3 Conclusions

In this paper we argued that feedbacks and interactions that are fast as compared to the time scale of global warming should be included when estimating the total anthropogenic aerosol effect. Doing so allows the total anthropogenic aerosol effect, which we cannot evaluate as a forcing precisely because it includes fast feedbacks and interactions and needs to be obtained from the RFP method, to be compared to the forcings due to well-mixed greenhouse gases. Thus, it can be included in future IPCC bar charts that compare the different radiative forcing agents. Moreover, replacing the global-mean aerosol forcing by its RFP is warranted because it is the overall aerosol flux perturbation that is needed for the global energy balance (Murphy et al., 2009).

4 Appendix: References for Figure 1

4.1 Cloud albedo effect:

Kaufman and Chou (1993), Jones et al. (1994), Boucher and Lohmann (1995), Chuang et al. (1997), Feichter et al. (1997), Lohmann and Feichter (1997), Rotstayn (1999), Lohmann et al. (2000), Kiehl et al. (2000), Jones et al. (2001), Williams et al. (2001), Ghan et al. (2001), Rotstayn and Penner (2001), Chuang et al. (2002), Kristjánsson (2002), Rotstayn and Liu (2003), Suzuki et al. (2004), Quaas et al. (2004), Dufresne et al. (2005), Ming et al. (2005), Chen and Penner (2005), Takemura et al. (2005), Quaas and Boucher (2005), Penner et al. (2006), Kvalevag and Myhre (2007), Quaas et al. (2008), Lebsock et al. (2008), Wang and Penner (2009), Storelvmo et al. (2009), Rotstayn and Liu (2009), Haerter et al. (2009)

4.2 Total aerosol indirect effect:

4.2.1 Cloud albedo and cloud lifetime effect:

Lohmann and Feichter (1997), Rotstayn (1999), Lohmann et al. (2000), Jones et al. (2001), Williams et al. (2001), Ghan et al. (2001), Lohmann and Lesins (2002), Menon et al. (2002), Kristjánsson (2002), Peng and Lohmann (2003), Kristjánsson et al. (2005), Ming et al. (2005), Rotstayn and Liu (2005), Takemura et al. (2005), Quaas et al. (2006), Storelvmo et al. (2006), Storelvmo et al. (2008a), Rotstayn and Liu (2009), Hoose et al. (2009)

4.2.2 Cloud albedo, cloud lifetime, direct and semi-direct effect:

Lohmann and Feichter (2001), Penner et al. (2003), Penner et al. (2006), Lohmann et al. (2007), Rotstayn et al. (2007), Posselt and Lohmann (2008), Posselt and Lohmann (2009), Quaas et al. (2009b)

4.2.3 Cloud albedo, cloud lifetime, direct effect and aerosol effects on mixed-phase clouds:

Lohmann and Diehl (2006), Jacobson (2006), Storelvmo et al. (2008a), Hoose et al. (2008b), Storelvmo et al. (2008b), Koch et al. (2009), Lohmann and Hoose (2009)

4.2.4 Cloud albedo, cloud lifetime, direct effect and aerosol effects on convective clouds:

Menon and Rotstayn (2006), Lohmann (2008), Unger et al. (2009)

4.2.5 Inverse estimates of the direct and indirect aerosol effects:

Andronova and Schlesinger (2001), Knutti et al. (2002), Gregory et al. (2002), Forest et al. (2002), Knutti et al. (2003), Forest et al. (2006), Stott et al. (2006), Shindell and Faluvegi (2009)

Acknowledgements. We like to thank Yi Ming, Steven Schwartz, William Collins, Sandrine Bony, Leo Donner and the other participants of the FIAS workshop on “Clouds in the perturbed climate system” in March 2008 for useful discussions and Sylvaine Ferrachat for technical help. UL was supported by NCCR Climate and by CSCS. SM was supported by the Office of Science at the U.S. DOE under Contract No. DE- AC02-05CH11231. SM and DK acknowledge support from the NASA MAP program. AJ was supported by the Joint DECC, Defra and MoD Integrated Climate Programme - DECC/Defra (GA01101), MoD (CBC/2B/0417_Annex C5). LR was supported in part by ACCSP.

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Tables

Table 1. Experimental set-up

Forcing agent	pre-industrial concentration	present-day concentration
CO_2	280 ppm	379 ppm
CH_4	0.715 ppm	1.774 ppm
direct aerosol effect	pre-industrial emissions (1750 or 1860)	present-day (year 2000) emissions
cloud albedo effect	pre-industrial emissions (1750 or 1860)	present-day (year 2000) emissions

Figure Captions

Fig. 1. Model, satellite and inverse estimates of the aerosol indirect effects over the last two decades. Per method or effects considered, each symbol represents one published estimate (one paper one vote). Blue represents estimates of the cloud albedo effect from GCMs (circles), GCMs combined with satellite measurements (squares) and satellite only (triangles). Red represents estimates of both the cloud albedo and cloud lifetime effect from GCMs (circles) and GCMs combined with satellite estimates (squares). The yellow circle represents an estimate of the cloud albedo, lifetime, direct and semi-direct effects. Black circles represent the aerosol effects on stratiform and convective clouds and green circles represent estimates of aerosol effects on liquid and mixed-phase clouds. The black stippled area refers to inverse estimates. In case of multiple estimates per paper, the vertical bars denote the standard deviation. See supplement for the individual papers, from which the estimates are obtained.

Fig. 2. Net, shortwave and longwave radiative flux perturbation versus TOA and tropopause forcing, respectively, from five GCMs. Vertical bars denote the interannual standard deviation in the radiative flux perturbation calculations.

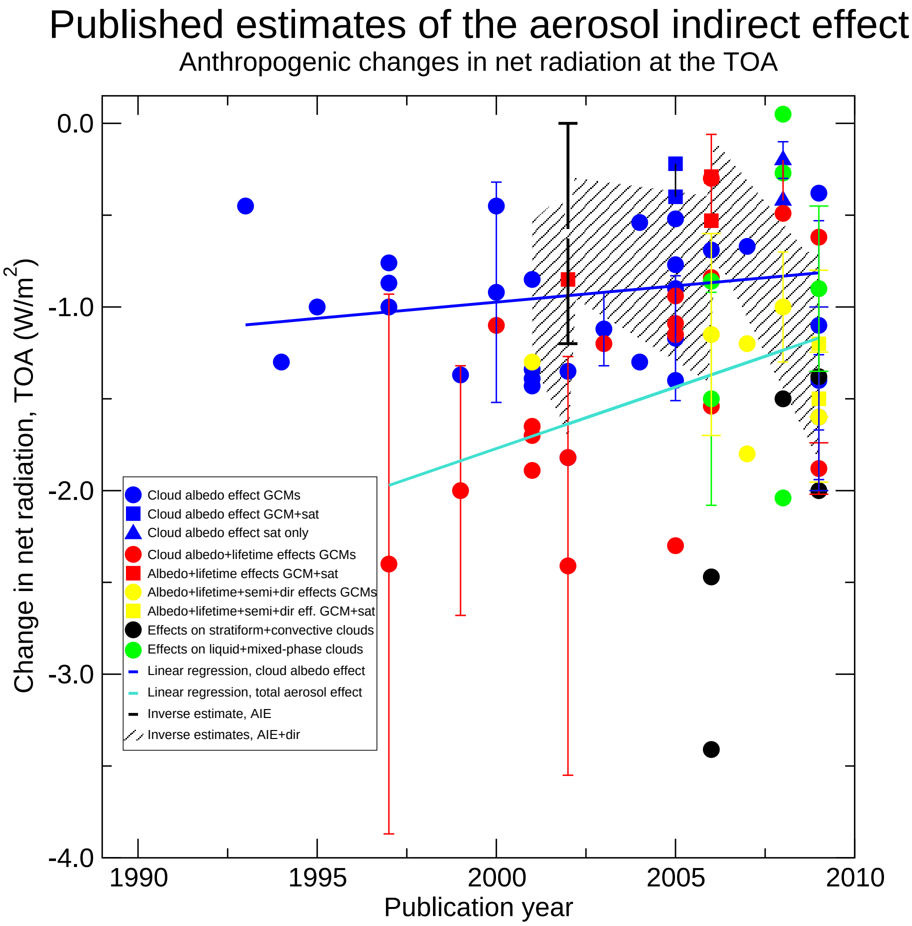
Fig. 3. As figure 2, but for the clear-sky net, shortwave and longwave radiative flux perturbation versus TOA forcing from four GCMs.

Fig. 4. Annual zonal means of F vs. RFP [W m^{-2}] for the different forcing agents from the HadGEM2 and ECHAM5 GCMs

Fig. 5. Annual zonal means of F vs. RFP [W m^{-2}] for the different forcing agents from the EC-Earth and GISS GCMs

Fig. 6. Annual zonal means of F vs. RFP [W m^{-2}] for the different forcing agents from the CSIRO GCM

Figures



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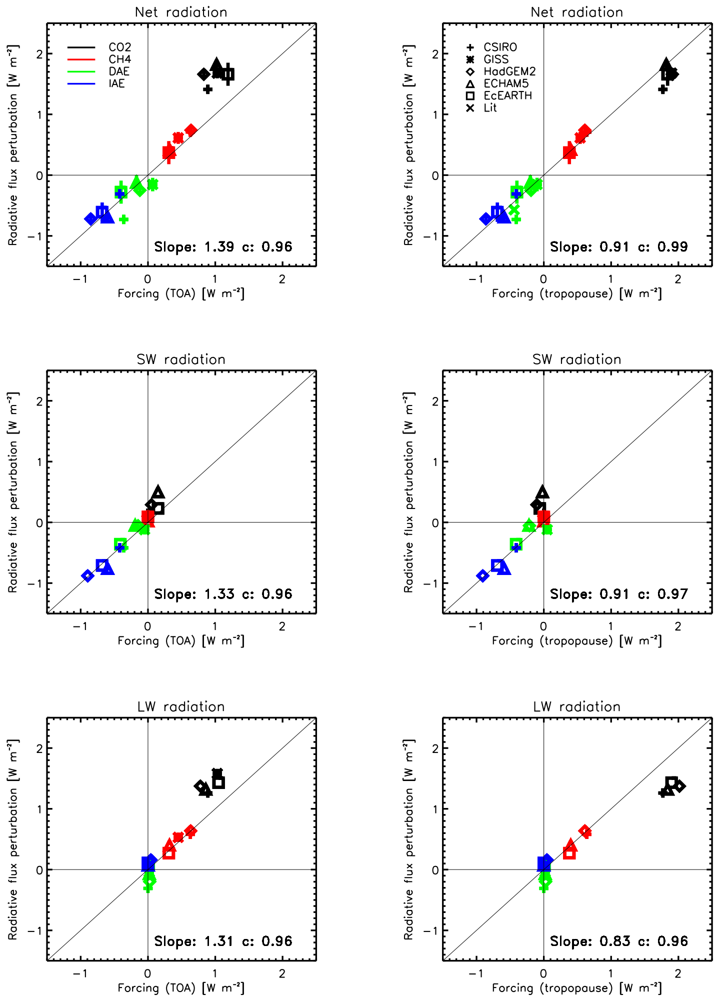

Fig. 2. Net, shortwave and longwave radiative flux perturbation versus TOA and tropopause forcing, respectively, from five GCMs. Vertical bars denote the interannual standard deviation in the radiative flux perturbation calculations.

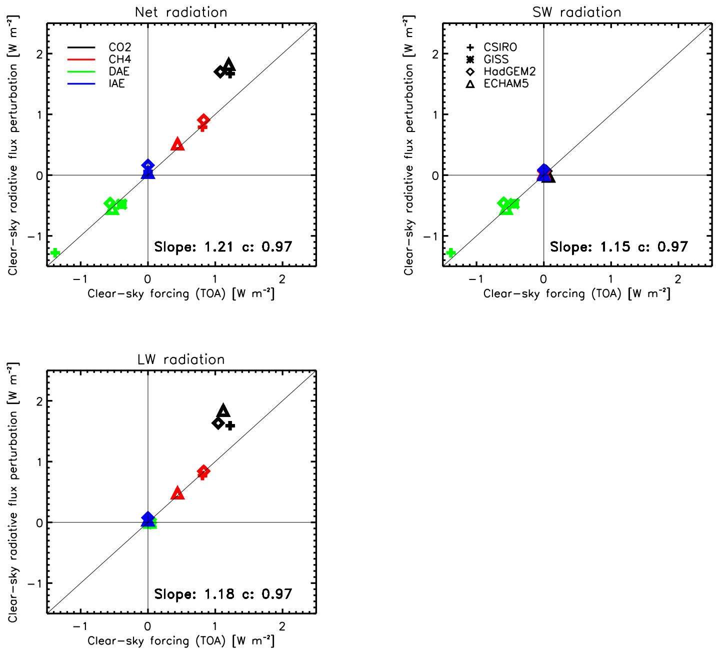

Fig. 3. As figure 2, but for the clear-sky net, shortwave and longwave radiative flux perturbation versus TOA forcing from four GCMs.

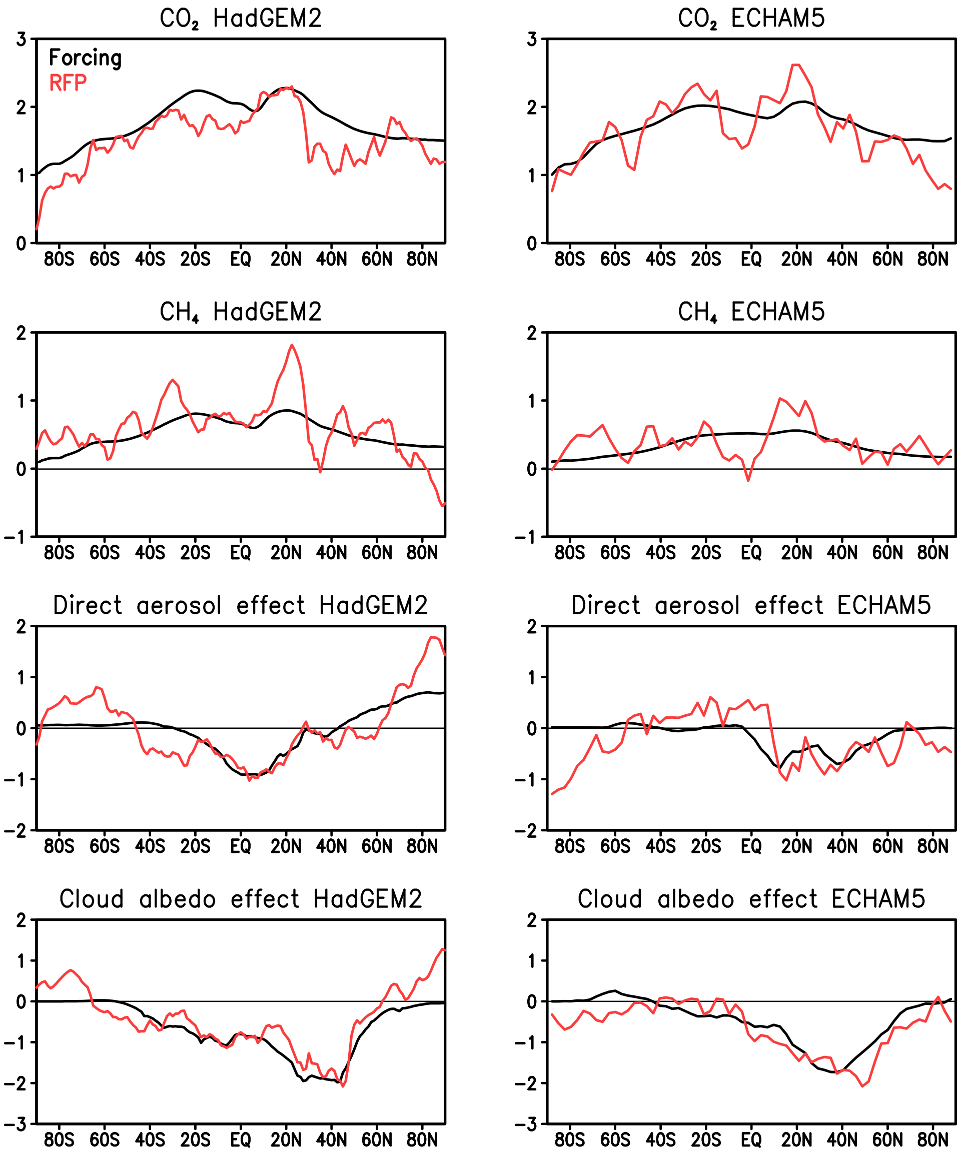

Fig. 4. Annual zonal means of F vs. RFP [W m^{-2}] for the different forcing agents from the HadGEM2 and ECHAM5 GCMs

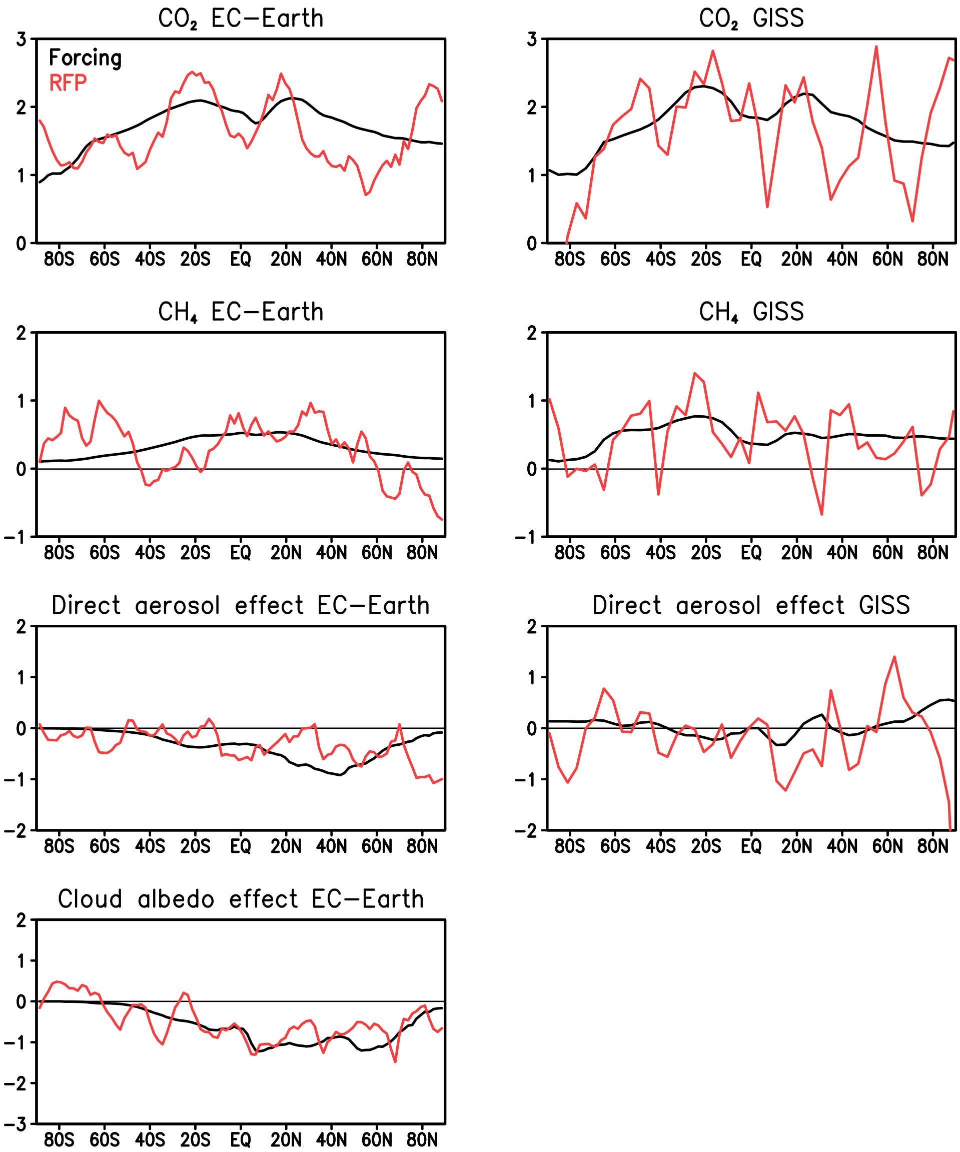

Fig. 5. Annual zonal means of F vs. RFP [W m^{-2}] for the different forcing agents from the EC-Earth and GISS GCMs

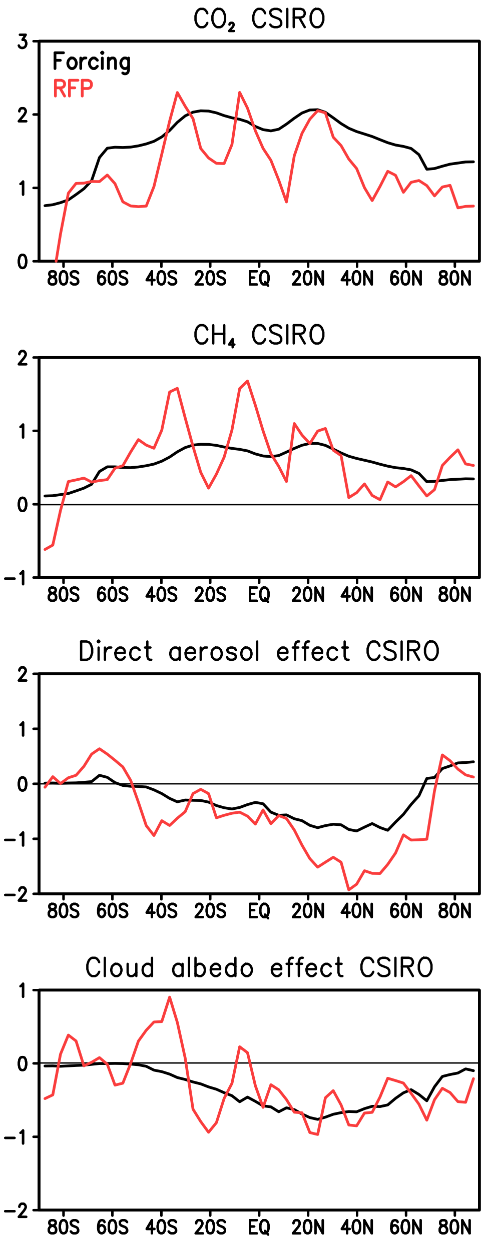

Fig. 6. Annual zonal means of F vs. RFP [W m^{-2}] for the different forcing agents from the CSIRO GCM