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Impact of parametric uncertainties on the present-day climate and on the anthropogenic aerosol effect

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Abstract

Clouds constitute a large uncertainty in global climate modeling and climate change projections as many clouds are smaller than the size of a model grid box. Some processes, such as the rates of rain and snow formation that have a large impact on climate, cannot be observed. These processes are thus used as tuning parameters in order to achieve radiation balance. Here we systematically investigate the impact of various tunable parameters within the convective and stratiform cloud schemes and of the ice cloud optical properties on the present-day climate in terms of clouds, radiation and precipitation. The total anthropogenic aerosol effect between pre-industrial and present-day times amounts to -1.00 W m^{-2} obtained as an average over all simulations as compared to -1.02 W m^{-2} from those simulations where the global annual mean top-of-the atmosphere radiation balance is within $\pm 1 \text{ W m}^{-2}$. The parametric uncertainty when taking all simulations into account has an uncertainty range of 25% between the minimum and maximum value. It is reduced to 11% when only the simulations with a balanced top-of-the atmosphere radiation are considered.

1 Introduction

Uncertainties in climate change projections stem from uncertainties in emission scenarios, structural uncertainties that measure the range of the mean responses in different models, internal variability and parametric uncertainties that are induced by uncertainties in the model parameters (Cox and Stephenson, 2007; Hawkins and Sutton, 2009). These authors showed that initially the internal variability dominates the overall uncertainty in climate change projections. As the internal variability reduces with time of projection, the total uncertainty decreases. After some decades the total uncertainty increases again caused by the increase in the scenario uncertainty.

Uncertainties in the scenario uncertainty increase with time of climate projections into the future because the scenarios depend on the demographic evolution, socio-

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economic development and technological changes and renovations. In terms of aerosols and aerosol-cloud-interactions since pre-industrial times the scenario uncertainty is caused by the different pre-industrial and present-day aerosol emission data sets. Nowadays most of the aerosol community uses the AEROCOM emissions representative for the year 1750 and for the year 2000 (Dentener et al., 2006). Nevertheless, uncertainties remain regarding for instance anthropogenic dust sources as it is not clear how important they are (Denman et al., 2007) or the question as to how much biomass burning can be considered natural and to have been there in pre-industrial times.

The structural uncertainty stems from different schemes or approaches used in different climate models. In terms of the anthropogenic aerosol effect, these are given by the complexity of the aerosol model, the cloud microphysics scheme and interactions between the two. State-of-the-art aerosol models solve at least prognostic equations for at least the mass mixing ratios of the major aerosol species sulfate, black and organic carbon, e.g. Koch et al. (2009); Rotstayn et al. (2007). Some models additionally solve prognostic equations for the number mixing ratios of the different aerosol compounds, and predict their mixing state, e.g. Stier et al. (2005); Wang and Penner (2009). The simplest way and oldest approach to account for aerosol-cloud interactions is to use empirical relationships between the aerosol mass and the cloud droplet number concentration (Boucher and Lohmann, 1995; Jones et al., 2001). Since then physically-based parametrizations have been developed (Abdul-Razzak and Ghan, 2002; Nenes and Seinfeld, 2003) and are used in some global climate models (GCMs) (Storelvmo et al., 2008; Ghan and Easter, 2006).

A large structural uncertainty related to the anthropogenic aerosol effect is caused by the representation of clouds in climate models as many clouds are smaller than the size of a model grid box. Also cloud microphysical processes occur on the subgrid scale and need to be parameterized. Some processes, such as the rain and snow formation rates, cannot be observed and are thus rather uncertain. As the rain and snow formation rates have a large impact on climate, they are used to tune the model

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in order to achieve radiation balance. This means that the precipitation formation rates are enhanced or decelerated in order to yield a top-of-the atmosphere radiation budget that is balanced to within 1 W m^{-2} and that the individual radiative fluxes agree within 5 W m^{-2} with the fluxes estimated from satellite data. These days most cloud micro-physics schemes solve at least one prognostic equation for cloud condensate whereas more complex schemes distinguish between water and ice and also predict the number concentrations of cloud droplets and ice crystals (Lohmann et al., 2007; Morrison and Gettelman, 2008) or solve prognostic equations also for the mass mixing ratios of rain and snow (Fowler et al., 1996).

Uncertainties in the first indirect aerosol effect by anthropogenic sulfate aerosols were first investigated by Pan et al. (1998). The first indirect aerosol effect or cloud albedo effect refers to an increase in cloud albedo due to more and smaller cloud droplets formed on the larger number of anthropogenic aerosols when keeping the liquid water content constant (Twomey, 1977). The cloud albedo effect is evaluated as the difference between pre-industrial times and the present-day. Pan et al. (1998) obtained a structural uncertainty of 0.5 W m^{-2} (range between -1.2 and -1.7 W m^{-2}). In the Forth Assessment Report (AR4) of the Intergovernmental Panel of Climate Change (IPCC), the median value of the cloud albedo effect from pre-industrial times to the present-day was estimated as -0.7 W m^{-2} (Forster et al., 2007). The structural uncertainty was evaluated as the 5 to 95% range between the different estimates and amounted to -0.3 to -1.8 W m^{-2} (Forster et al., 2007). Storelvmo et al. (2009) compared four different empirical relationships between cloud droplet number concentration and aerosol mass that have been used in the transient simulations of the IPCC AR4 report (Meehl et al., 2007). Storelvmo et al. (2009) applied these different relationships within the EC-Earth GCM to show that this leads to a spread of 1.3 W m^{-2} in terms of the cloud albedo effect. On the other hand, if aerosol concentrations, the parameterization of droplet concentrations and the autoconversion rate, that describes the rate by which cloud droplets collide to form rain drops, are all specified in different GCMs then the predicted cloud albedo effect varies only between -0.6 to -0.7 W m^{-2} in different

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GCMs, thus reducing the structural uncertainty to 0.1 W m^{-2} (Penner et al., 2006).

Feedbacks due to the cloud lifetime effect, semi-direct effect or aerosol effects on mixed-phase and ice clouds can either enhance or reduce the cloud albedo effect. As shown by Penner et al. (2006) if only the aerosol emissions are prescribed in different GCMs, but the GCMs are free in the way they account for cloud droplets and the auto-conversion rate, then the structural uncertainty of total indirect aerosol effects increases from the 0.1 W m^{-2} mentioned above to 1.1 W m^{-2} . If the GCMs are also free to choose their emission data base, then all publications of the total indirect aerosol effect can be compared. As aerosols are radiatively active in most GCMs, most GCMs that evaluate changes between pre-industrial and present-day times also include estimates of the direct aerosol effect. Evaluation of the total anthropogenic aerosol effect (sum of direct effect, cloud albedo effect and other aerosol-cloud effects) in the IPCC AR4 report was thus found to be -1.2 W m^{-2} ranging from -0.2 to -2.3 W m^{-2} (Denman et al., 2007).

Estimates of the cloud albedo effect alone and of the total anthropogenic aerosol effect have become less negative with time of publication (Lohmann et al., 2010). The least square fit line of the total anthropogenic aerosol effect approaches -1.2 W m^{-2} in publications of the year 2009. Since some newer studies that were not considered in IPCC AR4 obtained a rather large negative effect, while another found a small positive effect, the structural uncertainty evaluated as the total range in estimates of the total anthropogenic aerosol effect increased to 3.5 W m^{-2} (range from $+0.1$ to -3.4 W m^{-2}).

The parametric uncertainty received more attention in recent years. Murphy et al. (2004) investigated the parametric uncertainty for climate change simulations by varying six cloud parameters. A huge ensemble of multi-thousand members was conducted within the climate-prediction.net framework where initial conditions and parameter values were systematically varied (Piani et al., 2005). In terms of the cloud albedo effect, it was investigated by Pan et al. (1998). They obtained a huge range of the cloud albedo effect from -0.1 to -5.2 W m^{-2} suggesting that the parametric uncertainty exceeds the structural uncertainty. Haerter et al. (2009) used the ECHAM5 GCM to estimate the parametric uncertainty. They found that the uncertainty due to a single investigated

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parameters can be as large as 0.5 W m^{-2} , and the uncertainty due to combinations of these parameters can reach more than 1 W m^{-2} as compared to a cloud albedo effect from sulfate aerosols alone of -1.9 W m^{-2} obtained with their model set-up.

In this paper we investigate the parametric uncertainty in terms of the present-day climate and for the total anthropogenic aerosol effect between pre-industrial times and the present-day.

2 Model description

The version of ECHAM5 used in this study has been described in Lohmann and Hoose (2009). It includes the two-moment aerosol scheme HAM that predicts the aerosol mixing state in addition to the aerosol mass and number concentrations (Stier et al., 2005). The size-distribution is represented by a superposition of log-normal modes including the major global aerosol compounds sulfate, black carbon, organic carbon, sea salt and mineral dust. Updates to the aerosol scheme are briefly mentioned in Lohmann and Hoose (2009). They include the aerosol-size dependent below-cloud scavenging by (Croft et al., 2009), water uptake by aerosols following Petters and Kreidenweis (2007) and a revised aerosol nucleation scheme (Kazil and Lovejoy, 2007).

The stratiform cloud scheme consists of prognostic equations for the water phases (vapor, liquid, solid), bulk cloud microphysics (Lohmann and Roeckner, 1996), and an empirical cloud cover scheme (Sundqvist et al., 1989). The microphysics scheme includes phase changes between the water components and precipitation processes (autoconversion, accretion, aggregation). Moreover, evaporation of rain and melting of snow are considered, as well as sedimentation of cloud ice. It also includes prognostic equations of the number concentrations of cloud droplets and ice crystals and has been coupled to the aerosol scheme HAM (Lohmann et al., 2007). Cirrus clouds are assumed to form by homogeneous freezing of supercooled solution droplets (Lohmann et al., 2008), which is the dominant freezing mechanism for cirrus clouds (Kärcher and Ström, 2003).

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We assume that internally mixed dust and BC aerosols act as immersion nuclei while externally mixed dust particles act as contact nuclei (Hoose et al., 2008b). The parameterizations of immersion and contact freezing are based on those described in Lohmann and Diehl (2006). In addition we now also account for contact freezing by thermophoresis (Lohmann and Hoose, 2009).

3 Set-up of the simulations

The ECHAM5 simulations have been carried out in T42 horizontal resolution ($2.81^\circ \times 2.81^\circ$) on 19 vertical levels with the model top at 10 hPa and a timestep of 30 min. All simulations used climatological sea surface temperature and sea-ice extent. The simulation conducted to investigate the parameter space for the present-day climate have been integrated for one year after a 3 months spin-up. This simulation time would be too short to compare geographical features of the simulations to observations. However, based on our experience one year is sufficient in order to evaluate the global annual mean radiation balance at the top-of-the atmosphere (TOA), which is the goal of this study. These simulations will be referred to as climate or free simulations.

The simulations conducted to obtain the total anthropogenic aerosol effect (both for the present-day (PD) and for pre-industrial times (PI)) have been nudged to the ECMWF ERA40 reanalysis data (Simmons and Gibson, 2000) for the year 2000 so that changes in meteorology are minimized between the different simulations. The nudging time scales are 6 h for vorticity, 24 h for the logarithms of the surface pressure and temperature and 48 h for the divergence. Nudging can, however, not be used to tune the model to the present-day climate, because it changes the model climate. The nudged simulations have a higher convective activity and convective precipitation and a smaller shortwave cloud forcing (not shown). Thus, simulations that have a balanced TOA radiation budget in free mode can have a radiation imbalance of several W m^{-2} when run in nudged mode.

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The present-day simulations use aerosol emissions of sulfate, black and organic carbon from the AEROCOM data base for the year 2000 (Dentener et al., 2006). Mineral dust and sea salt emissions are calculated based on wind speed within the model. To isolate the total anthropogenic aerosol effect, all simulations were repeated with aerosol emissions of sulfate, black and organic carbon for pre-industrial times representative for the year 1750 (Dentener et al., 2006).

In order to investigate the parametric uncertainty we varied those parameters that are typically used to ensure radiation balance at TOA in the present-day climate. These includes the rate of rain formation by autoconversion (γ_r), the rate of snow formation by aggregation (γ_s), the inhomogeneity factor of ice clouds (γ_i) and the entrainment rate into deep convective clouds (ϵ). The parameterizations of the autoconversion and aggregation rate used in ECHAM5 are taken from those derived from cloud resolving models (CRM) (Khairoutdinov and Kogan, 2000; Murakami, 1990). When applied to a GCM they are likely to underpredict the rate of rain formation as the cloud water content in the cloudy part of the grid box will be less than that in a CRM. I.e. the rates of rain and snow formation are often increased in GCMs as compared to CRMs (Pincus and Klein, 2000). The inhomogeneity factor refers to the fact that a plane-parallel cloud always reflects more sunlight back to space than an inhomogeneous cloud, e.g. (Barker, 1996; Carlin et al., 2002). Therefore the optical depth of ice clouds is reduced to take inhomogeneities into account. The entrainment rate into deep convective clouds controls how much environmental air is mixed into the updrafts. As the environmental air is normally drier and colder than the updraft, entrainment of environmental air reduces the buoyancy in the updraft and the updraft stops at lower altitudes. The default values of the tuning parameters at the used resolution and the range over which they have been systematically varied are summarized in Table 1. In total we conducted 168 simulations in addition to the simulations using the default values of the tuning parameters.

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4 Present-day results

The vertically integrated cloud liquid water mass mixing ratio (liquid water path), cloud ice mass mixing ratio (ice water path), specific humidity (water vapor mass) and total cloud cover as a function of the tuning parameter for the autoconversion rate (γ_r) using the default value of the tuning parameter for the aggregation rate ($\gamma_s=800$) in the climate simulations are shown in Fig. 1. Varying γ_r primarily impacts the liquid water path. It is reduced from around 90 g m^{-2} to 40 g m^{-2} when increasing γ_r from 1 to 10. Changes in the entrainment rate and in the inhomogeneity factor of ice clouds are negligible for the liquid water path (Fig. 1). On the other hand, γ_r has no influence on the ice water path and on the total precipitation rate and only a small effect on the water vapor mass. The decrease in total cloud cover with increasing γ_r stems from a reduction in low level clouds (not shown).

The impact of varying γ_r on the radiation balance is shown in Fig. 2. Because of the decrease in liquid water path with increasing γ_r , the shortwave cloud forcing becomes smaller with increasing γ_r . The decrease in longwave cloud forcing with increasing γ_r is small because the ice water path is hardly influenced by γ_r and the decrease in mid and high level cloud cover with increasing γ_r is small (not shown). The TOA radiation budget is balanced only for $\gamma_r = 4$ and the highest value of the entrainment rate of deep convective clouds. For these simulations, the shortwave cloud forcing amounts to -50 to -52 W m^{-2} which is within 5 W m^{-2} of the observations if the ERBE satellite data of -50 W m^{-2} (Kiehl and Trenberth, 1997) or ISCCP satellite data of -51 W m^{-2} (Loeb et al., 2009) are used as a reference. However, they barely fall within 5 W m^{-2} of the observations if the CERES satellite estimate of -46.6 W m^{-2} is considered (Loeb et al., 2009). The comparison of the longwave cloud forcing with satellite observations is even less straight forward as the observations vary between 22 W m^{-2} as deduced from the TOVS satellite (Susskind et al., 1997; Scott et al., 1999), 26.5 W m^{-2} from ISCCP (Loeb et al., 2009), 29.5 W m^{-2} from CERES (Loeb et al., 2009) and 30 W m^{-2} from ERBE (Kiehl and Trenberth, 1997). All simulated values fall within this range.

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Figure 3 depicts the liquid and ice water path, water vapor mass and total cloud cover as a function of γ_s using the default value of $\gamma_r = 4$. As varying γ_s primarily impacts the ice water path, it is reduced from about 22 g m^{-2} to 6 g m^{-2} when increasing γ_s from 100 to 1200. The effects of varying the entrainment rate and the inhomogeneity factor of ice clouds are negligible for the ice water path. Varying γ_s has no systematic influence on the liquid water path. However, varying γ_r and γ_s strongly differs in that varying γ_s affects the water vapor mass significantly, but not varying γ_r . This is discussed below. The decrease in water vapor mass with increasing γ_s then leads to a larger decrease in total cloud cover than varying γ_r .

Increasing γ_s affects the latent heat and sensible heat fluxes whereas varying γ_r has no systematic effect on the heat fluxes. An increase in γ_s leads to a colder atmosphere everywhere. The relative humidity is increased in the upper troposphere but reduced near the surface. Thus, both the sensible and latent heat flux increase for larger values of γ_s (not shown).

Increasing γ_s also leads to a smaller shortwave and longwave cloud forcing (Fig. 4). The reduction in the shortwave cloud forcing is caused by the reduced ice water path and total cloud cover. As the cloud top pressure is not affected by changes in γ_s , the reduction in longwave cloud forcing is caused by the reduced ice water path and total cloud cover. The TOA radiation budget is balanced only for different combinations. It is balanced for $\gamma_s = 400$, the highest value of the entrainment rate in deep convective clouds and an inhomogeneity factor for ice clouds of 0.7. For $\gamma_s \geq 600$, the TOA radiation is balanced for the highest value of the entrainment rate of deep convective clouds irrespectively of the inhomogeneity factor for ice clouds. For the largest values of γ_s (1000 and 1200), even a smaller entrainment rate ($1.5 \times 10^{-4} \text{ kg m}^{-3} \text{ s}^{-1}$) combined with an inhomogeneity factor for ice clouds of 0.7 leads to a TOA radiative balance within 1 W m^{-2} . Because of the different observational estimates of the shortwave and longwave cloud forcing, we cannot conclude which of these combinations of the tuning parameters is the preferred one.

The ice water path and the total precipitation rate are influenced by the entrainment

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rate for deep convective clouds (ϵ) such that a larger value of ϵ implies less cloud ice. As more entrainment decreases the frequency of deep convection, there is less convective heating of the upper troposphere and less cloud ice is detrained. Also the convective precipitation decreases (not shown). Cloud water and ice that has not been converted into convective precipitation is detrained in the environment. The detrained cloud water and ice can be thought of the anvil of the convective cloud. The detrained cloud condensate is long-lived and of stratiform character. It is therefore added to the large-scale cloud water and ice. Thus, a decrease in the detrained cloud ice with increasing ϵ leads to a slightly reduced ice water path. Even though convective precipitation is decreased, the total precipitation slightly increases for a higher ϵ because more stratiform precipitation forms.

5 Impact of tuning on the anthropogenic aerosol effect

The importance of the tuning parameters on the total anthropogenic aerosol effect is shown in Fig. 5. The total anthropogenic aerosol effect is obtained from the difference in the TOA net radiation for the pre-industrial and present-day simulations. In this case, the nudged mode is used in order to keep the same meteorology while changing the emissions. The free simulations for which the radiative balance at TOA is within $\pm 1 \text{ W m}^{-2}$ are highlighted as well. The average anthropogenic aerosol effect from all simulations is -1.00 W m^{-2} as compared to -1.02 W m^{-2} from those simulations where the global annual mean TOA radiation balance is within $\pm 1 \text{ W m}^{-2}$. The values of the total anthropogenic aerosol effect in all simulations range from -1.12 W m^{-2} to -0.87 W m^{-2} . This amounts to an uncertainty range of 25% between the minimum and the maximum value, which is comparable to the parametric uncertainties obtained by Haerter et al. (2009). The uncertainty range of the simulations with a balanced TOA radiation budget is reduced to 11%, which constitutes a more representative estimate of the parametric uncertainty.

The anthropogenic aerosol effect is smaller with increasing γ_r because of the smaller

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liquid water paths for larger γ_r . The smaller liquid water path reduces the reflected shortwave radiation. In contrast, the anthropogenic aerosol effect increases very slightly when increasing γ_s and there is no systematic change when increasing ϵ or γ_i .

6 Conclusions

In this paper we investigated the impact of common tuning parameters on the present-day climate and on the anthropogenic aerosol effect. While the impact of changing the tuning parameter for rain formation in stratiform clouds is limited to stratiform clouds, changing the tuning parameter for snow formation also affects convection. Increasing the snow formation rate leads to a cooling of the upper troposphere which enhances convective activity and convective precipitation.

The TOA radiation balance falls within $\pm 1 \text{ W m}^{-2}$ for different combinations of the investigated tuning parameters. Because the different satellite estimates of the shortwave and longwave cloud forcing disagree by 4 and 8 W m^{-2} , respectively, it is not possible to conclude which combination of tuning parameters is the best one.

The total anthropogenic aerosol effect amounts to -1.00 W m^{-2} obtained as an average over all simulations as compared to -1.02 W m^{-2} from those simulations where the global annual mean TOA radiation balance is within $\pm 1 \text{ W m}^{-2}$. The parametric uncertainty when taking all simulations into account is 25% as compared to 11% when only the simulations with a balanced TOA radiation budget are considered. This uncertainty is much smaller than the structural uncertainty between different models (Penner et al., 2006; Lohmann et al., 2010).

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uncertainties**U. Lohmann and
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Tuning parameter	Description	Default value	Investigated values
γ_r	autoconversion rate	4	1, 4, 7, 10
γ_s	aggregation rate	800	100, 250, 400, 600, 800, 1000, 1200
γ_i	inhomogeneity factor of ice clouds	0.75	0.7, 0.9
ϵ	entrainment rate for deep convection ($\text{kg m}^{-3} \text{s}^{-1}$)	2×10^{-4}	1×10^{-4} , 1.5×10^{-4} , 2×10^{-4}

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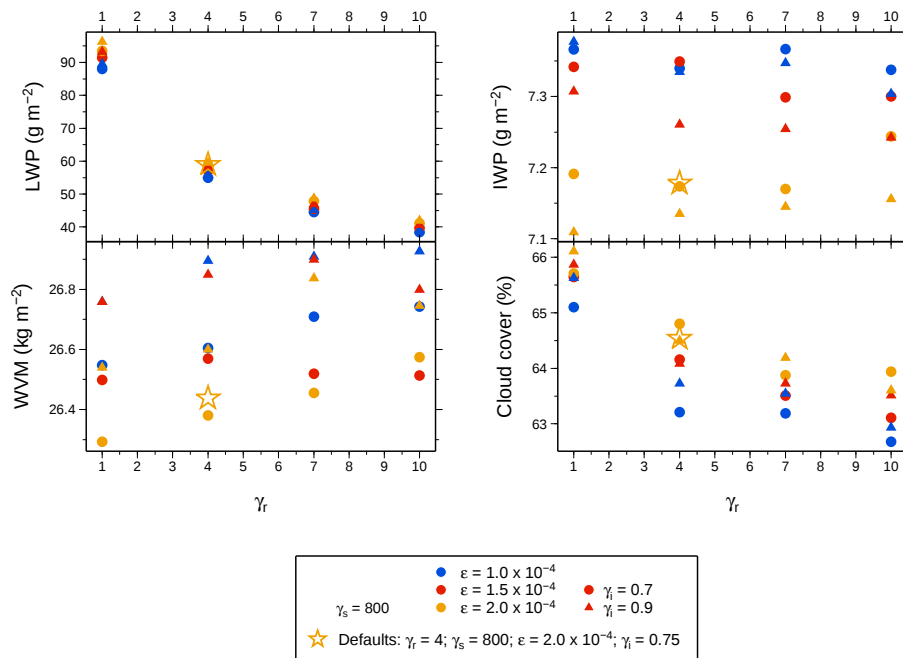


Fig. 1. Liquid water path (LWP), ice water path (IWP), water vapor mass (WVM) and total cloud cover as a function of γ_r in the climate simulations.

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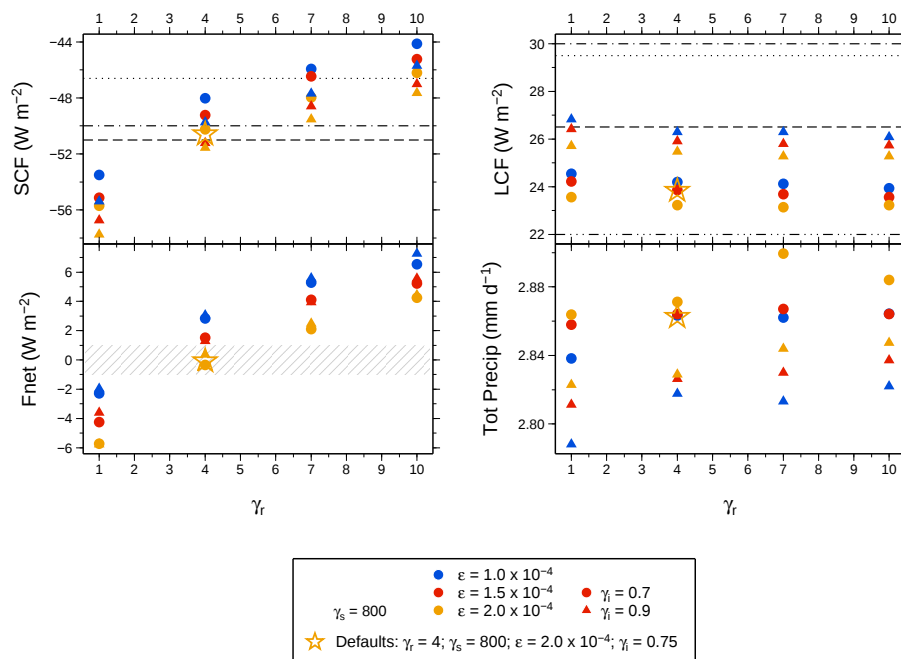


Fig. 2. Shortwave cloud forcing (SCF), longwave cloud forcing (LCF) and net radiation (F_{net}) at the top-of-the-atmosphere and total precipitation as a function of γ_r in the climate simulations. The observed estimates of the shortwave and longwave cloud forcing are shown as black lines (see text for details). The shaded area in the TOA net radiation refers to the desired range of $\pm 1 \text{ W m}^{-2}$.

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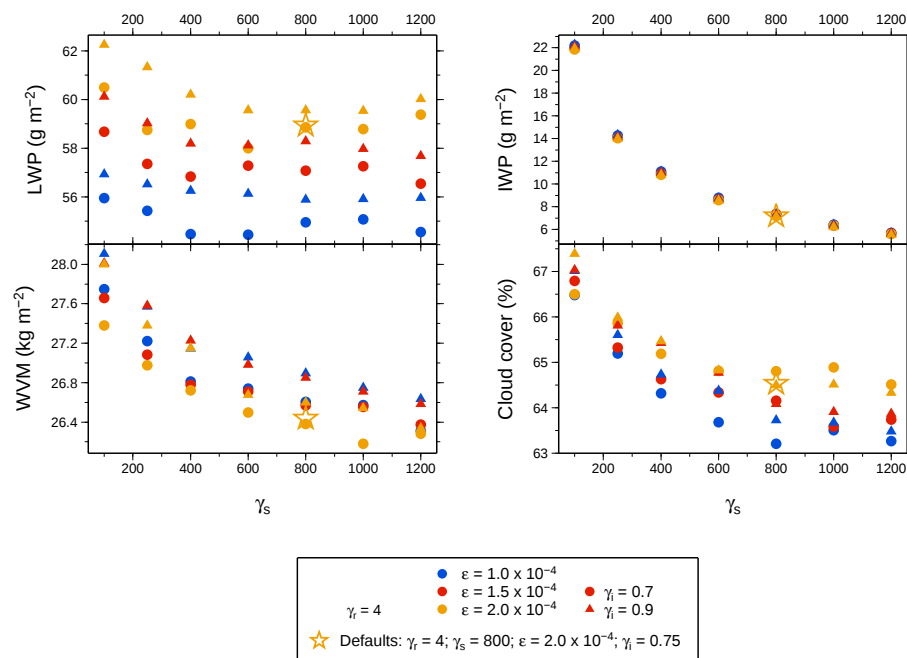


Fig. 3. As Fig. 1 but as a function of γ_s .

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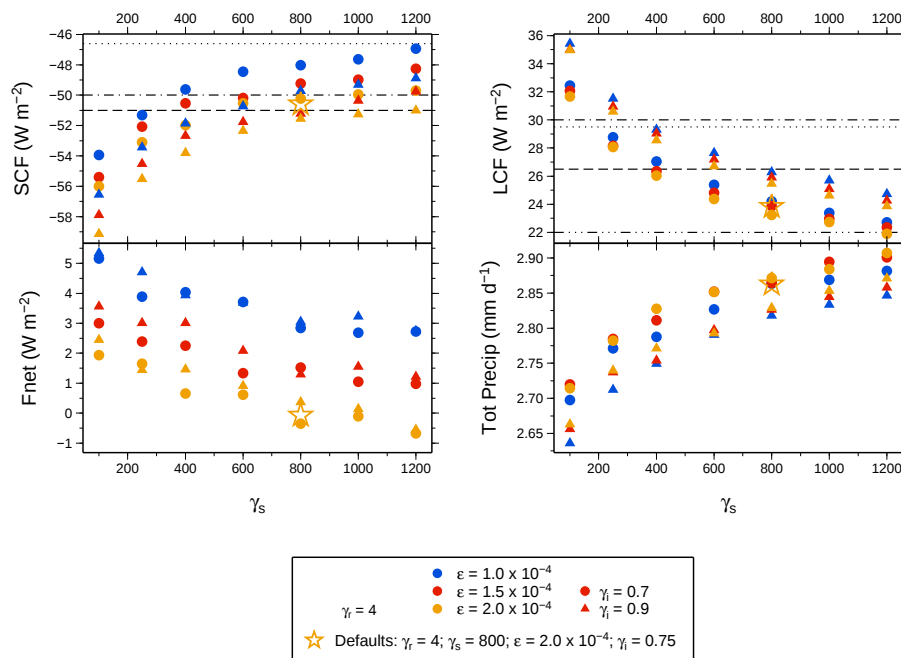


Fig. 4. As Fig. 4 but as a function of γ_s .

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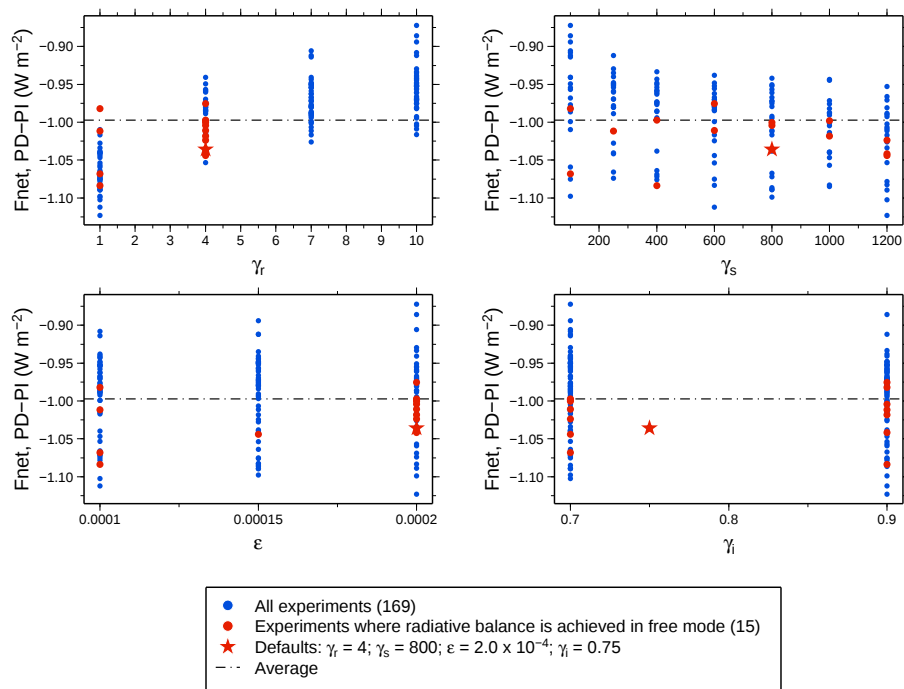


Fig. 5. Difference in the global annual mean net radiation at the top-of-the-atmosphere between pre-industrial times and the present day as a function of γ_r (top left), γ_s (top right), ε (bottom left) and γ_i (bottom right) obtained from the nudged simulations.

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