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Standard climate models radiation codes underestimate black carbon radiative forcing

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Abstract

Radiative forcing (RF) of black carbon (BC) in the atmosphere is estimated using radiative transfer codes of various complexities. Here we show that the 2-stream radiative transfer codes used most in climate models give too strong forward scattering, leading to enhanced absorption at the surface and too weak absorption by BC. Such calculations are found to underestimate RF by 10 % for global mean, all sky conditions, relative to the more sophisticated multi-stream models. The underestimation occurs primarily for low surface albedo, even though BC is more efficient for absorption of solar radiation at high surface albedo.

1 Introduction

Black carbon (BC) in the atmosphere has been investigated over many decades (Novakov and Rosen, 2013). The first estimate of radiative forcing of BC on a global scale was provided already two decades ago (Haywood and Shine, 1995). However, the diversity in existing estimates of the climate effect of BC is large (Bond et al., 2013; Boucher et al., 2013; Myhre et al., 2013). The causes for the diversity in estimates are manifold, from emissions (Amann et al., 2013; Cohen and Wang, 2014; Lam et al., 2012; Stohl et al., 2013; Wang, R. et al., 2014), lifetime and abundance (Hodnebrog et al., 2014; Samset et al., 2014; Wang, Q. Q. et al., 2014) to radiative efficiency (Samset et al., 2013; Zarzycki and Bond, 2010).

When estimating BC RF, the radiative transfer code is a crucial component. Accurate results can be achieved by using multi-stream line-by-line codes. However, these calculations are computationally demanding and are usually not applied for global scale simulations. In present climate models, simplified radiation schemes of various complexity are therefore used, and compared against line-by-line results, and each other, as consistency checks.

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Several radiation intercomparison exercises have been taken place (Boucher et al., 1998; Collins et al., 2006; Ellingson et al., 1991; Forster et al., 2011, 2005; Myhre et al., 2009b; Randles et al., 2013), yielding important suggestions for improvement to the radiative transfer codes. Randles et al. (2013) found that many of the presently used radiative transfer codes underestimate the radiative effect of absorbing aerosols, relative to benchmark multi-stream line-by-line codes. Further, one of the radiative transfer codes was run both as a multi-stream code resembling the benchmark codes, as well as run as a 2-stream code resembling the simpler codes used in climate models. The results indicated that the number of streams in the radiative transfer calculation, i.e. the number of angles through which radiation is allowed to scatter, is crucial for the differences found between the radiation codes. On average, the simpler codes underestimated the radiative effect of BC by 10–15 % relative to the benchmark line-by-line codes. In the present study we further investigate this potential underestimation of BC RF in many of the global climate models, and develop a physical understanding for why it occurs.

2 Models and methods

Simulations in the present paper were performed with a radiative transfer code using the discrete ordinate method (Stamnes et al., 1988). This model has previously been run in idealized experiments with prescribed vertical profiles of aerosol extinction (Randles et al., 2013) and used for global climate simulations (Myhre et al., 2009a). We used meteorological data from ECMWF, and specified aerosol optical properties (Myhre et al., 2009a) and aerosol distribution from the OsloCTM2 chemical transport model (Skeie et al., 2011). The radiative transfer code was run either in a multi-stream mode (8-streams and 16-stream) or with 2-streams and the Delta-M method (Wiscombe, 1977). To study the impact of the radiation code on global mean RF of BC, input fields and results from AeroCom Phase II were used. Here, aerosol BC abundances were specified for 1850 and 2000, and anthropogenic RF defined as the difference be-

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tween outgoing top-of-atmosphere shortwave radiative flux between these two years (Myhre et al., 2013).

3 Results

3.1 Global distribution of underestimated BC RF in models

Figure 1a shows the global mean, clear sky direct effect RF by BC, for a 2-stream simulation relative to a simulation with 8-streams. As in Randles et al. (2013) we find that the 2-stream calculation tends to give lower RF than the 8-stream one. The underestimation in the 2-stream simulation is shown here to be largest over ocean, with low surface albedo, whereas over regions with high surface albedo the 2-stream more closely reproduces the 8-stream simulation. Under clear sky conditions, the global, annual mean underestimation is 15 % (0.158 vs. 0.187 $W m^{-2}$) in the 2-stream relative to 8-stream simulation (RF (2-stream) divided by RF (8-stream)).

The radiative effect of clouds is also affected by the number of streams adopted in the radiative transfer simulations. This makes the top-of-atmosphere reflected solar radiation increase in 2-stream calculations, relative to 8-stream simulations. For all-sky conditions, the global mean underestimation of RF in the 2-stream simulation amounts to 7 %. However, modifying the scattering by clouds to get similar top-of-atmosphere solar flux as in the 8-stream simulation leads to a 10 % underestimation in the 2-stream simulation relative to the 8-stream simulation (0.254 vs. 0.283 $W m^{-2}$). The largest underestimation is over ocean, and over regions with small cloud cover, as shown in Fig. 1b.

3.2 Underestimation of BC RF as a function of altitude

Global mean RF of BC, as a function of BC located at various altitudes, is shown in Fig. 2. The figure shows results for both 2-stream and 8-stream simulations. A similar

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curve has previously been presented in Samset and Myhre (2011) for 8-steam simulations. The present curve is slightly modified, due to updated ozone and cloud fields. The same approach as in Sect. 3.1, to keep cloud scattering and therefore top-of-atmosphere radiative flux for the 2-stream simulation equal to the 8-stream simulation, has been applied.

Figure 2a clearly shows the increasing normalized RF (RF exerted per unit aerosol burden) by BC as a function of altitude, due to enhanced effect of absorbing material above scattering components. The underestimation in the 2-stream simulation is similar in magnitude for clear sky and all sky conditions, but is in relative terms larger for clear sky due to smaller absolute values (Fig. 2b).

For the all sky simulation the underestimation by the 2-stream vs. 8-stream simulation is close to 10 % for BC at all altitudes, except below 900 hPa. BC above scattering components such as clouds enhances the absorption by BC, as do the presence of scattering aerosol types, and Rayleigh scattering. Absorption by gases such as ozone and water vapour, as well as absorption by other aerosol types, reduces the absorption by BC. For all sky conditions, Fig. 2 shows a large degree of compensation by scattering and absorption by gases, and other aerosol types than BC. In a model simulation with only BC in the atmosphere, the normalized RF of BC was found to be 1 % higher in 2-stream simulations than in 8-stream simulations, showing the importance of the other atmospheric components for the correct determination of BC RF.

3.3 Physical description of the underestimation of BC RF

The radiative forcing due to aerosols is known to be a strong function of surface albedo (Haywood and Shine, 1997). This is illustrated in Fig. 3a, where the radiative effect of aerosols with different single scattering albedo has been calculated as a function of surface albedo. We reproduce the well-known characteristics of largest impact of absorbing aerosols over bright surfaces, and of scattering aerosols over dark surfaces.

Figure 3b shows the difference between 2-stream and 16-stream calculations, as a function of surface albedo, and for a range of aerosol single scattering albedos. 2-

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stream and 16-stream results deviate substantially between surface albedos of 0.05 and 0.2. These are surface albedo values where absorbing aerosols have a relatively weak radiative effect. An increasing single scattering albedo gives increasing underestimations of 2-stream results (Fig. 3b) and at the same time a decreasing radiative effect (Fig. 3a).

Our interpretation of the cause for the underestimation of 2-steam results relative to multi-stream results is lack of sufficient multiple scattering in connection to forward scattering and low surface albedo. Under such conditions the scattering is too strong in the forward direction in 2-stream approaches. In addition the low surface albedo, and thus strong surface absorption, hinders further multiple scattering. Multiple scattering in general enhances the radiative effect of absorbing aerosols.

To illustrate the importance multiple scattering for the abovementioned underestimation, additional simulations show that purely absorbing aerosols in a non-scattering atmosphere have differences between 2-stream and multi-stream results within only a few percent (less than 2 %), which is the typical deviation as shown in Fig. 3b, except for at low surface albedo.

The results shown in Fig. 3 are for a solar zenith angle of 30°, but are generally applicable for other solar zenith angles. However, note that the critical single scattering albedo for transitioning from positive to negative radiative effect decreases with increasing solar zenith angle.

The underestimation shown in Randles et al. (2013) can also be seen in Fig. 3b for single scattering 0.75 (close to 0.8 used in the paper) and for surface albedo of 0.2 of around 10 %.

4 Conclusions

Two-stream approximations using the Delta-M method, as employed by a majority of present climate models, are found to be relatively accurate for absorbing aerosols. The exception is over areas with low surface albedo. Here, the enhanced forward scattering

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hinders sufficient multiple scattering, causing an underestimation of the radiative effect of BC. Low albedo occurs in regions with low cloud cover, and low surface albedo such as ocean and snow free forest. In such cases the underestimation relative to more advanced radiation schemes can be of the order of 20–25 %.

On a global scale we simulate a 10 % underestimation for all-sky conditions, and 15 % for clear sky, for 2-stream relative to 8-streams. The implication of this underestimation is that recent estimates of global mean RF due to BC, e.g. in Myhre et al. (2013) and Bond et al. (2013), where the latter is based on radiative transfer calculations in Schulz et al. (2006), are around 10 % too weak, as they are primarily based on models with radiative transfer codes with 2-stream simulations. It must however be noted that other issues related to radiative transfer codes may lead to compensation of this underestimation, or additional underestimation. In addition, uncertainties in the abundance of BC, and in its optical properties, are much larger than 10 %. Even so, radiation schemes in global climate models should be improved to provide more accurate calculations of present and future radiative forcing due to BC.

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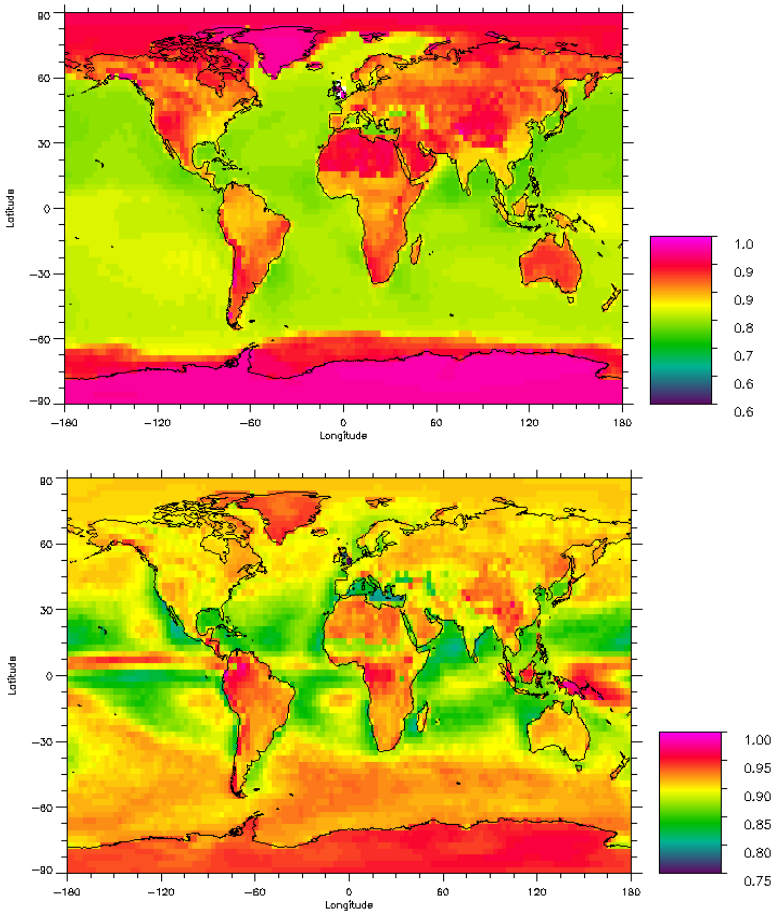

Figure 1. Geographical distribution of relative difference between annual mean RF of BC from 2-stream simulation relative to 8-stream simulation for clear sky (upper) and all sky (lower).

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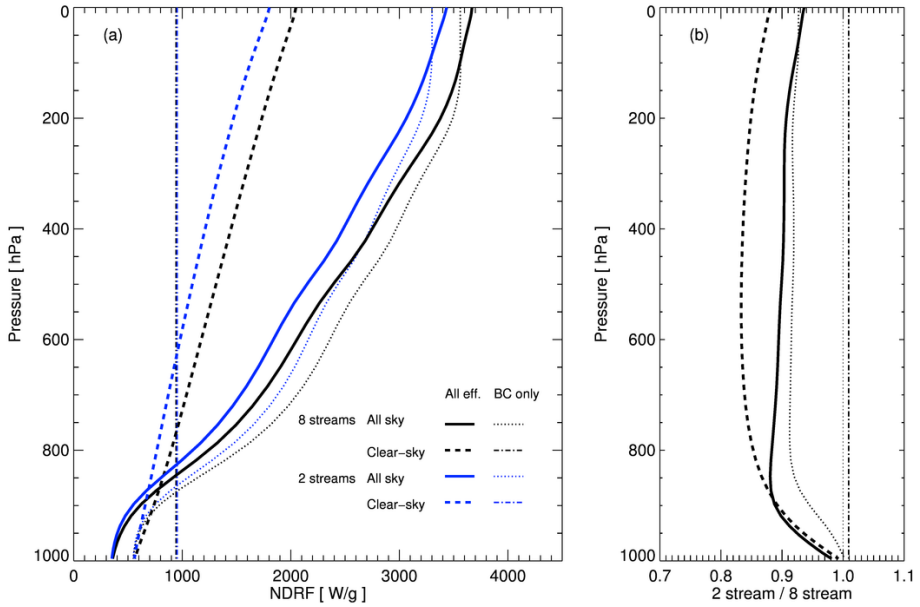

Figure 2. Normalized RF by abundance of BC as a function of altitude. The 8-stream simulations are shown in black and 2-stream simulations in blue and simulations are performed for clear-sky and all sky **(a)**. **(b)** shows the relative difference in normalized RF between 2-stream and 8-stream simulations.

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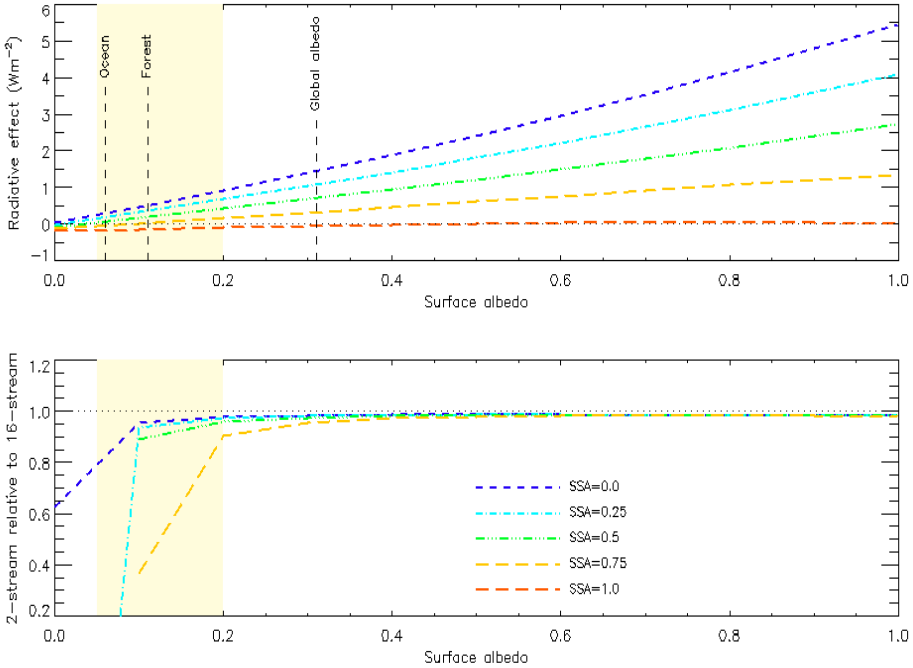

Figure 3. RF as a function of surface albedo for various single scattering albedo (upper), and relative differences between 2-stream and multi-stream simulations (lower). In cases where the sign of 2-stream and multi-stream simulations for a particular single-scattering albedo differs the results are left out of the lower panel.

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