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Biases in modeled surface snow BC mixing ratios in prescribed aerosol climate model runs

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Abstract

A series of recent studies have used prescribed aerosol deposition flux fields in climate model runs to assess forcing by black carbon in snow. In these studies, the prescribed mass deposition flux of BC to surface snow is decoupled from the mass deposition flux of snow water to the surface. Here we use a series of offline calculations to show that this approach results, on average, in a factor of about 1.5–2.5 high bias in annual-mean surface snow BC mixing ratios in three key regions for snow albedo forcing by BC: Greenland, Eurasia and North America. These biases will propagate directly to positive biases in snow and surface albedo reduction by BC. The bias is shown to be due to coupling snowfall that varies on meteorological timescales (daily or shorter) with prescribed BC mass deposition fluxes that are more temporally and spatially smooth. The result is physically non-realistic mixing ratios of BC in surface snow. We suggest that an alternative approach would be to prescribe BC mass mixing ratios in snowfall, rather than BC mass fluxes, and we show that this produces more physically realistic BC mixing ratios in snowfall and in the surface snow layer.

1 Introduction

Model studies indicate that black carbon (BC) deposited on snow and sea ice produces climatically significant radiative forcing at both global and regional scales by reducing surface albedo (“BC albedo forcing”) (e.g. Warren and Wiscombe, 1980; Hansen and Nazarenko, 2004; Jacobson et al., 2004; Flanner et al., 2007). Global, annual average radiative forcing by BC in snow has been assessed as +0.04 $\mathrm{W\,m^{-2}}$ using model estimates adjusted to observed snow concentrations (Bond et al., 2013; Boucher et al., 2013). BC snow albedo forcing has been cited in particular as a possible contributor to warming in the Arctic (e.g. Flanner et al., 2007; Koch et al., 2009), reduced springtime Eurasian snow cover (Flanner et al., 2009), melting of glaciers on the Tibetan Plateau and Himalayan mountains (Xu et al., 2009; Kopacz et al., 2011), and changes in the Asian hydrological cycle (Qian et al., 2011). Estimates of this BC albedo forcing and the resulting climate impacts rely on modeling and therefore on accurate model representation of surface snow BC concentrations.

A critical difference between forcing by BC in the atmosphere and BC in snow is that forcing by BC in the atmosphere scales with the *column burden* of BC (e.g. kg per m^2 of air column) but forcing by BC in snow scales with the *mixing ratio* of BC (e.g. kg BC per kg of snow) in the surface snow layer. This is because snow is a highly scattering medium so incident sunlight only penetrates to ∼ 10 cm depth, depending on the snow density, grain size and the mixing ratio of absorbing impurities. Therefore BC deeper in the snowpack does not produce significant forcing. Surface snow BC mixing ratios are determined by the mixing ratio of BC in snowfall (wet deposition), the settling of atmospheric BC onto the snow surface (dry deposition) and in-snow processes that alter the amount of snow (melting, sublimation) or the amount of BC (wash-out of BC with snow meltwater). It is perhaps unsurprising that sublimation is effective at raising surface snow BC mixing ratios. Empirical evidence has shown that when snow melts, the melt water washes down through the snowpack more efficiently than do particulate impurities, also leading to enhanced BC concentrations at the snow surface (Conway et al., 1996; Xu et al., 2012; Doherty et al., 2013). For models to accurately represent snow BC mixing ratios they must simulate all of these processes with fidelity.

To date, the Community Earth System Model version 1 (CESM1) is the only global climate model that accounts for all of these processes, through the SNow, ICe, and Aerosol Radiative model (SNICAR, Flanner et al., 2007) in the land component (known as the Community Land Model version 4 CLM4; Lawrence et al., 2012), which accounts for snow on land among other things. A more simplified treatment of BC in snow that is on sea ice and in the sea ice itself is also included in the most recent version of the CESM sea ice model component, CICE4 (Holland et al., 2012). In addition to treating processes that determine snow BC mixing ratios, SNICAR captures both fast and slow feedbacks that amplify the radiative forcing by BC in snow: surface snow warmed by BC absorption generally transforms to larger snow grain sizes, which further reduces snow albedo. In addition, the reduction in albedo for a given mixing ratio of BC is greater for larger-grained snow. These feedbacks further accelerate warming and lead to earlier snow melt which in turn leads to higher BC mixing ratios in surface snow as described above. Eventually this also leads to earlier exposure of the underlying surface, further reducing surface albedo (i.e. the classic “snow albedo feedback”) (Flanner et al., 2007; Flanner et al., 2009; Fig. 29 of Bond et al., 2013).

This comprehensive treatment in CESM1 made possible the recent Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) studies where BC albedo forcing was estimated for surface deposition fields derived from a suite of climate models. These deposition fields were used in offline prescribed-aerosol runs of the land and sea ice components of CESM1 (Lee et al., 2013; Shindell et al., 2013). The participating ACCMIP models in these studies each calculated BC atmospheric abundances and deposition rates using a common set of emissions. Estimated BC albedo forcing for the different models’ aerosol fields covered a wide range, reflective of differences in BC transport and deposition rates. Comparisons of the modeled snow BC mixing ratios with observed mixing ratios across the Arctic and Canadian sub-Arctic showed significant positive model biases for Greenland (a factor of 4–8), a factor of 2–5 low biases over the Arctic Ocean, and agreement to within a factor of 2–3 elsewhere, though with the exception of one model (CESM1-CAM5, which has version 5 of the Community Atmosphere Model) BC mixing ratio biases in the remaining regions were more often positive than negative (see Lee et al., 2013, Table 6).

Goldenson et al. (2012) also used CESM1 with prescribed aerosols to compute the climate impacts of BC in snow on both land and sea ice and BC in sea ice. They found significant impacts on surface warming and snowmelt timing due to changes in BC deposition in year 2000 vs. year 1850. They found that forcing by BC in snow on land surrounding the Arctic had a larger impact on Arctic surface temperatures and sea ice loss than did BC deposited on sea ice within the Arctic. On sea ice, Goldenson et al. found poor spatial correlation between modeled and observationally-estimated BC concentrations (see their Fig. 3), though the range of concentration is similar; on land, the two are better correlated but the model concentrations tend to be higher, by roughly a factor of two (Goldenson et al., 2012, Fig. 4).

Jiao et al. (2014) applied CESM to simulate BC in snow on land and sea-ice using deposition fields from the Aerosol Comparisons between Observations and Models (AeroCom) suite of global simulations. In comparison with estimates of BC in Arctic snow and sea-ice (Doherty et al., 2010), they found that models generally simulate too little BC in northern Russia and Norway, while simulating too much BC in snow elsewhere in the Arctic. As with Goldenson et al. (2012), they found poor spatial correlation between modeled and measured BC-in-snow concentrations, though the multi-model means, sub-sampled over the measurement domain, were within 25 % of the observational mean.

Here we show that the use of prescribed BC mass deposition rates, as was done in the Goldenson et al. (2012), Lee et al. (2013), Shindell et al. (2013) and Jiao et al. (2014) studies, produces significantly higher surface snow BC mixing ratios than would be given by runs with prognostic aerosol deposition. This is a direct result of BC deposition rates being decoupled from snow deposition rates in prescribed aerosol model runs, so that the mixing ratios of falling snow are physically unrealistic. In other words, the biases we find here do not reflect errors in input emissions or in modeled transport and scavenging rates but rather in the approach taken in the model to estimating surface snow BC mixing ratios.

2 Model calculations

Prescribed aerosol fields are based on prognostic aerosol model runs, where the resulting atmospheric concentrations and dry and wet mass deposition fluxes are saved as model output and this output is used as input to the prescribed runs. These prognostic model runs are initialized with emissions of aerosols and aerosol precursors that then form aerosols in the atmosphere. Aerosols are transported, dry-deposited to the surface, and scavenged in rain and snowfall according to the modeled meteorology.

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In prognostic aerosol models wet deposition of BC occurs only when there is rain or snowfall, and the mass of BC wet deposited scales with the amount of precipitation and tropospheric BC concentration, though the scaling will vary from model to model.

When prescribed, aerosol fields are typically independent of the meteorological fields in the model, as is the case in CESM1; the meteorological fields themselves in these runs may be either prescribed or prognostic. Further, the input aerosol fields are often interpolated in time from monthly means. Therefore the episodic nature of aerosol deposition in reality (owing to wet deposition) is generally absent in prescribed aerosol fields. This was the case for the prescribed aerosol studies of Goldenson et al. (2012) and Holland et al. (2012) and for all integrations of CCSM4 (i.e., CESM1-CAM4) that were submitted to CMIP5 and used in the Lee et al. (2013) and Jiao et al. (2014) studies. In the Lee et al. (2013) and Jiao et al. (2014) studies these BC deposition fields were then coupled with prescribed meteorology from CRU/NCEP reanalysis data 1996–2000 (Lee et al., 2013) or 2004–2009 (Jiao et al., 2014) to calculate surface snow mixing ratios of BC. The Climatic Research Unit (CRU)/National Center for Environmental Prediction (NCEP) data set is described at ftp://nacp.ornl.gov/synthesis/2009/frescati/model_driver/cru_ncep/analysis/readme.htm.

To test the effect of using decoupled BC mass and snow mass deposition rates on surface snow BC mixing ratios we conducted a series of offline calculations. The offline calculations used the same monthly-resolved, year-2000 BC mass deposition rates that were prescribed in 20th century integrations of CCSM4 that were submitted to CMIP5. These deposition fluxes themselves come from a separate prognostic model simulation (Lamarque et al., 2010). In one set of calculations, we use daily snowfall rates from a 10-year CESM1-CAM4 run using annually-invariant, year-2000 greenhouse gas and aerosol fields, following Goldenson et al. (2012); we will refer to these as the "CESM-met" (CESM meteorology) runs. In a second set of calculations, model snowfall rates were replaced with CRU/NCEP reanalysis daily precipitation for years 2004–2009 in order to mimic the runs reported by Jiao et al. (2014); we will refer to these as the "CRUNCEPmet" runs. The CRU/NCEP data set specifies precipitation rates but not whether it is rain or snow, so we made the simple assumption that when the reported surface air temperature was 0 °C or lower the precipitation was snowfall. In both cases, snow cover – specifically, the snow water equivalent in the surface snow layer for each day and gridbox – is the average across the 10 model years of the year-2000 CESM1-CAM4 run.

In our offline calculations we diagnose the BC mixing ratio in snowfall and in the model's surface snow layer. In CLM4, this layer is of variable thickness but is always between 1 cm and 3 cm and is 1–2 cm when snow depth exceeds 3 cm (Oleson et al., 2010). In our calculations the surface snow BC mixing ratio on day 1 is set to that from day 1 in our year-2000 prescribed aerosol CESM1-CAM4 run. The surface snow layer BC mixing ratio for subsequent days in the year are calculated offline so that on day n the surface snow layer BC mixing ratio $\mathrm{MR}_{\mathrm{BC}}^{n}$ (units: ng BC per g snow water equivalent) is given by:

$$\mathrm{MR}_{\mathrm{BC}}^{n} = \mathrm{BCdep}_{\mathrm{dry}}^{n}/\mathrm{SWE}_{\mathrm{surf}}^{n} + f_n \times \mathrm{MR}_{\mathrm{BC,snowfall}}^{n} + (1 - f_n) \times \mathrm{MR}_{\mathrm{BC}}^{n-1} \tag{1}$$

where $\mathrm{MR}_{\mathrm{BC,snowfall}}^{n}$ is the mixing ratio of BC in snowfall (ng g^{-1})

$$\mathrm{MR}_{\mathrm{BC,snowfall}}^{n} = \mathrm{BCdep}_{\mathrm{wet}}^{n}/\mathrm{SWE}_{\mathrm{snowfall}}^{n}; \tag{2}$$

$\mathrm{SWE}_{\mathrm{surf}}^{n}$ is the snow water equivalent (g m^{-2}) in the model surface snow layer on day n; $\mathrm{SWE}_{\mathrm{snowfall}}^{n}$ is the snow water equivalent of snowfall on day n (g m^{-2}); $\mathrm{BCdep}_{\mathrm{dry}}^{n}$ and $\mathrm{BCdep}_{\mathrm{wet}}^{n}$ are the dry and wet mass deposition rates (ng m^{-2}-sec) on day n; $\mathrm{MR}_{\mathrm{BC}}^{n-1}$ is the surface snow layer BC mixing ratio on day $n-1$; and f_n is the fraction of the surface snow layer water equivalent that falls as new snow on day n:

$$f_n = \mathrm{SWE}_{\mathrm{snowfall}}^{n}/\mathrm{SWE}_{\mathrm{surf}}^{n}. \tag{3}$$

If f_n is greater than 1.0, new snowfall contributes to the mixing ratio of both the surface-most layer and the second snow layer. Since our offline calculations are only tracking

MR_{BC} in the surface-most layer, if f_n is greater than 1.0 we simply set $f_n = 1.0$. All calculations are done at daily resolution. This is analogous to the way SNICAR calculates MR_{BC} in the model surface snow layer. Not included in our offline calculations of MR_{BC}, but accounted for by SNICAR, are the loss of surface snow water to sublimation and the effects of melting, both of which lead to higher values of MR_{BC}. By not including these in our offline calculations we are isolating how dry and wet deposition only affect MR_{BC}. While the focus here is on BC, the same conclusions would apply for deposition/surface snow mixing ratios of dust and organic aerosols.

In CESM1-CAM4.0, the BC deposition flux at a given time is interpolated from monthly input fields (Fig. 1). The result is daily mass deposition rates that are both temporally and spatially smooth. Daily precipitation rates in CLM, however, are not smoothed. Thus, monthly smoothed values of $BCdep_{wet}$ are being paired with meteorologically-variable values of $SWE_{snowfall}$ – i.e. precipitation and wet deposition are decoupled. MR_{BC} at each timestep n is determined by summed contributions of the ratio of deposited BC to deposited snowfall. Since the sum of a series of ratios ($MR_{BC,snowfall}$) does not equal the ratio of summed numerators ($BCdep_{wet}$) and denominators ($SWE_{snowfall}$) we expect this decoupling of deposition and snowfall will lead to biases in MR_{BC}. In addition, if there is a large amount of new snowfall, $MR_{BC,snowfall}$ will be anomalously low, but much of this low-mixing-ratio snow will be buried in the snowpack where less (or no) sunlight interacts with it. In contrast, if there is only a small amount of new snowfall, $MR_{BC,snowfall}$ will be anomalously high, and this high-mixing-ratio snow will be near the snow surface and interact with sunlight. Thus, low snowfall/high $MR_{BC,snowfall}$ precipitation events will have a greater influence on snow albedo than high snowfall/low $MR_{BC,snowfall}$ precipitation events.

As noted above, BC albedo forcing scales with the mixing ratio of BC in snowfall ($MR_{BC,snowfall}$) not the BC wet deposition mass flux ($BCdep_{wet}$) so it is important that $MR_{BC,snowfall}$ is physically realistic. Below we will show that $MR_{BC,snowfall}$ and MR_{BC} are biased high (and therefore albedo biased low) when $MR_{BC,snowfall}$ is calculated using smoothed, prescribed $BCdep_{wet}$ paired with daily-varying snowfall rates in Eqs. (2) and

(3), vs. when it is calculated using smoothed, prescribed $\mathrm{BCdep_{wet}}$ paired with similarly smoothed snowfall rates. This is based on a series of offline calculations of $\mathrm{MR_{BC}}$, using Eq. (1) and three different calculations for $\mathrm{MR}^{n}_{\mathrm{BC,snowfall}}$ (Eq. 2). Calculations are done for either 10 years, using $\mathrm{SWE_{snowfall}}$ values from the model (CESMmet; repeating year 2000 meteorology) or 6 years, using $\mathrm{SWE_{snowfall}}$ from the CRU/NCEP reanalysis data set (CRUNCEPmet; years 2004–2009 meteorology).

The first method of calculating $\mathrm{MR_{BC,snowfall}}$ is analogous to how BC deposition is treated in CESM1 when aerosol deposition fluxes are prescribed; i.e., time-averaged, smoothed prescribed $\mathrm{BCdep_{wet}}$ is paired with daily-varying $\mathrm{SWE_{snowfall}}$. The next two sets of $\mathrm{MR_{BC,snowfall}}$ calculations use $\mathrm{SWE_{snowfall}}$ values that have been increasingly time-averaged, and so are more physically consistent with $\mathrm{BCdep_{wet}}$, which as noted above is the product of averaging across multiple prognostic model run years. Specifically, our three sets of calculations of $\mathrm{MR_{BC,snowfall}}$ are as follows:

1. $[\mathrm{MR_{BC,snowfall}}]_\mathrm{d}$: Each day $\mathrm{MR_{BC,snowfall}}$ is calculated as the ratio of the prescribed daily $\mathrm{BCdep_{wet}}$ (e.g. Fig. 1) and daily $\mathrm{SWE_{snowfall}}$ as given by the model (NCARmet runs) or the reanalysis data (CRUNCEP runs).

2. $[\mathrm{MR_{BC,snowfall}}]_\mathrm{m}$: Within each month of the multi-year run, modeled $\mathrm{SWE_{snowfall}}$ and prescribed $\mathrm{BCdep_{wet}}$ are summed. Monthly values of $\mathrm{MR_{BC,snowfall}}$ are calculated from the ratio of the monthly-total $\mathrm{BCdep_{wet}}$ and monthly-total $\mathrm{SWE_{snowfall}}$ given by the model (NCARmet runs) or the reanalysis data (CRUNCEP runs).

3. $[\mathrm{MR_{BC,snowfall}}]_\mathrm{y}$: A monthly climatology of $\mathrm{SWE_{snowfall}}$ is computed for 6 years (CRUNCEPmet) or 10 years (CESMmet). Monthly values of $\mathrm{MR_{BC,snowfall}}$ are calculated from the ratio of the monthly-total $\mathrm{BCdep_{wet}}$ and the monthly climatology of $\mathrm{SWE_{snowfall}}$.

These, in turn, are used in Eq. (1) to calculate three set of surface snow BC mixing ratios, $[\mathrm{MR_{BC}}]_\mathrm{d}$, $[\mathrm{MR_{BC}}]_\mathrm{m}$ and $[\mathrm{MR_{BC}}]_\mathrm{y}$.

3 Results

When we use daily snowfall from CESM1-CAM4, the mixing ratio of BC in snowfall, $[\mathrm{MR}_{\mathrm{BC,snowfall}}]_\mathrm{d}$, is extremely variable (Fig. 2a), because $\mathrm{BCdep}_\mathrm{wet}$ is smoothly varying (Fig. 1) but snowfall is episodic. $[\mathrm{MR}_{\mathrm{BC,snowfall}}]_\mathrm{d}$ computed with snowfall from the CRUNCEPmet data (not shown) are similarly variable. If snowfall on a particular day approaches zero $[\mathrm{MR}_{\mathrm{BC,snowfall}}]_\mathrm{d}$ approaches infinity (i.e. the unrealistically high mean of Fig. 2a), though f_n simultaneously approaches zero; conversely, heavier snowfall events are associated with anomalously low values of $[\mathrm{MR}_{\mathrm{BC,snowfall}}]_\mathrm{d}$. In the real world, $\mathrm{BCdep}_\mathrm{wet}$ is, by definition, a function of precipitation rates, so actual $\mathrm{MR}_{\mathrm{BC,snowfall}}$ is much less variable. $[\mathrm{MR}_{\mathrm{BC,snowfall}}]_\mathrm{m}$ is dramatically less variable but still covers a significant range (Fig. 2b). When the smooth values of $\mathrm{BCdep}_\mathrm{wet}$ (Fig. 1) are combined with a 10 year monthly snowfall climatology the mixing ratios of BC in snowfall, $[\mathrm{MR}_{\mathrm{BC,snowfall}}]_\mathrm{y}$ (Fig. 2c), become much less variable and, importantly, systematically lower.

For albedo reduction, and therefore radiative forcing, of interest is how the mixing ratio of BC in surface snow, MR_BC, varies. We calculate this using Eqs. (1) and (3) and the three sets of $\mathrm{MR}_{\mathrm{BC,snowfall}}$ described above. Note that while averaged values of $\mathrm{SWE}_\mathrm{snowfall}$ were used to calculate $[\mathrm{MR}_{\mathrm{BC,snowfall}}]_\mathrm{m}$ and $[\mathrm{MR}_{\mathrm{BC,snowfall}}]_\mathrm{y}$, the fraction of surface snow replaced by new snowfall (f_n in Eq. 3) is always calculated using the daily-varying value of $\mathrm{SWE}_\mathrm{snowfall}$ from either CESM1-CAM4 (CESMmet) or the CRU/NCEP reanalysis data set (CRUNCEPmet). In other words, the rate of snowfall varies daily according to the model (CESMmet) or reanalysis (CRUNCEPmet) meteorology in all calculations but the BC mixing ratio in that snowfall is either $[\mathrm{MR}_{\mathrm{BC,snowfall}}]_\mathrm{d}$ $[\mathrm{MR}_{\mathrm{BC,snowfall}}]_\mathrm{m}$ or $[\mathrm{MR}_{\mathrm{BC,snowfall}}]_\mathrm{y}$. This allows for realistic evolution of the snowpack water mass while testing the effect of using different estimates of the mass mixing ratio of BC in snowfall.

Dry deposition fluxes in all offline runs are as given by the CAM4 prescribed aerosol fields (e.g. as shown in Fig. 1 for two model gridboxes). For each model day, the dry-deposited mass flux is mixed in with the mass of snow water in the model surface snow layer (Eq. 1). For reference, dry deposition accounts for only about 10 % of the total BC mass deposited to snow in CAM4.

As noted above, our offline calculations don't include the effects of sublimation and snowmelt on MR_{BC} whereas MR_{BC} in CESM1-CAM4 does. The difference in the offline $[MR_{BC}]_d$ values and the CESM1-CAM4 values of MR_{BC} are small relative to the overall variability in MR_{BC} (Fig. 3), except when there is surface snow melt (e.g. percolation and ablation zones of glaciers such as the Greenland site shown in Fig. 3a, and during the spring for seasonal snow, such as around day 150 for the Eurasian gridbox shown in Fig. 3b). The small differences outside of the melt season indicate that we can use our offline values of $[MR_{BC}]_d$ as a proxy for prescribed aerosol model MR_{BC} in comparisons to $[MR_{BC}]_m$ and $[MR_{BC}]_y$ in order to understand the effects on MR_{BC} of using decoupled BC and snowfall deposition.

Surface snow BC mixing ratios become both less variable and smaller as the wet deposition flux of BC varies in a more physically consistent way with snowfall, i.e. going from $[MR_{BC}]_d$ to $[MR_{BC}]_m$ to $[MR_{BC}]_y$ (Fig. 4). The values in Fig. 4 are examples for just one gridbox each in Greenland and Eurasia, two regions that account for a large fraction of Arctic spring and summer forcing by BC in snow in CESM1-CAM4 runs (see Fig. 5 of Goldenson et al., 2012). Figures 5–7 show seasonal averages of the ratio $[MR_{BC}]_d : [MR_{BC}]_y$ for all model gridboxes in the regions around Greenland, Eurasia and North America. Figures 8 and 9 show corresponding histograms of these ratios for winter, spring and (Greenland only) summer from all gridboxes in Figs. 5–7 for the CESMmet (Fig. 8) and CRUNECPmet (Fig. 9) calculations. From these it is apparent that decoupling BC deposition and the snowfall that should be driving that deposition leads to high biases in surface snow BC mixing ratios of, on average, a factor of 1.5–1.6 in N. America and Eurasia and 2.2–2.5 in Greenland (Table 1). In other words, when CESM is run in prescribed aerosol mode, the seasonally-averaged daily surface snow BC mixing ratios will, on average, be about 1.5–2.5 times higher than they would be if physically consistent BC and snowfall deposition rates were used. Within a given day or gridbox, biases can be lower (in some cases < 1.0) or higher than this, with significant implications for comparisons of observed and modeled MR_{BC} at given locations/times.

We further verified this bias by analyzing a set of paired CESM simulations described briefly by Jiao et al. (2014). One simulation involved CAM4 and CLM coupled with prognostic aerosol deposition, i.e., with self-consistent meteorology and deposition. The second simulation was conducted with CLM in standalone mode, driven with 6 hourly CRU/NCEP meteorology and with monthly-averaged prescribed BC deposition fluxes from the first run, thus mimicking the other simulations conducted by Jiao et al. (2014), Lee et al. (2013), Shindell et al. (2013), and Goldenson et al. (2012). We found that the annual Northern Hemisphere average concentration of BC in the surface snow layer was larger by a factor of 2.0 in the offline simulation, weighted by snow-covered area in each month and averaged over the same domains, despite the fact that time-averaged BC deposition fluxes were identical in both simulations. This analysis therefore supports the main conclusions drawn from our column modeling, but also incorporates the effects of snow melt, sublimation and snow layer recombination with snow water loss.

As noted earlier, prescribed aerosol wet deposition fluxes are based on prognostic model runs and so are influenced by the prognostic model's precipitation rates. Biases in the prognostic model's precipitation rates will therefore translate directly to biases in the aerosol mass deposition rates. Coupling these model-derived BC mass deposition rates with observed precipitation rates can therefore produce unrealistic values of MR_{BC} both (1) where there are systematic biases in the prognostic model's snowfall and (2) where the interannual variability in the model is decoupled from the observed snowfall rates used in the prescribed aerosol run or offline calculation (i.e., here, year 2000 of a prognostic aerosol model vs. 2004–2009 of CRU/NCEP). Thus, using reanalysis data for snowfall rates in offline estimates of BC albedo forcing such as those conducted for ACC-MIP (Lee et al., 2013) may introduce an additional source of bias in MR_{BC}.

As noted above we calculate values of MR_{BC} analogous to those in the "NCAR-CAM3.5" year 2000 results of Lee et al. (2013; see their Table 1) by using year-2000 prescribed BC mass deposition fluxes as described by Lamarque et al. (2013) and year 2004–2009 CRU/NCEP reanalysis precipitation (“CRUNEPmet runs”). In Table 1 we show the seasonally-averaged ratios $[MR_{BC}]_d : [MR_{BC}]_y$. These ratios include the effects of using the physically inconsistent daily BC deposition and snowfall rates (i.e. $[MR_{BC}]_d$) vs. using the more physically consistent “climatological” BC deposition and snowfall rates (i.e. $[MR_{BC}]_y$) and they include the effect of any differences between the model year-2000 snowfall and reanalysis 2004–2009 snowfall. The net effect is that the ratios $[MR_{BC}]_d : [MR_{BC}]_y$ are somewhat lower (Table 1) when using reanalysis snowfall (CRUNCEPmet) than when using model snowfall (NCARmet) indicating that differences in model vs. observed snowfall are compensating for some of the bias seen in the ratios from the NCARmet runs. However, ratios are also much more variable (i.e. Fig. 9 vs. Fig. 8). Again, this has implications for comparisons of prescribed aerosol model MR_{BC} values with observed surface snow BC mixing ratios from specific locations and time periods, as was done by Goldenson et al. (2012) and Jiao et al. (2014).

4 Discussion and conclusions

We have shown that prescribing surface BC deposition in a model with snowfall varying on typical meteorological timescales (i.e., daily or faster) that is uncorrelated with the BC deposition flux will produce high biases in time-averaged surface snow BC mixing ratios. The biases are significant at daily, seasonal and annual timescales when the BC deposition is prescribed in either a global climate model or in an offline BC surface process model that also prescribes observed daily snowfall rates. Since the prescribed aerosol mass deposition fluxes are uncoupled with daily (and higher frequency) snowfall and they tend to be smoothed in time, we consider coupling BC deposition fluxes with averaged snowfall rates to be the more physically realistic representation. Thus, we conclude that the ratios $[MR_{BC}]_d : [MR_{BC}]_y$ directly reflect a bias in prescribed aerosol model runs of CESM1. That is, all other model biases aside, our values $[MR_{BC}]_y$ are a more accurate representation of surface snow BC mixing ratios than are $[MR_{BC}]_d$, where the latter are equivalent to modeled surface snow BC mixing ratios outside of the snow melt season. Note that this bias is in addition to any other inherent model biases, e.g. in emissions, transport and scavenging rates, some of which may offset each other. Thus, correcting for this bias may not yield better agreement with observations; if this is the case, this simply means there are other sources of bias that also must be corrected.

The assertion that $[\mathrm{MR_{BC}}]_y$ is a more realistic representation of surface snow BC mixing ratios than $[\mathrm{MR_{BC}}]_d$ can be tested by basic comparisons of the average and, in particular, variability in modeled vs. observed surface snow mixing ratios. Comparisons to variability may be especially revealing, since the source of bias being addressed here appears to have dramatic impacts on not just the mean but the variability in snowfall (Fig. 2) and surface snow (Fig. 3) BC mixing ratios. Biases in emissions, transport and scavenging, on the other hand, should produce a more systematic bias in any given location. Observed mixing ratios of BC in snowfall and in the surface snow layer near the Greenland Dye-2 station, for example, can be compared to the modeled values $\mathrm{MR_{BC,snowfall}}$ (Fig. 2) and $\mathrm{MR_{BC}}$ (Fig. 4a). At Dye-2, newly fallen snow samples gathered from 1 May (day 121) to 1 July (day 182) 2010 had BC mixing ratios of $7.5 \pm 3.5\,\mathrm{ng\,g^{-1}}$ (Doherty et al., 2013). Snow profiles covering multiple years' snowpack at Dye-2 show that, outside of the summer melt season, $\mathrm{MR_{BC}}$ in the snowpack typically varies between $1\,\mathrm{ng\,g^{-1}}$ and $5\,\mathrm{ng\,g^{-1}}$ (Doherty et al., 2013), and $\mathrm{MR_{BC}}$ in surface snow at multiple sites across Greenland is typically $4 \pm 2\,\mathrm{ng\,g^{-1}}$ in springtime (Table 2 of Doherty et al., 2010). Both the average and, more strikingly, the variability in the observed mixing ratios are in much better agreement with $[\mathrm{MR_{BC,snowfall}}]_y$ and $[\mathrm{MR_{BC}}]_y$ than with $[\mathrm{MR_{BC,snowfall}}]_d$ and $[\mathrm{MR_{BC}}]_d$ or $[\mathrm{MR_{BC,snowfall}}]_m$ and $[\mathrm{MR_{BC}}]_m$.

We conclude that prescribed aerosol model runs of CESM1 have a factor of about 1.5–2.5 high bias in surface snow BC mixing ratios due to the use of climatological/smoothed BC mass deposition fluxes coupled with modeled, daily-varying snowfall. In CESM1 (i.e. in the SNICAR component of CLM) the surface snow layer used in our calculations of $\mathrm{MR_{BC}}$ is 1–3 cm deep. Sunlight usually will penetrate > 10 cm into the snowpack depending on snow density (Warren and Wiscombe, 1980), so mixing ratios over this full depth are relevant for albedo reduction and BC albedo forcing. SNICAR accounts for this, with albedo being determined by MR_{BC} in as many snow layers as is reached by sunlight (typically the top 2–3 layers). We expect the bias in mixing ratios will decrease as the depth of the snow layer considered increases. This is because one source of the bias is the differential impact on surface snow BC mixing ratios of low- vs. high-snowfall days. Days with greater amounts of new snowfall have lower values of $[MR_{BC,snowfall}]_d$ but some of the contribution of BC to the snowpack on these days is buried in lower layers of the snowpack (in SNICAR, the second model snow layer if new snowfall is greater than about 2 cm); in contrast, when there is only a trace amount of snowfall $[MR_{BC,snowfall}]_d$ will be very high and all of this BC will be retained in the surface snow layer. Thus, on average, there is a high bias in the amount of BC in the surface snow layer. The deeper the layer of snow considered, the less of an effect this will have on the average MR_{BC} of that layer. However, since the amount of sunlight drops off rapidly with snow depth, MR_{BC} in the top few cm of the snowpack has the strongest influence on albedo and most absorption of sunlight will occur in the top few cm of the snowpack, i.e. the surface snow layer in SNICAR. It is beyond the scope of this study to calculate the exact impact on modeled albedo for snow of different densities and therefore different sunlight penetration depths. It is sufficient to point out that:

- Using climatological, prescribed mass deposition fluxes coupled with daily precipitation rates produces a large positive bias in surface snow BC mixing ratios (MR_{BC}) that is significant across daily, seasonal and annual-average time-scales and at gridbox to broad regional (and therefore also global) geographic scales;

- Existing studies using CESM1 and prescribed aerosols to study BC albedo forcing (e.g. Goldenson et al., 2012; Holland et al., 2012; Lawrence et al., 2012; Lee et al., 2013; and Jiao et al., 2014; and all CMIP5 integrations with CCSM4) are biased by this effect;

- An alternate approach should be used in CESM to calculate surface snow mixing ratios of BC and other particulate absorbers. This also applies to any other model using or planning to use prescribed wet deposition fluxes to study the climate impact of albedo forcing.

While the examples shown here are all for higher latitude northern regions, BC albedo forcing has also been hypothesized to have a significant effect on climate and snow cover in the Himalayan and Tibetan Plateau (e.g. Xu et al., 2009, 2012; Qian et al., 2011). Accurate representation of snowfall rates in this region are particularly challenging for climate models; e.g. see Fig. 2 of Qian et al., 2011, which shows a significant positive biases in snow cover over the Tibetan plateau when using CAM3.1. These biases in modeled snow cover directly affect modeled BC albedo forcing, including in model runs with prognostic aerosols, since this forcing is zero anywhere with no snow. In prescribed aerosol model runs specifically, differences in snow cover will also likely affect the bias identified here, i.e. the ratio $[\mathrm{MR}_{\mathrm{BC}}]_{\mathrm{d}} : [\mathrm{MR}_{\mathrm{BC}}]_{\mathrm{y}}$, though it is not clear in which direction. In addition, if modeled snowfall in this region is systematically biased high, as appears likely to be the case in CESM1 for the Tibetan Plateau, prescribed BC wet deposition mass fluxes based on prognostic runs of this model are also likely biased high. When coupled with more realistic snowfall rates such as from reanalysis data (e.g. as done by Lee et al., 2013; Jiao et al., 2014), this will produce overall high biases in $\mathrm{MR}_{\mathrm{BC}}$ in this region.

We suggest that for wet deposition instead of prescribing mass deposition fluxes (e.g. $\mathrm{kg\,m^{-2}\,s^{-1}}$ BC deposition) the model should instead prescribe mass mixing ratios in snowfall (e.g. ng BC per g snowfall SWE, or ppb BC per snowfall water). These prescribed mass mixing ratios should be taken from a climatology of a multiyear integration of a prognostic aerosol model. The appropriate number of model run years will need to be determined; the 10 year averages used here to calculate $[\mathrm{MR}_{\mathrm{BC,snowfall}}]_{\mathrm{y}}$ appears to reduce variability to reasonable levels, but more rigorous tests are needed to determine if 10 years is sufficient or more years are needed. This could be determined by testing how both the mean and variability in snowfall mixing ratios changes with number of years averaged. Aerosol dry deposition will need to continue to be prescribed as a mass flux since it does not scale with snowfall.

In prescribed aerosol model runs, MR_{BC} in each model snow layer at timestep n could then be calculated directly as given in Eq. (1), as used here in our offline calculations. While this will produce an inconsistency in mass balance (the sum of BC remaining in the atmosphere plus BC deposited to the surface) in the prescribed model runs both the atmospheric BC concentrations and surface snow BC mixing ratios will be physically more realistic. This is preferable to maintaining mass balance since both are anyhow prescribed and the climatically important variable in studies of albedo forcing is the surface snow BC mixing ratio.

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References

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobon, M. Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G., and Zender, C. S.: Bounding the role of black carbon in climate: a scientific assessment, J. Geophys. Res., 118, 5380–5552, doi:10.1002/jgrd.50171, 2013.

Boucher, O., Randall, D., Artaxo, P., Bretherton, C., Feingold, G., Forster, P., Kerminen, V.-M., Kondo, Y., Liao, H., Lohmann, U., Rasch, P., Satheesh, S. K., Sherwood, S., Stevens, B., and Zhang, X. Y.: Clouds and aerosols, in: Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, UK and New York, NY, USA, 571–657, 2013.

Conway, H., Gades, A., and Raymond, C. F., Albedo of dirty snow during conditions of melt, Water Resour. Res., 32, 1713–1718, 1996.

Doherty, S. J., Warren, S. G., Grenfell, T. C., Clarke, A. D., and Brandt, R. E.: Light-absorbing impurities in Arctic snow, Atmos. Chem. Phys., 10, 11647–11680, doi:10.5194/acp-10-11647-2010, 2010.

Doherty, S. J., Grenfell, T. C., Forsström, S., Hegg, D. L., Warren, S. G., and Brandt, R.: Observed vertical redistribution of black carbon and other light-absorbing particles in melting snow, J. Geophys. Res., 118, 5553–5569, doi:10.1002/jgrd.50235, 2013.

Flanner, M. G., Zender, C. S., Hess, P. G., Mahowald, N. M., Painter, T. H., Ramanathan, V., and Rasch, P. J.: Springtime warming and reduced snow cover from carbonaceous particles, Atmos. Chem. Phys., 9, 2481–2497, doi:10.5194/acp-9-2481-2009, 2009.

Flanner, M. G., Zender, C. S., Randerson, J. T., and Rasch, P. J., Present-day climate forcing and response from black carbon in snow, J. Geophys. Res., 112, D11202, doi:10.1029/2006JD008003, 2007.

Goldenson, N., Doherty, S. J., Bitz, C. M., Holland, M. M., Light, B., and Conley, A. J.: Arctic climate response to forcing from light-absorbing particles in snow and sea ice in CESM, Atmos. Chem. Phys., 12, 7903–7920, doi:10.5194/acp-12-7903-2012, 2012.

Hansen, J. and Nazarenko, L.: Soot climate forcing via snow and ice albedos, P. Natl. Acad. Sci. USA, 101, 423–428, doi:10.1073/pnas.2237157100, 2004.

Holland, M., Bailey, D. A., Briegleb, B. P., Light, B., and Hunke, E.: Improved sea ice shortwave radiation physics in CCSM4: the impact of melt ponds and aerosols on Arctic sea ice, J. Climate, 25, 1413–1430, doi:10.1175/JCLI-D-11-00078.1, 2012.

Jacobson, M. Z.: Climate response of fossil fuel and biofuel soot, accounting for soot's feedback to snow and sea ice albedo and emissivity, J. Geophys. Res., 109, D21201, doi:10.1029/2004JD004945, 2004.

Jiao, C., Flanner, M. G., Balkanski, Y., Bauer, S. E., Bellouin, N., Berntsen, T. K., Bian, H., Carslaw, K. S., Chin, M., De Luca, N., Diehl, T., Ghan, S. J., Iversen, T., Kirkevåg, A., Koch, D., Liu, X., Mann, G. W., Penner, J. E., Pitari, G., Schulz, M., Seland, Ø., Skeie, R. B., Steenrod, S. D., Stier, P., Takemura, T., Tsigaridis, K., van Noije, T., Yun, Y., and Zhang, K.: An AeroCom assessment of black carbon in Arctic snow and sea ice, Atmos. Chem. Phys., 14, 2399–2417, doi:10.5194/acp-14-2399-2014, 2014.

Koch, D., Menon, S., Del Genio, A., Ruedy, R., Alienov, I., and Schmidt, G. A.: Distinguishing aerosol impacts on climate over the past century, J. Climate, 22, 2659–2677, doi:10.1175/2008jcli2573.1, 2009.

Kopacz, M., Mauzerall, D. L., Wang, J., Leibensperger, E. M., Henze, D. K., and Singh, K.: Origin and radiative forcing of black carbon transported to the Himalayas and Tibetan Plateau, Atmos. Chem. Phys., 11, 2837–2852, doi:10.5194/acp-11-2837-2011, 2011.

Lamarque, J.-F., Shindell, D. T., Josse, B., Young, P. J., Cionni, I., Eyring, V., Bergmann, D., Cameron-Smith, P., Collins, W. J., Doherty, R., Dalsoren, S., Faluvegi, G., Folberth, G., Ghan, S. J., Horowitz, L. W., Lee, Y. H., MacKenzie, I. A., Nagashima, T., Naik, V., Plummer, D., Righi, M., Rumbold, S. T., Schulz, M., Skeie, R. B., Stevenson, D. S., Strode, S., Sudo, K., Szopa, S., Voulgarakis, A., and Zeng, G.: The Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP): overview and description of models, simulations and climate diagnostics, Geosci. Model Dev., 6, 179–206, doi:10.5194/gmd-6-179-2013, 2013.

Lawrence, D. M., Oleson, K. W., Flanner, M. G., Fletcher, C. G., Lawrence, P. J., Levis, S., Swenson, S. C., and Bonan, G. B., The CCSM4 land simulation, 1850–2005: assessment of surface climate and new capabilities, J. Climate, 25, 2240–2260, doi:10.1175/JCLI-D-11-00103.1, 2012.

Lee, Y. H., Lamarque, J.-F., Flanner, M. G., Jiao, C., Shindell, D. T., Berntsen, T., Bisiaux, M. M., Cao, J., Collins, W. J., Curran, M., Edwards, R., Faluvegi, G., Ghan, S., Horowitz, L. W., McConnell, J. R., Ming, J., Myhre, G., Nagashima, T., Naik, V., Rumbold, S. T., Skeie, R. B., Sudo, K., Takemura, T., Thevenon, F., Xu, B., and Yoon, J.-H.: Evaluation of preindustrial to present-day black carbon and its albedo forcing from Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP), Atmos. Chem. Phys., 13, 2607–2634, doi:10.5194/acp-13-2607-2013, 2013.

Oleson, K. W., Lawrence, D. M., Bonan, G. B., Flanner, M. G., Kluzek, E., Lawrence, P. J., Levis, S., Swenson, S. C., and Thornton, P. E.: Technical Description of vserion 4.0 of the Community Land Model (CLM), NCAR Technical Note NCAR/TN-478+STR, Natl. Cent. for Atmos. Res., Boulder, CO, 2010.

Qian, Y., Flanner, M. G., Leung, L. R., and Wang, W.: Sensitivity studies on the impacts of Tibetan Plateau snowpack pollution on the Asian hydrological cycle and monsoon climate, Atmos. Chem. Phys., 11, 1929–1948, doi:10.5194/acp-11-1929-2011, 2011.

Shindell, D. T., Lamarque, J.-F., Schulz, M., Flanner, M., Jiao, C., Chin, M., Young, P. J., Lee, Y. H., Rotstayn, L., Mahowald, N., Milly, G., Faluvegi, G., Balkanski, Y., Collins, W. J., Conley, A. J., Dalsoren, S., Easter, R., Ghan, S., Horowitz, L., Liu, X., Myhre, G., Nagashima, T., Naik, V., Rumbold, S. T., Skeie, R., Sudo, K., Szopa, S., Takemura, T., Voulgarakis, A., Yoon, J.-H., and Lo, F.: Radiative forcing in the ACCMIP historical and future climate simulations, Atmos. Chem. Phys., 13, 2939–2974, doi:10.5194/acp-13-2939-2013, 2013.

Warren, S. G. and Wiscombe, W. J.: A model for the spectral albedo of snow. II: Snow containing atmospheric aerosols, J. Atmos. Sci., 37, 2734–2745, 1980.

Xu, B., Cao, J., Hansen, J., Yao, T., Joswia, D. R., Wang, N., Wu, G., Wang, M., Zhao, H., Yang, W., Liu, X., and He, J.: Black soot and the survival of Tibetan glaciers, P. Natl. Acad. Sci. USA, 106, 22114–22118, doi:10.1073/pnas.0910444106, 2009.

Xu, B., Cao, J., Joswiak, D. R., Liu, X., Zhao, H., and He, J.: Post-depositional enrichment of black soot in snow-pack and accelerated melting of Tibetan glaciers, Environ. Res. Lett., 7, 014022, doi:10.1088/1748-9326/7/1/014022, 2012.

Table 1. Means, medians and standard deviations of the ratios, $[MR_{BC}]_d$: $[MR_{BC}]_y$, shown in Figs. 5–9. Also given is the median ratio when $[MR_{BC}]_d$ and $[MR_{BC}]_y$ are calculated using daily snowfall from the CRU/NCEP reanalysis data set; means and standard deviations are not given because extremely high ratios in a few model grid boxes yield non-meaningful values.

	Greenland				North America			Eurasia		
	DJF	MAM	JJA	Annual	DJF	MAM	Annual	DJF	MAM	Annual
MODEL SNOWFALL (“NCARmet” runs)										
mean	2.66	3.03	2.68	2.68	1.63	1.58	1.57	1.64	1.62	1.59
median	2.24	2.51	2.33	2.34	1.64	1.58	1.57	1.60	1.54	1.53
std	1.43	1.82	4.38	1.21	0.40	0.46	0.38	0.53	0.34	0.34
CRU/NCEP SNOWFALL (“CRUNCEP” runs)										
median	2.14	1.97	2.36	2.17	1.53	1.46	1.47	1.66	1.37	1.46

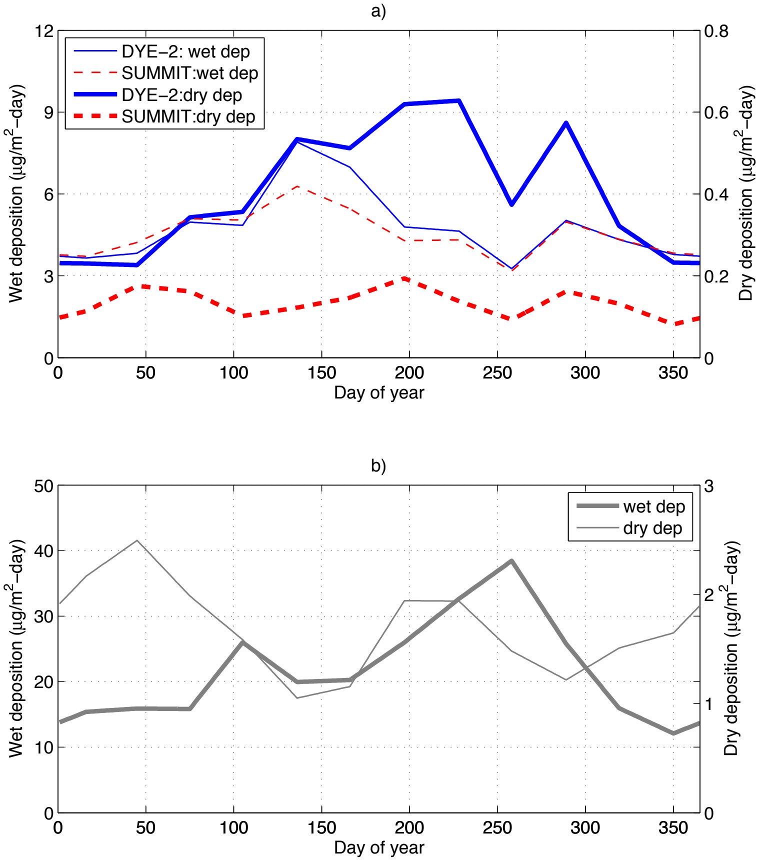

Figure 1. Examples of wet (left axis) and dry (right axis) BC mass deposition fluxes in CAM4.0 for year 2000 for **(a)** two model gridboxes in Greenland containing the Dye-2 (69.2° N, 315.0° E) and Summit research stations (72.3° N, 321.7° E), and **(b)** a single model gridbox in northern Eurasia (71.1° N, 85.0° E).

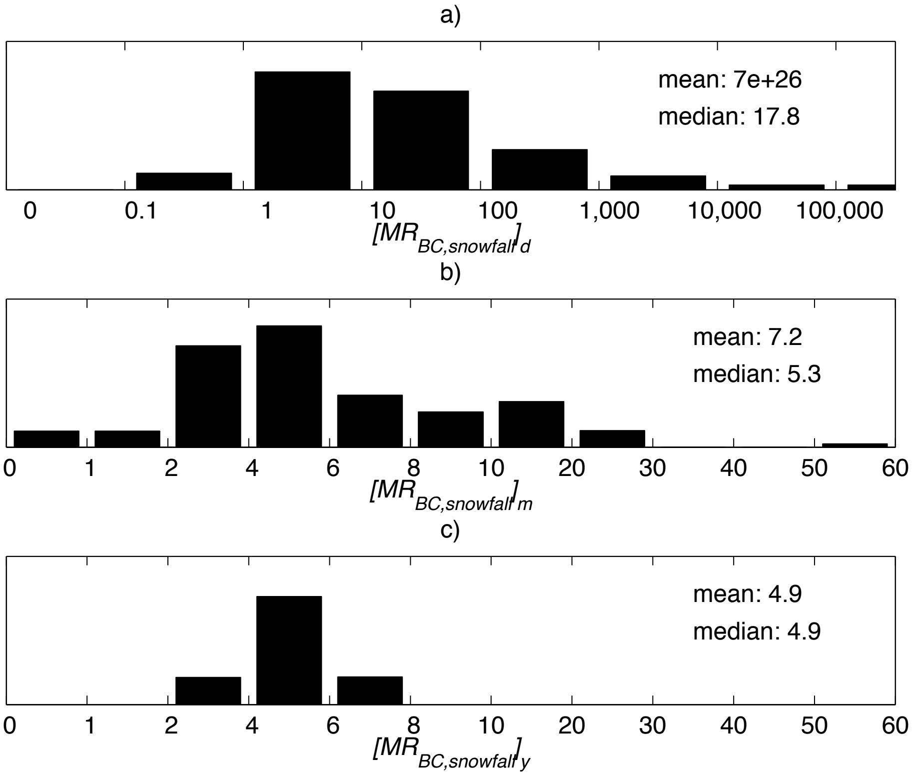

Figure 2. Relative frequency distributions of daily mixing ratios of BC in snowfall calculated using three different pairings of BC mass deposition fluxes and snowfall rates, as described in the text: **(a)** $[MR_{BC,snowfall}]_d$, **(b)** $[MR_{BC,snowfall}]_m$ and **(c)** $[MR_{BC,snowfall}]_y$. Note the differences in scale in **(a)** vs. in **(b)** and **(c)**. Data shown are for model snowfall rates for year 2000 (CESMmet runs) and for the Dye-2 Greenland gridbox as shown in Fig. 1a.

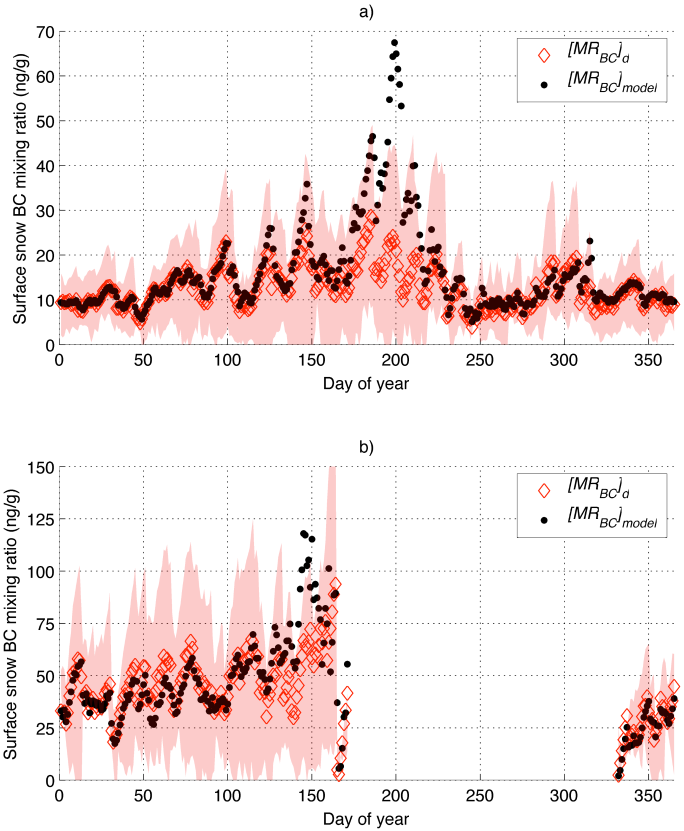

Figure 3. Surface snow BC mixing ratios (MR_{BC}) for **(a)** the Dye-2 gridbox shown in Fig. 1a and Fig. 2 and **(b)** the same northern Eurasia gridbox shown in Fig. 1b. The average (red diamonds) and standard deviation (red shaded area) across ten years of $[MR_{BC}]_d$ from the offline computation with CESMmet is shown, along with 10 year averages of MR_{BC} values from CESM-CAM4 (black dots). The CESM-CAM4 values include the effects of snow water loss to sublimation and melting, whereas the offline calculations (red) do not.

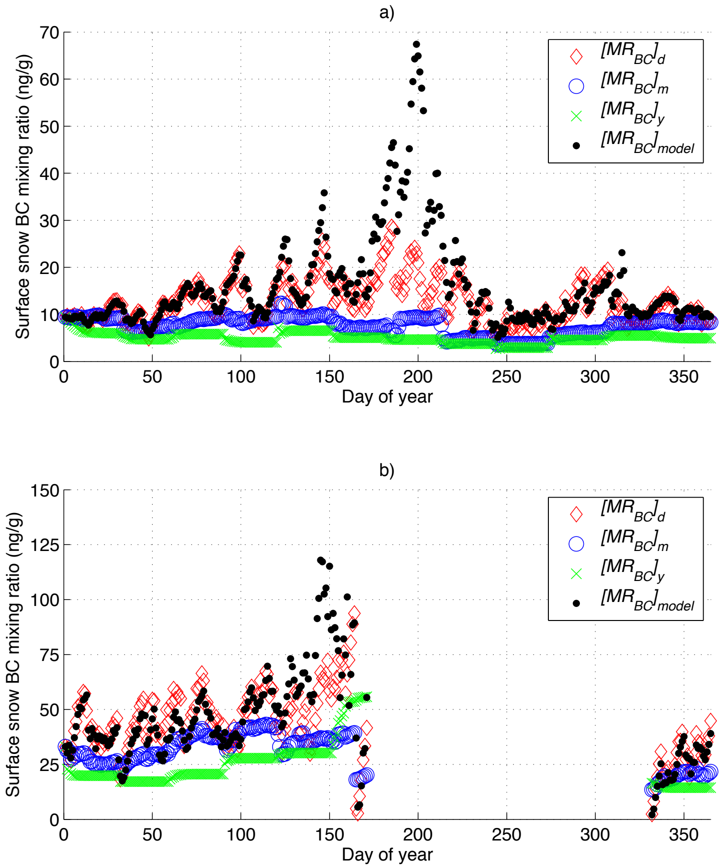

Figure 4. As in Fig. 3, but the 10 year average of $[MR_{BC}]_d$ (red diamonds) are now compared to $[MR_{BC}]_m$ (blue circles) and $[MR_{BC}]_d$ (green x's) from the offline calculation, again using CESMmet. As in Fig. 3, the black dots are MR_{BC} from CESM-CAM4.

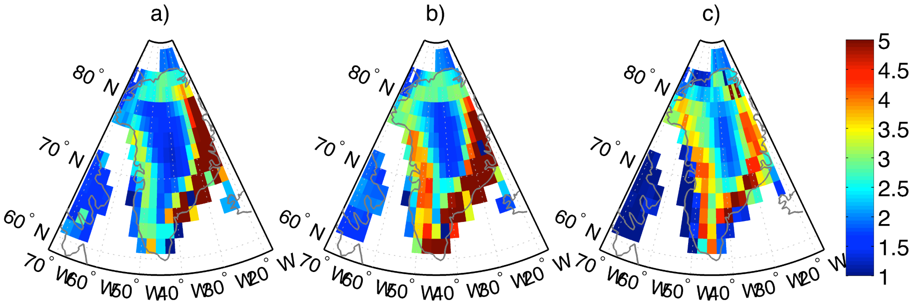

Figure 5. Three-month seasonal averages of the ratio $[MR_{BC}]_d$: $[MR_{BC}]_y$ for model gridboxes around Greenland for **(a)** winter (DJF), **(b)** spring (MAM) and **(c)** summer (JJA). These ratios indicate the effect on surface snow mixing ratios of having BC wet deposition fluxes and snowfall decoupled ($[MR_{BC}]_d$) vs. using a more physically consistent pairing of climatologically averaged BC wet deposition with 10 year average snowfall ($[MR_{BC}]_y$).

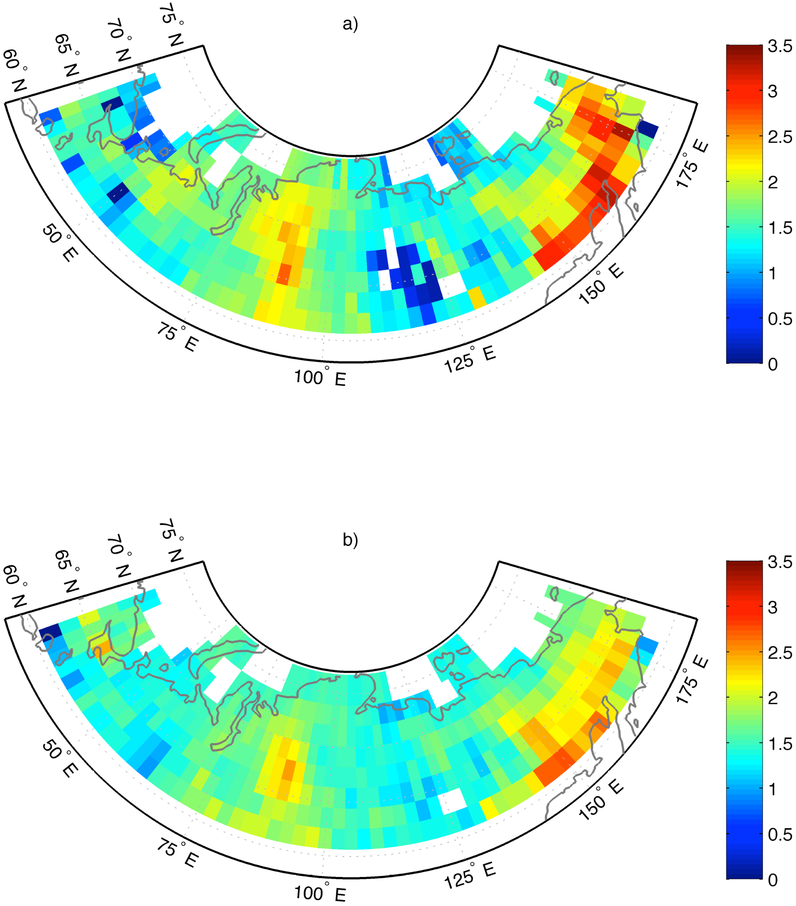

Figure 6. As in Fig. 5, but for the Eurasian region in **(a)** winter (DJF) and **(b)** spring (MAM).

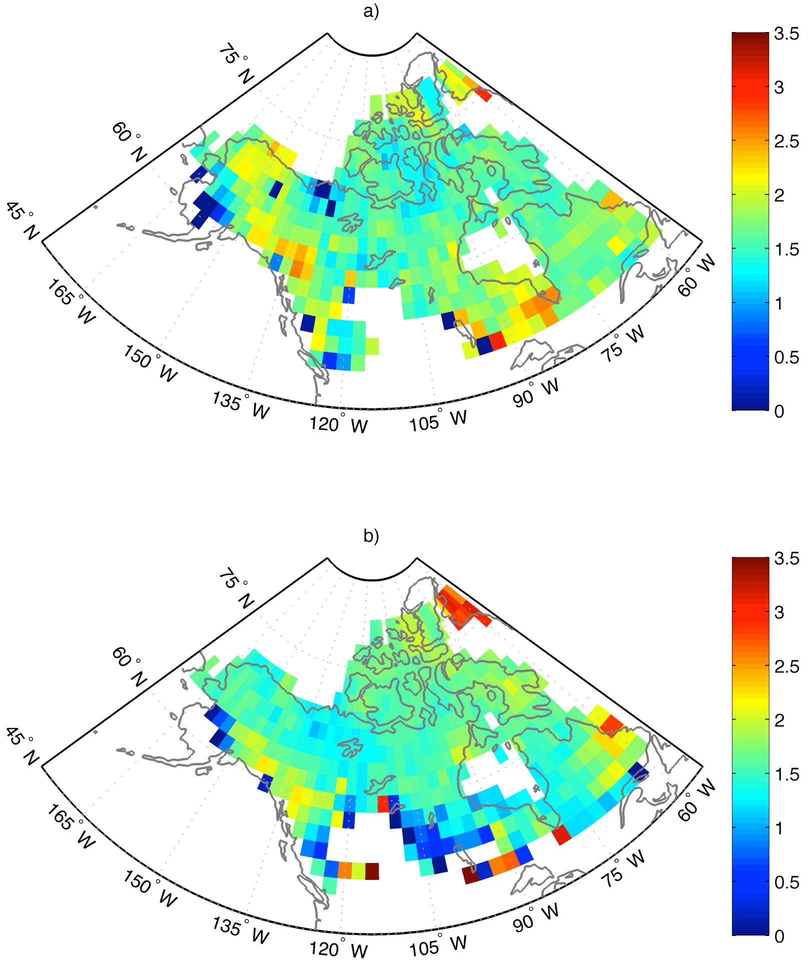

Figure 7. As in Fig. 6, but for the North American region.

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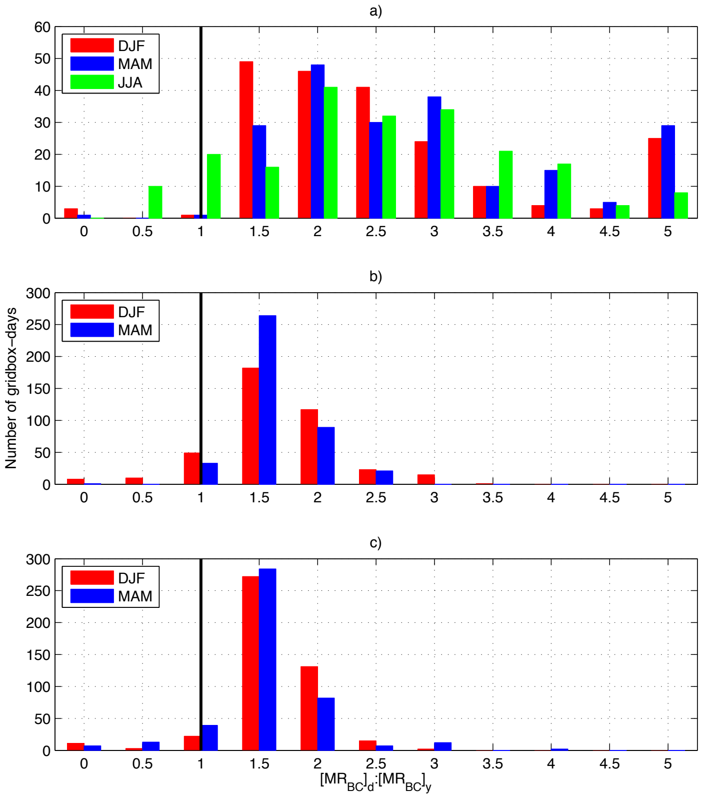

Figure 8. Histograms of the ratios shown in Figs. 5–8, for the regions around **(a)** Greenland, **(b)** Eurasia and **(c)** North America. Shown are seasonal averages for winter (DJF), spring (MAM) and summer (JJA; Greenland only) when the offline calculations use CESMmet. Ratios $[MR_{BC}]_d : [MR_{BC}]_y > 5.0$ are allocated to the 5.0 bin.

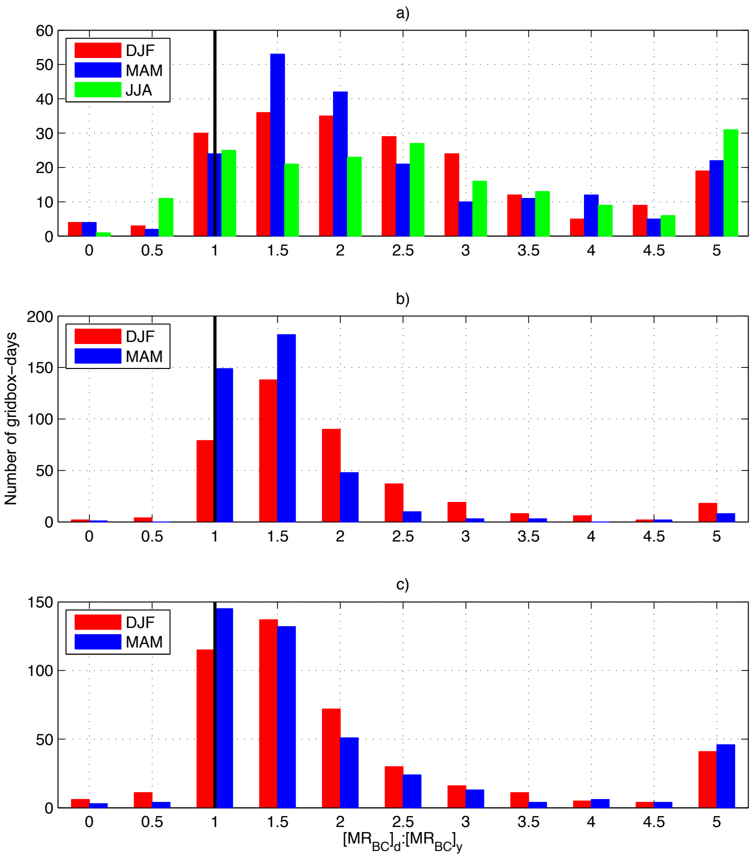

Figure 9. As in Fig. 8, but for offline calculations using the CRU/NCEP reanalysis $SWE_{snowfall}$ data to calculate $MR_{BC,snowfall}$ and therefore $[MR_{BC}]_d : [MR_{BC}]_y$.