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The sensitivity of global climate to the episodicity of fire aerosol emissions

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Abstract

One of the major ways in which forest and grass fires have an impact on global climate is through the release of aerosols. Most studies focusing on calculating the radiative forcing and other climate impacts of fire aerosols use monthly mean emissions derived from the Global Fire Emissions Database that captures only the seasonal cycle of fire aerosol emissions. Here we present the results of a sensitivity study that investigates the climate response to the episodicity of the fires, based on the standard approach which releases emissions every day, and contrasts that to the response when fires are represented as intense pulses of emissions that occur only over 1–2 days on a monthly, yearly, or five-yearly basis. Overall we find that in the modified cases with increased levels of episodicity, the all sky direct effect radiative forcing increases, the clear sky direct effect radiative forcing remains relatively constant, and the magnitude of the indirect effect radiative forcing decreases by about $1\,\mathrm{W\,m^{-2}}$ (from -1.6 to $-0.6\,\mathrm{W\,m^{-2}}$). In the long term, we find that an increase in aerosol emission episodicity leads to an asymmetric change in indirect radiative forcing in the Northern Hemisphere compared to the Southern Hemisphere contributes to a slight shift in the annual average position of the intertropical convergence zone (ITCZ). This shift is found to have a mixed effect on the overall performance of the model at predicting precipitation rates in the tropics. Given these results we conclude that future studies that look to assess the present day global climate impacts of fire aerosols should consider the need to accurately represent fire episodicity.

1 Introduction

Wildfire burning of forest and grass fires have long been known to have a significant impact on climate. Through the release of greenhouse gases and aerosols, as well as ecosystem changes, fires introduce numerous perturbations into the Earth system that both affect local and global climate (Bowman et al., 2009). To better understand the

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significance of fire impacts, recent studies have estimated the radiative forcing of each individual component from deforestation fires alone (Bowman et al., 2009), and from wild and deforestation fires (Ward et al., 2012).

Greenhouse gases and aerosols are two of the main components of fire impacts. Greenhouse gases, such as carbon dioxide, methane, nitrous oxide, and ozone (which is produced in the atmosphere from fire emissions), released from both deforestation and wildfires are thought to have a net positive radiative forcing on the order of $0.7\,\mathrm{W\,m^{-2}}$ (Ward et al., 2012). While there is uncertainty associated with these values, the radiative forcing due to greenhouse gases released by wildfires are known with more confidence than those associated with the aerosols released by fires (Bowman et al., 2009). Aerosols have both a direct effect on the radiation balance of the earth and a complicated indirect effect (Forster et al., 2007; Rosenfeld et al., 2008).

There exist observationally based datasets, used to estimate the present-day emissions of fire aerosols and in turn estimate their radiative forcing, which indicate when fires occur and how strong they are (Giglio et al., 2006; van der Werf et al., 2006; Tansey et al., 2008). Each of these datasets uses a slightly different methodology to estimate burned area and fire emissions. The GFED version 2, the dataset we use in this study, uses a suite of satellite products to determine area burned and fire type. These data, when coupled with vegetation and net primary productivity information, were used to estimate the quantity of different chemical emissions on a monthly mean basis (van der Werf et al., 2006). From the GFED versions 2 and 3, global monthly emissions data are available as monthly averages at a resolution of $0.5^\circ \times 0.5^\circ$ for the years 1997–2009 (van der Werf et al., 2006, 2010).

Recent modeling studies use these averages to guide monthly total fire aerosol emissions but emit the aerosols at every timestep, linearly interpolating between the monthly values to create smooth trends (e.g. Ward et al., 2012; Tosca et al., 2013). When the emissions are scaled as in these studies, and in Johnston et al. (2012), using AERONET aerosol observation data, this scheme well represents the mass of aerosols released each year by fires, and result in a radiative forcing estimate of a di-

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rect effect radiative forcing of $0.13\,W\,m^{-2}$ as well as an indirect effect radiative forcing of $-1.64\,W\,m^{-2}$ (Ward et al., 2012).

However, fires are episodic events, occurring infrequently in many locations and at irregular time intervals. As an illustration, Chen et al. (2009) derived a more realistic picture of fire emissions from the GFED dataset that included both a diurnal cycle and a dependence on meteorological conditions. Over a span of three months, during the 2004 North American fire season there were days of intense fire activity surrounded by days of lower amounts or zero fire activity (Chen et al., 2009). This characteristic episodicity, or degree of daily variability, of fire emissions is not captured by the recent modeling studies that focus on climate impacts (e.g. Ward et al., 2012). Using prescribed fire aerosol emissions schemes with finer temporal resolution, Chen et al. (2009) found significant differences in the resultant transport patterns of aerosols when compared with the results of a more smoothed out scheme. These findings suggest that a change in the temporal distribution of fire emissions may cause a change in their resultant spatial distribution, and modeling fires as less frequent, but more intense events could cause changes in the calculated radiative forcings and climate impacts.

Here we report the results of a sensitivity study that compares the radiative forcing and climate response of four fire emissions schemes derived from the GFED observations but with different episodicity of emissions. These schemes each release the same mass of fire emissions over a five year period, but with fires represented as events that last two days rather than entire months and occur at monthly, yearly, or five-yearly intervals. We would expect the true pattern of fire emissions to lie somewhere in between our modified scenarios and the control case based on the existing scheme. The results of the simulations presented here are used to establish a reasonable range of fire aerosol radiative forcings and long term climate impacts given the uncertainty in the temporal distribution of fire emissions.

2 Methodology

2.1 Model experimental setup

We use version 5 of the Community Atmosphere Model (CAM5) to simulate fire aerosol emissions, transport, and physics. All simulations use a 1.9° latitude by 2.5° longitude grid with a timestep of 30 min. The model was configured to use CAM5 bulk microphysics which represents aerosol scavenging and wet deposition, and the three mode modal aerosol model (MAM3) (Liu et al., 2012a). CAM5 includes the Morrison and Gettelman (2008) cloud microphysics scheme which simulates aerosol/cloud interactions for stratiform clouds (Liu et al., 2012b). Aerosols do not interact explicitly with the microphysics of convective clouds.

We conducted two sets of simulations with CAM5 to investigate the change in radiative forcing and the long-term climate impacts caused by a change in the temporal distribution of fire aerosol emissions (Table 1). All simulations were initialized with year 2000 climate for the atmosphere, land and ocean.

The radiative forcing, or "RF" simulations were run for six years each with prescribed sea surface temperatures (SST) to minimize climate drift, following Ward et al. (2012). They were branched from the end of two-year spin up simulations with no fire emissions. We made use of online radiation diagnostics within CAM5, which enabled online calculations of the radiative fluxes with and without aerosols. The last five years of the six year simulations were used in the analysis, with the first year used to spinup CAM5 with the different fire emission schemes.

The 30 yr long term climate runs or "LTC" runs used the same emissions patterns as the RF runs, but include atmosphere-ocean feedbacks simulated by a slab-ocean model (SOM). The slab-ocean model simulates the energy balance between the atmosphere and ocean using climatological average ocean mixed layer depths and sea surface temperatures (Kiehl et al., 2006).

The climatological values of the ocean heat fluxes, required to use the SOM simulations, are calculated from 20 yr of output from a fully-coupled control run (Bailey et al.,

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2012). We used a two degree fully-coupled simulation to create the climatological forcing file and then conducted a five year spinup run with GFED emissions for all four 30 yr simulations to branch off of. The five year spinup was sufficient to achieve balance between global annual average incoming and outgoing radiation. In each case analysis was based off the final 21 yr of the run to allow the model to adjust to the different emission schemes.

2.2 Fire emission schemes

To create simulations of different episodicity using prescribed fire aerosols, modifications were made to the standard way in which prescribed emissions are released in CAM5, using the GFEDv2 dataset. The GFEDv2 dataset contains observational estimates of the emissions of black carbon, organic carbon, and sulfate aerosols. We use the average annual cycle of GFEDv2 fire emissions from years 1997 to 2006. All fire emissions were released at the surface. Several studies have shown that a variable injection height for fire emissions has only a small impact on the distribution of fire aerosols in the atmosphere (Zhang et al., 2011; Tosca et al., 2011). We scale the fire emissions for all cases to better match observed aerosol optical depths (AOD's) following the method of Ward et al. (2012).

In general chemical transport models make use of a prescribed climatological monthly average flux of different species of aerosols at each location to produce a rudimentary representation of observed fire activity, so that at every time step, there is a linearly interpreted value of emissions between two monthly means (e.g. Tosca et al., 2013; Ward et al., 2012). Thus every day, there are emissions of fires using this default scheme, which we refer to as the "daily" case.

Three modified emissions schemes were designed to release the same mass of fire aerosols over a five year period as the daily case at each grid point with the only difference being the frequency of their release. In order of increasing episodicity we named the three modified cases the "monthly", the "annual", and the "five year" cases. The names of the emissions cases are meant to reflect the frequency of fire emissions

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events in each case. The ”daily” case releases emissions every day, the “monthly” case releases emissions once a month, the “annual” case releases emissions once a year, and the “five year” case releases emissions once every five years. All three of the modified cases simulated fires as events that occurred on two days rather than throughout entire months as in the “daily” case.

The monthly emissions case was designed so that the mass of fire aerosols that is released over an entire month is released on the 14th and 15th of that month. It is the least episodic of the three modified emissions cases. The annual emissions case takes the mass that is released over one year and releases it during the 14th and 15th of the month of maximum fire activity specific to each grid point. Finally, the five year emissions case did not use the same fire emissions pattern each year. It took the mass of fire aerosols that is released in 5 yr and released them on the 14th and 15th of the month of maximum fire activity during the first year of the simulation, then for the following four years used zero fire aerosol emissions. In the long term climate runs this pattern of emissions was repeated as a five year cycle. The surface fluxes are depicted in Fig. 1 (note the difference in scales in the two plots) for a location in central Africa with a maximum month of fire activity of February.

Additionally, all four emissions schemes contained year 2000 background anthropogenic aerosol emissions as prescribed by the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) (Lamarque et al., 2010). Emissions from industry, energy, waste products, agriculture, domestic sources, transportation and volcanoes are included. Some of these are constant fluxes, while others vary on a month to month basis. No modifications were made to these fields, which are the same throughout all four cases.

2.3 Radiative forcing calculations

Three radiative forcings were calculated for each sensitivity run: the all sky direct effect, the clear sky direct effect, and the indirect effect. The direct effect is the impact of fire aerosols on the radiative balance of the Earth due to the absorption and reflection

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of radiation and is broken down into clear sky and all sky conditions. Here we only assess the shortwave direct effect as the longwave direct effect from fire aerosols is not included in the model and should be small. The indirect effects of fire aerosol emissions are the combined radiative impact of changes made to clouds by aerosols. In CAM5 with MAM3 these include changes to cloud droplet number concentration and size, as well as changes in cloud lifetime and height. The three radiative forcings, all-sky direct effect, clear sky direct effect, and indirect effects, were calculated following Ward et al. (2012) using the global, annual average radiative fluxes from the last five years of RF simulations. We obtained the global average of the variables from the RF runs for each year and used those values to calculate the annual radiative forcing for each case.

3 Results

The four emissions schemes are designed to release nearly the same mass of fire aerosols in a five year period at all locations (Fig. 2). All four cases release 52 teragrams of black carbon, 430 teragrams of organic carbon, and 4.5 teragrams of sulfate in five years. This ensures that changes we see are not due to differences in total mass released, rather due to differences in the distribution of mass released across time. Because the lifetime changes (Table 2) and the distribution of aerosols in each case (Fig. 1), the aerosol optical depth also changes slightly between cases (Table 2). The aerosols themselves could be slightly changing the lifetime. With the exception of the lifetimes of fire aerosols in the five year case, all aerosol lifetimes are significantly different than those in the daily case at the 95% level.

3.1 Radiative forcing

Increased episodicity has very little impact on the magnitude of the clear sky direct effect (Fig. 4). Without the presence of clouds fire aerosols have a negative RF due to scattering and absorption of shortwave radiation (Wilcox, 2012). This cooling effect has

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been shown to be roughly proportional to the mass of aerosol in the atmosphere at the particular time (Papadimas et al., 2012). Since we release the same mass of aerosols into the atmosphere in each run over the five year period we averaged over, the clear sky direct effect radiative forcings are similar.

While the clear sky direct effect is not changed by the episodicity of the fires, the all sky and indirect effects are more complex. The globally and annually average cloud droplet number concentrations are about 15 to 20% lower in the monthly and annual emissions cases, compared to the daily emissions case, while total cloud fraction does not change substantially between the simulations. This could result from increased competition for water vapor in environments that have been overloaded with fire aerosols in the monthly and annual cases, leading to proportionally more particles remaining interstitial. In the modified cases this intense release of aerosols is followed by an extended period of no fire emissions during which there will be fewer fire aerosols acting as cloud condensation nuclei.

Clouds may become saturated with aerosols, which diminises the impact of additional aerosols on cloud albedo, and the first indirect effect (e.g. Chuang et al., 2002). In the more episodic cases, we release large quantities of aerosols in short periods of time. When aerosols are released in short and intense pulses (Fig. 1), the susceptibility of the cloud albedo to fire aerosols is diminished (relative to the daily case with more consistent but smaller releases of fire aerosols). The reduction in magnitude of the indirect effects in the monthly case with respect to the daily case is largest off the west coasts of South America and Central Africa, as well as Siberia (Fig. 4). Similar to Ward et al. (2012) these regions of strong negative forcing dominate the global indirect effect of fire aerosols in this model.

To compute the all sky direct effect radiation forcing we include scattering and absorption by aerosols above and below clouds, which have been modified themselves by aerosols. When these aerosols are included in our assessment of the direct effect, the RF becomes positive in all cases, whereas for clear sky the RF was negative. The absorption of shortwave radiation by fire aerosols (particularly black carbon) above high

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albedo clouds reduces the amount of radiation reflected by the clouds. The episodicity of fire emissions might be expected to have little impact on the all sky direct effect, because direct effect radiative forcing is roughly proportional to aerosol burden in the path of incoming radiation. However, in the days following a large emission event, such as in the modified emissions cases, the cloud albedos will be increased over those in the daily emissions case due to the indirect effects. These days coincide with the greatest potential for above cloud absorption from fire aerosols in the modified emissions cases. Therefore, while clouds are on average less reflective in the modified cases, we speculate that on the days when the greatest above-cloud fire aerosol absorption occurs the clouds are actually more reflective than in the daily case, leading to proportionally increased warming from aerosols above clouds.

It is evident from the calculations of global average radiative forcings, that the more episodic cases tend to increase the energy absorbed by the planet relative to the daily case. As we increase the episodicity of fire aerosol emissions, the total aerosol radiative forcing also increases (becomes less cooling). To gain insight into the locations where these changes are most significant, we broke down the all sky direct effect and indirect effect radiative forcings by latitude (Fig. 5). The most substantial changes in the aerosol indirect effects occur at the latitudes where substantial fire emissions and sensitive cloud regimes coincide (Fig. 6) (Ward et al., 2012).

3.2 Climate impacts

Modifying the episodicity of fire aerosol emissions in the LTC simulations led to substantial changes in the distribution of precipitation, and atmospheric circulation (Figs. 7 and 8). The most significant changes in precipitation rate occur near the equator (Fig. 7). In general, to the north of the equator we see an increase in precipitation rate, while to the south we see a decrease. These changes suggest that the Intertropical Convergence Zone (ITCZ) shifts northward on an annual average, and that the Hadley Circulation is affected by the change in emissions scheme (Fig. 8).

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Changing the frequency of fires to once per month, causes a northward shift of the ITCZ, indicated by the large negative difference in annual average zonal mean streamfunction between the modified cases and the daily (Fig. 8). The shift in ITCZ is likely a response to the asymmetric change in total aerosol radiative forcing across the northern and southern hemispheres (Fig. 6). As an example, Ming and Ramaswamy (2011) showed that anthropogenic aerosols, released primarily in the northern hemisphere, also led to an asymmetric negative radiative forcing, and resulting the ITCZ shift southward. In all modified cases, the northern hemisphere has a more positive radiative forcing relative to the daily than the southern hemisphere (Fig. 6). In the annual case, the difference is small, while in the monthly and five-year cases the difference is substantial.

While it is interesting that we see these consistent changes to the tropical precipitation pattern when we increase the episodicity of fire emissions, an important question is whether or not these changes improve model performance relative to observations. Comparisons to gridded precipitation observations (Xie and Arkin, 1997), suggest a mixed impact on the accuracy of precipitation estimates from the model (Fig. 9). In some locations, specifically in the central Pacific Ocean between latitudes −15 and 10 degrees, we see significant improvements in annual average precipitation rate estimates when compared to observations (Xie and Arkin, 1997) over the daily control case (between 25 % and 80 % improvement). In other locations, primarily latitudes between 10 and 30 degrees in the Pacific, where there is less precipitation, the more episodic cases perform significantly worse (results are around 50-300% better in the daily control case) (Fig. 9). These precipitation changes are consistent with a shift in ITCZ northward in the monthly case relative to the daily (Fig. 8). The daily case overestimates precipitation to the south of the equator in the Pacific, while it underestimates it in some locations to the north. The monthly case overestimates precipitation to a lesser degree to south of the equator in the Pacific and overestimates it to the north.

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4 Summary and conclusions

When studying the climate impacts of biomass burning emissions, it has become routine to include the seasonal cycle of emissions. This is due in part because observational data on monthly mean fire emissions is readily available (van der Werf et al., 2010), but also because the climate impacts of aerosol emissions depend strongly on the time of year they are emitted. The results of our study indicate, however, that global radiative forcings of fire aerosols, and long term climate dynamics, may be influenced not only by the seasonal cycle, but also by shorter time period variations in aerosol emission rates. This set of simulations was a sensitivity study, and thus use an arbitrary date for the release of the fire emissions. A better approach would be to use fire emissions that are synchronized with meteorological conditions, with an accurate synchronized prognostic fire algorithm.

With less frequent, but more intense aerosol emission events, we found that the indirect effect radiative forcing of fire aerosols was significantly weakened. When compared to the daily control case, the magnitude of the indirect effect radiative forcing in the monthly case decreased by $\sim 1\,\mathrm{W\,m^{-2}}$ (from -1.6 to $-0.6\,\mathrm{W\,m^{-2}}$). The impact was similar in the annual and five-year cases. This result suggests that the magnitude of the indirect effect of fire aerosols reported by previous studies (e.g. Ward et al., 2012; Collins et al., 2011) may be overestimated. If so, fires may have an overall neutral or slightly positive RF in the present day when all forcing agents are considered, as opposed to a negative forcing as reported by Ward et al. (2012). The overestimation is potentially the most important off the west coasts of tropical South America and Central Africa, as well as in high northern latitude locations including Siberia.

Since the changes in indirect effect radiative forcing were large over high latitudes in the Northern Hemisphere, the hemispheric balance of radiation was perturbed in long term climate simulations. As a result, the ITCZ shifted northward on an annual average, in the direction of higher radiative forcing (similar to Ming and Ramaswamy, 2011). This improved the simulation of precipitation for some regions, but not all.

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Daily fire emissions inventories have recently become available for global fires (e.g. van der Werf et al., 2010; Wiedinmyer et al., 2011). Due to the sensitivity of the model radiation and dynamics to the frequency of fire emissions demonstrated here, it is recommended to use a fire emissions dataset and model emissions scheme with a these higher temporal resolutions for assessing fire impacts on climate.

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Table 1. Details for the two sets of CAM5 simulations.

Name	Emissions Package				Ocean		Years
	daily	monthly	annual	five-year	data	slab	
RFdaily	x				x		6
RFmonthly		x			x		6
RFannual			x		x		6
RFfiveyear				x	x		6
LTCdaily	x					x	31
LTCmonthly		x				x	31
LTCannual			x			x	31
LTCfiveyear				x		x	31

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Table 2. Five year average fire aerosol lifetime (days) and AOD by case. Boldface values are NOT significantly different than the daily case based on a two-sample, two-tailed t-test at the 95 % level.

Case	BC Lifetime	OC Lifetime	SO_4 Lifetime	AODABS	AODVIS
Daily	4.31	4.51	3.85	0.0074	0.12
Monthly	5.10	5.75	4.05	0.0078	**0.13**
Annual	5.56	6.65	4.16	0.0082	0.13
Five Year	**8.63**	**21.1**	**4.74**	**0.010**	**0.14**

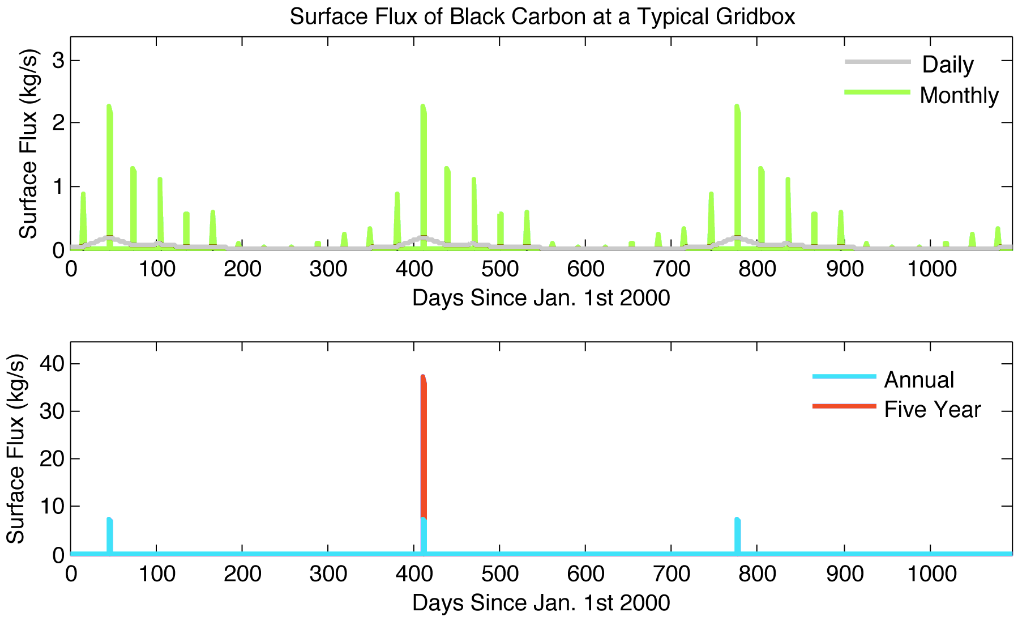

Fig. 1. The temporal distribution of fire emission rates at a typical model gridbox in each of the four cases implemented in this study.

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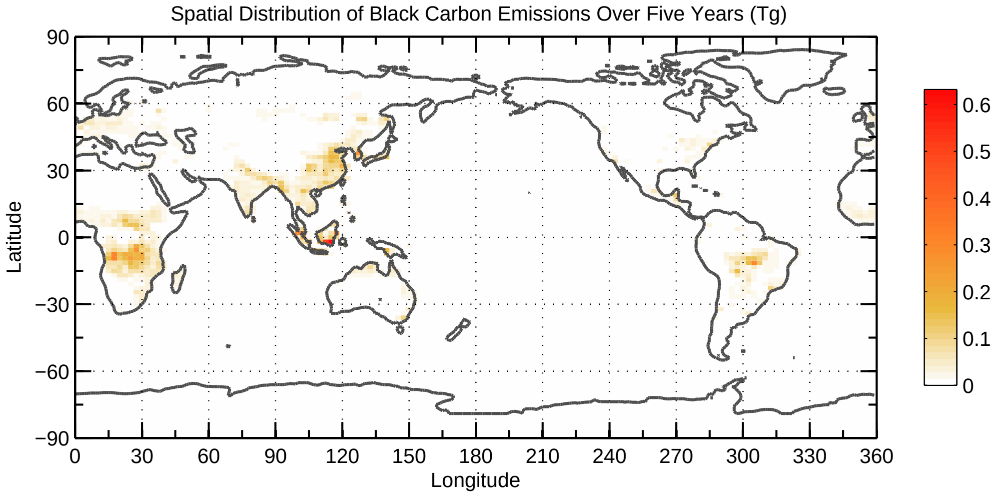

Fig. 2. Spatial distribution of black carbon emissions over five years in each case.

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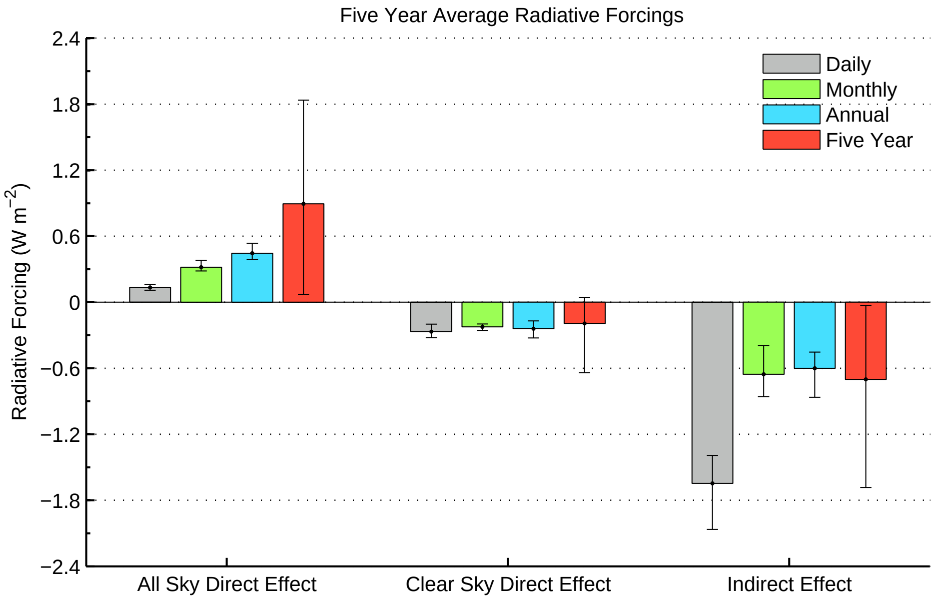

Fig. 3. Five year annual average radiative forcings broken down by effect and by experiment case. The error bars represent the range of individual year annual averages of radiative forcing over the five year period.

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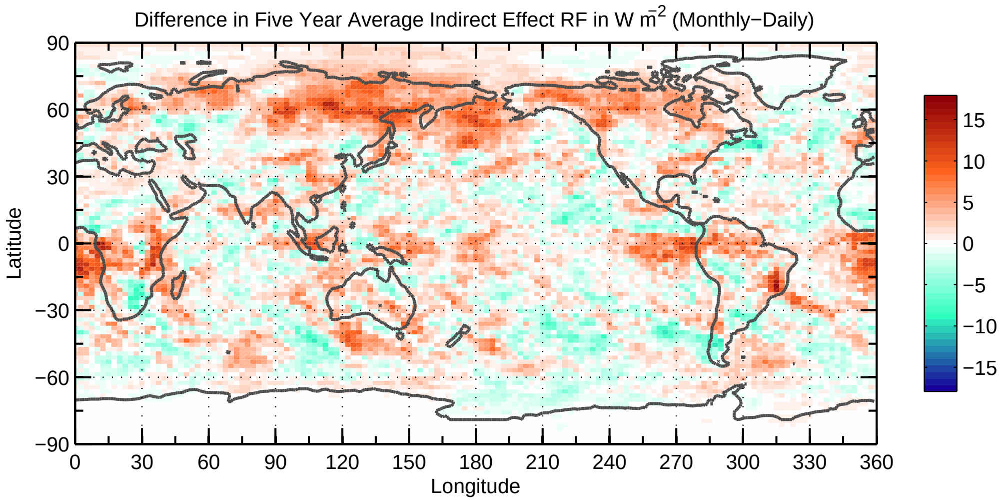

Fig. 4. The spatial distribution of the difference in the indirect effects from the monthly emissions case and the daily emissions case.

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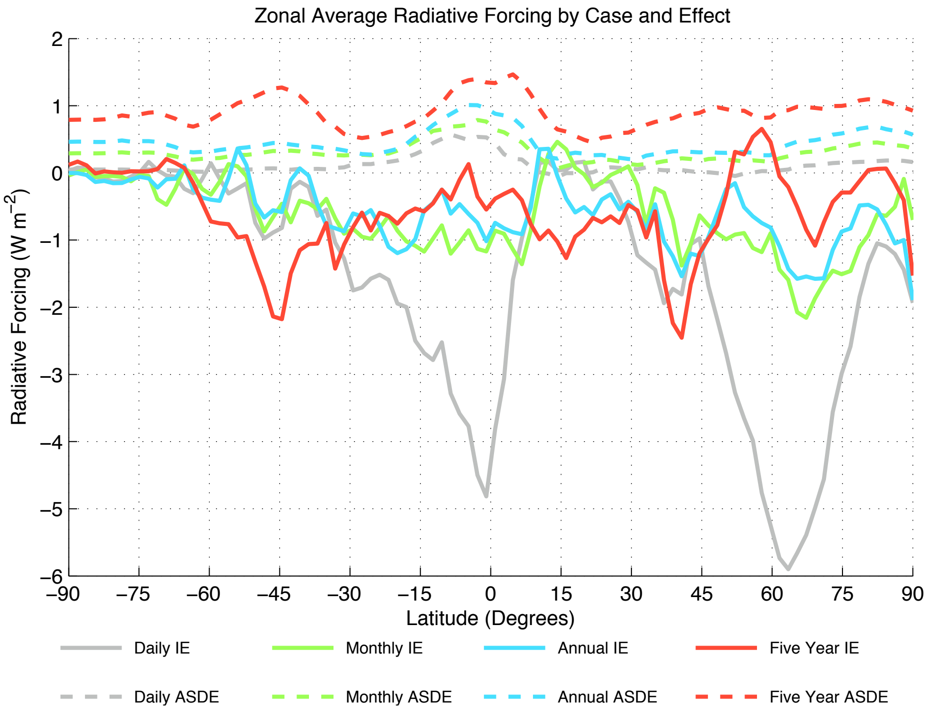

Fig. 5. Zonal average all sky direct effect RF and zonal average indirect effect RF by case.

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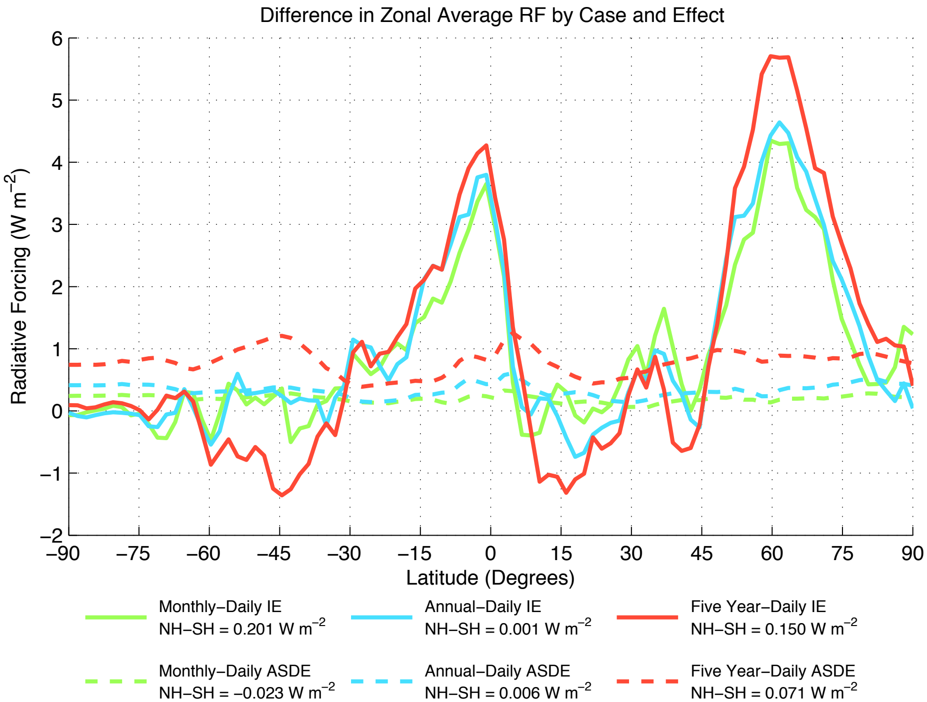

Fig. 6. Difference in zonal average RF between the modified cases and the daily case. All-sky direct effect (ASDE) is shown with dashed lines, indirect effects (IE) are shown with solid lines. In the plot legend, we have included the difference in Gaussian weighted average between the northern hemisphere and southern hemisphere in each case.

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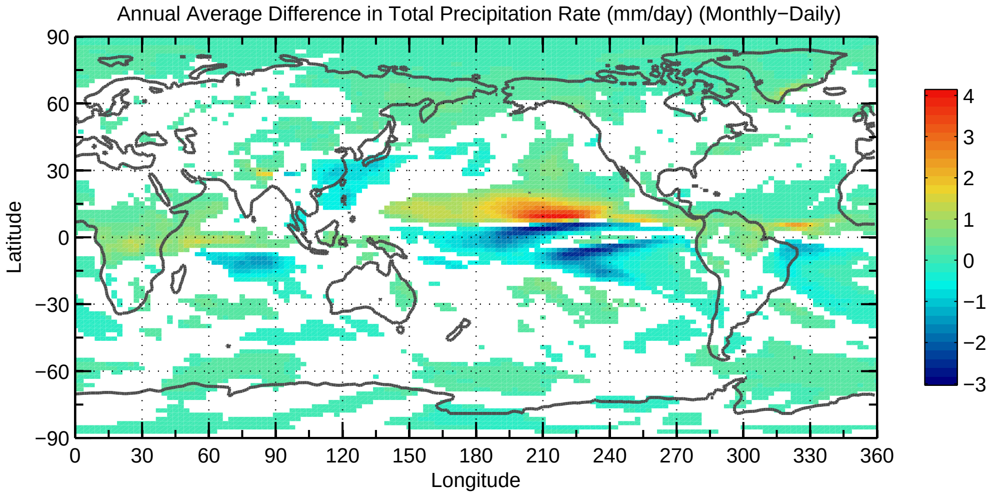

Fig. 7. Annual average difference in total precipitation between the monthly and daily cases.

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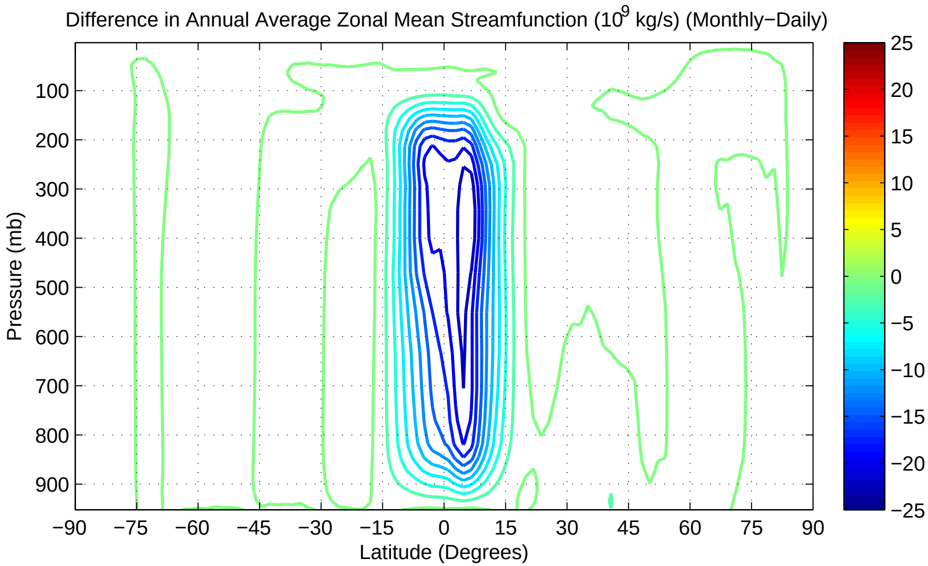

Fig. 8. The difference in annual average zonal mean mass streamfunction between the monthly case and the daily case. The stream function is calculated using the method described in Oort and Yienger (1996), and is positive for net northward mass transport and negative for net southward net transport.

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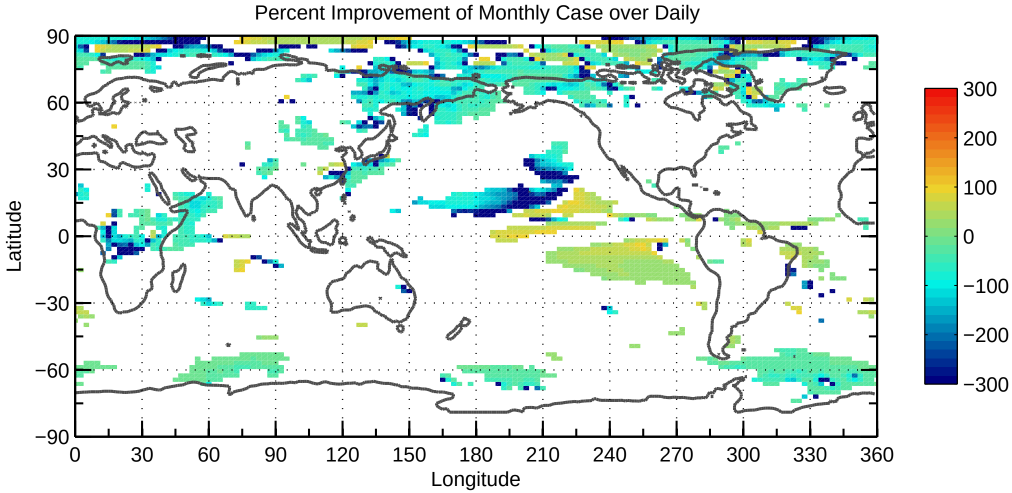

Fig. 9. Percent improvement in model prediction of precipitation rates by using monthly emissions relative to the daily emissions when compared to Xie and Arkin (1997) dataset. Changes are shown only at locations where the deviations from observations were statisically different at a 95% level using a two sample, two tailed t-test.

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