Letter

Direct radiative forcing of biomass burning aerosols from the extensive Australian wildfires in 2019–2020

Dong Yeong Chang1, Jongmin Yoon1,*, Johannes Lelieveld2,3, Seon Ki Park4, Seong Soo Yum5, Jhoon Kim6,7 and Sujong Jeong1

1 Department of Environmental Planning, Seoul National University, Seoul, Republic of Korea
2 Department of Atmospheric Chemistry, Max-Planck Institute for Chemistry, Mainz, Germany
3 Climate and Air Quality Research Department, National Institute of Environmental Research, Incheon, Republic of Korea
4 The Cyprus Institute, P.O. Box 27456, 1645 Nicosia, Cyprus
5 Department of Environmental Science and Engineering, Ewha Womans University, Seoul, Republic of Korea
6 Department of Atmospheric Sciences, Yonsei University, Seoul, Republic of Korea
7 Particulate Matter Research Institute, Samsung Advanced Institute of Technology (SAIT), Suwon, Korea

* Author to whom any correspondence should be addressed.
E-mail: ofjyoon@korea.kr

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Abstract

In 2019, an unusually strong positive Indian Ocean Dipole spawned hot and dry weather in southeastern Australia, which promoted devastating wildfires in the period from September 2019 to February 2020. The fires produced large plumes of biomass burning aerosols that prevented sunlight from reaching the Earth’s surface, and in this way elicited regional radiative cooling. We estimated the direct aerosol radiative forcing (ARF) resulting from these wildfires, based on Moderate Resolution Imaging Spectroradiometer space-based data and an empirical relationship from AErosol RObotic NETwork ground-based data collected in biomass-burning regions. The wildfire-derived air pollution was associated with an aerosol optical thickness of >0.3 in Victoria and a strongly negative ARF of between $-14.8$ and $-17.7 \text{ W m}^{-2}$, which decreased the surface air temperature by about $3.7 \degree \text{C}–4.4 \degree \text{C}$. This is of the same order of magnitude as the radiative cooling from volcanic eruptions. Although the atmospheric lifetime of biomass-burning aerosols is relatively short (about a week), the Australian wildfire pollution plumes extended across the Pacific Ocean to South America. Since climate change is expected to lead to more frequent and increasingly intense fires in many regions worldwide, the consequent biomass burning aerosols may become a significant radiative forcing factor, which will need to be accounted for in climate model projections for the future.

1. Introduction

The unusually severe fires in the southeastern part of Australia in 2019–2020 earned them the epithet of the ‘Black Summer’. These extensive, recurrent and severe wildfires started in June 2019 in Queensland (QLD), which was 2 months earlier than the typical fire season in northern Australia, before extending to eastern Australia (New South Wales (NSW) and Victoria (VIC)) and lasting until May 2020 in western Australia. The most severe fires developed in NSW and VIC from September 2019 to December 2020 and destroyed more than seventeen million hectares of forest (Chapman 2020, Gunia and Law 2020, Noble 2020). During the wildfires, an enormous volume of biomass-burning aerosols was emitted and travelled across the Pacific Ocean, even reaching South America in January 2020. The smoke plumes that result from extreme wildfires have a damaging health impact (Johnston et al 2011, Arriagada et al 2020). The severe fires of the ‘black summer’ were as devastating as the five most deadly Australian wildfires on record, with destructive impacts on ecology and society, air quality, and human health due to the close
proximity of major residential areas and animal habitats in Australia. Specifically, the fires were estimated to have caused 451 human deaths, including 417 premature deaths due to bushfire smoke exposure (Arriagada et al. 2020), and around a billion animals have been killed (Snape 2020, The University of Sydney 2020).

Historically, Australia is a region that experiences recurrent wildfires, and wildfires danger have been monitored by the Australian government via the Bureau of Meteorology (BOM) using the Forest Fire Danger Index (FFDI; McArthur 1966, 1967, Noble et al 1980), which is estimated from a record of dry weather condition dependent on meteorological variables (i.e. wind speed, temperature, humidity), the amounts of precipitation and evaporation. The FFDI for 2019 showed the highest FFDI values over eastern Australia, where the recent wildfires in 2019–2020 occurred. The high FFDI values in this case seem to have been influenced by unusual changes in sea surface temperature (SST) in the Indian Ocean (IO) that affect the weather in Australia. When the SST shows an anomaly characterised by cooler temperatures in the eastern IO and warmer temperatures in the western IO than normal, this is known as a positive Indian Ocean Dipole (IOD) (see figure S1 (available online at stacks.iop.org/ERL/16/044041/mmedia)). Positive IODs lead to less moisture for northwestern Australia, while southeastern Australia usually gets less rainfall and is hotter than normal in winter and spring (Ashok et al. 2003, Cai et al. 2009). These conditions eventually imposed fire-prone conditions during eastern Australia’s summer (Cai et al. 2009, Harris and Lucas 2019), which could be reinforced by El Niño-associated climatic phenomena, especially those occurring in the Central Pacific (Ashok et al. 2007, Wang and Hendon 2007, Taschetto and England 2009). The strong positive IOD in 2019 is illustrated by the time series of the Dipole Mode Index (DMI) that measures differences between SST anomalies over eastern and western IO (see figure S2) during the last two decades (2002–2019). This is consistent with the recent study of Lewis et al. (2020). A recently published climate modelling study of Wang and Cai (2020) also confirmed that successive climate-related phenomena (i.e. positive IOD and central Pacific El Niño events) bring about fire-prone conditions in southeastern Australia potentially leading to severe wildfires.

Although people have paid more attention to wildfire prevention in southeastern Australia where the FFDI value is calculated to be unusually high, indicating a high risk of wildfire, after ignition they might be very difficult to control, especially in areas where copious fuel is available such as the temperate climate zone. They emit large amounts of biomass-burning aerosols and greenhouse gases (e.g. carbon dioxide (CO$_2$), methane (CH$_4$), etc) and precursors of photochemical reactions that produce ozone (O$_3$), all exerting radiative forcings of the climate. Many climate studies have focused on the impacts of greenhouse gases released from wildfires with the aim of understanding the global long-term effects on climate change (Wild et al. 2001, Pfister et al. 2006, Real et al. 2007). The short-term (immediate) local strong radiative cooling effect of aerosols emitted from wildfires can be comparable to that of a volcanic eruption but has not received much attention. According to the study of Lehner et al. (2016), volcanic ash and sulfate aerosols temporarily cool the Earth’s surface to $−3$ °C via aerosol-radiation interactions. The eruption of Mt. Pinatubo in 1991 caused a negative radiative forcing of about $−3$ W m$^{-2}$ with a high aerosol optical depth (AOD) of about 0.15 (Ramachandran et al. 2000, Hansen et al. 2002). Although fires are sporadic events, they can impose strong effects on climate that are not negligible compared to other climate forcing agents. Since more frequent and severe fires are expected with climate change (Doerr and Santin 2016), more attention should be paid to the impact of wildfires on the climate.

In this study, we focused on the short-term response of the climate to wildfires and calculated the direct aerosol radiative forcing (ARF) at the top of the atmosphere (TOA) for a large-scale biomass-burning plume from Australian wildfires. To calculate the ARF, we used Moderate Resolution Imaging Spectroradiometer (MODIS) satellite observation data (i.e. aerosol optical thickness (AOT) and surface albedo (SA)) and an empirical relationship, which was driven by aerosol data obtained from AERosol RObotic NETwork (AERONET) stations located in representative biomass-burning regions (Yoon et al. 2019).

2. Data and methods

2.1. Observational satellite data

The monthly AOT at 0.55 μm, white-sky SA at 0.3–0.7 μm, active fires, and SST used in this study are Level-3 products from the MODIS satellite observations spanning the entire earth (data downloaded from https://neo.sci.gsfc.nasa.gov/). MODIS on Terra (Earth Observing System AM-1) and Aqua (Earth Observing System PM-1) are key payload imaging sensors that observe the entire Earth system every 1–2 d within visible and 36 infrared spectral bands. The Level-3 monthly MOD(MYD)AL2_M_AER_OD AOT at 0.55 μm, MCD43C3_M_BSA white-sky SA in the visible range of 0.3–0.7 μm are used mainly for estimating ARF. The SA for 2019–2020 has been estimated by a trend analysis from 2000 to 2017 (see figures S4 and S6 supplementary data), since the SA data is available from 2000 to 2017 from MODIS. The monthly averages of AOD and SA over the course of the last two decades (from 2019 to 2020) are provided in the supplementary data (figure S6). The active fire
Figure 1. Empirical relationship between aerosol optical thickness (AOT) at 0.55 $\mu$m, surface albedo (SA), and radiative forcing (ARF) at the top of the atmosphere from AERONET L2 inversion data for the biomass burning type. The magnitude of ARF is generally dependant on the aerosol loading (AOT), but the sign (i.e. cooling or warming) dramatically changes based on the critical SA (i.e. $SA = 0.461$) which induces no ARF regardless of AOT. The forcing efficiency (FE) is defined as direct ARF by a unit of AOT (i.e. when AOT = 1, FE is identical to ARF).

count (MOD14A1_M_FIRE) encompasses the number of fires in a 1000 km$^2$ area observed by MODIS Terra using the standard fire and thermal anomalies algorithm and is useful for monitoring the spatial distribution of active fires in Australia. The burned area data are obtained from the product of MCD64CMQ Grid Burned Area that based on the MCD64A1 algorithm (Giglio et al 2018). The MCD64A1 product wildly used for estimating fire emission (Giglio et al 2010, 2013). The long-term time-series of SST observed from MODIS, i.e. MYD28 daytime and nighttime SST derived from the 1- and 4-micron channels, are valuable for understanding the influence of climate on Australian climate and propensity for fires. The intensity of positive and negative IODs is estimated by the difference in SST anomalies between the western equatorial IO (50$^\circ$E–70$^\circ$E and 10$^\circ$S–10$^\circ$N) and the southeastern equatorial IO (90$^\circ$E–110$^\circ$E and 10$^\circ$S–0$^\circ$N), and is also known as the DMI. A positive phase of IOD means a DMI higher than 0. To analyse DMI, averages of SST for spring (September—November, 2002–2019) and anomalies of SST for 2019 were calculated and are shown in the supplementary data (figures S1 and S2). We also used the 2019 Australian landcover distribution (figure S3) obtained from the MODIS-IGBP file (available via http://lpdaac.usgs.gov) to illustrate the fire behaviour associated with fuel type. It is based on landcover data observed by TERRA and AQUA MODIS and is classified into 17 types of landcover (i.e. 16 vegetation types and water) using the International Earth-Biosphere Program (IGBP) classification algorithm (Belward 1996). For more information on the definition of IGBP classification, see Strahler et al (1999).

2.2. Direct radiative effect of biomass-burning aerosols

The ARF of biomass-burning aerosols is estimated from monthly mean MODIS satellite data, i.e. AOT at 0.55 $\mu$m and SA, using an empirical relationship between AOT, SA, and ARF (see figure 1). The empirical relationship is derived from data obtained from the AERONET stations representing typical biomass-burning aerosols (Yoon et al 2019). The magnitude of ARF is associated with the aerosol loading (AOT) and the direct aerosol radiative forcing efficiency, (FE; in W m$^{-2}$). In general, a large aerosol loading (i.e. high AOT) and higher FE (i.e. high absolute value of FE) enhance ARF (i.e. $ARF = FE \times AOT$). The FE is defined as the ARF (W m$^{-2}$) scaled by AOT (i.e. when AOT = 1, FE is identical to ARF); it depends on the aerosol type (e.g. biomass-burning, dust, urban-industrial aerosols); it is also strongly influenced by the SA, i.e. $FE = \alpha \times SA + \beta$, where $\alpha$ and $\beta$ are coefficients that vary depending on
aerosol type. Therefore, ARF can have different values depending on the reflectance of aerosols relative to that of the surface, which means that the same aerosol type and loading can impose different radiative effects depending on SA, i.e. warming forcing at relatively high SA and cooling forcing at relatively low SA. This is because albedo affects the light-absorbing properties of biomass-burning aerosols, which play an important role in determining the direct aerosol radiative FE (Stohl 2007). For biomass-burning aerosols, ARF is predicted to exert a cooling effect when SA is lower than 0.461, while it is predicted to exert a warming effect at relatively high SA (>0.461). A detailed description can be found in Yoon et al (2019).

We estimated the perturbation of surface air temperature in response to biomass-burning aerosols using a relationship between the surface air temperature and radiation budget at the TOA, following Gregory and Forster (2008). This is based on the key assumption that changes in surface air temperature ($\Delta T_S$) are positively correlated with changes in the net radiation forcing at the TOA ($\Delta F$), i.e. $\Delta F \propto \rho \Delta T_S$ (Cubash et al 2001, Collins et al 2013). $\rho$ has been suggested as a ‘transient climate response parameter’ (TCRP, K W$^{-1}$ m$^2$) in the study of Gregory and Forster (2008), and TCRPs can be used for any climate change scenario in which changes in global mean surface air temperature are calculated as a function of changes in radiative forcing. TCRPs are thus measures of the response of global mean surface air temperature to radiative perturbations. The TCRP can be conveniently applied for estimation of the surface air temperature response without the need to actually run and analyse model simulation results (Gregory and Forster 2008). The parameter can vary from one model to another, but within each model it is invariant (WMO 1986). In the one-dimensional radiative-convective model, a 1 W m$^{-2}$ change in radiative forcing corresponds to a 0.5 K change in surface temperature (i.e. $\rho = 0.5$ K W$^{-1}$ m$^2$; Ramanathan et al 1985). In this study, we have found the TCRP, i.e. $\rho = 0.248$ K m$^2$ W$^{-1}$, which is driven by linear changes in radiative forcing and surface air temperature simulated by the global ECHAM5/MESSy Atmospheric Chemistry—Climate (EMAC) model (see supplementary data; Chang et al 2021). We used this model to derive changes in temperature caused by changes in ARF estimated by observational data. Note that it is only a rough estimation of the direct radiative forcing effect in EMAC simulations. It only inferred how much the surface temperature is reduced by decreased incoming solar energy due to biomass burning aerosols. The actual effects of aerosol–radiation–climate interactions are spatiotemporally varied, and therefore need to be careful consideration of the heterogeneity of physicochemical aerosols distribution and surface reflectance for more accurate estimation, which differs from estimating the effects of well-mixed greenhouse gases.

3. Results

3.1. Analysis of active fire counts, burned areas, and AOT

The number of active fires, burned area data, and landcover distribution were analysed using MODIS derived products to understand the spatial distribution of fires and their characteristics. The AOT retrieved from Terra/Aqua MODIS represents the amount of aerosols generated by wildfires and is used to estimate the ARF. Figure 2 shows the seasonal distribution of the burned areas, active fires counts, and AOT at 0.55 µm for the four states of Australia (NT, QLD, NSW, and VIC) during the past two decades (2000–2020). The burned areas are largely distributed in both historically fire frequent regions in North Australia (NT, QLD) and unusually fire spots in Southeast Australia (NSW, VIC). The frequency of active fires shows that historically Australia is a region prone to recurrent wildfires, specifically in northern parts of the country during the spring season from September to November (Giglio et al 2013) and in southern parts of Australia during the summer season from December to February (Clarke et al 2011). The burned area and number of active fires in 2019–2020 in NSW and VIC show that the wildfires of this summer were unusual compared to the number of active fires in the last 20 years (figure 2). The number of active fires, burned areas and AOT show a positive relationship in general. However, the number of active fires does not fully explain the magnitude of ways wildfires affect climate. The analysis of burned areas (figures 3 and 6) are closely related to fuel types (figure S3). The AOT helps in estimating how extensively biomass is consumed during fires.

Wildfires are generally affected by both geographical climate type and weather conditions. Potential fuel types and fuel availability are determined by climate type and weather conditions (e.g. drought, wind, extreme heat) affect fuel moisture levels that are critical to fuel flammability and affect fire spread conditions as well. This is depicted in figure 2 as the differences of fire behaviours in forests between the northern states (NT and QLD), and the southern states (NSW and VIC); the latter showed corresponding changes of the AOT values and the number of active fires but with a greater variation for AOT values, whereas the former depicted an opposite tendency, i.e. a high number of active fires and large burned areas often met with smaller AOT values. A large portion of NT and QLD lies in the tropical savanna climate zones (BOM, bom.gov.au/climate; Beringer et al 2015) where fires quickly consume available light fuel (e.g. grass and shrubs; see figure S3), rapidly burn out, and therefore emit rather small amounts of aerosols, i.e. AOT < 0.1, with high numbers of active fires and large burned areas (figures 2 and 3). Most regions of VIC and NSW have temperate climates (BOM, bom.gov.au/climate), despite smaller burned areas,
but they consume vast amounts of biomass since more flammable materials are allowed by unusually dry and hot weather conditions due to unprecedented strong positive IOD and release of a large amount of aerosols into the atmosphere (e.g. AOT $> 0.2$).

The peaks of AOT at 0.55 $\mu$m reflect the temporal variation in the number of active fires (figure 2). In VIC, the two peak values correspond to bushfires in the summers of 2006–2007 and 2019–2020. During the two fire seasons, the positive IOD is also reflected
in the variability of the DMI that corresponds to unusually strong positive IOD phases (see figure S2 in the supplementary data). In 2003, lightning (natural ignition) triggered massive wildfires in the Alpine region and northeastern VIC, according to the Government of Victoria. If fires break out in very difficult-to-access geographic locations, they have more potential to spread out into a larger area as there are more chances of being out of control.

Figure 3 shows the distribution of accumulated burned areas and active fire counts over 6 months (September 2019–February 2020) as gleaned from MODIS/Terra data. The burned areas are marked with yellow, red, and dark red pixels that represent the area burned i.e. $10^3–10^4$, $10^5–10^6$, and more than $10^7$ hectares, respectively. The locations of active fires are marked with brown, yellow, and red pixels that represent the number of active fires, i.e. 1–5, 5–30, and more than 30 pixels/1000 km$^2$ d$^{-1}$, respectively. The 2019–2020 wildfires occurred in southeastern Australia, which is mainly composed of temperate broadleaf areas (see figure S3), as shown by the large number of red pixels in figure 3 (i.e. meaning more than 30 fires in 1000 km$^2$ d$^{-1}$). This could be explained by copious fuels (i.e. dense wood and broadleaf trees), which are sorts of slow-burning materials that take a longer time to burn and spread fires. On top of that, dry and hot weather allows more flammable conditions as reducing fuel moisture levels (Davies and Legg 2011). These overall conditions lead to high numbers of active fires with relatively small burned areas and release of a huge amount of biomass burning aerosols from wildfires as shown by high AOT values in NSW and VIC. A large number of active fires are also indicated in northern Australia (e.g. NT, QLD), a region with a historically high frequency of fires but these wildfires in northern Australia are less severe than those in southeastern Australia (e.g. NSW, VIC). This demonstrates that fuel availability and condition are crucial to determine the level of fire activity in Australia, a factor that is closely associated with the type of climate. The ignition and persistence of fires are also closely related to weather conditions as well as climate type. The interaction between climate and available fuel may explain the variability in fire incidence across different Australian regions (Williams et al. 2009).

### 3.2. Direct aerosol radiative effect for biomass burning

The radiative forcing of aerosols is highly dependent on the optical thickness of the aerosols, indicating that wildfires in southern Australia (NSW and VIC) have a much greater impact on climate than previous wildfires in northern and central Australia (NT and QLD)—see AOT and ARF in figure S6. Although the lifetime of biomass-burning aerosols is short, i.e. 7–10 d (Schum et al. 2018), wildfires are very difficult to extinguish, with the result that fires last for several weeks to several months under fire-prone conditions (dry and windy days). Figure 4 shows the AOT and ARF distributions for 1–8 January 2020, demonstrating the vast amounts of aerosols emitted from extensive wildfires and the strong cooling effects of these aerosols over southern Australia, large parts of the Pacific Ocean, and even South America. The NASA/CNES CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) satellite observed that Australian wildfire-smoke approached the stratosphere, i.e. ∼25 km above the surface (NASA Earth Sciences Disasters Program, cited 2020). These strong radiative forcings are also reflected in the monthly average values in figure S6, which shows the monthly averages for ARF (W m$^{-2}$), AOT, and SA from September 2019 to February 2020. Severe individual fires may not necessarily be reflected in an average monthly value. Nevertheless, the highly enhanced AOT in southeastern Australia demonstrates the significance of the fires that occurred in 2019–2020, especially those from November 2019 to January 2020 (figure S6). The heavy aerosol loading was transported through the Pacific Ocean and cooled the atmosphere, an effect that lasted longer than 3 months.

Compared to the average of the 20 year data, the severity of the Australian wildfires in 2019–2020 is clear. Figure 5 compares the regional mean values of AOT at 550 µm, SA, and direct ARF at the TOA for 2000–2018 and for 2019–2020. A high number of active fires over this 20 year period were concentrated in northern Australia (NT); such wildfires were extinguished rapidly, generated a small amount of aerosol, and therefore rather small radiative forcing. However, for the wildfires occurred in southern Australia in 2019–2020 (VIC), the number of active fires was relatively small, but AOT was very large, and therefore their radiative forcing was much stronger. The regional variability of AOT during the fire seasons shows the dependency of aerosol on the climatic conditions (figures 3–5). The highest AOT values of 2019–2020 (AOT > 0.3) in VIC reflect more flammable conditions (i.e. unusual drought and hot weather) caused by unprecedented strong positive IODs that allow substantial amounts of available fuel. It makes fires more persistent, resulting in higher emissions of aerosols to be released into the atmosphere. In general, aerosol loading positively correlates with the intensity of ARF, as shown in figure 5. These AOT values are more than twice as large as those (i.e. AOT < 0.1) caused by biomass-burning aerosols emitted from the tropical savanna climate zones in western and northern Australia, where fires occurred most frequently in the country.

According to the regional average of ARF, the most severe fires in NT, QLD, and NSW were those occurring from November 2019 to January 2020, followed by intense fire activity in VIC one month later.
Figure 4. The atmospheric path of biomass burning-aerosols emitted during the 'Black Summer' from Australia across the Pacific Ocean; AOT, SA, ARF from 1st to 8th of January, 2020.

Figure 5. Regional values (mean with ±1 standard deviation) of aerosol optical thickness at 550 µm (AOT), surface albedo (SA), and direct aerosol radiative forcing (ARF) at the TOA for 2000–2018 and 2019–2020 for Northern Territory, Queensland, New South Wales, and Victoria.

(December 2019 to February 2020). The estimated ARF of 2019–2020 wildfires in NT and QLD (−12.1 to −8.6 W m⁻²) during the summer are only half of the values in NSW and VIC (about −21.1 to −16.2 W m⁻²). The unprecedented cooling effects caused by the recent wildfires are estimated at about −5.9 to −1.9 W m⁻² for Australia as a whole on average and −17.7 to −14.8 W m⁻² for southeastern Australia on average over 6 months. Over the ocean, the direct radiative forcing due to massive biomass burning aerosols transported from wildfires is estimated to be −16.9 to −9.2 W m⁻² on average over 6 months. Based on the TCRP derived by the 3D-climate chemistry EMAC model, this perturbation of radiation forcing could decrease the surface air temperature by −1.5 °C to −0.3 °C in Australia as a whole and by −4.4 °C to −3.7 °C in southeastern Australia, respectively.
The global annual averaged radiative forcing caused by the 2019–2020 Australian wildfires is estimated to be about $-0.5$ to $-0.2$ W m$^{-2}$ in this study and the corresponding change in surface air temperature is $-0.13$ °C to $-0.04$ °C. This is comparable to the radiative cooling effect of short-lived aerosols released from volcanic eruptions, i.e. global mean cooling of $0.1$ °C–$0.3$ °C calculated from the aerosol-ocean general circulation models of the Coupled Model Intercomparison Project Phase 5 (CMIP5) summarized in Gregory et al (2015). The estimated ARF of Australian wildfires is even higher than the 7 year average of radiative forcings from volcanic sulfate aerosols from 2005 to 2011 (i.e. about $-0.1$ W m$^{-2}$) estimated by Ge et al (2016). This is consistent with the report by IPCC AR5 (2014) that the radiative forcing of volcanic eruptions for the years 2008–2011 is about $-0.11$ ($-0.15$ to $-0.08$ W m$^{-2}$) due to the lack of any major volcanic eruptions since 1991 (such as the eruption of Mr. Pinatubo). The IPCC climate models have considered the radiative forcing of volcanic eruptions to be the dominant cause of rapid and dramatic natural forcing, although volcanic eruptions are highly episodic.

The aerosol direct effects due to global fires have been estimated to be about $-1.51$ to $-1.21$ W m$^{-2}$ for the pre-industrial, recent and end-of-century periods (i.e. the year of 1850, 2000, and 2100) using the Community Atmosphere Model 5.0 (CAM5) (Ward et al 2012). The estimated radiative forcing, i.e. from trends in associated AOT, is rather small in magnitude reflecting a minor effect of global fires on climate change. However, the length of the wildfire season has increased by 18.7% globally from 1979 to 2013 due to global warming (Jolly et al 2015). The underestimated effects of fires are a common limit for most models as discussed in Koch et al (2009). General circulation models generally underestimate emissions from fires compared to terrestrial AERONET observational data (Matichuk et al 2008, Chin et al 2009, Tosca et al 2010, Johnston et al 2011). The climate response of fires should be considered in climate projections as reliable magnitudes. Although biomass-burning aerosols have relatively short lifetimes in the troposphere compared to volcanic sulfate aerosols in the stratosphere, they are emitted consistently for periods ranging from several weeks to several months until fires are extinguished. Furthermore, both wildfire frequency and severity have increased with climate change (Flannigan et al 2012, Jolly et al 2015, Doerr and Santín 2016), and therefore wildfires should be considered as an important radiative forcing factor.

4. Discussions and conclusions

This study highlights the pronounced impact of biomass-burning aerosols emitted from the unprecedented Australian wildfires in 2019–2020 on climate as an individual climate forcing agent. We calculated the monthly mean of direct ARF based on satellite observational data and estimated its impact on surface air temperature. During the 2019–2020 fire season (from September 2019 to February 2020), the overall Australian average ARF is estimated to be about $-5.94$ to $-1.91$ W m$^{-2}$ and the southeastern Australian average is estimated at $-17.74$ to $-14.81$ W m$^{-2}$. These values could decrease the surface air temperature by $-1.47$ °C to $-0.27$ °C on average for overall Australia and by $-4.40$ °C to $-3.67$ °C for southeastern Australia, respectively. This is comparable to the radiative cooling effect of aerosol particles from volcano eruptions. As wildfires may become more frequent and more severe in the near future (Flannigan et al 2012, Jolly et al 2015, Doerr and Santín 2016), we need to pay more attention to the impact of wildfires on the climate.

This study provides insights into how such devastating fires in Australia, exacerbated by rising temperatures, can perturb global climate through the radiative forcing change. While this study cannot accurately predict all the extensive global impacts of wildfires, we seek to convey the importance of considering strong negative radiative forcing in future climate projections. Most climate models do not properly account for the effects of sporadic fires, and also the interactions between fires and climate are not yet considered or poorly represented (Bowman et al 2009).

We believe that this study, in which we estimate the radiative forcing effects of extensive biomass-burning aerosols, can contribute to our understanding of the effects of wildfires on the climate.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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ORCID iDs

Johannes Lelieveld @ https://orcid.org/0000-0001-6307-3846
Seon Ki Park  https://orcid.org/0000-0002-8538-911X
Seong Soo Yum  https://orcid.org/0000-0002-0879-1615
Jhoon Kim  https://orcid.org/0000-0002-1508-9218
Sujong Jeong  https://orcid.org/0000-0003-4586-4534

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