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Attributed radiative forcing of air pollutants from biomass and fossil burning emissions☆

Ke Jiang [a], Bo Fu [a], Zhihan Luo [a], Rui Xiong [a], Yatai Men [a], Huizhong Shen [b], Bengang Li [a], Guofeng Shen [a,*], Shu Tao [a,b]

[a] Laboratory for Earth Surface Processes, College of Urban and Environmental Sciences, Peking University, Beijing, 100871, China
[b] School of Environmental Sciences and Engineering, Southern University of Science and Technology, Shenzhen, 518055, China

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ABSTRACT

Energy is vital to human society but significantly contributes to the deterioration of environmental quality and the global issue of climate change. Biomass and fossil fuels are important energy sources but have distinct pollutant emission characteristics during the burning process. This study aimed at attributing radiative forcing of climate forcers, including greenhouse gases but also short-lived climate pollutants, from the burning of fossil and biomass fuels, and the spatiotemporal characteristics. We found that air pollutant emissions from the burning process of biofuel and fossil fuels induced RFs of 68.2 ± 36.8 mW m^{-2} and 840 ± 225 mW m^{-2}, respectively. The relatively contribution of biomass burning emissions was 7.6% of that from both fossil and biofuel combustion processes, while its contribution in energy supply was 11%. These relative contributions varied obviously across different regions. The per unit energy consumption of biomass fuel in the developed regions, such as North America (0.57 ± 0.33 mW m^{-2}/10^{7}TJ) and Western Europe (0.98 ± 0.79 mW m^{-2}/10^{7}TJ), had higher impacts of combustion emission related RFs compared to that of developing regions, like China (0.40 ± 0.26 mW m^{-2}/10^{7}TJ), and South and South-East Asia (0.31 ± 0.71 mW m^{-2}/10^{7}TJ) where low efficiency biomass burning in residential sector produced significant amounts of organic matter that had a cooling effect. Note that the study only evaluated fuel combustion emission related RFs, and those associated with the production of fuels and land use change should be studied later in promoting a comprehensive understanding on the climate impacts of biomass utilization.

Notes

The authors declare no competing financial interest.

1. Introduction

The combustion process is a decisive and important factor in the promotion of human progress. Humans began using biomass fuels as fires for cooking, lighting, and heating a long while ago. Since the age of industrialization, fossil fuels have contributed significantly to the energy supply and consumption. Even now, fuel combustion is still the primary source of energy for human society. According to the International Energy Agency (IEA, 2021), in 2019, 90.3% of the world's total energy supply and 76.7% of the energy final consumption (both primary and secondary energies) was directly derived from fuel combustion, including coal, oil, natural gas, and biofuels. As an important part of the final energy consumption, 73.6% of electricity is also generated from fuel combustion, although nuclear and hydro power have developed rapidly in the energy sector (Graves et al., 2011).

Fuel combustion supplies large amounts of energy that is important to society, but it also causes a series of environmental problems. Hazardous air pollutants, such as sulfur dioxide, nitrogen oxides, and particulate matter, result in severe environmental problems, such as acid rain and photochemical smog (Kim et al., 2007), and serious indoor and outdoor air pollution that affects human health (Bruce et al., 2000; Shen et al., 2021, 2022a; Lee et al., 2020; Tomlin, 2021). Besides the impacts on environmental quality and human health, emissions from the burning process also significant affect global and regional climate by producing greenhouse gases (GHGs) like CO_2, as well as many short-lived climate forcers (SLCFs) (Lam et al., 2012; Huy et al., 2021). Burning of different

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* Corresponding author. Peking University.
E-mail address: gfshen12@pku.edu.cn (G. Shen).

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fuels, for example, two large categories of namely fossil and biomass fuels, has distinct characteristics and consequently different impacts on climate. It is believed that the burning of coals produces large amounts of CO_2, contributing significantly to the global warming. Coal combustion also produces SO_2, a precursor of sulfate in aerosol and having cooling effect (Kiehl and Briegleb., 1993). Climate impacts of CO_2 from the biomass burning process is thought to be smaller than the fossil fuel CO_2 by considering the photosynthesis (Walker et al., 2010; Cherubini et al., 2011), although some are non-renewable. Biomass burning also produce much less SO_2, but not zero, compared to coal combustion (Ren et al., 2021). Moreover, biomass burning is an important source of SLCFs like black carbon, organic matter, and non-methane hydrocarbons (Li et al., 2009; Chen et al., 2017; Shen et al., 2022b). A few studies have investigated the climate impacts of emissions form the biomass burning in sectors like residential combustion and power plants, showing considerable climate impacts of emissions from the biomass burning on the global and regional scales (Aunan et al., 2009; Kodros et al., 2015; Shen et al., 2019), but also highlighting relatively high uncertainty in climate impact assessment. For instance, Reddy and Boucher (2007) evaluated the effective radiative forcing of BC emitted from biofuel and fossil fuel burning as energy consumption, with an annual mean direct radiative forcing (RF) of 0.20 W/m^2. Aunan et al. (2009) evaluated climate impacts of household fuel combustion emissions in Asia, by taking CO_2 and also SLCPs like CH_4, BC, OC, and sulfate into the consideration. Kodros et al. (2015) assessed aerosol climate forcing of aerosols from biofuel emissions and its uncertainty in more details. Most available studies focused on emissions from a specific source, or only evaluated RFs of part climate forcers, as seen in Table s1. One recent study highlighted the counteraction of sulfate on positive radiative forcing in China, and pointed out that the Unite States and China accounting for 21.9 ± 3.1% and 8.6 ± 7.0% of global RF by taking all climate forcers into the considerations (Fu et al., 2021). To our knowledge, there are no studies that separately evaluate radiative forcing of emissions from the burning of fossil and biomass fuels, and take both GHGs and SLCFs into the considerable. It is interesting to look into the supply to energy generated and related climate impacts of burning biomass and fossil fuels.

In this study, we use radiative forcing (RF), the change in the net, downward minus upward, radiative flux at the tropopause or top of atmosphere (IPCC, 2013), to measure the climate effects of emissions from the biomass and fossil fuel combustion processes. The primary objective of this study is to evaluate the RF induced by combustion emissions at the global scale. This study includes the contributions of both long- and short-lived climate forcers, from fossil and biomass fuels, and the relationship of their contributions to the total energy consumption. The spatial and temporal distinct contributions of biomass and fossil fuel burning to the energy supply and climate forcing are also explored.

2. Methods

2.1. Energy consumption and pollutant emissions

The energy consumption and major air pollutant emissions induced by anthropogenic biomass and fossil fuel combustions at the national level from 1970 to 2014 were obtained from the Peking University (PKU)-Inventory, which is available for open access at http://inventory.pku.edu.cn/, and the Community Emissions Data System (Hoesly et al., 2018). As a global database, the PKU-inventory has energy consumption and major air pollutant emissions for most countries. The energy consumption database was mainly constructed from the International Energy Agency database (IEA), with additional inputs from several national statistics and field surveys in a few countries. The PKU-inventory estimates spatiotemporally resolved emissions of CO_2 and major air pollutants such as black carbon, organic carbon, sulfur dioxide (SO_2), ammonia (NH_3), nitrogen oxides (NO_x), carbon monoxide (CO), methane (CH_4) (only in China), and particles. These inventories have been used in several past studies and have been validated for their accuracy in comparison with other inventories and modeled ambient concentrations (Berezin et al., 2013; Wang et al., 2019; Xu et al., 2021; Luo et al., 2020). For methane that in other countries but China, nitrous oxides (N_2O), and non-methane volatile organic compounds (NMVOC), we referred to the Community Emissions Data System (CEDS). EDGAR v5.0 (https://edgar.jrc.ec.europa.eu/) emissions were also used as an assessment of the uncertainty in the combustion emissions estimates (as seen in Figure s1) (Crippa et al., 2020). Detailed energy consumption data of fossil and biomass fuels for each region are provided in the supplementary material **(**Table s2**)**. Data are also provided in the **Supplement Data**.

2.2. Model approach and attribution method

A reduced complexity biogeochemical model, OSCAR, was adopted to simulate global processes and calculate the RF (Gasser et al., 2017). OSCAR is a heavily parametrized model, in which some complex physical and chemical processes are reproduced by parameterized equations calibrated by more complex models. This reduces the operation time of the model and makes it better applied to the probabilistic framework. OSCAR is the box model rather than a precise spatially resolved one and some characteristics and variables (such as temperature) are regionally responsive. One year is the minimum time scale for the OSCAR operation, therefore, it cannot replicate seasonal processes and changes. OSCAR simulates all necessary components of the earth system related to climate change over an historical period. The long-lived species (e.g., CO_2, N_2O etc.) are predicted using a dynamic model, when short-lived species keep at chemical steady state with the change of drivers at each time step as common in simple models (Meinshausen et al., 2011). For example, the period from 1850 to 2014 was utilized in the present study, and the results were based on emissions data and module parameters calibrated by more complex models. The version used in this study was version 2.4 (available at https://github.com/tgasser/OSCAR/releases/tag/v2.4).

All natural and anthropogenic emissions from 1970 to 2014, with other initial emissions data, were constructed to drive the basic run of the model, the content of which was introduced in a previous work (Gasser et al., 2017; Li et al., 2016). A total of 14 compounds were assessed for calculating the RF that included the following: CO_2, CH_4, the change in the water vapor in the stratosphere due to the oxidation of CH_4 (H_2Os), N_2O, halogenated compounds (halo), the change in the ozone in the troposphere (O_3t), the reduction of stratospheric ozone caused by ozone depleting substance emissions (O_3s), sulfate aerosols (SO_4), primary organic aerosols (POA), black carbon aerosols (BC), nitrate aerosols (NO_3), secondary organic aerosols (SOA), the aerosol-cloud interaction (cloud), and the albedo change of snow due to BC deposition (BCsnow). Fuel combustion sources emit few halogenated compounds (ozone depleting substances), and the data is scarce. Hence, the RF induced by halo and O_3s was ignored in the assessment of the climate effects of fuel combustion emissions in this study (Stohl et al., 2009). For CO_2 from biofuel burning, following Bailis et al. (2015), we introduced the fraction of non-renewable biomass (mainly woody biomass) harvested in excess of the incremental growth rate in one area. For annual renewable biomass fuels such as straws and grasses, CO_2 emission was not quantified in the climate impact assessment.

To measure RFs induced by emissions from the burning processes of fossil fuels and biofuels during the study period, we adopted the normalized marginal method proposed by the United Nations Framework Convention on Climate Change (UNFCCC) (2002). Following the approach in Li et al. (2016), a base simulation was run to measure the global RF from 1850 to 2014. This number was rescaled to the reference value reported by the International Panel on Climate Change (IPCC) (AR5). For each atmospheric climate forcer, the scale factor was calculated by dividing the OSCAR simulation RF by the IPCC reference RF, and this was extended to historical time. $RF_x^0(year)$ indicates the rescaled basic global RF in a '*year*' that is induced by the climate forcer, x.

$$f_x = \frac{RF_x(2011, IPCC)}{RF_x(2011, OSCAR)}$$

$RF_x^0(year) = f_x \times RF_x^0(year, OSCAR)$. The estimated RFs for different species here are compared with the IPCC AR5 estimation (Figure s2), showing generally comparable results and consistent temporal trends.

To measure the isolated RFs contributed by the different emissions (regional and global combustion emissions from 1970 to 2014), we ran two simulations with a certain percentage ($\varepsilon = 0.1\%$) of the marginal reduction in the emissions studied and in all other emissions. Using the same method and scale factor, we measured and calibrated the forcing and $RF_x^2(year)$ from the two simulations. The contributions of these two portions of the emissions were then normalized to calculate the relative forcing induced by the studied emissions.

$$RF_x^{emis}(year) = RF_x^0(year) \times \frac{RF_x^0(year) - RF_x^1(year)}{2RF_x^0(year) - RF_x^1(year) - RF_x^2(year)}.$$

2.3. Uncertainty

The uncertainty of the estimates was primarily obtained from the combustion emission data and parameters of the OSCAR model. A Monte Carlo ensemble of 3000-time simulations was performed to address the uncertainty with the emission factors and combustion activities valued randomly in a normal distribution. In addition, the parameters were drawn from a pool of parameterizations calibrated by more complex earth system models. The drivers were also selected with equiprobability from the driving datasets. According to the analysis, the average value with one standard deviation was used in the estimate of the contribution to the RF and its uncertainty. More details are present in the Supplement Material (**s1** and Figure s1).

3. Result and discussion

3.1. Contribution of combustion source emissions to the global RF

Fig. 1 shows the RFs of each climate forcer in 2014 due to all emissions (including natural and anthropogenic emissions) and anthropogenic combustion source emissions (biomass and fossil fuels) from 1970 to 2014. The net RF induced by all emissions during this period was 2.10 ± 0.58 W m^{-2}, with a positive RF of 3.41 ± 0.34 W m^{-2} and a negative RF of −1.31 ± 0.40 W m^{-2}. Among them, the net RF contributed by emissions attributed to fuel combustion processes accounted for only 43 ± 12%. As climate forcers from non-combustion sources, e.g. CH_4, N_2O and halogenated compounds, also have substantial impacts on the global RFs. Both the combustion source and non-combustion source emissions should be regulated and controlled in response to climate change.

CO_2 was expectedly the largest contributor of the positive RF in both the all source and anthropogenic combustion source emissions, with the contribution from the anthropogenic combustion source emission of approximately 75 ± 9%. The remaining portion was from the land use change (LUC) and other anthropogenic non-combustion source (Wang et al., 2013; Gasser et al., 2020), as well as the oxidation of their other emissions. Tropospheric O_3 attributed to precursors like CO, NOx and VOCs (Jacob, 2000) from the fuel combustion was 0.19 ± 0.02 W m^{-2}. This was about 45.5 ± 5.4% of the total RF induced by O_3t from all sources.

For aerosols from fuel combustion, black carbon (BC) expectedly had the largest positive RF contribution of 0.34 ± 0.18 W m^{-2}, and anthropogenic fuel combustion emissions accounted for 56 ± 30% of the total from all sources (0.61 ± 0.30 W m^{-2}). The RF values of POA and sulfate from the fuel combustions made up to 51 ± 27% (−0.15 ± 0.08 W m^{-2} out of −0.29 ± 0.20 W m^{-2}) and 67 ± 30% (−0.25 ± 0.11 W m^{-2} out of −0.37 ± 0.23 W m^{-2}), respectively, of those induced by the emissions from all of the sources, indicating significant climate impacts of aerosols from the burning coal and biomass fuels, as energy sources, on the global scale. The IPCC reported that the RFs from BC and OC induced by the total fuels (fossil and biofuels) were 0.40 W m^{-2} and −0.09 W m^{-2} in 2011, respectively, which was within the uncertainty range (IPCC, 2013).

3.2. Fossil and biomass fuels shares in the energy consumption and climate forcing

The RF induced by emissions from the biomass- and fossil-fuel combustion were estimated separately, as well as their contributions to the energy consumption. As seen in Fig. 2, anthropogenic fuel combustion provided 13.6 ZJ (1 ZJ = 10^{21} J) of energy, of which biomass fuels and fossil fuels accounted for 11% and 89%, respectively. The contribution of fossil fuel to the net RF was 92%, which was slightly higher than its contribution to the energy consumption. This was because biomass fuel combustion contributed little to CO_2 emissions when considering the regeneration of annual renewable biomass fuel as mentioned in method.

When considering all the GHGs, including CO_2, CH_4, H_2Os, N_2O and O_3t, the contribution of biomass fuels to the RF achieved 8.3%, and this

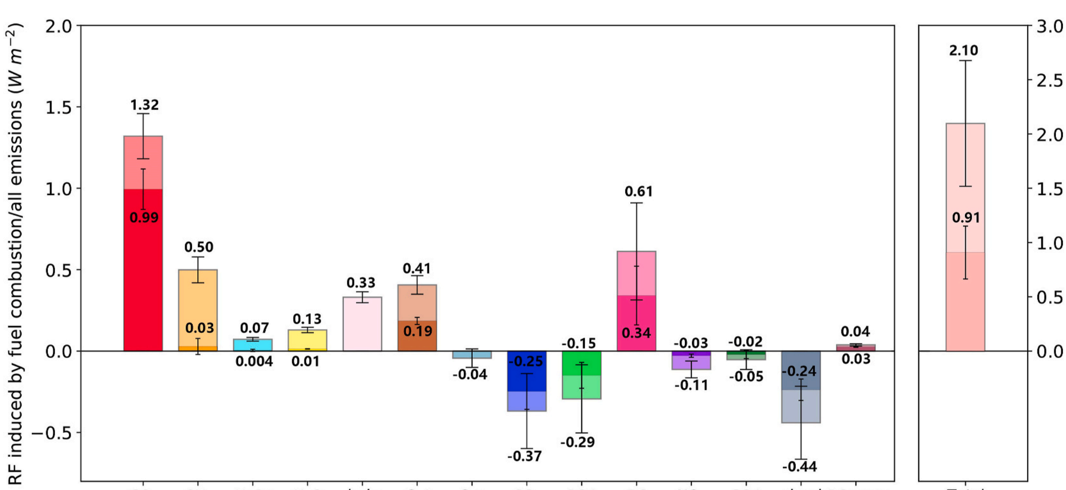

Fig. 1. The radiative forcing (W·m^{-2}) induced by fuel combustion emissions and all emissions from 1970 to 2014. Each bar represents the radiative forcing of the specific forcer. The dark bars and the whole bars indicate those from fuel combustion and all emissions (including natural and anthropogenic emissions), respectively.

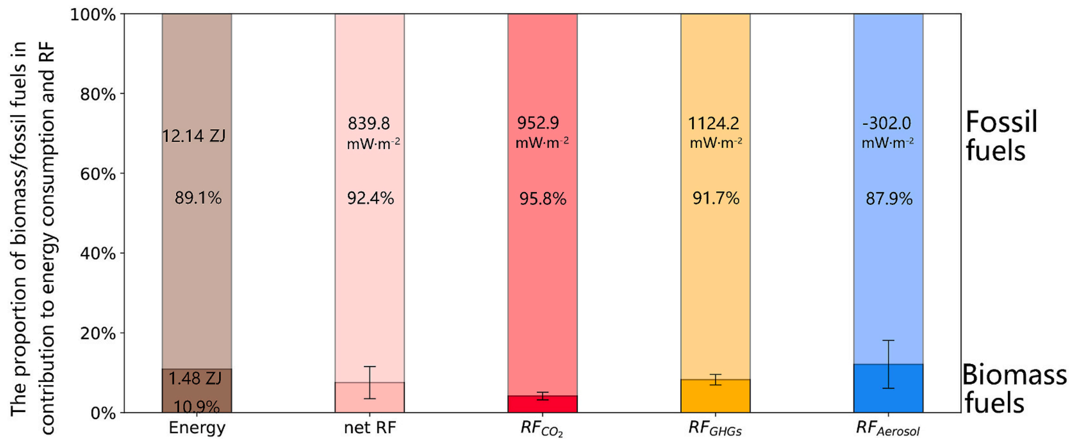

Fig. 2. Relative contributions from biomass fuel and fossil fuel combustions between 1970 and 2014 to the global total energy consumption, the net RF, the RF of CO_2, the RF of greenhouse gases (GHGs), and the RF induced by aerosols (including aerosol direct radiation effect and the aerosol-cloud interaction).

proportion was derived from relatively high proportions of RF from CH_4 (64%) and O_3 (19%) induced by biomass fuels, as seen in Fig. 3. High fractions of CH_4 and O_3 in household biomass burning emissions were also observed in Asia. However, CO_2 dominated the RF induced by fossil fuel combustion, and the climate impacts of emissions from the biofuel burning are primarily determined by short-lived atmospheric aerosols. In the net RF induced by aerosol, emission from the biomass burning only accounted for about 12%; however, the proportion varied substantially among different aerosol components (Figure s3). For the warming effect, mainly due to BC, biomass burning emission accounted for 39% of the total induced by BC from the burning of coal and biomass as energy sources. For the net cooling effect, the relative contribution of emissions from biomass burning was 34%, but it varied from less than 5% for sulfate to nearly 56% for POA.

Fig. 3 shows RFs of different species from the burning of biomass and fossil fuels. As seen, BC and POA were the most significant positive and negative forcers, respectively, in emissions from the biomass burning. It is necessary to note that, as mentioned above, the biomass burning only include those used as energy sources in supporting the society development. If emissions from open biomass burning and forest fires were considered, biomass does contribute largely to the RF of BC compared to the fossil fuels. Sulfate was one of the most important cooling climate forcers, but biomass fuels emitted much less SO_2 in comparison with fossil fuels (Ren et al., 2021; Zhong et al., 2020), and induced -8.3 ± 4.9 mW m^{-2}. As a result, 98% of the RF of sulfate was derived from fossil fuels, and this was also the largest negative RF contributor of fossil fuels. Aerosol-cloud interaction is another important cooling forcer, and biomass fuel and fossil fuel combustion emissions contributed 28% and 72%, respectively. It was previously estimated that the direct radiation effect (DRE) of the aerosol category from the biofuel combustion ranged from -0.02 W m^{-2} to $+0.06$ W m^{-2} globally, which was comparable to our results (0.025 ± 0.012 W m^{-2}) within the uncertainty. In addition, the aerosol indirect effect (i.e., cloud effect), from -0.02 W m^{-2} to $+0.01$ W m^{-2}, was slightly higher than our result (-0.065 ± 0.035 W m^{-2}). This was partly explained by the difference in the aerosol-cloud interaction simulation between these models.

3.3. Temporal evolution in the RF of fuel combustion emissions

Fig. 4 illustrates the global RF change due to anthropogenic biomass and fossil fuel combustion emissions. For biomass fuels, short-term emissions from the combustion source led to a tiny negative net RF in 1970 that was closely affected by the net ratio of BC to OC from biomass burning. While these emissions of aerosols changed slightly over time in the early years, the cumulative GHGs contributed largely to the increase in the net RF. For fossil fuels, high contributions of sulfate and cloud effect to the negative RF made its short-term climate effect to be cooling, as reported in a previous study (Kaufman et al., 1991; Schwartz, 1993).

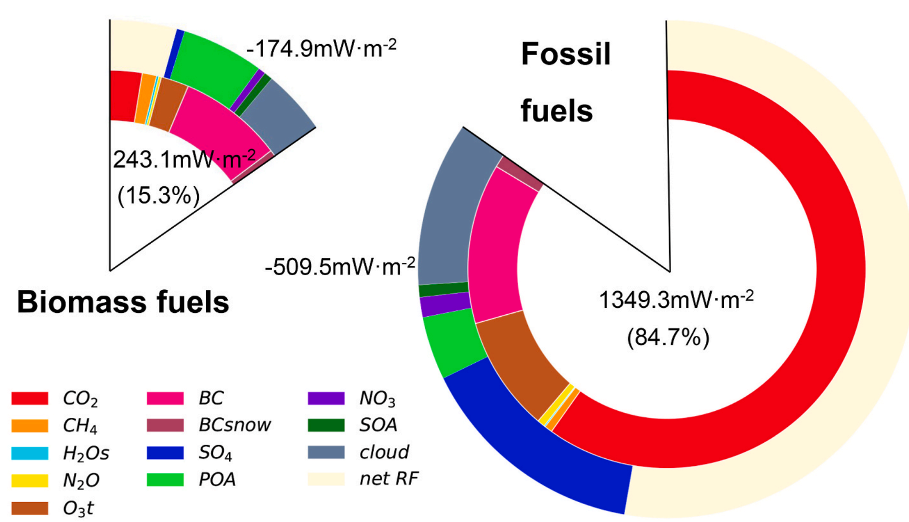

Fig. 3. Global RF of the different climate forcers induced by biomass fuel and fossil fuel combustion emissions from 1970 to 2014. The inner ring represents the positive RF, and the outer ring represents the negative RF, and the net RF was obtained by their difference.

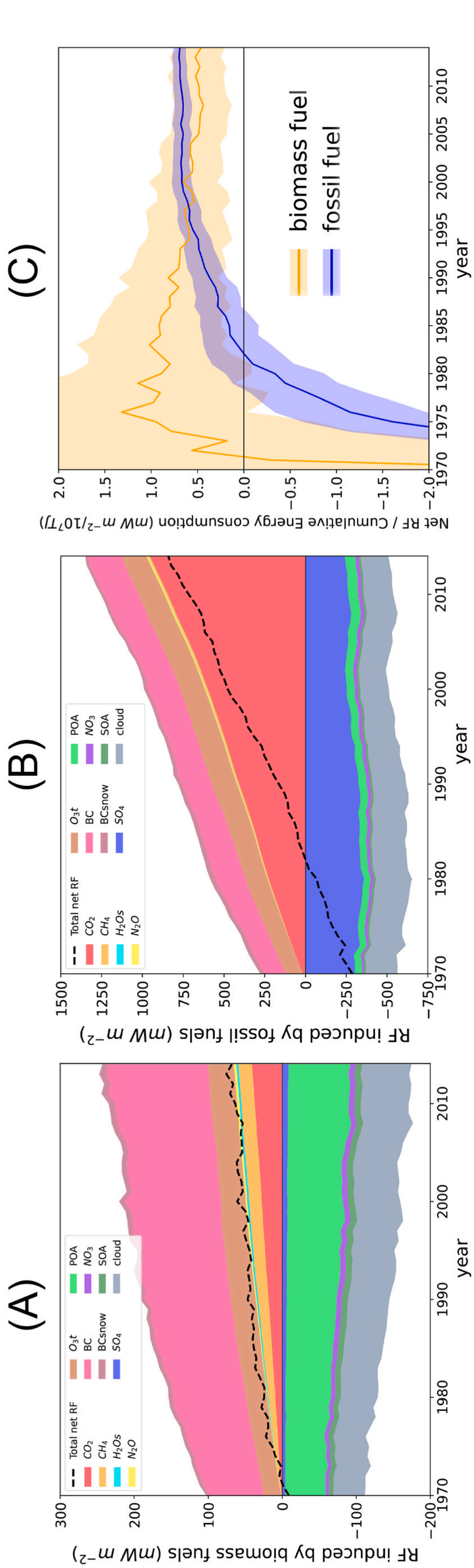

Fig. 4. The global RF induced by biomass (A) and fossil fuel (B) combustion emissions in a time series from 1970 to 2014, and the ratio of the net RF induced to the energy consumption of biomass and fossil fuels (C).

However, the cumulative effect of CO_2 led to a positive net RF increase.

To more clearly evaluate the association of the contribution to climate forcing and energy consumption from fossil and biomass fuels, we further calculated the ratio of net RF to the energy consumption amount (RF/E) for all fuels, fossil fuel and biofuels, respectively, on the global and regional scales. The ratio can reflect and be used to compare the bulk impacts of per-unit energy consumption on the RFs. The curves of the RF/E of biomass fuels and fossil fuels in time series with the uncertainties are shown in Fig. 4C. In the initial short period from 1970 to 1975, the total energy supplied by the biomass burning was low and GHGs accumulation was small, emissions of aerosols significantly affected the RF. It is noted that the uncertainty in RF/E in the early years was very high, as seen in Fig. 4C. This is because the uncertainty in aerosol RFs is generally larger than that in GHG RFs due to the knowledge and data limitation. After the late 1970s, the RF/E of the anthropogenic biomass combustion showed a downward trend, and this can be explained by the effect of vigorous clean biofuel utilization technologies, as they provided energy but had fewer climate warming impacts (Demirbas, 2007). Since 1982 ($\Delta T = 12$ yrs), it was revealed that the RF/E of fossil fuel began to be positive, and after that, the change rates of the RF/E were smaller when the cumulative consumed energy amounts were large. The RF/E of fossil fuels was smaller than that of biomass fuels prior to 1998 ($\Delta T = 28$ yrs), but then gradually flattened to 0.69 mW m^{-2}/10^{7}TJ with that of biomass fuels at 0.46 mW m^{-2}/10^{7}TJ in 2014. This trend suggested that in the near future, in providing the same energy from the burning process, climate forcers from the biomass burning may have smaller warming radiative effects than that from the burning of fossil fuels. This is associated with different compounds emitted by biomass fuels and fossil fuels that vary in forcing and their atmospheric lifetime.

3.4. Regional contributions to the positive and negative RFs

In this study, we divided the world into nine regions (proposed by Houghton) as adopted by the description of the OSCAR model with a little adjustment (Table s1) (Houghton and Hackler, 2001; Gasser et al., 2017). The net RF values contributed by biomass and fossil fuel combustion emissions from different regions are illustrated in Fig. 5 (A), and the detailed RF values of specific forcers in a time series can be referred to in the supplementary materials (Table s2 and Figures s4 and **s5**).

North America (NA), Western Europe (WE), and the former Soviet Union (FSU) were the three regions with high contributions to the net RF associated with emissions from fossil fuel combustion sources. The energy consumption in the developed countries of NA and WE produced large amounts of CO_2 resulting in a rapid increase in the RF associated with CO_2. In addition, their air pollutant controls effectively reduced the ambient SO_2, which is an important precursor of the sulfate producing cooling effect. This consequently led to significant increases in the net positive RF induced by emissions from fossil fuel combustion in these two regions (up to 247.6 ± 27.0 mW m^{-2} and 183.4 ± 25.7 mW m^{-2}, respectively). FSU had a similar feature, but the rising speed of the net RF was slower, and this was due to lower CO_2 emissions compared to those of NA and WE. A previous study also noted this trend (Murphy and Ravishankara, 2018), showing rapid increases in the net RF in NA, WE, and FSU, as seen in our study (Figure s4). In the China Region (CNR), rapid development and the extensive use of fossil fuels contributed largely to the RF of CO_2, but the large amount of SO_2 emissions played a considerable role in offsetting this (Fu et al., 2021). Hence, the net RF in the CNR was 101.2 ± 47.4 mW m^{-2}, lower than those from the NA and WE. The net RF of the CNR emissions increased obviously since the middle 2000s, and this was explained by the effective SO_2 control countermeasures in China (Lu et al., 2020). Previous studies pointed out significant contributions of Chinese and Indian emissions to aerosol radiation. Reddy and Boucher (2007) calculated the RF of BC from biomass and fossil fuel combustions in East and South Asia, which was 107 mW m^{-2}, and comparable with that of our evaluation in CNR and

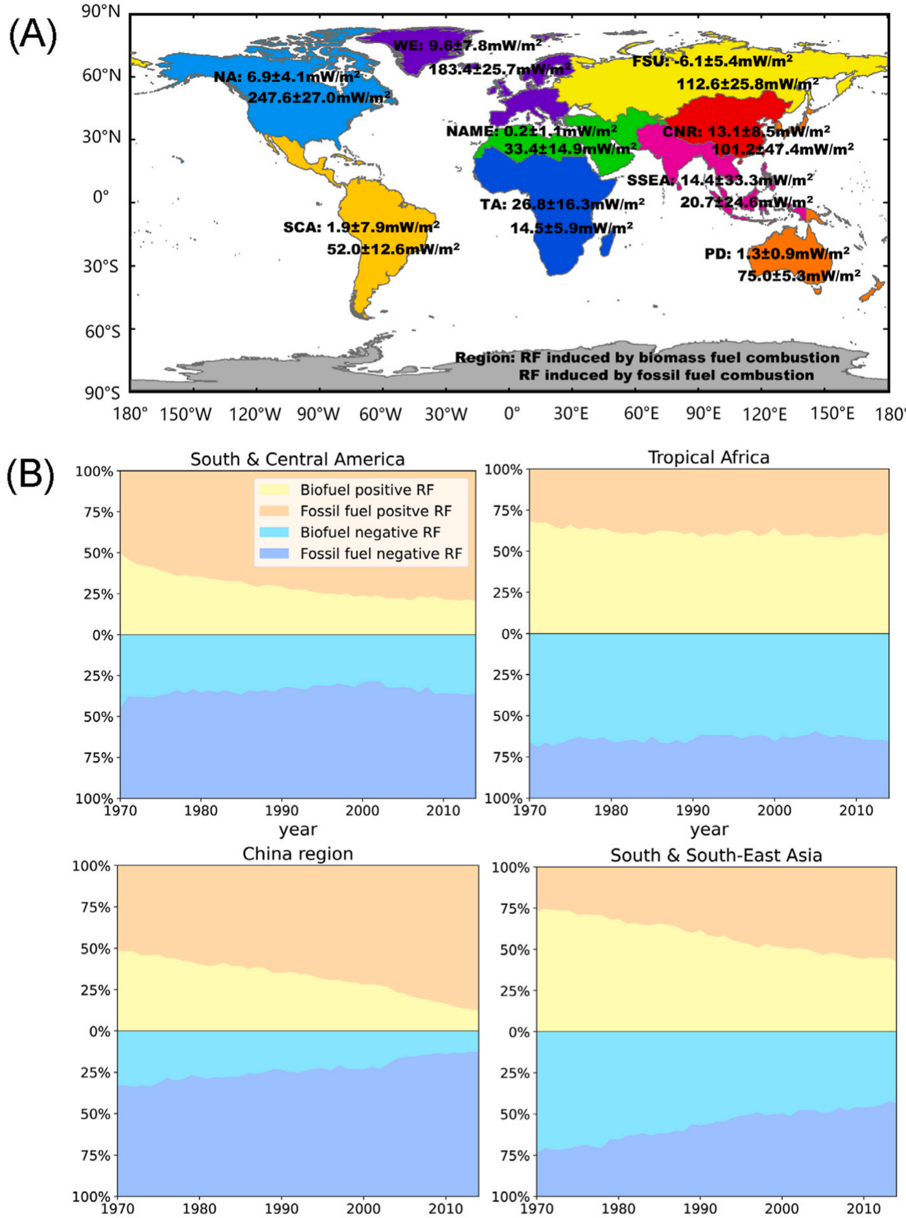

Fig. 5. The RF induced by biofuel and fossil fuel combustion emissions from 1970 to 2014 in the different regions (A). The proportions of positive and negative radiative forcing induced by emissions from biofuel and fossil fuel in South & Central American, Tropical Africa, the China region, and South & South-East Asia (B).

SSEA (120 ± 45 mW m^{-2}). An assessment by Gao et al. (2018) showed that the global direct RF induced by aerosol emitted by the two countries was – 42 mW m^{-2} and -19 mW m^{-2} in 2010, respectively. This was also close to our results in CNR and SSEA (−49 ± 35 mW m^{-2} and -18 ± 24 mW m^{-2}) despite slight differences in region division and emission sources covered in the estimation.

Regional differences in the net RF attributed to biomass burning emissions were not as large as that for fossil fuel combustion emissions. Relatively high contributions originated from tropical Africa (TA), South & South Eastern Asia (SSEA), and the CNR, where abundant biomass fuels are widely consumed as residential energies. Biomass fuel combustion contributed little to the long-lifetime GHGs, whilst the SLCFs dominated the trend of RF induced by biomass combustion emissions. Therefore, as fossil and biomass fuel combustion contributed differently to the climate forcers, the proportion of these two fuel types in both the positive and negative RFs varied obviously across the regions. Fig. 5B shows the proportion of fossil and biomass fuel combustion emissions in the positive and negative RF values in the four regions of the CNR, SSEA, TA, and SCA. With the rapid development of industrialization and urbanization, reduced biomass uses, primarily in the residential sector (Tao et al., 2018; Zhu et al., 2019; Shen et al., 2022b), and rapid increases of other energies like coal, gasoline, and diesels, resulted in a decline in the biomass burning emission contribution in the RF values. From 1970 to 2014, the contribution of biomass burning emissions declined from 49% to 12% in the positive RF and 33%–13% in the negative RF, respectively. Similar trends occurred in SCA and SSEA, but the declining rate was smaller. The large populations in these regions still use biomass fuels in their daily lives, and the clean transition trend was relatively slower (Gioda, 2019). This was more significant in the TA where biomass is the most important source of energy consumption, and the contribution of biomass fuel accounted for greater than 60% and changed very slightly from 1970 to 2014.

3.5. Regional disparities in the energy-climate nexus for biomass fuels

The ratio of the net RF to the energy consumption from 1970 to 2014 for each region and the entire planet was compared and is shown in Fig. 6. The results for the biomass fuels, fossil fuels, and total fuels are shown separately. TA had the highest RF/E of the total fuels, which was associated with its relatively high value of the RF/E for biomass fuels and large proportion of biomass fuel use. The RF/E of the total fuel emissions was low in SSEA, resulting from its low RF/E values in both biomass fuel combustion emissions and fossil fuel emissions. In those areas that consumed little biomass fuel in the energy supply, including developed regions like NA, ME, and FSU, the RF/E of the total fuel emissions was close to that of fossil fuel emissions.

For the RF/E from biomass burning, FSU was the only region where the net RF and the RF/E value (-4.1 ± 3.6 mW $m^{-2}/10^7$TJ) of the biomass burning emissions was negative. In FSU, large amounts of biomass fuels are burned in the fields, and in the agriculture burning category, the ratio of BC to OC was relatively lower (Wu et al., 2020). The RF/E was relatively high in TA and developed regions including NA, WE, and the pacific developed region (PD). The extensive use of traditional firewood in TA contributed largely to emissions of BC, as well as some GHGs. This resulted in a high RF/E for biomass fuels in this area. For developed regions (NA, WE, and PD), biomass fuels are primarily used in energy and industry and only accounted for a small portion of the total energy consumption. Though the GHGs emissions were small, the cooling effect associated with aerosols was also weak. Along with the positive RF contribution by BC deposited on snow, the net RF/Es in these four regions were higher than the others. The CNR and SSEA use large amounts of renewable biogenic materials, such as crop residue, dung cake, corncob, and brush wood, supplying a lot of energy with net-zero CO_2 combustion emissions. The combustion category also had high OC/BC ratios (Akagi et al., 2011; Huang et al., 2015), and this consequently resulted in low RF/Es for biomass fuels in the CNR and SSEA.

Regarding the RF/E for fossil fuel combustion, the RF/Es in the CNR and SSEA were relatively low due to the cooling effect of sulfate in aerosol. The values of the RF/E in other regions were generally very close, although different sub-fuel types, combustion technologies, and control technologies exist in these regions. Regional differences in the RF/Es indicated inequitable climate impacts and consequently differentiated responsibilities that should be assigned.

In a comparison of the fossil and biomass fuels, the energy-climate effects of these two were regionally different in historical change trends. The RF/Es for biomass and fossil fuels in each region in the time series are shown in Figure s6. SCA, NAME, the CNR, and SSRA had similar characteristics as seen in the global trend of the RF/E, that is that initially the RF/E for biomass fuel was higher, but the RF/E from fossil fuel combustion increased substantially. In some regions there were slightly different trends, such as in NA and TA. The RF/E from biomass fuel emissions in WE and fossil fuel emissions in FSU were consistently higher than for the other fuel types throughout the study period. The RF/E tended to be unchanged, and this was primarily determined by its long-lifetime GHGs emissions. Therefore, although under unit energy consumption, the emissions from the combustion process of biofuels has certain advantages in climate effect at the global and long-time scales, it is important to note regional and country differences and the time scale effect.

3.6. Implication and limitations

In this study, the RF induced by emissions from biomass and fossil fuel combustion were evaluated and specifically analyzed regarding their associations with the contribution to energy consumption. In previous studies, the contribution of biomass fuel use to reducing CO_2 emissions and the consequent climate forcing had been recognized (Sathre and Gustavsson, 2011; Gustavsson et al., 2015). SLCFs, being associated with short but possibly strong climate influence (Fu et al., 2020), should also be considered in an evaluation of a fuel's energy-climate effect. There could be short-term cooling effects of fossil fuel combustion emissions and warming impacts of biomass burning. This study specifically revealed that the cooling effect of historical continuous fossil fuel combustion emissions could possibly last for approximately 12 years, and estimated that it appeared that ~28 years for biomass fuels to produce obvious advantages in the combustion emission related RFs, while the impacts associated with the process of fuel production and land use change are not considered.

Several limitations of the study should be considered. Firstly, though uncertainties were quantified by running the Monte Carlo simulation with the consideration of variations and uncertainties in both emission inventories and parameters used, the outputs heavily relied on the OSCAR simulation. As mentioned in the Method section, the OSCAR model utilized parameterized equations to simulate some complex processes. Although these parameters are calibrated by complicated earth system models, and there are several values in each module, complex systems and some nonlinear reactions are still beyond its capabilities to simulate. The parameters in some modules, such as aerosol simulation, can vary largely, resulting in high uncertainties in the output RFs. Furthermore, as stated above, the scale of the results is somewhat rough due to the lack of temporal and spatial precision, and the effects of seasonal pollution emissions and transmission in some specific locations, as well as local climate effects of aerosols, are difficult to precisely quantify. Secondly, the present study only addressed emissions from the burning process of biomass and fossil fuels, and found that per-unit energy can have distinct climate impacts. Though replacing fossil fuels by biomass is attractive in reducing air pollutant emissions and receiving climate and health co-benefits, it is also necessary to note that the impacts on climate could be rather different in different time scales, that should be considered in assessment and in cation when generalizing the results (Sathre and Gustavsson, 2011; Sterman et al., 2018). There are also many criticisms on the concept of carbon neutral of biomass (Johnson, 2009; Searchinger et al., 2009). Moreover, the impacts of

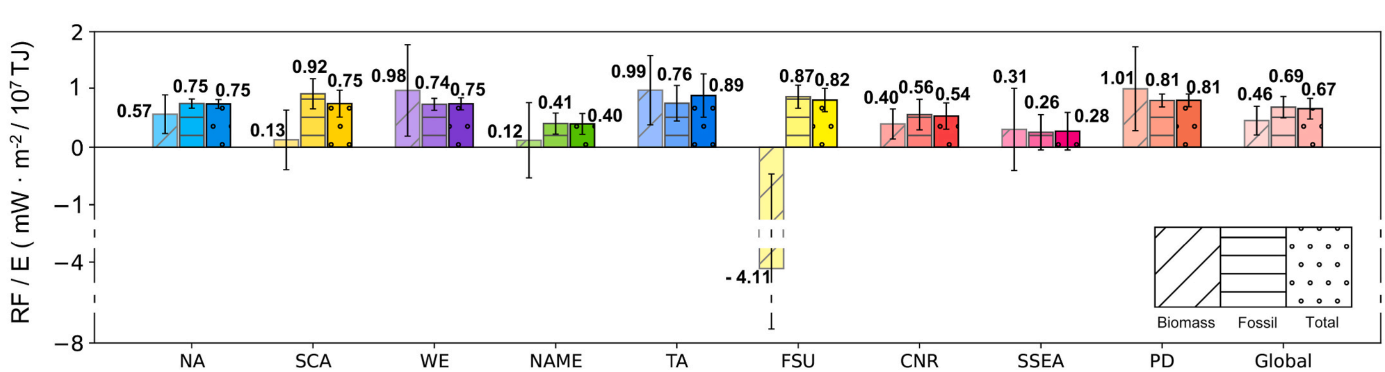

Fig. 6. The RF/E values of biomass combustion emissions, fossil fuel combustion emissions, and total fuel combustion emissions from the different regions.

different fuels in real world could be much complex, beyond the emissions from the burning process only. Different fuel subtypes and their utilization in different sectors have different emission characteristics, and consequently different health and climate impacts. Emissions from the production/transportation of fuels and those associated with land use change also affect climate significantly (Searchinger et al., 2008). A comprehensive life cycle assessment covering fuel exploitation, transportation, impact on land change and some socio-economic conditions may help to address this.

4. Conclusions

The study found that the net RF associated with combustion emissions accounted for 43% of the total RF at 2.10 ± 0.58 W/m^2 from 1970 to 2014. The RFs contributed by the combustion sources varied in regions, with high contributions of emissions from north America, western Europe and the former Soviet Union. Of the combustion-associated RFs, biomass burning emission contributed 7.6%, while the energy being produced from the biomass burning made up to 11% of the total energy from both biomass and fossil fuel combustions. The per unit energy consumption yielded distinct impacts on radiative forcing among different regions, owing to different energy consumption structure and pollutant emission profiles. The study highlighted the inclusion of climate forcers other than typical greenhouse gases such as short-lived climate pollutants, and regional-specific differentiated energy and climate policies in response to climate change.

Author contribution

Ke Jiang: Formal analysis, Data curation, Writing-original draft, **Bo Fu**: Formal analysis, Investigation, Data curation, Writing-original draft. **Zhihan Luo**: Writing-review & editing. **Rui Xiong**: Formal analysis, visualization. **Yatai Men**: Formal analysis, visualization. **Huizhong Shen**: Writing-review & editing. **Bengang Li**: Writing-review & editing. **Guofeng Shen**: Conceptualization, Writing-review & editing, Funding acquisition. **Shu Tao**: Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

The following information associated with the text is provided and available online free of charge:

The detailed description of the sources and evaluation of uncertainty; a brief summary of recent literature studies on RFs of emissions from fossil and biomass burning; the comparison between the estimated RFs for different species and the value reported by IPCC AR5; the RF proportion of each climate forcer from biomass and fossil fuel combustion; the specific countries and regions concluded in nine regions in this study; the RF of different forcers and energy consumption of biomass and fossil fuel, as well as RF/E in time series in the nine regions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2022.119378.

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