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Divergent Energy-Climate Nexus in the Global Fuel Combustion Processes

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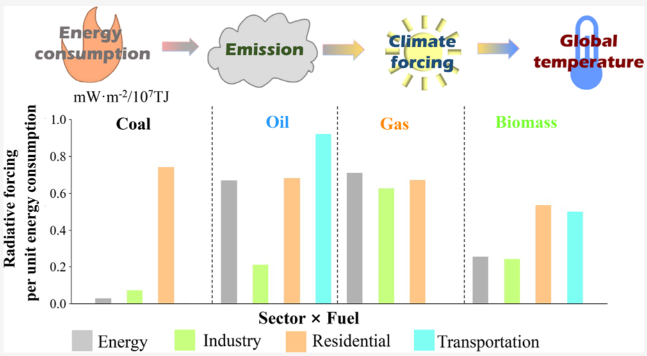
ABSTRACT: Fuel combustion provides basic energy for the society but also produces CO_2 and incomplete combustion products that threaten human survival, climate change, and global sustainability. A variety of fuels burned in different facilities expectedly have distinct impacts on climate, which remains to be quantitatively assessed. This study uses updated emission inventories and an earth system model to evaluate absolute and relative contributions in combustion emission-associated climate forcing by fuels, sectors, and regions. We showed that, from 1970 to 2014, coal burned in the energy sector and oil used in the transportation sector contributed comparable energies consumed (24 and 20% of the total) but had distinct climate forcing (1 and 40%, respectively). Globally, coal burned for energy production had negative impacts on climate forcing but positive effects in the residential sector. In many developing countries, coal combustion in the energy sector had negative radiative forcing (RF) per unit energy consumed due to insufficient controls on sulfur and scattering aerosol levels, but oils in the transportation sector had high positive RF values. These results had important implications on the energy transition and emission reduction actions in response to climate change. Distinct climate efficiencies of energies and the spatial heterogeneity implied differentiated energy utilization strategies and pollution control policies by region and sector.



KEYWORDS: *fuel combustion, energy-climate relationship, radiative forcing, global energy flow, regional disparity*

1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) estimated that the global mean surface temperature (GMST) has increased by 1.09 (0.95−1.20) °C between 1850−1900 and 2011−2020,[1] in which the change is closely related to carbon dioxide (CO_2), especially from fossil fuel combustion. Global climate change also endangers food security and water security.[2]

A variety of energy sources have been used, and the energy consumption structures are distinct by time and region. Coals and oils replaced traditional biomass fuels in the early industrialized countries, contributing to significant increases in human energy consumption.[3] The widespread use of electricity has led to more primary fuels (especially coals) being burned in the energy sector. The occurrence of environmental disasters and concerns on human health[4,5] promotes switching from dirty solid fuels to clean modern energies such as natural gas and biogas in many developing countries.[6,7] Usually, the combustion of fossil fuels such as coals and petroleum oils is believed to be the main source of ambient CO_2 causing global warming. International Energy Agency (IEA) estimated that energy-related CO_2 emission was 36.3 Gt in 2021, with nearly 92.3% (33.5 Gt) from fossil fuel combustion.[8]

In fact, besides CO_2, there are many other climate forcers, including long- and short-lived ones such as nitrous oxide, ozone, and various atmospheric aerosols. Combustion processes have significant contributions to many short-lived climate forcers (SLCFs), including black carbon and sulfate aerosols, and consequently induce temporary but strong climate impacts compared to CO_2.[9] It was previously reported that developed regions, including North America and Western Europe, consumed large amounts of fossil fuels and contributed significantly to the global radiative forcing (RF),[10] while in China and India, though there were also high energy consumptions, the cooling SLCFs such as sulfate and organic aerosols partly offset the warming effects of greenhouse gases (GHGs).[11] There are substantial differences in climate impacts between biomass and fossil fuel combustions when not only CO_2 but also many nonCO_2 climate forcers were taken into consideration.[10]

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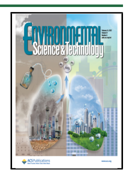

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The composition profiles from the burning of different fuels vary obviously, and even for the same fuel, there could be rather different emission characteristics when it was burned in different sectors or facilities, which consequently may result in divergent climate impacts among the sector-fuel combinations. Decomposition of climate forcing to sectors and fuels can provide scientific insights on detailed contributions of combustion process on climate and is expected to be more efficient in developing well-directed control countermeasures; however, this has not been answered. Several studies partly assessed the climate impacts of specific fuels and/or sectors. For example, Aunan et al. estimate the RF from residential fuel burning.[12] A comprehensive evaluation of climate impacts and relative contributions for different energies consumed in each sector globally and for different regions is not available yet.

In this study, using updated global emission inventories and an earth system model (OSCAR), we, for the first time, decomposed the climate forcing to different sectors and fuels by regions. RF, net energy flow, and temperature change attributed to emissions of different fuels by sector and region are quantitatively analyzed. Two new indexes are proposed to quantitatively assess the energy-climate relationship in the combustion process. We also conducted an ideal mitigation experiment to assess the consequent impacts on climate change of energy switching and emission reduction. Potential implications on policy are discussed. Note that the climate effects of direct combustion emissions from subdivided sources are assessed in the present study, whereas the energy-related emissions in other noncombustion processes and life-cycle assessment of energy are not addressed here due to the limitations in data available and high uncertainties in current evaluation models.

2. METHODS

2.1. Study Area and Indicators. Global anthropogenic combustion emissions were divided into 5 regions × 4 sectors × 4 fuels. The five regions include R5.2OECD, R5.2REF, R5.2ASIA, R5.2MAF, and R5.2LAM as detailed in Section 3. Four types of fuels (coal, oil, gas, and biomass) burned in four sectors of energy production, industry, residential, and transportation are considered (see Text S1 in the supporting material for detailed description). International shipping and aviation that could not be attributed to a specific region were considered separately and included in the oil burning in the transportation sector.

The RF is defined as the change in the net, downward minus upward, radiative flux (expressed in $W \cdot m^{-2}$) due to a change in an external driver of climate change.[1] As an important part of global energy budget,[1] the net energy flow (NEF), inflow minus outflow, to the earth system due to the relative RF could be calculated by the equation:

$$\mathrm{NEF}(t) = S_{\mathrm{Earth}} \times \sum_{i=t_0}^{t} \mathrm{RF}(i) \times T_{\mathrm{year}} \tag{1}$$

where S_{Earth} and T_{year} represent the surface area of the Earth and the total time (seconds) of 1 year, respectively. t_0 is the start time of the evaluation period, which is 1970 in this study.

To quantitatively evaluate the climate-energy relationship in the combustion process with the accumulative energy consumption, two indexes, RF/E and NEF/E, are introduced whose calculation formula is:

$$\mathrm{RF}/E(t) = \frac{\mathrm{RF}(t)}{\sum_{i=t_0}^{t} E(i)} \tag{2}$$

$$\mathrm{NEF}/E(t) = \frac{\mathrm{NEF}(t)}{\sum_{i=t_0}^{t} E(i)} \tag{3}$$

where RF(t) and NEF(t) represent the RF and NEF induced by the combustion emissions from t_0 to t, respectively, and the $E(t)$ represents the energy consumption of the combustion source in year t.

2.2. Earth System Model and Attribution Method. The earth system model OSCAR v3.1 is used for the simulation of the climate system since the industrialization (1750~). The model included all necessary components to simulate the past and future climate change,[13] which has been widely used to study the contribution of human activity to climate,[11,14,15] and also applied to IPCC AR6 to study the response of future climate to multiple scenarios. All dynamic changes of different climate forcers are described by parametric equations with sources and sinks. The emission sources are derived from multiple emission inventories, such as CEDS, EDGAR,LUH2, etc., and the parameters are selected from or calibrated by different more complex models or observations,[16] which were built in the model and could be accessed in https://github.com/tgasser/OSCAR/tree/v3.1.

This study considered 12 kinds of climate forcers that derived from combustion emissions, including five GHGs, carbon dioxide (CO_2), methane (CH_4) and the vapor from its oxidation in the stratosphere (H_2Os), nitrous oxide (N_2O), and tropospheric ozone (O_3t) and seven aerosol related forcers, black carbon aerosol (BC) and the albedo effect of its snow deposition (BCsnow), sulfate aerosol (SO_4), primary organic aerosol (POA), secondary organic aerosol (SOA), nitrogen aerosol (NO_3), and aerosol−cloud interaction (ACI). The atmospheric concentrations and the RF of each climate forcer, as well as the GMST, in each year were calculated based on the emission data of their precursors and the parameterized equations representing the atmospheric physicochemical processes as introduced in a previous study.[17] The associated emission and chemical precursors of each climate forcer are listed in Table S1.

Attribution is necessary to study the influence of specific human activity to climate system. This study relied on the normalized marginal attribution method to calculate the relative and absolute contribution (AC) to climate forcing of each combustion source. This method has been proposed in the methodological issue about assessment of contribution by the United Nations Framework Convention on Climate Change (UNFCCC).[18] Briefly, a basic simulation was run to simulate the real-world climate system from 1750 to 2014 based on the emission inventory and observation data built in the model, and the result (RF, GMST, etc.) was recorded as R_b. Then, we divided all the emissions from 1750 to 2014 into $\sum_i E_i$ and E_{other}, in which E_i represents emissions of each combustion source from 1970 to 2014 (i.e., the research object), and E_{other} represents all emissions since the industrialization except $\sum_i E_i$. For each E_i and E_{other}, we conducted a simulation with a marginal reduction ($-\varepsilon E$, ε = 0.1%) of the specific emission and the result was recorded as R_i or R_{other}. The marginal contributions were normalized to represent the relative contribution (RC) by the equation:

$$\mathrm{RC}_i = \frac{R_\mathrm{b} - R_i}{\sum_i (R_\mathrm{b} - R_i) + R_\mathrm{b} - R_\mathrm{other}} \tag{4}$$

Since OSCAR is a simplified climate model and needs calibration to enhance the accuracy of its outputs, the R_b was rescaled to calculate the AC as done in previous studies.[11,14] The rescale factor of RF of each climate force and GMST was confirmed by IPCC report value in a certain year t_x by the equation:

$$f_x = \frac{\mathrm{IPCC}(x, t_x)}{R_\mathrm{b}(x, t_x)} \tag{5}$$

where the x represents the RF of each forcer or GMST, and the t_x and $\mathrm{IPCC}(x, t_x)$ are shown in Table S2. The AC to the x of combustion source i could be calculated from:

$$\mathrm{AC}_{i,x} = R_{\mathrm{b},x} \times f_x \times \mathrm{RC}_{i,x} \tag{6}$$

2.3. Data Source and Uncertainty Analysis. The national-level combustion emission data from 1970 to 2014 used in this study of CO_2 and main air pollutants, including black carbon, organic carbon, sulfur dioxide (SO_2), ammonia (NH_3), nitrogen oxides (NO_x), and carbon monoxide (CO), were derived from Peking University (PKU) inventory, which contains 65 anthropogenic combustion sources and each one could be attributed to a certain fuel and sector. The energy consumption data for each combustion source in the PKU inventory was built based on available information from the IEA database, and field surveys and national energy statistics as a supplement. This inventory has been applied to many global and regional air pollution and subsequent impact studies.[19−22] The inventory is open accessed at http://inventory.pku.edu.cn/.

Other climate-related combustion emissions, including CH_4, N_2O, and nonmethane volatile organic compounds (NMVOC), were accessed from Community Emissions Data System (CEDS).[23] The CEDS only has the open data of individual sector or fuel, so the emissions from each fuel burned in each sector were interpolated based on the fuel energy consumption from the PKU inventory.

For each simulation, a 3000-time ensemble of Monte Carlo was performed to evaluate the uncertainty of the result. The uncertainty was mainly from two sources: the emission data to drive the model and the parameters to represent the process simulation. Averages and one standard deviation from the Monte Carlo simulation are reported.

3. RESULTS AND DISCUSSION

3.1. Combustion Emission RFs by Sector and Fuel. Figure 1 illustrates the RFs induced by different compounds from the anthropogenic sources between 1970 and 2014. As expected, CO_2 is the largest positive RF contribution, contributing 1000 ± 76 mW·m^{-2}. As one long-lived greenhouse gas, CO_2 emissions prior to 1970 and those from other noncombustion sources contributed to the left present-day global RF of CO_2. Combustion source BC, taking its snow deposition albedo effect into the consideration, had a positive RF of 325 ± 152 mW·m^{-2} and was the second largest following CO_2. Organic aerosols, including primary and secondary ones, derived from organic carbon and NMVOC oppositely contributed to a negative RF of −106 ± 57 mW·m^{-2}. Sulfate in particles originating from SO_2 from combustion emissions, mainly fossil fuels with less emissions from biomass

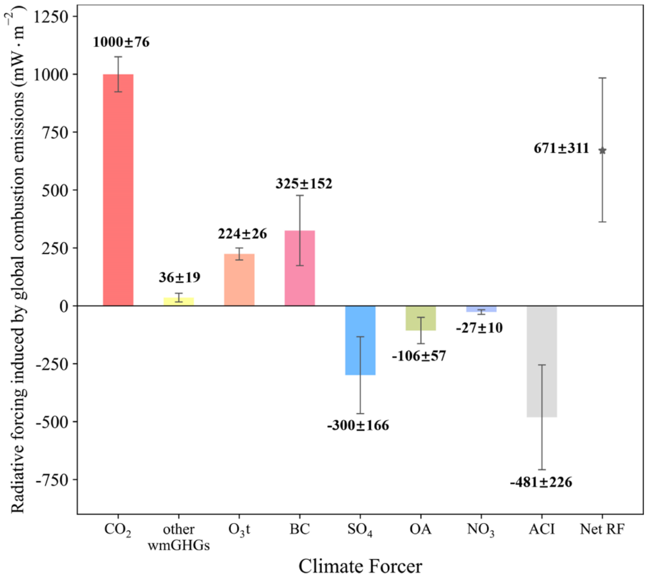

Figure 1. Radiative forcing (mW·m^{-2}) of each climate forcer induced by global anthropogenic combustion emissions from 1970 to 2014. Among them, other wmGHGs include CH_4, H_2Os, and N_2O; BC includes RF of BC and BCsnow; OA includes POA and SOA.

burning,[24] expectedly has a strong cooling effect, inducing a negative RF of −300 ± 166 mW·m^{-2}. This result is numerically greater than a previous estimate of −250 ± 110 mW·m^{-2},[10] primarily because this study included emissions from international shipping with significant SO_2 emissions.[25] The combustion process has a high contribution to aerosols emitted and also an intense ACI with an RF of −481 ± 226 mW·m^{-2}. Thus, by considering all climate forcers, the net RF induced by global fuel combustion emission was 671 ± 311 mW·m^{-2}. The NEF for each climate forcer was consistent with the RF quantitatively as seen in Figure S1.

We further decomposed combustion emission associated RF to different sectors and fuels, by considering the cumulative energy consumption, impact on net energy flow (NEF), and change of GMST due to each fuel combustion in each sector from 1970 to 2014. The proportion result is illustrated in Figure 2 with detailed values and uncertainties listed in Table S3. From 1970 to 2014, the whole society consumed a total of 14.2 ZJ energy from burning fuels. Coal combustion in energy production sector (*Ene.-Coal*) and oil used in the transportation sector (*Tran.-Oil*) contributed largely to the total energy consumed, accounting for 24 and 21%, respectively. Their impacts on climate, however, are rather different. The *Ene.-Coal* had a net RF of only 9 mW·m^{-2}, whereas the *Tran.-Oil* contributed to 40 ± 11% (266 ± 72 mW·m^{-2}) of net RF, that was much higher than emissions from others. In consideration of different climate forcers, the RFs of CO_2 under unit energy consumption in the *Ene.-Coal* and *Tran.-Oil* were relatively approximate (see Table S3) owing to comparable CO_2 emission factors (under unit energy, g/MJ) of these two fuels.[26] Therefore, the contributions of SLCFs predominately caused the observed difference in the RF between these two. As a main source of anthropogenic SO_2,[27] the *Ene.-Coal* expectedly contributed to large proportions of RF values induced by sulfate and ACI, accounting for 52 ± 30 (−157 ± 89 mW·m^{-2}) and 33 ± 19% (−161 ± 94 mW·m^{-2}), respectively. This offsets a vast majority of the positive RF, mainly induced by CO_2, from the *Ene.-Coal*. Oppositely, the

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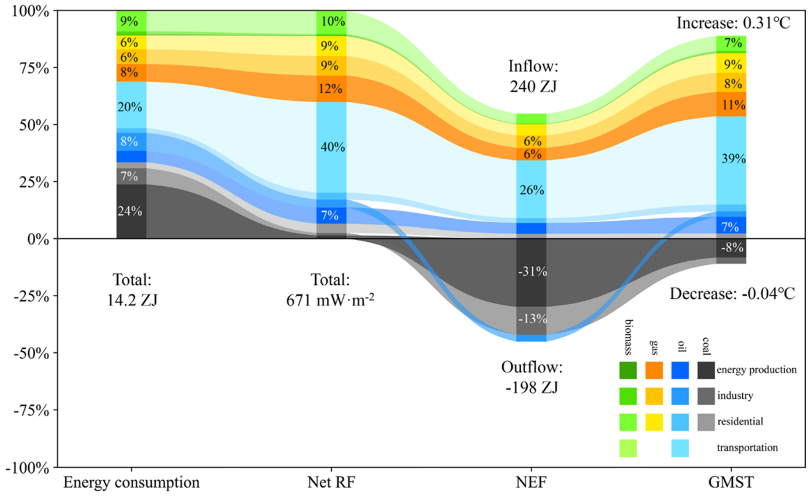

Figure 2. Proportion of contribution of each fuel combustion in each sector to accumulative energy consumption, net radiative forcing (RF) in 2014, net energy flow (NEF), and the change of global mean surface temperature (GMST) from 1970 to 2014. For NEF and GMST, all positive and negative values are added numerically as 100%.

Tran.-Oil generated more warming SLCFs such as BC and NO_x that are important precursors of O_3t, resulting in its net RF even higher than the RF of CO_2.

The consumptions of gas fuels in different sectors were comparable, and the impacts on climate were similar. As one relatively clean energy, gas combustion produces much less hazardous air pollutants compared to solid fuels[28] hence the majority of its RF is derived from CO_2. Global gas combustion generated a net RF of 194 ± 11 mW·m^{-2}, which was almost equal to its CO_2 contribution. Biomass is largely used in the residential sector,[29] accounting for 9% of global total fuel energy consumption, when other sectors employed mostly second-generation clean biofuels with little impacts on climate. Household biomass burning produced aerosols and many other air pollutants that negatively affected air quality and the climate;[30] however, the neutralization of positive and negative aerosols weakened its climate impacts.

The parameter, NEF, considered the accumulation of net RF in each year as described in Section 2. Generally, coal burning in the energy production and industry (*Ene.-Coal* and *Ind.-Coal*) still had negative NEF values at −131 ± 111 and −54 ± 40 ZJ, respectively. The net RF of these two sections was initially dominated by the SLCFs. The negative values indicated energy outflow from the earth while the accumulation of CO_2 was small. Although the net RFs continuously increased and then turned to slightly positive values in the 2010s, the positive energy inflow was incomparable to the prior enormous energy outflow and ultimately tallied to a negative NEF. Correspondingly, the *Ene.-Coal* and *Ind.-Coal* emissions during the 45 years finally contributed the GMST change of −29 ± 96 and −9 ± 28 m°C. Note that the high uncertainty suggests that their impacts on temperature have not yet been guaranteed despite the fact that the best estimate did suggest their cooling effects.

The NEF and the change in GMST are not always synchronous. Oil combustion in the industry sector (*Ind.-Oil*) contributed to a net RF of 24 ± 26 mW·m^{-2} and a NEF of −13 ± 24 ZJ but subsequently displayed an 8 ± 16 m°C warming impact. The main reason is that the influence of earlier energy influx on the current climate is less due to the warming's negative feedback by the Planck response.[31] For instance, by considering two ideal scenarios:[1] providing the earth system with 30 years of energy outflow, followed by 30 years of equivalent energy inflow (compared with baseline scenario);[2] same as,[1] but reverse the sequence of inflow and outflow. The scenario[1] is supposed to finally have a warming impact in comparison to the baseline scenario, whereas scenario[2] exhibits a cooling effect, which is displayed in Figure S2. In addition to the enhancement of the earth's radiation as the most apparent negative feedback, global warming would also lead to a slew of other direct and/or indirect feedback effects, which are not completely captured in this study.[17,32] The feedback process needs to be studied and evaluated later with comprehensive quantitative models available.[15,33]

3.2. Time Inconsistency in the Temporal Energy-Climate Relationship. Impacts on climate change and its degree of combustion emissions are strongly time-dependent, being closely related to the intensity and emission characteristics of combustion activities. The RF and NEF induced by emissions from the burning of different fuels for each sector over the time are illustrated in Figures S3−S10. The RF of long-lived GHGs expectedly cumulated over time, while the RF of SLCFs was mostly determined by the current-year emissions and had relatively higher variations compared to that of GHGs.[34] As discussed above, the *Ene.-Coal* and *Ind.-Coal* generally maintained a negative RF that gradually increased over time. The fluctuations in their SLCFs were primarily from the regional emission differences. However, for coals burned in the residential sector, it always showed a warming effect opposite to coals burned in the energy and industry sectors. This is explained by that the *Res.-Coal* produces much more BC during the incomplete burning compared to what the *Ene.-Coal* and *Ind.-Coal* did,[35,36] counteracting the negative RF of other components like sulfate.

The net RF of *Ind.-Oil* increased obviously before the 1990s, mainly due to less cooling effects from reduced levels of aerosols when end-of-pine controls were effectively taken. Then, due to low energy consumption and low CO_2 emissions, the RF increasing trend slowed down. Oil combustion in other sectors created a positive and continuously increasing trend in the net RF. With the contribution of SLCFs nearly stable, the increase in the gas-induce RF was mainly derived by the CO_2 emission and proportional to energy consumption. Gas consumption in the energy sector had expanded greatly over

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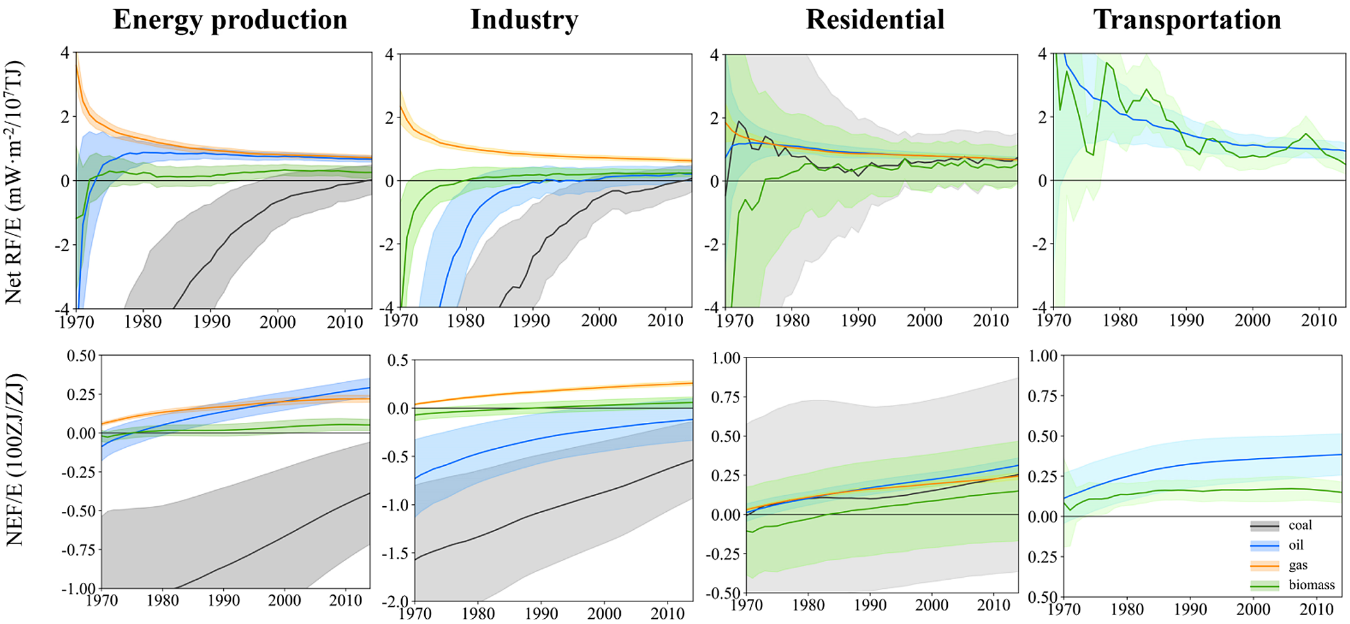

Figure 3. Time series of the ratio of net radiative forcing to cumulative energy consumption (RF/E) and the ratio of net energy flow to cumulative energy consumption (NEF/E) for different fuels in the energy production, industry, residential, and transportation sectors.

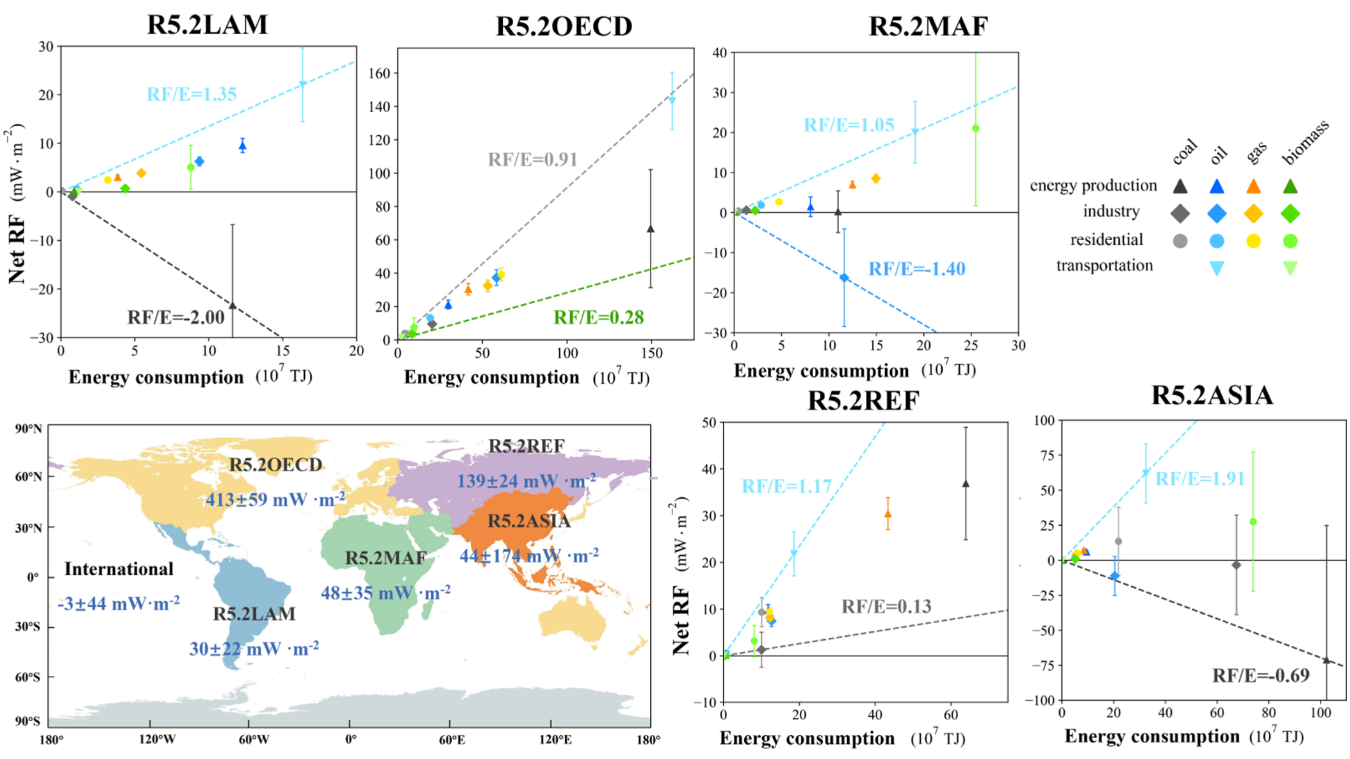

Figure 4. Five regions divided in this study, and their respective RF induced by total combustion emissions in 2014 (map); the net RF and accumulative energy consumption contribution of different fuels and sectors in 2014 (scatter plot), in which the fuel sectors with the highest and lowest RF/E are highlighted by dotted line, and the number aside is the RF/E (the slope of line).

the last several decades,[37] from 0.007 ZJ in 1970 to 0.055 ZJ in 2014. Gas use in the residential sector also increased largely over time under the household energy transition.[38] Despite different emission characteristics, the net RF for *Res.-Biomass* had a similar temporal trend compared to that for *Res.-Coal*.

To quantitatively assess short- and long-term climate impact efficiencies, RF/E and NEF/E (see Section 2) were calculated and compared in Figures 3 and S11. The RF/E of short-lived species declined gradually with the accumulation of energy (time) as it did not cumulate; therefore, the net RF/E was largely influenced by the RFs induced by the wmGHG emissions per unit energy consumption. Gas utilized in different sectors had comparable RF/E values at 0.63−0.71 $mW{\cdot}m^{-2}/10^7$ TJ. Most fuels consumed in the industry sector had low RF/E values, suggesting relatively small climate efficiencies, and for coal, oil and biomass fuels in the industry

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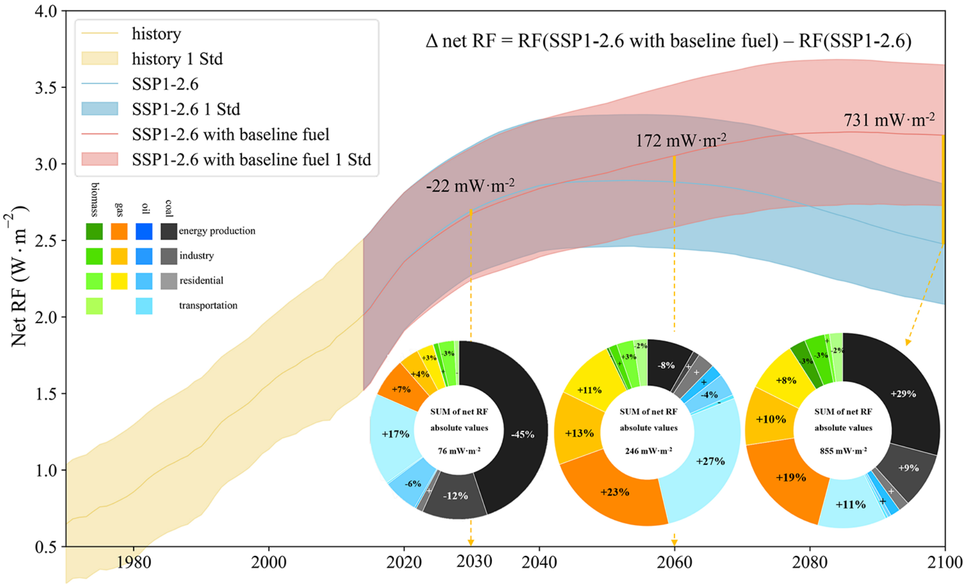

Figure 5. Net RF of historical simulation (1970−2014, the base year is 1750), SSP1-2.6 and SSP1-2.6 with baseline fuel. The orange solid line represents the net RF difference between the two future scenarios (SSP1-2.6 with baseline fuel minus SSP1-2.6) in 2030, 2060, and 2100, which could be regarded as the climatic effect of mitigation (the greater the positive value, the more favorable the climate). The pie chart shows the attribution of the net RF difference across sectors and fuels. The sum of all absolute values of net RF constitutes 100%.

sector, their emissions all experienced an increasing trend in the RF/Es from negative to somewhat positive values. Biomass outperformed coal and oil in terms of the RF/E value and its growth rate. On the contrary, residential fuel combustion had relatively high RF/Es, particularly for coal and biomass fuels, reaching 0.74 ± 0.77 and 0.53 ± 0.61 $mW{\cdot}m^{-2}/10^7$ TJ, respectively. The temporal trend of *Tran.-Oil* RF/E was similar to that of gas but showed a much larger reduction. Nevertheless, it was still the source with the highest RF/E at 0.92 ± 0.25 $mW{\cdot}m^{-2}/10^7$ TJ.

The NEF/E, indicating a long-term climate efficiency of the combustion process, also had different temporal trends for different sources. The NEF/E of SLCFs was nearly steady, but that of wmGHGs linearly rose. As a result, the NEF/Es of most source showed increasing trends, especially for fossil fuels that have significant contributions to wmGHGs emissions.[39] The NEF/Es of *Ene.-Coal*, *Ind.-Coal*, and *Ind.-Oil* increased more than other sources from 1970 to 2014, owing to not only significant emissions and build-up of wmGHGs but also the reduction of cooling forcer emissions per unit energy consumed due to energy switching and controls of sulfur in North America, Europe, and Former Soviet Union.[40,41] However, with high contributions of cooling aerosols to the NEF, the NEF/Es of these three sources remained negative in 2014. Being consistent with the RF/E, the *Tran.-Oil* had the highest NEF/E among all sources at 0.38 ± 0.13100ZJ/ZJ in 2014. Biofuels used in all sectors led a low NEF/E rise and contributed less to net CO_2 emissions. It can be inferred that substituting oil in transportation with biofuels offered attractive benefits in terms of climate impact efficiency of combustion process though additional land use effects during biofuel growing and harvesting should also be considered.[42,43]

3.3. Regional Climatic Contributions of Combustion Emissions. The climatic forcing of combustion emissions was attributed to five regions compatible with the shared socioeconomic pathways (SSP) database and CMIP6 emission pathways,[44,45] which include R5.2OECD, R5.2REF, R5.2ASIA, R5.2MAF, and R5.2LAM (Table S4). The RF contributions of various sectors and fuels, as well as their energy consumption, are shown in Figure 4.

R5.2ASIA, R5.2LAM, and R5.2MAF, as typical developing regions, had high similarities in the climate impacts of combustion emissions. R5.2ASIA and R5.2LAM have negative RF/Es of *Ene.-Coal*, which mainly derived from massive SO_2 emissions under fast increased energy demands and insufficient pollution controls,[11,46] resulting in the lowest net RF of total combustion sources in these two regions. The *Res.-Biomass* consumption is significant in these three developing regions, and all contributed to moderately positive net RF. Among them, the RF/E of *Res.-Biomass* in R5.2ASIA was relatively low due to the fact that more renewable annual biomass fuels, such as straw and corncob, were incompletely burned in these areas and produced a large number of organic aerosols.[47] Large amounts of traditional wood burning in Africa, especially nonrenewable ones,[48] produced GHGs and BC aerosols resulting in a higher RF/E value of *Res.-Biomass* in the R5.2MAF. The net RF induced by all combustion sources in R5.2OECD and R5.2REF is positive, and the RF/E of each source is close, particularly in R5.2OECD (between 0.28 ± 0.16 $mW{\cdot}m^{-2}/10^7$ TJ of *Ene.-Biomass* and 0.91 ± 0.29 $mW{\cdot}m^{-2}/10^7$ TJ of *Res.-Coal*). The *Ene.-Coal* in the two regions had positive RF/E, owing to the SO_2 reduction in R5.2OECD and energy transition in R5.2REF.

In all regions except R5.2OECD, the *Tran.-Oil* has the highest RF/E among all sources, but its values varied obviously in regions. The RF/E of *Tran.-Oil* in R5.2ASIA is the highest at 1.91 ± 0.65 $mW{\cdot}m^{-2}/10^7$ TJ. While the energy consumption of *Tran.-Oil* in R5.2ASIA expanded significantly over time, the emissions of compounds like BC and NMVOC resulted in warming impacts.[49] In R5.2OECD, though the consumption of *Tran.-Oil* was large, effective pollution controls of on- and off-road vehicles resulted in its low RF/E (0.88 ± 0.11 $mW{\cdot}m^{-2}/10^7$ TJ). The international aviation and shipping emissions led to negative RF due to high SO_2 and NO_x contribution.[50]

3.4. Insights on Climatic Impacts of Energy Switching and Emission Mitigations. In this study, we evaluated

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relative contributions of different energies by sector and region to the global climate change. Table S5 shows some comparisons with other studies although there are little information available in past studies and mostly focused on a specific sector-energy source, and those are different in basic data, time scale, models, and attribution methods, which increased difficulty and uncertainty in the comparison. For wmGHGs, the uncertainties of emission inventory and climate effects are relatively small. Zhang and Caldeira performed an ideal experiment to compare the direct thermal release and climate forcing due to CO_2 emissions in the combustion process of coal, oil, and gas.[51] Their ratio of time-integrated forcing of historical coal, oil, and gas combustion from 1970 to 2012 was calculated as 31, 27, and 21, respectively, which was close to the NEF/E of CO_2 of coal, oil, and gas in our study at 29 ± 5, 28 ± 3, and 23 ± 2 (ZJ/ZJ) in 2012, respectively. Since SLCFs do not accumulate, the current year's values were directly compared. Street et al. evaluated the RF of aerosols from some sectors in China and India.[52] In that study, the *Res.-Biomass* BC and OC and *Ene.-Coal* SO_4 had RF values of 104, −15, and −45 mW·m^{-2} in 2007, which are in the estimated variation range of our evaluation in R5.2ASIA of 69 ± 41, −32 ± 19, and −73 ± 43 mW·m^{-2}. Unger et al. estimated climate forcing of on-road transportation and energy sector,[53] and the results were close to our estimates of SO_4, BC, and OC in both sectors (see Table S5). Our assessment of RF of O_3 was higher, and the RF of ACI is also numerically higher in transportation, which could be partly explained by difference in processes and parameters between models. For example, the semidirect effect in OSCAR v3.1 strengthens the role of BC in ACI and thus increases the ACI derived from the transportation.

A simple but direct mitigation experiment was designed to verify the consequence in the emission mitigation on RF/E. The SSP data sets were adopted to simulate two future scenarios of 2015−2100.[45] The SSP1-2.6 was selected as the future scenario, and we ran the model to simulate the future climate system and calculate the net RF contributed by anthropogenic activities. In the second scenario, we modified the energy consumption and combustion emissions in SSP1-2.6 to the SSP1-baseline level[54] referred to as "SSP1-2.6 with baseline fuel," while maintaining the status quo for all other operations. The net RFs in time series of historical simulation SSP1-2.6 and SSP1-2.6 with baseline fuel are shown in Figure 5, as well as the attribution of their difference across sectors and fuels. The differences (SSP1-2.6 with baseline fuel minus SSP1-2.6) of RFs (ΔRF) and accumulative energy consumption (ΔE) between the two future scenarios were modeled and calculated for the ΔRF/ΔE (as well as ΔNEF/ΔE) for different fuels and sectors (Table S6). Note that the ΔRF/ΔE is calculated from the mitigation scenarios and RF/E is calculated following the attribution method. These two are comparable but not identical.[55]

The mitigation scenario (SSP1-2.6) does not receive climate benefits until 2040. By 2030, the net RF of SSP1-2.6 is even higher than that of SSP1-2.6 with baseline fuel. This is because the mitigation scenario greatly reduces coal consumption in the energy sector compared to baseline,[54] which has significant negative RF/E values in the short term. Consequently, the ΔRF of *Ene.-Coal* in 2030 would reach −34 mW·m^{-2}, surpassing all positive ΔRFs and directly resulting a negative Δnet RF. Simultaneously, the RFs for *Ind.-Coal* and *Ind.-Oil* are predicted to be negative. The effect of this emission mitigation would be 172 mW·m^{-2} of Δnet RF in 2060 with a 45-year scale as this study duration when the reduction of oil and gas usage contributes the most. Among all sectors and fuels, the *Tran.-Oil* also has the highest ΔRF/ΔE, suggesting its consistency with RF/E and the potential mitigation benefits for climate. At this time scale, the RF/E of *Ene.-Coal* and *Ind.-Coal* was still very low, significantly undermining their contribution to climate mitigation efforts. Over a longer time, span of 85 years, all sources exhibit positive ΔRF/ΔEs being mainly derived from wmGHGs as mentioned above. The mitigation of *Ene-Coal* finally has a ΔRF of 248 mW·m^{-2} in 2100, occupying the largest contribution of all sources. When considering the emission reduction of combustion processes to respond to climate change in the future, the time scale effect should be given more attention. It will take a long time for the *Ene.-Coal* to demonstrate its climate advantages in terms of emission mitigation; however, reduced *Tran.-Oil* would, to some extent, show warming inhibition in the near future.[56,57]

3.5. Implication and Perspectives. This study revealed substantially different climate impacts of coals burned in the energy sector and oils used in the transportation although these two energies provided similar amounts of energies for the society from 1970 to 2014. The study indicated that controlling traffic oil use may be more appealing in response to climate change and could be regarded as the primary direction of emission mitigation. Coals used in different sectors had divergent climate impacts. Those used in the residential sector exhibited a warming effect but exhibited cooling effects in other sectors. This phenomenon is especially noticeable in Asian emerging countries, such as China and India. Since 2014, the project of "Coal to Electricity" has been promoted in China's northern area in response to heavy pollution episodes in this region.[58] Despite the fact that this policy was originally intended to control air pollution and was reported to have no significant effect on carbon mitigation,[59] our assessment indicated that replacing the residential coal with electricity that derived from coal combustion in power plants may be quite beneficial to cooling the earth. The energy-climate relationship of fossil fuels burned in developed regions did not show apparent variabilities because fuels were purified. The low-carbon transition to biofuels or other renewable energy is expected as a unique avenue for effective climate mitigation policies.

The RF/E and NEF/E indicators proposed in this work have the potential to characterize the climate efficiency in future energy consumption and emission reduction, and an ideal experiment was conducted to certify that. Many integrated assessment models (IAMs) constructed future energy transition scenarios that need to be constrained to satisfy different climate targets.[54] The RF/E and NEF/E of different combustion sources could be introduced in IAMs to directly relate energy and climate, decreasing the complexity of equilibrium model solution. More efforts are anticipated to enhance the applicability of RF/E and the understanding of interaction between energy utilization and climate impact. Demands for different energies and the efficiency of their transformation should be clarified. Life-cycle assessment of fuels in each sector, that is not addressed in this study, is also a crucial aspect of thoroughly analyzing climate consequences of energy. Moreover, climatic feedback from energy usage might arise sufficient attention. Adequate mitigation scenarios must take the entire natural and social systems into consideration, ensuring that all outcomes are within the planet boundary.

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■ ASSOCIATED CONTENT

Supporting Information

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> Description of fuel types and sectors in this study; emissions and precursors of climate forcers; countries covered in different regions; a comparison with past studies; data of future mitigation scenarios; net energy flow by climate forcers; results of the ideal RF control experiment; and temporal RF and net energy flow for each combustion source (PDF)

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Author Contributions

G.S. conceived and designed the analysis, K.J., B.F., B.L., and S.T. contributed data and analysis tools, K.J. performed the analysis, K.J., Y.M., R.X., and G.S. analyzed results and visualization, K.J. and G.S. drafted the manuscript, and all authors read and approved the paper.

Notes

The authors declare no competing financial interest.

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