Short-lived climate forcers have a long-term climate forcing through the climate-carbon feedback

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Abstract

Short-lived climate forcers (SLCFs) are dubbed because of their shorter atmospheric lifetime in comparison with CO_2. SLCFs are generally assumed to have only a short-term effect on the climate system: should their emission cease, so would their radiative forcing (RF). However, SLCFs have an effect on the carbon cycle through climate-carbon feedbacks. In this study, we quantify the following feedback loop: SLCF change the climate, climate change modifies land and ocean carbon sinks, impacting the atmospheric CO_2, and therefore causing additional climate change. The compact Earth System Model OSCAR v2.2 is used to attribute the present-day RF of CO_2 to direct CO_2 emissions and to the climate-carbon feedbacks. This study illustrates and quantifies this long-term impact that short-lived species have on the climate system through the carbon cycle. It also indicates that past (and future) change in atmospheric CO_2 cannot be attributed only to CO_2 emissions.

Introduction

SLCFs are substances with a relatively short lifetime in the atmosphere compared to CO_2[1]. They include methane, ozone and aerosols (anthropogenic and natural), and their respective impact on clouds [2-5]. By warming or cooling the climate, SLCFs also affect the carbon cycle through the climate-carbon feedback loop[6-11]. Although there are differences in estimates of the climate-carbon feedback between models, it is a consensus that warming or higher temperature increases atmospheric CO_2 concentration[12], which is a positive feedback process. A few studies have estimated the influence of aerosol cooling effects on terrestrial carbon cycling, although there are large variations among the results[13-15]. In addition, it is understood that the climate effects of SLCFs through the climate-carbon feedback are longer-term compared to their own lifetime[16,17], but quantification of the time-scale of this effect remains limited.

In this study, we used the compact Earth system model OSCAR v2.2[18] to evaluate the contributions of SLCFs to the radiative forcing (RF) of CO_2 in 2010 through the climate-carbon feedback. Here, the role of SLCFs is through the direct radiative imbalance they cause and therefore impact on temperature. Other impacts, e.g. the impact of aerosols on diffuse radiation and therefore photosynthesis, the impact of ozone damage on plant function and therefore photosynthesis are not included. To do so, we proceeded in three steps. First, we attributed historical climate change to the radiative forcing caused by all anthropogenic and natural climate forcers, as reported by the IPCC in their fifth assessment report (AR5). Second, we attributed the historical change in atmospheric CO_2 concentration and its RF to fossil fuel (FF) CO_2 emissions, land-use change (LUC) CO_2 emissions, and to the climate-carbon feedback. Third, we combined the first two steps to attribute the climate-carbon feedback to the non-CO_2 climate forcers, which includes the SLCFs like methane, ozone and aerosols in particular. The 'marginal attribution method' is used here (see **Methods** for more details).

OSCAR is a model of reduced-complexity that embeds modules for the terrestrial carbon cycle, the oceanic carbon cycle, and the climate system that were all calibrated to reproduce the response of complex process-based CMIP5 Earth system models[18]. The carbon cycle in OSCAR consists of two components: ocean and land. The ocean carbon cycle includes the dissolution of anthropogenic CO_2 in the surface ocean and transport to the deep ocean. The land carbon cycle includes the response to change in CO_2 concentration or climate. The model was used in a previous study to investigate another aspect of the climate-carbon feedback[10]. And the model performs well compared to CMIP5 models in the same '1pct CO_2' experiment[19] when calculating the feedback sensitivities (Extended Data Fig.2-4). The RF attribution itself followed an established methodology that we previously used to quantify the contribution of Chinese emissions of greenhouse gases and aerosols to the global present-day RF[20]. To illustrate the attribution exercise and the model response to a perturbation of SLCF, we performed an idealized experiment before the main result. We removed one year of the volcano forcing of year 1964, to study the model's response to this pulse of SLCF, both in intensity and time scale.

Results

Figure 1 shows this response, calculated as the difference between the simulation without the volcanic SLCF pulse of year 1964 (Rm64) and a control simulation with it (Figure 1a). It shows that in OSCAR, the effects of a pulse of SLCF on temperature and atmospheric CO_2 concentration are lagging in time behind the pulse duration (Figure 1b and 1c). After removing the 1964 volcanic RF, the peak response of global mean surface temperature (GMST) was faster than the peak response of atmospheric CO_2 concentration, with time lag of a few years. Notably, the response of GMST returned to its base level at a faster pace than that of atmospheric CO_2. The response of atmospheric CO_2 is further split into the response of the terrestrial carbon cycle (Figure 1d) and that of the ocean carbon cycle (Figure 1e). Immediately after removing the 1964 negative volcanic RF, climate is warmer than in the control simulation (Fig. 1b), causing a positive anomaly of atmospheric CO_2 (Fig. 1c), because carbon sinks are transiently weaker (Fig 1d and 1e). This anomaly of CO_2 is then slowly re-absorbed as the system tends towards is former steady-state. This behavior is in line with what an earlier study also based on OSCAR [10].

We produced our main results by repeating such a perturbation experiment with every single RF reported in the IPCC AR5, and for several individual years or periods of the past (see Methods). First, the GMST change in 2010 against the preindustrial era (the year of 1750) was calculated (Figure 2a) and attributed to all climate forcers (Figure 2b). The largest positive contributions to GMST change come from atmospheric CO_2 (684±198 mK), other long-lived greenhouse gases (195±57 mK), methane (200±59 mK), and tropospheric O3 (165±48 mK). Aerosols (-387±114 mK), volcanoes (-67±23 mK) and LUC albedo (-52±19 mK) contributed the most to negative changes. It must be noted that aerosols here combine the net effect of both warming and cooling aerosols. Second, the radiative forcing of CO_2 in 2010 was attributed to FF-CO_2 emissions, LUC-CO_2 emissions and the climate-carbon feedback (Figure 2c). In 2010, we estimated CO_2 radiative forcing was 1.81±0.17 W m^{-2}, where CO_2 emissions contribute 1.71±0.28 W m^{-2}, split into 1.25±0.17 W m^{-2} from FF and 0.47±0.23 W m^{-2} from LUC, and the remaining 0.09±0.05 W m^{-2} came from the climate-carbon feedback. Finally, the contribution of the climate-carbon feedback to the RF of CO_2 in 2010 was attributed to each individual climate forcers. Following a similar hierarchy as that of the attribution of GMST change, atmospheric CO_2, other long-lived greenhouse gases and methane contributed the most to the feedback, reaching 118±7 mW m^{-2}, 38±7 mW m^{-2}, and 45±18 mW m^{-2}, respectively. The contributions of tropospheric O_3 (36±16 mW m^{-2}), aerosols (-86±41 mW m^{-2}), black carbon snow effect (15±7 mW m^{-2}), volcanoes (-25±13 mW m^{-2}) and LUC albedo effect (-12±6 mW m^{-2}) constituted the remainder.

It is reasonable that the greater its influence on temperature, the greater a forcer contributes to the climate-carbon feedback (Figures 1b and 1d). However, this strong correlation between the two attributions is somewhat mitigated by the specific effect each climate forcer has on the hydrological cycle[21,22], as precipitation does impact the carbon cycle in OSCAR. We acknowledge that our results are therefore model-dependent, and a simple model such as OSCAR still requires further development to keep track of features observed in the real climate system. Especially, the climate response for each climate forcer appears to be different on short time-scales[23], which is absent from this version of OSCAR. Nevertheless, the quantitative conclusion remains that warming SLCFs such as methane, tropospheric ozone, and black carbon may be regarded as indirect sources of CO_2 because they warm the climate, which makes weaker carbon sinks (positive climate -carbon feedback) and thus accelerate the growth rate of atmospheric CO_2 concentration. Accordingly, cooling SLCFs such as scattering aerosols may be considered as indirect sinks of CO_2.

Figure 3a shows how the present-day (2010) RF of CO_2 is attributable to past climate forcing caused by CO_2 emission and climate-carbon feedback. Figure 3b illustrates that SLCFs do influence atmospheric CO_2 concentration through the climate-carbon feedback over a much longer duration than their own lifetime. Schematically, the effect we quantify in Figure 3b is the result of the convolution between the typical responses illustrated by the experiment in Figure 1, and the time-series of radiative forcing of SLCFs. Therefore, only a strong anomaly in the RF can compensate the natural decay in the response. It is for instance the case with the Pinatubo volcanic eruption: we estimate that 8±4 mW m^{-2} of the total CO_2 RF in 2010 was actually due to the strong effect of stratospheric volcanic aerosols emitted by this event in 1990-1995. More generally, however, we find that older radiative forcing contributions from SLCFs impact less the present-day CO_2, owing to both the decay in the response and the increase in their historical RF value. For instance, tropospheric ozone and anthropogenic aerosols emitted in the 1970s caused 0.4±0.2 mW m^{-2} yr^{-1} and -1.0±0.5 mW m^{-2} yr^{-1} in 2010, whereas those emitted in the 2000s caused 1.3±0.6 mW m^{-2} yr^{-1} and -3.0±1.4 mW m^{-2} yr^{-1}, respectively.

Nevertheless, our results show that SLCFs have a long lasting influence on atmospheric CO_2 concentration through climate-carbon feedback and thus have long-term (50-60 years) radiative forcing, which is much longer than their own atmospheric lifetime. Again, the overall effect of SLCFs is found to be small compared to the total RF of CO_2, but this small value results from a compensating effect between warming and cooling SLCFs. Although each SLCF has a significant contribution in our simulations, the sign of total contribution is uncertain (-13±50mW m^{-2}). This is mainly due to the fact that the magnitude of the warming SLCFs and cooling SLCFs is about the same. As the climate system will remain perturbed by anthropogenic non-CO_2 species, the future evolution of this effect will depend on whether this compensation of warming and cooling SLCF will last in the future. If warming and cooling SLCFs have different reduction rates in the future, then this competition will weaken and the overall effect will be more prominent.

Conclusions

Previous studies on the influence of SLCFs focused mainly on the aerosol cooling effect[13-15]. While some found that aerosols increased the global carbon sink by cooling the climate[13], others argued it was not a significant effect[14]. The knowledge gaps were shown to come from uncertainties both in aerosol simulation and the carbon cycle process modeling[15]. Our study contributes to this debate, as our prescribed non-CO_2 RFs and probabilistic simulations with OSCAR, which emulates more complex model. As non-CO_2 RFs are prescribed using IPCC data, we avoid aerosol simulation in this study. And the probabilistic simulations with OSCAR show the results of several more complex models. We find that anthropogenic and volcanic aerosols contributed together -0.11±0.01 W m^{-2} out of the 1.81±0.17 W m^{-2} of the total RF of CO_2 in 2010. Although statistically significant, this is a rather small value, because insofar emissions of cooling and warming aerosols have opposed each other.

But aerosols are only one part of the picture: other SLCFs such as tropospheric ozone also have a significant warming impact on the climate system, and therefore on the carbon cycle. According to this study, warming SLCFs like methane, black carbon and tropospheric ozone, contributed 6% radiative forcing (102±26 mW m^{-2}) to the total RF of CO_2 in total, through climate-carbon feedback. Cooling SLCFs contributed slightly more (-115±43 mW m^{-2}), but with the opposite sign. Although the effects are relatively small in comparison with the total CO_2 radiative forcing (1.81 W m^{-2}) and offset each other, the long-term legacy climate forcing of SLCFs (50-60 years) should not be neglected in global climate modeling. Furthermore, as global SO_2 emissions continue to decline[24] (mainly due to stricter emission controls in North America, Europe and China), the contribution of sulfate aerosol cooling effect to global RF of CO_2 may be reduced, which may increase the overall SLCFs positive contribution to the RF of CO_2 in the future.

Our study is thus more comprehensive than previous estimates[13-15], although it is inherently limited by the simplicity of our model. One such limitation, already discussed earlier, is the lack of a differing response of the climate system when forced by different climate forcers. This caveat is supposed to be mitigated by the use of “effective” radiative forcing (ERF), as per definition the non-CO_2 ERF are supposed to be comparable to the CO_2 RF[1] (and our climate response is derived from a CO_2 forcing). Although not all climate forcers were evaluated in terms of ERF in the AR5, anthropogenic aerosols were, which adds a degree of confidence to our results.

To conclude, our study is a first step towards switching the attribution of the RF of CO_2 from concentration-based to emission-based, similarly to what was done for chemically active species in the AR5. The second-step analysis that remains to be carried out is the inclusion of direct effects caused by SLCFs on the carbon cycle: the deposition of aerosols containing nitrogen and phosphorus which increases productivity[25-27] and may decrease respiration[28], ozone phytotoxicity[29], and change in diffuse radiation from increased aerosol content in the atmosphere[30,31]. In addition, feedbacks between climate and natural aerosol should also be included in the future steps[32]. Existing studies do provide quantifications of these effects, but they remain to be integrated in a comprehensive and consistent attribution framework such as ours. Our work on the climate-carbon feedback already shows that non-CO_2 species are key perturbations of the carbon cycle, and achievement of the second step would likely strengthen that conclusion.

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Methods

Model and data.

This study uses a compact Earth system model, OSCAR v2.2[18], to simulate the climate effect of SLCFs through climate-carbon feedbacks and its time scale. OSCAR v2.2 is a reduced-form model already used in the climate change research community[20,33-35], and it includes all components of the Earth system necessary to simulate climate change: terrestrial and ocean carbon cycles, tropospheric and stratospheric chemistry, albedo changes, and climate responses. In addition, OSCAR v2.2 is a meta-model that emulates the sensitivity of higher resolution or complexity models. Parameters of the model are calibrated by outputs from complex Earth system models that participated in intercomparison projects. For example, the parameters for land carbon cycle are calibrated by seven CMIP5 models and the parameters for ocean carbon cycle are calibrated by three CMIP5 models. Although OSCAR v2.2 is not a gridded model, emissions and key responses of climate to forcing are regionalized. In OSCAR, regional temperatures are linear related to GMST and regional precipitations are calculated with regional temperatures and radiatively active species. Consequently, OSCAR is suitable for using in a probabilistic framework. We run simulations with different parameters as a Monte Carlo ensemble and then constrained with observations.

In this study, OSCAR v2.2 was driven by fossil fuel CO_2 (FF-CO_2) emission data, land-use change (LUC) data, and non-CO_2 radiative forcing (RF) data. FF-CO_2 emissions data comes from CDIAC[36] and EDGAR[37]. Land-use change data from the LUH v1.1 dataset[38], which is used with the bookkeeping module of OSCARv2.2 to calculate carbon emissions from LUC. Non-CO_2 climate forcers are prescribed by the Annex II of the IPCC AR5 WG1 report[1], including other greenhouse-gases and water vapor, stratospheric and troposphere ozone, aerosol, albedo change of land-use change and black carbon on snow, volcano, solar and contrails. We split the ‘other greenhouse-gases’ to methane and long-lived greenhouse-gases, by calculating methane radiative forcing with its historical abundances reported in the Annex II while other RFs remained unchanged. We chose the model prescribed non-CO_2 radiative forcing instead of driving the model with non-CO_2 emission data to limit the potential biases in our attribution. The prescribed radiative forcing data can be found in Supplementary Data.

Idealized experiment.

Before the main result of attributions, we performed an idealized experiment to illustrate the model response to a perturbation of pulse SLCF. A control simulation is run driven by CO_2 emissions and non-CO_2 RF from IPCC. Another simulation is run identically except that the volcano RF in 1964 is removed. The differences between the two simulations represent the climate and carbon cycle responses to the pulse of SLCF.

Attribution method.

In this study, the normalized marginal method was used to attribute the GMST and RF of CO_2. This method was advised by the UNFCCC[39] for attributions within the climate system that account its nonlinearity and feedbacks. It attributes contributions to causes proportionally to the marginal effects of the individual causes, and the total is equal to the whole effect, so it is named 'normalized marginal method'. This method was used in many earlier studies to attribute changes in a variable of the climate system to physical processes or to emissions[7,20,33,34].

The following uses mathematical language to describe the 'normalized marginal method'. Suppose an effect A is caused by n causes, denoted as equation (1). If we want to attribute effect A to the causes (x1,x2,…,x3) using the method, we first calculate the marginal effects of each cause, which is the difference in function values when a cause is changed slightly, as in equation (2). In this study, the slight ratio ε is 0.1% for OSCAR[18]. Then the relative contributions of the causes are calculated by normalization as in equation (3), and the relative contributions are available as in equation (4).

$$A = f(x_1, x_2, \dots, x_n) \qquad (1)$$

$$\Delta_i \mathrm{A} = \; f(x_1, x_2, \dots, x_i, \dots, x_n) - f(x_1, x_2, \dots, x_i - \varepsilon x_i, \dots, x_n) \qquad (2)$$

$$\alpha_i = \frac{\Delta_i \mathrm{A}}{\Delta_1 \mathrm{A} + \Delta_2 \mathrm{A} + \cdots + \Delta_n \mathrm{A}} \qquad (3)$$

$$\mathrm{C}_i = \alpha_i \times A \qquad (4)$$

In this study, we assume that 1) the climate change can be attributed only to the radiative forcing ignoring natural variability, 2) the RF of CO_2 is attributable to CO_2 emissions and the climate and 3) climate feedbacks of other non-CO_2 RF is negligible in the marginal simulations. These three assumptions allow us to obtain the main results following three attributions. First, historical climate change is attributed to the radiative forcing caused by all climate forcers (GMST $= f(RF_{CO_2}, RF_{CH_4}, \dots, RF_{solar})$). Second, the historical change in RF of CO_2 is attributed to CO_2 emissions and the climate change ($RF_{CO_2} = f(ECO_2^{FF}, ECO_2^{LUC}, climate\ varibles)$). Third, the contribution of the climate-carbon feedback is attributed to forcers including SLCFs ($RF_{CO_2} = f(ECO_2^{FF}, ECO_2^{LUC}, RF_{CH_4}, \dots, RF_{solar})$).

Monte Carlo setup and constraint.

In this study, we design a Monte Carlo ensemble (n=3000) to obtain the uncertainties of the results, taking advantage of the characteristics of OSCAR, in which random configurations are drawn from the pool available in OSCAR v2.2. As a meta-model, different configurations of OSCAR v2.2 emulate different higher complexity models. So the probabilistic simulations with OSCAR v2.2 are kind of model comparison, showing the uncertainties of model.

To reduce uncertainties and get a best-guess result, we followed *Steinacher et al*'s constraint method in their study[40]. Each member of the Monte Carlo ensemble is given a weight, following a chosen statistical likelihood, according to the deviations between their simulation results and historical observations in temperature and CO_2 concentration. Here, The weights w_i are calculated by Gaussian distribution probability density function $w_i = \frac{1}{\sqrt{2\pi}} e^{-\frac{(x_i-\mu)^2}{2\sigma^2}}$, where μ and σ are the average and standard deviation of the constraining data. The constraining data for GMST is from the HadCRUT4 dataset[41], and that for CO_2 is from IPCC AR5[1]. Ensemble members with better historical simulations were given higher weights, those with larger historical simulation deviations have lower weights. The best-guess value is then calculated as $\overline{x_w} = \frac{\sum w_i \cdot x_i}{\sum w_i}$ and the standard deviation is calculated as $\sigma_w = \sqrt{\frac{\sum w_i \cdot (x_i - \overline{x_w})^2}{\sum w_i}}$.

Validation of model and Monte Carlo framework.

Two validation works are conducted for this study. One is comparison of atmosphere

CO_2 concentration simulated by OSCAR v2.2 with Global Carbon Budget (GCB) assessment[42]. The other is comparison of feedback sensitivities calculated by OSCAR with CMIP5 models[19]

In Extended Data Fig.1, OSCAR v2.2 model results are driven by CO_2 emissions and non-CO_2 RFs with Monte Carlo setup and constraint. OSCAR modeled atmosphere CO_2 concentration meets well with GCB assessment, both in trend and values.

In Extended Data Fig.2-4, the feedback sensitivities calculated by OSCAR v2.2 are shown, following the same method which *Arora et al* used for CMIP5 models[19]. The magnitude and evolution of parameters that characterize feedbacks are calculated, based on results from biogeochemically, radiatively, and fully coupled simulations in which CO_2 increases at a rate of 1% yr^{-1}. All these results showed that OSCARv2.2 performs in line with CMIP5 model median, so we conclude OSCAR v2.2 is reliable in studying climate-carbon feedback.

Data availability

Input data used in this paper are all available online.

CDIAC: https://cdiac.ess-dive.lbl.gov/trends/emis/meth_reg.html.

EDGAR: http://edgar.jrc.ec.europa.eu/overview.php?v=42.

LUH v1.1 dataset:[38] IPCC annexes: https://www.ipcc.ch/report/ar5/wg1/.

Global carbon budget: https://www.globalcarbonproject.org/carbonbudget/index.htm.

Model availability

The code used to generate all the results of this study is available at https://github.com/pkufubo/OSCAR/tree/NCLIM-19122723. If more information or help about the code is needed, contact the corresponding author.

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Figure legends

Figure 1. Response of a pulse of SLCF on climate and carbon cycle (volcano activities in 1964 as an example). Two simulations are run: the control one is driven by RFs from IPCC, and the ‘Rm64’ one is the same except that the volcano RF in 1964 is removed. (a) The volcano RFs in control simulation (grey, dashed line), and in Rm64 simulation (blue, solid line). The only difference is the removing of volcano RF in 1964. (b) Relative to control simulation, ‘Rm64’ simulation has an increase of global mean surface temperature (GMST) and a return to the base level. (c) The response of atmospheric CO_2 concentration is similar, with a slower pace. (d) The land carbon sink’s response is decomposed in the response of heterotrophic respiration (RH, green line) and that of net primary productivity (NPP, blue line). The decrease of net land sink is represented by a black line (positive value means sink loss) (e) The ocean carbon sink’s response is decomposed in the response of the outgoing flux

(F_{out}, green line) and that of the ingoing flux (F_{in}, blue line). The decrease of ocean sink is represented by a black line (positive value means sink loss). The solid lines in panel b) to e) represent the mean, and the dashed lines represent the ranges of one standard deviation.

Figure 2. Attribution of global mean surface temperature change and RF of CO_2 in 2010 to climate forcers. (a) The global mean surface temperature (GMST) change in 2010, relative to the preindustrial era, which is attributed to climate forcers in (b). The climate forcers include CO2, other long-lived greenhouse gases (LL-GHG other), LUC albedo, solar irradiance and SLCFs. (c) CO_2 RF in 2010 is 1.81±0.17W m^{-2}. We attribute it to fossil fuel (FF-CO_2) emissions, land-use change (LUC-CO_2) emissions and the climate-carbon feedbacks. Contributions from emissions are noted with clear bars, and contributions from the climate-carbon feedbacks are noted with bars hatched by dots. The climate-carbon feedback makes a non-negligible contribution of 0.09±0.05 W m^{-2} to the total. (d), The climate-carbon feedback is further attributed into the contributions of the different climate forcers. All uncertainties are one weighted standard deviation of our Monte Carlo ensemble (n=3000; see **Methods** for details).

Figure 3. Contribution of historical emissions of all forcers to RF of CO_2 in 2010. (a) Attributions of RF of CO_2 in 2010 to historical CO_2 emissions (clear bars) and climate-carbon feedback (bars hatched by dots). (b) Attributions of the contributions to RF of CO_2 induced by climate-carbon feedback. Here, present-day RF of CO_2 is attributed to the same climate forcers as in Figure 2 and to different periods of emissions. Those years of forcing farther away from 2010 were grouped by bins covering a larger period to save computing resources, and since contributions from older periods are small. The area of each bar represents the contribution of a past forcing to the RF of CO_2 in 2010, so that summing the area of all the bars of one color gives back the corresponding RF shown in Figure 2d. It can be seen that SLCFs decades ago still contributed to the RF of CO_2 in 2010, which is a time interval longer than their lifetime. The uncertainties can be found in Supplementary Data Uncertainties of Fig3b.

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Author contributions

B.L., T.G., P.C., S. Piao designed the study. Simulations were performed by B.F. and T.G, with model input data prepared by B.F., X.L., Y.H., J.A., S. Peng and J.X. Figures were designed by B.F., B.L., W.L, T.Y and L.H. Writing was led by B.L., with substantial inputs from B.F., T.G., P.C., S.T. and Y.B. All authors participated in the study, the interpretation of the results, and the outline of the paper, through regular meetings and discussion.

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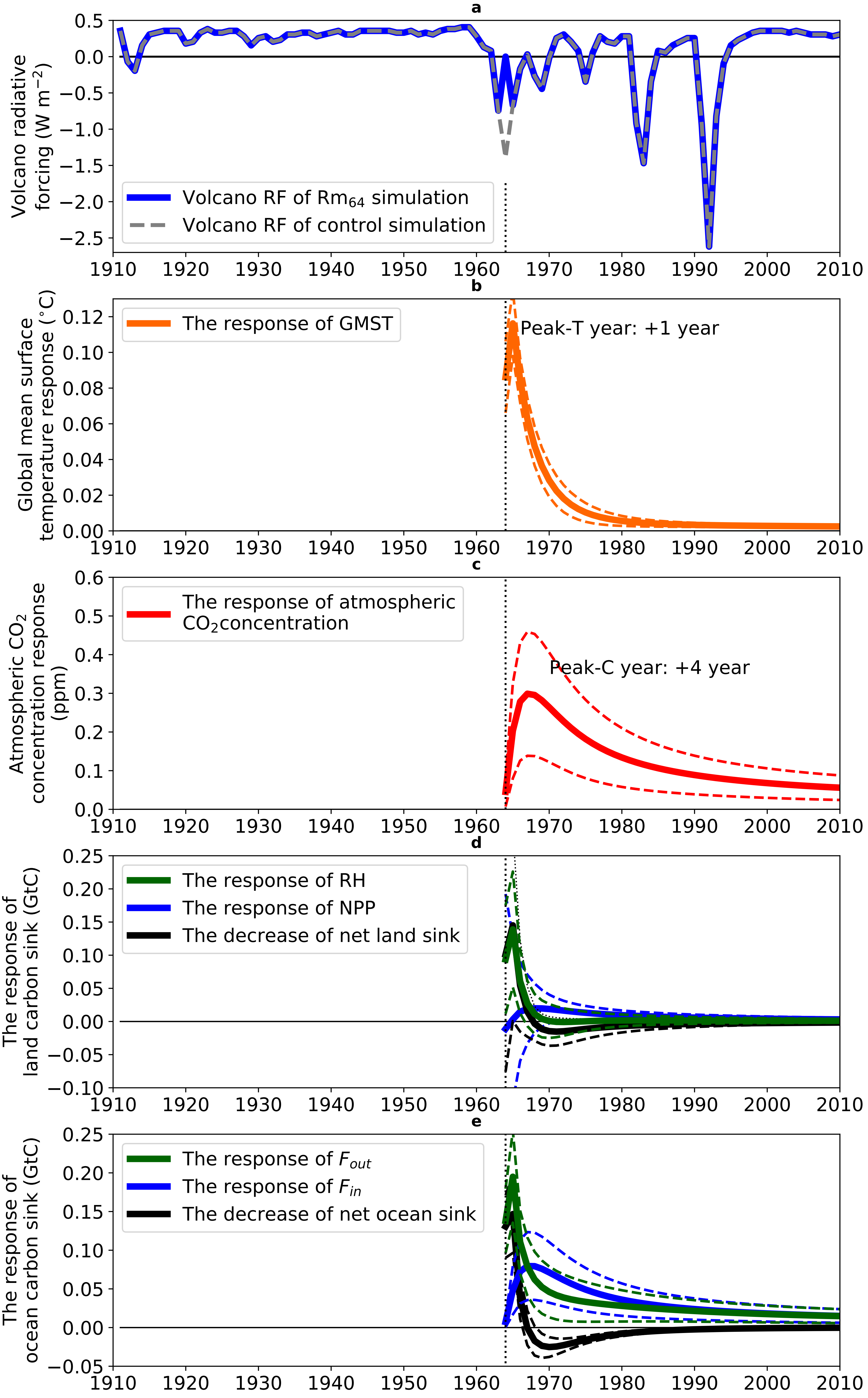
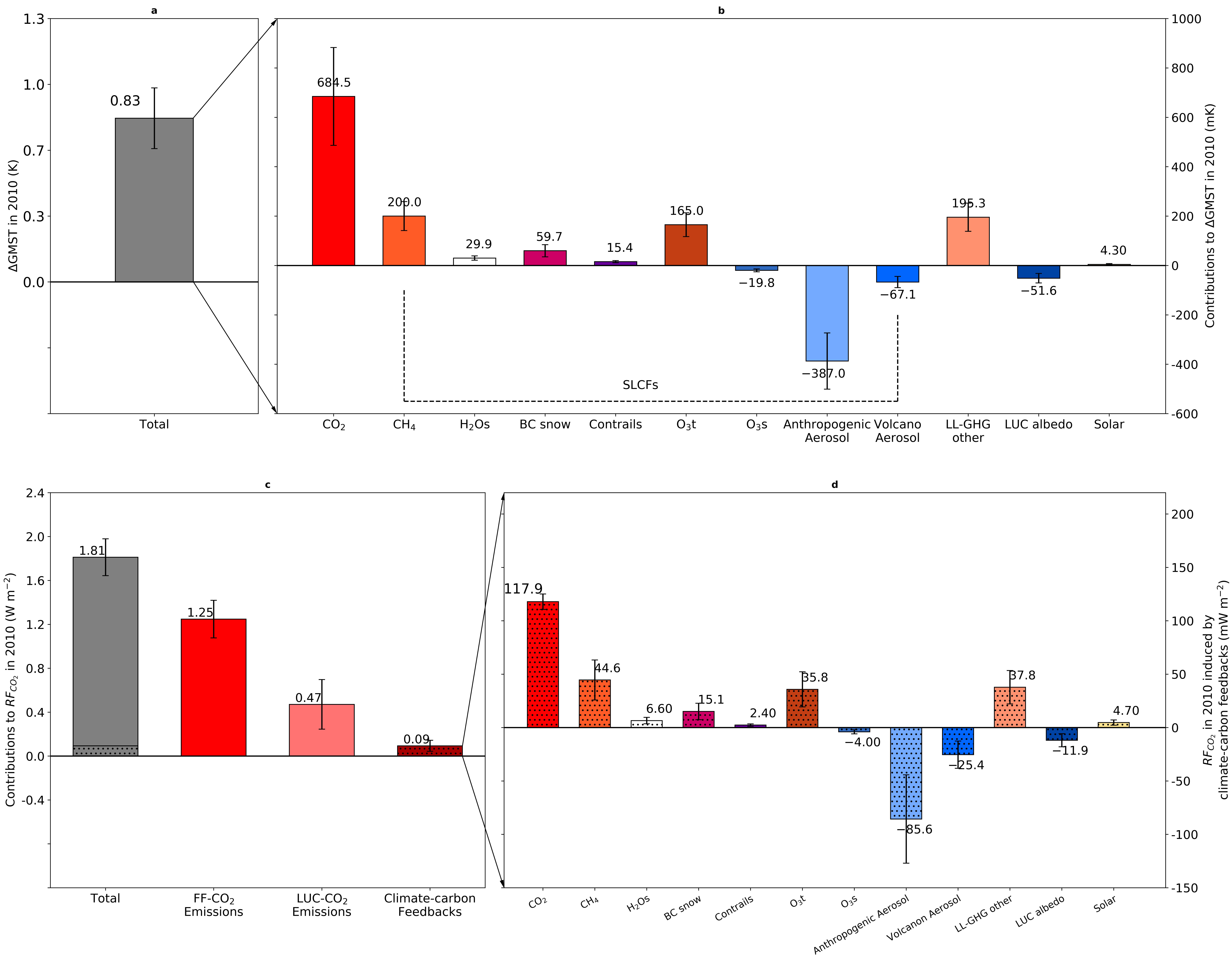
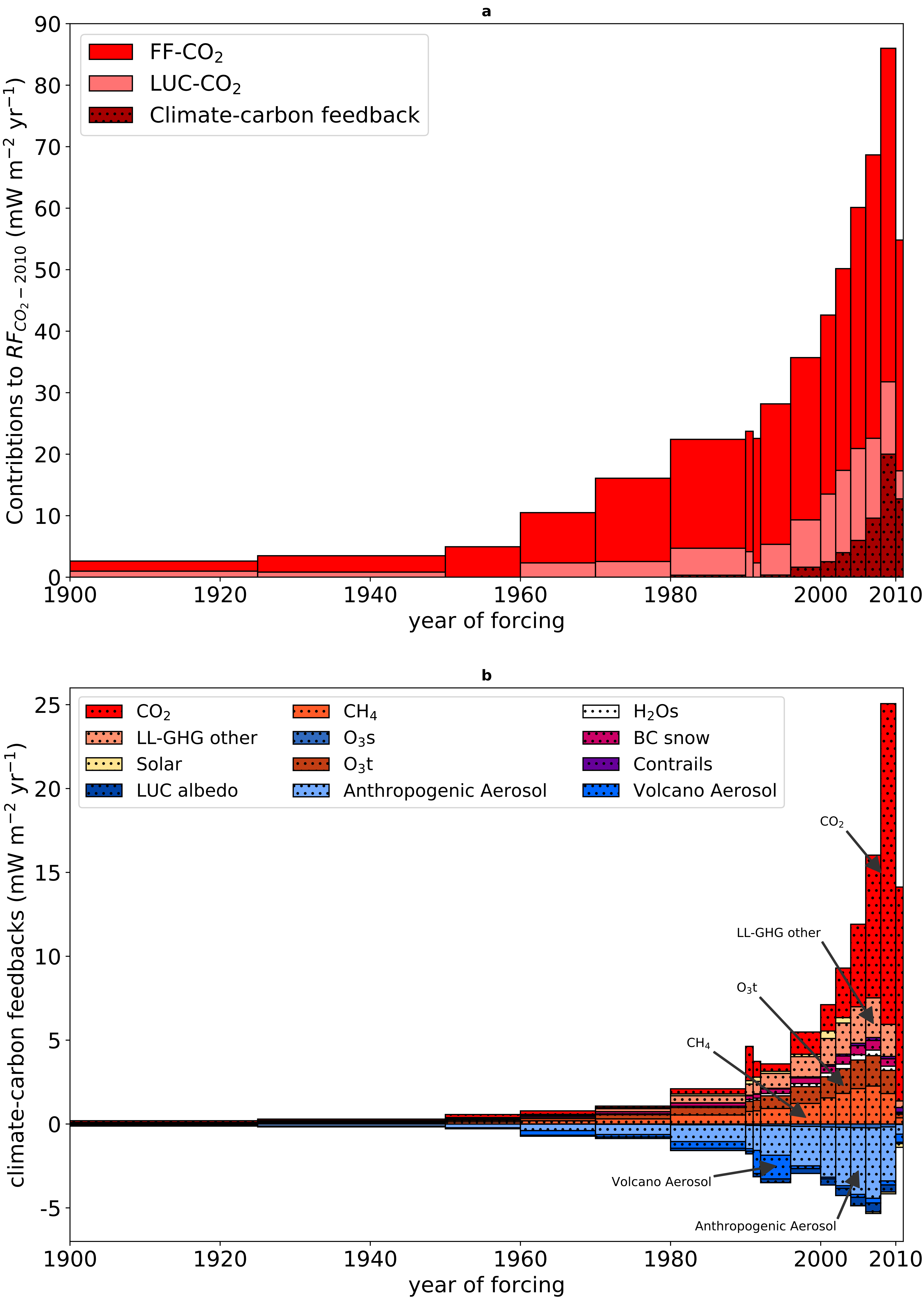
Competing interests

The authors declare no competing interests.


a
Volcano radiative forcing (W m^{-2})
Volcano RF of Rm_{64} simulation
Volcano RF of control simulation
b
Global mean surface temperature response (°C)
The response of GMST
Peak-T year: +1 year
c
Atmospheric CO_2 concentration response (ppm)
The response of atmospheric CO_2concentration
Peak-C year: +4 year
d
The response of land carbon sink (GtC)
The response of RH
The response of NPP
The decrease of net land sink
e
The response of ocean carbon sink (GtC)
The response of F_{out}
The response of F_{in}
The decrease of net ocean sink



a
1.3
1.0
0.7
0.3
0.0
ΔGMST in 2010 (K)
0.83
Total
b
684.5
200.0
29.9
59.7
15.4
165.0
−19.8
−387.0
−67.1
195.3
−51.6
4.30
SLCFs
1000
800
600
400
200
0
-200
-400
-600
Contributions to ΔGMST in 2010 (mK)
CO_2
CH_4
H_2Os
BC snow
Contrails
O_3t
O_3s
Anthropogenic Aerosol
Volcano Aerosol
LL-GHG other
LUC albedo
Solar
c
2.4
2.0
1.6
1.2
0.8
0.4
0.0
-0.4
Contributions to RF_{CO_2} in 2010 (W m^{-2})
1.81
1.25
0.47
0.09
Total
FF-CO_2 Emissions
LUC-CO_2 Emissions
Climate-carbon Feedbacks
d
117.9
44.6
6.60
15.1
2.40
35.8
−4.00
−85.6
−25.4
37.8
−11.9
4.70
200
150
100
50
0
-50
-100
-150
RF_{CO_2} in 2010 induced by climate-carbon feedbacks (mW m^{-2})
CO_2
CH_4
H_2Os
BC snow
Contrails
O_3t
O_3s
Anthropogenic Aerosol
Volcanon Aerosol
LL-GHG other
LUC albedo
Solar


a
FF-CO2
LUC-CO2
Climate-carbon feedback
Contribtions to RF_{CO2-2010} (mW m^-2 yr^-1)
year of forcing
b
CO2
CH4
H2Os
LL-GHG other
O3s
BC snow
Solar
O3t
Contrails
LUC albedo
Anthropogenic Aerosol
Volcano Aerosol
CO2
LL-GHG other
O3t
CH4
Volcano Aerosol
Anthropogenic Aerosol
Contribtions to RF_{CO2-2010} induced by climate-carbon feedbacks (mW m^-2 yr^-1)
year of forcing