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To cite this article: Estela A Monteiro *et al* 2024 *Environ. Res. Lett.* **19** 124012

IOP Publishing Environ. Res. Lett. 19 (2024) 124012 https://doi.org/10.1088/1748-9326/ad8807

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
29 February 2024

REVISED
30 September 2024

ACCEPTED FOR PUBLICATION
17 October 2024

PUBLISHED
31 October 2024

LETTER

FROT: A Framework to comprehensively describe radiative contributions to temperature responses

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Keywords: radiative contribution, radiative forcing, temperature stabilisation, Earth system feedbacks, ambitious climate mitigation

Supplementary material for this article is available online

Abstract

Different human activities and associated emissions of CO_2 and non-CO_2 radiative forcing agents and feedbacks determine the final state of Earth's climate. To understand and explain contributions to global temperature changes, many emission-based metrics have been employed, such as CO_2-equivalent or -forcing equivalent. None of these metrics, however, include dynamic responses from Earth system feedbacks in terms of carbon and heat redistribution, known to play an increasingly important role in ambitious mitigation scenarios. Here we introduce a framework that allows for an assessment of such feedbacks in addition to CO_2, non-CO_2 anthropogenic forcing and natural external variability contributions. FROT (Framework for Radiative cOntributions to Temperature response) allows for an assessment of components of direct radiative impact to the system (climate forcing), as well as Earth system feedbacks concerning heat and carbon. The framework is versatile in terms of applications and allows for exploring individual components contributions to, for example, temperature stabilisation simulations, or comparisons in different models and scenarios, as it can reasonably explain their simulated temperature variability. Here, we apply FROT to both an intermediate complexity and a fully coupled Earth system model, as we simulate highly ambitious mitigation scenarios. Comparing temperature stabilisation scenarios, we can show that both net-zero CO_2 emissions and small amounts of positive CO_2 emissions could lead to a stable global temperature trajectory. Our assessment reveals that the effects of non-CO_2 climate forcings, especially the development of sulphate aerosols in the atmosphere, and the dynamics of the carbon cycle, play a pivotal role in the final level of warming and in enabling a temperature stabilisation. Under highly ambitious climate mitigation scenarios it becomes crucial to include Earth system feedbacks, specifically ocean heat uptake, to understand interannual to decadal temperature development, since previously secondary processes now become increasingly dominant. Our framework offers the opportunity to do so.

1. Introduction

Over the past decades, international climate agreements have been established to mitigate anthropogenic impacts on the Earth system [1, 2]. These efforts stem from the widely accepted understanding that human activities are the primary driver of global climate warming [3, 4], affecting the planet's overall energy balance. Main contributors to global warming include the emissions of greenhouse gases (GHGs) and aerosols, along with their precursors, as well as changes in land characteristics [4]. Global warming in response to these anthropogenic activities is currently mediated by the uptake of carbon by land and ocean [5], and the uptake of heat mainly by the ocean [6]. Despite the high confidence in attributing climate change to human activities (e.g. [7, 8]), uncertainties persist, regarding future socio-economic developments [9, 10], Earth system responses [11] or current strength and future evolution of some individual contributions [11–13], for example.

The choice of metric to assess possibilities presented by future simulation in climate mitigation is crucial and should encompass all relevant climate forcing contributions. In the past decade, the primary metric has been cumulative CO_2 or CO_2 equivalent (CO_2-eq) emissions (e.g. [5, 14]), where non-CO_2 GHGs are converted to a CO_2-eq estimate [15–18] given their respective global warming potential ([19]). CO_2-centric metrics rely on the near-linear relationship between cumulative CO_2 emissions and global temperature increase, known as the transient climate response to cumulative CO_2 emissions (TCRE [20–22]), being associated, therefore, with the concept of remaining carbon budget [20, 23–25]. The TCRE enables the calculation of allowable carbon emissions until a specified temperature target is reached. However, the physical basis for this near-linear relationship has been proven for scenarios considering CO_2 only [26]. Incorporating non-CO_2 forcing requires making assumptions about its proportionality to CO_2 [27, 28] or accounting for an uncertain contribution from future non-CO_2 forcing [25, 29]. The assumptions about proportionality cannot be reliably projected into the future for ambitious climate mitigation scenarios, nor be well defined due to uncertainty in future mitigation activities [30, 31]. Another commonly employed metric is CO_2 forcing equivalent (CO_2–fe), which allows to take aerosol, land-use albedo, and other components into account, and relies on carbon cycle models estimations or emulators [32, 33] or additional model simulations [18, 34].

Natural climate dynamics, especially ocean heat and ocean and land carbon uptake, are gaining importance with respect to temperature responses in ambitious climate mitigation scenarios [35, 36]. Yet, current frameworks that aim to project temperature outcomes only consider anthropogenic forcing assuming inputs to the system, thus not accounting for dynamical responses and adjustments from the feedbacks at play. Neglecting these dynamic Earth system responses in the context of ambitious climate mitigation scenarios, in which anthropogenic forcing is projected to decrease, is especially prone to cause large relative deviations in temperature projections. Accordingly, there is a need for a more comprehensive assessment of the relative contributions to the future temperature changes including radiative contributions (RC) from anthropogenic forcing, natural forcing variability as well as Earth system's dynamic responses, which can then offer reliable and relevant guidance on the necessary efforts to meet climate targets.

Here we combine different existing approaches to provide such a comprehensive framework that allows for the inclusion of all components that impact atmospheric temperature development: FROT—Framework for Radiative cOntributions to Temperature responses. This model assessment tool builds upon the established energy balance theory, allowing us to include the effects from anthropogenic activities such as GHG emissions, aerosols and their precursors. It also considers natural climate forcing from volcanic and solar contributions, along with Earth system responses, including carbon cycle dynamics and ocean heat uptake. However, in its current form, FROT does not account for time-dependent variations in climate feedbacks. FROT connects all of the components in a common radiative metric with a unit of Wm^{-2}. By combining all relevant contributions—forcings and feedbacks—that affect the planet's atmospheric radiative burden (ARB), we can reconstruct and explain the variability in global surface air temperature. We demonstrate the proof of concept using an intermediate complexity model (UVic ESCM; section 3.1), and provide application examples comparing different temperature stabilisation (TempStab) scenarios (section 3.2). Additionally, we demonstrate FROT's versatility by applying it to a fully-coupled Earth System Model, the GFDL-ESM2M (section 3.3), all while taking into consideration needed assumptions and simplifications, such as time-invariant climate feedbacks.

2. Methods

2.1. Development of the assessment framework

In the following sections, we outline our approach and provide detailed explanations of our assumptions. We consider the energy balance concept [37], which relates planetary heat uptake (ΔN) with radiative forcing (RF) and radiative responses in terms of temperature changes (ΔT) through the climate feedback parameter (λ), as:

$$\Delta N(t) = \mathrm{RF}(t) - \lambda \Delta T(t) \Rightarrow \mathrm{RF}(t) - \Delta N(t) \propto \Delta T(t) \quad (1)$$

In order to appropriately assess the drivers behind temperature variability, we focus on the transient aspect of the radiative forcers and, where possible, dynamical responses of the Earth system. Therefore, we introduce here the concept of ARB, under which we combine the anthropogenic radiative forcing and the forcing related to natural external variability with the radiative responses of land and ocean carbon uptake, and the ocean heat uptake. To accommodate this comprehensive framework, we adapt a formulation employed by MacDougall *et al* [36], through which we can convert all components to RCs. Moreover, this approach focuses on exploring the temporal development of the contribution of the combined driving forces to temperature variability, rather than describing individual component's attributed effects to the temperature at a specific point in time. In the following sections, we will explore individual contributions to ARB in detail, clarify assumptions and simplifications regarding time-varying feedbacks, and finally relate ARB back to the temperature variability in section 2.1.5.

2.1.1. RCs from CO_2 emissions and carbon cycle responses

The change in atmospheric carbon burden ($dCO_{2,\mathrm{atm}}$) is the product of sources and sinks of CO_2 (*Emissions* and *Sinks*). In the context of our analyses, we differentiate these further into fossil fuel emissions [E_{FOS}], land use change emissions [E_{LUC}]), and sinks given from the carbon uptake by the land [S_{LAND}] and the ocean [S_{OCEAN}]), following [5]. To express their impact in terms of RC, we adapt the mathematical formulation employed in [36], accounting here for the time dependent character of such contributions:

$$\begin{aligned}
\Delta \mathrm{RC}_{\mathrm{CO_{2,\,atm}}}(t_i)
&= R \cdot d\mathrm{CO}_{2,\,\mathrm{atm}}(t_i)\\
&= R \cdot (\mathrm{Emissions} + \mathrm{Sinks})\\
&= R \cdot (d\mathrm{CO}_{2,\,\mathrm{FOS}}(t_i) + d\mathrm{CO}_{2,\,\mathrm{LUC}}(t_i))\\
&\quad + R \cdot (d\mathrm{CO}_{2,\,\mathrm{LAND}}(t_i) + d\mathrm{CO}_{2,\,\mathrm{OCEAN}}(t_i))\\
&= R \cdot \left(\int_0^{t_i} \frac{E_{\mathrm{FOS}}(t)}{C_A(t)}\,dt + \int_0^{t_i} \frac{E_{\mathrm{LUC}}(t)}{C_A(t)}\,dt \right)\\
&\quad + R \cdot \left(\int_0^{t_i} \frac{S_{\mathrm{LAND}}(t)}{C_A(t)}\,dt + \int_0^{t_i} \frac{S_{\mathrm{OCEAN}}(t)}{C_A(t)}\,dt \right)\\
&= \Delta \mathrm{RC}_{\mathrm{CO_{2,\,emit}}}(t_i) + \Delta \mathrm{RC}_{\mathrm{CO_{2,\,sink}}}(t_i), \qquad (2)
\end{aligned}$$

where $\mathrm{RC}_{d\mathrm{CO_{2,atm}}}(t_i)$ is the RC of the atmospheric carbon burden (Wm^{-2}), R is the radiative forcing from an e-fold increase in atmospheric CO_2 burden (Wm^{-2}), $E_{\mathrm{FOS}}, E_{\mathrm{LUC}}, S_{\mathrm{LAND}}, S_{\mathrm{OCEAN}}(t)$ are the component's CO_2 flux into and out of the atmosphere (PgCyr^{-1}) and $C_A(t)$ is the CO_2 content of the atmosphere (PgC) in the year t. This equation, therefore, reflects the impact that sinks or emissions of CO_2 have on the changes in atmospheric carbon burden and the impact in terms of radiative forcing. All fluxes are considered as entering the atmosphere in this notation, so the carbon sinks should have a negative sign. We calculate carbon flux contributions integrated over time to account for the cumulative impact of carbon on the atmosphere. Equation (2), therefore, allows for a cumulative approach to understanding individual contributions, with results shown as in figure 1(b), calculated from pre-industrial conditions. To estimate each component's contribution at a given year, we differentiate the RC at consecutive time steps (see figure 1(a)). Since the assessment framework presented is able to provide information with respect to individual contributions for each time step, we are able to observe the transient aspects of dynamical responses. For the most accurate results, we recommend to diagnose anthropogenic emissions from, especially, land use directly in the model and include them as model outputs. If this is not available, model inputs can be used.

2.1.2. RCs from anthropogenic non-CO_2 GHGs and aerosols

Anthropogenic non-CO_2 GHGs, like methane, nitrous oxide or CFCs, have a significant impact on the Earth's radiative balance [12, 39]. In addition to the previously mentioned well-mixed greenhouse gases (WMGHGs), other minor contributors are tropospheric and stratospheric ozone for example. Different methods are explored for calculating their (effective) radiative forcing [11, 12, 38, 40–42]. We refer to such previous studies on WMGHGs radiative forcing to directly include non-CO_2 GHGs [$\mathrm{RC_{WMGHGs}}$] in our framework.

In the same way, aerosols and their precursors significantly influence the Earth's climate by predominantly reflecting incoming solar radiation, resulting in atmospheric cooling. Yet, the assessment of aerosol radiative forcing contribution is more complicated than the one from WMGHGs, since the radiative forcing is spatially non-uniform and varies based on sources and interactions with clouds (e.g. [43]). In fact, aerosols contribute the largest uncertainty to changes in Earth's radiative forcing [12, 44]. For FROT but also for further climate studies we strongly recommend modelling groups to determine and make available the radiative forcing of aerosols in their simulations. If diagnosed, aerosols effective radiative forcing contributions [$\mathrm{RC_{aerosols}}$] can be incorporated in FROT alongside other components from non-CO_2 GHGs, based on their forcing anomaly to pre-industrial conditions as:

$$\Delta \mathrm{RC}_{\mathrm{non-CO_2}}(t_i) = \Delta \mathrm{RC}_{\mathrm{WMGHGs}}(t_i) + \Delta RC_{\mathrm{aerosols}}(t_i), \qquad (3)$$

with ΔRC as the anomaly in forcing RC of a specific component between year t_i relative to initial conditions, e.g. here pre-industrial state, (Wm^{-2}). Note that components that cool the climate have a negative sign in FROT.

As discussed in section 2.1.1, ideally, diagnosed forcing output would be used for the assessment, to allow for an understanding of their varying contributions to annual temperature variability. If this information is not available, forcing input to the model, as provided by emulators or integrated assessment models, can also be included.

2.1.3. RCs from natural external climate forcing

The main natural external climate forcing [RC_{nat}] that impacts global mean temperature originates from solar irradiance variability and volcanic eruptions. These two contributions are commonly diagnosed in terms of their radiative forcing impact, or are provided as radiative forcing input to models, which allows for a straight-forward inclusion in FROT,

$$\Delta RC_{nat}(t_i) = \Delta RC_{solar}(t_i) + \Delta RC_{volcanos}(t_i), \quad (4)$$

with ΔRC being the radiative forcing contribution between year t_i and pre-industrial conditions (Wm^{-2}), once again with negative values for contributions that cool the atmosphere.

2.1.4. Earth heat responses

The last contribution to be taken into account is the Earth heat response [RC_{EH}]. In our analysis, we considered this to be approximated by the ocean heat uptake. We define effective ocean heat uptake following the approach brought forward in MacDougall *et al* [36], resulting in total radiative forcing of:

$$\Delta RC_{EH}(t_i) = \epsilon * \Delta N_{heat\ uptake}(t_i), \quad (5)$$

with ϵ being a scaling variable for the efficacy of the planetary heat uptake (for calculations see [36, 37]) and ΔN being the contribution from ocean heat uptake between year t_i and pre-industrial conditions (Wm^{-2}), with negative values if this component cools the atmosphere. Although FROT is theoretically capable of incorporating time-varying feedbacks if this information would become available, we have chosen to treat ϵ as a constant, similar to what was done in [36], where the authors use efficacy values from the 1pctCO2 experiment [45]. As a consequence, we are not able to include the full impacts from the temporal variability of the efficacy (or associated surface pattern effect [46]), a process known to play an important role in defining temperature evolution in the atmosphere. In [36], the authors report efficacy to have a ±30% uncertainty associated with it, which applies similarly to the results presented here. As a result of such assumption, the results explored in section 3 do not include time-dependent climate feedbacks.

2.1.5. Comprehensive framework with contributions from all components

Once all the components mentioned in the sections before are included, FROT is able to provide an estimate of the ARB as:

$$\begin{aligned} ARB(t_i) &= \Delta RC_{CO_2,atm}(t_i) + \Delta RC_{non-CO_2}(t_i) \\ &\quad + \Delta RC_{nat}(t_i) + \Delta RC_{EH}(t_i) \\ &= [\Delta RC_{CO_2,emit}(t_i) + \Delta RC_{non-CO_2}(t_i) + \Delta RC_{nat}(t_i)] \\ &\quad + [\Delta RC_{CO_2,sink}(t_i) + \Delta RC_{EH}(t_i)]. \end{aligned} \quad (6)$$

ARB includes all components that contribute to the radiative forcing, including dynamic changes in atmospheric carbon content differentiated into sources and sinks of CO_2, contributions from non-CO_2 GHGs and aerosol forcing, as well as natural climate forcing, and the dynamic changes in planetary heat uptake as simulated by the respective Earth system models.

Since both time varying forcing and radiative responses are accounted for with ARB, we can expect its evolution to be proportional to that of the surface air temperature,

$$ARB \propto \Delta T \quad (7)$$

We find that ARB is able to follow simulated atmospheric temperature developments consistently for ambitious mitigation scenarios, since it encompasses all relevant components in these scenarios (see comparison with top of the atmosphere net radiation in figure S4). This proportionality is not given by the climate feedback parameter (λ), since this variable relates radiative forcing to temperature changes from pre-industrial conditions, while transient effects from Earth system dynamics are considered under FROT. It is not within the aim of this study to calculate the proportionality. Rather we want to provide an assessment framework that is able to show a comprehensive approach to radiative forcing components and responses in terms of their impacts on temperature variability, even if omitting some of the time-varying aspect of climate feedbacks. More explanations on the relation to equilibrium climate sensitivity can be found in sections 4.1, 4.2 and the supplementary material.

Lastly, we want to note, that further individual components implemented in distinct models not present in the analyses here could be included in FROT. This information is, however, model specific and to be assessed by the modelling groups. Features not made explicit in the current analysis include contributions from permafrost dynamics, individual non-CO_2 GHGs, aerosol-cloud interactions, and land (ice) heat uptake.

2.2. Model and scenario description

To demonstrate the application of FROT, we use the UVic Earth system model of intermediate complexity (UVic-ESCM 2.10 [47–49]:), which offers a good representation of Earth's carbon cycle and heat exchanges. The model has a 3.6° × 1.8° spatial grid, 19 ocean vertical levels, 14 terrestrial soil levels, dynamic vegetation with 5 plant functional types, and a permafrost module. For the analyses in sections 3.1 and 3.2, the Earth heat uptake is estimated as the total ocean heat uptake, which assumes heat uptake by the land, soil or ice to be negligible. This choice is in agreement with the analysed model's representation of the energy balance, and can be adapted to individual model's capabilities of representing the Earth system heat budget [6]. We simulated two comparable high-mitigation scenarios. The first scenario stabilises global mean surface temperatures at 1.5 °C within the 21st century [50], using the adaptive emission reduction approach (AERA—[51, 52]), which iteratively calculates the fossil fuel CO_2 emissions necessary for achieving and stabilising at 1.5 °C. Non-CO_2 GHGs, aerosols and land-use changes follow the SSP1-2.6 scenario. The second scenario (SSP1_zero2070_5_0_co2only [53]), also using UVic-ESCM 2.10 stabilises global warming at 2.0 °C, reaching net-zero fossil CO_2 emission in 2070 and maintaining this level until 2100. The model is forced with non-CO_2 GHGs emission-driven data from CO_2, CH_4, N_2O, CO, NO*x*, CF_4 and SF_6, with the newly developed atmospheric chemistry module based on FAIR v.1.3 [54, 55]. All non-CO_2 GHGs, aerosols and land-use changes also follow the SSP1-2.6 scenario. Both scenarios have a similar carbon budget, 1804 and 1816 Gt CO_2, respectively, between 2010–2100. Due to important differences in non-CO_2 GHGs and aerosol forcing in these two simulations, we anticipate substantial differences in climate forcing contributions and associated responses between the scenarios.

In addition, we use a 1.5 °C global temperature stabilisation scenario conducted with the fully coupled Earth system model (GFDL-ESM2M—[56–58]). The GFDL ESM2M includes a dynamic atmosphere, ocean and land carbon cycles, on a 1° tripolar grid for the ocean, having finer resolution close to the Equator, and an atmospheric resolution of 2 × 2.5°. The atmosphere is represented by 24 vertical pressure levels and the ocean with 50 depth levels. The 1.5 °C global warming stabilisation simulation of the GFDL ESM2M was also conducted with AERA and follows the RCP2.6 scenario for non-CO_2 radiative forcing agents and land-use change [52]. Further descriptions are given in the supplementary material.

3. FROT application and examples

3.1. Evaluation of individual components of the framework and proof of concept

We first evaluate whether RCs to atmospheric carbon burden including fossil fuel and LUC emissions as well as the ocean and land carbon cycle dynamics (see equation (1)) align with the radiative forcing from changes in atmospheric CO_2 concentrations over time in UVic ESCM for the 2 °C global TempStab scenario (figure 1(a)). The reconstructed radiative forcing agrees well with simulated CO_2 concentration changes forcing (compare black hatched bars with black lines in figures 1(a) and (b)), both for annual and cumulative estimates. From 2000 to 2055, fossil CO_2 emissions dominate positive forcing to the system, strongly decreasing and reaching zero by 2070. However, after 2055 remaining emissions are over-compensated by natural terrestrial and ocean carbon sinks, reducing CO_2 radiative forcing. CO_2-related components alone cannot coherently describe the observed variability in air temperature (purple lines in figures 1(a) and (b)). While the reduction in the forcing from carbon-altering components can be clearly associated with the reduction in annual temperature changes reaching a near temperature stability, short-term interannual fluctuations cannot be explained by these contributors alone.

A comprehensive radiative burden emerges once all contributors (i.e. carbon- and non-carbon- altering components) are considered (figures 1(c) and (d)), providing a full understanding of global temperature variability. Exploring the relevance of only non-CO_2 GHGs (orange and red bars in figures 1(c) and (d)) reveals their insufficient impact on the radiative forcing to explain the simulated temperature variability. Similar to CO_2 altering components, the overall decrease in the annual contribution from non-CO_2 forcing is mirrored by a general reduction in annual temperature increases. For this particular 2 °C-TempStab scenario, sulphate aerosol forcing appears crucial in modulating temperature variability between 2010 and 2030, the reduction of which contributes to an overall warming during that period. The non-CO_2 components' contribution nears zero around 2050, while air temperature persists in an oscillating behaviour, indicating the increasing dominance of natural external climate variability on the second half of the century.

In the initial years of the simulation, when CO_2 altering components (mainly FOS), as well as non-CO_2 GHGs and aerosols, strongly impact global radiative forcing, the natural variability appears to simply modulate the temperature change led by the atmospheric CO_2 radiative impact (green bars in figure 1(c)). While solar and volcanic forcings are independent and externally determined, ocean heat uptake responds to dynamics in the Earth system. As the scenario progresses and CO_2 and non-CO_2 forcings are phased out between 2050 and 2070 (figure 1(c)), natural external variability becomes more relevant. In fact, natural variability appears to be the leading cause for short-term air temperature fluctuations, again with the ocean modulating the temperature changes and compensating for solar radiation oscillations. The end of the century temperature fluctuations closely follow the net effect of the considered natural forcings, both in frequency and magnitude of changes (figure 1(c)).

In terms of relevant effects on longer timescales and for total temperature changes, the predominance of CO_2 sources and CO_2 regulating components (i.e., carbon cycle responses) becomes evident in cumulative impacts to temperature (figure 1(d)). The overall contribution of the atmospheric CO_2 burden dominates the cumulative effect derived

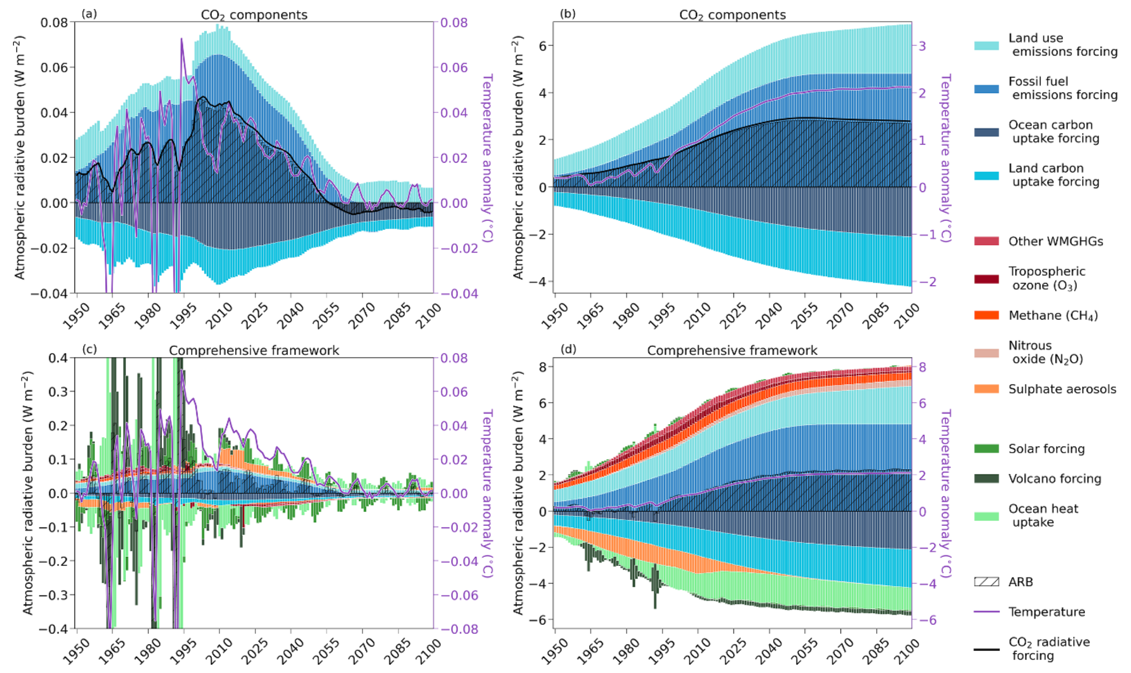

Figure 1. Introduction and proof of concept to framework for radiative contribution to temperature response (FROT): Stacked contributions to atmospheric radiative burden (ARB) from (a), (b) CO_2 altering contributors and (c), (d) all contributors (colored bars—see legend) for the 2 °C global TempStab using UVic ESCM 2.10 between 1950 and 2100. The term all contributors includes those from CO_2 panels—note the different vertical scale when comparing (a), (b) to (c), (d). Annual values are shown on the left panels, while cumulative fluxes are given on the right. Cumulative fluxes are calculated from pre-industrial conditions, i.e. the year 1850. The purple line represents the temperature variability (referring to right y axis), while the black line in (a), (b) shows the CO_2 radiative forcing (referring to the left y axis) calculated based on [38]. Similar to the individual forcing contributions, left panels show the temporal derivative of temperature and CO_2 radiative forcing, while their simulated/calculated values are shown on the right ones. The black hatched bars indicate the net burden from the sum of the contributors considered.

from the long atmospheric lifetime of CO_2, with impacts simulated to last for hundreds to thousands of years [48]. Conversely, short-lived climate forcers, like aerosols and GHGs as carbon monoxide or non-methane organic compounds, are strongly reduced by the end of the century, with less relevant impacts as the simulation progresses. Finally, the importance of ocean heat uptake for dampening temperature increase becomes clear, as seen in the cumulative impact, even if time-varying climate feedbacks are not included in this analysis.

3.2. TempStab scenario comparison

FROT can facilitate a comparative analysis on how each radiative component varies in relation to itself and others in distinct scenario simulations and, therefore, allows for drawing insights on processes leading to temperature changes. We compare two global mean TempStab scenarios, each with a carbon budget of 1810 Gt CO_2, but an end of the century temperature of 1.5 °C and 2 °C (1.5 °C-TempStab and 2 °C-TempStab, respectively). Despite the same carbon emissions budget, their end-of-the-century temperatures deviate by about 0.60 °C (purple line in figure 2)).

The FROT framework enables a comprehensive assessment of which contributors—forcing differences and Earth system dynamics—are responsible for the temperature differences in the two scenarios. FOS are implemented under different pathways in the scenarios. While the 2 °C-TempStab scenario has initially slightly higher emissions and steadies at net-zero by 2070, 1.5 °C-TempStab simulation maintains small positive fossil fuel CO_2 emissions until the end of the century (figures 2 and S1). Additionally, the distinct relative importance of aerosols and other GHGs leads here to substantial temperature difference. In the 2 °C-TempStab scenario a stronger aerosol decrease causes higher warming forcing of up to 0.59 Wm^{-2} between 2010 and 2025 compared to the 1.5 °C-TempStab simulation. After 2035, non-CO_2 WMGHGs contribute to further warming forcing of up to 0.47 Wm^{-2} in the 2 °C-TempStab scenario (figure 2).

Finally, the differences in contributions due to carbon emissions and heat and carbon responses lead to variations in the land carbon uptake and ocean heat uptake in the scenarios. A weaker land carbon uptake in the 2 °C-TempStab scenario (36% of the cooling forcing, compared to 40% in 1.5 °C-TempStab) leads to more temperature increase in

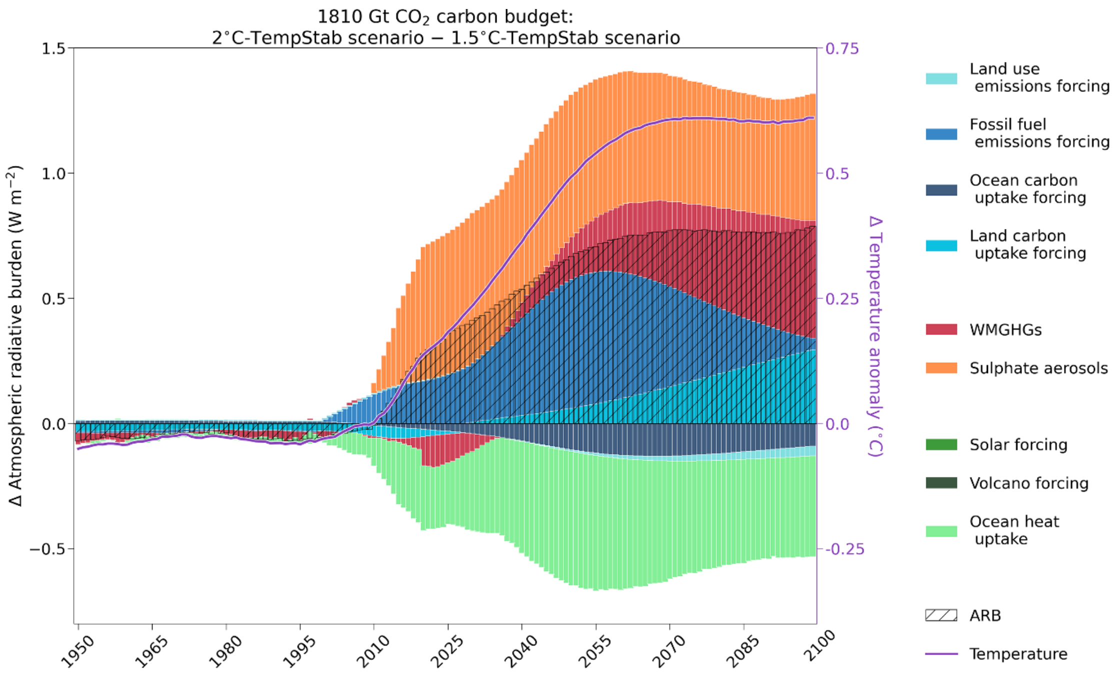

Figure 2. Differences between the 1810 Gt CO_2 carbon budget 2 °C and 1.5 °C global TempStab scenarios using UVic ESCM 2.10. Cumulative contributions from the individual components to atmospheric radiative burden (ARB) (colored bars—see legend) between 1950 and 2100. Cumulative fluxes are calculated from pre-industrial conditions, i.e. the year 1850. The purple line represents the temperature variability referring to the right *y* axis, while the black hatched bars indicate the net burden from the sum of the individual contributors, referring to the left *y* axis. The individual contributions for the 1.5 °C-TempStab simulation using UVic ESCM 2.10 can be seen on the supplementary information.

the 2 °C versus 1.5 °C-TempStab scenario. The relatively higher land carbon uptake in the 1.5 °C-TempStab simulation is dominated by lower soil respiration, rather than net primary production, despite the maintained positive emissions (see figure S2). Stronger fossil fuel mitigation at an early stage in the 1.5 °C-TempStab scenario contributes to lower end of the century temperature. The stronger ocean heat uptake in the 2 °C relative to 1.5 °C-TempStab scenario compensates up to 0.54 Wm^{-2} of the additional radiative forcing. The higher ocean heat uptake in the 2 °C-TempStab scenario (22% of the cooling compared to 14% in 1.5 °C-TempStab) is possibly associated with higher incoming shortwave radiation at the surface from lower atmospheric aerosol content and a different ocean heat content from higher CO_2 concentrations in the 2 °C-TempStab simulation (not shown).

3.3. Application of FROT to a fully-coupled Earth system model

Next, we explore the effects and contributions of various forcing and dynamic Earth system components in a fully-coupled Earth system model, the GFDL-ESM2M. The model's higher complexity, with a high internal natural variability compared to UVic ESCM, that lacks unforced variability, leads to a large difference when comparing variability in figures 1 and 2 with figure 3, and makes interpretation of results more challenging. When analysing the GFDL-ESM2M, the cumulative approach aids in understanding the TempStab scenario and we can observe that despite strong reductions, fossil fuel and land use CO_2 emissions do not reach net-zero during the 21st century (figures 3(a) and (b)). The radiative forcing contributions of non-CO_2 GHGs, in particular tropospheric ozone, are reduced throughout the century. Both components' groups reduction contributes to the aimed stabilisation.

Changes in aerosol cooling, in contrast to the UVic ESCM model, play a minor role in this model, with reduced cooling effect between 2000 and 2040. Land carbon uptake is overall stronger than ocean carbon uptake (46% cooling contribution against 41%, respectively), but also shows higher variability, weakly oscillating throughout the simulation. Ocean heat uptake reflects most of the model's internal variability (with a magnitude as high as 2 Wm^{-2}, see figures 3(c), and S3), with continuous uptake throughout the simulation of the 21st century, aiding the stabilisation of global mean temperature (figure 3(d)). The large importance of the ocean heat uptake is clear even in the absence of time-varying climate feedbacks. Evidently, it is the reduction of fossil CO_2 emissions and non-CO_2 GHG emissions that mainly contribute to the aimed halt of global mean temperature, eventually leading

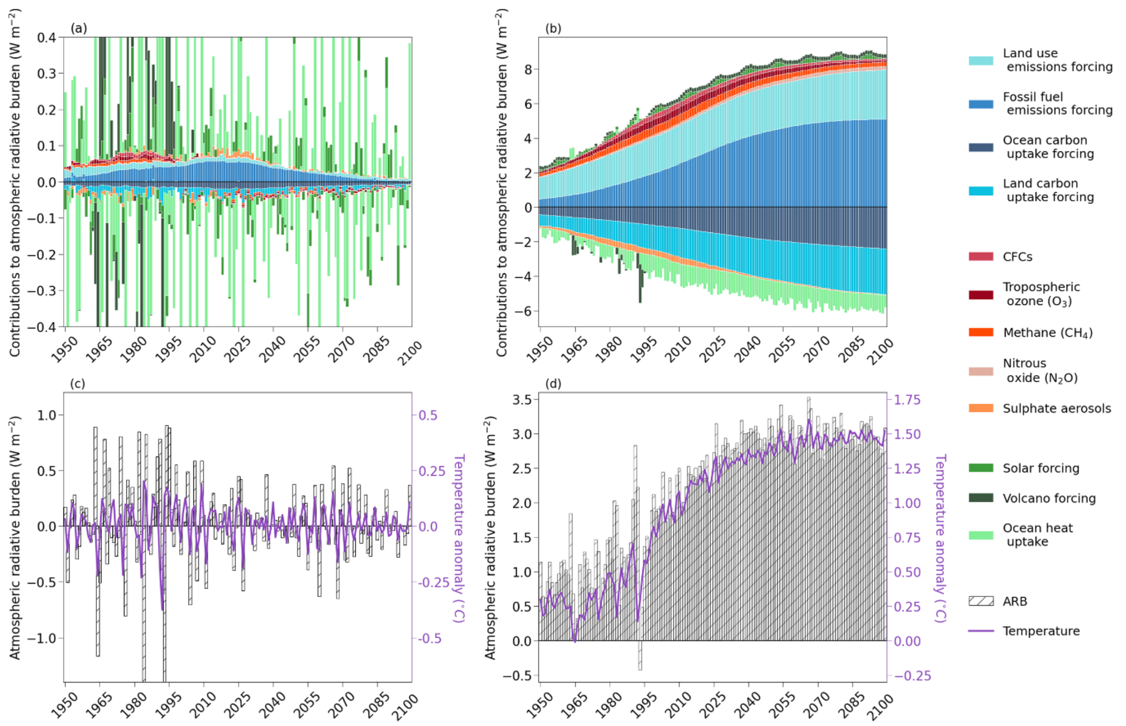

Figure 3. Application to a fully-coupled model (GFDL-ESM2M): Contributions to atmospheric radiative burden (ARB) from all individual contributors (coloured bars—(a), (b)) and the final atmospheric radiative burden (black hatched bars—(c), (d)) for the 1.5 °C global TempStab scenarios using GFDL-ESM2M between 1950 and 2100. Differentiated values are shown on the left column, while cumulative fluxes are given on the right. Cumulative fluxes are calculated from pre-industrial conditions, i.e. the year 1861. The purple line represents the temporal derivative of temperature in (c) and the simulated surface air temperature anomaly values on (d), referring to the right *y* axis. The black hatched bars indicate the net burden from the sum of the contributors considered.

to its stabilisation, modulated by the ocean heat uptake.

4. Conclusions

4.1. Scenario and framework outcomes

Our analyses demonstrate the value and versatility of the proposed FROT framework by assessing different forcing and responses contributions and their relative importance with respect to the Earth system's temperature development over time. FROT is applied to ambitious climate mitigation TempStab scenarios, where major anthropogenic forcing contributors decrease over the 21st century (i.e. fossil fuel and land use CO_2 emissions, non-CO_2 GHGs and aerosols). We highlight that stabilisation timing and, to an extent, the end of century warming depend upon the mitigation of non-CO_2-related components in our two simulations, as well as the carbon cycle and the ocean heat uptake dynamics. Considering the Earth system feedbacks to the radiative forcing of the planet is essential to estimate if and how temperature will stabilise in high mitigation scenarios. Moreover, the scenario comparison highlights the importance of early fossil fuel mitigation for temperature stabilisation, even in a context of highly ambitious emissions mitigation scenarios for an ambitious end of the century temperature target.

Different radiative forcing components can impact the efficiency and dynamics of one another's radiative processes. For example, methane affects the carbon cycle [59], while volcanic eruptions and changes in incoming solar radiation impact the ocean heat and carbon uptake [60, 61]. Likewise, aerosol content and its distribution in the atmosphere as well as its development over the 21st century strongly impact ocean heat uptake [62]. The inclusion of model's diagnostic outputs into FROT allows for the consideration of such interrelations. Even though such interactions and non-linearities are accounted for in model's implementations, our approach is obviously constrained by the limitations posed by a model's accuracy and proper process representation. Any uncertainty and lack in implementation will be translated into FROT and, therefore, must be acknowledged. Similarly, we must highlight the assumption used in the examples explored here of a constant efficacy of the planetary heat uptake, and associated climate feedbacks assumed therefore to be constant in time, which carries an uncertainty of up to 30% associated to it (see [36]). However, processes not represented in models conversely, would not impact the accounting of FROT, but neither would they affect the simulated temperature variability, leading to consistent results within the application of FROT.

Finally, as emphasised in the previous sections, FROT's primary goal is to explain different contributions to global air temperature changes based on forcing and responses, not to predict absolute temperature changes. An intuitive next step could be to estimate temperature from the ARB given by the framework. This relationship could, conversely, allow for inferences in terms of remaining forcing budgets associated with specific end of the century temperature goals. Any attempt in projecting real-world absolute temperature changes, however, would depend on a sufficient understanding of such proportionality in the real world. While we are able to diagnose and manipulate, for example, a model's climate sensitivity (see SI for more analyses), uncertainties of the real world Earth's climate system response to the net forcing remain to date (e.g. [4]), refraining us from this step. As pointed out previously, the proportionality between ARB and temperature is not given by the climate sensitivity per se, since this term is associated in particular to the net radiative forcing. The inclusion of Earth responses and dynamics in a transient manner in FROT allows for reasonably constant proportion between ARB and the temperature variability, even in the presence of highly ambitious climate mitigation scenarios (see for example SI figure S6 for details). Further evaluation of this proportionality would have to be thoroughly investigated even in models, based on, for example, experiments utilizing different efficiencies in heat uptake, transient climate responses or distinct radiative forcing components.

4.2. Framework outlook and limitations

CO_2-eq and CO_2-fe metrics or carbon budgets are valuable approaches that aim to provide a unified overview of climate forcing components and temperature evolution and to inform mitigation policies (e.g. [15, 16, 34]). They, however, lack the ability to include dynamic Earth system responses to forcing contributions. These internal feedbacks will play a key role in determining temperature stabilisation in ambitious mitigation pathways. We here introduce a framework that provides a more comprehensive approach for the assessment of the different components of anthropogenic and natural climate forcings and relevant Earth system dynamics. In a highly ambitious mitigation world, this level of complexity is in fact necessary for an assessment of temperature variability, therefore the solid relationship found between changes in ARB and the simulated temperature variability provides valuable information to the relative importance of the analysed climate components. FROT can, in addition and in a synergic manner with pre-existing carbon-centered methods, provide more detailed insights on the overall contributions to temperature change to inform ambitious mitigation policies.

FROT is not envisioned to predict global mean temperature, but rather aims to provide an approach to understand contributions of all relevant components to climate change and mitigation efforts, especially in a context in which humanity moves towards lower anthropogenic forcing. It delivers a comprehensive assessment tool to be utilized in better understanding model simulations and surface air temperature changes.

We have demonstrated that the framework is easily implemented for different models and scenarios, and allows for a comparison of forcing components and Earth system dynamics between model simulations. This highlights the relatively simple applicability and versatility of FROT. Especially the comparisons of stabilisation scenarios and its application to different models make FROT a useful tool for intercomparison projects. Further analyses of, for example, 1.5 °C scenarios could benefit greatly from this approach. The impacts of forcing or distinct implementation choices and their impact on Earth system dynamics can also be explored by applying the comprehensive framework.

Once again, it is clear that applying this framework, and the granularity of the application, will depend on the modelling structure and in how far information on the single components can be obtained. We are aware of the limitations of some models with respect to global mean sulphate aerosol forcing or even diagnostic land-use change emissions, among others. We nevertheless see value in obtaining and combining these variables, as we have shown that their respective contributions are important to consider in high ambition mitigation scenarios, and suggest modelling groups to provide more of such outputs in future rounds of model intercomparisons. In addition, although we point out that FROT is not limited to time constant efficacy, we acknowledge that a consideration of time dependence in the climate feedbacks within FROT would be an important step forward. It is clear from our results, however, that even in case of such needed simplifications, the conclusions obtained with FROT, taking into consideration the associated uncertainty level, are relevant and vastly useful for the climate community.

Data and code availability statement

The LTTG scenario data is available on the platform MESSAGEix Paris Long-Term Temperature Goal (LTTG) Scenario Explorer hosted by IIASA (https://data.ene.iiasa.ac.at/paris-lttg-explorer under SSP1_zero2070_5_0_co2only). The LUC patterns applied to the UVic-ESCM 2.10 simulations were compiled from the input4MIPs platform (https://esgf-node.llnl.gov/projects/input4mips/ under Land-Use Harmonization Data Set).

The underlying code for this study is available in [https://git.geomar.de/estela-monteiro/frot.git].

The underlying code are openly available at the following URL/DOI: https://git.geomar.de/estela-monteiro/frot.git.

Acknowledgments

EAM conducted the analyses. EAM and NM interpreted the results and were major contributors in writing the manuscript. EAM and DH developed the publicly available code. EAM, YS, TF, FB provided the model data and/or ran simulations. All authors read and approved the final manuscript. EAM thanks G. The authors thank Joeri Rogelj, Ivy Frenger and Andreas Oschlies for the valuable discussions of key results. The authors thank Ric Williams and two anonymous reviewers for their constructive comments and discussion points.

All authors declare no financial or non-financial competing interests.

EAM, DH, and NM are funded under the Emmy Noether scheme by the German Research Foundation (DFG) in the project 'FOOTPRINTS—From carbOn remOval To achieving the PaRIs agreemeNt's goal: Temperature Stabilisation' (ME 5746/1-1). YS, FAB and TLF are funded by the European Union's Horizon 2020 research and innovation programme under Grant Nos. 821003 (Project 4C) and 101003687 (Project PROVIDE). GFDL ESM2M simulations have been performed on the Swiss National Supercomputing Centre.

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