

Article

Methane and the Warming Blame Game

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Abstract

Methane emissions are responsible for approximately 0.5 °C, or about 30%, of total greenhouse-gas-induced warming. For many countries, methane represents an even larger share of their overall warming footprint. Assessing the warming contributions of individual methane-emitting countries to global warming is not straightforward due to methane's short atmospheric lifetime and the non-linear (convex) relationship between radiative forcing and the atmospheric concentration of this gas. This study addresses this challenge using a simple climate model in combination with a warming allocation approach derived from cooperative game theory. Applying this method, the warming contributions of several high-methane-emitting countries and regional groupings are quantified relative to the early industrial period. The analysis reveals that the commonly used marginal attribution method underestimates methane-induced warming by approximately 20%. This discrepancy is due to the substantial rise in the atmospheric concentration of methane since early industrial times.

Keywords: global warming; methane emissions; simple climate model; global warming attribution

1. Introduction

Assessments of the climate impact of national emissions have long been recognised as important inputs to climate policy. Many studies have allocated individual countries' contributions to climate change, focusing on historical warming, likely future warming, climate damage, or climate extremes [1–10]. Foremost among the motivations for this effort is the foundational UNFCCC principle of “common but differentiated responsibilities” (CBDRs) for climate change [11]. Historical responsibility may inform policymakers' considerations of equitable mitigation effort, climate justice, climate finance, obligations under loss and damage, or possible future liability and compensation claims [5,12–14]. The present study concerns *causal attribution* for warming. Evaluating *responsibility* requires additional normative judgements [5,7,15].

Methane (CH₄) is a short-lived climate forcer (SLCF) with a lifetime of ≈ 12 years in the current atmosphere [16,17]. It is also a major greenhouse gas, with a convex (square root) relationship between radiative forcing and atmospheric concentration [18–20]. Recent scientific and climate policy work [7,17,21–23] emphasises transient CH₄-induced warming, rather than CO₂ equivalents, to reflect the distinct climate physics of this gas. For carbon dioxide (CO₂), cumulative emissions and transient warming impact are interchangeable because they are simply linearly related through the transient climate response to cumulative emissions (TCRE) [24,25]. However, models [26,27] are needed to evaluate the warming impact of CH₄ and other non-CO₂ drivers over extended time periods. Simple climate



Academic Editor: Patrick Da Costa

Received: 13 June 2025

Revised: 22 August 2025

Accepted: 25 August 2025

Published: 27 August 2025

Citation: Wheatley, J. Methane and the Warming Blame Game. *Methane* **2025**, *4*, 20. <https://doi.org/10.3390/methane4030020>

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models (SCMs) relate radiative forcing to subsequent warming with fast components and slow components associated with multiple equilibration timescales [28].

In 1997, Brazil proposed that national mitigation targets should be linked directly to historical warming contributions [29]. Apart from political opposition, the Brazilian proposal faced methodological challenges [1,30,31]. As noted by den Elzen et al. [1] *“calculation of regional responsibility is not straightforward, because the climate system is not linear”*. An obvious source of non-linearity is convexity in forcing–concentration relationships of the major greenhouse gases, CO₂, CH₄, and nitrous oxide (N₂O), arising from saturation of their infra-red absorption bands [18,19]. The non-linearity problem was greatly reduced with the identification of TCRE as the key warming metric for CO₂ [24,25]. This meant that CO₂-induced warming could be allocated simply based on a country’s cumulative CO₂ emissions [3]. However, this simplification is not available for CH₄ and N₂O or short-lived climate forcers (SLCFs) that have a significant impact on climate. Matthews et al. [3] allocated CH₄-induced global warming according to the country’s share of cumulative CH₄ emissions. More recently, this ad hoc treatment of CH₄ was replaced by a warming-metric-based approach using GWP* [17,21] to account for atmospheric lifetimes [6]. However, as emphasised by Lynch et al. [22], linearised metrics such as GWP* have limitations when applied over extended time periods, where the atmospheric concentrations of CH₄ or N₂O change appreciably. The non-linearity addressed in this paper, derived from the physical properties of methane, can be contrasted with other important non-linearities arising in climate economics [32,33].

Most allocation studies use simple climate modelling, isolating a country’s warming impact using a marginal or “leave-one-out” (LOO) method [2,4,7,9,23]. SCMs capture the effect of short CH₄ lifetimes and convexity in a consistent way. Recently, Li et al. [7] applied an SCM and LOO with a range of equity principles to show that highly developed countries had already exceeded their “fair share” of the 1.5 °C warming budget before 1990. While intuitively reasonable, the marginal method may underestimate a country’s warming impact [31]. Thus, despite great progress, some of the long-standing methodological difficulties of warming attribution highlighted in the wake of the Brazilian proposal remain unresolved.

The first and most important step in resolving this problem is to recognise that warming allocation is not a purely physical science problem. The best that can be achieved is a method of attribution that reasonable parties would agree to, i.e., where no party is obviously disadvantaged. In other words, warming allocation should be treated as the outcome of a cooperative game. A formal solution to this problem is provided by warming Shapley values in Section 2 [34]. Warming allocations for country groupings are computed in Section 3. Implications for policymakers in countries with high shares of CH₄ in their emissions profiles are discussed further in Section 4.

2. Data and Methods

Allocating shares of warming to individual countries involves a number of methodological choices or perspectives [4]. Paris Agreement temperature ceilings are interpreted relative to the early industrial period of 1851–1900 [35], and most recent allocation studies use this baseline along with territorial accounting for emissions [6,7]. An SCM and marginal “leave-one-out” (LOO) warming allocation method is also normally used [1,2,4,5,7,9,23]. However, there is less consensus on which climate drivers should be included in the analysis (see Section 2.3)

2.1. Cooperative Games

Warming allocation requires a counterfactual approach of some kind. For instance, the warming impact of country i , $gsat_i$, could be computed by leaving out anthropogenic emissions from all countries except i . This “leave-one-in” (LOI) approximation overestimates warming due to CH_4 and N_2O . If i is a small country, atmospheric concentrations of greenhouse gases calculated in the unconstrained SCM remain close to their early-industrial values. This means that the forcing effect of the country’s methane emissions is overestimated relative to the current atmosphere.

In a cooperative game, individual players seek a reasonable allocation of total payoffs or costs, often informed by their shared knowledge of sub-coalition payoffs. The “true” warming of country i , $\delta GSAT_i$, can be identified with the warming Shapley value, often used in economics and finance to solve resource allocation problems precisely of this type [34,36]. $\delta GSAT_i$ is an appropriately weighted sum of marginal contributions over all possible country coalitions S :

$$\delta GSAT_i = \sum_{S \subseteq \mathcal{N}_i} w_S (gsat_{S \cup i} - gsat_S), \quad (1)$$

$\mathcal{N}_i$ is the set of all countries excluding i , and the sum is made over all unordered subsets S of $\mathcal{N}_i$. $gsat_S$ is the warming contribution of the emissions from coalition S computed in a climate model. The weights w_S are $\frac{N_S!(N-N_S-1)!}{N!}$, where N_S is the number of countries in coalition S , and N is the total number of countries. The weights satisfy $\sum_S w_S = 1$. Sums over coalitions include the null coalition of no countries.

Unlike the LOO “leave-one-out” or LOI methods, Equation (1) has the completeness property that $\sum_{i=1}^N \delta GSAT_i = gsat_{\mathcal{N}}$, i.e., global warming calculated in the SCM as warming from the “grand coalition” $\mathcal{N}$, is equal to the sum of the contributions from each country. Warming Shapley values therefore represent the reasonable causal attribution of the total observed warming impact $GSAT$ to each country without any missing or excess warming. Convexity of forcing–concentration relationships suggests that warming Shapley values $\delta GSAT_i$ lie in the interval (LOO_i, LOI_i) . This idea is explored further in Appendix C.

2.2. UNFCCC Groupings

Computationally exact evaluations of Equation (1) require $\sim 2^N$ model evaluations. Calculation based on all individual countries ($N \approx 200$) is not practical. In reality, climate negotiations involve country groupings. There are about 20 UNFCCC negotiating groups, and, in practice, it is sufficient to consider games with no more than 10–20 players. This reduces the sum in Equation (1) to a few million sub-coalitions.

UNFCCC groupings differ greatly in their historical responsibility for climate change. For example, the Umbrella Group, including the USA and other historically large industrial emitters, accounts more about one-third of current warming. At the other end of the scale, Small Island Developing States (SIDS) is an influential group of 36 small countries whose combined impact on warming is of order 1 m°C. A complication is that some countries are members of more than one UNFCCC grouping. Here, countries are assigned to the smallest group of which they are a member. For example, Brazil is a member of the four-member BASIC and ABU (Argentina–Brazil–Uruguay). As the latter is smaller, Brazil is assigned to ABU rather than BASIC, which then consists of China, India, and South Africa only. A total of 37 countries not obviously aligned with any UNFCCC grouping are assigned to Non-Group Members. Emissions in this grouping are dominated by Turkey and Taiwan. International aviation and shipping is assigned its own group. In some instances, smaller groups are coalesced into Non-Group Members to reduce computational burden. The specific groupings used in this study are provided in a Zenodo data repository [37].

2.3. Emissions Dataset

This study used country-level emissions data from the Community Emissions Data System (CEDS) [38]. This dataset covers the major greenhouse gases (fossil and industrial (FFI) CO₂ sources, CH₄ and N₂O) and air pollutants such as SO₂, NH₃, NO_x, black carbon, etc. Pre-1970 CH₄ and N₂O emissions absent from CEDS were imputed using a global estimate scaled by the country's share in 1970 [39]. Uncertainty in pre-1970 CH₄ emissions are not expected to affect current warming allocations significantly because of the short atmospheric lifetime of CH₄. This was confirmed by a sensitivity analysis (Appendix C). CEDS does not cover F-gas emissions that account for about 1% of global warming. This omission has no material effect on the conclusions of this study because radiative forcing is linear in the atmospheric concentration of these gases [20]. Land-use change (LUC) emissions are sometimes excluded in attribution studies due to “scientific and normative” issues [7]. Only FFI CO₂ is included in the results in Section 3, but land-use change (LUC) emissions are included in Appendix B using the dataset from Jones et al. [6]. It should be noted that emissions uncertainties at country level may be considerable, particularly for non-CO₂ gases [2,40]. This study is based on central CEDS estimates.

2.4. SCM and Model Ensemble

The process-based SCM Hector v3.2 [27] is a suitable choice for this study because of its speed (C++ implementation), flexibility, and elegant R interface. A total of 256 Hector model configurations (ensemble) were generated consistent with observed 2003–2022 warming of 1.03 ± 0.08 °C [35]. This was performed by screening a large parameter space of normally and log-normally (*ECS*, *Q*₁₀) distributed model parameters consistent with this temperature distribution [41]. Medians and mean absolute deviations (MADs) of the resulting model ensemble are shown in Table 1. The screening process induces correlations between Hector parameters, e.g., a significant positive correlation between equilibrium climate sensitivity *ECS* and aerosol forcing parameter *AEROSCALE*. The 256 model configurations generated by this procedure are provided in the Zenodo data repository for this paper [37].

Table 1. Median and inter-quartile range of the Hector SCM configurations used in this study [37]. The model parameters aerosol scaling (*AEROSCALE*), carbon fertilisation (β), ocean diffusivity (κ), equilibrium climate sensitivity (*ECS*), pre-industrial net primary production *NPP*₀, and respiration parameter *Q*₁₀.

Parameter	Name	Default	Median	MAD	Unit
AEROSCALE	Aerosol forcing scale factor	1.0	0.95	0.18	unitless
β	Carbon fertilisation	0.53	0.52	0.1	unitless
κ	Ocean diffusivity	2.38	2.37	0.12	cm ² s ^{−1}
ECS	Equilibrium climate sensitivity	3.0	2.98	0.49	°C
<i>NPP</i> ₀	Pre-industrial net primary productivity	56.2	56.1	13	P g C yr ^{−1}
<i>Q</i> ₁₀	Soil respiration	1.76	1.47	0.78	unitless

Computationally exact solutions of the warming allocation problem using the approach outlined in Sections 2.1–2.4 are readily feasible. For example, computing 1851–2022 warming Shapley values for 15 UNFCCC groups in 256 Hector model configurations required 154 h on a 64-core GPU. An R package implementation (<https://github.com/Phalacrocorax-gaimardi/allocateR>, accessed on 13 June 2025) can be downloaded from GitHub [42].

3. Results

The 1851–2022 warming allocations were computed for fourteen UNFCCC negotiating groups plus international aviation and shipping. Uncertainty in warming Shapley values was found by separate evaluation of Equation (1) for each of the 256 Hector model configurations. It was verified that global warming values, $gsat_N$, equal the sum of warming Shapley values for each configuration. The results are shown in Table 2.

The North American-dominated Umbrella Group has the largest allocation (280 m°C), followed by EU27 (120 m°C) and BASIC (110 m°C). Uncertainty in $\delta GSAT$ is highest for groupings with significant SO₂ emissions such as BASIC and OTHER, reflecting aerosol forcing uncertainty in Table 1. International aviation and shipping is likely to have a small net cooling allocation (-10 ± 10 m°C), a consequence of large historical SO₂ emissions from maritime fuels coupled with thermal inertia of the climate system. The effect of LUC-CO₂ estimates in these results are included in Table A1, Appendix A. In that case BASIC overtakes EU27 as the second largest contributor to global warming (UG 340 m°C, BASIC 140 m°C, EU27 120 m°C).

Table 2. Warming allocated to country groupings excluding LULUCF emissions. Mean temperature contributions are given in m°C with standard deviation errors. Medians of % LOO deviations relative to $\delta GSAT$ are shown with MAD errors.

Grouping	UNFCCC Grouping	$\delta GSAT$ m°C	LOO	% Deviation
UG	Umbrella Group	280 (23)	271 (23)	−3.3 (0.6)
EU27	European Union	119 (10)	116 (10)	−2.7 (1.1)
BASIC	BASIC	111 (30)	110 (29)	0 (3)
EIT	Economies in Transition	77 (9)	74 (9)	−3.7 (1.2)
ABU	Argentina–Brazil–Uruguay	39 (4)	34 (4)	−11.1 (0.4)
AS	Arab States	38 (7)	35 (6)	−8 (1)
OTHER ^a	Non-Group Members	27 (10)	27 (9)	1 (7)
LMG	Like-Minded Group	27 (10)	26 (9)	−4 (4)
ALBA	Bolivarian Alliance	18.1 (2.5)	15.6 (2.2)	−14 (1.3)
EIG	Environmental Integrity Group	16 (3)	15.3 (2.6)	−3.6 (2.2)
RN	Rainforest Nations	14.1 (2.5)	14 (2.1)	0 (4)
G77	G77 Group of Countries	3.1 (0.6)	3.2 (0.6)	2 (4)
CACAM	Central Asia, Caucasus, Albania and Moldova	2 (3)	2 (3)	−1 (25)
AILAC	Alliance of Latin America and the Caribbean	1 (3)	1.7 (2.7)	−7 (23)
SHIPPING	International Shipping and Aviation	−10 (10)	−7 (9)	−22 (6)
TOTAL	-	762 ± 106	739 ± 95	−3.2 ± 1.5

^a This combines Non-Group Members with some smaller groups such as SIDS.

Table 2 also shows LOO allocation values. $\delta GSAT \lesssim LOO$ in most cases as anticipated. $LOO > \delta GSAT$ can also arise as a consequence of a strong aerosol masking effect. The sum of LOO values deviates from $GSAT$ by $-3.2 \pm 1.4\%$ (median value ± MAD uncertainty). This number is sensitive to aerosol masking and increases to $-3.9 \pm 1.1\%$ when model configurations are restricted to below-median values of *AEROSCALE* as discussed in Table A1, Appendix A.

LOO underestimates the warming contributions of large historical emitters such as the Umbrella Group ($-3.3 \pm 0.6\%$) and the EU27 ($-2.7 \pm 1.1\%$). BASIC shows a smaller deviation (-0.5 ± 3.3) but with high uncertainty due to aerosol masking. Restricting to below-median values of aerosol forcing, LOO deviations increase slightly for Umbrella Group ($-3.4 \pm 0.5\%$) and EU27 ($-3.1 \pm 0.7\%$) and by a greater amount for BASIC ($-2.2 \pm 1.9\%$). CH₄ accounts for $\approx 18\%$ of UG warming, suggesting that LOO underestimates CH₄-induced warming by $\approx 19\%$. The accuracy of LOO for major historical industrial

emitters is largely explained by their low shares of CH₄ emissions relative to CO₂. However, groups such as ABU or ALBA show larger discrepancies.

Methane

Warming allocations to individual countries with significant historical CH₄ emissions are of particular interest. These can be found by separating the countries from their respective UNFCCC groups. Here, warming Shapley values were evaluated with a grand coalition consisting of 13 UNFCCC groups, IAS, New Zealand, Uruguay, and Ireland. These countries were selected because they have high shares of CH₄-induced warming since 1850, estimated to be 78% (URY), 71% (NZL), and 38% (IRL) when LUC emissions are excluded. Table 3 shows their warming allocations, along with three country groups from Table 2 with high shares of CH₄-induced warming, 77% (ALBA), 53% (AS), 69% (ABU).

Table 3. Warming allocations to high-methane-emitting groups and countries excluding LULUCF emissions. Mean temperature contributions are given in m°C with standard deviation errors. Medians of % LOO deviations relative to $\delta GSAT$ are shown with MAD errors.

Code	Entity	m°C		% Deviation
		$\delta GSAT$	LOO	
ABU	Argentina–Brazil–Uruguay	39 (4)	34 (4)	−11.2 (0.4)
AS	Arab States	38 (7)	35 (6)	−8 (1)
ALBA	Bolivarian Alliance	18.1 (2.5)	15.6 (2.2)	−14 (1.3)
NZL	New Zealand	2.30 (0.28)	1.98 (0.25)	−13.8 (1.1)
IRL	Ireland	1.81 (0.16)	1.65 (0.15)	−8.6 (0.4)
URY	Uruguay	1.34 (0.16)	1.15 (0.14)	−14 (0.9)

Table 3 shows discrepancies between LOO and warming Shapley values in the range of −8% to −14%. In these cases, the deviations are insensitive to aerosol masking, as can be seen from Table A2, Appendix A. The LOO deviations are consistent with an underestimate of CH₄-induced warming by 23% (Ireland), 20% (New Zealand), and 18% (Uruguay). The precise value likely depends on historical pattern of the country's CH₄ emissions.

With the exceptions of Ireland and the Arab States, countries in Table 3 have large LUC-CO₂ emissions post-1850 due to deforestation. Including these emissions has a large effect on the warming allocations, as seen in Table A4, Appendix B. The Brazil group warming allocation increases from 39 m°C to 92 m°C. New Zealand's allocation increases from 2.3 m°C to 3.7 m°C. LOO is now more accurate because CH₄-induced warming is proportionately smaller, and none of the deviations exceed −10% in Table A4.

4. Discussion

The results in Section 3 illustrate the 1851–2022 warming allocation problem using Hector v3.2 [27] and an extended CEDS dataset [38]. LOO is the reduction in global warming when a country's emissions are omitted. This marginal approach is by far the most commonly used allocation method [1,2,4,7–9,23]. However, Tables 2, 3, A5 and A6 illustrate the fact that LOO values sum to less than the global warming calculated when emissions from all countries are combined (grand coalition). This is undesirable because it means that 23 m°C (3.2%) of the warming in Table 2 is unallocated, for example. Li et al. [7] assumed a simple re-scaling of their LOO results to correct for this; i.e., if 3% of total warming is missing, then all LOO country allocations increase by 3%. However, the missing warming is equivalent to ≈ 50 Gt CO₂, far larger than the cumulative emissions of most countries. It is therefore important to determine the origin of the missing warming and where it should be allocated.

Methane's radiative efficiency was 55% higher in 1850 compared to today when its atmospheric concentration was $\approx 42\%$ of its current value [19]. This means that a country's marginal or LOO warming impact is reduced because of the collective CH₄ emissions of all other countries. A "leave-one-in" (LOI) allocation method removes this effect by neglecting the contribution of all other countries to increased concentration. In some respects, LOI is an equally plausible allocation method to LOO. However, the sum of LOI allocations is greater than calculated global warming. Therefore, neither LOO nor LOI can be regarded as a satisfactory solution to the warming allocation problem. This is discussed further in Appendix C.

Section 2.1 provides a formal solution to the causal attribution problem in terms of warming Shapley values. The sum of attributions now equals the global value with no unallocated warming. LOO and Shapley values for UNFCCC groupings are compared in Tables 2, 3, A5 and A6. Deviations are not uniform but are larger in countries with a higher share of CH₄ emissions. The numerical results suggest that LOO is accurate for CO₂-induced warming but underestimates CH₄-induced warming by $\approx 20\%$. For example, about 18% of the Umbrella Group's (UG's) warming is caused by CH₄. This LOO underestimates UG warming by -3.6% , in good agreement with Table 2. The success of LOO is largely explained by the fact that CO₂ is the dominant source of warming, particularly when LUC-CO₂ is included, and that the linear TCRE relationship is accurate over the historical period. Larger deviations with respect to LOO are expected when CH₄ emissions dominate but these are limited to not more than $\approx +20\%$.

Biogenic methane emissions present climate policy-makers with a diverse set of challenges. Technical mitigation options are often limited, while alternative metrics appear to give contradictory policy signals [21]. National climate policy frameworks, such as those based on carbon budgets, implicitly aim to define "acceptable" national shares of global warming. This study demonstrates that warming Shapley values are a practical tool in such national warming assessments. The results of Section 3 place countries such as Ireland or New Zealand somewhat further into carbon debt, while Brazil and Uruguay are closer to exhausting their warming budget than previously thought [7]. This *strengthens* the case for reductions in CH₄ emissions as an effective tool to lower a country's warming impact.

Several aspects of the warming allocation problem raised in this paper merit further attention from researchers. Firstly, implications for future national methane mitigation policies have not been considered in detail in this study, whose focus was current warming allocation. Shares of CH₄ and N₂O in national emissions footprints/profiles will increase in future as net-zero CO₂ is approached. This suggests that non-linearities could play a more prominent role in future. Secondly, the complex effects of short-lived air pollutants (primarily SO₂) in the warming allocation shown in Tables 2 and A1 warrant further study. Thirdly, CBDR requires additional normative judgements [15] that go beyond causal attribution question considered here. Only in a consequentialist or strict liability approach are these two concepts equivalent [13]. It is noteworthy that countries in the Global South often have significant shares of CH₄ and other non-CO₂ climate forcing in their emissions profiles. Fourthly, the attribution of sea-level rise and other climate variables could be investigated following the same approach. Finally, the possibility of introducing warming Shapley values directly in UNFCCC processes could be explored.

In conclusion, despite the apparent failure of the 1997 Brazilian proposal [29], the attribution of warming impacts to individual countries or country groupings is likely to remain an important driver of future climate policy. Warming Shapley values resolve the CH₄-induced warming allocation problem without leaving any unallocated or excess warming, which is desirable for climate policy framing at the national level.

Funding: This research was supported by the Department of Climate, Energy and the Environment, Government of Ireland.

Data Availability Statement: The original data presented in this study are available at <https://zenodo.org/records/15791808> (accessed on 13 August 2025).

Acknowledgments: The author acknowledges the High Performance Computing Service at University College Dublin for facilitating the research reported in this paper. The author also acknowledges helpful input from members of Ireland’s Carbon Budgets Working Group and Barry McMullin. The author would also like thank the Energy Institute, University College Dublin.

Conflicts of Interest: The author declares no conflicts of interest. The funders had no role in the design of this study; in the collection, analyses, or interpretation of data; or in the writing of this manuscript.

Abbreviations

The following abbreviations are used in this manuscript:

CBDR	Common But Differentiated Responsibilities
CEDS	Community Emissions Data System
GHG	Greenhouse Gas
GSAT	Global Surface Air Temperature
IPCC	Intergovernmental Panel on Climate Change
LOI	Leave-One-In Approximation
LOO	Leave-One-Out Approximation
SCM	Simple Climate Model
SLCF	Short-Lived Climate Forcer
TCRE	Transient Climate Response to Cumulative Emissions of Carbon Dioxide

Appendix A. Aerosols

Aerosols, primarily arising from SO₂ emissions, have a large but uncertain global cooling impact $\approx -0.5\text{ }^{\circ}\text{C}$ to $-0.8\text{ }^{\circ}\text{C}$ [43]. Aerosols have complex effects on warming allocation because both CO₂- and CH₄-induced warming can be “masked”. To help disentangle aerosol masking effects from CH₄-induced warming, Hector model configurations were selected with below-median values of the *AEROSCALE* parameter (i.e., ≈ 128 configurations). Table A1 shows warming allocations for UNFCCC groups with this restriction. GSAT is higher because of lower aerosol forcing, but this is partly offset by lower values of *ECS* in these model configurations. Reduced aerosol forcing has a significant impact on some UNFCCC groups and on International Shipping and Aviation. Other groups, notably the Umbrella Group and EU27, show weaker sensitivity.

Table A1. Warming allocations to negotiating groups restricted to model configurations with *AEROSCALE* < 1. Mean warming is shown $\pm$ standard deviation errors. Median LOO deviations relative to δ GSAT are shown $\pm$ MAD errors.

Grouping	UNFCCC Grouping	m°C		
		δ GSAT	LOO	% Deviation
UG	Umbrella Group	279 (24)	270 (23)	−3.4 (0.5)
BASIC	BASIC	132 (20)	129 (18)	−2.2 (1.9)
EU27	European Union	120 (10)	116 (10)	−3.1 (0.7)
EIT	Economies in Transition	80 (8)	77 (8)	−4.2 (0.9)
AS	Arab States	41 (5)	38 (5)	−8.1 (0.9)
ABU	Argentina–Brazil–Uruguay	39 (4)	35 (4)	−11 (0.4)
OTHER	Non-Group Members	34 (6)	33 (5)	−2 (3)
LMG	Like-Minded Group	34 (7)	32 (6)	−5.4 (2.2)
ALBA	Bolivarian Alliance	18.3 (2.5)	15.9 (2.3)	−13.4 (0.6)

Table A1. Cont.

Grouping	UNFCCC Grouping	δ_{GSAT}	$m^{\circ}C$ LOO	% Deviation
EIG	Environmental Integrity Group	17.7 (2.1)	16.9 (1.8)	−4.7 (1.5)
RN	Rainforest Nations	15.6 (1.7)	15.2 (1.5)	−2.4 (2.4)
CACAM	Central Asia, Caucasus, Albania, and Moldova	4.1 (2.1)	4.2 (1.8)	1 (8)
AILAC	Alliance of Latin America and the Caribbean	3.6 (1.9)	3.5 (1.6)	−3 (6)
G77	G77 Group of Countries	3.5 (0.5)	3.5 (0.4)	−0.3 (2.5)
SHIPPING	International Shipping and Aviation	−3 (7)	−2 (6)	−24 (30)
GSAT	Global Warming	820 ± 82	788 ± 77	−3.9 ± 1.1

Warming allocations for high methane emitters were considered in Section 3. Tables A2 and 3 show very similar warming allocations even though Table A2 is restricted to lower values of aerosol forcing. This confirms that the conclusions Section 3 are insensitive to aerosol masking effects.

Table A2. Warming allocations for high methane emitters restricted to model configurations with $AEROSCALE < 1$. Mean warming is shown $\pm$ standard deviation errors. Median LOO deviations relative to δ_{GSAT} are shown $\pm$ MAD errors.

Code	Entity	δ_{GSAT}	$m^{\circ}C$ LOO	% Deviation
AS	Arab States	41 (5)	38 (5)	−8.2 (0.9)
ABU	Argentina–Brazil–Uruguay	39 (4)	35 (4)	−11.1 (0.4)
ALBA	Bolivarian Alliance	18.3 (2.5)	15.9 (2.3)	−13.4 (0.6)
NZL	New Zealand	2.32 (0.28)	2.01 (0.25)	−13.4 (0.6)
IRL	Ireland	1.8 (0.16)	1.65 (0.15)	−8.6 (0.3)
URY	Uruguay	1.35 (0.16)	1.17 (0.14)	−13.7 (0.5)

Appendix B. Land-Use Change Emissions

LUC-CO₂ emissions are omitted from the results in Section 3. The effect of including them can be estimated using the gross LUC emission data of Jones et al. [6] and a central estimate of TCRE (0.45 °C/TtCO₂). Revised UNFCCC group warming allocations are shown in Table A3. Global warming increases to 1.06 °C when the estimated LUC-CO₂ emissions are included.

Table A3. Revised version of Table 2 including central LUC warming estimate for each group.

Code	UNFCCC Group	δ_{GSAT}	$m^{\circ}C$ LOO	% Deviation
UG	Umbrella Group	336 (23)	327 (23)	−2.8 (0.5)
BASIC	BASIC	141 (30)	140 (29)	−0.4 (2.6)
EU27	European Union	121 (10)	118 (10)	−3 (1)
EIT	Economies in Transition	111 (9)	108 (9)	−2.6 (0.8)
ABU	Argentina–Brazil–Uruguay	92 (4)	88 (4)	−4.64 (0.24)
LMG	Like-Minded Group	72 (10)	71 (9)	−1.2 (1.6)
RN	Rainforest Nations	41.8 (2.5)	41.7 (2.1)	−0.2 (1.2)
AS	Arab States	41 (7)	38 (6)	−7.5 (0.9)
OTHER	Non-Group Members	29 (10)	29 (9)	1 (6)
ALBA	Bolivarian Alliance	26.2 (2.5)	23.6 (2.2)	−9.5 (0.8)
EIG	Environmental Integrity Group	19 (3)	18.9 (2.6)	−2.9 (1.9)

Table A3. Cont.

Code	UNFCCC Group	$\delta GSAT$	$m^{\circ}C$ LOO	% Deviation
AILAC	Alliance of Latin America and the Caribbean	19 (3)	19.1 (2.7)	0.7 (2.8)
CACAM	Central Asia, Caucasus, Albania, and Moldova	6 (3)	7 (3)	4 (8)
G77	G77 Group of Countries	3.3 (0.6)	3.3 (0.6)	2 (4)
SHIPPING	International Shipping and Aviation	−10 (10)	−7 (9)	−22 (6)
GSAT	Global Warming	1050 ± 100	1030 ± 90	−2.52 ± 0.96

Table A4 shows warming allocations for agricultural CH₄ emitters including the estimated LUC-CO₂. ABU, Uruguay, and New Zealand have large LUC emissions since 1850, associated with agricultural expansion. This reduces the share of CH₄-induced warming relative to Table 3. For Ireland, most LUC emissions arose pre-1850 and are therefore excluded from Ireland’s warming impact.

Table A4. Revised version of Table 3 for major methane emitters but now including estimated LUC-CO₂ warming.

Code	Enitity	$\delta GSAT$	$m^{\circ}C$ LOO	% Deviation
ABU	Argentina–Brazil–Uruguay	92 (4)	88 (4)	−4.64 (0.24)
AS	Arab States	41 (7)	38 (6)	−7.5 (0.9)
ALBA	Bolivarian Alliance	26.2 (2.5)	23.6 (2.2)	−9.5 (0.8)
NZL	New Zealand	3.68 (0.28)	3.36 (0.25)	−8.6 (0.6)
IRL	Ireland	1.93 (0.16)	1.77 (0.15)	−8.1 (0.3)
URY	Uruguay	1.93 (0.16)	1.74 (0.14)	−9.6 (0.5)

Appendix C. Split-the-Difference Approximation

The simplest application of Equation (1) is to a hypothetical two-group world (A and B):

$$\delta GSAT_A = \frac{1}{2}(gsat_{A+B} - gsat_B) + \frac{1}{2}gsat_A \quad (A1a)$$

$$\delta GSAT_B = \frac{1}{2}(gsat_{A+B} - gsat_A) + \frac{1}{2}gsat_B \quad (A1b)$$

Equations (A1a) and (A1b) have the desired property that $\delta GSAT_A + \delta GSAT_B = gsat_{A+B}$, i.e., the sum of warming Shapley values equals the calculated total global warming $gsat_{A+B}$. Therefore, all warming is allocated as expected. The warming Shapley values $\delta GSAT_A$ and $\delta GSAT_B$ in Equations (A1a) and (A1b) are the averages of the respective LOO and LOI allocations.

Equations (A1a) and (A1b) express the likely outcome of climate negotiations in a two-player cooperative game. For example, suppose that A is the Global North and B is the Global South. As the Global North has larger absolute emissions, A is advantaged by using its LOI allocation rather than LOO because this lowers their share of total warming. Conversely, the Global South is advantaged by using LOO instead of LOI. To reach agreement on the warming allocation, parties agree to “split the difference”, leading to Equations (A1a) and (A1b).

This simple analysis suggests a “split-the-difference” approximation that allocates warming to countries as the average of LOO and LOI. Table A5 shows the resulting warming allocations for 21 countries plus International Aviation and Shipping compared to the

warming Shapley values. These values were calculated using default Hector v3.2 parameters in Table 1 (i.e., no model uncertainty estimate). $\frac{1}{2}(LOO + LOI)$ is more accurate than the LOO for high methane emitters and is quick to calculate. Table A6 shows equivalent results for UNFCCC negotiating groups instead of countries.

A useful application of this approximation is to check the sensitivity of warming allocations to pre-1970 CH₄ and N₂O emissions assumptions (Section 2.3). For example, for New Zealand, a $\pm 25\%$ adjustment in the pre-1970 emissions lead to a -0.5% to $+0.9\%$ change in 2022 warming. In the case of N₂O, the results are -0.3% to $+0.3\%$. The effect of N₂O uncertainty is proportionately large in comparison to the smaller warming impact of this gas because of its longer atmospheric lifetime (≈ 120 years) in comparison to CH₄.

Table A5. Warming Shapley values for UNFCCC negotiating groups compared to split-the-difference using default Hector parameters (i.e., no uncertainty estimate).

ISO3	$\delta GSAT$	m°C			% Deviation	
		LOI	LOO	$\frac{1}{2}(LOO + LOI)$	$\frac{1}{2}(LOO + LOI)$	
usa	191.1	199.3	184.3	191.8		−0.3
rem ^a	134.0	140.8	129.1	135.0		−0.7
eu27	116.9	120.7	113.9	117.3		−0.3
chn	97.2	96.6	97.6	97.1		0.1
rus	55.7	59.0	53.5	56.2		−0.9
gbr	35.0	36.5	34.0	35.3		−0.7
jpn	28.7	29.8	27.8	28.8		−0.3
bra	25.4	29.5	22.5	26.0		−2.5
ukr	16.5	16.9	16.3	16.6		−0.2
can	11.1	11.7	10.7	11.2		−1.2
kor	8.9	9.4	8.5	9.0		−0.3
idn	8.5	8.9	8.4	8.7		−2.0
ind	8.1	6.9	9.7	8.3		−2.4
aus	7.3	8.0	6.9	7.4		−1.4
irn	5.4	5.9	5.1	5.5		−2.1
twm	5.0	5.2	4.8	5.0		−0.2
mex	4.1	4.1	4.1	4.1		−0.1
kaz	−0.1	−0.5	0.3	−0.1		−34.1
zaf	−2.9	−4.4	−1.8	−3.1		−5.3
sau	−3.7	−4.7	−3.0	−3.8		−2.2
tur	−6.3	−7.4	−5.4	−6.4		−1.6
ias	−12.1	−15.8	−9.3	−12.6		−4.1
TOTAL	734.0	717.6	756.9	737.2		−0.4

^a A group containing emissions of all countries not listed.

Table A6. Warming Shapley values for UNFCCC negotiating groups compared to split-the-difference using default Hector parameters (i.e., no model uncertainty estimate).

Group	m°C		% Deviation	
	$\delta GSAT$	$\frac{1}{2}(LOO + LOI)$	$\frac{1}{2}(LOO + LOI)$	
Umbrella Group	277.3	278.2		−0.3
European Union	116.8	117.3		−0.5
BASIC	102.4	102.7		−0.3
Economies in Transition	75.0	75.5		−0.7
Argentina–Brazil–Uruguay	38.3	39.3		−2.5
Arab States	36.4	37.3		−2.5
Like-Minded Group	24.1	24.7		−2.4
Bolivarian Alliance for the Peoples of our America	18.1	18.8		−4.0
Environmental Integrity Group	15.1	15.1		−0.4
Least Developed Countries	14.0	14.3		−2.3

Table A6. Cont.

Group	m°C		% Deviation $\frac{1}{2}(LOO + LOI)$
	δ_{GSAT}	$\frac{1}{2}(LOO + LOI)$	
Rainforest Nations	13.5	13.7	−1.3
Africa Group Nations	12.7	13.0	−2.5
G77 Group of Countries	3.0	3.0	−0.3
Climate Vulnerable Forum	2.0	2.1	−4.1
Small Island Developing States	1.5	1.5	−1.8
Group of Mountain Partnership	1.0	1.0	1.0
Central Asia, Caucasus, Albania and Moldova	1.0	1.0	−4.7
Independent Alliance of Latin America and the Caribbean	0.7	0.8	−14.8
Non-Group Members	−6.6	−6.7	−2.3
International Shipping and Aviation	−12.2	−12.6	−3.4
TOTAL	734.0	740.0	−0.4

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