Article

Not peer-reviewed version

Methane and the Warming Blame Game

Joseph Wheatley *

Posted Date: 19 June 2025

doi: 10.20944/preprints202506.1541.v1

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

Article

Methane and the Warming Blame Game

Joseph Wheatley [1,2]

[1] School of Economics, University College Dublin, Ireland; joe.wheatley@ucd.ie
[2] Energy Institute, University College Dublin, Dublin, Ireland

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 methane-emitting countries is not straightforward due to methane's short atmospheric lifetime and the non-linear (convex) relationship between radiative forcing and 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 has long been recognised as an important input to climate policy [1]. Many studies have allocated countries contributions to climate change, focussing on historical warming, likely future warming, climate damages, or climate extremes [2–11]. Foremost among the motivations for this effort is the foundational UNFCCC principle of "common but differentiated responsibilites" for climate change [12]. 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 [6,13–15]. The present study concerns *causal attribution* for warming only. Evaluating *responsibility* requires additional normative judgement [6,8,16].

In 1997, Brazil proposed that national mitigation targets should be linked directly to historical warming responsibility [1]. Apart from political opposition, the Brazilian proposal faced methodological challenges [2,17,18]. As noted by den Elzen et al [2] *"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, carbon dioxide (CO_2), methane (CH_4) and Nitrous Oxide (N_2O) [19,20]. This difficulty was greatly reduced with the identification of Transient Climate Response to Cumulative Emissions (TCRE) as a key warming metric for CO_2 [21,22]. This meant that CO_2-induced warming could be allocated simply based on a country's cumulative CO_2 emissions [4]. However, this simplifciation is not available for CH_4 and N_2O or short-lived climate forcers (SLCFs). Matthews et al [4] allocated CH_4-induced global warming according to the country's share of cumulative CH_4 emissions. More recently, this ad hoc treatment of CH_4 was replaced by a warming metric-based approach using GWP* [23,24] to account for atmospheric lifetimes [7]. Linearised metrics such as GWP* have limitations when applied over long time periods, however [25].

Most allocation studies use simple climate modelling, isolating a country's warming impact using a marginal or "leave-one-out" (LOO) method [3,5,8,10,26]. Simple Climate Models (SCMs) capture the effect of short CH_4 lifetimes and convexity in a consistent way. Recently, Li et al [8], applied an SCM and LOO with a range of equity principles to show that highly developed countries had already

 doi:10.20944/preprints202506.1541.v1

exceeded their "fair share" of a 1.5 °C warming budgets before 1990. While intuitively reasonable, the marginal method may underestimate a country's warming impact [18]. 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 co-operative game. A formal solution to this problem is provided by warming Shapley values in Section 2 [27]. Warming allocations for country groupings are computed in Section 3. Implications for policymakers in countries with high shares of CH_4 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 perspectives [5]. Paris agreement temperature ceilings are expressed relative the early industrial period 1851-1900 [28] and more recent allocation studies use this baseline along with territorial emissions accounting [7,8]. An SCM and marginal "leave one out" (LOO) warming allocation method is also normally used [2,3,5,6,8,10,26]. There is less consensus which climate drivers should be included in the analysis (Section 2.3)

2.1. Cooperative Games

Warming allocation requires a counterfactual approach of some kind. The warming impact of country i, $gsat_i$, could be computed in an SCM by leaving out anthropogenic emissions from all other countries except i. This "leave-one-in" (LOI) approximation overestimates warming due to CH_4 and N_2O. For example, if i is a small country, atmospheric concentrations of greenhouse gases calculated in the unconstrained SCM remain close to their early-industrial values. Convexity in forcing-concentration relationships means the forcing effect of the country's emissions are overstated leading to an overestimate of warming.

The "true" warming of country i, $\delta GSAT_i$ can be identified with the warming Shapley value, often used in economics to solve resource allocation problems of precisely this type [27]. $\delta GSAT_i$ is an appropriately weighted sum of marginal contributions over all possible country coalitions S:

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

$\mathcal{N}_i$ is the set of all a countries excluding i and the sum is over all unordered subsets of $\mathcal{N}_i$. Here $gsat_S$ 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 $\sum_S w_S = 1$. The sum includes 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 $(\mathrm{LOO}_i, \mathrm{LOI}_i)$. This idea is explored further in Appendix C.

2.2. UNFCCC Groupings

Computationally exact evaluations of Equation 1 require $\sim 2^N$ model evaluations which is not practical for countries ($N \approx 200$). In reality, climate negotiations tend involve country groupings not

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 June 2025 doi:10.20944/preprints202506.1541.v1

individual countries. There are about 20 UNFCCC negotiating groups, reducing the problem to a few million 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 4-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. 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 for this study are provided in the Zenodo data repository for this paper [].

2.3. Emissions Datset

This study uses country-level emissions data from the Community Emissions Data System (CEDS) [29]. This dataset covers the major greenhouse gases (Fossil and Industrial (FFI) CO_2 sources, CH_4 and N_2O) and air pollutants including SO_2. Pre-1970 CH_4 and N_2O emissions absent from CEDS were imputed using a global estimate scaled by the country's share in 1970 [30]. 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. Land-use change (LUC) emissions are sometimes excluded in attribution studies due to "scientific and normative" issues [8]. Only FFI-CO_2 is included in the results of Section 3 but land-use change (LUC) emissions are included in Appendix B using the dataset from Jones *et al* [7]. Emissions uncertainties at country-level may be considerable, particularly for non-CO_2 gases [3,31].

2.4. SCM and Model Ensemble

The process-based SCM Hector v3.2 [32] is a suitable choice for this study because of its speed (`C++` implementation), flexibility and elegant `R` interface. 256 Hector model configurations (ensemble) were generated consistent with observed 2003-2022 warming 1.03 ± 0.08 °C [28]. This was done by screening a large parameter space of normally and lognormally (ECS,Q_{10}) distributed model parameters consistent with this temperature distribution [33]. Medians and mean absolute deviations (MAD) 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 $AEROSCALE$.

Table 1. Median and inter-quartile range of Hector ensemble used in this study. The parameters areaerol scaong, carbon fertilisation (β), ocean diffusivity (κ, Equilibrium climate sensitivity (ECS), pre-industrial net primary production NPP_0, respiration parameter $Q_(10)$.

Parameter	Name	Default	Median	MAD	Unit
AEROSCALE	Aerosol forcing scale factor	1.0	0.95	0.18	unitless
β	carbon ferilisation	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
NPP_0	Pre-industrial net primary productivity	56.2	56.1	13	$P\,g\,C\,yr^{-1}$
Q_{10}	Soil respiration	1.76	1.47	0.78	unitless

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 19 June 2025 doi:10.20944/preprints202506.1541.v1

The 256-member model ensemble is provided in the Zenodo data repository for this paper [34]. An R package implementation of Sections 2.1 and 2.4 with all necessary data to run the allocation is available from the GitHub site at xxxxxxxxxxxx.

3. Results

1850-2022 warming allocations were computed for fourteen UNFCCC negotiating groups plus International Aviation and Shipping. Uncertainty in warming Shapley values is found by separate evaluation of Equation 1 for each of the 256 Hector model configurations. It was verified that $gsat_{\mathcal{N}}$ equals 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 SO_2 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 SO_2 emissions from maritime fuels coupled with thermal inertia of the climate system. The effect of LUC-CO_2 estimates n 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	$m°C$		% Deviation
		$\delta GSAT$	LOO	
UG	Umbrella Group	280 ± 23	270 ± 23	-3.3 ± 0.6
EU27	European Union	120 ± 10	120 ± 9.6	-2.7 ± 1.1
BASIC	BASIC	110 ± 33	110 ± 29	-0.5 ± 3.3
EIT	Economies in Transition	77 ± 9.1	74 ± 8.5	-3.7 ± 1.2
ABU	Argentina-Brazil-Uruguay	39 ± 4.1	34 ± 3.7	-11.0 ± 0.4
AS	Arab States	38 ± 6.5	35 ± 5.9	-8 ± 1
LMG	Like-Minded Group	27 ± 10	26 ± 9.2	-3.5 ± 3.5
OTHER[a]	Non Group Members	27 ± 10	27 ± 8.7	1.0 ± 7
ALBA	Bolivarian Alliance	18 ± 2.5	16 ± 2.2	-14 ± 1
EIG	Environmental Integrity Group	16 ± 3	15 ± 2.6	-3.6 ± 2.2
RN	Rainforest Nations	14 ± 2.5	14 ± 2.1	-0.5 ± 3.7
G77	G77 Group of Countries	3.1 ± 0.64	3.2 ± 0.57	1.8 ± 3.9
CACAM	Central Asia, Caucasus, Albania and Moldova	1.9 ± 3.5	2.2 ± 3	-1 ± 25
AILAC	Independent Alliance of LatAm and the Caribbean	1.5 ± 3.2	1.7 ± 2.7	-7 ± 23
SHIPPING	International Shipping and Aviation	-10 ± 10	-7 ± 9	-22 ± 6
TOTAL	-	762 ± 106	739 ± 95	-3.2 ± 1.4

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±1.4% (median value ± MAD uncertainty). This number is sensitive to aerosol masking and increases to -3.9±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±0.6%) and the EU27 (-2.7±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,

 doi:10.20944/preprints202506.1541.v1

LOO deviations increase slightly for Umbrella Group (-3.4±0.5%) and EU27 (-3.1±0.7%) and by a greater amount for BASIC (-2.2±1.9%). CH_4 accounts for ≈ 18% of UG warming, suggesting that LOO underestimates CH_4-induced warming by ≈ 19%. The accuracy of LOO for major historical industrial emitters is largely explained by their low shares of CH_4 emissions relative to CO_2. However, groups such as ABU or ALBA show larger discrepancies.

3.1. Methane

Warming allocations for individual countries with significant historical CH_4 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 CH_4-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 CH_4-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	Enitity	$m°C$ $\delta GSAT$	LOO	% Deviation
ABU	Argentina-Brazil-Uruguay	39 ± 4.1	34 ± 3.7	-11 ± 0.4
AS	Arab States	38 ± 6.5	35 ± 5.9	-8 ± 1
ALBA	Bolivarian Alliance	18 ± 2.5	16 ± 2.2	-14 ± 1
NZL	New Zealand	2.3 ± 0.28	2 ± 0.25	$-14 \pm 1.$
IRL	Ireland	1.8 ± 0.16	1.7 ± 0.15	-8.6 ± 0.4
URY	Uruguay	1.3 ± 0.16	1.2 ± 0.14	-14 ± 1

Table 3 shows discrepancies between LOO and warming Shapley values in the range -8% to -14%. These numbers are insensitive to aerosol masking as can be seen from Table A2, Appendix A. The LOO deviations are consistent with an underestimate of CH_4-induced warming by 23% (Ireland), 20% (New Zealand) and 18% (Uruguay). The precise value is likely to depend on relative antiquity or recency of the country's CH_4 emissions.

Many of the countries in Table 3 have large LUC-CO_2 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 CH_4-induced warming is a proportionately smaller, and none of the deviations exceed -10% in Table A4.

4. Discussion

Methane is a short-lived-climate-forcer (SLCF) with lifetime ≈ 12 years in the current atmosphere [24,35]. It is also a major greenhouse gas, with a convex (square-root) relationship between radiative forcing and atmospheric concentration [19,20]. Recent scientific and climate policy [8,23–26] work emphasises CH_4-induced warming, rather than CO_2-equivalents, to reflect the distinct climate physics of this gas. For CO_2, cumulative emissions and transient warming impact are interchangeable because they are simply related through TCRE. However, an SCM [32,36] is needed to evaluate the warming impact of CH_4 and other non-CO_2 drivers particularly over long time periods. SCMs relate radiative forcing to subsequent warming with fast components and slow components associated with multiple equilibration timescales [37].

The results of Section 3 illustrate the 1850-2022 warming allocation problem using Hector v3.2 [32] and an extended CEDS dataset [29]. LOO is calculated as the reduction in global warming when a country's emissions are omitted. It an extensively used approximate allocation method [2,3,5,8–10,26]. However, Tables 2,3, A5 and A6 illustrate the fact that LOO values sum to less than global warming calculated in the grand coalition of all countries. This is undesirable because it means that 23 m°C of the warming in Table 2 is unallocated, for example. Li et al [8] used a simple re-scaling i.e., if 3% of total warming is missing then all LOO country allocations are increased by 3%. The missing warming is equivalent to $\approx 50\,\mathrm{Gt}\,CO_2$, far larger than the cumulative emissions of most countries.

Methane's radiative efficiency was 55% higher in 1850 compared to today because atmospheric concentration of was only $\approx$ 42% of its current value [20]. The means that the warming impact of a CH_4-emitting country is lowered by the 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 of 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. The results show that deviations are not uniform but are larger in countries with a higher share of CH_4 emissions. The numerical results suggest that LOO is accurate for CO_2-induced warming but underestimates CH_4-induced warming by $\approx$ 20%. For example, about 18% or the Umbrella Group's warming is caused by CH_4. This implies LOO underestimates warming by -3.6% in good agreement with Table 2. The success of LOO is largely explained by the fact that CO_2 is the dominant source of warming, particularly when LUC-CO_2 is included, and that linear TCRE relationship is accurate over the full historical period. Larger deviations are expected when CH_4 emissions dominate but these never exceed $\approx$ 20%.

Methane present climate policy-makers with an acute set of challenges. The findings 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 [8]. Furthermore, national climate policy frameworks, such as those based on carbon budgets, often implicitly aim to define an "acceptable" national share of global warming. This study suggests that warming Shapley values are an appropriate tool for such national assessments. The implications of this approach in future mitigation scenarios, particularly extended to 2100, require investigation. A robust allocation method is likely to benefit future policy.

Two points should be emphasised. Firstly, this study considered the global warming causal attribution problem relative to the early industrial period. It has not considered responsibility which may involve further normative judgements[16]. Only in a consequentialist or strict liability approach are these two concepts equivalent [14]. Secondly, this paper has no implications for the warming impact of methane at global level.

In conclusion, despite the apparent failure of the 1997 Brazilian Proposal [1], attribution of warming impact is likely to remain an important driver of future climate policy. Warming Shapley values to resolve the CH_4-induced warming allocation problem with no unallocated or excess warming.

Funding: This research was supported by the Department of Climate, Energy and the Environment, Government of Ireland. The author would also like thank the Energy Institute, University College Dublin.

Data Availability Statement: The original data presented in the study are openly available in Zenodo at [DOI/URL] or [reference/accession number]..

 doi:10.20944/preprints202506.1541.v1

Acknowledgments: We acknowledge the Research IT HPC Service at University College Dublin for providing computational facilities and support that contributed to the research results reported in this paper. The author acknowledges helpful input from members of the Carbon Budgets Working Group and Professor Barry McMullin.

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

Abbreviations

The following abbreviations are used in this manuscript:

IPCC	Intergovernmental Panel on Climate Change
GSAT	Global Surface Air Tenperature
CEDS	Community Emissions Data System
TCRE	Transient Climate Response to Cumulative Emissions of Carbon Dioxide
SCM	Simple Climate Model
GHG	Greenhouse Gas
SLCF	Short-Lived Climate Forcer
LOO	leave one out approximation
LOI	leave one in approximation

Appendix A Aerosols

Aerosols, primarily arising from SO_2 emissions, have a large but uncertain global cooling impact $\approx -0.5\,°C$ to $-0.8\,°C$. Aerosols also have complex effects on warming allocation because both CO_2 and CH_4-induced warming can be “masked”.

To help disentangle aerosol masking effects from CH_4-induced warming, Hector model configurations were selected with lower values of the $AEROSCALE$ parameter (i.e., $\approx$ 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 lsignficant impact on some UNFCCC groups and on International Shipping and Aviation. Other groups, notably the Umbrella Group and EU27, show weaker sensitivity.

 doi:10.20944/preprints202506.1541.v1

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

Grouping	UNFCCC Grouping	$m^\circ C$ $\delta GSAT$	LOO	% Deviation
UG	Umbrella Group	280 ± 24	270 ± 23	-3.4 ± 0.5
BASIC	BASIC	130 ± 20	130 ± 18	-2.2 ± 1.9
EU27	European Union	120 ± 10	120 ± 10	-3.1 ± 0.7
EIT	Economies in Transition	80 ± 9	77 ± 8	-4.2 ± 0.9
AS	Arab States	41 ± 5	38 ± 4.7	-8.1 ± 0.9
ABU	Argentina-Brazil-Uruguay	39 ± 4	35 ± 4	-11.0 ± 0.4
LMG	Like-Minded Group	34 ± 7	32 ± 6	-5.4 ± 2.2
OTHER	Non Group Members	34 ± 6	33 ± 5	-2.1 ± 3.1
ALBA	Bolivarian Alliance	18 ± 3	16 ± 2	-13 ± 0.6
EIG	Environmental Integrity Group	18 ± 2.1	17 ± 1.8	-4.7 ± 1.5
RN	Rainforest Nations	16 ± 2	15 ± 3	-2.4 ± 2.4
CACAM	Central Asia, Caucasus, Albania and Moldova	4.1 ± 2.1	4.2 ± 1.8	1 ± 8
AILAC	Independent Alliance LatAm and the Caribbean	3.6 ± 1.9	3.5 ± 1.6	-3.2 ± 6.4
G77	G77 Group of Countries	3.5 ± 0.5	3.5 ± 0.4	-0.3 ± 2.5
SHIPPING	International Shipping and Aviation	-3.3 ± 6.7	-1.6 ± 5.9	-24 ± 33
GSAT	Global Warming	820 ± 82	788 ± 77	-3.9 ± 1.1

Warming allocations for high methane emitters were considered in Section 3. Table A2 and Table 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.

 doi:10.20944/preprints202506.1541.v1

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

Code	Enitity	$m°C$ $\delta GSAT$	LOO	% Deviation
AS	Arab States	41 ± 5	38 ± 4.7	-8.1 ± 0.9
ABU	Argentina-Brazil-Uruguay	39 ± 4	35 ± 4	-11.0 ± 0.4
ALBA	Bolivarian Alliance	18 ± 3	16 ± 2	-13 ± 0.6
NZL	New Zealand	2.3 ± 0.28	2 ± 0.25	-13 ± 0.56
IRL	Ireland	1.8 ± 0.16	1.7 ± 0.15	-8.6 ± 0.35
URY	Uruguay	1.4 ± 0.16	1.2 ± 0.14	-14 ± 0.5

Appendix B Land use change emissions

LUC-CO_2 emissions are omitted from the results of Section 3. The effect of including them can be estimated using the gross LUC emissions data of Jones et al [7] and a central estimate of TCRE (0.45 °C/TtCO_2). The results for UNFCCC grouping allocations are shown in Table A3. Global warming increases to 1.06 °C when the estimated LUC-CO_2 emissions are included.

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

Code	Enitity	$m°C$ $\delta GSAT$	LOO	% Deviation
UG	Umbrella Group	340 ± 23	330 ± 23	-2.8 ± 0.48
BASIC	BASIC	140 ± 33	140 ± 29	-0.37 ± 2.6
EU27	European Union	120 ± 10	120 ± 9.6	-2.7 ± 1
EIT	Economies in Transition	110 ± 9.1	110 ± 8.5	-2.6 ± 0.78
ABU	Argentina-Brazil-Uruguay	92 ± 4.1	88 ± 3.7	-4.6 ± 0.24
LMG	Like-Minded Group	72 ± 10	71 ± 9.2	-1.2 ± 1.6
RN	Rainforest Nations	42 ± 2.5	42 ± 2.1	-0.15 ± 1.2
AS	Arab States	41 ± 6.5	38 ± 5.9	-7.5 ± 0.89
OTHER	Non Group Members	29 ± 10	29 ± 8.7	1 ± 6.4
ALBA	Bolivarian Alliance	26 ± 2.5	24 ± 2.2	-9.5 ± 0.77
AILAC	Alliance of Latin America and Caribbean	19 ± 3.2	19 ± 2.7	0.71 ± 2.8
EIG	Environmental Integrity Group	19 ± 3	19 ± 2.6	-2.9 ± 1.9
CACAM	Central Asia, Caucasus, Albania and Moldova	6.4 ± 3.5	6.8 ± 3	3.6 ± 8.1
G77	G77 Group of Countries	3.3 ± 0.64	3.3 ± 0.57	1.8 ± 3.7
GSAT	Global Warming	1060 ± 99.5	1030 ± 89.5	-2.52 ± 0.958

Table A4 shows warming allocations for agricultural CH_4 emitters including the estimated LUC-CO_2. ABU, Uruguay, and New Zealand have large LUC emissions since 1850 associated with

 doi:10.20944/preprints202506.1541.v1

agricultural expansion. This reduces the share of CH_4-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 including central estimates of LUC-CO_2 warming.

Code	Enitity	$m°C$ $\delta GSAT$	LOO	% Deviation
ABU	Argentina-Brazil-Uruguay	92 ± 4.1	88 ± 3.7	-4.6 ± 0.24
AS	Arab States	41 ± 6.5	38 ± 5.9	-7.5 ± 0.89
ALBA	Bolivarian Alliance	26 ± 2.5	24 ± 2.2	-9.5 ± 0.77
NZL	New Zealand	3.7 ± 0.28	3.4 ± 0.25	-8.6 ± 0.56
IRL	Ireland	1.9 ± 0.16	1.8 ± 0.15	-8.1 ± 0.34
URY	Uruguay	1.9 ± 0.16	1.7 ± 0.14	-9.6 ± 0.46

Appendix C Split-the-difference approximation

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

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

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

The warming Shapley values have the desired property that $\delta GSAT_A + \delta GSAT_B = gsat_{A+B}$ i.e., their sum equals the calculated global warming from A + B. Therefore all warming is allocated as expected.

The warming Shapley values $\delta GSAT_A$ and $\delta GSAT_B$ in Equations A1 are just the averages of their respective LOO and LOI allocations. If the groups are dissimilar, for example the Global North and Global South, then Equations A1 express the likely result of negotiations. As the Global North has larger absolute emissions and is advantaged by using its LOI allocation rather than LOO because this gives a lower warming allocation. 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 A1.

A "Split the difference" approximation 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 are calculated using default Hector v3.2 parameters in Table 1. $\frac{1}{2}(LOO + LOI)$ is more accurate than the LOO for high methane emitters. It is also avoids the need to select negotiating parties and is easy to calculate unlike Equation 1. Table A6 shows equivalent results for UNFCCC negotiating groups instead of countries.

 doi:10.20944/preprints202506.1541.v1

Table A5. Warming Shapley values for UNFCCC negotiating groups compared to split the difference using default Hector parameters.

ISO3	$m°C$				% deviation
	$\delta GSAT$	LOI	LOO	$\frac{1}{2}(LOO + LOI)$	$\frac{1}{2}(LOO + LOI)$
usa	191.1	199.3	184.3	191.8	-0.3
rem[b]	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
twn	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

Table A6. Warming Shapley values for UNFCCC negotiating groups compared to split the difference using default Hector parameters.

Group	$m°C$ $\delta GSAT$	$\frac{1}{2}(LOO + LOI)$	% deviation $\frac{1}{2}(LOO + LOI)$
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
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

References

1. UNFCCC. Brazil: PROPOSED ELEMENTS OF A PROTOCOL TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, PRESENTED BY BRAZIL IN RESPONSE TO THE BERLIN MANDATE, 1997.
2. den Elzen, M.; Fuglestvedt, J.; Höhne, N.; Trudinger, C.; Lowe, J.; Matthews, B.; Romstad, B.; de Campos, C.P.; Andronova, N. Analysing countries' contribution to climate change: scientific and policy-related choices. *Environmental Science & Policy* **2005**, *8*, 614–636.
3. Höhne, N.; Blum, H.; Fuglestvedt, J.; Skeie, R.B.; Kurosawa, A.; Hu, G.; Lowe, J.; Gohar, L.; Matthews, B.; Nioac de Salles, A.C.; et al. Contributions of individual countries' emissions to climate change and their uncertainty. *Climatic change* **2011**, *106*, 359–391.
4. Matthews, H.D.; Graham, T.L.; Keverian, S.; Lamontagne, C.; Seto, D.; Smith, T.J. National contributions to observed global warming. *Environmental Research Letters* **2014**, *9*, 014010.
5. Skeie, R.B.; Fuglestvedt, J.; Berntsen, T.; Peters, G.P.; Andrew, R.; Allen, M.; Kallbekken, S. Perspective has a strong effect on the calculation of historical contributions to global warming. *Environmental Research Letters* **2017**, *12*, 024022.
6. Wei, Y.M.; Wang, L.; Liao, H.; Wang, K.; Murty, T.; Yan, J. Responsibility accounting in carbon allocation: a global perspective. *Applied Energy* **2014**, *130*, 122–133.
7. Jones, M.W.; Peters, G.P.; Gasser, T.; Andrew, R.M.; Schwingshackl, C.; Gütschow, J.; Houghton, R.A.; Friedlingstein, P.; Pongratz, J.; Le Quéré, C. National contributions to climate change due to historical emissions of carbon dioxide, methane, and nitrous oxide since 1850. *Scientific Data* **2023**, *10*, 155.
8. Li, M.; Pelz, S.; Lamboll, R.; Wang, C.; Rogelj, J. A principle-based framework to determine countries' fair warming contributions to the Paris Agreement. *Nature Communications* **2025**, *16*, 1043.
9. Skeie, R.B.; Peters, G.P.; Fuglestvedt, J.; Andrew, R. A future perspective of historical contributions to climate change. *Climatic Change* **2021**, *164*, 24.
10. Callahan, C.W.; Mankin, J.S. National attribution of historical climate damages. *Climatic Change* **2022**, *172*, 1–19.

11. Lewis, S.C.; Perkins-Kirkpatrick, S.E.; Althor, G.; King, A.D.; Kemp, L. Assessing contributions of major emitters' Paris-era decisions to future temperature extremes. *Geophysical Research Letters* **2019**, *46*, 3936–3943.
12. United Nations. United Nations Framework Convention on Climate Change. Treaty, 1992. Adopted in New York on 9 May 1992, entered into force on 21 March 1994.
13. UNFCCC. Report of the Conference of the Parties on its Nineteenth Session, held in Warsaw from 11 to 23 November 2013. In Proceedings of the United Nations Framework Convention on Climate Change, 2014.
14. Adler, M.D. Corrective justice and liability for global warming. *University of Pennsylvania Law Review* **2007**, *155*, 1859–1867.
15. Alogna, I.; Bakker, C.; Gauci, J.P. *Climate change litigation: global perspectives*; Brill, 2021.
16. Müller, B.; Höhne, N.; Ellermann, C. Differentiating (historic) responsibilities for climate change. *Climate Policy* **2009**, *9*, 593–611.
17. Rosa, L.P.; Ribeiro, S.K.; Muylaert, M.S.; de Campos, C.P. Comments on the Brazilian proposal and contributions to global temperature increase with different climate responses—CO2 emissions due to fossil fuels, CO2 emissions due to land use change. *Energy Policy* **2004**, *32*, 1499–1510.
18. Trudinger, C.; Enting, I. Comparison of formalisms for attributing responsibility for climate change: Non-linearities in the Brazilian Proposal approach. *Climatic Change* **2005**, *68*, 67–99.
19. Hansen, J.; Fung, I.; Lacis, A.; Rind, D.; Lebedeff, S.; Ruedy, R.; Russell, G.; Stone, P. Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model. *Journal of geophysical research: Atmospheres* **1988**, *93*, 9341–9364.
20. Myhre, G.; Highwood, E.J.; Shine, K.P.; Stordal, F. New estimates of radiative forcing due to well mixed greenhouse gases. *Geophysical research letters* **1998**, *25*, 2715–2718.
21. Matthews, H.D.; Gillett, N.P.; Stott, P.A.; Zickfeld, K. The proportionality of global warming to cumulative carbon emissions. *Nature* **2009**, *459*, 829–832.
22. MacDougall, A.H.; Friedlingstein, P. The origin and limits of the near proportionality between climate warming and cumulative CO 2 emissions. *Journal of Climate* **2015**, *28*, 4217–4230.
23. Allen, M.R.; Shine, K.P.; Fuglestvedt, J.S.; Millar, R.J.; Cain, M.; Frame, D.J.; Macey, A.H. A solution to the misrepresentations of CO2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *Npj Climate and Atmospheric Science* **2018**, *1*, 16.
24. Cain, M.; Lynch, J.; Allen, M.R.; Fuglestvedt, J.S.; Frame, D.J.; Macey, A.H. Improved calculation of warming-equivalent emissions for short-lived climate pollutants. *NPJ climate and atmospheric science* **2019**, *2*, 29.
25. Lynch, J.; Cain, M.; Pierrehumbert, R.; Allen, M. Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short-and long-lived climate pollutants. *Environmental Research Letters* **2020**, *15*, 044023.
26. Wheatley, J. Temperature neutrality and Irish methane policy. *Climate Policy* **2023**, *23*, 1229–1242.
27. Algaba, E.; Fragnelli, V.; Sánchez-Soriano, J. *Handbook of the Shapley value*; CRC Press, 2019.
28. Forster, P.M.; Smith, C.; Walsh, T.; Lamb, W.F.; Lamboll, R.; Hall, B.; Hauser, M.; Ribes, A.; Rosen, D.; Gillett, N.P.; et al. Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence. *Earth System Science Data* **2024**, *16*, 2625–2658.
29. McDuffie, E.E.; Smith, S.J.; O'Rourke, P.; Tibrewal, K.; Venkataraman, C.; Marais, E.A.; Zheng, B.; Crippa, M.; Brauer, M.; Martin, R.V. A global anthropogenic emission inventory of atmospheric pollutants from sector- and fuel-specific sources (1970–2017): an application of the Community Emissions Data System (CEDS). *Earth System Science Data* **2020**, *12*, 3413–3442. https://doi.org/10.5194/essd-12-3413-2020.
30. Nicholls, Z.R.; Meinshausen, M.; Lewis, J.; Gieseke, R.; Dommenget, D.; Dorheim, K.; Fan, C.S.; Fuglestvedt, J.S.; Gasser, T.; Golüke, U.; et al. Reduced Complexity Model Intercomparison Project Phase 1: introduction and evaluation of global-mean temperature response. *Geoscientific Model Development* **2020**, *13*, 5175–5190.
31. Solazzo, E.; Crippa, M.; Guizzardi, D.; Muntean, M.; Choulga, M.; Janssens-Maenhout, G. Uncertainties in the Emissions Database for Global Atmospheric Research (EDGAR) emission inventory of greenhouse gases. *Atmospheric Chemistry and Physics* **2021**, *21*, 5655–5683.
32. Dorheim, K.; Gering, S.; Gieseke, R.; Hartin, C.; Pressburger, L.; Shiklomanov, A.N.; Smith, S.J.; Tebaldi, C.; Woodard, D.L.; Bond-Lamberty, B. Hector V3. 2.0: functionality and performance of a reduced-complexity climate model. *Geoscientific Model Development* **2024**, *17*, 4855–4869.
33. Brown, J.K.; Pressburger, L.; Snyder, A.; Dorheim, K.; Smith, S.J.; Tebaldi, C.; Bond-Lamberty, B. Matilda v1. 0: An R package for probabilistic climate projections using a reduced complexity climate model. *PLOS Climate* **2024**, *3*, e0000295.

doi:10.20944/preprints202506.1541.v1

34. Author, F.; Coauthor, S. Title of the Dataset or Software, 2025. https://doi.org/10.5281/zenodo.1234567.
35. Joos, F.; Roth, R.; Fuglestvedt, J.S.; Peters, G.P.; Enting, I.G.; Von Bloh, W.; Brovkin, V.; Burke, E.J.; Eby, M.; Edwards, N.R.; et al. Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmospheric Chemistry and Physics* **2013**, *13*, 2793–2825.
36. Smith, C.J.; Forster, P.M.; Allen, M.; Leach, N.; Millar, R.J.; Passerello, G.A.; Regayre, L.A. FAIR v1. 3: a simple emissions-based impulse response and carbon cycle model. *Geoscientific Model Development* **2018**, *11*, 2273–2297.
37. Geoffroy, O.; Saint-Martin, D.; Olivié, D.J.; Voldoire, A.; Bellon, G.; Tytéca, S. Transient climate response in a two-layer energy-balance model. Part I: Analytical solution and parameter calibration using CMIP5 AOGCM experiments. *Journal of climate* **2013**, *26*, 1841–1857.