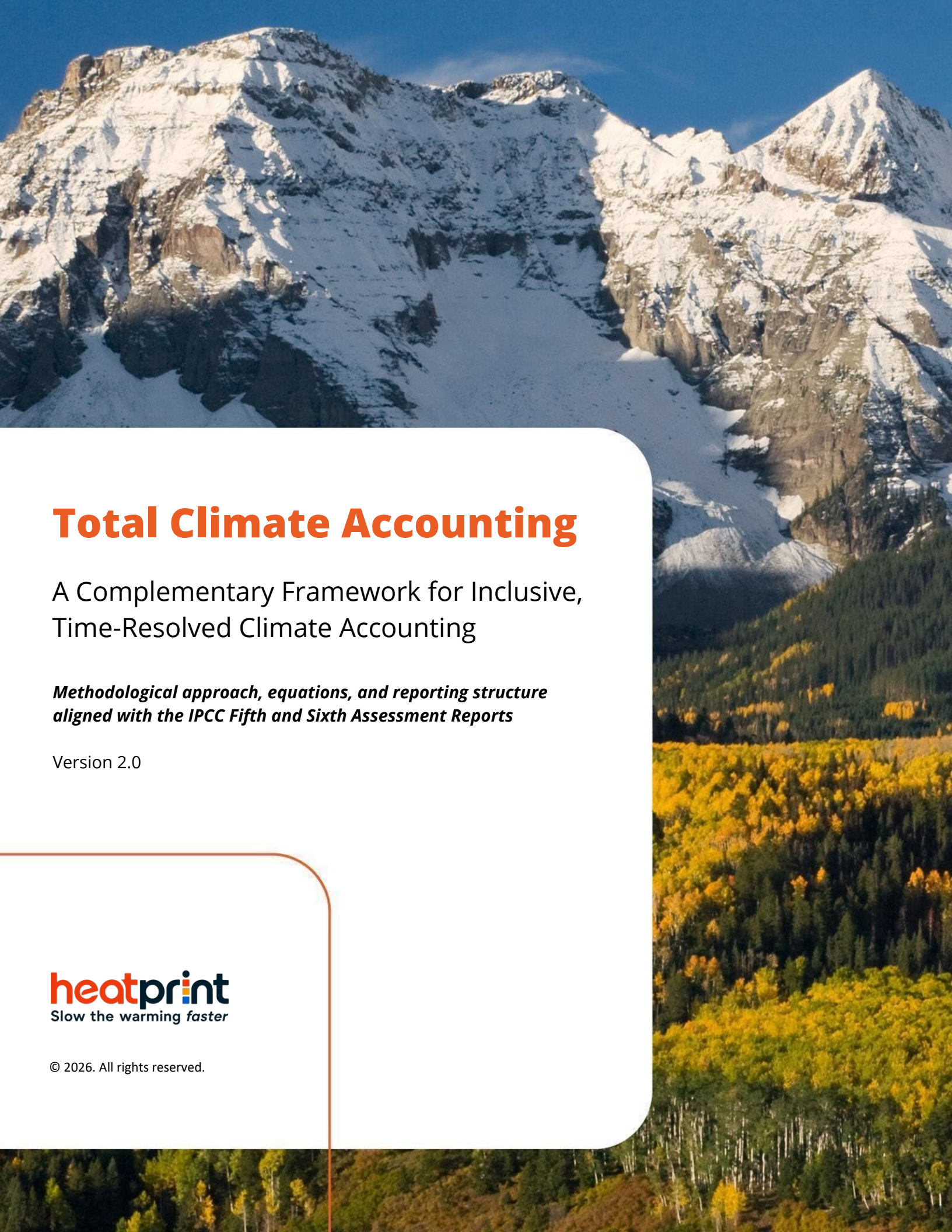


Total Climate Accounting

A Complementary Framework for Inclusive, Time-Resolved Climate Accounting

Methodological approach, equations, and reporting structure aligned with the IPCC Fifth and Sixth Assessment Reports

Version 2.0

heatprint
Slow the warming *faster*

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Total Climate Accounting

A Complementary Framework for Inclusive, Time-Resolved Climate Accounting

Version 2.0

Scientific review led by Dr. Drew Shindell (Duke University; National Academy of Sciences; Chair, CCAC Scientific Advisory Panel; IPCC AR5 Coordinating Lead Author, radiative forcing) and members of the UN-convened Climate and Clean Air Coalition

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1. Overview

1.1 Reliance on CO_2e GWP100

Climate accounting has historically been organized around annual emissions inventories of well-mixed greenhouse gases (GHGs), expressed in CO_2-equivalents (CO_2e) using the IPCC's Global Warming Potential (GWP) values, most commonly based on a 100-year time horizon (GWP100). This convention is reflected in the major reporting standards in widespread use, including the GHG Protocol Corporate Standard, ISO 14064-1, the UNFCCC inventory guidelines, and target-setting frameworks such as the Science Based Targets Initiative (SBTi). The convention has served well for tracking and comparing corporate, project, and national emissions over time in a universally consistent manner.

The IPCC has consistently noted, however, that the choice of a 100-year time horizon is a value judgment rather than a scientific necessity. As stated in AR5 Working Group I, Chapter 8: "There is no scientific argument for selecting 100 years compared with other choices. The choice of time horizon is a value judgement because it depends on the relative weight assigned to effects at different times." GWP100-based reporting carries an embedded weighting of climate effects across time that is useful for understanding long-term impacts, but does not align with the timeframes within which decisions need to be made.

The 2018 IPCC Special Report on Global Warming of 1.5°C and the AR6 Working Group I report (2021) underscore this concern. AR6 estimates that global mean surface temperature (GMST) is likely to cross +1.5°C above pre-industrial levels in the early 2030s under continued business-as-usual trajectories. The World Meteorological Organization confirmed that 2024 was the warmest year on record at approximately +1.55°C, part of a consistent upward-trending pattern of temperatures over the past several decades.[1]

Stabilizing global temperature near +1.5°C would require reducing global radiative forcing (RF) by at least 1.4 W/m² by or before 2030 relative to projected business-as-usual values, under the scenario assumptions used in the Radiative Forcing Protocol V2.1 (herein referred to as the "RF Protocol"), derived from AR5 and SR1.5, and aligned with AR6.[2]

This near-term RF reduction requirement – and more broadly, the need for decision-relevant climate information across multiple timeframes and across the full population of climate drivers – is the gap that Total Climate Accounting™ is designed to fill.

1.2 Total Climate Accounting

Total Climate Accounting is a new, "CO_2e+"climate accounting framework designed to help organizations understand not only how many tonnes of GHGs they emit or reduce, but to cover a more inclusive set of climate pollutants and to show how much those emissions or reductions contribute to raising or

[1] At the time of this writing, the strong El Niño currently underway, combined with the continuing trajectory of climate change, has the potential to topple previous temperature records in 2026 and 2027.

[2] Based on the AR5 RCP 8.5 scenario and the SR1.5 equilibrium climate sensitivity of 0.79 °C per W/m². This single value is used only to set the illustrative forcing target. Temperature projections under this Framework use the IPCC AR6 assessed ranges (see Appendix B).

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lowering the excess trapped atmospheric heat across multiple timeframes, including near-term timeframes that matter for risk, capital allocation, public health, and climate strategy.

Total Climate Accounting was developed as a market-ready application of the Radiative Forcing Protocol, relying on the same metric that underlies IPCC climate analysis, radiative forcing (RF), to disaggregate relevant climate drivers, apply appropriate radiative efficiency and atmospheric lifetime parameters, and report results over multiple timeframes. Under the Framework, RF outputs are converted into global heat expressed in terajoules, and may also be converted into carbon dioxide forcing equivalents. These calculations are further reinforced by user-friendly equivalencies and visualizations that make the results easier to understand and interpret.

1.3 Adding a Heatprint™ to a Carbon Footprint

The Total Climate Accounting Framework expands the conventional carbon footprint of an organization or project to include additional climate forcers and their combined atmospheric heat impacts over any timeframe. We call this a "Heatprint."

This integrated summary encompasses the long-lived and shorter-lived GHGs reported under conventional standards as well as additional short-lived climate pollutants (SLCPs) such as black carbon, organic carbon, tropospheric ozone precursors, and sulfate aerosol precursors. The framework also has the capacity to include non-emission climate forcers, such as changes in albedo.

The Heatprint extends climate reporting beyond a single CO_2e GWP100 value by quantifying, in physical heat units (terajoules), how much atmospheric energy is added or avoided by a source or intervention over time. It captures the distinct temporal signatures of long-lived GHGs such as CO_2 and N_2O, for which heat impact accumulates slowly but persists for centuries, and short-lived climate pollutants such as methane and black carbon, for which heat impact is concentrated in the first years to decades after emission. This makes it possible to evaluate the heat reduction potential of any reduction or removal project or strategy, and calculate the "climate ROI" – i.e., climate impact per dollar spent.

By disaggregating heat impact by pollutant and by timeframe, the Heatprint surfaces information that conventional CO_2e accounting obscures: that two activities with identical CO_2e values can deliver very different climate impact outcomes in the timeframes most relevant to near-term temperature stabilization, intervention sequencing, capital allocation, and planning. The Heatprint can be reported for any user-defined horizon, such as by 2030, by 2045, or 100 years, and it can be expressed as cumulative terajoules, instantaneous W/m^2, tonnes of carbon dioxide forcing equivalents (t CO_2fe), or through accessible equivalencies such as ice melted or homes powered.

Total Climate Accounting can be applied to organizations, products, projects, portfolios, climate action plans, or carbon-crediting activities where the necessary data are available.

1.4 Heatprint PBC

Heatprint PBC (formerly Global Heat Reduction) is a public benefit corporation dedicated to accelerating measurable reductions in atmospheric heat through science-based climate accounting. The company’s mission is to equip businesses, investors, governments, registries, project developers, institutions, foundations, and communities with the methods, metrics, and tools needed to address climate change

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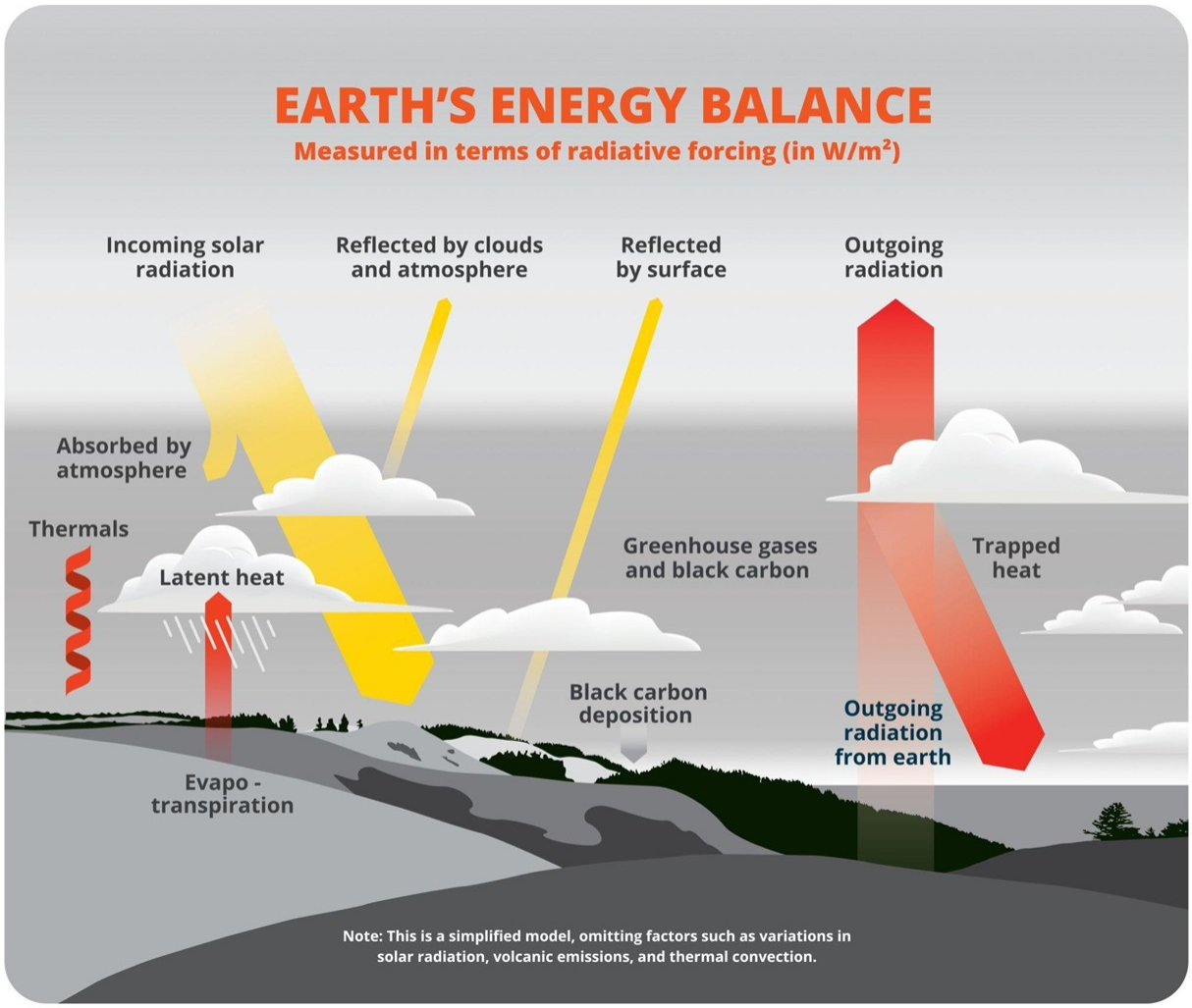
within the timeframes most relevant to near-term temperature stabilization as well as to achieve longer-term climate goals. Heatprint developed Total Climate Accounting in collaboration with technical partners and the broader climate science community, drawing on the RF Protocol developed by SCS Global Services and on the peer-reviewed scientific literature on climate forcers. Heatprint's Total Climate Accounting framework and reporting mechanism pairs comprehensive climate forcer assessment and time-resolved heat metrics so that decision-makers can prioritize interventions that deliver the greatest climate benefit within the timeframes that matter most.

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2. Scientific Basis: Radiative Forcing as the Underlying Metric

Radiative forcing (RF) is defined by the IPCC as the change in the net (downward minus upward) radiative flux at the top of the atmosphere, expressed in watts per square meter (W/m^2), due to an external driver not associated with climatic feedback loops. It is used by the IPCC to understand how GHGs, aerosols, and other climate forcers alter the Earth's energy balance (Figure 1).

Figure 1: Earth's Energy Balance



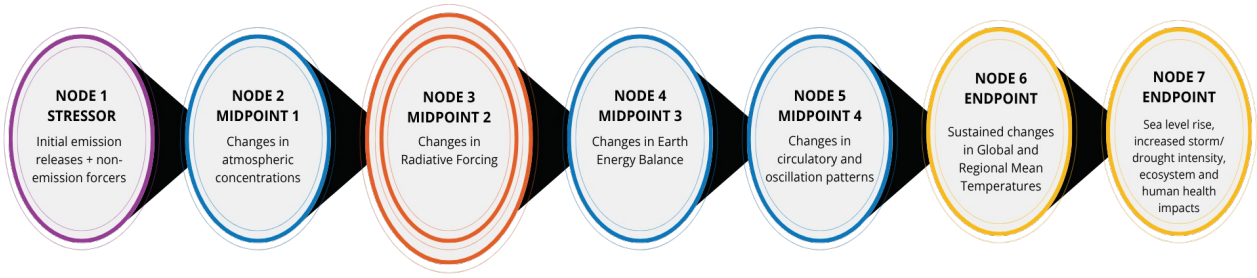
RF is also the physical basis from which CO_2e metrics are derived. Global Warming Potential (GWP) values compare the integrated radiative effect of a pulse emission of a gas to the integrated radiative effect of a pulse emission of CO_2 over a selected time horizon, most often 100 years. Total Climate Accounting relies on this underlying physics, such that climate impact can be evaluated by forcer, by source, and by timeframe rather than compressed into a single 100-year equivalence value. As part of this approach, RF is calculated as Effective Radiative Forcing as defined by IPCC, and includes rapid

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adjustments on clouds including indirect and semi-direct forcing cloud effects resulting from aerosols, as described in the RF Protocol.

RF occupies a position, or "node," in the stressor-effect chain (i.e., cause-and-effect biophysical pathway) that links anthropogenic and biogenic forcers to their ultimate climate endpoints – from initial emission release or forcing event, through atmospheric concentration changes, to forcing, to temperature change, to physical and ecosystem effects (Figure 2). Because RF is the proximal cause of temperature change and can be linked to specific emissions and activities with relatively high precision, it serves as a leading indicator of climate change endpoints.

Figure 2: Climate Change Stressor-Effects Chain



Node 3 (Changes in Radiative Forcing) is the node in the stressor-effects chain with the strongest quantitative linkage to both the initial stressor and the endpoints. It is the underlying metric used to establish stressor equivalencies, and if RF changes are sustained, will alter earth's energy balance and set into motion changes in atmospheric and ocean circulation systems, impact global and regional temperatures, and lead to extensive ecological and human health impacts. Temperature change (Node 6) may be modeled from Total Climate Accounting forcing results using the method in Appendix B. Such projections are reported separately from forcing and heat, as ranges, because the climate's sensitivity to forcing and the complexities of the Earth's climate system can add considerable uncertainty to temperature projections that the Total Climate Accounting itself does not carry.

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3. Assessment Process

3.1 Assessment Goal and Use Case

Each assessment begins by stating the intended use of the results. Common uses include organizational strategy, capital allocation, project comparison, carbon-credit valuation, supply-chain prioritization, municipal heat and air-quality planning, stakeholder reporting, and standards engagement. The use case determines the appropriate boundaries, timeframes, output formats, and level of data precision needed.

3.2 Boundary Setting

The assessment boundary defines: the entity, product, project, portfolio, or intervention being evaluated; the operational or value-chain sources included; the period of activity data used; and the time horizons over which impacts will be calculated. Where Total Climate Accounting is applied to organizations, boundaries may follow the logic of Scope 1, Scope 2, and Scope 3 accounting. Where it is applied to projects or carbon-crediting activities, boundaries define baseline and project scenarios, leakage considerations, material upstream or downstream effects, and exclusions.

3.3 Scope of Climate Forcers

RF calculations cover all relevant climate forcers, determined by materiality, methodological support, data availability, and decision relevance. Climate forcers are classified into three categories:

- **Well-mixed greenhouse gases (WMGHGs):** CO_2, CH_4, N_2O, SF_6, NF_3, hydrofluorocarbons (HFCs), perfluorocarbons, halogenated ethers, and other halocarbons reported under UNFCCC. Short-lived methane and HFCs are well-mixed, and therefore included in this category.

- **Non-well-mixed climate forcers (NWMCFs):** These short-lived forcers include black carbon, organic carbon, and sulfate aerosols (precursor: SO_2). RF varies by region and source.

- **Non-emission climate forcers (NECFs):** Surface albedo changes from black carbon deposition on snow and ice, and cloud-albedo enhancement by sulfate aerosols, included to the extent they can be characterized.[3]

3.4 Time Horizons of Analysis

The analysis timeframe is a defined period of interest, which may include past, present, and future years. The RF results are based on the effective RF at the end of each specified year and are calculated per pollutant every year over a period of 100 years from when the emission occurred. This enables the Heatprint to be calculated at multiple discrete points in time – typically near-term (1-20 years), medium-term (21-50 years), and long-term (51-100 years). Multi-horizon reporting provides visibility into all these timescales, surfacing differences in the trajectory of RF impact across forcer types.

[3] These effects are integrated into the radiative efficiencies of black carbon and sulfur dioxide; therefore, they are not reported separately.

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3.5 Treatment of Well-Mixed Greenhouse Gases

The RF of WMGHGs is calculated per pollutant using each pollutant's radiative efficiency (RE) and atmospheric decay. For CO_2, the AR5 four-term impulse response function is used. For non-CO_2 WMGHGs, an exponential decay is applied based on the average atmospheric lifetime reported in AR6. Methane's RE includes documented indirect effects: tropospheric ozone formation, sulfate aerosol effects, stratospheric water vapor, nitrate aerosol effects, and CO_2 formation (Shindell et al., 2009).

3.6 Treatment of Non-Well-Mixed Climate Forcers

For NWMCFs with atmospheric lifetimes of less than one year, RF is computed using region- and source-specific radiative efficiency values and an Atmospheric Residence Time Modeling Parameter (ARTMP). Default values are provided in the RF Protocol Annex A (Tables A.3 and A.4) for sulfur dioxide and for black/organic carbon, broken down by region and source type. Site-specific or modeled data are substituted for the default values where available.

3.7 Conversion to Global Heat

RF results, measured in watts per square meter, describe the extent to which organizations or projects are influencing the global energy imbalance, either positively or negatively. RF results are translated into global heat values, expressed as a commonly recognized, quantified amount of energy – i.e., terajoules. Cumulative terajoules are then calculated over any timeframe of interest. This conversion is useful because terajoules are more commonly recognized and intuitive for decision-makers than W/m^2 and can be used to compare interventions, explain time dynamics, and communicate the magnitude of heat added or avoided.

Global heat is reported with the timeframe, scope, and forcer coverage clearly identified. A one-year heat impact, a cumulative heat impact to 2030, '40 or '505, and a 100-year heat impact are examples of different outputs and should not be treated as interchangeable.

3.8 Conversion to CO_2 Forcing Equivalents

RF results may also be converted into tonnes of CO_2 forcing equivalents (t CO_2fe). This metric is used to compare the instantaneous or cumulative forcing of any pollutant to the forcing of one tonne of CO_2 over the same timeframe. As with global heat, the timeframe, scope, and forcer coverage is clearly identified when tonnes of CO_2fe are reported.

3.9 Energy Equivalencies

The Framework supports the translation of results into energy equivalencies to enhance communication. Examples may include the annual electricity usage of the average US home, tonnes of ice melted, or other context-specific comparisons. Equivalencies are not intended as substitutes for the assessment results; rather, they are communication tools used after the core calculation is complete.

The equivalencies used depend on the assessment context, audience, geography, and available conversion factors. Each equivalency discloses the conversion factor used and avoids overstating

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precision. For technical reporting, primary results remain disaggregated RF and heat values (TJ). Equivalencies are supplemental.

4. Data Requirements

Data requirements depend on the use case, assessment level, boundary, and climate forcers included. The assessment begins with the same basic information used to generate a GHG inventory or carbon footprint. In some cases, additional data elements are required to estimate heat impact, short-lived climate pollutants, source-specific effects, and project or scenario differences.

4.1 Core Data for Organizational Assessments

- Organizational and operational boundary definition, including facilities, activities, ownership or control approach, and reporting period.
- Scope 1 activity data such as stationary fuel use, mobile fuel use, process emissions, refrigerant use, and waste processing.
- Scope 2 electricity data, including consumption and grid region. Supplier-specific emission factors are used where available.
- Scope 3 activity data where included, such as purchased goods, transportation, use-phase, waste, fuel- and energy-related activities, and supplier-specific information.
- Location, source type, equipment type, technology, control devices, and operating conditions where these affect black carbon, aerosols, or other climate forcers.

4.2 Core Data for Project or Carbon-Crediting Assessments

- Baseline scenario definition, project scenario definition, and time period of analysis.
- Activity data for both scenarios, including production levels, throughput, fuel or energy use, material flows, equipment operation, and expected changes over time.
- Emission sources included and excluded, with rationale for exclusions.
- Project-specific parameters such as leakage rates, destruction efficiency, combustion conditions, technology controls, regional conditions, and upstream or downstream effects when material.
- When relevant, cost data used to calculate Climate ROI, with cost boundaries clearly documented.

4.3 Additional Site-Specific Data

Some assessments require data beyond a conventional GHG inventory. Examples include: equipment tier and particulate controls for mobile or stationary combustion; waste composition and management practices; refrigerant type and leakage rates; crop-residue management practices; and local environmental conditions that affect radiative efficiency. These data are collected when material and feasible.

4.4 Conservative Estimates, Assumptions, and Limitations

Where primary data are unavailable, the Framework supports the use of conservative estimates, peer-reviewed values, government datasets, or proxy assumptions, provided they are documented. Assumptions are made transparent, limitations are described, and uncertainty is communicated in a way

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that matches the intended use of the results. If a climate forcer is material but cannot be quantified with adequate confidence, the report identifies the omission and explains whether the result is likely to understate or overstate heat impact.

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5. Calculation Methods and Equations

The core equations used in the Total Climate Accounting framework, which are derived from the RF Protocol, depend on the level of assessment. The notation provided in the equations below follows the Protocol's Annex A. When relevant, default parameter values are noted.

5.1 General RF Aggregation

The total RF in a given target year t_F, considering all climate forcer effects occurring between an initial year t_o and t_F, is the sum of contributions from WMGHGs and NWMCFs:[4]

TCA Equation 1 — General RF for year t_F

$$RF(t_F) = RF_{WMGHG}(t_F, t_o) + RF_{NWMCF}(t_F, t_o)$$

Where RF_{WMGHG} is the RF from well-mixed climate forcers and RF_{NWMCF} is the RF from non-well-mixed climate forcers.

5.2 RF from CO_2 Emissions

The RF resulting from a pulse emission of one tonne of CO_2 is calculated using the four-term impulse response function from IPCC AR5 Chapter 8 Supplemental Material:

TCA Equation 2 — Unit RF for a CO_2 pulse

$$\mu RF_{CO2}(t) = RE_{CO2} \times \left(a_0 + a_1 \times e^{-t/\tau 1} + a_2 \times e^{-t/\tau 2} + a_3 \times e^{-t/\tau 3} \right)$$

Default parameter values (AR5): $a_o = 0.2173$, $a_1 = 0.2240$ ($\tau_1 = 394.4$ yr), $a_2 = 0.2824$ ($\tau_2 = 36.54$ yr), $a_3 = 0.2763$ ($\tau_3 = 4.304$ yr). The leading constant term a_o represents the long-term residual fraction. RE_{CO2} default = 1.7008×10^{-12} W/(m²·tonne) per AR6, updated to maintain consistency with IPCC reports.

5.3 RF from Non-CO_2 WMGHGs

For non-CO_2 WMGHGs (CH_4, N_2O, SF_6, HFCs, PFCs, etc.), a single-term exponential decay is used:

TCA Equation 3 — Unit RF for a non-CO_2 WMGHG pulse

$$\mu RF_{WMGHG}(t) = RE_{WMGHG} \times e^{-t/\tau}$$

Where τ is the average atmospheric lifetime of the WMGHG (years) and RE is the radiative efficiency in mW/(m²·Tg). Default values from AR6: CH_4 $\tau = 11.8$ yr, RE = 0.20 mW/(m²·Tg) (including indirect effects); N_2O $\tau = 109$ yr, RE = 0.358 (including indirect effects); SF_6 $\tau = 1000$ yr, RE = 21.8; HFC-134a $\tau = 14$ yr, RE = 9.21; NF_3 $\tau = 569$ yr, RE = 16.2. CO_2e reporting uses source-specific methane GWP100 values (Section 6.1).

[4] As noted previously, the non-emission forcing associated with black carbon and sulfate aerosols is integrated into the forcing of the respective pollutants and therefore no separate NECF is calculated.

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5.4 RF from Non-Well-Mixed Climate Forcers

For NWMCFs with atmospheric lifetimes less than the Atmospheric Residence Time Modeling Parameter (ARTMP, default one year), RF is treated as the average radiative forcing during the ARTMP period:

TCA Equation 4 — Unit RF for an NWMCF pulse

$$\mu RF_{NWMCF}(t) = RE_{NWMCF} \text{ for } t < \text{ARTMP}; \quad = 0 \text{ for } t > \text{ARTMP}$$

RE_{NWMCF} varies by region and source type. Default values for black carbon and organic carbon are tabulated in RF Protocol Annex A Table A.4. Default values for SO_2 (precursor to sulfate aerosols) are tabulated in RF Protocol Annex A Table A.3.

5.5 RF from Negative Climate Forcers

While most climate pollutants such as GHGs and black carbon contribute positively to radiative forcing (a warming effect), other pollutants such as organic carbon and sulfate aerosols contribute negatively (a cooling effect). In addition to their climate impacts, these pollutants are also associated with poor air quality and damage to human health and ecosystems. For full accountability and to promote transparency, negative forcers and precursor emissions are tracked and reported separately. When the heat reduction of a mitigation project or activity is being evaluated, such forcers are only added into net RF totals if they are decreased (hence adding to the positive RF). They are noted but not added into net RF totals if they are increased, as that could inadvertently incentivize increased emissions of these air pollutants.

5.6 Conversion to Global Heat

Once RF has been calculated for each forcer over the analysis timeframe, the results are converted into global heat (GH), expressed in terajoules. The conversion multiplies the RF rate (W/m²) by the number of seconds in the relevant period and by the surface area of the Earth, then applies a unit conversion from joules to terajoules:

TCA Equation 5 — Conversion from RF to Global Heat

$$GH(t_F) = RF(t_F) \times S \times SA \times C$$

Where S is the number of seconds in one year (31,557,600 s used as default; this value accounts for leap years); SA is the surface area of the Earth (510×10^{12} m² used as default); and C is the conversion factor from J to TJ (10^{-12}). The result is the cumulative global heat, in terajoules, associated with the radiative forcing calculated for the target year. Global heat may be summed over single or multiple years to produce a cumulative Heatprint over any user-defined timeframe.

5.7 Conversion to CO_2 Forcing Equivalents

RF may be converted to tonnes of CO_2 forcing equivalents (t CO_2fe) by dividing the forcing of a pollutant by the forcing of one tonne of CO_2 over the same timeframe:

TCA Equation 6 - Conversion from RF to CO_2 forcing equivalents

$$FE(t_F) = RF(t_F) \,/\, RE_{CO2}$$

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Where FE is the tonnes of CO_2 forcing equivalents, $RF(t_F)$ is the radiative forcing calculated for the target year, and RE_{CO2} is the radiative efficiency of CO_2 (1.7008×10^{-12} W/(m²·tonne) by default).

6. Reporting

Total Climate Accounting produces both conventional emissions information, consistent with established standards, and additional climate forcer and heat-impact outputs that are unique to this Framework. Reports include the scope and boundary of the assessment, data sources, assumptions, limitations, calculation methods, and outputs. The results are presented in both disaggregated and aggregated form so that users can understand the drivers behind the total values.

6.1 Reporting Outputs

A complete Total Climate Accounting report includes the following:

- **Disaggregated emissions inventory in metric tons (i.e., "tonnes").** Annual emissions are reported by pollutant, scope, and activity, including GHGs and additional short-lived climate pollutants such as black carbon, organic carbon, sulfate aerosol precursors, and tropospheric ozone precursors, pending data availability.
- **Heatprint.** An integrated, CO_2e-plus summary output that combines the conventional carbon footprint with the Heatprint and any additional climate forcers covered by the assessment. Total Climate Footprint includes:
    - **Carbon footprint in CO_2e.** Reported in t CO_2e using GWP100 by default. For methane, the IPCC AR6 GWP100 depends on the source: 29.8 for fossil methane and 27.0 for non-fossil (biogenic) methane. The value used is stated with its source category. Where credits or an inventory were issued at another value, such as the AR5 value of 28, the CO_2e is restated at the AR6 value for the source, and the issuing value is reported alongside it.
    - **Cumulative global heat**. Reported in terajoules across multiple time horizons, reported both disaggregated by pollutant and as a total. The selected time horizons may be specific target years (e.g., 2030, 2050), specific time intervals (e.g., 5 years, 10 years), or a combination of both. Disaggregated and total instantaneous radiative forcing in W/m² or t CO_2fe over the same timeframes is available on request.
    - **Equivalencies.** Communication-oriented translations of terajoule values (for example, annual cooling load of average homes, tonnes of ice melted, or other context-specific comparisons), each with the underlying conversion factor disclosed.
- **Data visualizations.** Charts, time-series graphics, and comparative views designed to make the temporal dynamics of climate impact legible to technical and non-technical audiences, and to highlight key findings.
- **Temperature projection (optional).** Projected change in global mean surface temperature derived from the Heatprint's time-resolved forcing using a reduced-complexity climate emulator, as set out in Appendix B. Always reported as a range, beside the forcing and heat results it was derived from, with the emulator, parameter set, horizon and reduction profile stated.

Heatprint results can be delivered as an overall total, per scope, per activity, or per pollutant, depending on the use case and project details. The level of disaggregation should be matched to the decision the assessment is intended to support.

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6.2 Application of the Heatprint

Because the Heatprint quantifies heat impact across multiple timeframes and by pollutant, it can be used in a wide range of contexts to complement conventional CO_2e accounting. Typical applications include:

- **Near-term climate strategy.** Identifying interventions that deliver the largest heat reductions over near-term horizons, where short-lived climate pollutants disproportionately influence outcomes.
- **Project and intervention comparison.** Comparing projects or technologies that look similar in CO_2e terms but have different physical heat outcomes across selected timeframes of interest.
- **Carbon-crediting evaluation.** Evaluating credits based on the amount of heat avoided over decision-relevant timeframes, including cases in which the tonnes of CO_2e are comparable.
- **Climate ROI.** When paired with cost data, computing heat avoided per dollar spent over a chosen time horizon, supporting capital allocation decisions.
- **Hotspot and sector analysis.** Pinpointing the sources, scopes, or activities responsible for the largest near-, mid-, or long-term heat impact, including SLCP-heavy sources that are understated in conventional CO_2e inventories.
- **Supply-chain prioritization.** Distinguishing among suppliers, materials, or pathways based on their full Heatprint rather than CO_2e alone.
- **Disclosure and stakeholder communication.** Reporting heat impact in terms that make climate impact tangible to investors, customers, employees, and regulators (e.g., terajoules, equivalencies, time-resolved charts)
- **Air-quality and public-health co-benefit framing.** Linking SLCP and aerosol-related heat impacts with the broader public-health benefits of mitigation, supporting cross-issue policy and corporate engagement.

6.3 Data Quality and Uncertainty

RF accounting carries uncertainty across multiple parameters, including atmospheric lifetimes, radiative efficiencies (with concentration adjustment), regional and source-specific NWMCF radiative effects, biogenic emission rates, carbon cycle feedbacks, and climate feedbacks more broadly. The Framework specifies that:

- data quality should be characterized in both quantitative and qualitative terms wherever feasible;
- site-specific data should be used where practicable;
- primary data should take precedence over secondary data; and
- conservative assumptions should be used where data are absent.

For NWMCFs with high regional variability, modeled emissions inventories should be cross-checked against satellite observations where available, with adjustments applied per the methods of Bond *et al.* (2013) for black carbon. Uncertainty in the climate's sensitivity to forcing applies only to optional temperature projections, not to forcing or heat results, and is reported as a range (Appendix B).

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7. Total Climate Accounting in Action

The following examples illustrate how Total Climate Accounting is applied in practice, what it reveals beyond a conventional GHG inventory, and how the resulting outputs support intervention design.

7.1 Municipal Solid Waste Management

A company managing municipal solid wastes commissioned a Heatprint in 2024 to better understand its existing carbon footprint and to analyze a potential mitigation investment. Total Climate Accounting was used to generate the company's Heatprint, and the assessment showed how its heat profile and dominant pollutants changed over time. This helped translate a conventional emissions inventory into a clearer view of heat hotspots and mitigation priorities.

A second analysis showed the time-resolved heat reduction impacts of composting compared to landfilling organic waste, drawing attention to the significant near-term benefits of methane mitigation from the composting activity, and making a quantitative heat reduction case for further investment in these efforts.

A third analysis looked at a proposed anaerobic digester scenario comparing baseline emissions with a modeled project scenario. The modeled project reduced estimated CO_2e emissions by about a third, while also reducing near-term and long-term heat by changing the treatment pathway for organic waste and replacing fossil CNG with renewable natural gas.

The results of all three assessments proved valuable for stakeholder communication. These applications demonstrate how Total Climate Accounting can support infrastructure decisions by showing both conventional emissions reduction alongside heat-impact trajectories.

7.2 Crop Residue Burning Case Study

Total Climate Accounting was used for a targeted case study to analyze the atmospheric heat reduction impact of avoided rice residue burning in Thailand. Using peer-reviewed literature and government data, the study evaluated relevant GHGs including methane and nitrous oxide, while reporting biogenic CO_2 separately consistent with standard carbon-accounting treatment. The assessment also expanded on traditional CO_2e accounting by including short-lived aerosol pollutants including black carbon, sulfur dioxide, and organic carbon.

This analysis illustrated the value of Total Climate Accounting for agricultural systems where black carbon and other short-lived forcers can dominate the near-term heat profile. By reporting heat impacts over 1-, 5-, 10-, 25-, and 100-year timeframes, the analysis showed how crop-residue burning can create a strong time-resolved heat and air-pollution signal that is not visible in a conventional CO_2e-only assessment. The results were used for stakeholder communication and informed the planning of additional site-specific analyses.

7.3 Comparing Well-Capping and CO_2-Based Carbon Credits

The Framework can also be applied to project or credit comparison. Heatprint conducted a pilot study in which a well-capping, methane-focused project was compared to a CO_2-emissions reduction project with the same t CO_2e (GWP100) claim. The well-capping project reduced 3.7 times more heat over the first ten years than the CO_2-only project (see Appendix B for the full calculation and its assumptions).

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As seen from this study, although two distinct interventions result in the same tonnage of CO_2e reduction based on GWP100, they may produce very different heat outcomes in the near-term. The Heatprint shows the timing and magnitude of avoided heat by pollutant and source, providing a basis for portfolio optimization, project sequencing, and value-based differentiation in voluntary carbon markets.

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8. Looking Ahead: Additions to the Framework

Total Climate Accounting is intended as a living framework. Two areas of active development are noted below, both reflecting the scientific community's evolving treatment of climate forcers and the growing demand for climate information that integrates with adjacent environmental, social, and economic accounting.

8.1 Emerging Climate Forcers and Methodologies

Several climate forcers are currently treated only partially in the Framework because the underlying methods or input data are still maturing. Heatprint is working to expand the Framework's coverage as the science and data quality permit:

- **Tropospheric ozone.** Ozone formed in the lower atmosphere from precursor emissions (NO_x, VOCs, CO, methane) is a powerful short-lived GHG. Source attribution and regional radiative-efficiency methods are advancing rapidly; the Framework will incorporate tropospheric ozone explicitly as a forcer once methods are sufficiently robust for routine corporate and project-level application.
- **Surface albedo.** The Framework already incorporates albedo change from surface deposition of black carbon on snow and ice and cloud-albedo enhancement from sulfate aerosols into the black carbon and sulfate forcing calculations, respectively. Land-cover change and urban surface modification also alter Earth's reflectivity and thus its radiative balance. The Framework will expand its treatment of albedo effects as remote-sensing and modeling tools mature to the point where they can be applied at the spatial and temporal scales relevant to organizational and project assessments.
- **Additional indirect effects.** As the IPCC and the broader literature update parameter values, such as methane indirect effects, aerosol-cloud interactions, and biogenic carbon dynamics, the Framework will adopt the revised values and document the updates.

8.2 Pairing Total Climate Accounting with Life Cycle Assessment

Decisions about products, projects, and supply chains rarely turn on climate alone. Life cycle assessment (LCA) is an internationally established framework for evaluating broader environmental impacts, such as water use, eutrophication, land use, toxicity, biodiversity, and resource depletion, across a defined life cycle.

Pairing Total Climate Accounting with LCA supports a more complete co-benefit and trade-off analysis, wherein the climate footprint and heat impact from Total Climate Accounting can be evaluated alongside the non-climate impact categories from LCA in a consistent system boundary. This integration is especially valuable for decisions involving alternative materials, energy sources, agricultural practices, or industrial processes, where climate gains may be accompanied by changes in other impact categories that decision-makers need to see explicitly.

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9. Conclusion

Total Climate Accounting is designed to augment conventional climate accounting by expanding beyond its specific limitations – the compression of physically distinct climate effects into a single 100-year CO_2e value, and the exclusion of non-gaseous climate forcers. By utilizing radiative forcing – the underlying physical metric from which CO_2e is derived – and converting radiative forcing into global heat in terajoules, the Framework generates outputs that are decision-relevant for the timeframes most pertinent to near-term temperature stabilization, capital allocation, and stakeholder communication.

The Framework preserves conventional CO_2e reporting and pairs it with the Heatprint, which extends the inventory to include previously omitted non-well-mixed climate forcers, and which expresses heat impact in physical units across user-defined time horizons. Together they provide a CO_2e-PLUS analysis: a layered reporting structure compatible with the GHG Protocol, ISO 14064-1, and the major reporting standards in current use.

There are three main takeaways:

- A tonne is not always a tonne for decision-making. Emissions with identical CO_2e values can produce very different heat outcomes over decision-relevant timeframes. Total Climate Accounting makes those differences visible.
- The value of an intervention depends on the timeframe over which it is evaluated. Reporting over multiple time horizons supports sequencing decisions that align mitigation with near-term goals, such as 2030 and 2050.
- Total Climate Accounting is methodologically rigorous and operationally practical. It uses peer-reviewed radiative forcing science and parameter values, integrates with existing GHG inventories, supports multiple levels of analysis based on an organization's needs, and produces outputs that can be communicated to technical and non-technical audiences alike.

Heatprint will continue to update the Framework as the underlying science evolves and as new climate forcers and methodologies become ready for routine application.

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10. Terms and Definitions

The following terms are used throughout this document. Definitions are intended to support consistent application and will be refined as methods, data, and external standards evolve.

Atmospheric Residence Time Modeling Parameter (ARTMP): The period over which the radiative effect of a short-lived NWMCF is modeled, with a default value of one year.

Climate Return on Investment (ROI): Heat avoided per dollar spent over a decision-relevant timeframe, used to compare interventions where cost data are available.

Climate Sensitivity: The global mean surface warming that results from a doubling of atmospheric CO_2 concentration. IPCC AR6 gives a likely range of 2.5–4°C, with a best estimate of 3°C.

CO_2e: Carbon dioxide equivalent. A common unit for aggregating GHGs by multiplying each gas by a selected GWP value and summing the results.

CO_2e-PLUS: A simple way to understand Total Climate Accounting's relationship to conventional accounting: CO_2e reporting remains in place, while the Heatprint adds outputs that show heat impact, pollutant-specific dynamics, and decision-relevant time horizons.

CO_2fe: Carbon dioxide forcing equivalent. A unit for expressing the instantaneous forcing of a pollutant normalized to the forcing of one tonne of carbon dioxide.

Global Heat: A conversion of RF into energy over a defined period, reported in terajoules. Global heat is used to communicate climate impact as cumulative heat added to, avoided in, or reduced from the Earth's energy balance.

Global Warming Potential (GWP): A metric comparing the integrated radiative effect of a pulse emission of a gas to CO_2 over a specified time horizon, commonly 20 or 100 years.

Heatprint™: The annual and cumulative heat impact of an organization, project, product, or portfolio, expressed in physical heat metrics such as terajoules (TJ) and, when useful, W/m^2 or other accessible equivalencies.

Non-Emission Climate Forcers (NECFs): Surface albedo changes from black carbon deposition on snow and ice, and cloud-albedo enhancement by sulfate aerosols, included to the extent they can be characterized.

Non-Well-Mixed Climate Forcers (NWMCFs): Climate forcers with concentrations and radiative effects that vary by region, season, source type, or atmospheric chemistry, including black carbon, organic carbon, sulfate aerosols, and ozone precursors.

Radiative Forcing (RF): The change in net (downward minus upward) radiative flux at the top of the atmosphere, expressed in W/m^2, due to an external driver not associated with climatic feedback loops.

Reduced-complexity climate emulator: A simplified climate model, such as FaIR, calibrated to reproduce the global temperature response of complex Earth system models at low computational cost, and run as a large parameter ensemble to represent uncertainty in the climate's response.

Short-Lived Climate Pollutants (SLCPs): Climate forcers with relatively short atmospheric lifetimes, such as methane, black carbon, tropospheric ozone, and some HFCs.

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Temperature projection: An optional output that estimates the change in global mean surface temperature resulting from a Heatprint's time-resolved forcing, using a reduced-complexity climate emulator. Reported as a range, beside the forcing and heat results it was derived from (Appendix B).

Total Climate Accounting (TCA): Heatprint PBC's framework for translating IPCC-vetted radiative forcing science into decision-useful climate assessment. Total Climate Accounting preserves conventional emissions accounting and adds a time-resolved heat lens across relevant climate drivers and timeframes.

Well-Mixed Greenhouse Gases (WMGHGs): GHGs that are sufficiently long-lived to be approximately uniformly distributed in the atmosphere, including CO_2, CH_4, N_2O, SF_6, NF_3, some HFCs, PFCs, and other halocarbons.

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Appendix A: FAQ

Q1: Does Total Climate Accounting replace the GHG Protocol or conventional CO_2e accounting?

No. Total Climate Accounting is designed as a complementary decision layer. Organizations should continue to prepare conventional GHG inventories where required or useful, as is embedded in the framework. Total Climate Accounting adds information about timing, heat impact, pollutant-specific dynamics, and intervention value.

Q2: Why is CO_2e included?

CO_2e remains the common language for disclosure, target-setting, and comparability. Total Climate Accounting includes CO_2e so that users can maintain continuity with existing reporting while gaining additional decision insight.

Q3: Why use radiative forcing?

Radiative forcing is the underlying physical metric used to understand how climate drivers alter the Earth's energy balance. GWP and CO_2e are derived from RF. Using RF allows Total Climate Accounting to preserve information that can be lost when all effects are compressed into a single long-horizon metric, and its use helps overcome the inherent uncertainty introduced when comparing the relative potency different gaseous forcers or comparing gaseous and non-gaseous forcers.

Q4: How does Total Climate Accounting relate to Scope 1, 2, and 3 boundaries?

For organizational assessments, Total Climate Accounting can use Scope 1, 2, and 3 activity data and boundaries as appropriate. The same data used for conventional inventories provide the starting point, with additional data added for other short-lived climate forcers, source-specific effects, and heat-impact calculations.

Q5: Can Total Climate Accounting be used to evaluate carbon-crediting projects?

Yes. Total Climate Accounting can compare baseline and project scenarios, and report heat avoided over selected timeframes. For instance, results can help distinguish projects that look similar in CO_2e terms but have different physical climate impacts.

Q6: Does Total Climate Accounting include non-GHG climate forcers?

Where data and methods support inclusion, yes. The Framework supports the inclusion of the non-well-mixed climate forcers such as black carbon, organic carbon, and SO_2 (sulfate aerosols precursor). Certain non-emission forcers, such as the albedo effect of black carbon on snow and ice, are included as well. Other NWMCFs and non-emission forcers will be added to the Framework as technologies mature.

Q7: How should uncertainty be handled?

Uncertainty should be documented through data-quality notes, assumptions, sensitivity analysis, ranges, or conservative estimates as appropriate. If a potentially material driver cannot be quantified, it should be disclosed and justified.

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Q8: Can Total Climate Accounting support target-setting?

Total Climate Accounting can inform heat-reduction milestones and intervention sequencing. Target-setting claims should be aligned with applicable standards and should clearly distinguish between emissions targets, heat-impact targets, and supplemental decision metrics.

Q9: Why is the Heatprint a necessary add-on to CO_2e/GWP100 accounting?

CO_2e is an emissions output metric. By contrast, the Heatprint is an impact metric quantifying the atmospheric heat those emissions add, which drives warming, across decision-relevant timeframes. Capital allocation, risk assessment, and alignment with global temperature targets require the impact signal, not just the output level.

Q10: Can Total Climate Accounting report temperature?

Yes, as an optional and separate output. The Framework's time-resolved forcing can be run through a reduced-complexity climate emulator to project the change in global mean surface temperature, as set out in Appendix B. Temperature projections are always reported as ranges, beside the forcing and heat results they come from, because the climate's sensitivity to forcing adds uncertainty that the accounting itself does not carry. For a single project, a temperature projection is a modeled estimate, never an observable result; it is most meaningful for portfolios, sectors and programs.

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Appendix B: Projecting Temperature from Radiative Forcing

Purpose and principles

This appendix sets out how Total Climate Accounting (TCA) results may be extended to projected change in global mean surface temperature. It adds an optional output and changes nothing in the core accounting: radiative forcing (W/m²) and global heat (TJ) remain the Framework's primary, verifiable results.

A temperature estimate developed under this appendix:

- *Is separate.* It may be reported beside forcing and heat, but never in place of them.
- *Is a range.* It reflects the IPCC AR6 assessed ranges of climate response, not a single value.
- *Uses Total Climate Accounting forcing values*. The emulator is driven by the same time-resolved forcing the accounting produces, so the accounting and the projection never disagree on the forcing.
- *States assumptions*. The emulator, version, parameter set, horizon and whether a reduction is sustained are always disclosed.
- *States uncertainty.* The uncertainty associated with the specific analysis is described, and if it is larger than the temperature range reported, will render the temperature estimate moot.
- *Respects scale*. For a single project, it is always a conditional, at-scale estimate, never an observable result.

B.1 Method

The projection runs TCA's annual forcing difference (project minus baseline) through the Finite Amplitude Impulse Response (FaIR) reduced-complexity climate emulator and reports the resulting temperature difference as a range.

1. **Forcing input.** Annual radiative forcing by forcer from TCA Equations 1–4, for the baseline and project scenarios over the analysis period, counted from the emission year as in Equation 5. The input is the difference between the two scenarios, by forcer so contributions can be reported separately.
2. **Emulator.** FaIR version 2.2 or later (open source, Apache 2.0 license), run in forcing-driven mode through its energy balance model, so the forcing TCA calculates is the forcing the emulator uses.
3. **Climate response.** The published FaIR calibrated and constrained parameter set (version 1.4.1, 841 members). It is constrained to the IPCC AR6 assessed ranges of equilibrium climate sensitivity and transient climate response, and to observed warming, ocean heat uptake, CO_2 concentrations and aerosol forcing (Smith et al., 2024).
4. **Ensemble run.** The forcing difference is run through every member of the parameter set. Results are reported as the median with the 5th–95th percentile range.

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5. **Horizons.** Temperature is reported at the same horizons as the Heatprint (for example 1, 10, 25 and 100 years after emission), and at calendar years relevant to the decision, such as 2035 and 2050.
6. **One-time vs sustained.** Pulse reductions and sustained reductions are modeled separately. For sustained reductions of short-lived pollutants, a stop case (reductions end after a stated year) is also reported, showing the warming that returns.
7. **Background conditions.** Because the run is forcing-driven and TCA uses fixed IPCC lifetimes and radiative efficiencies, results do not depend on a background emissions scenario.
8. **Methane in credit comparisons.** When comparing credits defined in t CO_2e, methane's radiative efficiency is set so that 100-year heat equals that of the same number of tonnes of CO_2 under the GWP100 used to state the CO_2e: the AR6 value for the methane's source (Section 6.1), with credits issued at another value restated first. The Heatprint then reconciles with the CO_2e claim at 100 years, and the near-term multiple does not depend on which GWP vintage was used. For physical inventories, the tabulated AR6 value in Section 5.3 is used.

MAGICC is not used for commercial reporting because its IPCC AR6 probabilistic parameter set is licensed for non-commercial use only.

B.2 Reporting requirements

Every temperature result must appear beside the forcing and heat it was derived from and disclose the following.

Item	What to state
Emulator	FaIR version and mode (forcing-driven or emissions-driven)
Climate parameters	Parameter set name and version; the transient and equilibrium response range it spans
Range	Median and the percentile range reported
Horizon	Years after emission, or calendar year
Reduction profile	One-time pulse, or sustained for stated years; stop case for short-lived pollutants
Forcers included	Which forcers drive the result, and any omitted (for example tropospheric ozone precursors)
Scale	Whether the result is for the actual project or a stated at-scale deployment

Limits on claims:

- No claim that a project "cooled the planet" or produced an observable temperature change.
- No presentation of a short-lived reduction as permanent cooling, or as a like-for-like offset for long-lived CO_2.
- No more precision than the range supports. One or two significant figures.

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- No temperature figure without its forcing and heat figures.

B.3 Modeled example: well-capping project

This example reproduces the well-capping comparison in Section 7.3 and adds the temperature layer.

Project. An orphaned-well plugging project on the American Carbon Registry: 85,145 credits issued at the methane GWP100 of 28 (the AR5 value) used in the project's monitoring report, or 3,041 t of methane. Because this methane is fossil, the claim is restated at the AR6 GWP100 for fossil methane (29.8): 90,619 t CO_2e. Under the convention in B.1, the near-term multiple is the same at either value. All avoided emissions are assumed to occur in the credit year, since the credits are issued at once. The comparison is the same number of tonnes of CO_2.

Heat method. Equations 2, 3 and 5, with forcing counted from the emission year. Methane's radiative efficiency is set from the GWP of 29.8 (B.1, item 8): 2.17×10^{-10} W/m² per tonne, against the tabulated 2.0×10^{-10}. Set from the registry's 28 instead, it would be 2.04×10^{-10}, and every multiple below would be the same.

Temperature method. FaIR v2.2.4 energy balance model, forcing-driven, run over all 841 members of calibration version 1.4.1. The parameter set's emergent transient climate response spans 1.3–2.4°C (median 1.8°C), against AR6's very likely range of 1.2–2.4°C. Its equilibrium sensitivity spans 2.0–5.0°C (median 3.0°C), against AR6's very likely range of 2–5°C (all 5th–95th percentiles). Transient response matters more than equilibrium sensitivity for the near-term results below.

Heat avoided, per 1,000 t CO_2e

Horizon	Well-capping (TJ)	CO_2-only (TJ)	Multiple
1 year	117	27	4.3x
5 years	498	122	4.1x
10 years	824	222	3.7x
25 years	1,268	476	2.7x
100 years	1,441	1,441	1.0x

Temperature avoided, full project (millionths of a degree C; 5th–95th percentiles, median in brackets)

Years after emission	Well-capping	CO_2-only	Multiple
1	0.052–0.091 (0.065)	0.012–0.021 (0.015)	4.3x
5	0.13–0.22 (0.17)	0.032–0.054 (0.041)	4.0x
10	0.11–0.19 (0.15)	0.033–0.058 (0.044)	3.2–3.4x (3.3x)

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25	0.043–0.10 (0.067)	0.031–0.059 (0.044)	1.3–1.8x (1.5x)
100	0.0023–0.022 (0.0084)	0.027–0.059 (0.039)	0.071–0.42x (0.22x)

At scale: 1 million t CH_4 a year abated from 2030 (degrees C; 5th–95th percentiles, median in brackets; physical tonnes at the tabulated efficiency)

Year	Sustained 20 years	Stopped after 10 years
2035	0.00016–0.00026 (0.00020)	same
2040	0.00034–0.00057 (0.00044)	same
2050	0.00059–0.0010 (0.00079)	0.00024–0.00047 (0.00035)
2070	0.00020–0.00051 (0.00032)	0.000070–0.00021 (0.00012)

What the example shows

1. **The near-term multiple is robust.** The project's temperature effect at 10 years varies nearly twofold across the parameter set, but its ratio to CO_2's stays between 3.2x and 3.4x. Comparisons between interventions hold up far better than any single temperature figure, which is why the Framework accounts in forcing and heat.
2. **Temperature lags heat.** At 10 years the temperature multiple (3.3x) sits below the heat multiple (3.7x), because the ocean takes time to respond. Reporting both avoids overstating either.
3. **Scale.** The whole project avoids about 0.17 millionths of a degree at its peak, around year 5. Even a sustained program abating 1 Mt of methane a year reaches under a thousandth of a degree by 2050.
4. **Timing.** Methane's temperature advantage is largest in the first decade and falls below CO_2's about 30 to 40 years after emission. Heat is equal at 100 years by construction. By then methane's temperature multiple has fallen to about 0.2x, because temperature tracks recent forcing while heat is cumulative. Beyond 100 years the heat multiple keeps falling below 1.0x, to about 0.6x at 200 years and 0.3x at 500 years, because about a fifth of emitted CO_2 stays in the atmosphere for many centuries (a_0 in Equation 2), while methane's forcing is gone within a few decades.
5. **Rebound.** Stopping the at-scale program after 10 years cuts its 2050 benefit by more than half, and by 2070 leaves under 40% of what sustaining it would.

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