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Modeling the non-CO_2 contribution to climate change

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Brief summary

Non-CO_2 climate drivers include other greenhouse gases, air pollutants, and changes to the land surface. Together, these non-CO_2 drivers have caused about a quarter of today's warming and will continue to be important into the future. Policies designed to address certain emissions such as methane can supplement Paris Agreement goals. This primer describes how simple and complex climate models can be used to describe warming trajectories and inform policy action regarding non-CO2 climate forcers.

Summary

Carbon dioxide (CO_2) is the best-known and most important driver of climate change, but the climate also responds to other anthropogenic forcers that have different sources, mitigation potentials, atmospheric residence times, and climate change potential. These drivers include non-CO_2 greenhouse gases, short-lived climate forcers such as aerosol and ozone precursors, and changes in the land surface. Smart targeting of these non-CO_2 drivers, in combination with a serious and sustained attempt to reach net zero CO_2 emissions, could result in substantial avoided climate damages. Evaluating the climate effect of non-CO_2 greenhouse gas emissions is not yet possible in most state-of-the-art climate models, though exciting developments are occurring. Simpler tools including reduced-complexity climate models and climate metrics are currently used to evaluate the climate impacts of non-CO_2 drivers. This primer discusses strengths and weaknesses of these approaches, and opportunities and outlook for future development.

The non-CO_2 issue

While carbon dioxide (CO_2) emissions are the most significant contributor to climate change, there are many other processes by which humans are altering the climate. Non-CO_2 drivers, including other greenhouse gases, short-lived climate forcers, and surface reflectivity changes, have accounted for about one quarter of the present-day warming of just over 1.0°C (fig. 1). Non-CO_2 greenhouse gases include methane (CH_4), nitrous oxide (N_2O), and halogenated compounds containing fluorine and chlorine such as the notorious ozone-depleting chlorofluorocarbons (CFCs). While the emissions and atmospheric concentrations of these other greenhouse gases are many times less than those of CO_2, they are substantially more efficient at trapping heat than CO_2 on a kilogram-for-kilogram basis.

Alongside greenhouse gases we also emit substantial amounts of air pollutants, in the form of particulates (aerosols) and reactive, short-lived gases. Sulfur dioxide (SO_2) is emitted when fossil fuels containing small amounts of sulfur, particularly coal, are burned. Upon oxidation in the atmosphere SO_2 forms sulfate aerosol particles, which are highly reflective, and exert a cooling effect on the climate because of the reduced net incoming sunlight from space. Other aerosols and aerosol precursors including organic carbon and ammonia (a precursor of nitrate aerosol) have similar net cooling effects, while black carbon (soot) aerosol has a net warming effect, being highly absorbing to both solar and thermal radiation.

In addition to their *direct* effect, some aerosols, particularly sulfates, are efficient cloud condensation nuclei. Liquid cloud droplets can easily form in the presence of aerosols. This results in more, smaller cloud droplets, which leads to brighter, more reflective clouds, further increasing the reflectivity of the atmosphere to incoming sunlight. While almost certainly a cooling effect, the strength of this *indirect* (aerosol-cloud) effect is still uncertain despite recent progress. Reducing this uncertainty would greatly improve our ability to predict future climate change.

Some other air pollutants such as volatile organic compounds (VOCs) and nitrogen oxides (NOx) are key precursors of ozone formation in the lower atmosphere; ozone is a powerful yet short-lived greenhouse gas. These precursor gases also impact the atmospheric lifetime of methane, and methane itself is notable as both a powerful greenhouse gas and a key precursor of ozone. The net climate effect of these species is therefore the results of a complex interplay of chemical processes.

Humans are also changing the Earth’s surface’s properties. While deforestation to make way for pasture and croplands emits CO_2 into the atmosphere (a warming effect), it also generally increases the reflectivity of the land surface as darker forests are replaced by brighter croplands (a cooling effect). The latter effect is accounted for separately as a non-CO_2 contribution to climate change. Contrails from aircraft can form high-level ice clouds under the right atmospheric conditions, which have a slight warming effect in addition to the direct climate consequences of jet fuel combustion.

Added together, the non-CO_2 climate drivers that have warming impacts contribute about 1°C of global warming, similar to the magnitude of temperature change observed. However, the non-CO_2 cooling drivers cancel out about 0.8°C of warming (fig. 1). At present the effects of the most dominant non-CO_2 emitted compounds, methane and sulfur dioxide, almost balance, warming and cooling the climate by about 0.5°C each respectively.

Furthermore, different climate forcers have different residence lifetimes in the atmosphere. Many greenhouse gases are long-lived, with atmospheric lifetimes of decades or centuries (solid regions of fig. 1 lower bar), whereas short-lived pollutants (hashed bars) and their byproducts exist in the atmosphere for only a matter of days or weeks. Methane (sparse hatching) sits between the two groups, with an atmospheric lifetime of around 11 years. To first order, the climate effect of long-lived species depends on the cumulative amount of past emissions, while that of short-lived species (including methane) is a function of the annual rate of emission. This is why reaching net zero CO_2 emissions is necessary to halt warming completely but reducing CH_4 emissions in the meantime has been identified as a potentially effective way to reduce the rate of warming in the near future. Effective methane mitigation could reduce the size and length of time spent overshooting 1.5°C, which is a trajectory that looks increasingly likely if we are to ever meet this long-term temperature target of the Paris Agreement.

[Insert figure 1 here: one column]

Many non-CO_2 compounds are co-emitted with CO_2 or with each other. Aside from sulfur in fossil fuels, BC, OC, NOx, CH_4, CO and VOCs are by-products of combustion. VOCs also have industrial sources and NOx is a product of agriculture. Methane is produced from cattle, landfill, rice paddies, and fossil fuel processing leaks. Major sources of N_2O include industrial processes and fertilizer use, and halogenated compounds are used in air conditioning, refrigeration and industrial processes. Therefore, while it is unlikely that all of the non-CO_2 warming contributions could be eliminated without reducing some of the cooling contributions at the same time, different emissions control strategies and climate change mitigation policies that target specific non-CO_2 emissions (particularly methane) have the potential to change the balance of non-CO_2 warming in the future.

Determining the climate impacts of non-CO_2 emissions

Modeling climate

A range of techniques are used to evaluate the climate impacts of non-CO_2 drivers (Box 1). State-of-the-art Earth system models are the most powerful climate modelling tools we have available, but require supercomputing resource. In many cases, the level of detail required for policy purposes is much less than that provided by an Earth system model: we may only need to know annual, global mean temperature change from an emissions scenario, for example to determine consistency of a given pathway with the Paris Agreement. We can therefore develop *emulators* which replicate the large-scale behavior of Earth system models but are flexible and run much faster.

The temperature contributions from emissions in fig. 1 was produced using an emulator. It may be surprising that determining the climate impacts of non-CO_2 emissions is not routinely performed using Earth system models. This is because in addition to computational complexity, most Earth system models do not have the capability to run with emissions of CO_2, and only one or two very state-of-the-art models can run with emissions of CH_4. For other greenhouse gases, the capability to run emissions-driven does not yet exist. On the other hand, more (but not all) Earth system models have the ability to determine aerosol and ozone burdens from short-lived forcers through atmospheric chemistry modules.

The journey from emissions to temperature change is only part of the story. While Earth system models can project regional climate and extremes, emulators typically do not, though emulation techniques to downscale global mean temperature to regional climates using *regional emulators* exist. Regional climate projections, whether from regional emulators or Earth system models, are necessary to drive *climate impact* models which may project changes in crop and fishery productivity, biodiversity, and heat stress to name just a few important impacts for humans and the natural world. Taking a step backwards, emissions scenarios are generated by *integrated assessment models* (socioeconomic models of population, the economy, energy system and land use change). There is therefore an entire process chain linking socioeconomic projections through to emissions, climate change and climate impacts (fig. 2).

[Insert figure 2 here: two columns]

Emulating Earth system models

Greenhouse gas climate impacts are ultimately driven by atmospheric concentrations. Therefore, the concentration of a greenhouse gas in the atmosphere depends on the balance of its emissions and losses; if emissions exceed losses, concentrations increase and vice versa. For non-CO_2 greenhouse gases, the main atmospheric loss pathway is by chemical or photolytic (sunlight-driven) reaction. In emulators, these loss pathways are often parameterized with one or a few atmospheric lifetimes per gas. These lifetimes may change with temperature or abundances of gases present in the atmosphere, simulating the impacts of climate or chemistry feedbacks. Initial atmospheric lifetimes are estimated from chemistry-climate models, or from estimates of atmospheric burden and rates of emission or removal compiled for instance by the World Meteorological Organization.

Determining the climate effect of a change in concentration of a greenhouse gas or the burden of a short-lived forcer requires calculating its *radiative forcing*. Radiative forcing describes the change in net energy input into the Earth system relative to the pre-industrial era (with candidate years being 1750 and 1850, though no single definition is used consistently). Radiative forcing is positive for increases in the abundance of species that warm the climate such as methane, and negative for those that cool the climate such as sulfate aerosol.

Radiative forcing is difficult to observe directly, as observations (e.g. by satellite) of the Earth's energy balance include both the radiative forcing and the change in energy due to the climate's response. It is possible to get very accurate calculations of radiative forcing using a high-resolution *radiative transfer* model, a computational model of optical physics that calculates longwave and shortwave energy flows through the atmosphere. For greenhouse gases, we can run several simulations in radiative transfer models with different atmospheric concentrations, and fit algebraic relationships to the results to estimate radiative forcing as a function of greenhouse gas concentrations.

For aerosols, ozone and clouds that are not uniform in the atmosphere and closely affected by precursor emissions, radiative forcing can be estimated from dedicated Earth system model experiments. Earth system models contain parameterized versions of radiative transfer models, as the high-resolution models are computationally heavy. Because Earth system models simulate the motions of aerosols and clouds based on their internal atmospheric models, this introduces “weather”-driven noise and longer simulations are required to ensure a robust radiative forcing signal. Nevertheless, algebraic relationships relating ozone and aerosol forcing to precursor emissions can be developed from these Earth system model results for use in emulators.

Radiative forcing drives global warming. There is inertia in the Earth system due to the large heat capacity of the oceans which take a lot of energy to warm up. Earth system models will model the flows of heat throughout the atmosphere and ocean, but it has been found that the global mean temperature response to a change in radiative forcing can be emulated well by assuming that the ocean has just two or three coupled layers that absorb and respond to warming. Less complex or “lightweight” models such as this are easy to fit to the responses of Earth system models.

Global warming potential and CO_2-equivalent metrics

The relationships used in emulators to describe each step of the emissions-concentration-forcing-temperature process can be exploited further to express an emission of a non-CO_2 greenhouse gas as an equivalent emission of CO_2 (reported as CO_2-eq or CO_2-e).

The best-known and most widely used emissions metric is the Global Warming Potential (GWP). GWP is the ratio of the time-integrated radiative forcing from a greenhouse gas divided by the time integral of the radiative forcing of CO_2. The GWP of a gas depends both on the efficiency of a greenhouse gas in trapping heat and its atmospheric lifetime. It also depends on the time horizon of the integration. The most common choice is 100 years (GWP_{100}) with 20- and 500-year time horizons also reported by the IPCC.

GWP_{100} has become a *de facto* standard CO_2-equivalent metric and is therefore incredibly policy-relevant. It is used by many countries when submitting periodic updates to emissions reductions pledges under the Paris Agreement. However, it suffers from several drawbacks. There is little objective basis for selecting 100 years as the time horizon, and emissions metrics are very sensitive to this choice, especially for shorter-lived gases. Methane has $GWP_{20} = 81$, $GWP_{100} = 28$ and $GWP_{500} = 8$, which means the relative importance of the gas can be altered ten-fold based on an arbitrary (often political) decision. Another weakness is that GWP_{100} is not always a good predictor of warming. And while GWPs for short-lived forcers exist, there are no authoritative standardized estimates produced by agencies such as the IPCC or World Meteorological Organization, and they are regionally variable and suffer from large uncertainties. Therefore, climate policies that rely on GWPs tend to ignore short-lived forcers. Additionally, there is inconsistency with the inclusion of indirect effects between greenhouse gases: methane and N_2O metrics include their secondary effects on tropospheric ozone formation (increasing the total radiative forcing from these gases, and hence their GWPs) but the stratospheric ozone destruction from CFCs is not included in their GWP values. If it was, their GWPs would be negative.

Numerous other metrics have been proposed in order to improve GWP. One step further down the process chain from radiative forcing to temperature (fig. 2) is the global temperature change potential (GTP). GTP is the change in global mean temperature at a particular point in time following a unit of emission compared to the same amount of CO_2.

Again, GTP is sensitive to time horizon, and like GWP, is not standardized for short-lived forcers. GWP* was developed to address both the subjectivity of time horizon and the fact that the reduction of short-lived greenhouse gas emissions is equivalent to a cooling, though the additional steps required in computing it have led to suggestions it is closer to a full reduced-complexity climate model than a metric, and there are concerns surrounding sensitivity to emissions variability. There are tradeoffs and limitations when attempting to evaluate non-CO_2 emissions with CO_2 equivalents that policymakers should be aware of, and improving emissions metrics is still an active research area.

Box 1: Modeling approaches for non-CO_2 drivers

Earth system models determine flows of air, heat and moisture around the atmosphere and ocean and may include modules for atmospheric chemistry, the carbon cycle and ice sheets. The atmosphere and ocean are divided into three dimensional discrete grids of around 1° in longitude and latitude and up to around 100 layers vertically, and the equations of motion are solved on discrete timesteps, usually several per model hour. They contain realistic topography and bathymetry and simulate observed climate phenomena including the El Niño-Southern Oscillation and realistic “weather”. However, they require supercomputers to run, and are therefore computationally and financially expensive.

Climate emulators are very simple climate models. Emulators may condense large-scale Earth system behavior into a few equations and parameters that are informed by physical or statistical knowledge. The parameters can be tuned to reproduce global mean behaviors from Earth system models under a range of climate scenarios. Emulators run much quicker than Earth system models and may produce a climate simulation in a fraction of a second on a normal desktop. This has the additional advantage that the parameters of the emulator can be varied to produce different (yet plausible) climate responses and run repeatedly, to provide uncertainty estimates of the climate response.

CO_2-equivalent metrics attempt to describe the climate impact of a non-CO_2 greenhouse gas by comparing it to an equivalent amount of CO_2. The most common example is the Global Warming Potential (GWP) over 100 years. Metrics are a very simple form of model and used widely in climate policy. They exploit many of the relationships used in climate emulators with the aim to distil non-CO_2 greenhouse emissions into a single number for each gas. Unfortunately, metrics can be very sensitive to a number of subjective choices and are inconsistently applied between greenhouse gases and short-lived forcers.

Policy relevance of non-CO_2 emissions

As with present-day climate, non-CO_2 forcers are expected to contribute significantly to future climate change. Figure 3a shows the total radiative forcing for eight categories (C1-C8) of a total of 1202 integrated assessment model scenarios from the IPCC’s Working Group 3 report, with increasing levels of end-of-century warming moving from C1 (consistent with Paris Agreement goals to limit warming to 1.5°C) to C8 (>4°C warming). This analysis was performed using emulators due to the sheer number of scenarios required to run. For each of the 1202 scenarios, hundreds of simulations were produced to sample the full assessed uncertainty in climate response, rendering on the order of a million runs per emulator across the scenarios. It would take too much time to perform these analyses with Earth system models, even if they could be driven with all necessary greenhouse gas emissions.

Figure 3b shows the non-CO_2 contribution to the radiative forcing as a percentage in two of the three emulators with available results for each category. Across warming levels, the non-CO_2 contribution to total radiative forcing is around 20% for a typical scenario and is always at least 10%, with the greatest contribution being in scenarios that limit warming to 1.5°C. It can clearly be seen that emissions of non-CO_2 greenhouse gases and short-lived climate forcers and changes in land cover are expected to continue to have a profound and net-positive contribution to warming over the course of this century across the full range of projected futures.

[Insert figure 3 here: two columns]

Recently, a heuristic model even simpler than emulators or emissions metrics has been introduced, by observing in Earth system models that warming scales linearly with cumulative emissions of CO_2. This gives rise to the powerful concept of *net zero*: warming stops when zero CO_2 emissions is reached. This holds over a range of plausible scenarios. The relationship can be inverted to give a remaining *carbon budget* of emissions until a temperature limit is reached (e.g. 1.5°C). Carbon budgets are widely used in policy discussions, for instance to allocate a small allowable total of remaining emissions equitably between countries. However, the remaining carbon budget needs to be adjusted for the present and assumed future climate impacts from non-CO_2 drivers which contribute to warming but do not contribute to cumulative CO_2 emissions. Assuming the combined effect of non-CO_2 drivers is a net warming (figs. 1 & 3), the remaining budget of allowable emissions of CO_2 must be reduced to compensate.

Future developments and opportunities

Emulators currently provide an invaluable part of analyses of climate mitigation policies surrounding non-CO_2 forcers. The potential to target specific non-CO_2 forcers to gain relatively low-cost and near-term emissions reductions is forming an important part of global climate policy. Recognizing methane's large contribution to present-day warming and near-term mitigation potential, over 150 countries signed the Global Methane Pledge to reduce their methane emissions by 30% by 2030, which may avoid a tenth of degree Celsius warming by mid-century if successfully and globally implemented. And highly-potent hydrofluorocarbons, a replacement for the ozone-depleting CFCs but with high heat-trapping potential per molecule, are a target for replacement in split air-conditioning units with propane gas, another substitution that could avoid around a tenth of a degree of warming if air conditioner use expands in line with projections.

Emulators can only be as good as the Earth system models they are calibrated to. Over the last two decades, we have witnessed a huge increase in the capability of aerosol schemes in Earth system models which are now routinely able to run with emissions of short-lived forcers to calculate aerosol and ozone burdens. Now, an increasing number of Earth system models are extending their capability to run with emissions of non-CO_2 greenhouse gases, particularly methane. In the not-too-distant future, fully emissions-driven runs may become routine in model intercomparison exercises.

In the meantime, emulators are currently being developed to extend beyond global mean temperature change using climate output from Earth system models, to temperature extremes, precipitation, and other variables. This is the next step in the process chain of reduced-complexity models – a step that should not neglect investigating the differentiation of CO_2 and non-CO_2 climate forcers (or lack thereof) – and is important for short-lived forcers which may drive different circulation and climate responses due to their more spatial heterogeneity compared to long-lived greenhouse gases.

Climate impacts also affect socioeconomic outcomes in the real world. For example, damages to infrastructure caused by extreme weather – becoming all the more frequent and intense due to climate change – will cause economic losses, hamper social development, and therefore affect productivity and emissions (negatively so, if the economic losses reduce capability for investing in clean technologies). No one model can currently describe every aspect of the human-Earth system, and a big-picture view requires coordination between Earth system scientists, integrated assessment modelers, climate impacts experts and emulator groups.

In summary, non-CO_2 forcers are important drivers of climate warming, and are not likely to diminish in importance in the future. Accurate modelling of their climate impacts can help inform climate policy and decisions that could avoid the very worst effects of climate change.

Acknowledgments

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Figure captions

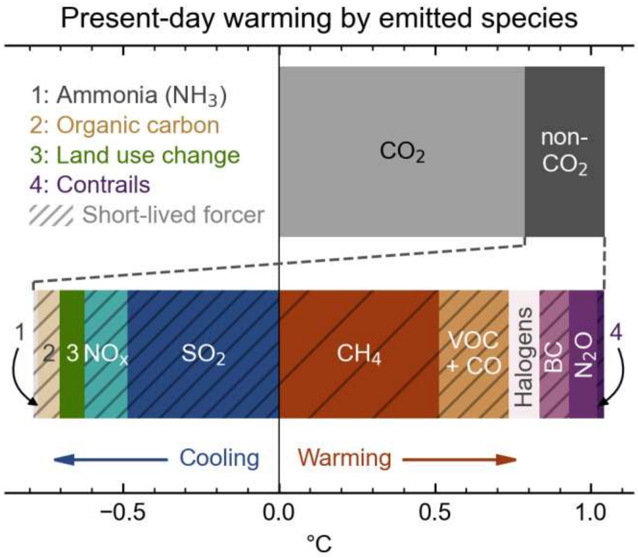

Figure 1: Present-day human-attributable warming by emissions source. Warming from 2010-2019 is compared to 1850-1900.Top bar shows the total human-caused warming split into CO_2 and non-CO_2 contributions. Bottom bar shows the contributions to non-CO_2 warming by source. Other than albedo effects from land use change, and contrails and contrail-induced cirrus, contributions are from directly emitted species. In the bottom bar, hatching shows short-lived climate forcers, solid bars represent long-lived greenhouse gases, and methane (CH_4) as a relatively short-lifetime greenhouse gas is indicated with sparse hatching. VOC+CO: volatile organic compounds plus carbon monoxide); BC: black carbon; NOx: nitrogen oxides; N_2O: nitrous oxide; SO_2: sulfur dioxide. Data are median projections from IPCC Sixth Assessment Report Summary for Policymakers, Figure 2c (Szopa et al. 2021). Note for clarity, uncertainties are not shown, and are in some cases large.

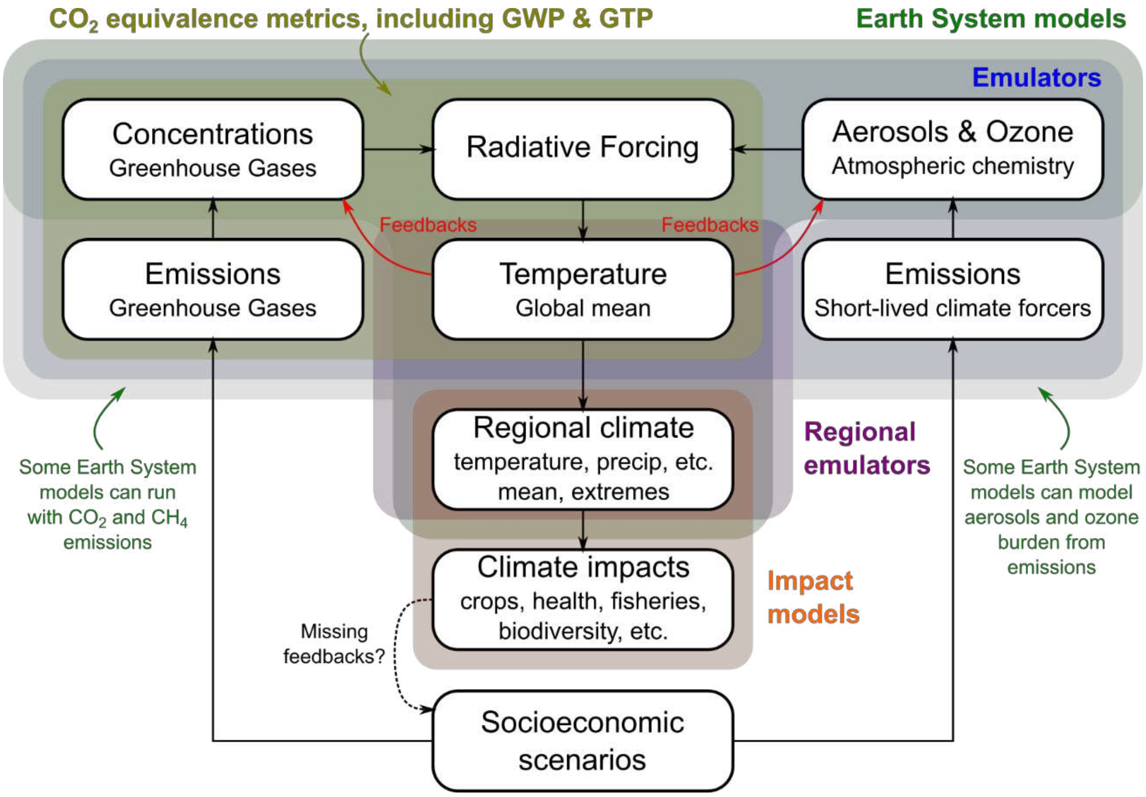

Figure 2: Process chain of emissions to climate impacts, showing the domain of various analysis methods. Earth System models are in green, emulators in blue, CO_2-equivalence metrics in yellow, regional emulators in purple and impact models in orange. Extended from Fuglestvedt et al. (2003). Refer to Box 1 for extended definitions.

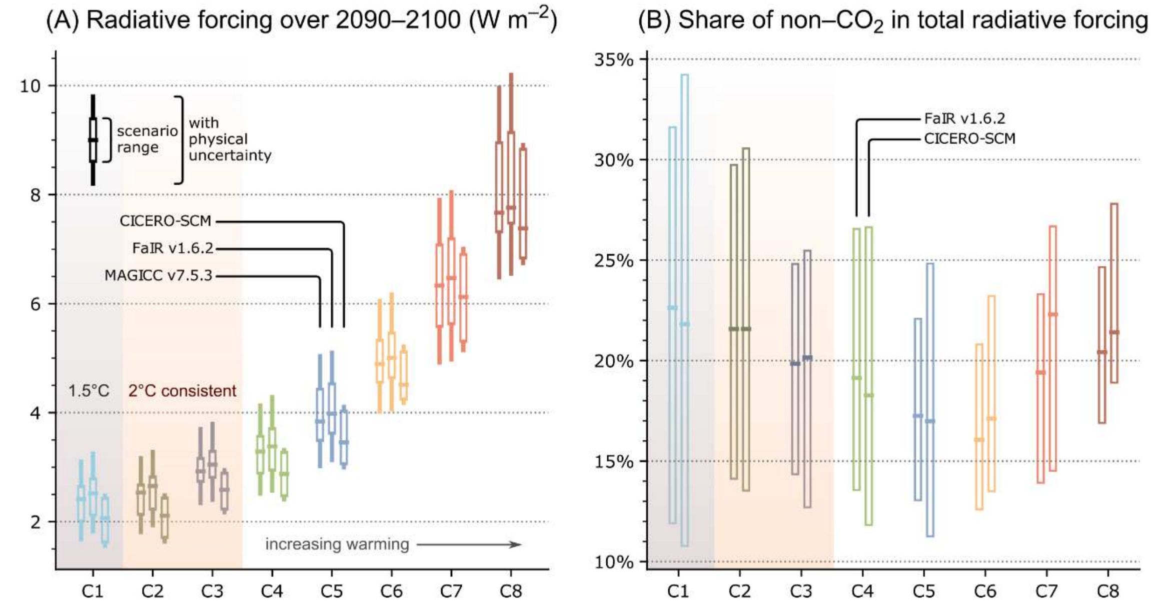

Figure 3: Predicted non-CO_2 contributions to climate change. A. Total radiative forcing in 2090-2100 for 8 groups of scenarios (total 1202) ranging from 1.5°C- (C1) and 2°C-consistent (C2, C3) to over 4°C (C8), using three different climate emulators (MAGICCv7.5.3, FaIRv1.6.2, CICERO-SCM). B. Non-CO_2 contribution to total radiative forcing in each scenario category in FaIRv1.6.2 and CICERO-SCM. Data is from the IPCC AR6 Scenario Explorer Database at data.ece.iiasa.ac.at/ar6/ (Byers et al. 2022).