Assessing the demand of negative emissions for Switzerland to reach net-zero in 2050
An ETH study for BAFU – Milestone 1

Marco Mazzotti and Viola Becattini

w/ Hidde Kolmeijer (7-9.22), Pietro Binel (10-12.22), and Vittoria Bolongaro (1-8.23)

ETH Zurich

January 19th, 2023

Study objectives and timeline

1. Conceptual framework (Dec 2022)

Establishing a conceptual and (simplified) modeling framework, in which to assess the climate impact of Swiss emissions from different sectors, particularly agriculture and aviation.

Milestone and exchange point 1 (19.01.23)

2. CO2-equivalence for non-CO2 emissions (Mar 2023)

Establishing CO2-equivalence between non-CO2 emissions and CO2-emissions for the two sectors of interest, i.e., agriculture and aviation by:

- considering different time horizons,
- using different scenarios,
- applying different approaches,
- developing portable methodologies.

Milestone and exchange point 2

3. Demand for negative emissions (June 2023)

Determining the demand for negative CO2 Emissions (NETs) to compensate for remaining GHG emissions for all the different cases considered above, targeting two objectives:

(i) net-zero GHG emissions by 2050, and

(ii) net-zero climate forcing by 2050.

Milestone and exchange point 3

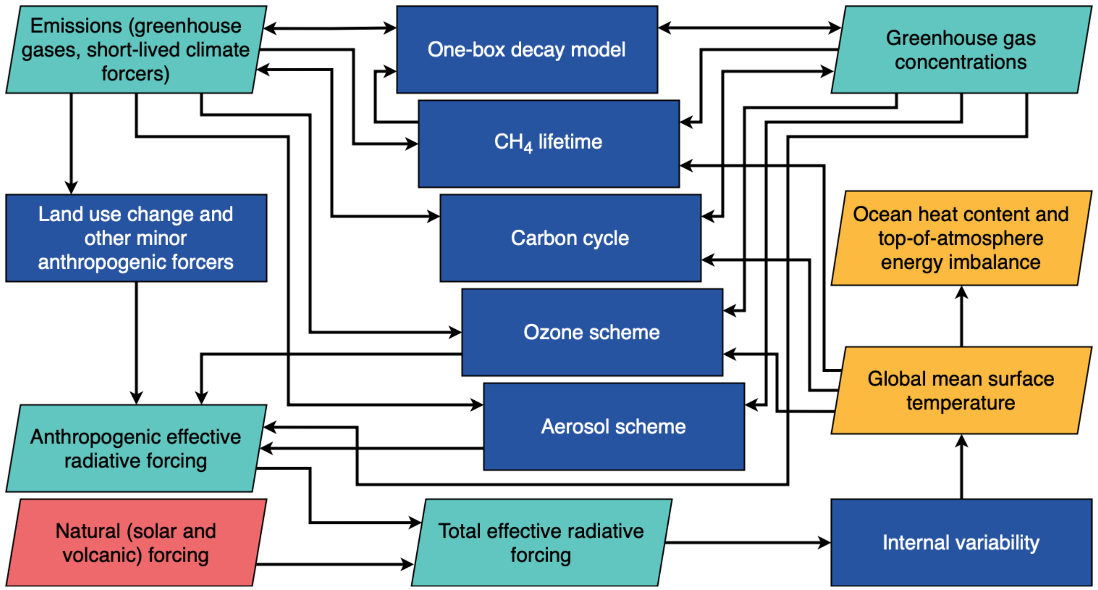
4. Climate strategy implications (Sep 2023)

Defining climate policy scenarios and assessing their implications.

Milestone and exchange point 4

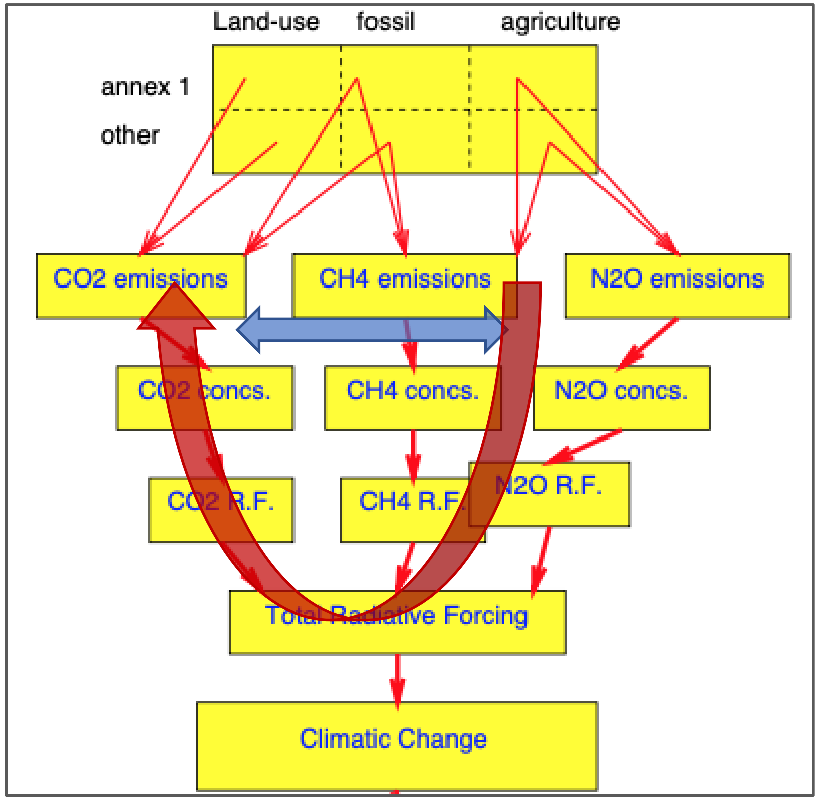
Climate models

- e.g., FaIR (Finite Amplitude Impulse Response)



Smith et al., *Geosci. Model Dev.* ***11*** (2018) 2273

- Chain of causality

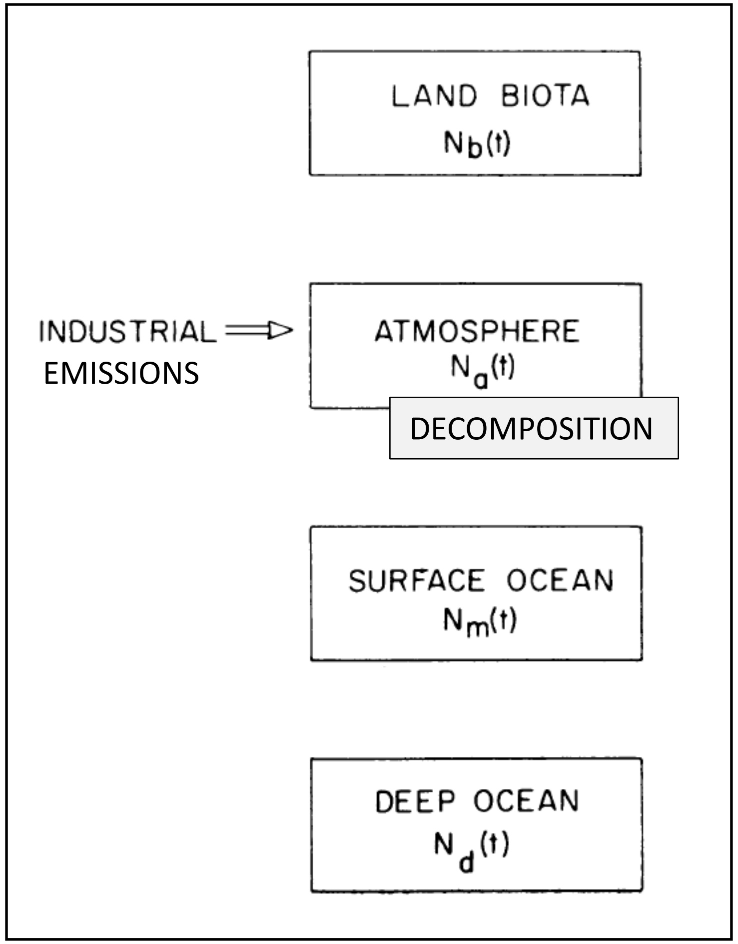


Enting, *CSIRO Atmos. Res. Tech. Paper* ***38*** (1998)

1. Conceptual framework – Objectives

- Establishing a conceptual and (simplified) modeling framework, in which to assess the climate impact of Swiss emissions from different sectors, particularly agriculture and aviation. This will be done by:
  i. modeling the correlation between GHG emissions and their concentration in the atmosphere;
  ii. establishing the relationship between Swiss GHG emissions, their contribution to altering the GHG concentration in the atmosphere, and their impact on radiative forcing;
     a) establishing the correlation between radiative forcing and temperature anomaly;
     b) introducing the differential perturbation approach;
  iii. clarifying the difference between CO_2 emissions (long-lived climate polluntants) and non-CO_2 emissions (short-lived climate pollutants);
  iv. assessing the accuracy of the simplified modeling framework by comparison with results from metrics calculation and available climate models, e.g., FAIR model.

i. GHG concentration vs. emissions (non-CO2)



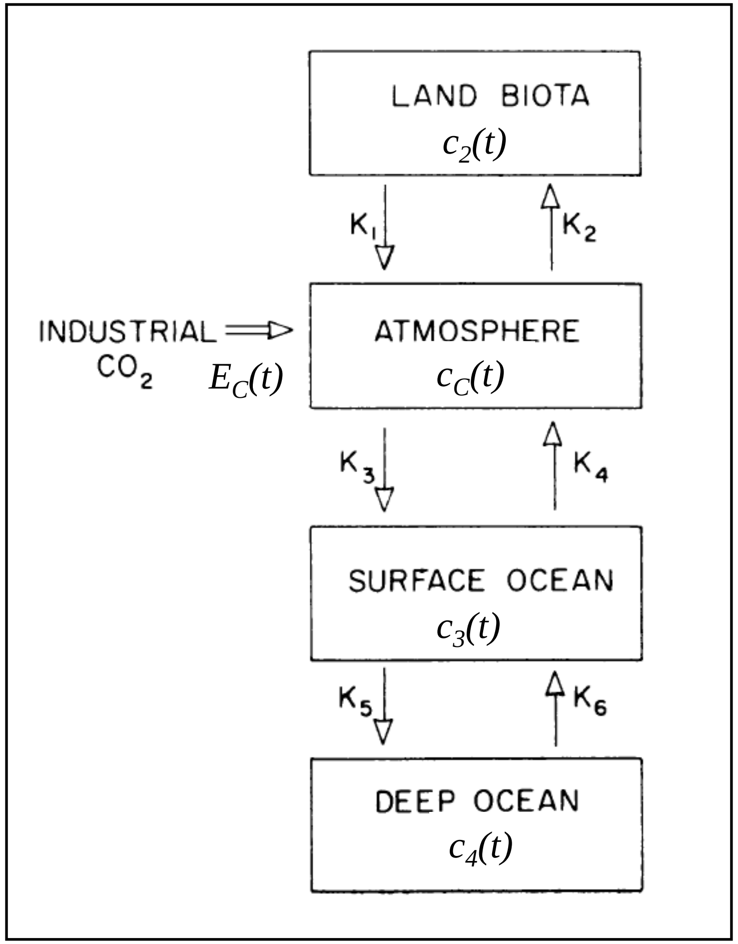
$$\frac{\mathrm{d}c_i}{\mathrm{d}t} = -\frac{c_i}{\tau_i} + E_i(t)$$

τ_{CH4} = 12 y
τ_{N2O} = 110 y

$$c_i(t) = c_{i,0} \exp\left(-\frac{t}{\tau_i}\right) + \int_0^t E_i(t') \exp\left(\frac{t'-t}{\tau_i}\right) \mathrm{d}t'$$

- The solution is given by the term describing the decay of the initial state (at t=0), plus the convolution integral of the emissions from t=0 on.
- The equations above apply to both SLCFs (e.g., CH4) and LLCFs (e.g., N2O).
- The difference between the two is quantitative, but not qualitative.

i. CO_2 concentration vs. emissions



$$\frac{\mathrm{d}\mathbf{c}}{\mathrm{d}t} = \mathbb{A}\mathbf{c} + \mathbf{E}(t)$$

j	0	1	2	3
τ_j [y]	∞	394	37	4
a_j [-]	0.22	0.22	0.28	0.28

$$\mathbf{c}(t) = \exp(t\mathbb{A})\mathbf{c}_0 + \int_0^t \exp((t-t')\mathbb{A})\mathbf{E}(t')\mathrm{d}t'$$

- Exchanges between compartments are linear in $c_i(t)$.
- Anthropogenic emissions are only into the atmosphere.
- CO2 does not decompone hence it is conserved.
- The greenhouse effect is due to CO2 in the atmosphere only.
- CO2 climate impact is indeed cumulative, for two reasons.

$$c_C(t) = c_{C,ss} + \int_0^t E_C(t')\left(a_0 + \sum_{j=1}^{3} a_j \exp\left(\frac{t'-t}{\tau_j}\right)\right)\mathrm{d}t'$$

ii. From GHG concentration to radiative forcing

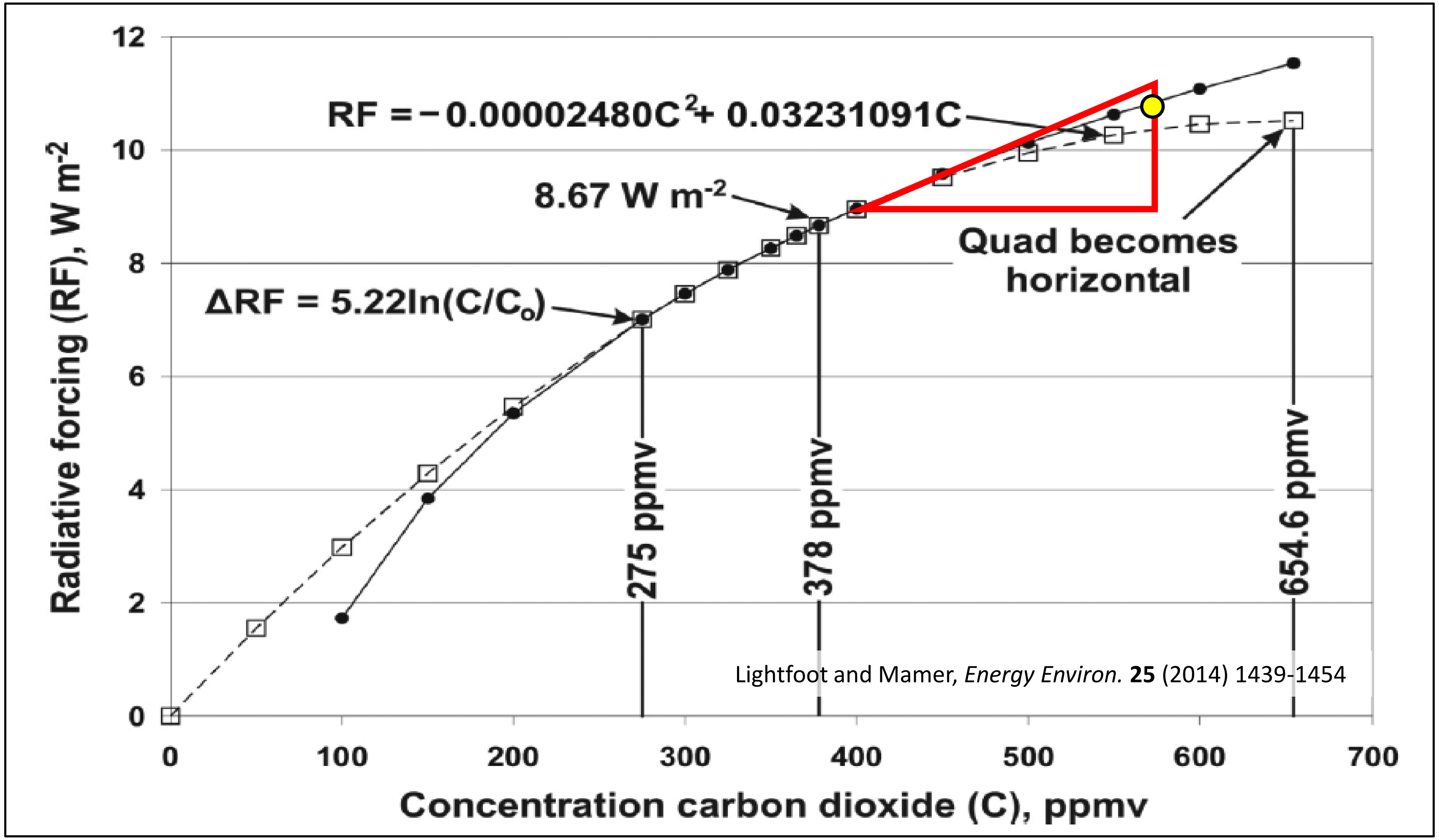
- Radiative forcing of a CFi is a non-linear function of its concentration: $F_i = f_i(c_i)$
- The overall radiative forcing is the sum of the contributions of all GHGs.
- For CO2 the functional relationship is logarithmic:

$$F_C(c_C) = \frac{F_{2x,C}}{\ln 2} \ln\left(\frac{c_C}{c_{C,ss}}\right)$$

$$\Delta F_i = \frac{\mathrm{d}f_i}{\mathrm{d}c_i}\Delta c_i = A_i \, \Delta c_i$$

$$A_C = \frac{F_{2x,C}}{c_C \ln 2}$$

ii. From GHG concentration to radiative forcing



Lightfoot and Mamer, *Energy Environ.* **25** (2014) 1439-1454

ii. From GHG concentration to radiative forcing

- Radiative forcing of a CFi is a non-linear function of its concentration: $F_i = f_i(c_i)$
- The overall radiative forcing is the sum of the contributions of all GHGs.
- For CO2 the functional relationship is logarithmic:

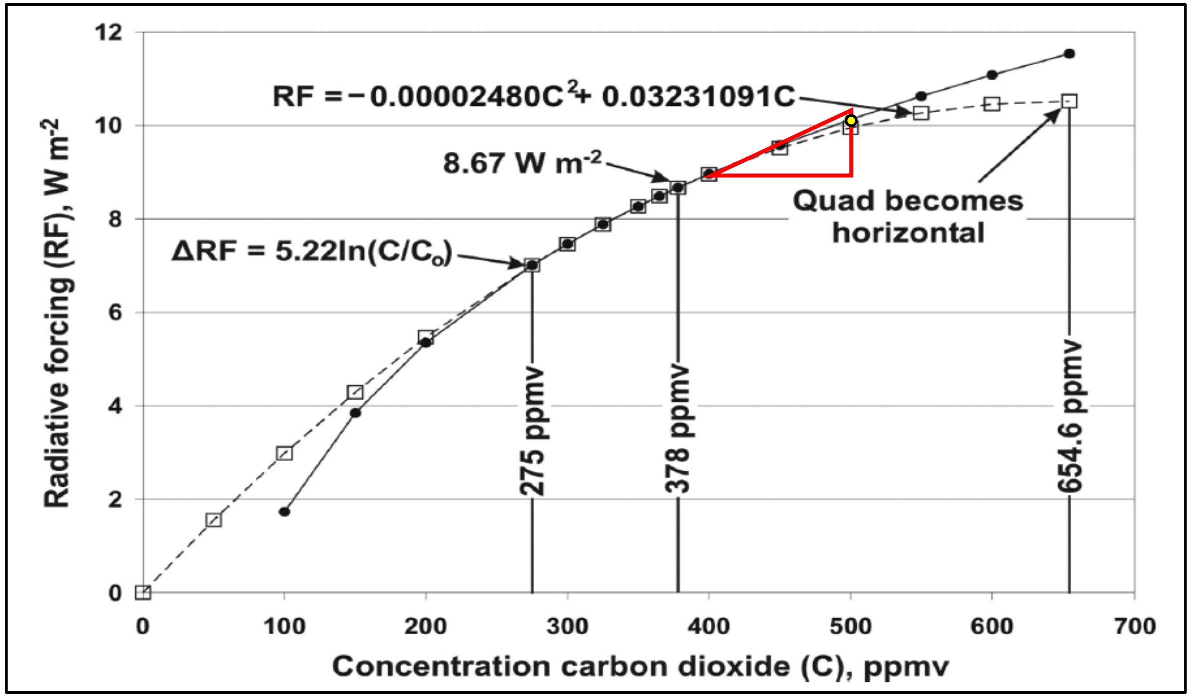
$$F_C(c_C) = \frac{F_{2x,C}}{\ln 2} \ln\left(\frac{c_C}{c_{C,ss}}\right)$$

$$\Delta F_i = \frac{\mathrm{d} f_i}{\mathrm{d} c_i} \Delta c_i = A_i \, \Delta c_i$$

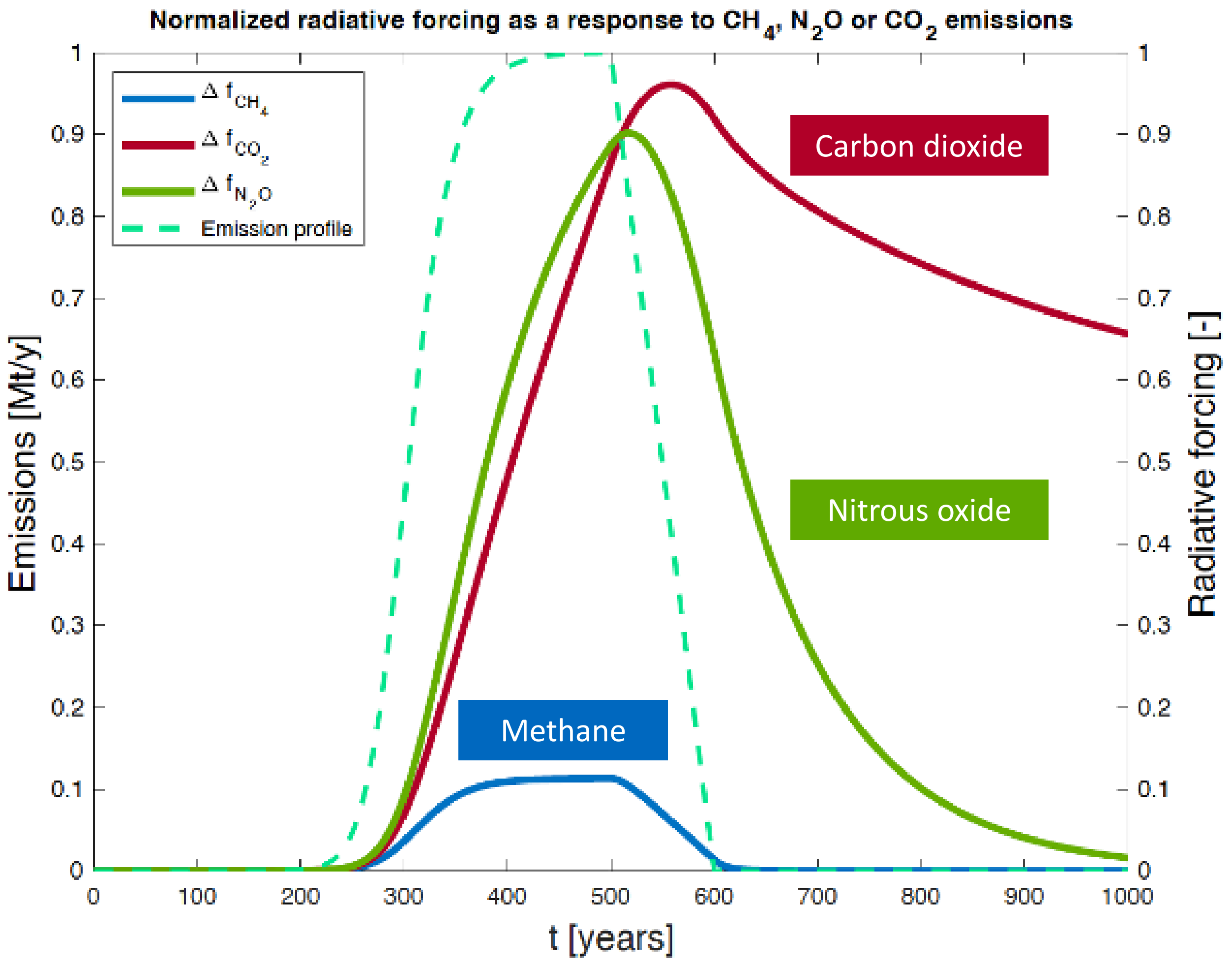
$$A_C = \frac{F_{2x,C}}{c_C \ln 2}$$

- CO2 radiation efficiency (slope of the tangent) depends on CO2 concentration, but not on its reference value.

Lightfoot and Mamer, *Energy Environ.* **25** (2014) 1439-1454



iii. SLCFs vs. LLCFs (short-lived vs. long-lived)



ii.a) Modeling T-anomaly vs. radiative forcing

- Two-layer energy balance model (s: land + near-surface ocean; d: deep ocean; $C_s/C_d \approx$ 0.07) to determine temperature anomaly, with respect to pre-industrial level.
- The solution evolves on two time scales, i.e., $s_1 \approx$ 4 and $s_2 \approx$ 250 years, as a linear functional of the overall radiative forcing, hence radiative forcing caused by one CFi has an equivalent warming effect as that of another CFj.

$$C_s \frac{\mathrm{d}T_s}{\mathrm{d}t} = F - \lambda T_s - \gamma(T_s - T_d) - \lambda'(T_s - T_d)$$

$$C_d \frac{\mathrm{d}T_d}{\mathrm{d}t} = \gamma(T_s - T_d)$$

$$T_s(t) = \sum_{j=1}^{2} c_j \left(\int_0^t F(t') \exp\left(\frac{t'-t}{s_j}\right) \mathrm{d}t' \right)$$

- Considering time scales, the classical equations used by climate scientists are recovered, e.g.:

$$\Delta T \approx \kappa_E \overline{E_C} \Delta t + \kappa_F \left(\Delta F_N + \rho \overline{F_N} \Delta t \right)$$

ii.b) Differential perturbation approach

- Let us consider the climate impacts of individual emitters, or individual countries, or individual sectors, whereby the corresponding emissions of the CFi are a small percentage of the global emissions, say in the order of a few percent or less (e.g., the whole Switzerland, or one of its specific economic sector).
- Then such emissions can be considered an emission differential, ΔE_i, with respect to all the other global emissions, which leads to a differential variation of the corresponding concentration Δc_i, which in turn yields a differential variation of the radiative forcing caused by that GHG, ΔF_i, and finally to a differential temperature anomaly, ΔT_s.
- Because of the linear functional relationship between emissions and concentrations, and between radiative forcing and temperature anomaly, and because of the linearization of the radiative forcing vs. concentration relationship, one can write the sequence of equations on the next slide.

ii.b) Differential perturbation approach

$$E_i(t) = E_{i,\mathrm{g}}(t) + E_{i,\mathrm{s}}(t) = E_{i,\mathrm{g}}(t) + \Delta E_{i,\mathrm{s}}(t)$$

$$c_i(t) = c_{i,\mathrm{g}}(t) + \Delta c_{i,\mathrm{s}}(t)$$

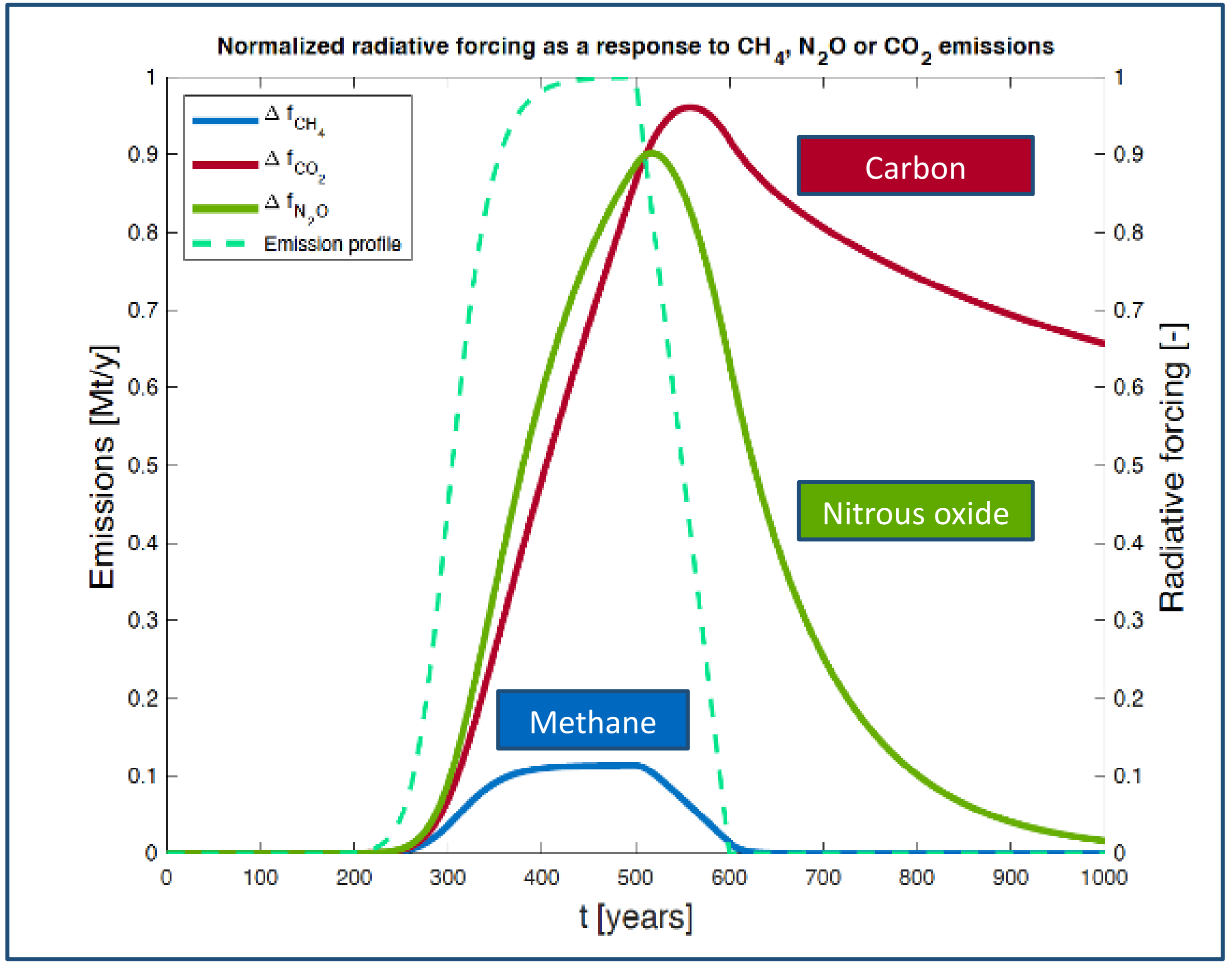
$$\Delta F_{i,\mathrm{s}}(t) = A_i\, \Delta c_{i,\mathrm{s}}(t) = A_i \int_0^t \Delta E_{i,\mathrm{s}}(t') \exp\left(\frac{t'-t}{\tau_i}\right) \mathrm{d}t'$$

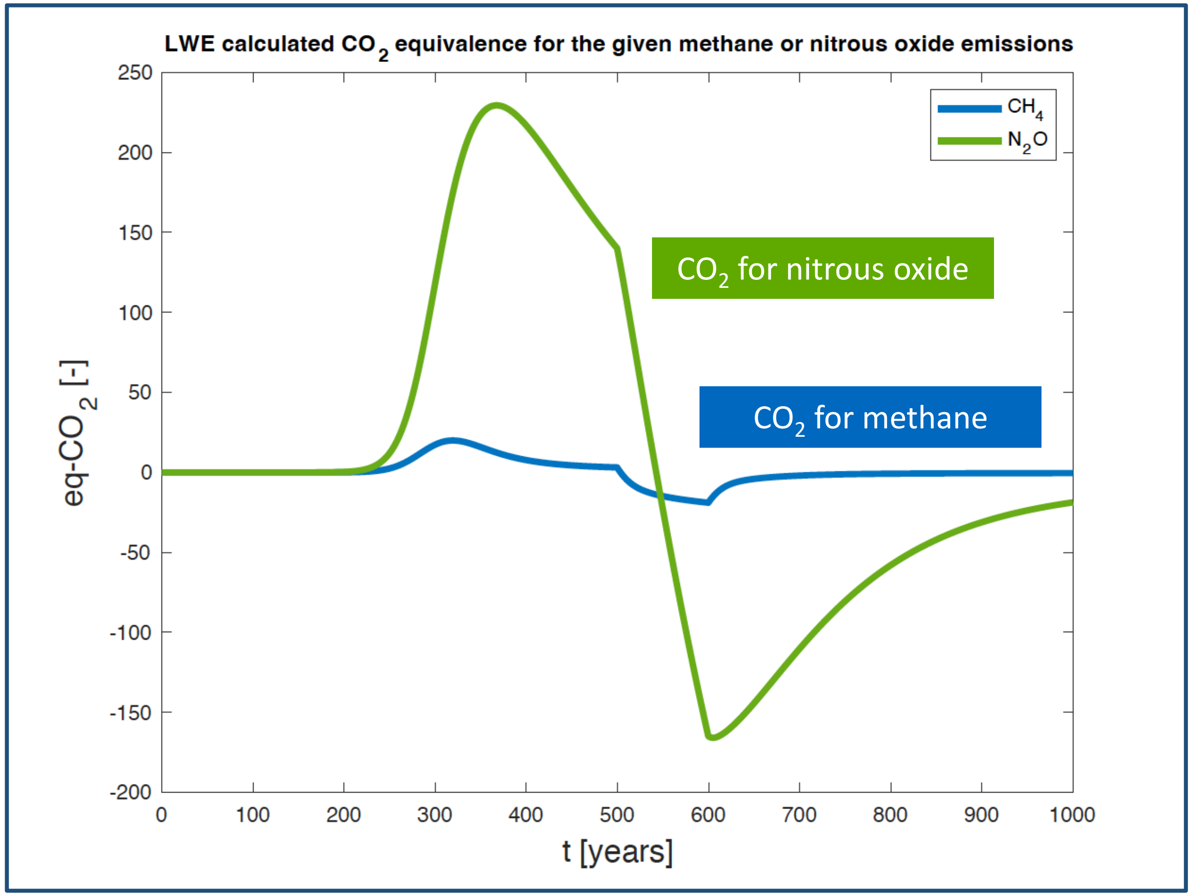
$$T_s(t) = T_{s,\mathrm{g}}(t) + \Delta T_{s,\mathrm{s}}(t) \qquad \Delta T_{s,\mathrm{s}}(t) = \sum_{j=1}^{2} c_j \left(\int_0^t \Delta F_{\mathrm{s}}(t') \exp\left(\frac{t'-t}{s_j}\right) \mathrm{d}t' \right)$$

- Through this approach, we can focus on specific emissions (national/sectoral) of interest, without the need to calibrate the model considering initial state or the evolution of past and future global emissions (but radiative efficiency depends on current state).
- Thereupon LWE can thus be established: $\Delta F_{i,\mathrm{s}}(t) = \Delta F_{C,\mathrm{s}}(t)$

Allen et al., *Environ. Res. Lett.* ***16*** (2021) 074009

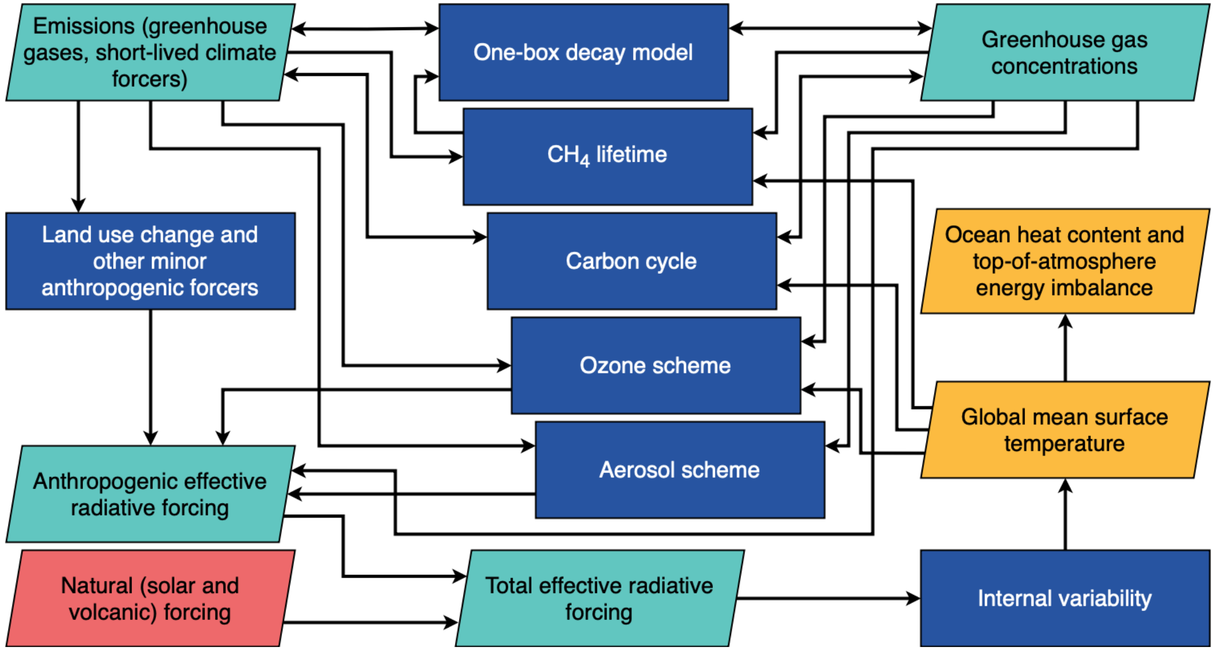
ii.b) Differential perturbation approach – LWE





iv. Comparison with FAIR model

- FaIR – Finite Amplitude Impulse Response simple climate model:
  i. reduced-complexity climate model used for scenario assessment
- The simplified model (emETH):
  i. is linear;
  ii. depends on a few parameters;
  iii. is transparent;
  iv. retains first order effects;
  v. has no nonlinear feedbacks.

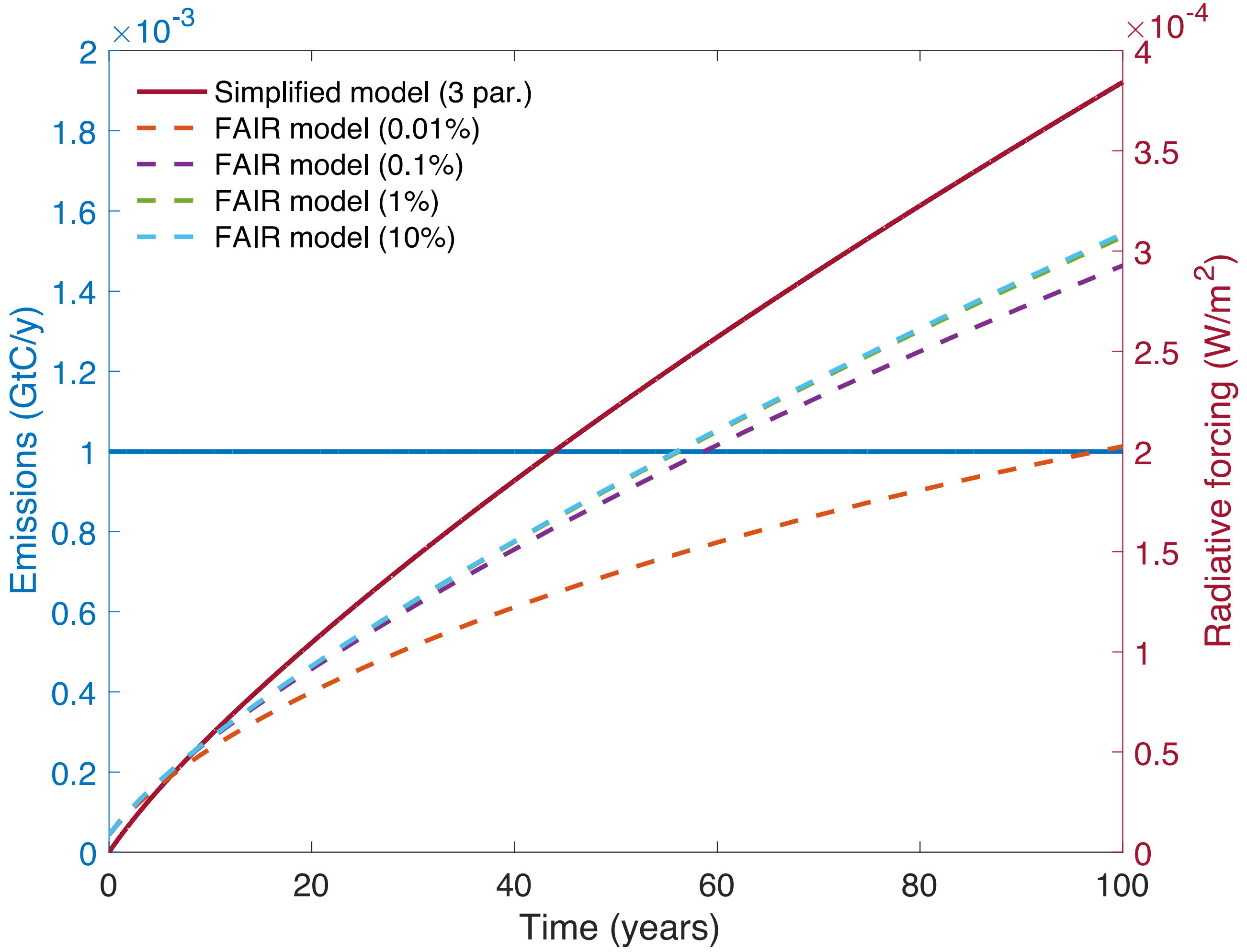


iv. Comparison with FAIR model

- FaIR – Finite Amplitude Impulse Response simple climate model
    i. is a “reduced-complexity climate model used for scenario assessment”.
- The simplified model (smETH)
    i. is linear,
    ii. depends on a few parameters,
    iii. is transparent,
    iv. retains first order effects,
    v. has no nonlinear feedbacks.
- In the scope of the project, with focus on climate policy, we aim at
    i. using emETH for scenario analysis,
    ii. simulating interesting cases with higher accuracy using FAIR,
    iii. providing BAFU with user-friendly version of emETH.

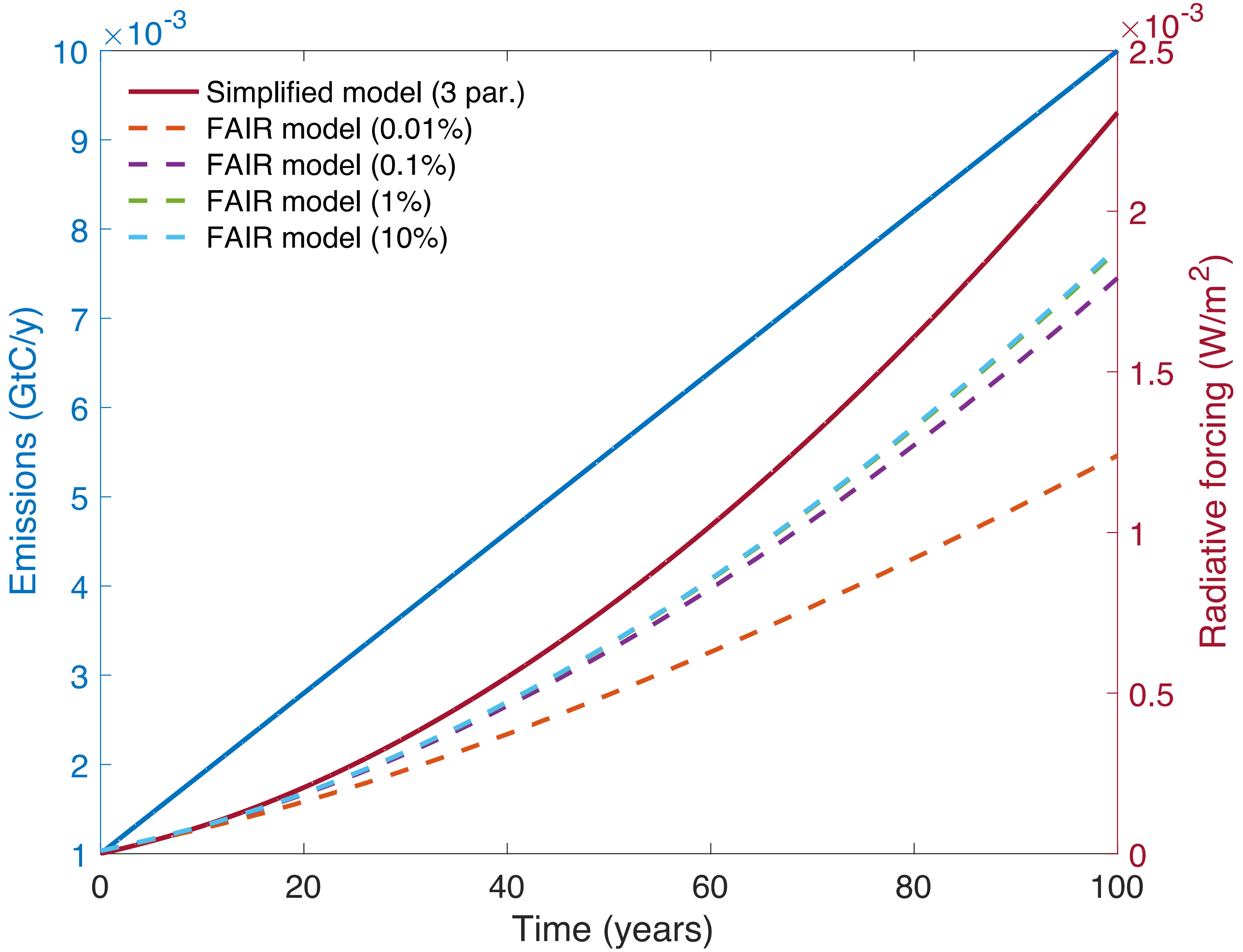
iv. Comparison with FAIR model – sustained

- CO_2 emissions: 0.001 GtC/year for 100 years, equivalent to 3.7 $MtCO_2$/year → "Specific emissions"
- FAIR model run for 4 cases, varying background emissions wrt specific emissions: e.g., dashed orange line (0.01%) shows the forcing calculated in FAIR as the difference between 10 GtC/y and 10.001 GtC/y. Similarly, blue dashed line (10%) shows the forcing calculated in FAIR as the difference between 0.011 GtC/y and 0.011 GtC/y.



iv. Comparison with FAIR model – ramping up

- CO_2 emissions increasing linearly from 0.001 GtC/year to 0.01 GtC/y over 100 years, equivalent to 3.7 $MtCO_2$/year → "Specific emissions"
- FAIR model run for 4 cases, varying background emissions wrt specific emissions
-

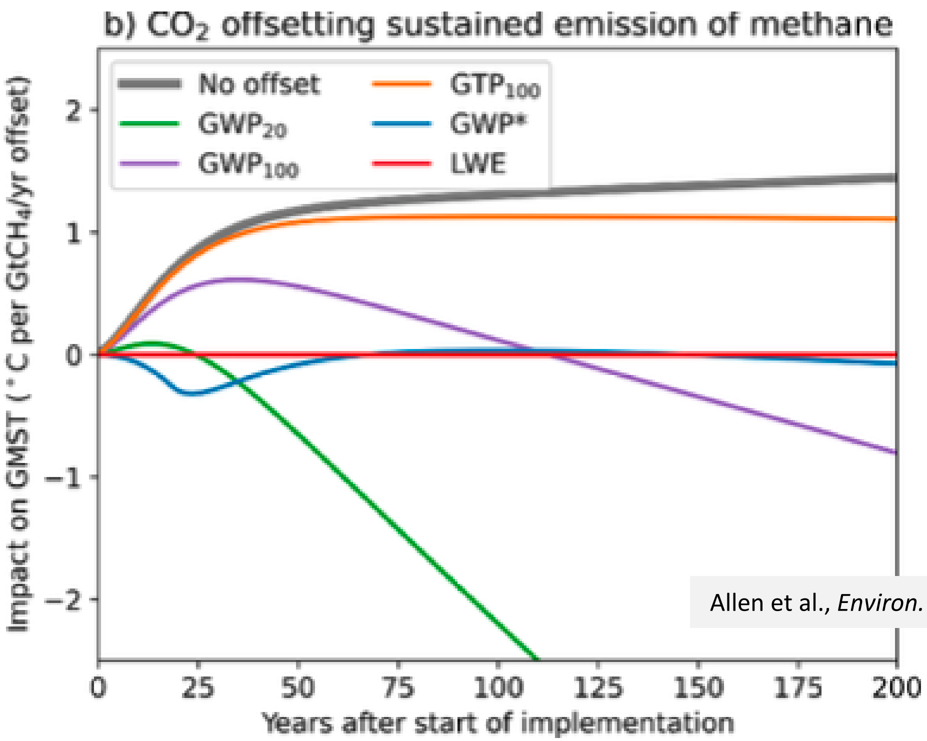


2. CO_2-eq. for non-CO_2 effects – Objectives

- Establishing CO2-equivalence between non-CO2 emissions and CO2-emissions for the two sectors of interest, i.e., agriculture and aviation by:
    i. considering different time horizons (not only from 1990 to 2060 as to EP 2050+, but also extending backward in the past, and possibly further into the future);
    ii. considering different reference conditions (1990 emissions levels, pre-industrial emissions levels, no emissions)
    iii. using different scenarios, e.g., Net Zero 2050 Standard, Business as Usual as to EP 2050+,..., including those proposed by the agricultural sector;
    iv. applying different approaches, i.e., metrics or models, namely GWP100, GWP20, GWP* and LWE (Linear Warming Equivalent);
    v. developing and implementing methodologies relevant for the different approaches, that are used not only in this study, but possibly also in future studies based on scenario analysis.

2. CO_2-eq. for non-CO_2 effects – Approaches

- software platform available: emETH
- including different metrics



Allen et al., *Environ. Res. Lett.* ***16*** (2021) 074009

2. CO_2-eq. for non-CO_2 effects – Approaches

- software platform available: emETH
- including different metrics
- acquired, analyzed, and implemented (partially) the EP2050+ data
- key questions:
  - what is the "global" reference?
  - what is the "specific" perturbation?
  - what is the onset point in time?

$$E_i(t) = E_{i,\mathrm{g}}(t) + E_{i,\mathrm{s}}(t) = E_{i,\mathrm{g}}(t) + \Delta E_{i,\mathrm{s}}(t) \qquad c_i(t) = c_{i,\mathrm{g}}(t) + \Delta c_{i,\mathrm{s}}(t)$$

$$\Delta F_{i,\mathrm{s}}(t) = A_i\, \Delta c_{i,\mathrm{s}}(t) = A_i \int_0^t \Delta E_{i,\mathrm{s}}(t')\, \exp\left(\frac{t'-t}{\tau_i}\right) \mathrm{d}t'$$

Allen et al., *Annu. Rev. Environ. Resour.*, 2022

ANNUAL REVIEWS

Annual Review of Environment and Resources

Net Zero: Science, Origins, and Implications

Myles R. Allen,[1,4] Pierre Friedlingstein,[2,3] Cécile A.J. Girardin,[1] Stuart Jenkins,[4] Yadvinder Malhi,[1,5] Eli Mitchell-Larson,[1] Glen P. Peters,[6] and Lavanya Rajamani[7]

[1]Environmental Change Institute, School of Geography and the Environment, University of Oxford, Oxford, United Kingdom; email: myles.allen@ouce.ox.ac.uk

[2]College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, United Kingdom

[3]Laboratoire de Météorologie Dynamique, Institut Pierre-Simon Laplace, CNRS-ENS-UPMC-X, Paris, France

[4]Department of Physics, University of Oxford, Oxford, United Kingdom

[5]Leverhulme Centre for Nature Recovery, University of Oxford, Oxford, United Kingdom

[6]CICERO Center for International Climate Research – Oslo (CICERO), Oslo, Norway

[7]Faculty of Law, University of Oxford, Oxford, United Kingdom

Annu. Rev. Environ. Resour. 2022. 47:19.1–19.39

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-112320-105050

Keywords

carbon budget, net zero, climate neutrality, nature-based solutions, greenhouse gases, carbon markets, Paris Agreement

Abstract

Allen et al., *Annu. Rev. Environ. Resour.*, 2022

This review explains the science behind the drive for global net zero emissions and why this is needed to halt the ongoing rise in global temperatures. We document how the concept of net zero carbon dioxide (CO_2) emissions emerged from an earlier focus on stabilization of atmospheric greenhouse gas concentrations. Using simple conceptual models of the coupled climate–carbon cycle system, we explain why approximately net zero CO_2 emissions and declining net energy imbalance due to other climate drivers are required to halt global warming on multidecadal timescales,

Increasing numbers of net zero targets have since been adopted by countries, cities, corporations, and investors. The degree to which any entity can claim to have achieved net zero while continuing to rely on distinct removals to compensate for ongoing emissions is at the heart of current debates over carbon markets and offsetting both inside and outside the UNFCCC. We argue that what matters here is not the precise makeup of a basket of emissions and removals at any given point in time, but the sustainability of a net zero strategy as a whole and its implications for global temperature over multidecadal timescales. Durable, climate-neutral net zero strategies require like-for-like balancing of anthropogenic greenhouse gases sources and sinks in terms of both origin (biogenic versus geological) and gas lifetime.

Allen et al., *Annu. Rev. Environ. Resour.*, 2022

Constructive ambiguity plays a vital role in negotiation, and net zero is not the first example of everyone agreeing that something is a good idea before agreeing exactly what it means. The advantage of net zero as a term is that is it just a number and therefore has to refer to something: net zero what? If the goal is net zero emissions, which gases, how are they aggregated, and which (biological and geological, natural and anthropogenic) sources and sinks are included? If the goal is net zero additional warming, on what timescale? Imposing a restrictive definition on net zero itself may simply be divisive, and energy might be better spent on understanding the implications of applying the term to different target quantities, which we hope will be supported by the quantitative framework provided in this review.