CO_2-Equivalence and the Transition to Stabilisation

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Abstract

The relations between the various greenhouse gases are specified in terms of two distinct forms of CO_2-equivalence: emission-equivalence and concentration-equivalence. Emission-equivalence is usually expressed in terms of radiative effect over a 100-year lifetime (i.e. a 100-year global warming potential). Concentration-equivalence reflects the instantaneous radiative effect of the concentrations and so corresponds to using the infinite-time limit of the global warming potential. These considerations are reflected in the concept that for stabilisation at any target concentration of CO_2, there is a 'carbon budget', i.e. a limit to the total amount of carbon that can ever be emitted [1, 9, 10]. Such a restriction does not apply for shorter-lived gases such as N_2O and CH_4. A more detailed analysis of the stabilisation profiles for CO_2 [4, 2] goes beyond the 'fixed CO_2 budget' and the allowable residual emissions provide a basis for defining 'CO_2-equivalent emissions' under stabilisation. The discussion draws on experience in contributing the Garnaut Review of Climate Change [6] in Australia.

1 Greenhouse gas equivalence?

Anthropogenic global warming is the consequence of a range of trace gases. Since mitigation measures entail costs, some quantitative measure is required for determining the relative importance of the gases in order to avoid costs that are disproportionate to the benefits. Two forms of CO_2-equivalence have been defined [7: glossary] in order to address such needs:

concentration equivalence which is defined as equivalence in radiative forcing and is the property of a mixture of gases, **and**

emission equivalence which looks at the integrated radiative effect of emissions, and compares gases using the 'Global Warming Potential' (GWP) defined by:

$$\mathrm{GWP}_X(\tau) = \frac{a_X}{a_{CO2}} \frac{\int_0^\tau R_X(t)\,dt}{\int_0^\tau R_{CO2}(t)\,dt} \tag{1}$$

where a_X is the radiative forcing per kg of gas X and $R_X(t)$ is a response function giving the proportion of gas X remaining in the atmosphere after time t — see 'Notation' section at end of poster.

Thus 'emissions equivalence' is really a family of definitions whose relations depend on the time horizon, τ. The Kyoto Protocol defines CO_2-equivalence using a 100-year GWP.

'Concentration-equivalence' also has a degree of variation in the definition, depending on whether or not various short-lived components such as aerosols and tropospheric ozone are included. One approach [2] is to include all components when analysing past and present conditions, and consider only the long-lived components when considering future commitments.

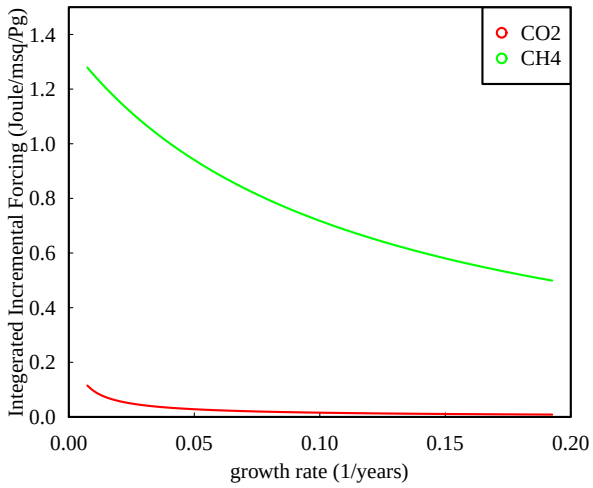
The limitations of setting targets on the basis of emission-equivalence are illustrated in specific examples by Reilly et al. [11], in particular in their figure 2a. Case 2' is stringent reductions of CO_2 only, while 3' is the "economically optimum" CO_2-emission-equivalent reductions. Using CO_2-emission-equivalence leads to large differences in temperature outcomes (presumably because it leads to large differences in CO_2-equivalent concentrations).

2 Analysis

The Laplace Transform formalism provides a powerful way of analysing systems that are linear (or which can be linearised). In particular, in a linear system with fixed emission growth rate, λ, $r_X(p)$ (which is the Laplace transform of the response function $R_X(t)$) can define an exact equivalence between greenhouse gases with a scaling α given by

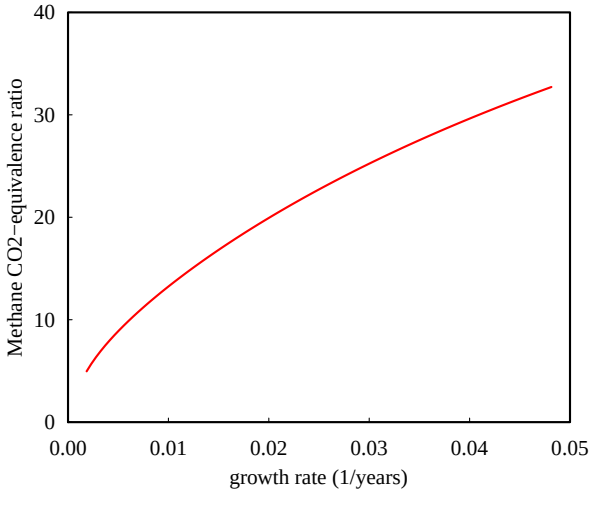
$$\alpha_X(\lambda) = \frac{a_X}{a_{CO2}} \frac{r_X(\lambda)}{r_{CO2}(\lambda)} = \frac{a_X}{a_{CO2}} \frac{\int_0^\infty e^{-\lambda t} R_X(t)\, dt}{\int_0^\infty e^{-\lambda t} R_{CO2}(t)\, dt} \tag{2}$$

Thus when emissions (and thus the increase in concentrations) exhibit exponential growth of 100λ percent per annum, emissions of each kg of CO_2 are equivalent to emitting $\alpha_X(\lambda)$ kg of gas X. While the time-horizon, τ, in the GWP definition (1) is generally motivated in terms of time-scales of interest, treating the GWP definition (1) as an approximation to (2) suggests that the equivalence is most meaningful when the 'time-scale of interest' corresponds the e-folding time of emissions growth.



Laplace transform of radiative forcing from pulses of CO_2, CH_4.

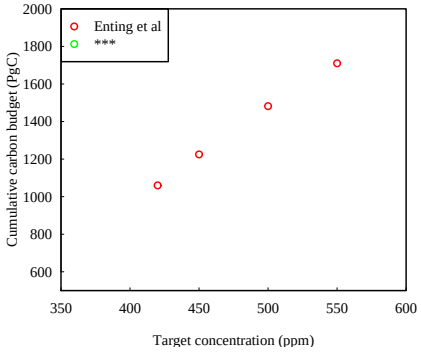
Ratios of Laplace transform of radiative forcing from pulses of CH_4 and CO_2, as function of 'growth rate', p
— the factor α_{CH4} defined by equation 2.



3 Carbon budgets and beyond

A number of analyses [e.g. 1, 6, 9, 10] have considered emission targets in terms of a 'carbon budget' — a limit to the total amount of carbon that can ever be emitted consistent with a given target concentration. There are two related considerations:

- the 'carbon budget' concept is a 'diagnostic statistic' of behaviour on times scales of order 100 years — it is not a mechanistic description of carbon cycle dynamics;
- it gives only an approximate description of stabilisation.

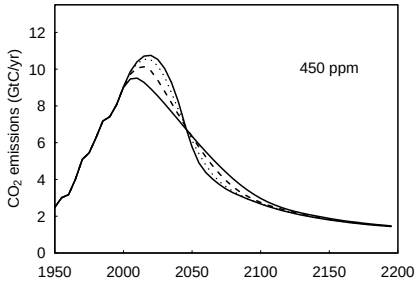


Estimates of the 'carbon budget' for various target concentrations [2].

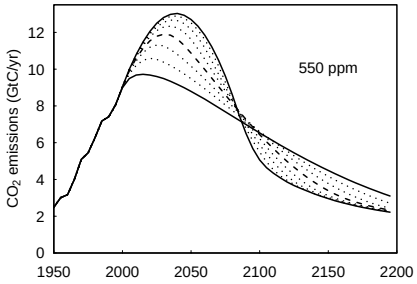
For others gases the budget concept is a much poorer approximation. Concentrations of non CO_2 gases can be stabilised with fixed emissions related to target mass, M_X^{target}, and atmospheric lifetime, T_X, by:
$E_X^{\text{stabilisation}} = M_X^{\text{target}}/T_X$

Thus equivalence between emissions of non-CO_2 gases corresponds to equivalence of a_X/T_X. This corresponds to the GWP with infinite time horizon, in which case, the GWPs of all non-CO_2 gases become zero — in the very long-term, only CO_2 matters in this approximation.

CO_2 can be re-integrated into this framework by appreciating that the 'carbon budget' concept is indeed an approximation. The examples below show that a small residual emission rate is consistent with stabilising concentrations.



Estimates of carbon emissions for various target concentrations (from [2]).



In these terms, an 'emission equivalence' factor, appropriate for stabilisation can be represented as:

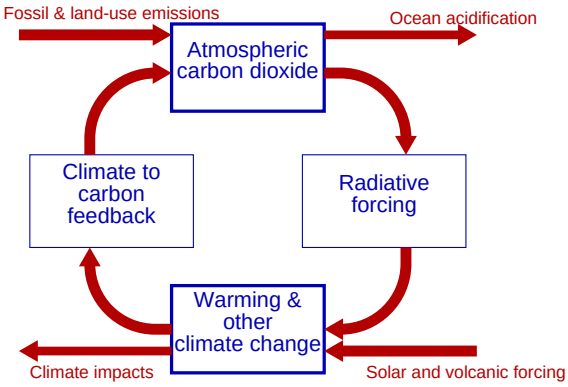
$$\alpha'_X = a_X/T_X \Big/ a_{\text{CO2}} \frac{\partial M_{\text{CO2}}^{\text{target}}}{\partial E_{\text{CO2}}^{\text{residual}}} \tag{3}$$

4 Feedbacks

Enting [3] used the Laplace Transform formalism to capture climate-to carbon feedbacks using response functions, $U(t)$, giving the warming response to radiative forcing, and $H(t)$ describing an additional CO_2 source from warming which is denoted $W(t)$. Denoting their respective Laplace Transforms, $u(p)$, $h(p)$ and $w(p)$) gives:

$$w(p) = u(p)[f(p) + a_{CO2}\, q(p)] \quad (4)$$

$$q(p) = r(p)[s(p) + h(p)\, w(p)] \quad (5)$$



whence

$$w(p) = \frac{u(p) f(p) + a_{CO2}\, u(p)\, r(p)\, s(p)}{1 - a_{CO2}\, u(p)\, r(p)\, h(p)} \quad (6)$$

$$q(p) = \frac{r(p)[s(p) + f(p)\, h(p)\, u(p)]}{1 - a_{CO2}\, u(p)\, r(p)\, h(p)} \quad (7)$$

Forcing from emissions, $S(t)$, or radiative change, $F(t)$, (with respective Laplace transforms $s(p)$, $f(p)$) is amplified by a feedback factor: $\kappa_{\rm FB} = 1/[1 - a_{CO2}\, u(p)\, r(p)\, h(p)]$.

For multi-decadal time-scales, the C4MIP study [5] gives $\kappa = 1.18 \pm 0.11$ from 11 models, ranging from κ = 1.04 to 1.44 (with only the CO_2 term included).

Generalising this to consider $H_X(t)$, the emissions of gas X in response to warming shows that the effect of radiative forcing, $f(p)$, or greenhouse gas emissions, $s_X(p)$, is amplified by feedback factor:

$$\kappa_{\rm FB} = \frac{1}{1 - u(p) \sum_X a_X\, r_X(p)\, h_X(p)} \quad (8)$$

Notionally, the carbon fluxes from feedbacks would need to be subtracted from emission targets in order to match targets calculated without reference to feedbacks.

However, to the extent that the CO_2 response, $R(t)$, $r(p)$ has been calibrated against 20th century changes, some climate-carbon feedbacks will have been implicitly included [2], in which case, the CO_2 feedbacks, at least on multi-decadal timescales, should be excluded from the sum in equation (8).

5 Beyond linearity?

With anthropogenic climate change already occurring, and a commitment to further change due to past emissions, mitigation needs to be considered in terms of reducing, rather than avoiding, dangerous impacts.

There is considerable uncertainty in aspects of the carbon-climate system, both in the feedbacks and the underlying response, parameterised above through $U(t)$, $u(p)$. [$u(0)$ is proportional to the climate sensitivity, while $u(p > 0)$ parameterises transient climate sensitivities.] Consequently, mitigation analysis needs to be in terms of ranges that span the uncertainty [e.g. 13].

There is great asymmetry in the distribution of risk associated with these ranges — damage functions grow faster than linearly and there is the possibility of instabilities, irreversibility and 'tipping points'.

For example although the 450 ppm (CO_2 concentration equivalent) target, is often thought of as notionally 'safe' with 2°C warming, 450 ppm of actual CO_2 increases pH in ocean to a point where aragonite becomes unstable even at the surface.

An 'extreme' possibility is reflected in Lovelock's view of a third hotter climate state [8], (in addition to the glacial and interglacial states). In a self-regulated system (which is how Lovelock's Gaia theory envisages the geosphere-biosphere system), once self-regulation fails, the establishment of a new conditions can be very abrupt.

Do these considerations change the way in which equivalence should be considered?

For example, can short-term reductions in CH_4 (at the expense of delaying CO_2 reductions) provide pathway to avoid tipping point? i.e. should emission-equivalence be defined with a shorter τ ($\ll 100$ years) rather than longer ($\gg 100$ years) as is implied by previous analysis?

There would seem to be two related pre-conditions for adopting such a changed definition of CO_2-equivalence:

- we know where the tipping point is; and
- in particular, the tipping point has not already been passed.

Neither of these can be asserted with any certainty.

6 Summing up

The two different forms of emission-equivalence each capture legitimate aspects of greenhouse gas forcing, but the existence of two approaches complicates discussion. In either case, CO_2-equivalence must be regarded as a diagnostic statistic. There are severe constraints on using CO_2 emission-equivalence (based in GWPs) as a computational tool. The limitations are discussed in generic terms by Smith and Wigley [12] and illustrated in specific examples by Reilly et al. [11]. (The Garnaut economic analysis [6] used GWP-based 'emission equivalence' with the 100 year time horizon).

When GWPs are defined with increasingly longer time horizons and used to define CO_2-equivalent emissions, the equivalence relations formally approach those defined by 'concentration-equivalence', but focus all constraints on CO_2. This result that 'only CO_2 matters' is equivalent to noting that CO_2 has a fixed 'budget' while other gases do not. Appreciating that the CO_2 budget is only an approximate description of carbon cycle responses has the potential to give a practical quantification of CO_2 emission equivalence under conditions of stabilisation via equation (3). These principles remain applicable when linear feedbacks are considered. The location of potential 'tipping points' in the earth system remains too uncertain to be the basis of any more 'targetted' trade-off between emissions of the different gases.

Notation

a_X Radiative forcing per kg of gas X.

$H_X(t)$ Response function specifying emissions of gas X from unit (global) temperature increase, with Laplace Transform $h_X(p)$.

p Transform variable in Laplace Transform, in years^{-1}.

$R_X(t)$ Impulse response function of emissions of gas X, with Laplace Transform $r_X(p)$.

$S_X(t)$ Emission history of gas X, with Laplace Transform $s_X(p)$.

t Time, in years.

T_X Atmospheric lifetime of gas X.

$U(t)$ Temperature response for unit pulse of radiative forcing, with Laplace Transform $u(p)$.

κ_{FB} Amplification factor from feedback loop(s).

λ Growth rate for emissions, concentrations etc in linear approximation.

$\xi \ldots \xi_k$ Gain around feedback loop ... from process k.

τ Time horizon for defining GWPs.

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