Submission to Caps and Targets Review

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Summary

This submission reviews a number of the scientific issues that should be taken into account when recommending caps and targets for Australian emissions of greenhouse gases. Starting from the position that actions by Australia need to be undertaken in the global context, this submission goes from issues affecting global targets through to discussions of burden sharing before noting issues specific to Australian caps and targets.

Two aspects are seen as essential:

- caps and targets must be constrained by the need for an achievable emissions trajectory beyond the planning period;
- caps and targets need to be robust in the sense of being able to be adapted to changes arising from increasing scientific knowledge.

A technical appendix expands on these issues, citing specific scientific studies. The objective of this submission is to elucidate some of the important concepts, implicitly defining the types of detailed calculations that will be required in setting caps and targets. Given the short timescale for submissions, no attempt has been made to give even an indicative quantification of these various issues. Such quantification needs to be part of the Climate Change Authority's Caps and Targets review.

Disclaimer

Due to short time provided for making submissions, it has not been possible to undertake a new search of the current literature. There will almost certainly be more up-to-date references, as well as a wider range of references, than what is provided here. Similarly, it has in general not been possible to perform new calculations for this submission. This submission represents personal judgements by the author and does not represent an official position by The University of Melbourne.

Global context

Since mitigation actions by Australia only make sense in a global context, Australia's caps and targets need to be considered in terms of global targets **and how these global targets might evolve over time.** Reasons that global targets might change are:

- an acceptance that, in the light of emerging scientific quantification of impacts, a target of 2 degrees is too high;
- an acceptance that a 50% chance of exceedance of the 2 degree target is an unacceptably high risk, especially if emerging technology reduces the difficulty of mitigating climate change;
- an acceptance of an alternative to the use of GWPs for quantifying non-CO_2 emissions;
- emerging science, clarifying current uncertainty between climate sensitivity vs cooling by aerosols, leading to a tightening of the current uncertainty range and a shift in the median (50%) point;
- emerging science, quantifying the role of feedbacks connecting the climate system and biogeochemical cycles, changing the current uncertainty range and giving a shift in the median (50%) point.

Carbon budget

The level of CO_2 mitigation required to avoid exceeding specified temperatures and/or CO_2 concentrations can be characterised in terms of a 'carbon budget' — the cumulative amount of CO_2 that can be emitted.

While scientific analysis of carbon budgets is in terms of a budget cap 'forever', the *CCA Caps and Targets Review Issues Paper* is phrased in terms of budgets for specific periods, i.e. implicitly partitioning the 'forever' budget into budgets for a shorter term (to be the subject of the review) and a longer term. Clearly, any proposed recommendation for a shorter term budget must:

- leave some of the 'total' budget available for the longer term;
- be able to leave some of the total budget available even if current estimates of the total available budget for Australia change due to changes (including specific formal rules) in the global budget or the way it is partitioned between nations.

The concept of a CO_2 emissions budget can be useful for analysing CO_2. However extending this to a 'CO_2-equivalent emissions budget' may well, for the reasons discussed below, lead to serious mis-allocation of mitigation effort.

Non-CO2 gases

Different gases are lost from the atmosphere at different rates. The significance of CO_2, apart from the very large amount of emissions, is that some CO_2 resulting from these emissions remains in the atmosphere for millennia.

- Comparisons between greenhouse gases can be made in terms of concentrations (usually in terms of CO_2-equivalent concentrations) or in terms of emissions (usually in terms of CO_2-equivalent emissions). These are two different things (see glossary) and failure to distinguish them (as in *CCA Caps and Targets Review Issues Paper*) can lead to badly flawed analyses.

- For many years, there has been a scientific awareness that the use of global warming potentials (GWPs) to define emission equivalence is highly problematic and can lead to perverse outcomes.

- For the purposes of defining a target of radiative forcing, the emission-equivalence defined using GWPs (as, for example in the Kyoto Protocol) over-weights the importance of short-lived greenhouse gases.

- Suggestions for dealing with a 'climate emergency' by giving yet more priority to methane reductions rather than CO_2 reductions are the equivalent of dealing with personal financial stress by applying for additional credit cards.

- A GWP-based approach would require that ongoing methane emissions from agriculture would need to be balanced by ever-increasing amounts of stored carbon, which is ultimately unachievable. Going beyond the crude approximation of using GWPs shows that the climate impacts of ongoing methane emissions from agriculture can be offset by one-off storage of carbon.

- Stabilising radiative forcing is consistent with ongoing emissions of methane and other short-lived gases. Stabilising radiative forcing from short-lived gases requires holding emissions at a fixed level. The actual level will affect the 'carbon budget' associated with any chosen target temperature.

Aerosols

The climatic role of aerosol particles in the atmosphere is significant but poorly quantified. A variety of mechanisms are involved. With high probability, the net effect is one of cooling. Thus aerosols are serving to mask some of the 'committed warming' from the long-lived greenhouse gases.

There is a risk that any significant reduction of aerosol emissions by China (e.g. for health and environment reasons) might lead to a relatively abrupt warming, and a consequent need to revise global (and thus national) mitigation targets.

Feedbacks

Climate-to-carbon feedbacks may lead to additional emissions of carbon that effectively reduce the size of the 'budget' available for future human emissions.

The current quantitative understanding of such feedbacks is relatively poor. In addition, because of the flexibility in what is classed as a feedback, any quantitative discussion requires careful specification of the effects that are being analysed.

Burden sharing

The 'carbon budget' concept focuses attention on how the remaining part of the available budget should be partitioned. In particular, to what extent should partitioning of the future component of the budget take into account the way in which past emissions have been distributed between nations.

Australia

There is global consensus on neither targets nor on burden-sharing regimes to partition any global target budget. Therefore Australian caps are targets must maintain enough flexibility to accommodate any future global measures.

Technical appendix

1 Global context

The basis of this submission is the assumption that caps and targets of Australia need to be framed in manner that is consistent with what is being done by the rest of the world.

Thus, setting targets for Australia needs to consider global targets **and how such targets may change over time**.

As a reference case, we consider a target, set at 450 ppm CO_2-equivalent concentration for long-lived greenhouse gases in the atmosphere. Such a level has been assessed as having a 50% chance of keeping global warming at or below 2°C above pre-industrial levels.

This target, and any associated emissions target, may need to change for a variety of reasons, including

- The uncertainties in the relation between concentrations and temperature can be expected to reduce over time from both improved understanding of the science and a longer observational record. Such reduction in uncertainty may mean a contraction towards one end or other of the current range of uncertainty and thus the median warming from 450 ppm CO_2-eq may, in the future, be found to be higher or lower than 2°C. In particular, improved understanding of the role of aerosols (see below) could be expected to reduce the uncertainty.

- A 2°C target may, in the future, be judged to be too high. It must be recalled that the 2°C is a global average — warming over continents (and at high latitudes) is expected to be greater. It can be expected that emerging science will lead to a better quantification of the climate impacts, even if only from the passage of time.

- Similarly, a 50% risk of exceedance of the 2°C target may be judged to be an unacceptably high risk.

- Climate-to-carbon feedbacks may release additional CO_2 that effectively needs to be included in the 'budget cap', thereby reducing the amount of direct anthropogenic emissions permitted within the global emissions budget.

2 Carbon budget

The term 'carbon budget' (as used here) refers to the amount of carbon (as CO_2) that can be emitted consistent with the atmosphere remaining under a specified CO_2 concentration.[1]

[1] This usage of the term 'carbon budget' is a relatively recent concept. An older usage refers to how the carbon fluxes to and from the atmosphere are partitioned between the different reservoirs.

This amount of carbon is approximately independent of the exact timing of the release although for a given target concentration, a very slow release allows a larger budget than does rapid release.

The concept of such a 'carbon budget' was analysed by Matthews et al. [2009] and Allen et al. [2009]. To a first approximation, the relation between the budget (i.e. the cumulative emissions) and the target concentration (expressed as an increase above the pre-industrial 280 ppm) is a simple proportionality. This can be described by the 'airborne fraction of cumulative emissions' (f_{AFCE}). This specifies what fraction of cumulative emissions remain in the atmosphere, the remainder being taken up by the oceans and terrestrial vegetation.

Thus the budget for a target concentration, C_{target}, can be expressed as:

$$E_{\mathrm{C:cumulative}} = (C_{\mathrm{target}} - 280) \times 2.13/f_{\mathrm{AFCE}}$$

where the factor 2.13 converts concentrations in ppm to atmospheric carbon content in GtC.

If the emissions are expressed in terms of Gt CO_2 then

$$E_{\mathrm{C02:cumulative}} = (C_{\mathrm{target}} - 280) \times 2.13 \times (44/12)/f_{\mathrm{AFCE}}$$

For long-term changes, beyond the period of peak emissions, the value of f_{AFCE} is about 0.3 [Matthews et al., 2009, Lauder et al., 2013]. (On time scales of millennia, it drops to around 0.1, becoming effectively zero after times of order 10^5 years.)

Analyses by Matthews et al. [2009] and Allen et al. [2009] indicate that while different pathways will lead to departures from this simple proportionality between emissions and concentration, when considering temperature changes there is a partial compensation, so that for temperature changes the dependence on the emission pathway is proportionally less than for concentrations, when each is related to cumulative emissions.

As noted above, the 'carbon budget' concept is an approximation. Calculations undertaken for the IPCC report on *Radiative Forcing of Climate Change* indicate that stabilising CO_2 concentrations is consistent with having a 'capped' budget, followed by a very small level of ongoing CO_2 emissions- perhaps as much as 1 GtC per year [for details, see Enting et al., 1994].[2] This rate is primarily determined by the rate at which the cumulative emissions would be transported to the deep oceans. Note however, that climate-to-carbon feedbacks (see below) could reduce the level of such 'allowable' ongoing CO_2 emissions.

Raupach et al. [2011] have reviewed some of these aspects of the carbon cycle.[3]

3 Non-CO2 gases

While CO_2 is the largest contribution to changes in the Earth's energy balance, other atmospheric constituents play a significant role, as shown in Figure 1 which is taken from Figure 2.4

[2] This is of order 0.1 tonne of carbon per year per person, assuming global populations stabilises at around 9 billion.

[3] It has not been possible to integrate these results into the present submission.

in the IPCC Synthesis Report of the Fourth IPCC Assessment of Climate Change.[4]

The extent to which the various greenhouse gases affect the Earth's energy balance is usually characterised in terms of radiative forcing. This provides a basis for defining 'equivalence' between greenhouse gases (or mixtures thereof) if they have the same radiative forcing. This equivalence is not exact (due to differences such as spatial distribution, see IPCC reports and references therein) but this 'concentration equivalence' provides an important way of describing multi-gas distributions.

In contrast to 'concentration-equivalence', any attempt to provide a workable definition of 'emission equivalence' encounters serious problems. This is because different gases are lost from the atmosphere on different time scales. Thus any definition of 'emission equivalence' needs to make a choice about how different time periods are compared. Having made such a decision the effects of nominally equivalent emissions may differ greatly when compared if time periods are being compared in a way that differs from the way that is used in the definition of equivalence.

There is an extensive literature, noting the limitations of the concept of emission-equivalence as defined using the GWP and/or proposing alternatives [e.g. O'Neill, 2000, Manne and Richels, 2001, Shine et al., 2005, Johansson et al., 2006, Shine, 2009]. A comprehensive review of alternative metrics is given by Fuglestvedt et al. [2003].

A specific example of how nominally equivalent emission pathways lead to disparate outcomes is given by Reilly et al. [1999]. One approach to specifying appropriate metrics for multi-gas pathways is to include time-varying economic weightings into the metric [see Fuglestvedt et al., 2003, and references therein].

There is a solution to the problem of defining 'equivalent emissions' metric that can be defined within atmospheric science, without economic weighting, thus allowing choices between equivalent reductions on the basis of lowest cost. The equivalence is in terms of the Forcing equivalent index (FEI) defined by Wigley [1998]. However it involves comparisons across multiple times and so is hard to operationalise.[5]

A special case of the generic FEI solution was described by Lauder et al. [2013] who determined that, on time scales of decades to many centuries, the effect of on-going agricultural emissions of methane could be balanced by a one-off storage of carbon. They proposed that a one-off sequestration of 1 t of carbon would offset an ongoing methane emission in the range 0.90-1.05 kg CH_4 per year. (This is applicable to agricultural methane emissions where the carbon component, which is oxidised to CO_2, originally came from atmospheric CO_2 through photosynthesis). Lauder et al. [2013] reported some indicative values for Australian rangeland grazing systems and noted that the levels of carbon storage would require revegetation of about 15% of the rangeland area.

Smith et al. [2012] had previously pointed out the appropriateness of offsetting on-going emissions of short-lived forcing agents against one-off reductions in CO_2 and other long-lived

[4] The IPCC's conditions for the use of such graphics requires that they not be changed.

[5] It is also hard to communicate, involving solution of a generic inverse problem. Thus Tom Wigley's 'solution' to the equivance problem has generally been ignored.

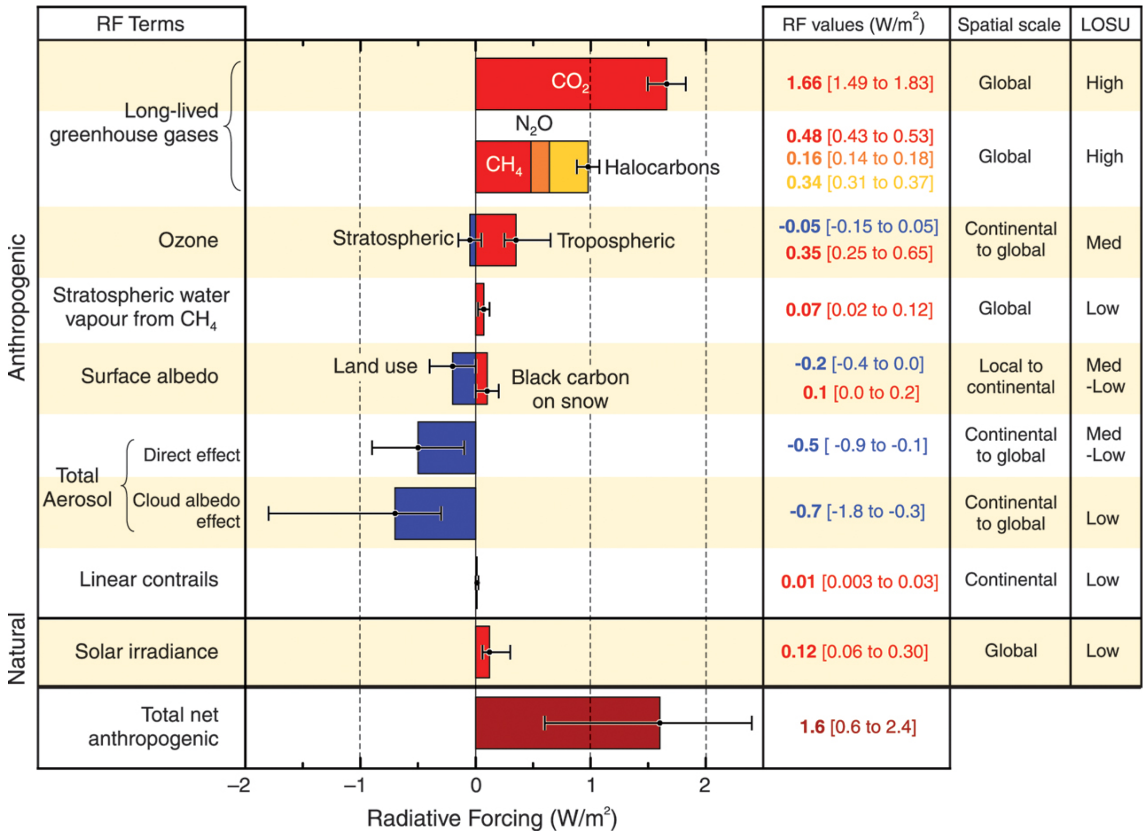

Figure 1: Contributions (with uncertainty ranges) for radiative forcing from various agents. Graphic from Figure 2.4 of the Synthesis Report of the Fourth IPCC Assessment.

radiatively active species.

Consequences of these results are:

- Any requirement for stabilising radiative forcing requires an effective cap on CO_2 emissions.
- A requirement for stabilising radiative forcing does not require an effective cap on cumulative agricultural CH_4 emissions — what is required is a cap on **ongoing** annual CH_4 emissions.
- One-off carbon storage can offset ongoing agricultural emissions of methane at a rate of 1 tonne of carbon for each 0.90–1.05 kg CH_4 per year, into the indefinite future.

4 Aerosols

Aerosol particles in the atmosphere make a significant but poorly quantified contribution to the energy balance of the Earth. A variety of mechanisms are involved, but, with high probability, the net effect is one of cooling. An important characteristic of aerosols is that they are quickly removed from the atmosphere. Aerosols typically remain in the troposphere for a few weeks and in the stratosphere for a few years.

Figure 1 (from the IPCC) shows the changes in radiative forcing, since 1750, for various forcing agents. As can be seen, the uncertainties in the contribution from aerosols is particularly large. A complicating aspect is that aerosol emissions are associated with fossil fuel use and thus reductions in such CO_2 emissions could lead to warming due to the reduction in aerosols, as noted by Wigley [1991]. In their study of these trade-offs, Hansen et al. [2000] noted the need for satellite observations to resolve these uncertainties. However, the NASA satellite intended for aerosol observations failed to reach orbit, and no replacement is scheduled.[6]

Specific questions with implications for global (and thus Australian) targets are:

- To what extent might targets need to change as the uncertainties concerning aerosols are resolved by more detailed measurements and/or more data as time progresses.
- In particular, to what extent is the cooling from aerosols masking the committed warming from long-lived greenhouse gases?
- To what extent is there a threat of a sudden increase in radiative forcing in the event of China (and to a lesser extent other nations) reducing aerosol emissions for health and other environmental reasons?

5 Feedbacks

A feedback process is one that couples the output of a system to its input, the feedback being *positive* if the output augments the input and *negative* if the output reduces the input.

In a linear system, the ratio of output to input is given by

$$\phi_{\text{with}-\text{feedback}} = \frac{\phi_{\text{without}-\text{feedback}}}{1 - \kappa_{\text{feedback}-\text{gain}}}$$

A consequence of the definition is that, whether or not a process is classified as a feedback depends on whether or not it is regarded as outside the system or as part of the internal behaviour of the system.

[6] A new discussion of this issue is on Dr. Hansen's website in his paper 'Doubling Down on Our Faustian Bargain'.

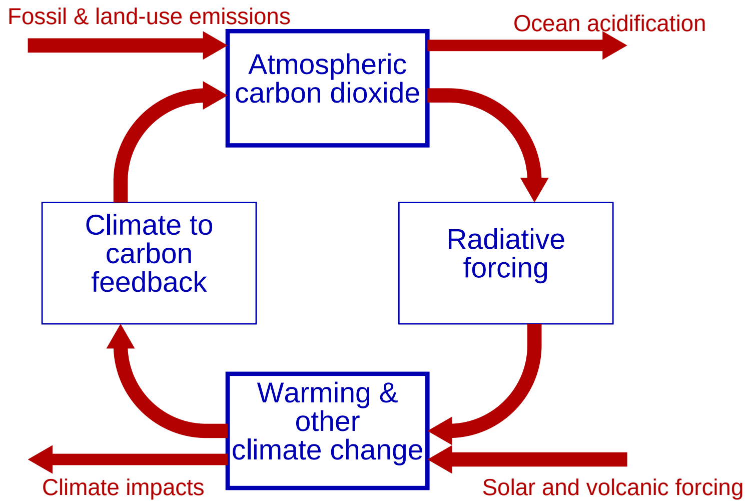

Figure 2: Schematic of climate-to-carbon feedback. Graphic from *Twisted: The Distorted Mathematics of Greenhouse Denial* (I. Enting, 2007).

For the purposes of determining caps from carbon budgets, the most important of the poorly quantified feedbacks are those connecting climate changes to changes in the carbon cycle. Figure 2 gives a schematic of the coupling (where all the feedbacks internal to either the climate system or the carbon cycle have been lumped into the respective sub-system behaviour).

A comprehensive (and widely cited) modelling study of climate-to-carbon feedbacks was presented by Friedlingstein et al. [2006]. This showed a wider spread in the amount of additional CO_2 expected from climate-to-carbon feedbacks over the 21st century. For quantitative applications, this study should be treated with caution because of poor specification of the constraints from 20th century observations and the definition of the 'no-feedback' cases. This raises questions as to whether all the models in the C4MIP intercomparison were really calculating the same thing.

Figure 3 illustrates the context-dependence of characterising changes in terms of feedbacks. This was presented by Enting, Clisby and Etheridge at the 2008 AMOS annual conference in Geelong. The red curve corresponds to a 'no-feedback' description of 20th century CO_2 changes while the back curve corresponds characterises changes as being due to both emissions and feedbacks from temperature. Since each fit is tuned to observations, the overall change is very similar, but in the 'feedback case' some of the growth and much of the shorter term variation is attributed to feedback (The blue curve shows the size of this contribution, quantified as 10$\pm$3 ppm increase over the 20th century).

Other empirical estimates of the strength of the climate-to-carbon feedback are given by Scheffer et al. [2006], although it appears that some of their expressions may be in error be a factor of $\ln 2$.

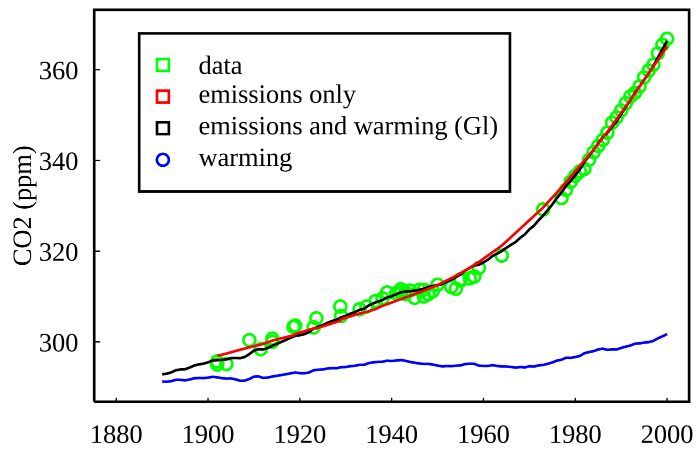

Figure 3: Fitting 20th century CO_2, with and without feedbacks from temperature. Fit with feedbacks implies 10 ± 3 ppm of the 20th century CO_2 increase is due to feedbacks. Analysis and graphic are from *Laplace Transform Analysis of the Coupled Climate-Carbon System with Application to Law Dome data*, by Enting, Clisby and Etheridge, presented at 2008 AMOS Conference.

6 Burden sharing

There is an extensive literature on how targets for reductions of emissions of greenhouse gases should be partitioned between nations. The Kyoto Protocol specified emission levels in the first commitment period only for developed nations.

Some of the approaches that have been considered are 'contraction and convergence' and the 'Tryptique' approach of sector-specific targets, proposed for defining national targets within the EU 'bubble' target for the Kyoto Protocol.

One approach that has received extensive study is the so-called 'Brazilian proposal', which aims to capture aspects of the 'historical responsibility' noted in the UNFCCC. The essence of the proposal was that nations' emission reductions should reflect 'historical responsibility'.

This proposal was investigated by a scientific working group under the auspices of the SBSTA. These studies considered various aspects of how such concepts could be operationalised, including:

- an appropriate metric for 'historical responsibility';
- time periods over which such a metric should be applied;
- times of emissions for which 'historical responsibility' should be calculated.

An overview of the results from the working group is given by den Elzen et al. [2005b]. When issues of historical responsibility are consider in the Caps and Targets review, the wide range of cases considered by den Elzen et al. [2005b] should provide an indication of which variations make a significant difference. Various groups that participated in the working group have published additional studies that may make coontibutions to the Caps and Targets Review, [e.g. den Elzen et al., 2005a, Höhne and Blok, 2005, Trudinger and Enting, 2005].

The 'carbon budget' concept focuses attention on how the remaining part of the available budget should be partitioned. In particular, to what extent should partitioning of the future component of the budget take into account the way in which past emissions have been distributed between nations.

7 Australia

Caps and targets for Australia need to reflect global approaches that have not yet been defined. Thus Australian targets need to retain the flexibility needed to be able to integrate with a range of different global targets and burden sharing regimes.

The need for a rapid decline in Australian emissions is indicated by both considerations of (forward-looking) 'contraction and convergence' as well as by (backward-looking) considerations of historical responsibility. To the extent that both forward and backward considerations come into play the extent of the requisite reductions will be even greater.

Glossary

† denotes definitions from IPCC reports.

airborne fraction This is the proportion of anthropogenic emissions (from fossil carbon and from land-use change) that remain in the atmosphere. The airborne fraction increases as the percentage growth rate of emissions increases (see for example [Enting, 2007]). The value over the 20th century has been about 0.5. [7]

airborne fraction of cumulative emissions This is the proportion of cumulative anthropogenic emissions that remain in the atmosphere. For exponentially growing emissions, it is the same as the (instantaneous) airborne fraction. When the airborne fraction of cumulative emissions is determined for cases involving stabilisation (i.e. no longer exponential growth) the airborne fraction of cumulative emissions is found, as expected, to be smaller than the (instantaneous) airborne fraction observed over the 20th century. Thus, for times somewhat after peak emissions, Matthews et al. [2009] suggest a value around 0.3, on the

[7] On occasion, the term airborne fraction has been used for the ratio of CO_2 growth rate to fossil emissions only. The author prefers to follow the Bern group and call this the 'apparent airborne fraction'.

basis of the same considerations as used by Lauder et al. [2013] in defining the CO_2 to CH_4 offset relation.

Brazilian Proposal A proposal, introduced as part of UNFCCC negotiations, that nations' emission reductions should reflect 'historical responsibility' for climate change.

carbon budget (1) A description of how the carbon fluxes to and from the atmosphere are partitioned between the different reservoirs. See for example [Le Quéré et al., 2009, Fig. 2].

carbon budget (2) An approximate description of the set of emission pathways consistent with stabilising atmospheric CO_2 at a particular level. In its simplest form, concentration targets correspond to particular amounts of cumulative emissions. The quantitative relation is through the "airborne fraction of cumulative emissions' (see definition above). The analyses by Matthews et al. [2009] and Allen et al. [2009] indicate that while different pathways will lead to departures from this simple proportionality between emissions and concentration, when considering temperature changes there is a partial compensation. Thus for temperature changes, the dependence on the emission pathway is proportionally less than for concentrations, when each is related to cumulative emissions.

equivalent carbon dioxide concentrations † The concentration of carbon dioxide that would cause the same amount of radiative forcing as a given mixture of carbon dioxide and other greenhouse gases.

equivalent carbon dioxide emission † The amount of carbon dioxide emission that would cause the same integrated radiative forcing over a given time horizon, as an emitted amount of well-mixed greenhouse gas or a mixture of well-mixed greenhouse gases. The equivalent carbon dioxide emission is obtained by multiplying the emission of a well-mixed greenhouse gas by its global warming potential for the given time horizon. For a mix of greenhouse gases it is obtained by summing the equivalent carbon dioxide emissions of each gas. Equivalent carbon dioxide emission is a standard and useful metric for comparing emissions of different greenhouse gases but does not imply exact equivalence of the corresponding climate change responses.

feedbacks A feedback process is one that couples the output of a system to its input, the feedback being *positive* if the output augments the input and *negative* if the output reduces the input.

Global Warming Potential (GWP) † An index, based on radiative properties of well-mixed greenhouse gases measuring radiative forcing of a unit mass of a well-mixed greenhouse gas in the present day atmosphere, integrated over a chosen time horizon, relative to that of carbon dioxide. The GWP represents the combined effects of differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing thermal infra-red radiation.

radiative forcing A measure of the extent to which a greenhouse gas is perturbing the radiative balance of the earth (relative to a notional 1750 level). Radiative forcing is usually expressed in units of Watts per square metre. (For further detail, see IPCC reports).

SBSTA Subsidiary Body for Scientific and Technical Advice. (for the UN FCCC).

well-mixed The qualification 'well-mixed' in the various IPCC definitions refers to the requirement that for forcing agents to have similar climate effects they need to have similar spatial distributions in the atmosphere. In practice this means having a relatively uniform distribution, like CO_2 which, apart from locations very close to strong sources or sinks, has its concentration varying by only a few percent from place to place.

Author background

Dr. Ian Enting is an honorary senior fellow at The University of Melbourne, attached to the Centre of Excellence for Mathematics and Statistics of Complex Systems. From 1980 to 2004 he was employed by CSIRO (DAP/DAR/CAR), working on carbon cycle modelling. He was one of the lead authors of the chapter 'CO_2 and the Carbon Cycle' in the IPCC Special Report on Radiative Forcing of Climate Change. He participated in the expert working group that analysed the so-called Brazilian Proposal under the auspices of SBSTA. He headed the University of Melbourne team that produced a commissioned report on "The Science of Stabilising Greenhouse Gas Concentrations" for the Garnaut Review of Climate Change.

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