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A new use of Global Warming Potentials to relate the impacts of cumulative
and short-lived climate pollutants

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Parties to the United Nations Framework Convention on Climate Change
(UNFCCC) have requested guidance on common greenhouse gas metrics in
accounting for Nationally Determined Contributions (NDCs) to emission
reductions. Metric choice can affect the relative emphasis placed on
reductions of ‘cumulative climate pollutants’ like carbon dioxide (CO₂)
versus ‘Short-Lived Climate Pollutants’ (SLCPs) including methane and
black carbon. Here we show that the widely used 100-year Global
Warming Potential (GWP₁₀₀) effectively measures relative impact of both
cumulative pollutants and SLCPs on realised warming 20-40 years after the
time of emission. If the overall goal of climate policy is to limit peak
warming, GWP₁₀₀ therefore overstates the importance of current SLCP
emissions unless stringent and immediate reductions of all climate
pollutants result in temperatures nearing their peak soon after mid-
century, which may be necessary to limit warming to “well below 2 °C.”
The GWP₁₀₀ can be used to approximately equate a one-off pulse
emission of a cumulative pollutant and an indefinitely sustained change in
the rate of emission of an SLCP. The climate implications of
traditional “CO₂-equivalent” targets are ambiguous unless contributions
from cumulative pollutants and SLCPs are specified separately.

Establishing policy priorities and market-based emission reduction mechanisms
involving different climate forcing agents all require some way of measuring
what one forcing agent is ‘worth’ relative to another. The GWP₁₀₀ metric has
been widely used for this purpose for over 20 years, notably within the UNFCCC
and its Kyoto Protocol. It represents the time-integrated climate forcing
(perturbation to the Earth’s balance between incoming and outgoing energy)
due to a one-off pulse emission of one tonne of a greenhouse gas over the 100
years following its emission, relative to the corresponding impact of a one tonne
pulse emission of CO₂. The notion of a temporary emission pulse is itself a rather
artificial construct: it could also be interpreted as the impact of a delay in
reducing the rate of emission of a greenhouse gas (see Methods).

This focus on climate forcing and 100-year time-horizon in GWP₁₀₀ has no
particular justification either for climate impacts or for the policy goals of the
UNFCCC, which focus on limiting peak warming, independent of timescale. While
it could be argued that, given current rates of warming, the goal of the Paris
Agreement to limit warming to “well below 2 °C” focuses attention on mitigation
outcomes over the next few decades, this focus is only implicit and presupposes
that this goal will actually be met. Individual countries may also have goals to
limit climate impacts in the shorter term. These are acknowledged by the
UNFCCC, but not quantified in terms of, for example, a target maximum warming
rate. Metric choice is particularly important when comparing CO₂ emissions with
SLCPs such as methane and black carbon aerosols. Black carbon has only recently been introduced into a few intended NDCs\textsuperscript{14} but may become increasingly prominent as some early estimates\textsuperscript{15} assign it a very high GWP\textsubscript{100}, even though the net climatic impact of processes that generate black carbon emissions remains uncertain\textsuperscript{16} and policy interventions to reduce black carbon emissions are likely to impact other forms of pollution as well. Here we combine the climatic impact of black carbon with that of reflective organic aerosols using forcing estimates from ref. 16 (see Methods).

At least one party to the UNFCCC has argued\textsuperscript{17} that using the alternative Global Temperature-change Potential (GTP) metric would be more consistent with the UNFCCC goal of limiting future warming. In its most widely used “pulse” variant\textsuperscript{2}, the GTP represents the impact of the emission of one tonne of a greenhouse gas on global average surface temperatures at a specified point in time after emission\textsuperscript{18}, again relative to the corresponding impact of the emission of one tonne of CO\textsubscript{2}. Figure 1 shows how both GTP and GWP values for SLCPs like methane and black carbon depend strongly on the time-horizon. For long time-horizons, SLCP GTP values also depend on the response time of the climate system, which is uncertain\textsuperscript{19,20}. This latter uncertainty is a real feature of the climate response that is not captured by GWP, and so is not itself a reason to choose GWP over GTP. Other metrics and designs of multi-gas polices have been proposed\textsuperscript{21,22}, some of which can be shown to be approximately equivalent to GWP or GTP\textsuperscript{23}, but since only GWP and GTP have been discussed in the context of the UNFCCC, we focus on these here.

For any time horizon longer than 10 years, values of the GTP are lower than corresponding values of the GWP for SLCPs. The time-horizon has, however, a different meaning between the two metrics: for GWP it represents the time over which climate forcing is integrated, while for GTP it represents a future point in time at which temperature change is measured. Hence there is no particular reason to compare GWP and GTP values for the same time-horizon. Indeed, figure 1 shows that the value of GWP\textsubscript{100} is equal to the GTP with a time-horizon of about 40 years in the case of methane, and 20-30 years in the case of black carbon, given the climate system response-times used in ref. 16, for reasons given in the Methods.\textsuperscript{24} Values of GWP and GTP for cumulative pollutants like nitrous oxide (N\textsubscript{2}O) or sulphur hexafluoride (SF\textsubscript{6}) are determined primarily by forcing efficiencies, not lifetimes, and are hence similar to each other and almost constant over all these time-horizons\textsuperscript{16}. So for a wide range of both cumulative and short-lived climate pollutants, GWP\textsubscript{100} is very roughly equivalent to GTP\textsubscript{20-40} when applied to an emission pulse, making it an approximate indicator of the relative impact of a one-off pulse emission of a tonne of greenhouse gas or other climate forcing agent on global temperatures 20-40 years after emission. The inclusion of feedbacks between warming and the carbon cycle can substantially increase GTP (and also, to a lesser degree, GWP) values, particularly on century timescales\textsuperscript{25}. Here we follow the traditional approach, used for the most widely-quoted metric values in ref. 16, of including these feedbacks in modelling CO\textsubscript{2} but not other gases.
Figure 2, panel a, shows the impact on global average temperature of a pulse emission of various climate pollutants, with the size of the pulse of each gas being ‘equivalent’ (in terms of GWP\textsubscript{100}) to total anthropogenic CO\textsubscript{2} emissions in 2011 (38 GtCO\textsubscript{2}): hence the pulse size is 38/GWP\textsubscript{100} billion tonnes of each forcing agent. SLCPs with high radiative efficiencies, like methane, black carbon and some hydrofluorocarbons, have a more immediate impact on global temperatures than notionally equivalent emissions of CO\textsubscript{2}, and less impact after 20-40 years. Hence, if the primary goal of climate policy is to limit peak warming, then given the time likely to be required to reduce net global CO\textsubscript{2} emissions to zero to stabilise temperatures, the conventional use of GWP\textsubscript{100} to compare pulse emissions of CO\textsubscript{2} and SLCPs is likely to overstate the importance of SLCPs for peak warming until global CO\textsubscript{2} emissions are falling.

This is not an argument for delay in SLCP mitigation – the benefits to human health and agriculture alone would justify many proposed SLCP mitigation measures, but it is an argument for clarity in what immediate SLCP reductions may achieve for global climate. The use of GWP\textsubscript{100} to compare emission pulses might still be appropriate to other policy goals, such as limiting the rate of warming over the coming decades, although the impact of policies on warming rates even over multi-decade timescales should always be considered in the context of internal climate variability. Some contributions to the rate of sea-level-rise also scale with integrated climate forcing.

Simply adopting a different metric that assigns a lower weight to SLCP emissions, such as GTP\textsubscript{100}, does not solve this overstatement problem, since any metric that correctly reflects the impact of SLCPs on temperatures 100 years in the future would underestimate their impact, relative to notionally equivalent quantities of CO\textsubscript{2}, on all shorter timescales. Any choice of metric to compare pulse emissions of cumulative and short-lived pollutants contains a choice of time horizon. It is, however, important for policy-makers to be clear about the time-horizon they are focussing on. One problem with the GWP\textsubscript{100} metric is that “warming” may be interpreted colloquially to mean “temperature rise by a point in time”, making the name misleading, because, in the case of SLCPs, GWP\textsubscript{100} actually delineates impact on temperatures in 20-40 years, not 100 years.

Figure 2b suggests an alternative way of using GWP\textsubscript{100} to express equivalence between cumulative and short-lived climate pollutants that is valid over a wider range of time-scales, suggesting a way to use GWP\textsubscript{100} to reconcile the “emission metrics” literature with the “carbon budget” approach. The solid lines show the impact on global temperatures of a sustained emission of 38 GtCO\textsubscript{2} equivalent (again computed using GWP\textsubscript{100}) of the short-lived climate pollutants shown in 2a, but now starting abruptly in year 1 and distributed evenly over the GWP time-horizon: hence a sustained emission rate of 38/(\textit{H}×GWP\textsubscript{100}) billion tonnes per year, where \textit{H}=100 years. These cause temperatures to increase and then approach stabilization after 20-40 years, depending on their lifetimes. The dotted line shows the impact of a pulse emission of 38 GtCO\textsubscript{2} in year one, reproduced from 2a. The correspondence between these temperature responses
is not exact, but much better than in 2a, at least over timescales from 30 to 100 years.

The reason is simple: a pulse emission of an infinite-lifetime gas and a sudden step change in the sustained rate of emission of a very-short-lifetime gas both give a near-constant radiative forcing. If the total quantities emitted of both gases over the 100-year GWP time-horizon is the same in terms of GWP$_{100}$, then the size of this radiative forcing, and hence the temperature response, will be identical (see Methods for a more formal derivation). The solid and dotted lines in figure 2b do not coincide exactly because CO$_2$ is not simply an infinite-lifetime gas, nor are the lifetimes of methane or black carbon completely negligible, although the effective residence times of CO$_2$ and these SLCPs are, crucially, much longer and much shorter, respectively, than the 100-year GWP time horizon.

A corollary is that a sustained step-change in the rate of emission of a cumulative pollutant such as CO$_2$ is approximately equivalent to a progressive linear increase or decrease in the rate of emission of an SLCP. This is illustrated in figure 2c, which compares the impact of a sustained emission of 38 Gt per year of CO$_2$ emissions (red dotted line) with SLCP emissions increasing from zero at a rate of 0.38 GtCO$_2$-e per year per year (solid lines). Again, although the correspondence is not exact, it is much better than the nominally equivalent emission pulses in 2a. The green dotted line shows that sustained emissions of cumulative pollutants (N$_2$O and CO$_2$) have similar impacts on these timescales. Finally, a progressive change in the rate of emission of CO$_2$ necessary to reach net zero CO$_2$ emissions to stabilise temperatures, could only be equated to an accelerating change in SLCP emissions. This last equivalence is somewhat moot because attempting to match the rates of reduction of CO$_2$ emissions required to limit warming to 2 °C would result in SLCP emissions soon having to be reduced below zero. In summary, therefore, a pulse (or sustained) emission of a cumulative pollutant may be approximately equivalent to a sustained (or progressively increasing) change in the rate of emission of an SLCP, but there is no substitute for a progressive reduction in the rate of emission a cumulative pollutant such as CO$_2$, which remains the sine qua non of climate stabilisation.

This correspondence between pulse emissions of cumulative pollutants and sustained emissions of short-lived pollutants (or the benefits of corresponding emissions reductions) has been noted before, but previous studies suggested that a new metric of sustained emission reductions would be required to relate them. Figure 2b suggests that the familiar GWP$_{100}$ might still be adequate for this purpose, provided it is used to relate sustained reductions in emission rates of SLCPs (agents with lifetimes much shorter than the GWP time-horizon) with temporarily avoided emissions of cumulative climate pollutants (any with lifetimes substantially longer than the GWP time-horizon).

There are obvious challenges to incorporating this second use of GWP$_{100}$ into the UNFCCC process. The Kyoto Protocol and most emissions trading schemes are predicated on emissions accounting over fixed commitment periods. Although possible in the new, more flexible, NDC framework, equating an open-ended
commitment to a permanent reduction in an SLCP emission rate with actual
avoided emissions of a cumulative pollutant within a commitment period would
be a significant policy innovation. Nevertheless, this approximate equivalence
may be useful in setting national or corporate climate policy priorities,
particularly where decisions involve capital investments committing future
emissions.

This second use of GWP\textsubscript{100} is also relevant to the long-term goal in the Paris
Agreement “to achieve a balance between anthropogenic emissions by sources
and removals by sinks” in order to hold the increase in the global average
temperature to well below 2°C above pre-industrial levels. Peak warming scales
approximately with cumulative CO\textsubscript{2} and N\textsubscript{2}O emissions (expressed as GtCO\textsubscript{2}-e
using GWP\textsubscript{100}) between now and the time of peak warming plus the sustained
rate of emission of SLCPs (expressed in GtCO\textsubscript{2}-e/\textsubscript{H} per year, with \textsubscript{H}=100 years if
GWP\textsubscript{100} is used to define GtCO\textsubscript{2}-e) in the decades immediately prior to peak
warming. So a sustained emission rate of 0.01 tonnes per year of methane has
the same impact on peak warming as a pulse of 28 tonnes of CO\textsubscript{2} released at any
time between now and when temperatures peak, GWP\textsubscript{100} of methane being 28.
As NDCs are updated, it would be useful for countries to clarify how they
propose to balance (individually or collectively) cumulative emissions of CO\textsubscript{2} and
N\textsubscript{2}O as these are reduced to zero or below with future emission rates of SLCPs.

Figure 2d shows the impact on global temperatures of actual 2011 emissions of
various climate pollutants, considered as a one-year emission pulse. Methane
and black carbon emissions in 2011 have a comparable or even larger impact on
global temperatures over the next couple of decades than 2011 CO\textsubscript{2} emissions,
but their impact rapidly decays, while the impact of current CO\textsubscript{2} emissions
persists throughout the 21\textsuperscript{st} century and for many centuries beyond.

Figure 2e shows the impact of 2011 emissions of various climate pollutants,
assuming these emissions are maintained at the same level for the next 100
years. The warming impact of the cumulative pollutants, CO\textsubscript{2} and nitrous oxide,
increases steadily as long as these emissions persist, while sustained emissions
of methane and organic and black carbon aerosols cause temperatures to warm
rapidly at first and then stabilize. A permanent reduction of 50-75\% in these
SLCPs could reduce global temperatures by over 0.5°C by mid-century.

The notion of ‘CO\textsubscript{2}-equivalent’ pulse emissions of cumulative and short-lived
climate pollutants will always be ambiguous because they act to warm the
climate system in fundamentally different ways. To date, this ambiguity may
have had only a limited impact, not least because emission reductions have so far
been relatively unambitious. As countries with relatively large agricultural
emissions of methane and significant black carbon emissions begin to quantify
their contributions to the UNFCCC, and as the stringency of commitments
increases consistent with the collective goal of limiting warming to “well below” 2°C, this situation may change[d2].

For their long-term climate implications to be clear, policies and Nationally Determined Contributions need to recognise these differences. GWP\textsubscript{100} can be used in the traditional way, comparing pulse emissions of different greenhouse gases, to specify how mitigation of both short-lived and cumulative climate pollutants may reduce the rate and magnitude of climate change over the next 20-40 years, but only over that time. To achieve a balance between sources and sinks of greenhouse gases in the very long term, net emissions of cumulative pollutants such as CO\textsubscript{2} need to be reduced to zero, while emissions of SLCPs simply need to be stabilised. GWP\textsubscript{100} can again be used, but in the second way identified here, to relate cumulative (positive and negative) emissions of CO\textsubscript{2} until these reach zero with future emission rates of SLCPs, particularly around the time of peak warming. Some NDCs are already providing a breakdown in terms of cumulative and short-lived climate pollutants, or differential policy instruments for different forcing agents[d3] and different timescales, all of which is needed for their climatic implications to be clear. The Paris Agreement proposes that Parties will report emissions and removals using common metrics, but a generic ‘CO\textsubscript{2}-equivalent’ emission reduction target by a given year, defined in terms of GWP\textsubscript{100} and containing a substantial element of SLCP mitigation, represents an ambiguous commitment to future climate. The conventional use of GWP\textsubscript{100} to compare pulse emissions of all gases is an effective metric to limit peak warming if and only if emissions of all climate pollutants, most notably CO\textsubscript{2}, are being reduced such that temperatures are expected to stabilise within the next 20-40 years. This expected time to peak warming will only become clear when CO\textsubscript{2} emissions are falling fast enough to observe the response. Until such a clear end-point is in sight, only a permanent change in the rate of emission of an SLCP can be said to have a comparable impact on future temperatures as a one-off pulse emission of CO\textsubscript{2}, N\textsubscript{2}O or other cumulative pollutant.

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Methods

The equality of GWP\textsubscript{100} and GTP\textsubscript{20-40} follows from the idealised expressions for GWP and GTP for a pulse emission given in ref. 2 (equations A1 and 3 in ref. 2, expressed as relative GWP and GTP respectively, and with decay-times replaced by decay rates):

\[
\text{GWP}_H = \frac{\frac{f_1}{f_1}(1-e^{-k_1H})}{\frac{f_0}{k_0}(1-e^{-k_0H})}
\]  

(1)

and
GTP_{H'} = \frac{F_1 (e^{-k_T H'} - e^{-k_T h'})}{F_0 (e^{-k_0 H'} - e^{-k_0 h'})} \tag{2}

where $F_1$ is the instantaneous forcing per unit emission and $k_1$ the concentration decay rate for a greenhouse gas, with $F_0$ and $k_0$ the corresponding parameters for a reference gas, $k_T$ is a typical thermal adjustment rate of the ocean mixed layer in response to forcing, and $H$ and $H'$ are the GWP and GTP time-horizons.

For example, a very short-lived greenhouse gas and very long-lived reference gas such that $k_1 H \gg 1$, $k_3 H' \gg 1$, $k_0 H << 1$, $k_0 H' << 1$ and $k_1 \gg k_T \gg k_0$, the terms in parentheses in the numerator and denominator of equations (1) and (2) are approximately unity, $k_0 H$, $e^{-k_T H'}$ and $(1 - e^{-k_T H'})$ respectively. Hence, using $k_1 - k_T \approx k_1$ and $k_T - k_0 \approx k_T$, we have

\[
\text{GWP}_H \approx \frac{F_1}{F_0 k_1 H} \quad \text{and} \quad \text{GTP}_{H'} \approx \frac{F_1 k_T}{F_0 k_1 (e^{k_T H'} - 1)}
\]

so GWP$_H$ equals GTP$_{H'}$ if $H' = \ln(1 + H k_T)/k_T$, or 21 years if $H = 100$ years and $k_T = (8.4 \text{ years})^{-1}$, as in ref. 16. Hence in the limit of a very short-lived gas and infinitely persistent reference gas, the GTP for a pulse emission evaluated at 21 years will be equal to the GWP$_{100}$. The expression becomes more complicated if $k_1 H' \approx 1$ as is the case of methane, but this limiting case serves to show that the equality of GWP$_{100}$ and GTP$_{20-40}$ arises primarily from the thermal adjustment time of the climate system.

The approximate equivalence of the temperature response to a one-tonne transitory pulse emission of a cumulative pollutant to sustained step-change in the rate of emission of an SLCP by $1/(H \times \text{GWP}_H)$ tonnes per year, where $H$ is the GWP time horizon, follows from the cumulative impact of CO$_2$ emissions on global temperatures. This means that the temperature response at a time $H$ after a unit pulse emission of CO$_2$ (AGTP$_H$(CO$_2$)) in ref.[2], multiplied by $H$, is approximately equal to the response after time $H$ to a one-unit-per-year sustained emission of CO$_2$ (AGTP$_H$(CO$_2$)), provided $H$ is shorter than the effective atmospheric residence time of CO$_2$, which is of order millennia. This is consistent with the concept of the “trillionth tonne” – that it is the cumulative amount of CO$_2$ that is emitted, rather than when it is emitted, that matters most for future climate[3]. Ref[2] also notes that the ratio AGTP$_H$(x)/AGTP$_H$(CO$_2$) is approximately equal to GWP$_H$(x) for time horizons $H$ much longer than the lifetime of an agent $x$.

Hence:

\[
\text{AGTP}_H(x) \approx \text{GWP}_H(x) \times \text{AGTP}_H(CO_2) \approx \text{GWP}_H(x) \times H \times \text{AGTP}_p(CO_2) \tag{3}
\]

provided $H$ is shorter than the effective residence time of CO$_2$ and longer than the lifetime of the agent $x$, as is the case when $H=100$ years and $x$ is an SLCP.

The interpretation of an “avoided emission pulse”, although central to most emission trading schemes, may be ambiguous in the context of many mitigation decisions, which may involve policies resulting in permanent changes in emission rates. Another way of expressing this notion of an ‘avoided pulse’ is in terms of the impact of delay in reducing emissions of cumulative pollutants: a five year delay in implementing a one-tonne-per-year reduction of CO$_2$ emissions would need to be compensated for by a permanent reduction of
5/(100 \times 28) = 1.8 \times 10^{-3} \text{ tonnes-per-year of methane (GWP}_{100} \text{ of methane being 28). This would only compensate for the direct impact of the delay in CO}_2 \text{ emission reductions, not for additional committed future CO}_2 \text{ emissions that might also result from that delay}^{28}.

**Treatment of Black Carbon emissions:** Focusing solely on absorbing aerosols gives a high estimated 'radiative efficiency' (impact on the global energy budget per unit change in atmospheric concentration) for black carbon, a strong positive global climate forcing\(^{15}(1.1 \text{ W m}^{-2} \text{ in 2011})\) and a GWP\(_{100}\) of 910. This figure has been argued\(^{16}\) to be too high, and the actual radiative impact of individual black carbon emissions depends strongly on the circumstances (location, season and weather conditions) at the time of emission. Many processes that generate black carbon also generate reflective organic aerosols, which have a cooling effect on global climate. Although ratios vary considerably across sources, policy interventions to limit black carbon emissions are likely also to affect these other aerosols, so it might be more relevant to consider their combined impact: the current best estimate\(^{15}\) net global radiative forcing of organic and black carbon aerosols in 2011 was 0.35 W m\(^{-2}\), giving a combined GWP\(_{100}\) of 290, used in the figures. Combined emissions of organic and black carbon aerosols are inferred from this GWP\(_{100}\) value assuming all radiative forcing resulting from these emissions is concentrated in the first year (i.e. a lifetime much shorter than one year). This is only one estimate of a very uncertain quantity: when both reflection and absorption are taken into account, including interactions between aerosols and clouds and surface albedo, even the sign of the net radiative impact of the processes that generate black carbon aerosols remains uncertain.

**Modelling details:** Figure 1: GWP values calculated using current IPCC methane and CO\(_2\) impulse response functions without carbon cycle feedbacks\(^{16}\). Radiative forcing (RF) of a pulse emission of organic and black carbon aerosols concentrated in year 1, scaled to give a net GWP\(_{100}\) of 290, consistent with ratio of 2011 RF values given in refs.\(^{15}\) and\(^{16}\). GTP values calculated using the standard IPCC AR5 thermal response model (solid blue lines) with coefficients adjusted (dotted blue lines) to give Realised Warming Fractions\(^{24}\) (ratio of Transient Climate Response, TCR, to Equilibrium Climate Sensitivity, ECS) of 0.35 and 0.85, spanning the range of uncertainty around the best-estimate value of 0.56. Figure 2: As figure 1 with radiative efficiencies and lifetimes provided in Table A.8.1 of ref.\(^{16}\) and representative mid-range values of TCR=1.5\(^\circ\)C and ECS=2.7\(^\circ\)C.
Figure 1: Values of Global Warming Potential (red) and Global Temperature-change Potential (blue) for methane and combined organic and black carbon as a function of time-horizon. Solid lines show metrics calculated using current IPCC response functions; dotted blue lines show impact of varying the climate response time (see Methods). Black dotted lines show the value of GWP_{100}. 
Figure 2: Impact of pulse versus sustained emissions of various climate forcing agents on global average temperatures. Colours indicate different greenhouse gases, with grey lines indicating combined impact of reflective organic and black carbon aerosols (see Methods) a) Warming caused by a pulse emission in 2011 with each pulse size being nominally equivalent, using GWP\textsubscript{100}, to 2011 emissions of CO\textsubscript{2}. b) Solid lines: impact of sustained emissions of SLCPs at a rate equivalent to 2011 emissions of CO\textsubscript{2} spread over the 100-year GWP\textsubscript{100} time horizon. Dotted line shows impact of pulse emission of CO\textsubscript{2} reproduced from (a). c) Solid lines: impact of SLCP emissions progressively increasing from zero at
0.38 GtCO₂-e yr⁻². Dotted lines: impact of sustained emissions of CO₂ and N₂O at 38 GtCO₂ (or equivalent) per year. d) Impact of actual 2011 emissions of each climate forcing agent expressed as a pulse. e) Impact of emissions sustained indefinitely at 2011 rates.

References:

30 Government of New Zealand (2015): Intended Nationally Determined Contribution, Submission to the UNFCCC, 
[http://www4.unfccc.int/submissions/INDC/](http://www4.unfccc.int/submissions/INDC/)