Broader perspectives for comparing different greenhouse gases

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Over the last 20 years, different greenhouse gases have been compared, in the context of climate change, primarily through the concept of global warming potentials (GWP). This considers the climate forcing caused by pulse emissions and integrated over a fixed time horizon. Recent studies have shown that uncertainties in GWP values are significantly larger than previously thought and, while past literature in this area has raised alternative means of comparison, there is not yet any clear alternative. We propose that a broader framework for comparing greenhouse gases has become necessary and that this cannot be addressed by using simple fixed exchange rates. From a policy perspective, the framework needs to be clearly aligned with the goal of climate stabilization, and we show that comparisons between gases can be better addressed in this context by the forcing equivalence index (FEI). From a science perspective, a framework for comparing greenhouse gases should also consider the full range of processes that affect atmospheric composition and how these may alter for climate stabilization at different levels. We cover a basis for a broader approach to comparing greenhouse gases by summarizing the uncertainties in GWP, linking those to uncertainties in the FEIs consistent with stabilization, and then to a framework for addressing uncertainties in the corresponding biogeochemical processes.

Keywords: greenhouse gas; global warming potential; forcing equivalence index; climate stabilization

1. Introduction

The concept of radiative forcing (RF) provides a robust way of comparing the contributions of different greenhouse gases to climate change based on their atmospheric concentrations at one particular point in time [1,2]. This creates a basis for evaluating the current effects of past anthropogenic emissions of greenhouse gases, as well as for developing approaches to different climate mitigation strategies, and so it is an important scientific concept for policy considerations.

However, greenhouse gases have different relative effects on the RF as well as different lifetimes in the atmosphere. This creates the need for a way of comparing the net effect of emissions of different greenhouse gases, which has

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led to a widespread use of the global warming potential (GWP) [3,4]. Continued evaluation of this emissions metric has shown that the scientific uncertainties in estimating it are significant [5], and that they have tended to increase, rather than decrease, with further analysis [6]. This is coming from growing recognition of uncertainties in the long-term response of the carbon cycle to future climate change, but also from considering the full range of potential indirect effects that can be caused by emissions of chemically reactive greenhouse gases [7].

Structural limitations in the GWP concept have also been recognized from the outset [8], and there have been several proposed alternatives for comparing greenhouse gases [9–11]. Some analyses have suggested that the GWP concept does not lead to economically optimal greenhouse-gas mitigation strategies [12], and the basis for comparisons between gases has also been dealt with more directly in terms of the economic implications of managing future emissions [13].

In addition to the growing range of scientific issues that arise from comparisons of different greenhouse gases, there are also issues from a policy perspective. For example, it appears that there is now some resistance in policy circles to continuing changes in the numeric values of GWPs, as has been done in Intergovernmental Panel on Climate Change (IPCC) assessment reports [2,14,15]. It has been argued that values used in the context of international policy should remain static at the 1995 values rather than become subject to continual revision by scientific studies [16].

The complexity that underlies quantitative comparisons of emissions of different greenhouse gases deserves broader consideration, and is an issue for both the international policy framework and for scientific research. Science and policy approach this issue from different perspectives, but both are directly linked to considering the magnitude of potential effects of future greenhouse-gas emissions on the environment. Furthermore, stabilizing anthropogenic forcing of climate change is a common factor that sets up a broader context than just considering pulse emissions into the present atmosphere.

In the context of climate stabilization, it is necessary to avoid the limitations of a fixed and arbitrary time horizon when comparing different greenhouse gases. Changes that keep the total GWP-weighted emissions constant are not sufficient for keeping to a pathway for the long-term stabilization of RF. In particular, stabilization requires an approach for comparing different greenhouse gases, which is consistent with net anthropogenic emissions of CO$_2$ having to be reduced to zero or negative values, because a significant fraction of these remains in the atmosphere for many thousands of years. Therefore, it is necessary to recognize that permanent reductions in emissions of short-lived gases like methane, even though associated with a high GWP, can only be treated as a basis for delaying, not avoiding, permanent CO$_2$ emission reductions.

In the context of scientific research, it is also necessary to go beyond considering marginal changes to the present atmosphere and consider the full range of potential changes in the physical, chemical and biological systems that affect atmospheric greenhouse gases. For example, climate change can have significant feedback effects on the global carbon cycle [17], leading to large changes in the removal rates for anthropogenic CO$_2$, which was the primary cause. Similarly, there are continuing large uncertainties in atmospheric oxidation rates, which remove several greenhouse gases [18], as well as evidence for significant short-term variations in those rates [19,20]. Future changes in atmospheric oxidation rates
could be caused by climate change and have a long-term significance, but at this stage, neither the magnitude nor sign of such changes are clear [21]. Removal rates for the major anthropogenic greenhouse gases depend on complex and potentially nonlinear systems, and therefore need to be considered in a context that goes beyond marginal changes to the present atmosphere.

In §2, we summarize concerns with the GWPs that are currently used to compare greenhouse-gas emissions. This covers recent increases in uncertainty for this metric, and raises questions about the scope of processes that should be taken into account. It is also relevant to note that GWP values are currently being continually revised to reflect changing concentrations of CO₂ and other greenhouse gases. Therefore, this does not provide the static framework for comparing greenhouse gases that would be useful for a simple policy perspective.

In §3, we go beyond GWPs to cover the importance of a dynamic approach for comparing changes in emissions of different greenhouse gases, which maintains consistency with a specific pathway to future climate stabilization. This is done by applying the forcing equivalence index (FEI), originally introduced by Wigley [11], to stabilization trajectories. In the context of climate stabilization, this provides a quantitative framework for considering fully compensating changes in the emissions of different greenhouse gases, which could arise from technological development leading to major structural changes in the options available.

Section 4 considers a complementary framework for comparing the roles of different greenhouse gases in climate change more broadly. It is based on a comparison of the rates of natural removal of greenhouse gases from the atmosphere in terms of the corresponding changes in RF. This provides a balanced way of considering the relative importance of changes in the global carbon cycle and in atmospheric chemistry, and can be relevant when considering focal points for ongoing research.

Section 5 provides a short summary of the key points coming from these complementary ways of comparing greenhouse gases and the processes that control them. The approaches considered here go well beyond the concept of GWPs as a basis for comparing different greenhouse gases. They are not intended to produce alternative simple indices, but rather to provide a broader framework for considering the time dimension and to recognize the significance of current uncertainties when considering future pathways to climate stabilization.

2. Issues with global warming potentials

A clear basis for comparing the effect of different greenhouse gases on climate is the concept of RF. This originated as ‘thermal trapping’ [1], but was rapidly developed and extended into a well-defined measure of the change in radiative balance caused by changes in the concentrations of greenhouse gases and aerosols, and also by changes in surface albedo and solar radiation [2]. While the relationship between RF and temperature change can vary somewhat across different forcing agents, this relationship appears to be quite uniform for the well-mixed greenhouse gases [22]. Furthermore, the equilibrium global temperature response to RF is expected to be linear over century time scales [14]; thus, this measure of the change in the atmosphere provides a clear basis for aggregating the effects caused by different greenhouse gases.
However, comparing the effects of emissions of greenhouse gases leads to a more complex situation because it needs to take into account the rate at which a gas is removed from the atmosphere, as well as its side effects on atmospheric chemistry. In this context, the GWP is an index giving the ratio of the increases in RF caused by pulse emissions of different greenhouse gases and integrated over a fixed time horizon \([3,4]\). CO\(_2\) is used as the reference gas, and GWPs with a time horizon of 100 years have become widely used in the policy framework.

There have been many research papers since 1990 on the uncertainties in GWPs and on possible alternative indices for comparing greenhouse gases that might have broader relevance \([5,10,23,24]\). The uncertainties in GWPs come from three different factors: the RF caused by an increase in greenhouse-gas concentration; the rate at which the concentration increase caused by a pulse emission declines over time; and the indirect effects that an increase in the gas may have on other radiatively active species. These processes, and their extension across the time horizon being considered, mean that GWP values have far more uncertainty than RF.

A recent study \([6]\) has shown that these uncertainties in GWP estimates are larger than previously reported. This arises primarily because of significant uncertainties in the global carbon cycle that controls the rate at which CO\(_2\) from a pulse emission will decline, and because consistency with the full range of carbon cycle and coupled ocean–atmosphere climate models used in the last IPCC assessment \([25]\) leads to significantly larger uncertainties in the GWP values than was estimated in that assessment \([2]\). Reisinger et al. \([6]\) also show that these uncertainties increase with the time horizon being considered because of fundamental questions involved in determining the details of long-term carbon-cycle responses to both the additional atmospheric CO\(_2\) and the resulting climate change.

Because GWPs are used to compare all other greenhouse gases to CO\(_2\), carbon-cycle uncertainties apply uniformly, but there are also specific uncertainties owing to incomplete knowledge of the lifetimes of the species being compared with CO\(_2\), and the range of indirect effects that can be caused by their increase. Recent analyses have shown a continuing uncertainty of about 10 per cent (1 standard deviation) in the concentration of the hydroxyl radical (OH), which is responsible for most of the removal of methane and some other greenhouse gases \([18]\). The methane lifetime has additional uncertainty owing to its removal by stratospheric processes and a soil sink. In addition, there is now strong evidence, based on carbon isotopic measurements, for an additional sink similar in magnitude to that of the stratospheric and soil chemistry processes and linked to atmospheric chlorine \([26–28]\). Whether or not this fourth sink for methane is variable or is undergoing a trend is still unknown, as are its implications for long-term pathways to climate stabilization.

Additional uncertainties in the indirect GWP components for methane were reflected in its significant increase between the last two IPCC Working Group I assessments \([2,14]\). Since then, a new analysis of the interactions between methane and aerosol chemistry suggests a case for a further significant increase in the GWP value, but this also leads to a consequent increase in its uncertainty \([7]\).

These continuing uncertainties could lead to ongoing changes in the best estimates of GWPs and so to difficulties for climate policy based on this form of greenhouse-gas comparison. This is complicated even further because...
some GWP values are dependent on the continuing changes in atmospheric concentrations of the gas concerned, and all are dependent on changing CO$_2$ concentrations. RF is proportional to the logarithm of the concentration for CO$_2$; to the square root of concentration for methane and nitrous oxide; and is linear in concentration for all other gases. This means that the incremental effect of a pulse emission of CO$_2$ decreases, as its concentration increases more rapidly than for any other gas. It has been noted that this decreasing effect of incremental changes in CO$_2$ on RF could be compensated for by a similar decrease in the rate of CO$_2$ uptake by the ocean [29], if the GWP was based on a non-steady state impulse response function. However, the present approach keeps CO$_2$ removal rates fixed, and so leads to increases in all GWPs as the CO$_2$ concentration increases. The logarithmic dependence of RF on CO$_2$ concentration means that about one-third of the 19 per cent increase in the methane GWP between the IPCC 2007 report [2] and the IPCC 1995 report [15] is due to the increase in atmospheric CO$_2$ concentrations that has taken place. The other two-thirds is due to new estimates of the indirect effects of methane added to the atmosphere.

So far, these incremental changes in GWP values owing to concentration changes are small, however, continuing increases in CO$_2$ will increase the GWP for all the other greenhouse gases. If one considers pathways to climate stabilization, such as recently given in the reference concentration pathways (RCPs) [30,31], then it is clear that continuing updates of the GWP could have quite significant implications in the future. Along the RCP3 pathway, which is aimed at stabilizing global warming at 2°C, the methane GWP would increase by about 33 per cent as the concentration of methane decreased to about 65 per cent of present-day levels, and CO$_2$ stabilized at levels about 10 per cent higher than its present-day levels.$^1$

Continual revision of the GWP value in the policy framework arising from such adjustments would lead to progressive increases in the carbon price for methane emissions, and so potentially towards a steadily shifting emphasis on further reduction of methane rather than CO$_2$. This may have short-term value, but is not consistent with long-term climate-change stabilization strategies. Furthermore, the use of a fixed time horizon for the GWP concept does not cover our understanding that about 20 per cent of CO$_2$ emitted to the atmosphere persists for tens of thousands of years, which is a critical factor when considering climate stabilization [32,33].

Stability in a metric for comparing greenhouse gases has been recognized as significant, and it has been proposed that the GWP values specified in the IPCC 1995 report [15] be retained in the policy framework rather than adjusting these to cover the values given in the more recent assessments [16]. An alternative approach that would allow for revisions based on scientific understanding, but not on progressive changes in atmospheric composition, would be to redefine GWPs to be based on atmospheric concentrations for a specific year, such as 2000. However, in the next section, we show why comparing emissions of greenhouse gases in the context of climate stabilization needs to follow a different approach.

$^1$This is based on assuming that the indirect part of the methane GWP scales linearly with the direct part, as has been used in the last two IPCC assessments, but that relationship is not yet clearly established in studies of future atmospheric chemistry.

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3. Comparing greenhouse gases for stabilization scenarios

An alternative framework for comparing emissions of different greenhouse gases was introduced by Wigley [11] as the FEI. This is based on determining the marginal changes in emissions of different greenhouse gases, which have exact compensating effects on the total RF, and so keep to the same multi-gas scenario over time. In this context, a constant change in the emissions of one greenhouse gas over time is balanced by a time-varying change for another one. Thus, the FEI specifically avoids the introduction of an arbitrary time horizon as used in GWPs. Instead, it quantifies the time dependence of changes in emissions of different greenhouse gases that keep to the same RF pathway.

Emission scenarios consistent with achieving climate stabilization have been developed in some detail [30,31], but changes in the emissions of different greenhouse gases that keep to the same total GWP-weighted emissions do not keep to the same RF over time. For example, if technological development led to faster reduction in methane emissions and there was a GWP-based compensating increase in CO$_2$ emissions, then the result would be inconsistent with climate stabilization.

In this context, it is important to consider the FEI in the context of climate stabilization. Here, we consider this as the basis for changes to a scenario for future emissions that are intended to achieve stabilization of total RF at about 3 W m$^{-2}$. Figure 1 shows the evolution of emissions and RF to the year 2300, as well as constant increases or decreases in methane emissions and the compensating changes in CO$_2$ emissions that balance out to give exactly the same total RF. Our results are illustrative, but are based on emulating 19 atmosphere–ocean general circulation models (AOGCMs) and nine carbon-cycle models using a version of the Model for the Assessment of Greenhouse-gas-induced Climate Change (MAGICC), which has been designed so it can be tuned to reproduce the global mean results for a very wide range of climate models [6,34]. Our approach is also closely consistent with the recent analyses of uncertainties in GWPs [6,34].

The effects of methane emissions on atmospheric chemistry and the implications for changes in RF are treated here in a way that is consistent with their inclusion as an indirect effect in the GWP. This way of considering pathways to climate stabilization is based directly on detailed models as mentioned above, but factors, such as the recent increase in the release of methane from natural sources in the Arctic region, suggest it may not be taking account of all the feedbacks that could occur [35,36].

The key aspect of this approach is that it quantifies how, in the context of climate stabilization, a permanent change in the emissions of a short-lived greenhouse gas can only justify a steadily diminishing change in emissions of CO$_2$. In the long run, emissions of CO$_2$ would still have to decline to the same level, regardless of the changes in methane emissions. This demonstrates the limits of GWPs for comparing greenhouse gases in the context of climate stabilization, which, as noted in §2, could result in an increase rather than decrease in the exchange rate between CH$_4$ and CO$_2$ over time with perverse long-term implications.

The time-varying ratio between exactly balancing changes in methane and CO$_2$ emissions that maintain a specific stabilization scenario is shown in figure 2. The average ratio reaches the values given by the methane GWPs with time horizons of
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Figure 1. Comparison of changes from pre-industrial values in the emissions of CO₂ and methane that are consistent with stabilizing greenhouse gases with a total RF of 3.4 W m⁻². The upper graph shows the total RF pathway that is followed with very minor variations between the three cases. The solid (blue) lines in the lower two graphs show the average across 171 model runs for the evolution of methane and CO₂ emissions that are consistent with that. The dotted (red) and dashed (green) lines show the averages for a fixed change in methane emissions and the compensating changes in CO₂ emissions that lead to the same RF. (Online version in colour.)

20, 100 and 500 years at times of 12, 54 and 172 years after the change in emissions occurs. This comparison shows that there are significant differences between considering pulse emissions in a stable environment and long-term changes in emissions trajectories, which remain consistent with future climate stabilization. Long-term changes in the balance of emissions of different greenhouse gases are likely to become increasingly determined by technological changes, and GWPs can not be used in that context to keep to the same climate-stabilization pathway on any long-term basis.

Figure 2 also shows the corresponding uncertainties in the FEI approach for considering marginal changes between emissions that keep to a pathway for climate stabilization. This shows the time-dependent ratio of changes in emissions of methane and CO₂, which are consistent with the stabilization pathway, and the full range and standard deviation of these ratios for 171 different combinations of carbon-cycle and climate-model parameters taken from the IPCC Working Group I fourth assessment report [25]. We have followed the approach recently developed

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Figure 2. The ratio of a change in methane emissions to the compensating change in CO₂ emissions that keeps to the stabilization scenario shown in figure 1. In (a), the central line is the median for the wide range of values covering combinations of carbon-cycle and climate-model parameters; the dark grey band shows the 1 standard deviation range around this; and the light grey band shows the full range. Open circles show where the median ratio matches the values of the GWPs for the 25, 100 and 500 year time horizons. (b) The relative uncertainty in the FEI value based on its 1 standard deviation range.

for considering the uncertainties in GWPs [6], and used the simple climate model (MAGICC) to emulate the results from complex climate and carbon-cycle models used in the Coupled Model Intercomparison Project phase three (CMIP3) and Coupled Climate–Carbon Cycle Model Intercomparison Project (C4MIP) intercomparisons [17,34]. The relative uncertainty in the ratios of emissions changes keeping to a stabilization pathway increases from about 10 to 35 per cent over the time frame from 0 to 250 years.

The FEI’s more explicit treatment of considering greenhouse-gas emissions in the context of climate stabilization raises the need to consider structural uncertainties in projections of future climate change. The uncertainties shown in figure 2 do cover this to some extent, but a robust approach to considering pathways to climate stabilization should also be extended to consider the implications of nonlinear changes in atmospheric chemistry that might arise from the combination of anthropogenic emissions and changes in global atmospheric chemistry and biogeochemistry. Issues, such as the stability of atmospheric oxidation rates, could be considered in the context of GWPs, but can be dealt with far more directly when considering potential changes in FEIs through use of coupled climate–atmospheric chemistry models.
4. Comparing the key processes controlling greenhouse gases in the atmosphere

As shown in the preceding two sections, there are significant uncertainties in numeric comparisons of the effects of emissions of different greenhouse gases on future climate change. Most of these uncertainties arise from the limits to our current understanding of the processes controlling the removal of gases and how these may change over the time scales that are relevant for considering the effects of emissions in the context of climate stabilization. Furthermore, much of the underlying research in this area has been showing growing evidence for changes in the removal rates of CO₂ and other greenhouse gases (e.g. [37,38]).

This section goes beyond considering marginal changes in emissions to a complementary perspective for comparing the relative importance of the natural processes that control different greenhouse gases and the importance of understanding potential changes in these. The aim is to develop a balanced and consistent framework for comparing the natural processes that control greenhouse gases and, as with the GWPs or FEIs, use RF as a consistent way of doing this. Thus, removal processes are represented as the corresponding rates of decrease in RF. While greenhouse-gas sources are primarily anthropogenic, there is growing evidence that climate change can also alter some natural sources [35,36], and while the focus here is on the natural removal rates, this could be extended to cover such climate-driven natural sources.

Using RF as a basis for comparing greenhouse gases raises the question as to whether water vapour should be included in this framework as well. However, the lack of any long-term trend in atmospheric relative humidity implies that changes in water content are only in response to warming, and so are important feedback effects, but not drivers of climate change [39]. From this perspective, figure 3 shows the rates of change in RF since 1960 that are directly related to concentration changes in the nine most significant greenhouse gases, CO₂, methane, nitrous oxide, CHClF₂ (HCFC-22) and the now declining CCl₃F (CFC-11), CCl₂F₂ (CFC-12), CClF₂ CCl₂F (CFC-13), carbon tetrachloride and methyl chloroform. Figure 3a shows the rates of changes in RF owing to the annual changes in concentrations, and so covers the net effect of both emissions and removal of these gases.

Figure 3b then shows the rates of reduction in RF that is being caused by the trace-gas removal processes. It is immediately clear that the ordering of gases by the magnitude of their RF removal processes is very different from the ordering in figure 3a based just on the relative changes in atmospheric concentrations. This shows that the relative importance of removal processes is obscured when only the net changes are considered. In addition, it is clear that the relative magnitudes of removal rates have changed over time.

Data used in figure 3 are taken from the Scripps Institution of Oceanography (http://scrippsc02.ucsd.edu/), Climate Monitoring and Diagnostics Laboratory (http://www.esrl.noaa.gov/gmd/dv/ftpdata.html) and Carbon Dioxide Information Analysis Center (http://cdiac.esd.ornl.gov/home.html) web pages as well as firn data for methane [40]. In some cases, the earlier values within the time period shown here have been estimated from probable rates of growth prior to the first reliable measurements. For example, atmospheric concentrations of nitrous oxide used here combine results from a review of ice-core data [41], for values prior to 1979, with global averages
Figure 3. (a) Rates of change in radiative forcing (RF) owing to the nine major greenhouse gases over the period 1960–2008. The vertical axis is linear, but has a split in scale in order to show the lower gases more clearly and the existence of negative annual changes in the RF owing to some gases. (b) The magnitude of the removal rates of these gases converted to the corresponding rate of decrease in RF. This uses a logarithmic axis to cover the wide range that is involved. (Online version in colour.)

based on data from the Advanced Global Atmospheric Gases Experiment (AGAGE) from 1979 onward (http://agage.eas.gatech.edu/data.htm). Estimates of the removal rates of CO₂ are based on budget closure with the sources defined by Boden et al. [42] for fossil-fuel emissions and Le Quéré
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While it is not shown here, the sources of these greenhouse gases can also be represented as the corresponding rate of input to RF. This rate was comparable for both methane and CO$_2$ over the period 1960–1980; however, the steadily increasing emissions of CO$_2$ have led to these driving a growing rate of increase in RF from 1983 to 1991 and then again from 2001 to 2007. For CO$_2$, this source rate has now become equivalent to an annual RF increase of about 65 mW m$^{-2}$ yr$^{-1}$, while for methane, the source input to RF has remained almost steady at about 45 mW m$^{-2}$ yr$^{-1}$ since 1985.

Figure 3b shows that the magnitudes of annual removals of CO$_2$ and methane are about 10 times more significant than the other greenhouse gases in the context of their control on RF. Furthermore, the rate of removal of methane by atmospheric chemistry is having a greater effect in offsetting increases in RF than the removal of CO$_2$ by its land and ocean uptake. The emergence of HCFC-22 as having the third most important removal rate for more than a decade now shows another clear difference from the net effect seen in figure 3a.

Currently, for the nine greenhouse gases considered here, the total RF input coming from emissions is about 120 mW m$^{-2}$ yr$^{-1}$. Of this, about 90 mW m$^{-2}$ yr$^{-1}$ is being offset by the removal rates for the gases, leaving a net increase in RF of about 30 mW m$^{-2}$ yr$^{-1}$. Over the last 40 years, the total annual emissions and removals of RF have each risen by about 80 per cent. The distribution of this input to RF across the different greenhouse gases has changed, and, while methane sources have contributed about 40 per cent of the total emissions RF throughout, the CO$_2$ contribution has risen above 50 per cent, while that of the chlorofluorocarbons has dropped, but is being compensated by the growing increase in HCFC-22.

About 85 per cent of the methane removal, as well as all the removal of HCFC-22 and methyl chloroform, are due to the OH. This very significant role that OH has on controlling RF is shown in more detail in figure 4 where the rate of removal of all these nine gases is broken into: OH oxidation; carbon sinks for CO$_2$; and all other removal processes. OH oxidation is generally a more significant control of anthropogenic forcing of the climate system than the global uptake of atmospheric CO$_2$.

This perspective on the control of RF shows the significance of possible changes in OH that might arise from the interactions between atmospheric chemistry and climate change. At this stage, there is little evidence for trends in OH [18,43], but several analyses indicate that a future reduction in OH can be caused by the effects of climate change on atmospheric chemistry [21]. This raises questions about the treatment of a feedback between the concentrations of OH and methane when calculating its indirect GWP component. There is evidence for some large fluctuations in OH that persist for several months or longer and are driven by one or more of: volcanic eruptions; large emissions of gases from biomass burning; or intense El Nino events [19,20]. There appears to have been a recovery of OH each time, but because of the complex and nonlinear processes that are involved, their role in limiting future climate change needs to be considered quite specifically rather than just by focusing on possible marginal effects of specific gases such as methane.

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Figure 4. RF removal rates grouped into the main processes removing greenhouse gases from the atmosphere as follows: oxidation by OH; removal of CO$_2$ by vegetation and oceans; and the other removal processes relevant for the nine greenhouse gases shown in figure 3. (Online version in colour.)

Figure 4 also shows the large interannual variability in CO$_2$ removal in the context of RF, which can vary by up to a factor of two. The issue of whether or not there is a long-term trend in the uptake of CO$_2$ has recently led to some different views [44–47]. However, the present analysis is not directly linked to this because it is based on RF, which does not depend linearly on the CO$_2$ concentration.

5. Conclusion

The strategic objective of climate stabilization is now a very important context for studying the anthropogenic drivers of climate change. From an economic and long-term policy perspective, it needs to become recognized that the current framework for comparing greenhouse gases using GWPs is not aligned with stabilization or with economic optimization. In addition, it is becoming increasingly important to develop ways of considering changes in emissions of different greenhouse gases that are closely aligned with keeping to a climate-stabilization goal. However, this raises the major issue of reducing scientific uncertainties that underlie all comparisons of emissions of different gases.

The standard way of comparing emissions of different greenhouse gases is through GWP values based on RF integrated over a fixed time horizon, but this does not provide a way of equating emissions of short- and long-lived gases in the context of climate stabilization. For this, it is necessary to cover the fact that a permanent reduction in emissions of a short-lived greenhouse gas can only justify a temporary increase in emissions of CO$_2$.

Furthermore, estimated uncertainties in GWP values have become larger owing to the wide range of potential CO$_2$ removal rates in the future and their dependence on climate change [6]. Uncertainties in the removal rates of methane [26–28] and a widening range of indirect effects for this gas [7] are also creating growing issues for the use of the GWP in a policy framework.
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Long-term changes in the emissions of different greenhouse gases can be considered in a way that is directly consistent with climate stabilization through use of the FEI concept [11]. This shows that a permanent decrease in emissions of a short-lived gas, such as methane, is balanced by an increase in emissions of CO$_2$, which must steadily decrease over time. However, there are still large uncertainties in this way of comparing the long-term effects of emissions of different greenhouse gases. This raises the need to consider safety margins in long-term plans for a pathway to climate stabilization to cover the uncertainty in changing atmospheric processes, as well as continuing technological and economic development.

Addressing the uncertainties in a systematic way requires a clear perspective for considering the relative roles of different removal processes for greenhouse gases and how these may be affected by future climate change. We have summarized how the natural removal processes can be considered in terms of their effects on RF, and this shows that the oxidation of methane and other greenhouse gases by OH is at least as important as the sum of oceanic and terrestrial vegetation removal processes for atmospheric CO$_2$. It is clear that we still need to have a better understanding of the way in which global changes may affect these two quite different types of greenhouse-gas removals in order to reduce uncertainty in how climate change can be managed in the long term.

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