Overshoot scenarios and their climate response

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This study assesses current research on overshoot scenarios including results in the IPCC AR5 and the scenario database prepared for that report. It then describes the climate response results from model experiments that AVOID 2 researchers conducted for a consistent view of overshoot scenarios. The results are very relevant to international policy negotiations for emissions reduction, and although not of interest to mainstream media these results will be of interest to the media who specialise in climate change. Interest is likely to be heightened over the period May to December 2015 due to the international climate change meetings taking place in those months.

NERC Results

There is no corresponding NERC funded work associated with the research carried out in this report.
Executive Summary

This AVOID 2 report reviews the current literature regarding “overshoot” scenarios where some aspect of the climate such as the temperature or GHG concentrations temporarily exceed a given target. The aim is to characterise such scenarios from Integrated Assessment Models (IAM) and where possible the climate to these scenarios, however most simulations with comprehensive climate models consider only highly idealised extreme scenario of future climate change.

The assessment of IAM literature includes some additional analysis of the IAM scenario database compiled by the IPCC for the 5th Assessment Report from more than 30 different models and several major international model intercomparison projects.

The natural uptake of CO$_2$ by the carbon cycle means that a small degree of atmospheric CO$_2$ concentration overshoot would be recoverable from by natural means. However a predominant feature of ambitious mitigation scenarios is the presence of slightly larger overshoot (in duration or magnitude) which could be facilitated by enhanced Carbon Dioxide Removal (CDR) technologies. These are almost exclusively assumed by IAM to be produced through the combinations of BioEnergy with Carbon Capture and Storage (BECCS) which is the subject of further scrutiny within AVOID reports D2a and D1a. The limits of CCS scalability or land and water availability for bio-fuels are likely to place additional constraints on the feasibility of the majority of the overshoot scenarios described in the IPCC 5th Assessment Report.

We show that uncertainty regarding BECCS availability is the leading order sensitivity for the possible magnitude and duration of a recoverable climate overshoot. Without BECCS the IPCC WG3 database indicates an upper bound to temperature overshoot of 0.1 °C for 40-50 years when still meeting a 2 °C target in 2100. If BECCS is available scenarios in the IPCC WG3 AR5 database suggest that the duration of the overshoot could be halved (25 years) or allowed to become 3 times the size (0.3 °C) with optimistic assumptions about CDR. It should be noted that the limits to the use of CDR in these IPCC WG3 scenarios are a consequence of minimising mitigation costs in these scenarios under a range of different scenario assumptions. Non-cost optimum scenarios incorporating more CDR would also be possible and allow larger overshoots, however availability of BECCS may turn out to be smaller than assumed in the IAM and lead to smaller possible overshoots while still meeting a 2 °C target in 2100.

Climate response to an overshoot of atmospheric greenhouse gas concentrations has been examined in a number of studies of idealised emissions and concentration scenarios in Earth System Models (ESM). There is consensus that stabilization of CO$_2$ concentrations, or even global temperatures, does not imply stabilization of all aspects of the climate at the same time. Many parts of the climate system have inherently long time-scale responses (e.g. ice sheets, carbon cycle, ocean heat content) which may take many hundreds to thousands of years to reach a new equilibrium.

An aspect of the physical response for which there has been insufficient study in the available scientific literature to draw firm conclusions about is the temporary resilience of large-scale components of the climate system, such as polar ice sheets or the Amazon forest, to abrupt or irreversible changes during a temperature overshoot of the scale detailed in the IPCC WG3 AR5 scenario database. Whilst it is broadly accepted that there is potential for such changes,
and that the probability of them occurring increases at higher temperature, the precise details of the trigger points are still too uncertain to draw robust conclusions about the relative increase in risk posed by temporarily overshooting a climate target.

Non-technical summary

This study reviews the scientific literature relating to climate change scenarios where one or more metrics of climate change temporarily overshoot a long-term target value before declining below the target level. The most common types of overshoot in the literature are “concentration overshoot” and “temperature overshoot”. Some pathways are designed to allow concentration overshoot without temperature overshoot, while others permit both together.

The two aims of this study are firstly to review the characteristics of realistic emissions scenarios which exhibit overshoot and secondly to assess the evidence for a robust climate response to an overshoot. While these two aspects of overshoot scenarios are both needed to inform decisions over appropriate action to tackle climate change and the setting of climate targets, existing research currently exists in two very distinct areas of the scientific literature. Characteristics of emissions scenarios are typically assessed in Integrated Assessment Model (IAM) studies, while studies into the climate signal of an overshoot scenario are typically examined using complex climate models.

Section 2 reviews the characteristics of overshoot scenarios from IAM literature along with some new assessment of the overshoot scenarios collated as part of the IPCC 5th Assessment Report, extending the analysis of IPCC WG3. We find that current IAM scenarios suggest only limited potential for overshooting any temperature or GHG concentration target and then decreasing below the target level by 2100. For scenarios with 2100 temperatures close to 2 °C above pre-industrial levels, possible overshoot before 2100 is to around 0.2 to 0.25 °C with a maximum overshoot duration of up to 60 years. The same “2 °C” scenarios may also overshoot their 2100 CO₂ concentrations by up to 50 ppm. A clear finding from current IAM is that overshooting a 2 °C by more than 0.1 °C will require the large scale use of combination of Bio-Energy in combination with Carbon Capture and Storage (BECCS) to actively remove CO₂ from the atmosphere. As such the availability of Carbon Capture and Storage technology and sufficient land for bio-fuels would have significant impacts on the feasibility of overshoot scenarios included in the IPCC WG3 AR5 database. The viability of BECCS is the subject of further ongoing analysis in AVOID 2.

Section 3 reviews research into the physical response of the climate system to a scenario of climate overshoot. This is typically based on highly idealised and extreme scenarios of future greenhouse gas (GHG) emissions and concentrations. Designed to elicit a large modelled response from the climate system these scenarios are not intended as plausible future emissions or concentration pathways. This leads to difficulty in relating the findings from such highly idealised studies to the potential climate changes from scenarios with realistic levels of overshoot, which are many times smaller. For example the concentration overshoot of CO₂ in idealised climate model studies may easily be 20 times larger than any plausible overshoot from current IAM.

Many aspects of the climate system response to an overshoot show behaviour which, to some degree, does not simply track the overshoot itself but takes a prolonged time to recover. In summary:
All studies of CO\(_2\) concentration overshoot find global temperatures reversible, but that the reduction on temperatures lags that of CO\(_2\) by the order of a decade;

Global average precipitation in overshoot scenarios increases with atmospheric CO\(_2\) and temperature, initially continuing to increase after CO\(_2\) and temperature have peaked and started to decline. Global precipitation subsequently decreases but with a lag relative to CO\(_2\) of up to 50 years. While there is consensus on the global mean precipitation response, regional changes in precipitation remain highly uncertain. Projections from different models show very different regional results, although all projections exhibit significant spatial variation in rainfall changes with some places drier and some wetter;

It is virtually certain that, as the climate warms, large areas of permafrost will experience thawing over multiple centuries. While the area of frozen to unfrozen ground is eventually fully reversible, any loss of organic carbon during the time thawed is effectively irreversible as this has accumulated over many millennia. This emitted carbon will act as a positive feedback on global warming although there is currently low confidence in the magnitude of frozen carbon losses to the atmosphere that may occur so estimates of additional emissions arising from a temperature overshoot are not currently available;

Despite the potentially significant contribution to sea levels from the melting of terrestrial ice sheets, and the instability they may potentially exhibit, uncertainties in our understanding of ice-sheet processes mean that while a temperature overshoot would likely increase overall ice loss, no studies have yet examined the additional ice loss volume and the risk of collapse relating specifically to climate overshoots of the magnitude currently considered plausible in IAM;

In contrast to land ice, annual mean Arctic and Antarctic sea-ice cover which do not contribute directly to sea level rise, are typically found to be entirely reversible once surface temperatures have recovered;

Ocean surface pH responds very quickly to atmospheric concentrations and is almost totally reversible however the resultant changes to marine ecosystems, for example through detrimental impact on calcifying organisms, may not be reversible;

All models in Fifth Coupled Model Intercomparison Project (CMIP5) project a weakening of AMOC under increasing CO\(_2\) levels. Many studies of overshoot scenarios find that while the weakening of AMOC during an overshoot is reversible, there may be a stronger AMOC during the decreasing phase of an overshoot;

The response of ocean temperatures to external forcing comprises mainly two time-scales: a relatively fast adjustment of the ocean surface, well-mixed layer and the slow response of the deep ocean. Simulations with coupled ocean-atmosphere general circulation models suggest a lag of several millennia for the deep ocean to be in equilibrium with external forcing. This long time-scale of the ocean response to external forcing implies an additional committed thermal expansion centuries after greenhouse gas concentrations are stabilised and minimal impact of overshoot on the overall response relative to this large-scale long-term feature.

The climate response to exaggerated overshoot scenarios examined in climate models suggests that there are a number aspects of climate change from which it will take
longer to recover, suggesting that there would be more prolonged impacts in overshoot scenarios.
1. Introduction

Climate targets are often discussed in terms of limiting some measure of the climate (e.g. Greenhouse gas (GHG) concentrations, radiative forcing or global average temperatures) to a given level at a particular time in the future, commonly the end of the century.

A number of studies have considered the idea of allowing the climate to temporarily exceed its eventual long-term target. This may occur by accident, for instance because emission reduction does not take place fast enough earlier in the pathway, perhaps due to a lack of an affordable low-carbon technology. Alternatively some overshoot may be planned in order to minimise the costs of mitigation. Some cases that have been examined allow the atmospheric concentration of CO$_2$ (or equivalent gases) to overshoot a target level, but keep the overshoot period sufficiently short to avoid the temperature overshooting its target. In other cases both the CO$_2$ equivalent concentrations and temperature experience an overshoot.

In realistic emissions scenario where some climate overshoot is allowed, the rate of removal of atmospheric CO$_2$ is a key determinant in the magnitude and duration of an overshoot. Under normal circumstances the absorption of CO$_2$ from the atmosphere by the terrestrial and ocean carbon cycle provides a mechanism by which the climate system may recover from an overshoot of CO$_2$ concentration (and hence radiative forcing) and also over time from a temperature overshoot.

Several studies have examined the time-scales involved in recovery from a CO$_2$ overshoot in modelling experiments where emissions are set to zero and the climate’s response examined. This allows diagnosis of the future warming that we are already committed to from historical emissions (Lowe et al 2009; Matthews and Caideira, 2008, Matthews and Zickfeld 2012; Plattner et al 2008; Solomon et al 2009; Frolicher and Joos 2010). Zeroed emissions are shown in all cases to lead to only very slowly declining atmospheric CO$_2$ concentrations as the natural removal of anthropogenic CO$_2$ by the land and ocean carbon cycles continues. As a result of this very slow reduction in CO$_2$, global temperatures remain approximately constant for several centuries following the elimination of emissions. This implies that larger overshoots and those requiring a rapid reduction in some climate metric following a peak may need enhanced removal of atmospheric CO$_2$, or other forcing agents.

A related aspect of the recent literature is the concept of cumulative carbon emissions, and its finding of an approximately linear link between a carbon budget and a particular level of warming (Allen et al 2009; Meinshausen et al 2009). It is clear from the cumulative emissions literature that for a sizeable temperature overshoot to occur the eventual carbon budget would need to be temporarily exceeded, but this amount would later need to be offset by enhanced carbon dioxide removal providing negative emissions. By analogy with the world of finance, this can be thought of borrowing an extra amount of carbon budget temporarily then “paying it back” later. There is also some evidence that a temporarily warmer climate might have a negative impact on carbon sinks (e.g. Cox et al., 1999), and so more budget might need to be paid back, or put another way, the pay back might also involve paying interest.
A further technical complication when studying overshoot pathways is the presence of natural variability in the real climate system, or that simulated within complex general circulation climate models. For clarity a decision needs to be made on the definition of overshoot; does it involve any exceedance of the eventual long-term level, for however short a period, or do we only consider it an overshoot when a longer-term average exceeds the target level? (see schematic in Figure 1 illustrating this for a generic climate variable). A pragmatic approach is to consider 10 or 20 year means when simulations that include natural internal variability are considered, although there is some variation in approach across different studies.

Also illustrated by Figure 1 is that how a target is defined is also complicated by whether a target is for a specific year or if the target is a level never to be crossed even in the distant future. This is an issue for very long term scenarios that may cross targets after this century, but as no realistic, bottom-up, process based scenarios of future emissions are available past 2100, we must limit consideration of realistic overshoot scenarios in section 2 to climate changes up to 2100.

Figure 1. Schematic illustrating annual (thin) and long term average (thick) time series of an arbitrary metric of the climate for scenarios meeting a given target with differing target definitions; strictly applied “not to exceed” (green); Lenient “Not to exceed” where the long term mean meets the target but overshoot from temporary variability is allowed (blue), and; lenient overshoot where the only constraint is that the long term mean meets the target by 2100 (red).
This literature review of overshoot scenarios broadly covers two aspects of overshoot scenarios. In section two the characteristics of bottom-up\(^1\) overshoot scenarios from the current generation of Integrated Assessment Models (IAM) are examined to distinguish trends and constraints on what are currently considered feasible mitigation scenarios. Section three then examines details of modelled climate response to idealised top-down scenarios which exhibit a peak and decline. Only a limited number of studies have examined overshoot scenarios in comprehensive climate models and these studies typically focus on quite extreme and prolonged overshoots rather scenarios that would be considered feasible. A later report, part two of this AVOID project, will develop new idealised overshoot scenarios constrained by recent estimates of technology availability.

\(^1\) “Bottom up” here means that the scenario has been built up from constraints such as future availability and costs of technology, population growth, energy demand and GDP development etc, and that the emissions are an emergent property of the constraints applied. Conversely “top down” means that emissions (or concentrations) are imposed, such as “peak in 2020, reduce CO2eq emissions by 5% per year thereafter”. In this case the socioeconomic scenarios that would give rise to these emissions are backed out from this. This is the same as the way the Shared Socio-economic Pathways (SSP) are being developed, with the RCP concentration imposed as a “top down” scenario (although they themselves where developed “bottom up” in the first place).
2. Scenarios from Integrated Assessment Models

In practice, the flexibility in future emissions pathways is constrained by limits on technology availability, economic constraints and rates of replacing existing infrastructure (Rive et al., 2007; Mignone et al., 2008; Meinshausen et al., 2009; Davis et al., 2010; Friedlingstein et al., 2011; Rogelj et al., 2013). Clearly there are also behavioural constraints but these are often left out of IAM studies.

IAMs are designed to examine the interaction between the climate system and the economic, political, technological and social factors which constrain future options for mitigating climate change and its impacts. By integrating understanding from across these diverse disciplines, IAM are invaluable tools for examining different aspects of climate change mitigation.

2.1 View from the Literature

Early IAM research into overshoot explored the implications of allowing overshoot pathways for reaching different GHG concentration targets (e.g., den Elzen and van Vuuren, 2007; van Vuuren et al., 2007; Rao et al., 2008) and were followed by the Energy Modelling Forum 22 (EMF22, Clarke et al. 2009). EMF22 examined scenario solutions from 10 leading IAM under constraints of “not to exceed” as well as experiments explicitly allowing overshoot so as to examine the possibility of making very large emissions reductions later in the century on the assumption that the technology required would be less costly. In common with other model inter-comparisons, the models in EMF22 varied in terms of their structure as well as in the technologies and associated assumptions. While this gave a wide spread in their results, the models included were not designed in such a way that as a group they would systematically sample uncertainty in their assumptions, structure or behavior. This is true of all other IAM inter-comparisons to date and is a key factor in interpreting what the range of results from any set of IAM can tell us about the implied uncertainty in their findings:

_All results are only to be considered as indicative of the response of the models used, the current knowledge they express and the questions asked of them in any collated scenarios. They are not an appropriate basis for a formal uncertainty analysis of feasibility and should not be considered definitive._

With this caveat in mind we first focus on the EMF22 study. They found difficulty in obtaining solutions as targets become more ambitious (e.g. lower temperature or lower atmospheric concentrations) and the ability to find overshoot scenarios was restricted by the availability of negative emissions from BECCS. Only a small minority of the models were able to meet the 450 ppmv CO$_2$-e (CO$_2$ equivalent based on 100 year global warming potential) target, and relied on either early emissions cuts (“full participation”) or overshoot with delayed emissions reductions (“delayed participation”). These models included the option for deployment of BECCS. However useful EMF22 was to developing IAM experiment design, there were simply not enough realisations of different scenarios to

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2 Note that as IAM contain much reduced complexity climate components there is no internal variability in their climate projections. As such their use is analogous to assuming a lenient application of a target where in reality some temporary overshoot would occur owing to the internal variability of the climate. See section 1 and figure 1 for more detail.
make more definitive statements on feasibility of particular targets and the role of overshoot in meeting these targets.

IAMs have since grown rapidly in their technological depth and, of significance to this review, most now include some form of enhanced carbon dioxide removal via BECCS, increasing the options for mitigation and enabling overshoot pathways to be examined in more detail (den Elzen and van Vuuren 2007; Tavoni and Socolow 2013).

A number of recent international projects have produced a range of emission scenarios using IAMs to simulate economic and technically feasible emissions pathways. Examples include AMPERE (EU FP7) and LIMITS. A database of these scenarios was constructed by IPCC WG3 for its 5th Assessment Report (AR5) and it consists of around 1200 post-IPCC Fourth Assessment Report scenarios. While some projects such as EMF22 have included experiments to explicitly examine “overshoot” scenarios, most available scenarios are the result of a range of different constraints being applied depending on the specific design of each project and the questions they examined. Across different projects this may mean constraints on availability or costs of different technologies or political constraints on the timing and level of mitigation action. So while not typically designed to explicitly examine the possible magnitude, duration, feasibility, costs and risks of allowing an overshoot of climate targets, the resultant scenarios assessed in the IPCC AR5 constitute a large number of plausible scenarios, many of which exhibit some degree of overshoot be it in GHG concentration or temperature, or both. This collection of scenarios is sufficiently large that some characteristics of overshoot scenarios from current IAMs can be established from them.

The broad characterisation of overshoot scenarios by IPCC AR5 is, however, limited. In line with earlier literature (Wigley, 2005; Meinshausen et al., 2006; den Elzen and van Vuuren, 2007; Nusbaumer and Matsumoto, 2008) the IPCC AR5 finds that overshoot scenarios offset emissions reductions in the early part of the century with greater reductions later on. For example, most scenarios reaching a median GHG concentration of 480ppm CO₂eq by 2100 (about 1.7 °C above pre-industrial for a mid-range climate sensitivity) include concentration overshoot. While this implies that the cost optimum solutions to reaching this GHG level involve an overshoot in concentrations in most IAMs, it does not preclude meeting these targets without an overshoot, albeit at extra cost. Those scenarios that do reach this level without an overshoot tend to be characterised by much faster decarbonisation of the energy system in the next two decades (Calvin et al., 2009). There may also be more emphasis on early demand side reductions.

The IPCC AR5 also concludes that a critical factor in the feasibility of most overshoot scenarios is the availability of Carbon Dioxide Removal (CDR) technologies. CDR technology is required on a large-scale if a large concentration overshoot is to be recovered from in a usefully short time-scale. The technology currently considered most viable within the IAM community is, as it was in EMF22, through deployment of BECCS. The majority of scenarios limiting warming to around 2 °C in the IPCC WG3 database require some degree of BECCS to at least offset emissions from sectors where emissions reductions are difficult such as aviation. Many scenarios however, particularly those with relatively large temperature/concentration overshoots, require levels of BECCs sufficient that net annual emissions become negative during the second half of the century, that is
that the amount being removed from the atmosphere by BECCS become larger than that being added to the atmosphere from other sources. A valid criticism of such a high level of reliance on BECCS for avoiding dangerous climate change is that CDR technologies have not been show to technically work at scale and the use of BECCS is ultimately constrained by the availability of CCS and of biomass supply, both of which are highly uncertain (van Vuuren et al., 2013; Fuss et al., 2014). Although the availability of other technologies, for example nuclear power, can also affect emissions pathways their effect is typically far less pronounced than for BECCS (Rogelj et al., 2012; Eom et al., 2014; Krey et al., 2014; Kriegler et al., 2014a; Riahi et al., 2014).

AR5 find that scenarios leading to atmospheric concentrations below 430 ppm CO₂eq (around 1.5 °C with a mid-range climate sensitivity) by 2100 have significant use of CDR and overshooting of the 2100 target levels earlier in the century (Rogelj et al., 2013(a); Luderer et al., 2013). Their assessment is augmented here by some additional analysis based on the modelling work of Bernie and Lowe (2014) to more specifically characterise the magnitude and duration of temperature overshoots from the scenarios examined by AR5.

2.2 Further analysis of the IPCC AR5 database of IAM pathways

Bernie and Lowe (2014) ran emission scenarios from the IPCC WG3 database of IAM scenarios through a simple climate model to establish comparability between the concentration, forcing, and climate outcome between scenarios. As more diagnostics were produced than in a similar process undertaken by the IPCC WG3, a more detailed analysis of overshoot scenarios was possible. Note that as these scenarios, as per IPCC AR5 WG3, are simulated with a reduced form climate model there is no internal variability as so any overshoot is the result of the long term trends rather than any year to year fluctuation.

The figures below indicate the median magnitude and duration of temperature overshoot for scenarios with 2100 median temperature of 2 °C (±0.1°C), where an overshoot is defined as any time the median temperature is above that in 2100. Scenarios where no CDR is available in the scenarios are shown in red. The magnitude of temperature overshoot as a function of CO₂ emissions from fossil fuel and industry (FFI) in 2100 shows that even modest temperature overshoot (~0.1 °C) would require FFI CO₂ emissions that were close to zero if not actually negative in 2100 (Figure 2). For larger overshoots the minimum level of net negative emissions from FFI grows rapidly to -7 GtCO₂/yr in 2100 for an overshoot of 0.2 °C. For reference, average emissions from FFI over the last decade have been around +33 GtCO₂ (Le Quéré et al., 2014). In terms of the carbon dioxide concentration overshoot (Figure 3) the WG3 2 °C scenarios imply that anything more than 25 ppmv (CO₂) would require negative emissions from FFI, with a 50 ppmv (CO₂) overshoot requiring 2100 FFI emissions of -10 GtCO₂/yr. Similarly for concentration of CO₂e (Figure 4) some scenarios find overshoots of 45 ppmv (CO₂e) without negative emissions whereas overshoots of over 70 ppmv (CO₂e) require 2100 FFI emissions of -10 GtCO₂/yr.
Figure 2. Year 2100 CO\textsubscript{2} emissions from Fossil Fuels and Industry (FFI) as a function of temperature overshoot for scenarios with a median 2100 temperature of 2 °C above pre-industrial (±0.1 °C). Overshoot is diagnosed from Bernie and Lowe (2014) and overshoot is relative to the median 2100 temperature. Scenarios including Carbon Dioxide Removal (CDR) are in blue. Scenarios with no CDR available are in red.

Figure 3. As Figure 2 but as a function of CO\textsubscript{2} concentration overshoot.
As well as the magnitude of overshoot the duration is also an important consideration for some impacts such as sea level rise. Figure 5 shows the duration of the median overshoot for 2 °C scenarios as a function of the magnitude of temperature overshoot. Longer lasting overshoots are able to reach higher values essentially as there is more time to recover. Crucially, for a given overshoot magnitude the scenarios with CDR can have shorter overshoots owing to the more rapid recovery owing to the reduction of forcing through CO₂ removal from the atmosphere. Similarly overshoot of a given duration can attain higher magnitudes and still recover in the same time-scale when CDR is available. For example without CDR overshoot might reach 0.12 °C with a duration of 47 years, but with CDR available the overshoot could be either reduced to 35 years or increased to 0.22 °C and still meet a 2 °C median warming in 2100.

While Figure 5 shows the relation of overshoot duration to its maximum magnitude. There is a large amount of scatter within the scenarios. This scatter is a function of the different internal assumptions that each IAM makes about technologies and in particular the amount of BECCS which is available. Overall there is clear correlation between the duration and magnitude of overshoot again indicating the time needed to recover from an overshoot. The results, as before, also show that the magnitude and duration of overshoot is dependent on the availability of BECCS.
Figure 5. Magnitude of temperature overshoot as a function of the duration of overshoot for scenarios with a 2100 median temperatures of 2 °C (±0.1 °C). Scenarios where BECCS is available are shown in blue while those where there is limited or no BECCS are shown in red.

The sensitivity of the possible overshoot to BECCS is further illustrated through examining scenarios from a single model in the WG3 database, GCAM3.0. In Figure 6 the scenarios from GCAM3.0 are split into three classes. Scenarios from AMPERE intended to lead to GHG concentrations of 450 ppm and 550 ppm with BECCS available are shown in red and green respectively, all other scenarios from GCAM3.0 are shown in blue while scenarios from other models are black. The GCAM3.0 450 and 550 scenarios from AMPERE have much larger and shorter duration temperature overshoots than either the other GCAM3.0 scenarios or the WG3 database as a whole. The suggestion is that this is related to more favourable assumptions about the future availability of BECCS.

Despite the utility of the scenario database from WG3 it is clear that there are a number of aspects where caution is vital if conclusions are not to be overstated. Firstly, it has not yet been shown that CCS can be made to work efficiently or economically at a large-scale and uncertainties remain both in the technology involved in the carbon capture as well as in the transportation and geological storage of the captured CO₂. As CCS is such a significant part of the majority of scenarios examined by WG3 the failure to technically implement this technology at scale and economically has significant implications for the feasibility of current scenarios of ambitious mitigation which characteristically include a significant overshoot.

Related to the importance of CCS is the demonstrated sensitivity of overshoot to the availability of BECCS. There are many issues relating the use of BECCS, in addition to those regarding CCS technology, that will also have a significant affect on its feasibility and utility at scale. These include the full life-cycle emissions and concerns over competition for water resources and land use for agriculture (van Vuuren et al., 2007) which are the subject of extensive ongoing research. If BECCS turns out not to be
available at a large enough scale to produce significant negative emissions most of the WG3 mitigation scenarios that are currently viewed as being feasible cease to be so.

![Figure 6](image)

**Figure 6.** Magnitude of overshoot of median temperature as a function of overshoot duration. Scenarios where BECCS is not available are sown in open squares while those with BECCS are shown as crosses. GCAM3.0 scenarios from AMPERE intended to lead to GHG concentrations of 450 ppm and 550 ppm with available BECCS are shown in red and green respectively, all other scenarios from GCAM3.0 are shown in blue while scenarios from other models are black.

We have already highlighted that the IAM results are not designed to sample uncertainty. With this caveats in mind, there is still however a great deal that the WG3 database can tell us about the characteristics of overshoot scenarios that are currently considered to be feasible.

Analysis of the IAM scenarios by WG3 shows that the current cost optimum scenarios to meeting ambitious climate targets typically involve some degree of overshoot in GHG concentration and likely also temperature. The implication of this is that scenarios which do not overshoot will have higher mitigation costs and that technologies such as CCS and crucially BECCS have been of central importance to the feasibility of most cost optimum mitigation scenarios.

The appeal of lower near term mitigation costs in overshoot scenarios must also be tempered by the implied increase in risk. If the planned reduction phase of the overshoot is not possible, because the climate response is larger than anticipated, BECCS is not available, or global emissions targets are missed, then the availability of additional mitigation measures or negative emissions may either be very costly else may not be possible at all. This may lead to a prolonged or increased overshoot, or simply to not avoiding dangerous climate change (see also Fuss et. al., 2014).
3. Climate response to overshoot scenarios

Simulations of RCP2.6 with complex general circulation climate models have been contributed to Fifth Coupled Model Intercomparison Project (CMIP5) experiments. This scenario is based on a concentrations pathway derived from an IAM emissions scenario which included significant emissions reductions. CMIP5 simulations indicates that this concentration pathway would lead to global average temperature increases in 2100 of around 1.7 ºC above preindustrial, with implied carbon emissions from ESM often (but not always) becoming negative before the end of the century (Jones et al., 2013). Similarly while the concentration pathway indicates a peak and decline in GHG concentrations, some but not all of the simulations suggest a peak and decline in global temperature as well. Owing to the experimental design of CMIP5 being that of intercomparison of different RCPs chosen to span a scientifically useful range of possible futures, it is hard to deduce which aspects of the climate’s response to RCP2.6 are explicitly the result of the presence of an overshoot (in the models where this occurs). As a consequence more can be gained here by looking at idealised overshoot pathways.

While idealised overshoots are typically beyond the magnitude and duration of technically plausible overshoots (as simulated in IAMs, see section 2) aspects of the climate response analysed in these idealised studies is still relevant to understanding the potential response of the climate in more plausible overshoot scenarios. The results would also of relevance to the issue of geo-engineering by solar radiation management (which are not explicitly considered here), which might allow larger overshoots of temperature.

While the climate changes associated with overshoot studies from the literature are reviewed here, it should be considered that they are all highly idealised and exaggerated scenarios designed to explicit a modelled response to the overshoot. As such no study reviewed here considered the impacts linked to the climate response to an overshoot and so no speculation other than in the broadest terms in made regarding additional climate impacts of overshoot scenarios.
Ramp up – ramp down scenarios of CO₂ concentration (Figure 7)

These typically increase CO₂ concentration in the atmosphere by a fixed percentage per year until they reach some multiple of pre-industrial values, and then reduce by a fixed percentage by year either immediately or after a period of stabilization of up to a few hundred years (Boucher et al 2012; Bouttes et al 2012; Wu et al 2010,2011,2014; Jackson et al., 2013). Rates of CO₂ increase and decrease are typically well outside historical or plausible future levels.

Figure 7. Illustrative ramp-up/ramp-down scenario for CO₂ taken from Boucher et al (2012). The rate of increase and decrease vary between different studies, with some also including decades of stabilised concentrations before the ramp-down, or the ramp-down starting from different CO₂ levels.
Transitions from a high emissions scenario to a low emissions scenario (Figure 8)

These prescribed concentration scenarios (Tsutsui et al. (2007); Yoshida 2005 and Tsutsui et al. (2007) tend to be based on the older scenarios used in AR4, typically with A1B transitioning to B1 (Tsutsui et al. (2007); Yoshida 2005 and Tsutsui et al. (2007) and include a very large and sustained overshoot of atmospheric CO$_2$ concentrations.

Figure 8. Overshoot scenario based on a transition between two well establish transient scenarios. This example taken from Yoshida (2005) includes a 50 year stabilisation at the maximum CO$_2$ concentration level.
Idealised emissions pathways with fixed cumulative emissions (Figure 9)

Here cumulative emissions are consistent but the timing of emissions reductions through the century are varied (Nusbaumer and Matsumoto, 2008; Zickfeld et al., 2012).

![Figure 9. Idealised overshoot scenario taken from Zickfeld et al (2012). Here all scenarios are constrained to have the same cumulative emissions of CO₂ but reduce gradually to zero, immediately to zero, or to overshoot the cumulative target and then use negative emissions to meet a 2300 cumulative emissions target.](image)

The remainder of this section of the report summarises the findings from studies of overshoot scenarios within the earth system modelling literature.

3.1 Temperature response

All studies of CO₂ concentration overshoot find global temperatures reversible, but that the decline will lag that of CO₂ by the order of a decade (Boucher et al., 2012; Samanta et al., 2010; Wu et al., 2010). This lag occurs as temperatures over the oceans are kept warm by the underlying ocean, whereas over land temperatures decrease more in time with atmospheric CO₂ (Boucher et al., 2012; Samanta et al., 2010). The lag of temperatures to CO₂ suggests that while the use of negative emissions from technologies such as BECCS would be feasible for a forced recovery of additional temperature increases arising from a CO₂ concentration overshoot, that temperature related impacts relating to the additional warming may take of the order of a decade to recede once CO₂ levels have been recovered.

Note that these idealised scenarios are of prescribed concentration. Other idealised scenarios, such as those in the recent IPCC AR5, have examined scenarios where anthropogenic CO₂ emissions are instantaneously reduced to zero. In these scenarios the time scale of natural
carbon uptake by the carbon cycle leads to a far slower reduction of atmospheric CO$_2$ than is the idealised case described here and so the temperature takes many centuries to recover.

Figure 10. Global average temperature time series from scenarios where CO$_2$ concentration is ramped up (black) and then down from 1.5x, 2x, 3x and 4x pre-industrial levels (Pink, blue, green and red respectively). Taken from Boucher et al. (2012).

3.2 Hydrological changes

A consistent behaviour noted in projections of the climate response to overshoot scenarios is significant hysteresis in the global water cycle, arising because global precipitation depends on both atmospheric CO$_2$ and temperature. Global precipitation is seen to increase with atmospheric CO$_2$ and to continue to increase after increase in CO$_2$ has stopped, subsequently decreasing with a lag of up to 50 years. Variations in global-mean precipitation found by Boucher et al. (2012) are dominated by changes over the oceans, while changes to precipitation over land are noisy and less systematic. The hysteresis in global mean precipitation in Boucher et al (2012) shows similar results to many other studies of ramp-up/ramp-down experiments with Earth System Models (ESM) (Wu et al., 2010, 2011, 2014; Cao et al., (2011); Gillet et al., (2011)) and in Earth system models of Intermediate Complexity (EMIC) in scenarios with idealised emissions scenarios with constrained cumulative emissions (Zickfeld et al., 2012). A similar behaviour is seen from the RCP2.6 in HadGEM2-ES in the study by Caesar and Lowe (2013).

While the hysteresis in global mean precipitation is clear, Boucher et al (2012) found only slight evidence when looking at the average over land areas. This suggests that for realistic overshoot scenarios that while any addition impacts associated with the overshoot though the hysteresis in precipitation will last for decades, that the magnitude of these overland may be relatively small in comparison with the impacts already in affect at the target level, regardless of any overshoot
Figure 11. Hysteresis in global precipitation taken from Wu et al (2010). The dashed black line indicates the timing of the CO$_2$ peak and decline. The red line indicates the global temperature (left axis) which lags the CO$_2$ concentration while the green indicates the hysteresis in global precipitations (right axis).

### 3.3 Carbon cycle

Model evidence for the response of the carbon cycle to overshoot scenarios is limited as few studies have included a comprehensive carbon cycle and examined this in detail although these is some consensus from the available research.

Ocean carbon storage responds more quickly to decreasing CO$_2$ levels and temperatures than ocean heat uptake (see later), and rapidly releases stored carbon back to atmosphere.

Land carbon storage continues to increase slowly immediately after atmospheric CO$_2$ stabilises and shows a significant hysteresis during scenarios with decreasing levels of atmospheric CO$_2$. Boucher et al. (2012) find that this hysteresis in the vegetation and soil carbon content in ramp-up/down scenarios is a result of the long time scales involved in competition between different types of vegetation, with a significant latitudinal difference. Tropical carbon stores respond quickly to the CO$_2$ concentration with little hysteresis, whereas the northern hemisphere trees continue to increase in the northern high latitudes after the peak in CO$_2$. This Northern high latitude signal is found to dominate the global response.

### 3.4 Permafrost and hydrate release

Despite the sophistication of the current generation of earth system models, researchers have recently begun to look at additional climate system processes and components to examine their potential for providing additional climate feedbacks. Arneth et al (2012) estimated the
potential size of a number of these and their study has been updated in the assessment of AR5.

One potential feedback that is currently being focused on is the potential release of methane and \( \text{CO}_2 \) from thawing permafrost, which may lead to significant additional warming (Burke et al., 2012, 2013; Whiteman et al., 2013). While still at a relatively early stage the representation of permafrost physical processes and its properties in climate models is becoming more accurate (Alexeev et al., 2007; Nicolsky et al., 2007; Lawrence et al., 2008a; Rinke et al., 2008; Koven et al., 2009; Gouttevin et al., 2012), although there are large disagreements in the calculation of current frozen soil extent and active layer depth (the seasonal depth to which it thaws in summer) due to differences in the land model physics in the CMIP5 ensemble (Koven et al., 2013).

Despite these uncertainties, AR5 conclude that it is virtually certain that large areas of permafrost will experience thawing over multiple centuries. Boucher et al. (2012) for example find approximately 20 % less permafrost area in a climate recovering after an overshoot. Although they find permafrost extent (the area of frozen ground) is eventually fully reversible, any loss of organic carbon during the time thawed is effectively irreversible as this has accumulated over many millennia. There is also very low confidence in the magnitude of frozen carbon losses to the atmosphere that would occur during thaw, and the relative proportions of these emissions that would be of \( \text{CO}_2 \) or \( \text{CH}_4 \). Another factor that would affect the release of carbon from thawing permafrost, but which is as yet uncertain in its impact is that heat generation due to decomposition of organic matter in permafrost may lead to a prolonged period of carbon release after any overshoot induced thawing (Khvorostyanov et al., 2008).

\[\text{Figure 12. Diagnosed permafrost area from CO}_2\text{ only ramp-up/down scenarios taken from Boucher et al (2012).}\]
Another feedback process currently missing from most earth system models, and which could be compounded by a warming overshoot, is the potential release of methane from marine hydrates (frozen deposits of methane in the seabed). Some shallow deposits are considered unstable to a moderate warming of ocean temperatures, but the size of the potential inventory, the physical process of their destabilisation, and the potential for any release to reach the atmosphere before being oxidised in the ocean are all highly uncertain at present. Despite the low confidence in current modelling abilities to simulate transient changes in hydrate inventories, the depths (and therefore pressures) and temperatures of most deposits mean that large scale destabilisation and release to the atmosphere during this century is considered unlikely (Collins et al., 2013).

3.5 Ice sheets

Ice sheets are the largest potential source of long-term future sea level rise but their contribution remains very uncertain.

There is considered to be a temperature threshold above which the Greenland ice sheet is susceptible to irreversible change (Gregory and Hubrechts, 2006; Robinson et al 2012), where the loss of elevation due to surface melting leads to warming temperature and increased melting (Crowley & North 1988). While the timescale for total collapse of the ice sheet is millennial it is not clear at what level of temperature increase ice-sheet loss may become irreversible so it is unclear how a plausible level of temperature overshoot would affect its long term stability. However thinning has been observed to increase in recent years and is projected to increase global mean sea level by up to 10 mm in the next 20 years (Favier et al., 2014).

For Antarctic ice sheets the floating portions of outlet glaciers, Ice shelves, are a key factor in their stability to temperature rise or potential overshoot. They buttress the inland glaciers helping to control the rate of ice leaving the continent and entering the ocean (Dupont & Alley, 2005). As Ice shelves are exposed to the underlying ocean they may weaken as ocean temperatures rise and this will, to some degree be enhanced by the additional heat uptake by the ocean during a temperature overshoot. If they melt rapidly or break away, ice flow on land would accelerate, causing ice-sheet loss (De Angelis & Skvarca, 2003). This process is particularly of relevant to the West Antarctic Ice Sheet (WAIS) as most of it is grounded on bedrock below sea level on retrograde slopes (deeper inland), a configuration believed to be inherently unstable and sensitive to small changes in the grounding line (where the ice begins to float; Mercer, 1968, Schoof, 2007).

Despite the potentially significant contribution to sea levels from ice sheets, and the instability they may potentially exhibit, uncertainties in our understanding of ice-sheet processes mean that while an overshoot of climate target, specifically temperature, would likely increases overall ice loss, no studies have yet examined the additional ice loss or potential increase in risk of collapse relating specifically to climate overshoots of the magnitude currently considered plausible (such as those considered in section 2).

3.6 Sea-ice

Boucher et al (2012) find that the annual mean Arctic and Antarctic sea-ice cover in HadGEM2-ES are entirely reversible in all scenarios they examine including those where CO₂
reaches up to 4 pre-industrial although its recovery has a 50 year lag over CO₂ but no lag over the surface temperature in line with earlier findings of Yoshida et al (2005), Samanta et al (2010) and Tietsche et al (2011).

Reversibility of Arctic sea ice in response to CO₂ concentrations is also seen in CCSM3 (Armour et al. 2011), HadCM3 (Ridley et al. 2012). Wu et al (2014) find that Arctic sea ice recovers in CO₂ ramp up/down experiments with HadCM3, but it does not reach pre-industrial levels owing to residual temperature increases (Ridley et al 2012) and enhanced oceanic heat transport associated with the AMOC overshoot (Wu et al 2011). There does not appear to be a threshold from which Arctic ice will not recover, and its eventual recovery does not appear to be determined by the rate of global cooling (Wu et al., 2014; Amour et al., 2011; Ridley et al., 2012).

In contrast to the Arctic, in the Antarctic there is a strong coupling between the heat content of the Southern Ocean’s surface and the deep ocean. As a result sea ice coverage in some simulations of a ramp up and ramp-down of atmospheric CO₂ concentration sea-ice exhibits a significant lag relative to the global or hemispheric mean surface temperature (Ridley et al., 2012; Li et al., 2013), so that its changes may be considered irreversible on centennial time scales.

Figure 13. Projected Arctic sea ice area from CO₂ ramp-up/down scenarios from Ridley et al (2012). (a-b) is ramp down after reaching a maximum. (a-c) is a stabilisation after reaching a maximum. (c-d) is a ramp-down after stabilisation at the maximum. b and d respectively indicate stabilisation after the ramp-down of CO₂ with and without a period of stabilisation at the maximum before the ramp-down. The figure illustrates that the Arctic ice area is reversible with respect to local air temperature, however the local air temperature itself exhibits hysteresis in its response to overshooting CO₂ concentration levels.

Consensus among the recent literature is that sea-ice in both hemispheres is reversible in line with local temperatures, but that other factors such as changes to the mixing of heat into the
upper ocean in the South, and overshoot of the AMOC in the north, may in practise extend the time scale over which sea-ice would recover. In the case of an overshoot of global temperatures this may mean that additional changes in the Southern Sea-ice may not be reversible, while those in the North are.

3.7 Ocean pH

The ocean surface pH responds very quickly to atmospheric concentrations and is almost totally reversible in the global mean, however the Impacts of ocean acidification on marine ecosystems, for example on calcification (Riebesell et al 2000; Iglesias-Rodriguez et al 2008), may not be reversible in the same way. Deeper ocean pH changes do not experience the reversibility experienced in the surface ocean.

3.8 Atlantic Meridional Overturning Circulation (AMOC)

Despite variations and bias in modelling the present day estimates of AMOC, the weakening of AMOC under increasing CO$_2$ levels is found in all models in CMIP5 (Collins et al., 2013).

In common with many studies of overshoot scenarios, Wu et al., (2011, 2014) find that while the weakening of AMOC during a ramp up phase is reversible, there is significant overshoot of present day levels (meaning a stronger AMOC) on the ramp down phase. Boucher et al. (2012) also find that the AMOC is reversible in all overshoot cases they examine though note that there is a 2-3 decade lag for higher CO$_2$ experiments in line with Nusbaumer and Matsumoto (2008).

Jackson et al. (2013) also find that the weakening during a on the ramp up phase followed by a strengthening on the ramp down is followed and an overshoot of pre-industrial levels once CO$_2$ levels have been stabilised. This finding was consistent across in a number of models examined in the study, and was also seen by Nohara et al. (2013), who also noted that the recovery lagged the CO$_2$ overshoot by several centuries.

If these results were extrapolated to consider the case of an overshoot scenario it may be expected that the slight extra weakening of the AMOC arising from a CO$_2$ overshoot may manage to recover past the level at the overshoot target. This would reduce the overall weakening of AMOC at the target level, however the magnitude of the AMOC overshoot from Jackson et al (2013) suggest that for plausible overshoot scenarios this effect is likely to be indistinguishable from the natural variability of the AMOC.
Figure 14. Examples of AMOC reversibility and overshoot seen across a number of models and idealised overshoot-type scenarios by Jackson et al (2013). In each panel atmospheric CO$_2$ concentrations are dashed and indicated on the right axis while AMOC strength are shown as solid lines with the magnitude on the left hand axis.

3.9 Ocean thermal expansion

The response of ocean temperatures to external forcing comprises mainly two time-scales: a relatively fast adjustment of the ocean mixed layer and the slow response of the deep ocean (Hansen et al., 1985; Knutti et al., 2008; Held et al., 2010). Simulations with coupled ocean-atmosphere general circulation models suggest time-scales of several millennia until the deep ocean is in equilibrium with the external forcing (Stouffer, 2004; Hansen et al., 2011; Li et al., 2013). Thus, the long time-scale of the ocean response to external forcing implies an additional committed thermal expansion centuries after greenhouse gas concentrations are stabilised (Meehl et al. 2005; Lowe et al. 2006; Plattner et al. 2008; Frolicher and Joos 2010; Gillett et al. 2011; Boutlles et al 2013, Zickfeld et al., 2012).
Figure 15. An illustration of the hysteresis of thermal expansion of the ocean under overshoot scenarios taken from Wu et al (2014). All experiments include a ramp up phase (black) followed by a ramp down phase (colours). The legend names for the ramp down phases (“rd”) indicate first the CO$_2$ levels reached as a multiple of pre-industrial (2 or 4) followed by either the year on year percentage decrease during ramp down, or the indication of an instantaneous “step” back to pre-industrial levels. Similar results are found in other studies from different models and with differing levels of CO$_2$ and rates of increase and decrease. Here higher levels of overshoot produce larger hysteresis and lower rates of recovery of CO$_2$ lead to much longer persistence of the thermal expansions.

Boucher et al (2012) find that when CO$_2$ concentration has risen to four times pre-industrial levels the model projects thermal expansion of about 40 cm. After the forcing declines from 4 × CO$_2$ the heat content continues to increase by a further 60% over the next century. The time between the peaks in forcing and ocean heat uptake varies strongly with the magnitude of the peak forcing, ranging from approximately 25 yr (1.5 × CO$_2$) to a century (4 × CO$_2$). This shows that only a rapid reduction in radiative forcing might be able to limit and reduce the thermal expansion component of sea-level rise before some of the most severe coastal impacts are realized. Overshoot of a temperature target would increase the cumulative heat uptake of the ocean. This dependence of thermal expansion on the evolution of surface temperature is also documented by Stouffer and Manabe (1999); Bouttes et al. (2013); Zickfeld et al. (2013). The longer time-scale of response of thermal expansion to changes in forcing than surface air temperature is because of the inertia introduced by slow processes which transport heat to, or extract heat from, the subsurface layers of the ocean (Wu et al 2014).
4. Discussion

Avoiding dangerous climate change poses a difficult challenge. Meeting longer term targets may mean temporarily overshooting that target in the near term, either intentionally or unintentionally. As such there is increasing interest in both the feasibility of overshoot scenarios and the climatic consequences of a temporary overshoot.

Section two of this report detailed scenarios from IAM which feature an overshoot in either greenhouse gas concentration or temperature. This includes the IPCC WG3 which collated over a thousand IAM scenarios from different projects, many of which contained some degree of overshoot. Temporary overshooting of climate targets is found to be a common feature of least cost scenarios mitigation scenarios under a wide range of constraints.

Central to the feasibility of most overshoot scenarios on shorter time-scales than possible due to solely natural removal of carbon from the atmosphere is the availability of negative emissions at scale through BECCS. Without available land for BECCS and the ability to scale CCS the scope of recovering from climate targets is limited. Given the technological and economic uncertainty regarding CCS and BECCS, the reliance of any emissions pathway on significant levels of BECCS implies higher risks of missing climate targets or higher costs of implementation (Van Vuuren et al., 2007; Fuss et al., 2013).

It is also suggested that the necessary caution is used in interpretation of the WG3 findings in terms of their ability to robustly address issues of uncertainty as the IAMs examined in WG3 are not designed to sample uncertainty in their implementation, and the scenarios they produce not been designed to evenly sample all possible futures. For both these reasons the WG3 database cannot be used as a basis for a formal assessment of uncertainty.

A final proposition relating to IAM, but drawn from the review of climate response in section 3, is that climate impacts in integrated assessment models, where modelled, commonly use a simple function of the global-mean surface temperature change (for example Hope (2009)). Such a simple form may be justified by the large uncertainties in damage costs and the historically monotonic increase in CO₂ concentrations, surface temperatures and climate impacts in most scenarios. However the prospect of a future with larger or protracted overshoot and non-linearity in different components of the climates responses to an overshoot (section 3) suggest that climate impacts or damages should not be parameterized solely as a function of temperature. Work is ongoing in AVOID and the EU project HELIX to better account a wider range climate change metrics and their impacts on society.

While many scenarios of what are currently considered plausible levels of climate overshoot exist in the IAM literature, studies of the consequences of overshoot in ESM tend to use highly idealised and typically very large climate overshoots. Such studies have generally been made to examine aspects of irreversibility in the climate system rather than explicitly quantifying the affects of an overshoot compared to stabilisation. While these scenarios are acknowledged as unrealistic they do elucidate some aspects of the expected climates response to overshoot scenarios and so are of relevance. Section 3 reviewed the main findings of recent research into the climatic response to idealised overshoot scenarios.

The growing body of research reviewed illustrates that stabilization of CO₂ concentrations or global temperatures does not imply stabilization of all aspects of the climate. Many parts of
the climate system which have inherently long time scale responses (ice sheets, carbon cycle, ocean heat content) may take many thousands of years to reach a new equilibrium.

While overshoots of the magnitude exhibited by the scenarios on WG3 would lead to some increase in magnitude and duration of some aspects of climate change, it is not clear to what extent the overshoot itself would increase the risk associated to climate change and its impacts. Additionally while there is little evidence that such climate changes would exhibit strong threshold behaviour there are some abrupt changes and hysteresis in the climate system associated with the longer time-scales of ocean heat uptake/release and the carbon cycle, most notably in the global hydrological cycle and sea level rise. These strong inertias and path-dependent hysteresis may have additional consequences for society. Given the prevalence of overshoot in IAM scenarios meeting ambitious climate targets, the climatic consequences and impacts relating to overshoot scenarios are an important science question for climate research. However as the feasibility of scenarios with significant overshoot is not well known such scenarios are currently lower priority for future organised model intercomparison exercises such as CMIP6 and ScenarioMIP\(^3\).

In part 2 of this study, to be published later this year, emergent constraints from the WG3 scenario database will be used to examine aspects of the feasibility of overshoot scenarios in more depth. An example of this is the assessment of the magnitude and duration of CO\(_2\) concentration overshoots possible without a temperature overshoot and the implied land use requirement for BECCS.

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5. References


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